ATLAS Pixel and Strip Radiation Damage Studies

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Overview

Motivation

Detector layout

IBL

Pixel

SCT

Radiation Types

NIEL fluence

Total Ionising Dose

Measurements

Leakage currents; IBL, Pixel and SCT

Readout chip current consumption; IBL

Depletion voltages; IBL, Pixel and SCT

Lorentz Angle; IBL and Pixel

Charge collection efficiency; IBL and pixel

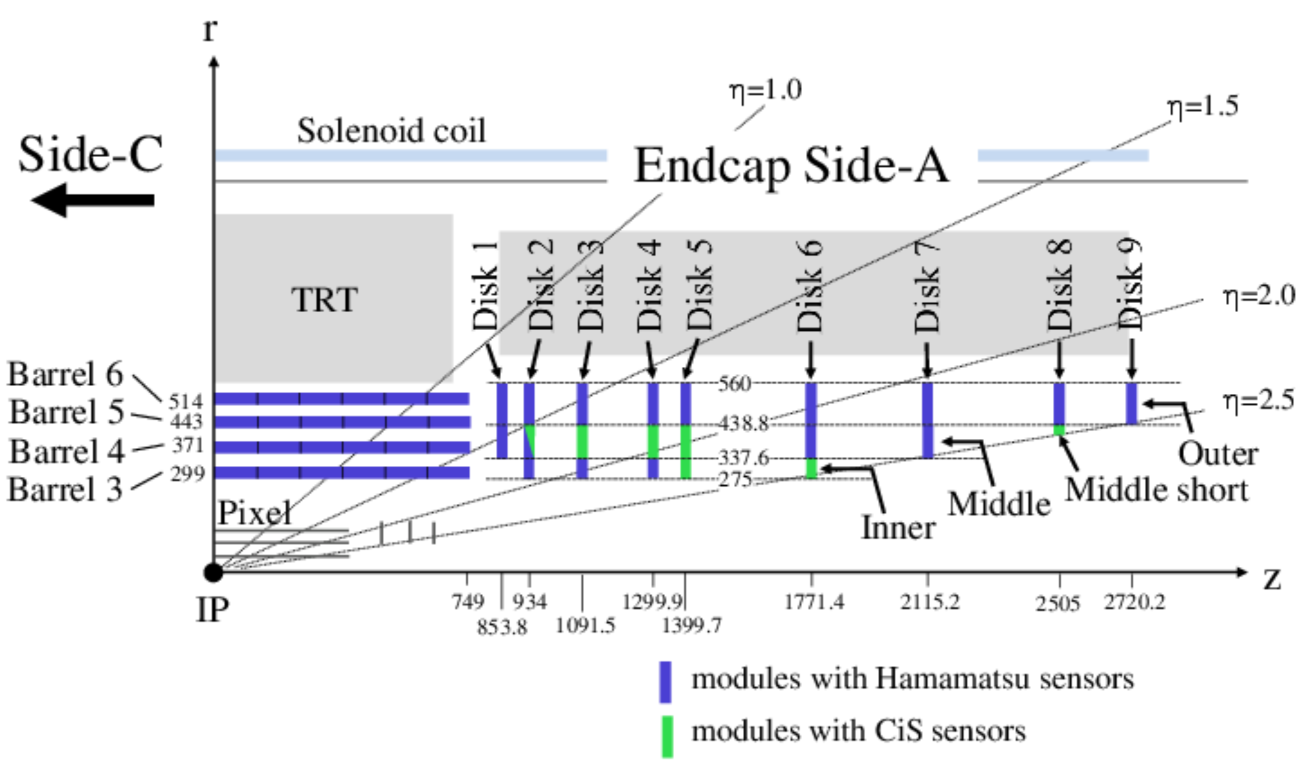
Summary

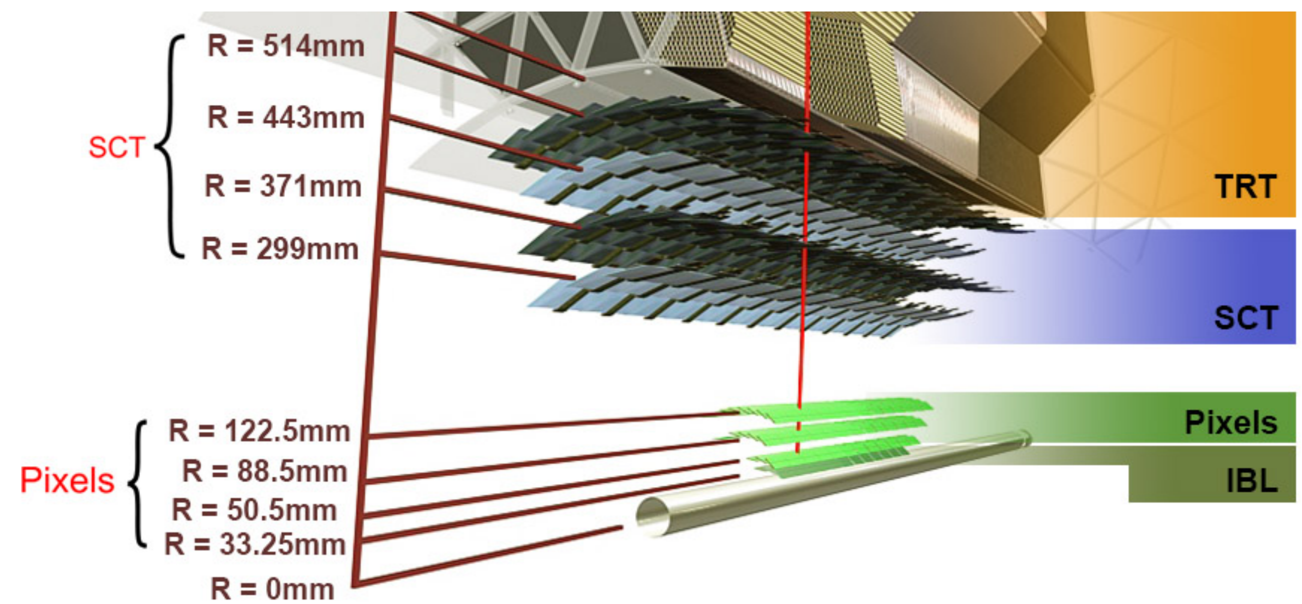
Motivation

Radiation damage is a key parameter **affecting the performance** of the silicon modules used in **ATLAS**

ATLAS have **simulations which predict the radiation levels in the ATLAS detector**; we can use these simulations to predict future performance of detector

Imperative we check the accuracy of these simulations and predictions of other sensor parameters, affected by radiation damage





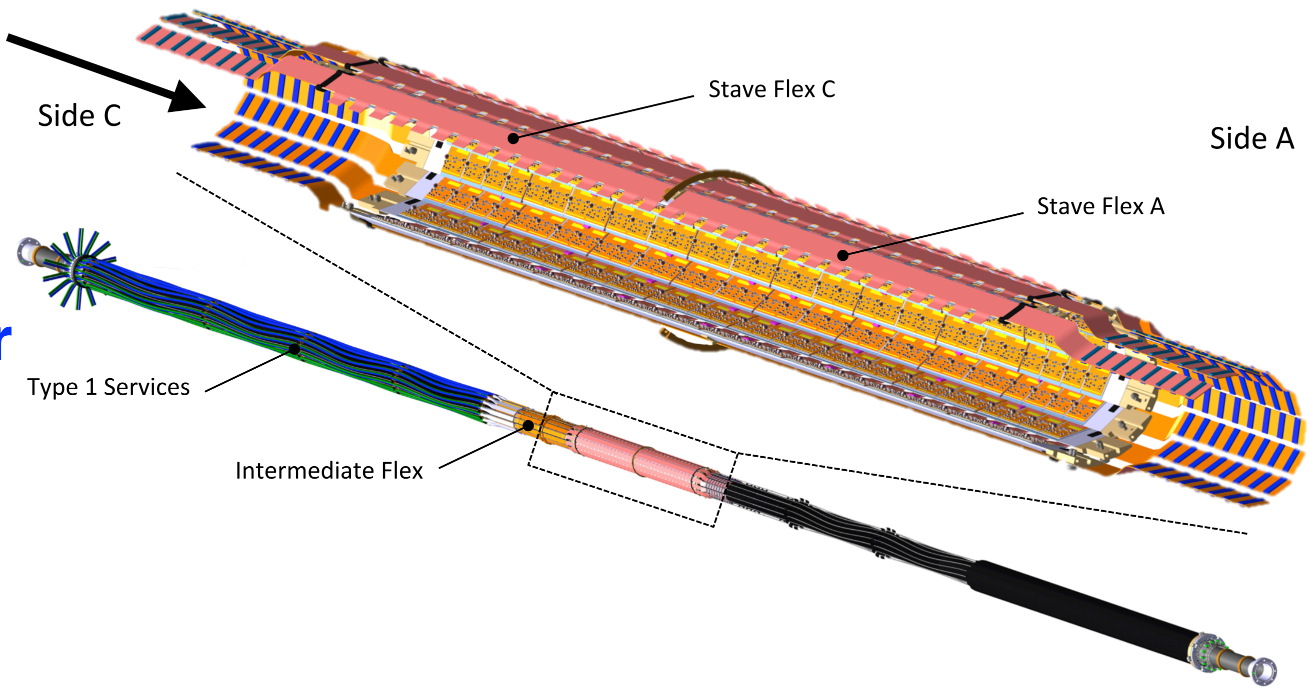
Results of these **measurements are fed back to ATLAS Radiation Simulation group**, can also be used to optimise operation conditions, and future detector designs

We also **use radiation damage measurements as inputs for simulations** of detector performance; see Ben Nachman's talk!

We have studies from IBL, Pixel and SCT

Detector layout: IBL

Barrel layer of hybrid silicon pixel modules, 30 mm from beam pipe, inserted in 2015. Looks like this

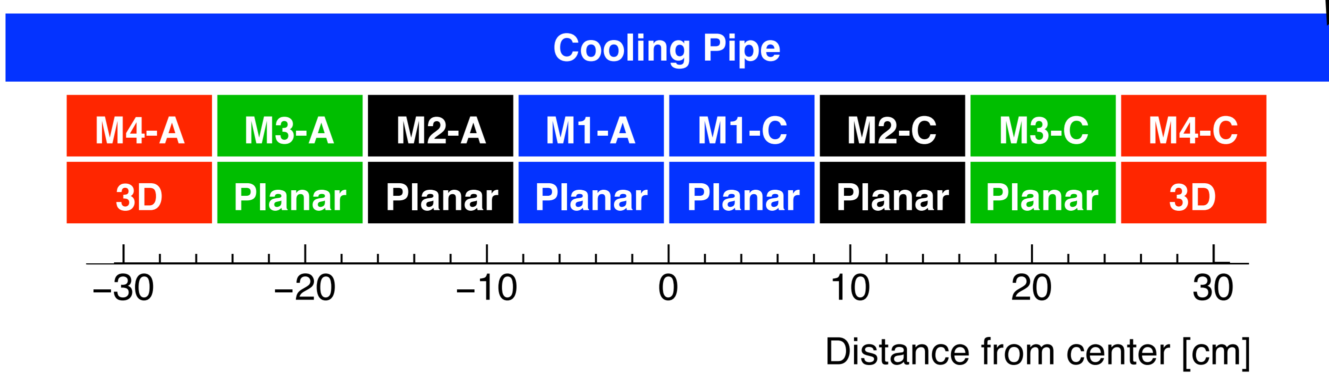


Operation temperature -4ºC in 2015, 20ºC until June 2016, 10ºC until 2017 and -15ºC thereafter

Planar bias voltage initially 80 V, rising to 350 V. 3D bias voltage 20 V till 2017, 50 V thereafter

Expected fluence range of 5-6 10^{12} 1 MeV n.eqv fb and TID of 0.3 mRad fb. Expect lifetime dose of 5×10^{15} 1 MeV n.eqv

14 staves, each containing 8 module groups, each module group contains 4 FE-I4B readout chips, bump bonded to IBL sensors with 50 x 150 µm pixels



Cooled using CO_2

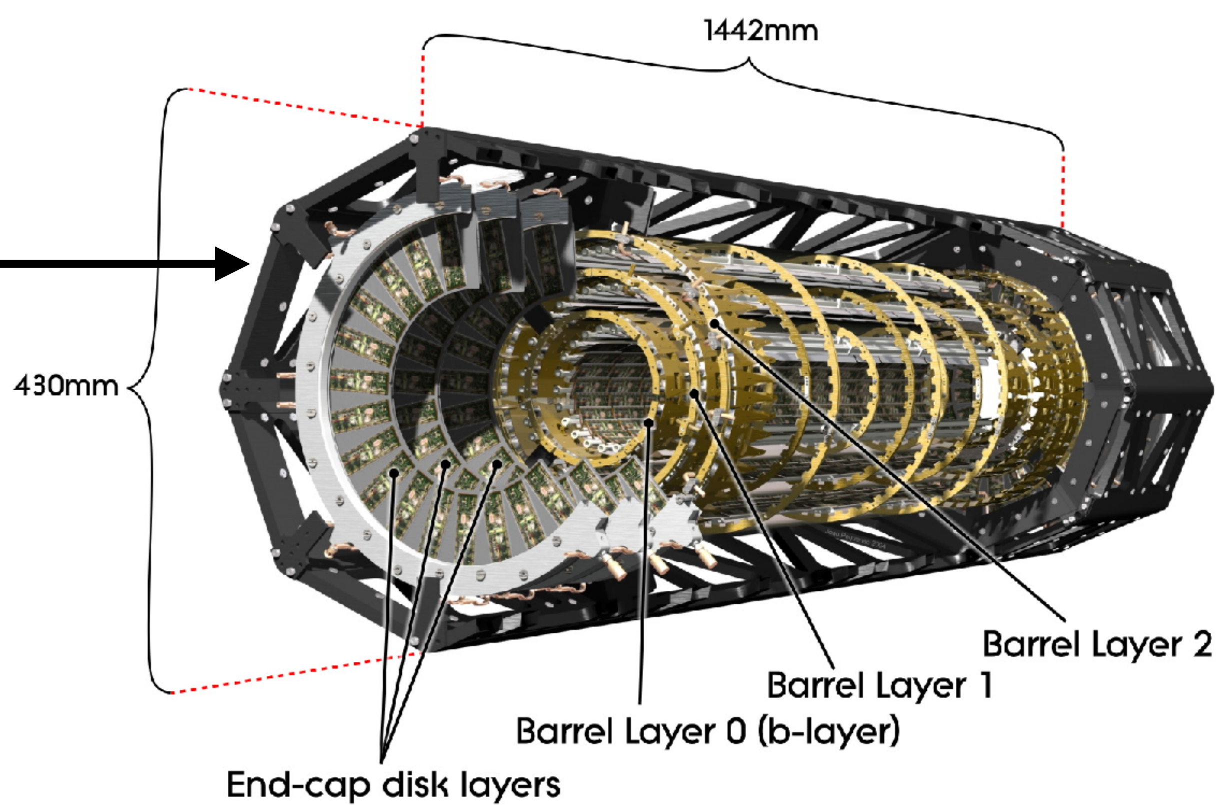
Module groups measure ~20x80 mm; **temperature, sensor leakage current and readout chip current draw recorded for each module group**

75% planar modules (M1-3, |z| = 0 - 240 mm) use 2 double-chips

25% 3D modules (M4, |z| = 240 - 320 mm) use 4 single chips

Detector layout: Pixel

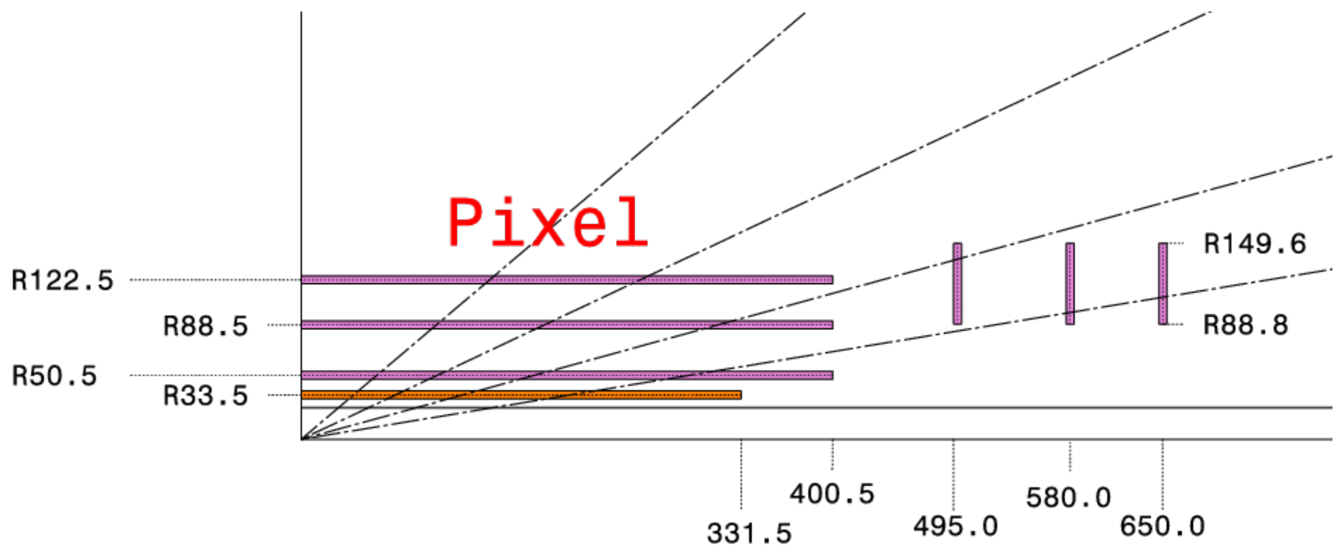
3 barrel layers of hybrid silicon pixel modules, 50, 88 and 122 mm from beam, called B-layer, layer 1 and layer 2, with **3 disk layers** at end. Looks like this →



Operation temperature -13°C in Run 1, -10°C in Run 2

Bias voltage initially 150 V, currently 350 V

Expected fluence range of 0.8-2.9 10^{12} 1 MeV n.eqv fb and TID of 0.16 mRad fb. (~ 50% IBL)
Expect lifetime dose of 2×10^{15} 1 MeV n.eqv



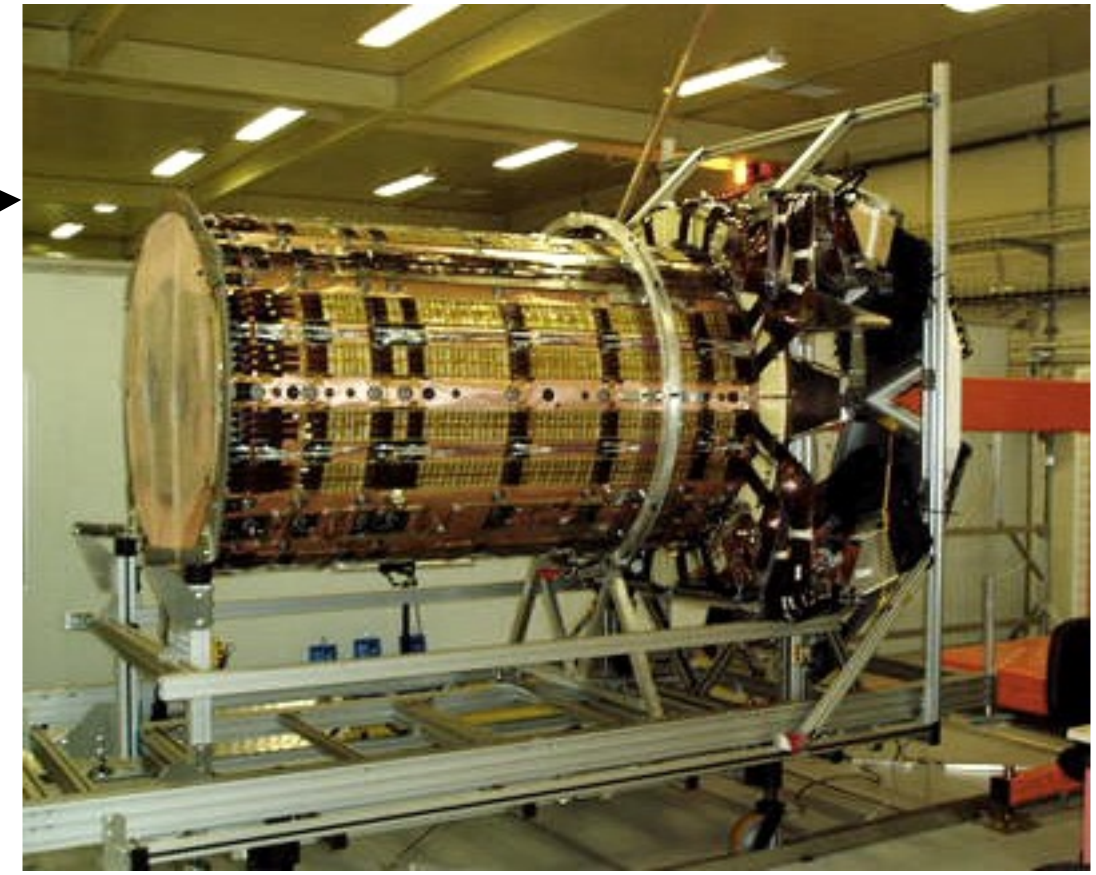
Pixel barrel uses 62.4 x 22.4 mm modules, with 50 x 400 µm pixels

Sensors read-out using FE-13 chips, bump-bonded to sensors

Cooled using C_3F_8 evaporative cooling system

Detector layout: SCT

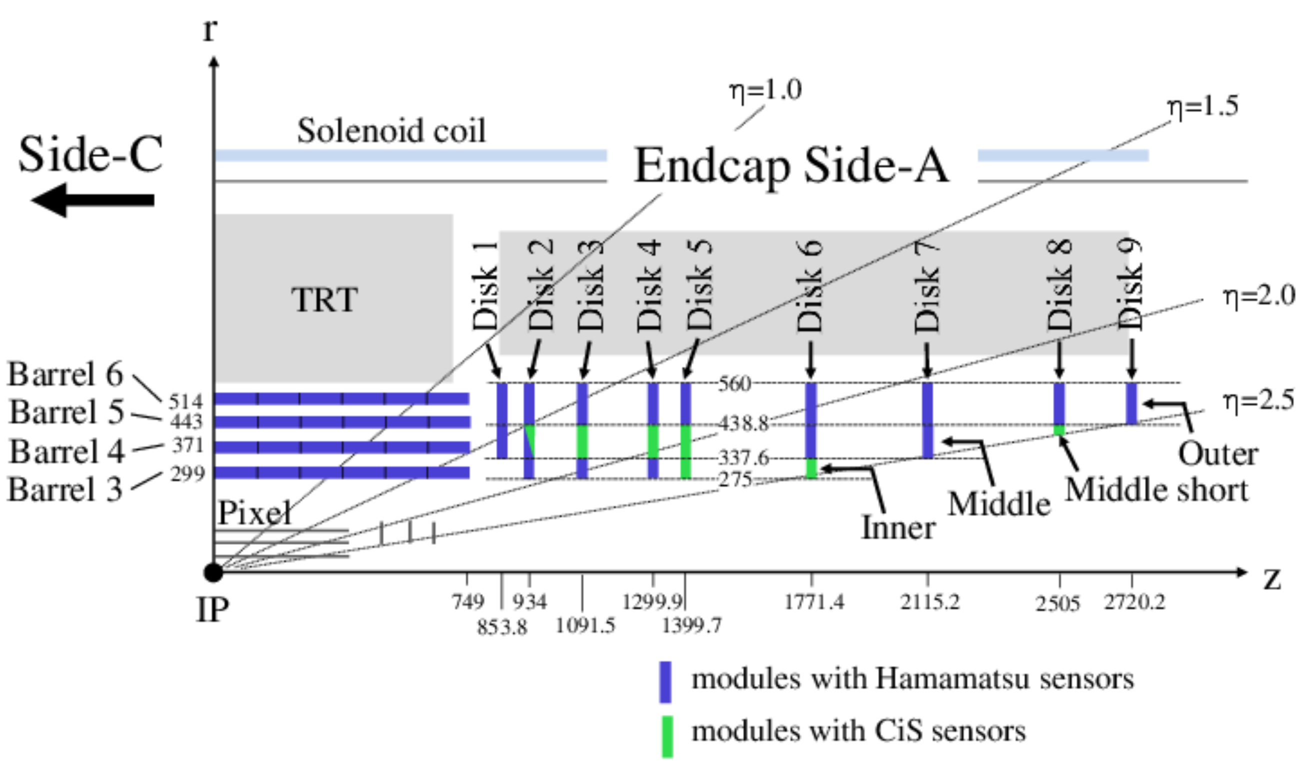
4 barrel layers of silicon strips, 300-514 mm from beam, labelled Barrel 3-6 respectively. **9 disk layers** at end. Looks like this!



Operation temperature ~-2ºC for layers B3-5, ~8ºC for layer B6 and disks

Initial bias at 150 V, rising to 450 V over lifetime

Expected fluence range of 0.2-0.3 10^{12} 1 MeV n.eqv fb and TID of 0.02 mRad fb (~5% of IBL)



SCT uses ~60 x 60 mm sensors, with ~80 µm strip pitch

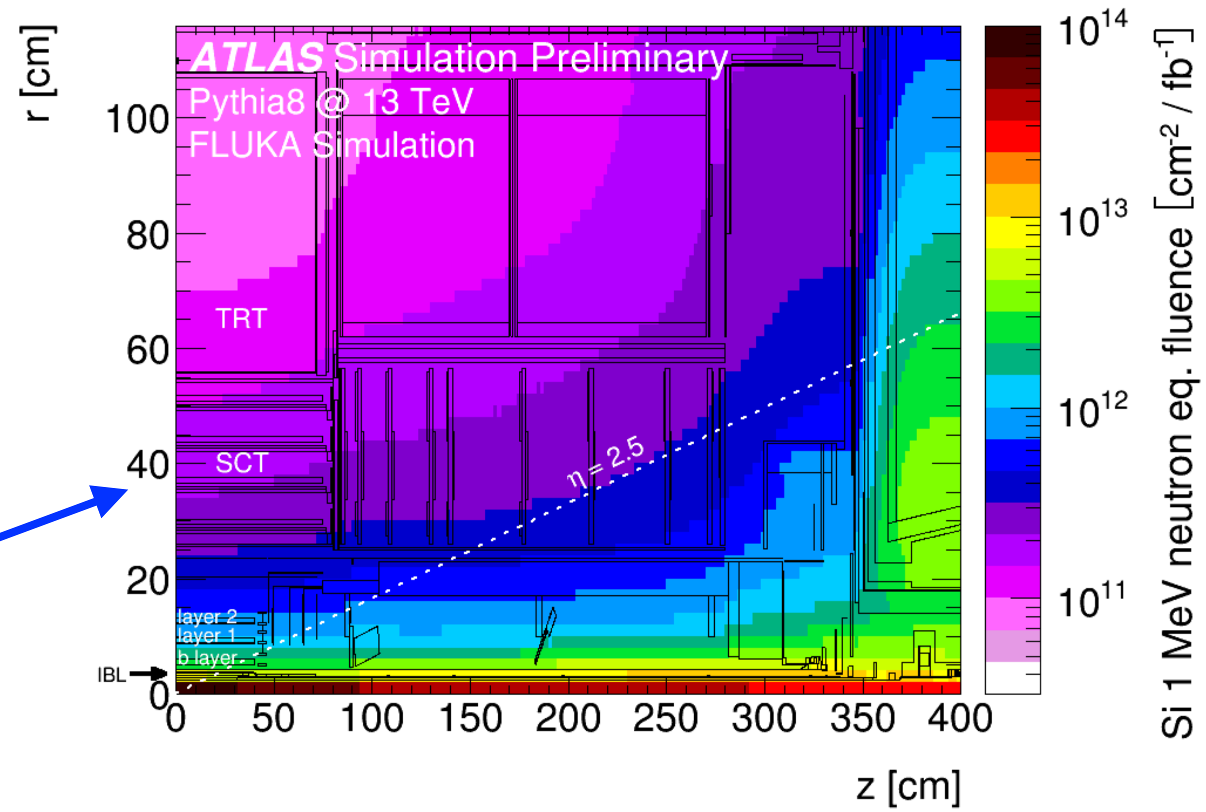
Sensors read-out using custom ABCD3TA ASIC

Cooled using C_3F_8 evaporative cooling system

Radiation Types: NIEL fluence

Main radiation damage mechanism for sensors is from Non Ionising Energy Losses (NIEL)

Fluence is proportional to integrated luminosity, the **ATLAS Radiation Simulation group calculates fluence rate for all areas of the ATLAS detector**, using Pythia and FLUKA



We **convert integrated luminosity to fluence, using the fluence rate** [10^{14} 1 MeV n.eqv cm^{-2} per fb^{-1}]

Hamburg/Sheffield-Harper models can accurately predict sensor leakage current as a function of fluence, temperature and time. Hamburg model was validated at 20-80^{o}C.

Fluence also affects depletion voltage of sensors; predicted by Hamburg model

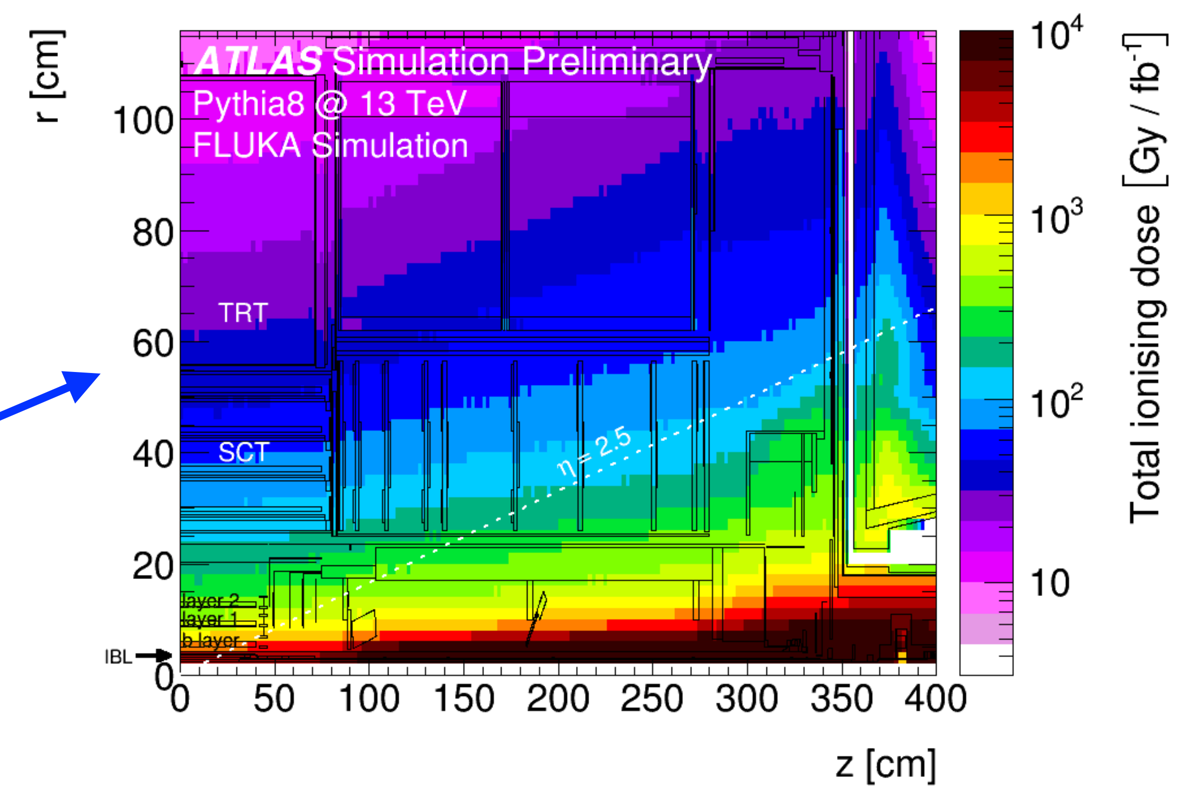
Can **measure the fluence rate for a sensor by plotting leakage current** against integrated luminosity, and fitting the Hamburg model to measurements

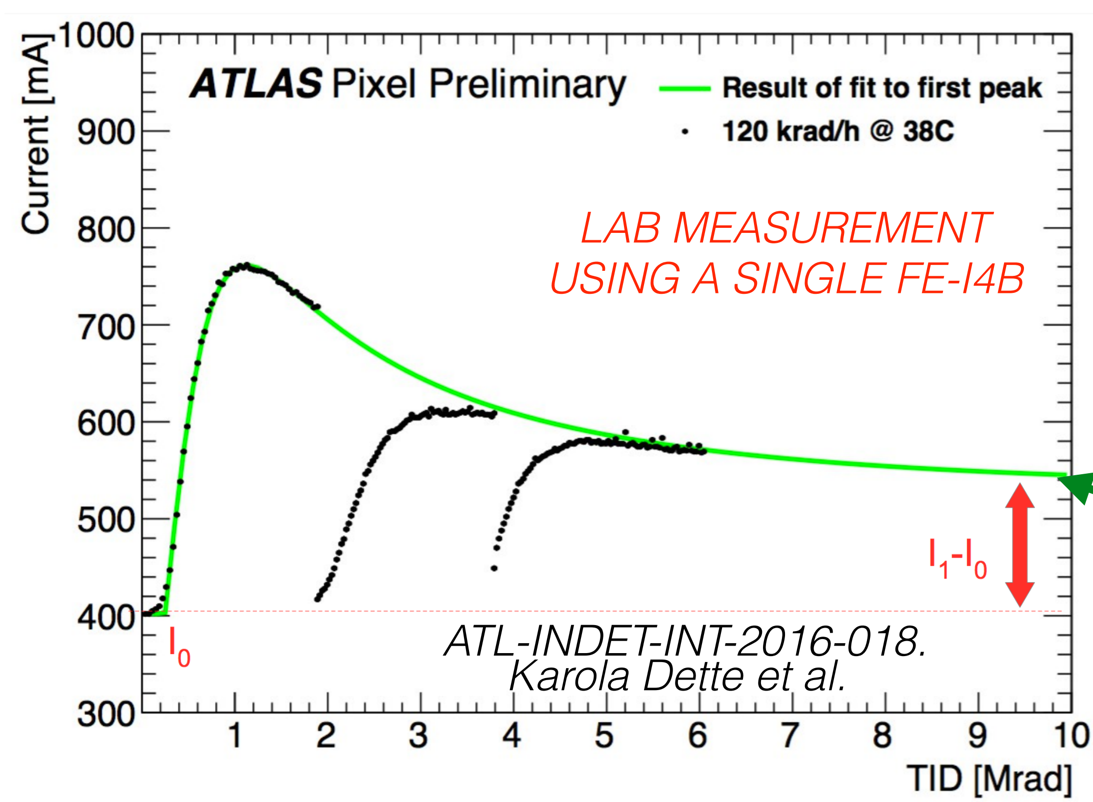
More information on simulations in Paul Miyagawa's talk

Radiation Types: TID

Main radiation damage for readout chips is from Total Ionising Dose (TID), measured in Mrad.

Again, TID is proportional to integrated luminosity, and the **ATLAS radiation simulation group calculates TID per ifb for all areas of ATLAS**, using Pythia and FLUKA





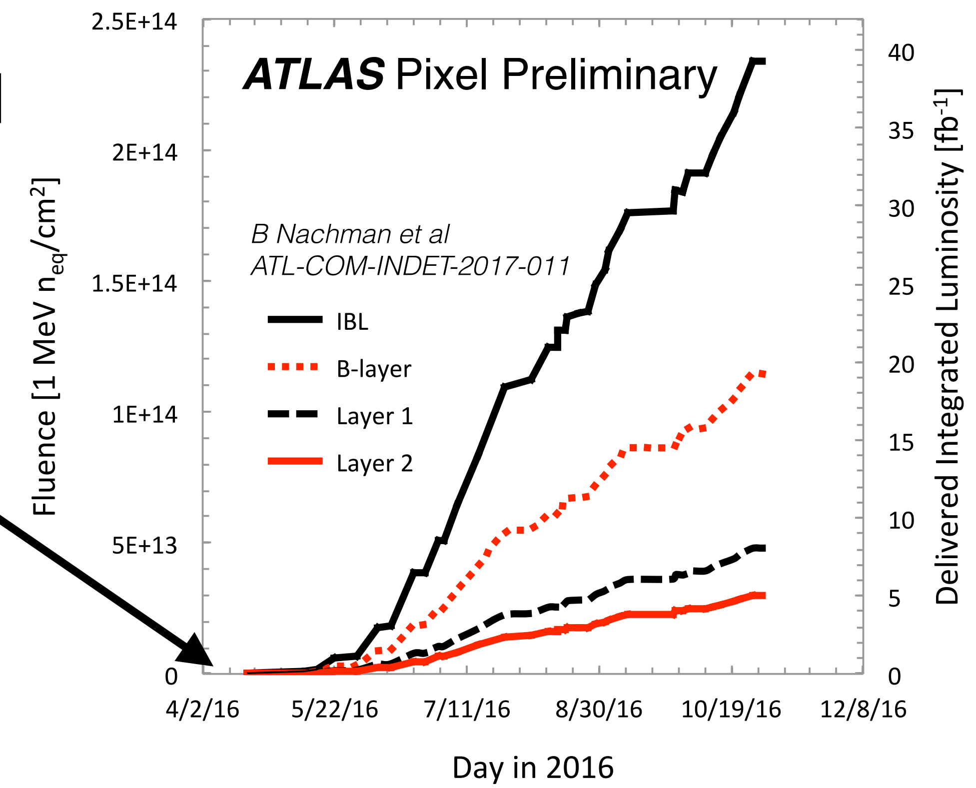
TID affects readout chip current consumption; there is not yet a model which accurately predicts this; see Backhaus paper

At best, **can state the maximum expected current consumption at a given TID**

We expect peak IBL current consumption at ~1 Mrad

Radiation Types: Summary

We have detailed **FLUKA simulations of fluence and TID rates for the entire ATLAS detector**, predicting **significantly different radiation levels for IBL, Pixel** and SCT



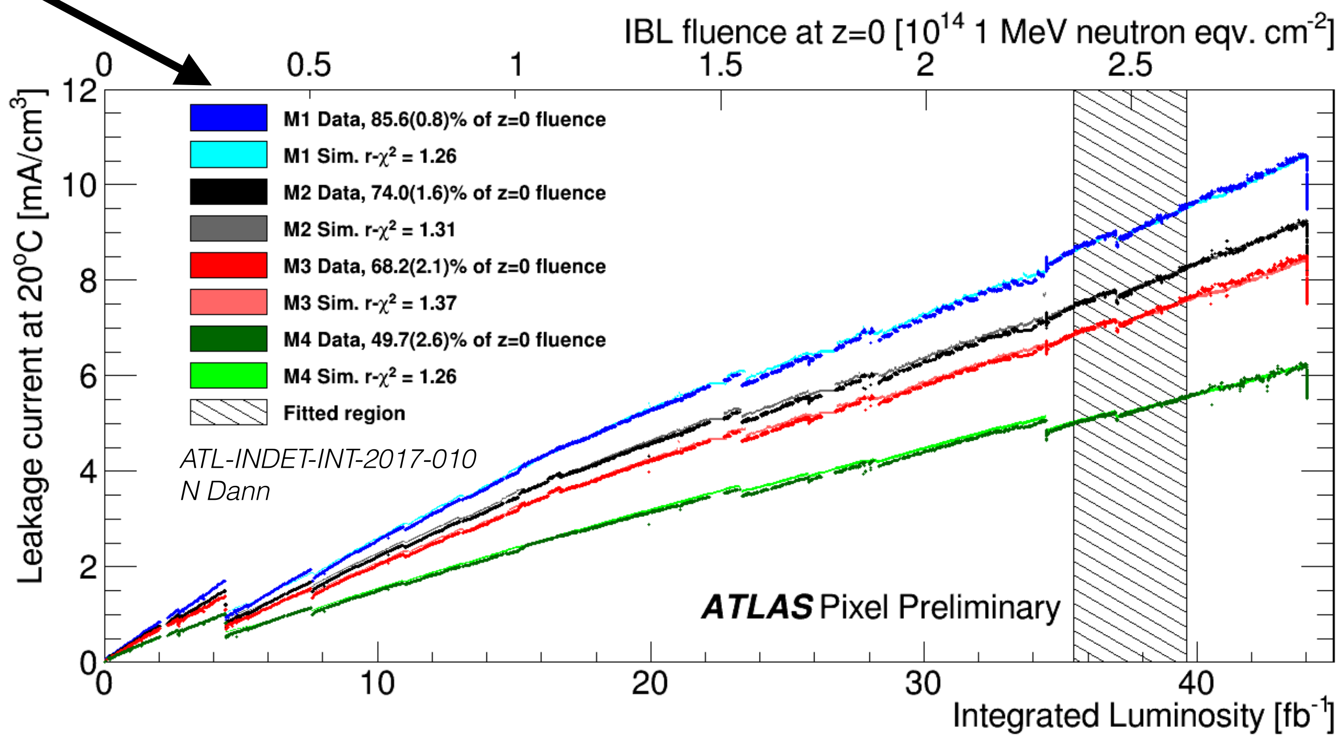
Would like to **validate FLUKA fluence simulations** with **leakage current measurements**

Summary table of radiation rates for each detector

	Fluence rate [10^{12} 1 MeV n.eqv cm^{-2} fb]	Percentage of IBL fluence [%]	TID rate [Mrad fb]	Total fluence [10^{14} 1 MeV n.eqv]	Total TID [Mrad]
IBL	5.9 - 6.6	100	0.30 - 0.35	6.23	33.04
Pixel barrel	0.8 - 2.9	~50	0.04 - 0.16	3.57	19.69
Pixel disks	0.8 - 0.8	~12	0.04 - 0.05	0.98	6.15
SCT barrel	0.2 - 0.3	~5	0.00 - 0.01	0.37	1.23
SCT disks	0.2 - 0.3	~5	0.00 - 0.02	0.37	1.23

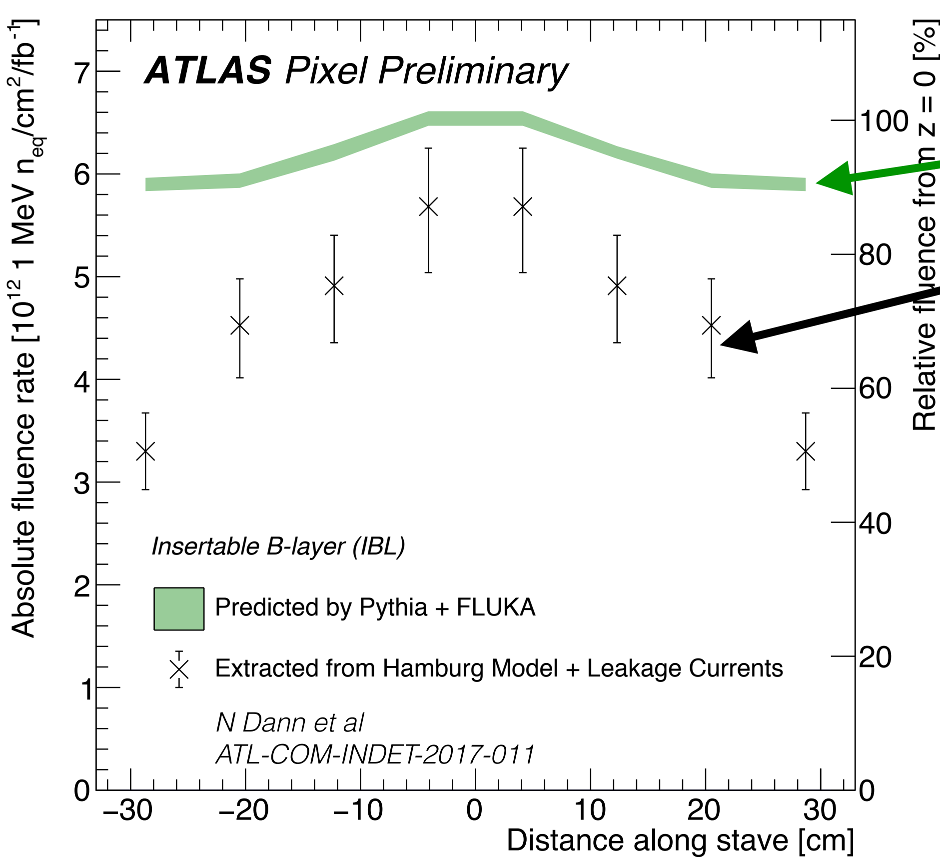
Measurements: IBL leakage currents

We investigated how **IBL leakage currents evolve as a function of integrated luminosity**, for all modules at **|z| = 0-80**, **80-160**, **160-240** and **240-320 mm**



We then **calculate IBL fluence rate** by fitting **observed leakage currents** with **prediction from Hamburg model**. There is a clear z-dependence in leakage currents.

Find **excellent agreement for 2016 data at T = 10°C** (r-χ^2<1.3). Poorer agreement elsewhere, due to temperature or under depletion



Compare **predicted rate** from Pythia + FLUKA with **measured IBL fluence rate**.

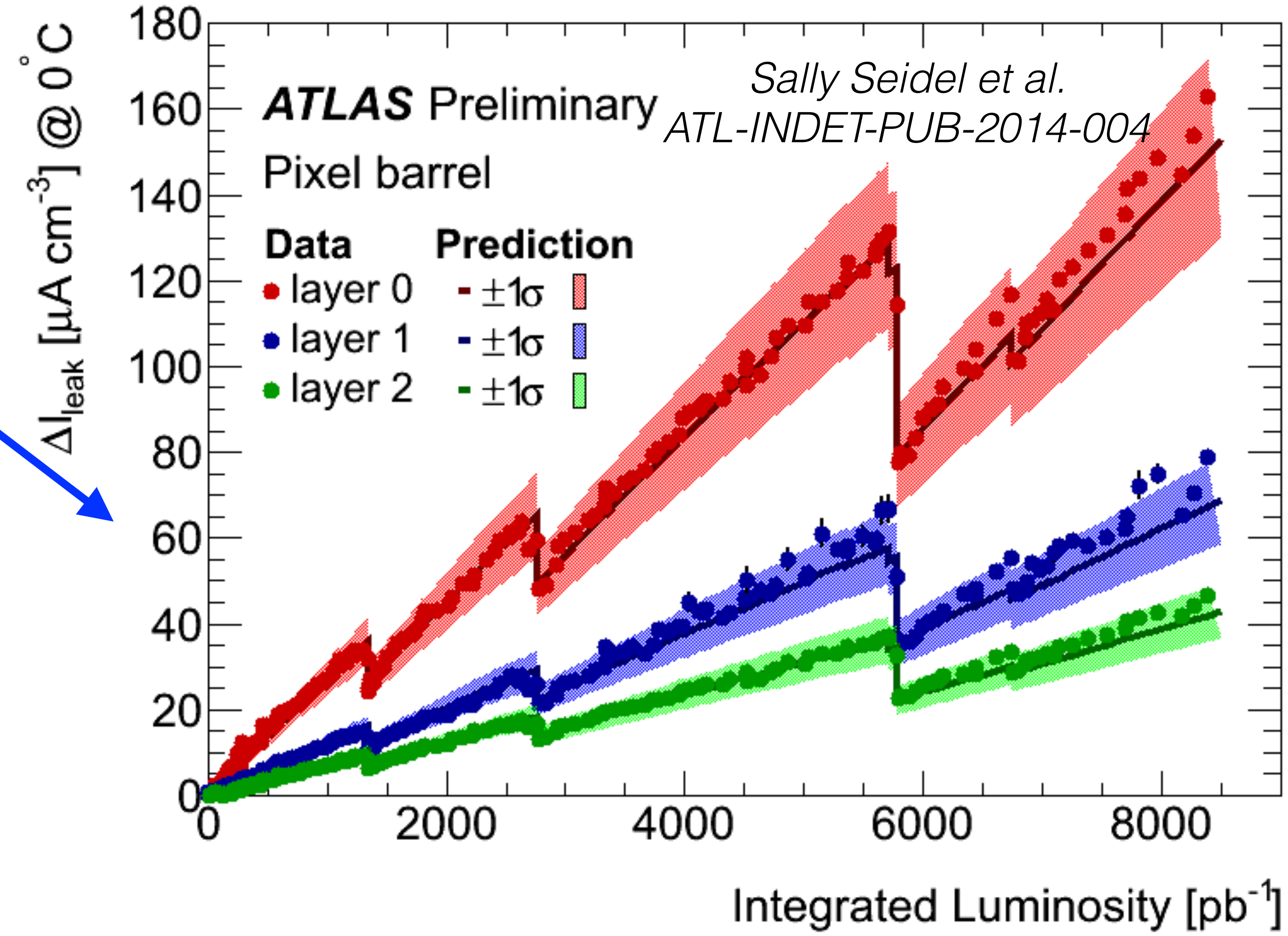
General agreement between simulation and data (correct order of magnitude, greatest fluence at |z|=0)

FLUKA simulation overestimates fluence rate by 15-40%, and **underestimates the z-dependence** (observed a 35% decrease, expected 10%)

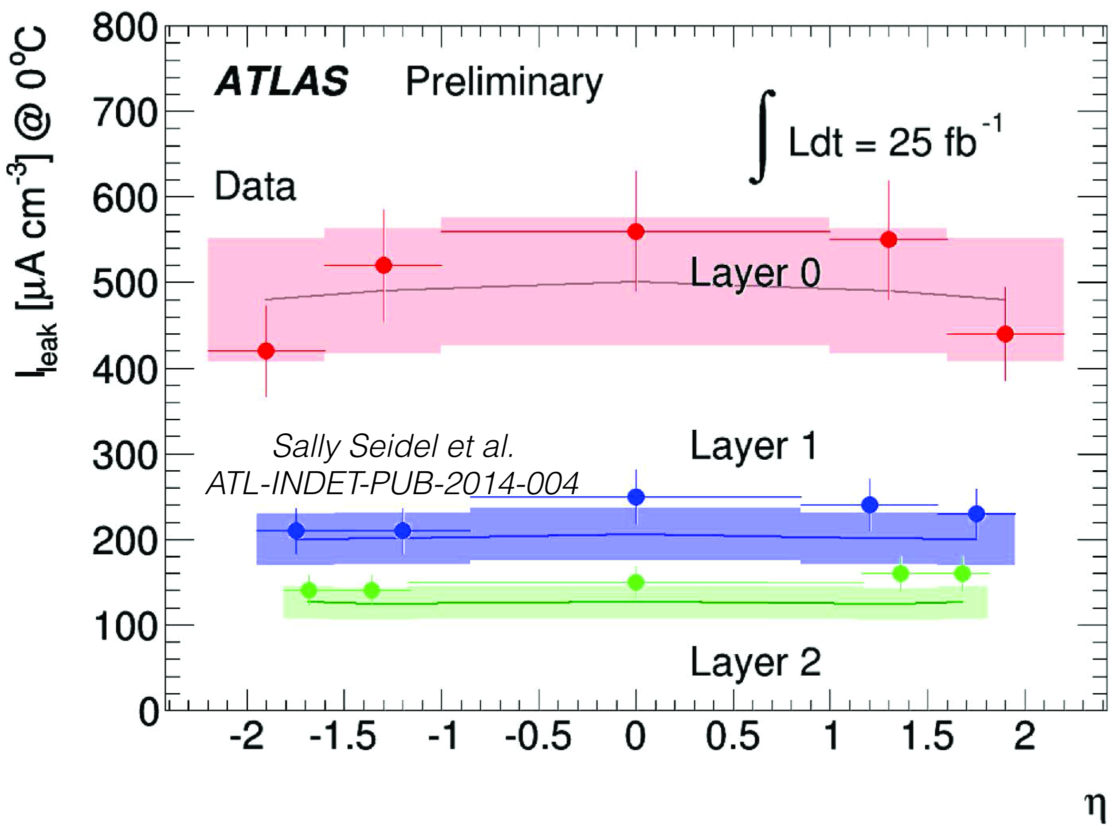
Measurements: Pixel Leakage Currents

ATLAS has also **investigated how B-layer leakage currents evolve** as a function of integrated luminosity in Run 1.

Compare **observed leakage current with modelled leakage current**, using simulated fluence rate values, for **B-layer**, **layer 1 and 2**



General agreement for all layers in Run 1, limited by large uncertainties on fluence-rate simulations



Also **investigated z-dependence of Pixel leakage current in Run 1** for **B-layer**, **layer 1 and 2**

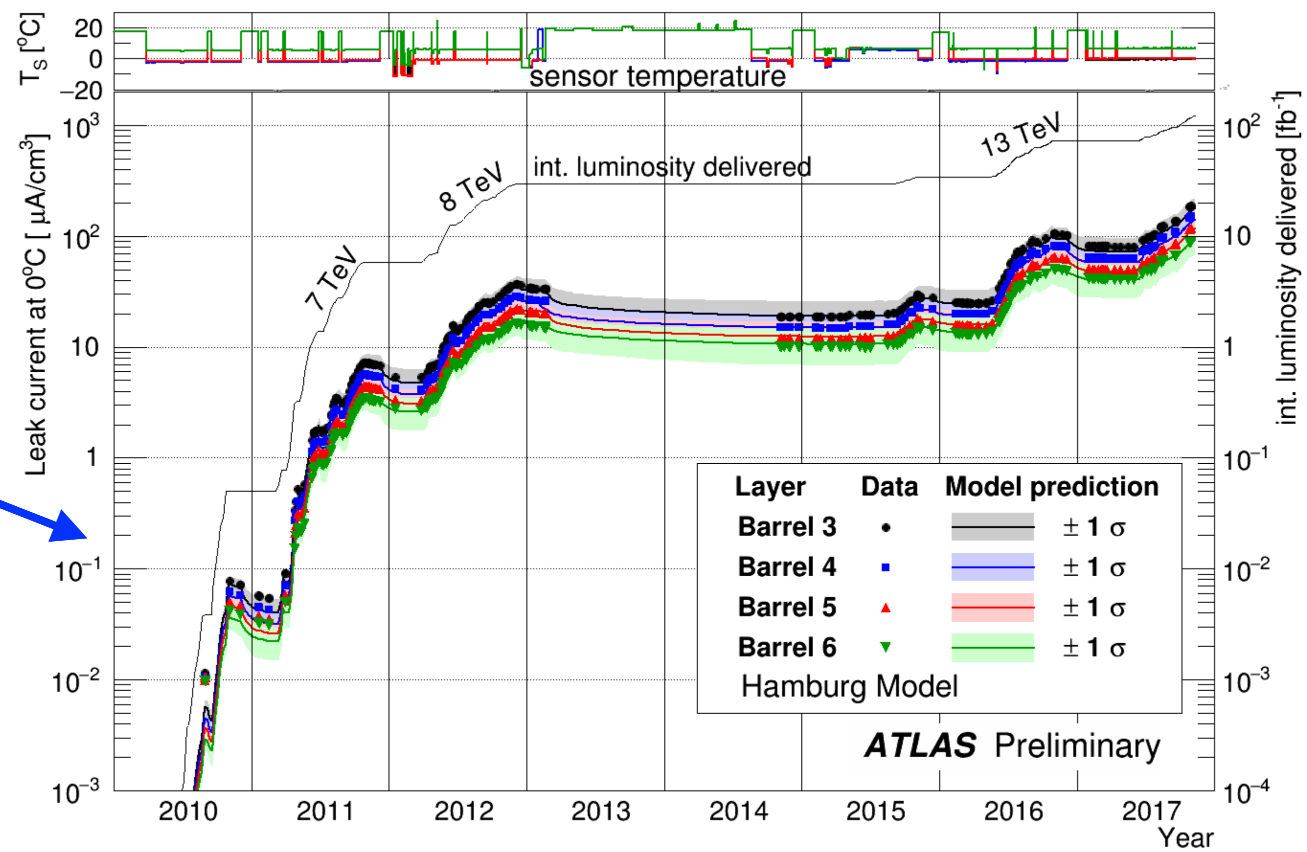
We can clearly **see a similar structure to the IBL**, with higher values in the central regions. **Structure is largest in the B layer, smallest in Layer 2**.

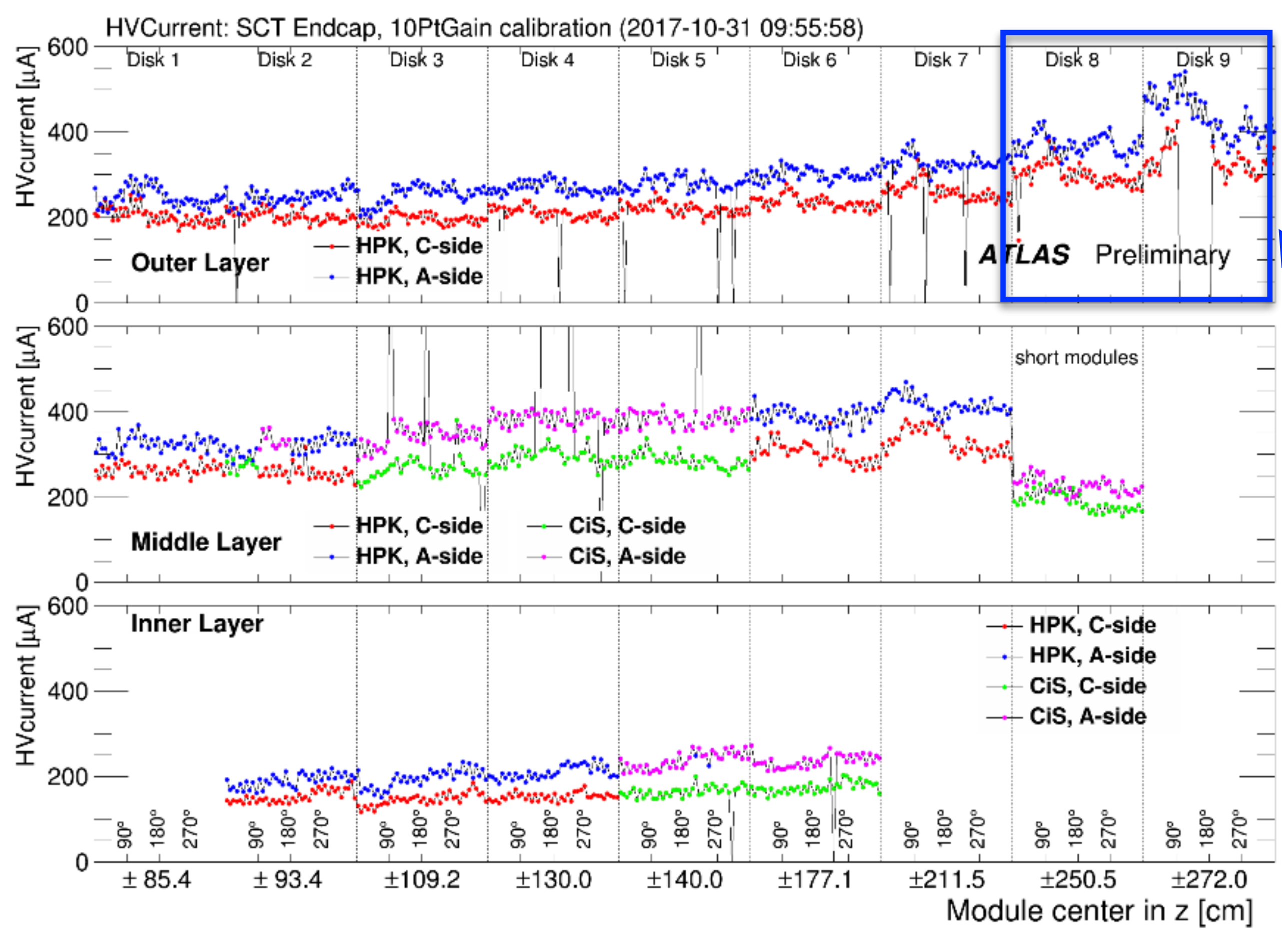
Measurements: SCT leakage currents

Investigated **evolution of SCT leakage current against time for all SCT layers**

Compare **observed SCT leakage current with modelled leakage current**, using simulated fluence rate values.

General agreement for all layers in Run 1 and 2.





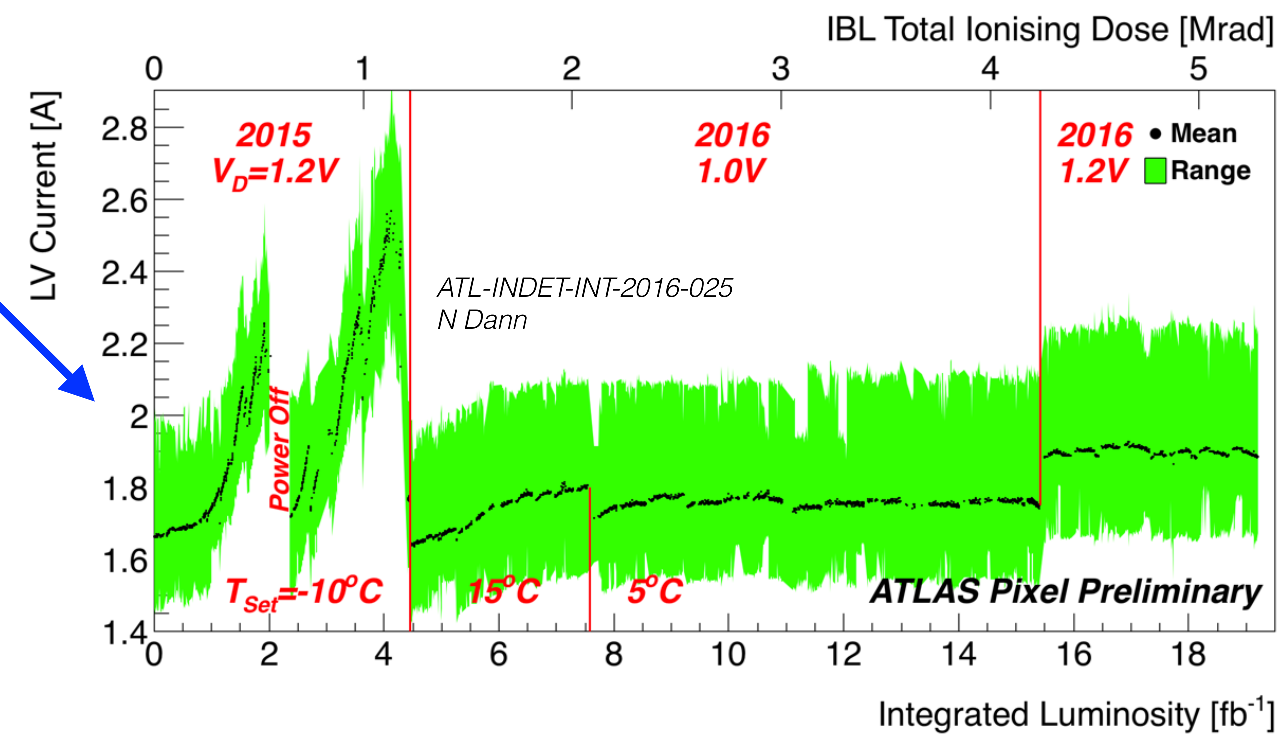
SCT barrel leakage currents show no significant z-dependance

SCT disks show much higher (~2x) leakage current in end disks (8&9), as predicted by FLUKA simulations

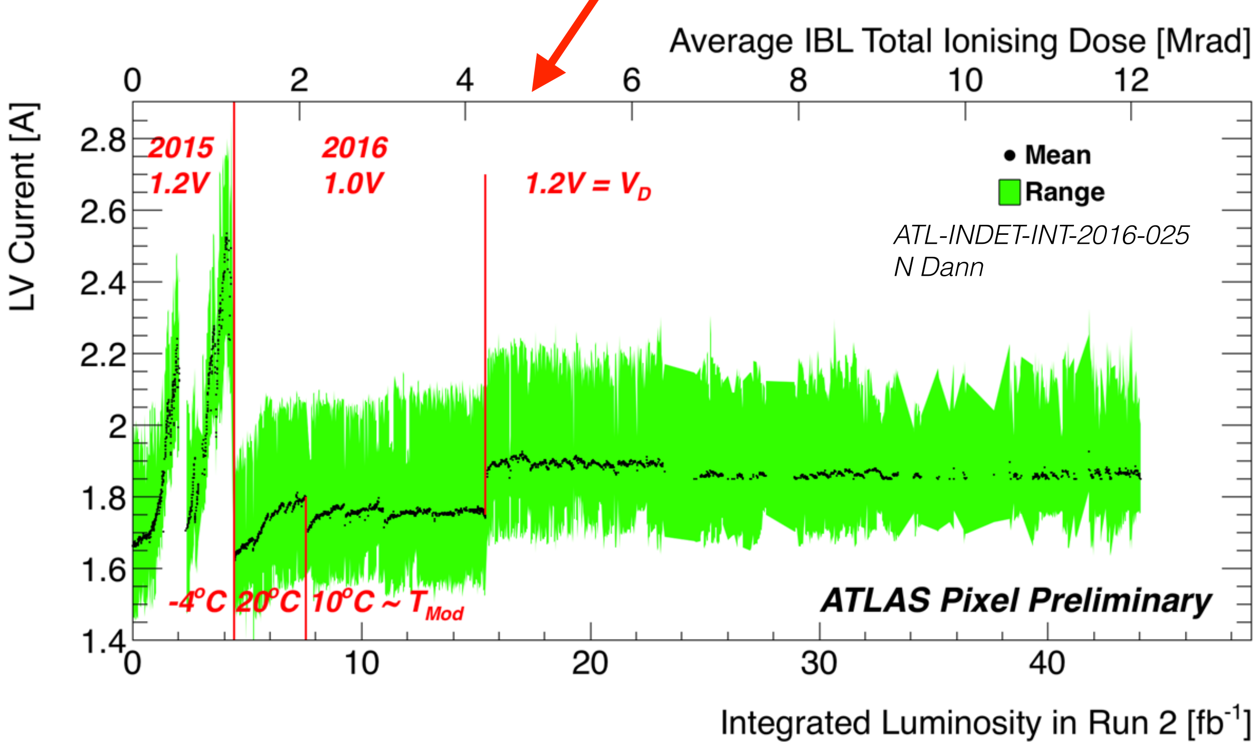
Measurements: IBL Readout Chips

Investigated how **IBL readout chip current consumptions evolved**

Clearly see **IBL readout chip currents increased dangerously in 2015**. Currents stable in 2016 after increasing operating temperature



Currents have remained stable since



There is **not yet a good predictive model for readout chip currents** as a function of TID

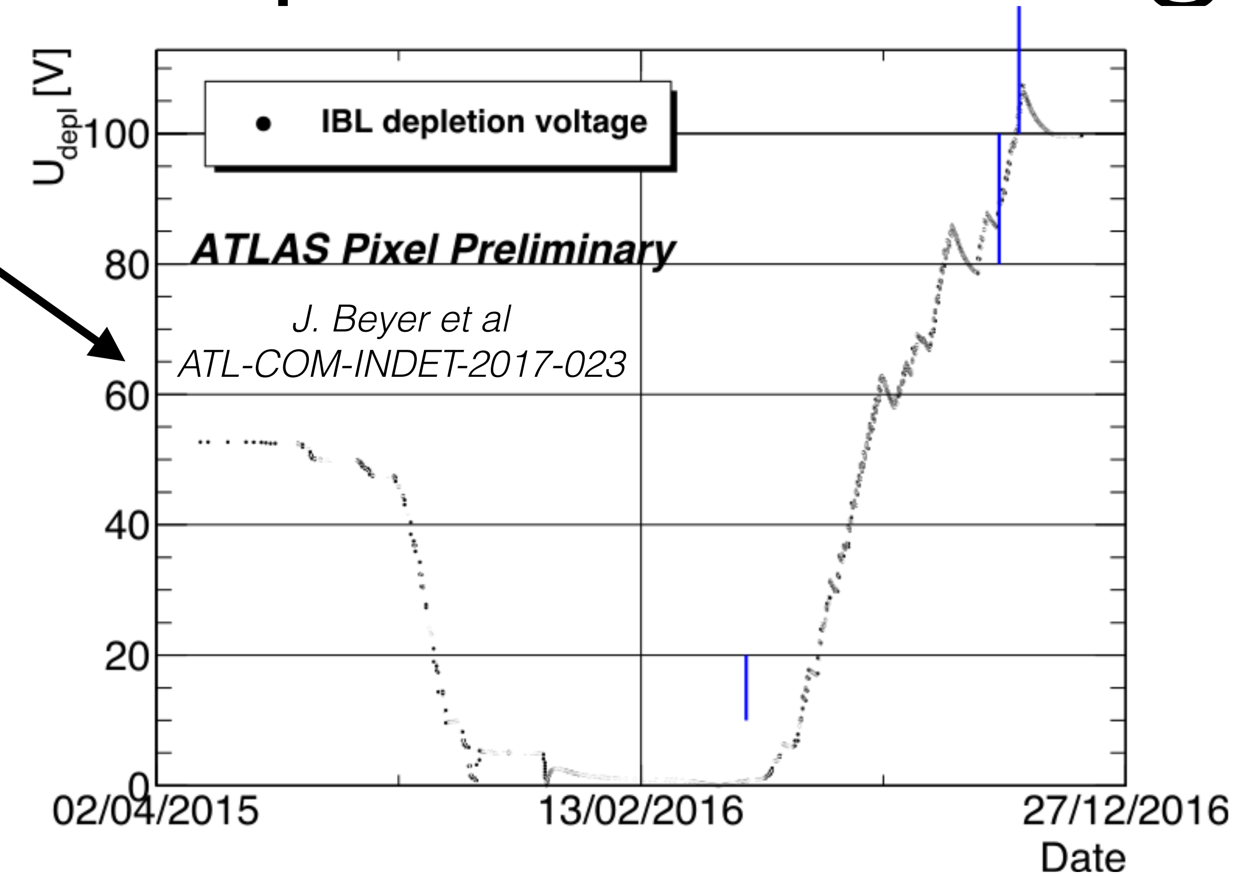
At best, we **expected to see a peak in chip current consumption at ~1 Mrad; results are consistent with this**

Changes in temperature/operating voltage may have hidden a later peak.

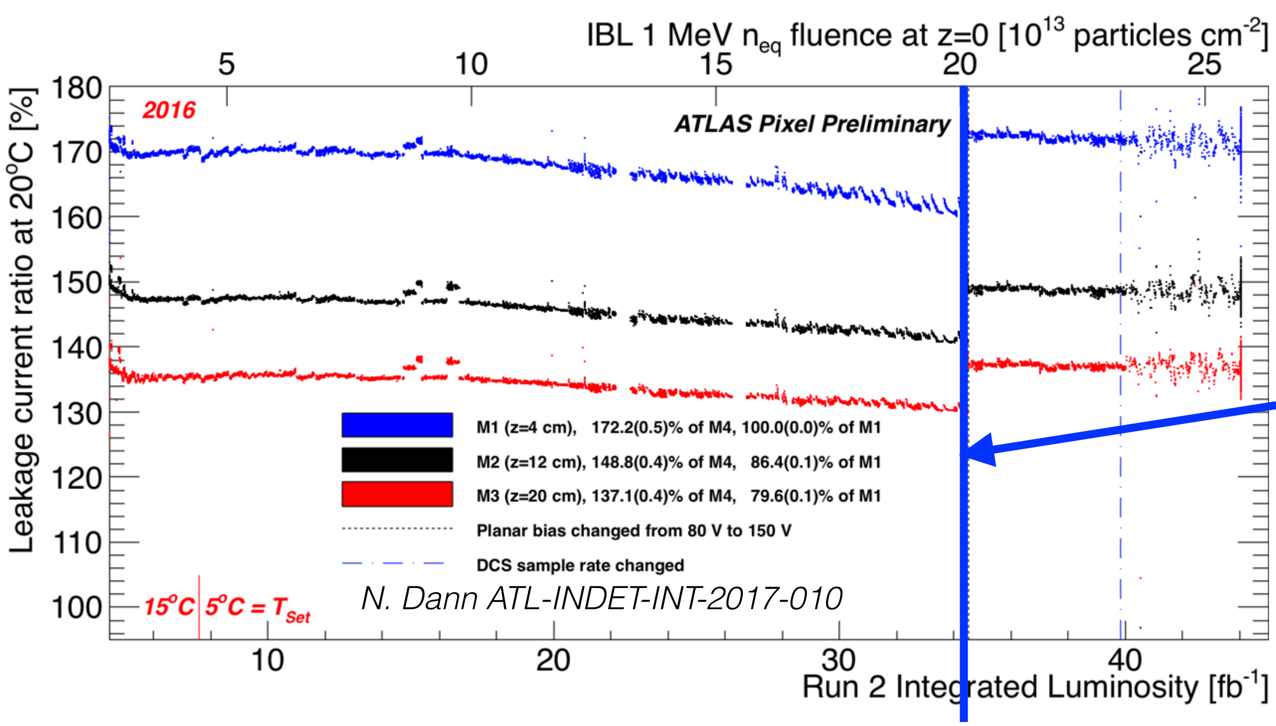
Measurements: IBL Depletion Voltage

Also investigated how **IBL depletion voltages evolve** in IBL planar sensors, comparing **predicted values** from the Hamburg model, against **measured data**

Hamburg model does not account for the first depletion voltage measurement, does accurately predict the rest



The **IBL sensors receive different fluence rates**, and thus **have different leakage currents**. The Hamburg model predicts the **ratio of leakage currents should be constant for all groups**



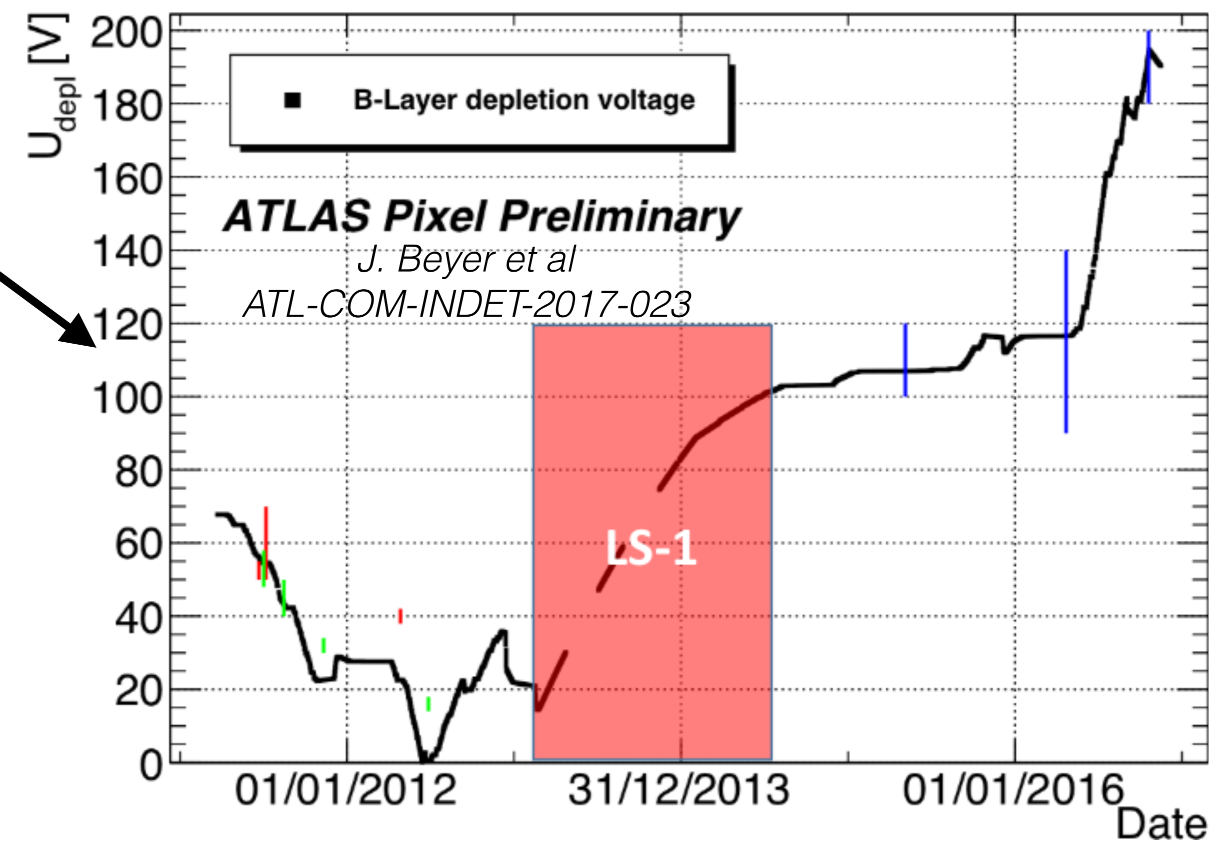
Planar bias increased

The **IBL leakage current ratios are clearly stable after the increase in planar IBL bias** in 2016, as predicted. We **compare 3D modules at |z| = 240-320 with planar modules** at **|z| = 0-80**, **80-160**, **160-240 mm**

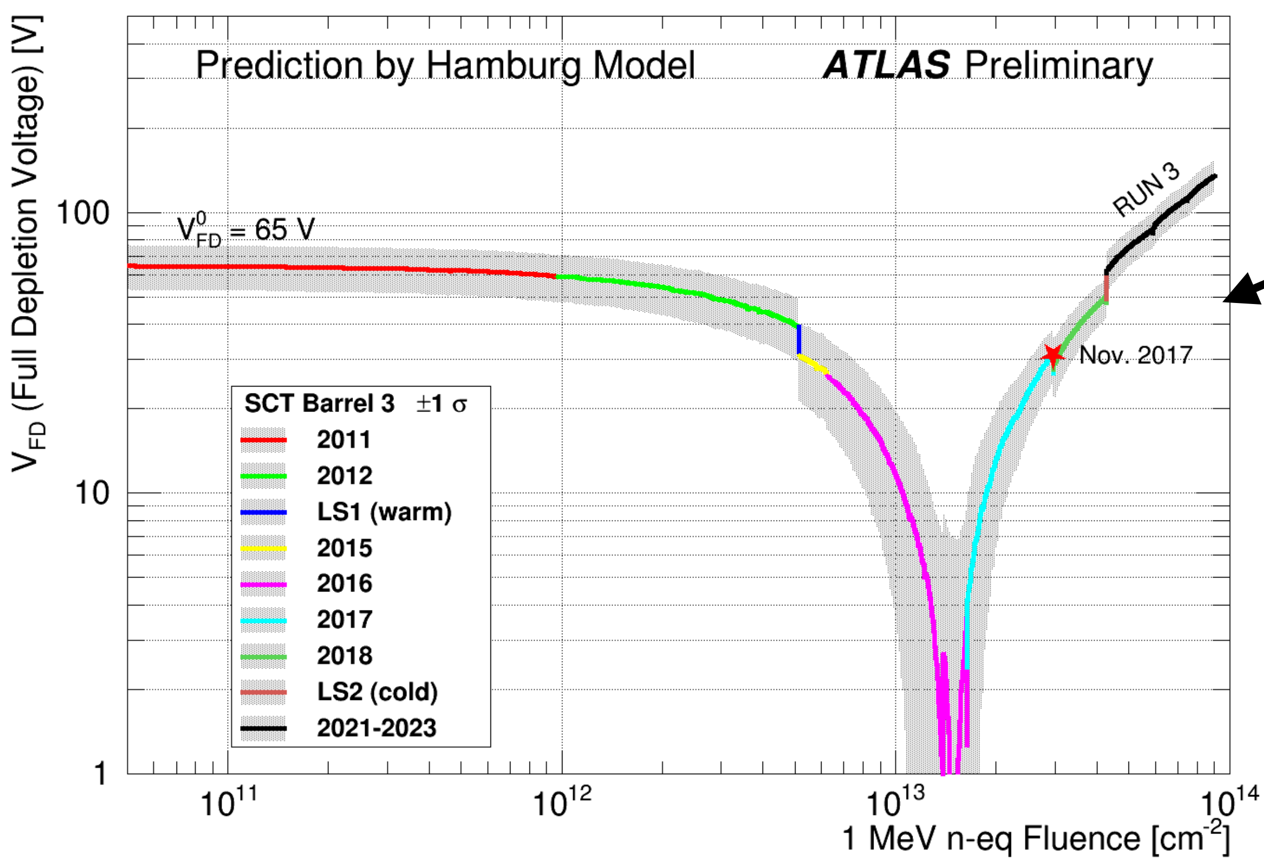
The **decrease in leakage current ratios** before this is **evidence that the modules were under depleted**

Measurements: Pixel/SCT Depletion Voltage

Depletion voltages have also been **simulated and measured in the B-layer** comparing **predicted values** from the Hamburg model, against measured data in **Run 1** and **2**



The **Hamburg model accurately predicts the measured depletion voltage values**



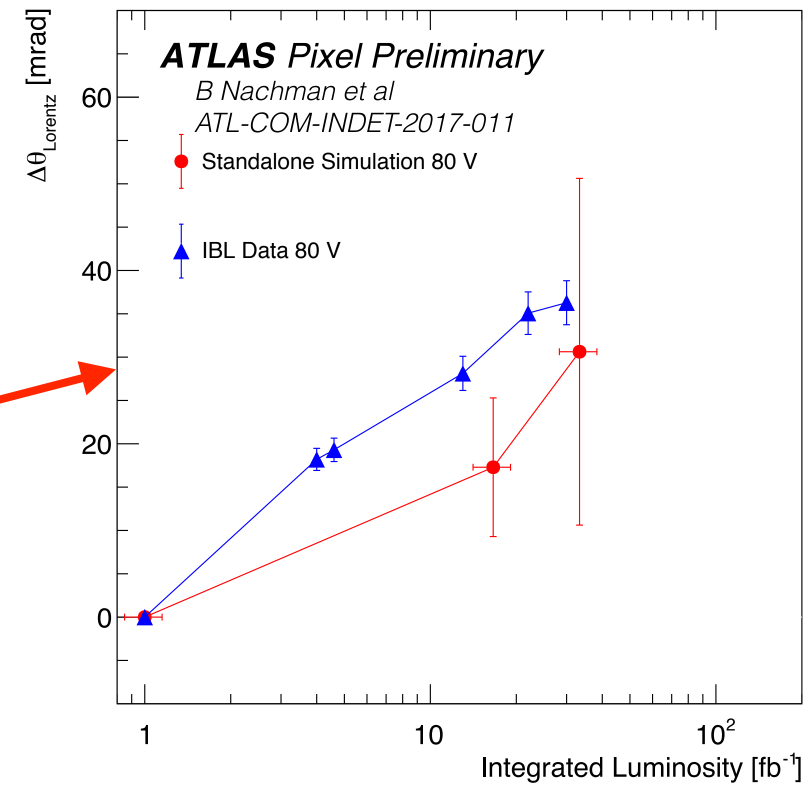
Depletion voltage simulations have also been done for **SCT Barrel 3**, but no measurements have been made yet

Hamburg model predicts Barrel 3 should have passed the type-inversion point, and that the depletion voltage will approach 200 V by 2023

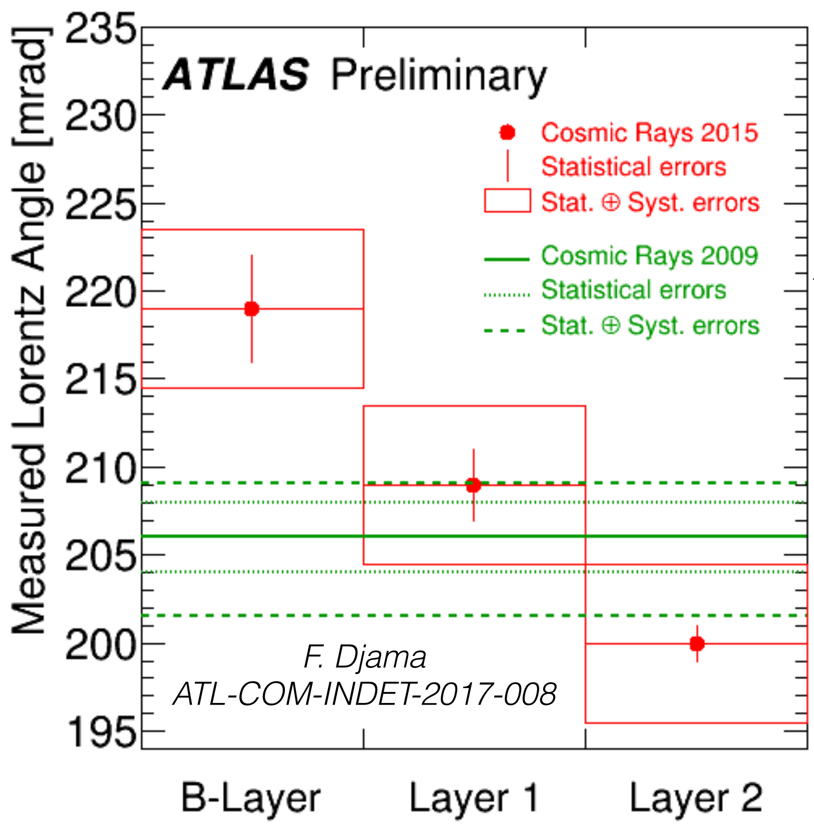
Measurements: Lorentz Angles

Charge carriers in ATLAS's silicon sensors are deflected by a magnetic field, the angle of this deflection is called the Lorentz angle

The **Lorentz angle can be measured**, and **varies as a function of radiation damage**. We **observe the expected increase of angle with integrated luminosity**



See Ben Nachman's talk for details on the simulation



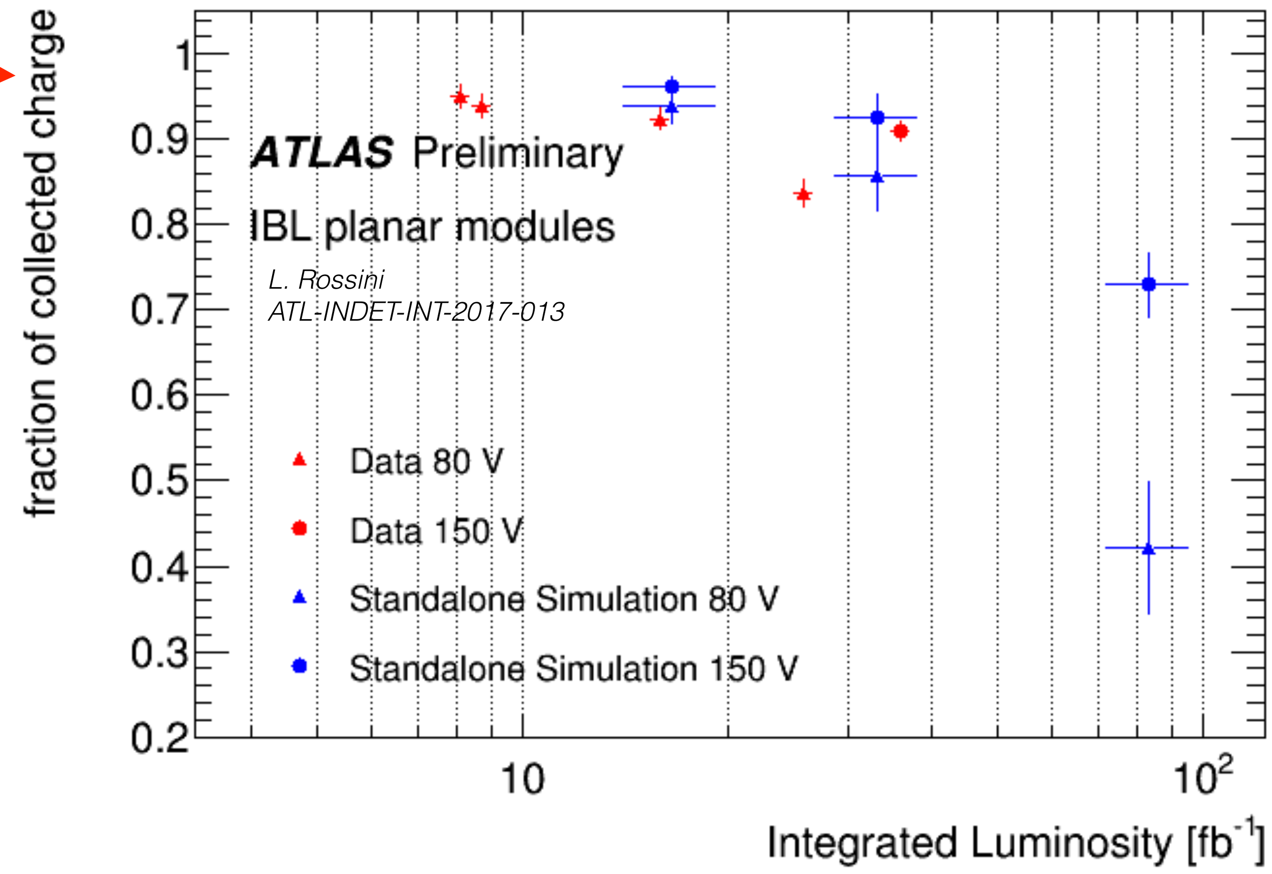
Also **found Lorentz angle for Pixel before Run 1** and **Run 2**

Can clearly see there was **no difference in Lorentz angle between layers, before Run 1**

Can clearly see **B-layer has highest Lorentz angle, Layer-2 has lowest, before Run 2**

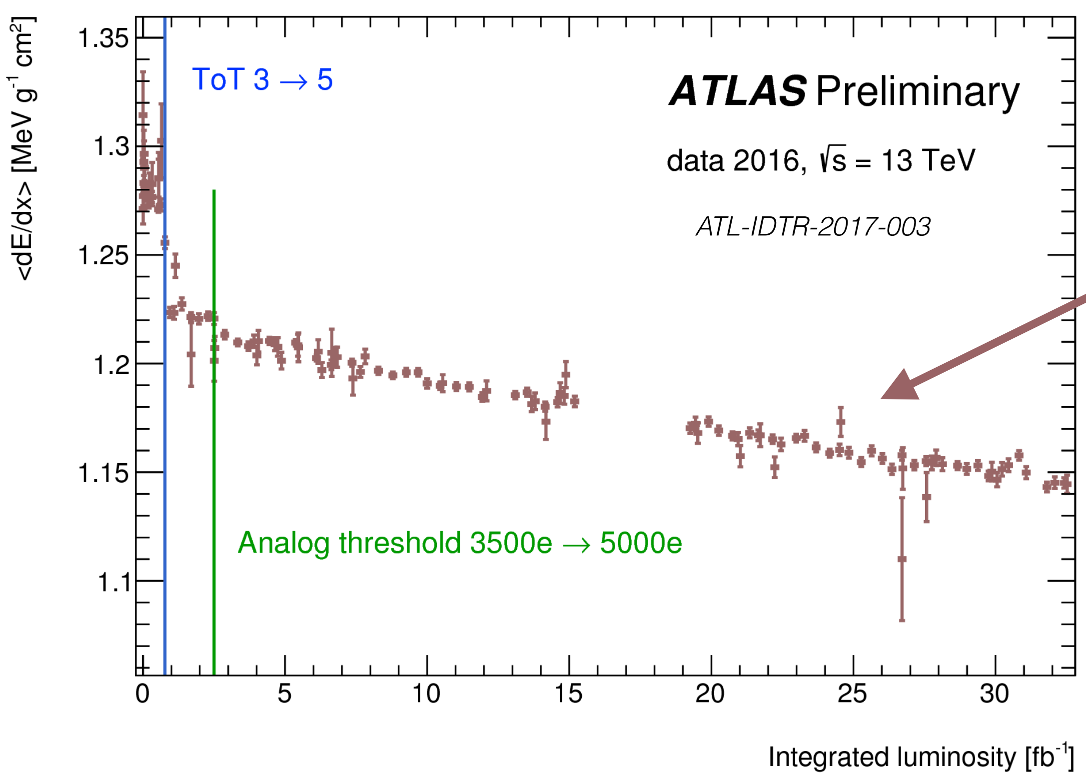
Measurements: IBL and Pixel Charge Collection

Measured how **IBL charge collection efficiency varied** as integrated luminosity increased; expect the efficiency to decrease due to radiation damage



Observe the expected decrease in charge collection efficiency

See Ben Nachman's talk for details on the simulation



Performed **similar measurements for B-layer, using dE/dx** instead

dE/dx value is related to the charge collection efficiency, and will decrease as radiation damage increases

Can clearly see the **gradual decrease in dE/dx due to radiation damage**, and the step changes, due to changing tuning thresholds in the readout chips

Summary

We have very **detailed models of fluence and TID per ifb for the entire ATLAS detector**

General agreement between FLUKA simulations and leakage current observations in IBL, B-layer, layer 1 and 2 and SCT

Significant difference in z-dependance of fluence for IBL. Smaller effect seen in Pixel. No z-dependence found for SCT Barrel

IBL readout chips affected by TID, observations consistent with FLUKA TID simulations

Hamburg model predicts depletion voltage evolutions; these generally **match measurements in the IBL and B-layer**

Lorentz angles have been measured for IBL; values increasing as expected, but observe lower angles than predicted. From pixel measurements, we clearly **see highest Lorentz angles in B-layer and lowest in Layer-2**

Charge collection efficiency is decreasing in IBL, in line with simulations

Back up

Temperature normalisation

(eq. 1) $$\frac{\Delta I}{V}(\Phi,T,t) = \alpha(T,t)\cdot\Phi = R(T)\cdot\alpha(T_R,t)\cdot\Phi$$

where $R(T)$ is the ratio between the leakage current measured at temperature T and a certain reference temperature T_R . *R(T)* is given by [6] as:

(eq. 2) $$R(T) = \frac{I(T_R)}{I(T)} = \left(\frac{T_R}{T}\right)^2 \exp\left(-\frac{E_g}{2k_B}\left[\frac{1}{T_R}-\frac{1}{T}\right]\right).$$

In this work all presented data have been normalized to T_R = 20°C using an effective energy gap of E_g = 1.12 eV. Most previously reported data on the annealing of the leakage current have been parameterized with a normalized annealing function g(t) consisting of a sum of exponentials [7,8]

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.55.2759&rep=rep1&type=pdf

[6] : S.M. Sze, Physics of Semiconductor Devices, 2nd ed. (Wiley, 1984)

Leakage current dependence on fluence

Change in leakage current (ΔI) in silicon sensors **mostly due to** electron-hole pair generation at radiation-induced **defects in sensor bulk**

Bulk defects mainly created by NIEL, **number of defects increases ~linearly with fluence** (Φ_{eq}), and **leakage current should be ~proportional to fluence**, mathematically where $\mathscr{V}$ is the sensor volume and α is the damage function

$$\Delta I = \alpha \, \Phi_{eq} \mathscr{V}$$

Complication; **defects can anneal over time**, with greater annealing at higher temperature => **expect leakage current to decrease over time**, => add time (t) and temperature (T_k) dependance to damage function α. Also add empirical ln term to account for long-term effects

$$\alpha(t, T_k) = \alpha_1 \exp(-t/\tau_1) + \alpha_0 - \beta \ln(t/t_0)$$

Final complication; $\alpha(t, T_k)$ is only valid for a single irradiation. IBL is irradiated multiple times => instead find and update $\alpha(t, T_k)$ and Φ for each luminosity block, then sum them together to find total ΔI, i.e.

$$\Delta I = \sum \alpha_i \Phi_i \mathscr{V}$$

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Leakage current dependence on fluence

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$$\Delta I = \sum \alpha_i \, \Phi_i \, \mathscr{V}$$

*(current = sum of all alpha parameters * fluence * volume)*

Finally, substitute fluence = constant conversion factor * integrated luminosity (Φ_i = F * L_i) can see that ΔI = F * $\sum \alpha_i$ * L_i

For **IBL, all modules** should **have same alphas**, any **differences in fluence** should **result in proportional differences in leakage current**; i.e.

$$\Delta I_1 \, / \, \Delta I_2 = F_1 \, / \, F_2$$

(current 1 / current 2 = conversion factor 1 / conversion factor 2)

Test this on next slide by plotting relative leakage currents in each module group (i.e. plot $I_{\text{module group 1}}$ / $I_{\text{module group 4}}$)

Can we predict leakage currents?

Record time (t), mean **temperature** (T_k) and use these to **find** the **damage function** α^i for every lumi block, **and** the **evolution** of all previous α^is

Find lumi delivered in every lumi block, **convert to fluence** (Φ^i_{eq})

Multiply all α^is by relevant Φ^i_{eq}, **sum results** to find total α

Temperature dependence studied in range 20 - 100 C, we're at ~10C. Recent studies find greater than expected annealing at room temperature => **model will** likely underestimate annealing and **overestimate leakage current**

Hamburg model parameterisation values

Change in leakage current (ΔI) with fluence (Φ_{eq}), where V is the sensor volume and α is the damage function

$$\Delta I = \alpha \, \Phi_{eq} \, V$$

Time (t) and temperature (T_k) dependance of damage function α

$$\alpha(t, T_R) = \alpha_1 \exp(-t / \tau_I) + \alpha_0 - \beta \ln(t / t_0)$$

$$\alpha_1 = 1.23\text{x}10^{-17} \text{ A/cm}$$

$$1/\tau_I = k_{0I} \exp(E_I/(k_B * T_k))$$

$$k_{0I} = 1.2\text{x}10^{13} \text{ s}^{-1}$$

$$E_I = 1.11 \text{ eV}$$

$$k_B = 8.62\text{x}10^{-5} \text{ eV/K.}$$

$$\alpha_0 = -8.9\text{x}10^{-17} \text{ A/cm} + (4.6\text{x}10^{-14} / T_k) \text{ A K/cm}$$

$$\beta = 2.9\text{x}10^{-18} \text{A/cm}$$