ATLAS INNER TRACKER PERFORMANCE AT THE BEGINNING OF THE LHC RUN 2*

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The ATLAS experiment performs studies of proton–proton collisions at the Large Hadron Collider (LHC) at CERN. The Inner Detector is a part of the ATLAS apparatus placed nearest the interaction point, designed to measure charged particles momenta and their trajectories, and to reconstruct vertices of decays of physics objects created in collisions. During the LHC technical stop in 2013–2015, the Inner Detector underwent several upgrades and improvements, most notably an additional Pixel Detector layer was installed. This document describes the improvements done in the Inner Detector and its combined performance in the first year of data taking after the LHC restart in 2015.

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1. Introduction

The Inner Detector (ID) is the central part of the ATLAS experiment [1] at the Large Hadron Collider (LHC) [2] at CERN. The ID is designed to provide charged particle momentum measurements with a precision of $\frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}} \sim 0.5\%\ p_{\mathrm{T}} \bigoplus 1\%$, and the track and vertex reconstruction within pseudorapidity range of $|\eta| < 2.5$. It is composed of three separate and independent sub-detectors built in different technologies. The closest to the interaction point are high precision semiconductor instruments — the new Insertable B-layer (IBL) [3], the Pixel Detector [4] and the Semiconductor Strip Tracker (SCT) [5]. The outermost system in ID is the Transition Radiation Tracker (TRT) [6] — a gaseous straw detector.

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The LHC Run 1 data taking started in 2010. The peak instantaneous luminosity recorded during Run 1 was 8.0×10^{33} cm^{-2} s^{-1}. The center-of-mass energy was initially $\sqrt{s} = 7$ TeV and was raised to 8 TeV in 2012. The Inner Detector demonstrated excellent performance during the whole Run 1 [7]. After more than 2 years of running and collecting around 30 fb^{-1} of data, the LHC entered a long technical stop (LS1) dedicated to upgrades necessary for increasing beam energy to $\sqrt{s} = 13$ TeV and peak instantaneous luminosity to 1.7×10^{34} cm^{-2} s^{-1}. With increasing luminosity, the number of simultaneous proton–proton (pp) interactions per bunch crossing, the so-called pile-up, gets bigger. The average number of pp interactions (μ) per beam crossing in Run 1 reached 40, while the design specification for the Inner Detector is $\mu = 26$. An example of the pile-up event recorded in 2012, with 25 reconstructed vertices is shown in Fig. 1. It is expected that the pile-up will increase in Run 2.

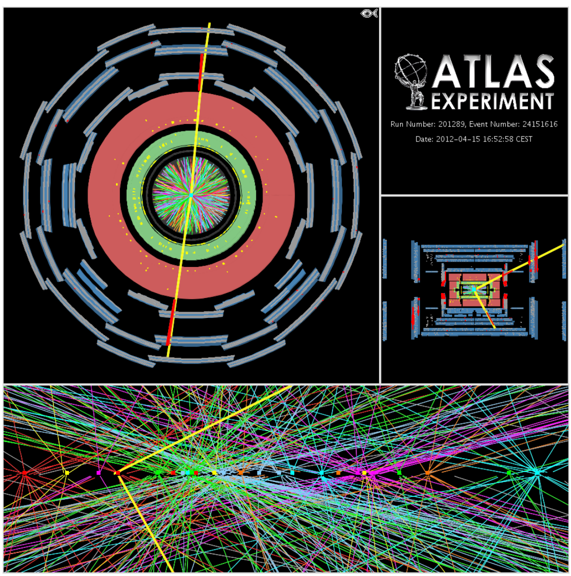

Fig. 1. A candidate Z boson event in the dimuon decay with 25 reconstructed vertices. This event was recorded on April 15, 2012 and demonstrates the high pile-up environment in 2012 running [8].

A high pile-up has a big impact on tracking detectors since they are particularly sensitive to the increase in particle multiplicity. As the luminosity increases, the number of interesting events per second grows, thus the rate of the Level-1 trigger is higher. A larger number of collisions results in a higher detector occupancy, and a higher data volume needs to be read out upon reception of the Level-1 trigger. Finally, the data taking can be disturbed by increasing number of readout chip errors caused by Single Event Upsets (SEUs), where a charged particle passes through on-detector electronics and changes a value stored in a memory cell [7].

The Inner Detector subsystems took advantage of the LS1 to undergo preparations for higher luminosity and pile-up conditions during Run 2 and to perform consolidation works after Run 1. In March 2015, the LHC restarted operations and the Pixel Detector, SCT and TRT were recommissioned after modernisation.

2. The Inner Detector activities during the long technical stop

2.1. The Pixel Detector and Insertable B-Layer

At the end of Run 1, 88 out of 1744 (5%) Pixel Detector modules were excluded from operations, which was due to various failures, mostly the failures of the electrical-to-optical converter boards and broken high voltage lines. The Pixel Detector was extracted from the experimental cavern and moved to the surface laboratory where all accessible module failures were repaired and electrical services were refurbished. The optical data transmission electronics was moved to a location outside the ID cryostat for easier access for reparations during short technical stops. New optical links were installed with an increased data bandwidth capability for Run 2. The bandwidth for Pixel Layer-1 can be increased to 160 MBit/s, and for Layer-2 to 80 MBit/s to withstand data transmission rates expected with the increased LHC instantaneous luminosity up to $3 \times 10^{34}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

The performance of the innermost layer of the Pixel Detector is critical for fulfilling the physics analysis requirements for tracking and vertexing. At the same time, this layer, due to its proximity to the interaction point, suffers from radiation damage effects and inefficiencies at high luminosities. To improve the precision of vertexing and tracking and to maintain a robust tracking despite effects arising from luminosity and radiation, a fourth layer of pixel detectors, the Insertable B-Layer (IBL), was installed between the existing Pixel Detector and a new smaller radius beam-pipe. The IBL was designed to withstand a high luminosity environment. It consists of 14 supporting structures — staves, mounted around a beryllium beam pipe at the radius of $R = 33.25$ mm from the beam line. Each stave includes 20 modules built in two different technologies. The central part of the stave is populated with 12 planar pixel sensors of type n^{+}–in–n. On each stave side, there are four 3D pixel sensors. Each pixel has a size of 50×250 μm^2. The intrinsic spatial resolution of the IBL readout is 10 μm in $r\phi$ and 75 μm in z.

2.2. The Semiconductor Tracker

Various consolidation and upgrade activities were carried out in SCT during LS1 to provide high quality data for physics analysis in Run 2. The most important improvements were done in the data acquisition system (DAQ), which was expanded to cope with the expected higher detector occupancies and high Level-1 trigger rates up to 100 kHz. 38 additional Read-Out-Drivers (RODs) were installed to remove a critical DAQ bottleneck and the number of the optical links for data transfer was increased accordingly. Hardware expansion together with the ROD firmware upgrade, including data compression, make it possible to read out SCT up to $3 \times 10^{34}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at 25 ns bunch spacing.

Before the restart of data taking, all of the ID subdetectors were recommissioned and all performance metrics were found to be comparable to Run 1. The active coverage in the various systems of the Inner Detector at the beginning of Run 2 is presented in Table I.

TABLE I

The Inner Detector Run 2 status from October 2015. The SCT operational fraction is expected to rise to 98.9% after including temporarily disabled modules [9].

Subdetector	No. of channels	Approx. operational fraction
Pixel	80 M	98 %
IBL	12 M	99.5 %
SCT	6.3 M	98.6 %
TRT	350 k	97.3 %

3. Combined Inner Detector performance

3.1. Material studies

The material composition and the structure of the Inner Detector have changed since Run 1, which is due to the Pixel Detector refurbishment and IBL installation. A precise knowledge of the material inside the tracking detectors is crucial for correct detector simulations. The material within the innermost barrel regions of the Inner Detector was studied using reconstructed hadronic interactions and photon conversion vertices from samples of minimum bias events collected at $\sqrt{s} = 13$ TeV in 2015 [10]. Figure 2 shows the radial distribution of hadronic interaction candidates reconstructed in the data and simulations. The structures of the tubes of the beam pipe at $r \approx 24$ mm, the Inner Positioning Tube (IPT) at $r \approx 29$ mm, and the Inner Support Tube (IST) at $r \approx 42.5$ mm are clearly visible and consistent between the data and simulation. The structure between IPT and IST at $30 < r < 40$ mm is the IBL stave. The default geometry model was found to be missing surface mount elements, *e.g.* capacitors located on the front-end chip in $r \approx 32$ mm. The corresponding amount of material was added to the updated geometry model. This correction significantly improves the agreement, as demonstrated in Fig. 2.

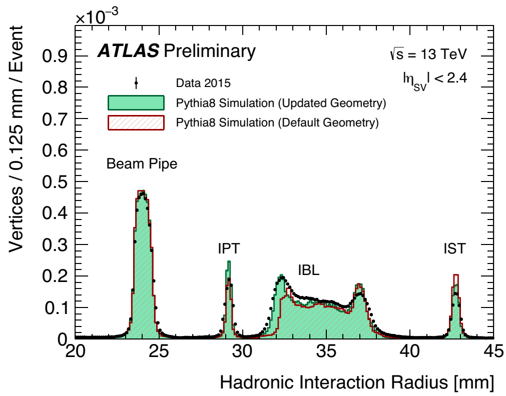

Fig. 2. Comparison of the radial distribution of hadronic interaction candidates between data and simulation for $20 < r < 45$ mm. The secondary vertices are required to have the pseudorapidity $|\eta_{\mathrm{SV}}| < 2.4$ [10].

3.2. Impact parameter resolution

The combined Inner Detector performance after upgrades done during the long technical stop was tested with *pp* collision data on LHC collected in 2015 with the center-of-mass energy of $\sqrt{s} = 13$ TeV. Track properties, such as the measured impact parameter resolution were studied. Comparison of

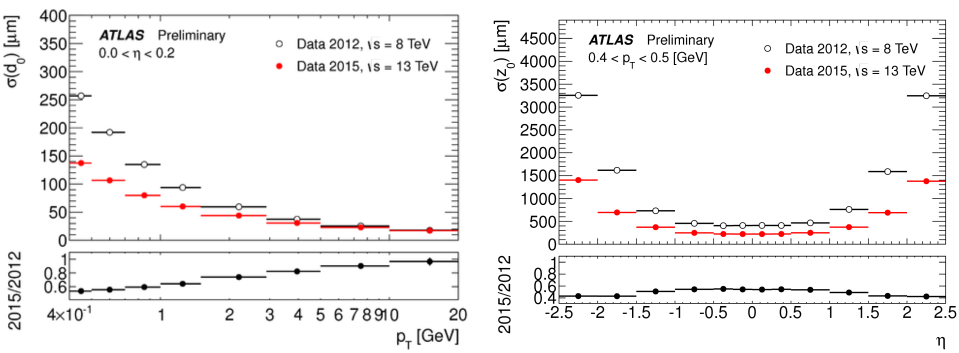

Fig. 3. Unfolded transverse impact parameter resolution measured from data in 2015 at $\sqrt{s} = 13$ TeV with the Inner Detector including the IBL, as a function of p_{T}, for $0.0 < \eta < 0.2$, (left) and η and for $0.4 < p_{\mathrm{T}} < 0.5$, (right) compared to that measured from data in 2012 at $\sqrt{s} = 8$ TeV [11].

Run 1 and Run 2 impact parameter resolutions is presented in Fig. 3. The influence of the IBL on the impact parameter resolution is visible. The impact parameter resolution has been unfolded to remove the contribution from the vertex resolution. The tracks were required to pass the loose selection criteria as described in [12].

4. Conclusions

The ATLAS Inner Detector underwent several upgrades and consolidation during the LHC technical stop in 2013–2015. The Insertable B-Layer was installed between the existing Pixel Detector and a new smaller radius beam-pipe. The ID was successfully restarted and demonstrated a good performance with data collected at LHC with pp collisions at $\sqrt{s} = 13$ TeV. The IBL improved the track impact parameter resolution.

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