The design of the AFP detector tracking system

2nd Workshop on Detectors for Forward Physics at LHC

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(on behalf of the AFP Collaboration)

29 May 2014
Outline

- Detector requirements
- Tracking sensors / mechanics
- Integration with Roman Pot

- Geant4 simulation results
  - Tracking resolution
  - Pile-up robustness
  - Track reconstruction efficiency
Main purpose: measurement of the trajectory of beam collision deflected protons coming from the ATLAS IP
  - Small dead inactive region on side close to beam
  - Very good spatial resolution (~10 µm)

Radiation hardness requirements:
  - Cope with non-uniform irradiation profile
  - Estimated dose: ~3x10^{15} neq/cm^2 (100/fb exposure)
  - For AFP + Run 2: factor of 1000 lower with dedicated low-µ runs (100/pb)
AFP Tracking Sensors

- **3D Silicon Sensors for IBL** - the design is suitable for AFP as well (size of 20 x 20 mm is ideal for AFP!)
- **CNM 3D Sensors:**
  - Column-like electrodes penetrate substrate
  - Slim edge (eg with standard diamond-saw cut)
  - Low bias voltage needed
  - FEI4B read-out chip (336 x 80 pixels)
Edge-slimming

- AFP prototypes can be slimed to \( \approx 100 \ \mu m \)
  (plot: IBL device slimmed to 120 \( \mu m \))

Non-uniform irradiation (IBL devices)

- Device irradiated at IRRAD1 (CERN) to \( 4 \times 10^{15} \) neq/cm\(^2\)
- Beam tests at CERN Aug 2012 (SPS) with FEI4A device
- **Efficiency: 98.0%** (irradiated side)
- Tilting the tracker planes: \( \approx 1\% \) increase in the efficiency (for tilting angle 13 deg)

Tracker could be installed inside **roman pot** - either alone or together with Time of Flight detector

- Cooling down the detector (-10°C): use relatively cheap air-cooling system based on Vortex tubes (baseline)
- Simple design with only few mechanical parts

First design version (considered for integration with HBP)

P. Sicho (Prague)
Integration with Roman Pot

- Enough space to accommodate both ToF and Si tracker in the same pot - if both detectors are “slightly” redesigned (size reduction)
  - Tracker should fit in a box of 55 x 75 x 70 mm (with recent ToF version)
  - Heat could be removed via PGS foils (Pyrolytic Graphite Foil) which would be attached to heat exchanger

P. Sicho (Prague)
AFP Geant4 Simulation

- Full Geant4 simulation of **Forward Region + AFP Stations** in the ATLAS Athena framework:
  - **Geo Models** of: Forward Region, Hamburg Beam Pipes (HBPs), AFP Silicon (SiD) and Timing (TD) Detectors
  - Forward Region simulation (for the 1st time)
    - Magnetic field specification
    - Contains beam pipe, collimators and beamscreens models
    - Plan to study the effect of dead material, starting from the closest (most affecting) regions
  - Description of **Sensitive Detectors** (+ data models)
  - **Reconstruction** algorithms for SiD and TD
  - **AFP D3PD** scheme prepared (D3PD maker for AFP)
    - D3PD dumper for AFP + ATLAS made

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Simulation Setup

- **Geant4 simulation setup (SiD):**
  - 2 AFP stations with Si detectors per ATLAS side (SiD 0 - 1 ← IP → SiD 2 - 3)
  - 6 Si layers/station separated by 10 mm (13 deg tilt in the x-z plane)
  - No staggering of the layers (yet)
  - 336 x 80 array of 50 x 250 μm² pixels per layer
  - *Kalman filter* is used for the tracking reconstruction
AFP SiD performance

- SiD tracking resolution
- **15 μm** RMS in x (plot)
- **72 μm** RMS in y
- Numbers above consistent with the formula:
  \[ \text{RMS} = \frac{\text{pixel\_size}}{\sqrt{12}} \]
- Staggering of the layers will improve the resolution, even with 4 Si layers configuration
- Expected tracking resolution wrt 4 staggered layers:
  8 μm in x, 20 μm in y
AFP SiD performance

- **Reconstructed track multiplicity** with $|x_{\text{slope}}| < 0.003$ and $|y_{\text{slope}}| < 0.003$ cut (per station) to separate proton tracks from showers
- Events are generated without any cut on the proton kinematics (i.e. $\xi < 1$)
- Approximately **50%** of protons in the sample **do not enter** the AFP acceptance region ($0.015 < \xi < 0.15$) which results in no reconstructed tracks

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**Graphs:**

- **ATLAS Simulation**
  - $\sqrt{s} = 14$ TeV
  - $\beta^* = 0.55$ m
  - 1/ev / dN_{tkk}
  - inner SiD
  - outer SiD
  - Tracks reconstructed in AFP 204 station
  - Tracks reconstructed in AFP 212 station

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The design of the AFP detector tracking system
AFP SiD performance

- **x-y track positions heatmap** for outer SiD station before (left) and after (right) track matching included for outer (AFP 212) station
- Tracks matched between inner and outer SiD stations are considered
- Positions are calculated in the ATLAS Coordinate System – beam center at \( x = -97 \text{mm} \)

The design of the AFP detector tracking system
AFP SiD performance

- **AFP proton track reconstruction efficiency** for different pile-up scenarios
- \( \approx 95\% \) in \( 0.02 < \xi < 0.11 \) and \( \mu = 0/1 \)
- Tracks matched between the inner (AFP 204) and outer (AFP 212) stations are included
- Events with track multiplicity \( \leq 2 \) in inner and track multiplicity \( \leq 5 \) in outer station are considered
- Optimization of cuts will further improve the tracking efficiency

\[ \text{ATLAS Simulation} \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \beta^* = 0.55 \text{ m} \]
Summary

- AFP sensor qualification
  - Edge-slimming of IBL sensors to 100 μm is possible
  - Non-uniform irradiation is not an issue

- The design of the AFP tracker
  - Very simple mechanics will ease the detector integration inside the RP (also with ToF)
  - AFP will benefit from IBL development in many other areas (FE chips, optoboard, readout system, etc.)

- Full Geant4 simulation of ATLAS Forward Region + AFP Stations in the Athena framework
  - Simulated detector performance in agreement with the expectations - based on the basic material calculations / estimates
  - There is a still possibility to improve efficiencies by more elaborated cuts
  - Future plans: include the AFP Roman Pot setup inside the full simulation (first Geant4 GeoModel of AFP RPs is ready!)
AFP SiD tracking cuts

- Tracks are reconstructed when $N_{\text{pix}} < 1000$ (per station)
- $\text{Trk\_quality} > 6$ ($quality = N_{\text{hits}} + \frac{\chi^2_{\text{max}} - \chi^2_{\text{trk}}}{\chi^2_{\text{max}} + 1}$, with $\chi^2_{\text{max}} = 2.0$ and cut on $\chi^2_{\text{trk}} = 2.0$)
- $|\text{Trk\_x\_slope}| < 0.003$, $|\text{Trk\_y\_slope}| < 0.003$
- $\text{Trk\_n} = 1 \text{ / station}$ ($\text{Trk\_n} \leq 2$ in inner + $\text{Trk\_n} \leq 5$ in outer station as a pileup robust setup)
- $|\text{Trk\_x}_{\text{SiD0}} - \text{Trk\_x}_{\text{SiD1}}| < 1.5\text{mm}$
- $|\text{Trk\_y}_{\text{SiD0}} - \text{Trk\_y}_{\text{SiD1}}| < 1.5\text{mm}$

$\chi^2_{\text{max}} = 2.0$ and cut on $\chi^2_{\text{trk}} = 2.0$ (same for the other pair of stations)
- **MC Samples**: 4 x 30k HERWIG++ DPE jets sample (with $20 < p_T^{\text{jet}} < 80$ GeV cut)
- Different pile-up conditions: $\mu = 0$ (signal only), 1, 5, 15
- Pile-up events are generated using **PYTHIA8**
• Kalman filter - optimal estimator of the state vector of a linear dynamical system <- minimization of the mean square estimation error

• State vector $x_k$:

$$x_k \equiv F_{k-1}x_{k-1} + w_{k-1}$$

  • $F_{k-1}$ - track propagator from layer $k-1$ to $k$
  • $w_{k-1}$ - process noise (e.g. multiple scattering)

• Track parametrization for AFP SiDs -> 2D position + slopes:

  • $x_k = (x_k, \frac{dx_k}{dz}, y_k, \frac{dy_k}{dz})^T$

  • $F_{k-1} = \begin{pmatrix} 1 & \Delta z_k & 0 & 0 \\ 0 & 1 & \Delta z_k & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$, $\Delta z_k$ - distance between layers $k$ and $k-1$