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

Chris Scheulen† on behalf of the ATLAS Collaboration

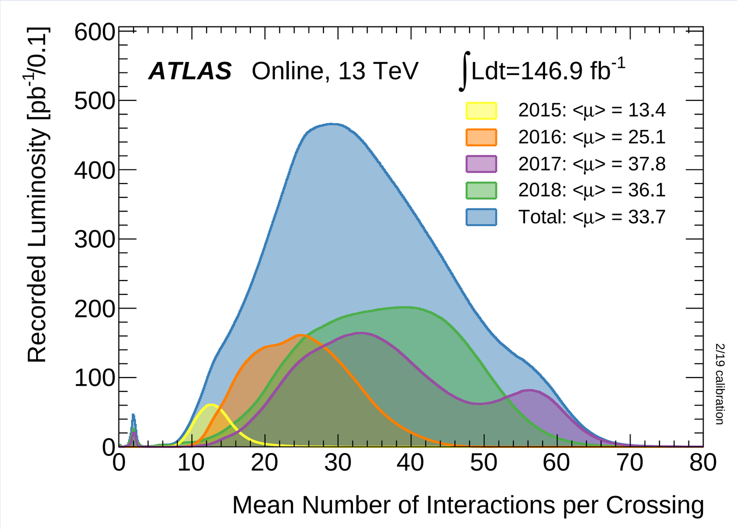
II. Physikalisches Institut, Georg-August-Universität Göttingen

1. Data Taking Conditions

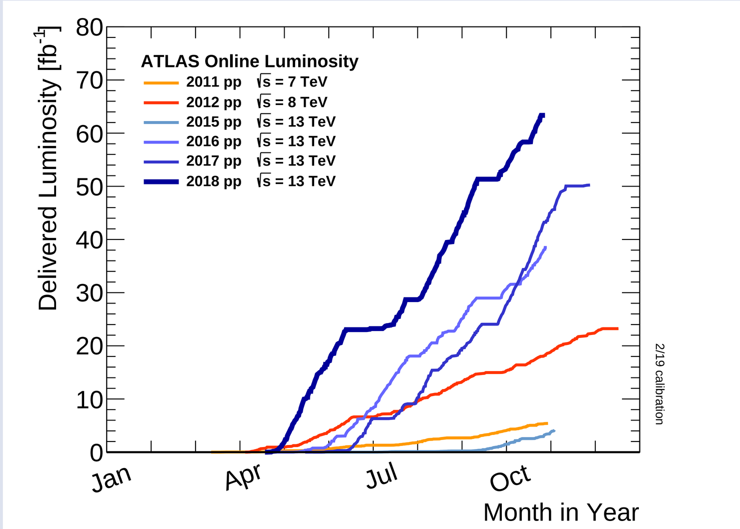
For Run 2 (2015 - 2018) compared to end of Run 1:

- Bunch crossing (BC) time (collision interval) halved from 50 ns to 25 ns
- Higher instantaneous luminosity (up to $2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) & collision energy increased from 8 TeV to 13 TeV
  - Avg. pile-up μ (particle interactions per BC) increased from ∼20 to ∼35
  - Peak $\mu \sim 60$ reached
- Overall luminosity $\mathcal{L}_{\mathrm{int}} = 156\,\mathrm{fb}^{-1}$ delivered by LHC (Run 1 and Run 2)

⇒ Challenging data taking conditions



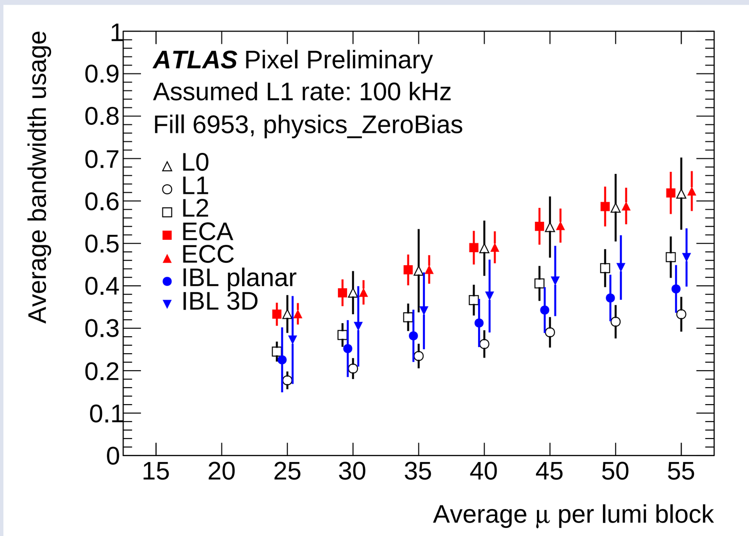
Pile-up distribution



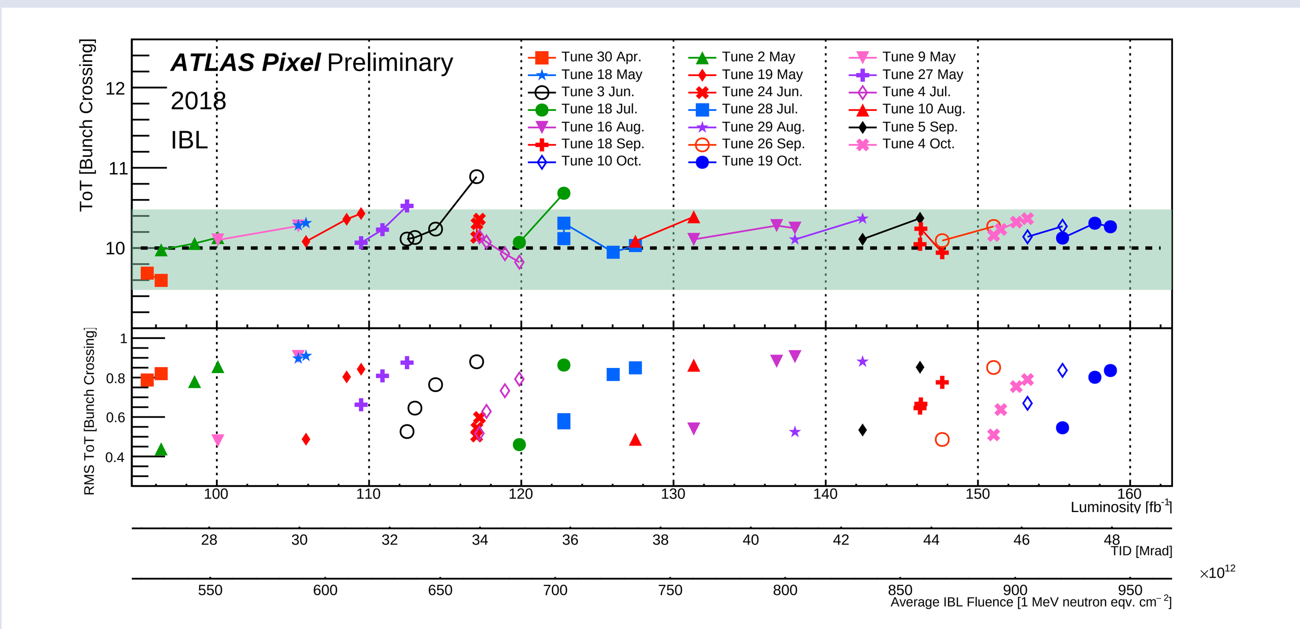
ATLAS recorded luminosity

2. Detector Operation

- Pixel detector data quality efficiency was 99.5 % in Run 2
- Analogue discriminator threshold adjustments due to bandwidth limitations with increasing pile-up
- Low voltage transistor leakage current dependence on total ionising dose (TID) in IBL front-ends
  - → Threshold & time-over-threshold (ToT, related to charge deposition and dissipation) drift due to TID
  - → Frequent retuning required



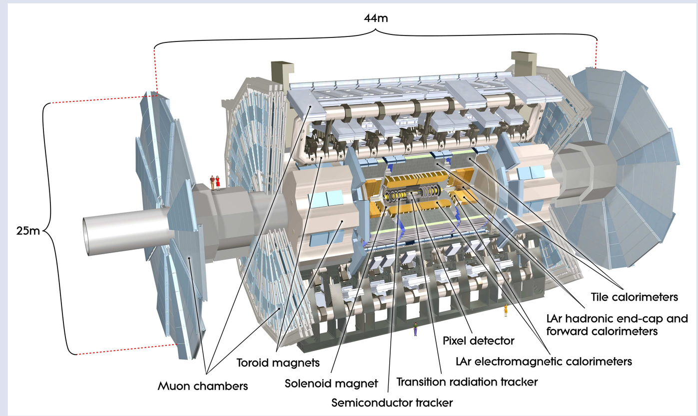
Bandwidth usage vs. avg. pile-up per lumi block (∼ 60 s) during 2018 with 3σ error bars. L0-L2 denote the Pixel layers, ECA/ECC the endcaps.



IBL time-over-threshold means and RMS values for recalibrations performed during 2018

The ATLAS Pixel Detector

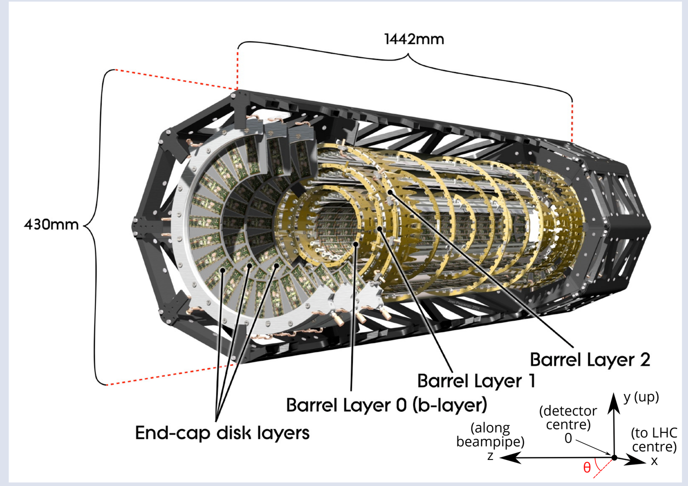
- Silicon pixel detector, innermost part of ATLAS detector
- Critical for particle tracking and b-tagging (flagging b-flavour jets)
- During Run 1 (2010 - 2012) 3 tracking layers and 3 disk endcaps per side
- Insertable B-layer (IBL) added during Long Shutdown 1 (2013 - 2014)
  - Planar sensors (in central region) and 3D sensors installed



Cut-away of the ATLAS detector

	Pixel (+Endcaps)	IBL
Pixel Size [μm²]	50×400	50×250
Target Spat. Resolution [μm²]	10×115	10×40
No. Channels	80×10^6	12×10^6
Front-End CMOS Technology	250 nm	130 nm
Radius [cm] (Pixel: Layers Only)	5.05 8.85 12.25	3.35
Max. Fluence [1 MeV n_{eq} cm^{-2}]	1×10^{15}	5×10^{15}
Max. Bias Voltage [V]	600	1000

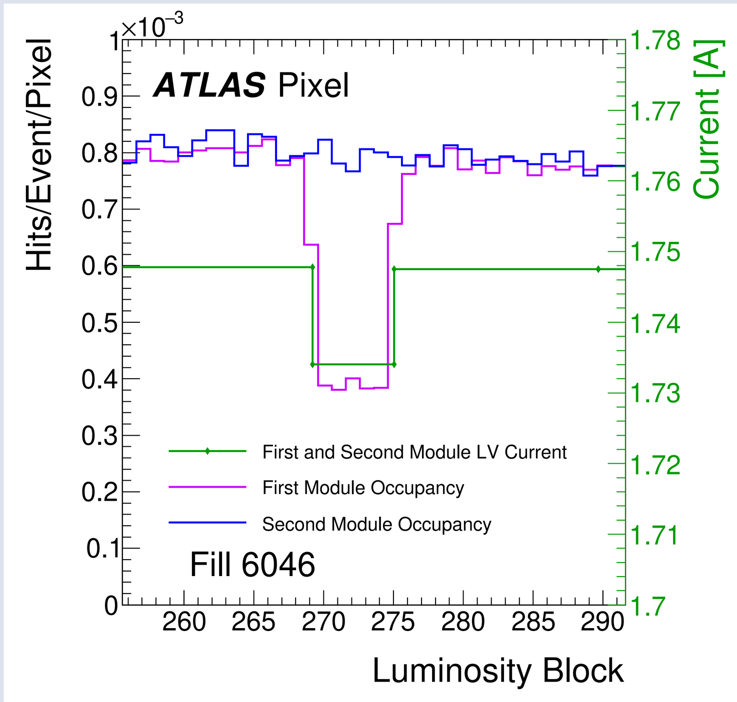
Technical design parameters of IBL and Pixel



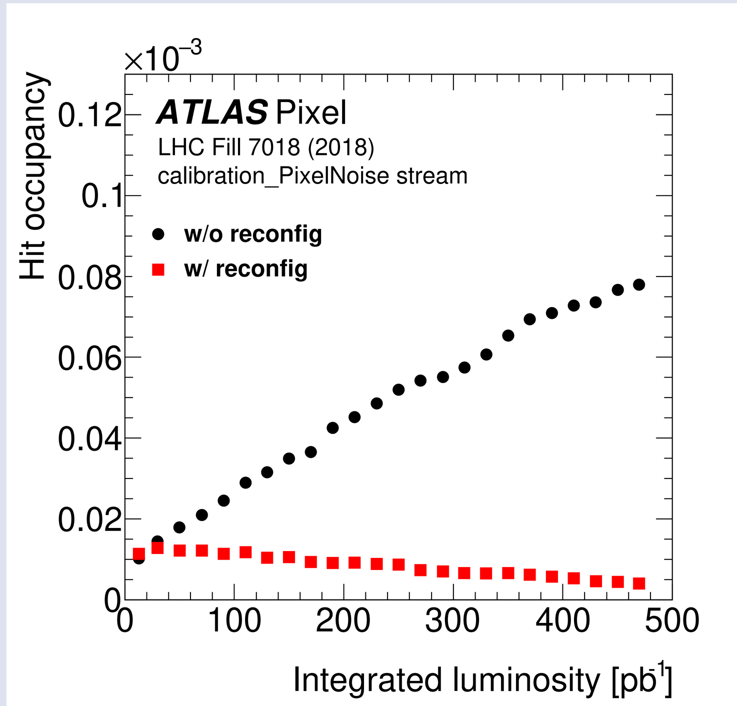
Schematic of the ATLAS Pixel detector (pre-IBL) with added detector coordinate system

3.1 Single Event Effects

- Ionising particles may corrupt single pixel or global front-end module registers
  - Altered registers usually not read back during data taking
  - Results in quiet (if pixel enable bit flips) or noisy pixels and low-voltage current changes depending on specific fault, mostly in IBL
- Periodic reconfiguration without additional dead-time of global (single pixel) registers successfully deployed (tested) during Run 2 [1]



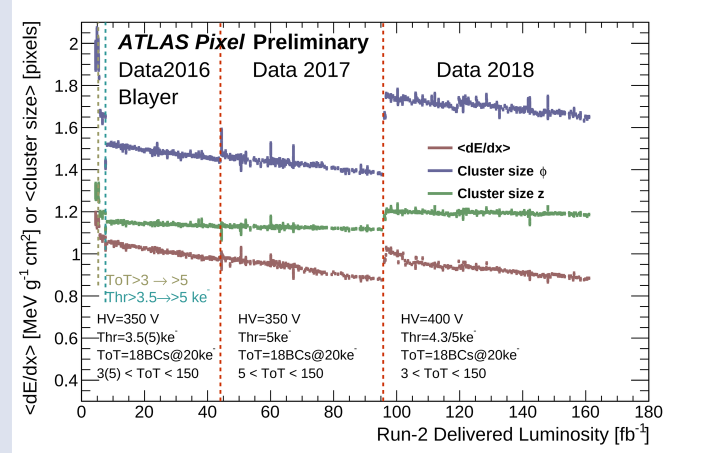
Single event effect in IBL global register. The resulting current change and occupancy drop is later fixed via manual reconfiguration.



Hit occupancy of IBL modules with (red) and without (black) automatic pixel register re-configuration during regular detector re-synchronisation periods to avoid introducing detector dead-time.

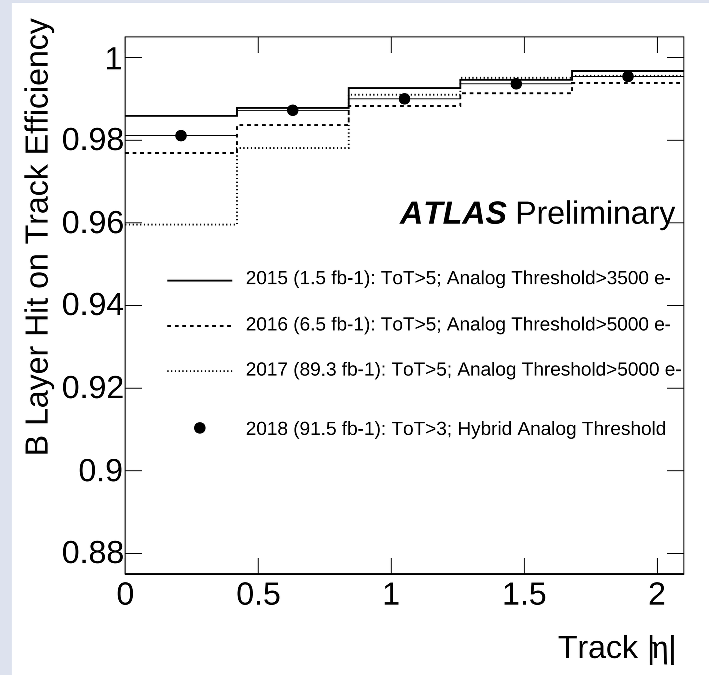
[1] G. Balbi, et al., JINST **15**, P06023 (2020)

3.2 Radiation Damage & Mitigation

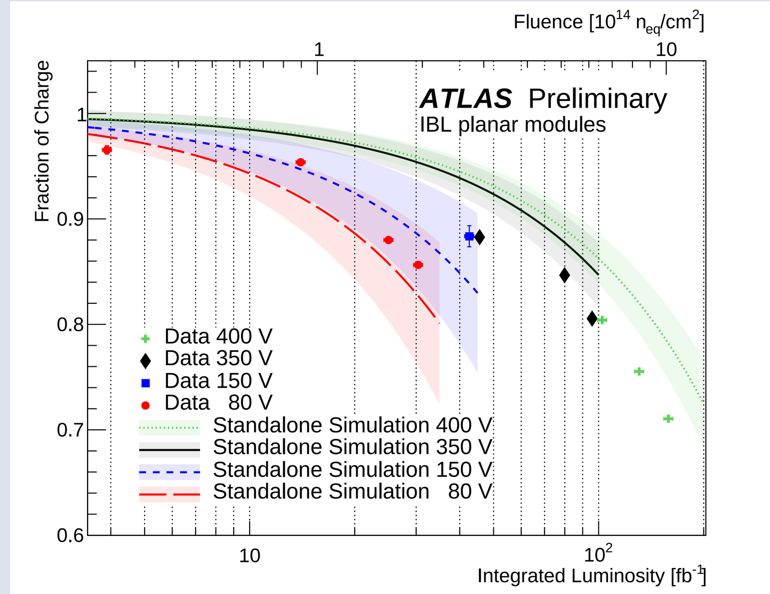


Evolution of $\langle dE/dx \rangle$ and cluster sizes for Pixel B-layer during Run 2. The steady decrease is due to radiation damage, the jumps due to changes in the calibration, especially the threshold.

- During Run 2, IBL received fluence of up to $\Phi = 1 \times 10^{15}$ 1 MeV $n_{\mathrm{eq}}\,\mathrm{cm}^{-2}$, less for outer layers
- Charge collection efficiency decreased due to charge trapping
  - Compensated with lower threshold
  - → Balance between bandwidth capabilities and radiation damage
  - η-dep. (hybrid) threshold used to address variable fluence in 2018
- Pixel bias voltage increased yearly to ensure full depletion
- Pixel digitisation model including fluence effects developed for Run 3 [1]



B-layer hit-on-track efficiency (tracks with a hit on the B-layer as a fraction of total tracks fulfilling selection criteria) vs. pseudorapidity $\eta = -\ln(\tan(\theta/2))$, i.e. polar angle proxy with central values near origin). The hybrid threshold is 4300 e⁻ in the four central modules and 5000 e⁻ elsewhere.



Charge collection efficiency in central IBL modules vs. integrated luminosity. Run 2 data is compared with a radiation damage simulation. At the end of Run 2, the efficiency has decreased to 70 %.

[1] M. Aaboud, et al. (ATLAS), JINST **14**, P06012 (2019), see poster 418 (*Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector*) as well for more details

Conclusions & Outlook

- ATLAS Pixel detector showed excellent performance during Run 2 despite large increases in luminosity, pile-up, and particle radiation
- Radiation damage visible for Pixel detector – especially for IBL – but did not significantly affect physics results yet
- Yearly increase of bias voltage for continued complete depletion, danger of B-layer bias voltage exceeding service limits during Run 3
- Radiation damage will be an ongoing concern for Run 3

⇒ First mitigation strategies were developed during Run 2, will be further refined during Run 3:
  - Hybrid threshold calibration for balance between bandwidth and radiation damage, plans to decrease thresholds overall
  - Automatic single (global) pixel register re-configuration in IBL (all modules)
  - New ATLAS Pixel digitisation model including fluence effects for understanding and anticipating calibration needs

† christian.scheulen@phys.uni-goettingen.de