Measurements of Sensor Radiation Damage in the ATLAS Inner Detector using Leakage Currents

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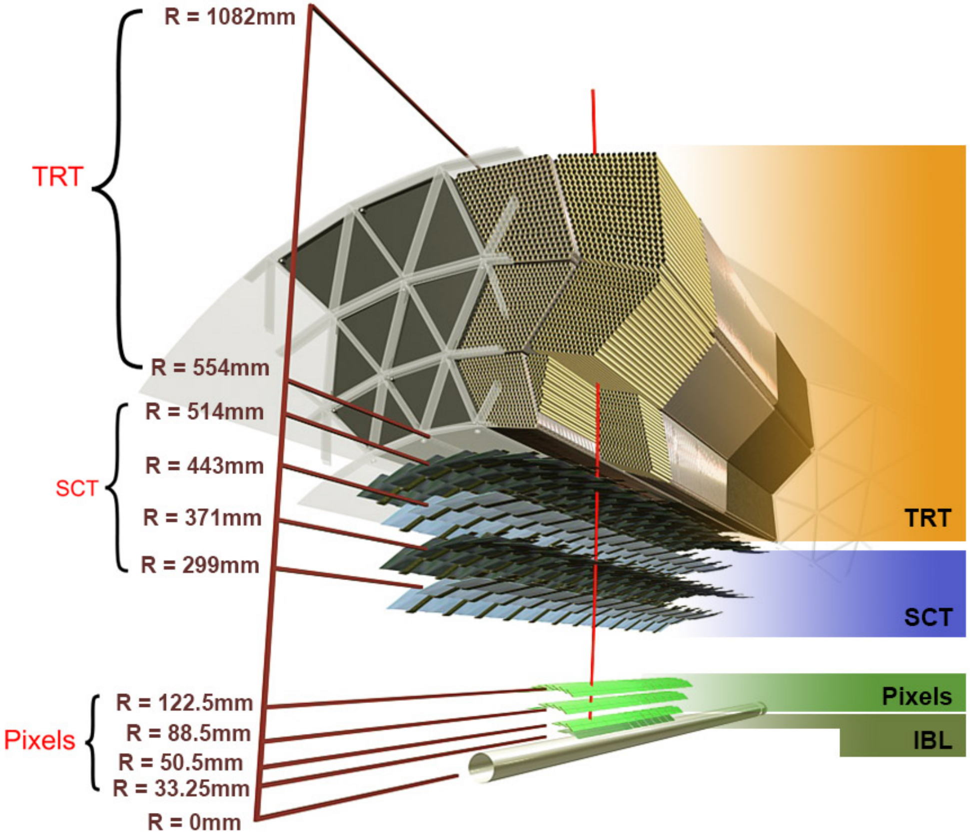
Introduction

- The ATLAS Pixel Detector and Semiconductor Tracker (SCT) are the subsystems closest to the interaction point – shown in the diagram.
  - As such, both subsystems will receive **high levels of radiation** throughout their lifetime
- Monitoring and modeling the bulk radiation damage to the Pixel Detector and SCT sensors is critical for
  - radiation protection
  - operational conditions
  - offline data analysis
  - upgrade design input
- One of the most well-characterized methods for monitoring silicon radiation damage is used in this study: **sensor leakage current.**



Expectations of the Measurement

- Leakage current in silicon sensors is an indicator of received non-ionizing fluence and radiation damage

$$\Delta I_{\text{leak}} = \alpha\, \Phi_{\text{eq}}\, V$$

  - Here, ΔI_{leak} is the difference in leakage current at fluence Φ_{eq} relative to the value before irradiation of the sensor depleted volume V, and α is the current-related damage coefficient

- The ATLAS-measured leakage current grows linearly with delivered integrated luminosity and demonstrates various annealing responses to temperature changes as expected

- The goal of this paper is to **compare I_{leak} with predictions of Φ_{eq}** either by transforming the leakage current to a fluence or by transforming the fluence into a leakage current **via α**.

Measuring I_{leak}

Measurement Details (I)

- Leakage current measurements are made using the HVPP4 subsystem data and the power supply leakage current data to confirm and augment the measurement
- The leakage current data are restricted to when high voltage is applied across the silicon sensors and when the LHC beams are declared stable
- **All fluence** received by the silicon sensors impacts the leakage current
  - The integrated luminosity used throughout this analysis includes the luminosity accumulated **outside of the LHC stable beams declarations**
  - The total integrated luminosity seen by the outer layers (all layers except IBL) for the full period of operation is **191.1 fb^{-1}**

Measurement Details (II)

- Sensor temperature data are used to normalize leakage current data to a reference temperature of 0 °C throughout the analysis
- This normalization uses the effective silicon band gap energy $E_{\mathrm{eff}} = 1.21$ eV throughout this analysis following previous studies[†]
- A dedicated study with the ATLAS Pixel Detector data of the proper E_{eff} to be used is included in the paper

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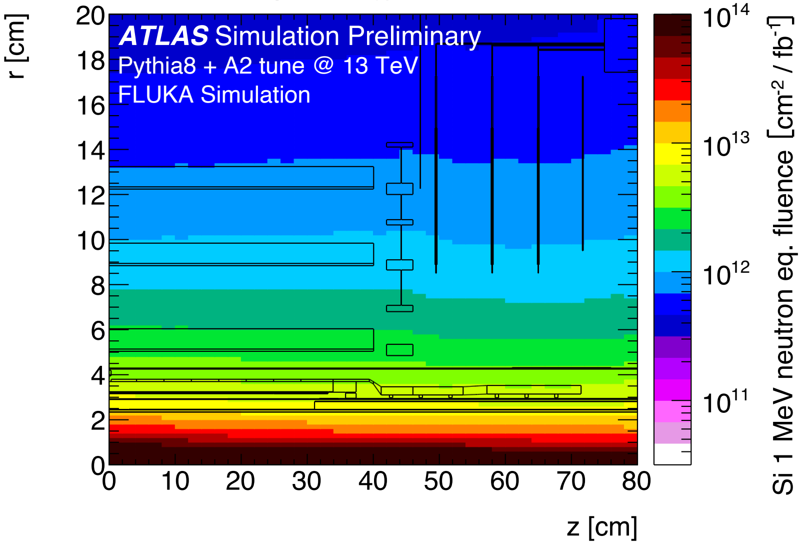
[†] A. Chilingarov, Temperature Dependence of the Current Generated in Si bulk, 2013 JINST 8(10) P1000, http://iopscience.iop.org/article/10.1088/1748-0221/8/10/P10003

Radiation Simulations

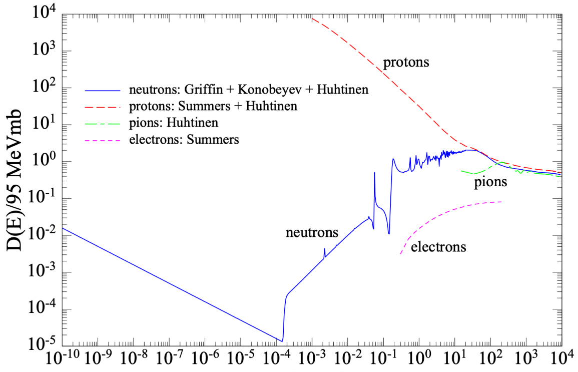
Simulating Φ_{eq}

- The complex radiation fields inside the ATLAS inner detector are simulated by propagating inelastic proton–proton interactions, generated by Pythia 8*, through the ATLAS detector material using the particle transport codes FLUKA**, † and Geant4‡
- These simulations provide Φ_{eq} in units of 1 MeV neq fluence / cm^2 / fb^{-1}
    - Φ_{eq} is computed using the NIEL hypothesis: 1 MeV neutrons applied to a sensor of surface area 1 cm^2 that cause damage equivalent to that of all particles that went through the sensor

FLUKA Simulation



NIEL Data



A. Vasilescu & G. Lindstroem

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* T. Sjöstrand et al., An Introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, arXiv: 441 1410.3012

** G. Battistoni et al., The FLUKA code: Description and benchmarking, AIP Conf. Proc. 896 (2007) 31

† A. Ferrari, P. R. Sala, F. A and J. Ranft, FLUKA: A multi-particle transport code (program version 450 2005), CERN, 2005, url: https://cds.cern.ch/record/898301

‡Geant4 - a simulation toolkit, Nuclear Instruments and Methods in Physics Research A 506 452 (2003) 250

Leakage Current Simulations Hamburg Model

- The Hamburg model* is based on this relationship:

$$\Delta I_{\mathrm{leak}} = \alpha\, \Phi_{\mathrm{eq}}\, V$$

- And by replacing α (the radiation damage coefficient) the equation becomes:

$$\Delta I = (\Phi_{\mathrm{eq}}/L_{\mathrm{int}}) \times V \cdot \sum_{i=1}^{n} L_{\mathrm{int},i} \cdot \left[\alpha_{\mathrm{I}} \exp\left(-\sum_{j=i}^{n} \frac{t_j}{\tau(T_j)}\right) + \alpha_0^* - \beta \log\left(\sum_{j=i}^{n} \frac{\Theta(T_j) \cdot t_j}{t_0}\right)\right]$$

- Where the variables are:
  - ΔI_{leak} is the difference in leakage current at fluence Φ_{eq} relative to the value before irradiation of the sensor depleted volume V, t_{i} is the time, and $t_0 = 1\mathrm{min}$
  - $\alpha_I = (1.23 \pm 0.06) \times 10^{-17}$ A/cm
    $\tau^{-1} = (1.2^{+5.3}_{-1.0}) \times 10^{13}\ \mathrm{s}^{-1} \times e^{(-1.11 \pm 0.05)\ \mathrm{eV}/k_{\mathrm{B}}T}$
    $\alpha_0^* = 7.07 \cdot 10^{-17}$ A/cm
    $\beta = (3.29 \pm 0.18) \times 10^{-18}$ A/cm

and $\Theta(T) = \exp\left[-\frac{E_I^*}{k_{\mathrm{B}}}\left(\frac{1}{T} - \frac{1}{T_{\mathrm{ref}}}\right)\right]$

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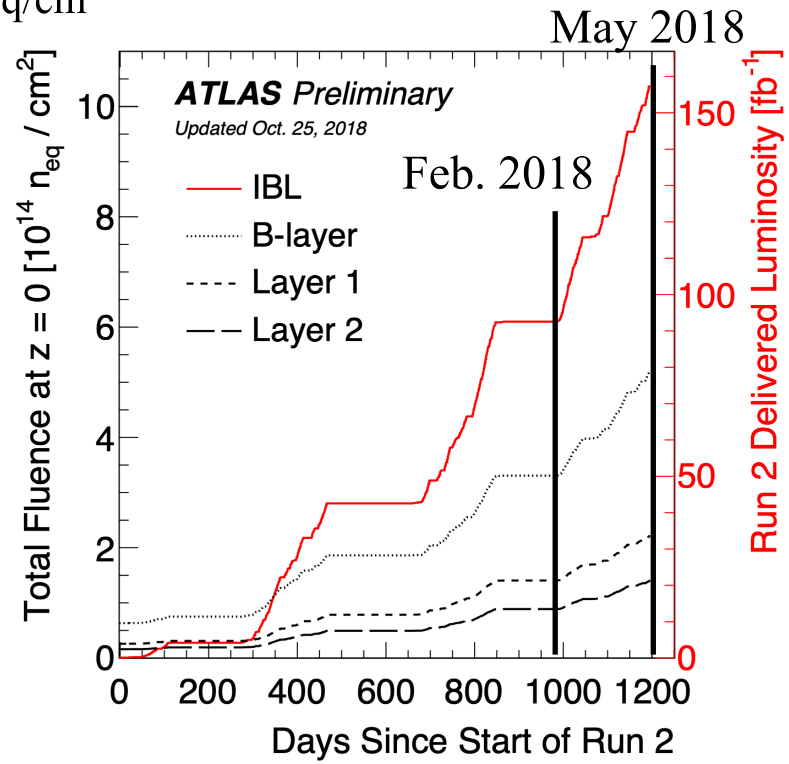
* M. Moll et al., Leakage Current of Hadron Irradiated Silicon Detectors - Material Dependence. Nucl. Instrum. Meth. A , 426(87), 1999.

Optimal E_{eff} Study with the Silicon Sensors on the Pixel Layers and Disks

E_{eff} Determination Study

- 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 $\times 10^{14}$ 1 MeV neq/cm^2
    - In May 2019, the IBL had received a fluence of ~ 1 $\times 10^{15}$ 1 MeV neq/cm^2 and the B-Layer had received ~ 5 $\times 10^{14}$ 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



May 2018

Feb. 2018

E_{eff} Determination Strategy

- The temperature of the Pixel detector modules is 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*:

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

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

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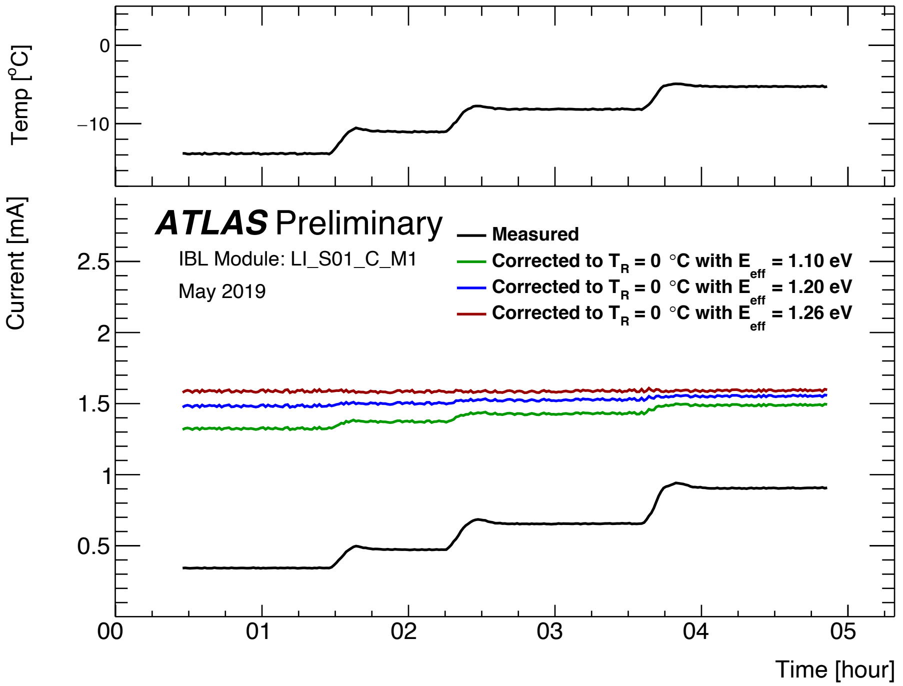
*S.M. Sze, Physics of Semiconductor Devices, 2nd ed., Wiley, New York, 1984.

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 for E_{eff} Study

determining σ^2

- A temporal 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)

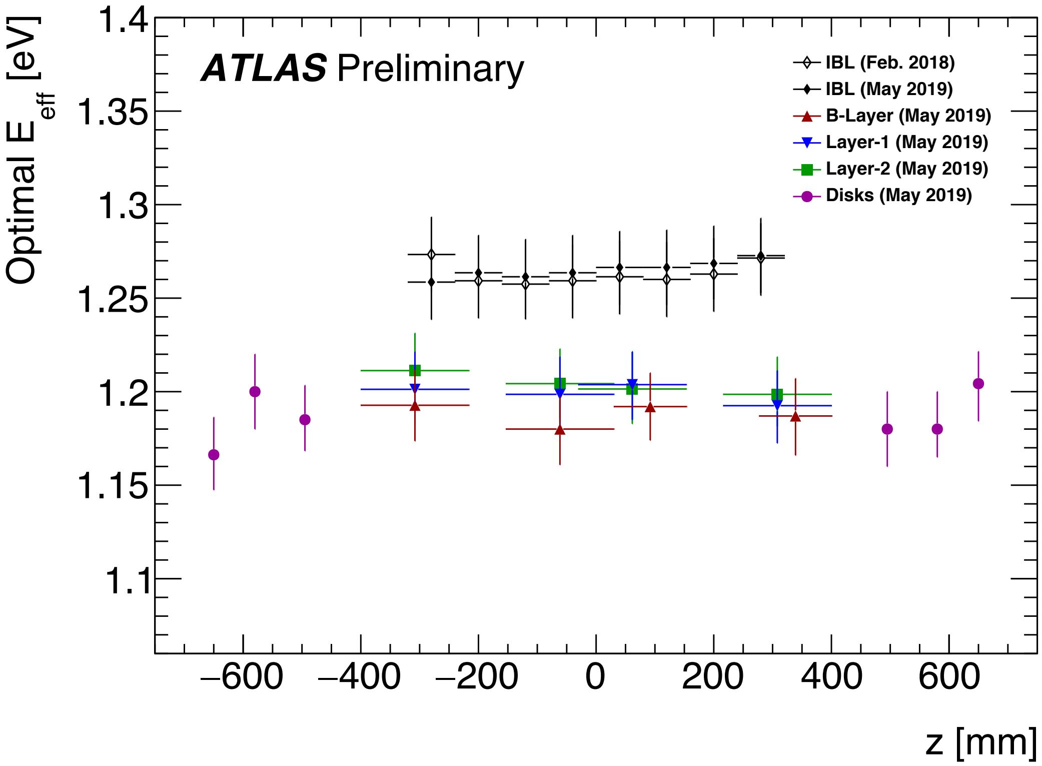
$$I(T_{\mathrm{R}}) = I_{meas} \times R(T + \mathbf{\Delta T})$$

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

T_R = 0 °C is used in this analysis

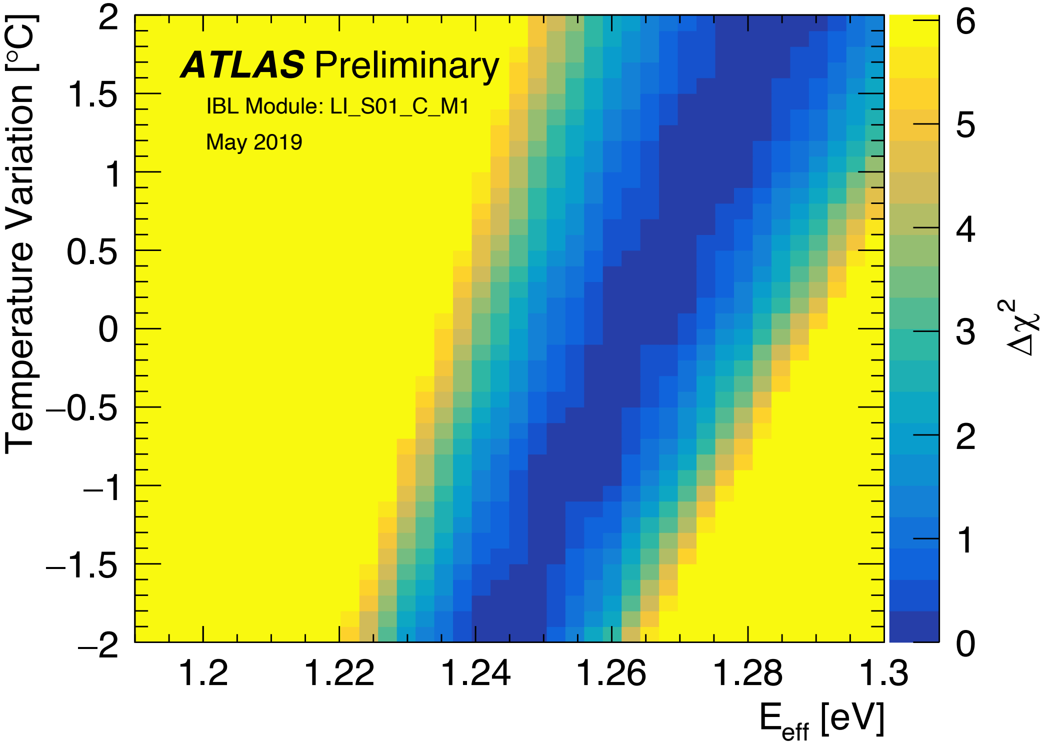
Summary of Results

- 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 of E_{eff} Study

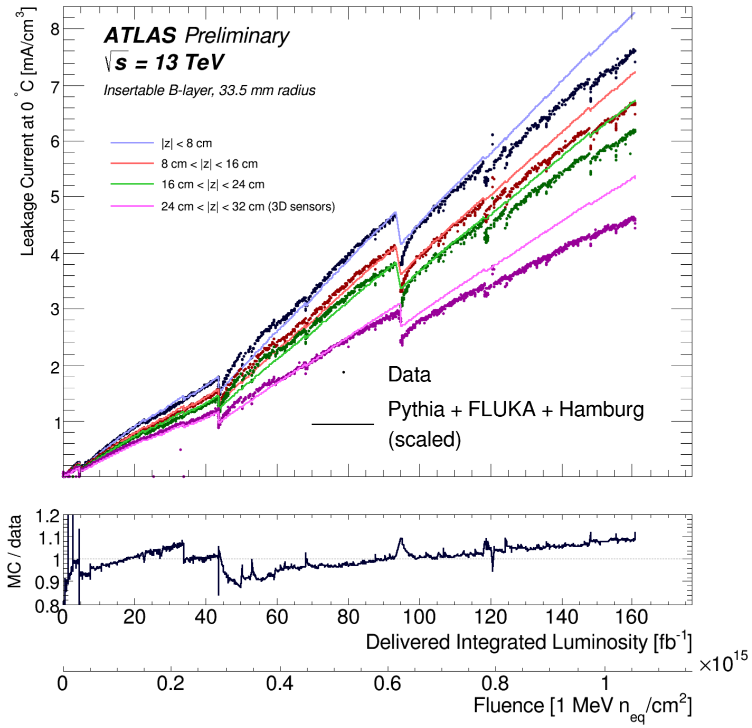
- The optimal E_{eff} search for all modules on the IBL and a representative sample of modules on B-Layer, Layer-1, Layer-2, and the Disks has been performed
- Uncertainties due to ±2 °C temperature variations have been determined
- The results per layer are summarized here
    - The optimal E_{eff}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

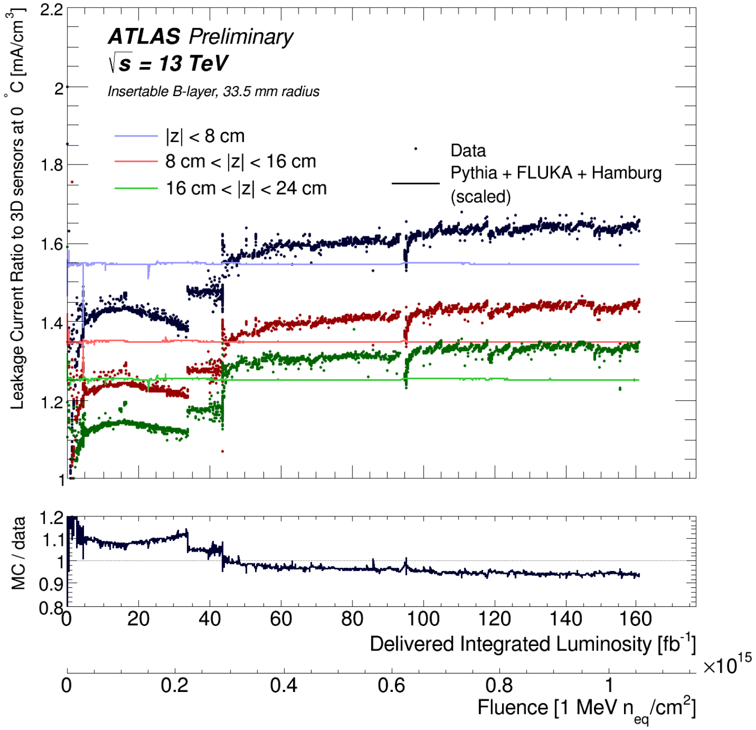
IBL: 1.26 eV $\pm\, 0.01(stat) \pm 0.02(sys)$
B-Layer: 1.18 eV $\pm\, 0.02(stat) \pm 0.02(sys)$
Layer-1: 1.20 eV $\pm\, 0.01(stat) \pm 0.02(sys)$
Layer-2: 1.20 eV $\pm\, 0.02(stat) \pm 0.02(sys)$
Disks: 1.19 eV $\pm\, 0.02(stat) \pm 0.02(sys)$

Leakage Current Measurements as a function of integrated luminosity

IBL Leakage Currents

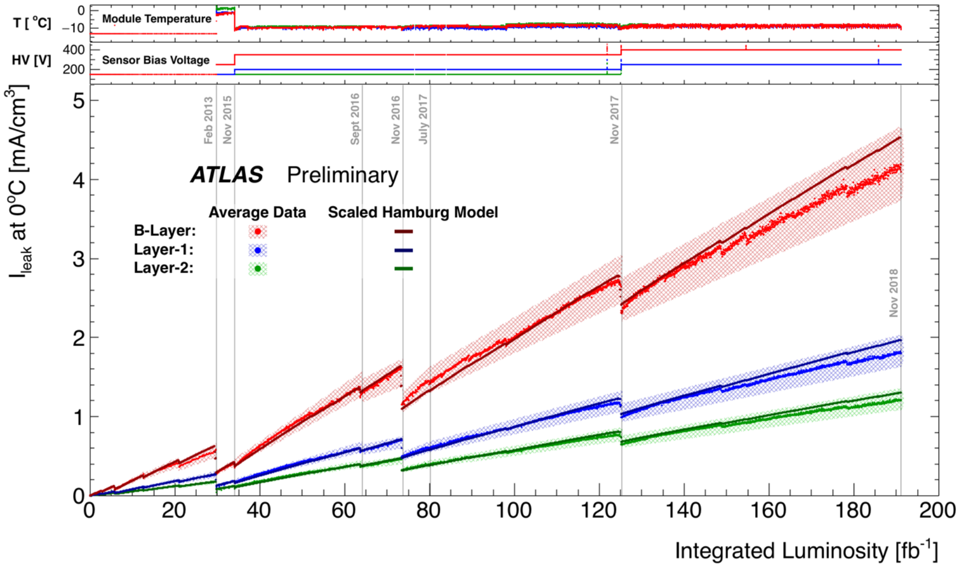
- (Left plot) the measured leakage current compared to Hamburg Model predictions for modules on the IBL as a function of delivered integrated luminosity during the LHC Run 2
    - The current is averaged over ϕ and also averaged over modules with a similar z
    - Both planar and 3D sensors are measured and shown in the figure
- (Right plot) the ratio of the measured leakage currents on planar sensors to the 3D sensors is shown
    - After the high voltage change in 2016, the ratio is nearly flat as the sensors were fully depleted.

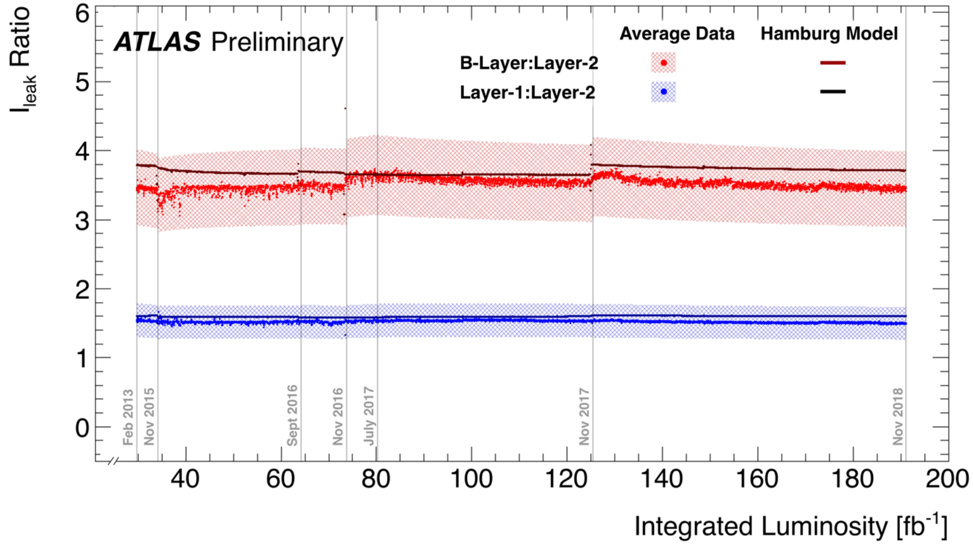




Outer Pixel Leakage Currents

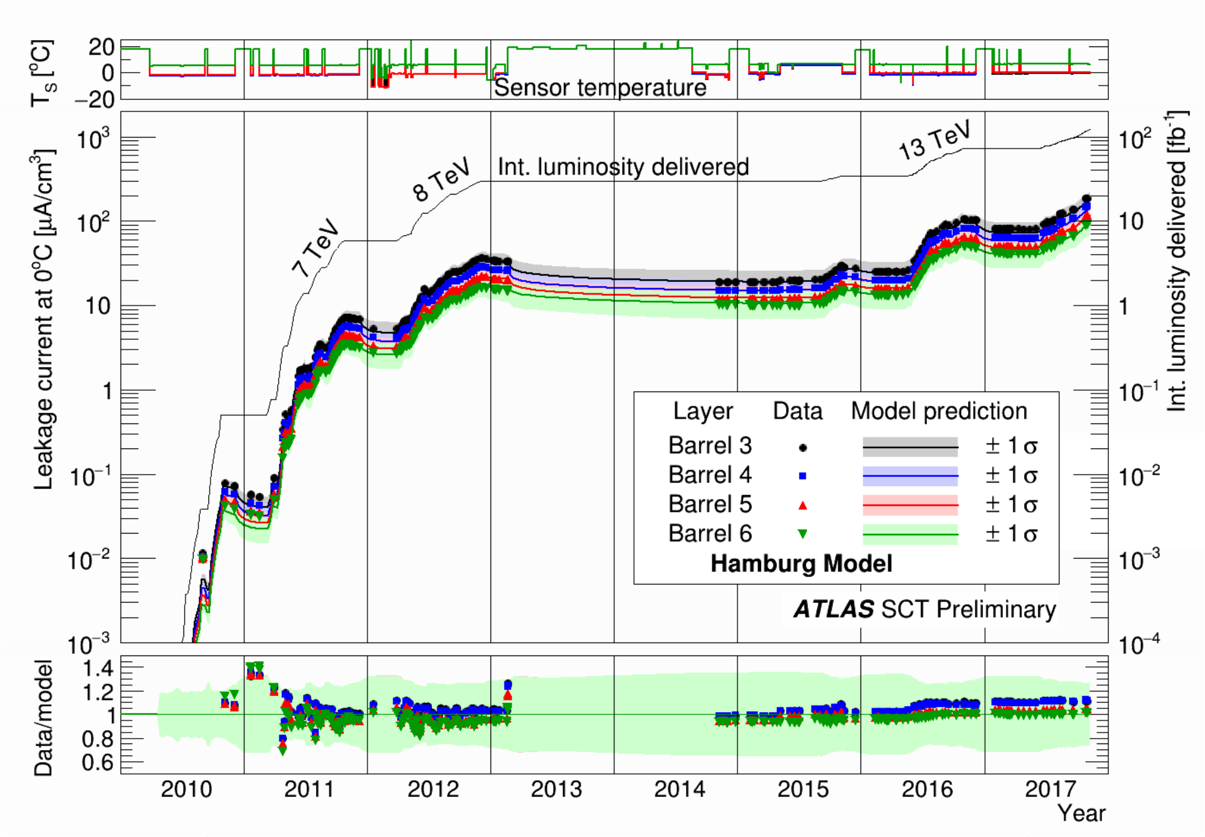
- (Top plot) average leakage current data compared to the average scaled Hamburg Model predictions for each barrel layer through 2018
  - The Hamburg Model predictions have been scaled to match the measured leakage current data
  - Measurements on each layer are averaged over a representative sample of modules in η and ϕ.
  - The measurements are consistent with expected higher levels of radiation for sensors closer to the beam line.
- (Bottom plot) Ratios of the various Pixel Detector barrel layer leakage current data and (unscaled) Hamburg Model predictions for LHC Run 2
  - The vertical axis is proportional to the ratio of the applied fluence
  - The relative fluence between the layers is well predicted





SCT Leakage Currents

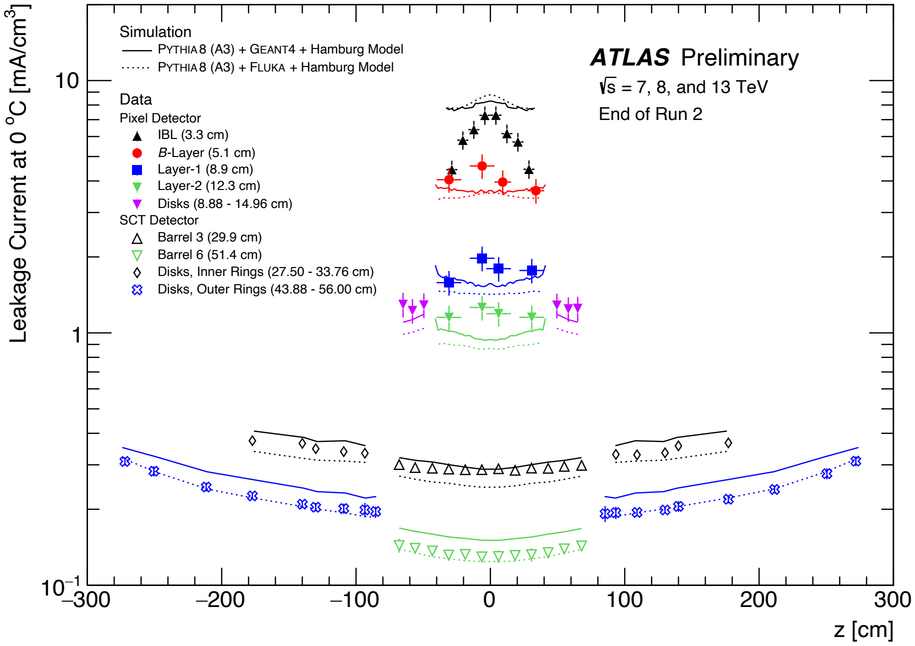
- Comparison between data (points) and Hamburg model predictions (lines with uncertainties shown by the colored bands) of the leakage current per unit volume at 0 °C of the barrel layers of the SCT detector
  - Sensor temperatures are shown in the top panel.
  - The bottom panel shows ratios of the leakage current data relative to model prediction

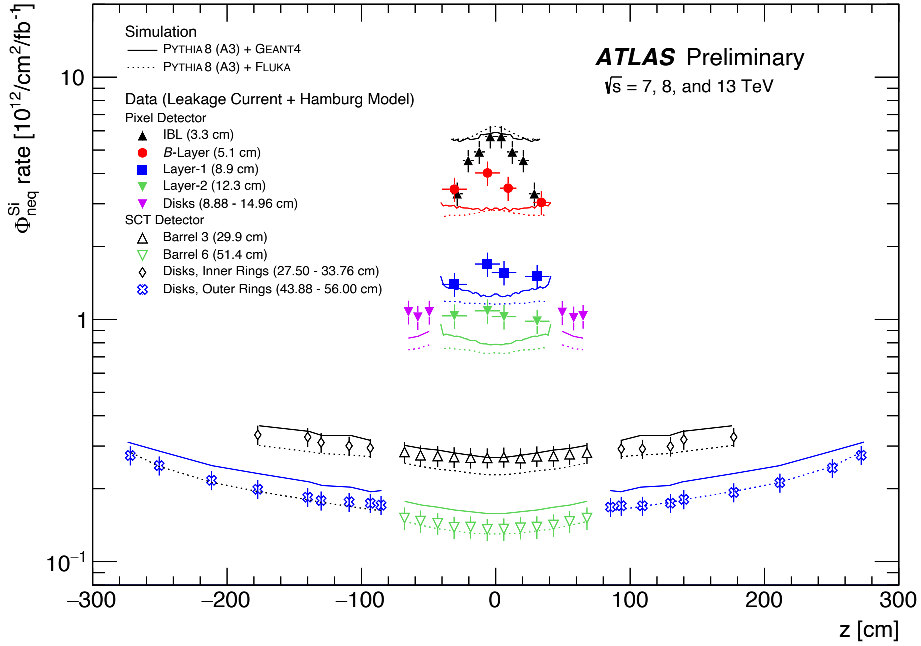


Leakage Current and Fluence Comparisons

Comparisons as a Function of z

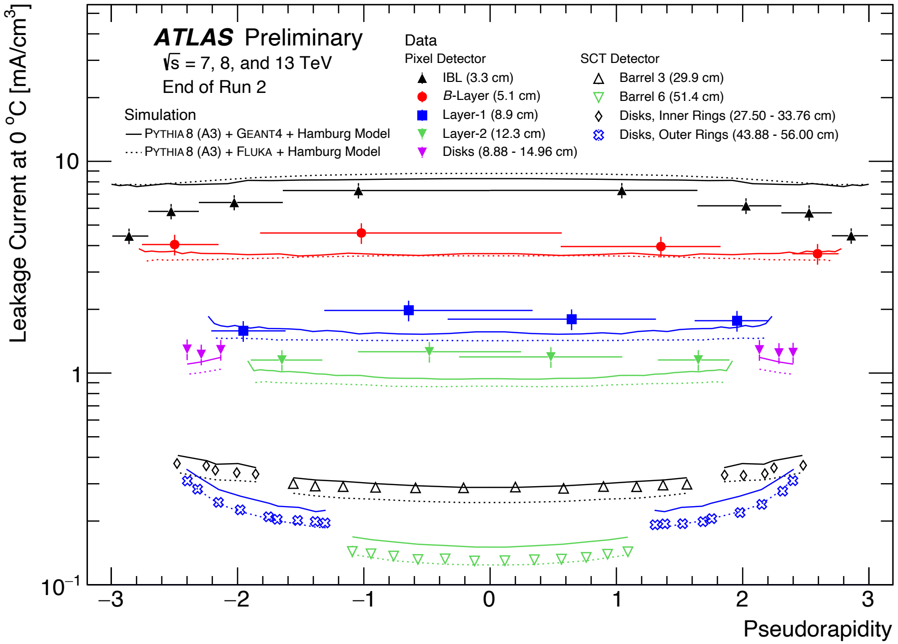
- (Left plot) leakage current at the end of Run 2 as a function of z for the entire silicon-based ATLAS inner detector is shown
- (Right plot) fluence-to-luminosity conversion factors as a function of z
- See stronger |z| dependence in data on inner layers compared with Geant4 and FLUKA
- The overall fluence appears to be up to 50% higher than the predictions for the intermediate layers between 5-15 cm from the collision point.

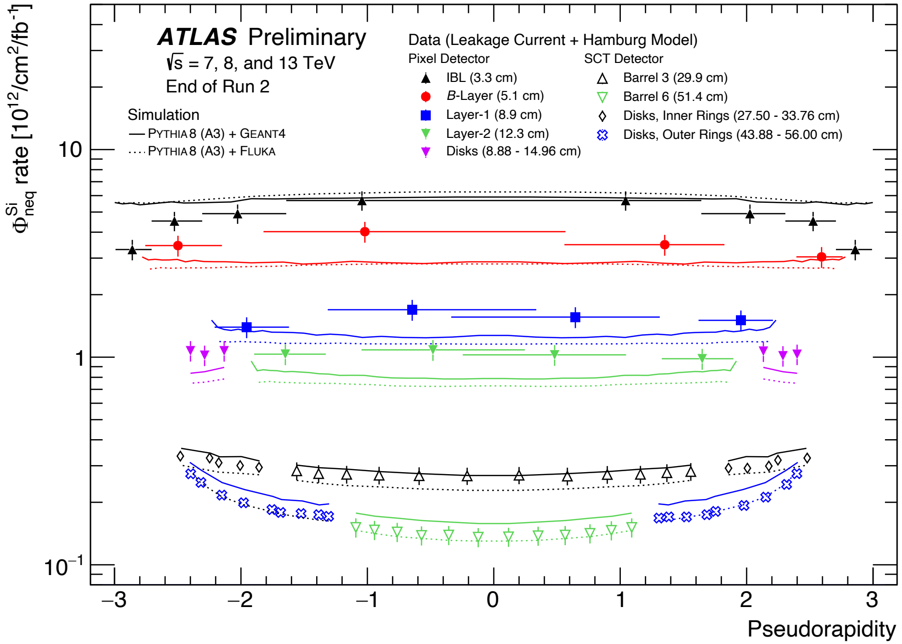




Comparisons as a Function of η

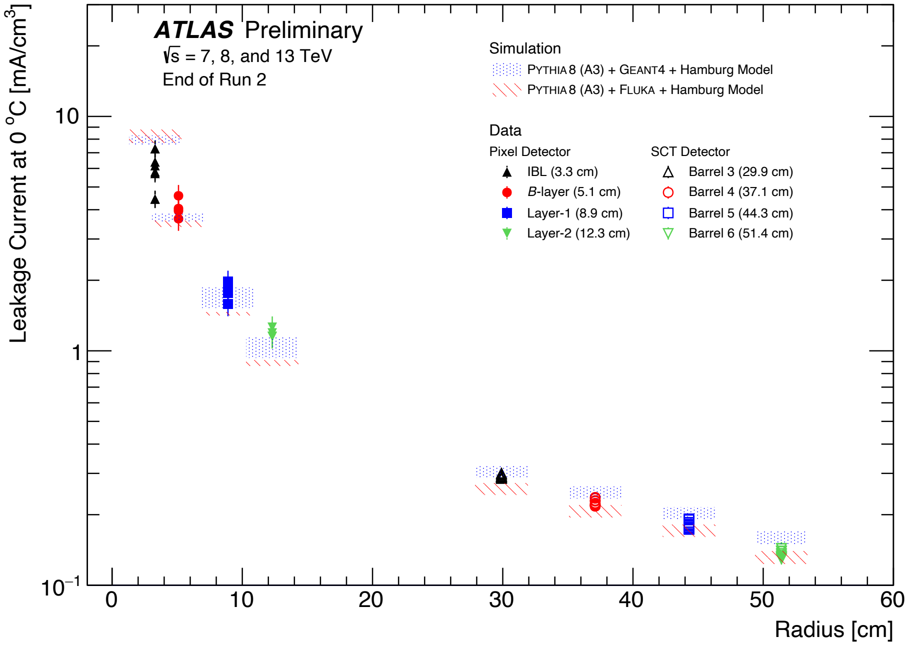
- Same data as shown on the previous slide – now shown as a function of η
- (Left plot) leakage current at the end of Run 2 as a function of η for the entire silicon-based ATLAS inner detector is shown
- (Right plot) fluence-to-luminosity conversion factors as a function of η

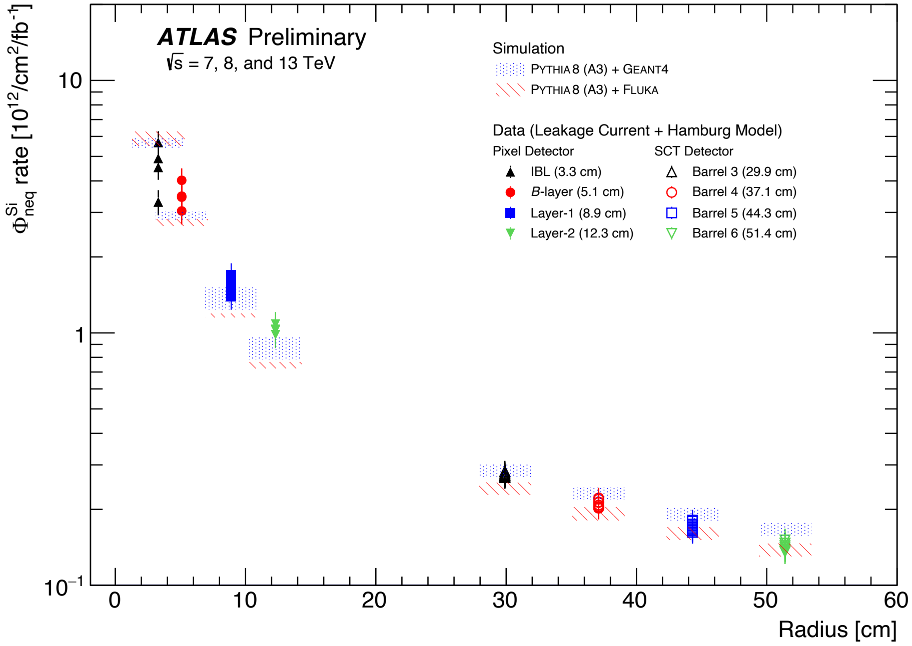




Comparisons as a Function of Radius

- The data are now shown as a function of radius:
  - Fluence falls off roughly as a function of r^2
- (Left plot) leakage current at the end of Run 2 as a function of r for the entire silicon-based ATLAS inner detector is shown
- (Right plot) fluence-to-luminosity conversion factors as a function of r





Concluding Remarks

- Measurements of the sensor leakage current for all the silicon detectors in the ATLAS tracking detector have been presented
- Across time and space within the detector, the existing models provide a reasonable description of the data, with two significant discrepancies:
  - There is a stronger |z| dependence on the innermost layers than predicted by simulations and
  - The overall fluence appears to be up to 50% higher for the intermediate layers between 5-15 cm from the collision point.
- The damage caused by the high fluences (10^{15} 1 MeV neq/cm^2 on the innermost Pixel layer and 6×10^{13} 1 MeV neq/cm^2 on the innermost SCT layer) has degraded the detector performance, but continued monitoring and modeling will allow for operational and offline analysis strategies for mitigating the impact on the physics output of the experiment.
- Sensors designed for the HL-LHC will need to cope with about an order of magnitude more fluence and the investigations presented here will provide valuable input.