The Insertable B-Layer of the ATLAS Experiment for the Run-2 at the Large Hadron Collider

Francesco Guescini^a, on behalf of the ATLAS Collaboration

^aUniversité de Genève, DPNC, Quai Ernest-Ansermet 24, 1211 Genève 4, Switzerland
Francesco.Guescini@cern.ch

Abstract

The Pixel Detector of the ATLAS experiment has shown excellent performance during the whole Run-1 of LHC. Taking advantage of the long shutdown, the detector was extracted from the experiment and brought to surface, to equip it with new Service Quarter Panels, to repair modules and to ease installation of the Insertable B-Layer (IBL). IBL is a fourth layer of pixel detectors and has been installed in May 2014 between the existing Pixel Detector and a new smaller radius beam pipe at a radial distance of 3.3 cm from the beam axis. The realization of the IBL required the development of several new technologies and solutions in order to overcome the challenges introduced by the extreme environment and working conditions, such as the high radiation levels, the high pixel occupancy and the need of an exceptionally low material budget. Two silicon sensor technologies have been adopted for the IBL modules: planar and 3D. Both of these are connected via bump-bonding to the new FE-i4 front-end read-out chip. Furthermore, the physics performance will be improved through the reduction of pixel size while, targeting for a low material budget, a new mechanical support using lightweight staves and a CO₂ based cooling system have been adopted. An overview of the IBL project as well as the experience in its construction is presented, focusing on adopted technologies, modules and staves production, qualification of assembly procedure, integration of staves around the beam pipe and commissioning of the detector.

Keywords: LHC, ATLAS, Pixel, IBL

1. Introduction

During the first shutdown of LHC [1], the ATLAS [2] detector underwent some upgrades of the Pixel Detector [3] in preparation for the Run-2 of LHC, which will take place between the years 2015 and 2017. The whole ATLAS Run-1 Pixel Detector has been extracted and brought to surface, where it has been equipped with new Service Quarter Panels and to allow for repair of broken modules. The Layer-2 DAQ hardware was also upgraded to withstand the data rates expected in Run-2. Moreover, the Diamond Beam Monitor was installed to perform bunch-by-bunch beam luminosity measurements [4]. Nevertheless, the main upgrade of the ATLAS Pixel Detector for Run-2 consists of a new inner pixel layer, the Insertable B-Layer (IBL), which is positioned between the former inner layer of the Pixel Detector (B-Layer) and a new, smaller, beam pipe, at a radial distance of 3.3 cm from the beam axis. Two silicon sensor technologies have been employed for the construction of the IBL modules: planar and 3D [5]. Sensors are connected with bump-bonds to a new generation 130 nm IBM CMOS FE-i4 front-end read-out chip [6].

2. Towards Run-2

The ATLAS detector has shown impressive performances throughout Run-1. A total of 21.7 fb^{-1} of integrated luminosity at 8 TeV energy in the center of mass have been collected, corresponding to 93.5% of the total luminosity delivered by the LHC.

A serious challenge to the capabilities of the detector was set by the high peak luminosity reached, $7.7 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ with 50 ns bunch spacing, and the number of collisions per bunch crossing, 20.7 on average with peaks above 30. These conditions are expected to worsen in Run-2, where the energy in the center of mass will be increased to 13 TeV, the luminosity will be of the order of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and the bunch spacing will be reduced to 25 ns, therefore leading to stronger out-of-time pile-up conditions, higher occupancy levels and more shared hits. From a performance point of view, this will lead to worse tracking, vertex reconstruction and flavor tagging [7][8].

3. The Insertable B-Layer

The Insertable B-Layer, IBL, is the 4th and innermost layer of the new ATLAS Pixel Detector (see figure 1). It has been designed for the purpose of improving tracking, vertexing and flavor tagging, as well as providing tracking redundancy in case of failures of the Layer 0, the so called *B-Layer*, and compensating for inefficiencies due to radiation damage and module failures.

3.1. Staves

The IBL has a modular structure composed of 14 units, the *staves*, symmetrically arranged around the beam pipe with an overlap in ϕ (see figure 2). The staves have a support structure made of carbon fiber laminate and carbon foam, with a titanium cooling pipe inside. The total length, including services,

Figure 1: Schematic representation of the IBL showing its modular structure. Some of the staves are not represented.

is 7 m but only the central 66.4 cm are instrumented. Due to the mechanical constraints given by the B-Layer, the IBL is located in the region between 31 mm and 40 mm from the beam axis. The installation of the IBL inside the Pixel Detector was possible thanks to the replacement of the beam pipe used in Run-1 with a smaller one. The extremely light design structure of the IBL allowed its radiation length to be $1.9\% X_0$ including the supports. Each stave is equipped with 20 pixel sensors: 12 double chip (planar) and 8 single chip (3D), for a total of 32 front-end chips per stave (see figure 2). The cooling of the staves is performed using two-phase CO_2 , with temperatures that can be as low as -40°C in the cooling pipe and -15°C on the sensors.

Figure 2: Schematic representation of one end of an IBL stave with the detail of a 3D module.

3.2. Modules

IBL modules have $50 \times 250 \mu\text{m}^2$ pixels, smaller than the $50 \times 400 \mu\text{m}^2$ pixels in the other Pixel Detector layers. Two different silicon sensor technologies have been employed for the construction of the IBL modules: planar and 3D [5].

Planar sensors. Planar technology is well known and was already used for the construction of the Run-1 ATLAS Pixel Detector. IBL planar modules use n^+ -in- n sensors and have slim edges, in order to reduce the geometrical inefficiency. Pixels are $250 \times 50 \mu\text{m}^2$ in size but the outermost pixels are twice as large, $500 \times 50 \mu\text{m}^2$, and partially overlap with the guard rings. The sensors measure $4.132 \times 1.859 \text{ cm}^2$ and are $200 \mu\text{m}$ thick. Planar modules are double chip, meaning that they are composed of a single silicon sensor with 160×336 pixels read

by two FE-I4 front-end chips. Double chip modules are located in the central region of the staves. Sensors were produced by CiS¹.

3D sensors. The 3D silicon technology has been adopted for the first time in a LHC experiment for the IBL. Due to the processes involved in the production, the decision was taken to have only single chip 3D modules, i. e. sensors with 80×336 pixels read by one FE-I4 front-end chip. The sensors are n^+ -in- p , measure $2.045 \times 1.875 \text{ cm}^2$ and are $230 \mu\text{m}$ thick. The use of 3D technology brings the advantage of having shorter collection distances and using lower depletion voltages but on the other hand gives a higher capacitance, hence larger noise values. Due to their better performance when hit by particles with a large incident angle, 3D modules have been placed in the forward regions, at the extremities of the staves, divided in two groups of four. 3D sensors have been produced by CNM² and FBK³.

Front-end chip. A new front-end read-out chip was developed specifically for the IBL modules: the FE-I4, which replaces the older FE-I3 used for the Run-1 Pixel Detector modules. The FE-I4 uses 130 nm IBM CMOS technology. It is designed for $250 \times 50 \mu\text{m}^2$ pixels and it has 80×336 channels and $8.7 \cdot 10^7$ transistors. It is $20.2 \times 18.8 \text{ mm}^2$ large and $150 \mu\text{m}$ thick. Due to the large fluences it will have to face at 33 mm from the interaction point, the FE-I4 is designed to withstand a flux of $5 \cdot 10^{15} \text{ 1 MeV equivalent neutrons per cm}^2$. The front-end is connected to the sensors with bump-bonds.

Almost 700 modules have been produced between January and October 2013, with a yield of 75% for the double chips and 62% for the 3D. Lower yield values were obtained in the first production batch due to a problem in the bump-bonding process, which caused open bumps and merged pixels. The issue was solved by performing a flux-free bump-bonding procedure. Optical inspections and electrical tests have been done on the modules at the production sites and at the stave loading site. A comprehensive list of tests was performed to ensure the quality, including I-V tests, analog and digital signal injection tests, threshold and noise tests. Modules have been subsequently ranked based on the number of bad pixels equivalents. Only those with less than 1% pixel defects per front-end have been loaded onto the staves.

4. Stave loading

After the selection of the best modules available, these were fixed onto the staves using two glue drops per front-end; a layer of thermal grease was deposited on the remaining surface to

¹CiS: Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH, Konrad-Zuse-Strasse 14, 99099 Erfurt, Germany.

²CNM: Centro Nacional de Microelectrónica (CNM-IMB-CSIC), Campus Universidad Autónoma de Barcelona, 08193 Bellaterra (Barcelona), Spain.

³FBK: Fondazione Bruno Kessler (FBK), Via Sommarive 18, 38123 Povo di Trento, Italy.

123 ensure good thermal conductivity. Flexible connectors, called 143
 124 *wings*, for clock, data and power were then glued on the mod-
 125 ules and the two wire-bonded together. 20 staves have been 144
 126 produced in a one year long effort (see figure 3). A total of 428 145
 127 modules has been loaded, out of which 28 are the modules re- 146
 128 placed after loading (see figure 4). Most of these 28 modules 147
 129 were replaced due to accidents which happened during load- 148
 130 ing and re-wire-bonding, very few because of front-end failures 149
 131 and just 2 because of failed quality assurance. Staves have been 150
 132 optically and electrically inspected after loading. 151
 152

5. Stave quality assurance

Extensive tests of the staves have been performed to ensure the quality and identify the best 14 to be loaded [10]. Optical inspections, electrical tests, tuning and calibration of the modules have been performed.

Figure 5 shows the results of the threshold measurements performed on the modules of the 14 IBL staves after tuning for a threshold of 1500 e^- and 10 ToT (1 ToT, Time over Threshold, corresponds to 25 ns) for a 16000 e^- signal at -12°C . The values obtained are well aligned along the desired threshold value.

Figure 3: stave loading workflow [9].

Figure 4: modules replaced divided by category [9]. 15 modules have been replaced due to failures during the stave loading procedure, 6 modules have been replaced after cleaning and re-wire-bonding at CERN Detector Silicon Facility, 5 because of front-end failures and 2 because of failed quality assurance.

133 Between September and October 2013, halfway through the
 134 process, the stave production was halted due to the observation
 135 of corroded wire-bonds and corrosion residuals (see figure 3).
 136 An investigation of the phenomenon revealed the presence of
 137 Cl and F associated with the corrosion products and the origin- 158
 138 of the problem was traced back to the staves being exposed to 159
 139 humidity. Half of the staves was then cleaned and wire-bonds 160
 140 re-done. The options of potting or coating wire-bonds with ure- 161
 141thane was investigated but in the end the decision was taken not 162
 142to apply either of these. 163

Figure 5: threshold scan results for the modules of the 14 IBL staves [10]. The x axis indicates the position of the front-end along the stave.

153 Figure 6 shows the results of the noise tests performed on
 154 the 14 IBL staves after tuning. The results are divided in normal
 155 and long pixels for the planar modules and CNM and FBK 3D
 156 modules. It is possible to observe that 3D modules have slightly
 157 larger noise values due to their design geometry.

Figure 6: noise scan results for the modules of the 14 IBL staves [10].

Source scans have been performed using a ^{90}Sr source to determine disconnected and merged bumps. Staves have been thermal cycled to investigate possible cases of fast aging and infant mortality. Staves were ranked based on the equivalent number of bad pixels. Each of the 14 best staves selected for the IBL integration has less than 0.2% equivalent bad pixels.

6. Stave integration

Staves have been integrated on the IBL Positioning Tube one by one and then electrically tested. The adjacent staves have also been tested in order to ensure that no damage had occurred during the procedure. The integration order was chosen to have, as much as possible, uniform performance of the IBL in the $\eta-\phi$ space and to avoid any possible concentration of bad pixels in a localized region. The whole procedure took almost two months and all of the modules were working. The final electrical tests performed on the assembled IBL confirmed the results obtained during quality assurance.

7. Installation and commissioning

IBL was lowered in the ATLAS cavern on May 5th, 2014 and successfully inserted in the pre-existent Pixel Detector two days later. The performance of the IBL was thereafter tested showing that all of the modules were working after the insertion.

Figure 7 shows the results of the noise scan. As already observed in figure 6, 3D modules, located at the edges of the staves, have slightly larger noise values.

Figure 7: noise scan results for the modules of the 14 IBL staves after IBL insertion [9].

The difference between the results of the noise tests performed during the quality assurance and those obtained during the commissioning in the pit show good consistency of the two (see figure 8). The large differences observed for the 3D modules located at the right end of the staves (A side) were caused by a noisy power line in the quality assurance system and are thus not imputable to malfunctions of the modules.

8. Expected performances

Preliminary studies on the expected performances of the ATLAS detector with the IBL are presented in [7]. The vertex reconstruction capabilities and the resolution on the impact parameters of tracks are expected to be significantly improved, especially for particles at low p_T . A notable improvement will be brought to the flavor tagging, with the light-jet rejection almost

Figure 8: difference between the noise scan results for the modules of the 14 IBL staves performed during quality assurance and those performed after IBL insertion [9]. The large differences observed for the last four modules on the A side are due to a noisy power line in the stave quality assurance system. All other differences are within acceptance.

doubled. The redundancy provided by the IBL on the B-Layer hits is expected to increment and exceed the b-tagging performance of ATLAS even in a scenario where 10% of the B-Layer is lost due to failures.

9. Conclusions

In order to cope with the increased pile-up conditions, larger occupancy and worse tracking conditions expected for Run-2, the ATLAS detector has been upgraded, during the first LHC long shutdown, with a fourth, inner silicon pixel layer: the Insertable B-Layer, IBL. For the realization of the IBL, several new technologies had to be specifically developed. The tests performed during the different stages of the IBL production show encouraging results. Preliminary studies on the ATLAS Pixel Detector for Run-2 show that the IBL can effectively be a valid response to the demanding conditions expected and reliably compensate for possible failures of the B-Layer.

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