Observation of Radiation Damage in the ATLAS Pixel Detector

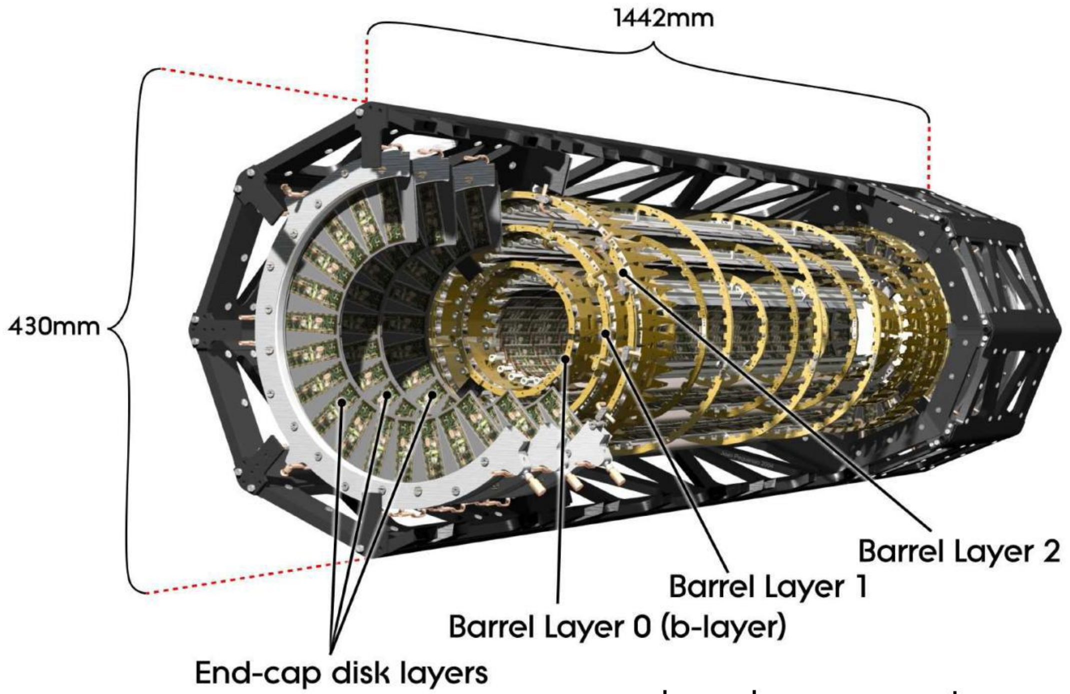
Markus Keil

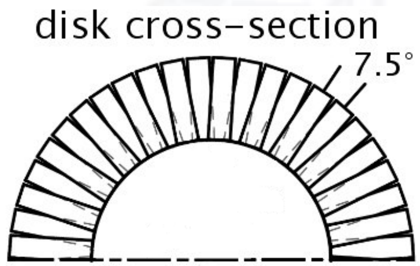
2nd Institute Of Physics, Georg-August-Universität Göttingen and CERN

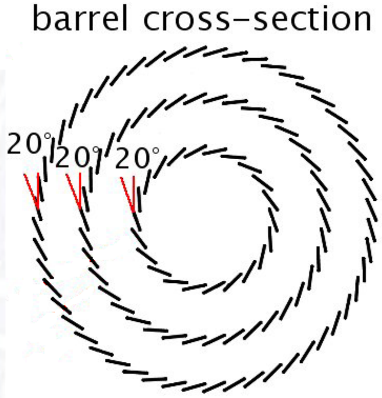
On behalf of the ATLAS Collaboration

The ATLAS Pixel Detector

- 3 hit-system for $|\eta| < 2.5$
  - 3 barrel layers
  - 2 x 3 endcap discs
- 1744 modules,
  80M readout channels
- Innermost barrel layer at 5 cm
  - Radiation tolerance
    500 kGy / 10^{15} 1MeV n_{eq} cm^{-2}
- Evaporative C_3F_8 cooling integrated in local support structures
  → Module temperatures < 0^oC
  (Average temperature -13^oC, warmest module at $-5\ ^oC$)

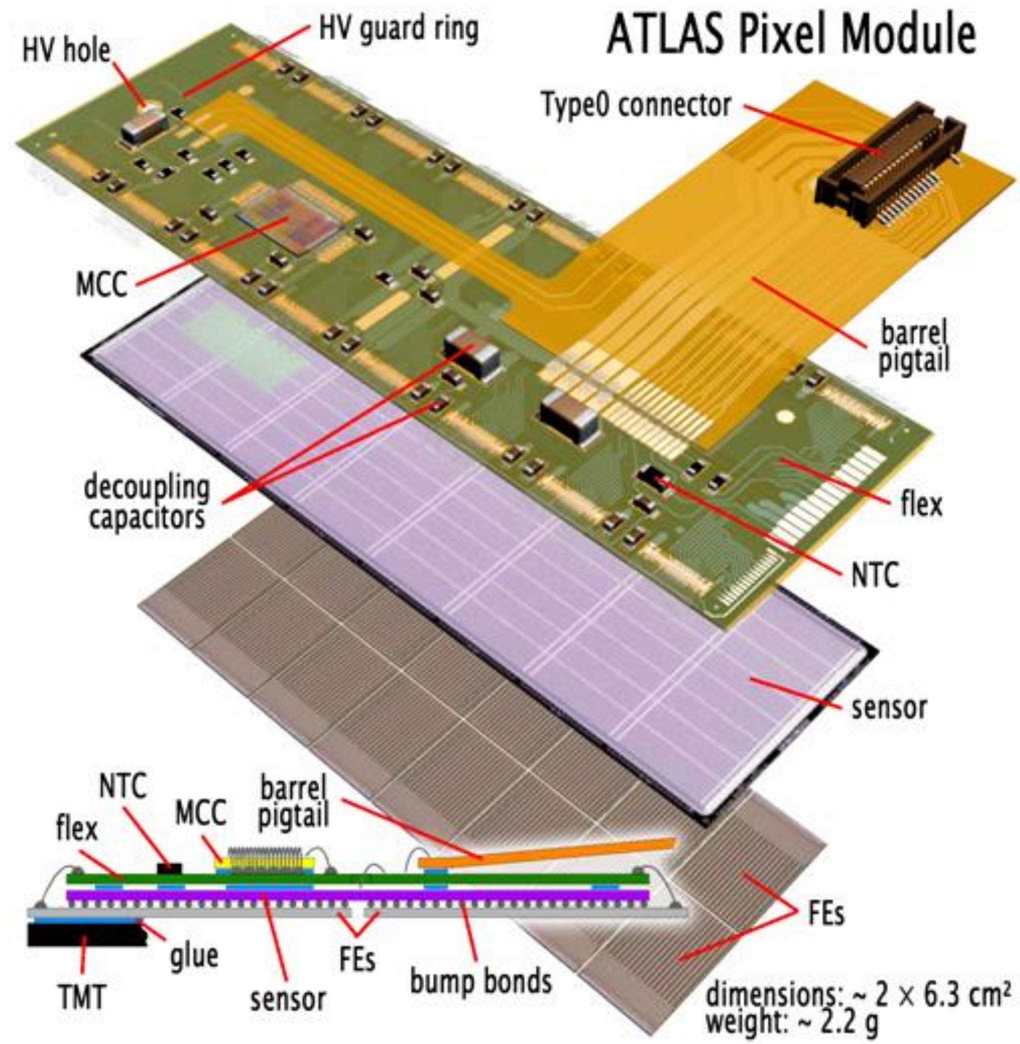




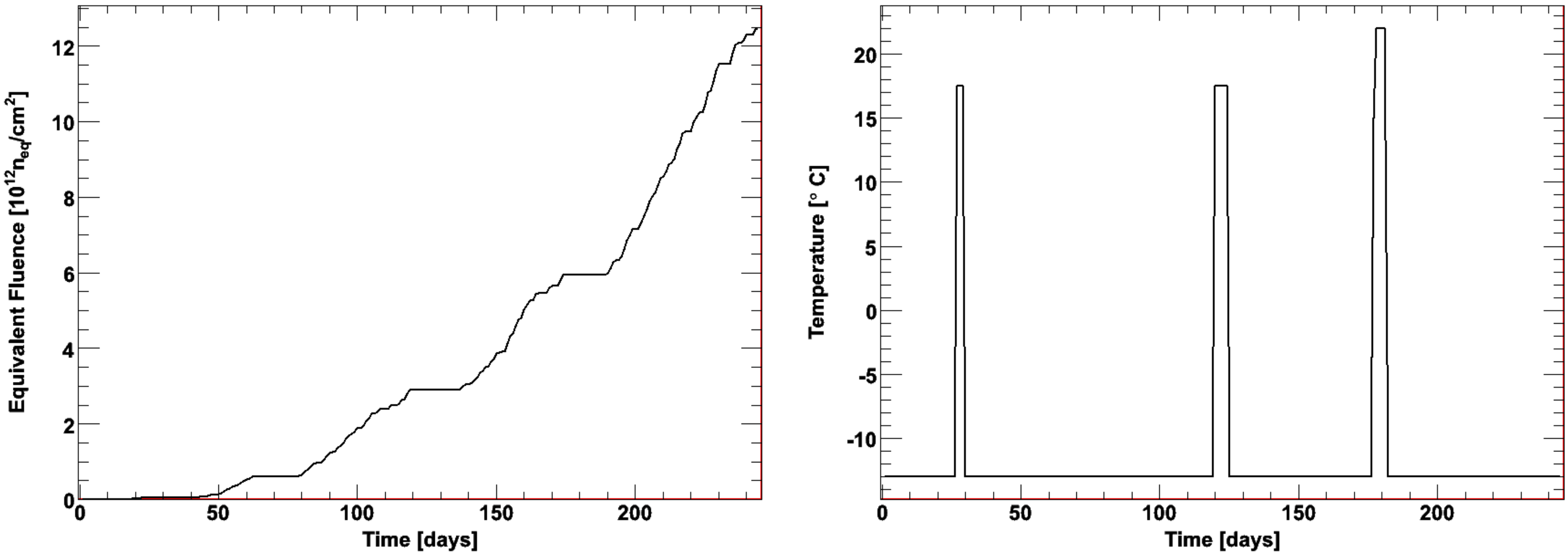


The ATLAS Pixel Detector Module

- Sensor:
  - 250 µm thick oxygenated n-on-n sensor
  - 47232 (328 x 144) pixels
  - Active area 16.4 x 60.8 mm2
  - Initial depletion voltage: approx. 50 – 60 V
- Readout:
  - 16 FE chips, 2880 pixels each
  - Zero suppression in the FE chip, MCC builds module event
  - Pulse height measured by means of Time over Threshold
  - Temperature measurement for each module by NTC on the flex kapton PCB



Fluence and Temperature



- Fluence from FLUKA and temperature profile during the 2011 run
  - Detector at < -10 deg C most of the time
  - Some periods of O(days) without cooling

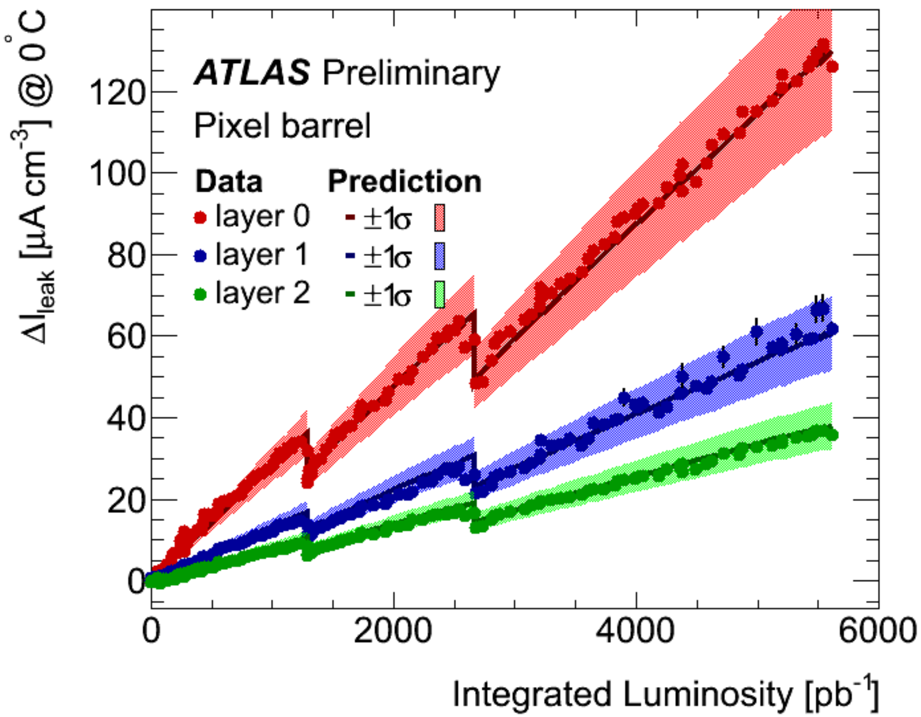
- Reverse-Bias Current
  - I) Per Power-Supply Channel
  - II) Per Module
  - III) Per Pixel

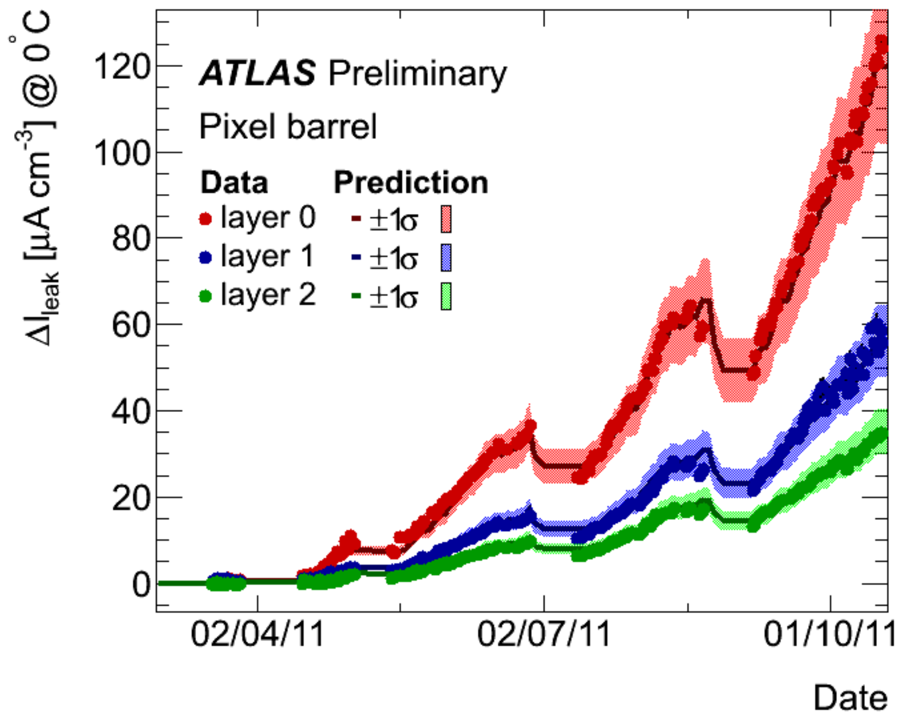
Reverse-Bias Current (I)

- Simplest method to measure reverse-bias current: power-supply current
  - Have monitored the power-supply current since the switch-on of the detector and are by now confident about calibration etc.
  - Precision: 80 nA
  - Drawback: Granularity is 6 or 7 modules (following measurements show current / module averaged over 6/7 modules)

- Measurement and analysis:
  - Read currents from DCS archive, excluding the first 10 mins of stable beam (ensure that high voltage is switched on and stable)
  - Correct for temperature to 0degC
  - Apply preliminary annealing correction
  - No correction for beam-induced current applied (O(100 nA))

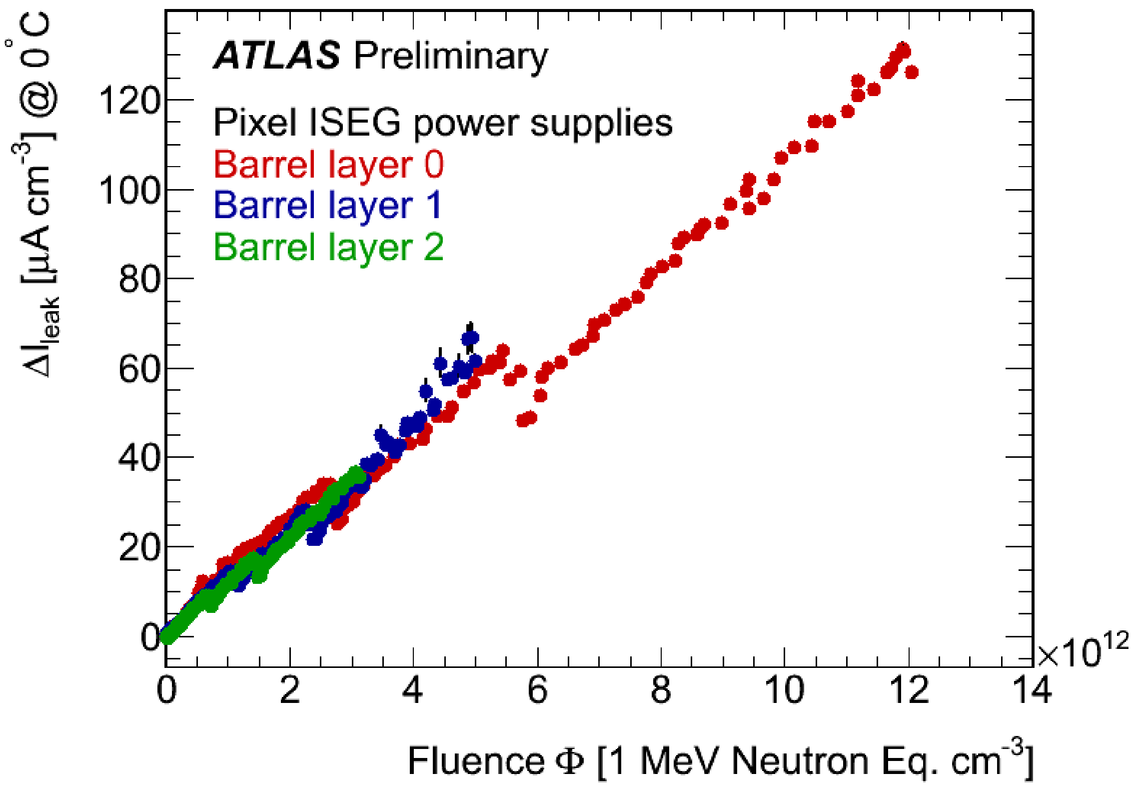
Reverse-Bias Current (I)





- Leakage current follows integrated luminosity; steps consistent with annealing during warm-up periods
- Prediction and measurement qualitatively agree very well, however prediction had to be scaled up
  - Layer 0: +15%, Layer 1 and 2: +30%

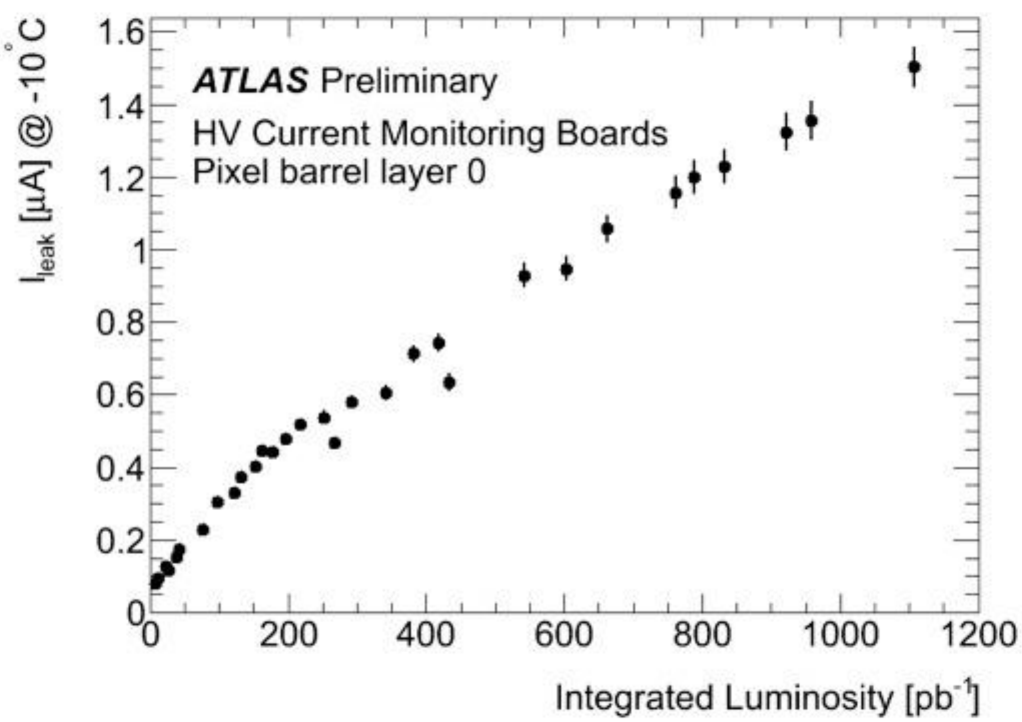
Reverse-Bias Current (I)



- Reverse-bias current vs. Fluence (FLUKA)
- Linear fit (ignoring annealing steps) yields α ~ 1.1 e-17 A/cm
- We would expect a value in the order of 6e-18 A/cm at 0 deg C, so this goes in the same direction as before (FLUKA prediction too low)

Reverse-Bias Current (II)

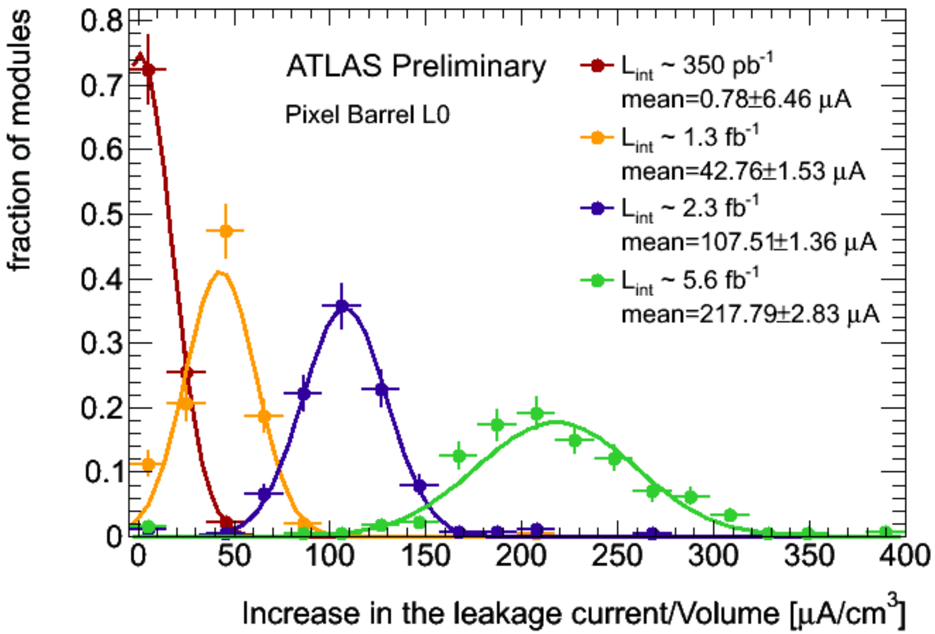
- Alternative measurement: started to install current monitoring boards in the HV-fanout crates in the counting room
  - One measurement per module, precision ~ 10 nA
  - Up to now 56 modules of the innermost layer instrumented, more during next shutdown
  - Work on calibration ongoing

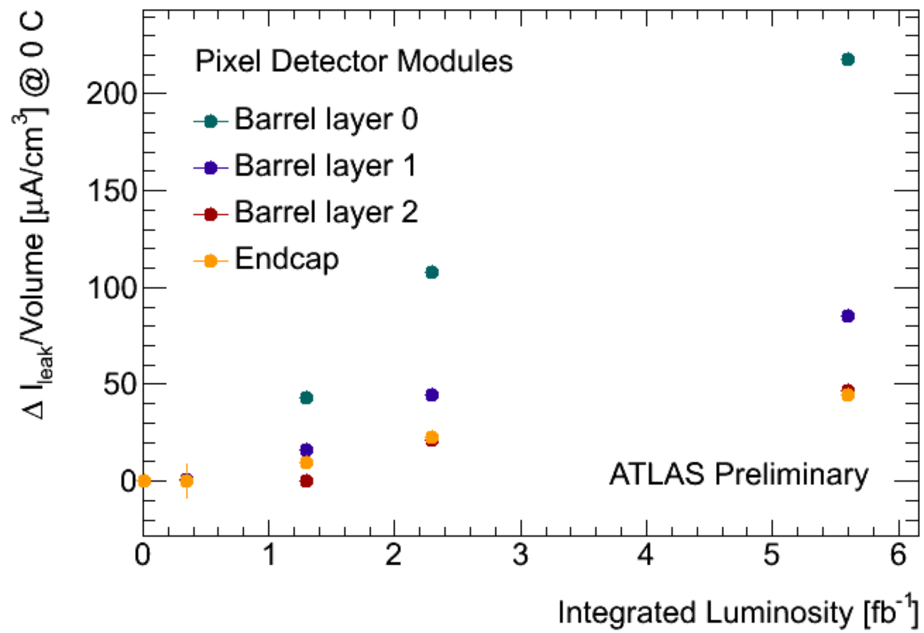


Reverse-Bias Current (III)

- Monleak Scan: allows to measure the single-pixel leakage current
  - The feedback branch of the single pixels is connected to an on-chip ADC
  - Digitises the current `Ileak + 2 * Ifeedback` with an LSB of 0.125 nA
  - Range optimised for irradiated modules, currently sensitive for innermost layer, starting to get sensitivity also on the others
  - Not intended to give an extremely precise measurement of the reverse-bias-current but a nice tool to see inhomogeneous distributions of the current

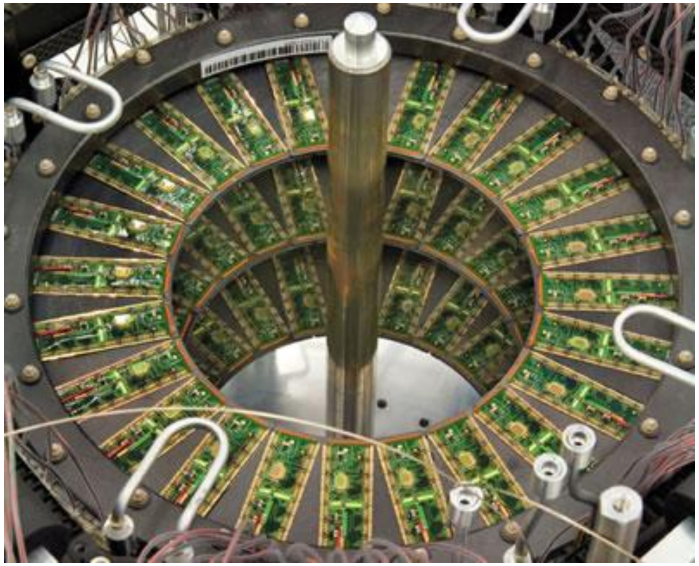
Reverse-Bias Current (III)

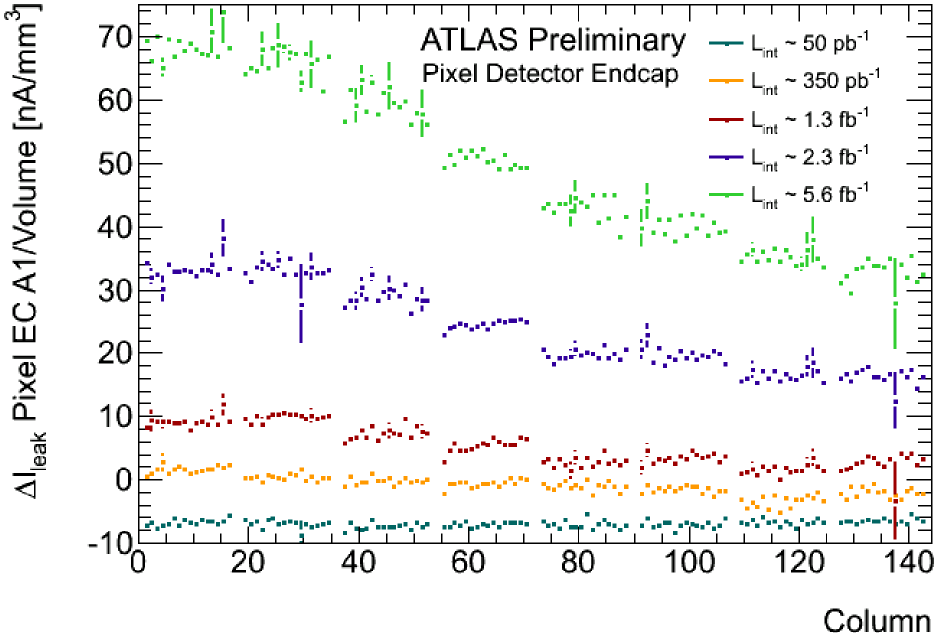




- Reverse-Bias Currents per module determined from Monleak data
  - Left: B-Layer, right development for all layers
- Absolute calibration and comparison with model still ongoing
- But allows already some toy examples with inhomogeneous distributions

Reverse-Bias Current (III)



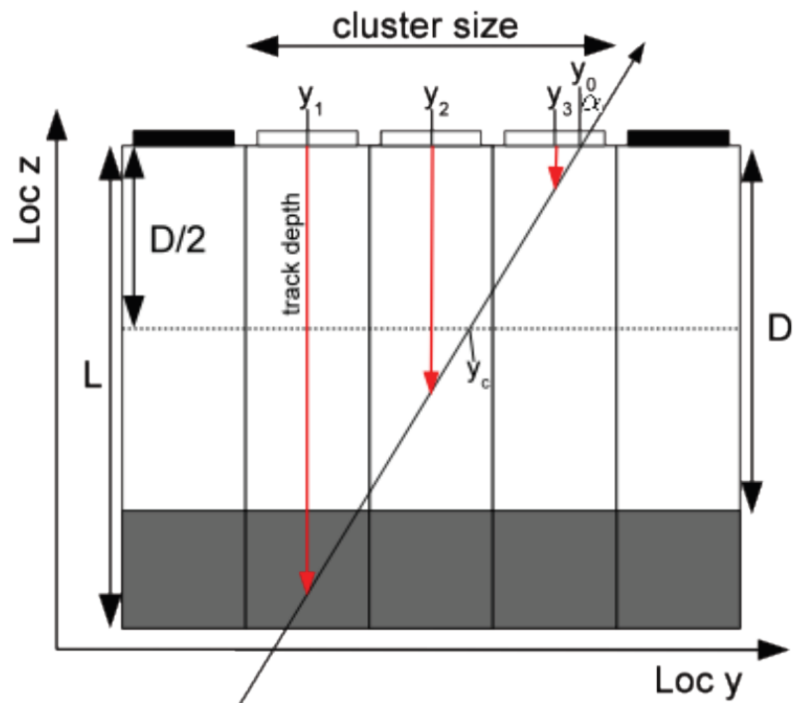


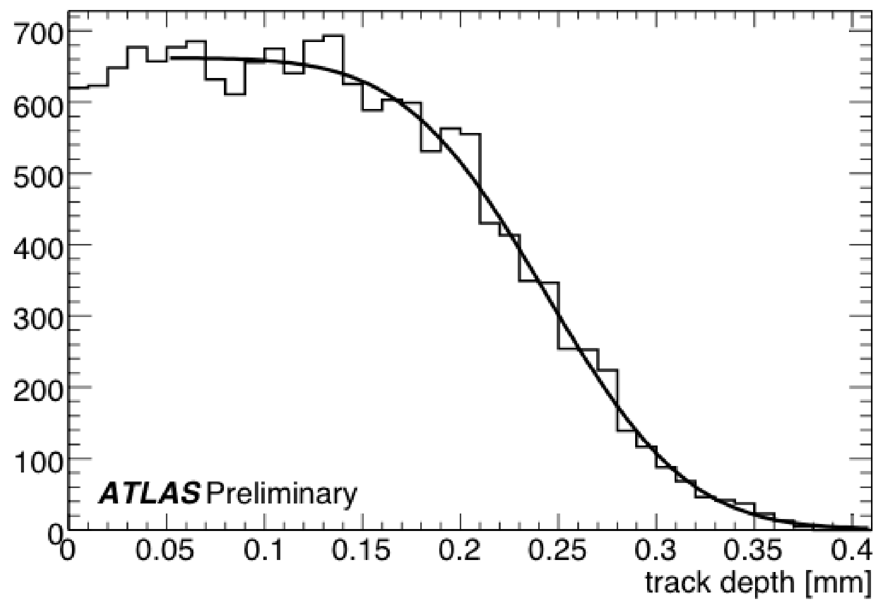
- Example of inhomogeneous leakage current distribution: endcap disc, modules oriented in R-direction ($R \propto$ column #)
  - Leakage current clear function of the radius
  - Chip effect not yet understood
  - Calibration and determination of pedestals underway

- Depletion Voltage

Depletion Voltage (I)

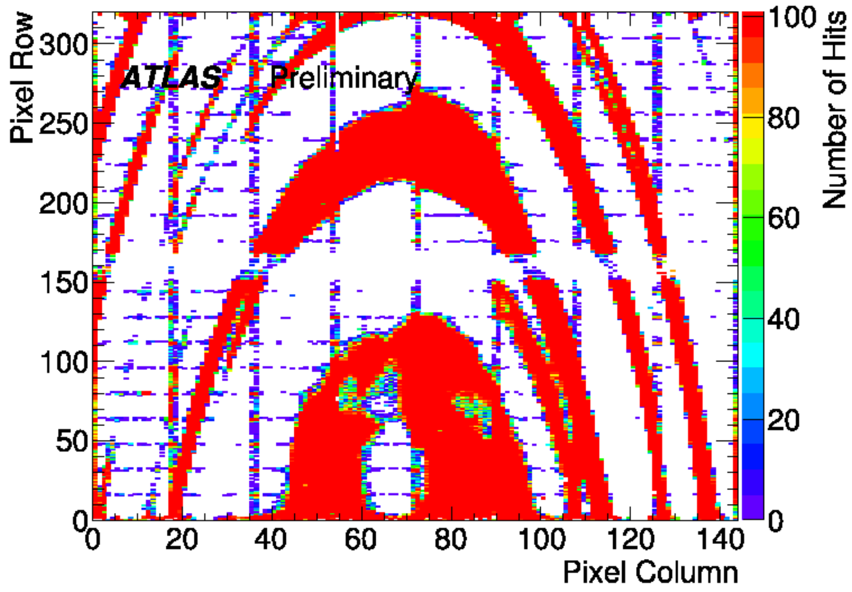
- After type inversion: determine depletion depth from inclined tracks
- Method:
  - Determine track segment depth for each pixel hit
  - error function fit yields depletion depth
  - Correct for threshold effects
- Before type inversion: hits only if sensor fully depleted
  - But: validation of method; analysis now yields (248.9 ± 1.2) μm, in agreement with sensor thickness

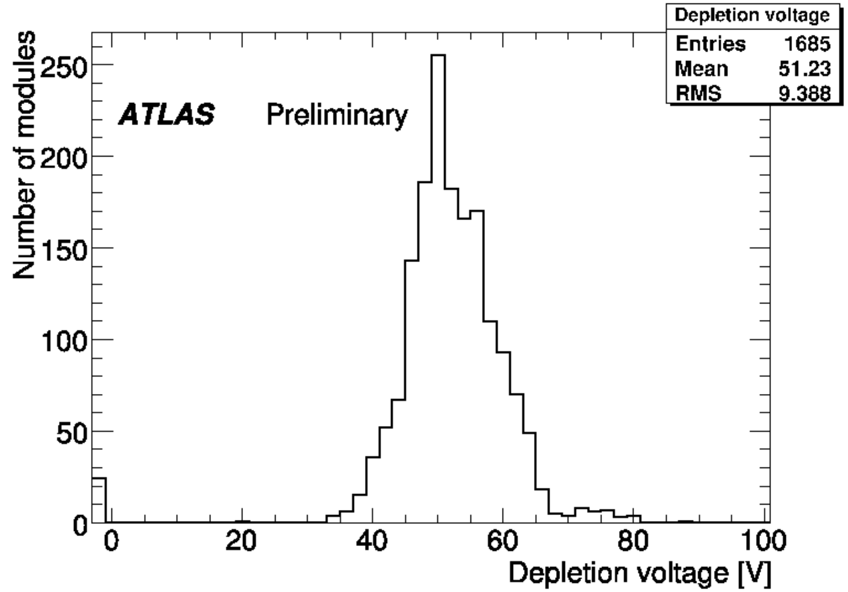




Depletion Voltage (II)

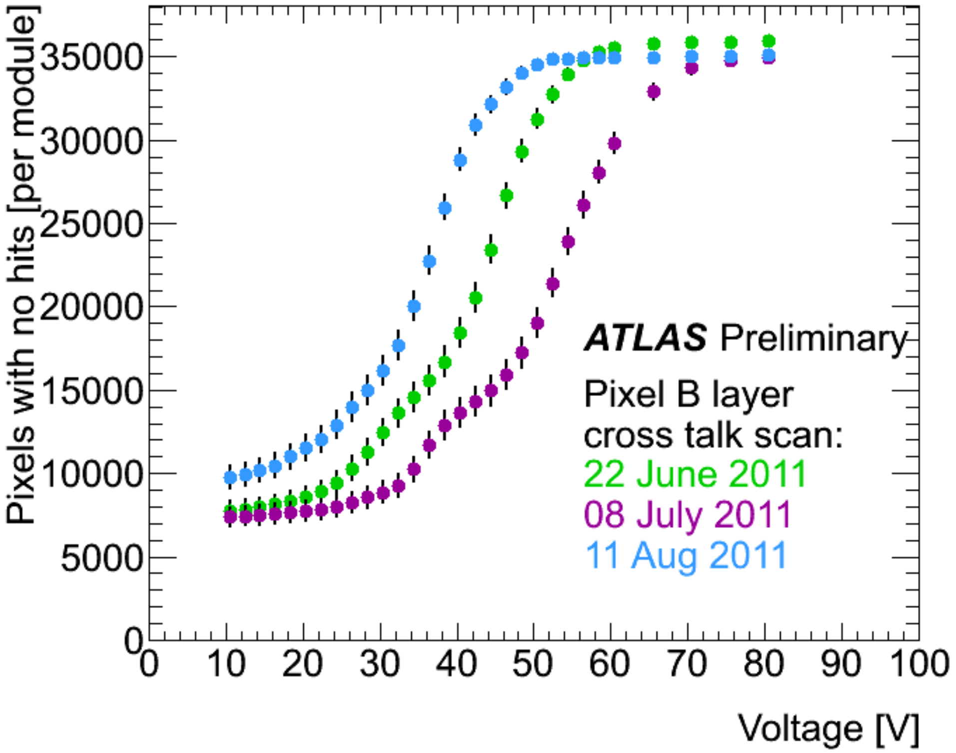
- Before type inversion: calibration scan based on inter-pixel cross-talk (advantage: no beam time needed)
- If not fully depleted: high-ohmic short between neighbouring pixels
- When fully depleted: pixels separated, only capacitive cross-talk
- Cross-talk scan: inject into one pixel and readout the neighbour
- Charge chosen high enough to cause hit before depletion, not high enough to cause hit when fully depleted
  - Right: results before irradiation





Depletion Voltage (II)

- Estimate point of full depletion from number of pixel with no hits
- Example shows decrease of depletion voltage from July to August (datataking)
- Between June 22 and July 8: 5 ½ days without cooling (sensors at room temperature), increase of the depletion voltage due to annealing



- More quantitative analysis and comparison with models underway

Summary

- Several measurement methods to monitor reverse-bias current and depletion voltage
  - Reverse-bias current: Per 6/7 modules, per module, per pixel
  - Depletion voltage: track based (after type inv., but validated now), calibration scan (before type inv.)
- Qualitatively measurements show clear signs of radiation damage as expected
  - Increase of leakage current with accumulated fluence
  - Decrease of depletion voltage
  - Signs of annealing in periods with no cooling
- For reverse-bias current (power supply measurement) quantitative agreement is obtained when scaling the expectation up by 15 (30)%

Open Issues

- Some open issues before making statements on quantitative comparisons
- General:
  - Converge on the models and be sure to use the correct parameters
- Reverse-bias current:
  - Temperature correction: temperature correction (incl. annealing) is based on the measurement of an NTC located on the flex PCB, which is glued to the sensor. ΔT between NTC and Si currently unknown (but expected to be small)
  - Surface current: currently evaluating I-V-curves to understand the contribution of the surface current
- Depletion voltage:
  - Try to extract depletion voltage trend from the crosstalk scans