Monitoring radiation damage in ATLAS

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On behalf of the ATLAS radiation damage working group

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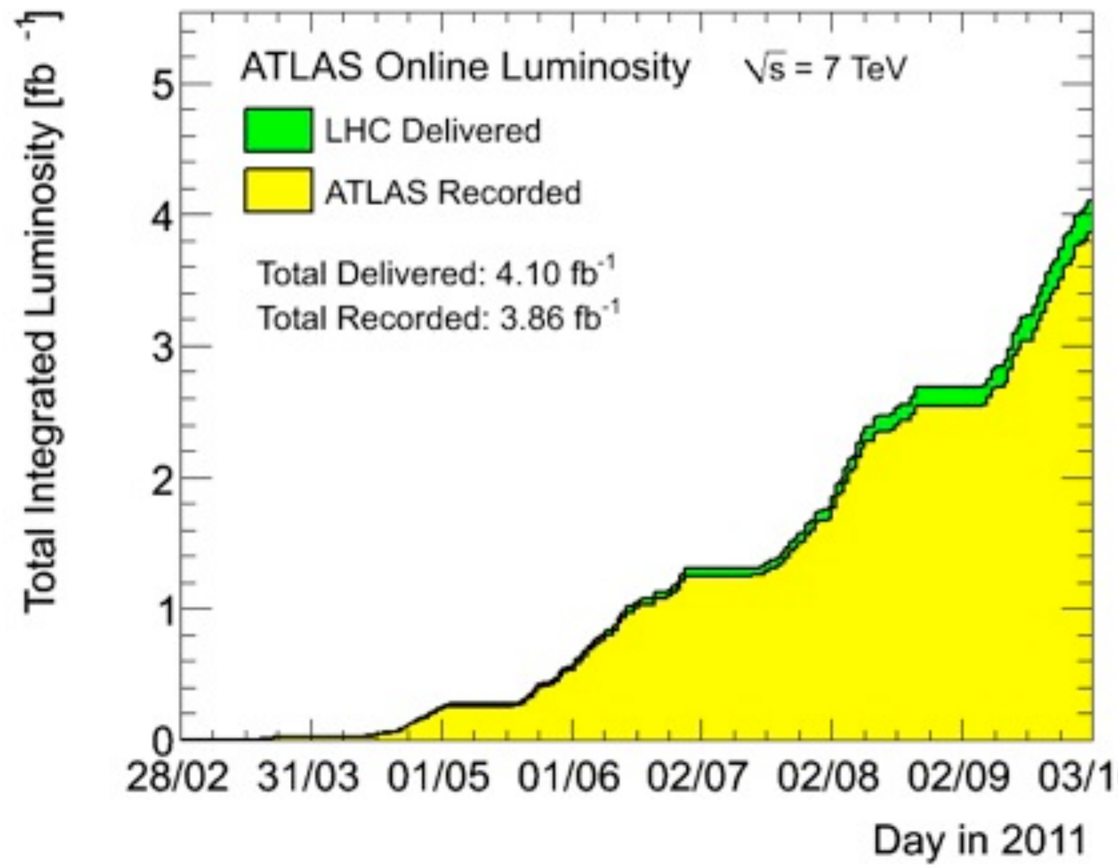
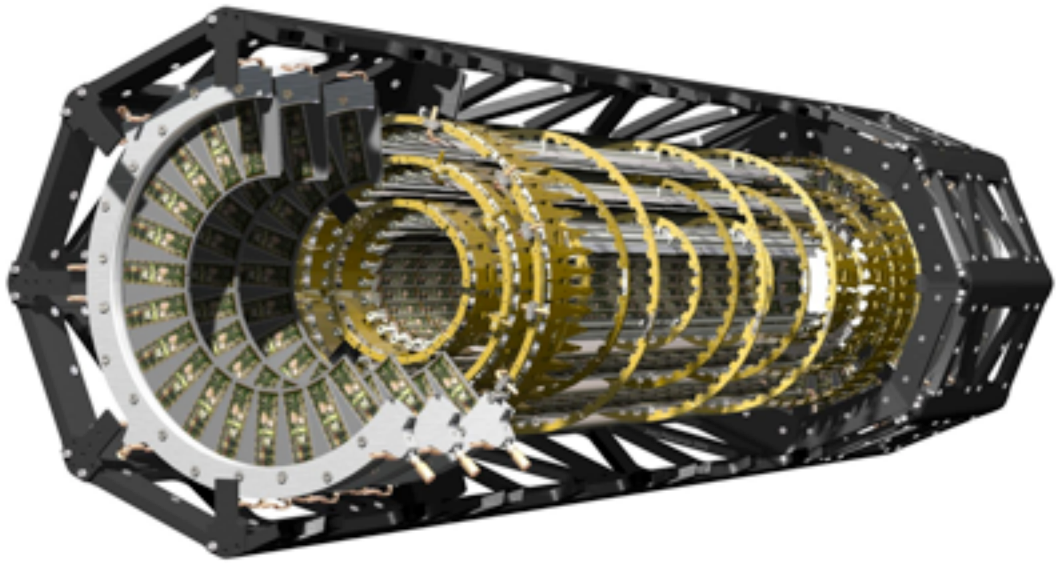
Radiation damage in ATLAS

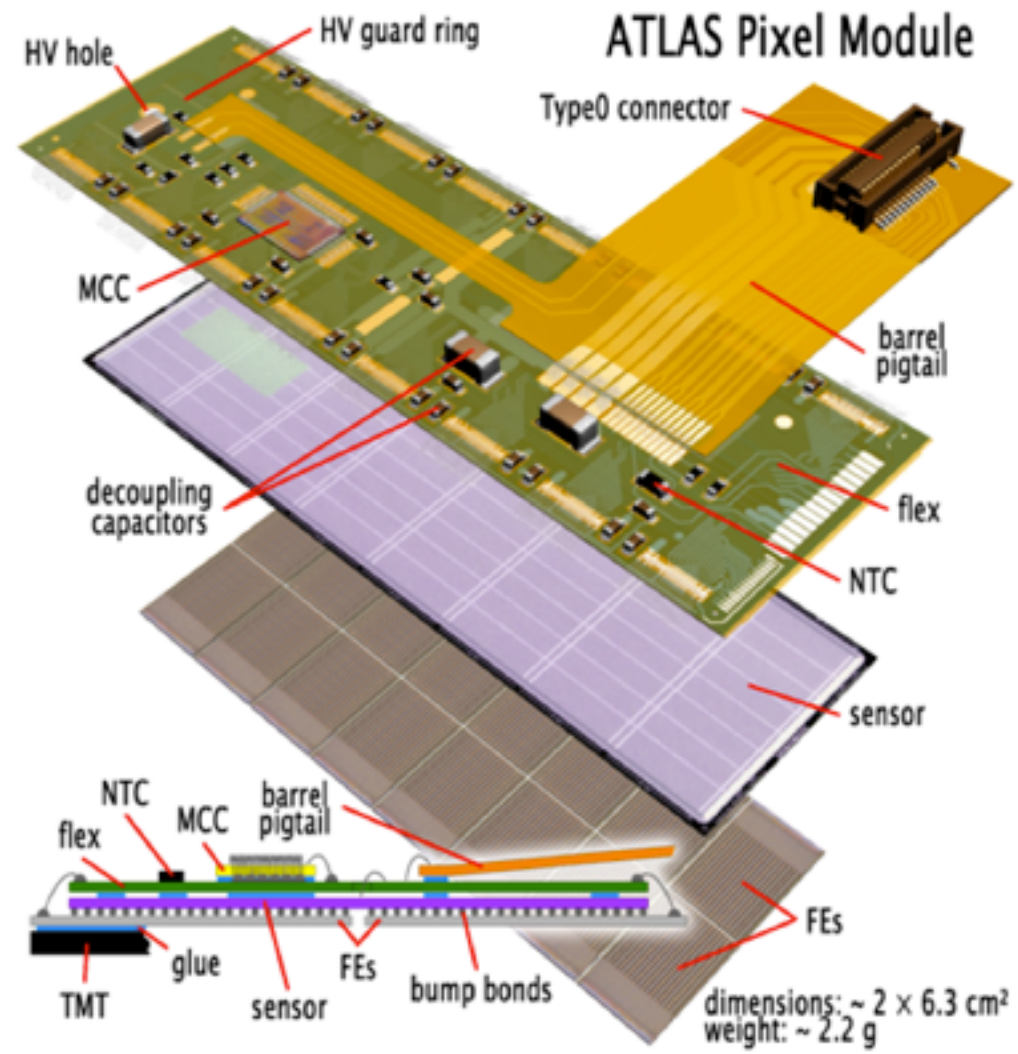
- The ATLAS silicon detectors (PIXEL and SCT) will be exposed to high a fluence of particles which will affect their performance.
  - The innermost pixel layer is expected to undergo type inversion after 10 fb^{-1} integrated luminosity (with optimal annealing).
- ATLAS has a dedicated program to simulate and monitor the radiation damage effects in its silicon detectors
  - Both Pixels and SCT have first simulations in place, and are regularly measuring the effects of the radiation damage in their detectors



layer	R [cm]	z [cm]	neq fluences [$10^{12} cm^{-2}/fb^{-1}$]	neq fluences [$10^{12} cm^{-2}/730\ fb^{-1}$]
Pixel B-layer	5.05	0 - 40.7	2.67	1922
Pixel barrel L2	12.7	0 - 40.7	0.46	335
SCT B3	30	0 - 75	0.16	130
SCT B6	52	0 - 75	0.089	65
SCT D9	44 - 56	272	0.14	102

The ATLAS Pixel Detector



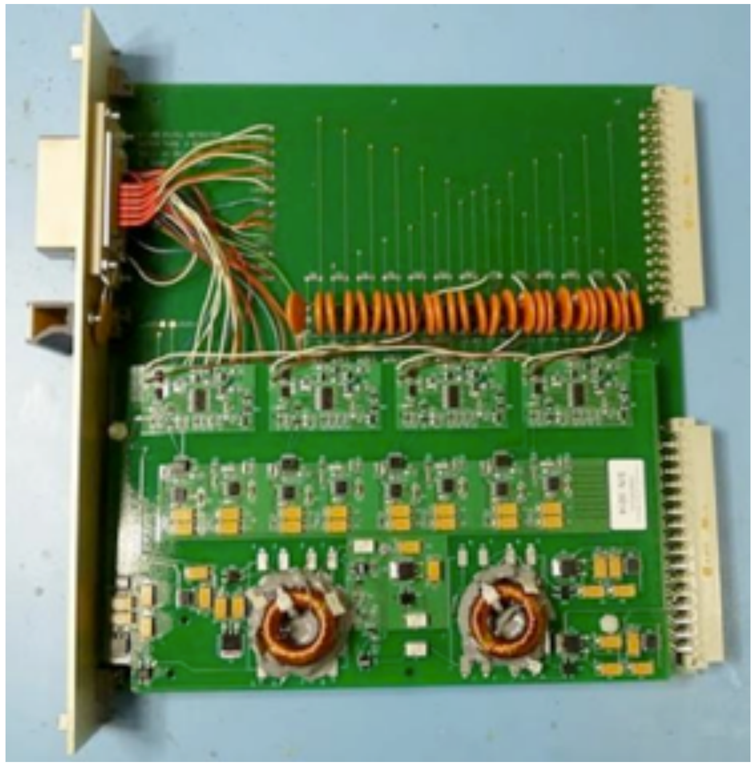


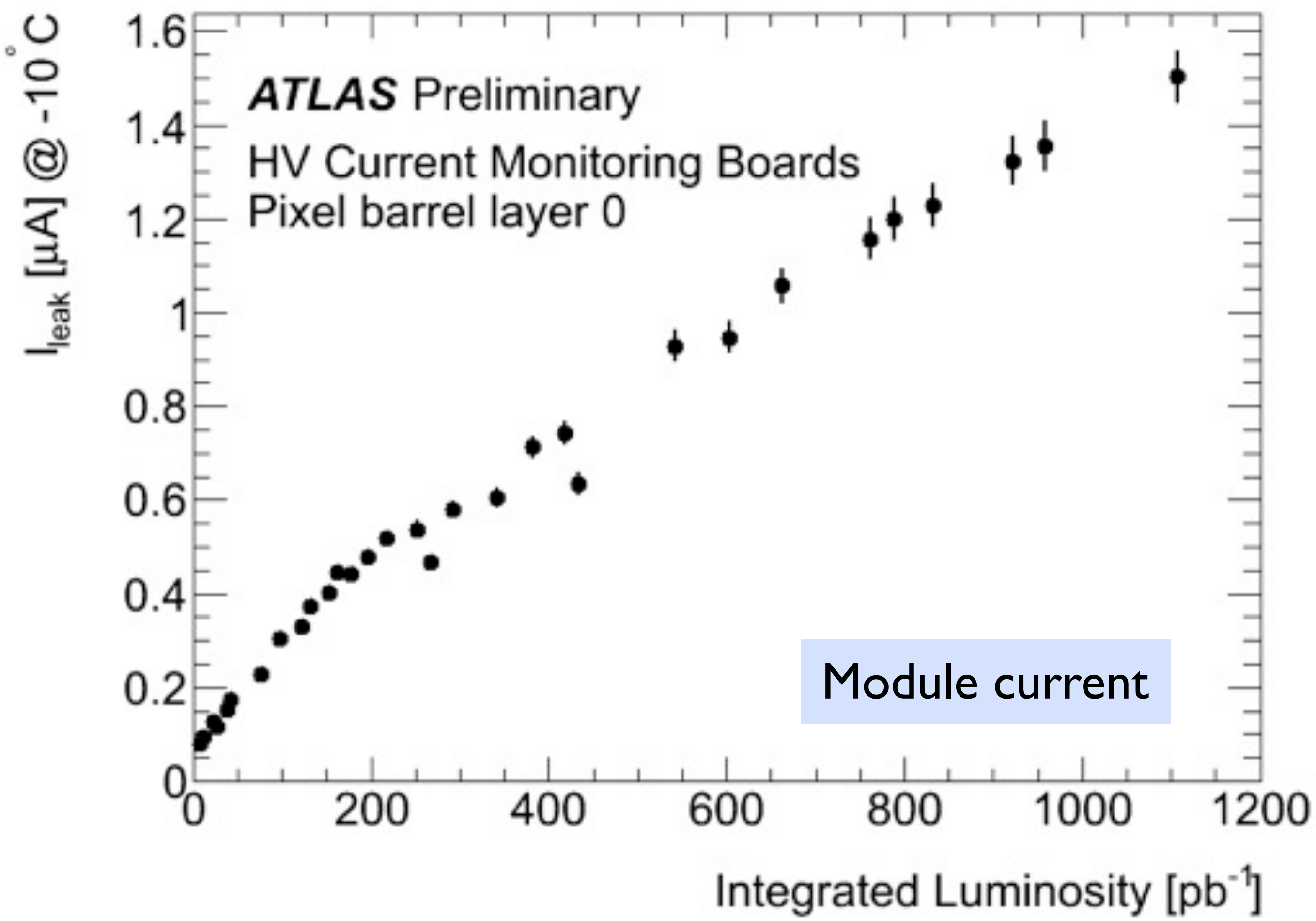
- **Basic properties**
  - 3 barrel layers with 1456 modules and 3 disks per endcap with 288 modules
  - Innermost layer at 50.5 mm - Radiation tolerance 50 MRad/10^{15} 1 MeV neqcm^{-2}
  - Evaporative C3F8 cooling integrated in the local support structures - cooled to an average temperature of -13 °C
- **Sensor**
  - 250 μm thick n-in-n Si sensor with a typical pixel size of 50x400 μm
  - 47232 (328x144) pixels, 46080 readout channels per module bump-bonded to 16 FE chips
  - Bias Voltage 150 - 600 V
- **Readout**
  - Pulse height measured with Time-over-Threshold (ToT)
  - Zero suppression in the FE chips, Module Chip Controller (MCC) builds the module event
  - Data transfer speed of 40-160 MHz, depending on the layer

Monitoring the leakage current

All currents corrected to T = -10 °C

- Current Monitoring Boards (CMB)
  - Dedicated hardware were installed in Feb/March 2011 to measure the leakage current per module, with a precision approaching ~10 nA
  - All layers in the barrel are already (partially)equipped with CMBs, with L0 having the largest granularity. Installation continues over technical stops to fully equip the detector



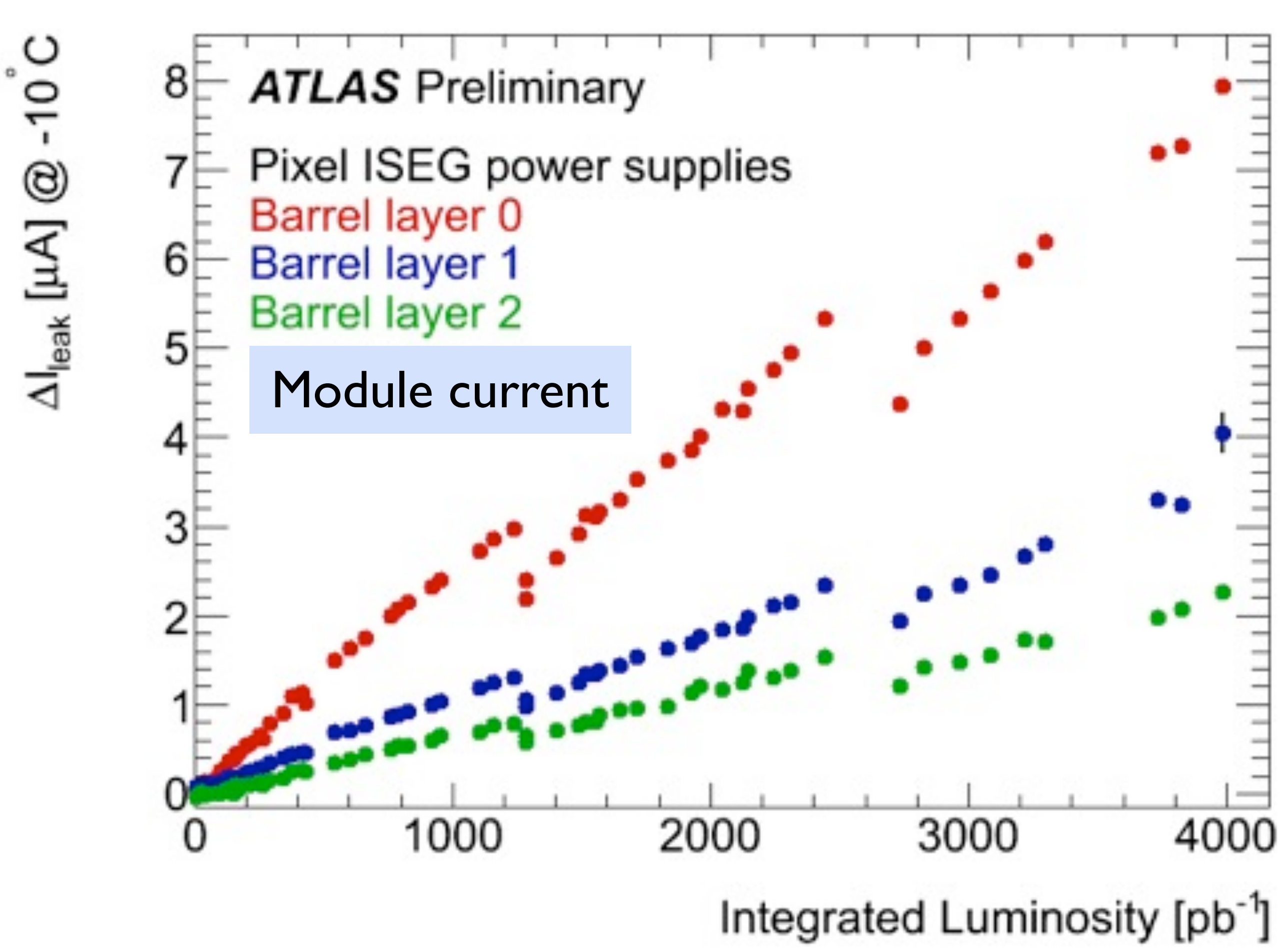


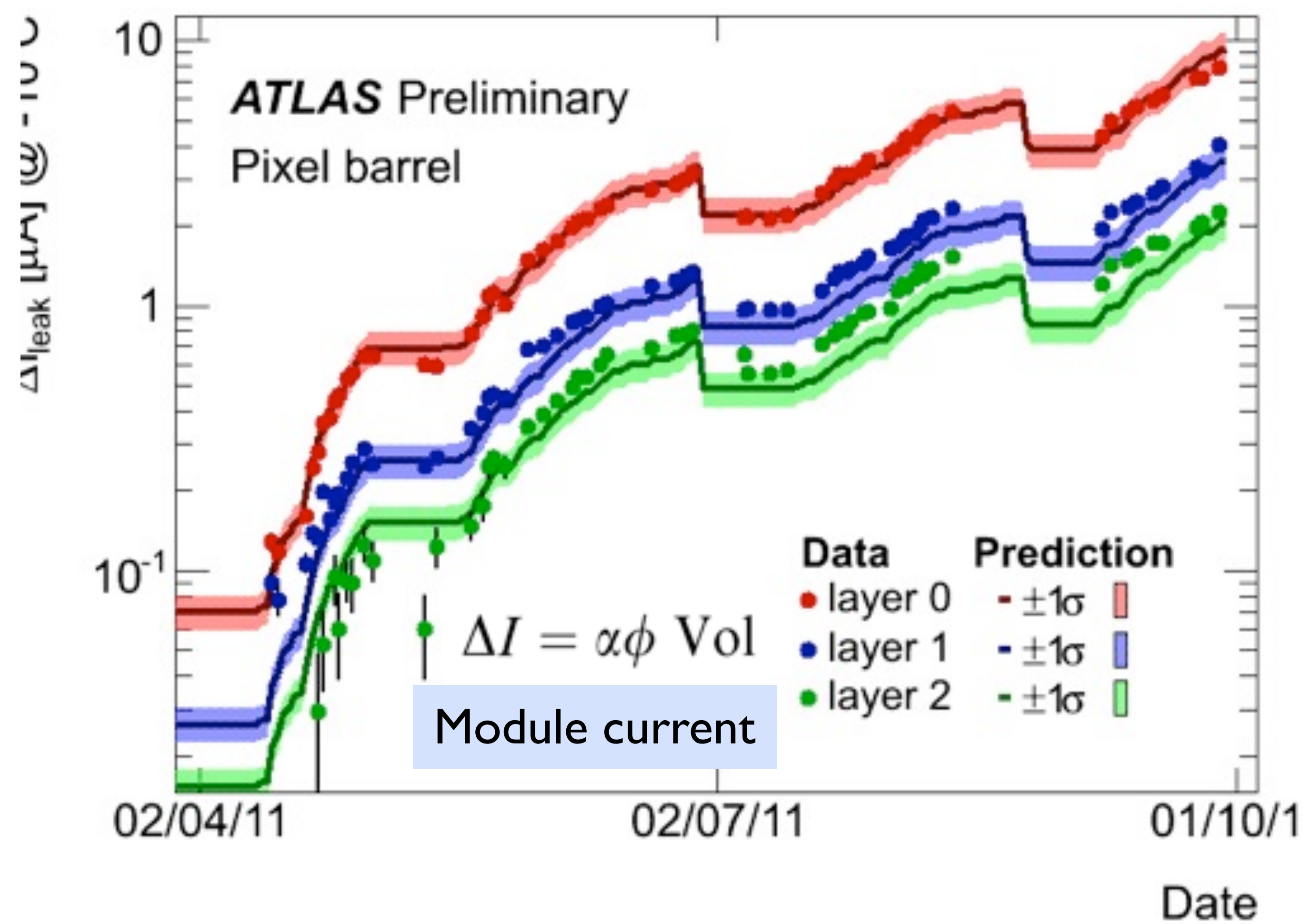
- Includes preliminary correction for beam induced ionization current
  - I_{hit} = $N_{bunches}$ x nLHC x pixel hit occupancy x charge per hit
- Validation of board calibration ongoing
  - Measuring currents without beam during technical stops

Monitoring the leakage current

All currents corrected to T = -10 °C

- Measurement from the HV power supplies
  - Measure the current at the output of the HV PS for groups of 6/7 modules with a precision of about 80 nA
  - 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 479(2002) 548-544.
  - Measurements are preliminary corrected for annealing periods in Summer as in M. Moll PhD Thesis

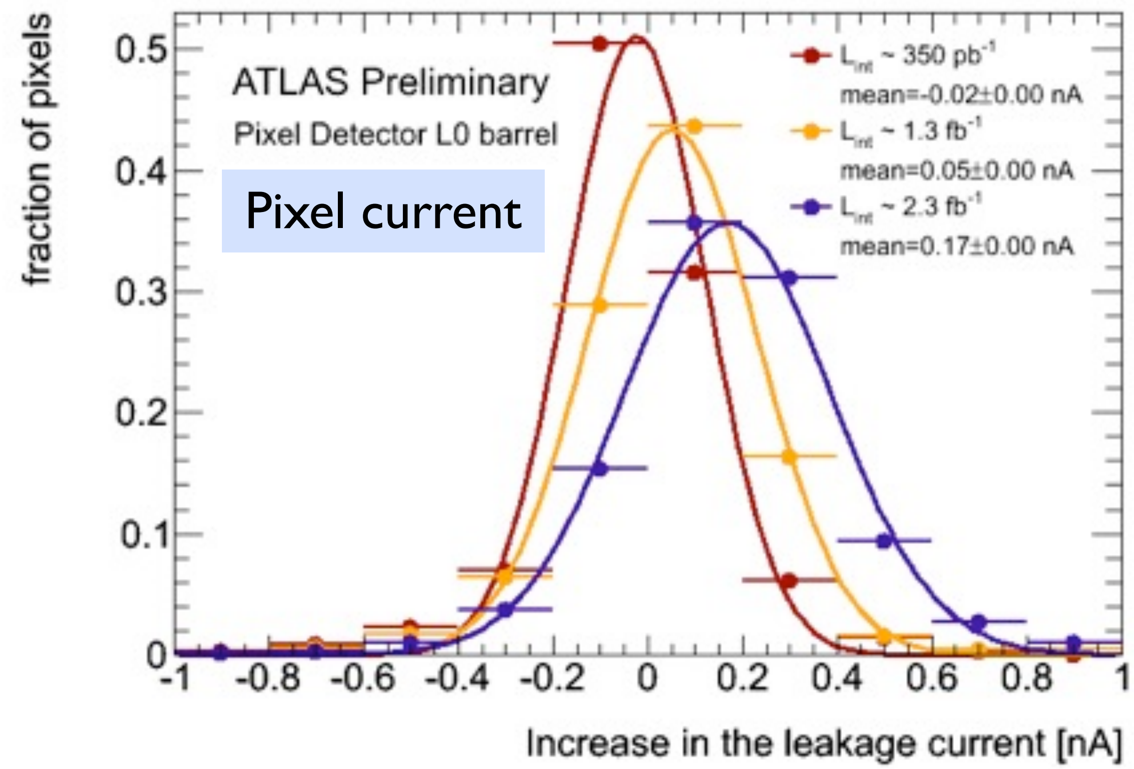


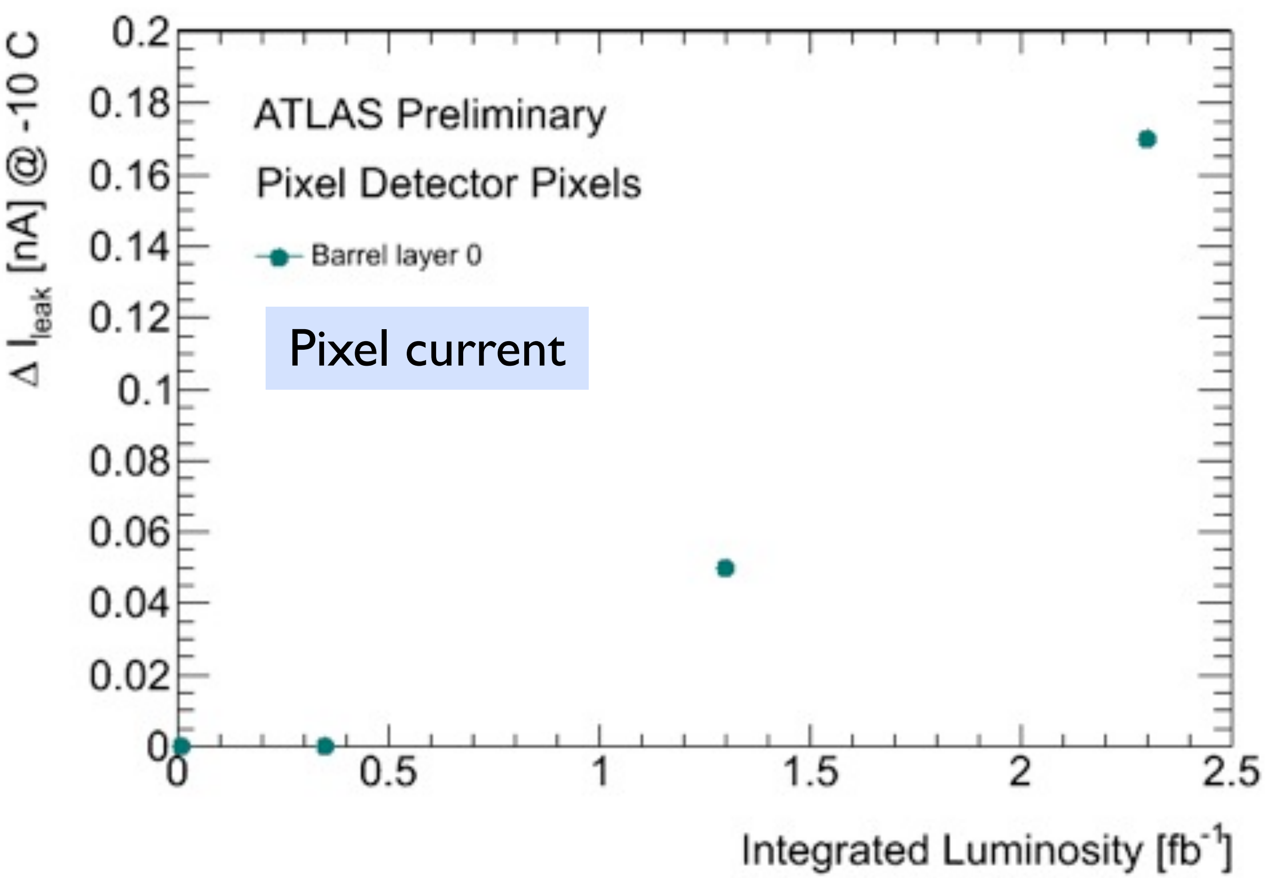


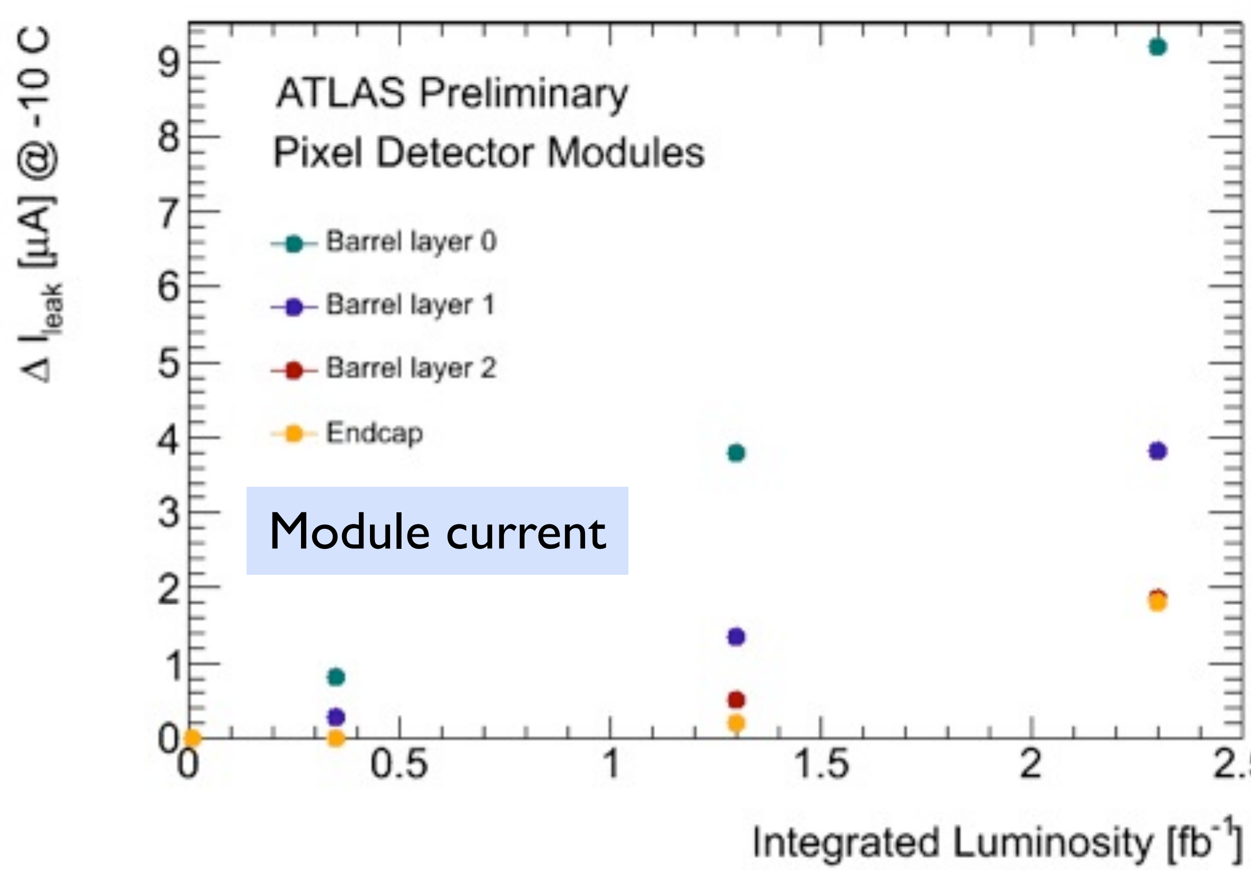
Monitoring the *pixel* leakage current

All currents corrected to T = -10 °C

- Pixel-by-pixel current ("monleak")
  - Measured by connecting an ADC in the FE chips to the feedback branch in every pixel
  - The measurement provides the monleak current: $I_{monleak} = 2xI_{feedback} + I_{leakage}$ with a LSB of 0.125 nA
  - Currently sensible for the innermost layer and the innermost disk modules, starting from an integrated luminosities > 1 fb^{-1}





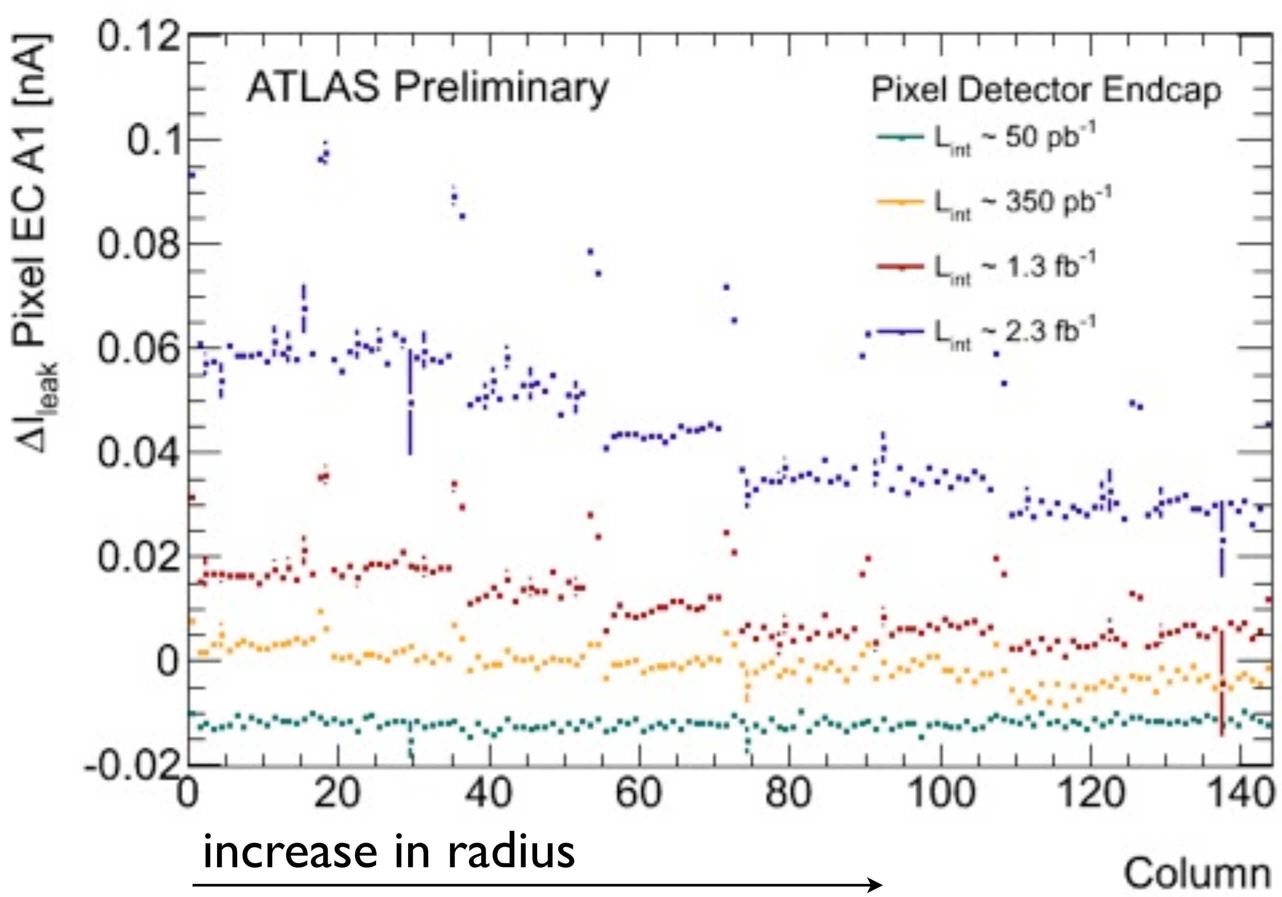


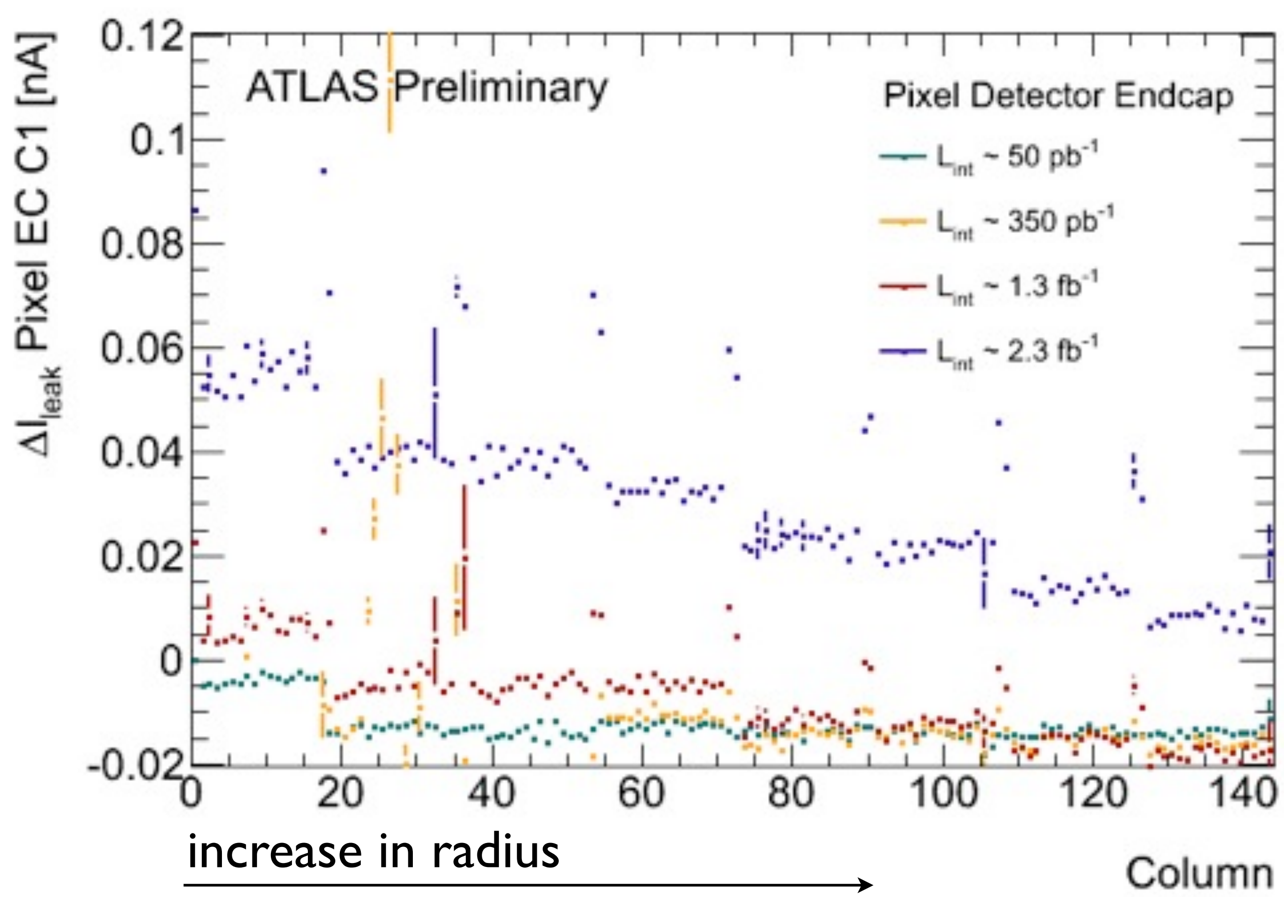
Monitoring the *pixel* leakage current

All currents corrected to T = -10 °C

Radial dependence of the pixel current increase in the endcaps

- Measured for the two innermost endcaps (no observed z dependence so it should be the same for the outermost two)
- Similar results for both sides, although a bit larger for Endcap A, indicating that irradiation might have been more intense for this side of the detector
- Effect of the larger capacitance of long pixels between FEs is seen, and also some dependence in between FEs that needs to be understood
- Decrease of the currents observed at lower luminosities provide the scale of the error in the measurement, since no effect is expected below 1 fb^{-1}



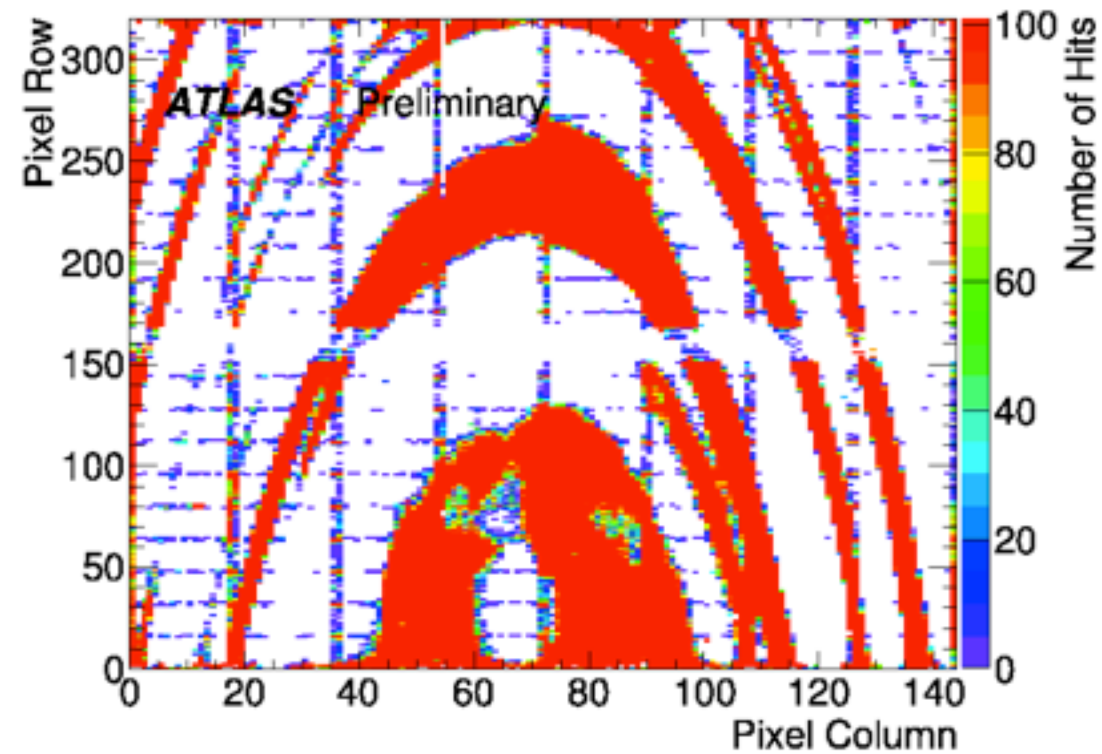


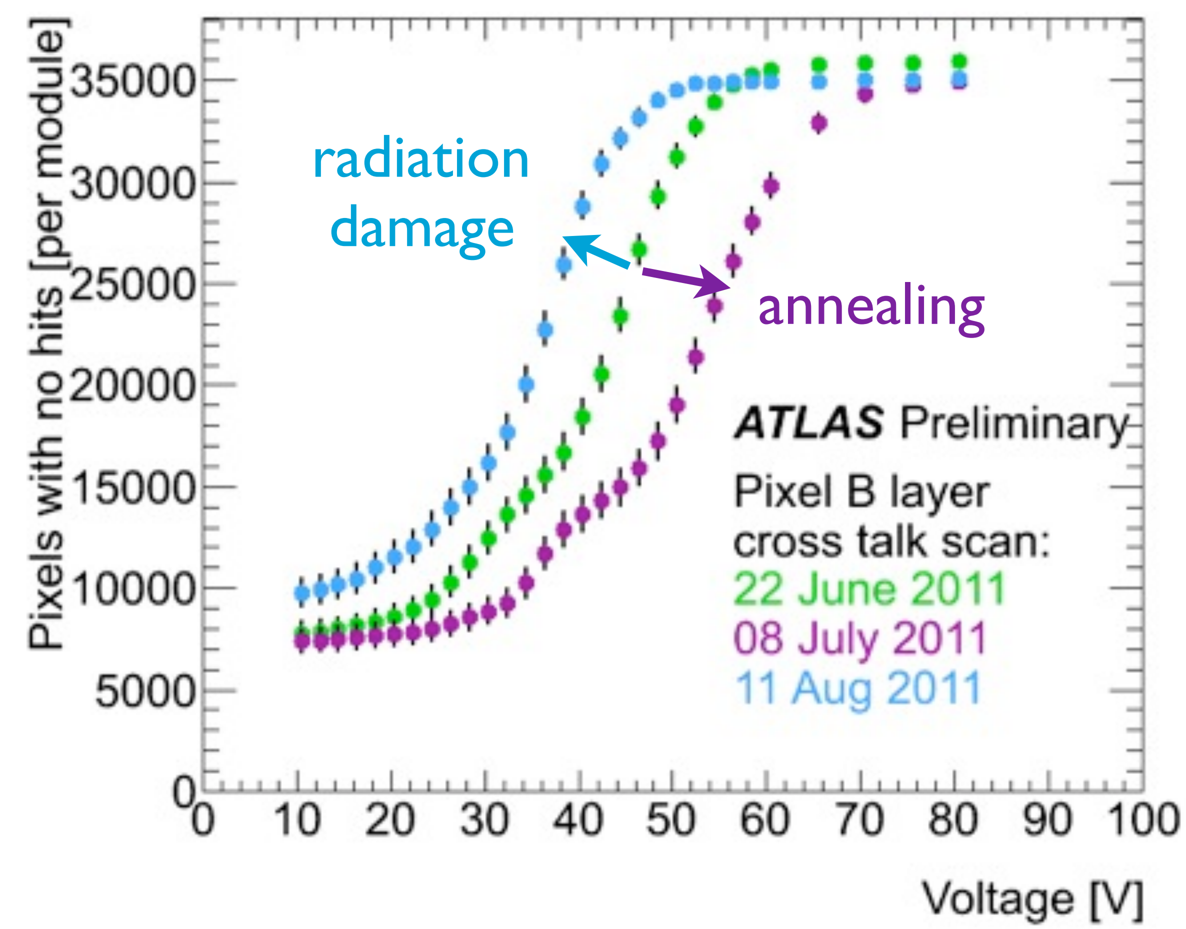
increase in radius

increase in radius

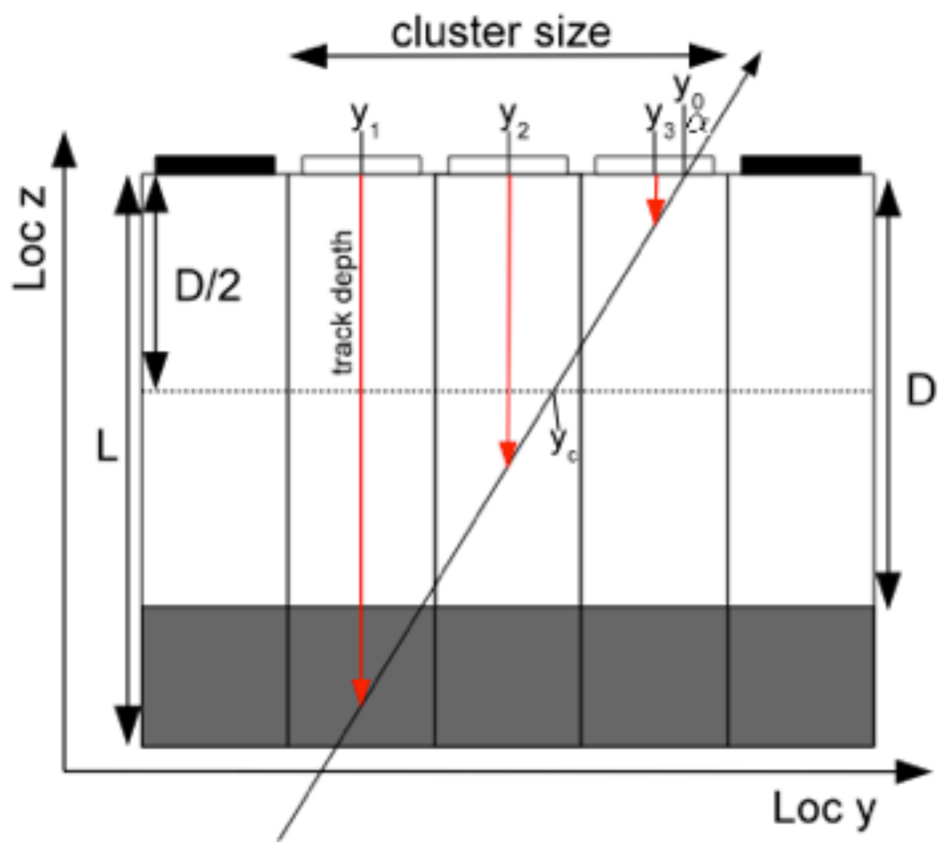
Depletion voltage measurement

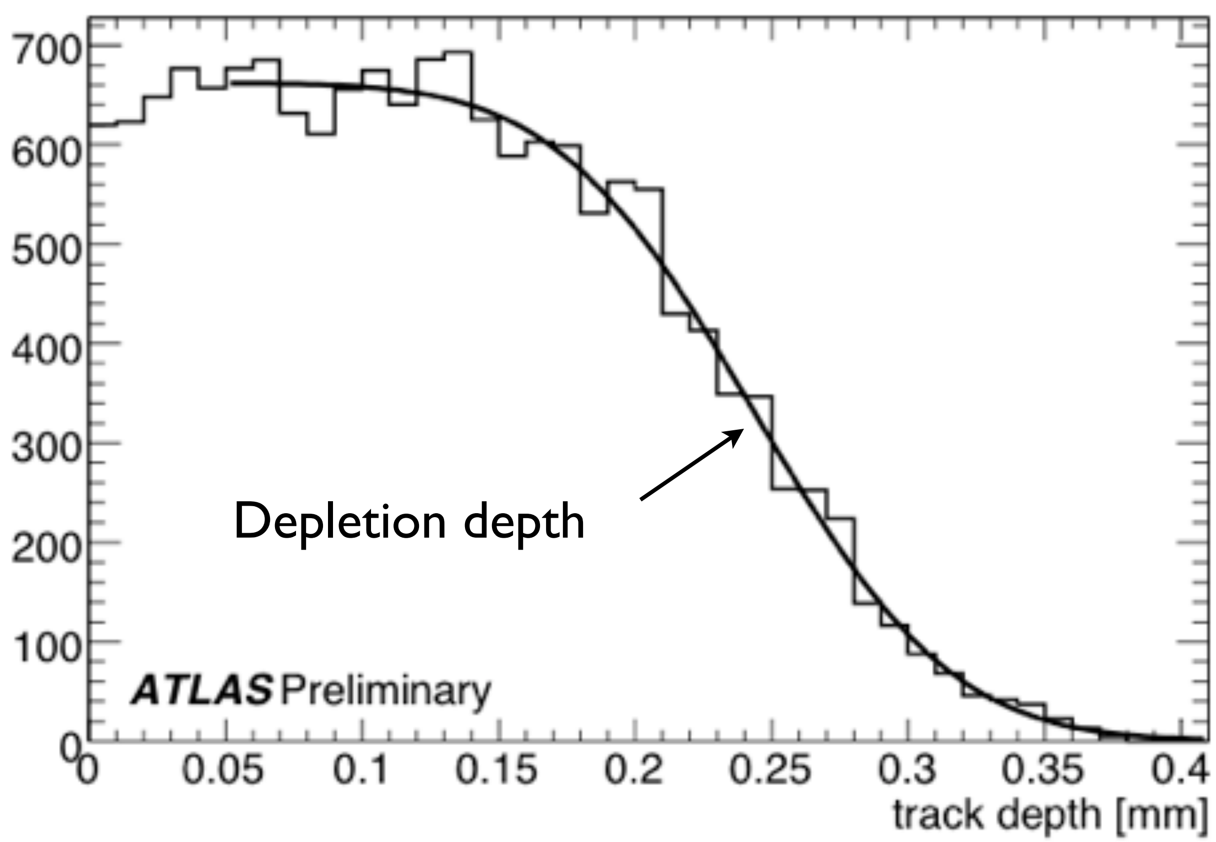
- Use cross-talk measurements (before type inversion):
  - Inject charge into one pixel, read out neighbor.
  - When not fully depleted, high-ohmic short between pixels. When fully depleted, pixels are isolated from each other.
  - Choose injected charge such that cross-talk hits are seen only for Vbias < Vdep
- Cross-talk scans are taken periodically during calibration periods
- Observe decrease in average depletion voltage from June to August.
- Annealing effects induced an increase of the Vdep from June to July
- Measurements after type inversion will be done with tracks, if cross-talk scan or measurements with noise are not sensible anymore





Depletion depth measurement





- 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.

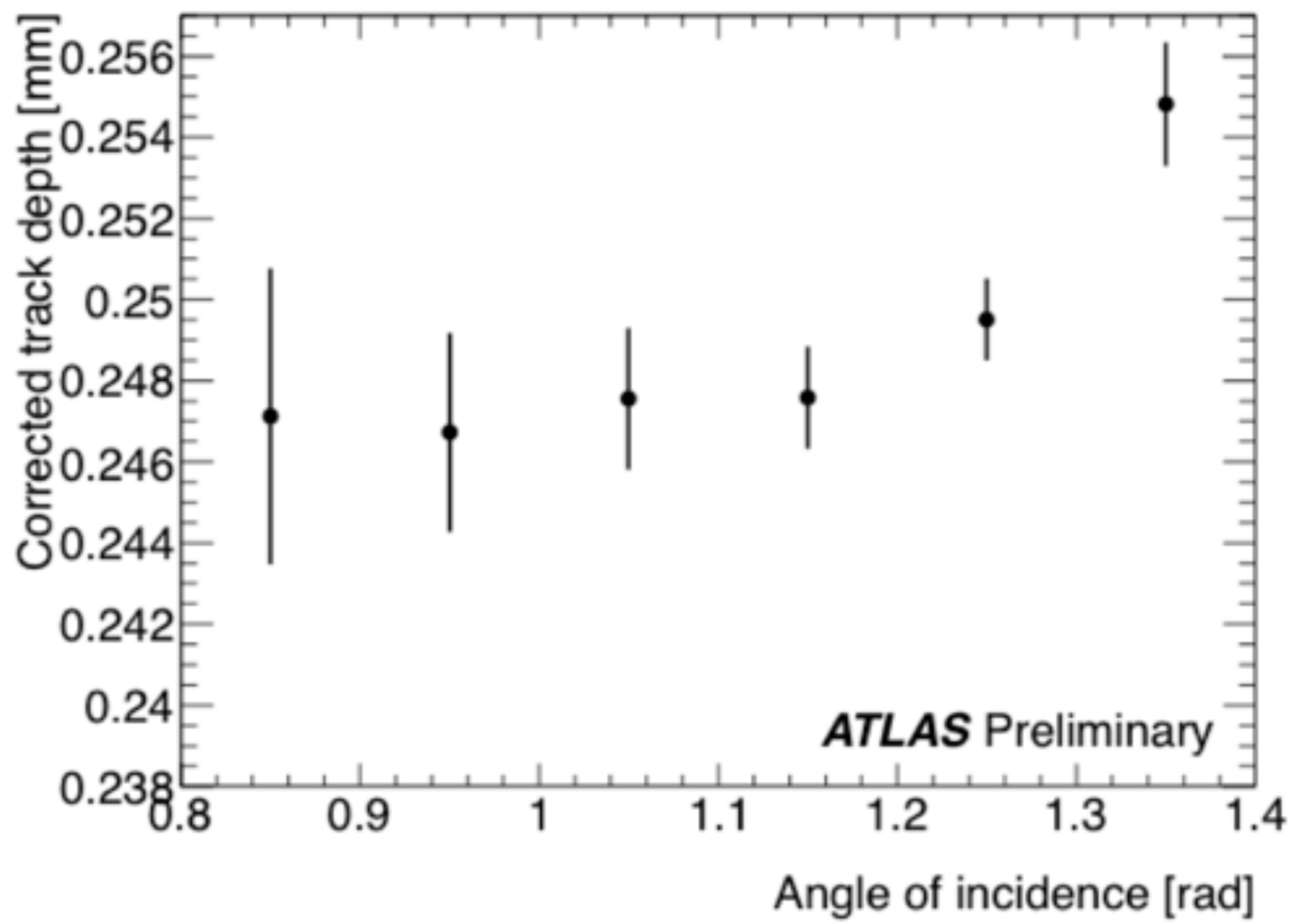
$$f(D' - x) = 1 - \left(\frac{a}{\sqrt{\pi}} \int_0^{\frac{D'-x}{\sqrt{2}b}} \exp(-t^2)dt\right)$$

  - Charge threshold effects are corrected for for the different angles

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

Depletion depth measurement

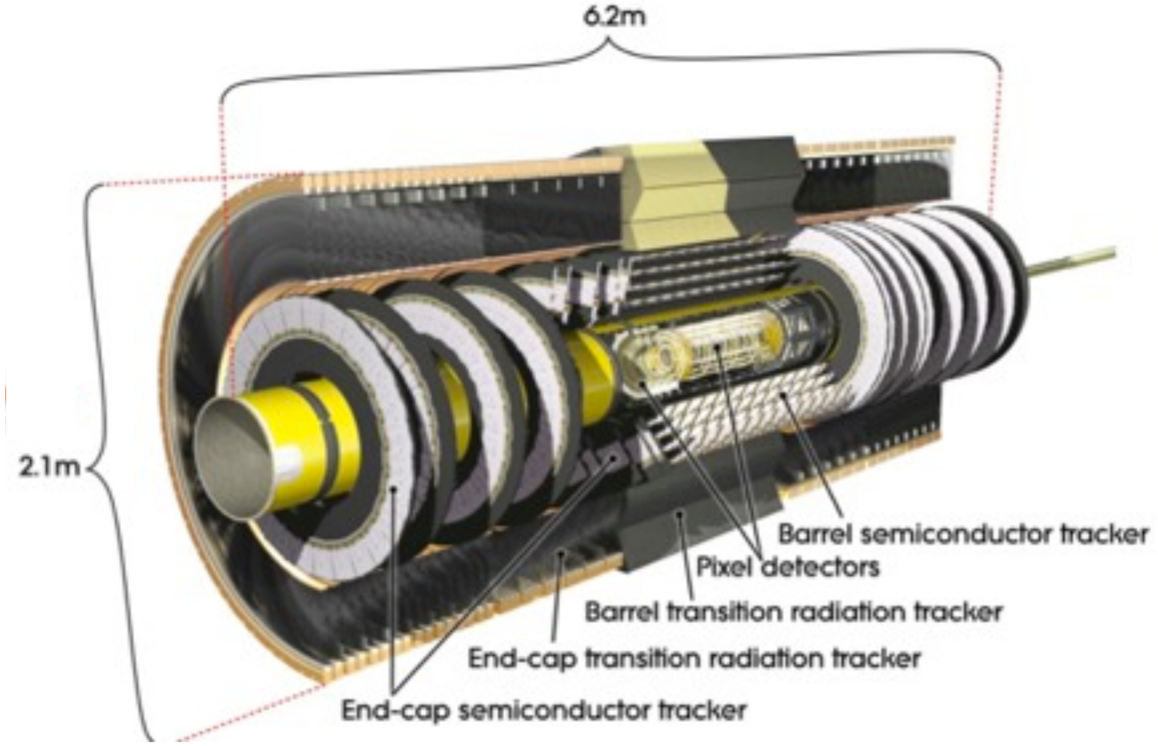
- Angle distribution for corrected track depth values
- The angle between the pixel normal and the longitudinal pixel direction is chosen, because in the barrel, the B-field is close to parallel to the long pixel direction so Lorentz drifts are negligible
- Measured depletion depth agrees with sensor thickness, as expected
- This method enables future monitoring of the depletion depth and depletion voltage after type inversion and is being tested against simulated samples with different depletion depths

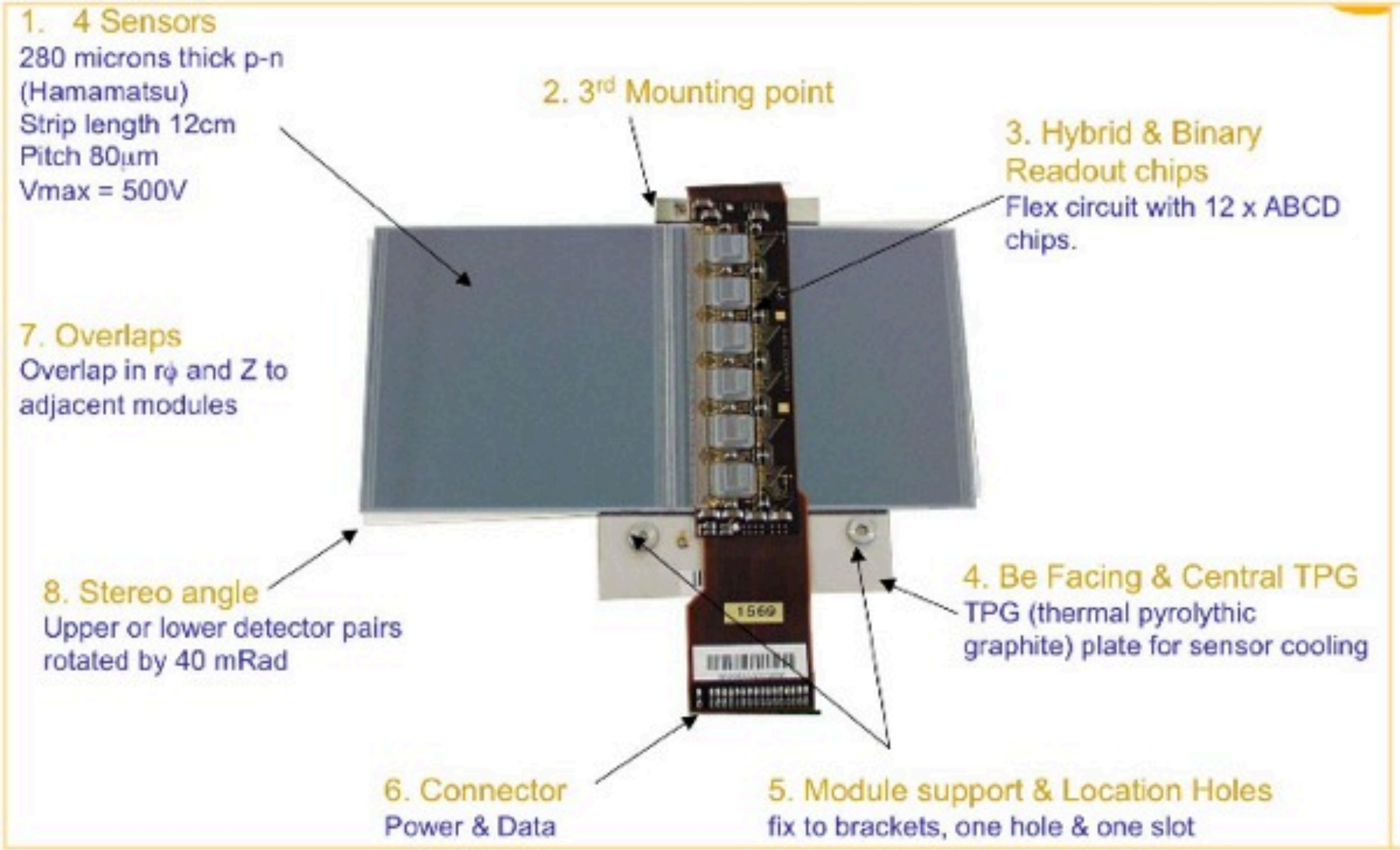


$$D = (248.9 \pm 1.2(\text{stat.}))\mu\text{m}$$

The ATLAS SemiConductorTracker

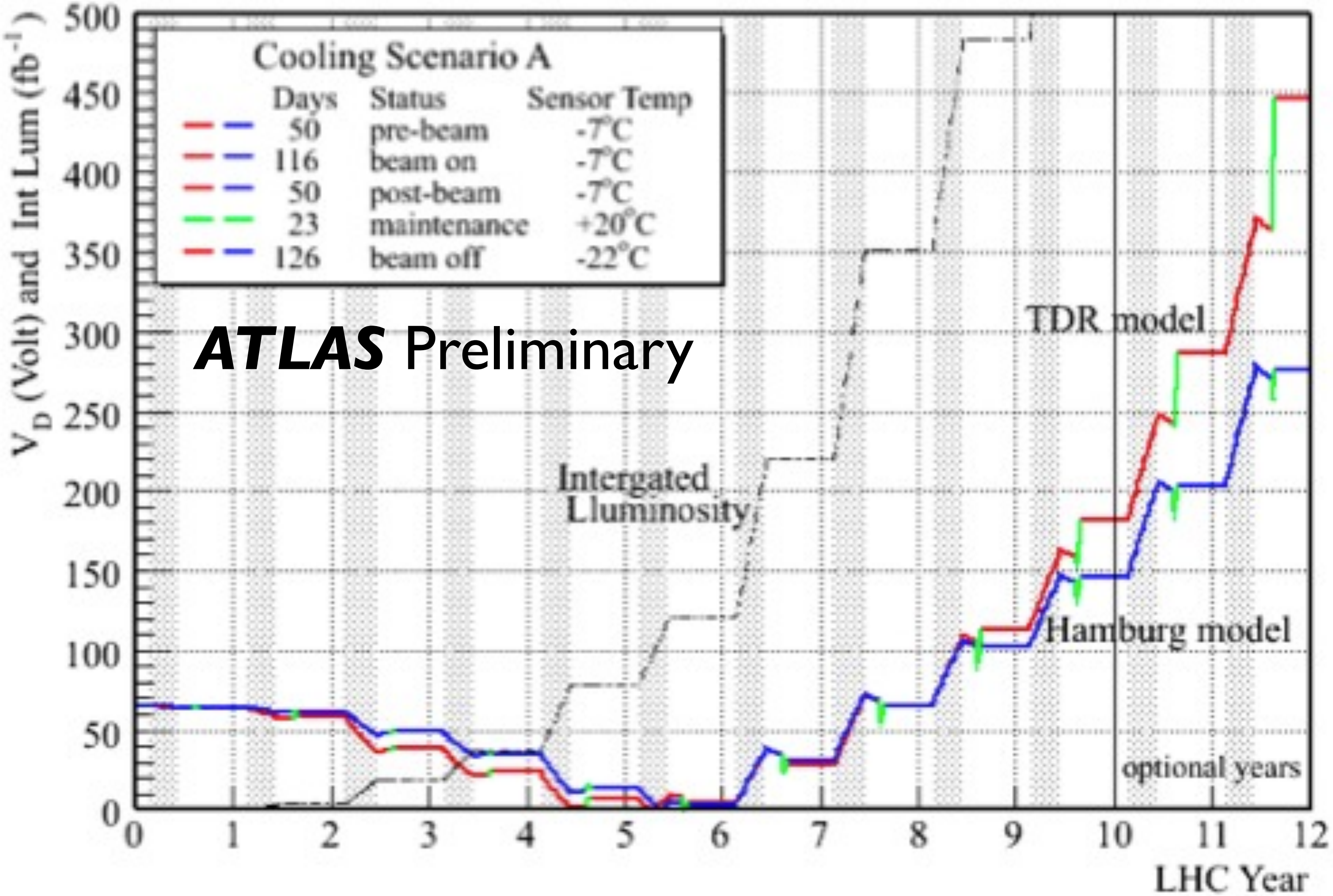
- Back-to-back p-in-n planar sensors, 285μm thick, 40mrad stereo angle
- Glued to thermally-conductive baseboard
- Bias voltage 150-500V (~65V/~85V depletion Hamamatsu/CiS)
- Strip pitch 80μm (barrel), 70-90μm (endcaps – constant phi) → 17μm resolution in bending plane





- Binary readout via ABCD3TA – Rad-hard DMILL technology – 12 ASICs per module, mounted on Cu-kapton flex hybrid
- Optical communication with off-detector readout electronics: – 1 TX (clock/command) fibre, 2 RX (data) fibres per module – Redundancy between neighbor modules.
- 4 types of endcap modules for hermetic coverage of disks

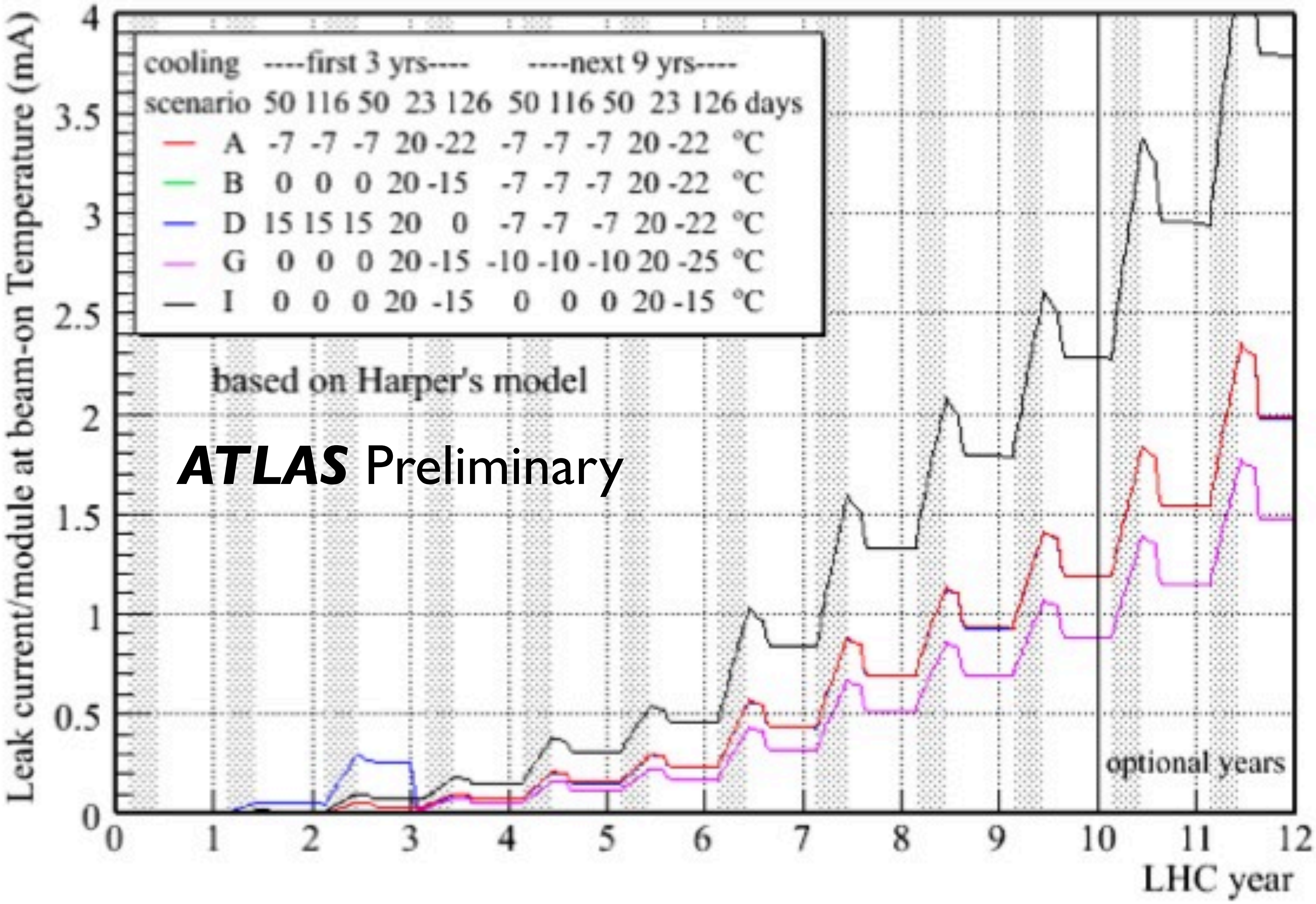
Depletion voltage predictions



New LHC luminosity profile [1]												
year	1 2010	2 2011	3 2012	4 2013	5 2014	6 2015	7 2016	8 2017	9 2018	10 2019	11 2020	12 2021
IL/year [fb^{-1}]	0.5	3.3	15	19	41	42	99	132	132	145	193	242
Integ. L [fb^{-1}]	0.5	3.8	19	38	79	121	220	352	484	629	822	1064

[1] from talk given by F. Zimmermann at ATLAS Upgrade Week, Nov.9-13, 2009

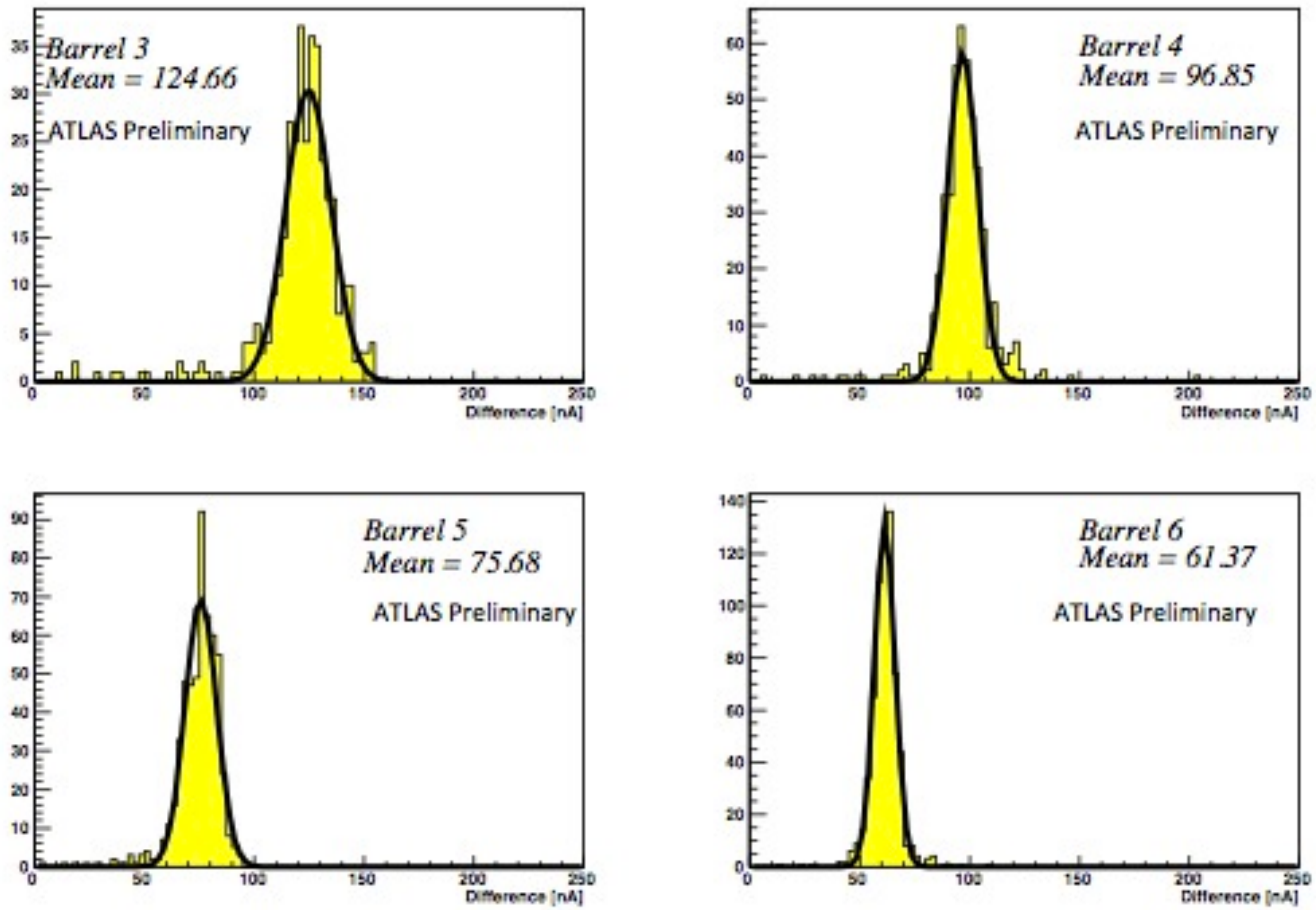
Leakage current predictions



- Barrel-3 for various cooling scenarios based on Harper's model (PhD Thesis, Sheffield)

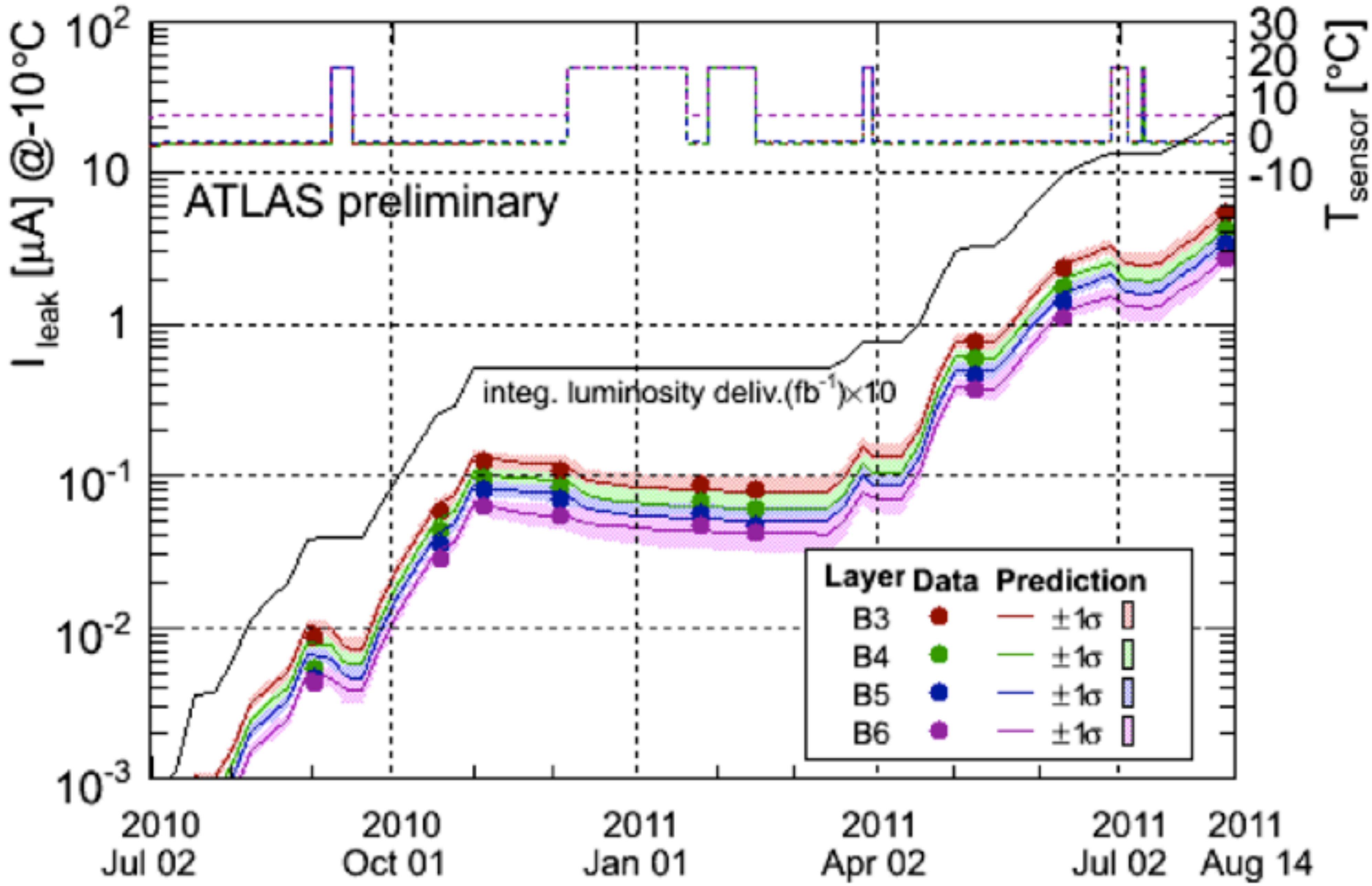
Leakage current measurements

- Measure current during MD (FSI off)
- Average over a period of time
- Correct current to -10C (temperature QA irradiations were performed at)



An example of the measurements made in the barrel

Comparison with model



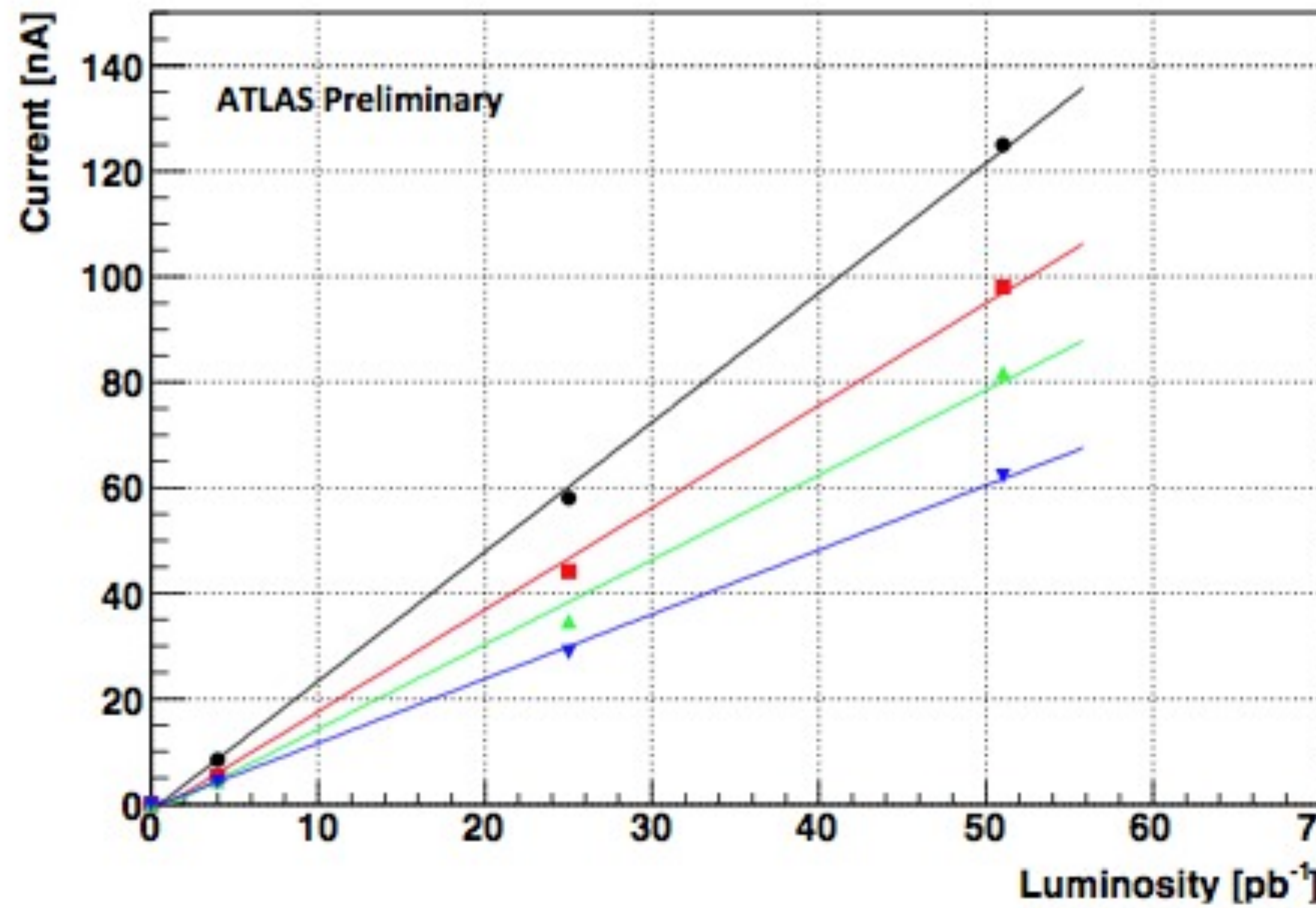
- Excellent agreement between prediction and measurement

Fluence

- 1 MeV neutron equivalent fluences obtained from increased leakage currents

$$\Delta I = I_{Measured} - I_{Initial} = \alpha\phi V$$

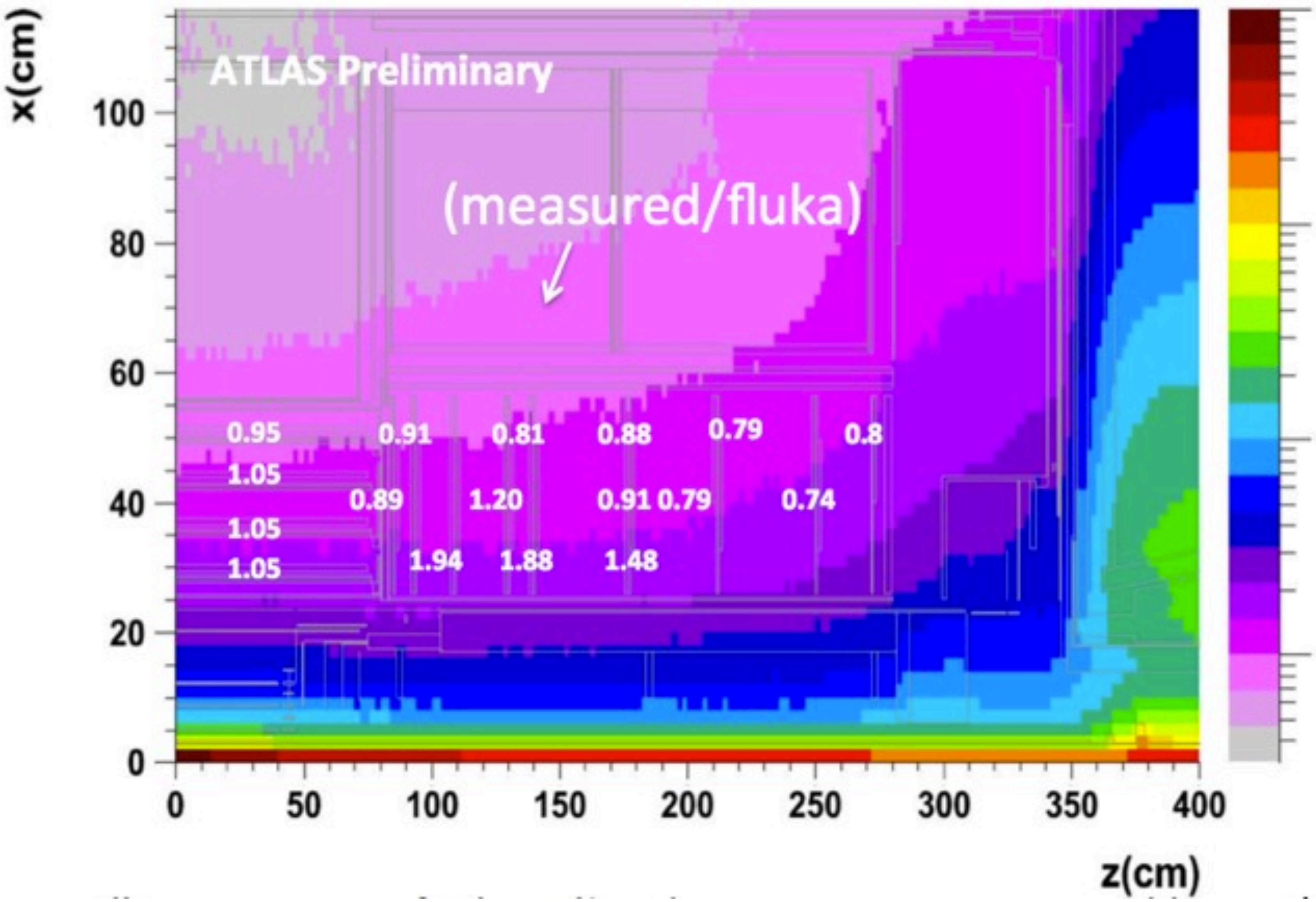
I: leakage current (measure)
α: damage parameter (known)
Φ: fluence (what we want)
V: active volume of detector (known)



- Linear increase in leakage currents with luminosity suggests fluences dominated by pp collisions (cf machine background)

Comparison of measured fluences with FLUKA

- Comparison of 1MeV n-eq fluences determined from SCT leakage current measurements with simulated FLUKA predictions @ 7 TeV

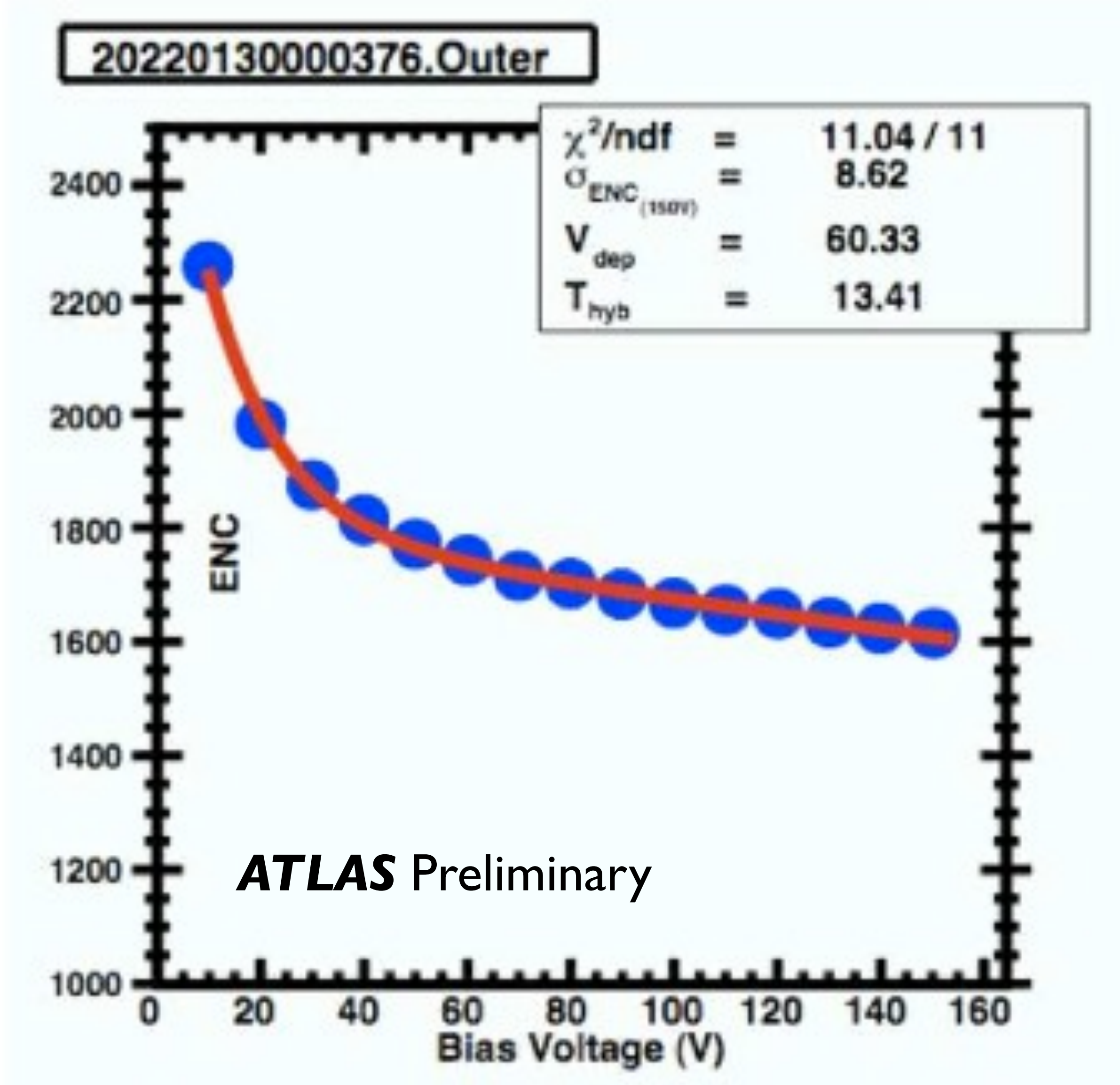


- Excellent agreement for barrel! EndCap comparisons reasonable too. (Indicated are differences for EC-C.)

- For inner rings we measure consistently higher than predictions – why? (For example, is it related to fact that inner rings are CiS detectors, compared to Hamamatsu elsewhere?)

Depletion voltage

- Capacitance contributes to the noise
- When bias voltage reaches full depletion voltage in silicon sensors the strip to backplane capacitance becomes minimal as well as the noise due to this capacitance
- Measurements were done at the start of LHC running, will be repeated at the end of this year



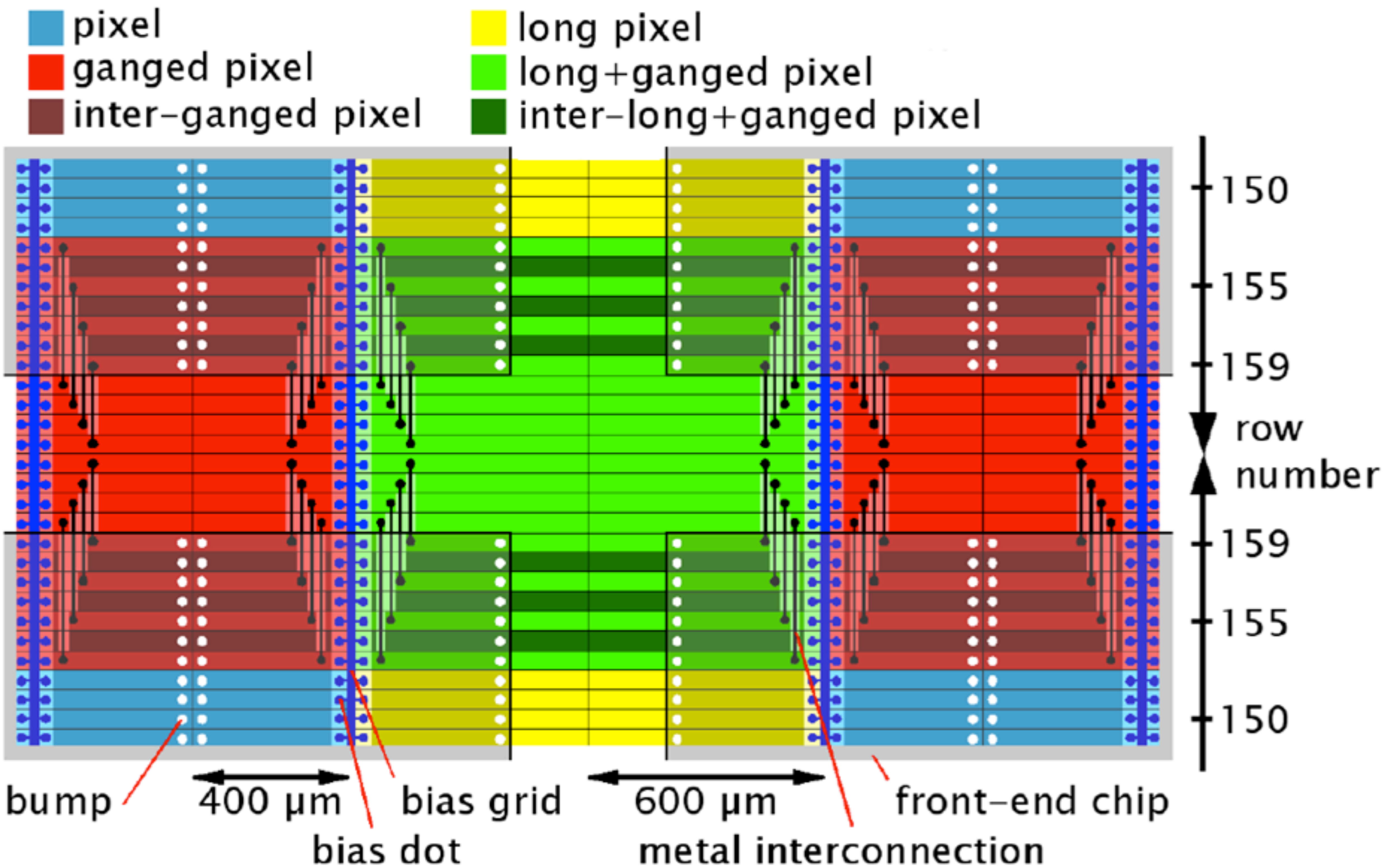
$$ENC = \frac{e^3}{36q_e}\left\{\frac{3}{T_p}(C_{tot}+C_{stray}+C_a+C_f)^2\left(4kT_cR_{bb}+\frac{2k^2T_c^2}{q_eI_c}+4kT_sR_s\right)\right.$$
$$\left.+\frac{5T_p}{3}\left(\frac{2q_eI_c}{\beta}+\frac{4kT_c}{R_f}+2q_eI_l+\frac{4kT_s}{R_{bias}}\right)\right\}^{\frac{1}{2}} \qquad (3.2)$$

Summary

- A carefully designed monitoring program is being developed to survey the radiation damage effects in the detectors
- First signs of radiation damage are seen at the pixel level, with a leakage current increase of about 0.16 nA for 1.3 fb^{-1} integrated luminosity for the innermost layer and observation of radial dependence for the endcap modules
- Measurements with CMBs and at the output of the PS show an increase of the leakage current in the modules of about 2 μA for 1.5 fb^{-1} and first comparisons with a model show a reasonable level of agreement
- SCT measurements of the leakage currents show excellent agreement with Hamburg model predictions, and fluence measurements have excellent agreement with FLUKA simulations
- Regular measurements of the depletion voltage show both annealing and radiation damage effects
- SCT Depletion voltage (noise scans) will be performed at the end of the year and compared to predictions
- Measured depletion depth with tracks to be compatible with the sensor thickness, as expected
- Working on adding annealing corrections to all of our measurements and looking forward to updating the results and to extend our studies to measure the radiation damage constant

Back up slides

The pixel inter-chip region



SCT bulk leakage current

references	Robert Harper's Thesis (2001, University of Sheffield)

$$I = g(\Theta(T_A)t_{ir}, \Theta(T_A)t^{'})\alpha\phi V$$

$$g(\Theta(T_A)t_{ir}, \Theta(T_A)t^{'}) = \sum_{i=1}^{n}\left\{A_i \frac{\tau_i}{\Theta(T_A)t_{ir}}\left[1-\exp\left(-\frac{\Theta(T_A)t_{ir}}{\tau_i}\right)\right]\exp\left(-\frac{\Theta(T_A)t^{'}}{\tau_i}\right)\right\}$$

$$\Theta(T_A) = \exp\left(\frac{E_I}{k_B}\left[\frac{1}{T_R}-\frac{1}{T_A}\right]\right)$$

$$\alpha_{eq}(-7°C) = (6.90 \pm 0.20)\times 10^{-18}\ \mathrm{A\cdot cm^{-1}}$$

i	τ_i(min)	A_i
1	$(1.2 \pm 0.2)\times 10^6$	0.42 ± 0.11
2	$(4.1 \pm 0.6)\times 10^4$	0.10 ± 0.01
3	$(3.7 \pm 0.3)\times 10^3$	0.23 ± 0.02
4	124 ± 25	0.21 ± 0.02
5	8 ± 5	0.04 ± 0.03