Monitoring radiation damage in the ATLAS silicon tracker

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on behalf of the ATLAS Collaboration

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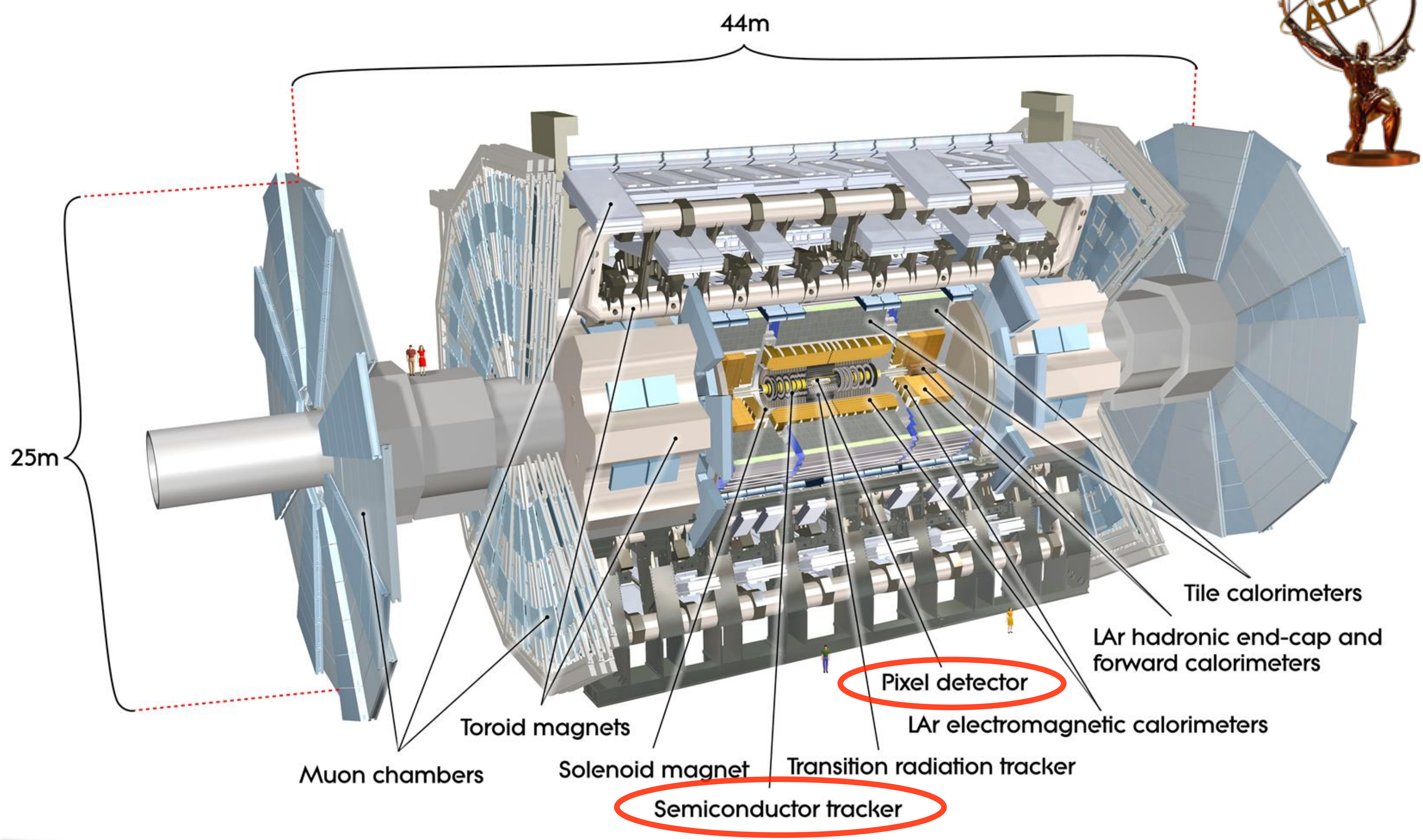
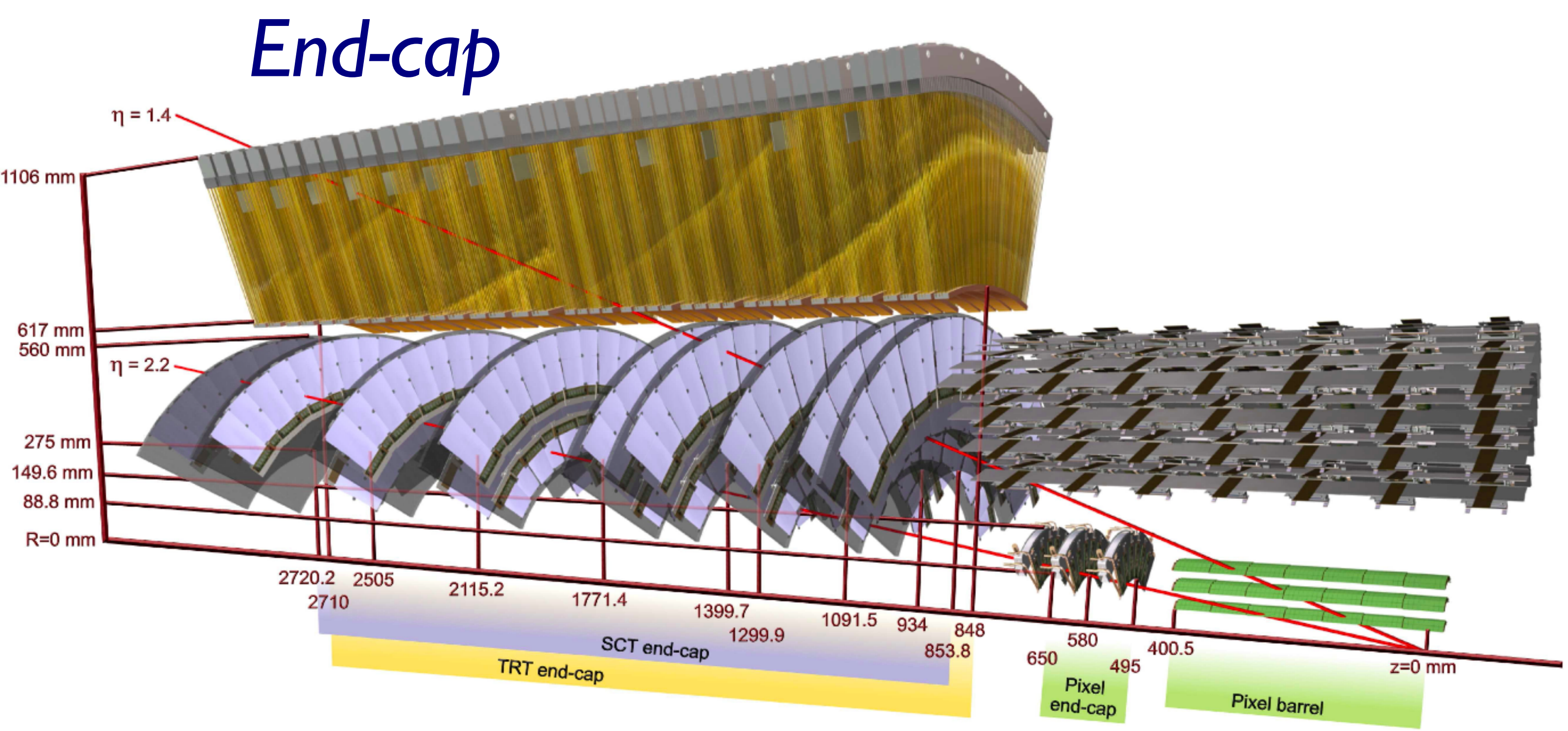
Outline

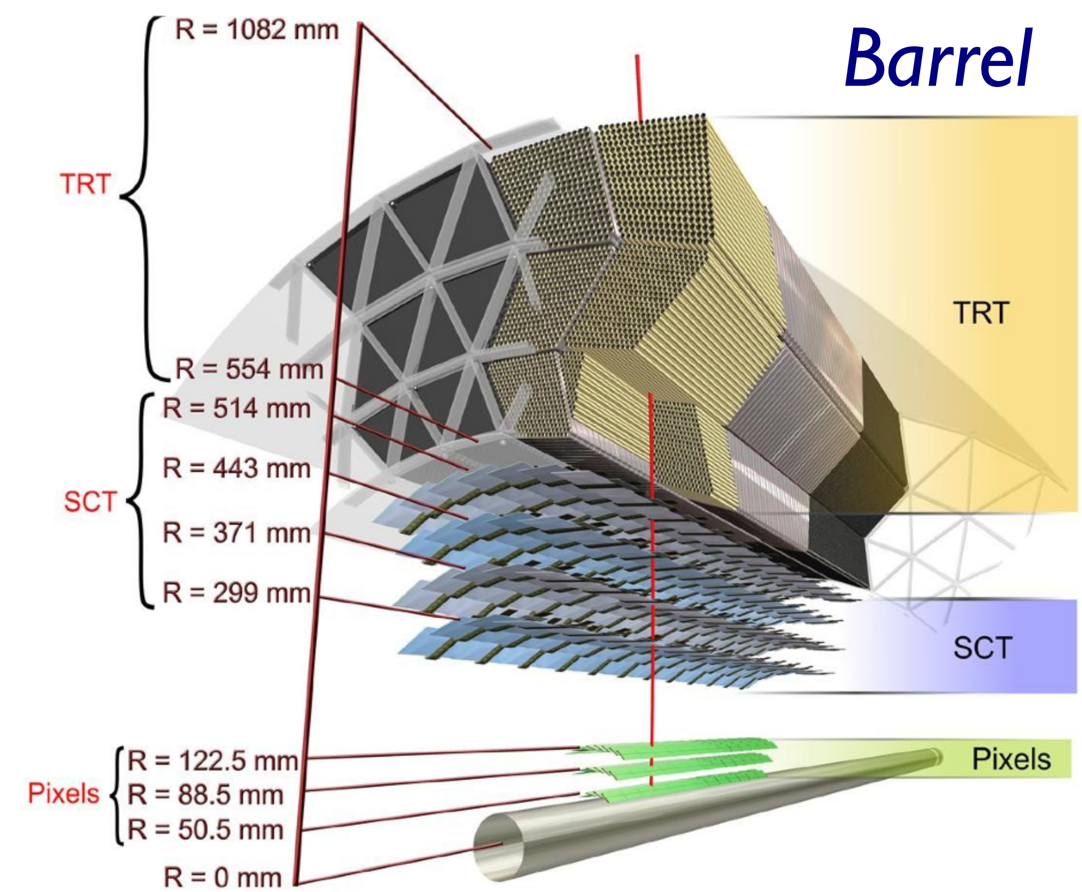
- The ATLAS silicon tracker:
  - Pixel sensors and micro-strips
- Accumulated fluence and radiation damage effects
- Sensor leakage current
  - Pixels: results from current monitoring boards
  - SCT
- Comparison with expectations
- Depletion voltage using cross-talk method
- Depletion depth monitoring with tracks
- Conclusions

The ATLAS detector



The ATLAS Inner Tracker

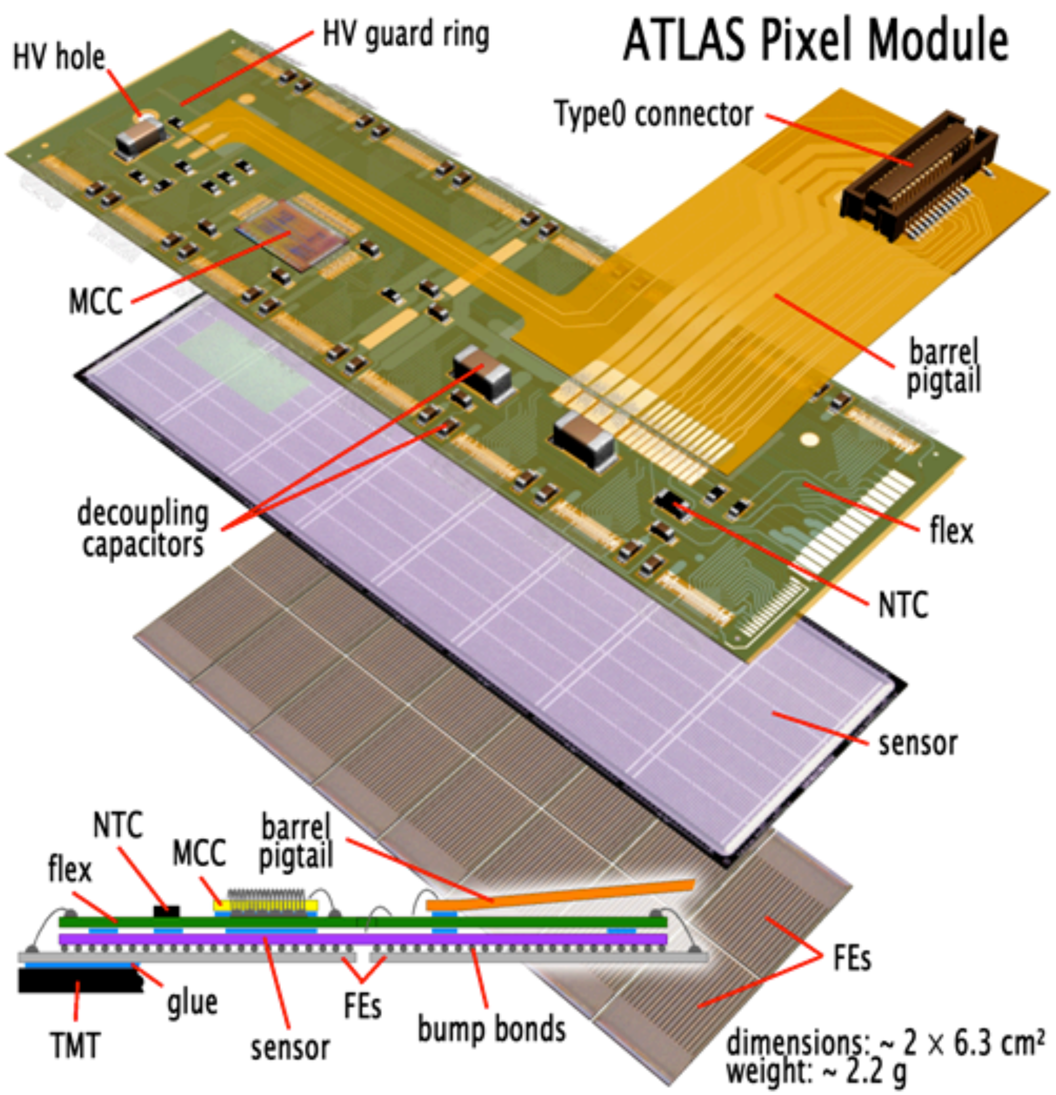


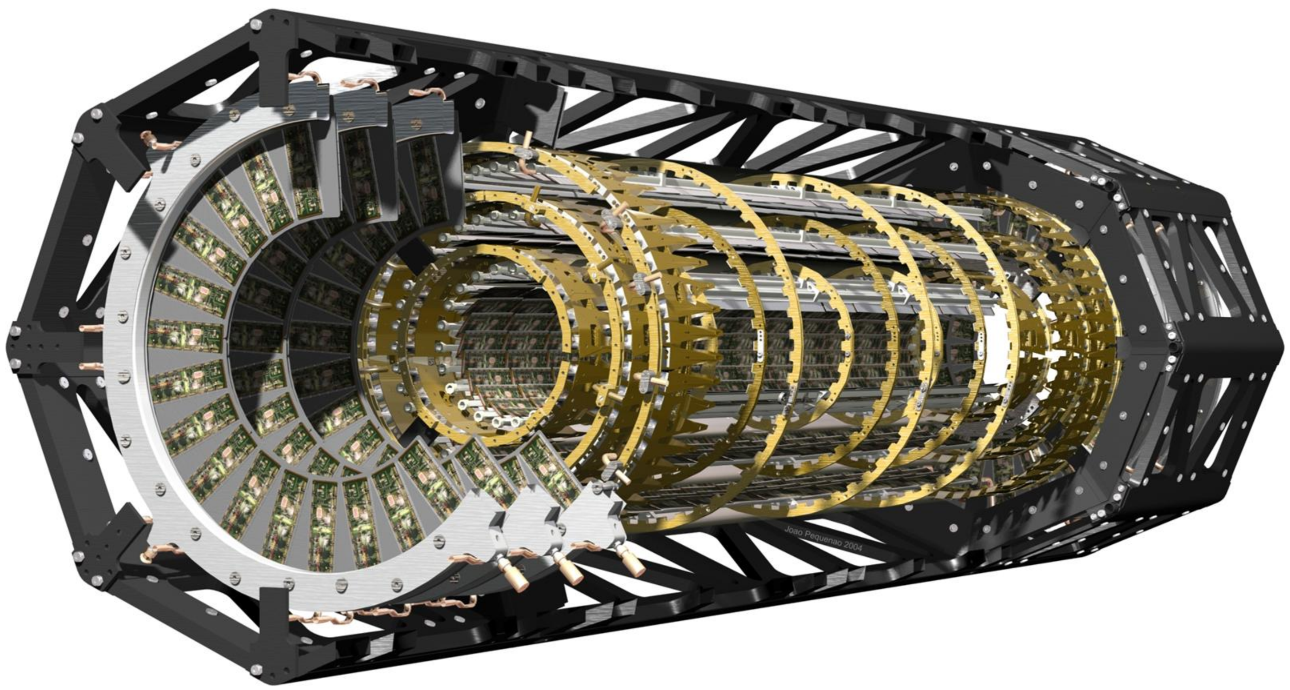


- Hermetic, high granularity silicon tracker to $|\eta| < 2.5$:
  - Pixel: 3 barrel layers + 2x3 end-cap discs.
  - SCT: ~4 track points from 4 barrels + 2x9 discs.

Detector	Type	Modules	Channels	Intrinsic resolution
Pixel	Silicon pixel modules	1774	~80M	10 μm in rϕ, 115 μm in rz.
SCT	Silicon micro-strip detectors	4088	~6M	17 μm in rϕ, 580 μm in rz.
TRT	Straw drift tubes	176	~350k	130 μm in rϕ

The ATLAS Pixel Detector module

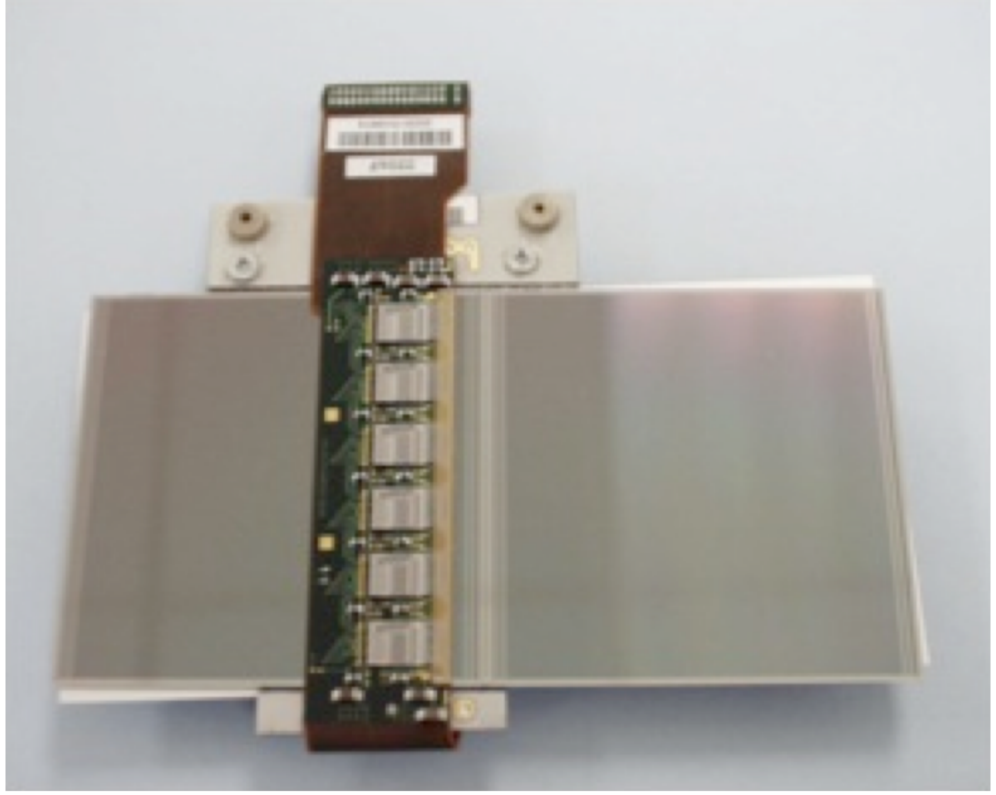


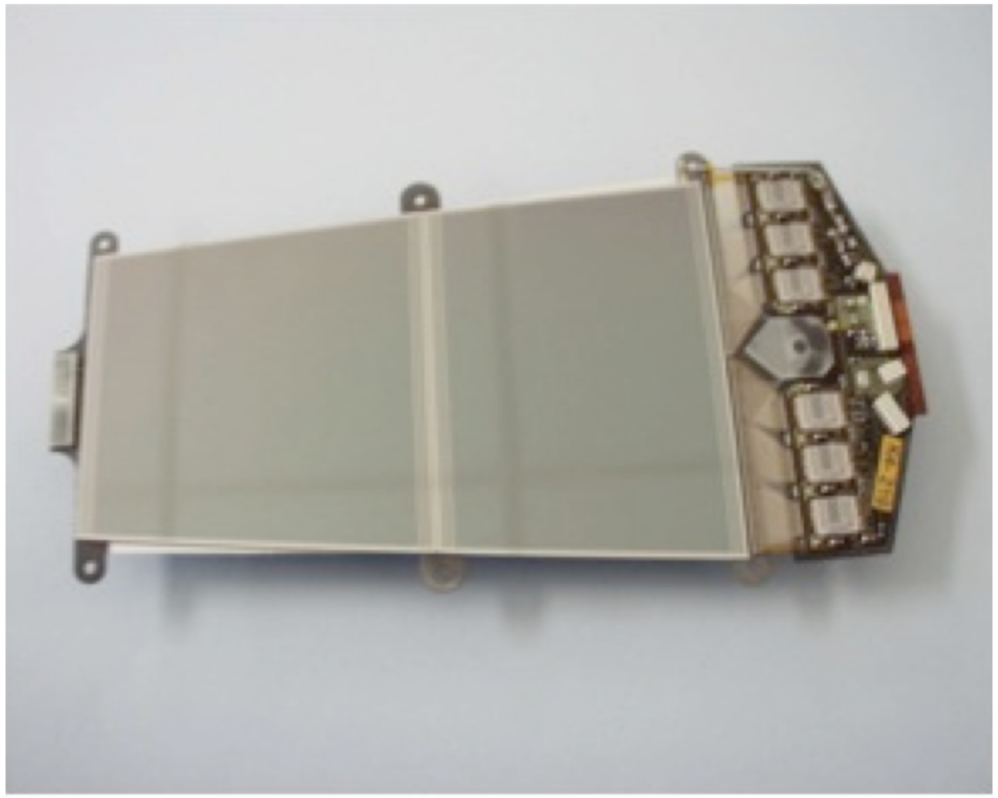


- **Readout:**
  FE = Front End
  MCC = Module Control Chip
  - 16 FE chips with zero suppression, MCC builds module event. Date rate of 40-160MHz depending on layer.
  - Deposited charge measured by Time over Threshold.
- **Innermost layer at 50.5mm:**
  - Radiation tolerance 500kGy/ 10^{15} 1MeV n_{eq} cm^{-2}
- **Evaporative cooling integrated in support structure:**
  - Modules cooled to average of -13 °C.
- **Sensor:**
  - 250 μm thick n-on-n type silicon, with typical pixel granularity, 50x400 μm.
  - 47232 (328 x144) pixels per module (46080 pixels bump-bonded to 16 FE readout chips).
  - V_{bias} = 150 V (600 V)

SemiConductor Tracker module

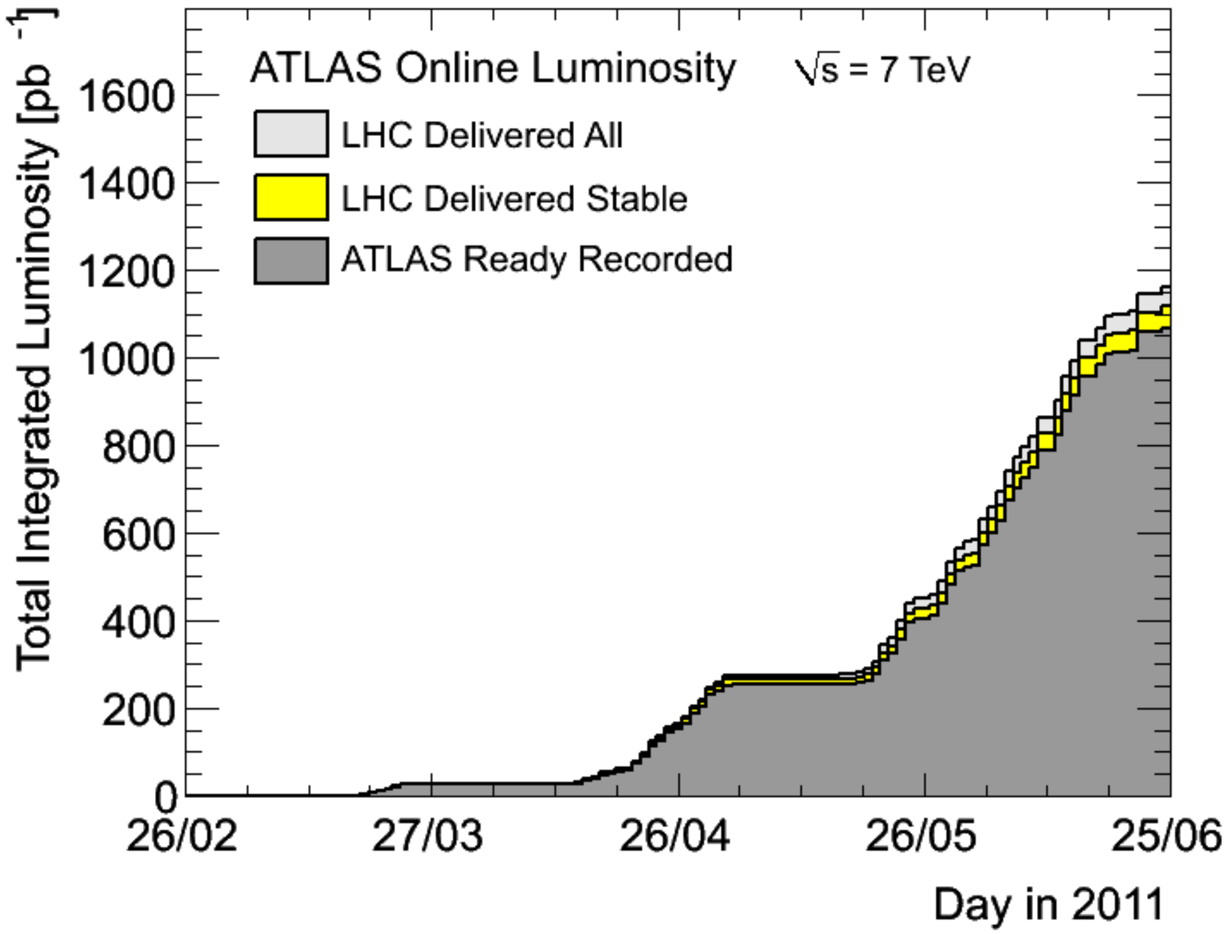
- Double-sided module of silicon micro-strips:
  - 768 p-type strips on n-type silicon per wafer.
  - Glued back-to-back with 40 mrad stereo angle enables 3D space points.
- Modules
  - Barrel: 80 μm strip pitch, ~13cm long
  - End-cap: 57-84 μm strip pitch and length varies from 55 mm -120 mm, depending on radial position of module.
- Read out
  - 6 "ABCD" read out ASIC chips per side.
  - Binary readout at p-strips (1 fC threshold).
  - 150 V bias voltage (before irradiation)





Effects of radiation damage

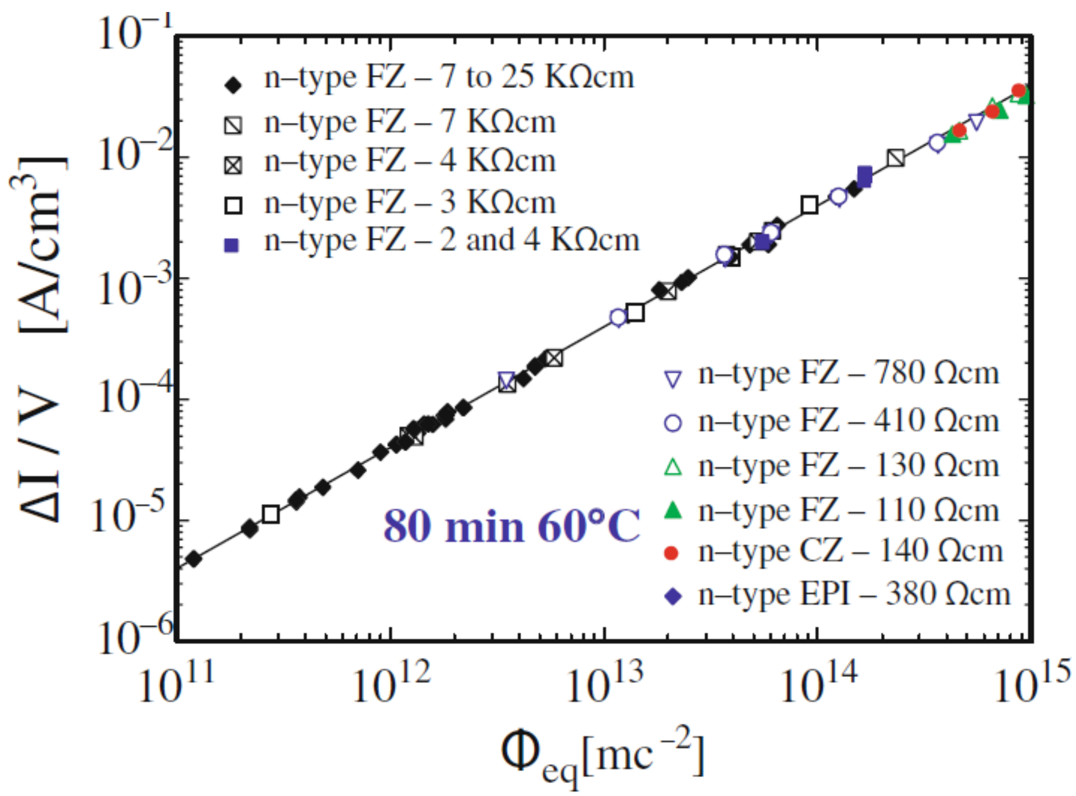
- As the delivered LHC luminosity increases, the pixel detector will receive doses of up to 50 MRad and a fluence of ~10^{15} n_{eq} cm^{-2} during the operational lifetime.
    - The innermost layer is expected to undergo type-inversion after 10 fb^{-1} integrated luminosity (with optimal annealing).



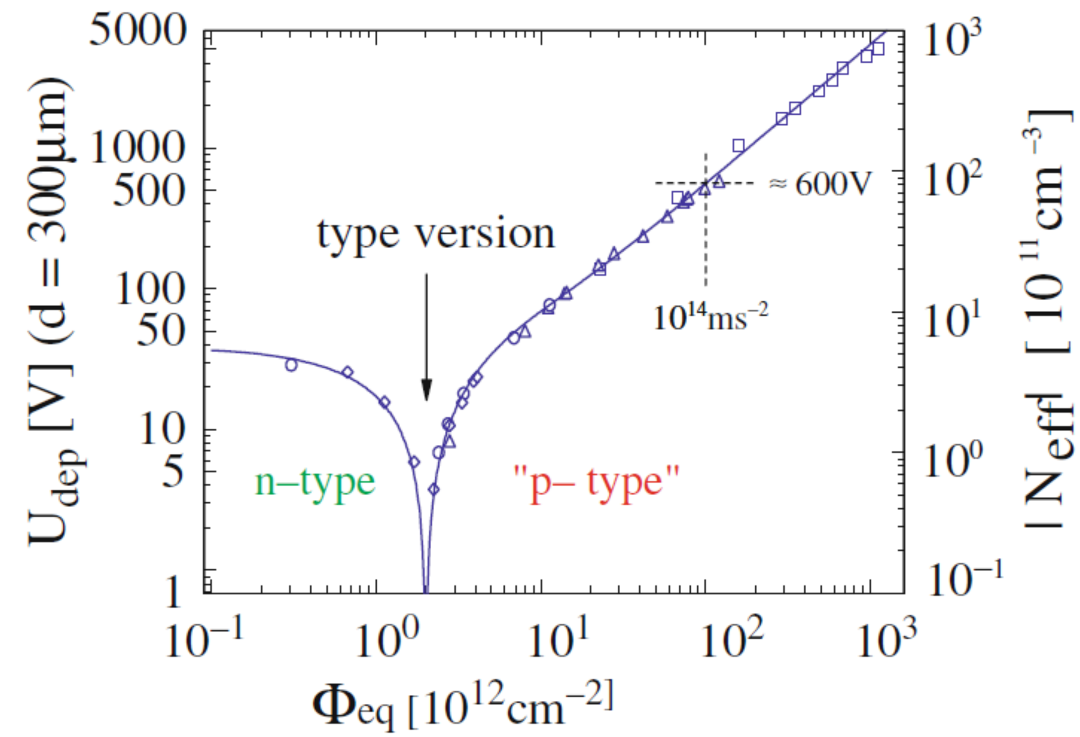
- Bulk damage resulting in crystal defects will alter the physical properties of the sensor and change the operating conditions:
    - The introduction of acceptor centres will modify the doping concentration and lead to type-inversion, after which the voltage required to fully deplete the sensor will increase.
    - Recombination/generation centres will increase the leakage current, affecting power consumption and signal to noise.
    - Charge trapping centres will reduce the charge collection efficiency, and hence degrade hit efficiency and track resolution, b-tagging etc.

Effects of radiation damage

Leakage current



Depletion voltage



From M. Moll and R. Wunstorf and others

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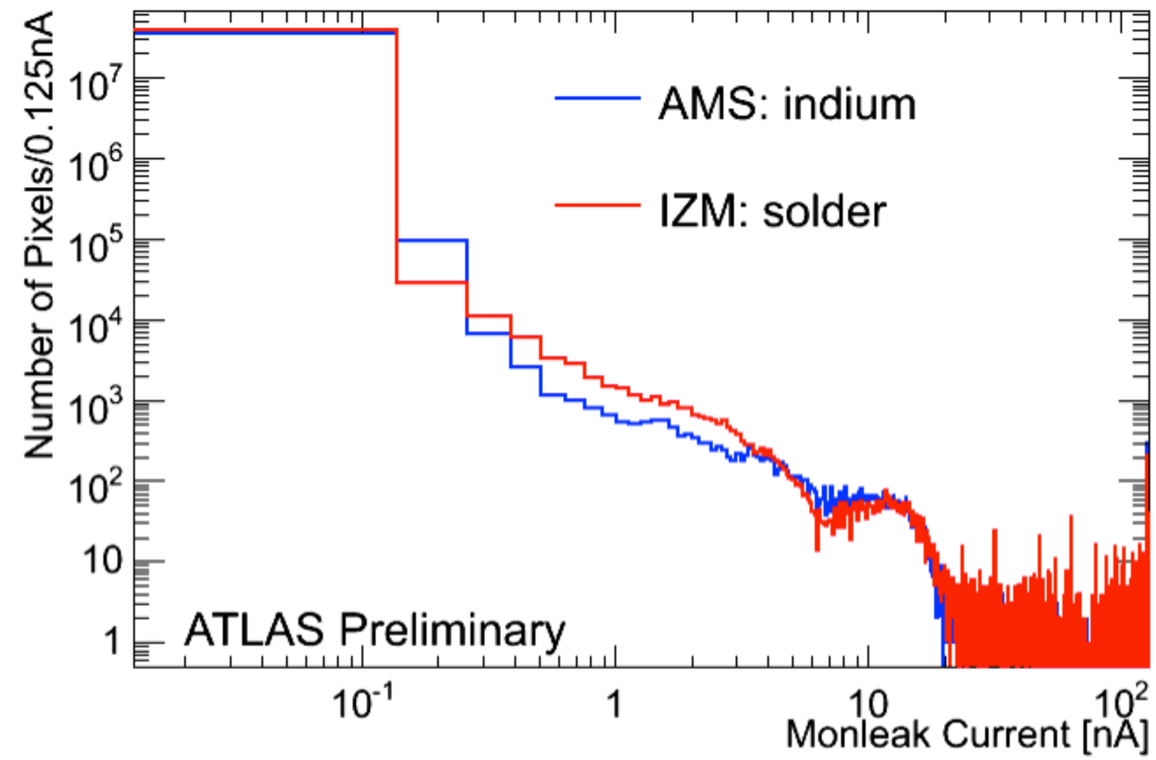
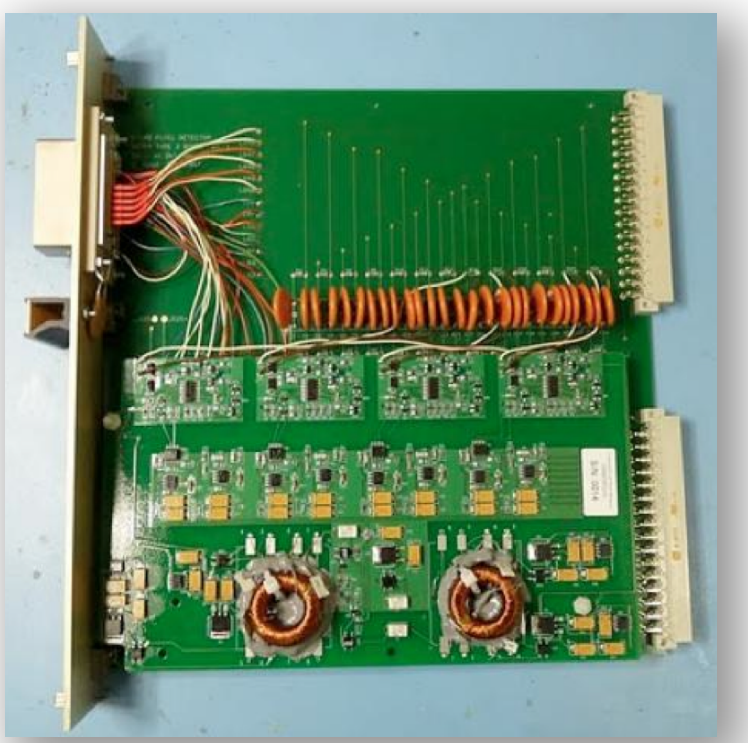
Pixel leakage current monitoring

- **Pixel-by-pixel measurements:**
  - The FE-chip enables measurement of leakage current per pixel ("Monleak")
  - Currently below sensitivity as the measurement range and resolution is optimised for after irradiation:

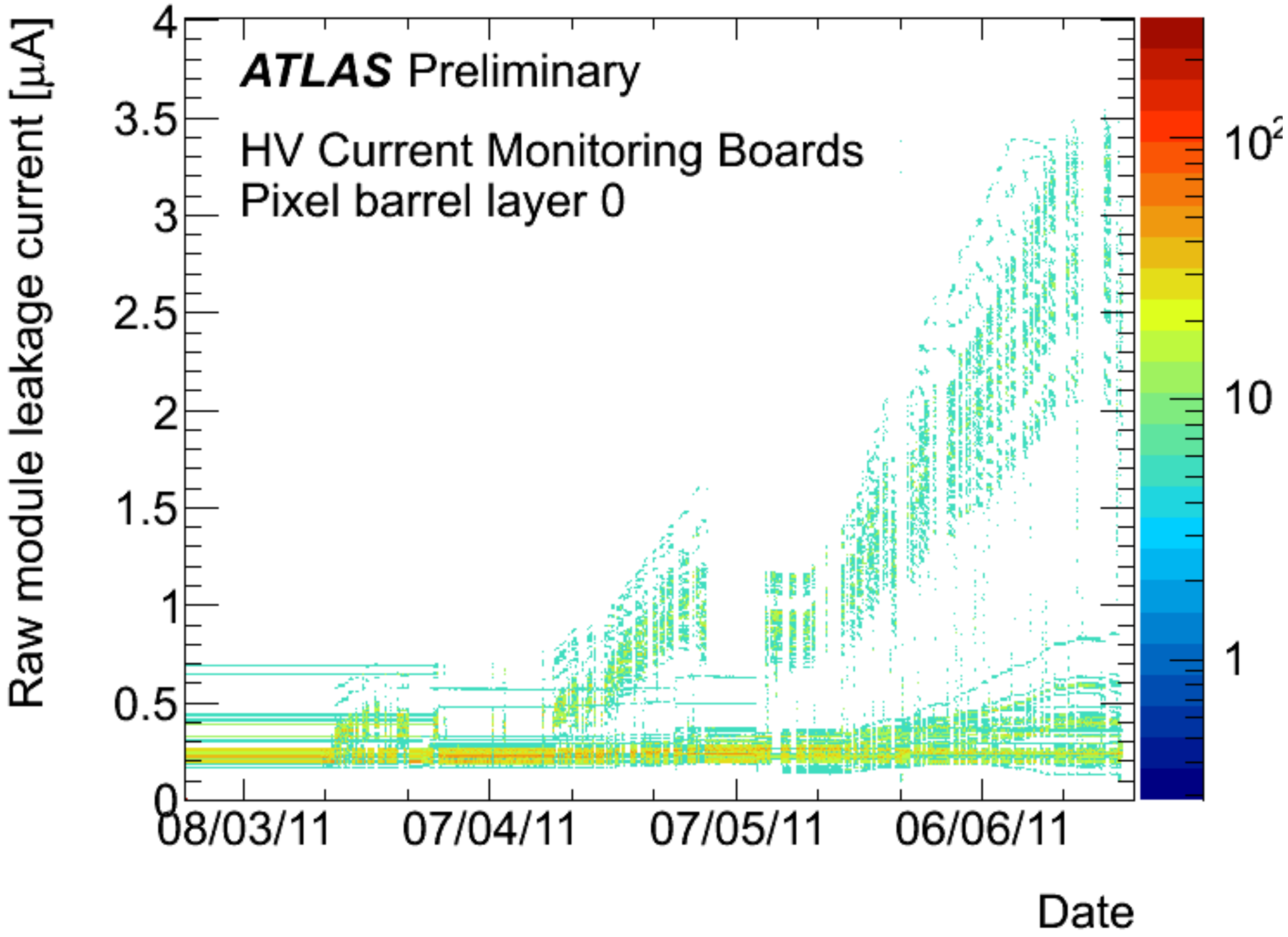
    LSB ~0.125nA

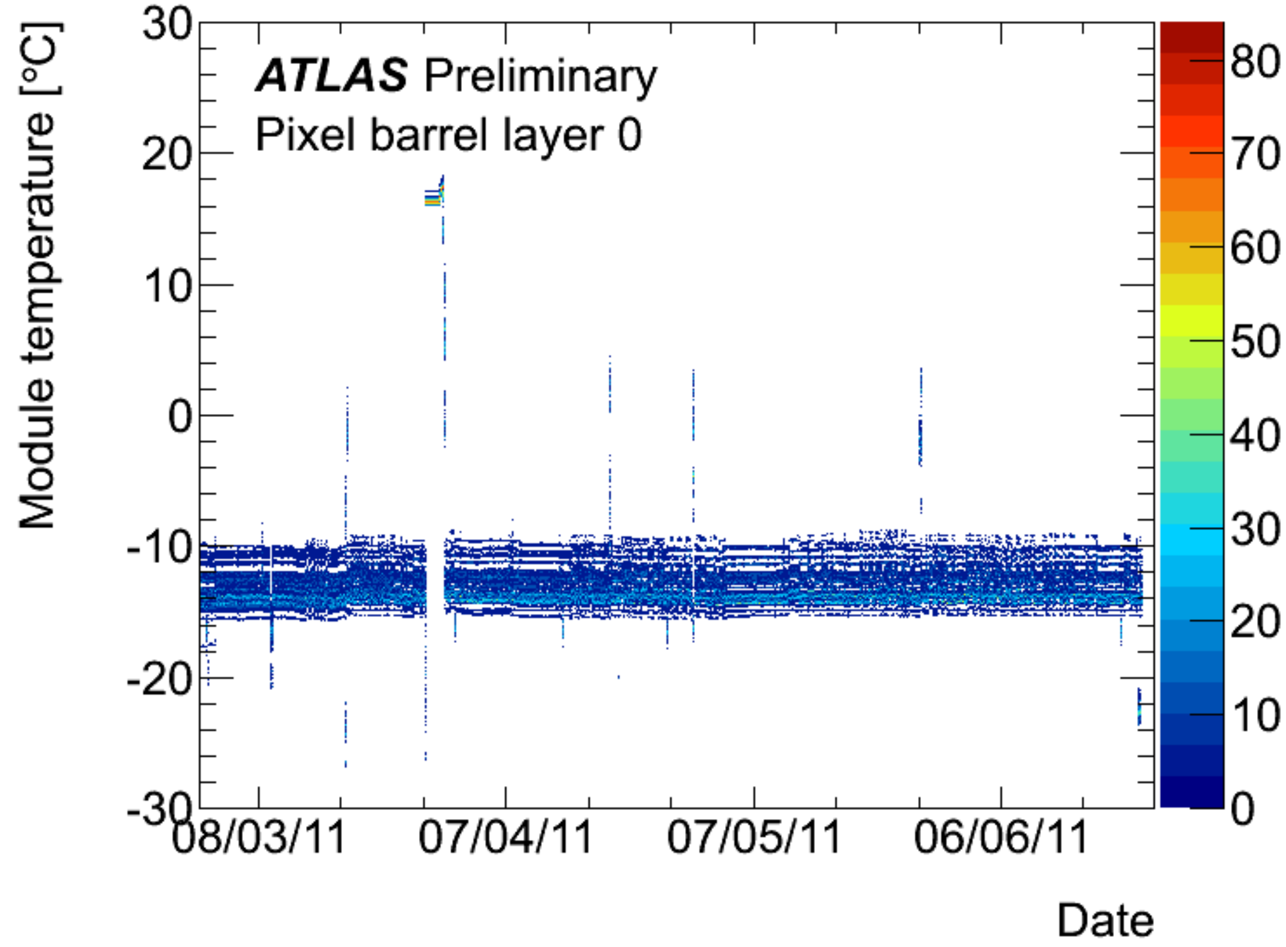




- **Current Monitoring Boards (results next slide)**
  - Dedicated hardware has been installed in Feb/March 2011 to measure the leakage current per module, with a precision approaching ~10 nA.
  - First 56 modules are equipped in the innermost layer, more planned during next maintenance day phase.
- **Power supply current monitoring**
  - The power supplies per half-stave of 6 or 7 modules can be monitored with a precision of ~80nA.

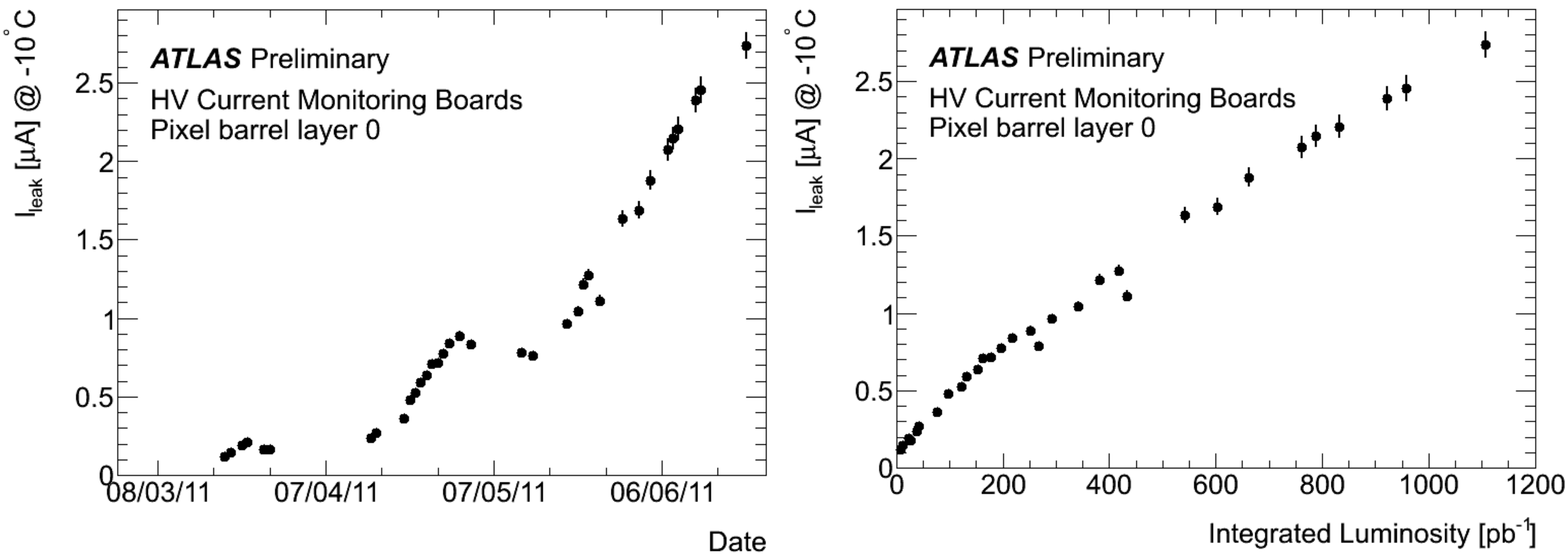
Pixel module raw CMB currents





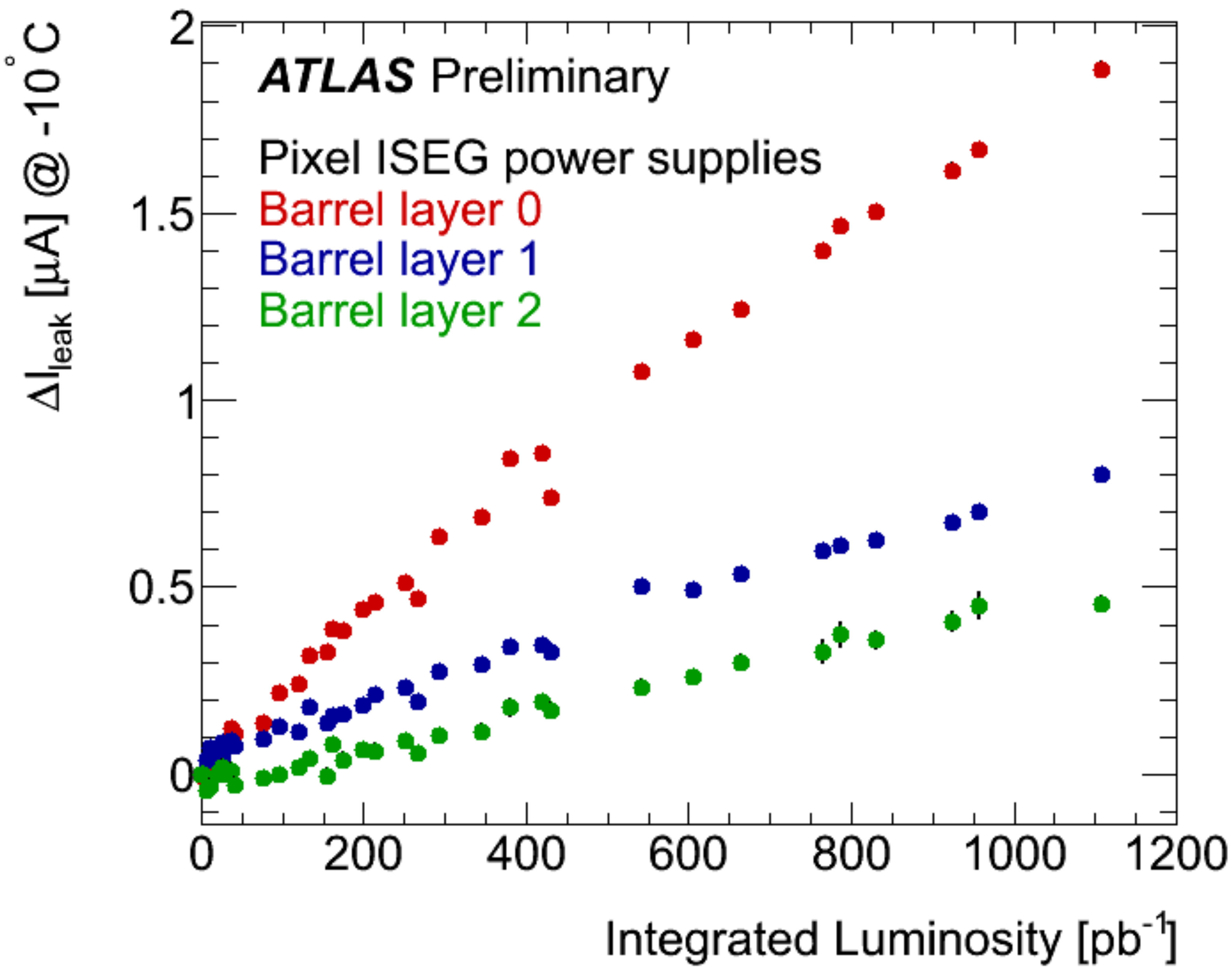
- Raw HV current measurements for the 56 modules in the innermost layer that are instrumented with Current Monitoring Boards.
- The Pixel silicon temperature remained relatively constant with some temporary fluctuations due to a detector cooling stoppage and various calibration scans.

Pixel leakage current from CMBs



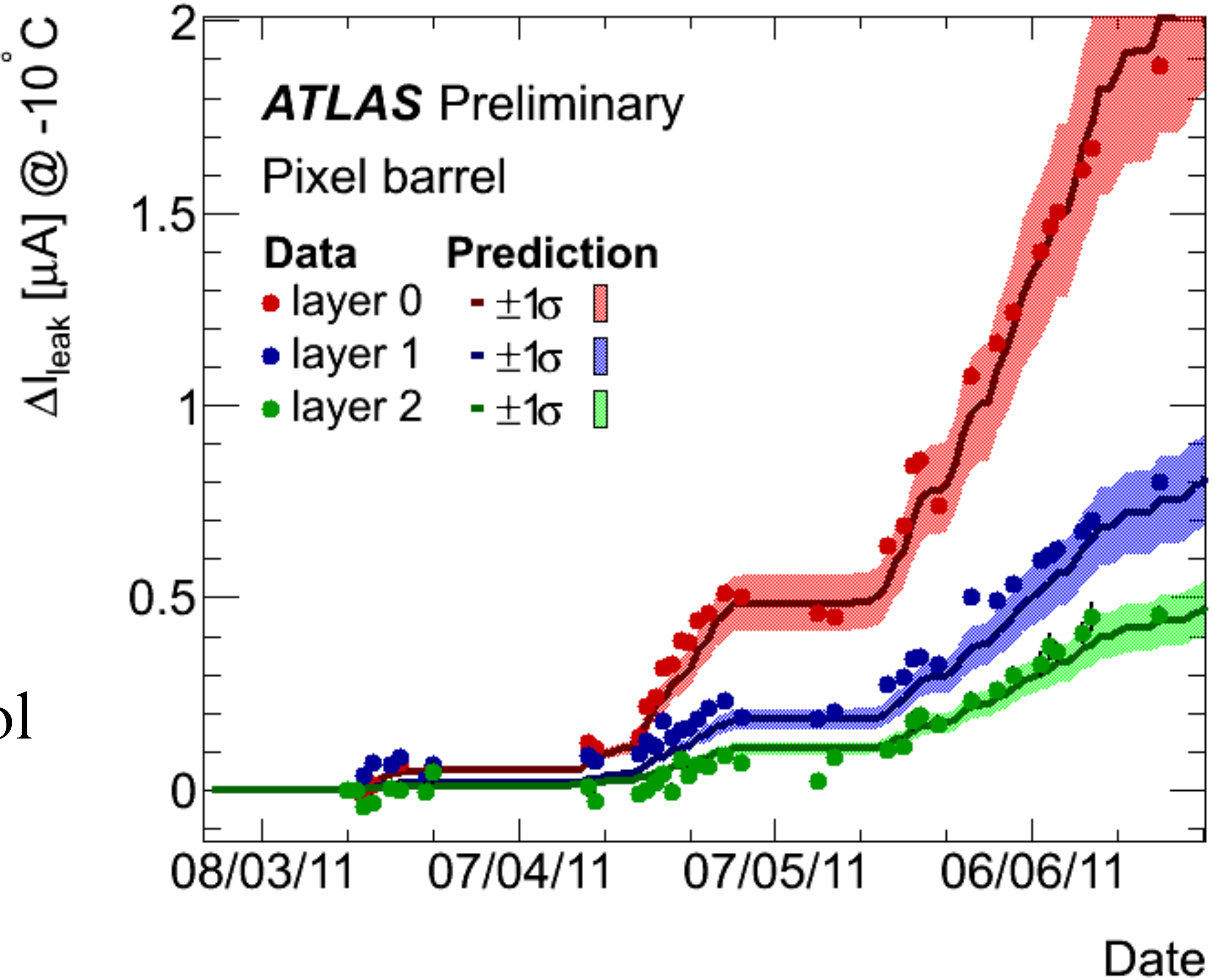
- Leakage current per module from CMBs after corrections for individual module temperatures to give leakage current at T_{REF} = -10 °C.
- Includes preliminary correction for beam induced ionization current:
  - $I_{hit} = N_{bunches} * \nu_{LHC}$ * pixel hit occupancy * charge per hit.
- Validation of board calibration ongoing:
  - Plan to measure currents without beam during next maintenance time.

Pixel leakage current vs fluence



- Leakage current per module from the barrel half-stave power supplies after correction for the temperature of each module in the half-stave, to give leakage current at T_{REF} = -10 °C.

Pixel current comparison with model



$$\Delta I = \alpha\phi \ \mathrm{Vol}$$

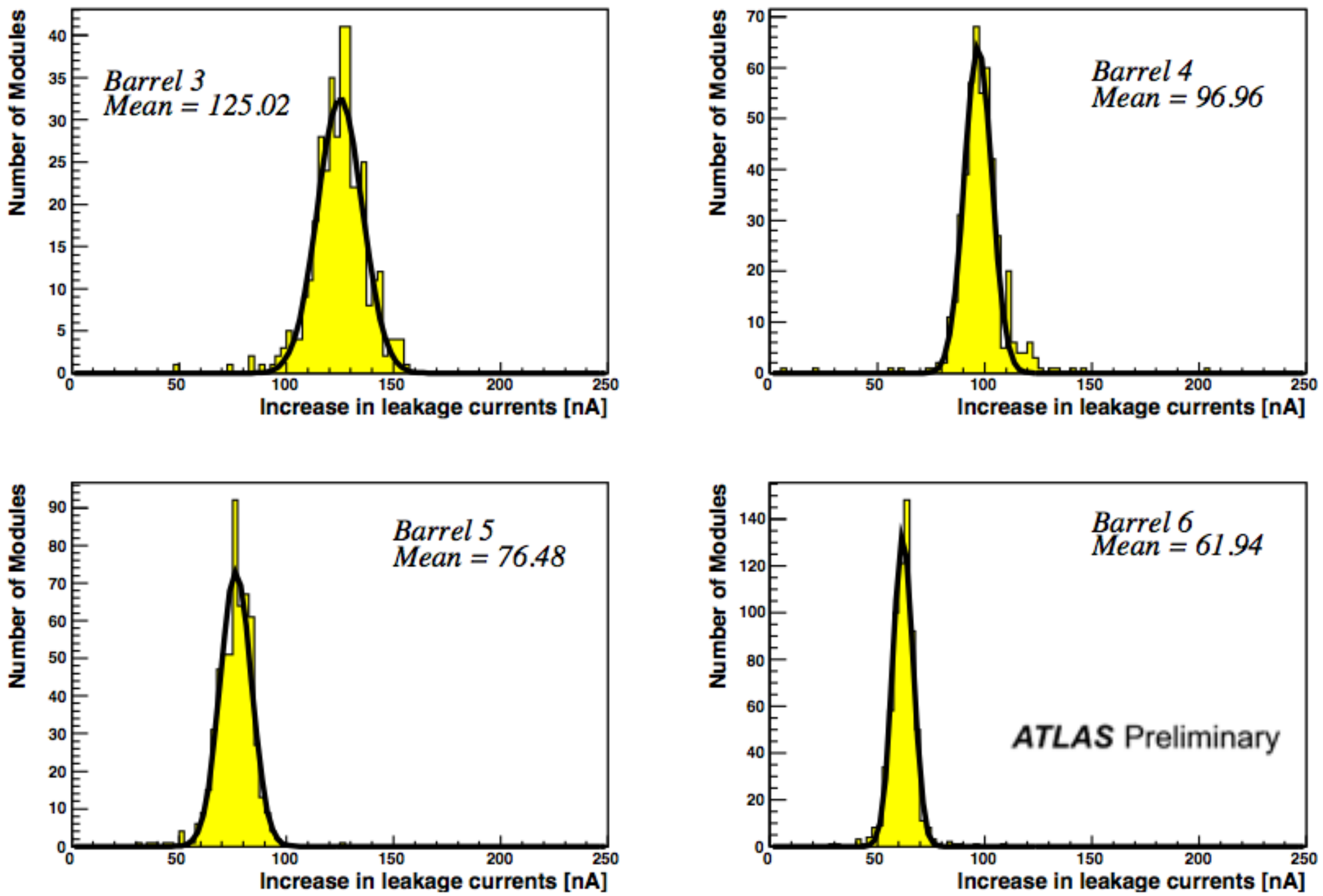
- Data is scaled to -10 °C and includes preliminary correction for beam ionisation current.
- Prediction is based on luminosity profile and expected fluence by barrel layer from Phojet + FLUKA simulations, scaled by the silicon volume and the damage constant, α, taken from NIM A 472(2002) 548-544. No correction for annealing (small).

SCT leakage current monitoring

- SCT module leakage currents have been regularly measured during the scheduled LHC maintenance days since the start of ATLAS running:
  - HV current measurement is without beam and with optical alignment system off (to eliminate induced photocurrent on some modules).
  - Current resolution of ~10nA.

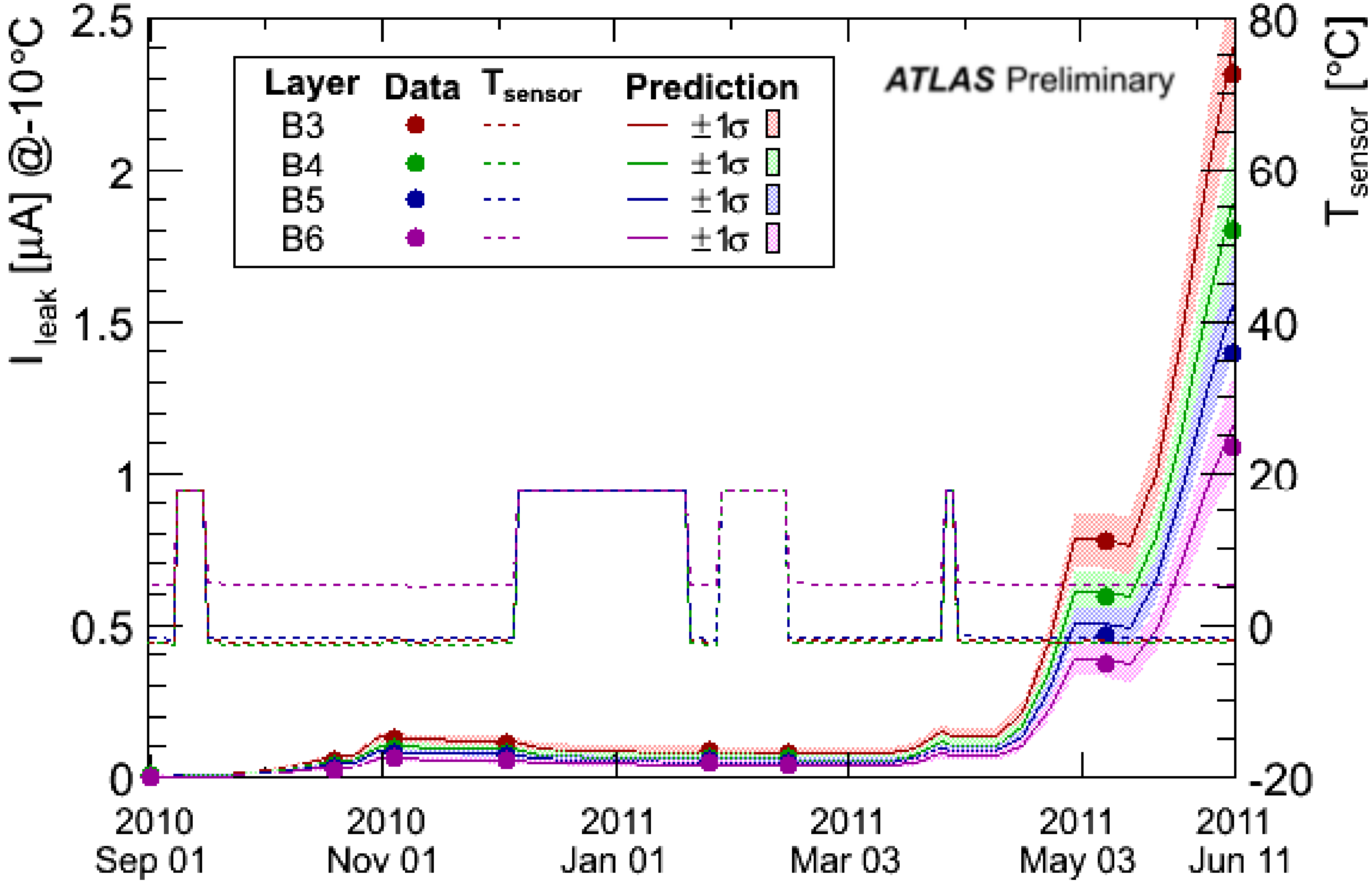
Histograms showing increases in SCT barrel leakage currents (normalized to -10°C) up to the end of proton running in 2010.

Radial effects of radiation damage observed with only 48.6 pb^{-1}



SCT leakage current comparison

- Data and predictions for the leakage current in SCT barrel layers 3 - 6:



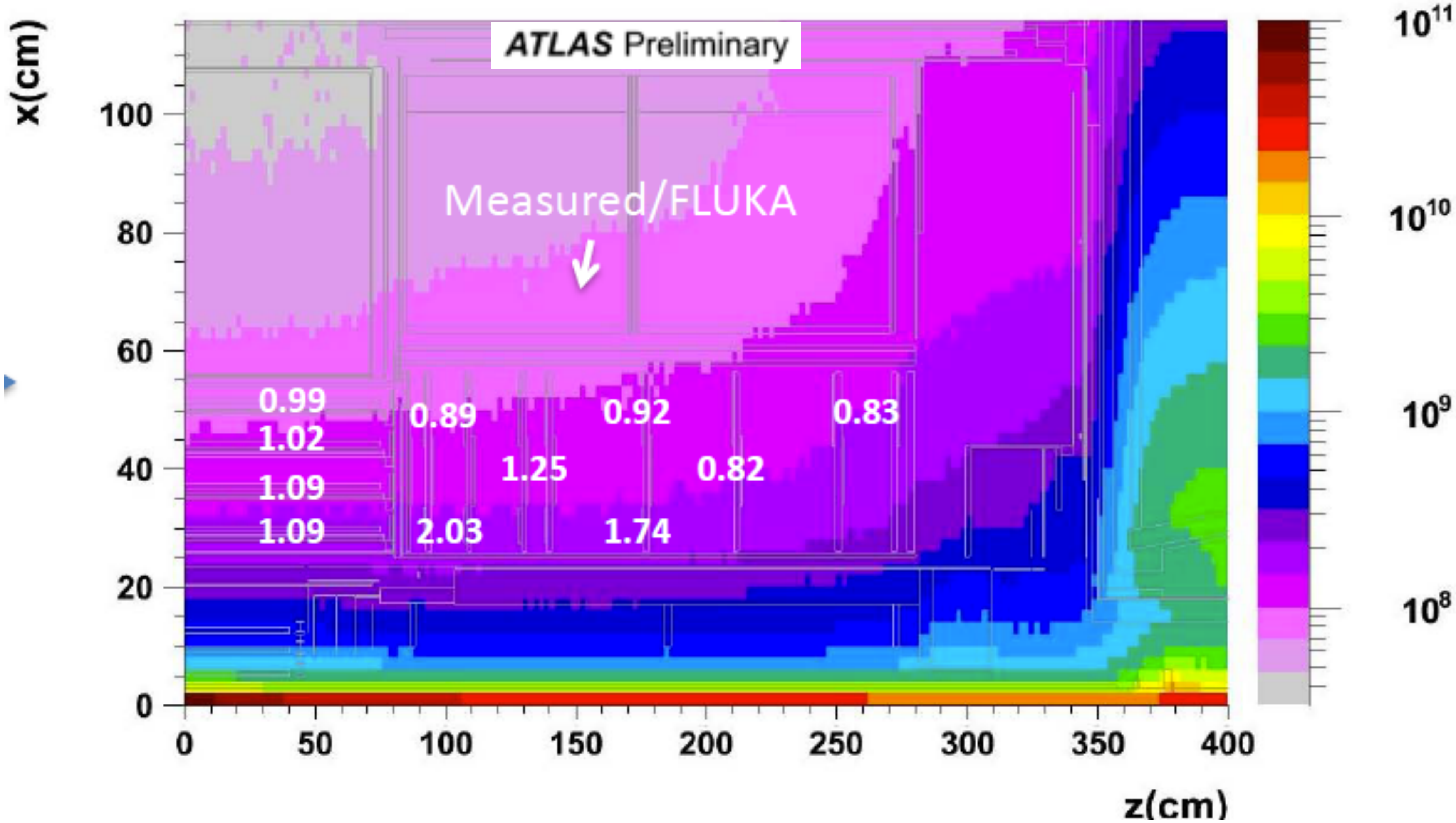
- Prediction is based on total 7 TeV luminosity profile and FLUKA simulations, taking self-annealing effects into account.
- Prediction uncertainties are mostly due to errors in the fraction of the slowest annealing component (11%) and luminosity measurement (4.5% in 2011). The uncertainty of FLUKA simulation is not included.

Fluence comparisons with FLUKA

- Determine 1MeV neutron equivalent fluence from SCT leakage current. (corrected for temperature, volume and use standard damage constant, α).
- Compare fluence with simulated FLUKA predication @ 7TeV.

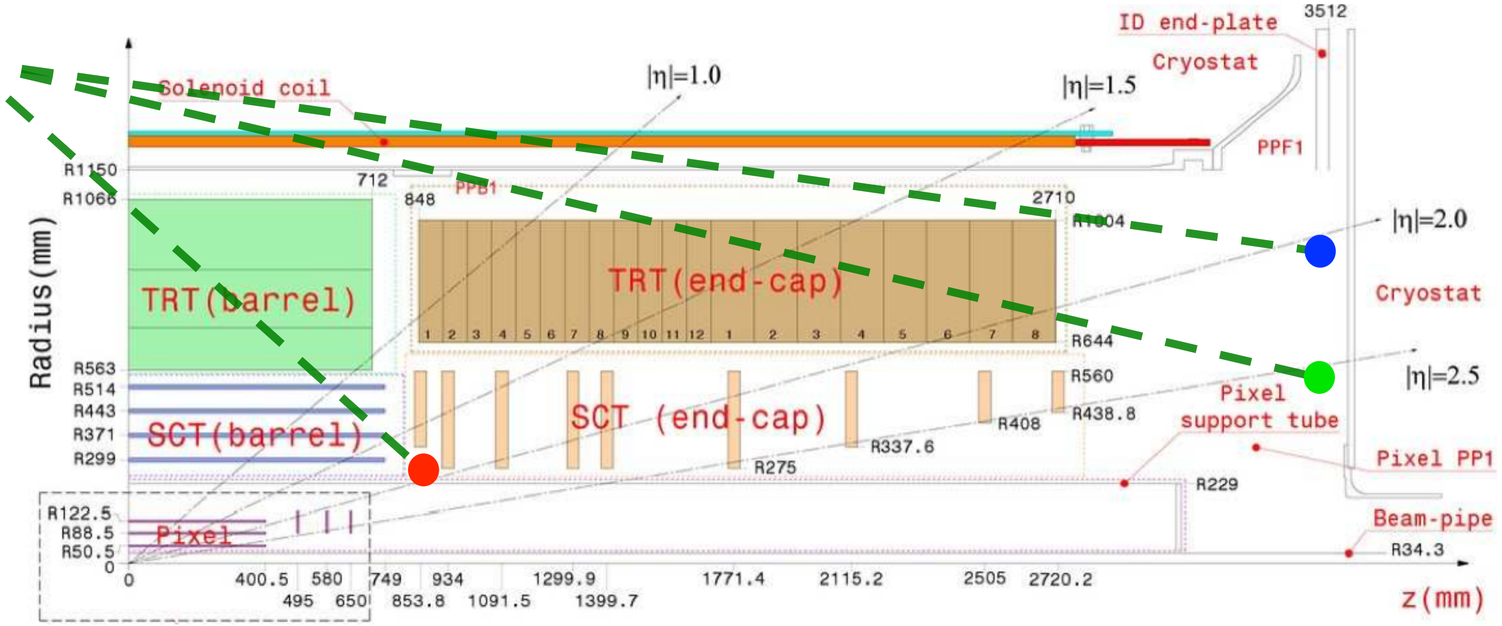
Numbers are ratio: Measured / FLUKA

- Good agreement in barrel regions at the level of ~10%.
- Larger differences in the inner end-cap regions.

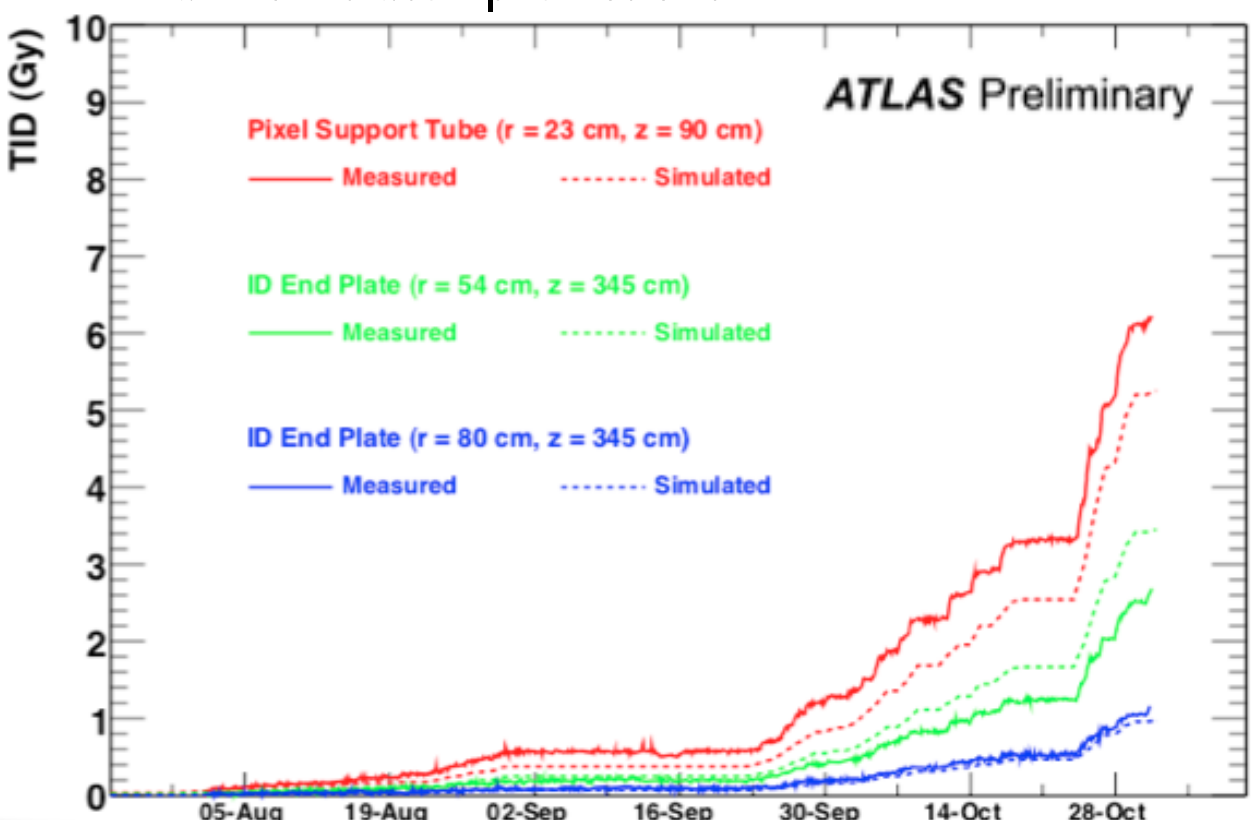


Inner Detector Radiation Monitors

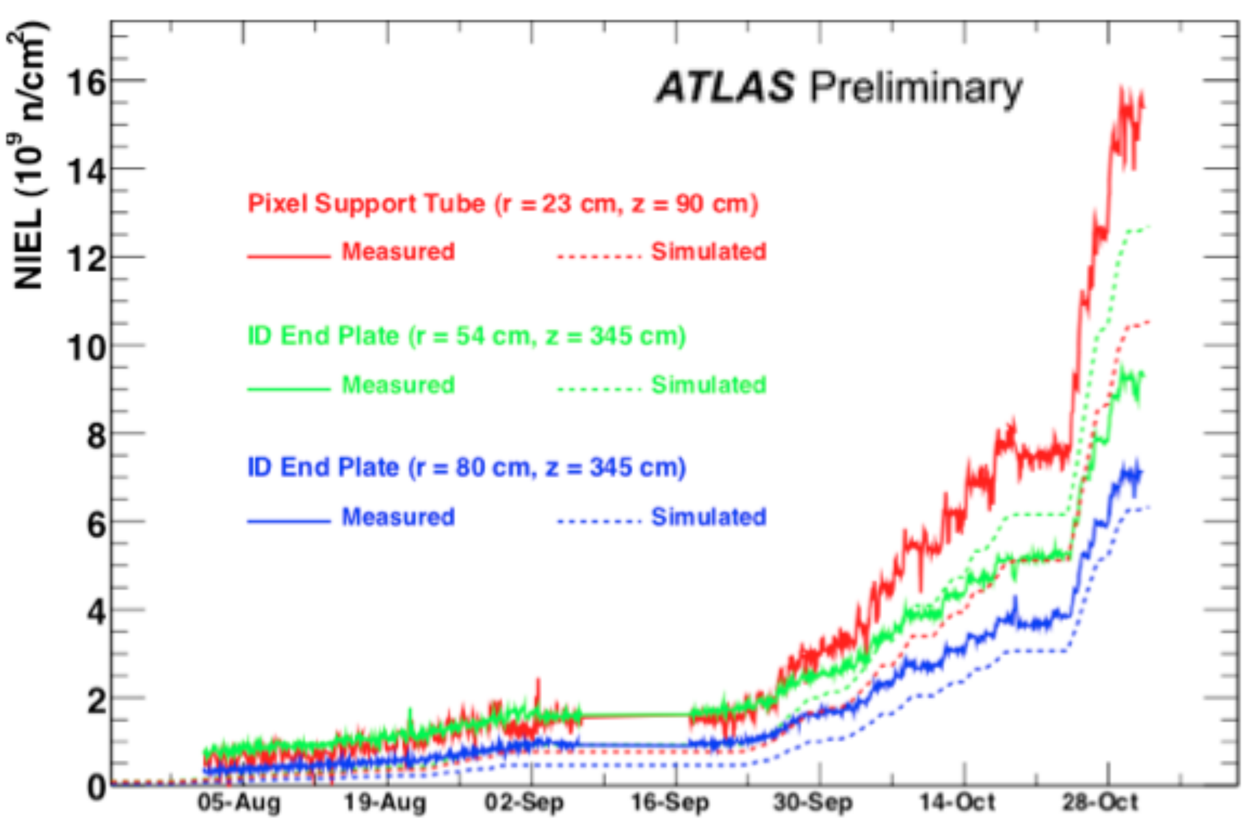
- Dedicated RADmon sensors within ATLAS tracker:
  - Radiation sensitive p-MOS transistors (RADFETs).
  - Calibrated diodes



Comparison of ionising-dose measurements and simulated predictions

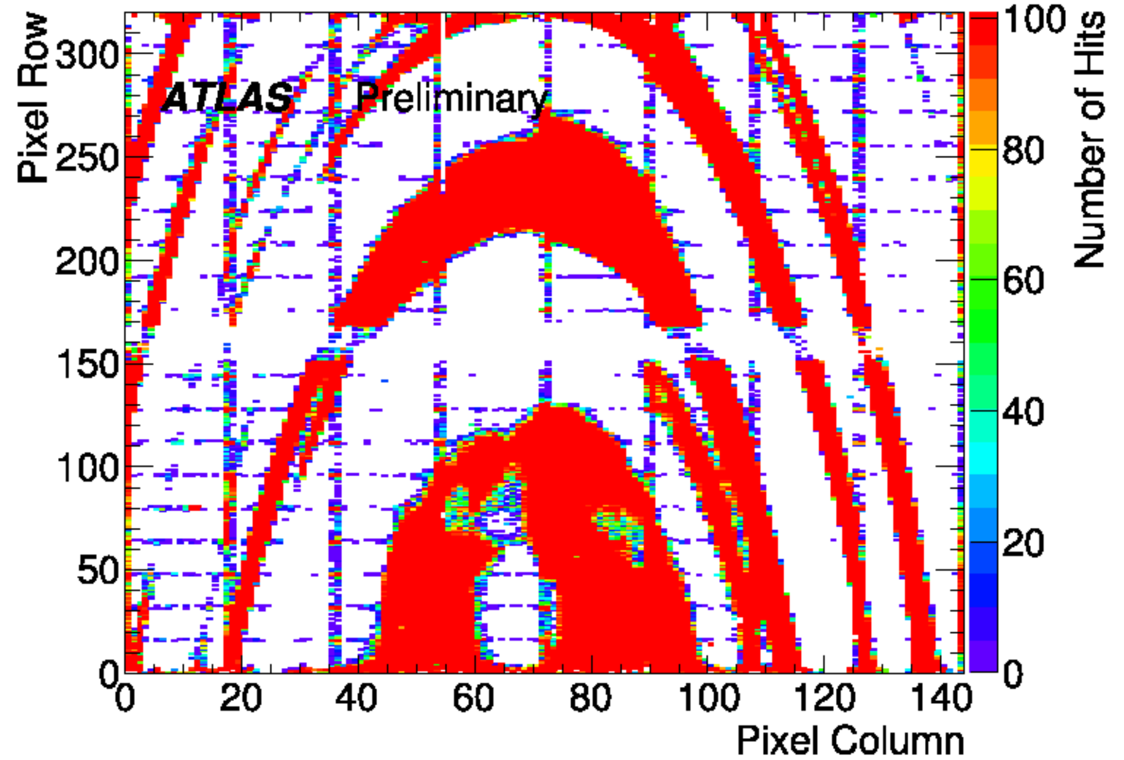


Comparison of NIEL (1MeV neatron equivalent) measurements and simulated predictions

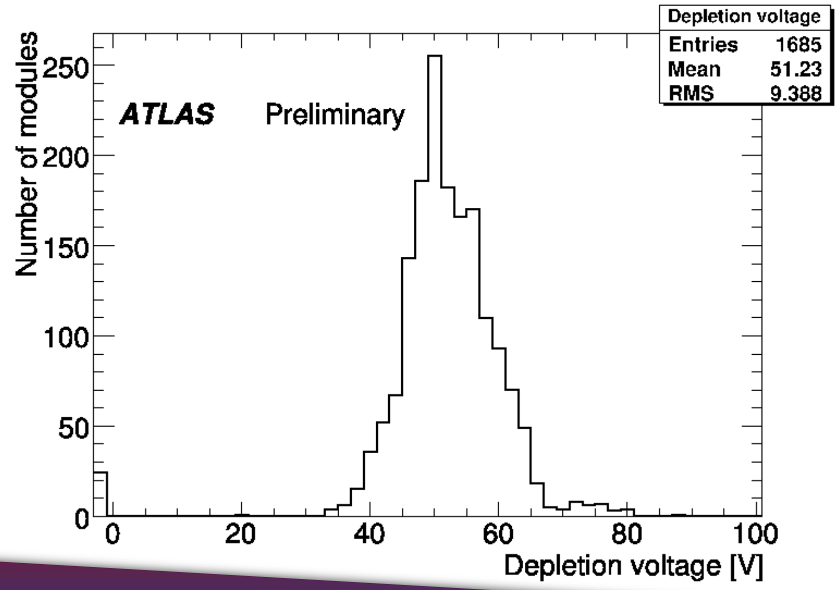


Pixel Depletion Voltage Method

- Radiation damage changes the effective doping concentration altering the depletion voltage.
- Aim: measure voltage needed for full depletion, V_{FD}, for all pixel modules.
- Idea: use cross-talk method (before type-inversion):
  - Inject charge into one pixel, read out neighbour.
  - When not fully depleted, high-ohmic short between pixels.
  - When fully depleted, pixels are isolated from each other.
  - Choose injected charge such that cross-talk hits are seen only for $V_{bias} < V_{pinch\text{-}off}$ ($\sim V_{FD}$)



Example: single module close to V_{FD}
White: already depleted pixels with no crosstalk hits.
Reveals structure of sensor production.

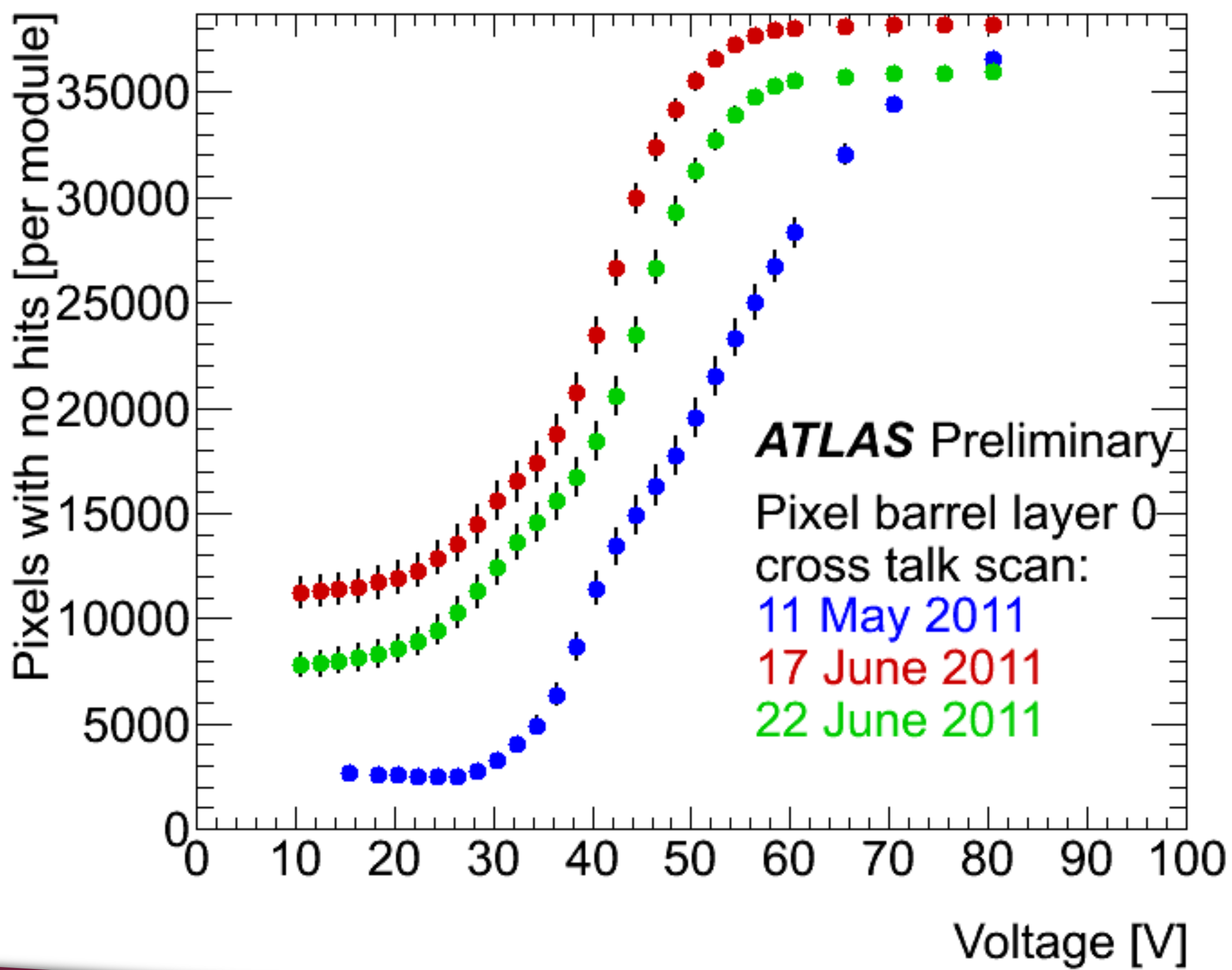


Depletion Voltage Results

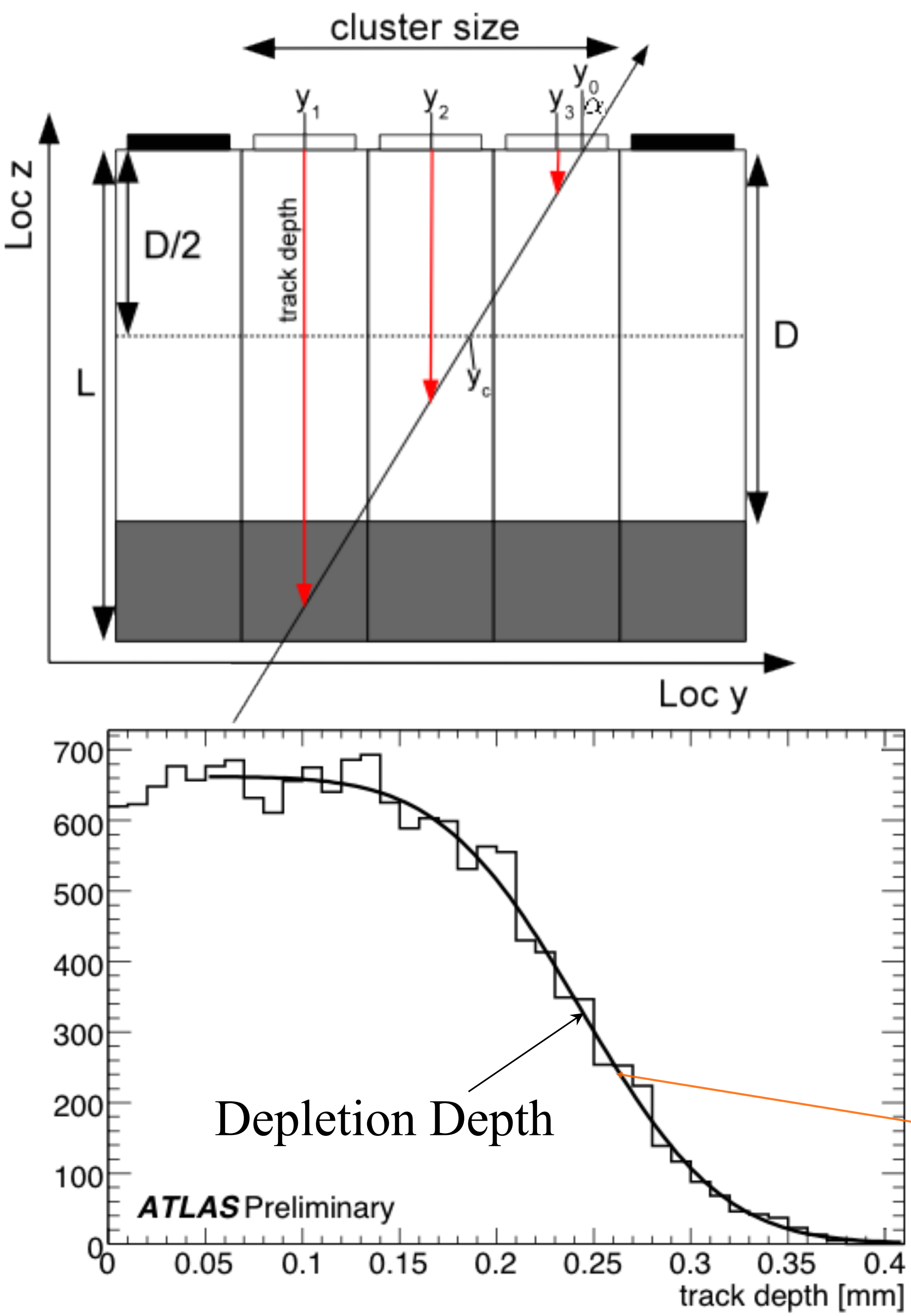
- Cross-talk scans taken during calibration periods (no beam):

Scan date	Layers	Charge injected	Integrated Luminosity since 1 March 2011
11 May 2011	Full pixel detector	Normal	267.5 pb^{-1}
17 June 2011	Barrel layer 0 only	Normal	1056.5 pb^{-1}
22 June 2011	Barrel layer 0 only	Increased	1107.4 pb^{-1}

- Observe decrease in average depletion voltage from May to June.
  - Radiation damage reduces the cross-talk for undepleted modules (more pixels with no hits when at low HV values.).
  - See similar difference between barrel layers in 11 May scan (worst for innermost layer).
  - Increased the charge injected in later scan on 22 June to compensate for reduced cross talk.



Depletion Depth with Tracks



- Aim: to calculate depletion depth of the pixel sensor using particle tracks.
- Enables continuous monitoring of the sensor performance after type inversion.
- Method: reconstruct the depth of track at centre of each pixel in the cluster, using the cluster size, incidence angle and the extrapolated track position.

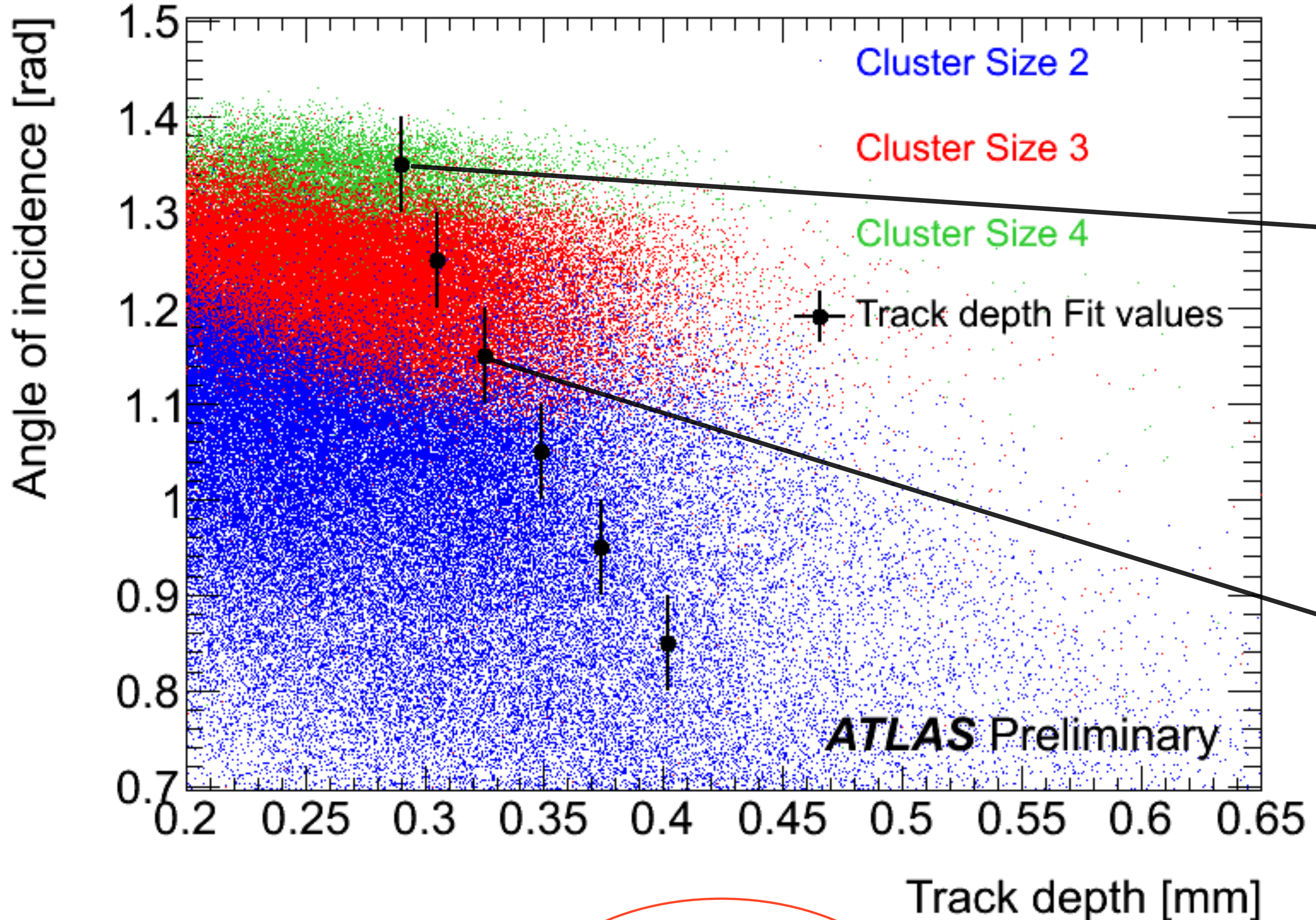
$$d = \frac{y_0 - y_i}{\tan \alpha}$$

- The track segment depth is plotted for a selected range of incidence angles and fitted with the error function.

$$f(D' - x) = 1 - \left(\frac{a}{\sqrt{\pi}} \int_0^{\frac{D'-x}{\sqrt{2b}}} \exp(-t^2) dt \right)$$

Track depth vs incidence angle

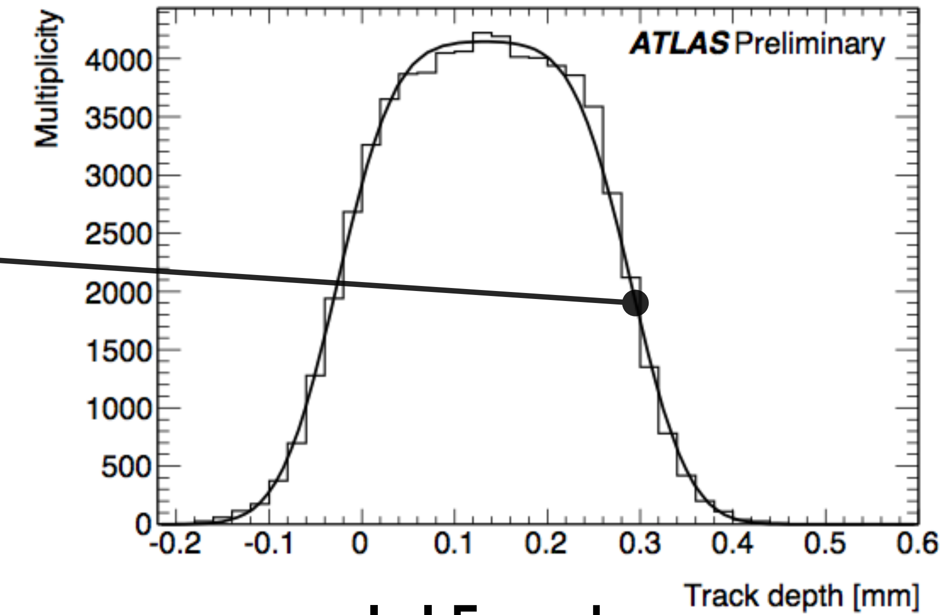
Dependence between track depth and angle of incidence:



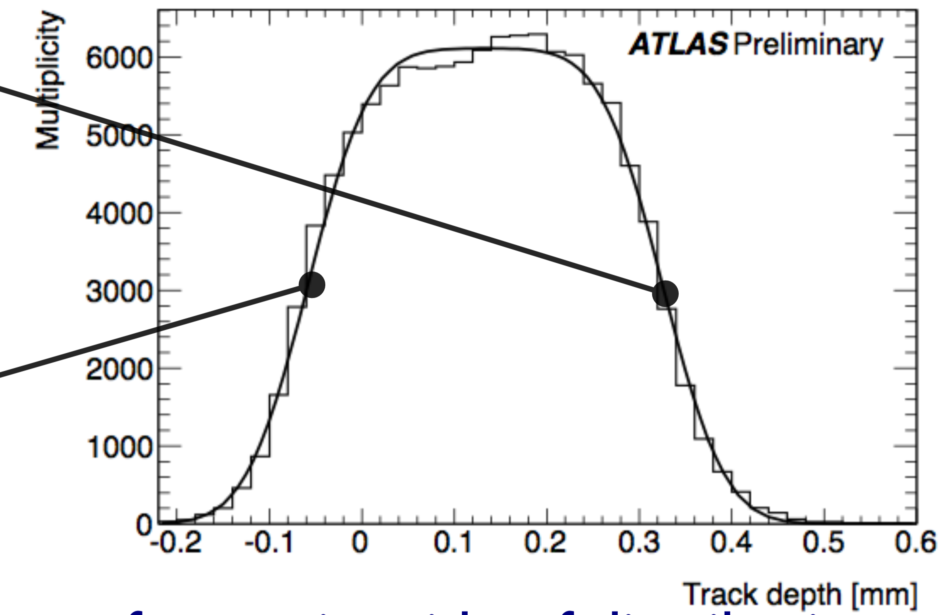
$$td_{corr} = td - \frac{\frac{P}{2} - Y \sin\alpha}{\tan\alpha}$$

- Fit slices of track depth distribution by incidence angle:

1.35 rad



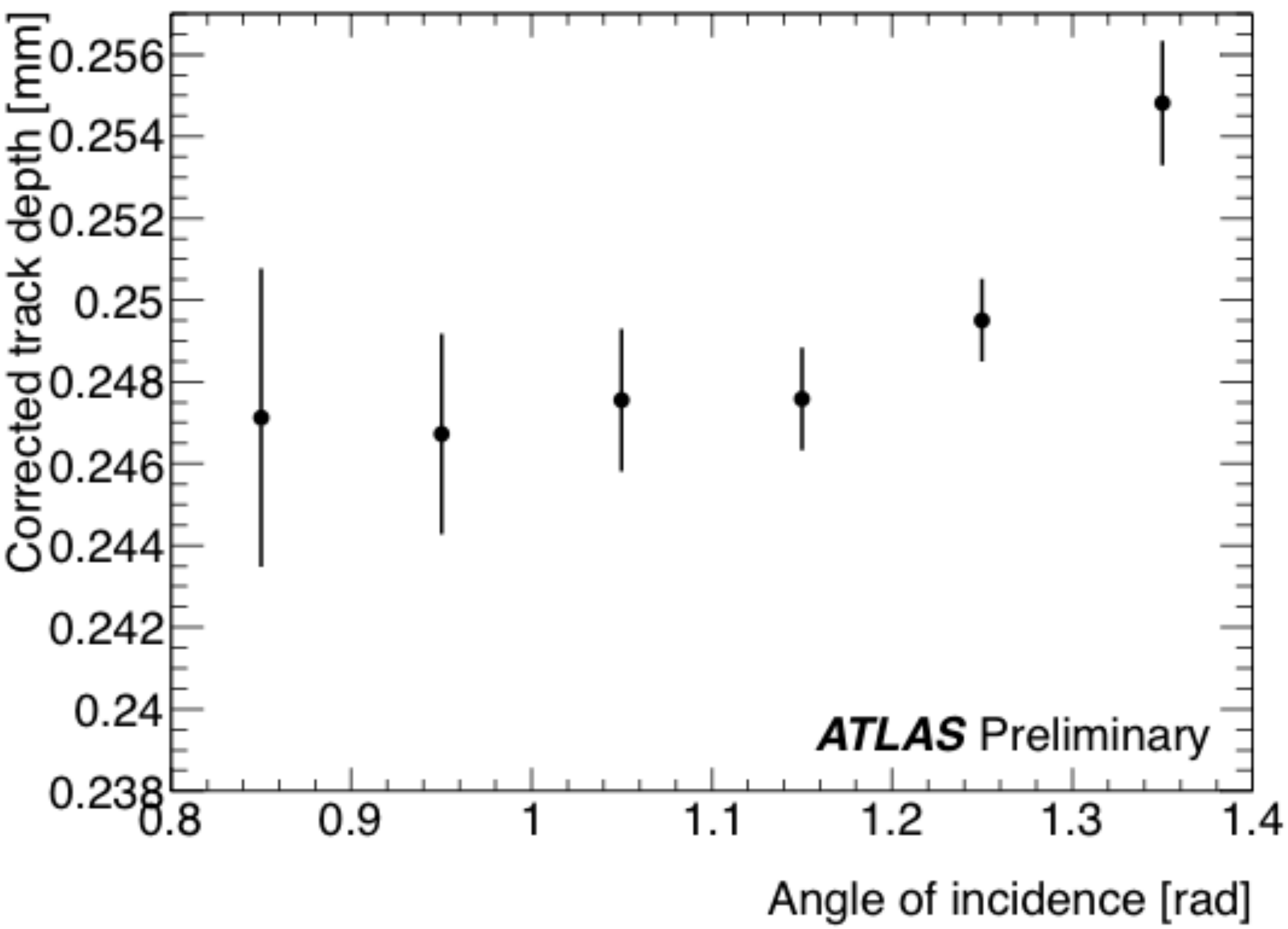
1.15 rad



- Can make use of opposite side of distribution to correct for charge threshold effect.

Depletion depth results

- Angle distribution for corrected track depth values:
- The angle between the pixel normal and the longitudinal pixel direction is chosen, because in the barrel, the B-field is close to parallel to the long pixel direction so Lorentz drifts are negligible.
- Measured depletion depth agrees with sensor thickness (currently fully depleted, and before type inversion).
- Enables future monitoring of the depletion depth after type inversion. (HV can be increased up to 600V with existing power supplies).



$$D = (248.9 \pm 1.2(\text{stat.}))\mu\text{m}$$

(statistical errors only)

Conclusions

- A careful monitoring program has observed the predicted, early effects of radiation damage in the ATLAS silicon tracker.
- As the luminosity surpasses 1 fb^{-1}, a clear increase in leakage current in the Pixel and SCT sensors shows the expected rise proportional to the fluence.
- First comparisons of data with simulation affirm the predictions with good agreement at the level of ~10% in the barrel regions.
- The latest bias scans reveal the depletion voltage is reduced in the ATLAS Pixel sensors before type-inversion and indicate that there is reduced cross-talk between adjacent pixels when under-depleted.
- A track-based method was presented to measure the depletion depth after type inversion, enabling continuous monitoring of the sensor performance.