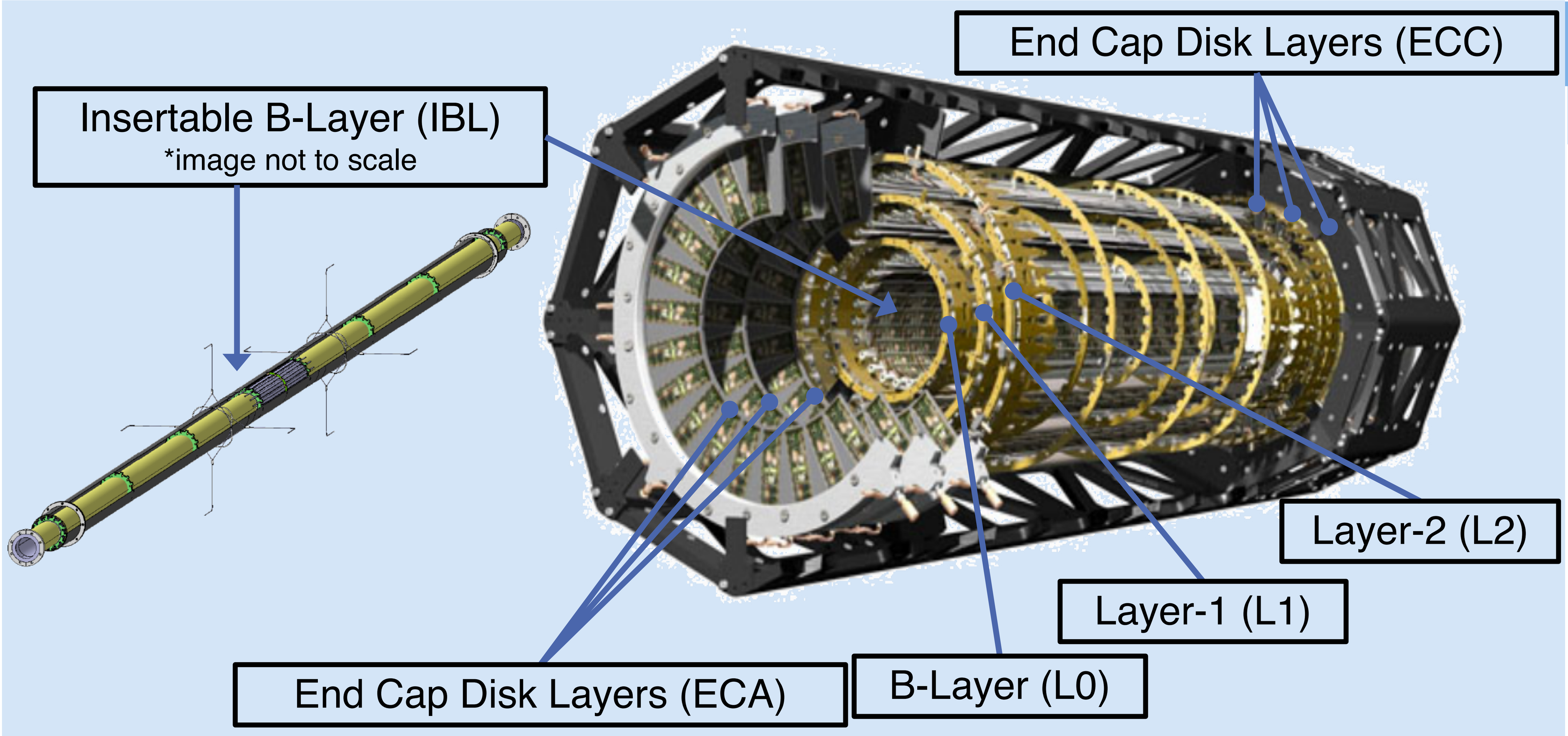
Operational Experience with and Performance of the ATLAS Pixel Detector at the Large Hadron Collider

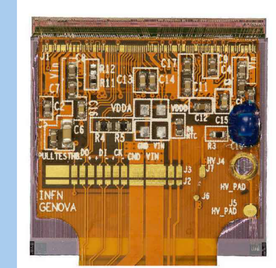
This poster summarizes the operational experience and requirements to ensure optimum data quality and data taking efficiency with the 4-layer ATLAS Pixel Detector. The detector has undergone significant hardware and software upgrades to meet the challenges imposed by the LHC's exceeding expectations for instantaneous luminosity by more than a factor of two (more than 2 $\times 10^{34}$ cm^{-2} s^{-1}). Emphasizing radiation damage effects, the key status and performance metrics are described in detail below.



ATLAS Pixel Detector

The ATLAS Pixel Detector is made up of four barrel layers and three disks per endcap

- The original detector (before to the installation of the IBL) has been used from start of LHC Run 1 (2011).
  - It has more than 80 million readout channels.
  - It is made up of n^{+}-in-n Si sensors with 250 μm thickness.
- The new innermost layer, the Insertable B-Layer (IBL), was installed before the start of LHC Run 2 (2015); it improves tracking performance and will compensate for the anticipated aging of the B-Layer.
  - It has a radial distance of 3.3 cm and a 10 mm envelope.
  - It has more than 12 million readout channels.
  - It is made up of planar and 3D Si sensor technologies with thicknesses 200 μm and 230 μm, respectively.



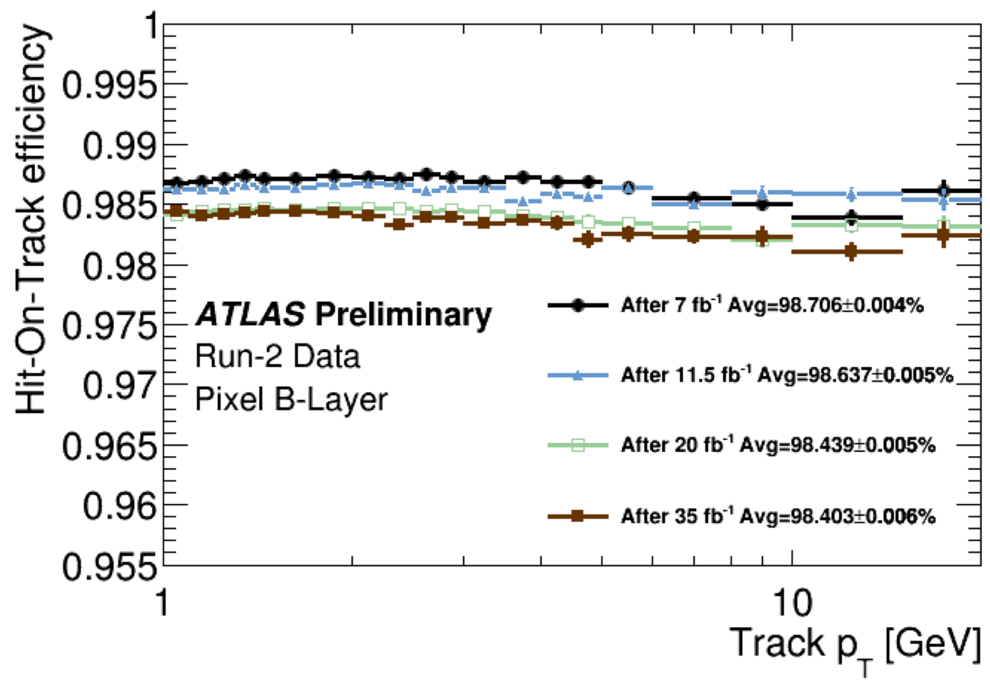
Picture of an IBL module.

Charge Collection Efficiency Related Effects

Hit-On-Track Efficiency

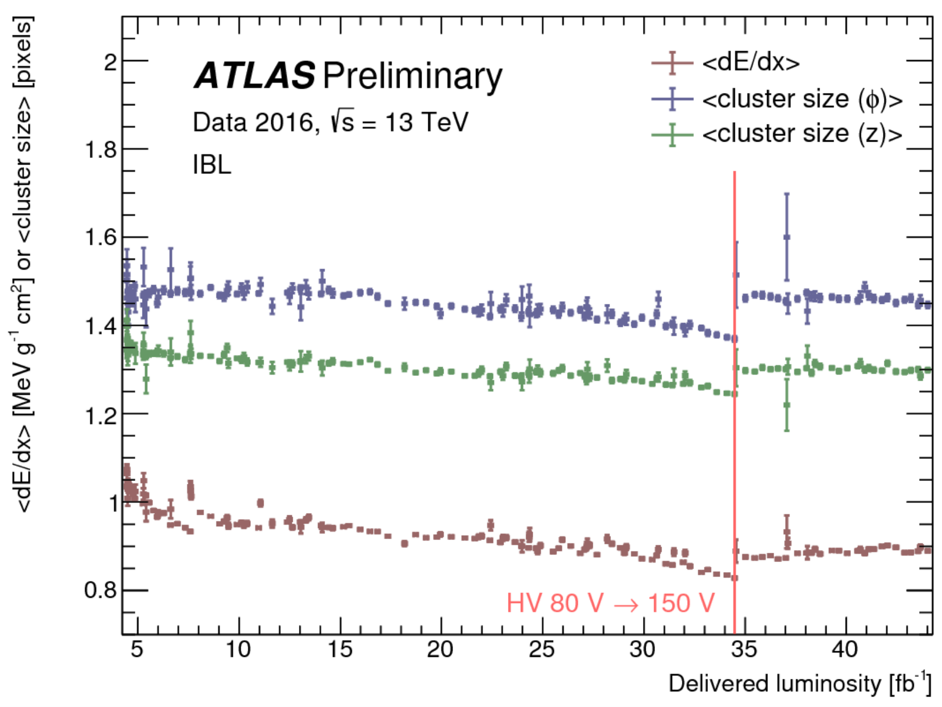
A decrease in hit-on-track efficiency with increasing integrated luminosity, attributed to radiation damage, was observed with the B-Layer in 2016.

- As the total integrated luminosity increases, the hit-on-track efficiency decreases due to radiation damage.
- The hit-on-track efficiency in the Pixel B-Layer is shown as a function of the track transverse momentum (p_T) measured with four LHC fills with increasing total integrated luminosity in 2016.



dE/dx

A gradual decrease in average cluster sizes and dE/dx throughout 2016 is visible, consistent with radiation damage. The effect of under depletion and improvement from increasing the bias voltage are visible.



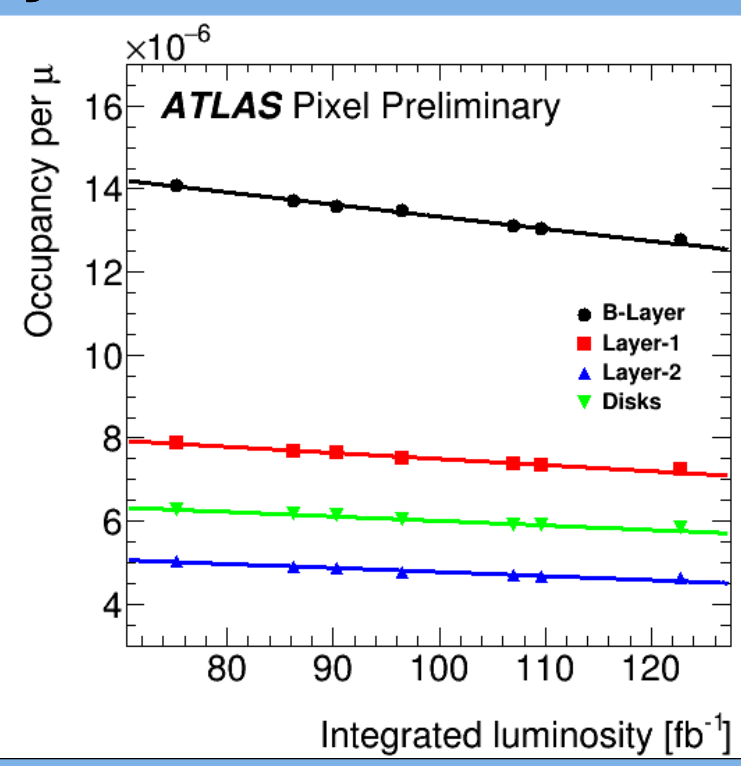
- The dE/dx is calculated from the collected charge in each cluster, corrected for the path length of the track in the module, the energy required to create an electron-positron pair, and the material density*.

* Eur. Phys. J. C (2017) 77: 673

Occupancy

A decrease of hit occupancy over the number of interactions per bunch-crossing (μ) due to radiation damage in the Pixel layers in 2017 was observed.

- The hit occupancy is the number of hits per pixel per event.
- The data points include error bars
- The absolute slopes of the fitted lines decrease for layers with lower occupancy per μ.



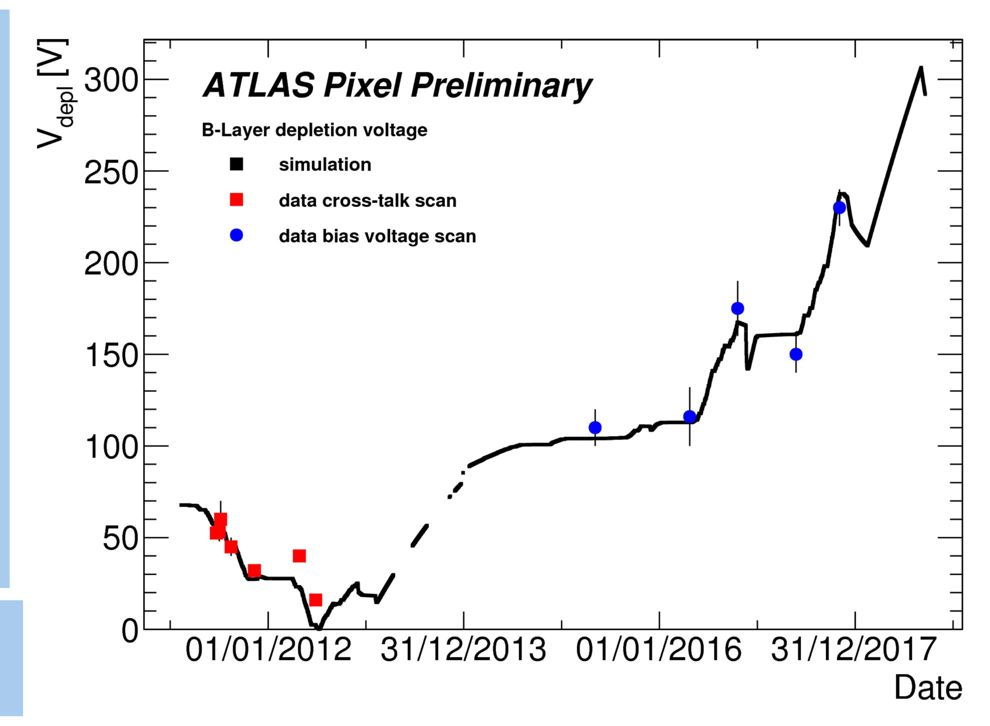
Sensor Characteristics

Depletion Voltage

The sensor bias voltage is increased before each data taking year using the predicted voltage to obtain full depletion.

- Measurements of the depletion voltage using the cross-talk scan and bias voltage scan methods are shown in the figure.
- Simulated depletion voltage of the B-Layer is shown according to the Hamburg model*.

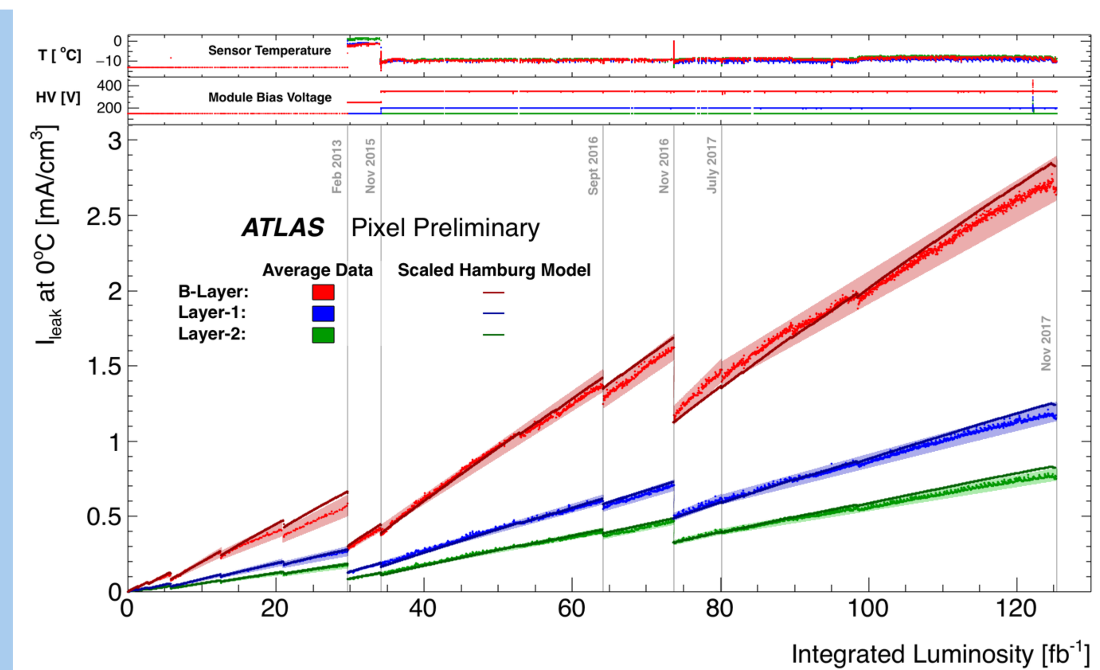
* M. Moll,'Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties', PhD thesis: Hamburg U., 1999 and references therein.

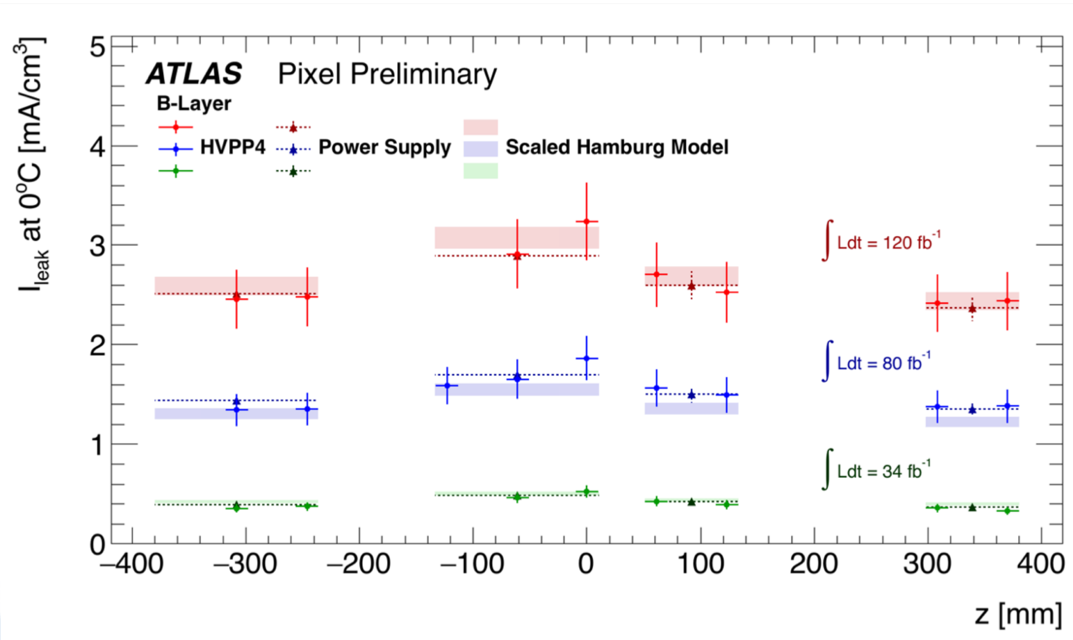


Leakage Current

Observed leakage current levels are increasing as a function of integrated luminosity. The expected annealing effects are also visible. The scaled Hamburg model matches the data and can be used to predict leakage current.

- Average measured leakage current data are consistent with expected higher levels of radiation for sensors closer to the beam line in the figure on the right.
- The average module sensor temperature and the average module bias voltage are shown.





- B-Layer leakage current data binned in z (the axis along the beam line) measured at three values of integrated luminosity using single module precision with the HVPP4 subsystem and multiple module precision with the module power supply subsystem, are shown on the left.

The effects of the radiation that the Pixel Detector has been exposed to are visible in charge collection efficiency data and detector characteristics. In order to counteract performance degradation, working points are optimized. Radiation damage is addressed through reduction of the thresholds to recover lost hits. The Insertable B-Layer (IBL) plays a crucial role in ensuring that the detector is operating with high efficiency. Keeping the temperature of the detector cold during operation and shutdown periods is essential for maintaining operable levels of the increasing depletion voltage and leakage current. Predictions of depletion voltage and leakage current match the data and can be used to extrapolate to the future.

Aidan Grummer (on behalf of the ATLAS Collaboration)