ATLAS Pixel Detector radiation damage monitoring with the High Voltage delivery system

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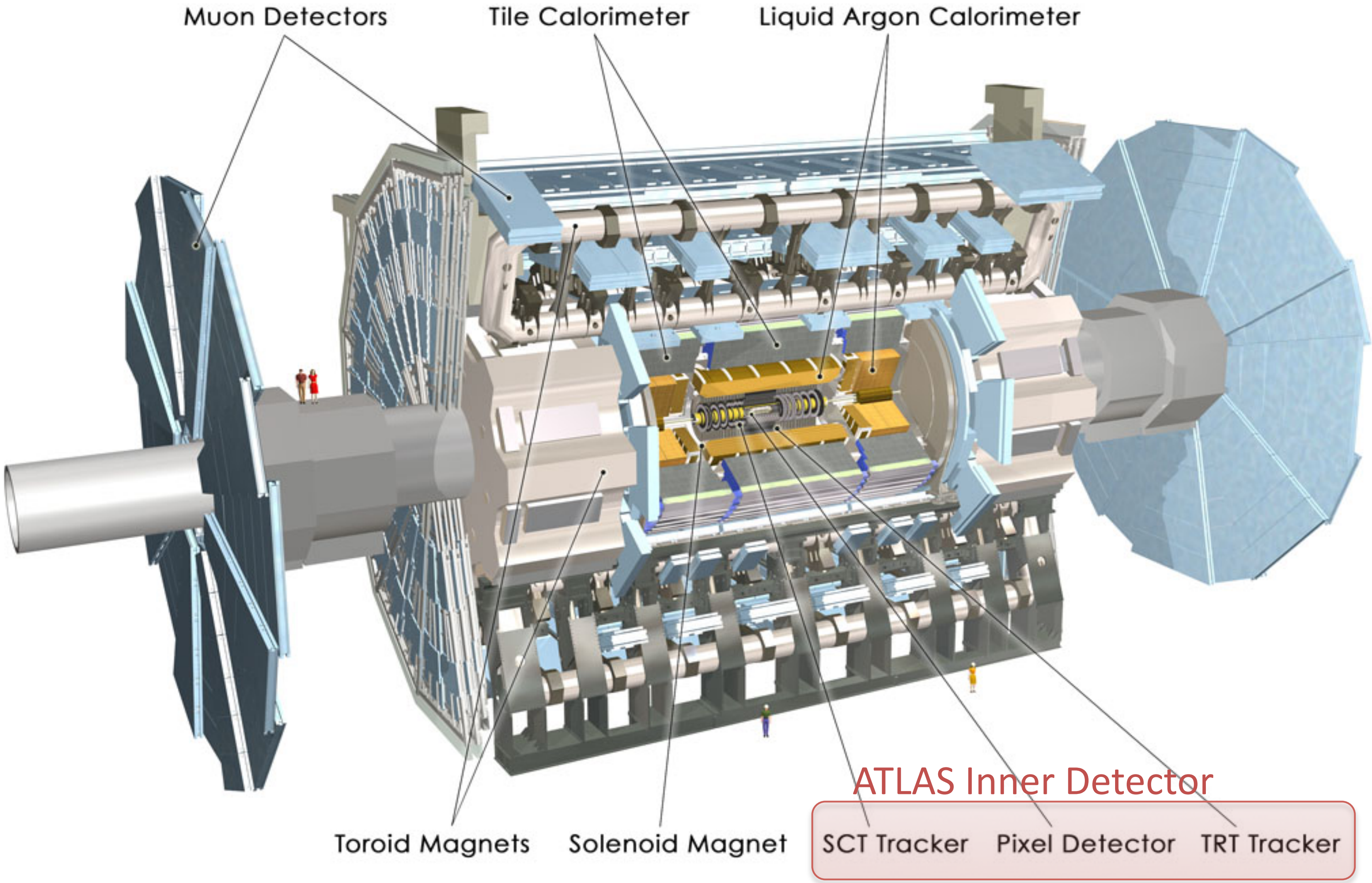
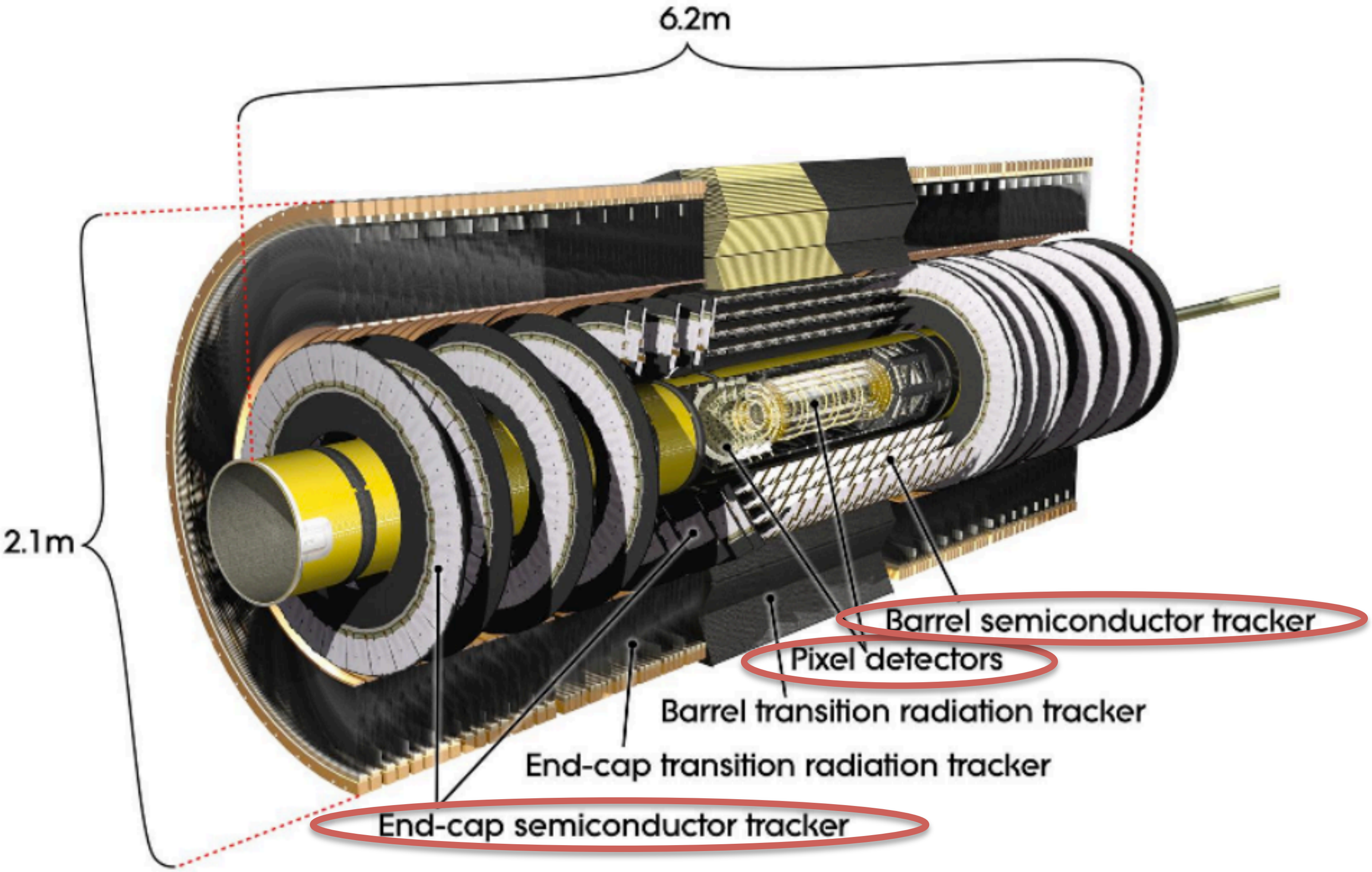
on behalf of ATLAS Radiation Damage Monitoring Group

The LHC ATLAS detector



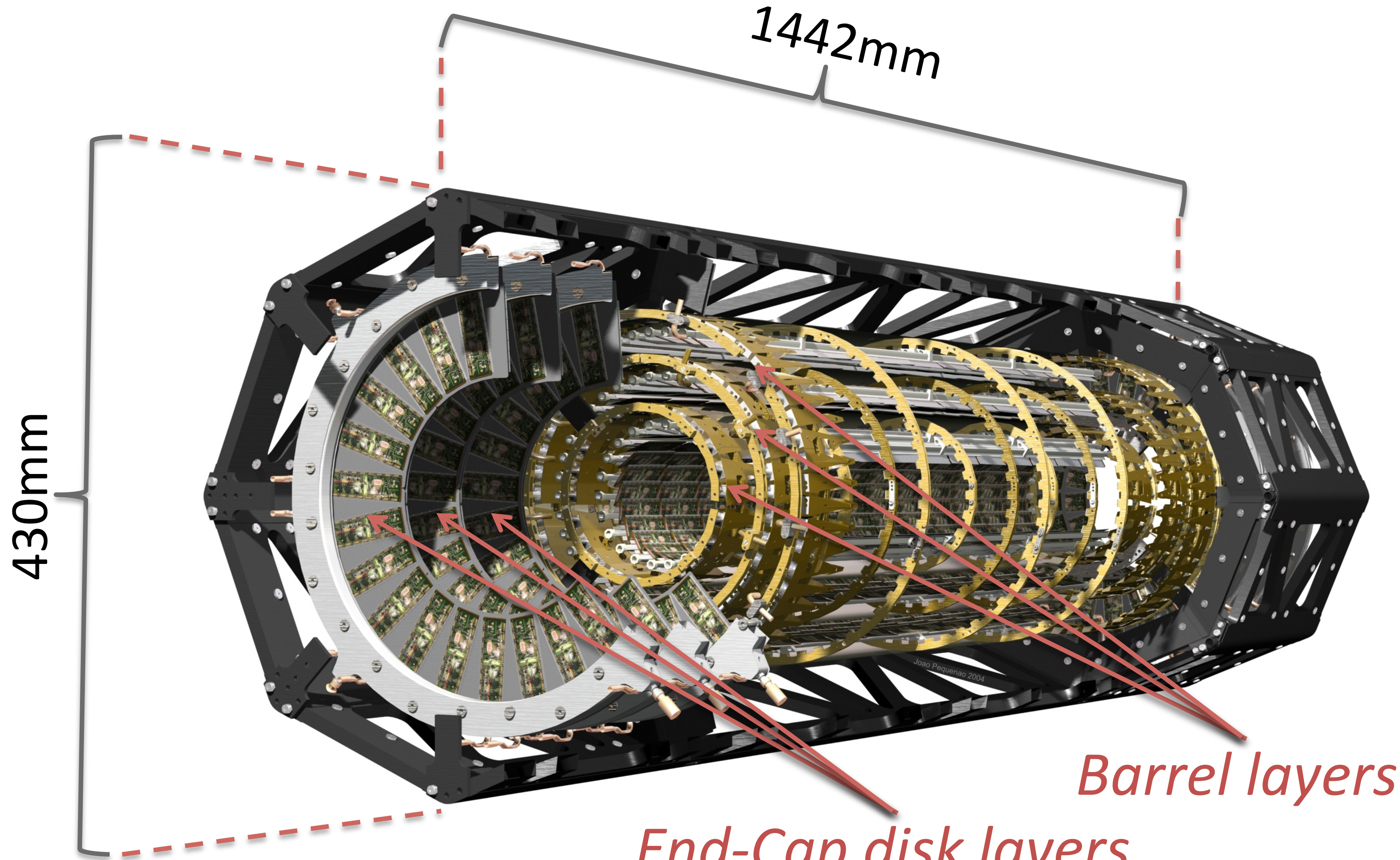
ATLAS Inner Detector



Other ATLAS ID talks on this conference:

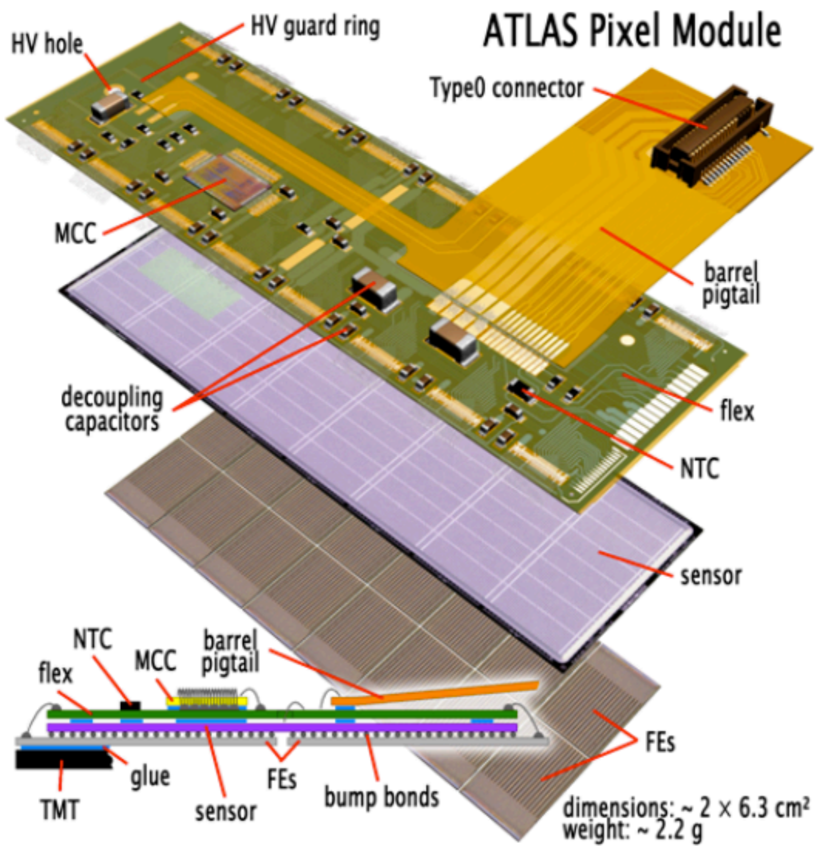
- Markus Keil "Leakage current measurements in the ATLAS Pixel Detector"
- Andre Schorlemmer "Measurements of the effective depletion voltage in the ATLAS Pixel Detector"
- Taka Kondo "Status of radiation damage of the ATLAS SCT detector"

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

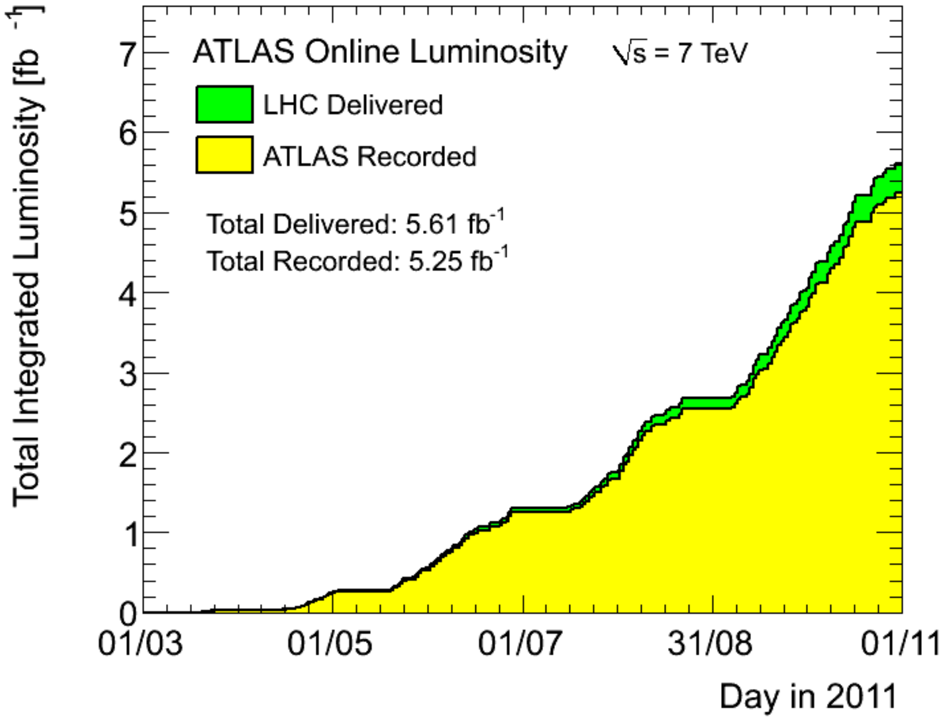


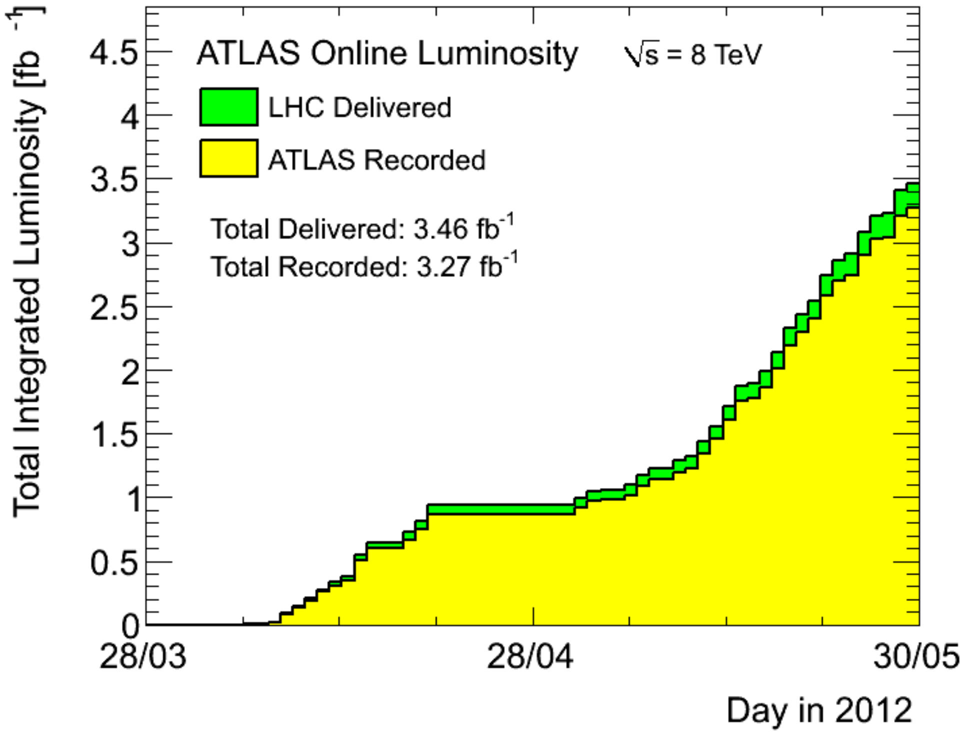
- More details in Markus Keil's talk today: "Leakage current measurements in the ATLAS Pixel Detector"

Readout:

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

LHC integrated luminosity delivered so far: ~9 fb^{-1}





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

2012 by May 29 @ 8 TeV : ~3.46 fb^{-1}

Total: ~9 fb^{-1}

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
- Layer 0 (innermost) is expected to undergo type-inversion after 10 fb^{-1} of integrated luminosity (with optimal annealing). We are close!
- 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*

Technical solution: HVPP4 (1)

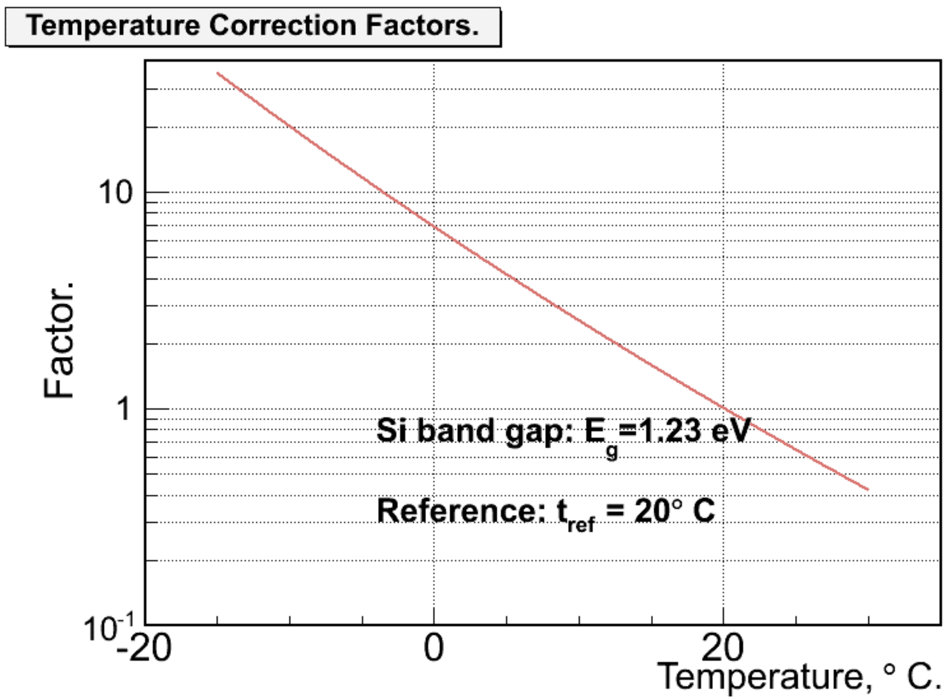
- High Voltage Patch Panel 4 (HVPP4) or connectivity point distributing HV into the ATLAS Pixel Detector
  - Fan in/out point between the HV power supply and cables carrying the HV to/from detector and other patch panels
  - Location: racks in US(A)15 ATLAS Detector caverns
  - High Voltage (HV) service 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)

Leakage current (1)

- Current measurements for some pixel modules to monitor the status of sensors and hence estimate the quality of ATLAS Pixel Detector data
- Use current measurement data to estimate the fluence *Φ[cm⁻²]*
- *Use of the ad hoc ATLAS radiation monitoring devices installed at several points of Pixel Detector*



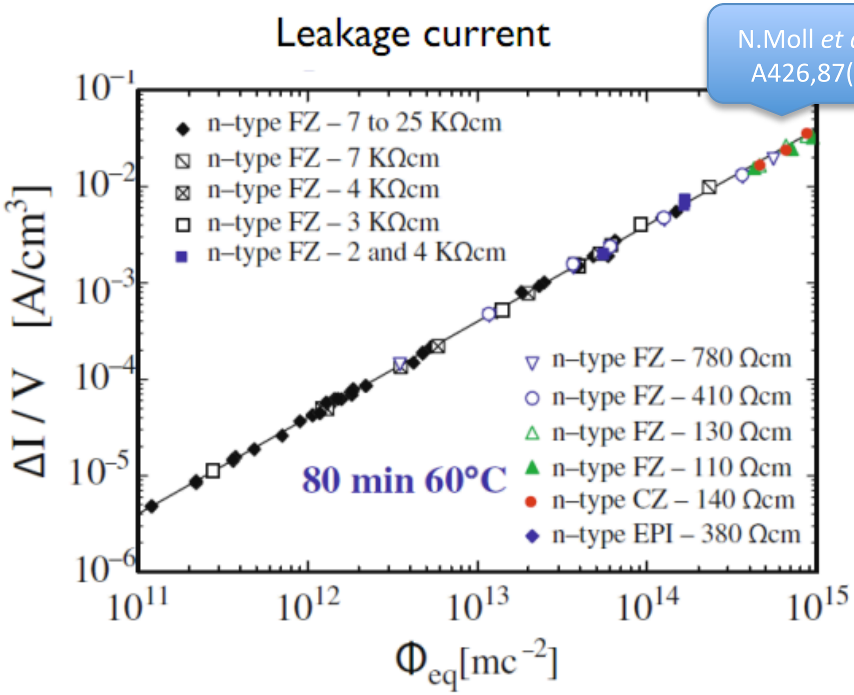
$$I(T) = I(T_R)/R(T), \text{ where}$$
$$R(T) = (T_R/T)^2 \cdot \exp\left(-\frac{E_g}{2k_B}(1/T_R - 1/T)\right)$$

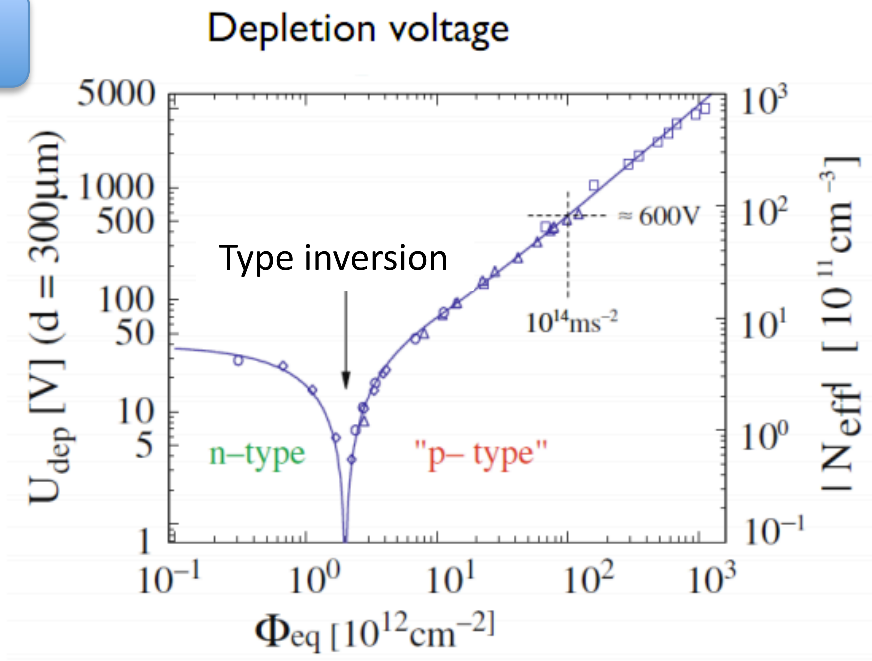
- Every pixel module is equipped with temperature probe and the data are read out into the detector condition database. The current measurement data should be corrected by the temperature factors ⇒

corrections are made to $T_R = (273.15 + 20)°K$

Leakage current (2)

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





Current measurements:

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

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

- 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 current (3)

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

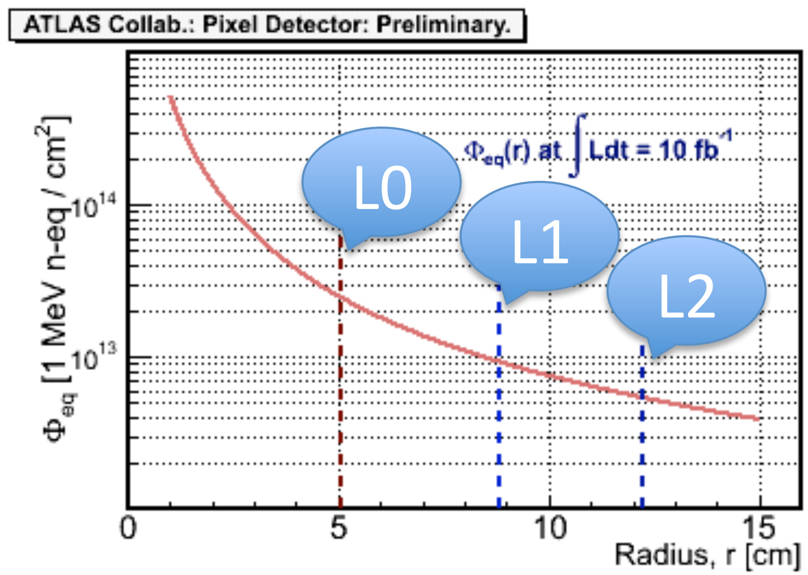
- 1 MeV n- equivalent $\Phi_{1MeV\text{-}eq}/1000\ fb^{-1}$
- LHC pp events with PHOJET+FLUKA
- The MC data fitted for r∈(2, 20)cm with
- Uncertainties of predictions:

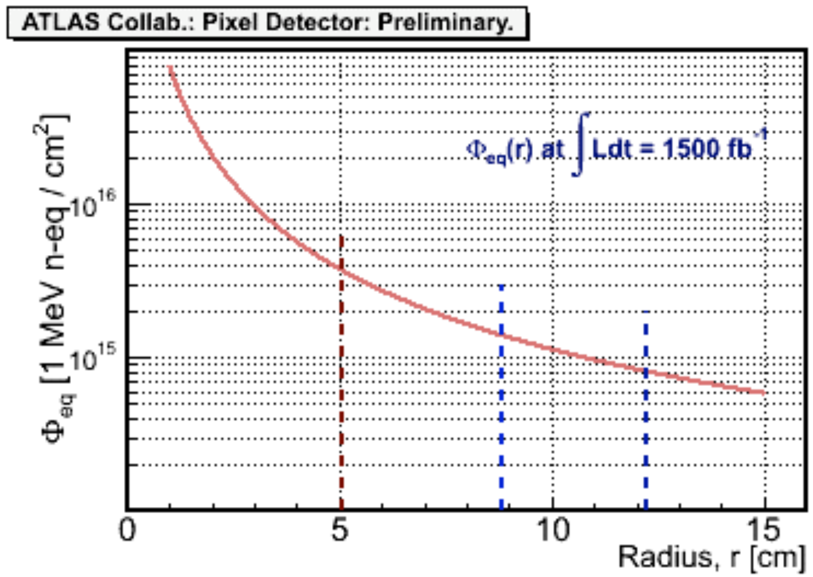
  pp-generator: ≈30%

  Calculation of 1MeV n- eq. using damage factors: ≈50%

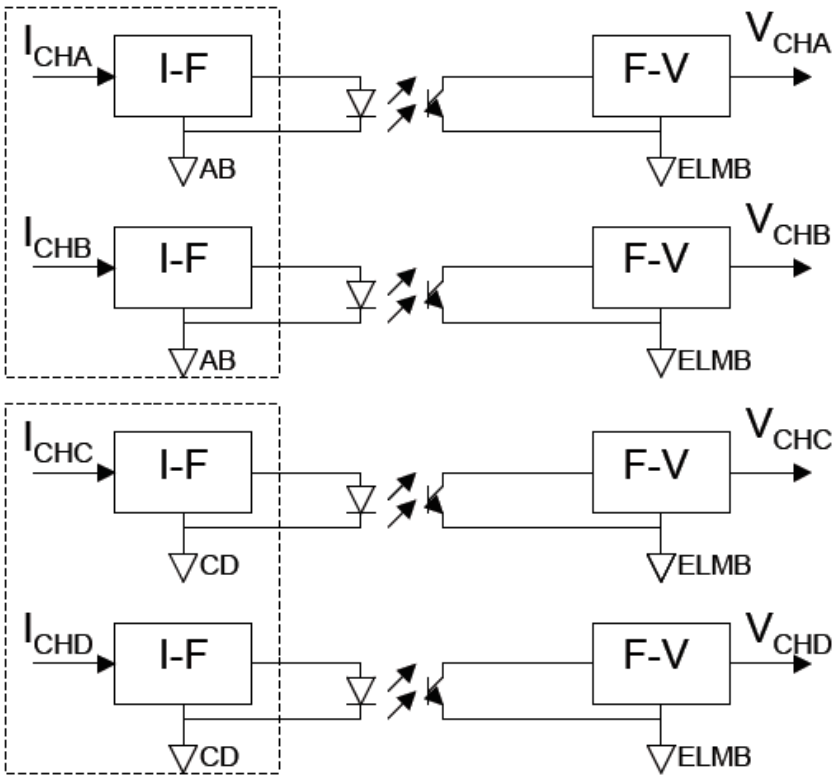
  In total: ≈58%

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





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), ~0.4×10^5

○ 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

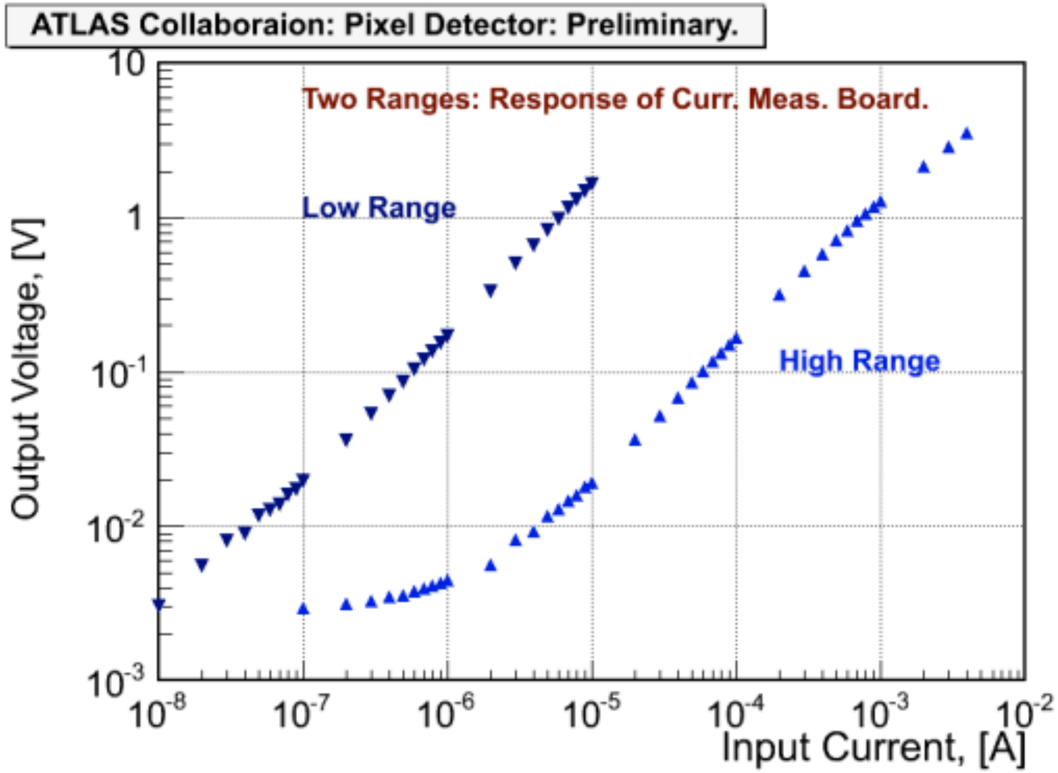
○ Frequency of operating circuit:

< 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: calibration



- Two ranges are implemented as large dynamic range should be covered: 5×10^{-8}A to 2×10^{-3}A
- Input is with a Keithley 237 in constant current mode
- Output voltage measured on HP34401A multi-meter
- The response is nicely linear
- Two ranges overlap at 10^{-6}A – 10^{-5}A

All CMBs:

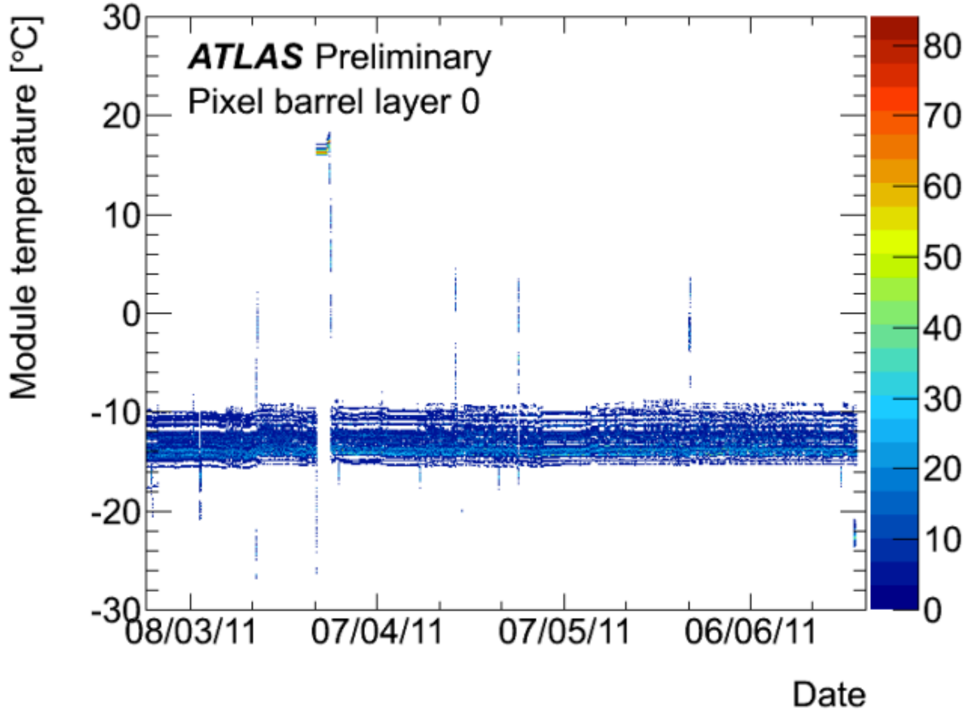
- *Produced and tested at UNM*
- *Calibrated at ATLAS Point1 on surface*
- *Then installed in two ATLAS Pit Rack areas*

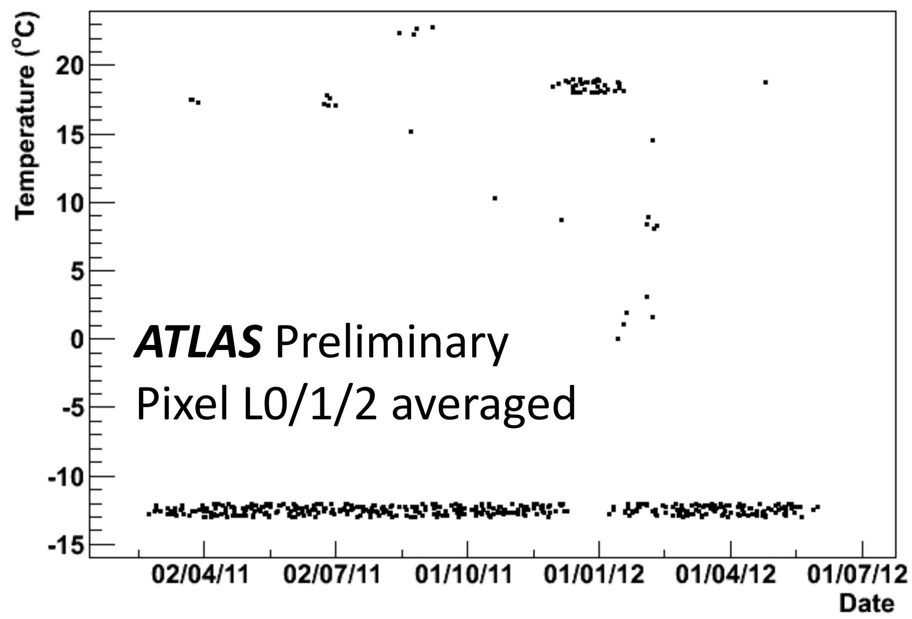
Current Measurement Board (4)

- 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): 4 CMBs installed; 16 L2 pixel modules instrumented;

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

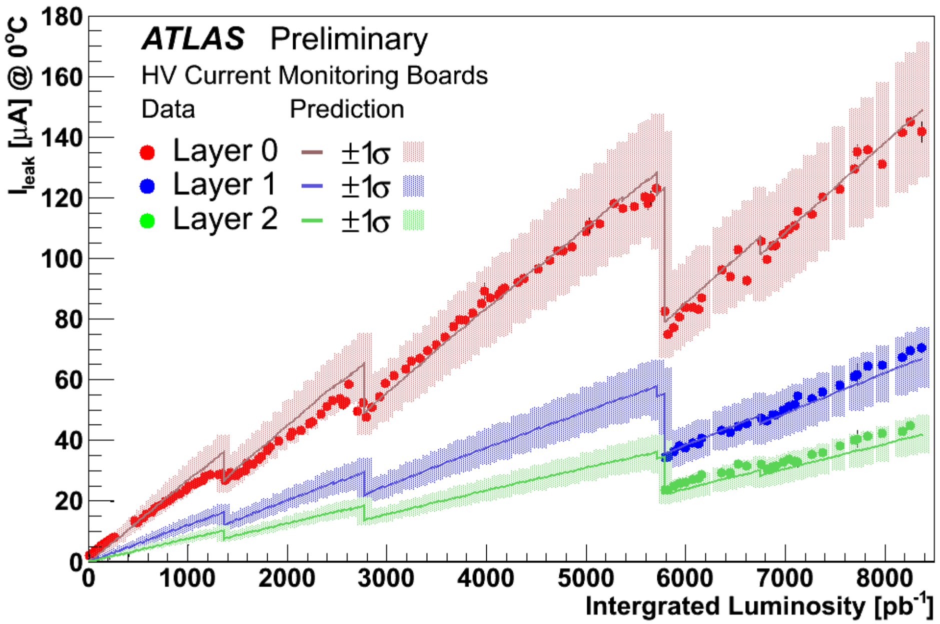
Temperature of pixel modules

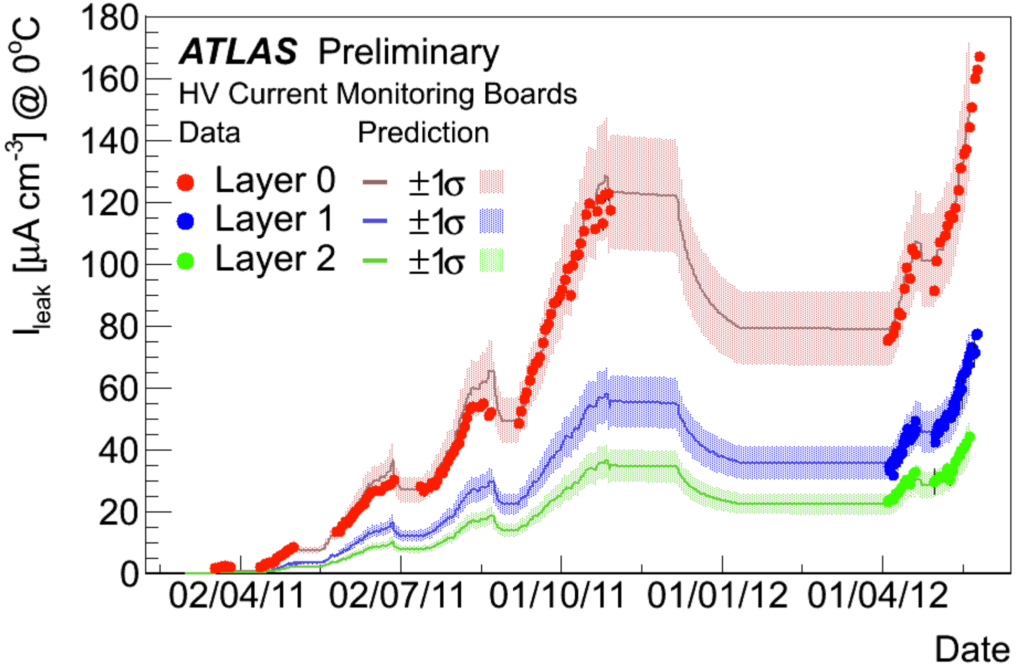




- Temperatures of 2011 (right) and 2012 (left) are almost constant (-13 °C), fluctuations due to cooling cuts (technical stops, winter shutdowns) or various calibration scans.
- In our analysis we use temperatures measured per module.

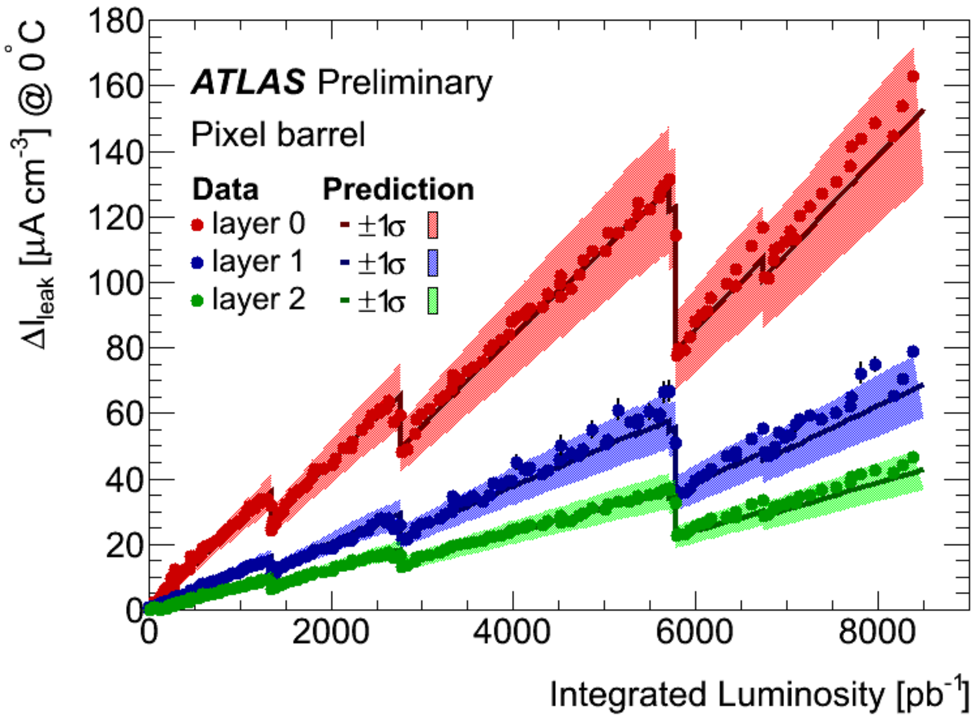
Leakage currents measured by CMBs

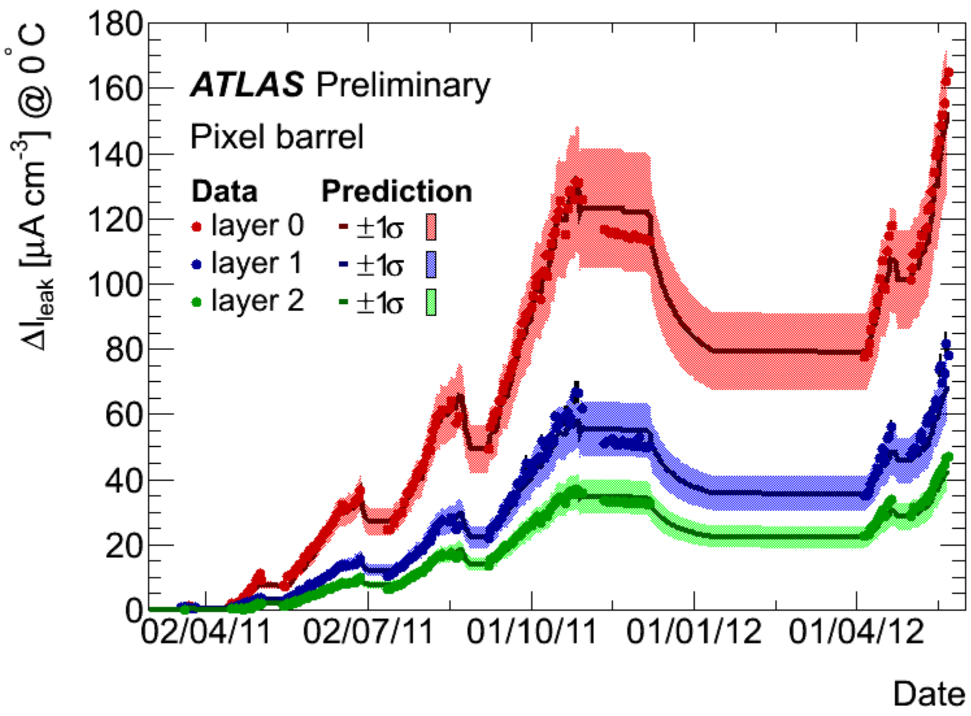




- Layer 0, 1, 2 leakage currents per module measured with CMBs. Corrections to modules temperature included. Left plot: leakage currents versus the LHC integrated luminosity. Right plot: leakage currents versus time. Annealing periods are clearly seen. Currents are normalized to $0^{o}C$.
- Plots are compared to 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. Model is scaled up by the factors 1.15 for the L0 and 1.25 for L1 and L2 – to be understood.
- Plots include (almost negligible) correction for beam induced ionization current:
  - $I_{hit} = N_{bunches} * \nu_{LHC}$ * pixel hit occupancy * charge per hit.

Leakage currents measured by *ISEG* power supplies





- Leakage currents measured at the output of the HV PS for groups of 6/7 modules with a precision of about 80 nA, more details in Markus Keil's talk today.
- Perfect agreement with HVPP4 CMB measurements.

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 9 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.
- First comparisons with a model show a reasonable level of agreement. Scaling factors to be understood.
- Fluence calculations are underway.
- ATLAS Radiation Damage Working Group collaborates with CMS and LHCb experiments, see more talks today!

BACKUP

Pixel Lifetime

- By comparing current with integrated luminosity
  - Fit current *I vs ∫ 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 *∫ 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

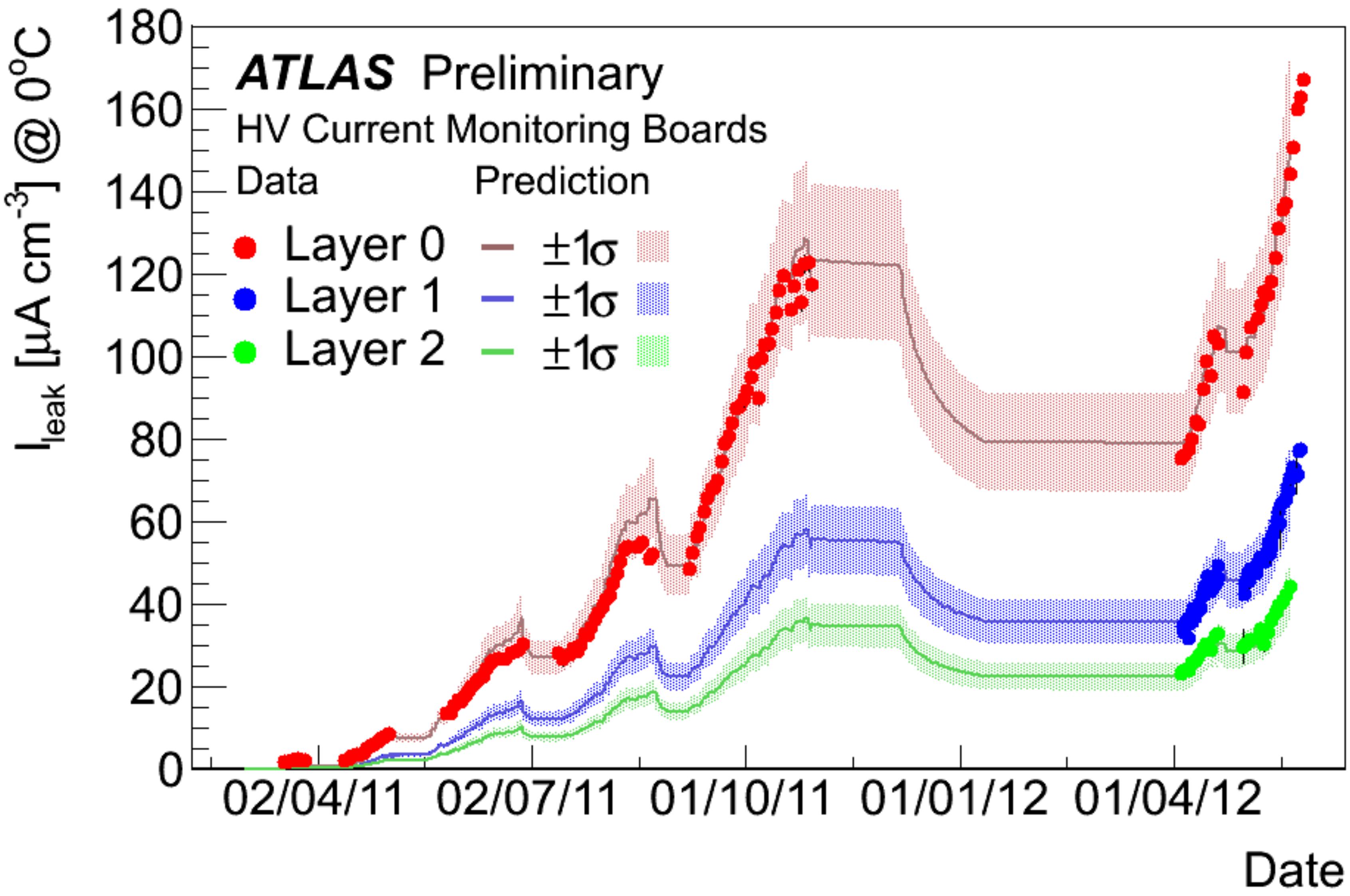
$$I_{ISEG} \leq 4000\mu A$$

  - 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:

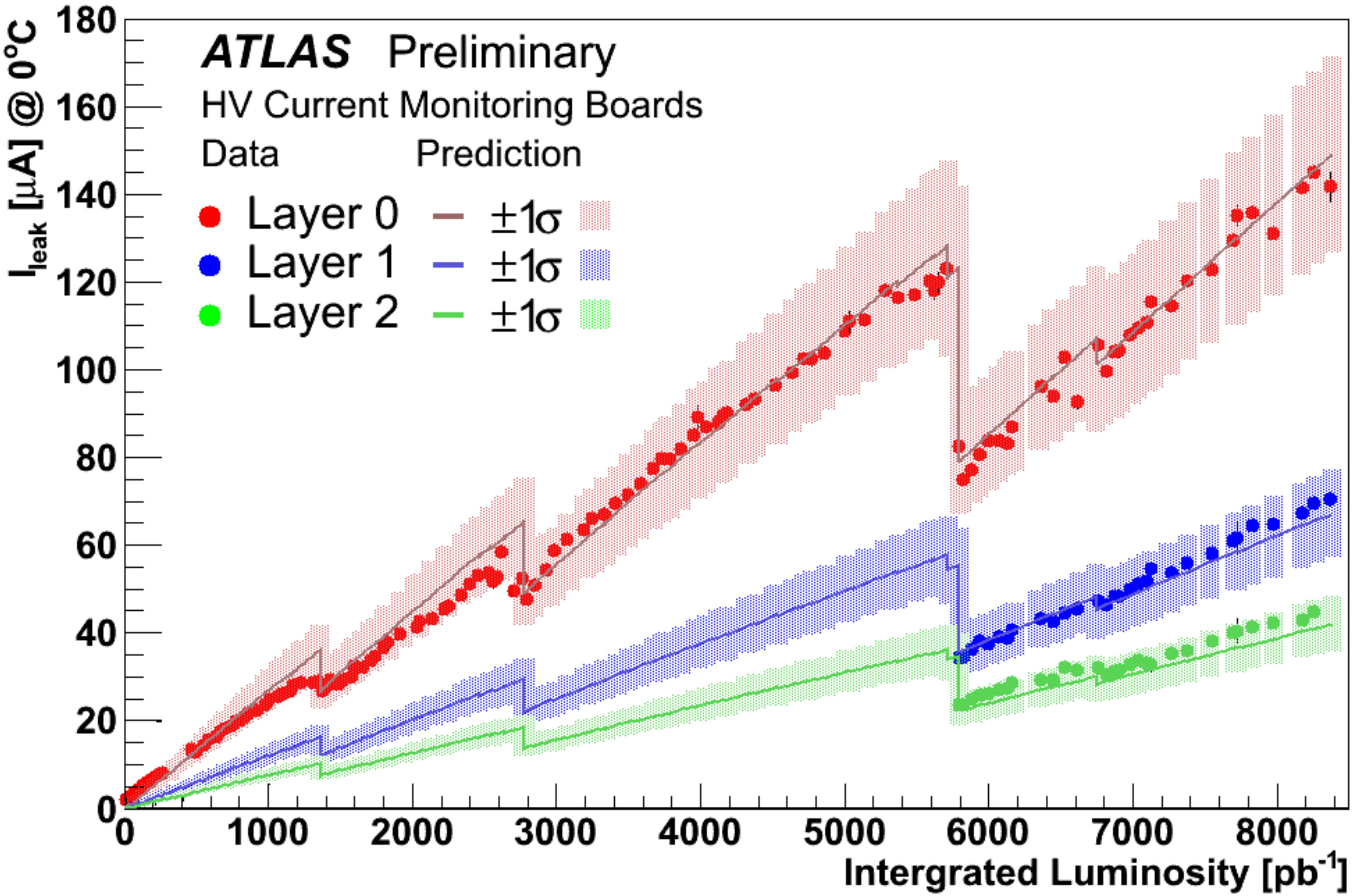
  The first years, operated at full depletion. The end is determined:
  - critical range of high currents causing thermal runaway and limiting bias voltage
  - or exceeding ISEG spec of $I_{ISEG} \leq 4000\mu A$
  - or exceeding ISEG spec on $V_{bias} \leq 600V$
- Later years of operation in partially 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 ∫ 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
0
1000
2000
3000
4000
5000
6000
7000
8000