The ATLAS Collaboration

Argentina
Departamento de Física, Universidad de Buenos Aires, Buenos Aires
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata

Armenia
Yerevan Physics Institute, Yerevan

Australia
Department of Physics, University of Adelaide, Adelaide
School of Physics, University of Melbourne, Victoria
School of Physics, University of Sydney, Sydney

Austria
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck

Azerbaijan
Institute of Physics, Azerbaijan Academy of Sciences, Baku

Brazil
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; Instituto de Física, Universidade de Sao Paulo, Sao Paulo

Canada
Department of Physics, University of Alberta, Edmonton AB
Department of Physics, Carleton University, Ottawa ON
Department of Physics, McGill University, Montreal QC
Group of Particle Physics, University of Montreal, Montreal QC
Department of Physics, Simon Fraser University, Burnaby BC
Department of Physics, University of Toronto, Toronto ON
TRIUMF, Vancouver BC; Department of Physics and Astronomy, York University, Toronto ON
Department of Physics, University of British Columbia, Vancouver BC
Department of Physics and Astronomy, University of Victoria, Victoria BC

Chile
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso

China
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; Department of Modern Physics, University of Science and Technology of China, Anhui; Department of Physics, Nanjing University, Jiangsu; School of Physics, Shandong University, Shandong; Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; Physics Department, Tsinghua University, Beijing 100084
Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; Department of Physics, The University of Hong Kong, Hong Kong; Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

Colombia
Centro de Investigaciones, Universidad Antonio Narino, Bogota

Czech Republic
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ATLAS
Forward Proton Phase-I Upgrade

Palacký University, RCPTM, Olomouc
Institute of Physics, Academy of Sciences of the Czech Republic, Praha
Czech Technical University in Prague, Praha
Faculty of Mathematics and Physics, Charles University in Prague, Praha

Denmark
Niels Bohr Institute, University of Copenhagen, København

France
LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette
Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne

Georgia
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; High Energy Physics Institute, Tbilisi State University, Tbilisi

Germany
Department of Physics, Humboldt University, Berlin
Physikalisches Institut, University of Bonn, Bonn
DESY, Hamburg and Zeuthen
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen
II Physikalisches Institut, Georg-August-Universität, Göttingen
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim
Institut für Physik, Universität Mainz, Mainz
Fakultät für Physik, Ludwig-Maximilians-Universität München, München
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München
Fachbereich Physik, Universität Siegen, Siegen
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal

Greece
Physics Department, University of Athens, Athens
Physics Department, National Technical University of Athens, Zografou
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki

Israel
Norway
Department for Physics and Technology, University of Bergen, Bergen
Department of Physics, University of Oslo, Oslo

Poland
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow
Institute of Nuclear Physics Polish Academy of Sciences, Krakow

Portugal
Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; Faculdade de Ciências, Universidade de Lisboa, Lisboa; Department of Physics, University of Coimbra, Coimbra; Centro de Fisica Nuclear da Universidade de Lisboa, Lisboa; Departamento de Fisica, Universidade do Minho, Braga; Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica

Republic of Belarus
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk

Romania
National Institute of Physics and Nuclear Engineering, Bucharest; National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;
University Politehnica Bucharest, Bucharest; West University in Timisoara, Timisoara

Russia
Joint Institute for Nuclear Research, JINR Dubna, Dubna
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow
Institute for Theoretical and Experimental Physics (ITEP), Moscow
National Research Nuclear University MEPhI, Moscow
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk
National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg
State Research Center Institute for High Energy Physics, Protvino

Serbia
Institute of Physics, University of Belgrade, Belgrade

Slovak Republic
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice

Slovenia
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana

South Africa
Department of Physics, University of Cape Town, Cape Town; Department of Physics, University of Johannesburg, Johannesburg; School of Physics, University of the Witwatersrand, Johannesburg

Spain
Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona
Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear
and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona
(IMB-CNM), University of Valencia and CSIC, Valencia

**Sweden**
Fysiska institutionen, Lunds universitet, Lund
Department of Physics, Stockholm University; The Oskar Klein Centre, Stockholm
Physics Department, Royal Institute of Technology, Stockholm
Department of Physics and Astronomy, University of Uppsala, Uppsala

**Switzerland**
Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern
CERN, Geneva
Section de Physique, Université de Genève, Geneva

**Taiwan**
Institute of Physics, Academia Sinica, Taipei

**Turkey**
Department of Physics, Ankara University, Ankara; Istanbul Aydin University, Istanbul; Division of Physics, TOBB University of Economics and Technology, Ankara
Department of Physics, Bogazici University, Istanbul; Department of Physics, Dogus University, Istanbul; Department of Physics Engineering, Gaziantep University, Gaziantep

**United Kingdom**
School of Physics and Astronomy, University of Birmingham, Birmingham
Cavendish Laboratory, University of Cambridge, Cambridge
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh
SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow
Physics Department, Lancaster University, Lancaster
Oliver Lodge Laboratory, University of Liverpool, Liverpool
School of Physics and Astronomy, Queen Mary University of London, London
Department of Physics, Royal Holloway University of London, Surrey
Department of Physics and Astronomy, University College London, London
School of Physics and Astronomy, University of Manchester, Manchester
Department of Physics, Oxford University, Oxford
Particle Physics Department, Rutherford Appleton Laboratory, Didcot
Department of Physics and Astronomy, University of Sheffield, Sheffield
Department of Physics and Astronomy, University of Sussex, Brighton
Department of Physics, University of Warwick, Coventry

**United States of America**
Physics Department, SUNY Albany, Albany NY
High Energy Physics Division, Argonne National Laboratory, Argonne IL
Department of Physics, University of Arizona, Tucson AZ
Department of Physics, The University of Texas at Arlington, Arlington TX
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA
Department of Physics, Boston University, Boston MA
Department of Physics, Brandeis University, Waltham MA
Physics Department, Brookhaven National Laboratory, Upton NY
Enrico Fermi Institute, University of Chicago, Chicago IL
Nevis Laboratory, Columbia University, Irvington NY
Physics Department, Southern Methodist University, Dallas TX
Physics Department, University of Texas at Dallas, Richardson TX
Department of Physics, Duke University, Durham NC
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA
Department of Physics, Indiana University, Bloomington IN
University of Iowa, Iowa City IA
Department of Physics and Astronomy, Iowa State University, Ames IA
Louisiana Tech University, Ruston LA
Department of Physics, University of Massachusetts, Amherst MA
Department of Physics, The University of Michigan, Ann Arbor MI
Department of Physics and Astronomy, Michigan State University, East Lansing MI
Department of Physics, Massachusetts Institute of Technology, Cambridge MA
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM
Department of Physics, Northern Illinois University, DeKalb IL
Department of Physics, New York University, New York NY
Ohio State University, Columbus OH
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK
Department of Physics, Oklahoma State University, Stillwater OK
Center for High Energy Physics, University of Oregon, Eugene OR
Department of Physics, University of Pennsylvania, Philadelphia PA
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA
Department of Physics, University of Washington, Seattle WA
SLAC National Accelerator Laboratory, Stanford CA
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY
Department of Physics and Astronomy, Tufts University, Medford MA
Department of Physics and Astronomy, University of California Irvine, Irvine CA
Department of Physics, University of Illinois, Urbana IL
Department of Physics, University of Wisconsin, Madison WI
Department of Physics, Yale University, New Haven CT
Figure 1. Sketch of the AFP detectors inside a Roman pot (top); the layout of LHC sector 6R1 showing the AFP stations at 205 and 217 m from the ATLAS IP (middle); and Feynman graphs illustrating the AFP physics program (bottom).
# Contents

1 Introduction 1

2 The AFP Physics Program 5
   2.1 Run Conditions 5
   2.2 Diffractive Processes 5
      2.2.1 Soft Diffraction 5
      2.2.2 Hard Diffraction 8
   2.3 Diffractive Measurements with AFP 10
      2.3.1 AFP0+2 10
      2.3.2 AFP2+2 12
   2.4 AFP at High Luminosity 15
      2.4.1 Physics in Run 3: The High-µ Physics Case 15

3 The LHC Optics and Radiation Environment 17
   3.1 LHC Optics for AFP Runs 17
      3.1.1 LHC Optics 17
      3.1.2 Geometrical Acceptance 18
      3.1.3 Collimators 21
      3.1.4 Summary 22
   3.2 Optics Stability 22
   3.3 Reconstruction of Forward Protons in AFP 24
      3.3.1 Proton Four-momentum Reconstruction Procedure 24
      3.3.2 Reconstruction Resolution 24
   3.4 The AFP Radiation Environment 24
      3.4.1 Radiation at ATLAS-ALFA and TOTEM 25
      3.4.2 GEANT4 simulation of radiation environment at AFP 25
      3.4.3 Summary 26
   3.5 Radiation Protection and Safety 26
      3.5.1 Installation 26
      3.5.2 Access for Detector Installation 27
      3.5.3 Access for Repairs 27
      3.5.4 Removal of Roman Pot Stations in LS2 27

4 The AFP Detector 31
   4.1 Overview 31
      4.1.1 The AFP Layout 31
      4.1.2 Detector and Beam Interface Requirements 32
      4.1.3 The AFP Beam Interface 33
      4.1.4 Tracking Detectors 33
      4.1.5 Time-of-Flight Detectors 33
   4.2 The AFP Detector for Run 2 34
      4.2.1 The AFP0+2 Detectors 34
      4.2.2 AFP0+2 Installation 35
      4.2.3 AFP2+2 Installation 36
   4.3 AFP Detector Simulation 37
      4.3.1 Forward region & AFP simulation 37
8.5 Alignment Methods ......................................................... 112
  8.5.1 General Considerations ............................................. 112
  8.5.2 Linear Variable Differential Transformer ...................... 113
  8.5.3 Dynamic Alignment – Kinematic Peak Method .................. 114
  8.5.4 Comparison of Hit Position Distributions ...................... 114
  8.5.5 Electromagnetic Bremsstrahlung .................................. 115
  8.5.6 Bremsstrahlung via Nuclear Forces ............................. 117
  8.5.7 Exclusive Muon Production ...................................... 117
  8.5.8 Alignment with ALFA ........................................... 118

9 Project Management ....................................................... 121
  9.1 AFP Project Organization .......................................... 121
  9.2 The AFP Work Breakdown Structure and Resources .............. 122
    9.2.1 Cost Estimates ............................................. 122
    9.2.2 Institutional Responsibilities ................................ 124
    9.2.3 Manpower Estimates ...................................... 124
  9.3 Project Scheduling ................................................... 124
  9.4 Further R&D and Planning for Run 3 ............................. 125

Summary ........................................................................... 129

Acknowledgements ................................................................ 130

The ATLAS Collaboration .................................................... 131

References .......................................................................... 149

Appendix-A Benchmark Study: the DPEjj Process............... A–1
  A.1 Signal Properties .................................................. A–1
  A.2 Background Processes .......................................... A–1
  A.3 Forward Protons in Soft Interactions ......................... A–3
  A.4 Trigger ............................................................... A–5
  A.5 Timing Detectors ................................................ A–6
  A.6 Measurement Feasibility ......................................... A–7
    A.6.1 AFP Tag Requirement .................................... A–7
    A.6.2 AFP Timing Requirement ................................ A–8
    A.6.3 Single Vertex Requirement ............................... A–10
    A.6.4 Conclusions ................................................ A–14
  A.7 Comparison with ATLAS Full Simulation ..................... A–14

Appendix-B LHC Optics and Proton Trajectories from IP1...... B–17
  B.1 LHC Optics around IP1 ........................................ B–17
  B.2 Proton Trajectories ............................................... B–17
  B.3 Transport Parametrisation ...................................... B–21

Appendix-C R & D for AFP Upgrades ................................. C–23
  C.1 R & D on Fast Diamond Detectors ............................. C–23
    C.1.1 Baseline Detector ......................................... C–24
    C.1.2 Beam Test Results ....................................... C–25
    C.1.3 Diamond Procurement and Cost ....................... C–27
  C.2 Fast Multi-Channel Sampling Chip R & D (SAMPIC) for Fast Timing ............ C–27
1 Introduction

The ATLAS Forward Proton (AFP) project promises a significant extension to the physics reach of ATLAS by tagging and measuring the momentum and emission angle of very forward protons. This enables the observation and measurement of a range of processes where one or both protons remain intact which otherwise would be difficult or impossible to study. Such processes are typically associated with elastic and diffractive scattering, where the proton radiates a virtual colorless "object," the so-called Pomeron, which is often thought of as a non-perturbative collection of soft gluons.

It was shown at the SPS, HERA, and the Tevatron that diffractive interactions may be accompanied by a hard scattering process, and that diffractive parton distribution functions (that is, the Pomeron structure) are measurable and have an important role in the detailed understanding of QCD.

Photoproduction physics has so far been studied primarily in electron accelerators, but high-energy bremsstrahlung from the proton at the LHC is a plentiful source of photons. Photoproduction processes can be studied using proton tagging, and for certain regions of phase space have cross sections comparable to Pomeron-induced processes.

The major physics topics of interest that can potentially be studied with AFP in pp interactions are briefly summarized here. Diffractive processes can also be measured in the context of heavy-ion collisions, and open up a new program of study in this field.

• The existence of rapidity gaps within the event is a hallmark of diffractive processes, and has long been of theoretical interest. By tagging events with a forward scattered proton, we can study the rapidity structure of diffractive events in a relatively unbiased way. AFP also makes possible the measurement of the double differential cross section $d^2\sigma/d\xi dt$, where $\xi$ is the fractional momentum loss of the proton, and $|t|$ is its four-momentum transfer squared.

• A variety of single-diffractive processes can be studied in which the diffractive structure is probed by a parton in the diffracted proton. These include single diffractive production of $W$, $Z$, and jets, which all have sufficient cross sections to be measured in a low pile-up (low-$\mu$) run. These are well-defined measurements, making use of standard ATLAS triggers, simply adding a proton tag at Level 1 if necessary. In fact, when AFP proton tagging is implemented, any analysis can use a proton finder to examine a reaction’s diffractive counterpart.

• The Pomeron is often viewed as gluon ‘ladder’, but hard diffractive interactions indicate a partonic structure that also includes quarks and enable this to be studied in detail. In some respects the Pomeron resembles a strongly interacting photon, in that it undergoes both direct and resolved interactions. In low pile-up runs, we can focus on the resolved process, due to its relatively high cross section as compared to the direct production of quark dijets. Finally, diffractive events involving a hard photon and a jet present an alternative direct measurement of the quark content of the Pomeron.

• High-luminosity running allows access to rarer processes and will focus on direct point-like aspect of photons and Pomerons. Forward proton tagging allows the LHC to function as an energy-tunable gluon-gluon or photon-photon collider. In Central Exclusive Production, recently measured by CDF, the entire momentum loss of the protons goes into the creation of the central system, providing a particularly clean environment to search for and characterize any new resonance. Since the central system is produced in a $J^{PC} = 0^{--}$ state, backgrounds from di-quark production are suppressed, and the mere observation of a resonance determines its quantum numbers.
• AFP provides 5 – 10 GeV per event mass resolution in CEP. This is more precise than typical direct measurements using the central detector, and is independent of the nature of the central system, thereby opening a window to the observation and measurement of challenging final states. The central state needs to be identified, but not necessarily well-measured by the central detector.

• The two-photon production of W pairs has a relatively large cross section and anomalous couplings should be measurable in this process with the 210 m stations during normal high luminosity data taking, or limits be put upon them. This has already been done successfully by CMS [1, 2] and ATLAS [3, 4] to improve existing anomalous coupling limits by about two orders of magnitude. Proton tagging will allow yet another two orders improvement in these limits.

The list is ordered in increasing demand for integrated luminosity, and the last topics can only be investigated by having AFP participate in standard runs. Initially however, AFP will focus on low-luminosity diffractive physics in special runs in Run 2, and this TDR mostly addresses this scenario. A presence of AFP in Run 3 is critically dependent on results derived from Run 2 data, and in particular from experience with the interplay between AFP and the LHC machine. If the Run 2 experience is positive, an AFP presence in Run 3 will be the subject of a separate review process and proposal.

In this document we provide the technical design of the ATLAS Forward Proton upgrade proposal: to add precision proton detectors on the outgoing beams of the ATLAS interaction point (IP) in Run 2, the so-called AFP2+2 configuration, with a total of four Roman pot stations.

Based on an initial joint ATLAS/CMS R&D effort that began in 2004 motivated by Central Exclusive Production of the Higgs boson [5], the AFP detectors combine precise silicon pixel position measurements with the LHC magnets to form momentum spectrometers, and feature high resolution time-of-flight detectors for pile-up background rejection and trigger. The Silicon pixel tracking system is modeled on the ATLAS IBL detector. The ultrafast Time-of-Flight detector is formed by L-shaped quartz bars mounted at the Cherenkov angle and read out by a fast Micro Channel Plate photomultiplier. The detectors will be mounted in Roman pots to be able to retract the detectors during proton injection into the LHC, and to insert the detectors to within a few mm from the circulating beam once stable beam conditions are established.

The original Letter of Intent for proton detectors at 220 m and 420 m was submitted to the ATLAS review process in 2009 [6], was successfully reviewed and the proponents encouraged to produce a Technical Proposal. Unfortunately, funding cuts of the UK groups in 2010 delayed the proposal [7] until 2011. While a case can be made for forward proton detectors at 420 m, it was decided to limit the project to stations in the 210 m area which is free of LHC instrumentation and beam elements. In Fig. 1 a sketch of the AFP detector layout for the 210 m stations is shown. The beam interface at 205 m contains the first Silicon tracking detector. The beam interface at 217 m contains a second, identical, tracking detector followed by the Time-of-Flight detector.

The Technical Proposal [7] was submitted to the Forward Detector group, and the internal review was successfully passed. The AFP project was included in ATLAS Letter of Intent Phase-I Upgrade [8], which was ratified by the ATLAS Collaboration Executive Board in February 2012 and endorsed by the LHC Experiments Committee during its session in March 2012. Additional physics [9] and technical [10, 11] reviews, both organized by ATLAS, were held in January and March 2014, respectively. They were both successfully passed. In June 2014 the project was approved as an ATLAS Upgrade project, pending the identification of resources, by the ATLAS Executive Board. In November 2014 a successful test beam at the CERN SPS demonstrated the successful integration of the AFP tracking, timing, and readout systems in a common TDAQ run. Finally, after the AFP
collaboration Kick-Off meeting held at CERN on 3 February 2015, the EB decision was confirmed by the ATLAS Executive Board, and endorsed by the Collaboration Board on 20 February 2015.

The installation of the AFP detectors is intended to proceed as quickly as possible, subject to full approval and availability of the required funding, with the full system intended to be available by the start of 2017 LHC running at the latest. A first phase installation of a single-arm two-station AFP, which does not require timing, could be attempted for the start of 2016 running depending on schedule and resources. Such a configuration would provide invaluable operational experience and measurements of background conditions, as well as being adequate for special low-luminosity runs providing studies of soft and hard single diffractive physics. After commissioning and successful operations of the full system in special runs, requests will be made to measure the beam environment in a few runs at standard luminosity, in order to prepare for potential standard luminosity operation at the end of Run 2 with the possibility of extending into Run 3.

This TDR is organized as follows: in Sect. 2 the program for Run 2 will be described. The details of a possible staged installation are given in Sect. 4.2. The detector and its beam interface are described in Sects. 4.1, 4.4, 4.5 and 4.6. The trigger system is discussed in Sect. 5.1. The detector simulation, including beam induced background is reported in Sect. 4.3. The intensive beam campaign culminated with that of the first integrated AFP prototype which is reported in Sect. 7. Sects. 5.2, 6.1 and 6.2 describe other important detector-related aspects such as, respectively, Data Acquisition, Detector Control System (DCS), and Infrastructure. Another crucial aspect is the alignment of the AFP stations; the alignment strategy is reported in Sect. 8. The organization, the resources, and manpower of the collaboration are found in Sect. 9.

For completeness, this TDR also describes ongoing upgrade R&D for participation in Run 3 (corresponding to the LHC phase I) in Sects. C.1 and C.2 of the Appendix. Such participation will critically depend on results obtained in Run 2; a possible Run 3 Physics case and its technical implementation will be subject of future reviews.
2 The AFP Physics Program

The AFP program for LHC Run 2 aims to perform measurements of soft and hard diffractive processes in dedicated runs a low pile-up (low-µ) environment. A short list of AFP physics processes of interest is given in Table 1 [12], and is detailed in the following sections.

Table 1. An overview of physics processes to be investigated by the ATLAS detector with the AFP apparatus [12]. Trigger terms are AFP Single Tag (ST) and AFP Double Tag (DT) and could be combined with ATLAS Jet, Lepton, Photon, and Missing Transverse Energy (MET) trigger conditions (the number indicates the transverse energy threshold in GeV).

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\int L dt$ [pb$^{-1}$]</th>
<th>Optimal $\mu$</th>
<th>$\beta^*$ [m]</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle spectra</td>
<td>1</td>
<td>&lt; 0.05</td>
<td>90, 0.55</td>
<td>AFP-ST, AFP-DT</td>
</tr>
<tr>
<td>Gap spectra</td>
<td>1</td>
<td>&lt; 0.05</td>
<td>90, 0.55</td>
<td>AFP-ST, AFP-DT</td>
</tr>
<tr>
<td>SD jj</td>
<td>1–100</td>
<td>0.01–1.0</td>
<td>90, 0.55</td>
<td>AFP-ST &amp; Jet15</td>
</tr>
<tr>
<td>DPE jj</td>
<td>10–100</td>
<td>0.5–5.0</td>
<td>90, 0.55</td>
<td>AFP-DT &amp; Jet15</td>
</tr>
<tr>
<td>SD W</td>
<td>&gt; 100</td>
<td>0.1–1.0</td>
<td>90, 0.55</td>
<td>AFP-ST &amp; Lep15 &amp; MET15</td>
</tr>
<tr>
<td>DPE $\gamma + jj$</td>
<td>&gt; 200</td>
<td>1.0–2.0</td>
<td>0.55</td>
<td>AFP-DT &amp; Jet/Photon</td>
</tr>
<tr>
<td>DPE $j - gap - j$</td>
<td>&gt; 100</td>
<td>0.1-2.0</td>
<td>0.55</td>
<td>AFP-DT &amp; Jet</td>
</tr>
</tbody>
</table>

In Sects. 2.2.1 and 2.2.2 general features of soft processes, soft diffraction, and hard diffraction are presented. In Sects. 2.3.1 and 2.3.2 the specific processes to be studied with the ATLAS forward detectors AFP and ALFA [13, 14, 15] are discussed. For each process a list of measurements, the physics motivation, and the required running scenario is given.

To explore the ATLAS detector capability enhanced with the AFP detectors, a detailed study using ATLAS full simulation was done for the benchmark process of central diffractive production of jets which proceeds via double Pomeron exchange: DPE$jj$. This study is presented in Sect. A. The final section describes measurements required in Run 2 to prepare for a possible participation of AFP in Run 3.

2.1 Run Conditions

As run conditions are not fixed and the optimal data-taking conditions differ by process studied, it is useful to discuss the measurement as a function of the average number of interactions per bunch crossing $\mu$, also loosely called pile-up.

The integrated luminosity as a function of $\mu$ is shown in Fig. 2. The lines represent a product of number of colliding bunches $n_{\text{bunch}}$ and run time $t$ in hours. For example, the collection of a 5 pb$^{-1}$ data sample at $\mu = 0.1$, requires $n_{\text{bunch}} \times t (\text{h}) = 10^5$ equivalent to 100 h (1 week) of running with $n_{\text{bunch}} = 1000$ colliding bunches.

2.2 Diffractive Processes

2.2.1 Soft Diffraction

The vast majority of studies in high energy hadron-hadron collisions involve a hard scale, e.g. high-$p_T$ jets or electroweak bosons, present in the event. Such processes are relatively well understood, due to the QCD factorisation theorem, which applies in this case and allows the use of perturbative calculations. On the other hand, hard processes are quite rare and contribute only to a small fraction of the total cross section. In contrast, the mechanisms of soft processes are poorly known because of their non-perturbative nature. Nonetheless, a good understanding of soft physics is...
important also for studies of high-$p_T$ processes. This is because soft processes are responsible for the phenomenon of the “underlying event”: every hard process is accompanied by multiple soft parton-parton interactions of the spectator partons. Moreover, at standard LHC luminosity, several - typically soft - proton-proton interactions occur in the same bunch crossing as the hard collision of interest, a phenomenon known as “pile-up” and characterized by the average number of interactions per bunch crossing $\mu$. The particles from soft pile-up interactions are superimposed on the interaction of interest and need to be subtracted. With the increase of the LHC luminosity leading to an increase of pile-up, a good understanding of soft effects will become ever more important.

Two general mechanisms are responsible for the soft proton-proton interaction: diffractive and non-diffractive. Non-diffractive processes involve the exchange of coloured objects, leading to the break-up of both interacting protons and particle production in the central and mid-rapidity regions, as illustrated in Fig. 3a.

In contrast, diffractive processes involve the exchange of a strongly interacting colour-less object (colour singlet), the Pomeron, which allows the interacting proton to remain intact. Several diffractive signatures can be distinguished. If both protons stay intact and no additional particles are produced, one deals with elastic scattering (Fig. 3b). Alternatively, one or both interacting protons may not stay intact but dissociate into a higher mass, multi-particle state. Such processes are called single diffractive dissociation (or single diffraction – SD) and double diffractive dissociation (double diffraction – DD); they are depicted in Figs. 3c and 3d, respectively.

In elastic scattering, single, and double diffractive processes, the final state particles are produced mainly in the forward direction, leaving large regions devoid of particles in central rapidities – rapidity gaps. It turns out that it is also possible to have diffractive interactions with central production of particles. Such processes are called central diffraction (CD) or double Pomeron exchange (DPE) processes, because they can be thought of as the interaction of two Pomeron, each emitted from one of the incoming protons. Usually, such processes are considered for the case where both protons stay intact (Fig. 4a), however it is also possible to think of central diffraction with one or both protons dissociated (Figs. 4b and 4c, respectively).

Intact protons observed in the forward detectors originate mainly from single and central diffrac-
Figure 3. Feynman diagrams of soft processes in hadron-hadron collisions: (a) non-diffractive interaction, (b) elastic scattering, (c) single diffractive dissociation, (d) double diffractive dissociation.

Figure 4. Feynman diagrams of soft central diffractive processes in hadron-hadron collisions: (a) two intact protons, (b) single proton dissociation, (c) double proton dissociation.

tive processes. However, because of baryon number conservation, one naturally expect protons in the final state of non-diffractive processes, and so too in diffractively dissociated states. On average the energy of such protons is much smaller than the typical energy of diffractive protons. The contribution of such processes may be observed in the ATLAS forward detectors (cfr. Figs. 16 and 17 with Fig. 5) as they have acceptance in the high-\(\xi\) region. This will permit the study of such mechanisms, which may be important not only for physics at the LHC, but also in cosmic ray physics where a good understanding of leading baryon production is of prime importance. It is worth stressing that the predicted cross sections vary significantly. This is illustrated in Fig. 5, with predictions from the Pythia 6 and Phojet generators.

Figure 5. Relative momentum distribution for diffractive protons and protons of non-diffractive origin. Predictions of Pythia 6 and Phojet generators are shown.

Besides measurements of various distributions of forward proton kinematics, it is also interesting to study correlations between the forward proton and other properties of the event (measured by the central ATLAS detector). These include the typical minimum bias observables, like the charged particle multiplicity, transverse momenta, energy flow, and rapidity gap size. In principle, all usual
minimum bias measurements can be performed with different proton tag combinations (no tag/single tag/double tag) and proton kinematics ($\xi$, $t$ and, for double tag events, acoplanarity). Such studies will provide valuable data and will improve the understanding of soft processes.

2.2.2 Hard Diffraction

The diffractive signature of a rapidity gap or a forward intact proton can be found also in events containing a hard scale. Two possible mechanisms are considered for explaining such types of interactions. The first assumes that hard diffractive processes occur via Pomeron exchange as in soft diffraction. In this approach, the Pomeron has a partonic structure, described by diffractive structure functions and diffractive parton distributions. These distributions can be used to calculate cross sections for hard diffractive processes by convolution with hard matrix elements.

It is possible that a hard diffractive process is accompanied by an additional soft interaction (of the same pair of initial protons). Such an additional soft interaction will spoil the diffractive signature of the event. This effect is taken into account in theoretical calculations using the concept of gap survival probability [16], which quantifies the decrease in cross section for hard diffractive processes caused by additional soft interactions.

An alternative model aiming to describe hard diffractive processes assumes that the diffractive signature does not originate from the hard process itself, but rather emerges during the formation of the final state due to the exchange of soft gluons. This model is usually referred to as soft colour interactions (SCI) [17].

Fig. 6 presents the comparison of the resolved Pomeron and soft colour interaction models of hard diffractive processes. One of the goals of the AFP physics program is to provide new data that can be used to discriminate between these models. In this report, the resolved Pomeron model is used for the majority of results, since at the moment it is more developed, better understood, and hence more popular in the diffractive community.

Similar to the case of soft diffraction, several types of hard diffractive interactions can be considered, see Fig. 8 (a). In single diffractive processes, only one proton is involved in the diffractive exchange and stays intact. The exchanged Pomeron reveals its partonic structure and the whole process can be treated as a hard, non-diffractive proton-Pomeron interaction.

The cross section for hard single diffractive process can be written as

$$d\sigma = S_{SD}^2 \cdot \Phi_P(\xi, t) \cdot f_{\xi}(x_1, \mu^2) \cdot f_{p}(x_2, \mu^2) \cdot d\sigma_{\text{hard}}(x_1, x_2, \mu^2),$$

(1)

where $S_{SD}^2$ is the gap survival probability, $f_{\xi}(x_1, \mu^2)$ is the parton distribution function (pdf) in the diffractive proton number 2 (bottom proton in the Figure), $\Phi_P(\xi, t)$ is the Pomeron flux, $f_{p}(x_1, \mu^2)$ is the parton distribution function (pdf) in the diffractive proton number 1 (top proton in the Figure), and $d\sigma_{\text{hard}}(x_1, x_2, \mu^2)$ is the hard cross section.
the parton distribution function in the Pomeron interacting with the scattered proton 1 (top proton in
the same Figure), \(d\sigma_{\text{hard}}(x_1, x_2, \mu^2)\) is the perturbative cross section for the hard parton-level subpro-
cess, and \(\mu\) is the hard scale in the process. It is worth pointing out that although the above formula
is similar to the one used for non-diffractive processes, here the QCD factorisation does not hold
because of the gap survival probability. This parameter can depend on various kinematic properties
of the final state, but for simplicity usually only the \(\sqrt{s}\) dependence is taken into account. On the
other hand, a different factorisation is present – the one between the Pomeron flux and the Pomeron
pdf.

The other type of hard diffraction involves two diffractive exchanges and results in two intact
protons in the final state, see Fig. 8 (b). In the resolved Pomeron model, such a process is thought
of as an interaction between two partons, each originating from a Pomeron. Similar to the soft case,
such a process is called central diffractive production or double Pomeron exchange (DPE). Its cross
section can be calculated as:

\[
d\sigma = S^2_{\text{CD}} \cdot \Phi_{\Psi}(\xi_1, t_1) \cdot \Phi_{\Psi}(\xi_2, t_2) \cdot f_{\Psi}(x_1/\xi_1, \mu^2) \cdot f_{\Psi}(x_2/\xi_2, \mu^2) \cdot d\sigma_{\text{hard}}(x_1, x_2, \mu^2), \tag{2}
\]

where the survival probability \(S^2_{\text{CD}}\) is different from the SD case.

In both types of hard diffraction discussed above, the interacting parton originating from the
Pomeron does not take the full energy. This introduces the concept of the Pomeron remnant, analo-
gous to proton remnants appearing in non-diffractive processes. Much like the proton remnants, the
Pomeron remnants usually escape undetected down the accelerator beam pipe.

The hard systems considered for AFP measurements in dedicated runs during LHC Run 2 are
jets, photon+jet, photons, and electroweak bosons. Fig. 7 shows the leading-order parton level
diagrams for these processes which can all be studied in SD. For the running scenarios assumed,
the jet and photon+jet processes can also be studied in CD/DPE configurations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Hard processes that can be studied in diffractive mode at the LHC: (a) jets, (b) photon + jet, (c) Drel-Yan process, (d) W boson production.}
\end{figure}

One may consider a process in which there are no remnants at all and the full Pomeron energy
goes into the hard state. Such a process is called central exclusive production (CEP). With forward
proton tagging, it provides a unique opportunity to detect all final state particles. CEP processes
are often described in terms of the KMR model [18] (see diagram 8c), which, in contrast to central
diffractive production, does not require the introduction of Pomeron structure. At present, the transi-
tion between central diffraction and central exclusive production is not understood and is well worth
investigating at the LHC.

The process of diffractive jet production provides an additional interesting possibility, typically
not related to proton tagging physics: the study of BFKL effects. The BFKL evolution [19, 20, 21]
is expected to manifest itself in the so-called jet-gap-jet processes, when the jets are produced in
elastic scattering of two partons via the BFKL Pomeron. As shown in Ref. [22], the BFKL model can
be tested by studying the shapes of the jet-gap-jet distributions.

The absence of color flow between the jets increases the chance of having a rapidity gap be-
tween the jets. In principle, the measurement of jet-gap-jet events does not require any forward
Figure 8. Possible types of diffractive production of jets: (a) single diffractive, (b) central diffractive (double Pomeron exchange), (c) central exclusive production.

Figure 9. Distribution of $\xi$ variable for protons, neutrons, anti-protons and anti-neutrons that are produced in minimum bias: single diffraction, double diffraction and non-diffractive interactions, as predicted by PYTHIA.

proton tagging. However, without proton tags, the background due to random fluctuations of the rapidity distance between two neighbouring particles in events with normal colour flow between the jets is large. This is because in jet-gap-jet events the gap can be destroyed by a soft underlying event, i.e. the cross section is reduced by the gap survival probability.

2.3 Diffractive Measurements with AFP

2.3.1 AFP0+2

In this section the AFP physics program of Single Diffraction (SD) is presented, in which one of the protons remains intact (guaranteeing a colorless exchange) and the other undergoes diffraction dissociation. SD processes typically have high to medium-high cross sections and require short special runs with low-pile-up (low-$\mu$) conditions to obtain best data sample purity.

Among all processes that can be measured with AFP, the SD processes have the highest cross sections. This translates to relatively small amounts of integrated luminosity and run time ($\sim 1 \text{ pb}^{-1}$) required. On the other hand, these measurements must be done in an experimentally very clean environment, thus the optimal pile-up condition is $\mu$ up to around 1.

Distributions of fractional energy loss $\xi$ for protons, neutrons, anti-protons and anti-neutrons produced in minimum bias (single diffraction, double diffraction and non-diffractive interactions) as predicted by PYTHIA are shown in Fig. 9. As is evident, SD protons start to dominate below 0.2, while at larger $\xi$ non-diffractive protons become dominant. The model predictions can be trusted
only up to $\xi \sim 0.1$, since the higher values of relative energy loss are experimentally unavailable and models are not tuned. In consequence, the AFP detector offers a good experimental measurement opportunities as its acceptance covers $0.015 < \xi < 0.15$, i.e. the part of the region which should be understood ($\xi < 0.1$) and extending extends into the poorly known region ($\xi > 0.1$).

By studying single diffractive jet production, one probes Pomeron universality between $ep$ and $pp$ colliders, i.e. if the same object is seen in diffraction at HERA and the LHC. Another interesting measurement is that of the gap survival probability. A detailed study into the applicability of this factorisation would be an interesting outcome of the AFP measurements. In particular, the presence of an additional contribution from Reggeon exchange [23] can be studied. Good experimental precision will allow for comparison to theoretical predictions and differential measurements of the dependence of the survival factor on (for example) the mass of the central system.

Comparisons may also be drawn between existing single diffractive jet data based on the correlation between the rapidity gap size and the fractional momentum loss $\xi$ of the scattered proton. Tagging of diffractive protons will also allow the QCD evolution of the gluon and quark densities in the Pomeron to be tested and compared with HERA measurements.

A feasibility study using stand-alone Monte Carlo generators (PYTHIA8 [24] and FPMC [25]) show that the SD+jets processes can be studied profitably using AFP. Results for $\beta^* = 0.55$ m optics are shown in Fig. 10. In the left plot the purity, (defined as the ratio of signal to the sum of signal and background events) is presented. In this figure, the black solid line is for events with a proton tag in the AFP detector whereas the red dashed line is for events with a proton tag and exactly one reconstructed vertex. Purities in excess of 50% are obtained for $\mu \sim 0.5$, growing rapidly to values $\sim 80\%$ for $\mu < 0.1$. The purity shown in this plot is for jets with $p_T > 50$ GeV, but is not significantly different for other $p_T$ thresholds.

![Figure 10](image)

Figure 10. Single diffractive jet production with protons tagged in the AFP detectors for $\sqrt{s} = 13$ TeV and $\beta^* = 0.55$ m: purity (left) and significance for jets with $p_T > 50$ GeV (right) as a function of average pile-up. The number of bunches multiplied by data collecting time (in hours) was assumed to be 1000. In the analysis the following cuts were considered: proton tag in the AFP detector whereas the red dashed line is for events with a proton tag and exactly one reconstructed vertex (black solid line) and tag + exactly one reconstructed vertex (red dashed line).

Studies for the AFP detector and $\beta^* = 90$ m optics are shown in Fig. 11. For such an optics configuration and for a 10 $\sigma$ distance from the beam, the purity and significance is similar to the case discussed above. The same conclusion is reached in the case of the ALFA detector and $\beta^* = 0.55$ m optics.

The AFP SD program, depending on beam optics, overlaps with and is complementary to the ALFA diffractive program because of the difference in $\xi$ and $t$ acceptance between the two detectors, which is most pronounced for the standard $\beta^*$ optics. This overlap/complementarity between AFP
Figure 11. Single diffractive jet production with protons tagged in the AFP detectors for $\sqrt{s} = 13$ TeV and $\beta^*= 90$ m: purity (left) and significance for jets with $p_T > 50$ GeV (right) as a function of average pile-up $\mu$. The number of bunches multiplied by data collecting time (in hours) was assumed to be 1000. In the analysis the following cuts were considered: proton tag in the AFP (black solid line) and tag + exactly one reconstructed vertex (red dashed line).

and ALFA is discussed in Sect. 3.1. In Table 2 a detailed list of Single Diffraction physics processes is given, together with the required luminosity and optimal pile-up $\mu$.

2.3.2 AFP2+2

In this section the AFP program for the study of central diffractive (CD) processes (DPE) is presented, in which both protons remain intact. Both AFP arms must be installed for CD measurements (AFP2+2). CD processes typically have medium to low cross sections and require special runs with low-pile-up ($\mu \sim 1$) conditions to obtain the best data purity.

The DPE jet production is sensitive to the gluon density in the Pomeron as is shown in Fig. 12 [31]. The central black line displays the cross section value for the gluon density in the Pomeron as measured at HERA and in addition includes a gap survival probability factor of 0.03. The yellow band shows the effect of a 20% uncertainty on the gluon density, taking into account the normalisation uncertainties. The dashed curves display the expected cross section sensitivity at the LHC to the gluon density distribution, especially at high $\beta$. The gluon density in the Pomeron diffractive PDF (dPDF) from HERA is modified by the factor $(1 - \beta)^\nu$.

Figure 12. Cross section of DPE jet production as a function of leading jet $p_T$ (left) and mass fraction (right). The different curves correspond to different modifications of the Pomeron gluon density extracted from HERA data (see text).
Table 2. Summary of Single Diffraction physics processes to be investigated using the ATLAS detector with the AFP apparatus.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Motivation</th>
<th>$\int Ldt [pb^{-1}]$</th>
<th>Optimal $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Single Diffraction with AFP0+2</td>
<td>Saturation, MC tuning, Cosmic Ray physics</td>
<td>1</td>
<td>$\mu \sim 0.01$</td>
</tr>
<tr>
<td>Single Diffractive jet Production [26]</td>
<td>gap survival probability, Pomeron structure</td>
<td>10 – 100</td>
<td>$\mu \sim 1$</td>
</tr>
<tr>
<td>Single Diffractive jet-gap-jet Production [27, 28, 29]</td>
<td>observation of a new process, test of BFKL dynamics</td>
<td>1 – 100</td>
<td>$\mu \sim 1$</td>
</tr>
<tr>
<td>Single Diffractive Production of $\gamma + \text{jet}$ [30]</td>
<td>observation of a new process, mechanism of hard diffraction, gap survival probability, Pomeron structure</td>
<td>10 – 100</td>
<td>$\mu \sim 1$</td>
</tr>
<tr>
<td>Single Diffractive $Z$ Production</td>
<td>gap survival probability, Pomeron structure</td>
<td>10 – 100</td>
<td>$\mu \sim 1$</td>
</tr>
<tr>
<td>Single Diffractive $W$ Production</td>
<td>gap survival probability, Pomeron structure and flavor composition</td>
<td>10 – 100</td>
<td>$\mu \sim 1$</td>
</tr>
</tbody>
</table>

Fig. 12 indicates that the cross section is indeed sensitive to the gluon density in the Pomeron. Such measurements therefore provide an important test of Pomeron universality. Moreover, these studies can be performed for an integrated luminosity as low as 10 pb$^{-1}$ since the cross section is relatively large: one expects 250 (at $p_T\text{(jet)} = 50$ GeV) to 20 events (at $p_T\text{(jet)} = 80$ GeV) per 2 GeV $p_T$-bin per pb$^{-1}$ of running.

Because the curves for various gluons densities have the same shape, it will be difficult to distinguish if the observed change in the absolute gluonic parton cross section is due to the gluon density or to the survival probability. Hence the introduction of the so-called mass fraction, defined as the ratio of the dijet mass to the total diffractive mass computed as $\sqrt{\xi_1 \xi_2 \sqrt{s}}$, where $\xi_{1,2}$ is the proton fractional momentum carried by each Pomeron and $\sqrt{s}$ the center-of-mass energy of 14 TeV. As observed from Fig. 12 (right), the curves corresponding to the different values of $v$ diverge faster at high values of the dijet mass fraction, indicating that this observable is indeed sensitive to the gluon density at high $x$, as expected because the mass fraction is equal to $\sqrt{x_1 x_2}$. The possibility of measuring DPE jets with the AFP detectors is discussed in detail in Sect. A.

The measurement of DPE production of $\gamma + \text{jet}$ can also be used to test Pomeron universality. Moreover, the quark content in the Pomeron can be probed with this process. The diffractive QCD fits performed at HERA assumed equality of quark distributions: $u = d = s = \bar{u} = \bar{d} = \bar{s}$, since the data were insensitive to differences in the quark content in the Pomeron. As will
be shown, the LHC data will allow us to check this assumption. For example, if a value of \( d/u \neq 1 \) is favoured by data, the HERA QCD diffractive fits will have to be modified. If the fits to HERA data lead to a large \( \chi^2 \), it would indicate that the Pomeron is not the same object at HERA and the LHC. On the other hand, if the HERA fits work under this new assumption, the quark content in the Pomeron will be further constrained.

Observables that probe the quark content in the Pomeron at the LHC are the transverse momentum of the leading jet \((p_T)\) and the proton-proton missing mass \(M = \sqrt{\xi_1 \xi_2}\). These variables are shown in Fig. 13 for different assumptions for the quark content of the Pomeron, varying \( d/u \) between 0.25 and 4. For comparison, predictions of the Soft Colour Interaction (SCI) model [32] are presented.

![Figure 13](image)

**Figure 13.** Ratio of the \( \gamma+\text{jet} \) over the dijet differential cross sections of the leading jet \( p_T \) (left). Ratio of the \( \gamma+\text{jet} \) over the dijet differential cross section as a function of the diffractive mass \( M = \sqrt{\xi_1 \xi_2} \) (right). The different curves correspond to different values of \( d/u \) inside the Pomeron. Proton-proton collisions at \(\sqrt{s} = 14\) TeV are assumed.

Another interesting process is a jet-gap-jet (JGJ) production. Such events feature a large rapidity gap with a high-\(p_T\) jet on either side. Across the gap, the object exchanged in the \(t\)-channel is a colour singlet and carries a large momentum transfer. When the rapidity gap is sufficiently large (which requires a high collision energy), the perturbative QCD description of JGJ events is performed in terms of a Balitsky-Fadin-Kuraev-Lipatov (BFKL) Pomeron [27]. The JGJ topology can also be produced in DPE [22] where no colour is exchanged between the protons, as well as in the \(t\)-channel between the jets. The fraction of DPE JGJ to all DPE jet events is larger than the corresponding fraction in ‘standard’ JGJ production, since in DPE events the penalty of the gap survival probability applies to both the DPE JGJ and the total DPE cross sections.

As for the AFP SD program and depending on the beam optics used, the AFP DPE program overlaps with and complements the ALFA diffractive program because of the difference in \(\xi\) and \(t\) acceptance between the two detectors. In Table 3 a detailed list of Central Diffraction physics processes is given, together with the required luminosity and optimal pile-up \(\mu\).

The Central Diffractive Production of jets (DPEjj), where the two forward protons are tagged inAFP, and the jets are measured in the central ATLAS detector, was chosen to serve as benchmark of the capabilities of the AFP detectors in the presence of pile-up backgrounds. The process was studied extensively with detector simulations, including full ATLAS simulations, and is presented in Sect. A.
Table 3. Summary of DPE physics processes to be investigated using the ATLAS detector with the AFP apparatus. The numeric labels 1, 2 refer to the forward protons measured in AFP.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Motivation</th>
<th>$\int L dt , [\text{pb}^{-1}]$</th>
<th>Optimal $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Central Diffraction with AFP2+2</td>
<td>$d\sigma/dt_{1,2}$, $d\sigma/dt_{1,2}$, $t$-Slope vs. $\xi$, Mass $M$ and $y$ of the central diffractive system, $\phi_1$ vs. $\phi_2$, $dN^d/dp_T$; vs. $I_{1,2}$, $\xi_{1,2}$, $M$.</td>
<td>general understanding of DPE processes</td>
<td>1</td>
</tr>
<tr>
<td>Central Diffractive jet Production</td>
<td>$d\sigma/dt_{1,2}$, $d\sigma/dt_{1,2}$, $t$-Slope vs. $\xi$, $d\sigma/dp_T^{\text{jet}}$, Mass $M$ and $y$ of the central dijet system, $\phi_1$ vs. $\phi_2$</td>
<td>gap survival probability for DPE processes, Pomeron structure, general understanding of DPE processes</td>
<td>10 – 100</td>
</tr>
<tr>
<td>Jet-gap-jet Production</td>
<td>$d\sigma/dt_{1,2}$, $d\sigma/dt_{1,2}$, $d\sigma/dM_{jj}$, $d\sigma/dp_T^{\text{jet}}$, $\phi_1$ vs. $\phi_2$</td>
<td>observation of a new process, test of BFKL dynamics</td>
<td>10 – 100</td>
</tr>
<tr>
<td>$\gamma + \text{jet}$ Production</td>
<td>$\sigma$, rapidity gap(s), Jet structure and $p_T$, Photon $p_T$ vs. $I_{1,2}$, $\xi_{1,2}$, and $M_{jj}$</td>
<td>observation of a new process, mechanism of hard diffraction, gap survival probability, Pomeron structure</td>
<td>10 – 100</td>
</tr>
</tbody>
</table>

2.4 AFP at High Luminosity

Apart from the physics program with low-$\mu$ special runs in Run 2, a second measurement goal of AFP in Run 2 is to measure backgrounds in the high luminosity LHC environment. This is needed to evaluate the potential reach for a future AFP program, i.e. the measurements of exclusive and two-photon exchange processes. These processes have cross sections too small for dedicated runs and must be studied with full luminosity during standard LHC operation. Moreover, Time-of-Flight measurement of the forward protons is required to reject pile-up backgrounds.

However, a prior understanding of the conditions that the AFP detectors encounter at standard luminosity is essential to judge the feasibility of such measurements. After AFP has been installed, commissioned, and acquired a good safety record in special runs, a request will be made to ATLAS Run Coordination and the LHC, for a few trial insertions of AFP pots at tail ends of stores in order to evaluate procedures, study rates, and make forward proton measurements.

2.4.1 Physics in Run 3: The High-$\mu$ Physics Case

The Run 3 environment, with increased luminosity and higher average $\mu$ up to 60 will present significant challenges to AFP operations. The processes of interest to the AFP Physics program at high-$\mu$, for instance the exclusive double-Pomeron and double-photon exchange processes, have small cross section and require efficient pile-up rejection and therefore must use time-of-flight detectors with time-of-arrival resolution of 10 ps or better. While AFP has been approved for low-$\mu$ physics in...
special runs during Run 2, the AFP Run 3 Physics program must be approved separately by a future Physics and Technical review within ATLAS. Good AFP physics output, good detector performance, and high run efficiency in Run 2 will be a crucial factor in a successful review outcome. The other deciding factor will be the standard-optics Run 3 running conditions, which will determine or limit the AFP detector capabilities, in particular the minimum distance of closest approach that is assumed safe for LHC and AFP operations.

However, if the AFP detectors will be able to operate at standard luminosity, a rich program of hard, high-mass physics is accessible with AFP. In particular, a program of measurements of Anomalous Quartic Gauge Couplings of type $\gamma\gamma$-VB-VB (VB=$W$, $Z$, or $\gamma$) is a very promising method to probe physics beyond the Standard model (SM) [34]. This method is able to set limits on the scale of new physics well beyond the scales accessible with direct production at the LHC. With the use of AFP proton tags and an integrated luminosity of 100 fb$^{-1}$, sensitivities are reached that are a factor 30-100 times better than reached with the central ATLAS detector alone.

The critical tool for the reduction of physics backgrounds is the matching requirement between the missing mass of the forward protons measured in AFP and the central mass measured with the central ATLAS detector. In the interesting case of the four-$\gamma$ coupling, which is absent to first order in the SM, an unprecedented sensitivity down to $6 \times 10^{-15}$ GeV$^{-4}$ is obtained, providing a new window on extra dimensions and strongly-interacting composite states in the multi-TeV range [35].

Because the central mass range of interest is large, the distance of closest approach between detectors and beam can be relaxed, and the possible impact on normal LHC running is much reduced.
3 The LHC Optics and Radiation Environment

3.1 LHC Optics for AFP Runs

The main purpose of AFP detectors is to study hard diffraction and search for new physics using the proton tagging technique. Because diffractive protons are usually scattered at very small angles (typically of the order of few microradians), the detectors will be placed about 210 m from the ATLAS Interaction Point (IP1). The magnets installed between IP1 and the AFP detectors deflect the protons, and the settings of these magnets will have a direct impact on the position of the proton at the detector location and, hence, the kinematic phase space available to AFP.

In this section the properties of the proton beam and scattered protons in the vicinity of the ATLAS Interaction Point (IP) for various LHC optics settings are discussed. From this, the geometrical acceptance of the AFP detectors is derived and the impact of the LHC collimators is presented. These studies are based on work reported in Ref. [36].

3.1.1 LHC Optics

The LHC consists of two separate rings with eight straight sections centered on Interaction Points (IP). During accelerator operation, proton (or lead) beams circulate in opposite directions in each ring. To keep the beams in their circular paths 1232 dipole magnets are used. Additionally, 392 quadrupole magnets are installed to keep the beams focused. The beams collide in four of the IPs: IP1 (ATLAS and LHCf), IP2 (ALICE), IP5 (CMS and TOTEM), IP8 (LHCb and MoEDAL).

The two proton beams in the LHC circulate in two horizontally displaced beam pipes which join into a common one about 140 m away from the Interaction Points. The clockwise-circulating beam (viewed from above the ring) is called beam1 and the anti-clockwise beam2.

The LHC magnetic lattice in the vicinity of the ATLAS IP is shown in Fig. 14. The quadrupole magnets are labelled with the letter Q and the dipole magnets with the letter D. The final focusing triplet (Q1 – Q2 – Q3) is positioned about 40 m away from IP1. Other quadrupoles (Q4, Q5 and Q6) are installed around 160 m, 190 m and 220 m from the ATLAS IP [37, 38]. Between IP1 and 210 m two dipole magnets, D1 at 70 m and D2 at 150 m, are installed. These magnets are used for the separation of ingoing and outgoing beams after the final focus section.

![Figure 14. LHC magnet structure close to the ATLAS Interaction Point.](image)

There are several correction magnets used to compensate imperfections in the main lattice. In addition, there are a number of other LHC elements installed close to the ATLAS Interaction Point:

- Beam Position Monitors (BPM),
- Target Absorber Neutral (TAN) – absorber for neutral particles leaving the IP, located in front of the D1 dipole magnet on the side facing the ATLAS detector,
• Target Absorber Secondaries (TAS) – absorber for particles which could reach the quadrupole triplet. TAS1 is located in front of Q1, whereas the second one is before the Q3 quadrupole magnet,

• TCL4 and TCL5 Target Collimators (Long) protect the superconducting magnets from quenching. TCL4 is installed before the D2 dipole and TCL5 before the Q5 quadrupole.

As will be discussed later in this Chapter, there is a plan to install a new collimator (TCL6) which is needed to increase acceptance of the AFP detectors.

In the following studies three different settings of the LHC magnets will be discussed:

• collision optics ($\beta^* = 0.55$ m) – ‘standard’ LHC setting optimised to maximise the luminosity value,

• high-$\beta^*$ optics ($\beta^* = 90$ m) – designed to measure the elastic scattering with ALFA detectors [39],

• high-$\beta^*$ optics ($\beta^* = 1000$ m) – designed to investigate the Coulomb-nuclear interference region with ALFA.

In terms of accelerator optics, the betatron function, $\beta$, is a measure of the distance from a given point to the point at which the beam is twice as wide. The lower the value of the betatron function at the IP ($\beta^*$)\(^1\), the smaller the beam size and the larger the luminosity. A detailed discussion can be found in e.g. Ref. [36].

Aside from the betatron function, another important parameter is the beam emittance $\varepsilon$, which is a measure of the average spread of the beam protons in position-momentum phase space. The LHC was designed to obtain $\varepsilon = 3.75$ $\mu$m-rad, but due to the outstanding accelerator performance this value is about $\varepsilon = 2$ $\mu$m-rad on average. In this Chapter the former value of the emittance is used in the calculations of the beam properties around the forward detectors, whereas the latter is employed when the beam behaviour at the IP is computed. Such an approach is consistent with the one taken by the LHC machine group and with realistic experimental conditions.

The LHC optics around the ATLAS IP determines the trajectories of protons as function of relative energy loss $\xi$, transverse momentum $p_T$, and azimuthal angle $\phi$, and is therefore of prime importance for the measurement capabilities of AFP. The $\beta^* = 90$ m and $\beta^* = 1000$ m optics for special runs, and the $\beta^* = 0.55$ m standard or ‘collision’ optics, as well as the resulting proton trajectories are described in Appendix B.

### 3.1.2 Geometrical Acceptance

For all measurements which are possible using the ATLAS forward detectors, it is important to understand the connection between the scattered proton energy and momentum and the trajectory position and the elevation angle in the detector. This dependence for various LHC optics is illustrated in Fig. 15. In these plots, the positions of elastically and diffusively scattered protons with various transverse momenta in the detector plane at the detector locations are shown. The detector is indicated by the rectangle superimposed on the figure. The distance from the beam centre is set to 15 $\sigma$ for the collision optics and 10 $\sigma$ for high-$\beta^*$ optics, where $\sigma$ is the rms width of the beam at the detector location, see Table 7.

Fig. 15 shows that protons scattered elastically ($\xi = 0$) will not reach the AFP detectors\(^2\). Protons scattered diffusively ($\xi \neq 0$) have a negative value of $x$, i.e. they pass outside the LHC ring.

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\(^1\)In this Chapter asterisk (*) denotes values at the Interaction Point.

\(^2\)Unless their $p_T$ is large enough which is possible but very improbable.
The geometrical acceptance is defined as the ratio of the number of protons with a given $\xi$, $p_T$, and $\phi$ that reach the detector to the total number of scattered protons having the same $\xi$ and $p_T$. Obviously, depending on $\xi$, $p_T$, and $\phi$, some scattered protons will not reach the forward detectors as they may be too close to the beam to be detected or hit an LHC element (collimator, beam pipe, magnet) upstream of the detector. In the calculations presented here the following factors were taken into account: i) the beam properties at the IP, ii) the beam chamber geometry, iii) the LHC lattice magnetic properties, and iv) the distance between the beam centre and the detector edge.

The geometrical acceptance of the first AFP station (located at 204 m from the IP1) is shown in
Fig. 16. The distance from the beam centre was set to 15 $\sigma$ for the collision optics and to 10 $\sigma$ for the high-$\beta^*$ optics (see Table 7) and 0.5 mm of dead material (0.3 mm for AFP floor plus 0.2 mm for detector inactive edge) was added. It should be noted that since the AFP detectors approach the beam in the horizontal plane, only the $x$ width is meaningful (see Ref. [40]).

Figure 16. Geometrical acceptance of the AFP detectors as a function of the proton relative energy loss ($\xi$) and its transverse momentum ($p_T$) for various LHC optics settings. The beam properties at the IP, the beam chamber and the detector geometries, the distance between the detector edge and the beam centre were taken into account. This distance was set to 15 $\sigma$ for collision optics and to 10 $\sigma$ for high-$\beta^*$ optics ($\xi = 3.75 \, \mu \text{m-rad}$ was used) and 0.5 mm of dead material was assumed.

Figure 17. Same as the previous figure, but for the ALFA detector. All conditions as above, but 0.3 mm of dead material was assumed for ALFA.

For the collision optics the region of high acceptance (> 80%) is limited by $p_T < 3$ GeV and $0.02 < \xi < 0.12$. These limits change to $p_T < 1$ GeV and $0.07 < \xi < 0.17$ and $0.1 < \xi < 0.17$ for the $\beta^* = 90$ and 1000 m optics respectively. As seen from Fig. 15b and c, the acceptances for $\beta^* = 90$ m with and without crossing angle are indistinguishable and therefore not shown separately in Fig. 16b.

3.1.2.1 Complementarity between AFP and ALFA

In this paragraph the geometrical acceptance of ALFA experiment is presented for comparison with AFP. The ALFA detectors are mounted in vertical Roman pots located at 237 m and 245 m on both sides of IP1 [41].

The results for the near ALFA station (located 237 m from the IP1) are shown in Fig. 17. The distance from the beam was set to 15 $\sigma$ (4.2 mm) for the collision optics, 10 $\sigma$ (6.6 mm) for $\beta^* = 90$ m optics and 0.5 mm of dead material was assumed for ALFA.
Figure 18. Ratio of the number of events that could be detected with the AFP detector when a given collimator is closed, to the number of events when it is wide open, as a function of the proton relative energy loss. The default distance of 15 σ is equal to 7.89 mm in case of TCL4 and 4.36 mm in the case of TCL5.

m and 10 σ (2.3 mm) for β∗ = 1000 m. Due to dead material an additional distance of 0.3 mm was added. For the collision optics the region of high acceptance (> 80%) is limited by pT < 0.5 GeV and 0.06 < ξ < 0.12, which is significantly smaller than for the AFP detectors. This changes drastically for the high-β∗ optics, as these settings are optimised for the elastic scattering measurement in which access to low pT values for ξ = 0 is crucial. The minimum accessible pT of the proton decreases with increasing β∗ and at high β∗ smaller t values are reached. It is worth mentioning that the minimum accessible pT depends strongly on the distance between the beam centre and the detector edge (see Ref. [40]).

Results presented in Figs. 16 and 17 demonstrate the complementarity of the acceptance between ALFA and AFP. As ALFA is designed measure the elastic scattering in dedicated high-β∗ runs its acceptance covers the region with ξ = 0. Unfortunately, this means that for the collision optics ALFA covers only small kinematic phasespace region of 0.06 < ξ < 0.12. This gap could be filled by using the AFP detectors which should measure protons with 0.02 < ξ < 0.12. In high-β∗ runs the AFP acceptance is shifted towards higher values of proton relative energy loss with the maximum value of ξ ∼ 0.17. Moreover, the high-β∗ runs where both AFP and ALFA participate will be used for studies of optics and alignment of the AFP detectors.

3.1.3 Collimators

During the LHC runs with low-intensity bunches the two collimators (TCL4 and TCL5), which are installed before the ATLAS forward proton detectors, are kept wide open. This situation is different for the high-intensity runs envisaged for a future AFP physics program – to prevent magnet quenching, the collimator jaws are set to a distance of ± 15 σ from the beam3. As illustrated in Fig. 18, such a setting would greatly reduce the AFP acceptance.

To make the measurement possible, the AFP Group requested the installation of additional TCL6 collimators in front of the Q6 magnets [7], which was done during LS1. The new collimation scheme assumes that the settings of TCL4 and TCL5 will be ± 30 σ (15.77 mm) and ± 50 σ (14.53 mm), respectively. The new TCL6 collimator is planned to be set at ± 40 σ from the beam. This solution keeps a good acceptance for diffracted protons and was accepted as a possible alternative to the present collimation scheme by the LHC Vacuum group.

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3The 15 σ distance is equal to 7.89 mm in case of TCL4 and 4.36 mm in the case of TCL5.
3.1.4 Summary

The settings of the LHC apparatus in the vicinity of the ATLAS Interaction Point are central to the physics studies that can be performed with the AFP detectors. The size of the beam at the IP determines the size of the interaction region and has a direct impact on the proton four momentum reconstruction (see Ref. [42]). The beam size at the AFP stations defines the minimal distance to which detectors can be inserted, which in turn determines the geometrical acceptance. For the AFP detectors the region of high acceptance (> 80%) is limited by:

- \( p_T < 3 \) GeV and \( 0.02 < \xi < 0.12 \) for the collision optics,
- \( p_T < 1 \) GeV and \( 0.07 < \xi < 0.17 \) for \( \beta^* = 90 \) m,
- \( p_T < 1 \) GeV and \( 0.1 < \xi < 0.17 \) for \( \beta^* = 1000 \) m.

Finally, the impact of the LHC collimators on the geometrical acceptance was discussed. Since they are wide open during the low intensity runs, they will not affect the measurements. This situation was shown to be different during higher intensity runs, which are potentially part of the AFP physics program. This is partly the reason for the installation of the new TCL6 collimators in front of the Q6 quadrupoles.

3.2 Optics Stability

The experience of ALFA [43] has demonstrated the need to allow for possible differences between the designed and actual values of the LHC optics. The elastic scattering events measured by ALFA have very constrained kinematics and provide a number of observables that are sensitive to the optics properties. This, after a lengthy analysis, yielded significant constraints on the optics. A similar analysis for the AFP detectors will be much more difficult, if not impossible. Therefore, it is important to investigate how the uncertainty in the optics affects the AFP measurements.

In the ALFA analysis, it was observed that the strengths of the quadrupole magnets can differ from the design values by 3 ‰. However, this value was found for a special, high \( \beta^* \) settings of the LHC. The currents in the quadrupole magnets for the high \( \beta^* \) optics are very different from the ones for the standard, low \( \beta^* \) running. It it natural to expect that in high \( \beta^* \) conditions the understanding of the magnets is worse. Since AFP will be running with the standard optics, in the following the uncertainty of 1 ‰ is assumed\(^4\). It is worth mentioning that strength variations of this order are very small, therefore all the effects can be considered linear.

In order to check the effect of the magnet calibration uncertainty, forward protons with different \( \xi, p_x \), and \( p_y \) values were transported through the LHC magnetic lattice for the seven following optics scenarios: i) the design \( \beta^* = 0.55 \) m optics, ii) the design optics but changing the strength of all triplet magnets (Q1-Q3) simultaneously changed by 1 ‰, and iii-vii) the design optics but changing the strength of Q1 through Q5 one at a time by 1 ‰. For each proton, the difference in its position in the design and each of the modified optics was calculated. Results are presented in Figs. 19 and 20, respectively for horizontal and vertical position components.

The results show that the change of proton position due to the change of optics depends mainly on the transverse momentum of the proton. Although some dependence on \( \xi \) can be observed, it is much less pronounced. For the horizontal position, the biggest effect is observed for changes in Q3 – the proton position changes by about 7 \( \mu \)m for every 100 MeV of \( p_x \). The sensitivity to the variations in the strength of Q2 is slightly smaller. In contrast, for the vertical component, the biggest change in position by far is observed for changes in the strength of Q2. Here, for \( p_y = 0 \) a shift of about 110 \( \mu \)m is observed. In addition, every 100 MeV of \( p_y \) changes the proton position by approximately 10 \( \mu \)m.

\(^4\)When AFP and ALFA are both participating in large \( \beta^* \) runs, ALFA elastic data can be used to constrain the optics.
The effect of changing the strengths of the triplet magnets is very different for $x$ and $y$ position components. For $p_x = 0$: $\Delta x = 0$, while for $p_y = 0$: $\Delta y \neq 0$. This is a consequence of the vertical crossing angle present in the ATLAS optics. Protons having $p_x = 0$ go through the triplet at $x = 0$ and the horizontal component of the magnetic force is zero. For the vertical component this is not true – for $p_y = 0$ there is a vertical component of the force, which depends on the strength of the magnet.

Since the $t$ spectrum of diffractive protons is steeply falling, the majority of the protons seen in the detector will have $p_T < 1$ GeV. Therefore, if the $p_T$ were not measured, a maximum possible systematic uncertainty due to optics corresponds to a 70 µm uncertainty for the horizontal position and 200 µm for the vertical position.

![Figure 19. Change of horizontal proton position due to changes in LHC optics.](image-url)
3.3 Reconstruction of Forward Protons in AFP

In the vast majority of physics analyses using the AFP detectors the important observables are the energy and transverse momentum ($p_T$) of the scattered proton. As shown in this section, the proton four-momentum at the Interaction Point (IP) can be reconstructed from the position measurements in the two AFP stations. The reconstruction procedure is not exact and several experimental effects must be taken into account. For a given LHC machine setting this determines the reconstruction resolution.

3.3.1 Proton Four-momentum Reconstruction Procedure

The reconstruction of the scattered proton’s momentum from the detector measurements can be done in various ways. Here it is performed by means of the minimisation of the following $\chi^2$ function:

$$\chi^2(p) = \frac{(x_1^D - x_1(p))^2}{\sigma_x^2} + \frac{(y_1^D - y_1(p))^2}{\sigma_y^2} + \frac{(x_2^D - x_2(p))^2}{\sigma_x^2} + \frac{(y_2^D - y_2(p))^2}{\sigma_y^2},$$

where $(x_1^D, y_1^D)$ denote the coordinates of the scattered proton trajectory position measured at the first station and $(x_1(p), y_1(p))$ – the coordinates calculated using the transport parametrisation for a proton with momentum $p$. The variables $x_2^D, y_2^D, x_2(p)$ and $y_2(p)$ refer to the positions at the second station. The parametrisation does not describe correctly the losses of particles due to the beam pipe or the collimator apertures, but this drawback is of minor importance for solving the four-momentum reconstruction problem. Proton transport is discussed in Appendix B.3.

3.3.2 Reconstruction Resolution

Using the reconstruction procedure described above, the proton kinematics at the IP can be reconstructed. Unfortunately, the procedure is not exact. First, only 4 variables are measured whereas 6 are unknown. In order to solve this problem the vertex position is fixed to be $(0, 0, 0)$. The proton position at the AFP detector station was smeared in order to take into account the detectors’ spatial resolution of 10(30) µm in $x(y)$. In addition, a conservative multiple scattering effect of 1 µrad was applied.

The precision of the momentum and energy reconstruction for the collision optics is shown in Fig. 21. In these plots the contribution of each effect mentioned above\(^5\) is presented. In the case of energy reconstruction, the main uncertainty comes from the detector resolution. The effects from lack of knowledge of the vertex and from multiple scattering are much smaller, except at the lowest $\xi$ values where the lack of knowledge of the vertex position is dominant. The reconstruction resolution grows from 5 GeV for $\xi = 0.04$ to 10 GeV for $\xi = 0.14$. These values for a given optics do not depend strongly on the center-of-mass energy ($\sqrt{s}$). In case of the proton $p_T$ reconstruction, all uncertainties contribute equally. The reconstructed $p_T$ resolution is about 0.1 GeV for $p_T < 1$.

3.4 The AFP Radiation Environment

The radiation at the 210 m from IP1 inside the tunnel has been measured at various points and has been simulated in great detail. Nevertheless, the radiation levels for the upcoming runs are hard to predict, especially inside the beam pipe aperture, and are of course subject to many factors that may also vary run-by-run.

\(^5\)In the presented plots the effect of the proton beam spread is not shown. However, its impact is known (see Ref. [42].) to be on a level of multiple scattering, thus it would not contribute significantly to the final reconstruction resolution.
All the following results were scaled to 100 fb$^{-1}$ of integrated luminosity, corresponding to one year of LHC running ($10^7$ s at $L = 10^{34}$ cm$^{-2}$s$^{-1}$). In the calculations it is assumed that the detectors are in their nominal measurement positions; if the detectors participate only in low-luminosity special runs, the fluences and doses received will be reduced by a factor of ~ 100 because of the lower dose rate received in the "parking" position. As a measure of non-ionizing radiation damage in silicon the particle fluxes (of protons, neutrons, pions, electrons, positrons, etc.) in the simulation were scaled to correspond to 1 MeV neutron equivalent ($n_{eq}$) fluence. Because the damage in silicon due to protons, pions, and neutrons is only well known up to energy of 23 GeV, equivalent fluences at higher energy were calculated assuming a similar hardness factor as for GeV particles.

### 3.4.1 Radiation at ATLAS-ALFA and TOTEM

Experience at high luminosity is available from the ATLAS-ALFA and the TOTEM Collaborations, both of which had radiation monitors on their detectors and pots. While ALFA had only a single 3-minute run at medium luminosity, TOTEM had several longer runs at high luminosity. ALFA radiation measurements, which seem to be most reliable and consistent, give doses of 10-30 Gy on the ALFA fiber detectors integrated over the 25 fb$^{-1}$ Run 1 Period [44].

TOTEM doses near the beam at 210 m can be found in Ref. [45]. TOTEM’s measured dose and fluence is $100 \pm 30$ Gy and $(2.5 \pm 1.0) \times 10^{12}$ $n_{eq}$/cm$^2$ respectively extrapolated to an integrated luminosity of 100 fb$^{-1}$. Most of the dose was received during standard running with the TOTEM detectors retracted, and the radiation doses are therefore indicative for distances of 50–100 mm from the beam.

FLUKA simulations were used to predict doses and fluences for the LHC [46]. At a few centimeters from the beam, the dose and fluences integrated over 100 fb$^{-1}$ are 200 Gy, $5 \times 10^{11}$ $n_{eq}$/cm$^2$, and $1 \times 10^{11}$ high energy hadrons per cm$^2$. These simulations are for $\beta^* = 0.55$ m optics and for beam-beam interactions only. The measured values approximately confirm the predictions from the simulations.

### 3.4.2 GEANT4 simulation of radiation environment at AFP

Experience at high luminosity from the TOTEM Collaboration shows that at normal operation conditions and nominal luminosity, the radiation resulting from colliding beam interactions dominates over all other sources. The radiation at the AFP stations has been simulated in detail using 80 mb of $pp$ inelastic cross section at 14 TeV centre-of-mass energy and a full GEANT4 simulation of the AFP and forward beam-line elements.

An example of the 2D distribution of $n_{eq}$ fluence is shown in Fig. 22 left. Two regions can be distinguished: a high-fluence central ‘line’ of diffractively scattered protons with energies mostly between 6 and 7 TeV, and a more-or-less uniform background of non-diffractive particles. This shape is due to the LHC magnet configuration between the IP and AFP. The central diffractive line reaches a maximum of $3 \times 10^{15} n_{eq}$/cm$^2$. The region outside the diffractive line is dominated by pair-produced $e^+ / e^-$ in the MeV to GeV energy range and sees an average fluence of $5 \times 10^{12} n_{eq}$/cm$^2$.

An example of the 2D distribution of dose deposited by ionization in the silicon tracker (SiT) is shown in Fig. 22 right. The deposited dose along the dense ‘line’ of diffractive protons has a maximum value of 700 kGy. The average dose in the non-diffractive region is 3 kGy.

The equivalent fluences of 1 MeV neutrons at larger distances from the beam are significantly different. An example of the 2D distribution of equivalent fluence is shown in Fig. 23. The equivalent fluence outside the beam-pipe at the parking position is $4 \times 10^{11} n_{eq}$/cm$^2$, i.e. ten times lower, and is again dominated by electrons and positrons. However, not all dead material around the beam-pipe
Technical Design Report
May 20, 2015
ATLAS
Forward Proton Phase-I Upgrade

(flanges, bellows, supports) is implemented in the full simulation and the calculated radiation outside
the beam-pipe is therefore only approximate.

3.4.3 Summary

From all information listed above, doses and fluences are assumed as listed in Table 4.

<table>
<thead>
<tr>
<th>Position</th>
<th>5 mm from beam</th>
<th>5 cm from beam</th>
<th>Tunnel Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics type</td>
<td>3D sensor &amp; FE-I4</td>
<td>PA-a</td>
<td>PA-b, Trigger, CFD, HPTDC</td>
</tr>
<tr>
<td>High-energy hadrons</td>
<td>&lt; 5 x 10^{15}/cm^2</td>
<td>5 x 10^{12}/cm^2</td>
<td>1 x 10^{11}/cm^2</td>
</tr>
<tr>
<td>n_{eq}</td>
<td>&lt; 3 x 10^{15}/cm^2</td>
<td>3 x 10^{12}/cm^2</td>
<td>5 x 10^{10}/cm^2</td>
</tr>
<tr>
<td>Dose</td>
<td>&lt; 700 kGy</td>
<td>200 Gy</td>
<td>50 Gy</td>
</tr>
</tbody>
</table>

Table 4. High-energy hadron fluence, fluence of 1 MeV equivalent neutrons, and doses integrated over
100 fb^{-1} assumed at the AFP position of 210 m from IP1 at the transverse positions indicated. The fluences
and dose at the 5 mm distance are the local maxima along the diffraction line in previous figures; the fluences
and dose at the other positions are averages over 1 dm^2.

The electronics closest to the beam is the FE-I4b front-end chip on the 3D silicon sensors, where
the dose and fluence is 700 kGy and 3 x 10^{15} n_{eq}/cm^2 respectively, still below levels expected for the
ATLAS IBL detector. The FE-I4 chip was tested up to 2.5 MGy and 5 x 10^{15} 1 MeV n_{eq}/cm^2 [47].
The IBL collaboration studied uniform irradiation of the 3D sensors and the FE-I4 chip. Dedicated
non-uniform irradiation studies have been performed to qualify the 3D sensors and the FE-I4 chip
for AFP, see Sect. 4.5.

The next closest electronics is the first stage preamplifier PA-a on the time-of-flight detectors at a
distance of 100 mm, covered by the TOTEM measurements. All other electronics, including voltage
regulators, will be located below the detector on the tunnel floor. In the appropriate sections of this
TDR the electronics irradiation tests are discussed, performed to verify adequate radiation hardness
and tolerance.

3.5 Radiation Protection and Safety

The activation of the AFP detector stations and detector components in the tunnel is a serious
concern. While the estimated doses as function of distance from the beam have been calculated
and partially measured, these numbers are based on simulations and extrapolations to 6.5 TeV
beam energy. The received dose varies significantly with the collimator settings of TCL4, TCL5, and
TCL6.

Hence, the discussion on radiation protection and safety around the AFP stations and detectors
is based on the general rules and procedures established by the ATLAS TC radioprotection person-
nel in close collaboration with the CERN radioprotection group. The general rules for radioprotection
at CERN are described in Safety Code F. The general ALARA (As Low As Reasonably Achievable)
principles are given in the Règles Generales de Sureté. These rules intend to minimize exposure of
personnel and to minimize the generation of radioactive waste.

A few scenarios are considered in which personnel are exposed and radio-activated material
from AFP needs to leave the tunnel.

3.5.1 Installation

Exposure to activated elements of the LHC ring around the 210 m area reserved for AFP is expected
for the first part of installation of the AFP in the tunnel: the installation of the AFP beam pipe with
dummy pipe sections as placeholders for the Roman pot stations. This involves the dismantling of the existing, possibly activated, beam pipe section in the 210 m area between Q5 and TCL6. Therefore work in the area will be strictly supervised by the radioprotection group to ensure that hourly and integrated dose limits are respected. Access for installation will only be granted after a reasonable ‘cool-down’ period has passed and radiation levels are deemed acceptable for work. In particular, the areas around Q5 and TCL6 will have to be strictly monitored. Area radiation monitors will be installed around the station locations as part of the AFP installation, and these will help in monitoring the area in subsequent accesses. The activated beam pipe section that is removed from the tunnel will be stored in a radiation zone on the surface for cool-down in accordance with the standard procedures for such material.

As the installation proceeds, the radiation from activation is expected to go down, and the Roman pot stations, the cable patch panels, the cable trays and cables, and the services (vacuum pump, cooling, crates, power, and electronics) will be installed. Again, this will be done under supervision of radioprotection and following strict guidelines of radioprotection and ALARA.

3.5.2 Access for Detector Installation
ALFA and TOTEM experience shows that access to install the detector inserts in the Roman pots is, if well-prepared, a matter of a 6-hour access. This presupposes training of personnel executing the maneuver with help of a mock-up or prototype station. It also requires that the detector infrastructure is very well prepared: patch panels and patch cables, cooling and cooling connections, secondary vacuum and connections, power connections, sensor cabling, and signal cabling to the readout and electronics. Therefore, AFP intends to perform a ’dress rehearsal’ installation of the detector package before the actual installation in the tunnel. In order to ensure lowest possible exposure in the tunnel, every step of the installation process of the Roman pot stations and the AFP infrastructure and services must be prepared and vetted thoroughly, well in advance of the actual installation.

3.5.3 Access for Repairs
Access for urgent repairs will have to be coordinated with and approved by ATLAS TC and radioprotection personnel. A clear description of the work flow, check list of work steps with time estimates, tooling required, waste generated, and instrumentation or components brought in or removed from the tunnel, must be provided before the access and must be reviewed by the radioprotection group. A report on the access must be done after the access is finished. Here again, a rehearsal of any new intervention will be important to reduce exposure in the tunnel.

Materials brought out of the tunnel must be scanned and stored in a radiological buffer zone until it either is declared safe, or can be stored until safe, or can be disposed of as radioactive waste with the proper classification.

3.5.4 Removal of Roman Pot Stations in LS2
Roman pot stations of TOTEM and ALFA have been removed during LS1 for refurbishment on the surface. After a cool-down period of several months, the stations were safe to remove from the tunnel and personnel could handle the stations and equipment freely in the lab without the need for radiological protections. The activation levels of the stations during Run 2 is currently unknown, but it may well be that the levels will be four times higher than observed after Run 1. The dose rates and integrated dose at and near the stations will be monitored to decide what steps to take if stations need to be removed at the end of Run 2.
Figure 20. Change of vertical proton position due to changes in LHC optics.
**Figure 21.** The resolution of the reconstructed proton energy (left) and transverse momentum (right). The experimental effects taken into account are: the AFP detector spatial resolution, the lack of information about the vertex coordinates, and multiple scattering.

**Figure 22.** (a) Equivalent fluence of 1 MeV neutrons through the SiT at 212 m. (b) Ionization dose deposited in the SiT.
Figure 23. The equivalent fluence of 1 MeV neutrons at the 212 m position. The circle corresponds to the wall of the 80 mm diameter beam pipe, and the rectangles to the parking and working positions of the SiT.
4 The AFP Detector

In this section the AFP detectors are discussed, beginning with an overview of the layout of the AFP arms, followed by a description of the single-arm layout anticipated early in Run 2. The extensive simulations of the AFP layout are discussed, followed by descriptions of the beam interface, the silicon tracker (SiT), and the time-of-flight (ToF) detector.

4.1 Overview

The ATLAS Forward Proton detectors aim to measure protons that are emitted from a central interaction in the very forward directions. Protons suffering a moderate energy loss and emitted at µrad angles with respect to the beams will remain inside the beam pipe but separate from the beam axis because of the accumulated dispersion in the beam elements. At 200 m from the ATLAS IP, they will be sufficiently separated from the nominal beam orbit so that they can be intercepted by Roman pots inserted into the beam pipe aperture. The deflection of the proton depends on the magnitude of the energy loss suffered, and also on the emission angle at the IP. The chosen AFP locations are selected because they are available (i.e. empty of essential beam elements and instrumentation), and because they are located at positions of sufficient integral dispersion to make interception and measurement viable.

To characterize the emitted proton fully, two measurements are required: the measurement of transverse position and the measurement of the local angles. Together, these measurement give the proton fractional energy loss \( \xi \) (\( \xi \equiv 1 - E_{\text{proton}}/E_{\text{beam}} \), where \( E_{\text{proton}} \) is the proton energy and \( E_{\text{beam}} \) is the nominal LHC beam energy), and on the four-momentum transfer squared \( t \), a function of the emission angle \( \theta \) (\( \sqrt{-t} \approx 2 \sqrt{E_{\text{proton}}E_{\text{beam}} \sin \theta/2} \)), see Sect. 4.3.5.1. Together with the intervening beam optics, these variables fully determine the emitted proton’s momentum four vector.

4.1.1 The AFP Layout

The locations available to AFP are at distances along the beam line between 204 m and 217 m from the ATLAS interaction point (IP) on both sides. They are shown in Fig. 24 and lie between the Q5 and Q6 quadrupoles. The ALFA stations are located behind the Q6 quadrupole, at locations around 240 m.

Another set of locations is available at a distance of 420 m. At that position, protons with lower \( \xi \) (\( \sim 0.002 - \sim 0.02 \)) can be measured, and the AFP acceptance would shift towards much lower diffractive masses. The 420 m positions lie inside the cold region, and while the cryostat is empty of beam elements in that location, its replacement by a cold transition cryostat is costly. Because of space constraints, the detector stations at 420 m must be smaller in size than the standard Roman pot stations considered for the 210 m locations. Finally, stations at 420 m are too far from the ATLAS IP to deliver a trigger signal in time to fit inside the current ATLAS Level-1 trigger latency.

AFP proposes to install its four Roman pot stations two on either side, denoted as the “2+2” configuration, during the Winter 2016-2017 shutdown. As a path towards the final set-up, the early installation of a single arm is proposed, the “0+2” configuration. This would allow performing part of the approved low-luminosity program while gaining crucial experience with and making exploratory measurements of the beam environment at higher luminosity. The proposed installation scenario is discussed in Sect. 4.2.

Radiation levels at the 210 m locations are important to the design and operation of AFP. While the levels outside the beam pipe are relatively well known from LHC radiation monitors around the beam pipe and in the vicinity of the ALFA detectors, the radiation environment inside the beam pipe
aperture is poorly known and is strongly dependent on distance to the beam, the beam optics, and the position of collimators.

4.1.2 Detector and Beam Interface Requirements

Requirements on the detector performance derive from the physics, and they will be different for different physics processes considered. The most demanding requirements arise when Double Pomeron (or Photon) Exclusive processes are considered, where two forward protons are emitted and a central system is produced in the ATLAS central detector. Such processes are rare and high luminosity running is required to study them. Such processes are taken as benchmark for the determination of detector and Beam Interface requirements.

From ALFA and TOTEM experience, it is evident that there is a significant physics background from soft single diffractive protons, while very close to the beam, at $5\sigma$ or less, the beam halo background rises sharply. It is foreseen that the distance of closest approach $d_x$ will be determined empirically under LHC control. The value of $d_x$ will depend on the beam optics (i.e. on $\beta^*$), on the luminosity or the mean number of interactions per bunch crossing $\mu$ (i.e. on number of protons per bunch, number of bunches, and the $\beta^*$, and on the cleanliness of the beam (i.e. the scraping history, lifetime, and store duration). Also, in case luminosity leveling is implemented at the highest luminosities, this introduces an additional factor in determining $d_x$.

4.1.2.1 Distance to the LHC beam  For many processes it is attractive to minimize $d_x$ as the cross section behaves as $1/\xi$. Fortunately, most such processes have high cross section and these can be studied at low or medium $\mu$. Thus ‘edgeless’ detectors are much preferred, because the distance $d_x$ is measured between the beam center and bottom of the Roman pot facing the beam. The effective $d_x^{effective}$ that sets the minimum measurable proton energy loss $\xi$ equals $d_x$, augmented with the beam window thickness and the size of the insensitive detector edge facing the beam.
4.1.2.2 Detector Accuracy and Resolution  
For most diffractive processes a good accuracy and resolution of the scattered proton in the transverse directions is important. Especially for the rare Double Pomeron/Photon Exchange processes it is crucial to have the best possible hit accuracy and resolution. Therefore the single station hit accuracy and resolution goal is set to 10 µm in x (horizontal), and to 30 µm in y (vertical). This resolution can be obtained using several planes of 3D pixel detectors, which have pixel size of 50 µm (x) × 250 µm (y). Four successive pixel detector planes, offset by a fraction of the pixel size in x and in y would provide the required resolution. It also implies that the positioning of the detector planes should be done with an accuracy of 10 µm or better, and that the detector package must be aligned with the same or better accuracy. In Sect. 8 possible alignment strategies of the pots are reviewed. In Sect. 4.5 the silicon 3D tracker is discussed, and in Sect. 4.5.4.3 its positioning procedure inside the Roman pot.

4.1.3 The AFP Beam Interface  
The search for a suitable beam interface started within the framework of the FP420 collaboration. Because of the tight constraints at 420 m, the beam interface of choice was the Hamburg beam pipe (HBP), a movable section of beam pipe with a thin “floor” and entry/exit windows that would allow the detectors to approach the LHC beam as close as a few mm’s. This design was fully engineered and its RF impact on the LHC beam evaluated. With sloping entry and exit windows (similar to the sloping collimator jaws in use at the LHC), the RF impact was shown to be equivalent to that of a Roman pot. With the use of beryllium or aluminum windows, the interaction length of windows and floor was shown to be acceptable.

However, the HBP device has not been used previously at the LHC and is therefore considered more risky. Moreover, the cost of a single HBP Station is estimated at 300 KCHF, about three times that of a Roman pot station. Roman pots have been used successfully at the LHC from the start, and a proven design that meets the AFP requirements exists. Hence, the AFP baseline beam interface chosen for the 210 m stations is the Roman pot. This device is discussed in detail in Sect. 4.4.

4.1.4 Tracking Detectors  
The AFP tracking detector must be able to approach the circulating beam closely, and therefore an “edgeless” device is required. The required resolution is 20 µm in the transverse direction. The radiation environment is more benign than for the first layers of the ATLAS inner tracker, but the irradiation varies strongly as function of the distance to the circulating beam. Because of the above requirements, the AFP baseline tracker device is the 3D silicon pixel tracker, used for the ATLAS IBL tracker [47, 48]. In addition, the choice of the 3D sensor allows the use of the well-tested FE-I4b frontend chip and indicates the use of the RCE-based DAQ system (see Sect. 5.2) used extensively for the 3D sensor testing. Beam tests by AFP have shown that the 3D sensors accommodate uneven irradiation without degradation. The AFP tracker is discussed in detail in Sect. 4.5.

Development is needed for the high-density interconnect from the FE-I4b chips to the optical I/O driver interface, and the precision holder for the 4-5 layers of tracker sensors.

4.1.5 Time-of-Flight Detectors  
When the average number of interactions per bunch crossing, µ, increases, forward proton time-of-flight information becomes necessary to reject backgrounds. The level where timing becomes needed depends on the process under study, see for example the improved purity that can be
reached with timing in the DPE-dijet process shown in Fig. 11. The background stems from protons (measured in the two AFP arms) that come from different interactions in the same bunch crossing, i.e. from “pile-up”. Precision proton time-of-flight measurements $t_{\text{Right}}$ and $t_{\text{Left}}$ in the Right and Left AFP detector arms permit the determination of the longitudinal origin of the proton pair as $z_{\text{AFP}} = c(t_{\text{Left}} - t_{\text{Right}})/2$. The matching of $z_{\text{AFP}}$ with interaction vertices measured by the ATLAS tracker provides rejection of pile-up vertices if the time-of-flight resolution is sufficiently small.

In Sect. 4.6 the baseline AFP time-of-flight detectors is discussed in detail. The proposed Quartz Cerenkov detectors are segmented and thereby able to provide a Level-1 trigger with an estimate of the proton energy loss $\xi$. The timing resolution is shown to be better than 20 ps, and the radiator, photodetector, and associated analog and digital electronics are sufficiently radiation hard.

For the AFP low-luminosity physics program, a time-of-flight detector is not required. In particular, for the first AFP phase consisting in a single-arm two-station set-up, the time-of-flight system is of no great use except possibly for triggering. However, installing a time-of-flight detector from the very beginning will yield valuable operational experience with the detector, and allow the characterization of the time profile of the protons from central interactions and from various background sources.

### 4.2 The AFP Detector for Run 2

The AFP physics program will start with special runs at low-$\mu$, focusing on high-rate diffractive physics processes. Moreover, the first running with the horizontal AFP pots will be needed to debug the detector as well as explore the environment close to the LHC beam. While both ALFA and TOTEM have collected data in special and standard runs in Run 1, the AFP detector is sufficiently different that exploratory running is needed.

The most likely AFP plan, in view of the AFP financial resources and time constraints, is to install in two stages. The first stage would be the installation of a single AFP ‘arm’ with two Roman pot stations, the ‘0+2’ AFP configuration (AFP0+2). With the AFP0+2 configuration, single diffraction physics data could be taken in low-$\mu$ special runs. From the detector viewpoint, these runs would also allow for detailed detector debugging and commissioning, as well as a careful study of the beam environment. AFP0+2 only contains tracking, because time-of-flight detectors are not required for the single-arm physics program.

The aim would then be to install the AFP0+2 detector during the Winter 2015-2016 shutdown, which is currently estimated to last 9 weeks. This installation period is uncomfortably close in view of the required construction task. Moreover, the short shutdown duration may not be sufficient for a radiologically safe access for the installation of two RP Stations with all the requisite infrastructure such as cables, cooling, secondary vacuum, motion controls, and monitoring sensors. While the AFP0+2 installation schedule is certainly ambitious, it is felt strongly that the rewards of an early installation would be significant. It must be noted, that the installation time is dominated by the RP Station installation and the installation of the infrastructure, in particular the long cable installation from the stations to USA15. Based on ALFA and TOTEM experience, the detectors themselves can be installed or exchanged during a short 6-hour intervention.

The full AFP2+2 configuration would be reached by installation of the second detector arm during the Winter 2016-2017 shutdown, which is projected to last 19 weeks.

#### 4.2.1 The AFP0+2 Detectors

The detectors that would be installed for a start-up AFP0+2 configuration are two silicon tracking detectors and a Level-1 Trigger. The tracking detectors are the baseline 3D silicon trackers described in Sect. 4.5 consisting of four 3D sensor layers each. The early AFP trigger will be provided by the a
majority coincidence of hit tracker planes. The majority coincidence will be sent to the ATLAS central trigger processor.

After installation of the time-of-flight (ToF) detector, see Sect. 4.6, a fast majority trigger signal is available from the time-of-flight hodoscope, which incorporates high resolution timing information as well as a rough estimate of the energy loss of the triggering proton. The ToF detector is not required for AFP0+2, but will be needed for background rejection in the later AFP2+2 configuration at high luminosity. However, early installation of a ToF detector is desirable for reasons of background timing studies and might be attempted if the schedule permits.

4.2.2 AFP0+2 Installation

As noted above, the time-critical items for AFP installation are the installation of the RP Stations and the installation of the infrastructure for a single arm. The infrastructure is mostly common for the two stations in a given detector arm, and therefore the AFP0+2 configuration provides significant cost savings over a AFP1+1 configuration while allowing good physics and exploratory measurements to be made.

The installation of the AFP Stations and its infrastructure requires an extensive preparation in terms of procurement of the proper cables, documentation of the work (workpackage), and documented coordination with the proper divisions of the LHC well ahead of the actual installation period. Engineering Change Request (ECR) documents are required for each task. While such ECRs have been done for ALFA and TOTEM, AFP will require approval of its own set of ECR documents by the LHC. From past experience, the time required for an ECR to be approved is of order 2-3 months, as it goes from ATLAS Technical Coordination (TC) to the CERN Engineering (EN) division, through the LHC Machine Committee (LMC), to final sign-off.

4.2.2.1 RP Station Installation

The installation of a single Roman pot requires a number of significant engineering interventions in the LHC machine, see Table 5. As for the ALFA Stations, AFP will prepare a ‘dummy’ beam pipe (BP) section that can replace an RP station in the case of an emergency that requires a RP Station to be taken out of the machine. The full 9 m BP section that contains both RP stations (or the dummy BPs that replace them) is bracketed by a pair of Ultra-High Vacuum (UHV) isolation valves that permit interventions without breaking the vacuum in the rest of the sector. The precision Beam Position Monitor (BPM) is part of the new 9 m replacement BP section and is connected directly ahead of the 212 m station, ‘inside’ the isolation valves.

<table>
<thead>
<tr>
<th>Task</th>
<th>Task description</th>
<th>Time estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Isolate BP sector</td>
<td>1 hr</td>
</tr>
<tr>
<td>2</td>
<td>Break vacuum</td>
<td>2 hr</td>
</tr>
<tr>
<td>3</td>
<td>Remove BP</td>
<td>4 hr</td>
</tr>
<tr>
<td>4</td>
<td>Install new BP</td>
<td>8 hr</td>
</tr>
<tr>
<td>5</td>
<td>Sector Pump down</td>
<td>7 days (?)</td>
</tr>
<tr>
<td>6</td>
<td>Install RPs</td>
<td>4 days</td>
</tr>
<tr>
<td>7</td>
<td>RP Pump Down</td>
<td>7 days (?)</td>
</tr>
</tbody>
</table>

Table 5. List of LHC engineering intervention tasks for required for AFP Roman pot station installation. Notes: BP=Beam Pipe; RP dummy=BP section placeholder for a RP station. Each RP dummy has a set of UHV isolation valves allowing its replacement with an RP Station.

The RP Stations must be fully certified by the LHC before installation and this will take of order one month. Required certification procedures are He-leak testing, over-pressure test, emergency
extraction of the pot, motor tests, and the certification of the position transducers and limit switches. The certification must be accompanied by a description of the implemented accident prevention and mitigation. This includes a detailed description of the installation procedure (steps listed in Table 5) and the de-installation procedure in the (unlikely) case a RP Station prevents proper LHC operation. Fortunately, AFP can use the ALFA and TOTEM installation experience and use their procedural and certification documents as perfect examples.

4.2.2.2 Installation of Single-Arm Infrastructure With the proper preparation, detector installation is relatively fast, about half a day, as it involves the installation of the feed-through plate which supports the AFP detector(s). The lengthiest part of the detector installation is the hook-up and testing of the signal and DCS cables, and the services for vacuum and cooling. Especially the first-time hook-up will be lengthy because it includes the first-time cabling from patch panels and equipment and must be done carefully. If installation time is strictly limited, a ‘dry-run rehearsal cabling’ must be prepared and done beforehand in the laboratory, such that the cables, their lengths, and their routing are well determined and tested ahead of the installation in the LHC tunnel. This involves a mock-up of the LHC environment around the AFP station.

Further interventions in the LHC tunnel are required to install the necessary infrastructure to operate the RP Stations and the AFP detectors. This infrastructure contains both the cables for signals, power, and controls; as well as equipment in the tunnel necessary for operating the detectors, see Tables 13 and 6 in Sect. 6.2. Preparation for the installation will involve the mock-up mentioned above.

The cable patch panel and ancillary equipment installation tasks must await the completion of the RPS installation, but can proceed in parallel with the beam pipe and RPS bake-out and pump-down. During bake-out, the detectors are not installed and the RP is open to the atmosphere. Detector installation takes place only after the proper beam vacuum is reached as certified by the LHC.

Ancillary equipment in the LHC tunnel is required for proper AFP operations and consists of 1) the Beam Position Monitor (discussed above); 2) the vacuum pump system for the secondary vacuum that must be maintained inside the RP; 3) the AirCooler cooling system that cools the RP and the silicon detectors inside the RP; and finally 4) the local support electronics and power systems below the detector on the tunnel floor. A preliminary installation schedule of this equipment is listed in Table 6.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Task description</th>
<th>Time estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Beam Position Monitor</td>
<td>Installation with new BP and RPS (see Table 5)</td>
<td></td>
</tr>
<tr>
<td>2 Vacuum pump</td>
<td>Vacuum pump for secondary vacuum in RP</td>
<td>2 day (?)</td>
</tr>
<tr>
<td>3 Cooling</td>
<td>Vortex cooling (AirCooler II) for the RP</td>
<td>1 day (?)</td>
</tr>
<tr>
<td>4 Electronics</td>
<td>Electronics for signals, monitoring, power</td>
<td>4 days (?)</td>
</tr>
<tr>
<td>5 Commissioning</td>
<td>Commissioning of services &amp; electronics</td>
<td>1 week (?)</td>
</tr>
</tbody>
</table>

Table 6. List of ancillary AFP equipment installation tasks in the LHC tunnel. Some of the installation tasks may be done in parallel.

4.2.3 AFP2+2 Installation

The full AFP program, both for low-μ as well as for the high-μ physics, requires the precision time-of-flight detectors for removal of pile-up background and purification of the data sample. The AFP2+2 installation will essentially be a 2016 repeat of the single-arm production and installation effort in 2015, with the advantage that all steps have been done already for one arm. If AFP0+2 installation...
was not attempted in the Winter 2015–16 shutdown, the AFP2+2 installation would proceed as a single two-arm installation step in the 19 week Winter 2016–17 shutdown period.

4.3 AFP Detector Simulation

The Roman pot (RP) (see page 48 and Sect. 4.3.2.1) has been selected as the AFP beam interface, with detectors placed at 205 m and 217 m from the ATLAS IP. The space constraints inside the Roman pot force a modification of the original Quartz Cherenkov timing detector [49] proposed for AFP, which has straight radiator bars mounted at the Cherenkov angle with respect to the beam.

In the following sections a description is given of the ATLAS forward region and the AFP detector components: the RP, the silicon tracker (SiT), and the time-of-flight detector (ToF). The simulation described here assumed the stations to be located at 204 m and 212 m as described in the original AFP LoI. The new locations promise slightly improved acceptance and resolution compared to the results presented here.

The AFP data/algorithm model is presented with details on digitization, reconstruction for both SiT and ToF, together with so-called AFP fast timing simulation. The event storage in the analysis data files (D3PD) is explained in the last section. The structure of the AFP data in the new ATLAS Object Data format (xAOD) will be the same. Using the full simulation machinery, the detector performance is presented together with a discussion of radiation and background conditions.

4.3.1 Forward region & AFP simulation

In order to calculate particle positions and momenta as a function of hit position, mapping tools are commonly used. Such tools take particles from an event generator or particles simulated by Geant4 inside ATLAS volumes and calculate the expected hit positions and momenta using matrices that describe the magnetic optical lattice in the forward region.

Forward region packages [50] allow full Geant4-based simulations of particles in the forward region of the ATLAS experiment. This enables the simultaneous simulation of all forward detectors, i.e. in addition to AFP also of the ZDC (Zero Degree Calorimeter) and ALFA (Absolute Luminosity For ATLAS) detectors.

There are several advantages of such an approach. First, the full simulation runs under Geant4 and therefore the simultaneous simulation of multiple forward detectors is possible. Next, secondary particles emerging in the forward region are simulated. For example, showers developing on beam screens of magnets can be studied. Furthermore, it is possible to move and rotate magnets and vary their fields to study effects of such displacements and field variations. However, the calculational speed of such full simulations is typically very slow: the simulation of a thousand events may take few hours when using the full physics list. In contrast, the mapping algorithms are very fast and the processing of a thousand events on the same computer will take a few seconds.

A validation of the full simulation against the existing tools — Mad-X [51, 52] and ALFA_Beam-Transport — was done and the difference of transport using the presented model is less than 0.3 µm.

4.3.2 Detector model & AFP GeoModel

4.3.2.1 Roman pot model After studies of RF impedance and considerations of cost the Roman pot beam interface was chosen as the AFP baseline. This forced changes in the construction of the detectors, especially of the quartz radiator Cherenkov timing detector. The model based on the Roman pot was incorporated in the simulation, see Fig. 25.
4.3.2.2 Silicon detector  An initial model of the SiT has been augmented by water cooling \[53\]. The model was later changed into the newest design \[54\].

The final version of the detector will consist of 4 layers staggered in the $x$ and $y$ directions to achieve best spatial & angular resolutions. (The requested detector resolution, set by physics analysis goals, is 10 $\mu$m in the $x$ direction.)

On the basis of earlier studies (using non-tilted planes and pixels of $50 \times 250$ $\mu$m$^2$) \[55\] and because after tilt of the SiT planes by $\sim 13^\circ$ their detection efficiency is close to 100%, already 4 silicon planes should provide the required resolution and efficiency for the intended physics measurements and studies.

AFP’s GeoModel tool allows parameterized staggering of planes in both horizontal and vertical directions together with horizontal movement of detectors (the direction of the horizontal Roman pot motion) and overall vertical positioning.

4.3.2.3 Time-of-flight detector  In the simulations the quartz timing detectors \[49\] are implemented. An example of the signal (Cherenkov photons induced by a proton) is shown in Fig. 26.

A full parametrization of the Quartic detectors exists via Athena JobOption control scripts - it allows various functions, e.g. to change number of trains, dimensions of bars, spacing, etc. If two quartz ToF detectors are used, their parameterizations in JobOption are independent \[56\]. The material properties of quartz were mostly taken from \[49\].

Since the simulation of optical processes in GEANT4 is very time-consuming, a Fast Cherenkov model of the quartz radiator bars has been implemented \[57\], which speeds up the simulation by
Necessitated by the adoption of the RP beam interface for AFP, a new radiator shape, the “LQbar”, was devised. It is derived from a modified Lbar design [49]. Several LQbar types, see Fig. 27, were implemented in Geant4 which allowed the comparison of benefits and drawbacks in light dispersion and losses, and estimates of signal strength [58].

The results of existing simulations are in agreement with results from beam tests in CERN, see Sect. 7.

### 4.3.3 AFP Data model

The AFP data model was implemented in the ATLAS data processing and analysis framework (Athena) and provides AFP simulation hit collections and a corresponding digitization output, coming from both the SiT and the ToF. Hit collections store information about hit position, time, deposited energy, and other parameters needed to resolve affected detector [59] such as the detector ID number or pixel position in the SiT. There is one hit/digitization/reconstruction collection per detector type.

The digitization collection [60] for the SiT stores the ID number of the station, the sensor planes, and the pixels that were hit; and for the ToF contains station ID number, the detector and the bar ID numbers that were hit, together with the amplitude of the signal and the constant fraction discriminator time.

The reconstructed SiT information, stored in the corresponding collection, contains values of track coordinates and slopes, information about the algorithm used, detector ID numbers, the number of hits and gaps used for track reconstruction, and the quality of the reconstructed event.

Similarly, the reconstructed ToF detector information consists of the algorithm used, the detector ID, train ID, reconstructed time for a given train of radiator bars, the number of bars used in the train and possible pulse height saturation information of the bars.

The structure of the AFP Derived Physics Data (D3PD) ntuple reflects the content of the above-mentioned collections which are stored in corresponding data objects. The information is completed by the Truth data object for simulated events.

The AFP information in the new Run 2 ATLAS Object Data (xAOD) files will be structured in the same way.
4.3.4 Digitization of Hits

The AFP digitization algorithm was written within the general ATLAS scheme which includes the possibility to add pile-up events. Prior to the digitization stage, GEANT4 hits from pile-up are overlaid to simulate the expected bunch spacing and number of bunch-crossings.

4.3.4.1 Digitization in the Silicon Tracker

For reasons of speed and flexibility, we treat each silicon sensor as a single sensitive volume and there is no physical splitting into pixels at this step. The start and end positions of each hit (in the global coordinate system of the ATLAS GeoModel) are transformed into local sensor coordinates. In the digitization step, the full track stub is split over corresponding pixels and for each pixel its coordinates (in pixel units: row and column numbers) and deposited energy are stored in the output data record. Since an electron-hole pair is produced for each 3.6 eV of deposited energy, the number of carrier pairs in each pixel is calculated in the AFP_Digitization algorithm. The pixel fires in case the number of pairs is higher than a pre-set threshold. At present, noise is not included in the AFP silicon digitization (and therefore no fake hits are generated). The expected noise is much lower than the threshold; a fact confirmed by all existing test beam measurements. Nevertheless, noise (e.g. due to different conditions in the LHC tunnel) could be added in future. For each pixel, its coordinates (in pixel units: row and column number) and deposited energy are stored, together with the ID numbers of the station, detector (sensor plane) and, for future purposes, pixel discriminator time.

4.3.4.2 Digitization in the Time-of-Flight Detector

For the time-of-flight (ToF) detectors, the number of Cherenkov photons and their arrival times is collected. The response of the photomultiplier tube (PMT) to the Cherenkov photons is used to calculate the PMT output signal shape, and the signal is subsequently processed with a constant fraction discriminator (CFD) function to obtain a digital representation of the pulse time (TDC). A digital representation of the pulse amplitude (ADC) is also recorded.

Each photon is allowed to convert to an electron with a probability which is the product of two factors: a wavelength-independent geometrical collection efficiency (60%) and a wavelength-dependent quantum efficiency of the PMT photocathode (<25%). The conversion of a single photon to an electron is simulated by time-smearing (rms 40 ps) and by adding a delay (200 ps) to the signal start time. Next, each electron is a source of a cascade of a Poisson-distributed number of electrons (a relatively small gain of $5 \times 10^4$ was assumed) which form a pulse with rise time (400 ps) and fall time (400 ps). The pulse peak value is calculated as the highest number of electrons per 5 ps time bin observed in the pulse. The TDC time is calculated as the time when the pulse surpasses a constant fraction (50%) of its peak value as shown in Fig. 28. All parameters in the digitization algorithm can be changed via the Athena JobOption control file.

During the reconstruction step, all PMTs with a peak value above threshold in a single row of quartz radiator bars are used to estimate the arrival time of a track candidate. In the simulation, the bars are considered fully independent detectors.

The development of timing detectors is continuing and the same is true for the corresponding digitization algorithms. An up-to-date and detailed description of digitization and reconstruction steps will be given in the next AFP software note [61] and published at an appropriate time.

4.3.5 Reconstruction of SiT & ToF

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6 The smearing by 40 ps covers the effect of the PMT transit time jitter only. Contributions from the pre-amplifier, CFD, and High Precision Time Digital Converter (HPTDC) are not yet implemented.
4.3.5.1 Silicon tracker reconstruction For track reconstruction from silicon tracker hits, the Kalman filter [62] technique was employed. This approach minimizes the mean square estimation error, and is the optimal estimator of the state vector of a linear dynamical system.

In case of the AFP SiT, a track pattern can be described by its 4-D state vector (straight-line motion), which can be parametrized as follows:

$$\mathbf{x} = (x, \frac{dx}{dz}, y, \frac{dy}{dz})^T,$$

where $x$, $y$ and $z$ are the spatial coordinates in the ATLAS coordinate system and $z$ is the direction along the beam. In its linear form, the evolution of the state vector is described by the discrete system of linear equations:

$$\mathbf{x}(z_k) \equiv \mathbf{x}_k = \mathbf{F}_{k-1} \mathbf{x}_{k-1} + \mathbf{w}_{k-1},$$

where the matrix $\mathbf{F}_{k-1}$ relates the state at detector plane (step) $k-1$ to the state at step $k$. A random variable $w$ describes the noise which can account, for example, for the effect of multiple scattering on the state vector.

Typically, there are 20 or fewer hits per tracker. Therefore, to save disk space and CPU power, the track reconstruction algorithm is invoked only if there are fewer than 1000 hit pixels in a given tracker - otherwise this is considered the signature of a particle shower.

4.3.5.2 Time-of-flight detector reconstruction In order to reconstruct a time from the Time-of-Flight (ToF) detector, only radiator bars with at least 10 effective photo-electrons are considered. The ToF track is formed from a straight train of bars above threshold. The time associated with the ToF track is calculated as an average of times measured with unsaturated bars in the track. Corrections for the different $z$-positions of the bars are applied (1 ps between adjacent bars). Finally, a correction for the $y$-position of the proton track is applied if the $x$-position of the reconstructed SiT track matches the position of the reconstructed ToF track.
4.3.6 Background Simulations

AFP aims to measure protons originating from primary interactions at the ATLAS IP. In that sense, real primary protons from soft or 'pile-up' interactions in the IP form part of the genuine physics signal and are, for low-luminosity runs, an interesting component of the AFP physics program. For the high-luminosity program AFP-Phase I, which is not the main part of the AFP-Phase 0 program, pile-up protons are a physics background that must be rejected by fast time-of-flight and kinematic cuts.

The most important quality criteria for the AFP measurement are the proton efficiency and background signal rate. The proton efficiency is defined as the fraction of protons that would have reached the AFP geometric acceptance but are lost or badly measured. Intimately connected to this is the rate of background particles seen in the AFP detectors. In the following sections sources of AFP backgrounds, proton efficiency, and ambiguities in the AFP measurements are discussed.

4.3.6.1 Backgrounds

While the AFP signal consist of primary IP protons, the AFP background consists of particles (protons or other particles like electrons, pions, muons) detected in the AFP, but that do not directly originate in the IP. This background has multiple origins and can be categorized as follows:

**Beam halo:** protons/particles that travel with the core of the bunches for a significant fraction of a turn up to many turns, before (typically) being intercepted by an AFP detector along the way. Beam halo in this sense, consists of protons/particles in the 'wings' of the beam profile distribution, and the amount of halo intercepted is strongly dependent on the distance of closest approach of the pot bottom to the circulating beam. Beam halo is reduced (temporarily) by scraping (via collimators) but is subsequently replenished by electromagnetic beam-lattice scattering, intra-beam scattering, and beam-beam elastic scattering in the interaction regions (IRs). Of course, the definition of beam halo and beam core is somewhat vague, but one may define beam halo to include all beam particles in the beam profile distribution beyond the point where it starts to depart from a Gaussian profile. The halo density and profile is strongly affected by the tune of the machine. Finally, the insertion of near-beam detectors causes an increase in the halo rate; the ALFA detectors observed a rate increase when TOTEM Roman pots were inserted [63].

**Beam-gas background:** Beam protons may interact with the residual gas inside the beam pipe producing scattered protons or showers of particles that may impact the AFP detectors. Primary scattering products may also interact with collimator jaws, beam screens, beam pipe wall, and other material upstream of AFP and cause secondary shower products that enter the detectors. Beam-gas background is typically only a small component of the total background (as defined above) when only the beam pipe between the IP and AFP is considered. However, when integrated over the LHC circumference, the total contribution to the lifetime reduction of the machine is significant, although still sub-dominant [64]. It is also one of the sources feeding (elastically scattered) protons into the beam halo. Scattering off the electron space-charge cloud, formed by electrons emitted from the beam pipe walls by synchrotron light, is causing backgrounds similar to beam-gas scattering. As everywhere else around the LHC, the station surfaces facing the beam should be coated with a thin layer of the non-evaporable getter (NEG) TiZrV to adsorb trace gases and to help quench secondary electron emission.

**IP secondary interaction background:** High-energy primary particles produced in the IP in forward directions may cause interactions upstream of AFP, and the secondaries (or tertiaries) may reach the AFP detectors. Together with genuine (primary) protons from the IP, this is the dominant radiation source at the LHC and the elaborate LHC collimator hierarchy has been designed to deal with this radiation and protect the superconducting elements in the machine. In time and in space, the IP secondary interaction background resembles beam gas background. The background
contains high-multiplicity jets that may (partially) end up in the AFP detector(s).

**Back scattering background:** When AFP is operating, the upstream collimator settings will have to be adapted to not obscure the sensitive AFP detector area. This reduces, to some extent, showering in upstream collimators. At already a low-μ of about 2, the losses on Q6 become unsustainable, especially with the AFP detectors inserted, such that a collimator TCL6 behind AFP is required for Q6 protection; this is derived from TOTEM run experience in 2012, see below. In turn, TCL6 will also cause some 'back scattering' into the far AFP station, which will contribute to background, out of time by 10 ns or more.

**Self-interaction background:** Each AFP station is itself a target for particles inside the beam aperture and will cause interactions depending on the interaction length seen by traversing particles. Each near station is also a source of showers that will be seen in the far station.

### 4.3.6.2 Signal efficiency and proton survival

The signal for AFP is an IP proton that is well measured in both AFP stations of a given arm. The proton inefficiency is that fraction of protons that would have reached the AFP geometric acceptance but is lost or badly measured because of one of the following effects:

**Detector Efficiency:** The detector efficiency is independently measurable in beam tests and is a function of rate, pixel size, dead area, dead pixels, radiation dose, etc.. The AFP tracker uses IBL-type pixel sensors. The AFP intent is to make the detector efficiencies of individual tracker and ToF detector layers very high, implement multiple layers and offsets in the transverse direction, so as to attain an overall detector efficiency of both stations combined in excess of 95%.

**Beam-gas Interactions:** At the normal LHC operational vacuum of $10^{-10}$ mbar, the loss of signal protons due to collisions with the gas in the intervening beam pipe is completely negligible, because the nuclear collision length $\lambda_T \approx 500$ m at 1 bar.

**Signal Interactions in the Station:** When the signal proton has an inelastic interaction in a station its tracker and/or ToF measurement may become unusable. This effect depends on the total interaction length of the detector station and detector material upstream (and nearby downstream) of the measurement itself. For this reason, the total nuclear collision probability will be kept well under 2% for the first (Roman pot) station. The nuclear collision probability of the tracker package is estimated to be $\approx 0.7\%$ for a 4-layer detector, and about 9%(18%) for trains of 4(8) quartz radiator bars of the ToF detector.

The inelastic interaction of a genuine primary proton with the AFP station or detector material yields highly collimated jets. If the proton interacts in the near station, its global measurement is considered lost, because the shower will have opened up too much at the second station. An inelastic interaction of a signal proton in the far station will, depending on the actual location, cause high Cerenkov light yield in the ToF detector and/or high ionization in the tracker. Depending on the actual pulse height of the signal, the dynamic range of the detectors, and the depth the interaction in the second detector the second station’s space-and-time measurement may or may not be 'lost'.

These effects are being studied with full detector simulation using the ATLAS Athena framework with the GEANT4-based forward material implementation (beam pipe and screens, collimator jaws, magnetic fields, and AFP and ALFA).

A first qualitative simulation of the effects of secondary interactions upstream of AFP has been carried out, see Fig. 29 and for more details [65]. The study visualized examples of interactions upstream (including the near AFP station) and their showering into the AFP detectors.

Note, that interactions with the station bottom are not part of this source of signal inefficiency, but contribute to the signal overlap inefficiency discussed next.

**Signal Overlap and Ambiguities:** Signal overlap inefficiency occurs when another in-time particle, whether a genuine proton or a background, hits the same detector pixel as the signal and
Overlap particles are not considered a serious issue in the tracker, because of its high degree of pixelation. However, a high track multiplicity in either tracker from upstream showers, causes global (i.e. two-station) track ambiguities that may or may not be resolvable. The level of the overlap inefficiency depends on the hit rate, hit multiplicity, and on the details of the local and global AFP track reconstruction algorithm. This ‘ambiguity inefficiency’ is considered an intrinsic part of the overlap inefficiency.

In the ToF detector, the in-time particle or shower background has the possibility to ‘flood’ the fast time-of-flight detectors which have limited spatial pixelation. Overlap particles hitting the same ToF pixel as the signal proton, may deform the ToF signal and give rise to an unreliable ToF measurement.

The magnitude of the overlap inefficiency is dependent on the optics, luminosity, machine lattice, upstream material (beam pipe, screens, flanges, collimators, etc.), and beam conditions, and is therefore inherently difficult to calculate. To estimate the overlap inefficiency, full simulations, or better yet: in-situ measurements, must be performed.

Beam halo and beam gas interaction backgrounds are currently not implemented.

In the following section the results of some full-simulation detector performance studies are discussed.

### 4.3.7 Detector performance

To demonstrate the expected AFP performance using full GEANT4 simulation, the configuration listed below is used. This configuration does not completely correspond to the latest detector design configuration but is sufficiently close for the simulation to remain valid.

- Two AFP stations per ATLAS side (arm) placed at $z = \pm 204$ and $z = \pm 212$ m from the IP. The thickness of the front window is set to 300 µm.
- Each station contains one SiT, the far stations (at 212 m) contain a ToF in addition.
• Single SiT includes six silicon planes, separated by 10 mm (with a 13° tilt in the $x - z$ plane).

• Each Si layer has a sensor thickness of 250 µm and contains an array of $336 \times 80$ pixels of size $50 \times 250$ µm$^2$.

• Single ToF includes an array of $4 \times 8$ quartz bars (in $x - z$ plane), each of size $6 \text{ mm} \times 6 \text{ mm} \times 150$ mm.

• All AFP detectors are placed at $d = 1.8$ mm from the beam center (relatively to the edge of the active region of each detector).

In order to reconstruct the tracks in AFP Si detectors, a number of quality cuts are introduced. A track is defined as a good one if the following criteria are fulfilled:

• Reconstruction quality: $\text{trk}_\text{quality} > 6$ (where $\chi^2_{\text{max}}$ is taken to be 2.0 and $\chi^2_{\text{trk}}$ is the output from Kalman filtering). This cut prevents considering tracks with too small number of pixels, $N_{\text{hits}} < 6$, used for the reconstruction.

• Small slopes: $|\text{trk}_x|/|\text{dz}| < 0.003$ and $|\text{trk}_y|/|\text{dz}| < 0.003$. This cut selects for tracks which are almost parallel to the beam, as expected for diffractive protons.

• Small amount of tracks reconstructed in a given station: (a) $n_{\text{trk}} = 1$ - default requirement, (b) $n_{\text{near}}^{\text{far}} \leq 2$ and $n_{\text{far}}^{\text{far}} \leq 5$ - robust set-up for high pile-up performance studies. This cut removes events with potential proton-nuclear interactions in the detector material.

In addition to the requirements above, reconstructed tracks segments in the near and far station are required to be matched to each other, with a maximum distance: $|\text{trk}_{x,\text{near}} - \text{trk}_{x,\text{far}}| < 1.5$ mm and $|\text{trk}_{y,\text{near}} - \text{trk}_{y,\text{far}}| < 1.5$ mm.

For proton tracking-timing studies, a “good” event must also pass the following timing requirements:

• The number of collinear ToF radiator bars used for time reconstruction, $n_{\text{rec}}^{\text{ToF}} = 8$, including a maximum number of saturated bars, $n_{\text{sat}}^{\text{ToF}} \leq 4$.

• The extrapolated proton track trajectory must match a collinear set of bars (a “train”) with reconstructed timing. If more than one track is pointing to the same train of bars, ToF reconstruction is not attempted. This occurs in about 5% of events for the two trains closest to the beam at high pile-up $\mu \sim 50$.

The difference between the true $x$ position of the proton in the AFP station and a reconstructed track value is shown in Fig. 30a. The obtained reconstruction resolution equals 14.8 µm (72 µm) in $x$ ($y$). This is consistent with the values expected from the size of simulated pixels in a non-staggered set of tracking planes. In the final detector version the SiT planes will be staggered. Staggering is expected to further improve the reconstruction resolution to 10 and 30 µm in $x$ and $y$, respectively, see also Sect. 7.2.1.

The reconstruction resolution of the ToF is equal to 15 ps with the current implementation of ToF. This value translates to 2.3 mm z-vertex position reconstruction resolution, as can be seen in Fig. 30b.
4.3.7.1 Showers  As expected, not all forward protons reach the AFP station. If the energy lost by a proton is large enough, it will hit the LHC aperture before the AFP station. In such case a particle shower might be created, spoiling the measurement by populating the near or far AFP stations with a large number of tracks. A shower could also be produced inside the near station causing high multiplicity in the far station. This is shown in Fig. 31a, where apart from protons, there are some tracks caused by showers. In order to clean the event from these, the selection criteria described above are applied. This removes almost all shower tracks in the sample (Fig. 31b).

Figure 30. (a) Reconstructed track $x$ position resolution for the far (AFP 212) SiT. (b) Reconstructed $z$-vertex position resolution using all ToFs.

Figure 31. $x, y$ track positions heatmap for the far SiT station before (a), and after (b), track segment matching is required. Positions are calculated in the ATLAS Coordinate System (beam center is shifted). Tracks matched between near and far SiT stations are considered.
4.3.7.2 High pile-up environment  To study the effect of pile-up interactions on the AFP proton reconstruction quality, simulated events with $\mu=0$, 1, 5, and 15 are considered. A robust set of SiT+ToF cuts is chosen to account for the reconstruction of additional diffractive protons arriving from the pile-up interactions. Fig. 32 presents the track reconstruction efficiency for single-arm SiT detectors (in AFP 204 and 212 stations) as a function of proton relative energy loss. The tracking efficiency reaches 95% in $0 < \xi_p < 0.1$ for low pile-up contamination and 90% for $\mu=15$.

The full proton reconstruction efficiency for single-arm detectors (including ToF information from the timing detector) can be also defined. The average efficiency of the proton track plus time reconstruction is found to be $\approx 85\%$ for $\mu=0$, 1 and $76\%$ for $\mu=15$. These values demonstrate the excellent performance expected with the AFP detectors even in a high pile-up environment.

![Proton track reconstruction efficiency for single-arm SiT detectors for different pile-up scenarios as a function of relative proton energy loss $\xi_p$. Only tracks with segments matched between the near (AFP 204) and far (AFP 212) stations are included.](image)

**Figure 32.** Proton track reconstruction efficiency for single-arm SiT detectors for different pile-up scenarios as a function of relative proton energy loss $\xi_p$. Only tracks with segments matched between the near (AFP 204) and far (AFP 212) stations are included.

4.4 The AFP Beam Interface

The AFP beam interface of choice is the Roman pot (RP). The RP beam interface has been adopted by the ALFA and TOTEM collaborations and has shown to work reliably at the LHC. At the higher luminosities of the last LHC run period, the original rectangular pot shapes used to house the ALFA and TOTEM detector planes presented a significant impedance to the circulating bunches, and beam losses and heating of the pot material limited the insertion of the pots. Both ALFA and TOTEM have modified the electrical shape of the pot into a cylinder closely fitting inside the pot bellows by using filler shapes, thereby eliminating the resonant cavities that are at the origin of the losses and heating.

Thus, the present TOTEM horizontal pot design is cylindrical, leaving only a 2.5 mm clearance gap between the outer bellows cylinder and the pot itself. The remaining energy radiated into the gap is absorbed by ferrite elements at the end of the gap, and the generated heat is dissipated into the main Roman pot support structures. TOTEM's cylindrical pot design [66] is copied for the AFP pot with the small modifications discussed below.

The AFP Roman pot station contains the pot and the mechanics allowing it to enter the beam pipe aperture. The cylindrical pot's orientation and its motion are horizontal, transverse to the beam direction. Again, TOTEM's horizontal station is perfectly suited for AFP, and therefore the TOTEM Roman pot station design [66] is adopted.
The support table on to which the RP station is mounted is particular to the location and cannot simply be copied from the TOTEM design. However, the support table is mechanically very simple, and the 3-piece ALFA table design (a base plate and two lateral walls) is a very good starting point for the AFP design. The ALFA support table (tripod) is bolted to the LHC tunnel floor. On its top, three 3-axis adjustable feet connect the Roman pot station to the station support structure which consists of a bottom plate with two ‘side-plates’ onto which the station support brackets are mounted. A detailed design of this structure, combining elements of the TOTEM and ALFA station support structures, has high priority.

### 4.4.1 The Roman Pot

The starting point for the AFP RP design is the TOTEM cylindrical pot [66], which was produced by CERN and fully qualified for use in the tunnel. However, the TOTEM RP design is not well suited for the AFP time-of-flight detector, because the AFP ToF requires a 50mm × 50mm flat area on the RP bottom interfacing between the quartz Cerenkov radiators and the LHC beam vacuum, see Fig. 33. Also, the AFP silicon tracker sensor is 20.0 mm wide in y (vertical, the long direction of the pixels), a bit wider than the 16.6 mm width of the internal groove’s flat area on the inside of the TOTEM Pot, thus increasing the dead region before the 3D sensor by an additional 300 µm. This means that the pot for the ToF detector must have its thin beam window machined from the outside (i.e. the beam side) rather than the inside of the pot as in the TOTEM design. Although this is not a significant difference from a structural perspective, the AFP design was fully analyzed using the finite element method. The material of the pot, as for many LHC beam elements, is type 316LN stainless steel, a low-carbon, nitrogen-enhanced version of Type 316 molybdenum-bearing austenitic stainless steel. Its properties are listed in Table 7.

![Figure 33. The groove forming the beam window in the 2 mm thick bottom of the TOTEM Roman pot. The beam side is the bottom, and the detector side is the top of the window. The groove is 16.6 mm wide in its flat region, with rounded edges of 4.8 mm radius on either side.](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>515 MPa</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>205 MPa</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>190 – 210 GPa</td>
</tr>
<tr>
<td>Elongation at break (in 50 mm)</td>
<td>60%</td>
</tr>
</tbody>
</table>

**Table 7.** Mechanical properties of grade 316LN stainless steel.

The engineering for the AFP RP was done by the University of Alberta at Edmonton. The design drawing of the RP bottom “cup” containing the thin window, is shown in Fig. 34. As shown, the
Figure 34. The AFP Roman pot design. Left: the design drawing of the bottom “cup” of the Roman pot, containing the 300 µm thick window. Right: the perspective drawing of the AFP Roman pot, including the cup, tubular section, and the vacuum flange.

300 µm thick window is machined by removing a 1.7 mm thick and 20 mm wide layer of material from the 2.0 mm thick bottom and wall of the cup. The proposed method of material removal is standard CNC milling (after filling the cup with a removable backing). An alternative method is to use electric discharge machining (EDM); the University of Alberta has an EDM machine and the estimated fabrication time for a prototype is 3 days.

In normal operation, the pot’s internal volume that houses the detectors is kept at zero pressure. This secondary vacuum is provided by a dedicated vacuum pump near the stations. However, the secondary vacuum may need to be broken for installation or replacement of detectors and components. Moreover, a variety of accident scenarios must be foreseen: the accidental loss of the secondary vacuum being the most likely. Loss of beam vacuum, while the secondary vacuum inside the pot is maintained, is an example of a very rare accident scenario. The catastrophic loss of vacuum, of the secondary or of the beam vacuum, is extremely unlikely. Therefore, the pressure differential to be considered is at most 1 atm.

The design was submitted to a finite element analysis (ANSYS). A quarter section of the cup, shown in Fig. 34, was calculated using the following boundary conditions: symmetry constraints along the edges of the quarter cuts, atmospheric pressure inside the pot, and vacuum on the outside. Several variations of the design (varying the radius of the machined window edge and the width of the thin part of the window) were tried to determine the best balance of strength and function. The finite element mesh size was reduced in critical areas to search for local stress maxima until the calculation converged for the nodes and elements.

The ANSYS results are shown Fig. 35 for stress (left figure) and for displacement (right figure) for the case where the pot’s inside is at atmospheric pressure and the outside at vacuum. The calculated stress maximum of 164 MPa occurs in the window a few cm before the bend at the cylindrical edge. Conservatively assuming an elastic modulus of 190 MPa, the design has a safety factor of 1.3 against yield and 3.2 against ultimate strength. As expected, inverting the sign of the differential pressure, assuming vacuum inside the pot and atmospheric pressure on the outside, did not change the results. In the latter exercise, the buckling pressure was calculated at a differential pressure of 440 kPa, i.e. 4 atm.
4.4.1.1 RF Behavior  During the last LHC run, significant heating was observed in the TOTEM and ALFA pots at medium and high luminosity, which was attributed to the transverse and longitudinal impedance presented by the RPs to the beams with large numbers of bunches. The ohmic heating resulting from induced currents on the pots and nearby vacuum elements led to an unacceptably high temperature rise of 30 °C or more. Although this effect was expected, a work program was started to calculate the RP impedances precisely and to implement cures.

Using a variety of simulation with different RP shapes and coating, it was found that a cylindrical shaped pot, leaving the smallest possible ‘gap’ between the bellows housing and the outer pot wall, presents the lowest transverse and longitudinal impedance. In Fig. 36 the results are shown of a series of such simulations done by the TOTEM Collaboration [67]. The calculated longitudinal impedance $Z_{\text{long}}$ (in mΩ) is plotted as function of the pot’s distance to the LHC beam center (in mm) for two shapes: the rectangular shape employed by the TOTEM and ALFA vertical pot (round markers) and the new TOTEM cylindrical pot design (triangular markers). Also plotted is the calculated power loss (in W) in the pot materials as function of the pot’s distance to the LHC beam center (in mm) for two different shapes. In this simulation, the clearance gap between the outer pot wall and the bellows cylinder is taken to be 2.5 mm.

Coating the steel pot with copper or aluminum lowers the ohmic resistance and reduces the heating further. However, copper is not an ideal ultra-high Vacuum (UHV) material and bare aluminum has a high secondary emission coefficient making it unsuitable for use inside the LHC beam pipe. Overcoating with a layer of Non-Evaporable Getter (NEG) has been attempted by ALFA and is indeed feasible, but the long-term stability of a NEG coating on thin pot surfaces close to the circulating beam is not guaranteed and has so far precluded its use on ALFA and TOTEM pots.

The flange of the Roman pot is fitted with ferrite elements. Eight circular segments form a full circle that faces the narrow gap between the cylindrical pot and the bellows flange of the “Vacuum Chamber Assembly” (marker number 1 in Fig. 38). Each ferrite segment is separately attached to the inside flange of the RP. The shape of the ferrites and the attachment method most suitable to heat conduction has been researched by the ALFA collaboration and will be copied for AFP.
Figure 36. The results of RF simulations done by the TOTEM Collaboration [67]. Left: The calculated longitudinal impedance $Z_{\text{long}}$ (in $\Omega$) is plotted as function of the pot's distance to the LHC beam center (in mm) for two shapes: the rectangular shape employed by the TOTEM and ALFA vertical pot (round markers) and the new TOTEM cylindrical pot design (triangular markers). Right: The calculated power loss (in W) in the pot materials is plotted as function of the pot's distance to the LHC beam center (in mm) for two shapes: the rectangular shape employed by the TOTEM and ALFA vertical pot (round markers) and the new TOTEM cylindrical pot design (triangular markers).

4.4.1.2 Feed-through Plate The Roman pot is mounted on the flange of the bellows section of the Central Vacuum Chamber Assembly in Fig. 38). The pot is closed off by a precision feed-through plate, which contains the feed-throughs for signals and services as listed in Table 8 and is mounted with the detector holders for tracking and timing. The plate seals the secondary vacuum inside the pot that is needed for machine safety and to prevent elastic deformation of the thin beam windows.

<table>
<thead>
<tr>
<th>Feed-through Function</th>
<th>Number of Connections</th>
<th>Connector Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon tracker</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-Density Interconnect</td>
<td>4 × 9 signals, incl. grounds</td>
<td>Potted</td>
</tr>
<tr>
<td>Low Voltage</td>
<td>4 × 2 power lines, incl. grounds</td>
<td>UHV Power</td>
</tr>
<tr>
<td>High Voltage</td>
<td>4 × 2 power lines, incl. grounds</td>
<td>UHV μD</td>
</tr>
<tr>
<td>Temperature Probes (PT1000)</td>
<td>4 × 2 signals</td>
<td></td>
</tr>
<tr>
<td>Time-of-flight detector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analog signals</td>
<td>8 × 2 signals, incl. grounds</td>
<td>Potted JVC – SMA-F</td>
</tr>
<tr>
<td>High Voltage</td>
<td>2 × 4 power lines, incl. grounds</td>
<td>UHV SHV</td>
</tr>
<tr>
<td>Temperature Probes (PT1000)</td>
<td>2 × 2 signals</td>
<td>Potted JVC – μD</td>
</tr>
<tr>
<td>Services</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Probes</td>
<td>3 × 3 signals</td>
<td>UHV μD</td>
</tr>
<tr>
<td>Temperature Probes (PT1000)</td>
<td>4 × 2 signals</td>
<td>UHV μD</td>
</tr>
<tr>
<td>Radiation sensor</td>
<td>3 × 2 signals</td>
<td>UHV μD</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>2 air-hose connections</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Table 8. Feed-through connections for the AFP Roman pot. The list of feed-throughs is shown for a RP equipped with both a silicon tracker and a time-of-flight detector. Abbreviations used are HDI= High-Density Interconnect, μD = Micro-‘D’ connector.

The feed-through for the HDI of each 3D silicon sensor plane is to be defined, but the most likely solution is to pursue a dedicated design solution for the limited number of data and control
signals. For silicon low voltage and high voltage signals, a number of UHV connectors exists to choose from. Temperature sensor signals, probably two per plane, are connected via miniature μD UHV connectors on the feed-through plate.

The time-of-flight detector signals are relatively few. The 8 (up to 16) coaxial analog signals will be routed via dedicated feed-through boards, which adapt the JVC connectors from the preamps to SMA connectors outside the pot. ToF LV is carried on these same coax cables. The PMT HV, three voltages plus ground, will be transferred by 3 SHV bulkhead connectors. Finally, the Temperature probes are incorporated in the coaxial signal feed-through.

Additional services are required for pressure, pot temperature, and radiation monitoring. These services will be using UHV μD feed-throughs. The heat exchanger (for the 3D silicon tracker cooling) is serviced by a pair of air-hose feed-throughs of a type to be determined.

The design of the feed-through plate is tightly linked to the final detector holder designs, and will start after these designs have stabilized.

4.4.1.3 Cooling

The electronics inside the secondary vacuum of the RP, in particular the 3D silicon tracker electronics requires cooling. Each of the four layers of 20mm × 18mm 3D silicon sensors is read by a single FE-I4b front-end chip of approximately the same size. The FE-I4b consumes up to 1 W of power, and therefore the total power generated inside the pot by the 3D tracker is 10 W or less, including peripheral electronics. This heat is conducted via 30 mm wide strips of thin copper or Pyrolytic highly oriented Graphite Sheets (PGS) to a heat exchanger located below the feed-through plate. PGS has a uniquely high thermal conductivity in excess of 800 W/K/m.

The time-of-flight detector uses between 100 mW (for 3 VDC) and 300 mW (for 5 VDC) per channel, i.e. 2.4 W or less for an 8 channel detector; its heat is dissipated via the coaxial shielding of the signal cables.

The heat exchanger receives cold air from a Dry Air Vortex Cooling system, a device developed by the Czech Technical University group. The 17 kg AirCooler II device, see Fig. 37, has shown to deliver 450 L/hr cooled air with a temperature drop of ΔT = 50° using input dry air at 17°C. In the test, 50 W of cooling power was provided at a DUT temperature of −40°C. Such a system can easily cool the Roman pot and detectors. The device contains only passive vortex tubes and no moving parts and is inherently radiation hard. Preliminary tests in the lab with a totem pot show excellent performance.

4.4.2 Roman Pot Station

The AFP Roman pot station (RPS) is an exact copy of the TOTEM Horizontal station design, see the main assembly drawing in Fig. 38. The numbered markers in the drawing refer to the third column in the table of legends in the figure. The drawing is extracted from the CERN EDMS system. The RPS is a compensated system (see the balance arms marked as number 12), with a linear slide assembly (number 10), and driver motor (number 11) of the same type as used for the LHC collimator movement. The RP is not marked in this zoom; it is inserted between the Slide (number 10) and the Central Vacuum Chamber Bellow, best seen in the transverse cut shown in Fig. 38 right. The addition of springs (number 19) provides mechanical retraction of the RP in case of power failure.

The Central Vacuum Chamber assembly was fabricated for TOTEM by the Czech company Vakuum Praha [68] (VP). Other components were fabricated by the CERN workshops. VP is able and willing to produce and assemble all the components of the RPS, with the exception of motors, linear drive, and the various electrical and meteorological components such as switches and transducers. This simplifies the production of the RPS significantly.
Based on ALFA experience, a single modification to the central vacuum chamber assembly (number 1) is considered, as explained below. The positioning of the detectors with respect to fiducial marks on the RPS is of crucial importance. Because there are no simple and high-cross section physics processes available for absolute alignment of the AFP detectors, AFP relies in the first instance on the alignment of the RPS with respect to the associated beam Positioning Monitor (BPM). As discussed in the section on alignment, BPMs are available that yield a beam position measurement accuracy (with respect to the sensor body) of 10 µm or better. The transfer of the BPM position to the position of the detectors inside the RP is very non-trivial and includes the transfer of bench measurements of the mounted detector positions in the pot via the linear transducer position measurement of the insertion depth, to the fiducial marks on the RPS. ALFA experience is such that the relative positioning of the detectors with respect to the beam is 0.2-0.3 mm at best. Fortunately, the ALFA process of choice, elastic scattering, is self-calibrating, and in addition, ALFA has a vertical detector pair with overlap detectors thereby measuring the distance between up and down detectors directly. No such possibility exists for the single horizontal pot of AFP.

Therefore the insertion of a quartz window in the vacuum chamber assembly in the wall opposite the RP bottom is being considered, see Fig. 39. A 25 mm diameter quartz window will allow a direct measurement of the position of the pot’s bottom (and hence of the detectors that are positioned against the bottom) and a direct connection of this position to the survey markers on the Roman pot slide assembly.

According to LHC experts and RF experts, the quartz porthole should not have any negative impact on the LHC vacuum behavior or on the RF impedance of the RPS.
Figure 38. The Roman pot station assembly, from CERN EDMS Drawing number LHCXRPM_0175. The right figure shows the transverse cut and position of the Roman pot inside the main bellow. The numbered markers are referring to the following components: 1) Beam pipe flange; 2) Central Vacuum Chamber assembly; 3) Bellow of the Compensation Vacuum Chamber connected to the beam vacuum on the Central Vacuum Chamber assembly; 4) tube connecting the beam vacuum to the Compensation Vacuum Chamber assembly; 9) Central Vacuum Chamber assembly support; 10) Slide Assembly holding the feed-through plate, the Roman pot flange, and the bellow flange; 11) Collimator stepper motor driving the slide assembly; 12) Balance arms; 13) Central Block assembly; 16) LVDT; 19) emergency extraction springs.
4.5 The Silicon Tracker

The AFP design foresees a high resolution pixelated silicon tracking system placed at 210 m from the ATLAS interaction point (IP). Combined with the magnet systems of the LHC accelerator, the AFP tracker will provide the momentum measurement of the scattered protons. The full AFP tracker will consist of four units (stations), each composed of four pixel sensor layers, which will be placed in Roman pots, two on each side of the ATLAS IP ("2+2"). However, for the first AFP phase ("0+2") the tracker will be reduced to two Roman pots at only one side of the IP (see Section 4.1).

4.5.1 Tracking Requirements

To ensure a good momentum resolution, the AFP tracker is required to provide a high spatial resolution of 10 µm (30 µm) per station in $x$ ($y$) direction (see Sect. 4.1).

Furthermore, it is vital for the physics program to measure very small scattering angles. To this end the detectors will be placed almost perpendicular to the beam (under a small tilt of 15° to minimize possible inefficiencies due to the columnar electrodes of the 3D technology chosen, which represent dead material) with one side only 2-3 mm away from it. This leads to another two critical requirements for the pixel detectors:

1. The inactive region of the detector side facing the beam has to be minimized to about 100-200 µm.

2. While in the measurement position only a few mm away from the beam, the detectors have to withstand a highly non-uniform irradiation profile with a high maximum fluence along the
line of diffractively scattered protons and several orders of magnitude lower elsewhere (see Sect. 3.4). In the Roman pot parking position, a more uniform radiation is expected. Thus, the level of uniformity as well as the magnitude of the maximum fluence depend on the exact run scenario: for standard optics, the maximum fluence is $3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ per 100 fb$^{-1}$. In special low-luminosity runs, the fluence and dose present no particular challenge.

4.5.2 Pixel Modules
The most critical component of the AFP tracking system is the pixel module. It consists of a 3D pixel sensor bump-bonded (connected) to a front-end chip which in turn is glued and wire-bonded to a flexible printed circuit (flex). The flex provides clock and command signals and routes the data output. The AFP module will consist of a single FE-I4B front-end chip, which will provide $336 \times 80$ pixels with a pixel size of $50 \times 250 \mu m^2$, comprising a total active area of $1.68 \times 2.00 \text{cm}^2$. The AFP single-chip 3D pixel modules are similar to the ones used in the ATLAS Insertable B-Layer (IBL) detector, and have demonstrated radiation tolerance. However, some important modifications have to be implemented to meet the specific requirements for AFP (slim edge and non-uniform irradiation as described above).

4.5.2.1 3D Sensors
In 3D pixel sensors, n- and p-type column-like electrodes penetrate the substrate defining the pixel configuration. Though the fabrication process is complex, the technology is less demanding in terms of bias voltage and cooling than the standard planar approach, and the reduced drift path makes 3D devices more radiation hard. In recent years significant progress has been made in the development of 3D sensors, which culminated in the sensor production for the ATLAS IBL [69]. The AFP pixel detectors will be based on the 3D double sided sensors developed by CNM (Centro Nacional de Microelectronica, Barcelona, Spain) and FBK (Fondazione Bruno Kessler, Trento, Italy) for the IBL.

The AFP 3D sensors for the first AFP phase were already fabricated at CNM on Float Zone, p-type, 100 mm diameter, wafers, with $<100>$ crystal orientation, 230 $\mu$m thickness, and a very high resistivity (10 to 30 k$\Omega$ cm) [70]. Columnar electrodes, 10 $\mu$m wide (mask design value), were obtained by Deep Reactive Ion Etching (DRIE) and dopant diffusion from both wafer sides (n$^+$ columns from the front side, p$^+$ columns from the back side), without the presence of a support wafer. By doing so, the substrate bias can be applied directly on the back side. The sensor design features an array of $336 \times 80$ pixels with a pixel size of $50 \times 250 \mu m^2$. Each pixel consists of 2 n$^+$-junction columns and 6 surrounding p$^+$-ohmic columns. Fig. 40 shows details of the 3D sensor layout.

The CNM production for AFP concluded in July 2014. Unfortunately, due to a machine problem, a large portion of the 13 wafers of the run were damaged and only 5 wafers finished the production. Moreover, out of the 40 sensor tiles from those wafers, only 9 sensors have been qualified as good (breakdown voltage $V_{\text{bd}} > 20 \text{ V}$) before bump-bonding. Another 4 sensors are of medium quality ($V_{\text{bd}} > 10 \text{ V}$). It is thus critical to achieve a high yield during the module assembly process to obtain the 8 pixel modules needed for the "0+2" phase. CNM has already (mid-February 2015) launched a new run in order to provide more sensor tiles for AFP modules.

The performance of the 3D pixel sensors has been extensively studied during the IBL qualification, and additional tests have been performed to check their adaptability for AFP. The performance results are presented in Sect. 4.5.3.

4.5.2.2 Front-end Electronics
The pixel readout electronics will be the FE-I4B [71, 72]. The sensors are DC coupled to the chip with negative charge collection. Each readout channel contains an independent amplification stage with adjustable shaping, followed by a discriminator with independently adjustable threshold. The chip operates with a 40 MHz externally supplied clock. The
time over threshold (ToT) with 4-bit resolution together with the firing time are stored for a latency interval until a trigger decision is taken. The FE-I4 chip can also send a trigger signal via the HitOr line, which is formed as the logical OR of all fired discriminators on the FE-I4 chip.

The FE-I4 chip has been extensively tested for the ATLAS IBL detector. The radiation hardness has been well established to doses of 250 Mrad and beyond, surpassing the AFP requirements. The trigger capabilities have also been proven, as the chip is used to trigger the ATLAS Diamond Beam Monitor (DBM) detector.

As used for AFP, the FE-I4 will not be thinned and its thickness is 700 µm.

4.5.2.3 Bump-bonding Technology

The FE-I4 front-end chips and the 3D sensors are interconnected through bump-bonding. The bump-bonding technique consists of the following steps: (a) deposition of metal bumps in the pixel readout channels of the electronics chip and metallization of the sensor pixel pads, (b) flip of the electronics onto the sensors in such a way that the sensor pad is aligned with the metal bump on the electronics side, and (c) the application of thermal and pressure cycles that establishes the permanent contact. The first part of the process is generally called under bump metallization (UBM). The steps (b) and (c) are called flip-chipping. The difficulty lies in the fact that the thermal cycles (heating up to 230°C is needed for SnAg bumps) can induce bowing in the substrate and thus create un-connected bumps.

Technologically, the flip-chipping process is very demanding. Furthermore, this process is one of the most expensive factors for current hybrid detectors (i.e. detectors with separate production of sensors and readout electronics).

IFAE has experience with the bump-bonding process [73], and has a clean room equipped with a FC-150 Süss Microtech flip-chip bonder, a reflow oven, and other machines related to assembly of micro-electronics. Since the institute has unrestricted access to the machines, the flip-chipping and reflow processes are done in a much shorter time than at commercial companies. Furthermore, the testing procedure is done on site as well, giving immediate feedback on the assembly process. The output of the bump-bonding process is the so-called “bare assembly”.

4.5.2.4 Flexible Printed Circuit

After flip-chip, the bare assembly (that is, the flip-chip assembly of a sensor and a front-end chip) is electrically tested on a probe station through the p-side of the sensor and the analog ground of the front-end. This is the critical qualification step of the 3D sensor, as the on-wafer current-voltage measurements of CNM sensors (done on the 3D guard-ring) have
not shown good correlation with final results during the IBL module production [74].

A flexible printed circuit (flex) is glued to the bare assemblies that show good electrical behavior. The position of the assembly on the flex is to be done with reasonable but not extreme precision (200 µm). It is important to have visual access to the sensor alignment marks and to allow wire-bonding of the flex to the front-end. The flex provides the low and high voltages to the assembly, as well as the command and data lines to the front-end chip. A preliminary design of the flex has been done by the University of Oslo and is presented in Fig. 41. In order to improve the heat dissipation of the pixel assembly, which will be in vacuum, the front-end has to be in contact with the holder plane (which is to be cooled, see Sect. 4.5.4.4).

Figure 41. First design of the flexible printed circuit for AFP by the University of Oslo. On the right hand side the FE-I4 assembly is indicated.

4.5.2.5 Module Assembly The process of adding and wire-bonding a flexible printed circuit to a bare module is called module assembly. This turns the bare module into a flex module. Flex modules can be fully tested and qualified (see next section), and are the critical components of the AFP tracker. The flex module handling and assembly techniques will follow closely the IBL procedures [75].

4.5.2.6 Module QA The AFP flex modules will be fully tested and qualified before being assembled in the tracker planes. The qualification will consist of the following tests: i) mechanical verification, ii) current-voltage characterization, iii) threshold and noise scans, and iv) characterization with radioactive sources.

The flex modules will be qualified according to a qualification score and the best modules will be used for the AFP tracker.

4.5.3 Performance of the 3D Pixel Modules

In the course of the IBL production and qualification, the performance of FE-I4 3D silicon pixel modules produced by CNM and FBK has been studied already in great detail as published in [74, 75]. The most important results on the resolution and efficiency, before and after uniform irradiation up to 5×10^{15} n_{eq}/cm^2, are summarized below in Sect. 4.5.3.1.

In addition, the AFP pixel group has performed extended studies on the modification of IBL 3D pixel sensors in order to fulfill the AFP-specific needs, i.e. the slim edge of 100-200 µm at the side opposite the wirebonds and surviving the expected non-uniform irradiation. These studies have been presented in [76] and are reproduced below in Sects. 4.5.3.2 and following.

Lastly, in November 2014 the AFP integration test beam has been performed with a system of five FE-I4 3D pixel modules and the Quartic timing detector. There, cross-checks of the efficiencies and resolutions of the individual pixel modules have been performed, as well as a first study of the performance of a system of four to five pixel modules as foreseen for the final AFP tracker. These results are presented in Sect. 7.2.1.
4.5.3.1 Performance of IBL FE-I4 3D Pixel Modules before and after Uniform Irradiation

During the IBL qualification, the pixel module performance has been studied extensively in the laboratory and in various test beams [74, 75].

For non-irradiated 3D pixel sensors, average hit efficiencies of 99% and above are found at bias voltages of only 20 V, tuned thresholds of 1.5 to 1.6 ke− and under perpendicular beam incidence (hence the inefficiency due to the 3D columns, which represent dead material, is found to be negligible before irradiation even for perpendicular incidence). After uniform proton or neutron irradiation up to 5×10^{15} n_{eq}/cm^2, the pixel sensors are found to maintain average hit efficiencies of about 98 to 99% at bias voltages of about 160 V, tuned thresholds of 1.5 to 1.6 ke− and under a 15° inclined beam incidence angle with respect to normal incidence (normal incidence leads to about 1% additional efficiency loss after irradiation for CNM sensors and a bit more for FBK sensors due to the completely through-going 3D-column structure of the latter).

The spatial resolution of one pixel plane depends on a number of different parameters such as the incidence angle, the cluster size, the calibrated threshold and ToT, the presence of delta electrons, the cluster-center algorithm, etc. In case of only one-hit clusters, i.e. in the complete absence of charge sharing between pixels, the binary resolution of pitch/√12 is expected (i.e. 14.4 µm in the short 50 µm pixel direction and 72.2 µm in the long 250 µm pixel direction). For configurations that allow clusters with more than one hit, the resolution can be improved due to charge sharing and interpolation. In a test beam, the overall resolution (for all cluster sizes) for perpendicular beam incidence and before irradiation has been measured as 15 µm (73 µm) in the short (long) pixel direction (telescope resolution subtracted), using either the ToT-weighted or unweighted cluster center [77]. However, it is interesting to note that in the short direction the large majority of the events has a better resolution: 12 µm for cluster size 1 in the short direction (79% of the events) and 10 µm for cluster size 2 in the short direction (19% of the events). Less than 2% of the events have cluster sizes >2 due to delta electrons with a much degraded resolution of about 70 µm. Their influence can be, however, minimized if those clusters are down-weighted with their large resolution in the track fit. In the long direction, 98% of the events have cluster size 1. For AFP-relevant tilts of 10–15° beam incidence with enhanced charge sharing (the large majority of events has a cluster size of 2 in the short direction before irradiation) such systematic studies are still on-going. For the FEI4, only the all-cluster-size resolution in the short direction at 15° incidence after irradiation to 5×10^{15} n_{eq}/cm^2 has been measured as 15 µm using the ToT-weighted cluster center [74]. For the predecessor of the FEI4 (FEI3) used in the ATLAS Pixel Detector, a large resolution improvement at these inclined angles with respect to perpendicular incidence has been observed and values as good as 7 µm per plane have been measured using sophisticated charge interpolation algorithms (it should be noted that the ToT resolution of the FEI3 is better) [78]. A new test beam campaign is planned to study this systematically also for the FEI4.

Note that a system of four pixel modules per station as foreseen for AFP and studied during the AFP November 2014 test beam (see Sect. 7.2.1) improves the spatial resolution over a single module, thereby fulfilling the AFP per-station-resolution requirements.

The noise of the 3D pixel modules is measured to be typically 130–140 e− per pixel.

4.5.3.2 Performance of Slim-Edge 3D AFP Pixel Prototypes before and after Non-Uniform Irradiation

This section, based on [76], presents the performance of CNM and FBK 3D pixel prototypes for AFP after edge slimming and non-uniform irradiation. Different cutting techniques were studied to achieve AFP-compatible slim inactive edges. After early promising results [79] based on the advanced Scribe-Cleave-Passivate (SCP) technique, a simple diamond-saw cut was investigated. Concerning radiation hardness, the IBL 3D sensors have proven to withstand a uniform fluence of 5×10^{15} n_{eq}/cm^2 as mentioned above. However, in case of non-uniform irradiation like the
one predicted for AFP, a scenario might occur in which the breakdown voltage of the non-irradiated region (which is usually lower than in irradiated silicon) is lower than the voltage needed to provide a sufficiently high electric field in the irradiated area for efficient charge collection. Thus, studies of non-uniform irradiations were performed. After first tests using a focused 23 GeV p beam [79], a more localized fluence deposition was achieved using aluminum masks with holes in a 23 MeV p beam. The performance of the slim-edge and non-uniformly irradiated devices was studied using electrical characterizations and test beams.

Production of Slim-edge AFP Pixel Modules

CNM and FBK sensors have different terminations of the pixelated area. CNM uses a 3D guard ring of n⁺ columns that terminates the sensitive pixel area and drains leakage current from outside. It is surrounded by a p⁺-column fence that terminates the depletion region growing from the guard ring and prevents it from reaching the side wall. In contrast, FBK only uses a p⁺-column fence that terminates the depletion region growing from the last pixel. Nevertheless, that depletion region still can float into regions beyond the geometrical boundaries of the last pixels, thereby allowing an extension of the sensitive region (due to the absence of a guard ring). The designs of both CNM and FBK IBL 3D sensors already include a cut line only 200 µm away from the two external pixel columns (left and right) in order to abut IBL sensors along that direction. The AFP-relevant bottom side opposite to the wirebonds, however, incorporates an insensitive 1.5 mm wide region for a bias tab that is only needed for single-sided 3D processes, i.e. not in the CNM and FBK cases. For the slim-edge AFP prototypes, a large part of this is cut away with a diamond saw, leaving a remaining edge extension of about 90 µm (FBK) and 150 to 215 µm (CNM) as shown in Table 9.

It should be noted that these devices were built from spares of the IBL production, thereby not always fulfilling the IBL quality criteria regarding e.g. leakage current and breakdown voltage.

Table 9. Overview on produced slim-edge AFP 3D pixel detectors and measured properties of the slimmed bottom edge at 20 V (FBK) and 30 V (CNM).

<table>
<thead>
<tr>
<th>Sample</th>
<th>FBK-S1-R9</th>
<th>FBK-S2-R10</th>
<th>CNM-S3-R5</th>
<th>CNM-S5-R7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge extension after cut</td>
<td>91 µm</td>
<td>87 µm</td>
<td>215 µm</td>
<td>150 µm</td>
</tr>
<tr>
<td>Sensitivity extension beyond last pixel</td>
<td>77 µm</td>
<td>75 µm</td>
<td>1 µm</td>
<td>7 µm</td>
</tr>
<tr>
<td>Remaining insensitive edge</td>
<td>14 µm</td>
<td>12 µm</td>
<td>214 µm</td>
<td>143 µm</td>
</tr>
</tbody>
</table>

Performance of the Slim-edge AFP Pixel Modules

Fig. 42 shows the current-voltage (IV) characteristics of the studied slim-edge AFP sensors after bump-bonding and assembly to an IBL flexible circuit board. The FBK sensors exhibit a low current below 1 µA up to a sharp breakdown voltage of about 30 V. By contrast, the CNM sensors show a steady current increase up to about 50 µA, still below the breakdown voltages of 70 to 100 V. Such curves are typical of the IBL-spare quality class and do not show any abnormal behavior that could be attributed to the edge slimming. This is consistent with a previous study on FBK sensors which shows that no strong current increase occurs up to a diamond-saw cut at about 75 µm distance to the edge pixels [80] (unfortunately, for CNM sensors it is not possible to obtain IV curves for the whole sensor before bump-bonding).

The measured mean noise of about 150–160 e⁻ for the CNM devices and 200 e⁻ for the FBK devices is a bit higher than the IBL average of 130–140 e⁻, but typical of the IBL-spare quality class used here. Most of the devices show no excess noise at the edges. Only CNM-S5-R7 exhibits up to 40% higher noise in the pixel rows close to the slimmed edge, which however has no impact on the operation with a standard threshold of 2 ke⁻.
The hit efficiency was determined in test beams at DESY using 4 or 5 GeV electrons, in June and July 2014. The ACONITE telescope based on EUDET was used to extrapolate beam tracks in the devices under test with a precision of about 15 µm at the electron energies used. Two devices under test (each time one of the four AFP prototypes and a regular-edge IBL CNM reference sensor) were placed simultaneously under a perpendicular beam incidence angle between the telescope planes. Bias voltages of 20 V (FBK) or 30 V (CNM) were applied and the threshold of the FE-I4 readout chip was tuned to $2–3 \text{ke}^-$ . The overall efficiencies of the AFP prototypes were measured to be 97–99%, similar to the one of the reference sensor (98–99%). The efficiency around the edge of the last pixel row at the slimmed bottom side of the sensor is shown in Fig. 43 for one CNM and one FBK AFP prototype. Similar results were obtained for the second CNM and FBK devices as well as for the edge efficiency around the non-slimmed top side of the sensors. The efficiency was found to be stable up to the last pixel row for CNM devices (the smearing of the step is due to the telescope pointing resolution), and even beyond in case of the FBK sensors due to the absence of a 3D guard ring as discussed in section 4.5.2. Table 9 includes the width of the sensitive region beyond the edge of the last pixel row as obtained from the 50% efficiency point. The sensitivity extension of about 75 µm for the FBK sensors implies a remaining insensitive edge of less than 15 µm. However, it has to be considered that such a behavior, which is beneficial from the efficiency point-of-view, implies a degradation of the position resolution of the last row. Also the CNM sensors with insensitive edges of 143–214 µm fulfill the AFP requirements.

**Non-Uniform Irradiation of AFP Pixel Modules**

The studies of non-uniform irradiation presented below were targeted at the harsh requirements of a potential high-luminosity AFP run scenario with an integrated luminosity of about $100 \text{fb}^{-1}$. A simulation of the expected radiation level is presented in Sect. 3.4. For this run scenario, the AFP pixel modules will be most of the time in their measurement position only a few mm away from the beam. It is expected that the total accumulated fluence of diffractively scattered protons with energies up to slightly below 7 TeV reaches a maximum of about $3 \times 10^{15} \text{n/cm}^2$ along a few mm wide line. Already very close to that line, the fluence is expected to be orders of magnitude lower within the same pixel detector. In contrast, for the planned initial low-luminosity run scenario, the detector will be placed most of the time in the parking position with a more uniform radiation background, and moreover, while in the measurement position close to the beam, the luminosity during the dedicated low-µ runs will be much reduced. Hence, a much lower level of non-uniformity

![Current-voltage characteristics for the AFP slim-edge 3D pixel prototypes.](image-url)
In absence of a multi-TeV p irradiation facility, proof-of-principle non-uniform irradiation experiments at existing facilities of lower proton energies have been performed. It should be noted that even theoretically the proton damage in silicon is only well studied up to 23 GeV. Irradiation campaigns have been performed at two different facilities with different degrees of non-uniformities:

1. A focused 23 GeV p beam at CERN-PS was used to give a maximum equivalent fluence of $4 \times 10^{15} n_{eq}/cm^2$ (see [79]). The fluence spread was relatively large (a region of more than 1 cm diameter received a fluence of more than $10^{15} n_{eq}/cm^2$ and even peripheral pixels acquired a fluence of $10^{13} - 10^{14} n_{eq}/cm^2$, see Fig. 44, top left).

2. A more localized irradiation with an abrupt transition between irradiated and non-irradiated area was achieved by using 5 mm thick Al masks which can shield 23 MeV p at KIT (proton irradiation facility at the Karlsruhe Institute of Technology, Karlsruhe, Germany) and let them pass only through a hole. Either a circular hole of 3 mm diameter was used or a slit-like hole of 4 mm width and 12 mm effective length over the sensor with fluences of $2 - 3.6 \times 10^{15} n_{eq}/cm^2$ (see Fig. 44, top centre and top right).

In the second scenario the non-uniformity is apparently more extreme. The level of non-uniformity for the high-luminosity runs expected from simulations lies in between the first and second scenario. The samples used, together with the level of irradiation, are listed in Table 10. CNM-S5-R7 and CNM-S3-R5 already include the slim edge as discussed in the previous section.

The performance of these samples is again measured in test beams at DESY with 4 or 5 GeV electrons or at CERN-SPS with 120 GeV pions at temperatures between -15 and -50°C to reduce the leakage current (dry-ice cooling). Table 10 shows an overview on the tuning and parameters of the FE-I4 chip and the resulting efficiencies for different regions of the sensor at the maximum applied voltage (limited by leakage current and/or a noise increase). The different regions are also

![Figure 43. Efficiency in the region of the AFP-relevant bottom edge as a function of distance from the edge of the last pixel row for CNM-S5-R7 (top) and FBK-S1-R9 (bottom).](image-url)
Figure 44. Irradiation mode (top) and measured efficiency maps (bottom). The efficiency is only measured for a part of the sensor since the smaller telescope planes give reference tracks only for that area (the map for CNM-57 consists of two separate measurements). The CERN-PS plots are reproduced from Ref. [79].

<table>
<thead>
<tr>
<th>Device and Irradiation Details</th>
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</thead>
<tbody>
<tr>
<td>Irradiation type</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>Fluence [$10^{15}$ $n_{eq}$/cm$^2$]</td>
</tr>
<tr>
<td>Sample</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurement and chip parameters</th>
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<tbody>
<tr>
<td>Threshold [ke$^{-}$]</td>
</tr>
<tr>
<td>ToT at 20 ke$^{-}$</td>
</tr>
<tr>
<td>Single small hits rejected</td>
</tr>
<tr>
<td>$V_{bias}$ [V]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured hit efficiency [%]</th>
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</thead>
<tbody>
<tr>
<td>Unirr. region</td>
</tr>
<tr>
<td>Irr. region (centre)</td>
</tr>
<tr>
<td>Irr. region (ring)</td>
</tr>
</tbody>
</table>

Table 10. Samples and irradiation details of the non-uniformly irradiated devices (top), parameters during the test beam measurements (centre) and measured hit efficiency for different sensor regions (bottom).
well visible in the measured efficiency sensor maps as shown in Fig. 44. The sensor irradiated with the focused PS beam is only subdivided into the irradiated side (with the maximum fluence) and the non-irradiated side (to be precise: the side that received a low fluence). In contrast, for the samples irradiated through the Al mask at KIT, a clear distinction is visible between the non-irradiated region, the centre of the irradiated region, and a ring around the edge of the hole. Almost full efficiency of 98–99% is obtained in the non-irradiated region of CNM-57 and FBK-12-02-08, similar to the non-irradiated reference sensor. The overall lower efficiency for CNM-S5-R7 and CNM-S3-R5 is explained by an unfavourable setting in the FE-I4 chip (HitDiscConfig=2) that leads to the rejection of single small hits (i.e. with time-over-threshold $T_{oT} < 3$). In a recent test beam CNM-S5-R7 has been remeasured with more favourable settings, and in a preliminary analysis a higher efficiency similar to the other devices is confirmed. The efficiency in the irradiated region (only the centre in case of the masks) approaches within 1% the one in the non-irradiated area in all cases. However, there is a ring of lower efficiencies around the hole at the KIT irradiation. The values there vary substantially between 58–90%.

The reason for the low-efficiency ring is still under investigation. It is conceivable that the edge region might have obtained a higher equivalent fluence due to scattering of the p at the edge of the Al hole, thereby losing energy, which leads to an increase in their displacement damage cross section in silicon. Alternatively, it might be a real sensor effect in situations with such an abrupt transition between irradiated and non-irradiated regions within one single silicon sensor, leading to a large gradient in defect density and leakage current. Or it might be an effect of the readout chip.

To check the first hypothesis, another irradiation was performed at KIT with the same Al masks with the slit-like hole to $3.5 \times 10^{15} n_{eq}/cm^2$, this time with a $4 \times 4$ array of small circular p-on-n silicon pad diodes (0.5 mm diameter, 1.5 mm pitch, 300 µm thickness). A position-resolved dosimetry was obtained from measuring the leakage current (at 20°C and after annealing for 80 min at 60°C) and using the linear relation between the current and the fluence with the damage parameter $\alpha = 4 \times 10^{-17} A/cm$ [81]. At this high fluence, no real plateau was observed in the IV curves, but at about 400 V the slope was decreasing and the fluence values evaluated at 400 V were consistent with the nominal fluence reported by KIT. No difference was found between the centre of the hole and the edge, thereby excluding a higher equivalent fluence (at least as obtained from the leakage current).

### Summary and Conclusions

Slim-edge and non-uniformly irradiated 3D pixel detectors from FBK and CNM were studied with electrical characterizations and beam tests in view of applications at forward detectors like AFP.

It was shown that it is possible to reduce the unpixelated edge extension opposite the wirebonds with a simple diamond-saw cut down to 87–215 µm width without compromising the leakage current, noise and hit efficiency. The FBK design without a 3D guard ring even leads to efficient regions up to 77 µm beyond the edge of the last pixel row, thereby further reducing the insensitive area to less than 15 µm, which is only surpassed by sensors with fully active edges to date.

3D detectors were non-uniformly irradiated with either a focused beam at CERN-PS or holes in Al masks at KIT to fluences expected after the high-luminosity run scenario at AFP (several $10^{15} n_{eq}/cm^2$). High efficiencies of at least 97% both in the non-irradiated and irradiated parts were obtained (for favourable chip-parameter settings). Only in a narrow ring around the edge of the hole for irradiations with the Al mask a lower efficiency was observed. Leakage-current measurements in non-uniformly irradiated arrays of small diodes did not show any hints of a higher fluence in the edge region. Further investigations are needed to clarify its origin. However, from simulations it is expected that the final level of non-uniformity lies in between the two irradiation scenarios investigated here, even for the high-luminosity runs. In any case, the initial low-luminosity AFP program
requires only an orders of magnitude lower maximum fluence and level of non-uniformity.

To conclude, slim-edge 3D pixel detectors have demonstrated their ability to fulfil the AFP requirements for detectors very close to the beam.

4.5.4 Silicon Tracker Mechanics

4.5.4.1 Requirements  The silicon tracker is an assembly of 4 planes each having a 3D sensor bonded to an FE-I4 readout chip. The mechanical construction and overall tracker dimension has to allow the installation inside the Roman pot which has a diameter of 141 mm. Although the AFP collaboration foresees, in a first phase, to install only the tracker planes in the Roman pot stations, some place is reserved for the ToF detector (time-of-flight Detector). The construction of the silicon tracker should allow its easy and relatively fast installation or removal directly in the LHC tunnel, where the access time is usually very limited.

As already mentioned, the purpose of the silicon tracker is the precise measurement of points along the trajectory of beam deflected protons. As the protons are due to beam collisions deflected at very small angles the sensitive area of the sensors has to be very close to the beam. The aim is 2 mm, assuming the thin bottom of the Roman pot can theoretically safely approach the beam to $1.5 \sigma_{beam}$, corresponding to approximately 1.5 mm. It is obvious that with such strict requirements, the tracker mechanics or the plane holder has to be in direct mechanical contact with the floor of the Roman pot in order to ensure a minimal distance between the silicon sensor active area and the thin pot floor. In addition, the silicon sensors are rather fragile and they have to be protected against any mechanical stress. One has to consider also the possible bow of the thin floor in the case of different pressure conditions in the LHC beam pipe (primary vacuum) and in the pot volume which is considered as the secondary vacuum area but having atmospheric pressure when opened. This represents a constraint not only on the strength of the thin window but also brings the risk of damage to the fragile sensors. Therefore, the tracker holder has to be held by a gentle spring force to the pot's floor and the fixation of the tracker should allow movement backwards in case of floor deformation.

The tracker holder should have low mass and materials should be selected to allow operation in the secondary vacuum. Also, as the detector should be operated at low temperature it is necessary to provide appropriate cooling. In order to keep the silicon sensors at a temperature of about $−5^\circ C$ it is considered to use relatively simple local cooling stations based on Vortex tubes providing very cold air reaching a temperature of about $−40^\circ C$. The cold air will be led via pipes inside the Roman pot where a small heat exchanger will be mounted close to the tracker holder. The power dissipation of the tracker with four planes is expected to be less than 5 W; even after heavy irradiation (IBL fluences) the 3D sensor power dissipation is less than 0.01 W/cm$^2$, while the front-end contribution is about 0.2 W/cm$^2$.

The precision of the track measurement is the fundamental requirement for the tracker, hence low thermal expansion of the materials used and the overall mechanical stability of the tracker mechanics is essential.

The AFP collaboration aims to possibly install two horizontal Roman pot stations in the Winter 2015-2016 shutdown, with identical silicon trackers mounted in each Roman pot.

4.5.4.2 Design A preliminary design of the AFP tracker foresees a simple compact block of four planes assembled together with a gap of about 10 mm between planes. No final choice of materials has yet been made, but, because of the required properties, materials with a low CTE coefficient which also provide high mechanical stiffness and stability are preferred. Thus, materials such as a Si/Al alloy (e.g. CE7), aluminum nitride or a carbon fibre composite are considered as base materials for the manufacturing of the mechanical parts of the tracker.
The plates are 1 mm thick, with a window underneath the silicon chip modules, and are covered with a thin layer of high thermal-conductivity foil. Such a layer should be thin enough to avoid any deterioration of tracking capabilities. Among the materials being seriously considered are thin Pyrolytic Graphite Foils (PGS). This material is usually very thin (100 µm or less) and the published thermal conductivity is significantly larger than, for instance, copper. It is obvious that such thin PGS foil will need to be reinforced by an additional layer acting as a carrier to provide a solid support for the FE chip. This reinforcement can be done with a thin layer of polyamide. The power for the FE chip, the bias voltage of the 3D sensor, and the I/O signals are provided via flexible hybrid connection (flex). The flex-hybrid is glued directly to the thermally conductive layer of the detector plate and electrically connected through wire-bonds to the FE chip. The other side of the flexible hybrid is directly plugged to a connector at the intermediate card (PCB) which is glued to the feedthrough plate of the Roman pot. This feedthrough plate also contains the pumping port for the secondary vacuum in the pot, as well as feedthroughs for the heat exchanger.

The bare tracker assembly is shown in Fig. 45 (Left), and the tracker assembly with foils and flexible hybrid is shown in Fig. 45 (Right). A comparison of materials with different thermal conduction coefficients is given in Fig. 46.

**Figure 45.** The proposed Tracker assembly. Left: the Bare Tracker Assembly of four planes; Right: the Tracker assembled with PGS foils (grey) and flex (green) interconnects.

**Figure 46.** A list of coefficients of thermal conductivity of high conductivity materials.
4.5.4.3 Module Loading  In order to obtain precise measurement of deflected protons it is essential to have a good resolution especially in horizontal direction ($x$). The size of the pixel cell is 50 µm ($x$) $\times$ 250 µm ($y$). While this already provides good resolution, the resolution is further improved by staggering of the silicon layers by a fraction of the pixel cell size. The current plan is to offset the second and third planes in $x$ by 17 µm and 33 µm respectively. The planned offsets in $y$ are 65 µm for the second plane, 185 µm for the third plane, and 125 µm for the last plane. Such precise positioning is challenging and requires very accurate assembly procedures. The placement and gluing of SiT modules has to be done with a high-resolution pick-and-place machine, using pattern recognition to achieve absolute and relative position accuracy of better than 5 µm. The glue curing process has to be well under control to avoid any shifts during curing. The mounting procedures and its accuracy will be prototyped and tested in the lab using rejected module assemblies.

The planes will also be calibrated to precision markers or dowel pins after the glueing process under a measurement microscope. Placing the planes together should not be difficult. The planes are aligned each other with a pair of precise dowel rods and are clamped together. Of course, the relative plane-to-plane offsets and rotations will be extremely well calibrated by high energy tracks that pass all layers.

4.5.4.4 Integration  The overall possible arrangement of individual parts is shown in Fig 1. It serves to illustrate the concepts and the design work is still ongoing. That is also the reason why technical details are not presented here. On the left side one can see four silicon tracker planes with flex hybrid strips connected to the connectors at the intermediate board which passes out through the cover. A local heat exchanger is shown as blue box placed at the right side in the pot. Grey strips represent the high thermal conductivity foils and are attached to the heat exchanger body. Cooling pipes providing the cooled air to and from the heat exchanger are shown as well. In the front, the ToF detector is shown. This detector will be added later during the second installation phase (AFP2+2).

A careful heat flow analysis of the module assembly with input radiation from the RF-heated pot, the FE-I4 chip, and heating from the non-uniform ionization dose; and heat dissipation via PGS foils to the heat exchanger inside the pot, remains to be done.

4.6 The Time-of-Flight Detector

An high-resolution Time-of-Flight (ToF) detector will be needed for reduction of pile-up backgrounds at high-$\mu$. Already at modest $\mu \sim 1$, while not crucial, a 30 ps resolution ToF will improve purity and signal-to-background, as is demonstrated in Sect. A. Thus, for the approved AFP run scenario of special low-$\mu$ runs, the ToF is not essential and is not an AFP priority. However, a ToF will be essential for standard luminosity running, and having a ToF early in run 2 will allow a study of its performance in-situ and possibly at tail-ends of standard runs.

Overlap background to AFP physics processes of interest due to multiple proton-proton interactions in the same bunch crossing will become prevalent at the LHC as the instantaneous luminosity increases. Much of this background can be removed by kinematical matching between the central system as measured by the central detector and inferred from the momentum lost by protons measured in the AFP silicon detectors. For many processes however, the background may still be too large to make a significant measurement, motivating the development of a fast time-of-flight detector to aid in background rejection.

Consider a bunch crossing with a hard collision producing a central massive system and two unrelated pile-up interactions in the same crossing both producing oppositely directed forward protons. If the protons were from the same interaction as the central system, the position of the vertex as measured by the central tracks will be consistent with the position determined from the time difference
of the forward protons. At high instantaneous luminosity, where the average number of interactions per crossing exceeds 50 (µ ≥ 50), the timing system should have the following characteristics:

- 10 ps or better resolution
- acceptance that fully covers the 16.8 mm × 20 mm proton tracking detectors
- high efficiency, >90%, for protons
- high rate capability of O(5) MHz per PMT pixel (and electronics channel)
- segmentation in x (horizontal) for multi-proton timing
- Level 1 trigger capability
- radiation hard or tolerant for >100 fb⁻¹ integrated run operation
- robust and reliable

In this section, the ATLAS Proton Timing (APT) detector system, consisting of a quartz Cherenkov detector coupled with a microchannel plate photomultiplier tube (MCP-PMT) is described, including the full electronics, local trigger formation, and digitization, followed by performance information.

### 4.6.1 A Quartz-Cherenkov Time-of-Flight Detector System

Since single diffractive collisions that produce a single forward proton are relatively common (about 10% of the total cross section), an interaction of high interest, say DPE or DPhE, which yields two forward protons, may easily be faked by the occurrence of two single-diffraction interactions in the same bunch crossing. Apart from kinematical matching, the only possible rejection of this background to DP(h)E processes is to measure the arrival time difference of the forward protons in the two arms with pico-second accuracy. For a genuine DP(h)E two-proton event, the arrival time difference of the forward protons \( \Delta t = t_{\text{Left arm}} - t_{\text{Right arm}} \) is directly related to the interaction vertex location \( z_{\text{vertex}} \) (z measured along the beam from zero at the ATLAS IP and positive toward the ‘Right’ arm) as: \( z_{\text{vertex}} = c\Delta t/2 \). Thus, a \( \sigma_t = 10 \text{ ps} \) time-of-flight resolution translates into a \( \sigma_z = 2.1 \text{ mm} \) vertex resolution. The vertex location derived from fast timing is compared to the location measured from the ATLAS inner detector tracking; if the two locations differ, the protons stem from unrelated background events. Extensive simulations have shown that a 10 ps time-of-flight measurement provides a background rejection factor around 20.

As discussed above, the AFP detector uses traditional Roman pots to interface to the LHC beam pipe. Diffractive protons are bent in the horizontal plane and the Roman pot insertion is therefore in the horizontal (x) direction, the axis of the cylindrical pot. The proposed APT (ATLAS Proton Timing) detectors are a modified version of the original Quartic detector, proposed by FP420 [82] and further optimized by AFP for use with a Hamburg (movable) beam pipe. The Quartic detector consisted of straight synthetic quartz (\([83]\)) Qbars positioned at the Cherenkov angle with respect to the proton flight direction, and functioning both as a radiator producing Cherenkov light, and as a light guide that funnels the light to the phototube. The AFP APT detector is very similar in concept. However, space constraints imposed by the cylindrical Roman pot housing require that the light be brought out perpendicular to the beam. Thus, the APT quartz bars must be bent out of the \( z \) (beam) - \( y \) (vertical) plane into the \( x \) (horizontal) direction (parallel to the Pot axis).

The LBar concept proposed by Albrow for CMS [66] has the perpendicular light guide bar needed to bring out the light from the Roman pot, but its radiator is parallel to the beam, making it too bulky to share a Roman pot with a silicon detector, or to have enough measurements to obtain the resolution
necessary for high luminosity operation. Therefore a hybrid LQbar solution was adopted which combines the best features of the two earlier designs: the radiator oriented at the Cherenkov angle and the perpendicular light guide. Fig. 47 shows a drawing of the LQbar concept, and a picture of the prototype implemented for the November 2014 AFP Beam Test. Cherenkov light travels up the bars and is converted to a signal by a specialized 4 × 4-pixel Microchannel-Plate Photomultiplier known as the mini-Planacon, made by Photonis [84].

In the following sections the various components of the new timing detector are discussed.

4.6.1.1 Micro-Channel Plate Multi-Anode PMT R&D The lifetime of the MCP-PMT defined as the time it takes for the PMTs quantum efficiency (QE) to be reduced by 50%, is believed to be limited by cumulative effects of the bombardment by positive ions. Until recently, the useful life of a typical MCP-PMTs was limited to an accumulated charge of 0.3 to 0.5 C/cm² of photocathode area, implying that these phototubes would need to be replaced every few weeks when operating at predicted Run 2 standard luminosities. Thus, the development of a long-life MCP-PMT was deemed essential for this detector concept to succeed.

In order to improve the lifetime, it is necessary to reduce the amount of damaging positive ions reaching the photocathode. This can potentially be achieved by a number of means, most of which require a significant redesign of the PMT to inhibit the positive ions by adding an ion barrier, a third MCP, or improving the tube vacuum. A different approach was developed by Arradiance Inc. [85], namely the application of atomic layer deposition (ALD) to coat the MCP pores with a thin layer of alumina, thus suppressing positive ion creation, while maintaining the QE and timing characteristics of the uncoated device.

Under an US NSF SBIR Phase 1 grant, Arradiance Inc., UTA, and Photonis [86] collaborated to construct and test PMTs containing ALD-coated MCPs; the first tubes tested by Photonis and UTA showed a lifetime in excess of 2 C/cm². Building on the experience gained from the NSF grant, there have been a couple of further iterations. Figure 48(a) shows the result of MCP-PMT lifetime tests at Erlangen University (Lehmann et al), on several types of tubes including an early ALD-modified 10 µm pore 64-channel Planacon (red points), which is observed to have no loss of QE out to about
6 C/cm$^2$, and a lifetime of about 8 C/cm$^2$, a factor of 10-20 over expectations for a typical MCP-PMT tube 5 years ago. Figure 48(b) shows that a version of the ALD-modified tube with 25 µm pores and extended dynamic range (low resistance glass) operating at a gain of $10^5$ is capable of withstanding a 5 MHz proton rate (12 pe/proton), with little degradation in timing resolution, while a new mini-Planacon with the same light input and gain, can operate comfortably at about 10 MHz with a 20-30% better resolution.

A 5 MHz proton rate with 10 pe's in a single $5 \times 6$ mm$^2$ pixel at $5 \times 10^4$ gain, corresponds to a current of about 1 µA/cm$^2$ and would give 10 C/cm$^2$ in $10^7$ seconds (100 fb$^{-1}$) implying a lifetime of a year or so without further R&D. Fine tuning the ALD processing is expected to give another factor 2-3 in lifetime, and an active ion barrier built by Photonis and tested at UTA should give another factor of at least four. The rate and lifetime issues therefore seem to be under control and are no longer a major limitation. Nonetheless, thanks to a recent DOE grant, R&D to further study causes of damage and increase the MCP-PMT lifetime will continue at UTA.

4.6.1.2 Detector Layout and Performance

The timing detector has been developed over the past eight years using a combination of simulation, laser tests, and beam tests. Simulations have ranged from simple ray tracing programs to full GEANT simulations [58]. The basic radiator layout has remained constant: an array of quartz bars oriented at the average Cherenkov angle with respect to the beam. In the AFP ToF baseline, the horizontal x-acceptance is subdivided into 4 intervals, ranging from a few mm from the beam for protons with low $\xi$ to 20 mm for large $\xi$ protons. Each x interval is covered by a succession (‘train’) of two quartz bars measuring the same diffractive proton, see Fig. 47; trains may be expanded to four bars depending on the resolution target. Because the central missing mass $MM$ measured from the two protons is directly related to their $\xi$, $MM^2 = \xi_1\xi_2(2E_{beam})^2$, a selection for events in which a large missing mass is produced can be formed already at the first trigger level.

The proton density in the 210 m region is a strong function of distance from the beam, as shown in Sects. 3.1 and 4.3, and requires smaller-width bins closer to the beam to roughly equalize the rate among the four trains. If this were not done, the bins closest to the beam would have a higher fraction.
of multi-proton events at high luminosity, and the corresponding PMT pixels would be damaged more quickly. In the 2012 test beam it was found that the time resolution of a single Qbar is about 20 ps at the CFD level, independent of $\Delta$ bin width over the range of interest (2 to 5 mm) confirming predictions from simulation. Thicker radiator bars in $z$ (along the proton path) present more quartz to the protons, thereby yielding more light and resulting in better resolution. Consequently the baseline detector uses 6 mm thick bars, which is the maximum thickness consistent with the ($6.25 \text{ mm}$)$^2$ MCP-PMT pixel size.

Since the bars are oriented at the Cherenkov angle, the length of the bars decreases with increasing $z$ such that the effective path length of the Cherenkov light to the PMT is independent of where the photon is emitted along the path of the proton. The total light path length is increased by light guides needed to channel the light from the radiator to the PMT. In the Qbar case the light guide is simply an extension of the radiator, but in the LQbar design the light guides are along $x$ (horizontal and orthogonal to the beam), to meet the requirements of the Roman pot. Simulations and test beam show that an LQbar collects 30-40% less light than a Qbar of the same length and width, with much of the losses occurring near the 45° mirror at the elbow, where the radiator is connected to the light guide. Not surprisingly, the timing resolution is correspondingly degraded. Even so, with a train of only two LQbars, the resolution including the full electronics chain is at the 30 ps level, which meets the requirements for operation in special runs.

\subsection{4.6.1.3 Timing at High Luminosity}

At the luminosity anticipated for the special runs multi-proton events are not a major concern. These effects must be accounted for, however, if a high luminosity running period is considered. In addition to the rate and lifetime issues, there are concerns about how high luminosity affects cross talk between channels. The timing resolution in a given train could potentially be degraded if a neighboring train also has a proton. A portion of the Cherenkov signal can spill over from pixels in one train to the other, affecting the leading edge of one or both trains. Photon spill-over may occur at the interface between the LQbars and the photocathode window of the PMT, and electron shower spill-over may occur between adjacent anode pixels in the tube. A related concern is the effect of two protons in the same train, which could degrade the resolution and lower the efficiency. The severity of these effects would be expected to depend on the arrival time difference between the protons, but there is currently no simulation of MCP-PMT response detailed enough to yield much insight into the problem.

To overcome the lack of adequate simulation a data-driven approach was devised, by experimentally simulating multi-proton events at the UTA Picosecond Test Facility (PTF) using fibers to put two signals tuned to the expected level of detector response and separated by various time intervals into the same train or neighboring trains. With two protons in the same train it is often possible to reconstruct the early proton time with somewhat degraded resolution if the events are separated by a few hundred ps or more, but not the second proton's time unless it is late by a few ns. Since the bunch crossing lasts about one ns, it is likely that most events with more than one proton in a train will be lost. Adjacent trains are much less sensitive: the early train hit is almost completely unaffected by cross talk, which was found to typically have a magnitude of about 10.

In conjunction with developing a data driven understanding of multi-proton events, it is worth examining the magnitude of the problem. From a PYTHIA8 study, there is a 2% probability per interaction that a proton is produced somewhere in the total acceptance of both detector arms at 210 m (a "hit"). Thus, for $\mu = 50$ interactions per bunch crossing, one expects one proton hit/crossing on average for total proton rate of 32 MHz across the whole detector (80% of the 40 MHz of bunches are filled).

Although a rate of 8 MHz could be managed by the new mini-Planacon, it is preferable to keep the rate to 5 MHz or less and to reduce the multiple interaction effects, so a two arm version of the
detector would be ideal. By centering the device to equalize the rates, one would take maximum advantage of the parallel cut to improve the resolution where it is needed most. The average rate/train for any rate-equalized set of 4 adjacent trains in the two arms would be 4 MHz/train for \( \mu = 50 \), or 0.125 proton hits/crossing on average. This sets the approximate scale of pixellation required to obtain reasonable rates.

From Poisson statistics, an average of one (background proton), implies an average probability/train (8 rate-equalized trains total) of 0.125. Thus, 12% of signal protons will overlap with a background proton hit (which may also arrive later and then not be detrimental to the ToF measurement.) From a different viewpoint, the chance of accidentally getting a two-arm coincidence from pile-up only is 15%.

While a finer subdivided detector will have a smaller inefficiency, the only way to maintain rejection power as the luminosity or \( \mu \) increases is to further improve ToF resolution, because the increase in combinatorics from multiple proton ToF measurements increases the number of vertex predictions from timing approximately quadratically. Only with better time resolution can these solutions be correctly matched to interaction vertices that are well measured with the central ATLAS tracking system.

It is noted that the backgrounds are concentrated at low-\( x \) (low-\( \xi \)). Hence, for low-mass signals which typically have high production cross section, low-Luminosity special runs are the preferred operational scenario. For high-mass, low-cross section physics, the low-\( x \) region is of less interest and the detectors can be moved further from the beam thus reducing backgrounds and trigger rates.

### 4.6.1.4 Detector Holder

The proposed detector holder, holding the LQbars in place and in tight optical contact with the MCP-PMT is shown in Fig. 47. The device is a square MCP-PMT holder (holding the 10 \( \mu \)m pore Photonis MCP-PMT which has \( 4 \times 4 \) anode pixels of \( 6 \times 6 \) mm\(^2\) size spaced by 0.25 mm.

The lightguides in the LQbar ToF prototype are 6 mm wide in the beam direction, and 5 mm wide in the transverse (\( x \)) direction. The 2-bar trains are optically isolated and held in place by aluminum isolation sheets of 1.00 mm thick, and held by 5.25 mm thick ‘pillars’ that are positioned precisely onto the PMT housing. The bars are separated from the sheets and each other by 0.13 mm diameter stainless steel wire that both keeps them optically free from touching any surface as well as under a slight pressure to keep the bars securely in place. The ‘wiring’ of the LQbar ToF took about 1.5 hrs for a \( 4 \times 2 \) bar system.

Because the experience with the prototype was positive, the final device will closely resemble the prototype.

### 4.6.2 Fast Timing Electronics

The MCP-PMT output signal is approximately Gaussian with a 700 ps full width at half maximum (rms \( \approx \) 300 ps). Photon statistics (the mean number of photo-electrons is about 10) affect the signal amplitude but preserve the shape precisely. At a PMT gain of \( 5 \times 10^4 \), the PMT output signal peak value is about 5.4 mV. The goal of the electronics is to preserve the fast signal shape information and derive the best possible timing of the signal, independent of the signal amplitude.

The approach chosen by the AFP timing group is low-noise amplification followed by constant-fraction discrimination (CFD) and high-precision time digitization (HPTDC) and readout, see Fig. 49 where the various components and their locations are depicted [87].

Other approaches are possible, as discussed for example in Ref. [88]. Although the sampling methods described there are better performing, the CFD method adopted here is close to optimal [89].
Figure 49. A schematic diagram of the components of the fast timing electronics chain described in the text, together with their physical locations in the LHC tunnel.

The AFP Fast Timing electronics chain must maintain the performance of the Cherenkov detector and photodetector preceding it. That means that the timing resolution of a single electronics channel must be in the 5 ps range in order to not affect the single-channel performance of the detector. Since the early days of AFP, an electronics chain was used successfully consisting of a variable-gain preamplifier (PA), a constant-fraction discriminator (CFD), and a time-digitizer based on the CERN high-precision TDC chip (HPTDC). During five beam tests over the past four years, the performance of these three components has been well verified. In 2011 a two-year Advanced Detector Research grant from the U.S. Department of Energy was awarded, which has enabled further development of the components and add trigger and Time-over-Threshold capability to the system.

When a proton traverses a row of quartz bars of the Quartic detector, a programmable multiplicity trigger circuit forms a single-proton trigger signal. The presence of this row trigger indicates with a high degree of certainty that a proton has crossed a particular detector row, corresponding to a particular energy-loss interval. Because the rate capability of the HPTDC is limited to 10 MHz or less, the presence of a row trigger will be required before the corresponding signals are presented for digitization to the HPTDC. This trigger row circuitry has been designed and satisfactorily simulated, and will be tested in a 2015 beam test.

Finally, a crucial ingredient of the fast timing system is the accurate synchronization of the timing detectors on both sides of the ATLAS IP. The Reference Clock circuit (REFCLK) is designed to keep an absolute timing accuracy of 4 ps or better at the detectors, so that the time difference between the two detector arms, and therefore the vertex position, can be deduced with the required accuracy.

In the electronics design for AFP, one profits from the enormous advance in development in high-gain, low-noise, small-size RF amplifier gain-blocks driven by the telecom industry. These gain blocks employ InGaP/GaAs HBT (Hetero-junction Bipolar Transistor) technology. Typical gain blocks have gains of 20 dB over a wide frequency band ranging from 100 MHz to several GHz, have noise figures of NF=3 dB or less, and have built-in input and output impedances of 50 Ohm. This technology has provided robustness, increased reliability, high-speed performance, and - important to our application - improved radiation hardness compared to Si, SiGe, and GaAs technologies. The basic circuit of the gain blocks chosen is a Darlington configuration (inverting) of two InGaP/GaAs HBTs in a three-terminal SMT package (RF-in, RF-out and DC Bias combined, and Ground).
In the baseline proposal, the amplified signals travel from the detector at 205 and 217 m, to instrumentation crates below the detectors, a short distance of about 2-3 m. The minimum required overall gain of the analog electronics chain is about $200 \text{ mV} / 3 \text{ mV} \approx 70 \times$ or 37 dB. Allowing for up to 3 dB of attenuation for the trigger pick-off, the electronic gain of the electronics must be 40 dB, which implies the use of two gain blocks with about 20 dB each. Note, that because of the inversion of the signal polarity in a single gain stage, the number of gain blocks must be even if the signal’s polarity is to be preserved.

All electronics is to be located near the detector, and extensive irradiation tests have been done to investigate this cost-saving feature of the AFP ToF electronics. Irradiation results are discussed in Sect. 4.6.3 below.

4.6.2.1 Preamplifiers The PMT is used at a low gain of about $5 \times 10^4$ to maximize the lifetime of the tube in the high-rate LHC environment close to the circulating beam. The typical PMT output signal at this gain is about 8 mV for 10 photoelectrons. The AFP CFD used has a dynamic range from 250 - 1200 mV (a new design is in the works with a further improvement in dynamic range).

In order to match the CFD dynamic range, and to provide for gain variations as function of PMT pixel and ageing, the preamplification is done in two successive 20 dB stages. The first stage PA-a is located directly on the base of the PMT. The 8-channel preamplifier PCB is based on a low-noise (NF=0.7 dB) InGaP E-PHEMT MMIC gain block (gain 18.6 dB at 1 GHz) [90]. The PA-a has been tested under power and demonstrated to be radiation tolerant, see Sect. 4.6.3.

The first preamplifier stage is connected by mini coaxial cable to the second preamplification stage (PA-b) located at floor level below the detector, where the high-energy proton flux is expected to be a factor 20 lower.

The PA-b provides DC power (5 V) to the PA-a via the coaxial connection. Separate fuses are provided for the PA-a power and for the PA-b power on each PA-b daughter board. Two temperature sensors will be located on the mother board that seats the 8 single-channel daughter boards. The PA-b further includes (in order): a programmable 3-bit attenuator (range 1 dB - 15 dB ), a 2 Way-0° splitter (−4 dB insertion loss) providing a trigger pick-off, and a gain block (gain 22(20) dB at 1(4) GHz). The PA-b has successfully survived the same irradiation runs and doses as PA-a.

In the lab, the heating of the PA-a was tested in vacuum under power and connected to feed-throughs via the eight 45 cm-long SMA pigtails, and the temperature remains below 68°C. The addition of a braided ground strap/heatsink reduces the maximum temperature reached to 48°C. The final version of the preamplifier board will contain such a heat-conducting strap and a PT100-1000 SMD sensor for temperature monitoring.

4.6.2.2 Local Trigger Logic A trigger board has been designed and will be produced in the near future. The design is based on the 8-channel GaAs Discriminator MMIC ‘NINO’ (developed and produced by CERN [91]), followed by programmable majority circuitry to form a ‘N out of M’ type trigger combination on the sequential ‘train’ of radiators traversed by the same proton. The option to include a (properly timed) bunch crossing gate is implemented. The circuit board has been laid out but not yet been produced.

The trigger signals from several adjacent quartz bar sequences are combined into a bit stream and sent over fast air/foam-core coax cables to the ATLAS Central Trigger Processor. The trigger information from the two AFP arms can be used to form a large proton-proton ‘missing mass’ trigger and can be combined with various central ATLAS trigger terms.

4.6.2.3 Constant Fraction Discriminator The Constant Fraction Discriminator principle has long been used to correct for time walk in cases where the signal fluctuates in amplitude but is constant in
shape. The AFP design was initially developed for FP420 by the Université Catholique de Louvain, and was further developed for AFP by the HEP group at the University of Alberta at Edmonton. The measured time-walk is 5 ps or less over the range 250 - 1200 mV. The design is currently revisited to obtain a larger dynamic range and to implement a time-over-threshold functionality, which will allow off-line timing corrections if so required. Moreover, the new CFD design includes an optional bunch crossing gate to reduce output rates.

A single CFD channel is implemented on a small $28 \times 70$ mm$^2$ daughter board, with RF I/O connectors for signal in and signal NIM out, and differential LVPECL outputs.

4.6.2.4 High Precision Time Digitizer The High Precision Time Digitizer board, HPTDC, has been designed and built by the University of Alberta at Edmonton. The HPTDC module employs 3 HPTDC chips and has a total of 12 data channels with a maximum data rate up to 10 MHz. The HPTDC chip [92] was designed by the CERN Micro-Electronics group. The chip is executed in 0.25 µm, 3.3 V CMOS technology and packaged in a 225-pin (27 mm)$^2$ BGA; it is not designed to be radiation-hard, but is expected to work correctly up to levels of 30 krad and more; all internal registers are self-checking and error codes are generated if a malfunction is detected.

The HPTDC chip receives an external 40 MHz clock which drives an internal 12 bit counter and is internally multiplied into a phase-locked 320 MHz clock (3 bits, 3.125 ns least count). A set of 32 delay gates (5 bits) connected as a phase-locked variable-voltage oscillator interpolates the least count interval to a 98 ps least count. By sampling the signal in four equal intervals inside this time period (using three more regular signal channels, each offset by an additional 25 ps delay), the finest time-bin becomes 25 ps. In laboratory tests a rms resolution of 13 ps was measured.

Because the HPTDC chip has four on-chip memory banks, each serving a group of 8 channels, the highest through-put rate is achieved when the chip receives only four signals; in that case the chip will work without dead time up to an event rate of about 8 MHz. The HPTDC front end is flexible, and the fast 40 MHz reference clock signal gated with the trigger will be connected to the first channel on all three chips for internal chip-to-chip reference, leaving a maximum of nine more inputs (eight will be used) for the CFD timing signals.

The HPTDC has a built-in pulse duration measurement capability, but only if operated in the 100 ps least count mode. For 25 ps precision and ToT functionality two input channels per signal, located on different chips, must be used. Thus, the ToT functionality, although testable with the current design, will require a new HPTDC module layout.

The HPTDC hit data are stored in 32-bit words, one word per start time (“hit”), and one per pulse duration. When using four channels per HPTDC ASIC, a bunch crossing (25 ns) may produce up to 4 data words per chip and per 25 ns. These data are stored on-chip in four 256-word memory buffers. Hence, the on-chip pipeline is 6.4 µs deep, sufficient for the ATLAS L1 trigger latency.

Upon a trigger from the ATLAS central trigger framework, the HPTDC chip data are transferred to an on-board FPGA, optionally formatted, and transferred to the output interface. The fast I/O interface will be using the optoboard (as for IBL) for communication control and data acquisition to USA15.

In beam tests the intrinsic resolution of the current HPTDC was determined to be 16 ps (after proper self-calibration to remove non-linearity). This is, after the photodetector, the dominant contributor to the per-channel resolution. Note that the 16 ps resolution of the HPTDC is per channel and that the contribution for a system of four quartz bars in sequence would be 8 ps. New HPTDC ASIC development with smaller feature size are ongoing at CERN and may lead to significant improvements in the near future. This and previous versions of the HPTDC board have been used successfully at various beam tests. The HPTDC and new developments were presented in Ref. [93].
The baseline location of the HPTDC is in the electronics crate at floor level near the detector stations. This close location is an important cost saver, because it limits the length of high-quality, low dispersion cable runs between the CFD and the HPTDC.

The radiation tolerance of the HPTDC is not guaranteed. The HPTDC ASIC is expected to be radiation tolerant to a degree sufficient for it to be located on the tunnel floor, near the detectors. Passive irradiation of the HPTDC chips, see Sect. 4.6.3, did not affect their performance when the chips were put in a working HPTDC module. The FPGA firmware has been re-designed to provide the appropriate checking of HPTDC registers for SEUs. Moreover, the FPGA itself has to be radiation tolerant, which can be done by choosing a radiation-hard part (expensive!) or going to a fuse-programmable part. Alternatively, the FPGA can be programmed to do self-checking and organized with majority decisions in critical paths. It is the latter choice that will be pursued.

4.6.2.5 Reference Clock

A major component of any time-of-flight system using two widely separated detector arms (424 m apart measured along the beam line), is a synchronizing Reference Clock. As for other components, the requirement is that the two local detector clocks are synchronized to well within 5 ps.

The 40 MHz signal from the LHC is multiplied to 480 MHz before being sent to the tunnel by the transmitter board. In the alcove, the receiver board, which is part of the feedback loop (described below) provides a stabilized 480 MHz signal, which is then divided to yield a stable 40 MHz reference signal for use in the HPTDC modules. The master clock must be precisely synchronized, independent of cable delay fluctuations, induced, for example, by changes in ambient temperature. This is accomplished by using a phase locking mechanism that uses feedback from a phase comparison between the master clock frequency of 480 MHz and the signal that goes through a coaxial cable to the detector station. A voltage controlled oscillator (VCO) launches a signal down the cable where it is reflected at the end. The reflected signal interferes with the original in a directional coupler which mixes the signals and produces a DC level. The phase-dependent DC level is fed back to the narrow band VCO. Thus, the synchronized multiplier/divider counters, the variable attenuation, and the electronically tunable phase shifter, all work to maintain a constant number of wavelengths in the cable with low timing jitter, ensuring sufficient accuracy. The system is based on a design developed at Stanford Linear Accelerator Center (SLAC), which attained sub-picosecond jitter performance. Tests of the circuit show that the circuit can reduce the jitter of a 40 MHz input signal from 100 ps to 1.5 ps. While the design is not fully complete at this time, initial tests indicate the desired performance can be reached.

In addition to the synchronized local clock, clock fanouts at the local detectors are required. It is intended to implement these with high performant LVPECL Clock FanOut buffers from Micrel.

4.6.3 Irradiation tests of ToF components

Precision timing requires that all ToF electronics, including the digitizers, be placed close to the detector, because long cable runs will degrade performance by signal dispersion, noise pickup, and propagation speed variations with time. Moreover, long high-quality multi-channel cable runs are expensive, and this cost must be weighed against the cost of increased radiation tolerance needed near the detector.

Several irradiation campaigns were conducted for the elements in the ToF electronics chain: the 1st and 2nd stage preamplifiers, the CFD boards, and the HPTDC ASICs. The set-up used in the February 2014 irradiation campaign with the LANSCE 800 MeV proton beam in Los Alamos by the University of New Mexico group is shown in Fig. 50a. The proton beam has a FWHM cross section of $\approx 15$ mm, with a rather flat top of about 9 mm diameter (FW at 80% of maximum). The beam.
intensity is $10^{11}$ protons/cm$^2$/pulse, and the beam pulses have a 1 Hz frequency. The same facility was used to certify the FE-I4 radiation hardness.

The beam was centered on 4 PA-a channels, 4 PA-b channels, and 4 CFD boards, see Fig. 50b, covering all sensitive components within the FWHM of the beam spot. The required regulated power was brought in from outside (in AFP, the voltage regulators are at floor level and are radiation hard.) HPTDC ASICs were also placed in the path of the beam for passive irradiation. Aluminum foils were analyzed afterwards to determine the total received illumination. In terms of dose, the received dose is about 75% in protons and 25% in gamma radiation.

In view of the expected radiation environment at the AFP locations, see Sect. 3.4, the requested irradiation was for $1 \times 10^{13}$ p/cm$^2$, i.e. about 100 beam pulses of $1 \times 10^{11}$ p/cm$^2$/pulse, and to verify operation before and after each step of $1 \times 10^{12}$ p/cm$^2$ or 10 pulses. The irradiation request was for the equipment to be under power and being read out, monitoring the width of the fixed time difference distribution of a test pulse with respect to the trigger. Unfortunately, the distance between set-up and safe area for the readout was underestimated and only two of the four CFD output pulses could be monitored on a fast oscilloscope. The irradiation over, the monitored channels were still operating without visible deterioration in gain or rise-time.

After cool-down, the electronics was tested at Stony Brook and no deterioration was found in pulse shapes and delays. The 8-channel PA-a motherboard and pigtails were slightly darkened, indicating a high received dose. The irradiated PA-b and CFD channels were used in the November 2014 beam test reported in Sect. 7, and performed as expected. The received irradiation as derived from the dosimetry foils is $2.3 \pm 0.2 \times 10^{13}$ p/cm$^2$ upstream of the set-up and $2.1 \pm 0.2 \times 10^{13}$ p/cm$^2$ downstream. The received dose was 9 kGy.

The HPTDC ASICS received the same fluence and dose passively (the existing non-radhard HPTDC board could not be irradiated). Afterwards, the chips were mounted on a working HPTDC motherboard and they tested fine in the lab, with no noticeable deterioration in timing performance in the test bench.

In terms of the radiation expected at the AFP locations, the received irradiation represents the expected integrated fluence for 400 fb$^{-1}$ (four years at a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$) at 50 mm from the beam for PA-a, and is a factor $10^3$ higher than expected for 100 fb$^{-1}$ at floor level for the other components tested. In addition, during much of Run 2, AFP pots will only be inserted in special,
Figure 51. (a) the time difference between a reference detector and the average time of six Quartic bars using CFDs read out by a LeCroy Wavemaster 8620 oscilloscope (b) the same quantity readout by the HPTDC board.

4.6.4 Timing system performance

The proposed ToF system, including the Quartic detector, was extensively studied using simulations, beam tests, and laser tests. Fig. 51(a) from a January 2012 test beam at Fermilab shows the time difference between a reference signal and the average time from six quartz bars. The reference signal is obtained using a 3 x 3 x 15 mm$^2$ quartz bar interfaced with a silicon photomultiplier. Taking into account the resolution of the reference signal (about 14 ps), the 20 ps overall resolution implies that the six bar system resolution is also about 14 ps. Using the Alberta prototype HPTDC instead of the oscilloscope to read out the CFD signals, the overall resolution increases to 26 ps as shown Fig. 51(b), but the increase is dominated by the HPTDC resolution of the siPM, while the HPTDC resolution is smaller than the bar resolution and has little effect on the 6-bar Quartic measurement. The resulting resolution for this six-bar Quartic/Planacon system through the readout chain is about 15 ps.

The resolution of a single bar detector with its readout channel is composed of different parts, see Table 11: the photon arrival time fluctuations from the source to the photocathode, the transit time jitter in the PMT, the effect of noise in the electronics, the remaining time-walk in the CFD, and finally the resolution (and non-linearities) in the HPTDC. To the proton time resolution one should add (in quadrature) the resolution of the reference clock in a system that measures the difference in arrival times of the protons. Other effects, such from long signal cables, can be ignored in the planned AFP layout. While many of the effects can be simulated, the better approach is to use the measured performance for the various contributions, as was done here.

The measured resolution in the recent AFP beam test (Sect. 7), while not finalized, is in reasonable agreement with the expectation above: using the fast sampling scope, the measured single-bar resolution is 30 ps (at 1900 V).

One concern about the Quartic detector is nuclear interactions in the fused silica bars. Recent full GEANT4 simulations show that the probability is about 7.0% for a nuclear interaction in an 4 bar Quartic with 6 mm wide bars oriented at the Cherenkov angle (roughly 2% per bar). This would lead to a degradation of the resolution as bars after the interaction would saturate the amplifiers, resulting in biased time measurements. This effect could be reduced by a factor of two by implementing an up-down detector as shown in Fig. 52(a). This design also would effectively add more segmenta-
### Table 11. List of components with their contribution to the single-channel time resolution of the Quartic Cherenkov detector and its readout.

<table>
<thead>
<tr>
<th>Component</th>
<th>Resolution</th>
<th>limiting factor or future improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 × 6 mm$^2$ Radiator and 10 µm pore MCP-PMT</td>
<td>30 ps</td>
<td>6 µm pore MCP-PMT may give up to 30% further improvement in resolution and hardness</td>
</tr>
<tr>
<td>Pramplifiers</td>
<td>&lt;5 ps</td>
<td></td>
</tr>
<tr>
<td>CFD</td>
<td>5 ps</td>
<td>new CFD aims to get 3 ps and larger dynamic range</td>
</tr>
<tr>
<td>HPTDC</td>
<td>15 ps</td>
<td>new HPTDC ASIC aims for 5 ps resolution</td>
</tr>
<tr>
<td>Reference Clock</td>
<td>3 ps</td>
<td></td>
</tr>
<tr>
<td>TOTAL (single channel)</td>
<td>34 ps</td>
<td>22 ps (?)</td>
</tr>
</tbody>
</table>

In the Fall 2012 test beam at CERN, several improvements were made, including using a 10 µm pore MCP-PMT, using bars with 6 mm length (in the beam direction) instead of 5 mm to produce more light, and a better mechanical design. These factors decreased the single bar resolution to the point where the six bar Quartic was determined to have a resolution of 11 ps. Fig. 52(b) shows the time difference between an improved reference counter (11 ps resolution) and a 2 × 6 × 150 mm bar, which alone has a 20 ps resolution (without the HPTDC). The 2 mm wide bar was compared to a 5 mm wide bar and was found to have the same resolution, a critical validation of the variable bin size detector. A detector composed of these bars would give a time resolution of about 11 ps.

A fast timing detector system demonstrating a system resolution of about 11 ps was developed. The current system is capable of 10 ps without any major adjustments, and further refinements are expected.
Figure 52. (a) A conceptual diagram of an up-down Quartic detector that would use half the quartz of an eight channel Quartic by capturing the light 180 degrees away from the standard bar (this light escapes in the standard configuration). (b) The time difference between a reference detector and a single $2 \times 6 \times 150$ mm bar using CFDs read out by a LeCroy Wavemaster 8620 oscilloscope.
5 The AFP Trigger and Data Acquisition System

5.1 Trigger System

A first-level (L1) trigger from AFP is required for the AFP physics programme, in particular for those processes where either the backgrounds are large or standard triggers (e.g. MBTS) are prescaled. In such cases the local trigger formation must be done within a few 100 ns in order to be within the ATLAS first-level (L1) acceptance window, which is limited to 2.15 µs. Moreover, the L1 trigger should be flexible or programmable in terms of configuration, e.g. a single-arm or a two-arm coincidence, the selected $x$ or $\xi$-range, etc.; and finally it should have low fake rate with high and measurable efficiency. In this section the L1 and high-level trigger (HLT) formation for AFP is discussed.

For the first stage of the AFP program, the single-arm AFP0+2 configuration, a L1 trigger based on the HitOR from the FE-I4 chips will be implemented. The HitOr signal is formed as the logical OR of all fired pixel discriminators on the FE-I4 chip [94]. The HitOr signal is available between about 50 ns after the charge injection, the precise value depending somewhat on the amount of charge in the ‘hit’ (‘time walk’) and on the value of the ‘DisVbn’ parameter, which sets the current supplied to the discriminators on the chip. The HitOR trigger will have a time resolution of order 5 ns or better, sufficient for the identification of the bunch crossing. The HitOR LVDS signals from the four detector planes will be combined to form a majority trigger, probably using the radhard HitBus ASIC developed for the ATLAS Diamond Beam Monitor [95]. The block diagram for the TDAQ system of AFP0+2 is depicted in Fig. 53. Four FE-I4 tracker modules are located at the 205 m station, and another four modules plus a single HPTDC module for the time-of-flight digitization in the 217 m station.

![Figure 53. The TDAQ Block Diagram for the single-arm AFP configuration (AFP0+2).](image-url)

To distribute clock and control signals to the FE-I4 modules (and eventually to the HPTDC module, see Sect. 4.6.2), the PatchPanel Zero (PP0) boards developed for the DBM [95] are used. The PP0 boards are designed to receive data from up to 6 FE-I4 modules and also to receive the 1.5 V CMOS level HitOR outputs from the FE-I4 modules. The HitOR output from the FE-I4 is a wired-OR of all enabled pixels in the FE-I4. The HitOR processor implemented in the PP0 can be programmed...
to mask out individual channels and perform an AND and/or OR on input signals and produce a majority vote. The output, in form of serial bits in LVDS with Bi-phase Mark Coding, is sent on two output lines DTOTA/B, each for three modules. The copper twisted pairs with the DTOTA/B signals arrive at the optoboard designed to convert the electrical signals into light to be sent over hundreds of meters to the USA15. The optoboard may be modified by adding the trigger logic. The main task of this logic would be to receive the LVDS coded data streams from the PP0s, extract the trigger decision from each series of 3 channels, make an OR and form the single-arm NIM output signal for transmission over fast foam-core coaxial cable to the ATLAS CTP.

While sufficient for the approved AFP program, the HitOR tracking trigger cannot be used for pile-up rejection based on proton time-of-flight. For standard luminosity running, the AFP time-of-flight (ToF) system is to be used: the ToF also serves as trigger detector using the discriminated analog signals from the LQbar counters.

5.1.1 L1 Trigger propagation delay

The AFP L1 trigger must be formed fast because of the very limited time available for the AFP detectors located at 210 m away from the ATLAS IP. The two main contributions to the total AFP Trigger propagation delay are the forward proton time-of-flight from the ATLAS IP to AFP212, and the trigger signal return from AFP212 to USA15 via the galleries. The latter delay contribution is minimized by using fast (and thick) low-loss cable, for example 0.6" diameter LMR-600 coax which has a signal propagation speed of 0.87c. Higher speed (and lower loss) coaxial cables exist, e.g. the Andrews (COMSCOPE.com) 7/8" diameter AVA5RK-50 (0.91c) or the 1-5/8" diameter AVA7RK-50 (0.92c), which save some 60 ns in delay and have reduced signal loss at the cost of a higher price. The trigger logic will most likely be located below the AFP212 detector. The trigger logic propagation delay at AFP212 and in USA15 is estimated to be well below 50 ns. In Table 12 the various contributions to the AFP total trigger delay are tabulated. For running at standard luminosity, the AFP trigger delay must be minimized in order to minimize the ATLAS deadtime, ideally not larger than the current longest trigger delay without AFP which is about 1.7 µs. This puts a premium on ultrafast cable and trigger logic.

5.2 Baseline trigger system for AFP0+2

The baseline trigger for AFP0+2 is based on the ‘HitOrOut’ functionality of the FE-I4 frontend chip of the AFP tracking detectors described above. For AFP2+2, the ToF system will provide the

<table>
<thead>
<tr>
<th>Path</th>
<th>Length [m]</th>
<th>Velocity/c</th>
<th>Delay [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton flight from P1 to 217 m</td>
<td>217</td>
<td>1</td>
<td>724</td>
</tr>
<tr>
<td>Propagation delay in Trigger detector</td>
<td>3</td>
<td>0.66 (RG-58/U)</td>
<td>≤5</td>
</tr>
<tr>
<td>50 Ω cable from detector to Local Crate</td>
<td>15</td>
<td>0.90</td>
<td>1075</td>
</tr>
<tr>
<td>Local Trigger formation logic</td>
<td>≤50</td>
<td></td>
<td>≤100</td>
</tr>
<tr>
<td>Fast Trigger cable via UPS to USA15</td>
<td>300</td>
<td>0.90</td>
<td>1969</td>
</tr>
</tbody>
</table>

Table 12. Components contributing to the total AFP Trigger propagation delay, starting from the bunch crossing time. Note, that the maximum ATLAS L1 Trigger latency is about 86 bunch crossings of 25 ns, i.e. 2.15 µs. The propagation delays in the logic include local cabling and are estimated conservatively.
local trigger. Thus, if possible, the trigger driver and receiver circuitry should anticipate the use of both input trigger types, possibly even in combination.

5.1.2 L1 Trigger capability

The AFP ToF trigger circuitry provides a proton tag from each arm. The tag signal is formed from the preamplified signals of the ToF LQbar counters. The details of the AFP L1 trigger electronics is described in Sect. 4.6, and only the trigger functionality is described here. The proton tag trigger is formed by requiring the coincidence in a 30 ps time window of a programmable minimum number of trigger counters (LQbars) in a ‘train’ of counters. The ToF may have from 2 to 4 successive LQbars in a single train, and there are 4 trains that subdivide the $x$-acceptance of the ToF, see Sect. 4.6.

A maximum of four triggered trains can be produced per bunch crossing, and the AFP Single-Arm Trigger consists of a train of up to five 2 ns long logic NIM pulses: a start pulse followed by four 4 ns long ‘buckets’, one for each of the four trains of the ToF. The start pulse is formed by the local bunch crossing signal (which is also used by the local trigger logic to gate the train triggers), followed by successively delayed trigger tags for each train trigger present. The local bunch crossing signal is retimed by the local 40.08 MHz reference clock, and contains the precise bunch crossing information from the LHC at the ATLAS IP. Proton time-of-arrival time information is therefore encoded in the time delay between the start pulse and any of the train trigger pulses. This time information is rough, because the NINO discriminator [96] is used to determine the train trigger and its time-walk is of order 20 ps.

The single-arm trigger signals from both arms are sent to the AFP L1 Receiver in the USA15 cavern on low-loss coaxial cables via the UPS galleries to minimize the cable propagation delay. An AFP L1 receiver design does not exist at this time, but the ALFA design serves as a proof-of-principle. The simplest design will contain a receiver circuit for each arm followed by a combinatorial section. The output stage delivers the AFP L1 trigger to the ATLAS Central Trigger Processor. The receiver reshapes and decodes the single-arm trigger signals and the combinatorial section implements logic that forms the AFP L1 trigger(s). In case the AFP 2 + 2 configuration is available, a rough mass trigger may be implemented at this stage, and a rough, 20 ps accuracy, vertex position may be calculated with a Look-Up Table.

5.1.3 High-Level Trigger

The optimal High-Level Trigger (HLT) strategy will depend on the detector configuration, the instantaneous luminosity and the physical process to be measured.

For the AFP0+2 scenario, in low luminosity dedicated runs, the physics processes of interest that have been described in section 2, correspond to diffractive production of jets, photons, photons+jets or electroweak bosons.

The trigger strategy will depend on the signatures of the final state. The processes with leptons (electrons or muons) or photons in the final state can be triggered by the central lepton or photon triggers with high efficiency and reasonable rates for $p_T$ thresholds around 20-25 GeV, depending on the luminosity. If required, a coincidence with a diffractive proton, both at L1 or at the HLT, can be used to lower the $p_T$ threshold of the leptons.

The processes with jets in the final state will be affected by the very large rates of the background non-diffractive jet production. In this case it will be mandatory to combine, both at L1 and at the HLT, the AFP trigger signal with the central detector jet trigger signatures.

The HLT can improve the track reconstruction in AFP, using the full detector information. For the AFP2+2 detector, the trigger strategy will be similar: processes with leptons or photons in the final state can be triggered with the standard ATLAS leptons/photons triggers with reasonable
thresholds, while processes involving jets will need of a combination with two detected protons in AFP.

For the low luminosities a coincidence of a proton on each side of the interaction region plus a central trigger single jet signature at L1 will be sufficient, while as the luminosity increases a better combination of the kinematical information can be done in the topological trigger processor. To ensure good acceptance for a large range of jet transverse momenta, the full scan HLT jet reconstruction can be initiated by a minimum bias L1 trigger (very low jet $p_T$) or by a L1 jet (medium or high jet $p_T$) in coincidence with a pair of forward protons in AFP. The HLT will provide improved track and timing reconstruction in AFP and improved (very close to offline) jet reconstruction, allowing the calculation of kinematical information (such as invariant mass or longitudinal and transverse momentum) for the central system and comparison with the same information obtained from the protons detected in AFP.

The early installation of the AFP0+2 detector would allow the in-situ measurement of trigger rates, evaluating the contributions from beam backgrounds and physics processes that are needed to prepare the AFP2+2 trigger strategy.

5.2 Data Acquisition

The challenge of extremely large data volumes and high trigger rates has made the Trigger and Data Acquisition (TDAQ) system a central component for generations of collider experiments. A DAQ system based on the Reconfigurable Computing Element (RCE) provides improved input/output (I/O) capabilities and a more compact design compared to previous systems in HEP [97]. It consists of two building blocks: (i) A generic computational element, which can support different models of computation, including arbitrary parallel computing implemented through combinatorial logic or DSP-style elements, or a traditional procedural-based software operating on a CPU. In addition, this element must provide efficient, protocol-agnostic mechanisms to transfer information into and out of the element. (ii) A mechanism to allow these elements to communicate with each other both hierarchically and peer-to-peer. The connectivity between elements must allow for low latency, high-bandwidth communication.

5.2.1 The RCE-based AFP DAQ

The RCE-based system will be used for the readout of AFP detector, which shares much of the commonality for its tracking detector with the ATLAS IBL Silicon tracker. An electrical test set-up was commissioned for the new readout chip developed for IBL, the FE-I4 ASIC. This test system is essentially a portable data acquisition system (DAQ) that has been used very successfully to test and characterize the FE-I4 pixel readout chips, and was used afterwards to test the IBL modules and staves loaded with 6-32 modules each. The system was also successfully used in the November 2014 AFP Beam Test at CERN, to read out 5 Silicon 3D Tracker planes and three HPTDC chips of the LQbar Time-of-Flight detector. The RCE-based system combines the hardware developed at the SLAC National Laboratory, with a software environment developed for existing pixel detector, and forms a complete DAQ system with a powerful hardware and software user interface.

The DAQ hardware is an adaptation of an existing modular system consisting of building blocks based on the Advanced Telecommunications Computing Architecture (ATCA) packaging standard [98], which provides adaptable, high performance I/O on an industry-standard backplane. The new DAQ does away with the crate and backplane, and instead uses a custom high speed I/O (HSIO) computer interface board also developed at SLAC. Only the Reconfigurable Cluster Element (RCE) of the modular ATCA system is used, interconnected through high speed Ethernet. The RCE-based hardware requires little or no hardware customization for different detector systems. The only cus-
tomization that will be needed is at the online software level, which has been ported and adopted from the already existing ATLAS online software.

We have also considered the use of the IBL-ROD system for the AFP TDAQ, but this was rejected for lack of experienced manpower within the AFP group. Experience with and support for the RCE-based DAQ was readily available in the AFP collaboration, and the interfacing to the silicon and timing (HPTDC) front-ends is trivial and flexible.

5.2.2 The Time-of-Flight HPTDC Digitizer Readout

The AFP High Precision Time-to-Digital Converter (HPTDC) chip on the 4-chip HPTDC board is interfaced with the TDAQ via an on-board FPGA which decodes commands and formats the HPTDC data output stream. The HPTDC board has 12 LVPECL inputs coming from the Constant Fraction Discriminator (CFD). The time of the rising edge of each input is captured continuously with bins of 24.4 ps and a 5 ns dead time. A trigger command from the TDAQ or elsewhere selects hits falling within a programmable time window and sends these out to the DAQ system. The TDC is clocked either by an on board 40 MHz clock or via a clock input allowing distant TDCs to be synchronized to the same timebase.

The HPTDC connects to the RCE-based DAQ system using the same RJ45 interface as used by the FE-I4 Front-End chip of the Silicon Tracker. The Input commands are identical in nature to those of the FE-I4 chips with exception to the ‘WrFrontEnd’ command which accepts a 647 bits instead of 672 bits to match the TDC configuration bitstream length and makes use of the address field to address the three TDC chips. Some of the FE-I4 commands are not implemented in the TDC but are still decoded.

The output data also uses the same headers as the FE-I4 chip with exception of the Data Record which is expanded from 24 bits to 32 bits to accommodate the full timing precision and has different sub-fields specific to the TDC data.
6 Detector Control System and Services

6.1 Detector Control System

The Detector Control System (DCS) is responsible for the coherent and safe operation of the AFP detector. It provides tools to bring the detector into any desired operational state and it continuously monitors the operational parameters, a subset of which can be archived in data bases for later checks. The DCS signals any abnormal behaviour and allows for manual and automatic actions. Lastly, it serves as a homogeneous interface to the detector and its infrastructure.

The ATLAS experiment uses the industrial Supervisory Control and Data Acquisition (SCADA) system Siemens WinCCOA ([99]). A set of standards, tools (so-called framework components) and guidelines has been prepared for all CERN experiments in the framework of the Joint Control Project (JCOP) [100]. Furthermore, the ATLAS central DCS group provides ATLAS-specific rules, guidelines, and framework components [101, 102]. The AFP DCS should respect the ATLAS rules and recommendations and will profit from JCOP tools as much as possible.

The AFP silicon tracking system is derived from the IBL detector. Services such as low and high voltage supplies will be very similar to those used in the IBL. Hence the DCS for the silicon tracker will be modeled on the IBL DCS [103].

The Roman pots, which house the detectors, and the stations are very similar to those of the ALFA detector. Thus, the ALFA DCS [104] serves as a prime example in the operation of the Roman pot motion and its position monitoring.

The ATLAS I/O standard board, the Embedded Local Monitor Board (ELMB) [105], will be used in many places within the detector, mainly for monitoring of different parameters such as temperature, currents, voltages, etc., but also for control. The ELMB is radiation tolerant and insensitive to magnetic fields. At the heart of the ELMB is an ATmega128 microcontroller with remotely upgradable firmware and a CAN bus [106] interface for communication. The ELMB contains 64 analog inputs multiplexed to 16-bit Analog-to-Digital Converter ADC, 32 digital input/output channels and a Serial Peripheral Interface (SPI). It can be embedded within custom designed modules to facilitate the connection to a variety of sensors. The ELMB’s are powered from a CAN PSU (CAN Power Supply Unit) [107]. The OPC UA (Unified Architecture) server developed by ATLAS is used for control and readout.

6.1.1 AFP Hardware Architecture for the DCS

Fig. 54 presents an overview of proposed AFP hardware and services to be controlled by the DCS. The scheme is based on this TDR, on the AFP Technical Review of September 2012, and on presentations dedicated to the silicon tracker [108] and the timing detectors [109], and on the DCS proposal [110].

A standard ATLAS DCS PC Dell PowerEdge R620 running Linux SLC6, WinCCOA 3.11, and VM 2008 is used for overall control. The VM2008 is needed to operate the OPC DA (Data Access) servers (firmware from Wiener and ieseg), because they only execute on the Windows platform. The 16 port SYSTEC USB CAN module [111] is used to interface the DCS PC to the CAN bus.

The hardware is located in 3 places: (i) at the detectors and Roman pots, (ii) the crates with the readout electronics, voltage regulators, optoboards, and the vortex coolers on the tunnel floor below the detector, and (iii) the power supplies and the computer in the USA15 counting room.

The entire hardware can be split in 4 main categories: low voltage, high voltage, environmental monitoring, and the infrastructure.
6.1.1.1 The Low Voltage system

Detector modules require dedicated powering, which should be exactly adapted to the need of the loads. Furthermore, the protection of Front-End chips against overvoltage is necessary. Therefore a two-stage low voltage power supply system has been proposed: the Wiener PL512 power supply in USA15 as the first stage and separate local LV Voltage Regulator stations for both detectors (SiT and the ToF), as the second stage.

The LV Voltage Regulator (VR) system based on the IBL solution will be used [112]. LV and Vvdc VR boards with radiation-hard VRs and a VR Controller card are installed in the dedicated VR crate. The VR crate is located on the tunnel floor below the detector and can be cooled from the Vortex AirCooler. The LV VR boards supply the FE-I4 chips and ToF electronics, while the Vvdc VR board delivers the proper voltages for the optoboard. The VR Controller card is equipped with a non-standard ELMB and controls the regulators and monitors their voltage levels. In addition, several (8) NTC’s are located in temperature-critical locations within the crate and are read with a standard ELMB.

The VR system does not perform current measurement in individual supply lines and therefore an extra ELMB module is used to precisely measure the inputs to the LV VRs. The LV Patch Panel PP4 copied from the IBL system and located in USA15, is dedicated for this purpose. It splits one output from the PL512 power supply into 4 parallel lines leading to the local station and the ELMB measures the current in each line.

The ToF detector needs boards with radiation-hard voltage regulators (placed in the AFP Crate in the Tunnel floor) to supply the relevant electronics. They will be ELMB controlled.

Optoboard modules need a dedicated power supply. The SCOL (Supply Control - OptoLink) is a standalone device copied from the IBL system and located in USA15. The optoboards require three different voltages. One of these, Vvdc, is routed through the dedicated LV Voltage Regulators Vvdc board in the local VR crate for protection of the optolink chip. The power supply is ELMB controlled/monitored.

For the first stage LV power a Wiener PL512 power supply is used [113]. The PL512 contains...
12 independent channels, each with an output voltage range up to 17 V, and has hardware interlock capability. It is controlled over Ethernet and communicates with the DCS computer via the included Wiener OPC firmware.

The LV hardware interlock protects sensors and electronics against overheating. It automatically switches off the power supply related to the source of over-current or over-temperature. The solution used by the IBL will be adapted to the AFP needs. The system is completely hardware based and does not require any software intervention, thus providing maximal safety. The status can be monitored with an ELMB if requested.

### 6.1.1.2 The High Voltage system

High Voltage is used for depleting the silicon sensors of the SiT detector and for supply of the ToF Photomultiplier(s). The iseg HV system [114] has been chosen. The system consists of HV iseg Crate ECH 238-UPS and 2 modules: EHS F205nF_ID 16 channels - for the SiT and EHS 230n-F 16 channels - for the ToF.

The control and monitoring is performed via CAN Bus, by means of the iseg OPC firmware.

### 6.1.1.3 Infrastructure

Infrastructure includes monitoring of RPOs positions and movements, monitoring of the hardware interlock status, temperatures in the cooling system, control and monitoring of ToF electronics and common infrastructure in the USA15.

The control and monitoring system of the Roman pot movement is under responsibility of the LHC and is fully integrated with the LHC control system. The AFP DCS will have access to information about status, motor steps and LVDT’s published by the LHC. It will also have a possibility to publish emergency commands. This part of the DCS will be designed in a similar way to the ALFA detector DCS [104].

The Vortex Cooling apparatus is described in 4.4.1. The AirCooler systems will be equipped with a few temperature sensors, PT1000 or NTC’s. If flow control or input air pressure control is required, additional sensors and controls will be implemented by ELMBs described in paragraph 6.1.1.4.

Several programmable ToF electronics devices (such as gain control and trigger configuration as described in the section 4.6) will be controlled and monitored by the DCS.

The AFP infrastructure systems located in USA15, such as the RCE-DAQ [115] crate and the CAN Bus power supplies [107] will be monitored by DCS.

### 6.1.1.4 Environmental monitoring

Environmental monitoring includes the temperature, pressure, and radiation measurements in the detector area, the temperatures in the AFP crates (LV Regulator System, AFP-ToF crate) and in the cooling apparatus. Values will be read by ELMB’s embedded either in ATLAS standard ELMB motherboards or in custom designed dedicated boards.

Sensors should be equipped with the appropriate cabling and connectors for easy connection to ELMB motherboards. ELMB motherboards will be placed as close as possible to the sensors. The mechanical structure should be defined for safe and reliable fixation of the boards.

The ELMBs are supplied from a CAN PSU (CAN Power Supply Unit) [107] located in USA15. CAN cables provide both power and signals. The proprietary ATLAS OPC UA server is used for ELMB control and readout.

### 6.1.2 AFP DCS software

The AFP DCS software must be able to be integrated in the global ATLAS DCS hierarchy. The proposed architecture, integrated in the ATLAS DCS, is shown in Fig. 55.

The software is running on the AFP Local Control Station (the AFP DCS PC) and handles all DCS operations. The Forward Subdetector Control Station is dedicated for high level control of
all forward sub-detectors, allowing also stand-alone operations. The ATLAS Global Control Station controls all sub-detectors, collects data from external systems interfaced to the ATLAS DCS, such as the LHC collider status information or the Detector Safety System (DSS) [116], and sends the data to sub-detectors via dedicated DCS Information Servers.

The DCS software consists of three layers. The Field Management layer establishes communication between different hardware units. OPC servers are used for the middleware communication layer. The DIM [117] TCP-IP-based communication mechanism is used for data exchange between different platforms, for example passing FE-I4 environmental information from DAQ to DCS or reading/publishing Roman pot movement/position data.

The Process Management layer is responsible for overall data processing, storing data to databases, mapping, and calculations. The WinCCOA SCADA serves as the main software here. The set of JCOP framework components facilitates integration with standard hardware devices and implementation of control applications. Two views of the detector structure can be created using the framework tools: a Hardware View, and a Logical View. The Hardware View represents as faithfully as possible the detector hardware and infrastructure (e.g. power supplies channels, ELMB channels) and allows for easy integration and basic operations; while the Logical View provides mapping between the hardware structure and the detector. Both views are kept in the WinCCOA project but may also be stored in the configuration data base.

The Supervision layer is responsible for overall detector operation and visualisation. The JCOP Finite State Machine FSM [118] toolkit will be used to build a representation of the detector as a hierarchical, tree-like structure of well-defined subsystems, called FSM units. The hierarchy permits a high degree of independence between parts of a tree, allowing concurrent use during tests and integration phases, and control during operation, either automated or user-driven.

The partitioning of the system is based on functionality and/or geographic positions within the detector. It is usually based on the detector’s Logical View. Each FSM unit represents a part of the detector, for which the behaviour can be described with a limited set of states. A state can change spontaneously or as a result of a command. Commands can be issued at any level of the hierarchy; they propagate downwards, as states propagate up in the tree. Each FSM node is connected with 2 GUI operator panels.

The AFP FSM tree is shown in Fig. 56. The tree consists of 3 main nodes: the Infrastructure, the SiT Detector, and the ToF Detector. The Infrastructure node includes all AFP equipment, while detector parts are at first split functionally into High Voltage, Low Voltage and Temperature; and then geographically to individual chips.
6.2 AFP Common Infrastructure and Services

The AFP off-detector hardware will be partly installed in the LHC tunnel near the Roman pot stations and partly placed in Atlas underground service area USA15. Optionally, some hardware could be located in the US15 service area as this will significantly reduce cable runs and the voltage drop over the cables between the LV power supplies and the AFP voltage regulators. The AFP services can be divided into following categories:

- Services for Roman pot station operation, BPM monitoring, secondary vacuum pumps etc. (LHC responsibility)
- DAQ and Trigger services
- DCS services (LV, HV system, optoservices)
- Environmental sensors and Interlock
- CanBus services
- Local Cooling station services

A diagram of services for the silicon tracker of one RP station is shown in Fig. 57. The scheme does not show the services related to the detector cooling. The grey block on the left represents the silicon tracker. The services start at the feedthrough panel ‘PP1’, and lead towards two boxes placed nearby. The closest box is the small enclosure containing the small optical interface card named ‘optoboard’. The other side of this box provides a panel with optical MPO connectors that connect to the optical cable plugs and a small connector for optoboard control signals. The second, larger, ‘Vreg’ box in the scheme represents the crate with voltage regulator cards providing the precisely
regulated voltage for FE-I4 chips. The crate also acts as a patch panel for HV and DCS signals which are connected with PP1 with shorter cables. All the long cables lead through the tunnel to the USA15 level 1 area where 3 racks are available to accommodate AFP off-detector hardware.

### 6.2.1 Cables and Cable Routing

There are two possible routing paths for the AFP cables. The standard path from the LHC tunnel to USA15 goes via the US15 area towards USA15 which adds an estimated 120 m extra length to the total run. The standard path will be used for all standard, non time-critical services such as LV, HV, and DCS cables.

A shorter path is required for time-critical signal cables such as coaxial cables for trigger, clock, and optical data fibres. A shorter routing path exists and leads directly from the LHC tunnel to UX15 via the so-called UPS galleries and from there to USA15. This path is about 280 m long, compared to 400 m for the standard path.

The installation of services in the LHC tunnel is a critical task as access is very limited. The only possible installation period is the upcoming Winter 2015/2016 shutdown when the accelerator is halted for a scheduled 9 weeks. The AFP collaboration intends to install all AFP services in the 1-8 ATLAS arm together with two RP stations over this short shutdown period.

The cable services are listed in Table 13. Although the time-of-flight detector will not be installed in the single-arm installation phase, its detector services must be installed at this time. The services needed to operate RP and are under LHC responsibility. Short local cables are not listed here. CERN is responsible for the overall integration in the experimental area, especially in the LHC tunnel with particular emphasis on matters regarding safety. The AFP collaboration is responsible for RP stations and detectors and will provide the equipment and material necessary for the installation. Special coordination with ATLAS is necessary at the time of installation.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Type</th>
<th>Length</th>
<th>Destination</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch panels for cable terminations</td>
<td></td>
<td></td>
<td></td>
<td>1 day?</td>
</tr>
<tr>
<td>1 BPM cables</td>
<td>Coax</td>
<td>TBD</td>
<td>RR-13 (?)</td>
<td>1 day?</td>
</tr>
<tr>
<td>1 RPS DCS</td>
<td>TBD</td>
<td>TBD</td>
<td>RR-13 (?)</td>
<td></td>
</tr>
<tr>
<td>2 HV</td>
<td>3 × 4 twp-AWG22/MC</td>
<td>380 (260) m</td>
<td>USA15(US15)</td>
<td>4 days</td>
</tr>
<tr>
<td>2 LV</td>
<td>3 × 4 twp-AWG14</td>
<td>380 (260) m</td>
<td>USA15(US15)</td>
<td></td>
</tr>
<tr>
<td>2 PP2 Power</td>
<td>2 twp-AWG14</td>
<td>380 (260) m</td>
<td>USA15(US15)</td>
<td></td>
</tr>
<tr>
<td>3 CanBus</td>
<td>9 twp-AWG17</td>
<td>380 m</td>
<td>USA15</td>
<td>4 days</td>
</tr>
<tr>
<td>3 DCS (Detectors)</td>
<td>3 × 4 twp-AWG26</td>
<td>380 m</td>
<td>USA15</td>
<td></td>
</tr>
<tr>
<td>3 VVDC</td>
<td>2 twp-AWG14</td>
<td>380 m</td>
<td>USA15</td>
<td></td>
</tr>
<tr>
<td>3 Optoservices</td>
<td>2 × 4 twp-AWG18</td>
<td>380 m</td>
<td>USA15</td>
<td></td>
</tr>
<tr>
<td>4 DAQ</td>
<td>8 × 12 ribbon</td>
<td>290 m</td>
<td>USA15 via UPS</td>
<td>4 days</td>
</tr>
<tr>
<td>4 Trigger</td>
<td>Foam-core LMR600</td>
<td>290 m</td>
<td>USA15 via UPS</td>
<td></td>
</tr>
<tr>
<td>4 Reference Clock</td>
<td>Foam-core LMR600</td>
<td>290 m</td>
<td>USA15 via UPS</td>
<td></td>
</tr>
<tr>
<td>4 Spare</td>
<td>Foam-core LMR600</td>
<td>290 m</td>
<td>USA15 via UPS</td>
<td></td>
</tr>
</tbody>
</table>

Table 13. Preliminary list of AFP cables to be installed for one arm of AFP. The cables in the same group (first column) can be installed together. Groups can be installed in parallel if manpower allows. Note: DCS= Detector Control System; MC= MultiCore, RPS= Roman pot station.

The DCS cables are for RP station control, detector control, and for measurements of position, pressure, temperature, voltages and currents. These cables run downstream to the shielded alcove.
RR-13 (located at 250 m), where they are connected to the LHC network. The fast coax BPM cables also run to receivers in the RR-13.

A single multi-core (16 or 32 cores) HV cable (of the type used for ATLAS LAr) could be used instead of individual twisted-pair (twp) cables, to deliver the HV for the silicon tracker and for the time-of-flight system. Along the same path, a low-voltage, high-current cable provides the power for the local voltage regulators that serve the detector electronics. Finally, the fast L1 Trigger signal travels over a low-density foam-core coax (propagation speed $\geq 0.9c$) and must reach USA15 along the fastest possible path, the 290 m distance that uses the UPS Gallery to reach USA15. For use of the time-of-flight, a second fast coax is required for the Reference Clock signal. Therefore it seems advantageous to pull three fast coax cables together using the third coax as a spare.

The three cable groups must be prepared beforehand, and the cabling of the three groups could proceed in parallel given enough manpower. It is crucial for smooth progress of the cabling tasks that the patch panels PP1 that will receive the cable ends and interface to the local cables, are in their final positions.
7 Beam Test of the First Integrated AFP Prototype

Beam test studies are essential to understand the performance of the AFP detector and its basic components in response to high-energy particles. The timing and the tracking modules have been tested independently in a large number of dedicated beam tests over recent years. The results are included in Sects. 4.5.3 and 4.6.4. Furthermore, it is critical to demonstrate that the individual AFP detector components can be operated together as an integrated system. To this end, in November 2014 an integration beam test was carried out at CERN-SPS (120 GeV pions) with a first unified AFP prototype, which combined tracking and timing prototype detectors (excluding the Roman pot housing). A common trigger for all sub-systems was provided and all detector parts were read out by a common Data Acquisition (DAQ) system, which resulted in a common data format. In this section, the design of this first unified AFP prototype and the results of the integration beam test are presented.

7.1 Design of the First Integrated AFP Prototype

The AFP prototype was built of five tracking planes and a Quartic timing system as shown in Fig. 58. Note that the coordinate system during this beam test differs from the standard AFP coordinate system in other sections. In this beam test, the short-pixel direction with 50 \( \mu \text{m} \) pitch is oriented along the vertical direction (\( y \)) and the long-pixel direction with 250 \( \mu \text{m} \) pitch in the horizontal direction (\( x \)). The \( z \) direction is along the beam axis.

The pixel modules consisted of spare 3D sensors from the IBL production (three by FBK, two by CNM) bump-bonded to the FE-I4B readout chip and assembled on an IBL-type flexible circuit.
board. The FBK sensors had already AFP-compatible slim edges as described in Sect. 4.5. The modules were mounted using aluminum frames on a base plate, facing the beam under perpendicular incidence. Four modules (number 0 to 3) were placed with a pitch of 3.75 cm in front of the timing system, a configuration similar to the design of the final AFP detector (due to space constraints in the Roman pot, however, the pitch will be somewhat smaller). However, for this beam test an additional module (number 4) was placed behind the timing system with a distance of 13.75 cm to module 3 to allow a monitoring of particle interactions in the quartz material of the LQbars. Such interactions would give rise to multiple additional hits in the last pixel plane.

The timing system consisted of four rows (called trains 1–4) of two LQbars (A and B) as shown in Fig. 59. The Cherenkov radiators (the horizontal bars) were oriented with the Cherenkov angle of 48° with respect to the beam axis. Thus, the created Cherenkov light passed along the long direction of the radiators to the kink, where the light was reflected down so that it continued along the vertical light-guide bars to a 4x4 multi-pixel Micro-Channel-Plate Photomultiplier (MCP-PMT). The radiators of the upper train were 3 mm high in vertical direction, those of the lower trains 5 mm. The length of the radiator bars in the short horizontal direction was 6 mm, the length in the long horizontal direction ranged from 35 to 57 mm. At the left side, the radiators were cut such that this edge was parallel to the beam, giving an effective edge length of about 9 mm. The LQbars were mounted in an aluminum holder with 1 mm thick isolation plates between the light-guide bars of different trains and 125 μm thin spacer wires between those of the same train. At the radiator level, the different trains were optically isolated using mylar foils. In addition to the Quartic timing system, three fast timing reference detectors consisting of quartz bars (3 × 3 mm² cross section, 1 cm long in beam direction) coupled to silicon photomultipliers (SiPM) were placed behind the AFP prototype (not foreseen for the final AFP detector). The signals of all timing detectors were amplified, discriminated using Constant Fraction Discriminators (CFD) and digitized with the 11-channel High-Precision Time-to-Digital Converter (HPTDC) board as described in Sects. 4.6 and 5.2.

As a combined DAQ system, the RCE readout as described in Sect. 5.2 was used, which is the system foreseen for the final AFP detector. It consists of a High-Speed Input-Output (HSIO) board with up to eight input channels. The first five channels were used for the FE-I4 tracking planes and the last one for the HPTDC timing board. The HSIO was connected via optical fibre to an RCE ATCA crate outside the beam area. Whereas the operation of the RCE system with the FE-I4 chip had been extensively proven already before, e.g. in the IBL stave testing, its operation with the HPTDC system still had to be implemented and optimized before and during the beam test. Dedicated software is available for calibration and data-taking runs, which includes also online monitoring.

The trigger of the combined system was given by signals from the tracking system. Each FE-I4 chip gives a so-called HitOr signal if at least one pixel fires (see Sect. 5.1). A custom-made electronic
circuit board was used to combine the HitOr signals of planes 0, 3 and 4 to form a coincidence signal (TTL), which was used to trigger the readout of the FE-I4 pixel devices and the HPTDC via the RCE system.

For testing purposes and specific time resolution studies, the timing signals were also recorded with a LeCroy SDA760ZI oscilloscope in addition to the HPTDC-RCE system.

7.2 Operation and Results of the Integration Test Beam

The integration test beam took place at the H6B beamline of CERN-SPS with 120 GeV pions in November 2014. Bias voltages of 10 V were applied to the pixel sensors 0, 2, 3 and 4, whereas only 4 V could be applied to sensor 1 (due to the IBL-spare quality class). The pixel devices were tuned to a threshold of 3 ke\(^{-}\) and a time-over-threshold (ToT) of 10 (in units of 25 ns) for a charge of 20 ke\(^{-}\). Voltages between 1750 and 1950 V were applied to the MCP-PMT and between 30.3 and 31 V to the SiPM, varying for different runs. The system operation appeared to be stable, e.g. half-day runs without user interaction were possible. Altogether, 38 M events were collected at typical rates of a few hundred Hz.

7.2.1 Performance of the Tracking System

Many parameters of the tracking system could be monitored already at the online level (see Fig. 60). 2D hit occupancy maps for each tracking plane were used for performing and monitoring the alignment of the beam with respect to the detectors. Good correlations between the hit column (and row) numbers of two consecutive pixel planes, respectively, indicated that real tracks were recorded and that the inter-plane alignment precision was at the mm level. Moreover, the ToT sum of all hits (roughly indicating the cluster charge) and the timing of the recorded hits with respect to the trigger signal were monitored online and behaved as expected.

The offline hit clustering and track reconstruction was performed with the software framework Judith [119]. Neighboring hits are grouped into clusters and the cluster position is determined as the ToT-weighted mean of the hit pixel centers in each direction. Fig. 61 (left) shows that about 90% of all events have only one hit cluster per pixel plane. The cluster multiplicity of plane number 4 (behind the quartic system) is consistent with the one of the others, indicating that possible interactions in the quartic material are negligible, at least for a secondary-particle separation larger than the pixel resolution. From Fig. 61 (right) it can be seen that most of the clusters (about 80%) consist of only one pixel hit as expected for perpendicular incidence.

Subsequently, tracks are reconstructed from the clusters by fitting a linear function for each direction (\(x\) and \(y\)) after applying a track-cluster-finding algorithm. As input resolutions for the \(x^2\) fit the binary resolutions (pitch/ \(\sqrt{12}\)) of 72.2 and 14.4 \(\mu m\) in \(x\) and \(y\), respectively, are taken, motivated by the presence of mostly one-hit clusters and roughly consistent with previously measured FE-I4 resolutions (see Sect. 4.5.3.1). A more advanced weighting using resolutions individually measured for different cluster sizes is under study. Alignment is performed in two steps: first a coarse alignment based on the inter-plane correlations between two consecutive pixel layers is applied; subsequently a fine alignment is performed based on the track residual distributions (i.e. the difference between the projected track position on each layer and the cluster position). Shifts in \(x\) and \(y\) and rotations around the \(z\) axis are corrected for. For more details see [119].

Track reconstruction of the AFP-prototype beam test data has been performed for different scenarios:

1. The all-plane scenario includes all five planes into the track fit, which is mostly used for the
Figure 60. Online monitoring distributions. Top left: the 2D hit occupancy map of one pixel sensor. Top right: the correlation between the rows of two consecutive pixel planes. Bottom left: The ToT sum of all hits in the event (simple cluster charge distribution). Bottom right: The timing of the recorded hits with respect to the trigger signal.

1. The analysis of the timing detector below as it gives the best precision at the timing detector position.
2. The first-four-plane (AFP-like) scenario takes only the first four equidistant planes into account, thereby being the most realistic with respect to the final AFP configuration.
3. In the DUT scenarios, specific planes are excluded from the track fitting and thus be treated as independent, unbiased devices-under-test (DUT) for efficiency or resolution studies.

The performance of track reconstruction is found to be similar for all scenarios (the following plots and numbers refer to the all-plane scenario): for about 98% of the events exactly one track is reconstructed as seen from Fig. 62. Events with no reconstructed tracks are at the 0.4% level. The reconstructed tracks are found to be parallel to the beam axis with an RMS angle in $x$ and $y$ of about 0.1°.

For the following analyses event cleaning cuts have been applied. Events with exactly one track and one cluster per plane have been selected to reduce combinatorial background and events with material interactions. For the analyses of the timing performance a track $\chi^2$ fit probability of at least 10% has been required in addition.

The resolution of each pixel plane as well as of the whole tracker system is an important performance parameter. The setup of this beam test is not ideal for precision resolution measurements, but studies have been performed nevertheless to gain first experience with the tracker system and to
determine the resolution at least roughly and for monitoring. First of all, it has to be qualitatively distinguished between two different situations: one in which the measured hit position can only assume discrete values (also called binary or digital), e.g. if only one hit per pixel occurs or if the purely geometrical center of hit pixels is taken; and secondly a situation in which charge sharing between pixels takes place and the position can be interpolated using the charge (or here ToT) information, giving a continuous distribution (also called analog). For this beam at perpendicular incidence, the 1D cluster size in the long FEI4 pixel direction is 1 in 98% of the cases, so that to a good approximation the digital situation applies. In the short pixel direction, however, there is a mixed situation of cluster size 1 in about 85% of the cases (digital) and cluster size 2 in about 12% of the cases (to which analog algorithms can be applied). The remaining events with larger cluster size must be influenced by noise or, in particular, delta rays since they are geometrically not possible. In the AFP design, a tilt of 10–15° in the short direction is foreseen, thereby enhancing charge sharing and hence shifting towards the analog situation for that direction.

The distinction between digital and analog situations is also important for the attempt to measure and predict the resolutions. One method to measure the per-plane resolution without a track fit (but using the alignment constants from a previous Judith track fit) is the triplet technique which defines a residual variable \( r_{\text{triplet}} \) from the hit position \( x_1 \) of three successive equidistant planes as

\[
    r_{\text{triplet}} = \frac{x_1 + x_3}{2} - x_2.
\]

For a continuous Gaussian distribution (i.e. approximately for the analog case), the per-plane resolu-
Figure 63. Left: The triplet residual $r_{\text{triplet}}$ using planes 0, 1 and 2. Right: The track-DUT residual $r_{\text{track-DUT}}$ for plane 1 as a DUT. The RMS and $\sigma$ of a fitted Gaussian correspond in both cases to the full histogram.

Figure 64. The expected track precision in the short pixel direction ($y$) for different track-reconstruction scenarios assuming a continuous distribution of hit measurements (analog case) with 15 $\mu$m resolution. The positions of the five pixel planes are indicated by the green lines.

Resolution can be obtained from the RMS as $RMS_{\text{plane}} = \sqrt{\frac{3}{2}} \cdot RMS_{\text{triplet}}$. For the digital case, this method is not valid and the result is highly biased as the distribution is dominated by discrete spikes that only depend on the offset between the planes with respect to each other (e.g. in case of perfect plane alignment, the only measured value will be 0). Hence, the method cannot be applied to the long pixel direction. Fig. 63 (left) shows the distribution for the short direction including $RMS_{\text{triplet}}$ and $\sigma_{\text{triplet}}$. The resulting resolution value of $RMS_{\text{plane}} = 16.7 \mu$m is roughly similar to the all-cluster-size RMS of 15 $\mu$m obtained in beam tests with the precise EUDET telescope (see Sec. 4.5.3.1). This is reassuring and indicates that despite the mixed digital-analog case the residual method roughly works without a large bias in the short direction. Hence it serves as a cross-check of the plane resolution during this beam test as well as of the alignment. The core of the distribution with $\sigma_{\text{plane}} = 14.0 \mu$m is narrower since it is not so sensitive to delta rays.

Also for the prediction and measurement of the full-tracker resolution it has to be distinguished between the digital and analog situations. In the analog case with a continuous distribution, the track resolution $\sigma_y$ can be predicted from the uncertainties of the straight-line parameters (slope $s_y$ and offset $b_y$) and their covariance $\text{cov}_{s_yb_y}$ as

$$\sigma^2_y(z) = \sigma^2_{s_y} + z^2 \cdot \sigma^2_{b_y} + 2z \cdot \text{cov}_{s_yb_y}.$$  

This is shown in Fig. 64 in the short direction (assuming it can be treated with analog methods) for the different track-reconstruction scenarios with an input per-plane resolution of 15 $\mu$m. For the
first-four-plane scenario (AFP-like), it can be seen that the track uncertainty is symmetric around its minimum in the middle of the four planes. The minimum track uncertainty is half of the resolution per plane, i.e. $7.5 \mu m$ (it scales with $1/\sqrt{N_{planes}}$). On the contrary, in the long pixel direction with the purely digital situation, the tracker resolution will only depend on the plane offsets. E.g. in case of perfect alignment (no offset of planes), no improvement is achieved since each pixel plane gives a redundant measurement. In the case of staggering the modules by 1/2 (1/4) of a pitch in the long direction, the track resolution in the middle of the four pixel planes for the first-four-plane scenario (AFP-like) is improved to 1/2 (1/4) of the binary one-hit resolution, namely $36 \mu m$ ($18 \mu m$).

The actual staggering present in this test was random since no precision alignment was available. The actually obtained plane offsets are estimated from the alignment constants determined in the track reconstruction and give a track precision of $39 \mu m$ in the long direction for the middle of the first four planes.

For the analog case, the convolution of the per-plane and the tracker resolution can be measured by excluding one plane (DUT) from the track fit and calculating the residual $r_{\text{track-DUT}}$ as the difference between the DUT cluster center and the track position extrapolated to the DUT. In the digital case the method fails again due to the discreteness effects explained above. Motivated by the good agreement in the short direction between the triplet per-plane resolution (see above) and external precise measurements, it is tried to apply the track-DUT residual method to the short direction despite the mixed digital-analog situation. Fig. 63 (right) shows the track-DUT residual distribution for plane 1 as a DUT. The tails stem from badly reconstructed tracks (they are correlated with a large track $\chi^2$), leading to a large RMS. The analysis is still ongoing to try to improve the track reconstruction, e.g. by weighting down events with large cluster size and correspondingly worse resolution due to delta rays, which is not yet implemented. The core of the peak is narrower with a fitted Gaussian $\sigma$ of $17.8 \mu m$. This value is consistent with a track resolution of roughly $11 \mu m$ (obtained by subtracting $\sigma_{\text{plane}} = 14 \mu m$ as extracted above). However, the plane-1-as-DUT scenario studied here differs from the final AFP-like scenario. Fig. 64 indicates that the track resolution in the middle of the four planes of the AFP-like scenario is about $3 \mu m$ less than the track resolution at the position of DUT 1 in the DUT scenario. Hence, the resolution for the AFP-like scenario is indicated to be better than $10 \mu m$, fulfilling the design goal for AFP.

Finally, it should be noted again that the setup of this beam test is not ideal for precision resolution measurements and method uncertainties remain. Thus, an AFP-tracker-resolution measurement with a four-plane FEI4 system inside the precise EUDET telescope at different angles is foreseen for the next beam test for a definitive answer. Further optimisation studies to improve the cluster-position algorithms as well as the track fitting are envisaged, and it should be noted again that the final AFP tracker will be tilted by 10–15° in the short direction, giving an improved charge sharing and hence resolution.

Using the DUT track-reconstruction scenarios, the per-plane hit efficiencies are determined. However, this can only be done for the unbiased pixel planes 1 and 2 that were not used for triggering. Fig. 65 displays the resulting efficiency map for plane 2 (biased at 10 V) with an average efficiency of 98.2%, consistent with previous beam test results of IBL-spare-quality-class devices. The efficiency of plane 1 was found to be only slightly lower (97.5%) despite a bias voltage of only 4 V.

### 7.2.2 Tracking-Timing Correlation

The main objective of this beam test was the integration of the tracking and timing subsystems with a common trigger and readout. To verify that this integration works and that the recorded tracking and timing data are inter-related with each other on an event-by-event basis, the spatial tracking-timing correlation was studied. Fig. 66 shows the number of events as a function of the track vertical
7.2.3 Performance of the Timing System

In this section, the performance of the timing system is presented. Often, track information was useful to predict externally whether a certain LQbar was passed by a particle. For this, in the following, well-reconstructed tracks from the all-plane track-reconstruction scenario were used, giving the best track precision at the position of the timing system.

The hit efficiency of each LQbar was determined using events with tracks passing through the bar of interest, respectively. Fig. 67 (left) shows the two-dimensional hit efficiency map as a function of reconstructed track position for the first bar (A) of each train at $V_{MCP-PMT} = 1900$ V. Fig. 67 (right) displays the MCP-PMT voltage dependence of all the bars. Whereas at 1800 V, there is a significant spread between the efficiencies of different bars ranging from 82 to 97%, the efficiencies at 1900 V are all above 99%.

Another important parameter is the cross talk between the bars of different trains. The cross
Figure 67. The hit efficiencies of the LQbar timing channels. Left: the efficiency map as a function of reconstructed track position for the first bar (A) of each train at \( V_{MCP-PMT} = 1900 \) V. Right: the average efficiencies as a function of \( V_{MCP-PMT} \).

Figure 68. The cross talk (XTalk) of the LQbar channels to the bars in the neighboring (left) and next-to-neighboring trains (right) as a function of \( V_{MCP-PMT} \).

talk for a bar of interest is determined as the fraction of events in which neighboring bars fire if a track is passing through the bar of interest. Fig. 68 shows the cross talk to the neighbors and next-to-neighbors for all bars as a function of \( V_{MCP-PMT} \). Whereas the cross talk to the neighbors is at the few-percent level at 1800 V, it increases steeply up to 65 to 90% at 1900 V. As the LQbars themselves are optically well isolated between adjacent trains as explained above, any cross talk has to originate from the PMT level. Possible explanations for this cross talk include optical leakage at or in the photo-cathode window or the lateral spread of the photo electrons in the PMT. Further studies to understand its origin are envisaged. Whereas a high level of cross talk is disadvantageous for the use of the timing detector as a position-resolved trigger, it has no influence on the timing performance if the bars really hit by the particle can be selected, as demonstrated below.

The noise rate of the bars (i.e. the signal firing rate when not hit by a track) was measured to be at the level of a few to 60 kHz, depending on the exact bar and slightly increasing with \( V_{MCP-PMT} \). This corresponds to noise occupancies in the order of \( 10^{-4} \) to \( 10^{-3} \) for a 25 ns window.

The time resolutions of the LQbars were measured from the time differences between them and the fast SiPM reference, respectively. This was done on the one hand using an oscilloscope as a readout and on the other hand with the RCE-HPTDC system. The time difference measured with the oscilloscope from the signals after the CFD is shown in Fig. 69 for the bars 1A and B. The time resolutions were obtained from the standard deviations of Gaussian fits, after quadratically subtracting the contribution of the SiPM resolution, which was mea-
Figure 69. The time differences between the LQbars of the first train (1A and 1B) and a fast SiPM reference at $V_{MCP-PMT} = 1900$ V measured with the oscilloscope.

Table 14. The time resolutions of different LQbars and the train average for different $V_{MCP-PMT}$ measured with the oscilloscope with respect to the SiPM reference (SiPM contribution subtracted). The uncertainties include statistical uncertainties estimated to be 2 ps as well as systematic uncertainties from run-to-run variations (those were studied only for train 2 at 1900 V, and the largest uncertainties found there are assigned to the other measurements).

<table>
<thead>
<tr>
<th>$V_{MCP-PMT}$ [V]</th>
<th>1750</th>
<th>1800</th>
<th>1850</th>
<th>1900</th>
</tr>
</thead>
<tbody>
<tr>
<td>LQbar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td>63 ± 5</td>
<td>45 ± 5</td>
<td>36 ± 5</td>
<td>31 ± 5</td>
</tr>
<tr>
<td>1B</td>
<td>85 ± 5</td>
<td>52 ± 5</td>
<td>37 ± 5</td>
<td>30 ± 5</td>
</tr>
<tr>
<td>Average Train 1</td>
<td>64 ± 5</td>
<td>44 ± 5</td>
<td>31 ± 5</td>
<td>25 ± 5</td>
</tr>
<tr>
<td>2A</td>
<td>-</td>
<td>48 ± 5</td>
<td>36 ± 5</td>
<td>32 ± 5</td>
</tr>
<tr>
<td>2B</td>
<td>-</td>
<td>42 ± 5</td>
<td>31 ± 5</td>
<td>30 ± 4</td>
</tr>
<tr>
<td>Average Train 2</td>
<td>-</td>
<td>42 ± 5</td>
<td>29 ± 5</td>
<td>25 ± 4</td>
</tr>
</tbody>
</table>

sured to be 11 ps. The results are presented in Tab. 14 for the single LQbars of the first two trains at different $V_{MCP-PMT}$ (bars of other trains were not measured since there was no overlap with the $3 \times 3$ mm$^2$ SiPM cross section). The uncertainties include statistical uncertainties estimated to be 2 ps as well as systematic uncertainties from run-to-run variations. Those were studied only for train 2 at 1900 V and significant variations of up to 12 ps were found, whose origins are not yet fully understood. External conditions such as readout channels, optical inter-bar isolations, signal splitters, etc. varied from run to run and their influences were not studied systematically during this beam test since the focus was laid on the integration. For a better understanding further systematic tests and optimizations are needed and planned. The values in Tab. 14 for train 2 at 1900 V correspond to the mean of five different runs$^7$. The largest estimated systematic uncertainty for train 2 at 1900 V (5 ps) was also assigned to all other LQbars and voltages, for which the resolutions were obtained from one single run only. The resolutions are found to generally improve with $V_{MCP-PMT}$, and at 1900 V, values as good as 30 ps per single LQbar were achieved, similar to the results of earlier beam tests (see Sect. 4.6.4). Also included in Tab. 14 are the results for the resolution of the average time of the two LQbars in one train (A and B). At high $V_{MCP-PMT}$ values, the train average improves the resolution with respect to the best single-bar measurement (e.g. to 25 ps at 1900 V), whereas at low $V_{MCP-PMT}$ no improvement is found. In general, the observed improvement is less than expected.

$^7$Out of which the best single measurement obtained was 25 ps for LQbar 2A, 29 ps for 2B and 22 ps for the train average.
for uncorrelated measurements (e.g. for two bars of the same resolution an improvement of $1/\sqrt{2}$ is expected). The correlation factor is measured to be about 50–60%. Correlation between the bars of the same train has been observed and studied before in previous beam tests (see Sect. 4.6.4), and optimization of the LQbar configuration will be carried out in future tests in order to further improve the resolution of a multi-LQbar system by reducing this correlation.

Time resolutions were also measured with the HPTDC+RCE system. The time resolution of the SiPM reference is found to be $\sigma_{\text{SiPM}+\text{HPTDC}} = 18$ ps, which gives an HPTDC contribution of $\sigma_{\text{HPTDC}} = 14$ ps after subtracting the SiPM resolution measured with the oscilloscope as described above. This is within the range of values between 12 and 18 ps measured in the laboratory and previous beam tests (see Sect. 4.6.4). The LQbar time resolutions including the HPTDC contributions are listed in Tab. 15 for different $V_{\text{MCP-PMT}}$ values. Similarly to the oscilloscope measurements, the resolution is found to improve with $V_{\text{MCP-PMT}}$ and at 1900 V it reaches values as good as 38 ps for a single LQbar (2B) and 35 ps for the average of train 2 at 1900 V. As the measurements with the oscilloscope and the HPTDC-RCE system have been performed at different times during the beam test under different external conditions, it is not possible to directly correlate them with each other, which would be e.g. necessary if the individual HPTDC contribution for each LQbar channel was intended to be extracted from a comparison. It should be noted that the optimization of the time performance and a fine calibration of the HPTDC has not been the priority during this integration beam test. It is expected that better resolutions can be achieved with more careful optimizations and calibrations, which is envisaged in future tests. Nevertheless, already the integrated ToF system tested here with only two LQbars per train and no further optimization achieved a time resolution close to the required design value of 30 ps for initial low-luminosity AFP runs.

### 7.3 Conclusions and Outlook

A system-integration beam test with a first AFP prototype combining tracking and timing sub-detectors and a common readout has been performed. It was demonstrated that the recorded tracking and timing data are correlated with each other, proving the successful integration. Good performances of the tracking and timing systems were found, surpassing or roughly meeting the requirements of the initial low-$\mu$ AFP runs even without dedicated optimizations. Further systematic studies and optimizations of the detectors are envisaged in laboratory measurements and the next AFP beam test in September 2015 to further improve the performance, and it is planned to test the integration of the detectors into the AFP Roman pots before installation.
8 AFP alignment

8.1 Misalignment vs Cross Section

A misalignment of the AFP detectors can affect the measurements in several ways. First, if the position assumed for the detectors is wrong, the acceptance calculation will produce incorrect results. This, in turn, affects the MC simulation, the acceptance correction and biases the cross section measurement.

The AFP acceptance depends primarily on the horizontal position of the detectors. Therefore, the effect discussed will depend on the distribution of the proton horizontal position ($x$). This distribution is presented in Fig. 70 for several diffractive processes: soft single diffractive interaction, single diffractive jet production with two cuts on the leading jet transverse momentum (20 and 100 GeV), and single diffractive production of $Z$ boson. One can observe that these distributions are quite different in shape. For the soft process, the distribution is peaked at zero, because of the large number of events with very small momentum loss. The harder the process, the higher the $\xi$ value needed to produce the corresponding final state. Consequently, the peak at zero decreases and the distribution flattens.

The effect of a possible misalignment can be estimated by looking how a visible cross section changes if the detectors are moved by $\Delta x$. Naturally, it makes sense to study the relative change of the cross section, which is given by the formula:

$$\frac{\Delta \sigma}{\sigma} = \sigma(x_0) - \sigma(x_0 \pm \Delta x) \approx \pm \frac{d\sigma}{dx} \bigg|_{x=x_0} \cdot \frac{1}{\sigma(x_0)} \cdot \Delta x,$$

where $x_0$ is the distance between the beam centre and the detector, while $\sigma(x_0)$ is the visible cross section for a given $x_0$. The fiducial cross section can be calculated from the $x$ distribution by integration:

$$\sigma(x_0) = \int_{x_0}^{\infty} \frac{d\sigma}{dx} dx$$

The cross section change is proportional to the $x$ distribution value and inversely proportional to the fiducial cross section. The dependence of the changes in cross section on the distance from the beam are presented in Fig. 71 for several processes and $\Delta x = 100 \, \mu$m. The largest changes occur for very small distances (where soft processes have large $d\sigma/dx$) and for very large distances (where $\sigma$ is small). For the typical distance used for the measurement, i.e. a couple of millimeters, the change is at the sub-percent level for very hard processes and up to 2 % for soft processes.

8.2 Misalignment vs Reconstruction

Misalignment of the AFP detectors also affects the measurements by biasing the reconstruction of the proton kinematics. Here, one needs to consider all possible degrees of freedom. A single AFP arm consists of two stations, near and far, each measuring the $x$ and $y$ component of the proton position. Each of these measurements can be affected by misalignment, leading to four possible misalignments: $\Delta x_{\text{near}}$, $\Delta y_{\text{near}}$, $\Delta x_{\text{far}}$ and $\Delta y_{\text{far}}$.

It is useful to define combinations of the above variables, the absolute misalignments

$$\Delta x = (\Delta x_{\text{near}} + \Delta x_{\text{far}})/2, \quad \Delta y = (\Delta y_{\text{near}} + \Delta y_{\text{far}})/2,$$

and the relative misalignments:

$$\delta x = \Delta x_{\text{far}} - \Delta x_{\text{near}}, \quad \delta y = \Delta y_{\text{far}} - \Delta y_{\text{near}}.$$
Then, $\Delta x$ and $\Delta y$ affect only the measurement of the track position, while $\delta x$ and $\delta y$ affect only measurement of track elevation angles. In the following, four misalignment scenarios will be considered, corresponding to setting $\Delta x$, $\Delta y$, $\delta x$ and $\delta y$ to 100 $\mu$m, respectively.

The proton kinematics is described in terms of three parameters: the relative momentum loss $\xi$, the four-momentum transfer $t$, and the azimuthal angle $\varphi$. In order to check how misalignment affects the reconstruction of these variables, a sample of soft single diffractive protons generated with Pythia has been transported to the AFP detectors. Then, the position of protons in the AFP detectors has been changed accordingly to the considered misalignment scenario. Eventually, the kinematics reconstruction has been performed, as discussed in Ref. [121].

The effect of the misalignment on the reconstruction is twofold. First, the reconstructed value of the variable will on average differ from the true value. In addition, the difference will have some spread around the average. It is emphasized that this spread is not due to any randomness from the simulation; the procedure used is fully deterministic – a proton with a given kinematics $(\xi, t, \varphi)$ will always be reconstructed in the same way:

$$(\xi, t, \varphi) \rightarrow (\xi + \Delta \xi, t + \Delta t, \varphi + \Delta \varphi).$$

However, each of errors, $\Delta \xi$, $\Delta t$ and $\Delta \varphi$, may depend on the full kinematics of the proton, e.g. $\Delta \xi = \Delta \xi(\xi, t, \varphi)$. When considering the effect of misalignment on any single variable, e.g. $\xi$, it makes sense to average over $t$ and $\varphi$. This leads to the concept of the average value and the spread of $\Delta \xi$:

$$\Delta \xi_{\text{average}} = \left\langle \Delta \xi(\xi, t, \varphi) \right\rangle_{t, \varphi}, \quad \Delta \xi_{\text{spread}} = \sqrt{\left\langle (\Delta \xi(\xi, t, \varphi) - \Delta \xi_{\text{average}})^2 \right\rangle_{t, \varphi}}.$$  

Plots of the average and spread for $\xi$, $t$, and $\varphi$ are presented in Figs. 72 – 77.

### 8.3 Rotation vs. Reconstruction

Vertical and horizontal misalignments are not the only possible wrong assumptions about the AFP detector positions. It is also possible that the angular position placement of the detectors is incorrect. Therefore, it is necessary to study how small rotations affect the reconstruction of the proton kinematics.

In principle, three rotations are possible: in the $(x, y)$, $(x, z)$ and $(y, z)$ planes. However, the nominal position of the detector is in the $(x, y)$ plane. Therefore, small rotations in the other planes

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**Figure 70.** Distribution of proton horizontal trajectory position for various diffractive processes [120].

**Figure 71.** Relative error on the cross section due to 100 $\mu$m absolute horizontal misalignment for several diffractive processes [120].
Figure 72. The average reconstruction error of the proton’s relative momentum loss due to a 100 µm misalignment [120].

Figure 73. The spread of the relative momentum loss reconstruction error due to a 100 µm misalignment [120].

Figure 74. The average reconstruction error of the proton four-momentum transfer due to a 100 µm misalignment [120].

Figure 75. The spread of four-momentum transfer reconstruction error due to 100 µm misalignment [120].

Figure 76. The average reconstruction error of the proton’s azimuthal angle due to a 100 µm misalignment [120].

Figure 77. The spread of azimuthal angle reconstruction error due to 100 µm misalignment [120].
have a negligible effect – of the order of $\theta^2$, where $\theta$ is the rotation angle considered. Therefore in the following the focus is on the effect of a rotational misalignment in the $(x,y)$ plane.

Another important issue is the center of the rotation. In principle, it is possible to perform rotations around any point. However, two rotations by the same angle around two different origins differ only by a constant shift of the detector:

$$R_\theta(\vec{x} - \vec{x}_1) = R_\theta(\vec{x} - \vec{x}_2) + \Delta \vec{x},$$

where $R_\theta(\vec{x})$ is the rotation operation of point $\vec{x}$ around $(0,0)$ and $\Delta \vec{x} = R_\theta(\vec{x}_2 - \vec{x}_1)$. Therefore in reality, positional and rotational alignments are connected.

For detector rotations, in contrast with detector shifts, it is not possible to define absolute and relative misalignments that affect only the measurement of the track position and elevation angles. Therefore, we consider three misalignment scenarios:

- near station rotated by 1 milliradian,
- far station rotated by 1 milliradian,
- both stations rotated by 1 milliradian,

in which the rotations is performed around the edge of the AFP detector (the one close to the beam) at the point where the density of diffractive protons is the highest. In addition, the fourth scenario is added: rotation of the near station around the beam centre.

The effects of all the scenarios on the reconstruction of $\xi$, $t$ and $\varphi$ (the average error and the error spread) are presented in Figs. 78 – 83.
Figure 78. The average reconstruction error of the proton relative momentum loss due to 1 mrad rotation of the detectors [120].

Figure 79. The spread of the reconstruction error of the proton relative momentum loss due to rotation of the detectors [120].

Figure 80. The average reconstruction error of the four-momentum transfer due to 1 mrad rotation of the detectors [120].

Figure 81. The spread of the reconstruction error of the four-momentum transfer due to 1 mrad rotation of the detectors [120].

Figure 82. The average reconstruction error of the azimuthal angle due to 1 mrad rotation of the detectors [120].

Figure 83. The spread of the reconstruction error of the azimuthal angle due to 1 mrad rotation of the detectors [120].
8.4 Requirements for Alignment Precision

A detailed discussion of the above results can be found in Ref. [120]. Here, the conclusions are briefly summarized – the requirements for AFP alignment precision.

First, the requirements for the precision of the alignment depend on the types of physics measurements to be performed with AFP.

The simplest measurement is the tagging of forward protons, requiring the presence or absence of a proton track in the forward detector. No additional information about its position is used and no kinematics reconstruction is needed. The goal of such a measurement is simply to measure the visible cross section for the appropriate detector position. This measurement is influenced only by the effects discussed in Section 8.1. For a 10% cross section accuracy, the horizontal alignment must have 500 µm precision.

Naturally, one will want to measure also various differential distributions related to proton kinematics. For these measurements one needs a precise reconstruction resulting in stricter requirements for alignment. In order to obtain a 10% resolution in \( \xi \), the required relative horizontal alignment precision of the stations is 100 µm and 200 µm for the absolute horizontal alignment precision. If the physics of interest is restricted to only high \( \xi \) values, the requirement on the absolute alignment precision can be relaxed. The measurements of \( r \) and \( \phi \) depend mainly on the relative alignment of the stations, and require precision of the order of 10 µm in both \( x \) and \( y \).

Finally, for low-cross section central exclusive production (CEP) measurements (which are the aim for the AFP program in LHC Run 3), the reconstructed track kinematics is needed for pile-up background rejection. An CEP process consists only of a central state (e.g. two jets) and two forward protons; no other particles are produced. In such events one can impose energy and momentum conservation by matching the kinematics of the central state to that of the forward protons. For background events, where the central state and forward protons originate from unrelated collisions (pile-up), no kinematic match is expected. For effective background rejection in selection of CEP event samples, the required relative horizontal precision is 25 µm, and 100 µm for the absolute horizontal alignment precision.

8.5 Alignment Methods

8.5.1 General Considerations

The reconstruction procedure in a magnetic spectrometer requires the knowledge of the positions of the detectors relative to the field, using the measured hit positions to reconstruct the track kinematics. For a general non-uniform magnetic field, the knowledge of the hit positions with respect to the beam is insufficient for reconstruction: depending on the beam position, the proton may have traversed regions of different magnetic field.

In special cases, the knowledge of the deviation from the beam is sufficient to determine the kinematics of the track. This is the case for the ALFA detectors and is a consequence of the fact that for elastically scattered protons the effective transport is, to a very good approximation, linear. Therefore, any perturbation of the beam position or direction at the IP affects the beam and the scattered protons in the same way and can be simply corrected for by comparing to the beam position. In this case, the reconstruction does not depend, to first order, on the actual position of the beam if the detectors are aligned with respect to the beam.

The AFP detectors are intended to measure protons that have lost a significant part of their energy. In this case the non-linearities of the transport are significant and the linear approximation is no longer accurate, see Fig. 84. A perturbation of the beam will affect protons of different energy differently. Because of these non-linearities the alignment with respect to the actual beam position
is no longer a natural choice and the alignment with respect to the magnetic field seems more appropriate. Since the nominal beam orbit and the beam pipe are at fixed positions relative to the magnetic field, they are also good references for alignment.

![Proton position in the AFP detector for \( \beta^* = 0.55 \text{ m} \) optics as a function of the proton relative momentum loss \( \xi \). Solid lines represent the dependence as predicted by Mad-X [51]. Dashed lines represent the linear approximation (extrapolated from \( \xi = 0 \)).](image)

Figure 84. Proton position in the AFP detector for \( \beta^* = 0.55 \text{ m} \) optics as a function of the proton relative momentum loss \( \xi \). Solid lines represent the dependence as predicted by Mad-X [51]. Dashed lines represent the linear approximation (extrapolated from \( \xi = 0 \)).

The above choice is further justified by considering the reconstruction. The procedures developed for AFP (see Sect. 3.1.3) take advantage of the small transverse size of the beam spot (16 µm for low \( \beta^* \) optics) – the lack of knowledge of the exact position of the interaction vertex does not compromise the reconstruction resolution. The position of the beam spot (the average position of the interaction vertex) is an input to the method.

A big advantage of alignment with respect to the magnetic field is that the \( \xi \) reconstruction does not depend on the beam elevation (vertical crossing angle) at the IP. This direction is represented by the average transverse momentum of the beam protons at the IP. A change in beam direction at the IP, which leads to a change in the beam position at the AFP detectors, does not affect the \( \xi \) reconstruction.

If the alignment is performed traditionally, i.e. with respect to the actual beam position, the reconstruction procedure becomes more complicated. In particular, apart from the information about the beam spot position, the knowledge of the beam elevation angle at the IP is needed.

To sum up, the theoretical considerations\(^8\) suggests that the non-linearities in the proton transport, which are non-negligible for the AFP case, make the nominal beam orbit the favoured reference axis for AFP alignment. Naturally, the procedures in the final implementation of the alignment will further evolve when the detectors are operating and the procedures are confronted with the data.

8.5.2 Linear Variable Differential Transformer

For the alignment with respect to the center of the beam pipe, the main input can be provided by the Linear Variable Differential Transformer (LVDT) measurements.

In principle, the LVDT information should be sufficient for the alignment, but it is advantageous to have independent, data-driven methods that provide monitoring and a cross-check of the LVDT measurements.

\(^8\)A more detailed discussion of this topic, with a mathematical description of the problem, can be found in Ref. [122].
8.5.3 Dynamic Alignment – Kinematic Peak Method

A dynamic alignment method was used at the Tevatron by the CDF Collaboration [123]. It is based on the fact that the actual shape of the reconstructed spectrum of the four-momentum transfer in single diffractive interactions depends on the alignment of the detectors. In fact, the reconstructed value of the cross section at $t = 0$ decreases for misaligned detectors (cf. Fig. 85). The justification of the method can be found in Ref. [124].

The applicability of the method depends on the properties of the beam optics. A detailed analysis [124] shows that for the standard LHC tune (low $\beta^*$ optics) the method is sensitive to the relative alignment between two AFP stations in both horizontal and vertical direction. Unfortunately, there is no sensitivity to the absolute alignment of each station.

![Figure 85. Reconstructed four-momentum distribution for different values of: relative horizontal misalignment between stations $\delta x$ (left), relative vertical misalignment $\delta y$ (right).](image)

The kinematic peak method is data-driven. The process of single diffractive dissociation has a very large cross section leading to high statistics data samples. At high luminosity running, protons originating from single diffractive interactions in pile-up collisions will be present in a majority of the recorded events. Thus, there is no point in triggering on such protons for alignment purposes only. At moderate and low luminosity the triggering would possibly be advantageous. However, the large value of the cross section should allow collection of these events with ATLAS standard minimum bias triggers.

Naturally, for single-tagged events some amount of halo background is expected. It should be possible to reject a part of this background based on the measured correlation between position and angle of the track. Since the cross section for soft single diffractive processes is large, we do not expect a high background contamination. This will have to be verified once the first data are available.

8.5.4 Comparison of Hit Position Distributions

This method aims at finding the change of lateral position of the detectors between two runs. It relies on the simple observation that detectors in two different positions sample the same hit position distribution but in different, however partially overlapping, intervals. If the distribution is non-exponential then it is possible to find the relative distance between the two measured distributions by comparing their shapes. This provides a relative alignment of a single detector between two measurement
periods (runs or time periods in a run). It is worth stressing that only the shapes can be compared since the normalisation of the distribution depends on the value of the collected luminosity, which may not be known.

The method uses the protons from minimum bias interactions. These mainly come from single diffractive dissociation. In this method the actual production process is unimportant, in contrast to the kinematic peak method. The best way to compare the distributions is the Wilcoxon–Mann–Whitney statistical test (also Mann–Whitney \( U \) test) \cite{125}. In this test, the two measured samples are ordered together. Then, a statistic \( U \) is calculated, based on how observations from the first sample are ordered with respect to the observations from the second sample.

Figure 86. Illustration of how the shapes of two statistical distributions can be compared to extract a relative shift between them.

The alignment procedure assumes some lateral displacement \( d \) between the detectors in two different data periods\(^9\). All events in one of the samples are translated by this value. Then the ranges of both samples are set to the range that is expected to be common, assuming distance \( d \) (events outside the chosen range are removed from the samples). Then the statistical test is performed, resulting in a \( p \)-value – see Fig. 86.

This procedure delivers the \( p \)-value as a function of the difference between the detector positions in two time periods: \( p(d) \). Then a search of the maximum of the \( p(d) \) function is performed. The \( d_0 \) value, for which the maximum is observed, is the value of misalignment obtained from this method. An example is presented in Fig. 87, where the \( p(d) \) function is calculated for three pairs of distributions with different numbers of events. In each pair the position of the detector was changed by 200 \( \mu \)m. For \( 10^4 \) events, the reconstructed offset is around 300 \( \mu \)m, giving an error of 100 \( \mu \)m. For \( 10^5 \) events the error is about 25 \( \mu \)m, while for \( 10^6 \) events it is about 13 \( \mu \)m.

8.5.5 Electromagnetic Bremsstrahlung

Another method for aligning the AFP detectors makes use of the electromagnetic bremsstrahlung process where Coulomb interaction between two colliding protons leads to a photon emitted from one of them, see Fig. 88.

In the bremsstrahlung process both final state-protons and the photon have small polar angles (typically \( 1/\gamma \) where \( \gamma \) is the proton Lorentz factor). In addition, the energy of the photon is practically equal to the momentum lost by the radiating proton on the same side. Therefore, the measurement of the photon energy with the ZDC detector provides an energy measurement of the scattered proton’s energy. This, in turn, allows the alignment of the AFP detectors. Additionally, a comparison

\(^9\)A macroscopic example is two data taking periods with two distinct positions of the detector. A microscopic example is two runs with “the same” detector position taken during two fills of the machine i.e. after the repositioning of the detectors.
of photon energy with the AFP position could be used to investigate the scattered proton energy calibration.

The cross section for the electromagnetic bremsstrahlung is large, providing relatively high rates of the events. The obtained statistics would be enough to provide precise alignment. The high cross section value suggests working in low luminosity scenario. The experimental signature of bremsstrahlung is following:

- AFP tag on one side (the proton on the other side normally does not lose energy and falls outside the detector acceptance),
- photon measured in ZDC on the same side,
- central detector empty.

The AFP acceptance is roughly $0.02 < \xi < 0.12$. This translates into an energy range of the photon of $140 \text{ GeV} < E_{\gamma} < 840 \text{ GeV}$. In addition, one needs to account for the requirement of absence of pile-up interactions in the same bunch crossing, which decreases the number of events by a factor $\exp(-\mu)$, where $\mu$ is the average multiplicity of pile-up interactions.

The main experimental difficulty is to obtain effective background discrimination and rejection. The background consists of minimum-bias processes in which a final state proton with energy significantly smaller than the beam energy is observed (typically coming from recombination) and a substantial amount energy in neutral particles is emitted in the forward direction (the ZDC tag) – for example an energetic $\pi^0$ decaying into photons. Additionally, such background events have to show a lack of “measurable” final-state particles in ATLAS. Such topologies can be caused due to multiplicity fluctuation (in non-diffractive processes) or due to a large rapidity gap (in diffractive processes). Presently available MC generators can be used to study such backgrounds.

The rates for bremsstrahlung, as well as two background estimates are presented in Fig. 89 as a function of a lower limit on the photon energy. The rates were calculated assuming $\mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, including the probabilistic factor reflecting loss of signal due to additional, background $pp$ interactions. The requirement of an empty ATLAS detector was implemented by requiring no charged particles in the LUCID detector. Such a procedure is sufficient to obtain an order of magnitude estimation of the expectations. One finds that the background rates are much larger than the signal rates.

![Figure 87. The $p$-value of compatibility between two statistically independent $x$ position distributions as a function of assumed shift between them.](image-url)
8.5.6 Bremsstrahlung via Nuclear Forces

Recently, calculations of the bremsstrahlung process accompanying elastic scattering of protons were published [126, 127]. Fig. 90 shows a simplified diagram of the process.

There, the energy-conserving electromagnetic exchange is replaced with the one mediated by strong forces. This greatly enhances the cross section for the process. A simple estimate from Fig. 91 suggest a value cross section larger by three orders of magnitude than that of the “classic” bremsstrahlung. This should make it possible to disentangle the process from the background. One also should mention the $pp \rightarrow pp\pi^0$ process [128], which could be used in a similar fashion and is certainly worth further investigation and feasibility studies.

8.5.7 Exclusive Muon Production

Another possibility for the AFP detector alignment is offered by the exclusive muon pair production in the two-photon process, $p + p \rightarrow p\gamma^+\gamma^- p \rightarrow p\mu^+\mu^- p$, see Figs. 92. This method exploits the ATLAS ZDC acceptance is depicted.
muon system.

The main disadvantage of this process is its small cross section (Fig. 93). Therefore, only events with a single AFP proton tag can be considered. The detailed study [129] resulted in a conclusion that in order to align the detectors with 10 µm precision a sample of 100 $p\mu^+\mu^-p$ events is needed. A requirement of the transverse momentum of both muons greater then 10 GeV and a single AFP tag (detector 1.5 mm from the beam) implies a data sample corresponding to an integrated luminosity of about 0.1 fb$^{-1}$. This is equivalent to 2 weeks of running with $\mathcal{L} = 10^{33}$ cm$^{-2}$s$^{-1}$. This time is doubled if the detectors are positioned 2 mm from the beam.

![Figure 92. Feynman diagram for exclusive muon pair production in the two photon exchange process.](image1)

![Figure 93. The cross section for lepton pair production as a function $1/(\text{GeV}/c)/p_{\text{thr}}^T$ for events in which the transverse momenta of both leptons are larger than the transverse momentum threshold, $p_{\text{thr}}^T$.](image2)

### 8.5.8 Alignment with ALFA

The ALFA detector measures elastic scattering and hence the total $pp$ cross section and the absolute LHC luminosity. These are some of the most precise measurements at the LHC and rely strongly on a proper alignment. For this reason ALFA implemented dedicated Overlap Detectors (OD), which are used for the alignment.

The AFP detectors can also be aligned using the ALFA detectors. This can be done in two ways. The first method is to insert the AFP detectors at the end of the ALFA measurements in a dedicated large $\beta^*$ run and to register protons scattered elastically. Of interest would be events that contain a hit in the AFP on one side of the ATLAS IP and in ALFA on the other side. Using the correlations between the kinematics of two elastic protons, their collinearity and the previously aligned ALFA detectors, it should be possible to align the AFP detectors.

Another method, which can be applied for both large $\beta^*$ as well as for standard LHC runs, uses the protons that traverse both the AFP and ALFA detectors located on the same side of the IP. This method is more complicated, since one more degree of freedom is involved (the energy of the proton), which is important because of the Q6 magnet between AFP and ALFA. In addition, for this method, only the near AFP station can be inserted because of the relatively large nuclear interaction length ($4 – 7 \%$ for 2 – 4 quartz radiators) of the quartz Cherenkov timing detector located in the far AFP station.

Finally, it is noted that this method provides alignment with respect to the ALFA detectors, which in turn are aligned with respect to the actual beam position. This will lead to further corrections as
was discussed in the beginning of this section.
9 Project Management

9.1 AFP Project Organization

The AFP Project is an ATLAS Upgrade project in the ATLAS Forward Detector (FWD) organization, see Fig. 94. The FWD project is directed by the FWD Project leader (PL). The AFP PL responds directly to the FWD PL, and works closely with the AFP Project Engineer, the ALFA PL, the ALFA Technical Coordinator (TC), and the ATLAS TC. The AFP PL will be stationed at CERN, in particular for the critical next two years.

The AFP PL chairs the AFP Technical Management Board (TMB), the day-to-day governing body in which the Physics Coordinator, the Project Engineer, the ALFA TC, and the AFP Level 2 managers have membership. The FWD Institute Board (IB) will decide on matters of finance and institutional responsibilities.

Below the AFP Project Leader, several tasks are implemented, shown in the organigram and based on the Level 2 tasks in the Work Breakdown Structure (WBS) discussed in the next section. Each Level 2 manager answers directly to the AFP PL and is member of the AFP TMB.

Some important activities (physics analysis, software development, simulations, and offline reconstruction) are already shared between ALFA and AFP and are not represented in the WBS. The task of the ALFA/AFP Physics Coordinator is to coordinate the early physics activities for both ALFA and AFP: simulations, defining the physics channels of interest, coordination with ATLAS planning, formulation of the ALFA/AFP trigger menu, integration of ALFA/AFP physics into the ATLAS physics groups, and other matters directly linked to the forward physics program.

The ATLAS policies that govern the ATLAS organization also apply to the FWD/AFP organization. In particular, the AFP PL shall be elected or endorsed by the FWD Institute Board for a 2-year term. The official representative of AFP (and of the other ATLAS Forward Detectors ALFA, LUCID, ZDC) to the ATLAS Executive Board is the FWD PL. More information about the Forward Detectors Organization is given in https://edms.cern.ch/document/1070334/2. The FWD PL and the AFP PL are members of the ATLAS Upgrade Steering Committee. When the AFP detector is fully installed and commissioned, the AFP Upgrade Project will be merged into a common ALFA/AFP project within the FWD system and the separate AFP structure will cease to exist.

The sharing of resources between the operational ATLAS detector ALFA and the AFP project is natural given the similarity in physics goals and the relatively modest resources of the two groups. The Forward Detector Management Board has defined a number of activities common to the two groups:

- A common ALFA/AFP working group tightly linked to the ATLAS Standard Model/Soft QCD group which helps to prepare run requests to the LHCC for diffractive physics.

- A common software/simulation group serving the needs of both ALFA and AFP.

- Common ALFA and AFP mailing lists to keep all members of the groups informed about the ongoing activities.

- Common ALFA/AFP collaboration meetings during the year.

- Participation of the AFP members in ALFA runs starting in 2015 in order to share experience on operations.

These actions are considered a starting point for future unification of the ALFA/AFP activities after the AFP detectors have been installed.
Figure 94. Organigram of the AFP Upgrade Project, and its relationship to the ATLAS Upgrade Steering Committee, the Executive Board, and the ATLAS forward detector organization. The yellow boxes indicate the tasks in the AFP project which each have a Level-2 task manager. The light-blue task boxes indicate tasks that are shared between the ALFA and AFP projects.

9.2 The AFP Work Breakdown Structure and Resources

The AFP Detector project is organized in a Work Breakdown Structure (WBS), see Table 16. Each Level 2 task has a manager responsible for its organization.

At Level 3, the systems and tasks are subdivided further into components such as 3D chips, front-end electronics, interconnects, and other relevant sub-tasks. At Level 4 the individual components are further subdivided into Design, Prototype, Testing, Production, etc.. Each Level 2 task has an associated “cost book”, a workbook with multiple spreadsheets, each specifying costs, labour, and risk for the associated Level 4 task.

9.2.1 Cost Estimates

Costs and labor are estimated based on known prices and extrapolated from previous production experience with prototypes and similar items. The CORE cost is the direct production cost of the research equipment intended for installation; it includes components, production, outsourced manufacturing and assembly by sub-contractors, installation, and commissioning. It excludes the cost of infrastructure used for production at participating institutions and excludes related travel and direct institutional labor by scientists, engineers, and technical and administrative staff. Costs in the cost books are evaluated in the local currency (EURO, CAD, USD, CHF) and converted to CHF (using rates of 1 EUR = 1.04 CHF, 1 CAD = 0.77 CHF, and 1 USD = 0.94 CHF).

In Table 16 a summary of the CORE cost breakdown for each Level 2 task is reported, extracted from the WBS tables. The costs listed are for the full AFP (AFP2+2) configuration: two arms with two Roman pot stations and one time-of-flight detector per arm, appropriate for runs in 2017. The total CORE cost of the AFP project is estimated at 967 KCHF. This does include the estimated cost of installation of cables, but not yet the installation cost of the new beam pipe sections and Roman Pot stations in the tunnel as these costs are not yet known and depend on the division of the installation

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tasks between ATLAS and the CERN technical divisions, which is under discussion.

Anticipating a possible partial installation during the Winter 2015-2016 shutdown, the last column of Table 16 details the 552 KCHF cost (excluding installation) of the single-arm configuration (APF0+2) which contains no time-of-flight detector.

In the next paragraphs the cost estimates are detailed further.

**WBS 1.1 Roman Pot Stations.** The Roman pot stations (RPS) are a direct copy of the TOTEM RPS (the horizontal pot station assembly) and the ALFA RPS (the station support structure). AFP will construct a first prototype station (‘module 0’) that will be used for acceptance testing, RF studies, and motion performance in the lab. This station might later serve as a first production station to be installed in the tunnel. The second and third station will be ordered in 2015 as well. Two more stations will be ordered in 2016. The cost of a single RPS is estimated but is still under negotiation with the possible manufacturer.

The support structure is straightforward, with the only requirements being long-term stability, and adjustability of the position and alignment. Its cost is estimated at 7.5 KCHF/support.

The Roman pot (RP) itself has been designed, and is very similar to the cylindrical RP pioneered by TOTEM for reduced RF impedance in the machine. The only difference is the thin window, which for AFP is machined from the outside of the RP, because the silicon tracker and time-of-flight detector require a flat inside bottom of the RP. AFP will produce two ‘module 0’ RPs. The first will undergo leak tests, UHV outgassing test, RF tests, and finally destructive testing to measure the ultimate failure limit. The second module 0 RP will be used in the lab, while the production RPs will be used in the tunnel. We anticipate to produce all RPs for the full system in the same cycle, after the first module 0 has been accepted. The cost estimate is based on the materials cost and the estimated machining costs.

The RP feedthrough flange is listed as a separate item because it holds all signal and service feedthroughs for the detector(s) and the heat exchanger, and serves as the platform for the detector support(s). Its final design is integrated with the designs of the supports for the silicon tracker, the timing detector, and the heat exchanger for the cooling.

**WBS 1.2 Silicon Tracker.** The silicon tracker costs are well known because they are based on the IBL production costs. Because of the small numbers required for AFP, it was decided to not split production for the AFP0+2 and AFP2+2 phases. Much of the basic production has been done: sensors, FE-I4 ASICs, metallization, flex connectors; and the only unknowns are the cost of producing the final ‘tracker card’ and the ‘tracker card cage’ that holds the four tracker cards in each RP and is mounted on the RP feedthrough flange. The latter items are in the final-design phase, and no difficulties are expected.

**WBS 1.3 Time-of-Flight Detector.** The time-of-flight (ToF) detector will be needed for the full AFP implementation to help with the rejection of pile-up protons. Because this detector was vigorously developed in the US and Canada, its costs are well-established. The module 0 detector, holder, and electronics chain exists and has been used in the November 2014 beam test.

**WBS 1.4 Trigger and Data Acquisition.** The final design of the Level-1 trigger electronics (module 0) based on the ToF detector exists and its cost is well-established. The trigger based on the SiT hits is in first design; a pre-prototype was used in the November 2014 beam test. However, the trigger signal driver (which combines the signals from the two stations in an arm) does not exist. Also, the Level-1 trigger receiver and fast combinatorial logic near the CTP has not yet been designed. It is anticipated that this receiver/trigger logic will resemble the new ALFA trigger card, and this design is the likely starting point for the AFP design. Because the initial trigger requirements are not demanding, it is foreseen that this item may evolve over the next two years.

The Data Acquisition is based on the RCE system used by several ATLAS groups and developed by the SLAC group. The system was used successfully in the AFP integration beam test in November
2015. The cost of the system is well-known.

**WBS 1.5 Infrastructure.** The cost of most infrastructure items is well understood. The HV and LV equipment is the same as existing equipment used inside ATLAS, and the local voltage regulator boards in the tunnel are the same as used by the IBL. The cable list is well-known, and cable costs are coming from the CERN store or from vendor quotes. The cooling cost is well-understood because several vortex coolers have been built previously for other users. The cost of the secondary vacuum system is based on the systems built for TOTEM and ALFA.

The cost of the DCS is estimated based on the DCS used for ALFA and for the IBL. Because of the uncertain availability of radiation-hard ELMBs used for digitization of the environmental and current sensors, the cost is not completely understood yet.

The larger uncertainty arises from the cost of the LHC related items: the AFP beam pipe and the Beam Position Monitors (BPMs). The cost of producing the beam pipe and associated hardware is under discussion with the TE-VSC-BVO department, as is the cost for installation by TE-VSC-ICM. The BPMs cost estimate is based on an early price quote of the BPM-SX with the DOROS DAQ; this price will be updated soon.

**WBS 1.6 Beam Tests.** The cost of the expected two beam test campaigns is based on the cost of the November 2014 beam test at CERN.

**WBS 1.7 Installation.** Installation costs are under discussion. The cable and patch panel installation cost, the only large installation cost items, are based on a recent estimate by PH-DT on the costs for the same in the recent TOTEM Upgrade.

### 9.2.2 Institutional Responsibilities

In Table 17 a summary is given of the institutional responsibilities that were agreed upon at the AFP Kick-Off meeting on February 3, 2015. The list of commitments is expected to further evolve over the next months and years. At the moment of the writing of this document AFP has an active membership of ~20 physicists (including ~5 PhD students) and ~5 experts for technical support. This is sufficient to cover the production and installation of the detector and the following phases.

### 9.2.3 Manpower Estimates

The AFP project leader will be stationed at CERN. Physicists and PhD students will continue to take responsibility for the physics simulations, software development for track and timing reconstruction, and data analysis.

AFP has identified the required technical personnel from its member institutions to be stationed at CERN, and found a suitable project engineer, mechanical/electrical engineers and technicians from member and non-member institutions. Scheduling of availability at CERN is ongoing, with a projected significant presence starting by June or July 2015.

Also identified is 0.2 FTE of an off-site mechanical engineer/designer for the time-of-flight (detector holder). On-site physicists and students will contribute to many of the tasks, in particular in the area of DCS software, TDAQ, and tests and calibration.

### 9.3 Project Scheduling

In the AFP project schedule, all WBS tasks are contained in the master schedule, with the proper inter-dependencies applied. An extract of the AFP Gantt chart with tasks and milestones for the AFP project is shown in Table 18. Because of the intention to possibly install a single AFP arm during the Winter 2015-16 shutdown, the schedule for 2015 is very tight, whereas the 2016 production schedule is more relaxed. Many preparatory tasks (cabling, beam pipe production, silicon sensor
production, prototyping and production of the pots and two Roman pot stations) are scheduled in 2015 to prepare a single AFP arm. In contrast, 2016 sees a continuation of Roman pot station production and the production of the time-of-flight detectors.

It is assumed that in early November the decision must be taken whether or not to proceed with the (partial) installation of the first AFP arm and services during the upcoming Winter shutdown. To this end, an Installation Readiness Review is foreseen in early November 2015 for the single-arm installation, and again in November 2016 for the full installation.

Two prototype Roman pots are foreseen, one prototype for destructive pressure testing. The second prototype may serve as the first production pot and serve in various tests in the lab and test beams. The first Roman pot station, if accepted, will serve as the first production station. Depending on the schedule, one of the stations will be retained in the lab for various tests.

The critical path in the schedule is formed by the production of the two (or two plus prototype) Roman pot stations in view of the estimated 12-week production time per station. The TE-VCS department will need a minimum of three weeks to certify a Roman pot station for leakage and outgassing before installation in the LHC.

Preliminary milestones have been defined; a representative list with dates is given in Table 18. The schedule will be refined over the coming months, in close iteration with ATLAS TC and CERN PH-DT, Beams (BE), Engineering (EN-MEF, EN-MME), Technology (TE-VSC, TE-MPE) and Safety Departments. Close contact will be maintained by participation and presentation by the AFP PL/PE in TREX meetings.

9.4 Further R&D and Planning for Run 3

The AFP project has the capability to take data also in Run 3, if the physics, the Run 2 experience, and the LHC working conditions justify this. The AFP presence in Run 3 is subject to prior ATLAS review and approval, which will possibly be initiated at some point late in Run 2.

The goals for data-taking after Run 2 would include running in normal physics operation, and may require an adaptation of the detectors and triggering. While no changes are expected to be needed for the AFP 3D trackers, the time-of-flight detector may require additional granularity and improved digitization to reach the required 10 ps timing accuracy at high pile-up. Depending on experience obtained in Run 2, it may be that the AFP trigger will be required to perform some pile-up rejection already at Level-1. These various improvements are the focus of an ongoing R&D program. The main items under investigation are the technology and radiation hardness of the tracker and time-of-flight detectors. The AFP groups already started these activities in the past years, namely:

- Arlington, Texas for performance improvement of the MCP;
- Olomouc for the quartz radiation hardness;
- Stony Brook, Olomouc, and Alberta for radiation hardness of LQbar timing electronics;
- Prague CTU and IFAE for 3D performance under heavy non-uniform irradiation;
- Saclay for fast sampling digitization (SAMPIC) for time-of-flight detectors;
- INFN Bologna, Lecce, and Roma 2 for timing with solid state detectors and front-end electronics development.

All these groups intend to continue their R & D studies for the Run 3 detector. It is not excluded that some of these studies will be performed, as in the recent past, in collaboration with the CMS/TOTEM groups, or with other LHC groups. This implies also the participation in 1-2 beam tests of approximately 1-2 week per year until 2017.
<table>
<thead>
<tr>
<th>Item</th>
<th>AFP2+2</th>
<th>AFP0+2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WBS 1.1 Roman Pot Stations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roman Pots</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>RP Station production</td>
<td>92</td>
<td>55</td>
</tr>
<tr>
<td>Station Support Tables</td>
<td>38</td>
<td>22</td>
</tr>
<tr>
<td>Motors/Slides/Transducers</td>
<td>83</td>
<td>50</td>
</tr>
<tr>
<td>Feedthrough Flanges</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Interlock System</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Cost RPS</td>
<td>273</td>
<td>173</td>
</tr>
<tr>
<td><strong>WBS 1.2 Silicon Tracker</strong></td>
<td></td>
<td></td>
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<tr>
<td>3D Sensors</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>FE-I4b ASICs</td>
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<td>13</td>
</tr>
<tr>
<td>Bump-bonding</td>
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<td>18</td>
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<tr>
<td>Flex</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Assembly</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Tracker cards and holder</td>
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<td>37</td>
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<tr>
<td>Cost SiT</td>
<td>194</td>
<td>165</td>
</tr>
<tr>
<td><strong>WBS 1.3 Time-of-Flight</strong></td>
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<td></td>
</tr>
<tr>
<td>Detector</td>
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</tr>
<tr>
<td>FE-Electronics</td>
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<td>0</td>
</tr>
<tr>
<td>BE-Electronics</td>
<td>44</td>
<td>0</td>
</tr>
<tr>
<td>Holder</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Cost ToF</td>
<td>119</td>
<td>0</td>
</tr>
<tr>
<td><strong>WBS 1.4 Trigger &amp; DAQ</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCE Data Acquisition</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Optoboards</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>L1 Trigger</td>
<td>25</td>
<td>17</td>
</tr>
<tr>
<td>L2 Trigger</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cost TDAQ</td>
<td>38</td>
<td>29</td>
</tr>
<tr>
<td><strong>WBS 1.5 Infrastructure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>High Voltage</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Low Voltage</td>
<td>29</td>
<td>22</td>
</tr>
<tr>
<td>DCS</td>
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<td>8</td>
</tr>
<tr>
<td>Beam Position Monitor</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Secondary Vacuum</td>
<td>31</td>
<td>17</td>
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<tr>
<td>Cables</td>
<td>82</td>
<td>35</td>
</tr>
<tr>
<td>AFP Beam Pipe</td>
<td>34</td>
<td>17</td>
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<td>Cost Infrastructure</td>
<td>280</td>
<td>153</td>
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<tr>
<td><strong>WBS 1.6 Test Beam</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost Beam Tests</td>
<td>12</td>
<td>6</td>
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<tr>
<td><strong>WBS 1.7 Installation</strong></td>
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<td></td>
</tr>
<tr>
<td>Beam pipe and RPS</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>Cables</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Cost Installation</td>
<td>51</td>
<td>26</td>
</tr>
<tr>
<td><strong>TOTAL COST</strong></td>
<td>967</td>
<td>552</td>
</tr>
</tbody>
</table>

Table 16. CORE costs of the Level-2 components of the AFP Work Breakdown Structure in KCHF.
<table>
<thead>
<tr>
<th>Institution</th>
<th>Country</th>
<th>CORE Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alberta</td>
<td>Canada</td>
<td>Roman pot design and production, Time-of-flight back-end electronics</td>
</tr>
<tr>
<td>Cracow AGH UST</td>
<td>Poland</td>
<td>Analysis, Soft/Sim, Reco, trigger</td>
</tr>
<tr>
<td>Cracow IFN PAN</td>
<td>Poland</td>
<td>Analysis, alignment/optics, HV and LV, DCS</td>
</tr>
<tr>
<td>IFAE Barcelona</td>
<td>Spain</td>
<td>Silicon pixel modules, test beams</td>
</tr>
<tr>
<td>Milano</td>
<td>Italy</td>
<td>LV regulator system in tunnel</td>
</tr>
<tr>
<td>Olomouc</td>
<td>Czech Rep.</td>
<td>Time-of-flight detector</td>
</tr>
<tr>
<td>Prague AS</td>
<td>Czech Rep.</td>
<td>Silicon sensors and FE-I4</td>
</tr>
<tr>
<td>Prague CU</td>
<td>Czech Rep.</td>
<td>Roman pot station</td>
</tr>
<tr>
<td>Prague CTU</td>
<td>Czech Rep.</td>
<td>Cooling</td>
</tr>
<tr>
<td>Oslo-Bergen</td>
<td>Norway</td>
<td>FE-I4 flex, Silicon tracker holder</td>
</tr>
<tr>
<td>LIP Lisbon</td>
<td>Portugal</td>
<td>High level trigger, DCS</td>
</tr>
<tr>
<td>Stony Brook</td>
<td>USA</td>
<td>Time-of-flight front-end electronics</td>
</tr>
</tbody>
</table>

### Table 17. The AFP institutional responsibilities by participating country.
Table 18. Representative list of AFP construction and installation tasks and milestones for the AFP project. In the first part of the table, the tasks and and milestones for the AFP0+2 configuration are listed. The second AFP arm and the time-of-flight detectors will be prepared during 2016. Two Installation Readiness Reviews are foreseen for early November in 2015 and in 2016.

<table>
<thead>
<tr>
<th>Date (±4 days)</th>
<th>Tasks and milestones in 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nov 2015</td>
<td>AFP0+2 Installation Readiness Review</td>
</tr>
<tr>
<td>1 Jun</td>
<td>Completed the certified list of AFP cable bundles, trays, and routing</td>
</tr>
<tr>
<td>1 Oct</td>
<td>Secondary vacuum &amp; cooling ready for installation</td>
</tr>
<tr>
<td>1 Oct</td>
<td>Cable bundles &amp; trays prepared and ready for final certification</td>
</tr>
<tr>
<td>1 Jul</td>
<td>AFP beam pipe design done and signed-off</td>
</tr>
<tr>
<td>1 Oct</td>
<td>AFP beam pipe produced</td>
</tr>
<tr>
<td>8 Oct</td>
<td><strong>Milestone:</strong> AFP beam pipe ready for certification by the LHC</td>
</tr>
<tr>
<td>1 Nov</td>
<td>AFP Beam pipe certified for installation in the LHC</td>
</tr>
<tr>
<td>1 Aug</td>
<td>1\textsuperscript{st} Roman pot certified for leakage, pressure, &amp; RF</td>
</tr>
<tr>
<td>1 Sep</td>
<td>2\textsuperscript{nd} &amp; 3\textsuperscript{rd} Roman pot certified for leakage</td>
</tr>
<tr>
<td>1 Aug</td>
<td>Full motorization and cabling package ready in the lab</td>
</tr>
<tr>
<td>1 Aug</td>
<td>Full RP station infrastructure ready in the lab</td>
</tr>
<tr>
<td>1 Sep</td>
<td><strong>Milestone:</strong> 1\textsuperscript{st} station accepted at CERN</td>
</tr>
<tr>
<td>1 Oct</td>
<td>1\textsuperscript{st} station fully equipped, operational, and calibrated</td>
</tr>
<tr>
<td>1 Dec</td>
<td>2\textsuperscript{nd} station fully equipped, operational, and calibrated</td>
</tr>
<tr>
<td>1 Dec</td>
<td><strong>Milestone:</strong> stations ready for LHC certification</td>
</tr>
<tr>
<td>21 Dec</td>
<td>Two Roman pot stations ready for LHC installation</td>
</tr>
<tr>
<td>1 Jul</td>
<td>Feedthroughs, heat exchanger, tracker card, and card cage design review</td>
</tr>
<tr>
<td>1 Sep</td>
<td>Silicon hybrids ready</td>
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<tr>
<td>1 Nov</td>
<td>Silicon tracker cards ready</td>
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<tr>
<td>1 Nov</td>
<td>Silicon tracker card cage ready</td>
</tr>
<tr>
<td>1 Dec</td>
<td><strong>Milestone:</strong> Detector flange integration done</td>
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<th>Date (±4 days)</th>
<th>Tasks and milestones in 2016</th>
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<tr>
<td>1 Nov 2016</td>
<td>AFP2+2 Installation Readiness Review</td>
</tr>
<tr>
<td>1 Apr</td>
<td>4\textsuperscript{th} &amp; 5\textsuperscript{th} Roman pot certified for leakage</td>
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<tr>
<td>1 Apr</td>
<td>Full motorization and cabling packages ready in the lab</td>
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<tr>
<td>1 Jun</td>
<td>4\textsuperscript{th} &amp; 5\textsuperscript{th} Roman Pot Station fully equipped, operational, and calibrated</td>
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<tr>
<td>1 Sep</td>
<td><strong>Milestone:</strong> remaining RP Stations ready for LHC certification</td>
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<tr>
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<td>Time-of-flight detector, holder, and feedthrough design review</td>
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<td>1 Aug</td>
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Summary

This Technical Design Report describes the physics and the technical details of the ATLAS Forward Proton (AFP) detectors, to be placed in the outgoing LHC beams at 210 m from the ATLAS interaction point. The initial physics program aims to study diffractive processes in special low-luminosity runs. Because diffractive processes generally have high cross sections, it is argued that significant diffractive physics results can be obtained with a few weeks of special runs in the LHC Run 2 period. Amongst those are the study of the soft events, known as the underlying event in hard scattering processes; studies of diffractive production of W and Z bosons; the study of the soft and hard Pomeron and its structure in terms of quarks and gluons; and tests of the BFKL mechanism. Of particular interest is the Double Pomeron Exchange process, which features two forward protons and a pair of centrally produced jets. The measurement of this process forms the beginning of studies of hard central diffraction which eventually will lead to the need for higher luminosity. Ultimately, if AFP running at standard luminosity is demonstrably safe and has been approved, the tagging of forward protons at standard luminosity enables exciting new studies of central exclusive production and of anomalous quartic gauge boson couplings, a possible harbinger of new physics.

Technical details of the detector and its installation are discussed. The beam interface is the horizontal cylindrical Roman pot, which has been approved for the TOTEM detectors. The high-resolution radiation hard AFP tracker uses the same pixel detectors and front-end as the ATLAS IBL detector. Time-of-flight detectors are required to measure the interaction vertex in two-proton central diffraction at modest and standard luminosity to improve the rejection of backgrounds from single-diffraction protons. The novel timing detectors for AFP are quartz Cherenkov hodoscopes with radiation hard or tolerant electronics. The integration of the AFP first level trigger and data acquisition are described. The integration of the tracker and timing detectors and readout was demonstrated in a beam test at CERN.

The installation of the AFP detectors is intended to proceed as quickly as possible, subject to full approval and availability of the required funding, with the full system intended to be available by the start of 2017 LHC running at the latest. A first phase installation of a single-arm two-station AFP, which does not require timing, may be attempted as early as during the scheduled 9-week long Winter 2015-2016 shutdown, depending on schedule and resources. Such a configuration would provide invaluable operational experience and measurements of background conditions in 2016, as well as being adequate for special low-luminosity runs providing studies of soft and hard single diffractive physics. The second arm or the full system will be installed during the 19-week shutdown planned for Winter 2016-2017. After commissioning and successful operations of the full system in special runs, requests will be made to measure the beam environment in a few runs at standard luminosity, in order to prepare for potential standard luminosity operation at the end of Run 2 with the possibility of extending into Run 3.
Acknowledgements

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The ATLAS Collaboration

Argentina
Buenos Aires
G. Otero y Garzon, R. Piegaia, H. Reisin, S. Sacerdoti

La Plata
M.J. Alconada Verzini, F. Alonso, F.A. Arduh, M.T. Dova, F. Monticelli, H. Wahlberg

Armenia
Yerevan
H. Hakobyan, G. Vardanyan

Australia
Adelaide
P. Jackson, L. Lee, N. Soni, M.J. White

Melbourne
E.L. Barberio, A.J. Brennan, E. Dawe, D. Jennens, T. Kubota, M. Milesi, G. Nunes Hanninger,

Sydney
C.W. Black, C. Cuthbert, K.D. Finelli, G.-Y. Jeng, A. Limosani, A.K. Morley, N.D. Patel,
A.F. Saavedra, M. Scarcella, K.E. Varvell, I.J. Watson, B. Yabsley

Austria
Innsbruck

Azerbaijan
Baku
O. Abdinov, F. Ahmadov, N. Huseynov, N. Javadov, F. Khalil-zada

Brazil
Rio de Janeiro UF
Y. Amaral Coutinho, L.P. Caloba, C. Maidantchik, F. Marroquim, A.A. Nepomuceno, J.M. Seixas

UFJF
A.S. Cerqueira, L. Manhaes de Andrade Filho

UFJF
A.S. Cerqueira, L. Manhaes de Andrade Filho

USP
M.A.B. do Vale

USP
M. Donadelli, J.L. La Rosa Navarro, M.A.L. Leite

Canada
Alberta
A.I. Butt, P. Czodrowski, J. Dassoulas, D.M. Gingrich, S. Jabbar, A. Karamaoun, R.W. Moore,
J.L. Pinfold, A. Saddique, F. Vives Vaque

Carleton
V. Bortolotto

Hong Kong HKUST
V. Bortolotto, K. Prokofiev

Nanjing
S. Chen, Y. Li, C. Wang, H. Zhang

Shandong
L. Chen, C. Feng, P. Ge, B. Liu, L.L. Ma, X. Zhang, Y. Zhao, C.G. Zhu

Shanghai
M. Cano Bret, J. Guo, L. Li, H. Yang

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LPNHE-Paris

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Orsay LAL

Saclay CEA

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Tbilisi SU
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Dortmund

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M. Düren, K. Kreutzfeldt, H. Stenzel

Goettingen

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Heidelberg PI

Heidelberg ZITI
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**Munich MPI**

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**Wuerzburg**

**Wuppertal**

**Greece**

**Athens**
S. Angelidakis, S. Chouridou, D. Fassouliotis, N. Giokaris, C. Kourkoumelis, A. Manousakis-Katsikakis, N. Tsirintanis

**Athens NTU**

**Thessaloniki**

**Israel**

**Technion Haifa**
H. Abreu, S. Cheatham, A. Di Mattia, E. Gozani, R. Kopeliansky, E. Musto, Y. Rozen, S. Tarem, N. van Eldik

**Tel-Aviv**
H. Abramowicz, G. Alexander, N. Amram, A. Ashkenazi, G. Bella, O. Benary, Y. Benhammou, M. Davies, E. Etzion, A. Gershon, O. Gueta, Y. Oren, Y. Silver, A. Soffer, N. Taiblum

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Roma Tre

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Y. Nagasaka

KEK

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R. Takashima

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K. Kawagoe, S. Oda, H. Otono, J. Tojo

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T. Fusayasu, M. Shimojima

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Tokyo Tech

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Cracow IFJ PAN

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J.A. Aguilar-Saavedra

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A. Hrynevich

Romania
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ITIM
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F. Ahmadov, I.N. Aleksandrov, V.A. Bednyakov, I.R. Boyko, I.A. Budagov, G.A. Chelkov,
A. Cheplakov, M.V. Chizhov, D.V. Dedovich, M. Demichev, M.I. Gostkin, N. Huseynov, N. Javadov,
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I. Yeletsikkh, A. Zhemchugov, N.I. Zimine

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V.V. Sulin, V.O. Tikhomirov, K. Zhukov

Moscow ITEP
A. Artamonov, P.A. Gorbounov, V. Khovanskiy, P.B. Shatalov, I.I. Tsukerman

Moscow MEPhI
A. Antonov, K. Belotshkiy, O. Bulekov, V.A. Kantserov, D. Krasnopetsev, A. Romanious, E. Shulga,

Moscow SU
A.S. Boldyrev, L.K. Gladilin, V.A. Kramarenko, A. Maevskiy, V.I. Rud, S.Yu. Sivoklokov,
L.N. Smirnova, S. Turchikhin

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Petersburg NPI
A. Basalaye, A. Ezhilov, O.L. Fedin, V. Gratchev, M. Levchenko, V.P. Maleev, Y.F. Ryabov,
V.A. Schegelsky, E. Sedykh, V. Solovyev

Protvino IHEP
A. Borisov, E. Cheremushkina, S.P. Denisov, R.M. Fakhruddinov, A.B. Fenyuk, D. Golubkov,
A. Kamenshchikov, A.N. Karyukhin, A.S. Kozhin, A.A. Minaenko, A.G. Myagkov, V. Nikolaenko,
A.A. Solodkov, O.V. Solovyanov, E.A. Starchenko, A.M. Zaitsev, O. Zenin

Serbia
Belgrade IP
T. Agatonovic-Jovin, D. Bogavac, I. Bozic, A. Dimitrijevska, J. Krstic, M. Marjanovic, D.S. Popovic,
Dj. Siljacki, Lj. Simic, M. Vranjes Milosavljevic, N. Vranjes, L. Živković

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J. Antos, D. Bruncko, E. Kladiva, P. Strizeneck, J. Urban

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B. Maček, M. Mikuž, T. Sfiligoj
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Cape Town
A. Hamilton, S. Meehan, S. Yacoob

Johannesburg

Witwatersrand
K. Bristow, G.N. Hamity, C. Hsu, D. Kar, L. March, B.R. Mellado Garcia, X. Ruan

Spain
Barcelona

Madrid UA
V. Arnal, F. Barreiro, J. Cantero, H. De la Torre, J. Del Peso, C. Glasman, J. Llorente Merino, J. Terron

Valencia

Sweden
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Stockholm KTH
B. Lund-Jensen, P.E. Sidebo, J. Strandberg

Uppsala

Switzerland
Bern

CERN
Cambridge

Edinburgh

Glasgow

Lancaster

Liverpool

London QMUL

London RHBNC

London UC

Manchester

Oxford
The ATLAS Collaboration

Stony Brook

Tufts
P.H. Beauchemin, E. Meoni, K. Sliwa, J. Wetter

UC Irvine

UI Urbana
M. Atkinson, A. Basye, R. Caminal Armadans, V. Cavaliere, P. Chang, S. Errede, K. Lie, T.M. Liss, L. Liu, M.S. Neubauer, R. Shang, I. Vichou

Wisconsin

Yale
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Appendix A  Benchmark Study: the DPEjj Process

In this section a detailed study is presented of the AFP detectors physics performance of the for the flagship process of double Pomeron exchange production of jets (DPEjj). The analysis was performed with the FPMC event generator. These stand-alone results were then confronted with the ATLAS full simulation.

A.1 Signal Properties

Experimentally, there are three main variables which characterise the DPE jet production events: the fractional momentum loss of the first (second) intact proton \(\xi_1\) (\(\xi_2\)), and the transverse momentum of the leading jet \(p_T\). The first two decide whether the event will be inside the AFP geometric acceptance and, thus, will be recognised as a DPE production.

Fig. 1 (left) shows the distributions of the relative momentum loss of one of the protons for three ranges of jet transverse momentum. One can see that the distribution is increasing with the increase of \(\xi\). This is due to the logarithmic scale on the abscissa. Typically, for the diffractive events the \(1/\xi\) distribution is expected resulting in a constant distribution in this plot. The presence of the \(p_T\) cut effectively decreases the probability of having small \(\xi\) values, explaining the behaviour of plotted curves. In addition, one can see that increase of the minimum \(p_T\) value leads to the increase of the distribution steepness. This means that the measurement of jets with higher transverse momentum requires acceptance in larger \(\xi\) values. In addition, one has to keep in mind that it is important to measure this process in whole available range of \(\xi\) and \(p_T\), in order to probe the Pomeron structure in \(\beta\) and \(Q^2\) ranges as wide as possible.

Fig. 1 (right) shows the missing mass distributions for different leading jet transverse momentum ranges (solid lines). With the increase of the \(p_T\), the distributions shifts towards the greater values of \(M_X\). This is natural, since a given \(p_T\) defines the minimal value of the central system mass. One can see that even for small jet transverse momentum the missing mass can be very large. This is due to the presence of the Pomeron remnants, which can carry a large fraction of the momentum. Hence, this plot shows that the \(\beta\) values are usually small. The dashed lines represent the cases in which both forward protons are within the AFP acceptance. Naturally, this requirement reduces the probability to observe the event.

The missing mass \(M_X = \sqrt{\xi_1 \xi_2}\) depends only on the product of \(\xi_1\) and \(\xi_2\). Obviously, the greater the difference between \(\xi_1\) and \(\xi_2\) is, the greater the boost of the central system. Thus, the interplay between \(\xi\) values is important. The correlation between \(\xi_1\) and \(\xi_2\) for two ranges of jet \(p_T\) is presented in Fig. 2. One sees that the amount of boosted events is large, for both small and large values of jet transverse momentum. From this one concludes that within the range of AFP acceptance (0.015 < \(\xi\) < 0.15) jets with small transverse momentum will be rather boosted, whereas the ones with high \(p_T\) rather not.

A.2 Background Processes

Since DPE jet production has the highest cross section among all hard DPE processes, there is no other DPE process that would form a background. Unfortunately, the fact that multiple interactions may occur during a single bunch crossing introduces combinatorial (pile-up) backgrounds.

The signature of central jets and two forward protons can be mimicked by non-diffractive (ND) jet production. Since in the case of non-diffractive jet production forward protons are destroyed\textsuperscript{10},

\textsuperscript{10}In a ND event, a high-\(p_z\) and high-rapidity proton can be produced in the hadronization of the forward proton remnants, but this is much rarer than backgrounds from pile-up.
**Figure 1.** Kinematic distributions in DPE jet production: relative momentum loss of one of the intact protons (left) and missing mass (right).

**Figure 2.** Correlations between the relative momentum losses of both forward protons produced in DPE jet process for two ranges of jet transverse momentum: $20 < p_T < 30$ GeV (left) and $100 < p_T < 110$ GeV (right).
such event must be accompanied by independent soft interactions producing forward protons. One can distinguish two situations:

- there are two independent soft interactions, each of them producing one proton (Single Tag, ST); the combination ND+ST+ST (Fig. 3 (left)) will mimic the DPE signal,
- there is one soft interaction producing two protons (Double Tag, DT); the combination ND+DT (Fig. 3 (centre)) will mimic the signal.

The probability of having a DT interaction is much smaller than having a ST one. However, only one DT interaction and two ST interactions are needed to mimic the DPE signature. It is worth to keep in mind that since the cross section for non-diffractive production is about four orders of magnitude larger than the one for the DPE production, the probability of having the additional forward protons from soft events is non-negligible, even at low pile-up values. In the low pile-up environment, where the probability of having many vertices is strongly suppressed, both ST and DT contributions are important and need to be considered.

The third important background comes from the hard Single Diffractive jet production (SD). The cross section is about two orders of magnitude smaller than the one for the non-diffractive jet production, but only one ST interaction is required to mimic the DPE signal, as illustrated in Fig. 3 (right).

![Figure 3. Pile-up background to the DPE jet production: non-diffractive jet production with two single tag soft interactions (ND+ST+ST, left), non-diffractive jet production with one double tag soft interaction (ND+DT, centre), single diffractive jet production with one single tag soft interaction (SD+ST, right).](image)

### A.3 Forward Protons in Soft Interactions

As explained in the previous Section, the backgrounds to the DPE jet process are due to the presence of soft processes with forward protons in the event. Such protons can be created in two ways. The first possibility is by a soft diffraction:

- single diffractive dissociation, leading to final state with one forward proton (ST type interactions),
- central diffraction (soft DPE process), leading to final state with two forward protons (DT type interactions)\textsuperscript{11}.

It should be mentioned that not all soft single diffractive interactions are of ST type and not all central diffractive interactions are of DT type. For example, in the case of central diffraction, one of the forward protons can have a momentum too large or too small to be tagged by the AFP detector,

\textsuperscript{11}One has to remember that the process of central diffractive production is not implemented in all MC generators, which leads to large underestimates of the DT interaction probability.
so the event will be seen as ST. The soft diffraction mechanism is understood for $\xi < 0.1$ and is dominant in this range.

The second possible mechanism produces a forward proton in the ND and DD events. It may also turn a SD event into a DT event type. In this mechanism the forward proton originates from the proton remnants (in non-diffractive processes) or from the dissociated state (in diffractive processes). A diagram and a sketch of such an interaction in the case of double diffractive dissociation process is presented in Fig. 4. The presence of a proton in the final state is somewhat natural because of baryon number conservation. Usually, these protons have too small momentum to be seen in AFP. However, the tail of the distribution reaches into the AFP acceptance and this mechanism becomes important for $\xi$ values above 0.1. One has to keep in mind that this $\xi$ region was not investigated experimentally and different models predict different results. The predictions depend on the hadronisation model used in the MC generator and its tuning.

![Figure 4. An example of a soft double diffraction interaction with two forward protons present in the final state.](image)

The cross sections and probabilities of having ST and DT interactions for various soft processes are listed in Tables 1 (left) and (right), correspondingly. Events were generated using two tunes implemented in PYTHIA 8.165 MC: default (POMFLUX=1, Schuler and Sjöstrand [130]) and MBR (POMFLUX=5 [131]). One can see that the dominant source of single tag interactions comes from the single diffractive process. Other contributions are smaller, but not negligible. The prediction for double diffractive and non-diffractive processes are similar. A significant difference can be observed for single diffraction, where the MBR model predicts much smaller cross-sections. For double tag interactions the dominant contribution comes from the central diffractive process, which is not present in the PYTHIA 8 default, causing a large difference between the minimum bias predictions.

<table>
<thead>
<tr>
<th>Single Tag (ST) Interactions</th>
<th>Double Tag (DT) Interactions</th>
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<tr>
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<table>
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<th>ND</th>
<th>MB</th>
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<td></td>
<td></td>
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<td></td>
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<table>
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<th>CD</th>
<th>ND</th>
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<td>cross section [µb]</td>
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Table 1. Probabilities and cross sections for soft processes with single (left) and double (right) AFP tag for various processes: Single Diffractive Dissociation (SD), Double Diffractive Dissociation (DD) and Central Diffraction (CD). The Minimum Bias (MB) is a weighted sum of all processes. Calculations were performed using two models implemented in PYTHIA 8.165 MC: default and MBR.
Due to the pile-up, an event can consist of several interactions. The probability of having two protons inside the AFP acceptance as a function of pile-up is shown in Fig. 5. In this figure both contributions: coming from ST+ST and DT events are shown. For each event the interaction multiplicity was generated randomly from the Poisson distribution with the average \( \mu \). Then every interaction was assigned to be of ST, DT or none type accordingly to the probability, see Table 1. This allowed to calculate what fraction of events have double tag due to ST and DT interactions for a given pile-up value. For an average pile-up multiplicity significantly smaller than 1 DT interactions are the dominant source the double tagged events. With increasing value of \( \mu \), the probability of double tag due to ST interactions grows more rapidly than the one due to DT interactions and becomes dominant for pile-up significantly larger than 1. The precise value of \( \mu \) at which the two contributions are equal depends on the MC model and is about 0.8 for \textsc{Pythia} 8 default, and 2.5 for \textsc{Pythia} 8 MBR.

A.4 Trigger

Events with central jets can be triggered by ATLAS single-jet triggers. Rates for three different jet \( p_T \) thresholds, predicted by the FPMC generator, as a function of pile-up are shown in Fig. 6 (left). In this calculation 2808 colliding bunches were assumed. From the figure one finds that the rates for \( \mu = 1 \) \((L = 3 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1})\) is about 200 Hz for \( p_T(jet) > 100 \text{ GeV} \), 8 kHz for \( p_T(jet) > 50 \text{ GeV} \), and 300 kHz for \( p_T(jet) > 20 \text{ GeV} \).

It is worth comparing these numbers to real data taking conditions. For example, in the 2010 run (with beam energy of \( E_{beam} = 3.5 \text{ TeV} \), 93 colliding bunches, 150 ns of bunch separation in the trains, and peak \( \mu = 2.22 \)), the lowest unprescaled trigger chain was for jets with \( p_T > 75 \text{ GeV} \). Jets with \( p_T > 15 \text{ GeV} \) were prescaled by factor of \( 10^4 \), jets with \( p_T > 30 \text{ GeV} \) by \( 10^3 \) and jets with \( p_T > 45 \text{ GeV} \) by \( \sim 10^2 \).

Judging from these numbers and taking into account that AFP plans to operate with 2808 bunches, jets with \( p_T \) below 100 GeV will be prescaled roughly by factor \( 10^4 \) for \( p_T(jet) > 50 \text{ GeV} \) and \( 2 \cdot 10^5 \) for \( p_T(jet) > 20 \text{ GeV} \).

Assuming no overwhelming halo background, these prescales can be significantly reduced once a trigger based on a double tag in AFP is considered. This is because the probability to have a

**Figure 5.** Probability of having double tagged event in the AFP acceptance \((0.015 < \xi < 0.15)\) without (left) and with (right) timing cut. Two contributions: from soft event with two protons (solid lines) and (at least) two events with one proton (dashed lines) in the AFP acceptance are shown. Two diffractive models from \textsc{Pythia} 8.165 were used: Schuler and Sjöstrand (\textsc{PomFlux} = 1, red lines) and MBR (\textsc{PomFlux} = 5, black lines). The cut on AFP timing (30 ps resolution) was set to 9 mm.
Figure 6. Left: non-diffractive jet event rates for three different jet $p_T$ thresholds as a function of pile-up. Right: Rates of the events with non-diffractive, single diffractive and DPE jets inside ATLAS detector and protons in both AFP arms for three different jet $p_T$ thresholds as a function of pile-up. In calculations 2808 colliding bunches (25 ns) were assumed.

proton in both AFP arms is very low at small values of pile-up, see Fig. 5 (left). Expected rates of events with ND, SD, and DPE jets inside the ATLAS detector and protons in both AFP arms are shown in Fig. 6 (right) as a function of pile-up $\mu$ for three different jet $p_T$ thresholds. Depending on the value of pile-up, these rates are from $10^4$ ($\mu \sim 0.25$) to 200 ($\mu \sim 5$) times smaller than rates without the double tag selection. For example, for $\mu = 1$ the reduction factor is of about 4000, which will allow to keep jet events with $p_T(jet) > 50$ GeV unprescaled and reduce the prescale of jets with $p_T(jet) > 20$ GeV to 10 – 50.

A.5 Timing Detectors

In order to reject the remaining background, AFP will be equipped with fast timing detectors. Since the bunch length is finite, the precise time of the interaction is unknown. Thus, only the difference between the proton arrival times $t_i$ is meaningful:

$$z_{AFP} = c(t_1 - t_2)/2,$$

where $t_1(t_2)$ is the arrival time of the first (second) proton, and $c$ the speed of light.

The longitudinal vertex position reconstructed from the AFP timing measurement can be compared to the position reconstructed in the ATLAS Inner Detector. The distribution of the difference between these two values, $\Delta z$, will be Gaussian with a width of $c\sigma(t)$ for the DPE process. For the background it will also be Gaussian, but with the width of the order of the longitudinal width of the beam spot. Timing resolution is the dominant uncertainty, since the hard vertex is, in the majority of cases, reconstructed with an order-of-magnitude better precision in the inner detector.

The spread of the $\Delta z$ distribution is much smaller for the signal than for the background. Therefore, one can use this information to distinguish between them. This can be done by requiring a small value of $\Delta z$. The value of the cut determines the background rejection and the signal efficiency. This
interplay is typically presented in the form of the ROC curve, as in Fig. 7. The background rejection is of the order of 90 % for a signal acceptance of: 0.45 (30 ps), 0.5 (20 ps), 0.63 (10 ps). Obviously, the better the timing resolution, the larger the background rejection.

![ROC curve for timing detectors with different resolution. Both protons were required to be in the AFP acceptance (0.015 < \( \xi \) < 0.15) and the mean pile-up value was set to 1.](image)

**Figure 7.** ROC curve for timing detectors with different resolution. Both protons were required to be in the AFP acceptance (0.015 < \( \xi \) < 0.15) and the mean pile-up value was set to 1.

A.6 Measurement Feasibility

A.6.1 AFP Tag Requirement

In order to estimate the background contamination of the collected signal, one needs to multiply the single and double tag probabilities by the cross sections for the relevant hard processes considering given pile-up conditions\(^{12}\). This is presented in Fig. 8 as a function of the average pile-up \( \mu \). The left plot was done for the **PYTHIA 8.165** default and the right one for **PYTHIA 8.165 MBR**. As was mentioned, backgrounds originate from three sources: i) non-diffractive jet production with two ST soft events (ND ST+ST, green line), ii) non-diffractive jet production with one DT event (ND DT, red line), and iii) single diffractive jet production with one ST event (SD ST, blue line). The background from SD jets is much smaller than ND jet production. Since for both SD ST and ND DT events only one additional soft event is required, the shape of the distributions is the same. For ND ST+ST two additional soft events are required, causing a much steeper decrease with decreasing pile-up value.

In these figures differences between the two MC models are visible. The number of double tagged events (important for \( \mu < 1 \)) is about 50% smaller for the default **PYTHIA** tune. On the other hand, this tune predicts 20% more single tagged events (important for \( \mu > 1 \)) than MBR. In addition,

\(^{12}\)It is worth noticing that the ratios of non-diffractive to single diffractive to DPE jet production are not dependent on the jet transverse momentum. Therefore, there is no need to distinguish them on the plots presenting B/S ratios or purities.
these plots indicate that the double tag requirement alone is not sufficient to separate the signal from the background, unless the pile-up value is very small, $\mu < 0.1$.

**Figure 8.** Double Pomeron Exchange Jet Production: ratio of background to signal events as a function of mean pile-up $\mu$. The probability of having minimum-bias proton in the AFP acceptance ($0.015 < \xi < 0.15$) was obtained by the PYTHIA 8.165 MC generator. Two diffractive models were used: Schuler and Sjöstrand (POMFLUX = 1, left) and MBR (POMFLUX = 5, right). Three dominant backgrounds are shown: Non-Diffractive Jets overlaid with soft event with two protons (red line), Non-Diffractive Jets overlaid with (at least) two soft events with proton (green line) and Single Diffractive Jets overlaid with (at least) one proton (blue line).

### A.6.2 AFP Timing Requirement

The selection based on timing requirement significantly improves the background rejection. This, in turn, results in much cleaner sample. The background to signal ratio after requesting a double AFP tag and timing cut assuming a 30 ps detector resolution and a $|\Delta z| < 9$ mm cut is presented in Fig. 9. The left(right) plot shows the predictions from PYTHIA 8.165 default(MBR). The contributions of the ND+ST+ST, ND+DT and SD+ST events are presented. Including the 30 ps timing detectors, an improvement of about one order of magnitude is observed.

Differences between models implemented in PYTHIA 8 are shown again in Fig. 10. For clarity, only the overall sum is plotted. The green(yellow) band reflects the 20%(50%) difference between probabilities of having a ST(DT) event.

In order to obtain a significant result, the measured signal cannot be smaller than the fluctuations of background. One of the useful variables is the purity, defined as:

$$
\text{purity} = \frac{\sigma_{\text{DPE}}}{\sigma_{\text{DPE}} + \sigma_{\text{SD}} + \sigma_{\text{ND}}},
$$

where $\sigma_X$ is a cross section for process $X$. Purity of DPE jet sample is shown in Fig. 11 (left). Without timing requirement (black line) the purity rapidly decreases from 0.6 for $\mu \sim 0.2$ to $\sim 0.01$ for $\mu = 5$. Having 30 ps AFP timing detectors installed (red lines) significantly increases the purity. In this case it decreases linearly from about 0.95 ($\mu \sim 0.2$) to about 0.4 for $\mu \sim 2$.

The statistical significance, defined as the ratio of number of signal to the square root of sum of signal and background events, is presented in Fig. 11 (right) for three different jet $p_T$ thresholds. Without the timing requirement (blacks lines), the distribution is peaked around $\mu \sim 0.6$. The inclusion
**Figure 9.** Double Pomeron Exchange Jet Production: ratio of background to signal events as a function of mean pile-up. Probability of having minimum-bias proton in the AFP acceptance ($0.015 < \xi < 0.15$) was obtained by PYTHIA 8.165 MC generator. Two diffractive models were used: Schuler and Sjöstrand (PomFlux = 1, left) and MBR (PomFlux = 5, right). Three dominating backgrounds are shown: Non-Diffractive Jets overlaid with soft event with two protons (red line), Non-Diffractive Jets overlaid with (at least) two soft events with proton (green line) and Single Diffractive Jets overlaid with (at least) one proton (blue line). The cut on AFP timing (resolution of 30 ps) was set to 9 mm.

**Figure 10.** Double Pomeron Exchange Jet Production: ratio of background to signal events as a function of mean pile-up without (left) and with (right) timing detectors. The probability of having minimum-bias proton in the AFP acceptance ($0.015 < \xi < 0.15$) was obtained by PYTHIA 8.165 MC generator. Two diffractive models were used: Schuler and Sjöstrand (PomFlux = 1) and MBR (PomFlux = 5). Green(yellow) band reflects the 20%(50%) difference of having Single(Double) Tag event in the presented models. The cut on AFP timing (resolution of 30 ps) was set to 9 mm.
of the AFP timing detectors moves the peak up to pile-up values of about 1.5 and increases the significance as well.

The DPE jets selection based on the AFP double tag and timing provides a good background rejection, assuming that the background description can be trusted. This is a safe assumption, since it is possible to obtain the background from data-driven methods, for example by selecting jets with no or a single AFP tag.

A.6.3 Single Vertex Requirement

As was shown in the previous Section, a significant measurement can be done only using the AFP double tag and timing requirements. In this Section, the possibility is considered of further increasing purity by requiring exactly one reconstructed vertex in the event. Such a cut will remove the majority of background, since in background processes at least one additional soft interaction is needed to mimic the DPE+jets signal. Of course, any signal events accompanied by pile-up will also be rejected and therefore, this cut works best when the mean pile-up is about 1.

However, not all minimum bias vertices can be reconstructed in the ATLAS detector. The main reasons of this inefficiency are: $i$ particles produced in forward direction, outside the tracker range; $ii$ ATLAS tracking detector inefficiency; and $iii$ vertex merging$^{13}$. These situations are illustrated in Fig. 12. In the left picture a signal event is shown. In the middle the principle of the cut is illustrated: non-diffractive and single diffractive backgrounds are rejected since they are accompanied by at least one soft event. In some cases, secondary particles are produced outside the coverage of the tracker or too close to the hard vertex (right figure), and such background events will not be rejected.

The probability of having a reconstructed track depends on its transverse momentum and pseudorapidity, as presented in Fig. 13. One concludes that the ATLAS inner detector becomes efficient for charged particles with transverse momentum above 100 MeV, with a reconstruction efficiency of 10% at $p_T \approx 100$ MeV. Then the efficiency grows rapidly and is about 75% for $p_T \sim 500$ MeV.

$^{13}$ The vertex merging effect occurs if soft event is produced close to the hard one.
Figure 12. Left: DPE jet production – hard vertex with two forward protons and no additional pile-up events. Middle: rejection of Non-diffractive and single diffractive backgrounds due to the presence of one soft event(s). Right: cut inefficiency: particles produced outside tracker range or too close to the hard vertex.

For studies presented in this note, for each generated charged particle the probability of being reconstructed was calculated. The exact value of the probability was set accordingly to the pseudo-rapidity at which the particle was produced and its transverse momentum, see Fig. 13. Only particles which passed this cut were considered for further analysis, effectively mimicking the real response of the ATLAS detector.

The probability to reconstruct a soft vertex when a given number of tracks is required is shown in Table 2 and Table 3 for protons with energy loss below ($\xi < 0.015$) and within ($0.015 < \xi < 0.15$) the AFP acceptance, respectively. The last column contains a weighted sum of all previous processes, taking into account their cross sections and probabilities of having a proton in a given $\xi$ range. For events with protons having $\xi < 0.015$ the probability to reconstruct minimum bias vertex is of about $30 – 40\%$. When the proton is required to be in the AFP acceptance, the probability to reconstruct a vertex increases to $80 – 87\%$. It is worth mention that these estimates are conservative, assuming the track selection as in Ref. [132]. In the reality, the selection criteria for tracks used for the vertex reconstruction are less restrictive.
Table 2. Probability of reconstructing the vertex when given number of tracks is required. The last column contains a weighted sum of all previous processes, taking into account their cross sections and probabilities of having a proton with $\xi < 0.015$ generated by PYTHIA 8.

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<th>Min. number of tracks</th>
<th>Probability</th>
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Table 3. Probability of reconstructing the vertex when given number of tracks is required. The last column contains a weighted sum of all previous processes, taking into account their cross sections and probabilities of having a proton with $0.015 < \xi < 0.15$ generated by PYTHIA 8.

<table>
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<tr>
<th>Min. number of tracks</th>
<th>Probability</th>
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<tr>
<td>5</td>
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</table>

As mentioned before, the requirement of exactly one reconstructed vertex decreases the number of signal events. This is shown in Fig. 14 for three different jet $p_T$ thresholds. The peak of the distributions is around $\mu$ slightly greater than 1. For this pile-up value the number of signal events is about 40% smaller compared the situation without the single-vertex requirement.

The cuts applied result in a significantly better purity, as is shown in Fig. 15 (left). Depending on the minimal number of tracks required to reconstruct the vertex ($n_{trk}$) and the distance below which the vertices are merged ($\Delta z$), the purity of the sample is around 0.88(0.92) for $n_{trk} \geq 2$, $\Delta z > 1$ mm ($n_{trk} \geq 4$, $\Delta z > 2$ mm) for $\mu = 1$. In addition, as seen from Fig. 15 (right), the significance is only slightly smaller than in the case without the cut.
Number of the DPE JJ events in 100 h

![Graph](image)

**Figure 14.** Number of signal events after the AFP double tag, timing and one vertex requirements.

Purity of the DPE JJ sample

![Graph](image)

**Figure 15.** Purity (left) and significance (right) of the DPE jet sample after the AFP double tag, timing and one vertex requirements.
A.6.4 Conclusions

Despite the initial difference of about four orders of magnitude in the background and signal cross sections, AFP offers the possibility to measure jets produced in Double Pomeron Exchange process at low pile-up values. A significant measurement can be done using only the AFP double tag and timing requirements. The requirement of a single reconstructed vertex increases the purity to $\sim 0.9$ for $\mu = 1$. The cut flow discussed in this section is summarised in Fig. 16. The number of bunches, $n_{\text{bunch}}$, was set to 2808, and a mean pile-up of 1 and 100 h of data collecting was assumed.

![Double Pomeron Exchange jet analysis - cut flow](image)

Figure 16. Cut flow for Double Pomeron Exchange jet analysis. After the jet selection ($p_T > 50$ GeV) the following cuts were required: double tag in AFP, timing cut (30 ps resolution) and one reconstructed vertex. The colour bands represents different cut efficiencies, accordingly to uncertainty of having forward proton in soft event and soft vertex reconstruction conditions.

It is worth stressing that the colour bands represent different cut possibilities rather than an uncertainty. At the time of the DPE measurement, the probability of having a forward proton in the AFP acceptance will be measured by CMS/TOTEM or AFP detectors, so Monte Carlo generators will be tuned. Also the vertex reconstruction efficiency will be known accordingly to the ATLAS Inner Detector performance.

A.7 Comparison with ATLAS Full Simulation

In order to directly compare the output from the stand-alone studies and the ATLAS full simulation, see Sect. 4.3, the cross section after a given requirement was calculated. The results are summarised in Fig. 17 and the differences between cut definitions for stand-alone and full simulation studies are explained in Table 4. From these results one deducts that the main differences result from different generator predictions and jet reconstruction algorithms rather than from pile-up treatment or detector description. Looking into the final numbers, one can see that the purity of the sample remains the same whereas the significance is a factor 2 smaller with the full simulation.
Table 4. Differences between the cuts used in stand-alone and full simulation studies.

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<th>Requirement</th>
<th>Stand-alone analysis</th>
<th>ATLAS full simulation</th>
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<td>$p_T &gt; 20$ GeV</td>
<td>FPMC generator, Hera Fit 2006b, cone R = 0.7, hadron level</td>
<td>HERWIG++ generator, Hera Fit 2007, AntiKt R = 0.4, calorimeter clusters</td>
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<td>double tag</td>
<td>$0.015 &lt; \xi &lt; 0.15$</td>
<td>full forward region and AFP simulation, exactly one reconstructed track in each AFP station</td>
</tr>
<tr>
<td>timing eff.</td>
<td>factor from AFP stand-alone simulation applied</td>
<td>full simulation results</td>
</tr>
<tr>
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<td>Gaussian smearing of 15 ps (6 mm cut)</td>
<td>time and vertex reconstruction (6 mm cut)</td>
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<td>one vertex</td>
<td>approximate vertex reconstruction efficiency, merging distance cut &lt; 2 mm</td>
<td>ATLAS vertex reconstruction, merging distance cut &lt; 1.5 mm</td>
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Figure 17. Cut flow for DPE jet study with stand-alone analysis and full ATLAS+AFP simulation.
Appendix B  LHC Optics and Proton Trajectories from IP1

The beam optics between point 1 and the AFP detectors determines the size of the beam at the AFP detectors. The optics also determines the trajectories of protons that have $\xi > 0$ and have a range of $t$ and $\phi$ values as they are produced in collisions in the ATLAS interaction region. Together, the specific optics and the resulting trajectories of forward protons determine the measurement capabilities of AFP. In the following sections the various optical scenarios, their stability, and the calculated proton trajectories are discussed in detail.

B.1  LHC Optics around IP1

The beam size at the IP1, for various LHC optics and energies, is listed in Table 5. For the optics considered, the beam at the IP is symmetric in the $(x, y)$ plane. In Table 6 the values of the beam divergence for various $\beta^*$ optics modes, proton energies and emittances are summarised. All these results were obtained using the MAD-X program [51, 52] and the relevant LHC optics files [38].

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</tbody>
</table>

The beam size at the AFP detector location determines the minimum distance at which the detectors can be safely inserted. Therefore, this knowledge is important for the event simulations and data analysis, as it defines the kinematic regions that are accessible for given optic settings. These results are listed in Tables 7 and 8. It is worth recalling that $\text{beam1}$ and $\text{beam2}$ are not identical, but the differences in their transverse size at the location of forward detectors are negligible.

B.2  Proton Trajectories

Proton trajectories are usually described in a curvilinear, right-handed coordinate system $(x, y, s)$. The local $s$-axis is tangential to the reference orbit at a given point of the beam trajectory. The two other axes are perpendicular to the reference orbit and are labelled $x$ (in the bending plane) and $y$ (perpendicular to the bending plane).

The trajectories in the nominal orbit trajectory reference frame for various LHC optics and different proton energies are shown in Fig. 18. It can be observed that the proton deflection in the $x$-axis
Table 7. LHC beam transverse size in $x$ at the AFP stations for various $\beta^*$ optics modes, proton energies and emittances.

<table>
<thead>
<tr>
<th>$\beta^*$ [m]</th>
<th>beam transverse size in $x$ [mm]</th>
<th>$E_{\text{beam}} = 3500$ GeV</th>
<th>$E_{\text{beam}} = 4000$ GeV</th>
<th>$E_{\text{beam}} = 7000$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\epsilon = 2$ $\mu$m-rad</td>
<td>$\epsilon = 3.75$ $\mu$m-rad</td>
<td>$\epsilon = 2$ $\mu$m-rad</td>
<td>$\epsilon = 3.75$ $\mu$m-rad</td>
</tr>
<tr>
<td>0.55</td>
<td>0.20 0.27 0.19 0.26 0.14 0.19</td>
<td>0.61 0.83 0.57 0.78 0.43 0.59</td>
<td>0.79 1.08 0.74 1.01 0.56 0.76</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>1.08 0.20 0.13 0.18 0.10 0.14</td>
<td>0.93 0.63 0.46 0.59 0.36 0.49</td>
<td>0.67 0.92 0.63 0.86 0.48 0.65</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.67 0.92 0.63 0.86 0.48 0.65</td>
<td>0.55 0.76 0.52 0.71 0.39 0.54</td>
<td>0.19 0.26 0.18 0.24 0.13 0.18</td>
<td></td>
</tr>
</tbody>
</table>

Table 8. LHC beam transverse size in $y$ at the AFP stations for various $\beta^*$ optics modes, proton energies and emittances.

<table>
<thead>
<tr>
<th>$\beta^*$ [m]</th>
<th>beam transverse size in $y$ [mm]</th>
<th>$E_{\text{beam}} = 3500$ GeV</th>
<th>$E_{\text{beam}} = 4000$ GeV</th>
<th>$E_{\text{beam}} = 7000$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\epsilon = 2$ $\mu$m-rad</td>
<td>$\epsilon = 3.75$ $\mu$m-rad</td>
<td>$\epsilon = 2$ $\mu$m-rad</td>
<td>$\epsilon = 3.75$ $\mu$m-rad</td>
</tr>
<tr>
<td>0.55</td>
<td>0.49 0.67 0.46 0.63 0.35 0.47</td>
<td>0.46 0.63 0.43 0.59 0.33 0.45</td>
<td>0.16 0.22 0.15 0.21 0.12 0.16</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>0.46 0.63 0.43 0.59 0.33 0.45</td>
<td>0.55 0.76 0.52 0.71 0.39 0.54</td>
<td>0.19 0.26 0.18 0.24 0.13 0.18</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.16 0.22 0.15 0.21 0.12 0.16</td>
<td>0.55 0.76 0.52 0.71 0.39 0.54</td>
<td>0.19 0.26 0.18 0.24 0.13 0.18</td>
<td></td>
</tr>
</tbody>
</table>
direction (outside the LHC ring) becomes larger with decreasing proton energy i.e. with increasing proton relative energy loss:

$$\xi = 1 - \frac{E_{\text{proton}}}{E_{\text{beam}}}.$$ 

One observes that when the trajectory deflection is large enough (e.g. trajectory with $\xi = 0.16$) the proton interacts with the LHC structures and is lost. One also notes that the trajectory reaches a maximum displacement from the nominal orbit at distances between 160 m and 200 m.

As seen in Fig. 19, the introduction of a non-zero crossing angle causes the proton trajectories to be deflected in the quadrupole triplet. In consequence, the proton position at the detector location in the $(y,z)$ plane depends on its energy.

The trajectories of protons scattered with the nominal energy and different values of the $p_x$ momentum component are plotted in Fig. 20 for collision and high-$\beta^*$ optics. These trajectories depend on the beam energy, therefore all plots are done for $\sqrt{s} = 7$ and 14 TeV. As can be seen the spread decreases with increasing $\sqrt{s}$.

In all the optics presented, the trajectories are focused to a point behind the AFP detector location. In the case of the collision and $\beta^* = 90$ m optics the maximum deviation from the nominal orbit

---

**Figure 18.** Energy dependence of the proton trajectory in the $(x,s)$ plane for various LHC optics. Protons were generated at $(0,0,0)$ with transverse momentum $p_T = 0$. The crossing angle in the horizontal plane ($\theta_c$) was set to 142.5 µrad for the collision optics and to zero for the high-$\beta^*$ optics. Trajectories are plotted for $\sqrt{s} = 7$ TeV, but are valid also for other energies as they scale with $\sqrt{s}$. 

---

**Appendix B: LHC Optics and Proton Trajectories from IP1**

_B–19_
Figure 19. Energy dependence of the proton trajectory in \((y, s)\) plane for various LHC optics. Protons were generated at \((0, 0, 0)\) with transverse momentum \(p_T = 0\). The crossing angle in the horizontal plane \((\theta_c)\) was set to 142.5 \(\mu\)rad for the collision optics and to 50 \(\mu\)rad \(\beta^* = 90\) m. Trajectories were plotted for \(\sqrt{s} = 7\) TeV, but are valid also for other energies as they scale with \(\sqrt{s}\).

Figure 20. Transverse momentum dependence of the proton trajectory for various LHC optics for \(\sqrt{s} = 7\) and 14 TeV. Protons were generated at \((0, 0, 0)\) with different \(p_T\) momenta. The crossing angle in the horizontal plane \((\theta_c)\) is set to 142.5 \(\mu\)rad for the collision optics and equal to zero for the high-\(\beta^*\) ones.
is in the Q3 quadrupole. For $\beta^* = 1000$ m this maximum is around the Q5 and Q4 magnets. It may be noted that this deviation increases with increasing value of the betatron function.

The proton behaviour at the nominal energy and different values of the $p_y$ momentum component for various LHC optics is shown in Fig. 21. It should be stressed that the actual shape of the beam trajectory depends on its energy.

**Figure 21.** Transverse momentum dependence of the proton trajectory for various LHC optics for $\sqrt{s} = 7$ and 14 TeV. Protons were generated at $(0, 0, 0)$ with different $p_y$ momenta. The crossing angle in the horizontal plane ($\theta_c$) is set to 142.5 µrad for the collision optics and equal to zero for the high-$\beta^*$ ones.

### B.3 Transport Parametrisation

At the interaction point proton kinematics can be fully described by six variables: position $(x_{IP}, y_{IP}, z_{IP})$ and momentum $(p_{xIP}, p_{yIP}, p_{zIP})$. The later can be expressed in terms of the relative energy loss ($\xi = 1 - \frac{E_{\text{proton}}}{E_{\text{beam}}}$) and elevation angles ($\theta_{IP} = p_{yIP}/p_{xIP}, \phi_{IP} = p_{zIP}/p_{xIP}$). Each AFP station can measure the position of the proton trajectory in the $(x, y)$ plane. This allows us to calculate the elevation angle of a proton trajectory $x' = \tan(\frac{\xi - x_{IP}}{y_{IP}})$, where $x_{IP}$ is the proton trajectory position in the near(far) AFP detector and $s_{(1, 2)}$ is the location of the AFP station along the LHC. The equation for $y'$ is similar. For simplicity, in this Section the symbol $\zeta$ will be used to represent $x, y, x'$ and $y'$.

The LHC magnet structure in the vicinity of the ATLAS detector is described by the drift spaces, the dipole and the quadrupole magnets (see Sect. 3.1). Therefore, a linear transport approximation can be applied to describe the scattered proton transport [40]. Following Ref. [42], the transport can be effectively described by the following equations:

$$\begin{align*}
\zeta &= A_x x + B_y y + C_z z + D_x z x + E_z z y + F_x y x + G_z z y x + H_y y x y + \ldots
\end{align*}$$

#### Appendix B: LHC Optics and Proton Trajectories from IP1

**B–21**
where \( A_\xi, \ldots, H_\xi \) are polynomials in the relative energy loss (\( \xi \)) of rank \( k_{A_\xi}, \ldots, k_{H_\xi} \):

\[
A_\xi = \sum_{n=0}^{k_{A_\xi}} a_{\xi,n} \cdot \xi^n, \quad \ldots, \quad H_\xi = \sum_{n=0}^{k_{H_\xi}} h_{\xi,n} \cdot \xi^n.
\]

The absence of magnets with multipole field expansion moments higher than the quadrupole terms implies that the horizontal trajectory position (elevation angle) does not depend on the vertical momentum component or the vertical vertex coordinate, and vice versa. For the AFP detectors and \( \beta^* = 0.55 \) m optics, a sufficient description of the scattered proton transport is given by:

\[
\begin{align*}
x &= \sum_{n=0}^{k_{A_x}} a_{x,n} \cdot \xi^n + \sum_{n=0}^{k_{B_x}} b_{x,n} \cdot \xi^n \cdot x_{IP} + \sum_{n=0}^{k_{E_x}} e_{x,n} \cdot \xi^n \cdot x'_{IP}, \\
y &= \sum_{n=0}^{k_{A_y}} a_{y,n} \cdot \xi^n + \sum_{n=0}^{k_{C_y}} c_{y,n} \cdot \xi^n \cdot y_{IP} + \sum_{n=0}^{k_{F_y}} f_{y,n} \cdot \xi^n \cdot y'_{IP}, \\
x' &= \sum_{n=0}^{k_{A_x'}} a_{x',n} \cdot \xi^n + \sum_{n=0}^{k_{B_x'}} b_{x',n} \cdot \xi^n \cdot x_{IP} + \sum_{n=0}^{k_{E_x'}} e_{x',n} \cdot \xi^n \cdot x'_{IP}, \\
y' &= \sum_{n=0}^{k_{A_y'}} a_{y',n} \cdot \xi^n + \sum_{n=0}^{k_{C_y'}} c_{y',n} \cdot \xi^n \cdot y_{IP} + \sum_{n=0}^{k_{F_y'}} f_{y',n} \cdot \xi^n \cdot y'_{IP}.
\end{align*}
\]
Appendix C  R & D for AFP Upgrades

In order to prepare for participation by AFP in standard running at high average pile-up during Run 3, the AFP R&D program focuses primarily on background rejection from further improvements in the proton Time-of-Flight, both by increased pixellation, and by improved timing resolution. This R&D program is not part of this Technical Design Report for the AFP detector in Run 2, but because it is of high interest to the future of forward physics at the LHC, it is described in the next two sections of this Appendix.

C.1 R & D on Fast Diamond Detectors

Diamond detectors, an alternative solution to the quartz-based Cherenkov timing detector in run III, are investigated by three INFN groups from Bologna, Lecce, and Roma Tor-Vergata. Several advantages are foreseen by a diamond sensor solution in terms of radiation hardness, granularity, trigger capability, and compactness.

Diamond detectors produced by Chemical Vapor Deposition (CVD) have a potential for high temporal resolution due to their intrinsic fast response to ionizing radiation (less than 100 ps rise time). Diamond detectors are successfully used in measurements of time-of-flight in nuclear physics for medium-heavy ions, where the signal intensity is high, obtaining a temporal resolution of about 28 ps [133].

Assuming a readout electronics chain capable to correct for time walk and with a negligible time digitization error (employing, for example, very fast constant fraction discriminators and TDCs, for on-line corrections, or very fast waveform digitizers, for off-line corrections) one estimates the achievable time resolution using the formula [134]:

$$\Delta t = \frac{t_{\text{rise}}}{S/N},$$  \hspace{1cm} (7)

where $t_{\text{rise}}$ is the signal rise time, approximately given by the maximum of the charge collection time and the electronics rise-time, $S$ is the collected charge in diamond due to a passing ionizing particle, and $N$ is the electronic noise, which for diamond is entirely due to the front-end noise, because the leakage current is negligible. For best time resolution it is necessary to minimize the signal rise time, minimize noise and maximize the signal. These goals require the development of low-noise and high-speed front-end electronics and the use of innovative geometric and circuit designs for the diamond sensors.

In our application the limiting factor is the charge collected for a minimum ionizing particle (MIP) which in diamond is quite small. We expect about 3600 e$^-$ signal in diamond for a MIP charge collection distance of about 100 µm. It is worth mentioning that the relativistic rise in ionization energy loss for a 7 TeV proton compared to a 1 GeV proton should give a 30% signal increase. Considering a diamond sensor with a 300 µm charge collection distance, we expect a signal of about 10800 e$^-$ and a collection time of about 3 ns (the drift velocity for both free charge carriers is about 100 µm/1ns in saturated conditions). Assuming an electronics noise of about 500 e$^-$ and an electronic rise-time negligible with respect to the sensor collection time, the estimated time resolution using equation 7 is about 140 ps. This is typically the time resolution reported in the literature for MIP detection with diamond [133].

Several improvements are possible with respect to the results reported in the literature and should allow a resolution goal of 30 ps resolution per detector plane:

• An increase in the signal is obtained by tilting the detector with respect to the tracks. In a test beam in October 2012 at CERN this effect was clearly observed as a steady increase of the
average signal with tilt angle. For the most extreme tilt, i.e. the sensor plane parallel to the track, the measured signal-to-noise ratio was measured to be about 130.

- A reduction of collection time is possible by using thinner diamond sensors while preserving the signal size using a sandwich configuration. This is currently under investigation (see Multi-Layer-Crystal-Device concept reported in Ref. [135]). Another method for reducing collection time without affecting signal size might be possible by using the 3D diamond sensors developed by the RD42 collaboration [136]. These “3D” diamond sensors are constructed by forming columnar electrodes in the diamond bulk with the use of femtosecond laser pulses. In this way graphite pillars of about 10 µm in diameter with a pitch of 50 µm can be made in sensors 500 µm thick. If the “3D” technology will be proven radiation-hard and reliable, important gains in collection time (proportional to the pillar pitch) and in the signal amplitude (proportional to the diamond sensor thickness) are possible.

- A decrease in electronics noise by a factor of two or three with an equivalent rise-time less than the diamond collection time. The group of INFN Roma Tor-Vergata has already developed amplifier prototypes with such performance with SiGe transistors. Based on this initial success, a VLSI chip was submitted with 8 amplifier channels using SiGe technology.

These ideas are strongly pursued by the different groups and any progress made is going to be included in the baseline design presented below. To make the diamond detector solution competitive with the quartz Cherenkov detector for run III, we must indeed reach better performance and in a cost-effective manner.

![Diamond Detector Layout](image)

**Figure 22.** a) Grazing diamond detector layout with eight adjacent layers parallel to the incident particles. b) Area covered in the $x−y$ plane for the diamond detector baseline layout.

### C.1.1 Baseline Detector

For the baseline a conservative approach is proposed that could be built with existing technology. In order to boost the signal without affecting the noise and collection time, several diamond detector layers are stacked together such that the layer planes are parallel to the incident particles, see Fig. 22a. The planar geometry allows the use of both types of charge carriers in saturation conditions (electric field higher than 1 V/µm) where the output signal is less sensitive to the charge fluctuations intrinsic to the ionization process. Such a stacked configuration can be built with diamond sensors because the electrode thickness is at most a few hundred nm, resulting in a negligible dead area.
In this proposal we consider only polycrystalline diamond for which 6 or 8 inch wafers are commercially available, in contrast to mono-crystalline diamond where the size is limited to about 4.5x4.5 mm\(^2\). For a MIP incident orthogonal to the sensors, i.e. particles passing parallel to the drift direction of the free charge carriers, the induced signal is by about 36 e\(^-\)/\(\mu\)m times the charge collection distance. Instead, for MIP particles incident parallel to the sensors, i.e. particles passing orthogonal to the drift direction of the charge carriers, the induced signal is boosted by the ratio \(L/d\), where \(L\) is the length and \(d\) the thickness of the sensor. For polycrystalline diamond this ratio can be as large as 50, with a corresponding improvement in time resolution improvement down to tens of ps.

A further advantage of the grazing diamond geometry is the reduced signals produced by non-parallel secondary particle tracks, which now remain below the electronic threshold. In fact, secondaries produced in interactions with the detector material cross the detector layers with an incident angle different from the primary particles, see Fig. 22a.

The diamond detector is aimed for standard low beta runs where the signal region in the \(x-y\) plane is expected to have a rectangular shape of about \(15(x) \times 4(y)\) mm\(^2\) rotated by about 20 degrees above the \(x\) direction in AFP. Indeed, diamond sensors are suitable to cover an area of unusual shape and it is possible to envisage a detector layout tailored to the expected signal region such as the one proposed in Fig. 22b. An adapted design presents material cost savings and reduces the number of electronics channels, making a diamond-based time-of-flight detector more affordable without compromising the final performance. Using polycrystalline diamond sensors of \(20 \times 20\) mm\(^2\) area and 0.5 mm thickness, the proposed design needs 8 such sensors per time-of-flight detector, i.e. a total of 16 diamond sensors for AFP. In order to keep the detector capacitance at the input of the front-end below 2 pF, the readout electrode is formed by 20 strips 20 mm long and 1 mm pitch. With this readout granularity the number of front-end channels per sensor is 20, for a total of 320 channels for an 8-layer detector.

A drastic reduction in channel counting is possible with the use of the INFN Roma Tor-Vergata SiGe front-end electronics, which has an intrinsic noise largely independent from the sensor capacitance [135]. However, it can be argued that the channel count is likely to be determined by considerations of occupancy and pile-up backgrounds in the real environment at the LHC.

With the sensor geometry chosen, a particle crossing the sensor with a grazing angle gives a signal about 40 times bigger than the signal expected at normal incidence. In order to profit from the huge boost in signal, particular care must be taken to avoid signal degradation in the electronics chain. Furthermore, the grazing geometry has an important impact in terms of the total material budget. Along the primary particle direction the thickness is about 20 mm, which is about 16% of a radiation length and 8.2% of nuclear interaction length.

C.1.2 Beam Test Results

Experimental studies were done at two test beams to investigate the best time resolution achievable with the grazing diamond concept.

The first beam test took place at DESY at the TB 22 beam line, which provides electrons with energies of about 5 GeV with small divergence. The second beam test took place at CERN at the H6 beam line, which provides pions with energies of about 120 GeV. The experimental set-up was similar in both cases and is shown in Fig. 23 for the DESY test beam. The test consisted in the measurement of the time-of-flight of particles with two polycrystalline diamond detectors mounted parallel to the beam, extracting the time resolution for a MIP-like particle crossing the sensors along their long dimension.

Two polycrystalline diamond detectors were used, the first providing a start signal and the second the stop signal. The diamond detectors consisted of \(10 \times 10 \times 0.5\) mm\(^3\) sensors with four metalized electrode strips 6.5 mm in length and with 1.5 mm pitch surrounded by a square guard ‘ring’ of 8 mm
on a side, and a metalized electrode pad on the opposite sensor side. The strip electrodes and the back-side pads were connected to SMA connectors and the signals were directly amplified by fast charge amplifiers with 100 MHz bandwidth and a 8 mV/fC gain (CIVIDEC C6 [137]) or by broadband amplifiers of 2 GHz bandwidth, voltage gain 100 and input terminated at 50 Ω (CIVIDEC C2). The high voltage was applied at the electrode pads. The analog signals were digitized by a 17-channel fast 20 GS/s digitizer with 12 bit resolution (CAEN DT5742). The digitized waveforms were analyzed off-line. The two pad signals from the two detectors were discriminated by two constant fraction discriminators and put in temporal coincidence to provide a trigger.

In the DESY beam test the 5 GeV electrons are expected to suffer significant multiple scattering because they cross about 2 cm of diamond material and 5 mm of aluminum of the detector housings. In addition, electrons scattered from surrounding material could create fake triggers but with worse time resolution because of their different path length from the non-scattered electrons. To mitigate these effects the DESY pixel tracking telescope was used to reconstruct and select good tracks to clean up the timing data. The DESY pixel telescope was fully supported by DESY and consisted of two stations of three planes of MIMOSA monolithic pixel sensors each.

The measured time resolution was improved as expected [138]. In fact, the more parallel the tracks selected were with respect to the two diamond detectors, the better the measured time resolution. Furthermore, a mild dependence of the time-of-flight measured was observed on the vertical distance between the track and collecting electrodes. After correcting for this systematic effect, the distribution of the time-of-flight between the two detectors is depicted in Fig. 24a, giving a time resolution of $93 \pm 24$ ps, as measured from the standard deviation of the time-of-flight distribution divided by $\sqrt{2}$, assuming the time resolution of the two detectors to be equal.

In the CERN beam test the 120 GeV pion tracks are parallel but secondary particles are expected to be produced for a non-negligible fraction of events. An external tracking telescope was not available to measure track multiplicity and the track impact position on the detectors. The time-of-flight distribution is shown in Fig. 24b for events giving signals in all four channels of both detectors in order to select tracks that are parallel to the sensors. The time-of-flight distribution has two clearly visible narrow peaks but their origin is still not understood. Nevertheless, again taking the standard deviation of the distribution divided by $\sqrt{2}$, the time resolution per detector is about 61 ps.
C.1.3 Diamond Procurement and Cost

Currently, two vendors are capable of manufacturing high-quality diamond sensors: a UK vendor (Element Six Ldt.) and a US vendor (II-VI infrared), both qualified by the RD42 collaboration [139]. These vendors will deliver $2 \times 2 \text{ cm}^2$ diamond samples with a typical charge collection distance of about 300 µm. The cost of such samples is about 5 kEuros per sample and thus the baseline design cost amounts to about 80 kEuros.

C.2 Fast Multi-Channel Sampling Chip R & D (SAMPIC) for Fast Timing

At the higher luminosity of the LHC in phase II, starting in 2019, higher pixelisation of the timing detector will be required in order to fight the large pile-up environment [140]. For this reason, a R&D phase to develop timing detector developments based on Silicon sensors [141], and diamonds (see Sect. C.1 has started. This R&D aims at installing a prototype of such a high-pixellation time-of-flight detector at the LHC in the TOTEM experiment as soon as they are available.

In parallel to the sensor R&D, a new timing readout chip has been developed in Saclay, which is the subject of this section. It uses waveform sampling to reach the best possible timing resolution: single-threshold and multi-threshold circuits are much more affected by the negative effects of time walk and jitter on the time resolution. The goal of this chip called SAMPIC [142, 143, 144, 145] is to obtain sub-10 ps timing resolution, 1 GHz input bandwidth, zero dead time at the LHC, and data taking at up to 10.2 Gigasamples per second. The waveform TDC is a new concept that can reconstruct a signal by very fast sampling. Inside SAMPIC, the timing measurement is performed in a three-step hierarchy: (i) a coarse time determination using a time-stamp Gray Counter (6 ns step), (ii) followed by a medium-resolution time determination when the delay-line oscillator loop is locked on the clock to define the region of interest (150 ps step), and (iii) a fine time determination where sampling is done in the region of interest (a few ps resolution). The parameters of the SAMPIC chip are given in Fig. 25.

To test the ultimate resolution of SAMPIC under ideal conditions, an extensive testing campaign has been carried out on the chip itself. Fig. 26 describes the results on the time difference resolution as a function of the signal amplitude obtained by splitting a signal into two copies, and delaying the second copy by 4.73 ns. After calibration, we obtain a resolution on the time difference that is better...
**Table 1. Parameters of the SAMPIC chip.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>AMS CMOS 0.18μm</td>
</tr>
<tr>
<td>Number of channels</td>
<td>16</td>
</tr>
<tr>
<td>Power consumption</td>
<td>180 (1.8V supply) mW</td>
</tr>
<tr>
<td>Discriminator noise</td>
<td>2 mVrms</td>
</tr>
<tr>
<td>SCA depth</td>
<td>64 Cells</td>
</tr>
<tr>
<td>Sampling Speed</td>
<td>&lt;3-8.4 (10.2 for 8 channels only) GSPS</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1.6 GHz</td>
</tr>
<tr>
<td>Range (Unipolar)</td>
<td>1 V</td>
</tr>
<tr>
<td>ADC resolution</td>
<td>8 to 11 (trade-off time/resolution) bit</td>
</tr>
<tr>
<td>SCA noise</td>
<td>&lt;1.3 mVrms</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>9.6 Bit rms</td>
</tr>
<tr>
<td>Conversion time</td>
<td>0.2-1.6 (8bit-11bit) ps</td>
</tr>
<tr>
<td>Readout time (can be probably be /2 )</td>
<td>25 + 6.2/sample ns</td>
</tr>
<tr>
<td>Time precision before correction</td>
<td>15 ps rms</td>
</tr>
<tr>
<td>Time precision after timing INL correction</td>
<td>&lt; 5 ps rms</td>
</tr>
</tbody>
</table>

**Figure 25.** Parameters of the SAMPIC chip.

**Figure 26.** Resolution of the SAMPIC chip. The resolution on the time difference between two electronic channels was measured to be about 5 ps for a signal amplitude of 500 mV or higher, i.e. a single-channel resolution of about 3 ps.

than 5 ps, which indicates a single-channel resolution of about 3 ps for a signal amplitude larger than about 500 mV.

SAMPIC has also been tested in combination with a new type of silicon detector, the so called Ultra-Fast Silicon Detector [146], that employs internal multiplication to achieve a larger signal, well suited for timing applications. Employing a split 1064 nm laser beam, tuned to reproduce the signal amplitude typical of a minimum ionizing particle, pairs of sensors were illuminated and the jitter of each sensor was measured with SAMPIC. Fig. 27 shows the result of this test: a promising resolution of 30 ps per channel.

Beam tests were performed in November 2014 to further test SAMPIC together with diamond and silicon detectors. Future improvements of the SAMPIC chip include dead time reduction using the ping-pong method.

The cost of the SAMPIC readout is estimated to be of the order of $10/channel, a considerable improvement to the present cost of a few $1000 per channel, allowing the use of the chip in medical applications such as PET imaging detectors. The holy grail of an imaging 10 ps PET detector now seems feasible: with a resolution better than 20 ps, image reconstruction is no longer necessary and real-time image formation becomes possible.
Figure 27. Preliminary results on timing resolution using SAMPIC readout of a silicon detector excited by a laser pulse.
## Appendix D  ATLAS AFP Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analogue-to-Digital Converter</td>
</tr>
<tr>
<td>AFP</td>
<td>ATLAS Forward Proton (detectors)</td>
</tr>
<tr>
<td>ALFA</td>
<td>Absolute Luminosity For ATLAS (detector)</td>
</tr>
<tr>
<td>ALD</td>
<td>Atomic Layer Deposition</td>
</tr>
<tr>
<td>AOD</td>
<td>Analysis Object Data (event data file format)</td>
</tr>
<tr>
<td>ATP</td>
<td>ATLAS Proton Timing (detector)</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
</tr>
<tr>
<td>ATCA</td>
<td>Advanced Telecommunications Computing Architecture</td>
</tr>
<tr>
<td>ATLAS</td>
<td>A Toroidal LHC ApparatuS (collaboration/detector)</td>
</tr>
<tr>
<td>AWG</td>
<td>American Wire Gauge</td>
</tr>
<tr>
<td>BBIM</td>
<td>Building Block Interlock and Monitoring</td>
</tr>
<tr>
<td>BFKL</td>
<td>Baltisky-Fadin-Kuraev-Lipatov (model)</td>
</tr>
<tr>
<td>BC</td>
<td>Bunch Crossing</td>
</tr>
<tr>
<td>BGA</td>
<td>Ball Grid Array</td>
</tr>
<tr>
<td>BLM</td>
<td>Beam loss monitor (radiation detector)</td>
</tr>
<tr>
<td>BMC</td>
<td>Bi-phase Mark Coding</td>
</tr>
<tr>
<td>BPM</td>
<td>Beam position monitor</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network (LAN standard)</td>
</tr>
<tr>
<td>CEP</td>
<td>Central Exclusive Production (process)</td>
</tr>
<tr>
<td>CERN</td>
<td>European Organization for Nuclear Research</td>
</tr>
<tr>
<td>CFD</td>
<td>Constant-Fraction Discriminator</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Control (machining)</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>CTP</td>
<td>Central Trigger Processor</td>
</tr>
<tr>
<td>D3PD</td>
<td>Derived Physics Data (file/format)</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analogue Converter</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition (system)</td>
</tr>
<tr>
<td>DB</td>
<td>DataBase</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DCS</td>
<td>Detector Control System</td>
</tr>
<tr>
<td>DD</td>
<td>Double Diffraction</td>
</tr>
<tr>
<td>dPDF</td>
<td>diffractive Parton Distribution Function</td>
</tr>
<tr>
<td>DPE</td>
<td>Double Pomeron Exchange</td>
</tr>
<tr>
<td>DPhE</td>
<td>Double Photon Exchange</td>
</tr>
<tr>
<td>E-PHEMT</td>
<td>Enhancement Mode Pseudomorphic High Electron Mobility Transistor</td>
</tr>
<tr>
<td>ECR</td>
<td>Event Counter Reset</td>
</tr>
<tr>
<td>EDM</td>
<td>Electric Discharge Machining</td>
</tr>
<tr>
<td>EDMS</td>
<td>Engineering Data Management System</td>
</tr>
<tr>
<td>ELM</td>
<td>Embedded Local Monitor Board</td>
</tr>
<tr>
<td>FE</td>
<td>Front-End</td>
</tr>
<tr>
<td>FE-I4</td>
<td>Front End ASIC Iteration 4</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
</tr>
<tr>
<td>FSM</td>
<td>Finite State Machine</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>HBP</td>
<td>Hamburg beam pipe (beam interface)</td>
</tr>
<tr>
<td>HBT</td>
<td>Heterojunction Bipolar Transistor</td>
</tr>
<tr>
<td>HEP</td>
<td>High Energy Physics</td>
</tr>
<tr>
<td>HERA</td>
<td>Hadron Elektron Ring Anlage ($\mu - \mu$ Collider)</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>High Luminosity LHC</td>
</tr>
<tr>
<td>HPTDC</td>
<td>High Precision TDC (ASIC/module)</td>
</tr>
<tr>
<td>HSIO</td>
<td>High Speed I/O</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>IB</td>
<td>Institute Board</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>IBL</td>
<td>Insertable B layer</td>
</tr>
<tr>
<td>JCOM</td>
<td>Joint Control Project</td>
</tr>
<tr>
<td>JGJ</td>
<td>Jet-Gap-Jet (topology)</td>
</tr>
<tr>
<td>KIT</td>
<td>Karlsruhe Institute of Technology (irradiation facility)</td>
</tr>
<tr>
<td>KMR</td>
<td>Khoze-Martin-Ryskin (model)</td>
</tr>
<tr>
<td>LAN</td>
<td>Large Area Network</td>
</tr>
<tr>
<td>LANSCE</td>
<td>Los Alamos Neutron Science Center</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
</tr>
<tr>
<td>LQbar</td>
<td>L-shaped QUARTIC bar</td>
</tr>
<tr>
<td>LSB</td>
<td>Least Significant Bit</td>
</tr>
<tr>
<td>LVDS</td>
<td>Low-Voltage Differential Signalling</td>
</tr>
</tbody>
</table>
Appendix D: ATLAS AFP Acronyms