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

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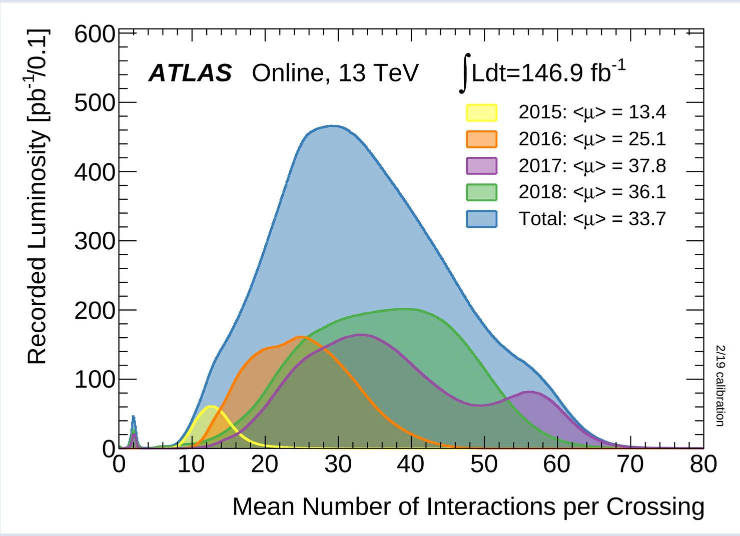
1. Data Taking Conditions

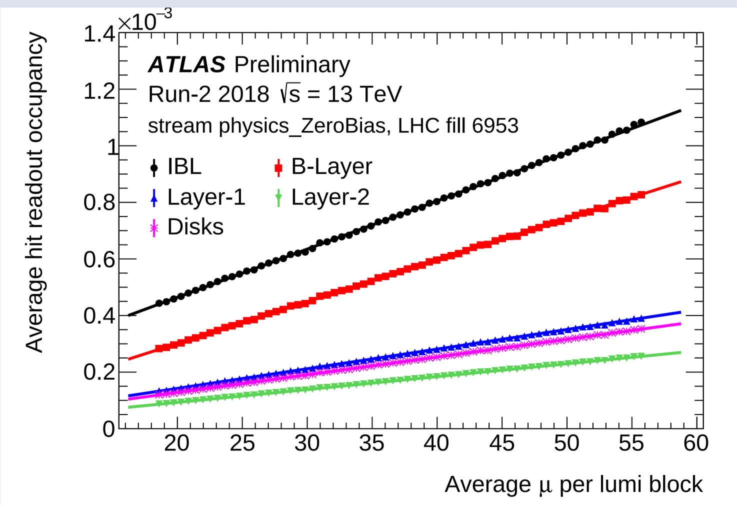
LHC Run 2 conditions (2015 - 2018) compared to end of Run 1 (2011-2012):

- Bunch crossing (BC) time (collision interval) halved from 50 ns to 25 ns
- Higher instantaneous luminosity (up to $2 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$) & collision energy, increased from 8 TeV to 13 TeV
  - → Peak $\mu \sim 60$ reached
- Overall luminosity $\mathcal{L}_{\text{int}} = 156\,\text{fb}^{-1}$ delivered by LHC (Run 2)

⇒ Challenging data taking conditions



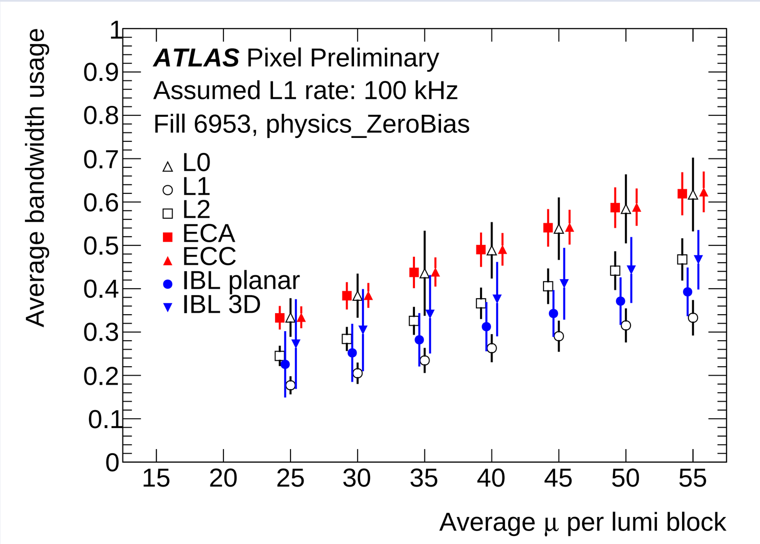
Pile-up distribution



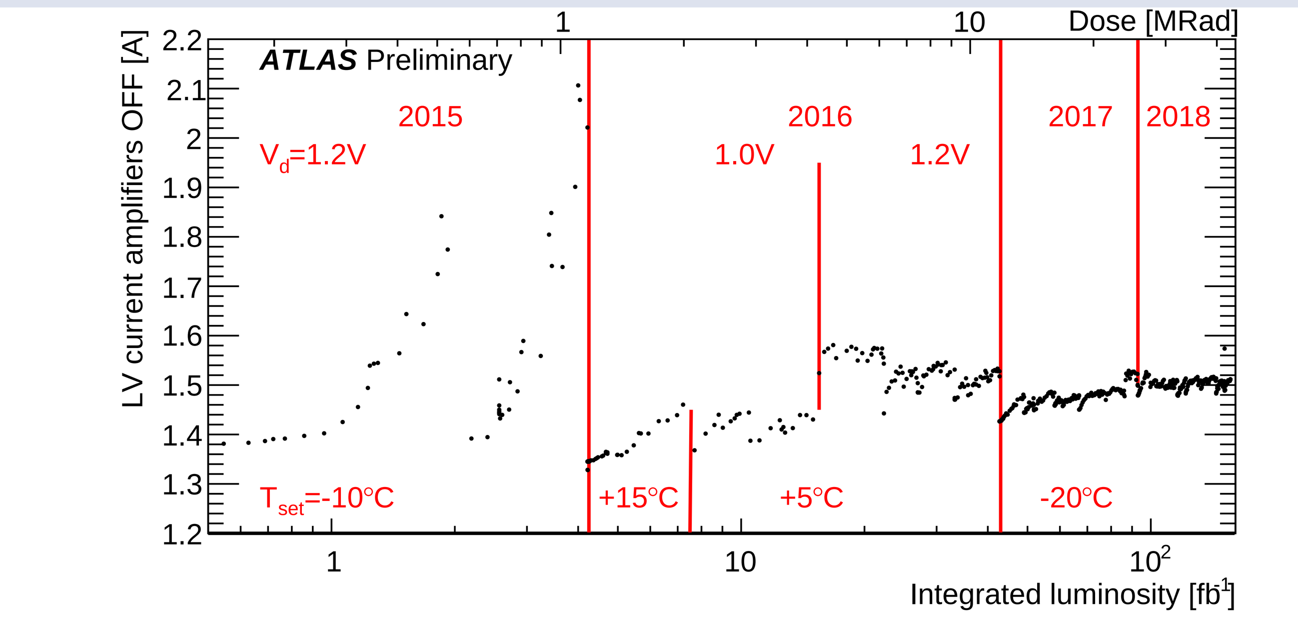
Average hit readout occupancy plotted against average pile-up

2. Detector Operation

- Pixel detector data quality efficiency was 99.5 % in Run 2, with <5% non-working modules
- Desynchronisation errors below 1%
  - → a lot of effort for readout upgrades and DAQ Fw/Sw developments necessary
- Low voltage transistor leakage current dependence on total ionising dose (TID) in IBL front-ends
  - → Was a big problem
  - → Threshold & time-over-threshold (ToT, related to charge deposition) drift due to TID
  - → Frequent retuning required
- Some optoboards failed (most likely due to humidity)
- Optimise threshold due to bandwidth limitations with increasing pile-up



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.



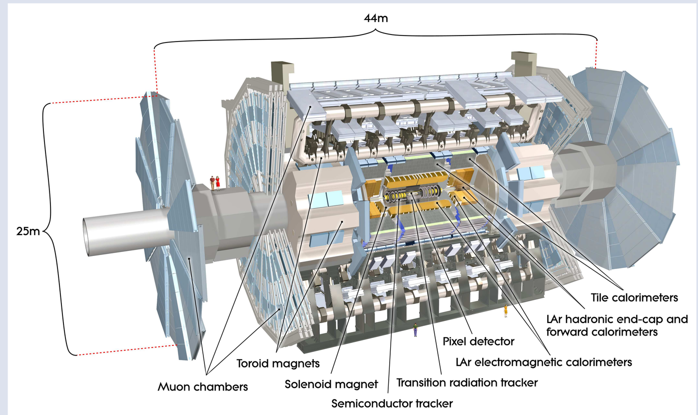
IBL low voltage module current shown as a function of integrated luminosity and TID.

The ATLAS Pixel Detector

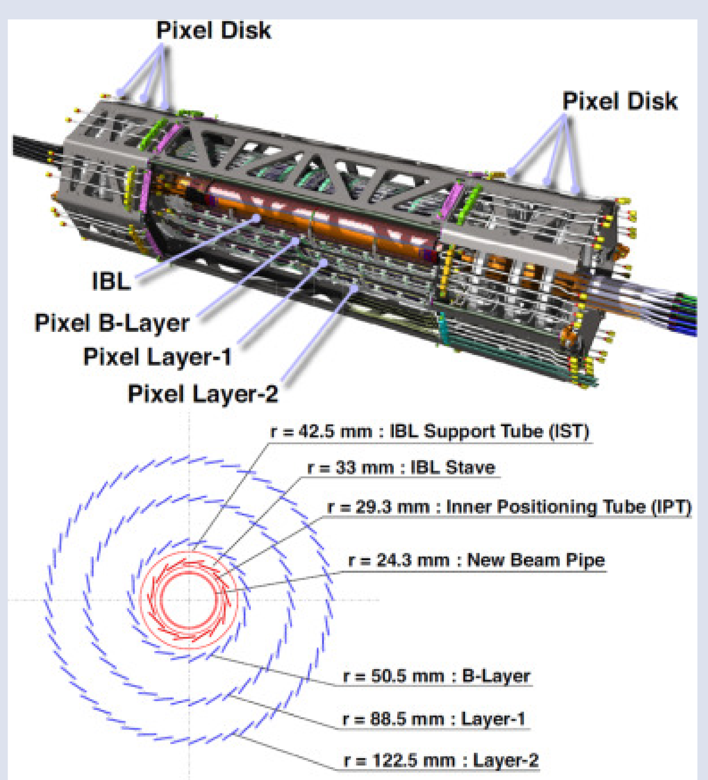
- Silicon pixel detector, innermost part of ATLAS detector
- Critical for particle tracking and b-jet-tagging
- During Run 1 (2010 - 2012) 3 barrel layers and 3 disk endcaps per side
- A 4th barrel layer (Insertable B-Layer - IBL) was added during Long Shutdown 1 (2013 - 2014)
  - → Planar sensors in central region and 3D sensors in the forward area

	Pixel (+Endcaps)	IBL
Pixel Size [μm²]	50×400	50×250
Target Spat. Resolution [μm × μm]	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



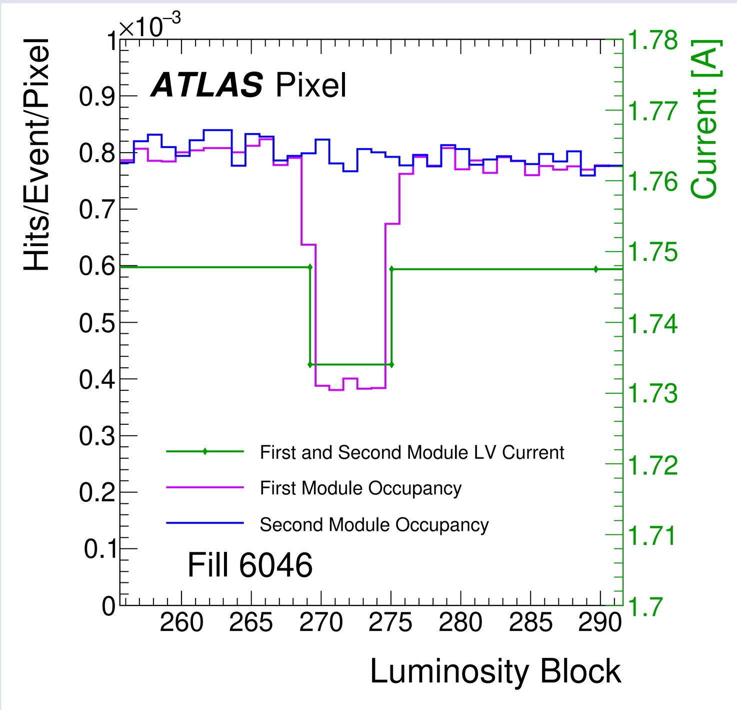
Cut-away of the ATLAS detector



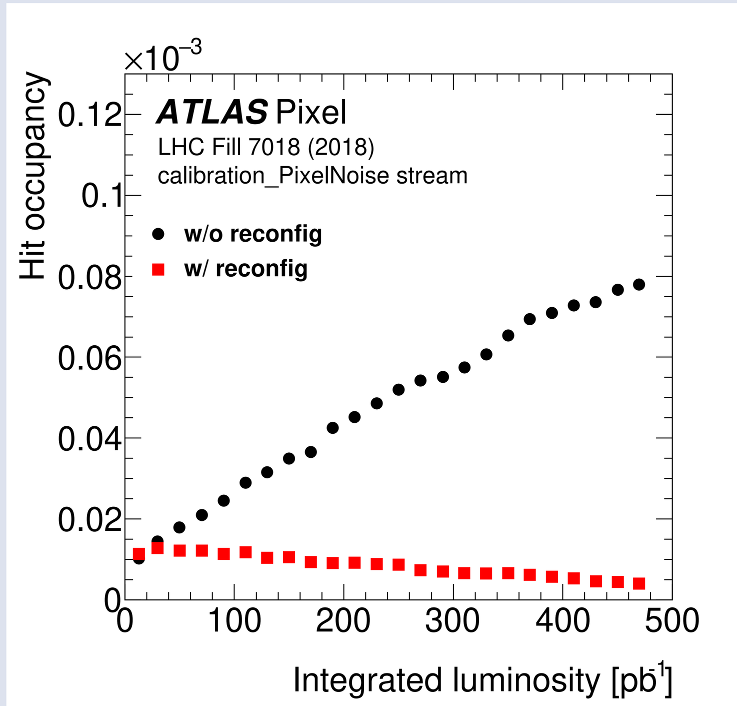
Schematic of the ATLAS Pixel detector

3.1 Single Event Effects (SEE)

- Front-end memory cells designed to be radiation-hard
- Ionising particles may corrupt single pixel or global front-end module registers
  - → 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 (every 5 sec.) 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.

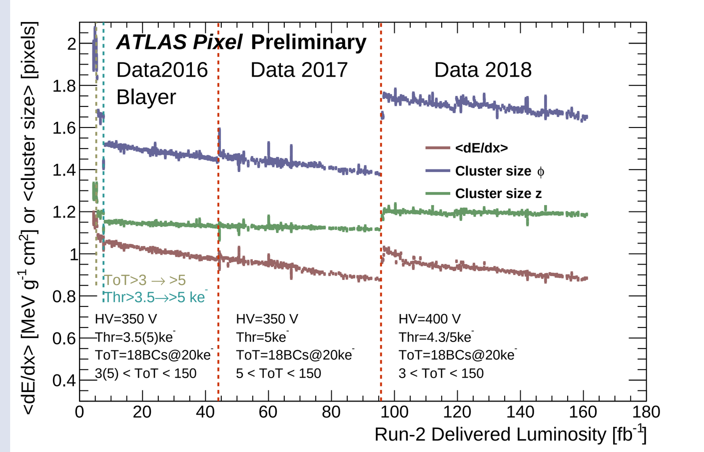


Hit occupancy of IBL modules with (red) and without (black) automatic pixel register re-configuration during regular detector re-synchronisation periods to avoid introducing detector dead-time.

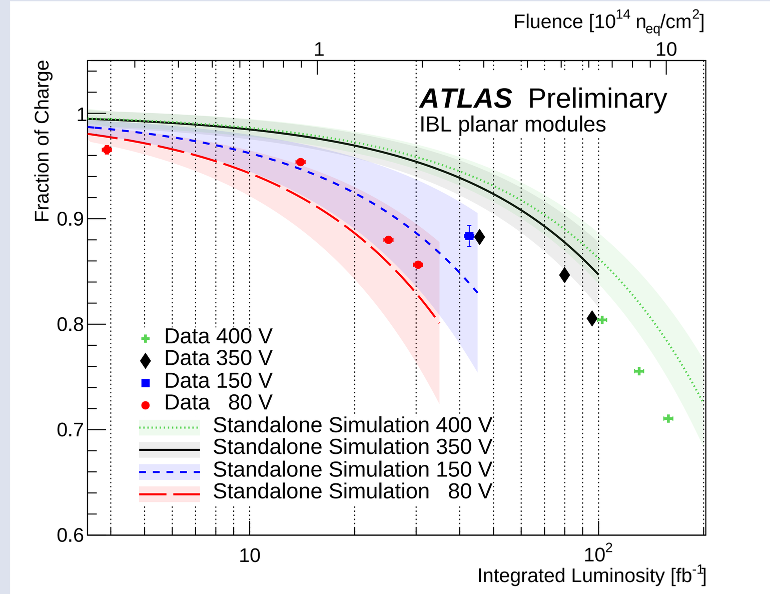
[1] G. Balbi, et al., JINST **15**, P06023 (2020)

3.2 Radiation Damage & Mitigation

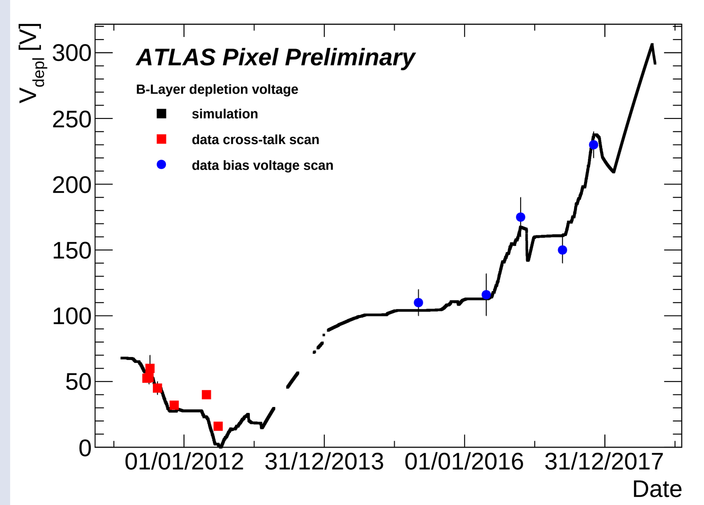
- During Run 2, IBL received fluence of up to $\Phi = 1 \times 10^{15}$ 1 MeV $n_{\text{eq}}\,\text{cm}^{-2}$, less for outer layers
- Charge collection efficiency decreased due to charge trapping
  - → Compensated with lower threshold
  - → Balance between bandwidth capabilities and radiation damage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



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.



Decreasing 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 %.



Simulated full depletion voltage of the B-Layer of the ATLAS Pixel Detector according to the Hamburg model. The prediction for 2018 assumes 70 fb^{-1} of integrated luminosity to be delivered to ATLAS.

[1] M. Aaboud, et al. (ATLAS), JINST **14**, P06012 (2019)

Operation Plans for Run 3

- 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, 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
- Pixel detector kept cold during long shutdown 2 to minimise reverse annealing
- Radiation damage will be an ongoing concern for Run 3

⇒ Operation conditions optimised during Run 2; further refined in Run 3:

- → Optimise 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 → also used in official ATLAS MC production

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