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Operational Experience and Performance with the ATLAS Pixel detector at the Large Hadron Collider

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The tracking performance of the ATLAS detector at the Large Hadron Collider (LHC) relies critically on its 4-layer Pixel detector, that has undergone significant hardware and readout upgrades to meet the challenges imposed by the higher collision energy, pileup and luminosity. The record breaking instantaneous luminosity of $2 \times 10^{34}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, corresponding to an average number of 60 proton-proton collisions per bunch crossing was reached in 2017 and regularly achieved in 2018. The consequent Pixel strategy to contain the readout bandwidth limitations is discussed. The key status and performance metrics of the ATLAS Pixel Detector in Run 2 are summarised and the operational experience and requirements to ensure optimum data quality and data taking efficiency are described. A special emphasis is given to radiation damage effects showing signs of degradation which are visible but which are not impacting yet the tracking performance: dE/dx, occupancy reduction with integrated luminosity, under-depletion and annealing effects that are not insignificant for the inner-most layers.

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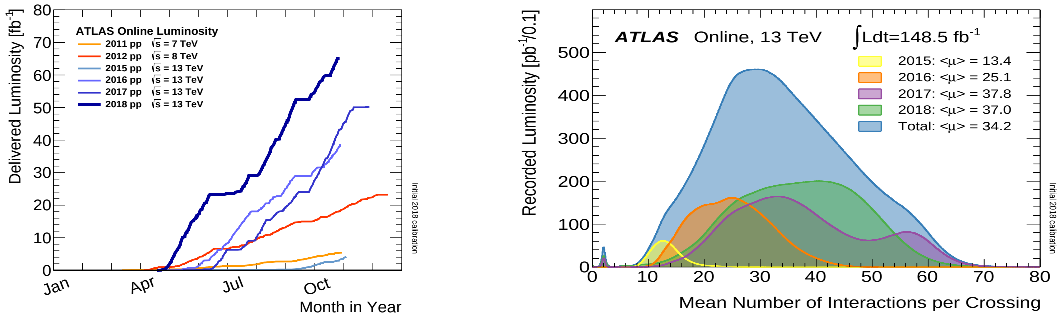
1. Introduction

LHC Run 2 (2015-2018) was a challenging period for the ATLAS experiment [1], and in particular for its Pixel Detector [2]. With respect to Run 1 (2010-2012), the collision energy reached 13 TeV and the design luminosity was exceeded. An integrated luminosity of $\sim 65\,\text{fb}^{-1}$ was delivered in 2018, twice as much as collected during the entire Run 1 (see Fig. 1a). This remarkable result was achieved thanks to a significant increase in the instantaneous luminosity, from $5 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$ obtained in 2015 to the 2018 record of $2.14 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$. In particular, the number of proton-proton collisions per bunch crossing, also known as pile-up (μ), had an increase of its average peak value from ~ 20 to ~ 60 (see Fig. 1b). It should be recalled that the LHC design luminosity is $1 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$, corresponding to an average μ of $\sim$25.



(a) (b)

Figure 1: The evolution of the integrated luminosity delivered by LHC during Run 1 and Run 2 data taking (a) and the evolution of the average pile-up during the four years of Run 2 (b) [3].

2. The Pixel detector upgrades in Run 2

The ATLAS silicon Pixel detector consists of three concentric barrel layers with mean radii of 50.5 mm (B-Layer), 88.5 mm (Layer1) and 122.5 mm (Layer2), centered around the beam axis, and two end-caps with three discs each, forming a three-hit system up to η[1] = 2.5. The detector consist of 80 million channels to be read out. At the end of Run 1, the Pixel detector started a series of upgrades to cope with readout limitations and detector issues that could have arisen with the expected luminosity increase. The first concern was the radiation damage. The B-Layer, being the closest to the beam pipe, would have reached its expected lifetime; for this reason, it was decided to add a new innermost layer, the Insertable B-Layer (IBL) [4] at a radius of $\sim$ 33 mm from the beam line, with 12 million channels to read out. The IBL [5] was crucial to improve vertexing and tracking, but also to provide redundancy in case of failures or radiation damage in the three layers Pixel detector, guaranteeing an excellent performance of the ATLAS tracker over the full lifetime up to the High-Luminosity LHC phase ($\sim$2023). Considering that the ATLAS Level 1 trigger rate was $\sim$100 kHz and the μ values were stably above the design value (25), bandwidth limitations needed to be addressed. For this reason, the Pixel Data Acquisition System (DAQ) hardware was upgraded using the one developed for the IBL during the following winter shutdowns (2015-2016, 2016-2017 and 2017-2018), doubling the readout speed wherever it was possible.

[1] $\eta = -ln(tan\frac{\theta}{2})$, where θ is the polar angle measured from the beam (z) axis.

3. Detector performance in Run 2 and first observations of radiation damage effects

Thanks to the enhanced debugging and monitoring capabilities of the new readout electronics, the 4-Layer Pixel detector reached a stable and excellent performance in Run 2. One example can be observed in Fig. 2, where the level of de-syncronization was brought and kept below 1% in 2017, despite the increase of instantaneous luminosity with respect to 2016. The B-Layer hit-on-track efficiency was kept above 98% even if a slow decrease as a function of the integrated luminosity could be observed already in 2016 (see Fig. 3a). At the same time, a gradual decrease in average cluster size and dE/dx (consistent with radiation damage) throughout 2016 was visible (see Fig. 3b). A big drop in dE/dx and cluster size was observed at the beginning of 2016 due

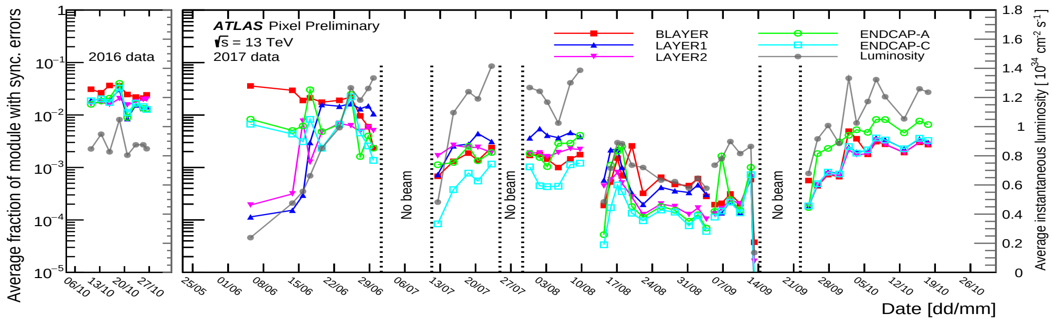
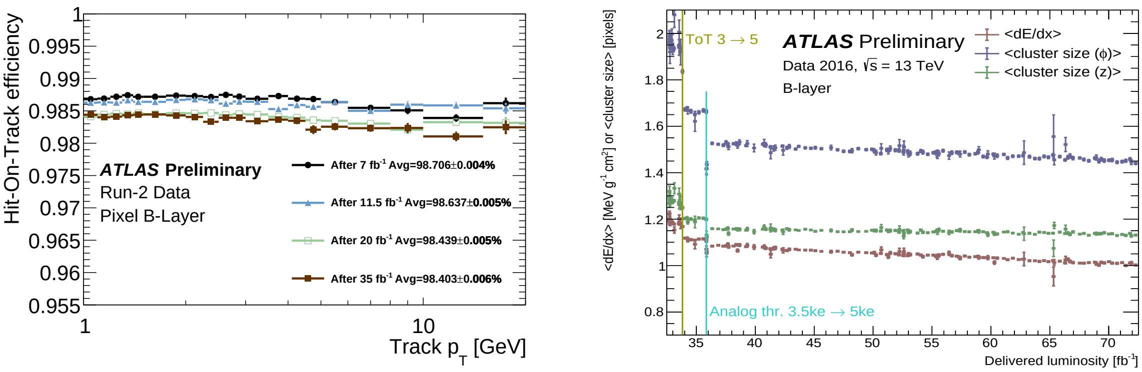


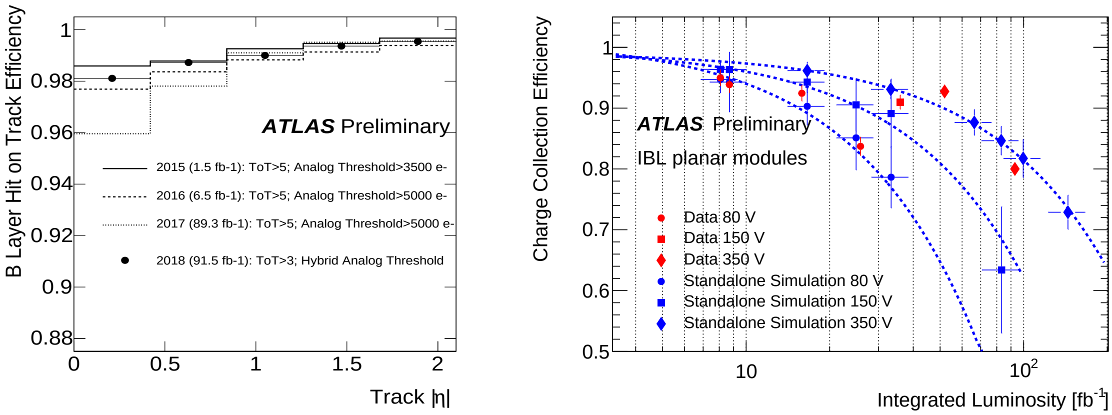
Figure 2: The evolution of the readout de-syncronization in 2016/2017 in the different layers. See Ref. [6].



(a) (b)

Figure 3: Hit-on-Track efficiency in the B-Layer as a function of track p_T collected after four different integrated luminosities in Run 2 (a). The dependence of the average cluster size and dE/dx on the delivered integrated luminosity and critical detector parameters like analog or digital threshold (b). See Ref. [6].

to the increase of analog and digital thresholds, expressed in kilo-electron (ke) and in Time Over Threshold (TOT) units (see Fig. 3b). These cuts were needed to limit the detector occupancy that had increased drastically due to the rising values of μ, bringing the B-Layer close to its readout bandwidth limitations. However, by the end of 2017, the effect in charge collection was such that the B-Layer hit-on-track efficiency dropped to 96% at low η (see Fig. 4a). For this reason, in 2018 the thresholds were lowered and optimised depending on the η position, increasing the efficiency as it was at the beginning of Run 2. The corresponding increase of occupancy was considered and estimated to be within the readout limitations. The more recently installed IBL showed also reduction of charge collection efficiency (see Fig. 4b); this effect was compensated by increasing the bias voltage at the beginning of each year and lowering the threshold in 2018.



(a) (b)

Figure 4: Evolution of the B-Layer hit-on-track efficiency as a function of the η of the track (a). Charge collection efficiency in IBL as a function of the integrated luminosity during Run 2 (b). See Ref [6].

4. Conclusions

The ATLAS Pixel Detector has operated in Run 2 with luminosities and pile-up which significantly exceeded the original design values, delivering excellent tracking performance and data quality/efficiency. The insertion of IBL during LS1 and the upgrades of the Pixel DAQ system during the winter shutdowns improved the overall Run 1 performance and addressed the bandwidth limitations. The effects of the radiation damage are visible in charge collection efficiency and hit-on-track efficiency. In order to counteract performance degradation, bias voltage and threshold working points have been continuously optimised during Run 2.

References

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