Operational experience and radiation damage at LHC ATLAS Experiment

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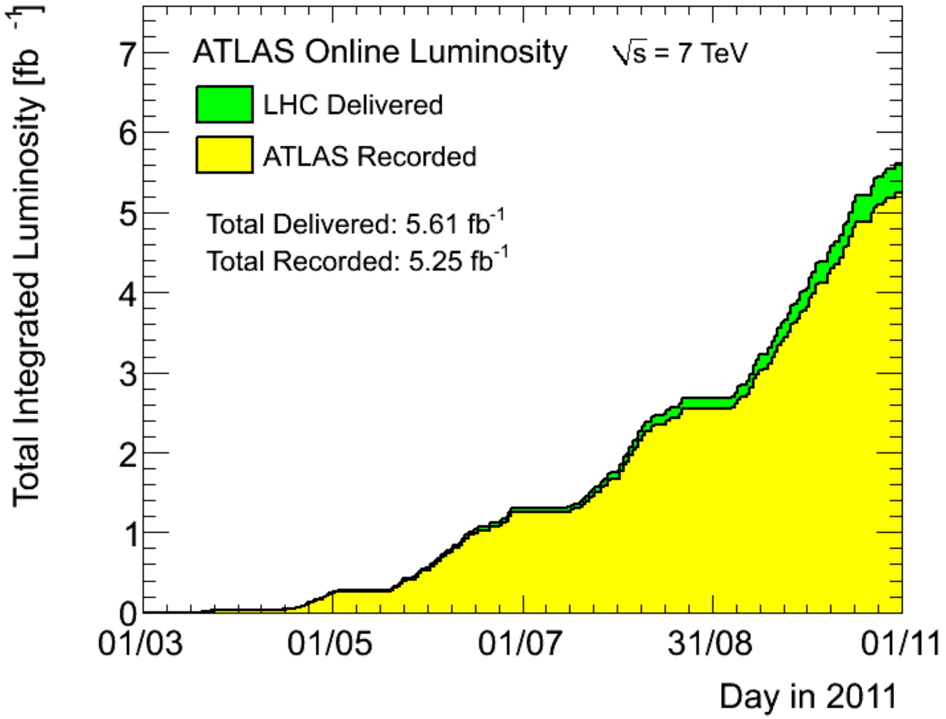
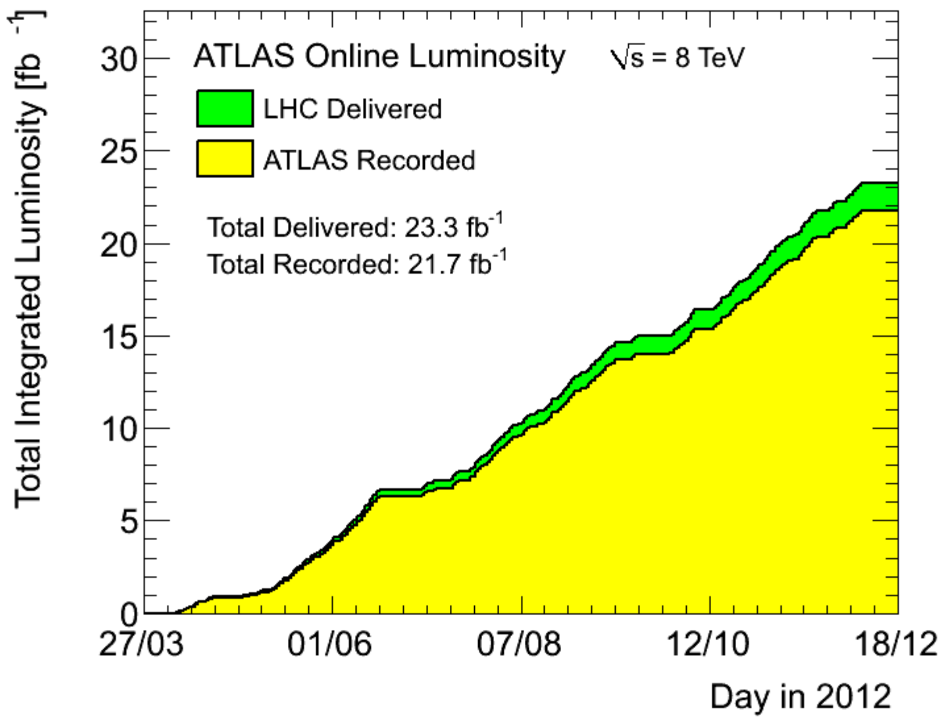
on behalf of ATLAS Radiation Damage Monitoring Group

LHC integrated luminosity delivered: more than 29 fb^{-1} in total



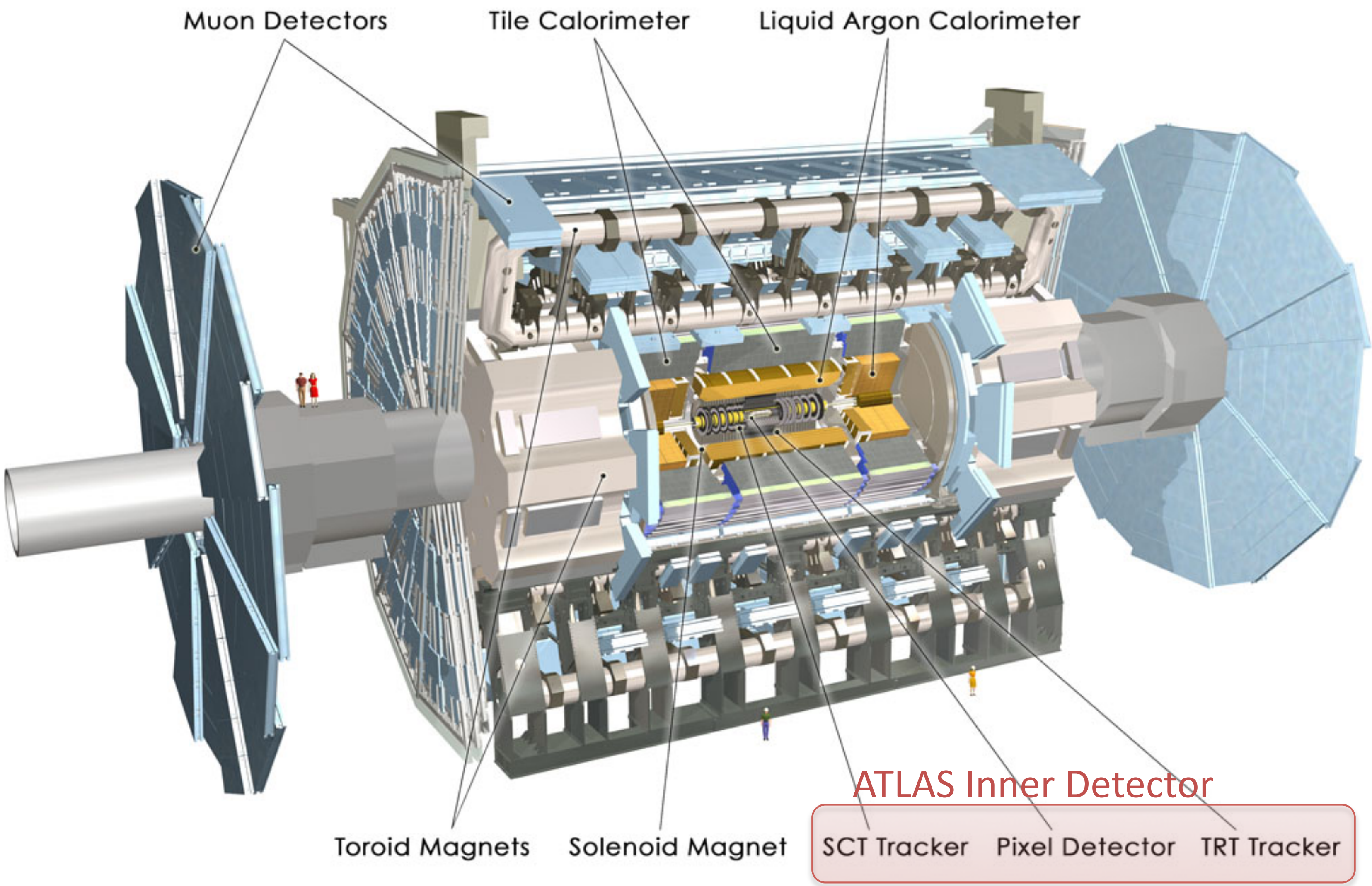


2011 pp run @ 7 TeV: 5.61 fb^{-1}

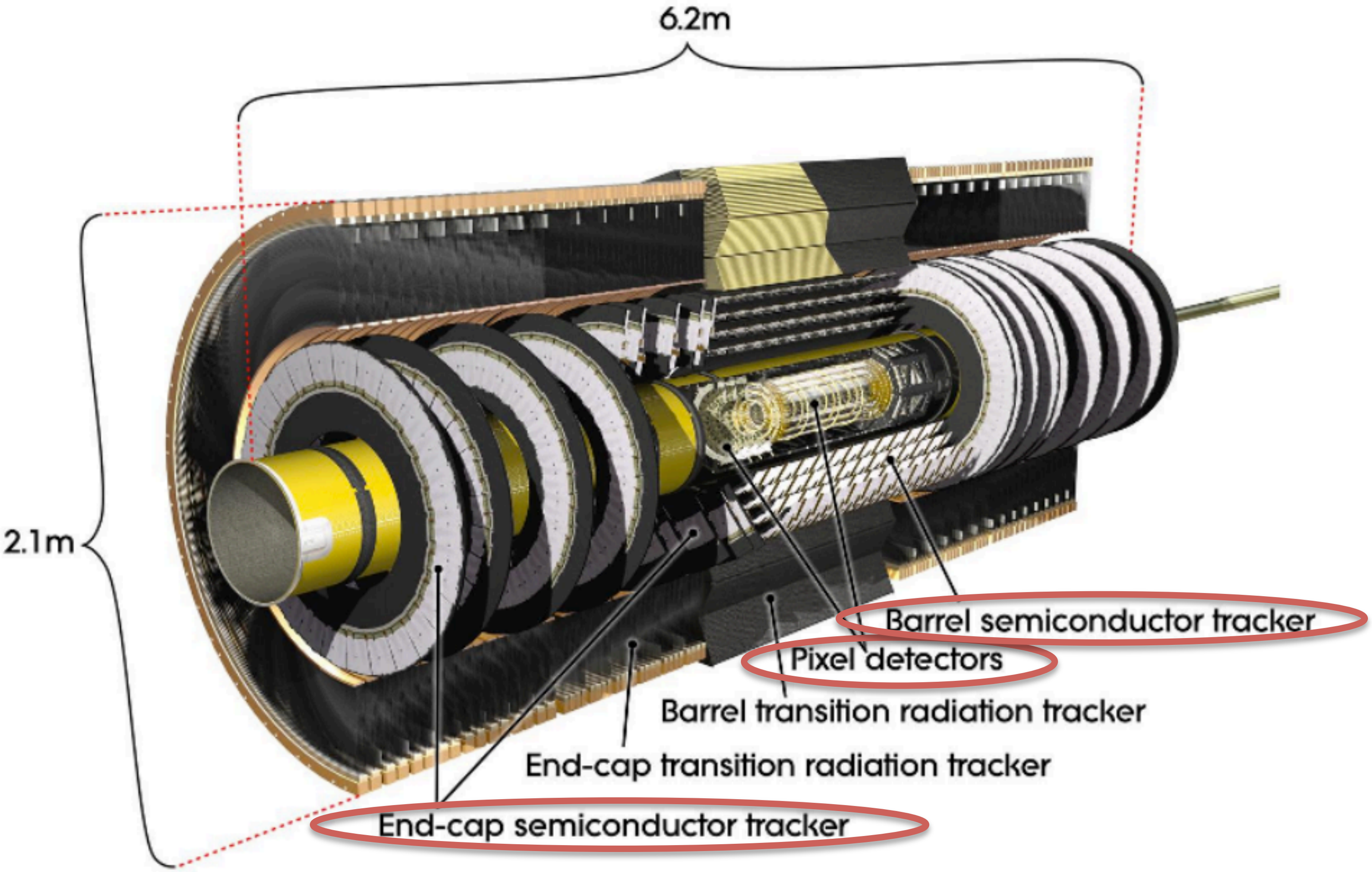
2012 pp run @ 8 TeV: 23.7 fb^{-1}

Total: ~(29.4 ± 3%) fb^{-1}

The LHC ATLAS detector



ATLAS Inner Detector



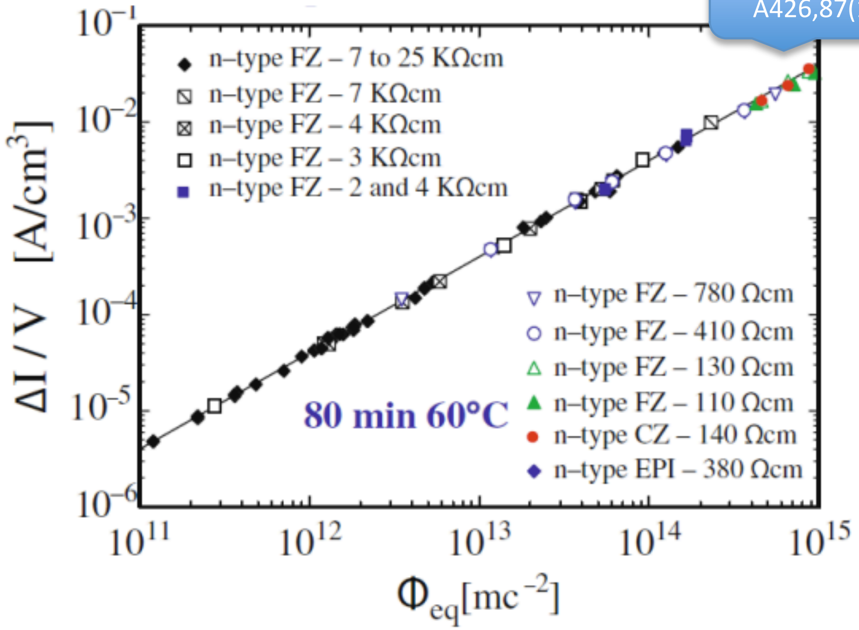
Covered in this talk:

- Pixel Detector
- SemiConductor Tracker (SCT)

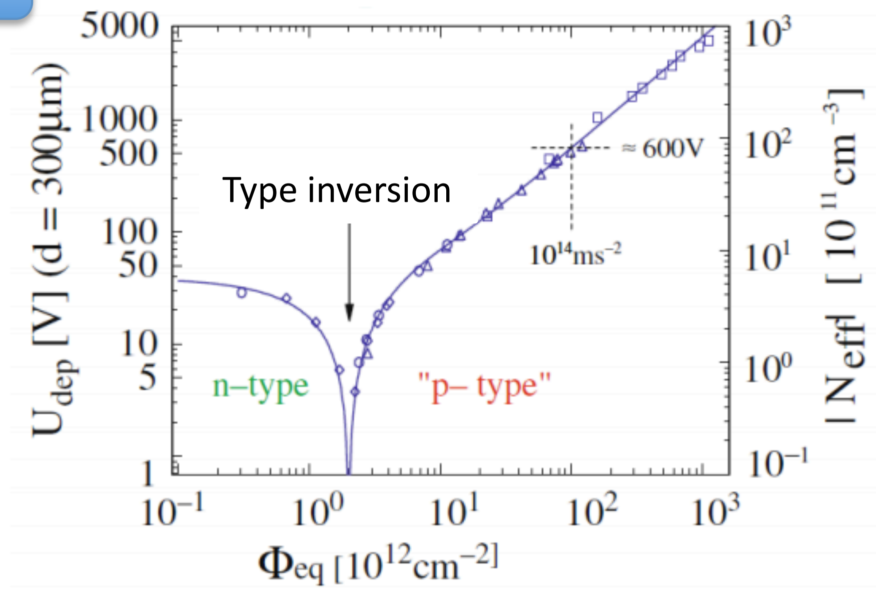
Leakage currents in silicon

Leakage current

N.Moll *et al*, NIM A426,87(1999)



Depletion voltage



Current measurements:

- Based on the phenomenology developed by G. Lindstrom with M. Moll and E. Fretwurst

$$\Delta I = \alpha \cdot \Phi_{eq} \cdot V$$
$$\alpha(20^\circ C) = (3.99 \pm 0.03) \cdot 10^{-17}\ \mathrm{A/cm}$$

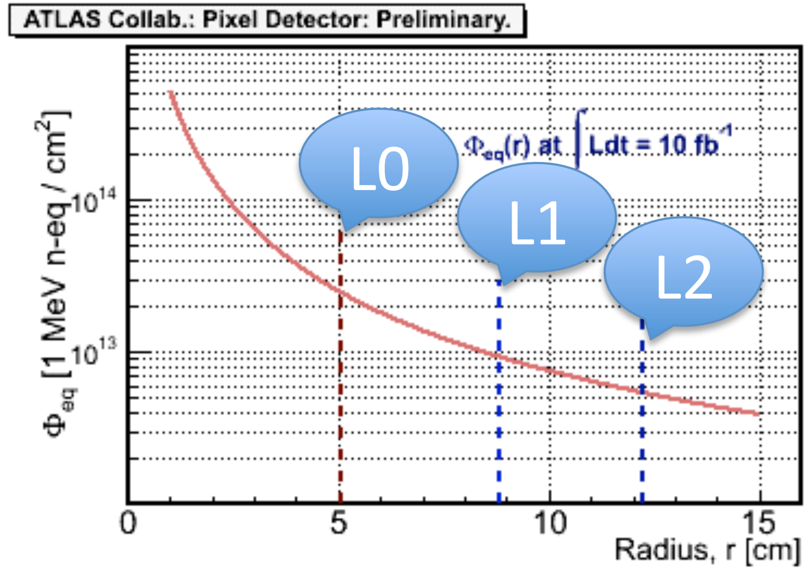
- Observed a universal behavior for silicon sensors: the increase in leakage current w.r.t. the one before the irradiation is proportional to the accumulated fluence

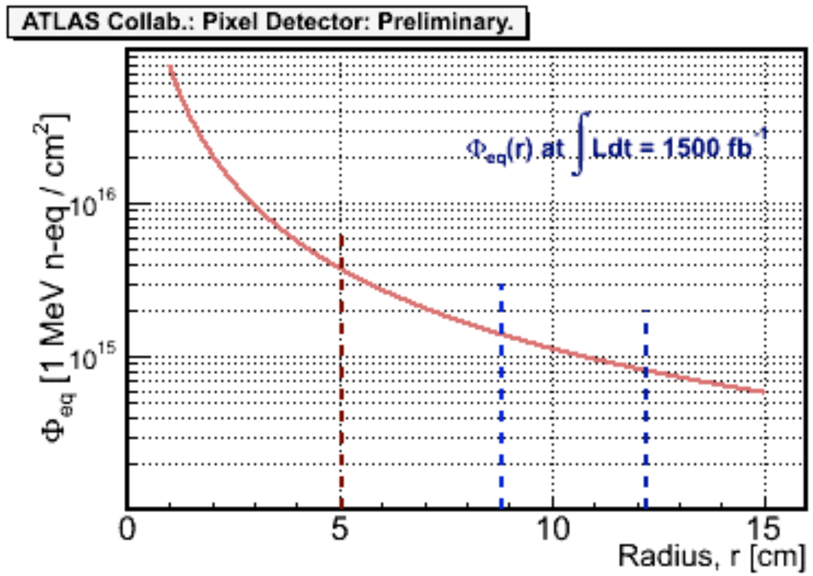
Leakage currents, ATLAS Inner Detector simulation

Use the fluence calculations in ATLAS Inner Detector area made by ATLAS Radiation Task Force, CERN-ATL-GEN-2005-001
Latest update by Ian Dawson in
http://indico.cern.ch/conferenceDisplay.py?confId=52704

- 1 MeV n- equivalent $\Phi_{1MeV\text{-}eq}/1000\ fb^{-1}$
- LHC pp events with PHOJET+FLUKA
- The MC data fitted for r∈(2, 20)cm with
- Uncertainties of predictions:
  - pp-generator: ≈30%
  - Calculation of 1MeV n- eq. using damage factors: ≈50%
  - In total: ≈58%

- Use these parameterization to predict the fluences for Layer-0,1,2

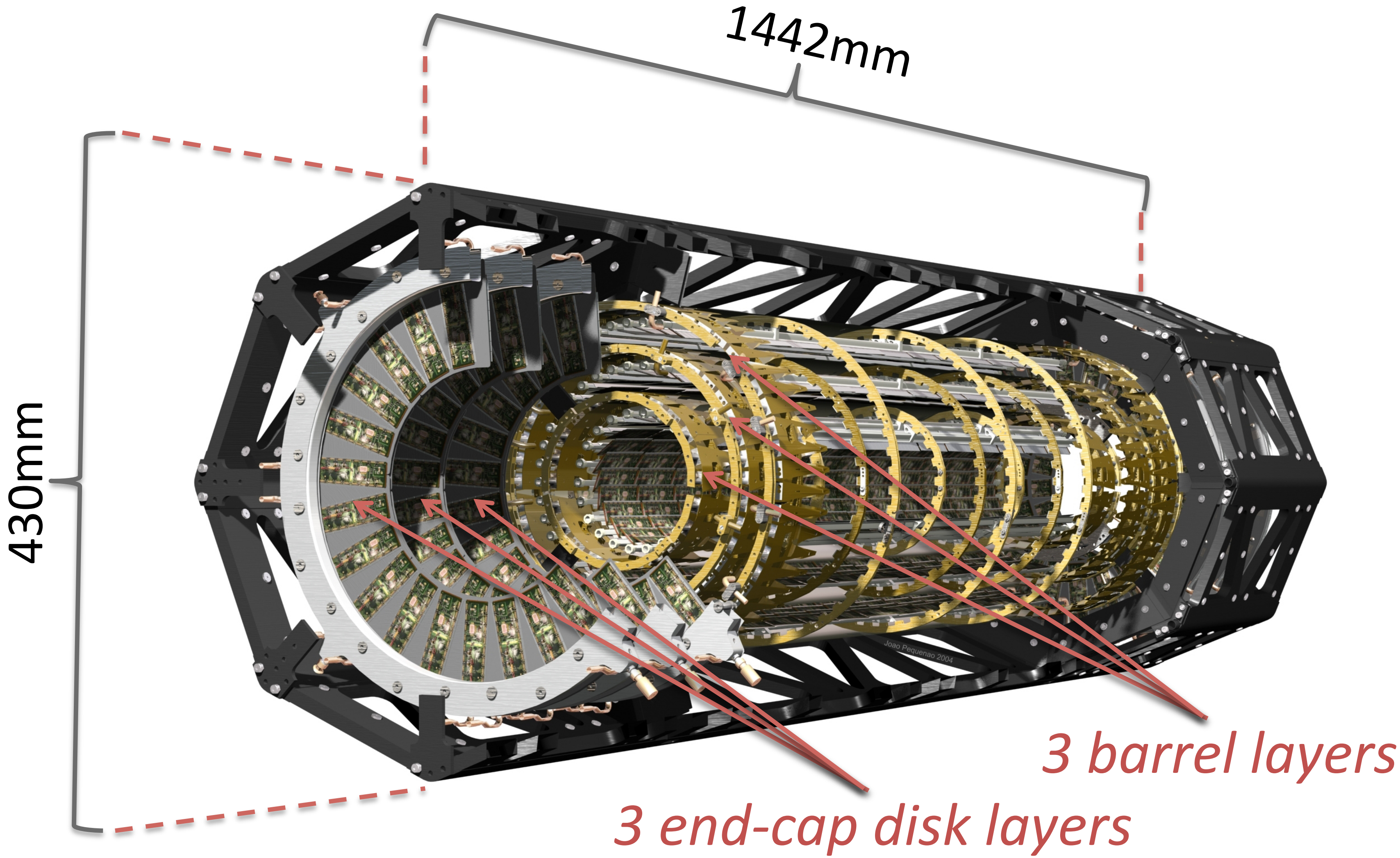




Radiation Damage

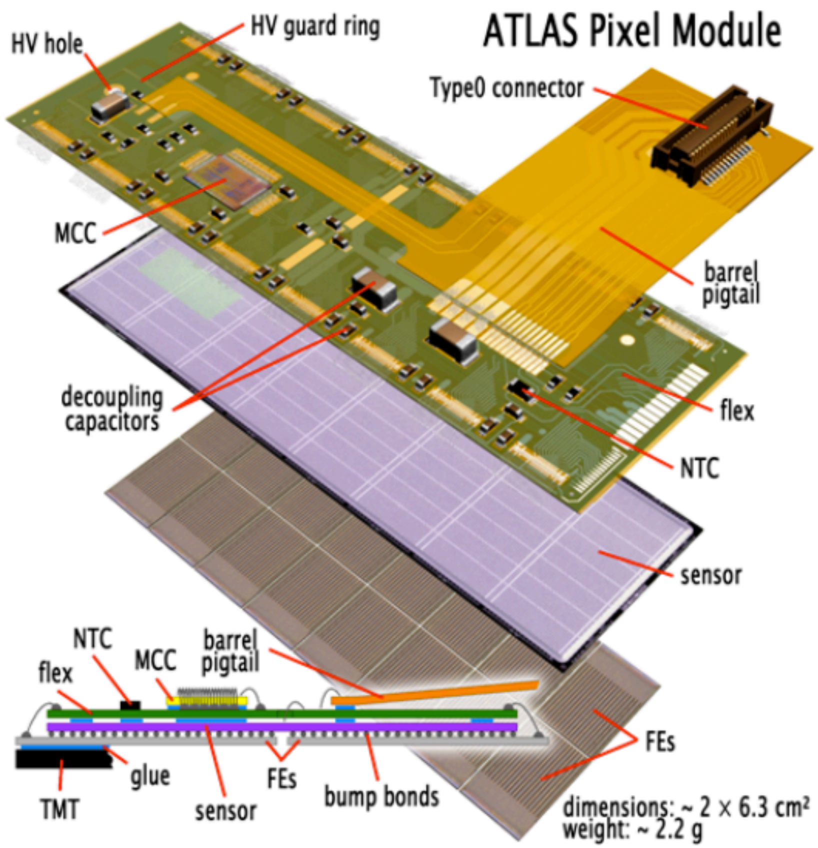
- Dominant radiation damage
  - *Displacement defects in a bulk*
  - *Due to Non-Ionizing Energy Losses (NIEL)*
  - *Flow of charged $\pi^{\pm}$ from ATLAS Interaction Point*
- Increases a reverse leakage current → increased power consumption
- Degrades charge collection efficiency → degrade hit efficiency and track resolution
- Changes the effective doping concentration → depletion voltage will increase
- Particle Fluence
  - *$\Phi[cm^{-2}]$= N (neutron, E=1MeV)/1cm^2 of detector area*
  - *Expected: $\Phi[cm^{-2}] \sim \int Ldt\ [fb^{-1}]$*
  - *The amount of fluence is a main factor contributing to the radiation damage*
- The level of the leakage current reveals an amount of the radiation damage contained in a detector volume
  - *Strongly depends on the particle fluence through a detector area*
  - *Temperature dependent*

ATLAS Pixel Detector (1)



ATLAS Pixel Detector (2)

- Pixel sensor consists of 256±3 μm thick n-on-n bulk
- Each sensor has 46080 channels
  - *readout by 16 FE chips with zero suppression*
  - *combined into 1 module: 6.08x1.64cm² area*
- Total: 1744 nearly identical modules; 1.7m² area
- Radiation tolerance:
  500 kGy/ 10^{15} 1MeV n_{eq} cm^{-2}
- Average operational T= -13°C, with evaporative C3F8 cooling integrated in the local support structures
- V_{bias} = 150 (600 ISEG max) V



Readout:

- *Deposited charge via ToT*
- *MCC builds module event.*
- *Data rate of 40-160MHz depending on layer.*

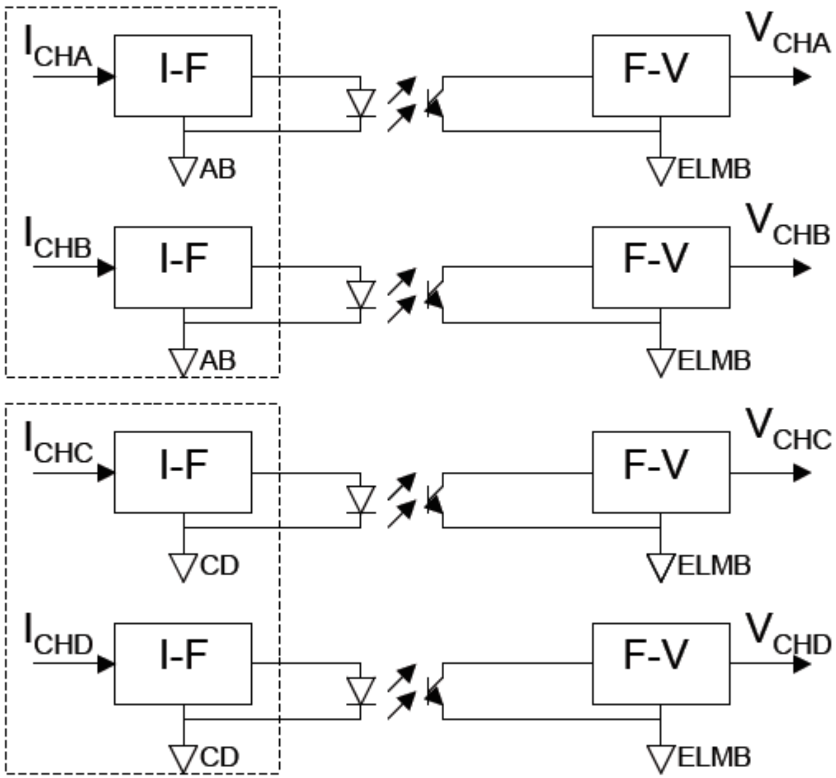
Technical solution in Pixel: HVPP4 (1)

- High Voltage Patch Panel 4 (HVPP4) or connectivity point distributing HV into the ATLAS Pixel Detector
  - Fan in/out point between the HV power supply and cables carrying the HV to/from detector and other patch panels
  - Location: racks in US(A)15 ATLAS Detector caverns
  - High Voltage (HV) service is to bias the silicon pixel sensors at the heart of Pixel Detector
- *ISEG* Power Supply channel: $V_{DC} \leq 700V$, $I \leq 4mA$
  - Distributes HV with the modularity 1 HV Power Supply (*ISEG*) channel to 6/7 pixel modules
  - Modularity should be possible to be reconfigured to 1 *ISEG* channel to 2/3 pixel modules once the leakage current exceeds the *ISEG* specifications
- HVPP4 system provides the reconfigurable patch panel between HV cables coming from Pixel detector (PP1) and ISEG HV channels

Technical solution: HVPP4 (2)

- HVPP4 system includes the Current Measurement Boards to monitor the leakage current for each individual pixel sensor
- The Current Measurement Board should be able to measure the leakage currents in a wide range: 0.01µA ... 1mA, ~10^5 range
- The measured current values are digitized, transmitted via CANbus to the DCS by CERN developed DAQ board ELMB.
- PVSS software is reading out the data from ELMB boards and downloading the data to PVSS/COOL database (large DCS storage)

Current Measurement Board (1)



- Circuit is a current-frequency converter
- Optically coupled to a freq-voltage converter.
- 4 circuits per board
- 2 digital readout channels per one analog channel; with different AD/DC gain
- Isolated in pairs of channels from each other and from the readout system

Current Measurement Board (2)

- Range of input currents to be measured: (0.05 μA , 2 mA), ~0.4x10^5
- Output voltage: 0 - 5 V_{DC} compatible with ELMB digital board
- Isolation: isolated in pairs of channels from each other and from the readout system
- Frequency of operating circuit:
  < 100 KHz
- Interface: attached to HVPP4 Type II board

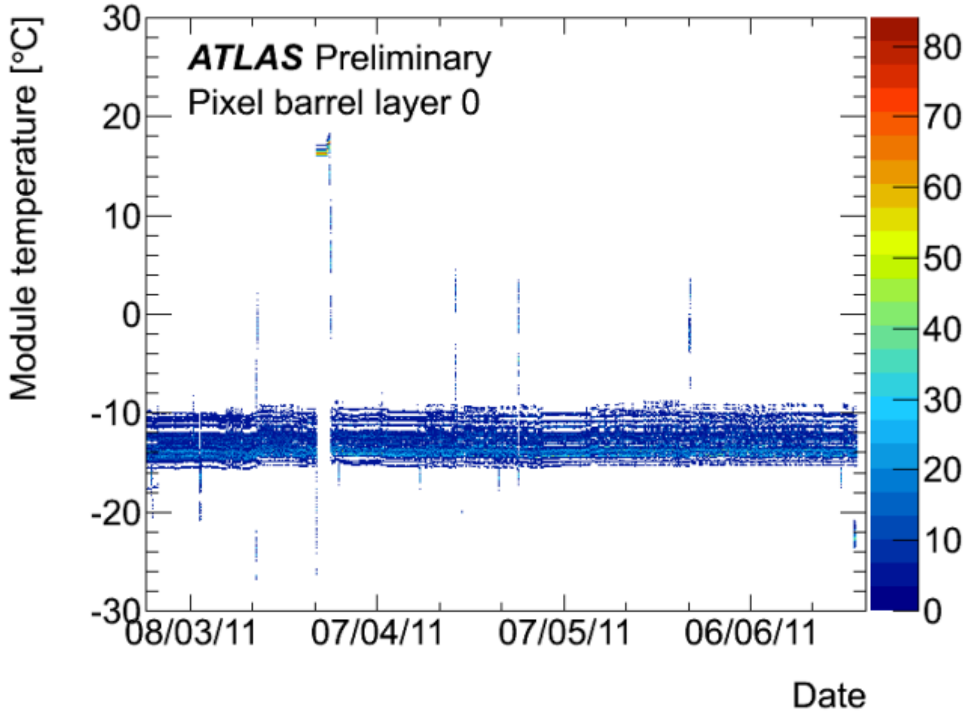
- The precision of CMBs is about 10 nA
- The precision of Pixel power supply current monitoring is about 80 nA

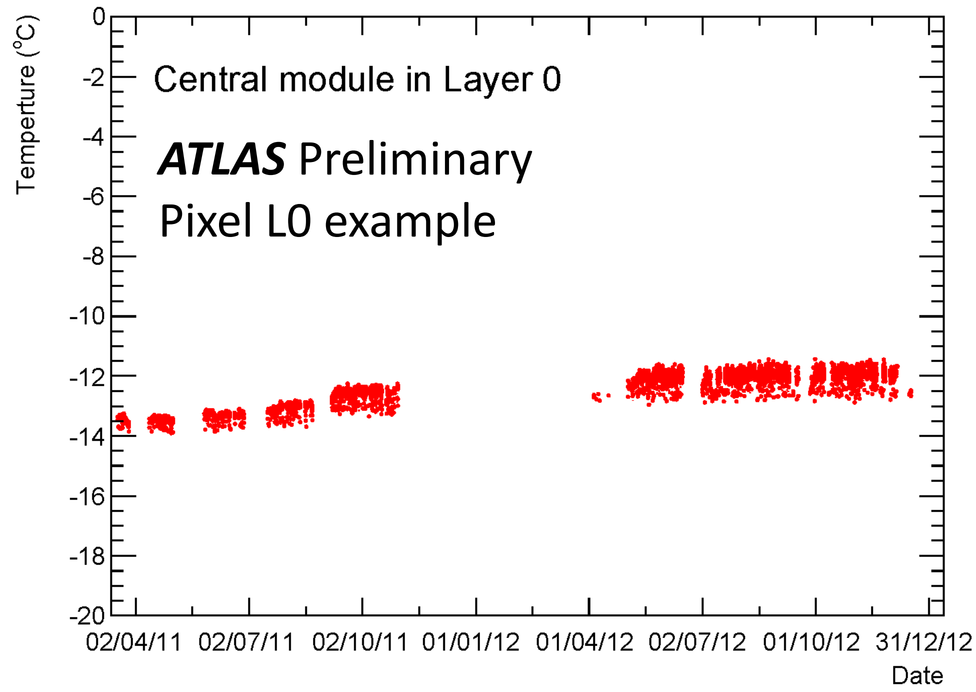
Current Measurement Board (3)

- Current status of the ATLAS HVPP4 system:
  - Layer 0 (innermost): 21 CMBs installed; 84 L0 pixel modules instrumented;
  - Layer 1 (midst): 16 CMBs installed; 64 L1 pixel modules instrumented;
  - Layer 2 (outermost): 16 CMBs installed; 64 L2 pixel modules instrumented;

- Hardware installation was completed during June 2012 LHC/ATLAS technical stop

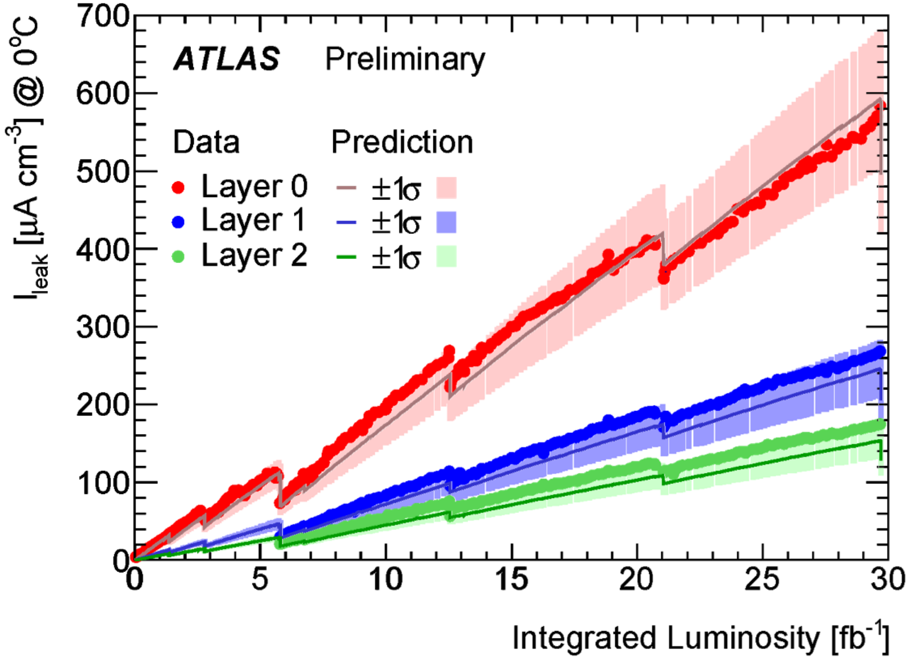
Temperature of pixel modules

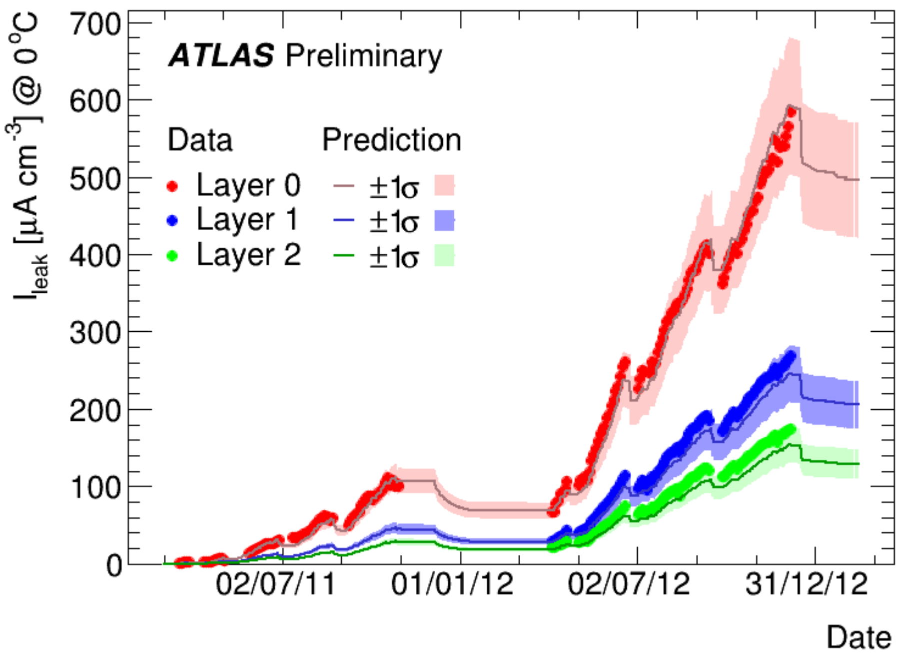




- Temperatures of 2011 (right) and 2012 (left) are almost constant (about -13 ^{o}C), fluctuations due to cooling cuts (technical stops, winter shutdowns) or various calibration scans.
- In our analysis we use temperatures measured per module.

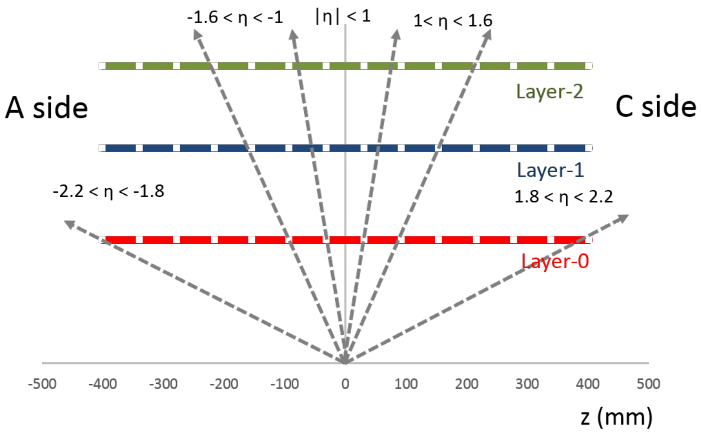
Leakage currents measured by the CMBs

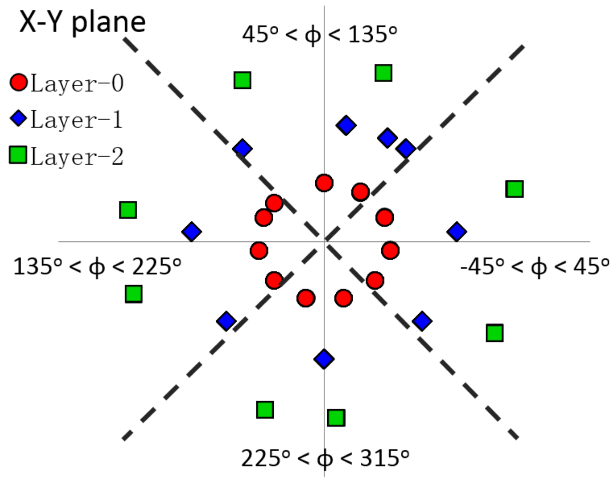


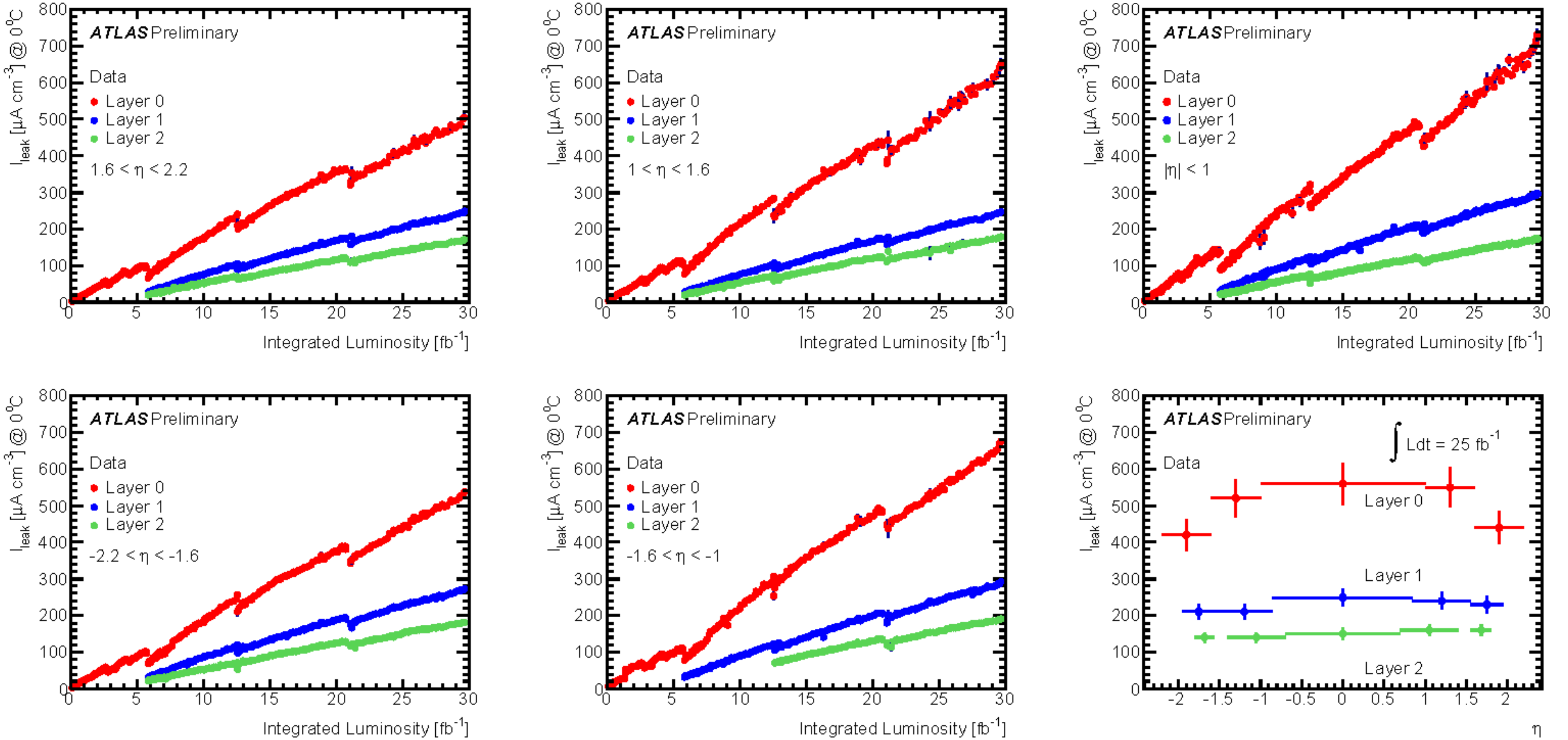


- Layer 0, 1, 2 leakage currents per module measured with the CMBs. Corrections to modules temperature included. Left plot: leakage currents versus the LHC integrated luminosity. Right plot: leakage currents versus time. Annealing periods are clearly seen. Currents are normalized to 0°C.
- Plots are compared to Hamburg/Dortmund model predictions. Prediction is based on luminosity profile and expected fluence by barrel layer from Phojet + FLUKA simulations, scaled by the silicon volume. Code by Olaf Krasel, Jens Weber, Daniel Muenstermann, TU Dortmund/CERN.
- Plots include (almost negligible) correction for beam induced ionization current:
  - $I_{hit} = N_{bunches} * \nu_{LHC}$ * pixel hit occupancy * charge per hit.

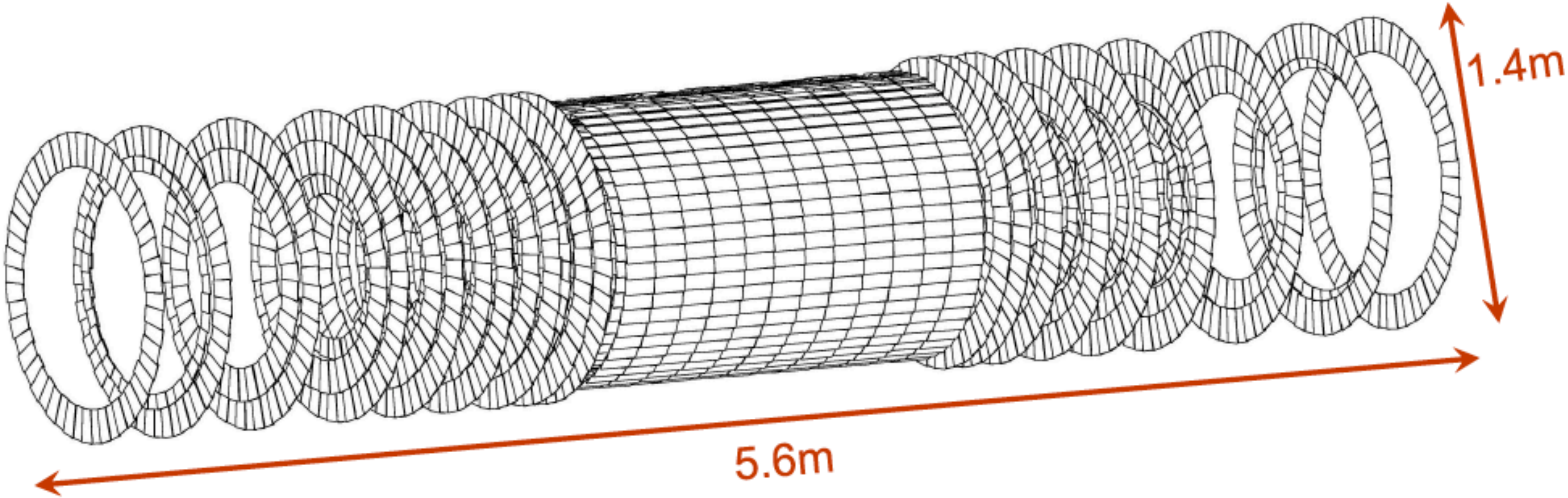
Preliminary study of the η/ϕ distributions







SemiConductor Tracker (SCT)



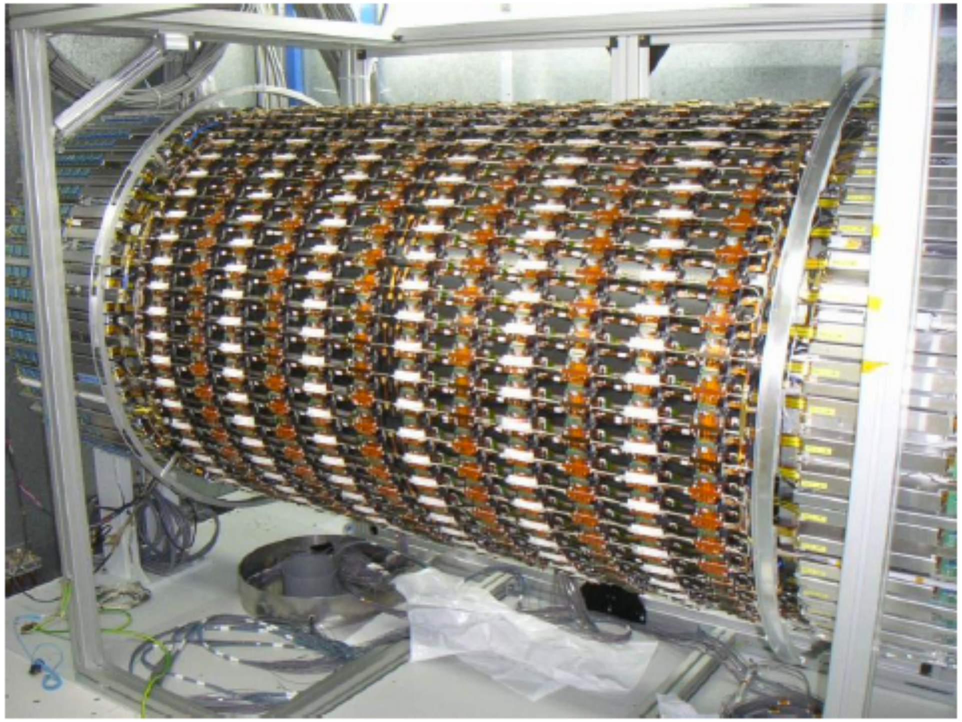
- 61 m^2 of silicon with 6.3 million readout channels
- 4088 silicon modules in 4 barrels and 18 end-cap disks
- C3F8 Cooling, operating temperatures -7°C to +6°C

SCT Sensors

- Single sided p-on-n
- 285mm thick
- 768+2 AC-coupled strips

Barrel (4 layers, |Z|<80.5cm)

- 8448 barrel sensors (4/module)
- 64.0 x 63.6mm
- 80mm strip pitch
- 100% Hamamatsu Photonics
- Radii:
  - 29.9cm (384 modules @ -2.0^{o}C)
  - 37.1cm (480 modules @ -2.0^{o}C)
  - 44.3cm (576 modules @ -1.3^{o}C)
  - 51.4cm (672 modules @ +6.0^{o}C)



Endcap (9+9 layers)

- 6944 wedge sensors
- 56.9-90.4mm strip pitch
- 82.8% Hamamatsu Photonics 17.2% CiS (some oxygenated)

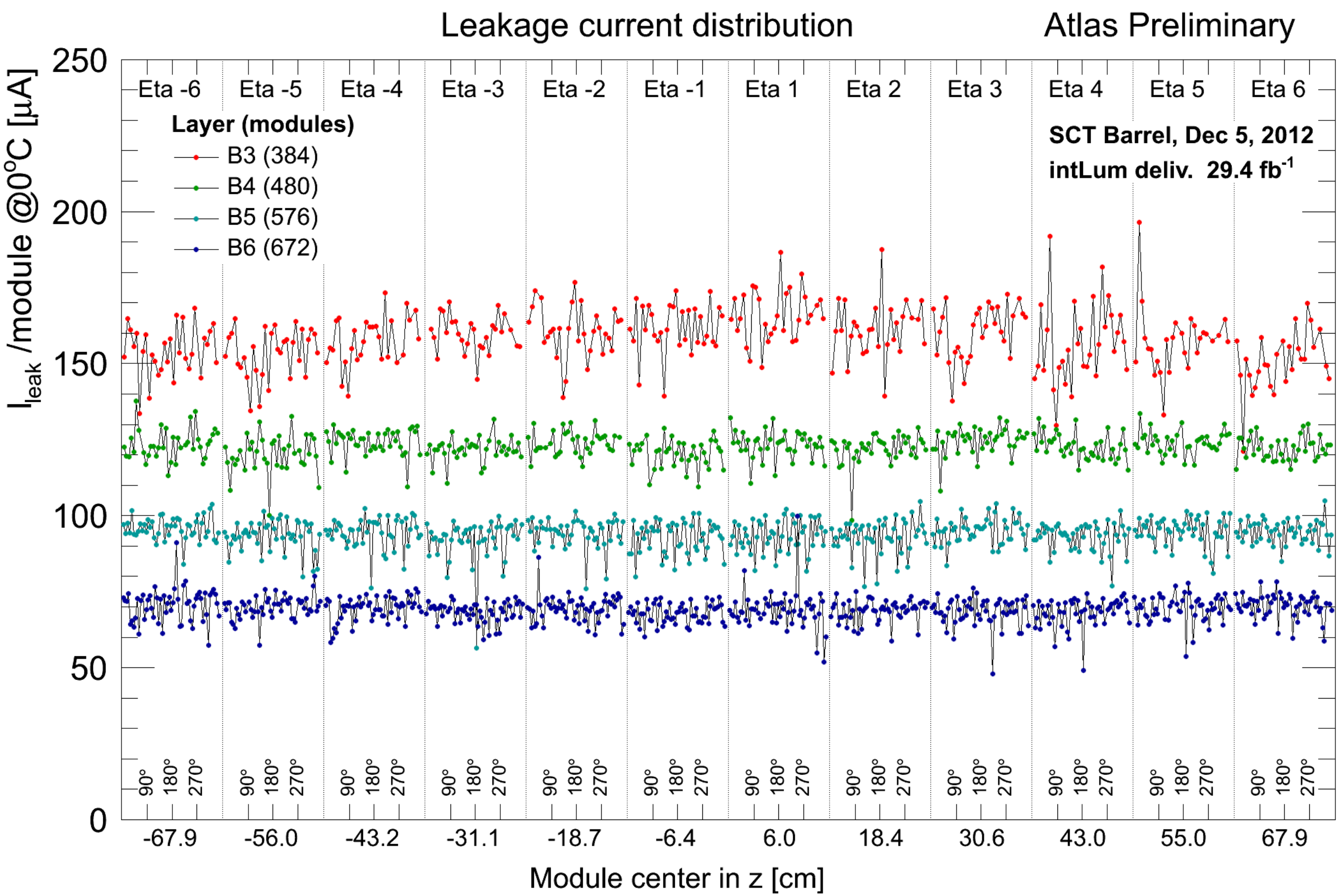
Leakage currents in SCT

- Measured by the HV (150V) power supply.
- Normalized to 0^{o}C in the same way as for the Pixels:

$$\frac{I(T_{0°C})}{I(T_{sensor})} = \left(\frac{T_{0°C}}{T_{sensor}}\right)^2 \exp\left(-\frac{E_{gen}}{2k_B}\left[\frac{1}{T_{0°C}} - \frac{1}{T_{sensor}}\right]\right)$$

- E_g=1.21 eV, following the RD50 recommendation.
- Temperatures measured by sensor.
- 17.5^{o}C is used as a value for the shutdown periods.

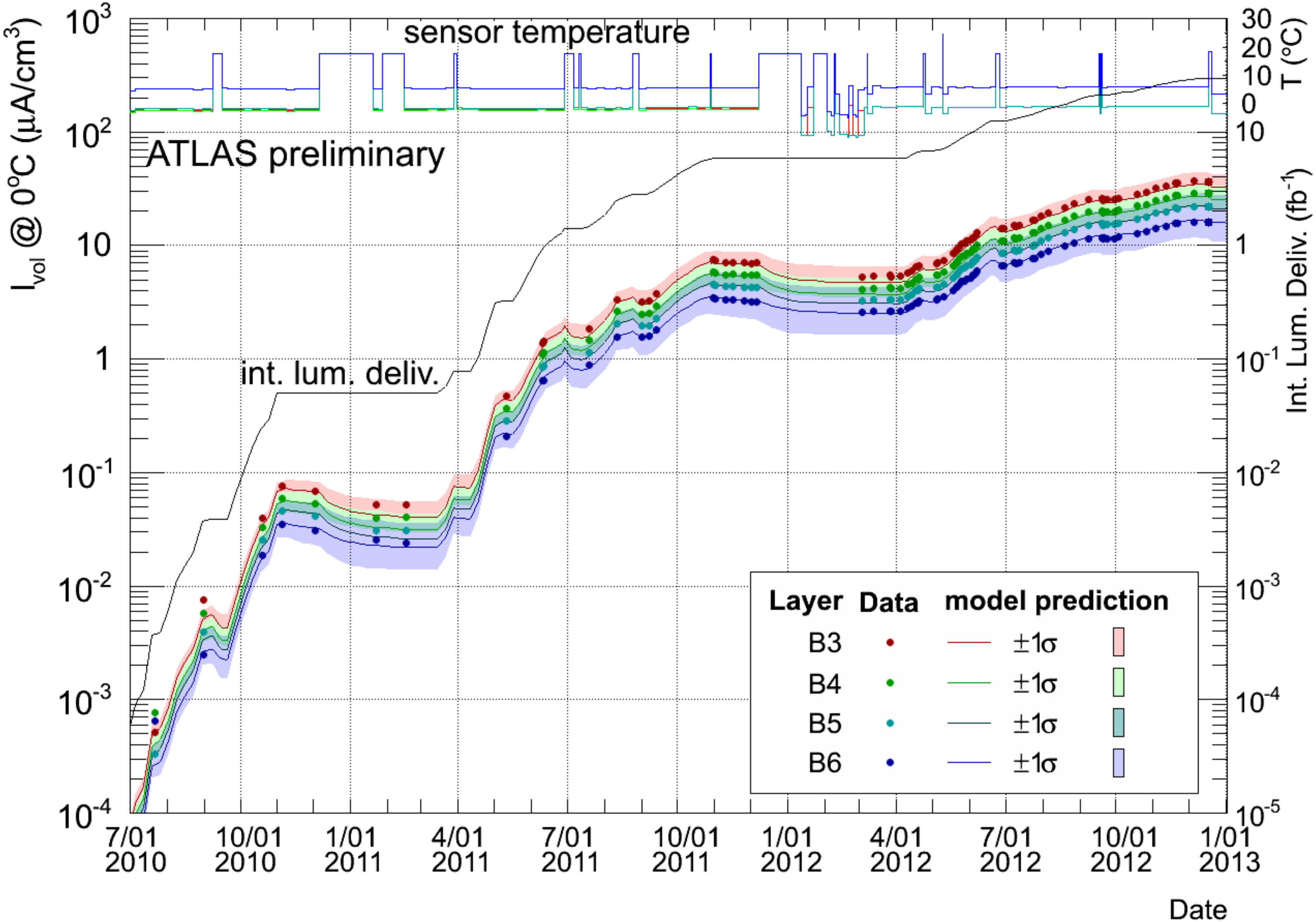
SCT leakage currents distribution



- Example: one day in December 2012.
- Barrel modules, 97.5% okay (voltages, temperatures).
- Modules grouped 12 groups at the same z (beam direction) position.
- Good uniformity in η/z is observed (except the B3, central part, ~7% excess)

Models used for the SCT leakage current predictions

- Hamburg/Dortmund model (same as for Pixels).
- Harpers model (R. Harper, Thesis of University of Sheffield, Oct. 2001).
- FLUKA 7 TeV simulation (same as for Pixels).
- Total integrated luminosity (including non-stable beam conditions).
- Uncertainties of the models are produced by varying parameters $\pm 1\sigma$, assuming independency (added in quadratures).
- FLUKA simulation uncertainties not included.



Nice agreement between the data and the model predictions. The Harper model predicts ~15% less, but within uncertainties. There are no model parameter adjustments.

Conclusion

- ATLAS has a dedicated hardware to monitor the radiation damage effects in the Pixel detector via the leakage currents. The precision is 10 nA (Current Measurement Boards) and 80 nA (Power Supplies).

- Clear signs of radiation damage and annealing periods are seen at the pixel level, with a leakage current increase of about [8-16] nA per 10 fb^{-1} integrated luminosity for the innermost layer (5cm from the beam).

- Measurements with Current Measurement Boards are consistent with the output of the *ISEG* Power Supplies and with Hamburg/Dortmund model predictions.

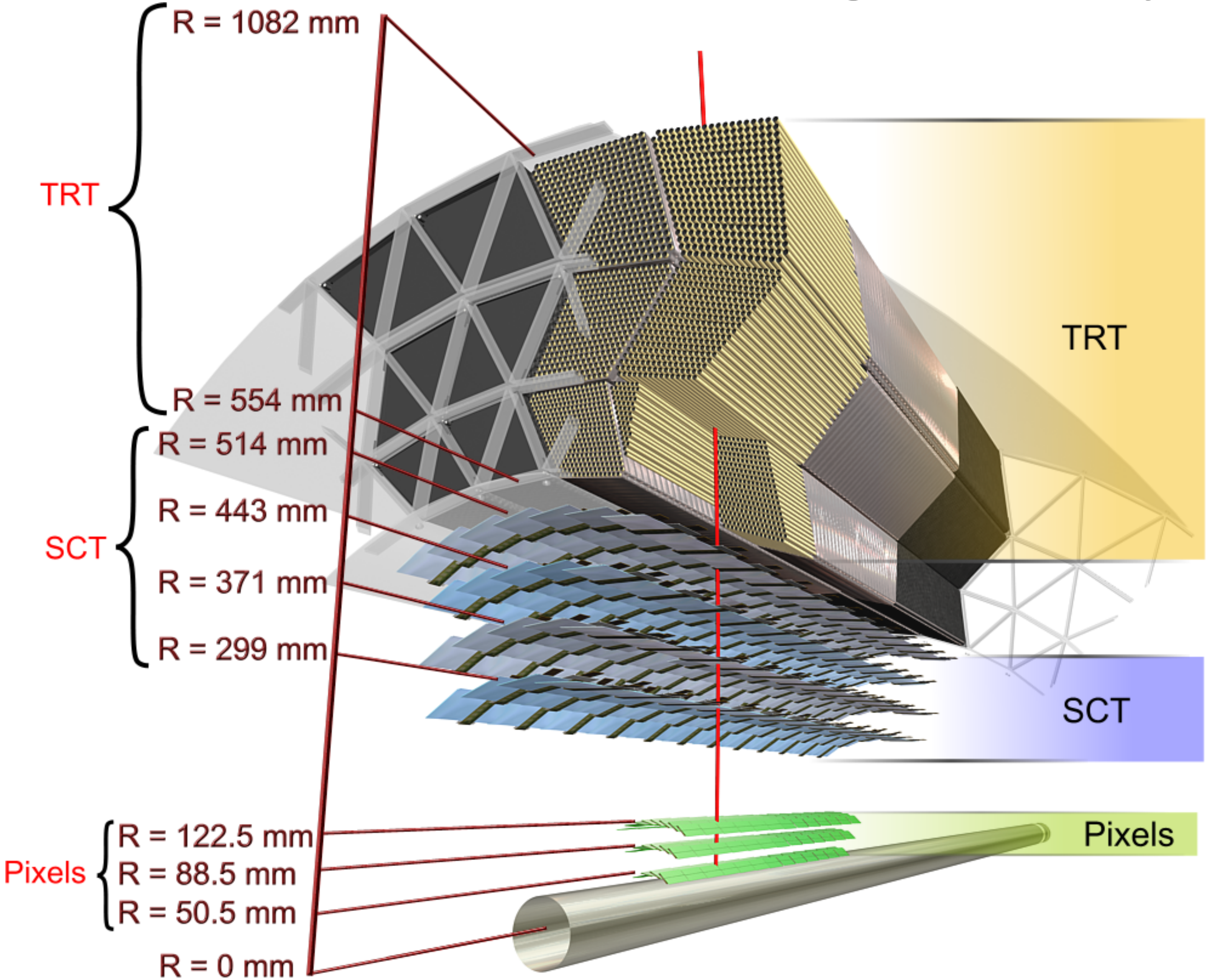
- SCT leakage currents were constantly monitored with the 150V power supplies, as well as SCT modules temperatures. Good uniformity in z is observed in the barrel layers.

- Nice agreement is observed with Hamburg/Dortmund and Harpers models for the SCT, within 1σ (20%) without parameter adjustments, meaning that the observed currents are mostly due to bulk generation current, the leakage current models with self-annealing terms are well applicable and the ATLAS flux simulation is quite reasonable.

- Both ATLAS Pixel and SCT Papers are in the final stage of approval and soon to be public.

BACKUP

ATLAS Inner Detector geometry



Pixel Lifetime

- By comparing current with integrated luminosity
  - Fit current *I vs* $\int Ldt$ with linear function, *I* is temperature-corrected
  - The fit can predict the amount of current *I* the pixel modules will draw after a certain $\int Ldt$ collected with the ATLAS Pixel Detector
- Contrary to CDF SVX II, the ATLAS pixel S/N ratio is NOT an issue: the lowest noise level determined by the sensor's design
- However high enough leakage current in ATLAS
  - can lead to excessive power and thermal runaway which basically limits the bias voltage that can be applied
- A single ISEG channel can sustain the current

$$I_{ISEG} \leq 4000\mu A$$

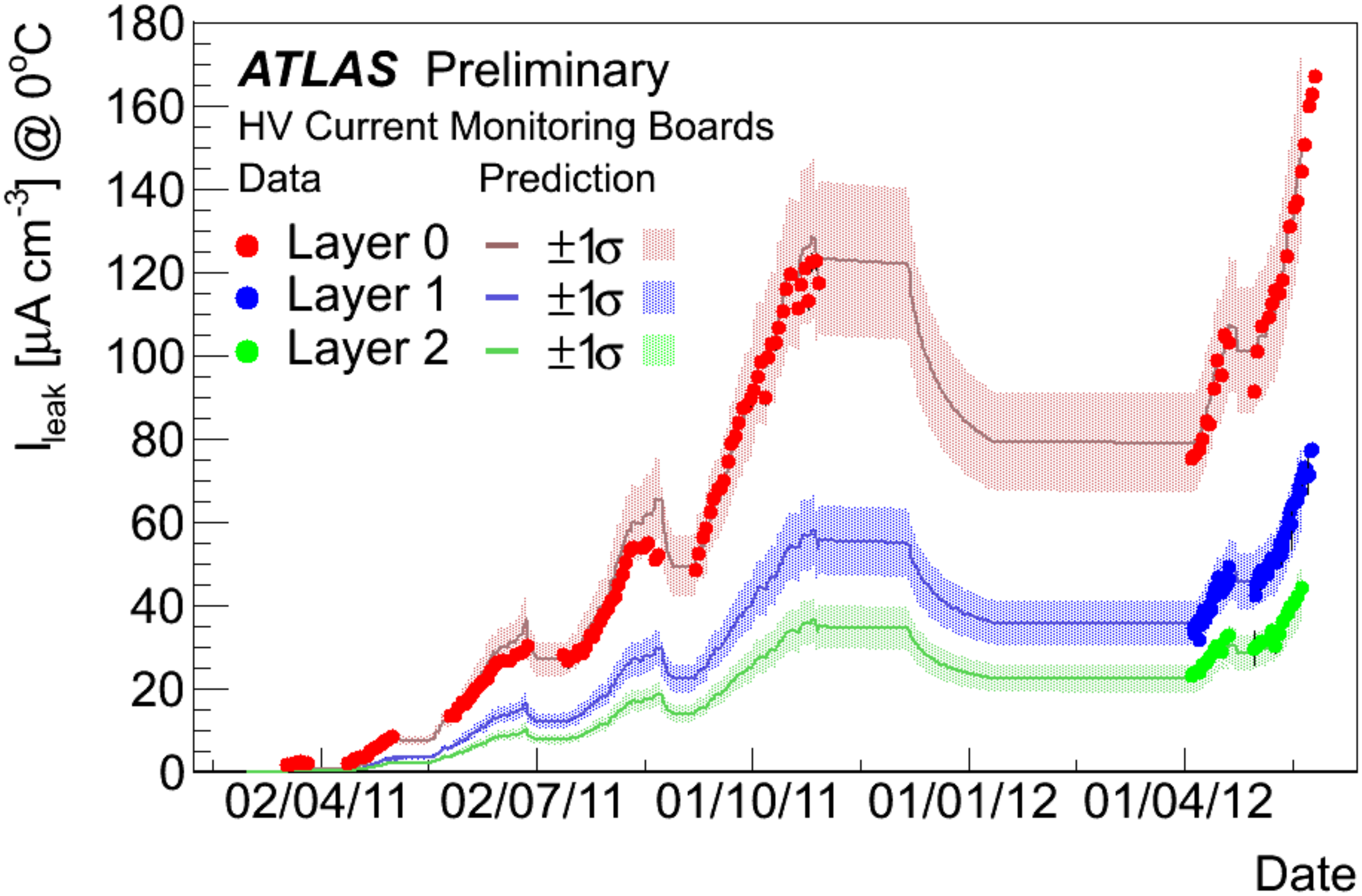
  - Initially 6/7 modules per ISEG channel
  - Max. current per sensor module is $I_{sensor} \leq 570...670\mu A$
- Two periods of a pixel sensor's life:

The first years, operated at full depletion. The end is determined:

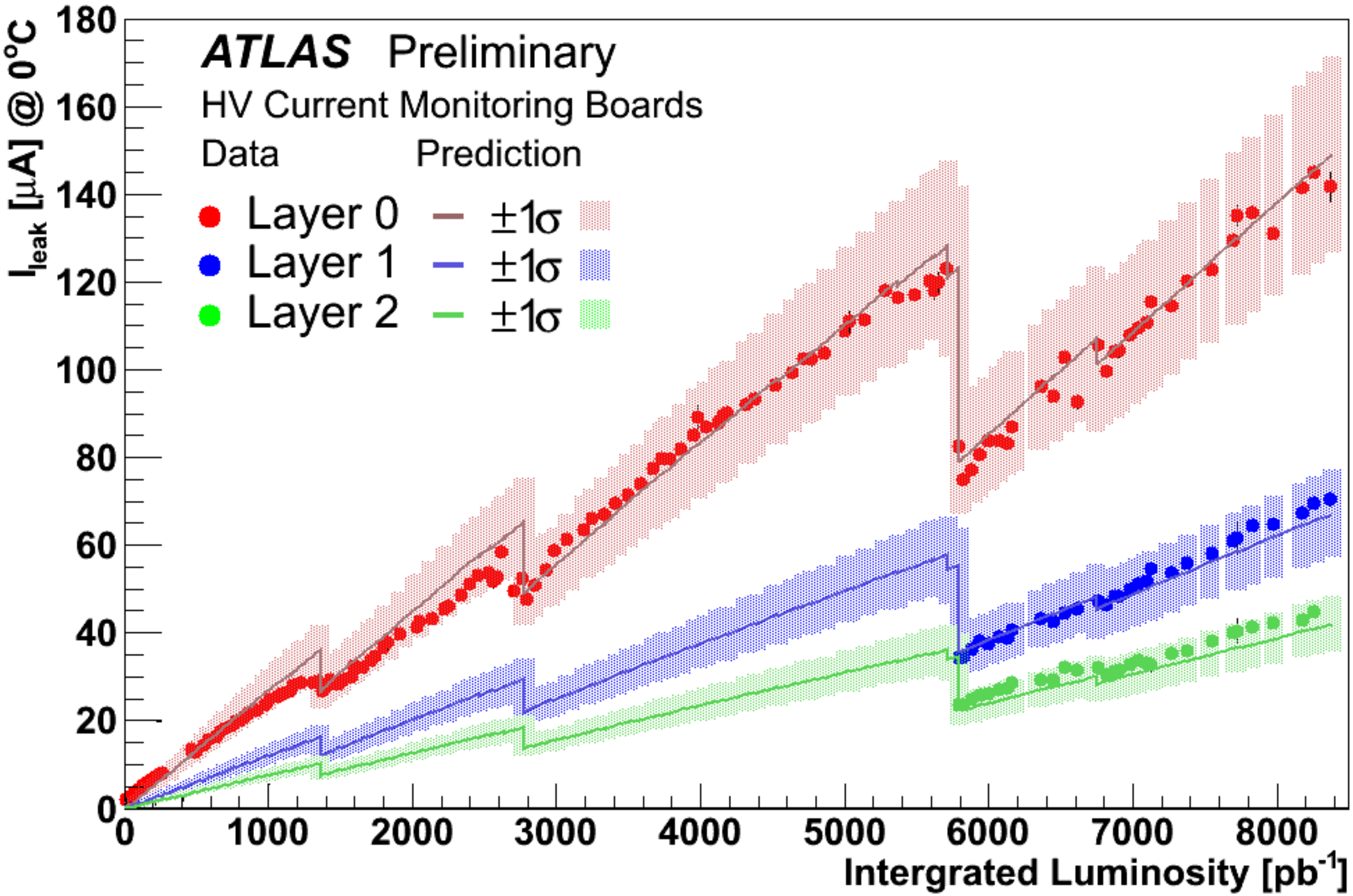
  - critical range of high currents causing thermal runaway and limiting bias voltage
  - or exceeding ISEG spec of $I_{ISEG} \leq 4000\mu A$
  - or exceeding ISEG spec on $V_{bias} \leq 600V$
- Later years of operation in partially depleted mode.
  - the sensor draws high current, still within the safety margin or at the maximum available bias voltage
  - but its pixels' hit efficiencies gradually diminish with $\int$ Ldt (or absorbed $\Phi_{1MeV\text{-}eq}$)

ATLAS Pixel Detector (3)

Barrel region					End-Cap region				
Layer number	Mean Radius, mm	Number of Modules	Number of Channels	Active Area, m^2	Disk number	Mean *z*, mm	Number of Modules	Number of Channels	Active Area, m^2
0	50.5	286	13,176,880	0.28	0	495	48	2,211,840	0.0475
1	88.5	494	22,763,520	0.49	1	580	48	2,211,840	0.0475
2	122.5	676	31,150,080	0.67	2	650	48	2,211,840	0.0475
Total		1456	67,092,480	1.45	Total (both end-caps)		288	13,271,040	0.28



ATLAS Preliminary
HV Current Monitoring Boards
Data
Prediction
Layer 0
Layer 1
Layer 2
±1σ
±1σ
±1σ
I_{leak} [μA cm^{-3}] @ 0°C
180
160
140
120
100
80
60
40
20
0
02/04/11
02/07/11
01/10/11
01/01/12
01/04/12
Date



ATLAS Preliminary
HV Current Monitoring Boards
Data
Prediction
Layer 0
Layer 1
Layer 2
±1σ
±1σ
±1σ
I_{leak} [μA] @ 0°C
Intergrated Luminosity [pb^{-1}]
0
20
40
60
80
100
120
140
160
180
1000
2000
3000
4000
5000
6000
7000
8000