The upgraded Pixel Detector of the ATLAS Experiment for Run 2 at the Large Hadron Collider

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1. Introduction

The ATLAS Pixel Detector [1] is the innermost part of the ATLAS Detector [2]. It consists of three barrel layers and three disks on each detector side. This three-layer system was originally installed in 2007 and its services were upgraded during the long shutdown in 2013/2014 (LS1). The three layers of the Pixel Detector provide 3-dimensional space points which are crucial for the reconstruction of primary and secondary vertices in ATLAS. Their excellent resolution is mandatory for the detection of long-lived particles, such as hadrons containing b-quarks.

The three-layer pixel system was designed for an instantaneous luminosity of $1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. During the Run 2 and Run 3 at the LHC, the luminosity is expected to be $\geq 2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, which will result in an increase of the number of simultaneous vertices (pile-up). In order to retain the excellent secondary vertex reconstruction efficiency in the presence of high pile-up (>50 primary vertices) a fourth pixel detector layer was built. The new layer is called Insertable B-Layer (IBL) and is constructed as the innermost layer at ∼3.3 cm from the beam line and has a reduced pixel pitch in the beam direction. It is mounted on a smaller radius beam pipe, which allowed its installation inside the three-layer pixel system. Therefore, the new ATLAS Pixel Detector consists of four pixel layers, a unique vertex detector layout in the current LHC experiments. The impact parameter resolution improves by nearly a factor of two for low transverse momentum tracks [3] in the new layout, which additionally increases the pattern recognition robustness by providing an additional space point.

Fig. 1 illustrates the layout of the new 4-Layer system on the top, and the radial position of the barrel layers including the beam pipe and the carbon fiber support tubes (IPT and IST) at the bottom. The tracking volume of the 4-Layer system extends to a pseudo rapidity of η = 2.5.

2. Maintenance of the existing ATLAS Pixel Detector

The three Pixel Detector barrel layers and discs started operation at the beginning of the LHC Run 1 with 1.5% non-operational

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**ABSTRACT**

During Run 1 of the Large Hadron Collider (LHC), the ATLAS Pixel Detector has shown excellent performance. The ATLAS collaboration took advantage of the first long shutdown of the LHC during 2013 and 2014 and extracted the ATLAS Pixel Detector from the experiment, brought it to surface and maintained the services. This included the installation of new service quarter panels, the repair of cables, and the installation of the new Diamond Beam Monitor (DBM). Additionally, a completely new innermost pixel detector layer, the Insertable B-Layer (IBL), was constructed and installed in May 2014 between a new smaller beam pipe and the existing Pixel Detector. With a radius of 3.3 cm the IBL is located extremely close to the interaction point. Therefore, a new readout chip and two new sensor technologies (planar and 3D) are used in the IBL. In order to achieve best possible physics performance the material budget was improved with respect to the existing Pixel Detector. This is realized using lightweight staves for mechanical support and a CO2 based cooling system.

This paper describes the improvements achieved during the maintenance of the existing Pixel Detector as well as the performance of the IBL during the construction and commissioning phase. Additionally, first results obtained during the LHC Run 2 demonstrating the distinguished tracking performance of the new Four Layer ATLAS Pixel Detector are presented.

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modules. Until the end of Run 1 this number increased to 5% [4], which corresponds to 88 out of 1744 modules, randomly distributed over the three detector layers with different failure symptoms. During the maintenance of the Pixel Detector the defect modes could be analyzed. The largest fraction of modules was disabled due to failures of the electrical-to-optical converter boards (optoboards) and broken high voltage connections, see Fig. 2 [5]. The optoboards mainly failed due to broken solder connections and the HV lines due to wire bond failures and open solder connections. Thus both failure modes are not related to the radiation damage.

The installation of the new Service Quarter Panels (nSQP) provided a relocation of the optoboards outside the Inner Detector volume, a place accessible in a much shorter time. All defects originating from broken data transmission lines and faulty optoboards were therefore repaired during LS1. Additionally all faulty connections outside the active Pixel Detector volume were repaired during the process of reconnection after the nSQP installation. Faulty connections within the active volume were not accessible and thus could not be repaired.

The full detector package was tested on the surface before it was re-installed in ATLAS in December 2013. During the first half of 2014 the refurbished three-layer Pixel Detector was reconnected and tested. Fig. 3 summarizes the failures detected in the tests on the surface and after the full re-connection in the ATLAS detector. The number of modules to be disabled was decreased to 33, resulting in 1.89% disabled modules. The biggest improvement was achieved in the B-Layer, where the disabled fraction was reduced from 6.3% to 1.4%, and Layer-2, where the the 7.0% faulty fraction was reduced to only 1.9%. The nSQP and newly installed data fibers allow the bandwidth of the transmitted data to be increased when the new readout boards are installed in future LHC shutdowns. For Layer-1 the bandwidth can be increased to 160 Mbit/s, and for Layer-2 to 80 Mbit/s. This corresponds to a factor two with respect to the bandwidth during Run 1 and increases the bandwidth limitation to a corresponding instantaneous luminosity up to $3 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$.

3. IBL construction and integration on the surface

The IBL is constructed of fourteen local support and cooling structures (staves), which are loaded with 20 hybrid pixel detector modules each. The staves consist of an extremely lightweight $\Omega$-shaped carbon foam structure for heat conduction from the modules to the cooling fluid. The cooling is realized using CO$_2$ bi-phase cooling in the titanium pipe, which is integrated in the carbon foam. The carbon foam is surrounded by a 150 $\mu$m carbon fiber laminate, which is glued to the carbon foam, to reinforce the stave stiffness. Two types of modules are used for IBL, planar double chip modules and 3D single chip modules [6]. Both module types are read-out using the FE-I4 readout chip [7]. The FE-I4 holds a pixel matrix organized in 80 columns and 336 rows. The planar modules consist of a single silicon sensor produced at CIS, Erfurt, Germany, which is connected to two FE-I4 chips. The 3D silicon modules make use of 3D silicon sensors for the first time in large scale in a collider experiment, which were produced by FBK, Trento, Italy and CNM, Barcelona, Spain, and are read-out by single FE-I4 chips. The IBL 3D sensors are a double readout-column design with 50 $\mu$m pitch between the vertical readout-electrodes. Twelve planar modules are placed in the central region of each stave and four+four 3D modules are loaded at each extremity, as
indicated in Fig. 4. The reason for including 3D-sensors in the IBL is the expected superior radiation hardness due to the decoupling of the sensor thickness from the drift distance of the charges. However, the radiation testing in the R&D phase showed no improvement in radiation hardness compared to the planar sensors.

Each individual production part of IBL has passed an intense Quality Assurance test (QA) prior to its further integration. The IBL modules are the smallest individually functional unit of the detector and passed a full performance validation before being loaded to the staves. A total number of 20 staves were been equipped with modules, out of which 18 have been fully qualified [8]. During this stave QA the discriminator threshold of the full stave has been adjusted to equivalent signals at its input between 3000e and 1500e. This corresponds to a signal over threshold of about 5.3 and 10.7, as the expected signal before significant radiation damage occurs is in the order of 16,000e. The resulting threshold distribution is an important performance characteristic of the IBL detector. Fig. 5 presents the threshold distribution as a function of the chip position along all the staves. The threshold is well adjusted independent of the chip position, with a maximum deviation from the 1500e target below 2.7% ( <40 e).

The fraction of faulty pixels is measured on each stave using high statistics radioactive source tests and noise hit probability measurements. The pixels showing a failure in any of the tests are counted and the fraction of faulty pixels is computed for each readout-chip. The acceptance criteria for IBL staves is set to a fraction of faulty pixels below 1%. All fully qualified staves fulfill this criteria, see Fig. 6. The staves are ranked based on the η-weighted fraction of faulty pixels and the best ranked 14 staves are integrated on the beam pipe. As shown in Fig. 6, the 14 integrated staves have only 0.09% faulty pixels, demonstrating the excellent quality of the IBL in terms of operational channels.

After the integration of each stave onto the Inner Positioning Tube (IPT) a quick functionality validation test has been performed without the possibility of cooling the staves. No performance degradation has been observed. The noise distribution as a function of the chip position in this measurement is shown in Fig. 7. The average noise of the planar modules is between 120e and 130e. The 3D sensors have a higher detector capacitance, leading to a noise of ~180e. The slightly higher noise of the modules on the A-Side originates from the slightly higher detector capacitance of the FBK sensors, and the fact that the FBK modules are mainly loaded on the A-side, while the CNM modules are mainly loaded on the C-side.

4. IBL insertion and commissioning in the ATLAS detector

On May 7th of 2014 the IBL detector and the new beam pipe were inserted into the ATLAS Pixel Detector, which had been
re-inserted and connected to cooling and electrical services earlier. Fig. 8 was taken during the insertion process and demonstrates the mechanical challenge during this crucial step of the project. The IBL detector package had a total length of ∼7 m and a clearance of only 2 mm to the fragile Pixel Detector. During the following six weeks the IBL was connected to power, read-out, and cooling services, and the commissioning of the full detector system could start. The first step was the performance validation using the stave test system used on the surface (RCE).

The performance of the IBL profits from the final cooling and power system in the ATLAS cavern, as can be seen in the noise difference between the commissioning and the stave QA shown in Fig. 9. During the commissioning phase the final data acquisition system was fully integrated into the ATLAS Trigger and Data Acquisition framework [9], and elaborately tested. These tests included data taking periods in common with the full ATLAS detector measuring cosmic ray particles. One of the first tracks measured in these cosmic runs is shown in the event display of Fig. 10. The eight hits in the SCT barrel layers, six hits in the barrel layers of the Pixel Detector and two hits in the IBL are reconstructed to a track bent in the magnetic field. Minimum Ionizing Particles generate a Landau shaped charge distribution with a most probable value of ∼16 ke in the 200 μm thick planar sensors of the IBL, and ∼18.4 ke in the 230 μm thick 3D sensors. The readout-chips generate a charge information in terms of time-over-threshold (ToT) in units of bunch crossings (25 ns). The chips are tuned to respond with a ToT of ten bunch crossings to an injected test signal equivalent to ∼16 ke, irrespectively of the sensor type. The ToT distributions of the IBL measured during the cosmic ray data-taking runs are shown in Fig. 11.

5. IBL distortion

The cosmic ray data-taking runs during the commissioning have been performed at different temperatures of the IBL staves. A temperature dependence of 10 μm/K has been observed for the mean value of the residual in the detector alignment at the center of IBL. Fig. 12 shows the mean residual obtained in a cosmic ray data-taking run for different temperatures with respect to the alignment at −20 °C. The displacement of the residual is in agreement with a bowing of the staves with the boundary condition of the stave ends being fixed by the stave support structure on the Inner Positioning Tube (IPT). The coefficient of thermal expansion mismatch between the carbon fiber support structure of the stave and the electrical service cable glued to the backside of the stave has been identified as origin of the observed stave bow. Preliminary results of mechanical finite element analysis (FEA) of the stave structure are in agreement with the observations. A detailed characterization program including further simulations as well as measurements on production staves has been started. The effect of the residual displacement on the impact parameter resolution has been simulated. A local residual displacement of ≤2 μm, corresponding to a temperature difference of 0.2 K, is negligible in the impact parameter resolution of the Inner Detector, as shown in Fig. 13. A temperature difference below 0.2 K can be guaranteed by the cooling system, taking the readout chip
current consumption change due to the digital activity change with the occupancy variation during the LHC runs into account.

6. Tracking performance of the ATLAS Inner Detector in Run 2

The tracking performance of the ATLAS Inner Detector has been significantly improved since the insertion of the IBL, demonstrated in a large multiplicity of measurements, and despite the described distortion of the IBL the alignment and installed material is well understood. Two examples to demonstrate this are presented here.

The shape of the measured $K^0_S$ invariant mass distribution is especially sensitive to the alignment of the Inner Detector and to the material budget of the inner tracking system, the mechanical support, and the beam pipe. Fig. 14 shows a comparison of the $K^0_S$ invariant mass distribution measured in the early Run 2 collision data to the simulated distribution including the material and expected alignment in the simulation. The very good agreement of the shapes of the distributions of the data and of the simulation demonstrates the good understanding of the alignment and material description.

The impact parameter resolution is improved nearly by a factor of two. This is in good agreement with the expected impact parameter resolution improvement from the simulations prior to the IBL construction [3]. As an example, Fig. 15 shows the impact parameter resolution in the longitudinal direction (along the beam) as a function of the transverse momentum of the tracks [12]. The impact parameter resolution of the Run 1 data, without IBL, and of the Run 2 data, with IBL, are shown. The improvement is a result of adding a new point measurement at the very small radius of IBL and with higher precision, due to a decreased pixel size (250 μm) in the longitudinal direction with respect to the three Pixel Detector layers (400 μm).
7. Conclusions

The original three-layer ATLAS Pixel Detector performed very well during the LHC Run 1. Still, the ATLAS Collaboration took benefit of the first long shutdown to maintain the pixel detector. During this maintenance the fraction of disabled modules was reduced from 5% at the end of Run 1 to 1.9% after the reinstallation in the ATLAS detector. At the same time, the DBM and the IBL were constructed and installed in the ATLAS detector. The IBL was built with an excellent quality of only 0.09% faulty channels. During the commissioning of the IBL the distortion of the staves was recognized, which does not affect the detector performance in case temperature is kept stable within 0.2 K. This result is confirmed by a large multiplicity of tracking performance measurements. In all of these the performance of the new 4-Layer ATLAS Pixel Detector has met its design goals in the early collision data of 2015.

References


Fig. 15. Unfolded longitudinal impact parameter resolution measured from data in 2015, $\sqrt{s} = 13$ TeV, with the Inner Detector including the IBL, as a function of $p_T$ compared to that measured from data in 2012, $\sqrt{s} = 8$ TeV. The data in 2015 is collected with a minimum bias trigger. The data in 2012 is derived from a mixture of jet, tau and missing $E_T$ triggers [12].