Measurement of the effective silicon band gap energy with the ATLAS Pixel detector

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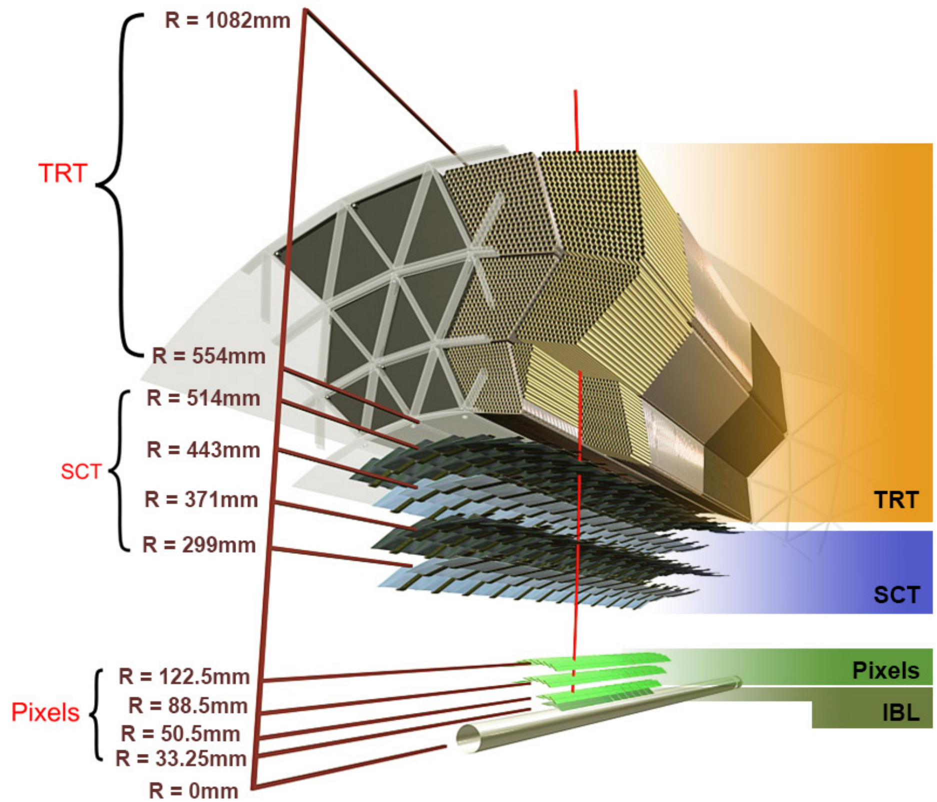
Introduction

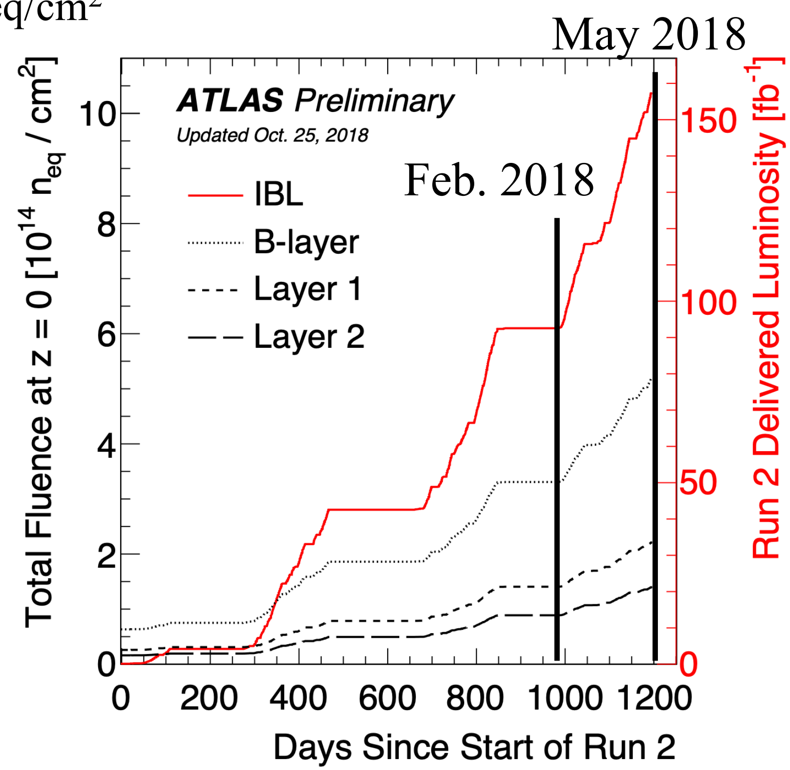
- The best value of the effective silicon band gap energy (E_{eff}) for use in normalizing silicon sensor leakage current to a reference temperature is investigated
- Prior to this study, E_{eff} = 1.21 eV has been widely used in the community †
- The study presented today investigates all layers in the ATLAS Pixel detector
  - For all modules on IBL
  - For a representative sample of modules on B-Layer, Layer-1, Layer-2, and the Disks



† A. Chilingarov, Temperature Dependence of the Current Generated in Si bulk, 2013 JINST 8(10) P1000, http://iopscience.iop.org/article/10.1088/1748-0221/8/10/P10003

Sensor Conditions

- Data for this study were collected in:
  - Feb. 2018 for IBL modules
  - May 2019 for all layers and disks in the ATLAS Pixel detector
- The fluence history since the start of Run 2 is shown in the figure
  - In Feb. 2018, the IBL had received a fluence of ~ 6×10^{14} 1 MeV neq/cm^2
  - In May 2019, the IBL had received a fluence of ~ 1×10^{15} 1 MeV neq/cm^2 and the B-Layer had received ~ 5×10^{14} 1 MeV neq/cm^2
- B-Layer, Layer-1, Layer-2, and the Disks were installed before Run 1 and underwent annealing during LS1
- IBL was installed during LS1, and received higher fluence due to its proximity to the beam line (3 cm)
- The sensors are currently being kept cold to prevent annealing



Strategy

- The temperature of the Pixel detector modules are set to several fixed values and both the temperature and the leakage current are measured.
- The analysis is performed by applying the temperature correction equation to the leakage current data for a range of E_{eff} values (from 0.5 eV to 1.5 eV, steps of 0.01 eV)
- A linear fit is performed to each temperature corrected leakage current and the χ^2 value of each fit is determined
- The optimal E_{eff} value corresponding to the minimum χ^2 is determined for each module in the study

The Temperature Correction Equation*:

$$I(T) = I(T_R)/R(T), \text{ where } R(T) = (T_R/T)^2 \cdot \exp\left(-\frac{E_{eff}}{2k_B}(1/T_R - 1/T)\right)$$

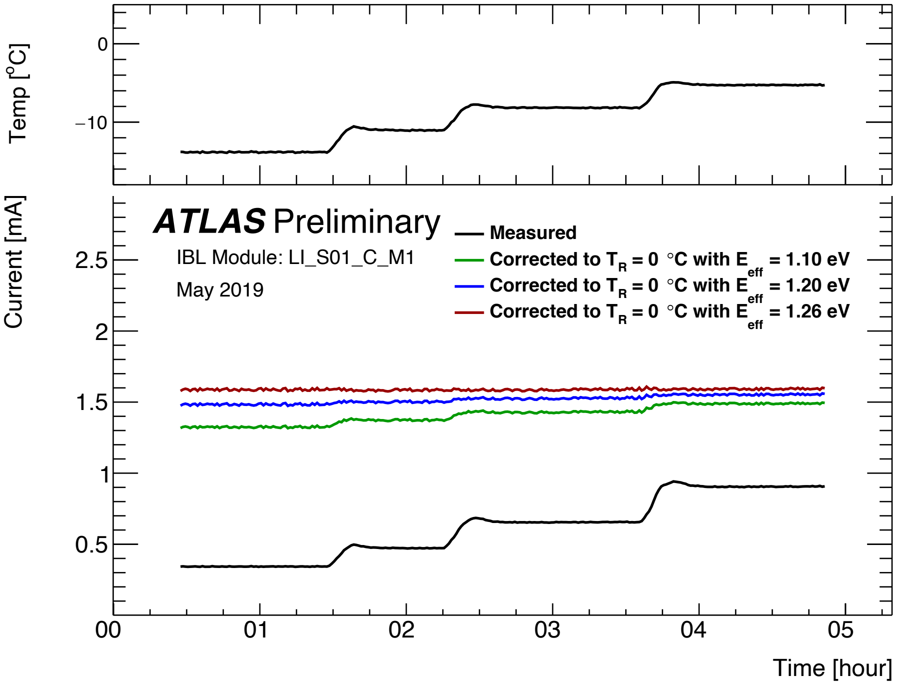
$T_R = 0\ ^{o}C$ is used in this analysis

*S.M. Sze, Physics of Semiconductor Devices, 2nd ed., Wiley, New York, 1984.

Performing the Study

- The impact of using different E_{eff} values in the temperature correction equation for one module on IBL is depicted in the figure.
  - (Top panel) The temperature of the Pixel Detector modules was set to several fixed values, and measured with the module temperature sensor.
  - (Lower panel) The leakage current data are measured (black line) and show a clear temperature dependence.
  - The leakage current is corrected to a reference temperature $T_R = 0$ °C with (green, blue, and red lines) several values of E_{eff}.

- The optimal value of E_{eff} in the temperature correction equation is the value that results in corrected leakage current data that best fits a line of zero slope.



χ^2 Determination

determining σ^2

- A region where the data are expected to stay constant is selected, and the standard deviation is computed for the leakage current and temperature data, separately.
- The temperature uncertainty is propagated through the leakage current temperature correction equation:
  - This is done for the mean temperature plus or minus the standard deviation of the temperature in the time window
- Changing the value of E_{eff} has an impact on σ^2 of:
  - 10% between 1.21 eV and 1.3 eV
  - 10% between 1.12 eV and 1.21 eV
- A change in σ^2 is effectively a scale factor in the χ^2 equation

- The χ^2 is determined using the data and fitted line for the full time span of the temperature scan data:

$$\chi^2 = \sum_{i=1}^{n} \frac{(x_i - \mu)^2}{\sigma^2}$$

Temperature Uncertainty

- An investigation on the temperature uncertainty has been performed.
- To determine the uncertainty due to temperature, a temperature variation (ΔT) is applied to the measured temperature and the search for the optimal E_{eff} value is repeated
  - This procedure is repeated for temperatures in the range -2 °C to 2 °C (in steps of 0.1 °C)

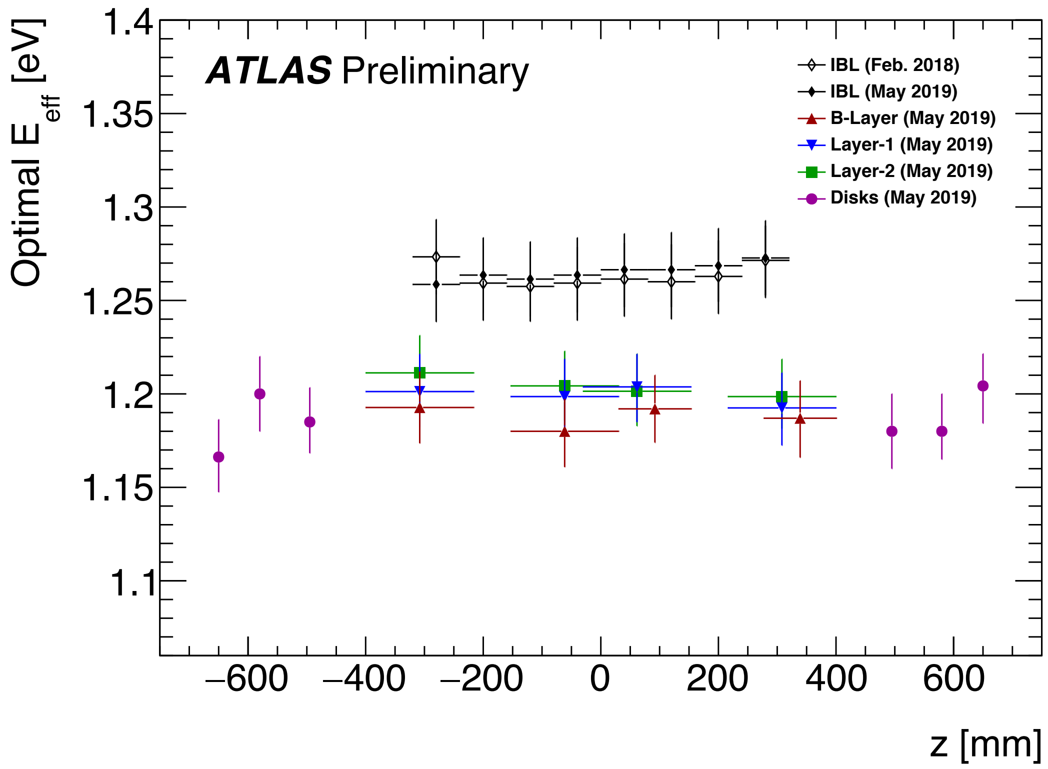
$$I(T_{\mathrm{R}}) = I_{meas} \times R(T + \mathbf{\Delta T})$$

$$R(T + \mathbf{\Delta T}) = \left(\frac{T_{\mathrm{R}}}{T + \mathbf{\Delta T}}\right)^2 \cdot \exp\left[-\frac{\mathbf{E_{eff}}}{2k_{\mathrm{B}}}\left(\frac{1}{T_{\mathrm{R}}} - \frac{1}{T + \mathbf{\Delta T}}\right)\right]$$

T_R = 0 °C is used in this analysis

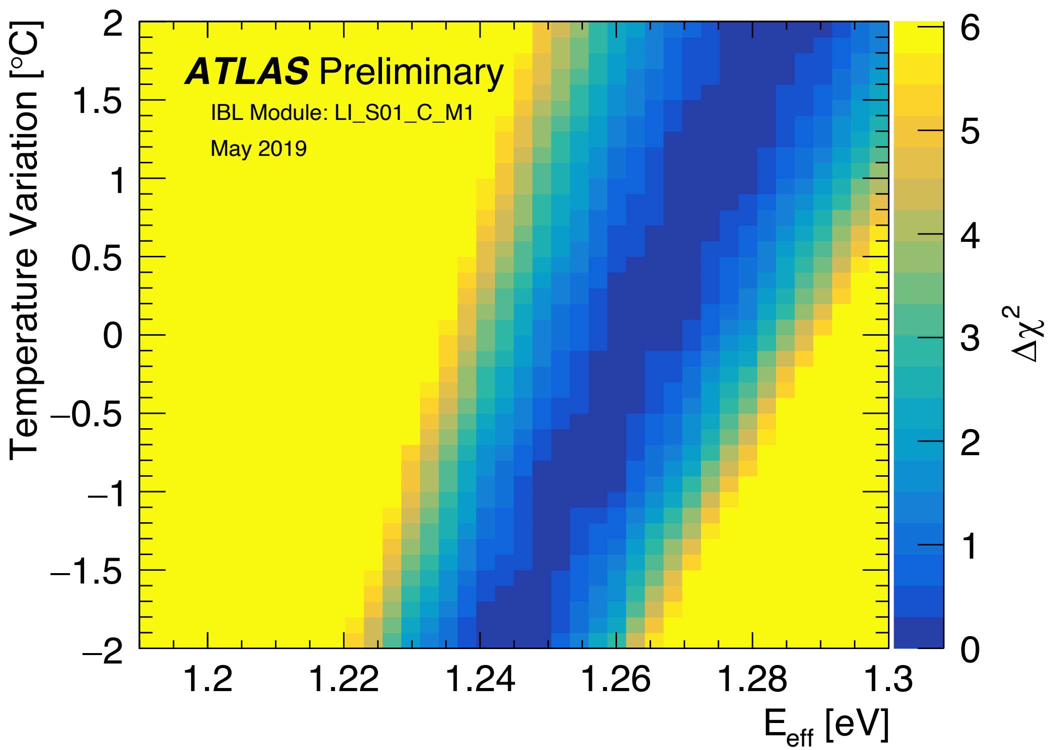
Summary of Results

- The optimal E_{eff} value is determined for each module and then the average value is computed in bins of z (the direction along the beam line) for each layer and disk.
  - The vertical errors bars represent the impact on the optimal E_{eff} value of ±2 °C uncertainty in the module temperature
  - Horizontal error bars represent the z bin ranges



Check Temperature Uncertainty and E_{eff} Simultaneously

- The χ^2 figure of merit is determined for a range of E_{eff} values and variations of the module temperature data
  - Figure shows the study for one module on IBL (LI_S01_C_M1)
  - Steps of 0.01 eV for E_{eff} and steps of 0.1 °C for temperature variation are investigated independently



Summary

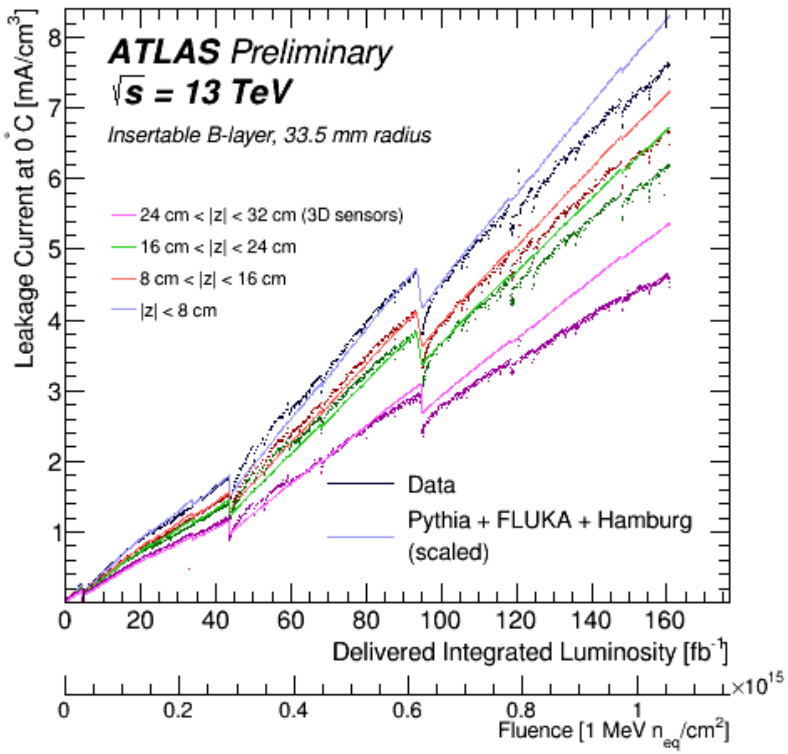
- The optimal E_{eff} search for all modules on IBL and a representative sample of modules on B-Layer, Layer-1, Layer-2, and the Disks has been performed
- Uncertainties due to ±2 °C temperature variations have been determined
- The results per layer are summarized here
  - The optimal E_{eff} value for IBL modules is higher than the nominal E_{eff} = 1.21 eV
  - The optimal E_{eff} value for the other layers is in agreement with E_{eff} = 1.21 eV

IBL: $1.26\text{ eV} \pm 0.01(stat) \pm 0.02(sys)$
B-Layer: $1.18\text{ eV} \pm 0.02(stat) \pm 0.02(sys)$
Layer-1: $1.20\text{ eV} \pm 0.01(stat) \pm 0.02(sys)$
Layer-2: $1.20\text{ eV} \pm 0.02(stat) \pm 0.02(sys)$
Disks: $1.19\text{ eV} \pm 0.02(stat) \pm 0.02(sys)$

Additional Slides

IBL Leakage Currents

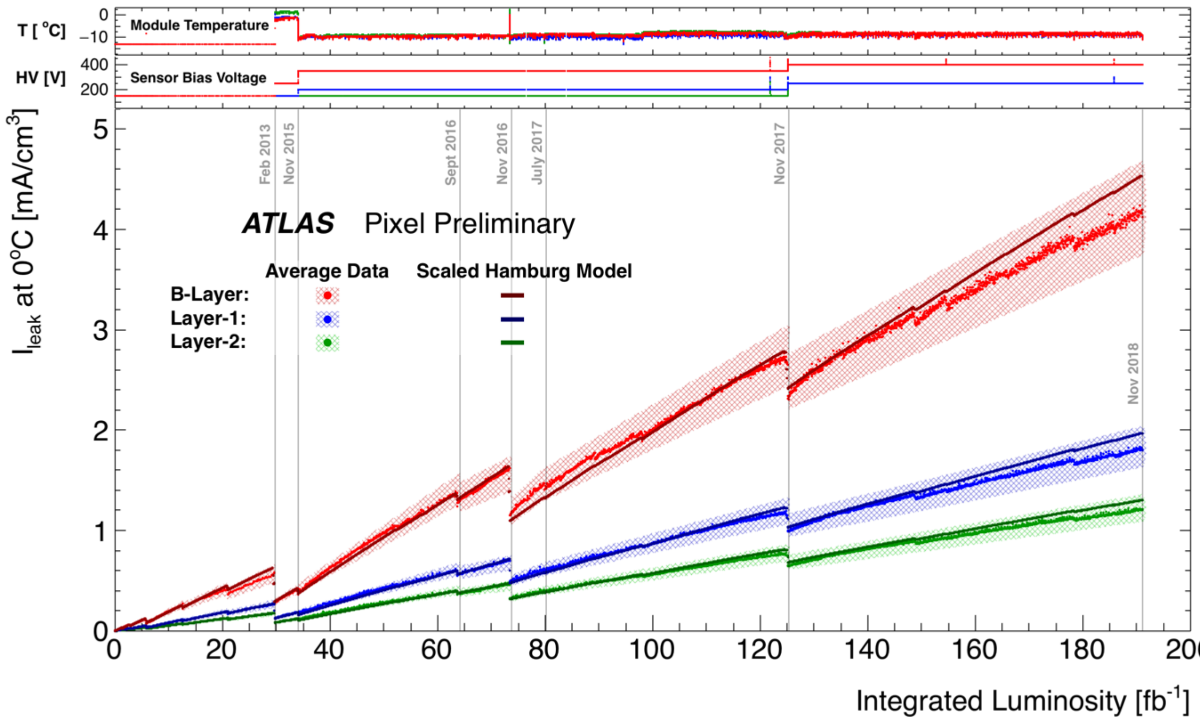
- The measured leakage current in modules from the Insertable B-layer (IBL) as a function of delivered integrated luminosity during the LHC Run 2
- The current is averaged over ϕ and also averaged over modules with a similar z



- Both planar and 3D sensors are measured and shown in the figure
- The high voltage was changed during 2016 from 80 V to 150 V, then to 300 V at the start of 2017 and then to 400 V at the start of 2018
- The high voltage of the 3D sensors was 20 V in 2015 and 2016, and increased to 40 V for the remainder of the run

Leakage Current in Pixel Barrel

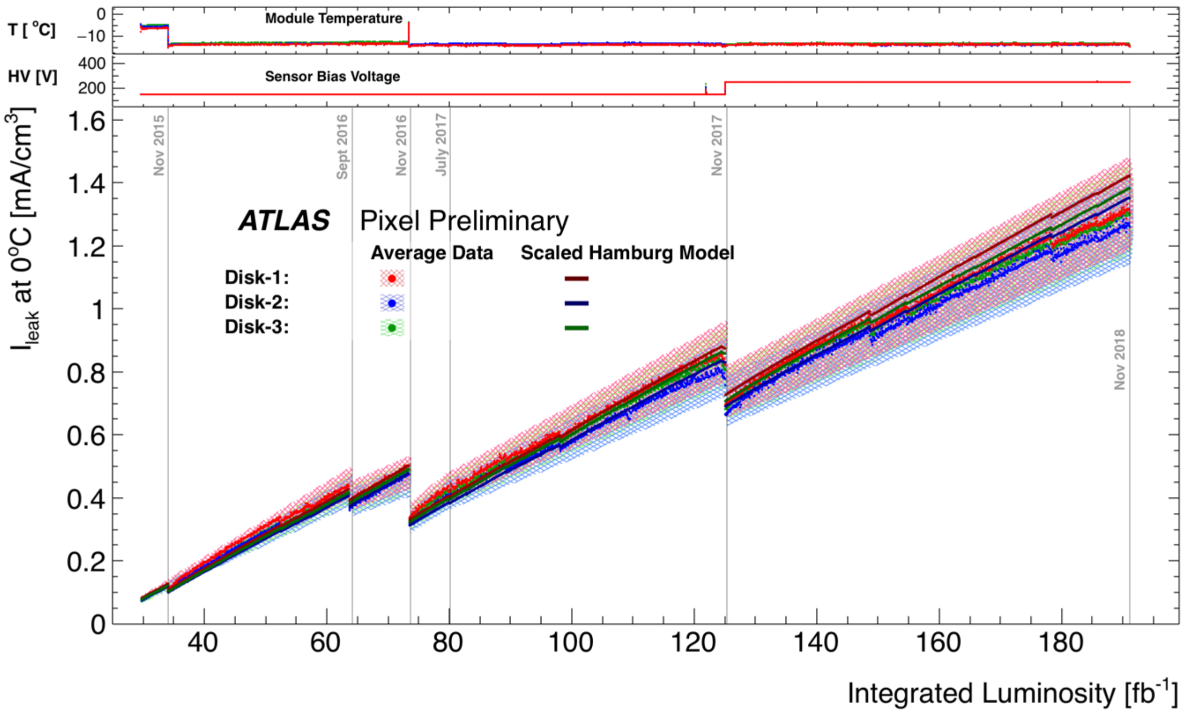
- Average leakage current data compared to the average scaled Hamburg Model predictions for each barrel layer through 2018
- The Hamburg Model predictions have been scaled to match the measured leakage current data



- Measurements on each layer are averaged over a representative sample of modules in η and ϕ.
- The measurements are consistent with expected higher levels of radiation for sensors closer to the beam line.
  - The B-Layer is located at r = 50.5 mm, 59 Layer-1 at 88.5 mm, and Layer-2 at 122.5 mm

Leakage Current in Disks

- Average measured leakage current data of a representative sample of modules in the ATLAS Pixel detector disks for the LHC Run 2 period of operation.
- Disk-1, Disk-2, and Disk-3 show comparable values of leakage current.



- Hamburg Model predictions for the leakage current on the Disks are also shown
- Each disk corresponds to both side A and side C of the Pixel Detector.
- The average module temperature and average sensor bias voltage are shown in the top panels