Radiation Damage Observation in the ATLAS Pixel Detector Using the High Voltage Delivery System

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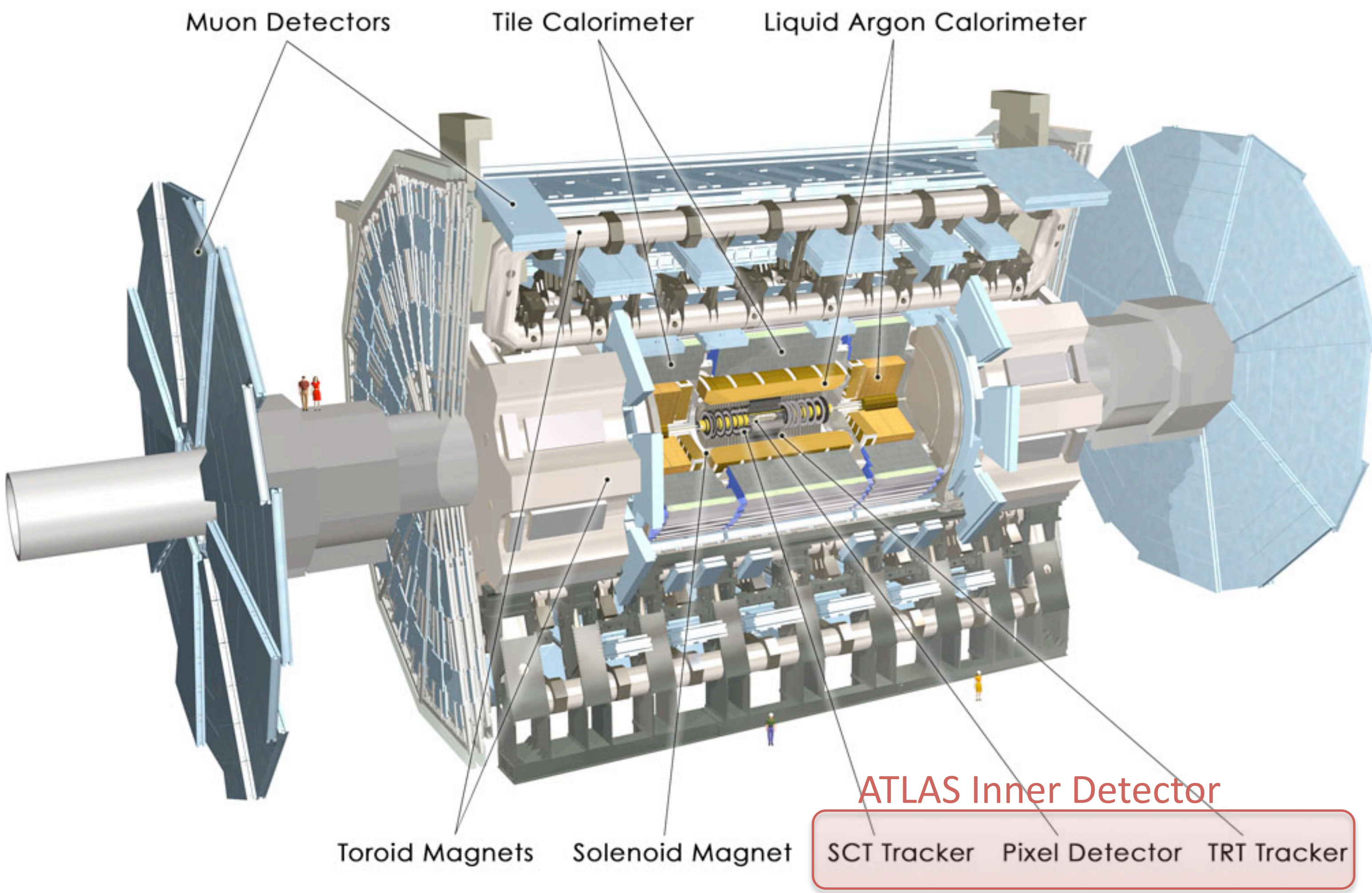
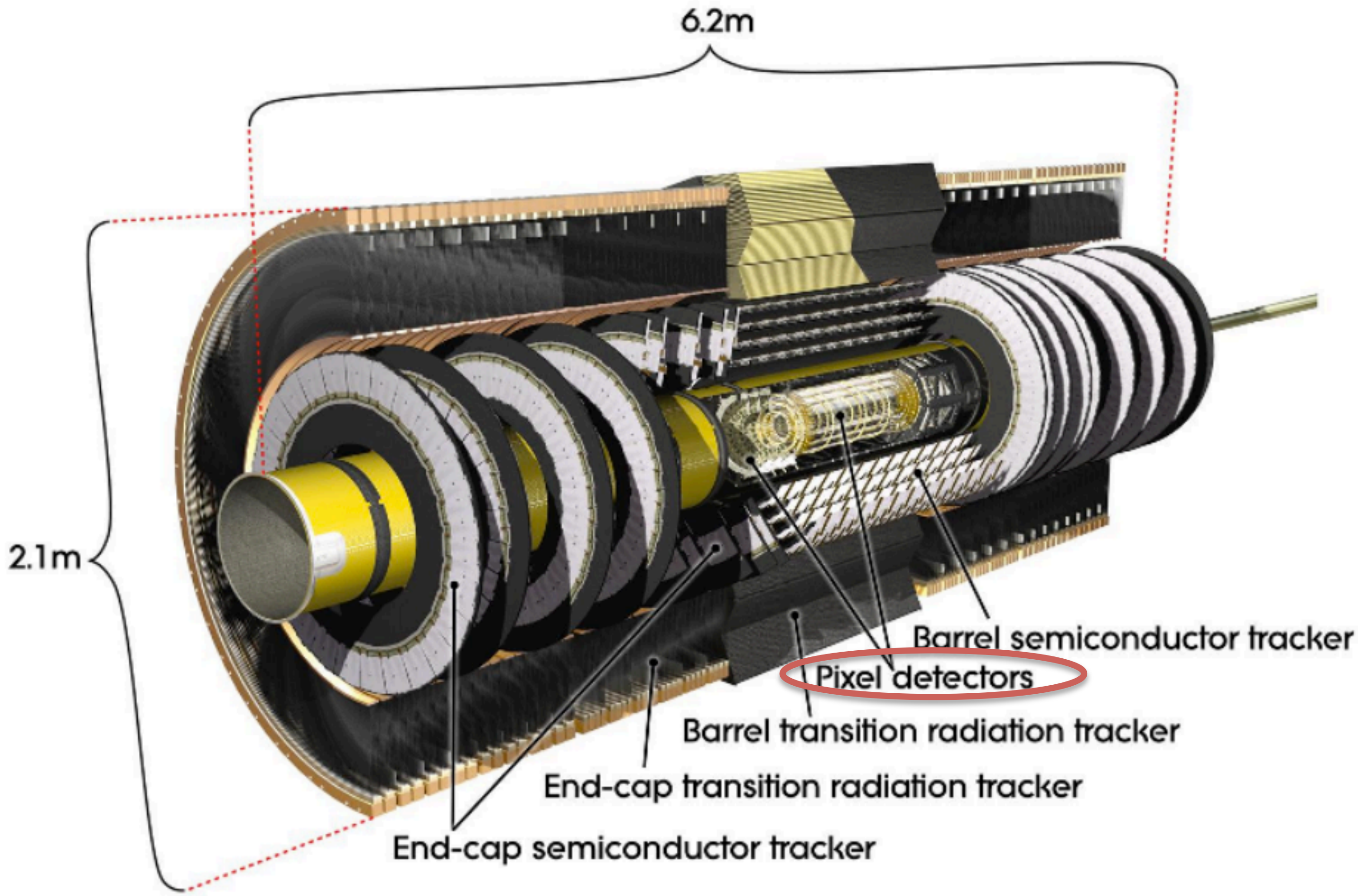
on behalf of the ATLAS Collaboration

The LHC ATLAS detector



ATLAS Inner Detector

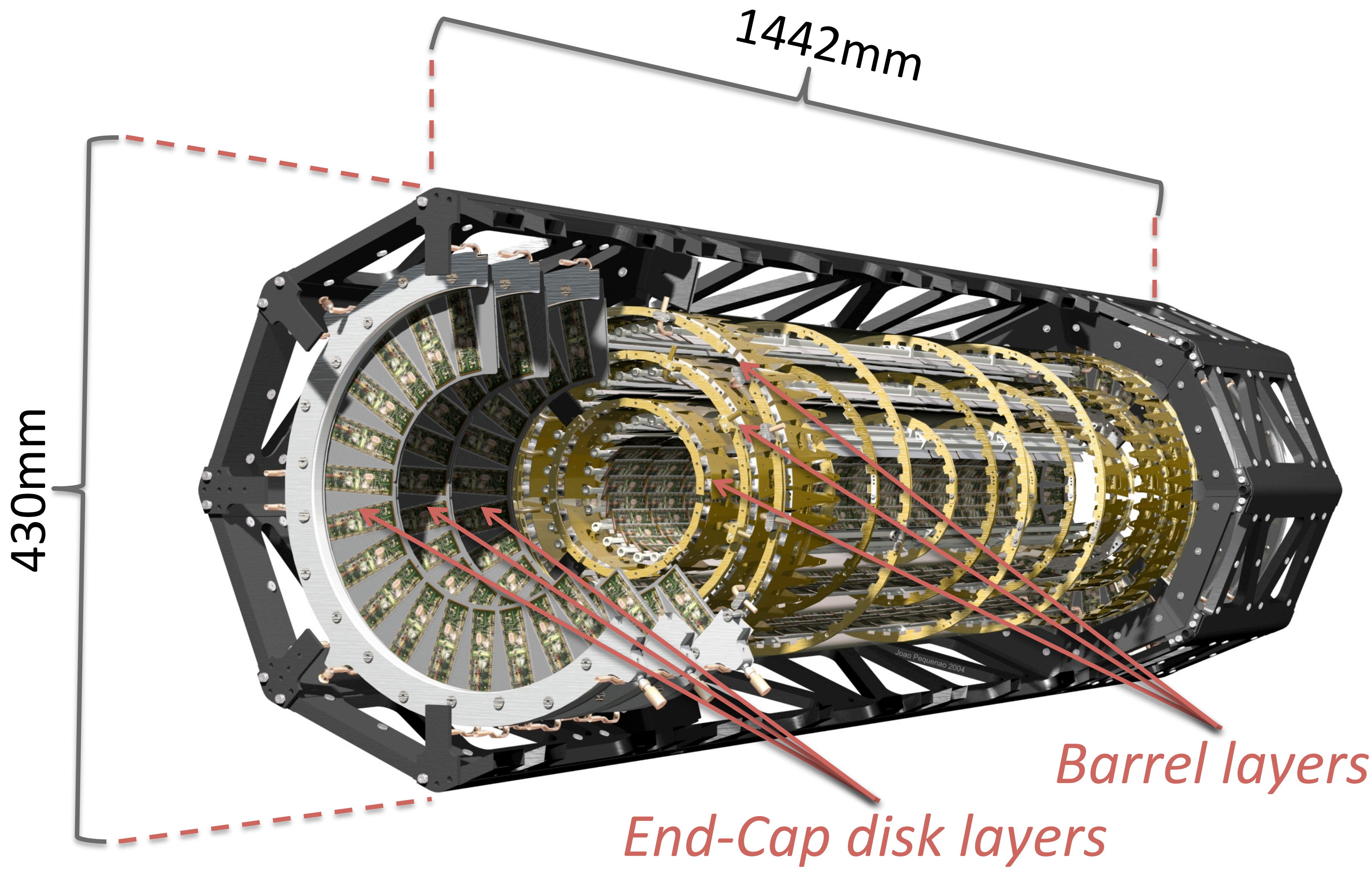


ATLAS Inner Detector

Other ATLAS ID subsystems presentations at this conference:

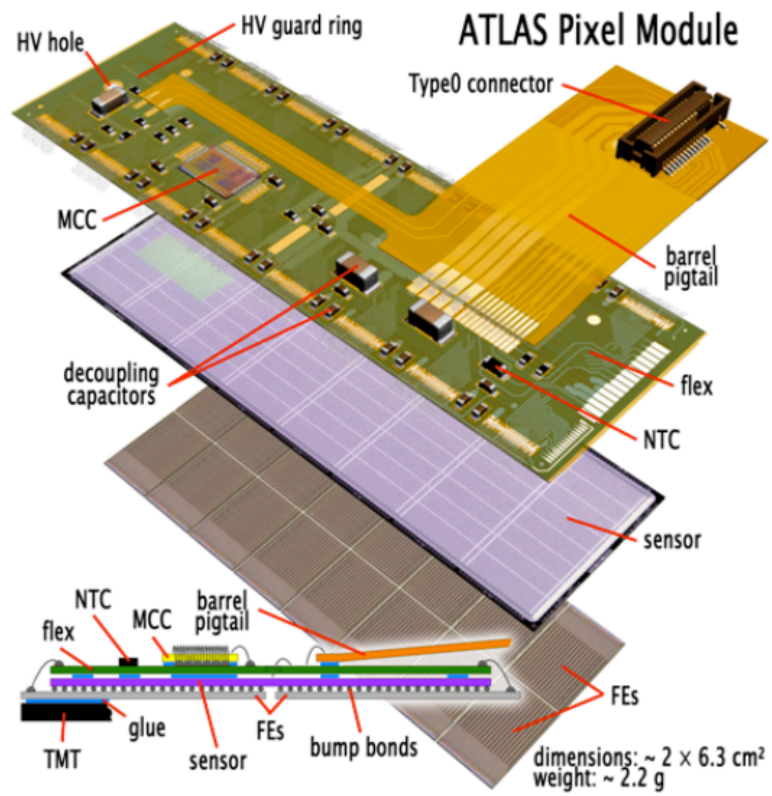
- S. Marti i Garcia, "Track Based Alignment of the Inner Detector of ATLAS," poster.
- C. Cuenca Almenar, "Triggering on hadronic tau decays in ATLAS: semiconductor tracking detectors in action," poster.
- C. Da Via, "3D Slim Edge Silicon Sensors: Processing, Yield, and QA for the ATLAS IBL Production," Dec. 5.
- R. Klingenberg, "Recent Progress of the ATLAS Planar Pixel Sensor R&D Project," Dec. 5.
- S. Grinstein, "Overview of the ATLAS Insertable B-Layer (IBL) Project," Dec 6.
- I. Rubinskiy, "Irradiation and Beam Tests Qualification for ATLAS IBL Pixel Modules," Dec 6.
- R. Nagai, "Evaluation of Novel n-in-p Pixel Sensors for ATLAS Upgrade with Testbeam," poster.
- S. Diez Cornell, "Silicon Strip Detectors for the ATLAS Tracker Upgrade," Dec. 6.
- D. Robinson, "ATLAS Silicon Microstrip Tracker Operation and Performance," Dec. 7.
- C. Lapoire, "Operational Experience with the ATLAS Pixel Detector at the LHC," Dec. 7.

ATLAS Pixel Detector (1)



ATLAS Pixel Detector (2)

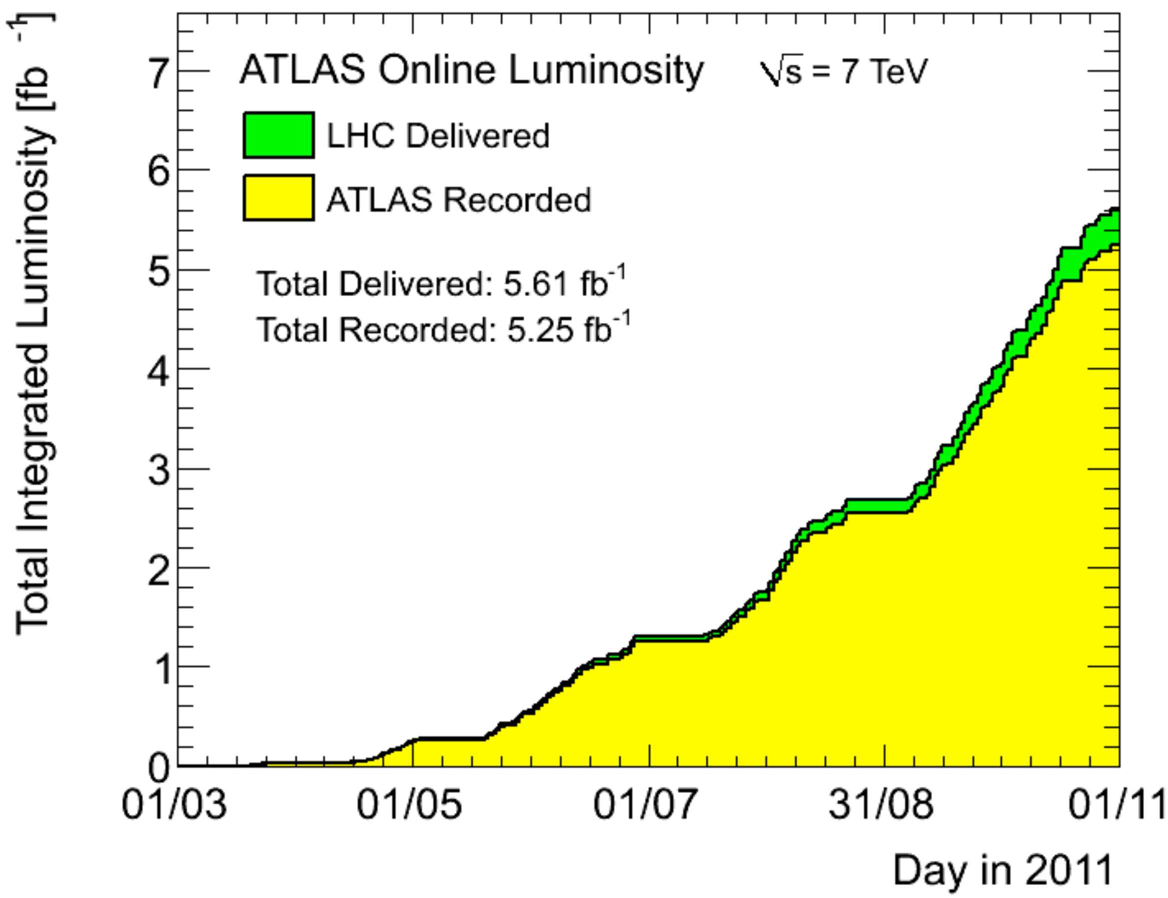
- Pixel sensor consists of 256±3 µm thick n-on-n bulk
- Each sensor has 46080 channels
  - *readout by 16 FE chips with zero suppression*
  - *combined into 1 module: 6.08x1.64cm^2 area*
- Total: 1744 nearly identical modules; 1.7m^2 area
- Required sensor radiation tolerance:
  500 kGy/ 10^{15} 1MeV n_{eq} cm^{-2}
- Average operational T= -13^{o}C, with evaporative C3F8 cooling integrated in the local support structures
- V_{bias} = 150 V. Note power supply (ISEG) has 700 V max.



Readout:

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

LHC luminosity delivered so far: ~5.6 fb^{-1}



Radiation Damage

- Dominant radiation damage
  - *Displacement defects in the bulk*
  - *Due to Non-Ionizing Energy Losses (NIEL)*
  - *Flow of charged $\pi^{\pm}$ from ATLAS Interaction Point*
- Increases the 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). Inversion expected in mid 2012 run. No inversion yet.
- 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 the main factor contributing to the radiation damage*
- The level of the leakage current reveals the amount of radiation damage sustained in the detector volume
  - *Strongly depends on the particle fluence through the detector area*
  - *Temperature dependent*

Technical solution: HVPP4 (1)

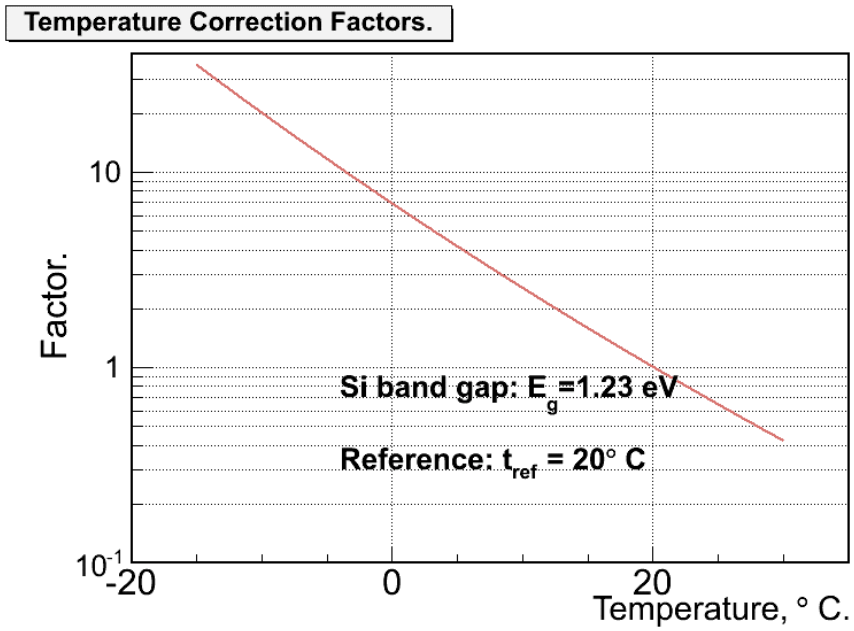
- High Voltage Patch Panel 4 (HVPP4), connectivity point distributing HV into the ATLAS Pixel Detector
  - Fan in/out point between the HV power supply and cables carrying the HV to/from detector and other patch panels
  - Location: racks in US(A)15 ATLAS Detector caverns
  - High Voltage (HV) service biases the silicon pixel sensors at the heart of Pixel Detector
- Pixels use ISEG Power Supply channels: $V_{DC} \leq 700V$, $I \leq 4mA$
  - Distributes HV with modularity 1 HV Power Supply (ISEG) channel to 6/7 pixel modules
  - Modularity must be reconfigurable to 1 ISEG channel to 2/3 pixel modules once the leakage current exceeds ISEG specifications
  - These too can measure I_{leak}, but only in ganged groups of 6/7.
- HVPP4 system provides a reconfigurable patch panel between HV cables coming from Pixel detector (PP1) and ISEG HV channels

Technical solution: HVPP4 (2)

- HVPP4 system includes Current Measurement Boards (CMB) to monitor the leakage current for each individual pixel sensor
- The Current Measurement Board must measure leakage currents over a wide range: 0.01µA ... 1mA: ~10^5 range
- The measured current values are digitized, transmitted via CANbus to the DCS by the CERN-developed A/D converting 16-bit DAQ board ELMB.
- PVSS software reads out the data from ELMB boards and downloads the data to PVSS/COOL database (large DCS storage).

Leakage current (1)

- Current measurements on some pixel modules are used 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}]*
- *Various other ATLAS radiation monitoring devices (pin diodes, RADFETs) installed adjacent to Pixel Detector.*
- *The ISEGs provide a direct but less precise comparison.*



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

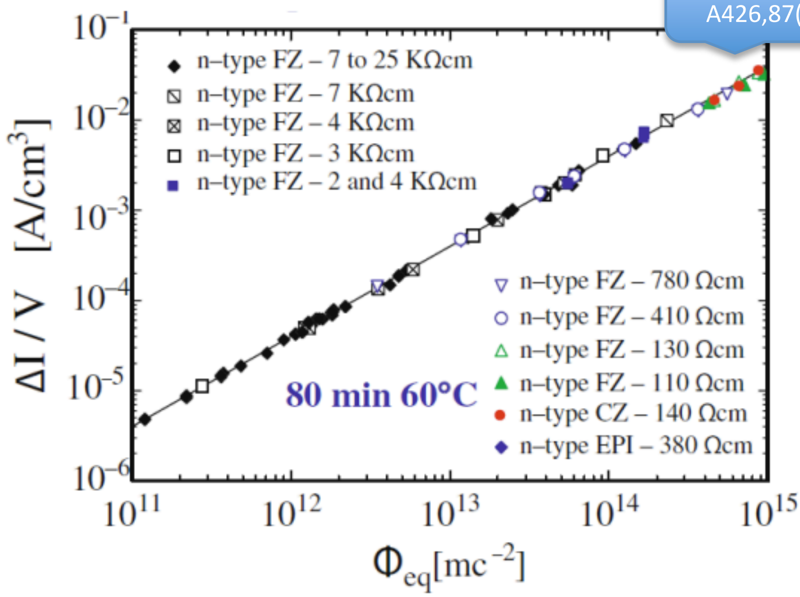
- Every pixel module is equipped with a temperature probe. These data are read out into the detector condition database. The current measurement data are scaled to the temperature factors ⇒

scaling is made to $T_R = (273.15 - 10)$°K

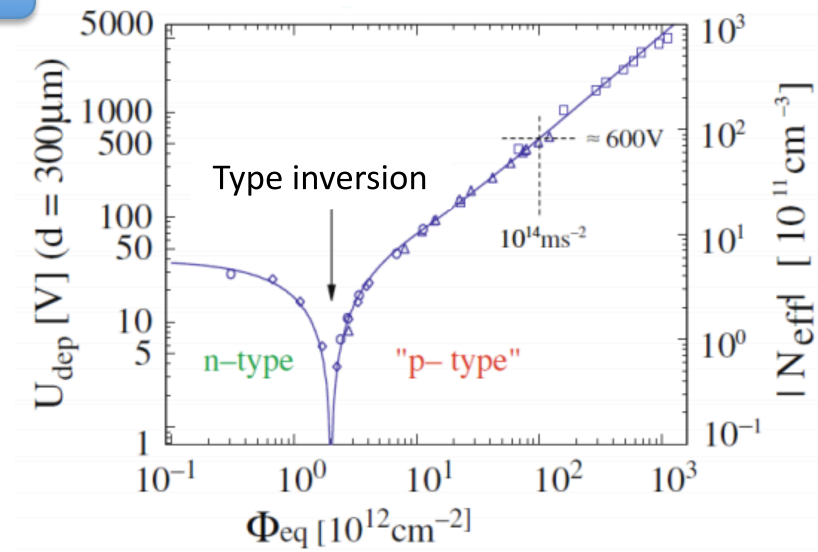
Leakage current (2)

Leakage current

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



Depletion voltage

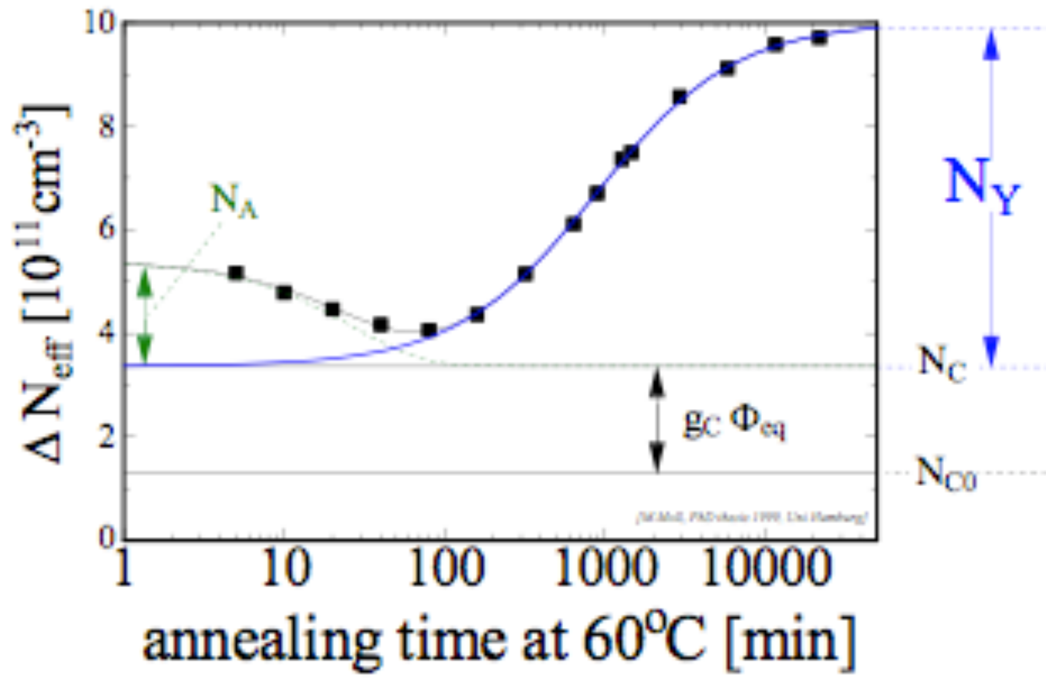


Current measurements:

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

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

• Those authors observed a universal behavior for silicon sensors: increase in leakage current is proportional to accumulated fluence. Annealing is modeled as: (next page)



Hamburg Model

$$\Delta N_{eff} = N_A(\Phi, t) + N_C(\Phi) + N_Y(\Phi, t)$$

$$N_A(\Phi, t) = g_a e^{-t/\tau_a} \Phi$$ (short term annealing)

$$N_C(\Phi) = g_c \Phi + N_{c0}(1 - e^{-c\Phi})$$ (stable damage)

$$N_Y(\Phi, t) = g_Y(1 - e^{-t/\tau_Y})\Phi$$ (long term annealing)

Leakage current (3)

ATLAS uses fluence calculations in the ATLAS Inner Detector area made by the ATLAS Radiation Task Force, CERN-ATL-GEN-2005-001

Latest update in

http://indico.cern.ch/conferenceDisplay.py?confId=52704

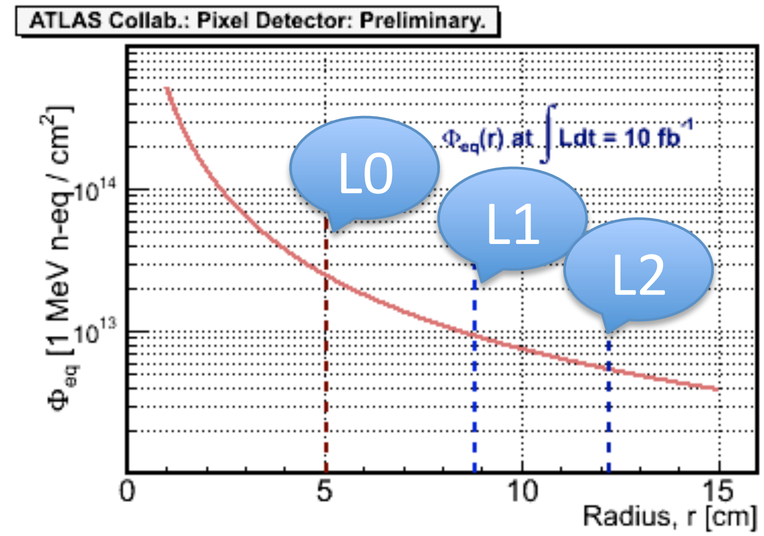
- 1 MeV n- equivalent $\Phi_{1MeV\text{-}eq}/1000\ fb^{-1}$
- LHC pp events with PHOJET+FLUKA
- The MC data fitted for r∈(2, 20)cm with
- Uncertainties of predictions:

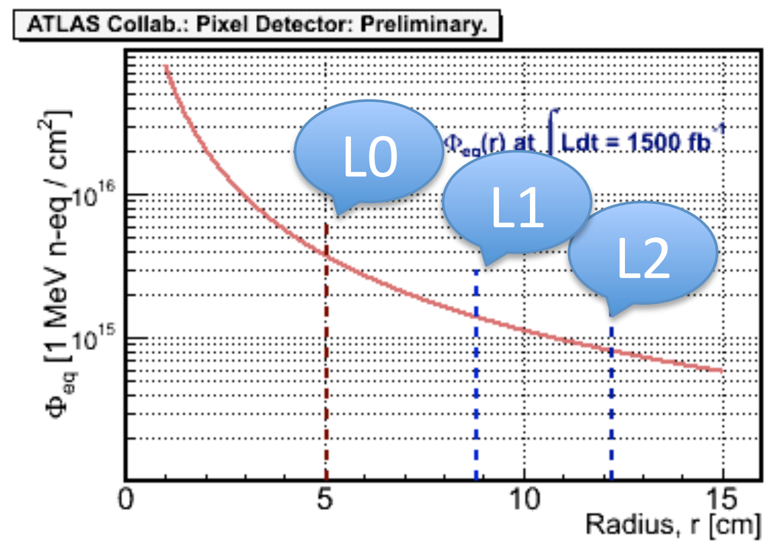
  pp-generator: ≈30%

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

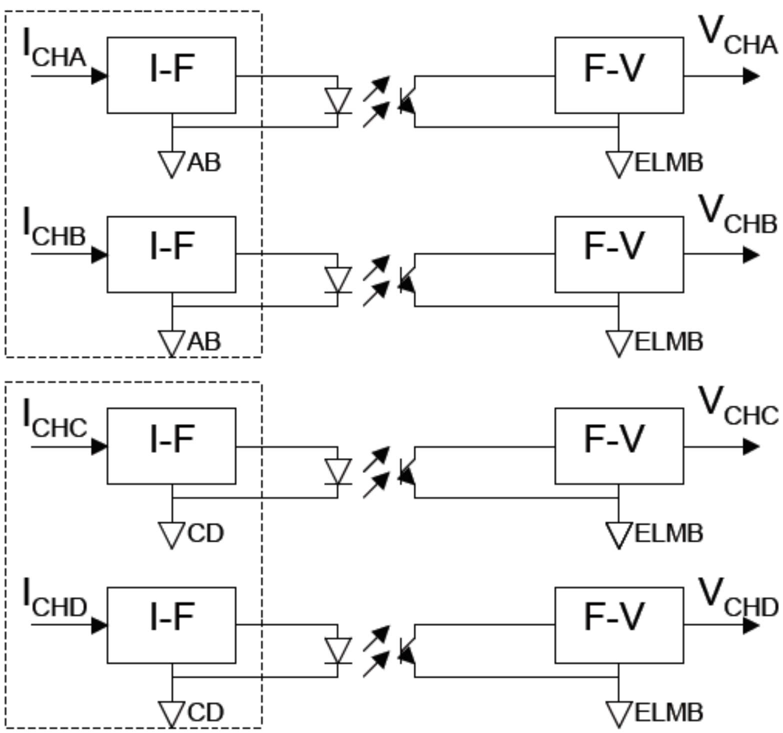
  In total: ≈58%

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





Current Measurement Board (1)



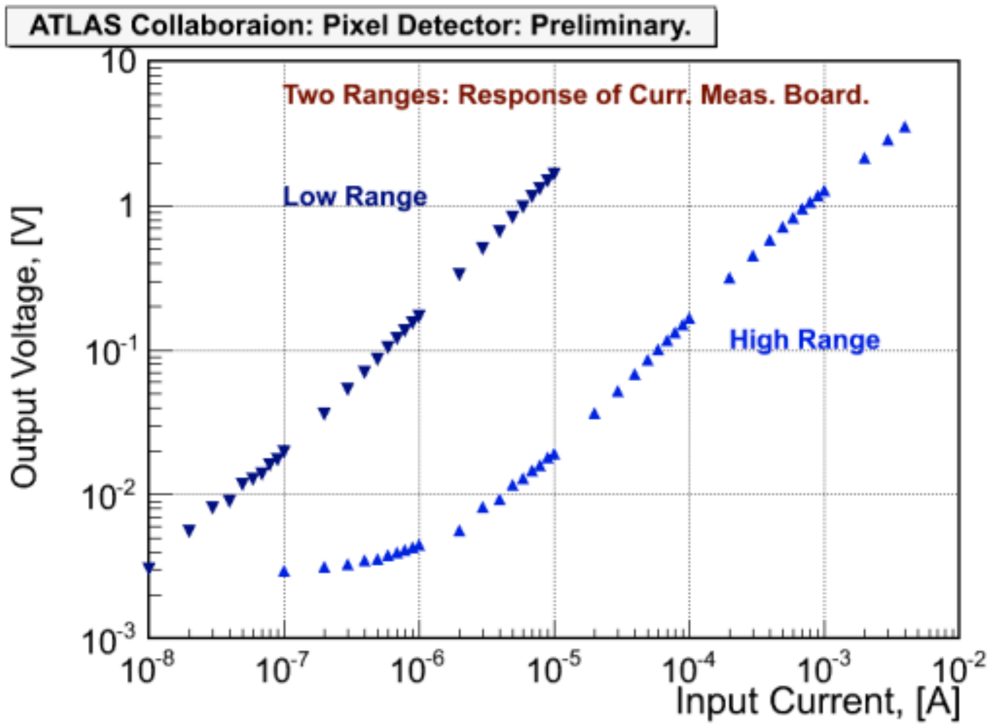
- Circuit is a current-frequency converter
- Optically coupled to a freq-voltage converter.
- 4 circuits per board monitor selected channels in the 13-circuit HVPP4 boards.
- 2 digital readout ranges per analog channel; with different analog gain
- Isolated in pairs of channels from each other and from the readout system

Current Measurement Board (2)

- Range of input currents to be measured: (0.01 μA , 1 mA), ~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%

Current Measurement Board (3)



- Two ranges are implemented to ensure that the large dynamic range $1x10^{-8}$A to $1x10^{-3}$A are covered.
- Calibration input with a Keithley 237 in constant current mode.
- Calibration output voltage measured through the ELMB with PVSS
- The response is nicely linear
- The two ranges overlap at 10^{-6}A – 10^{-5}A.

All CMBs:

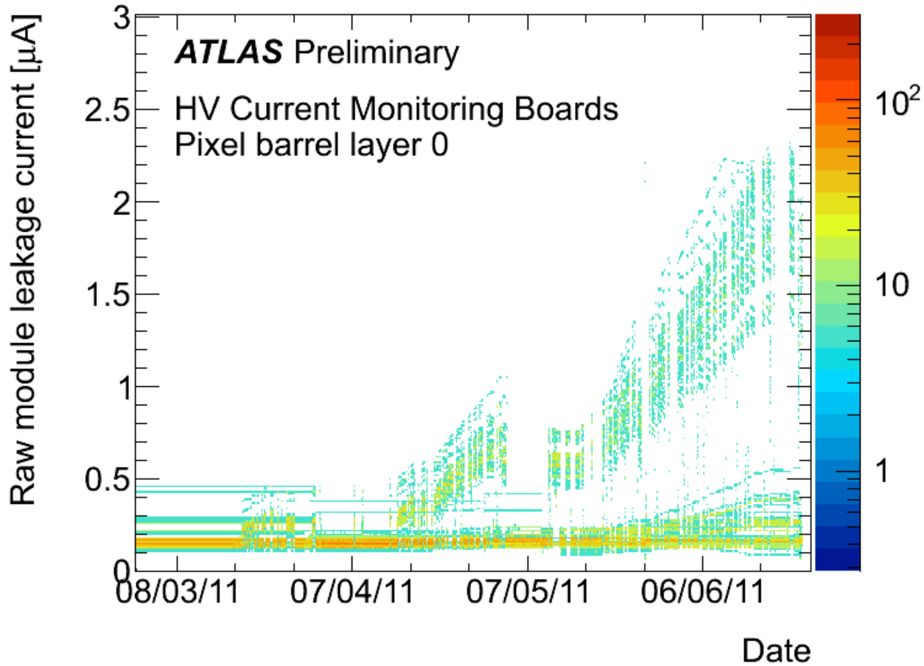
- *Designed, produced and tested at UNM*
- *Calibrated at ATLAS Point1 on the surface*
- *Then installed in two ATLAS Pit Rack areas*

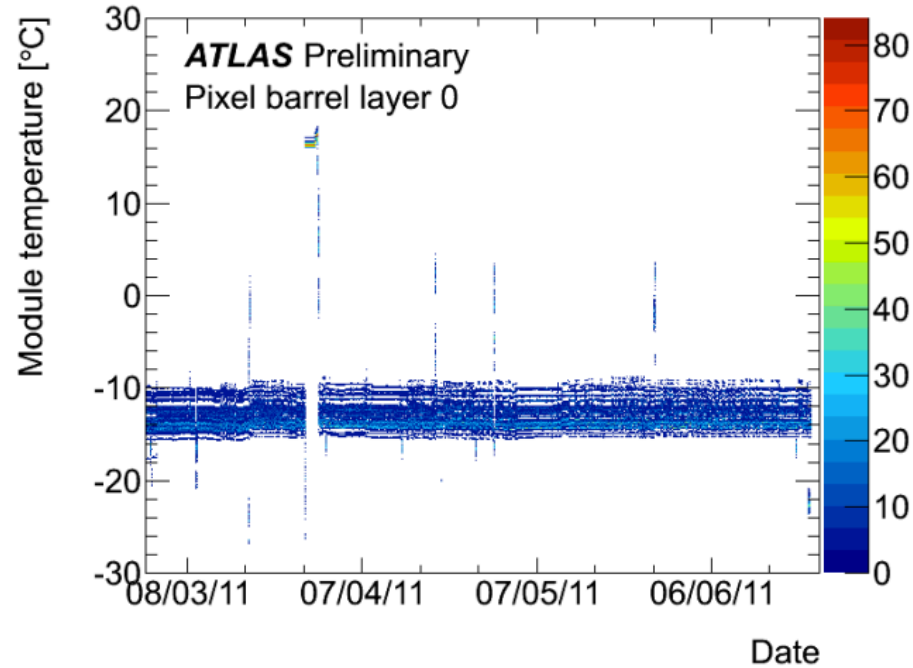
Current Measurement Board (4)

- Current status of the ATLAS HVPP4 system:
  - Layer 0 (innermost): 22 CMBs installed; 88 L0 modules instrumented;
  - Layer 1 (middle): 2 CMBs installed; 8 L1 modules instrumented;
  - Layer 2 (outermost): 2 CMBs installed; 8 L2 modules instrumented;

- Hardware installation to be completed during Winter 11-12 shutdown

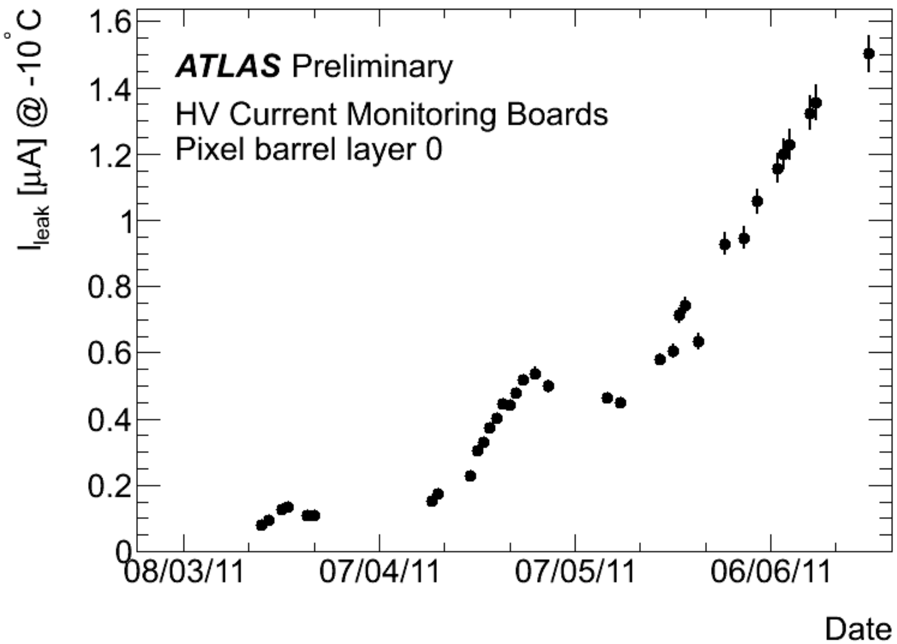
Results (1)

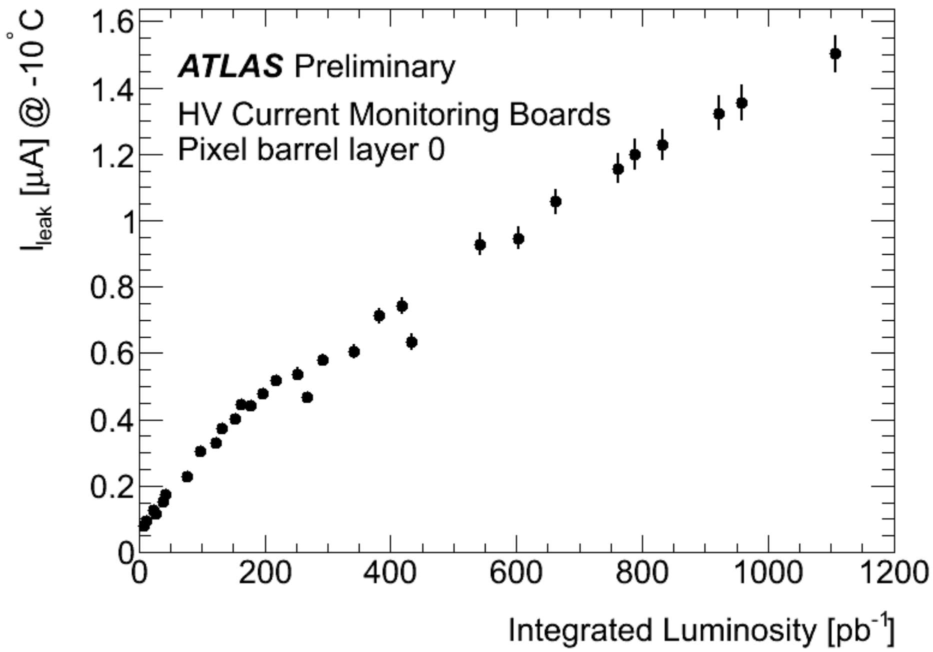




- Raw HV leakage current measurements with HVPP4 CMBs, high gain/low range channels, Layer 0 (left)
- Modules' temperature (right), almost constant (-13 °C), some fluctuations due to cooling cuts or various calibration scans

Results (2)

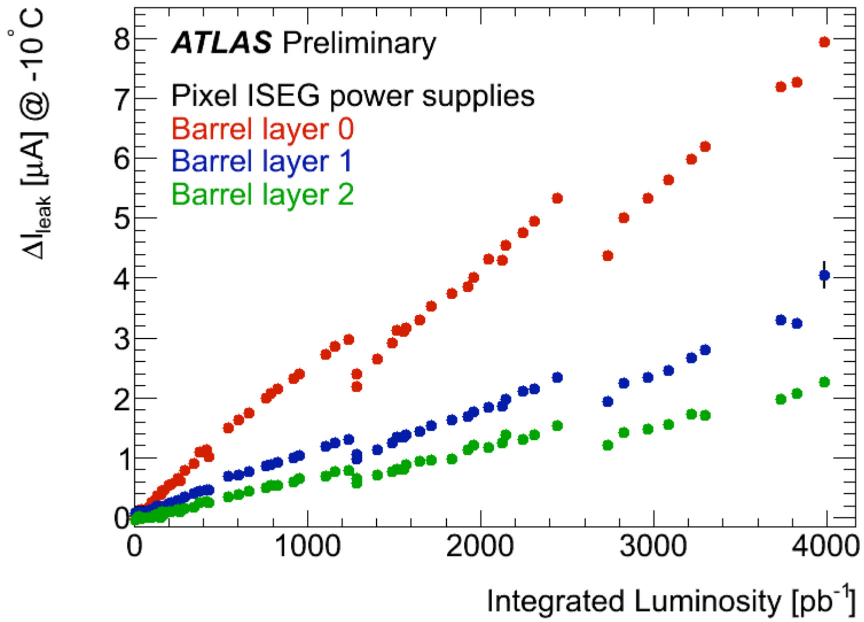


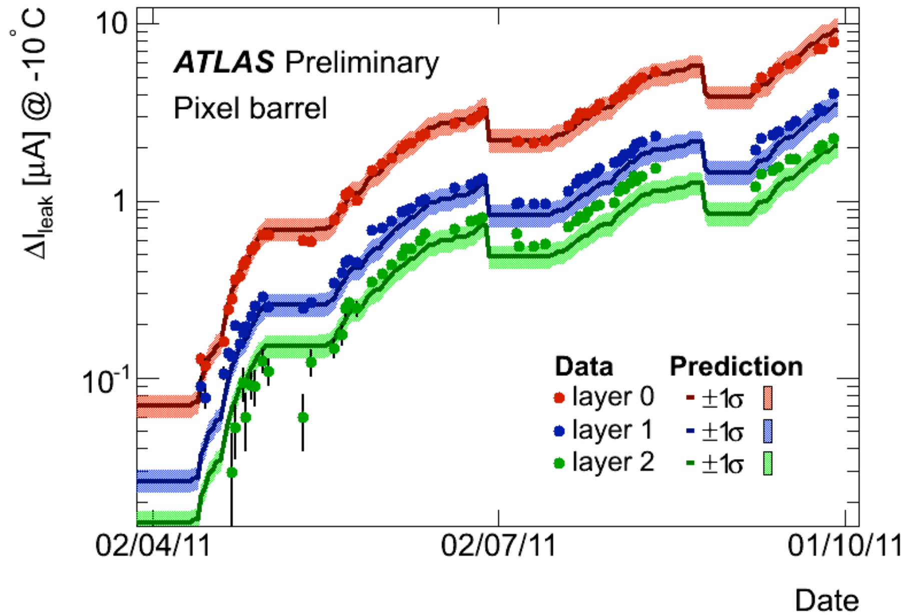


- Layer 0 leakage currents per module measured with CMBs. Corrections to modules' temperature are included.
- Plots include preliminary correction for beam induced ionization current:
  - $I_{hit} = N_{bunches} * \nu_{LHC}$ * pixel hit occupancy * charge per hit.
- Annealing is visible.
- Additional CMB calibrations foreseen:
  - During the next LHC Technical Stop we plan to safely measure the leakage currents without beam.
- Comparison with Hamburg Model is in progress.

Results (3): comparison with model

- Comparison with the Hamburg Model is available for the ISEG data:





- 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 when the Pixel cooling was off.
- Similar comparison for CMB's individual modules is in progress.

Conclusions

- ATLAS has dedicated hardware to monitor radiation damage in the Pixel detector via the leakage currents. The precision is 10%.
- 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 (5 cm from the beam).
- Measurements with Current Measurement Boards and at the output of the Power Supplies show an increase of the leakage current in the modules of about 2 μA for 1.5 fb^{-1}.
- Annealing is visible, and preliminary comparison to the model is reasonable.
- The ATLAS Radiation Damage Working Group collaborates with CMS and LHCb experiments. Comparison with the Hamburg Model is in progress.

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