Radiation Damage of the ATLAS Pixel Sensors Using Leakage Current Measurement System

Igor V. Gorelov

(on behalf of ATLAS Collaboration)

University of New Mexico

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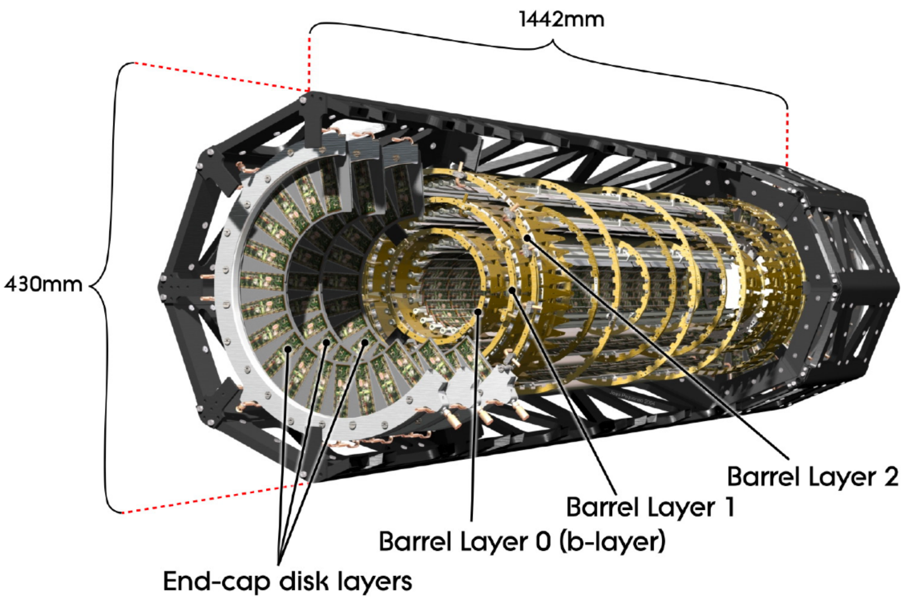
Outline

- Introduction
- Radiation Damage
- Annealing
- Leakage Current Measurement System
- Technical Solutions
- Current Measurement Board
- Leakage Current Data
- Summary

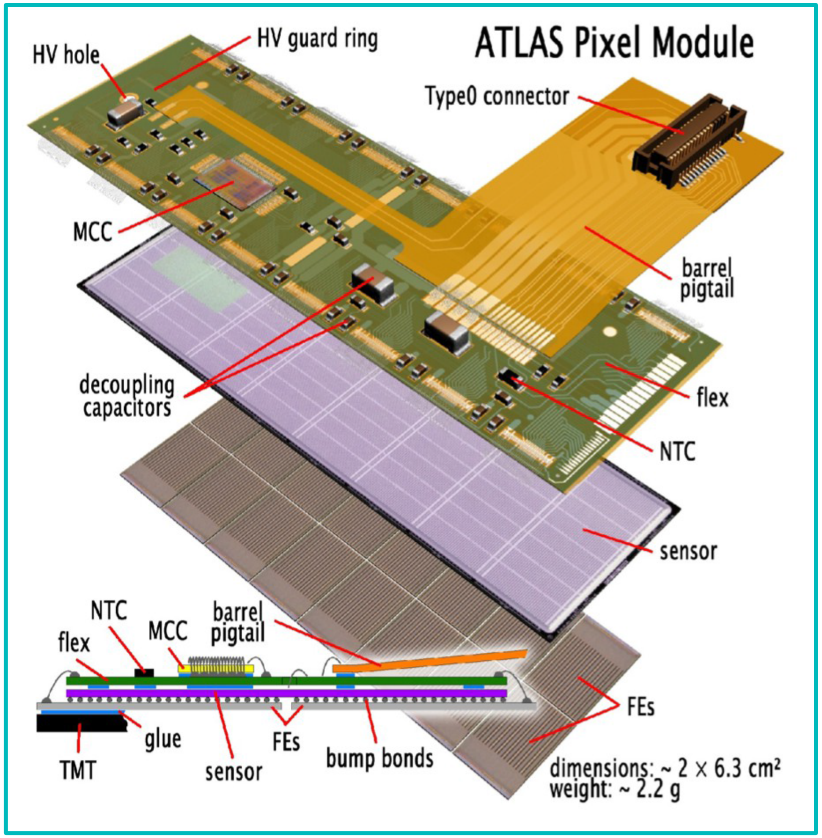
ATLAS Pixel Detector



Introduction (I)

ATLAS Pixel Detector: Geometry

- Planar n+ -on- n sensors on 256 ± 3μm thick n-bulk wafer
- Innermost layer: r = 50.5 mm w.r.t. beamline
  - Radiation tolerance 500kGy / 1 × 10^{15} n_{eq}/cm^2
- evaporative cooling system integrated into support structure:
  - Operational average temperature: T = -13°C
  - Scheduled maintenance warm-up periods: T = +20°C
- The max. bias voltage spec: 600 V
  - while detector systems have been tested at bias HV ≤1kV



Introduction (II)

ATLAS Pixel Detector: Geometry

Barrel Region of ATLAS Pixel Detector

Layer Number	Mean Radius [mm]	Number of Staves	Number of Modules	Number of Channels	Active Area [m^2]
0	50.5	22	286	13,178,880	0.28
1	88.5	38	494	22,763,520	0.49
2	122.5	52	676	31,150,080	0.67
Total		112	1456	67,092,480	1.45

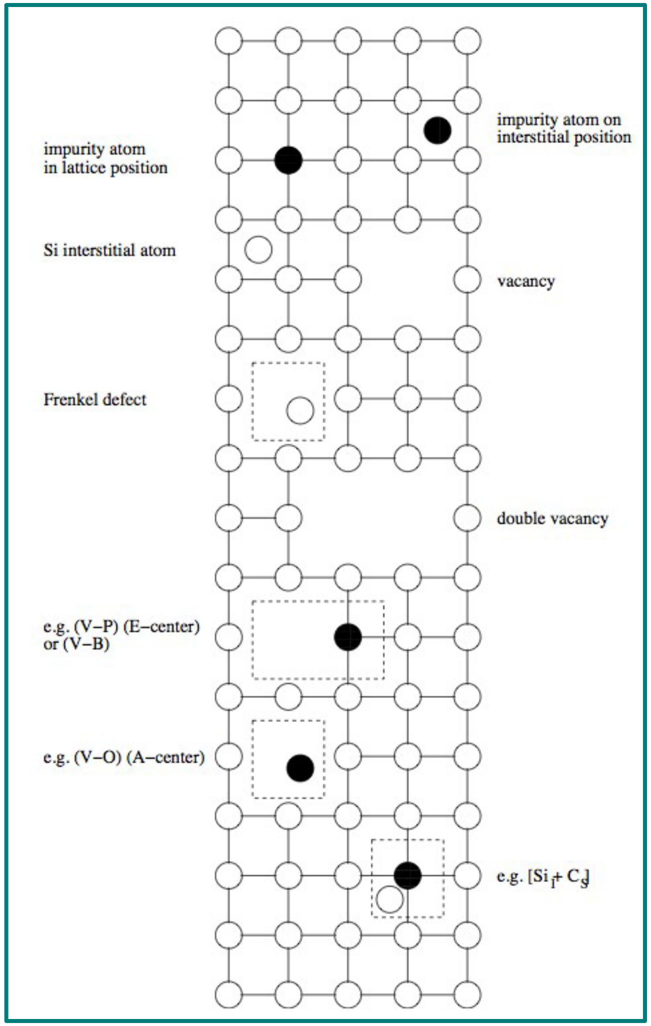
End Cap Region of ATLAS Pixel Detector

Disk Number	Mean *z* [mm]	Number of Sectors	Number of Modules	Number of Channels	Active Area [m^2]
0	495	8	48	2,211,840	0.0475
1	580	8	48	2,211,840	0.0475
2	650	8	48	2,211,840	0.0475
Total one endcap		24	144	6,635,520	0.14
Total both endcaps		48	288	13,271,040	0.28

- Total number of modules: 1456 + 2×144 = 1744
- Each sensor with 46,080 channels …
- In total: 67,092,480 (barrel) + 2×6,635,520 (disks)
  = 80,363,520 channels
- Total instrumented area: ~1.7m2

Radiation Damage (I)

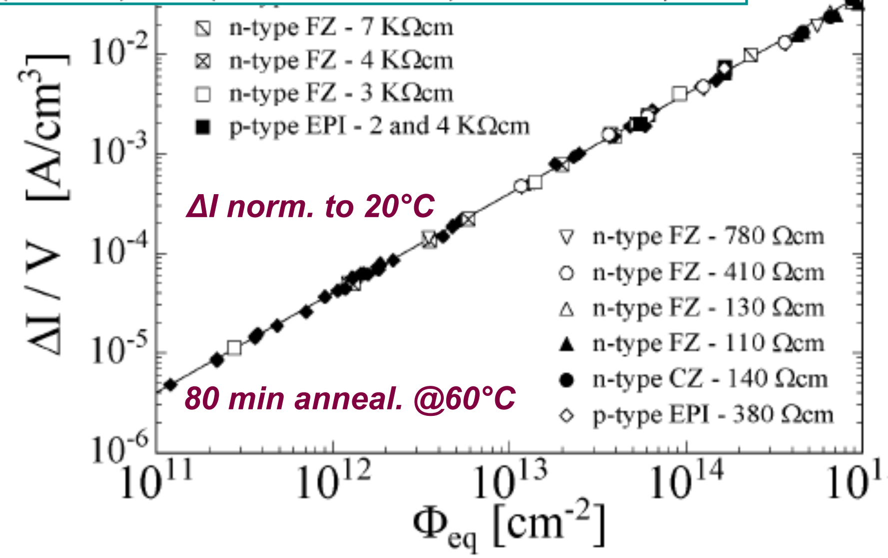
- Dominant radiation damage
  - Displacement defects in a bulk
  - Due to Non-Ionizing Energy Losses (NIEL)
  - Flow of charged $\pi^{\pm}$ from ATLAS I.P.
- Three effects:
  - Charge carrier trapping
    - localized trapping centers
    - if the time to re-emit the trapped charge carrier is longer than the shaping time then the charge collection efficiency degrades
    - loss of induced charge causing reduction of signal
    - dominant at $\Phi \geq 1 \times 10^{15}\ n_{eq}/cm^2$
  - Leakage current
    - electron-hole generation on defect centers increase the leakage current, degrading signal/noise and requiring more cooling (-13°C)
  - Change of N_{eff} concentration and voltage V_{dep}
    - effectively inversion into "p-type"
    - increasing of V_{dep}
    - requiring higher bias voltages
    - effect should be visible at $\Phi < 1 \times 10^{15}\ n_{eq}/cm^2$



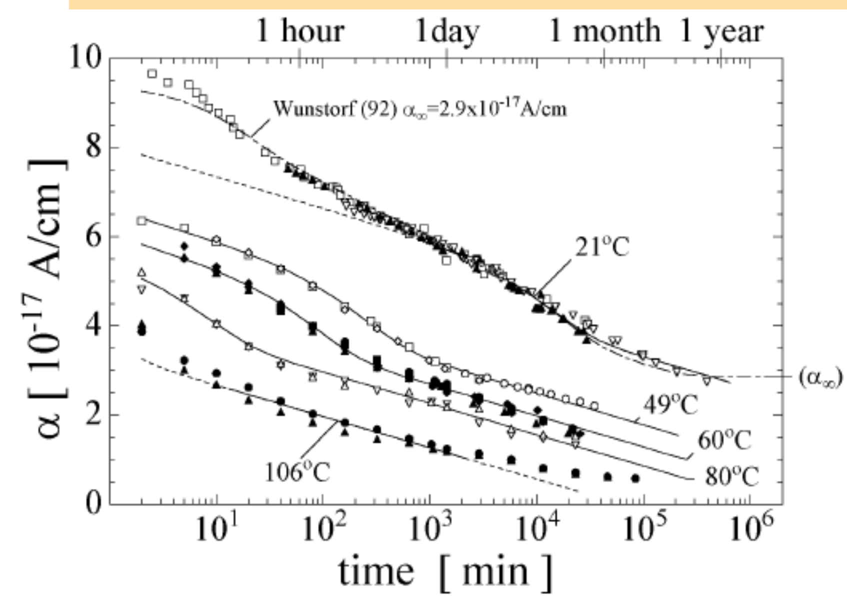
Annealing (I)

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

- **Defects in a crystal bulk can anneal**
  - **Diffusion: defects migrating until gettering at sinks; form new complex defects.**
    - **examples: interstitials and vacancies mobile at room temperatures**
  - **Dissociation.**
  - **Strongly temperature dependent**
  - **Have different activation energies depending on the defect type**
- **Trapping: beneficial annealing**
  - **the electron trapping times increase for realistic annealing times resulting in higher signal yield**
- **Leakage current: beneficial annealing**
  - **leakage current reduced during annealing; typically factor of 2 can be annealed**
  - **then operation at cool temperatures**



Source: M. Moll *et al., NIM* A426 (1999) 87



Annealing (II)

- **Depletion voltage U_{dep} and effective doping concentration $|N_{eff}|$**
  - the change observed for $|N_{eff}|$ ($=U_{dep}$) measured immediately after irradiation
  - donor removal and acceptor generation finally result in *n-type to p-type inversion* of the bulk
  - in contrast to the damage rate , α, depletion voltage V_{dep} (N_{eff}) time dependence is subject to both beneficial, N_A and reverse annealing, N_Y :

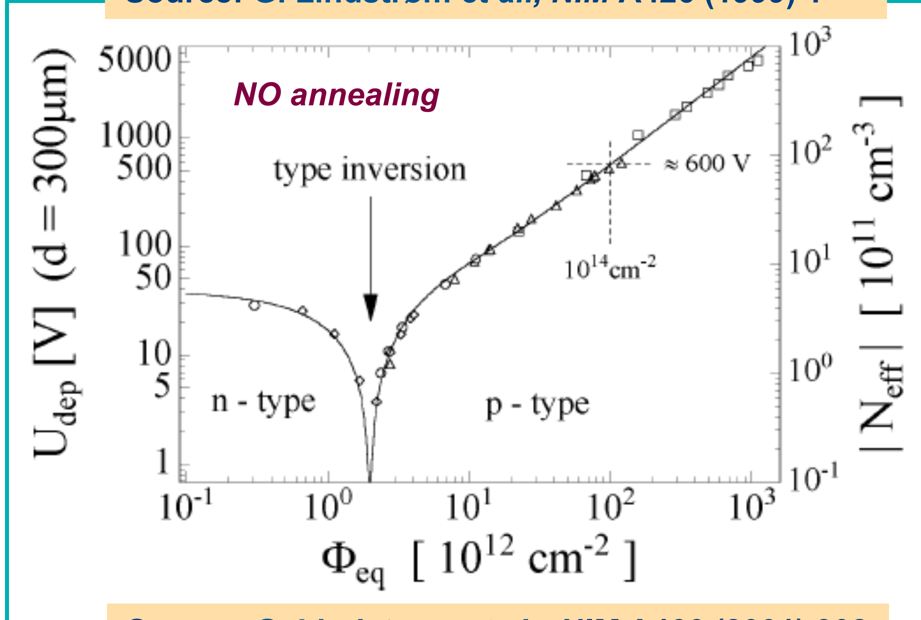
in contrast to the damage rate , α, depletion voltage V_{dep} ($|N_{eff}|$) time dependence is subject to both beneficial, N_A and reverse annealing, N_Y.

Hamburg Model:

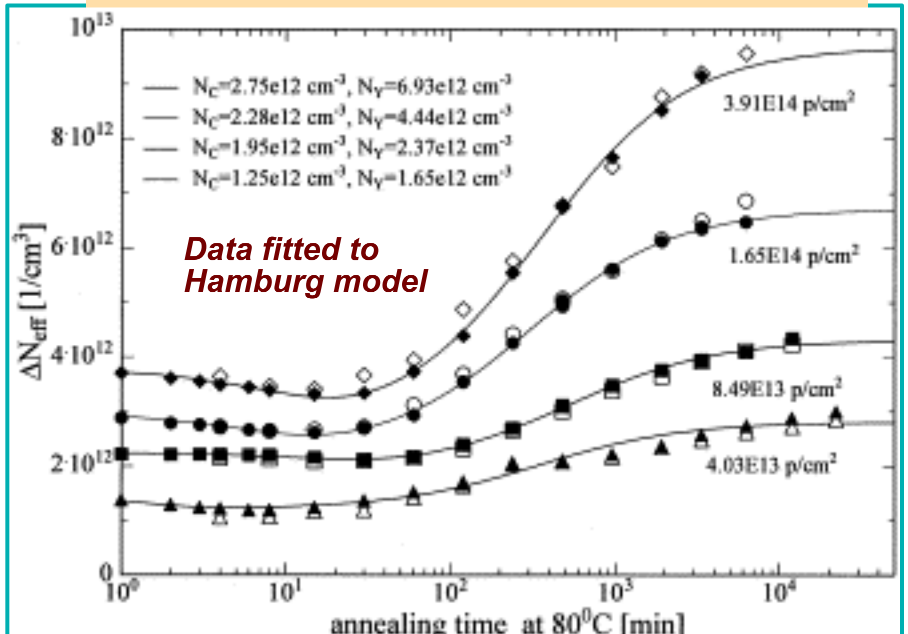
$$\Delta N_{eff}(\Phi_{eq}, t(T_a)) = N_{eff,0} - N_{eff}(\Phi_{eq}, t(T_a)$$

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

Source: G. Lindstrøm *et al., NIM* A426 (1999) 1



Source: G. Lindstrøm *et al.,* NIM A466 (2001) 308

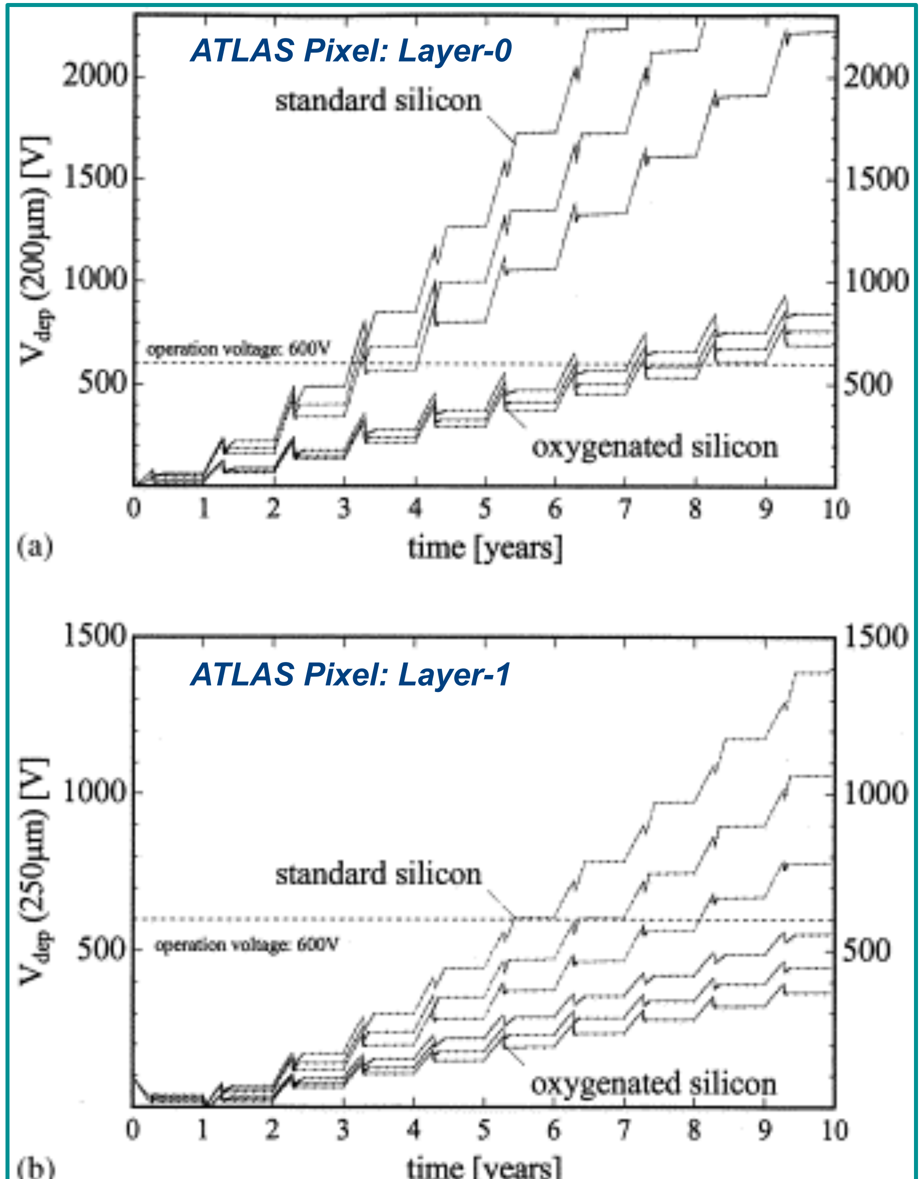


Realistic Annealing Predictions (III)

- **Realistic LHC scenario for ATLAS pixel sensors**
  - **Hamburg model is applied**
  - **Warm-up Scenarios for maintenance periods:**
    - **3 days @ T_A=20°C and 14 days @ T_A= 17°C**
    - **30 days @ T_A=20°C**
    - **60 days @ T_A=20°C**
  - ***beams ON* : T_{oper} = -13°C**
  - **to keep depletion voltage for the planned running period**

  V_{dep} ≤ 600V (ATLAS Pixel spec.)

  the reverse annealing should be suppressed:
    - **the pixel detector modules must be kept cold when *beams are OFF* except of a short maintenance period**



Source: R. Wunstorf, NIM A466 (2001) 327

Leakage Current Measurement System

- **Monitoring of ATLAS pixel sensors with leakage current measurements done in situ and in real time**
  - ***no special runs required***
- **Leakage current is measured for individual sensors (typically 4 per half-stave) with staves instrumented evenly over every layer**
- **The currents should be monitored over long period**
  - **wide dynamical range**
  - **$\Phi_{1MeV\,eq} \leq 1.0 \times 10^{+15}$ cm^{-2}**
- **Differential analysis of the radiation damage in various parts of the detector vs integrated lumi ($\propto \Phi_{eq}$)**
- **Measure the leakage currents against integrated luminosity ($\propto \Phi_{eq}$) and compare with the model predictions**
  - ***calibrate the model parameters with experimental data***
  - ***use the adjusted model to project the depletion voltage development in time at various LHC / ATLAS data taking scenarios***

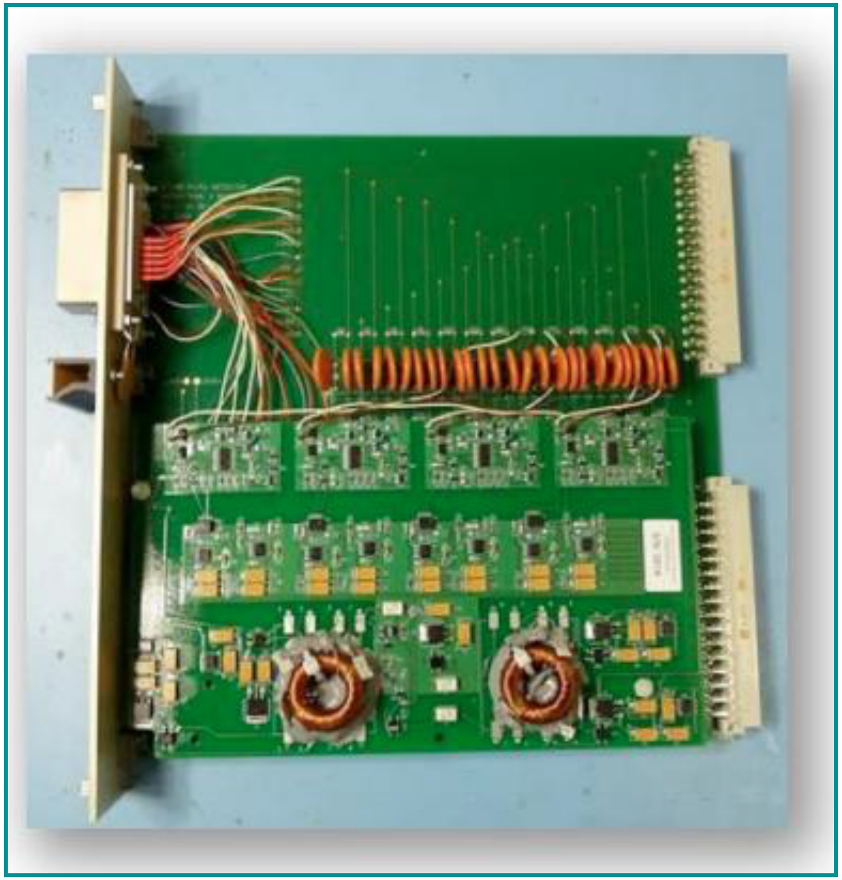
Technical Solution: Leakage Current Measurement System

- Main system unit: Current Measurement Board (or *CMB*)
  - ***Direct measurement of an individual pixel sensor module leakage current via HV lines***
- Implemented: within the reconfigurable HV patch panel (or *HVPP4*) between HV cables coming from Pixel detector (*PP1*) and power supply (*Iseg*) HV channels
  - Current Measurement Board *(CMB)* is mounted on a corresponding HV fan-out board of *HVPP4*
- Power Supply (*Iseg*) current measurements
  - the power is delivered per half-stave comprising 6 or 7 modules
  - ***the measurements of a leakage current drawn by ganged 6 or 7 modules are provided***
- The measured current values are digitized, transmitted via data (CAN) bus to the DCS by CERN developed digital board *(ELMB)*
  - 64 digital channel
  - served by 16 bit ADC
  - digitizing voltages fed by *CMB*
  - current data from Iseg power supply channels
- PVSS software is reading out the data from *ELMB* boards and downloading the data to DCS database (large DCS storage)
- Physics analysis on the radiation damage proceeds offline using data accessed from DB

Current Measurement Board (I)

- $(0.05\,\mu\mathrm{A}\,,\,2\,\mathrm{mA})$, dynamical range of $\sim 0.4 \times 10^5$
- CMB output voltage: $(0\,,\,5)\mathrm{V_{DC}}$ to comply the digital board ELMB specs
- the circuitry: a current to frequency converter, optically coupled to a frequency to voltage converter
- the board is a multi-layer PCB with
  - 4 current measurement circuits
  - high gain + low gain channels / circuit : 4×2
- the pairs of channels are isolated from each other and from the pixel module readout system

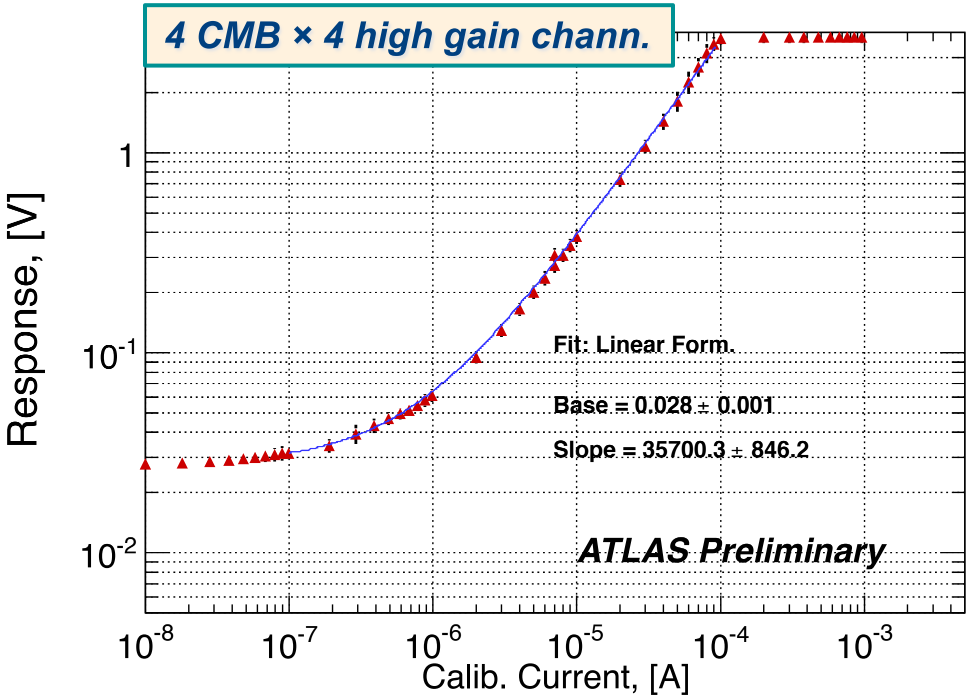
NO in situ calibration system is available.

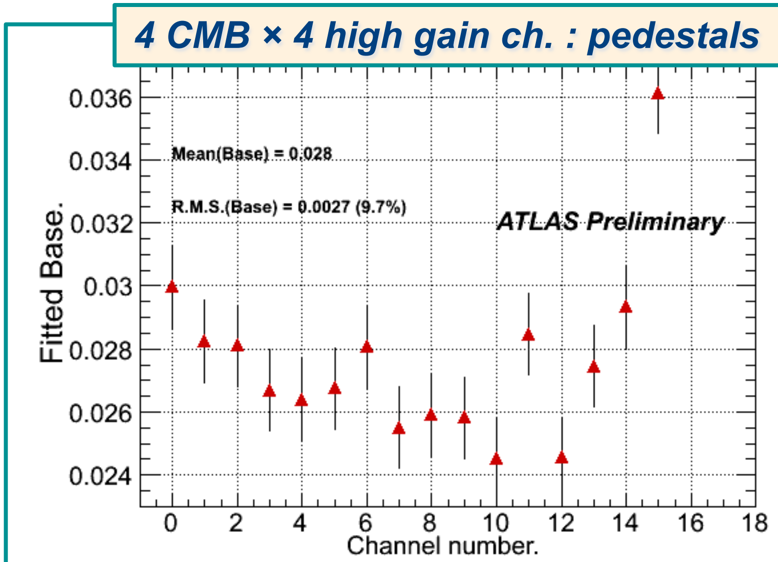


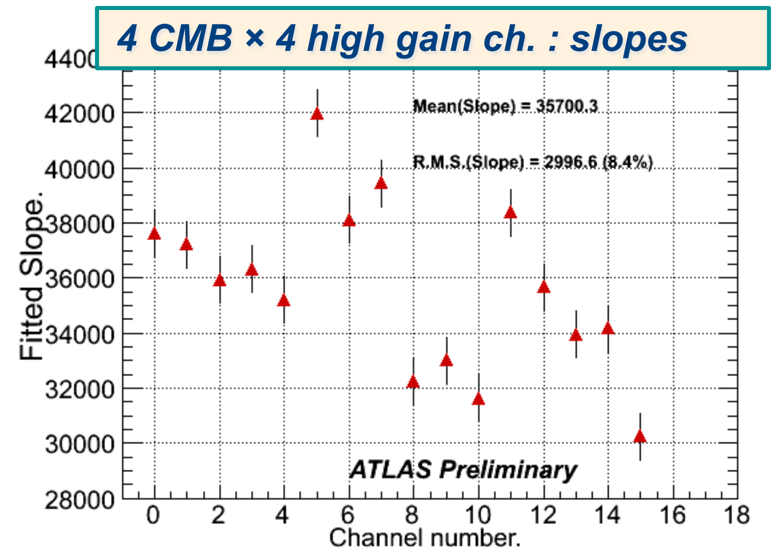
- realistic voltage range (present setting) for ADC: $(0.0,\,1.0)\,\mathrm{V}$
  - $(0,\,65535)$ of 16-bit
  - high gain: $LSB = 15.3\,\mu\mathrm{V} \approx 0.5\,\mathrm{nA}$
  - low gain: $LSB = 15.3\,\mu\mathrm{V} \approx 18\,\mathrm{nA}$

Current Measurement Board: Calibration (II)

Calibration runs made with a test stand on surface (bldg. SR1)





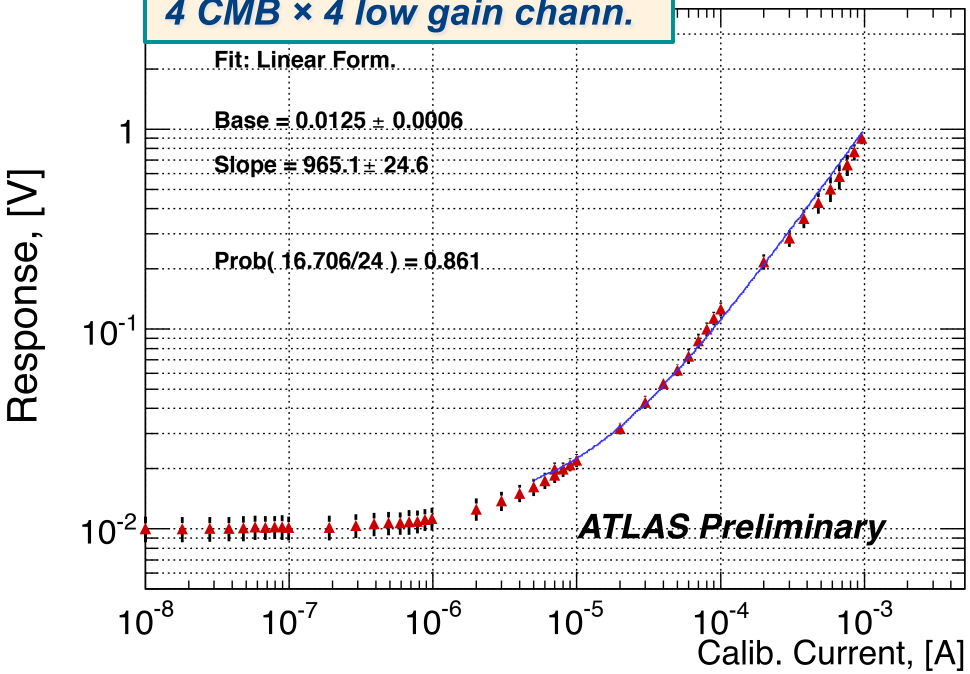


Fit individual channels with linear form:
and store intercept (pedestal) and slope per CMB/channel

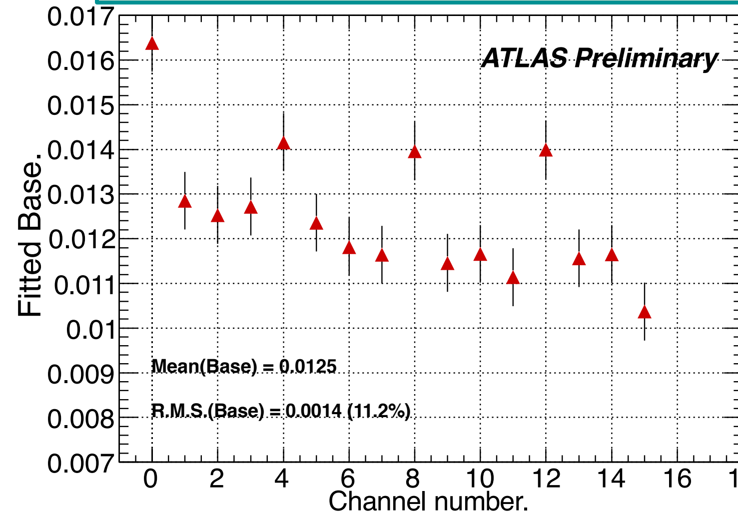
Current Measurement Board: Calibration (III)

Calibration runs made with a test stand on surface (bldg. SR1)

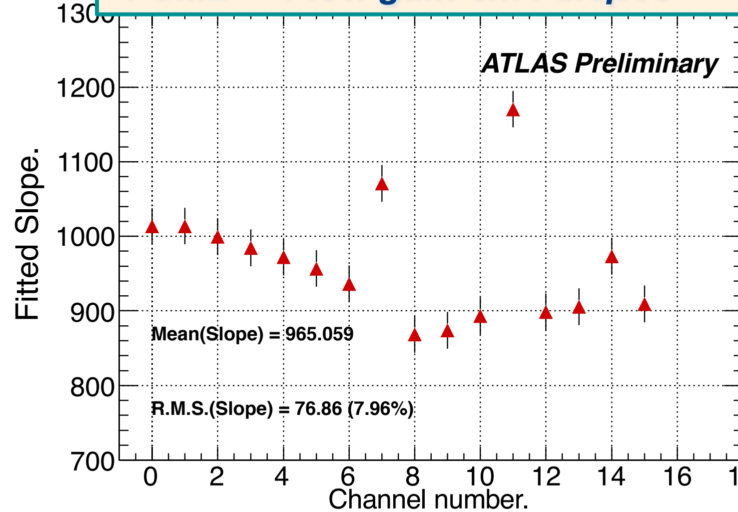
4 CMB × 4 low gain chann.



4 CMB × low gain ch. : pedestals



4 CMB × 4 low gain ch. : slopes



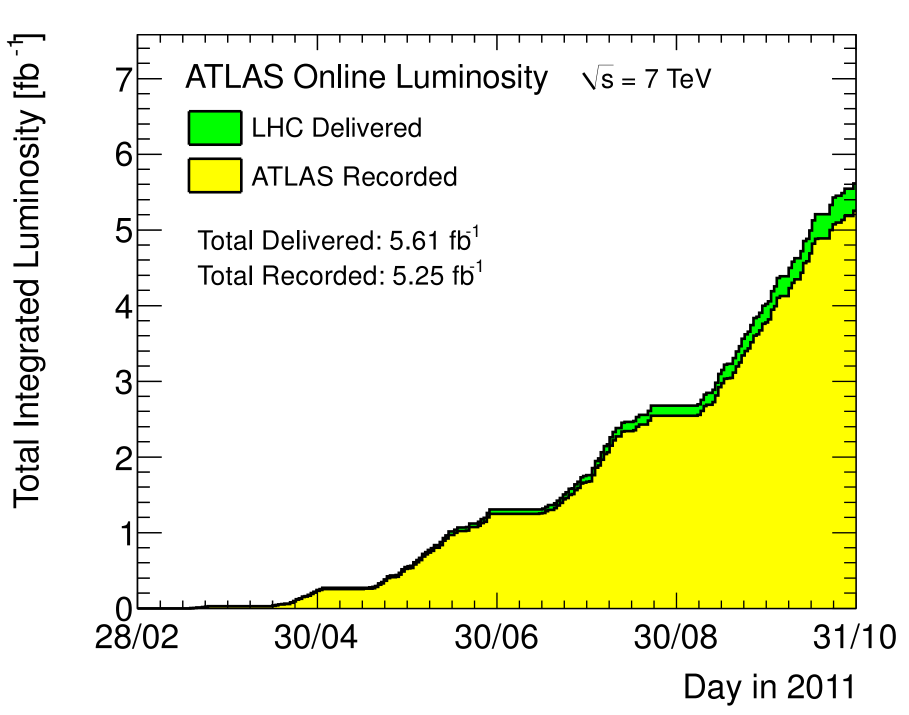
Fit individual channels with linear form:

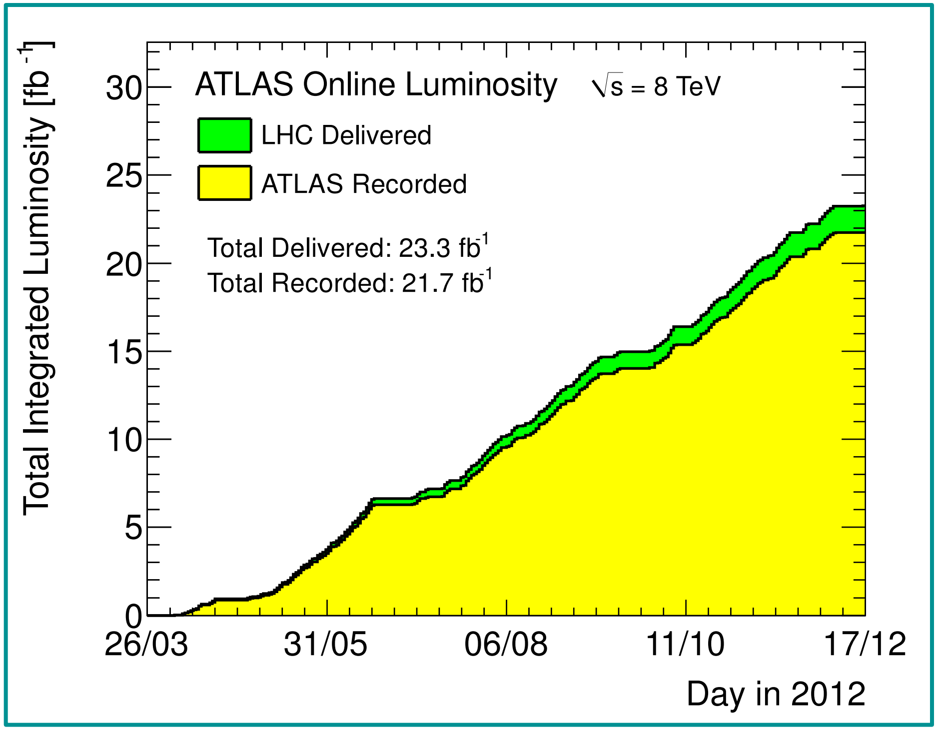
and store intercept (pedestal) and slope per CMB/channel

Current Measurement Boards: Status (IV)

- Barrel only
- Select pixel modules to instrument the barrel area in a uniform way along z and ϕ
- Layer 0 (innermost):
  - **21 CMBs installed**
  - $\mathbf{21 \times 4 = 84}$ modules instrumented
- Layer 1 (intermediate):
  - **16 CMBs installed**
  - $\mathbf{16 \times 4 = 64}$ modules instrumented
- Layer 2 (outermost):
  - **16 CMBs installed**
  - $\mathbf{16 \times 4 = 64}$ modules instrumented
- The hardware installation, analog CMB and digital ELMB boards, completed in June 2012

Luminosity Collected: 2011-2012





$$\int \mathcal{L}\,dt \propto \mathbf{\Phi_{1MeV\,eq}}$$

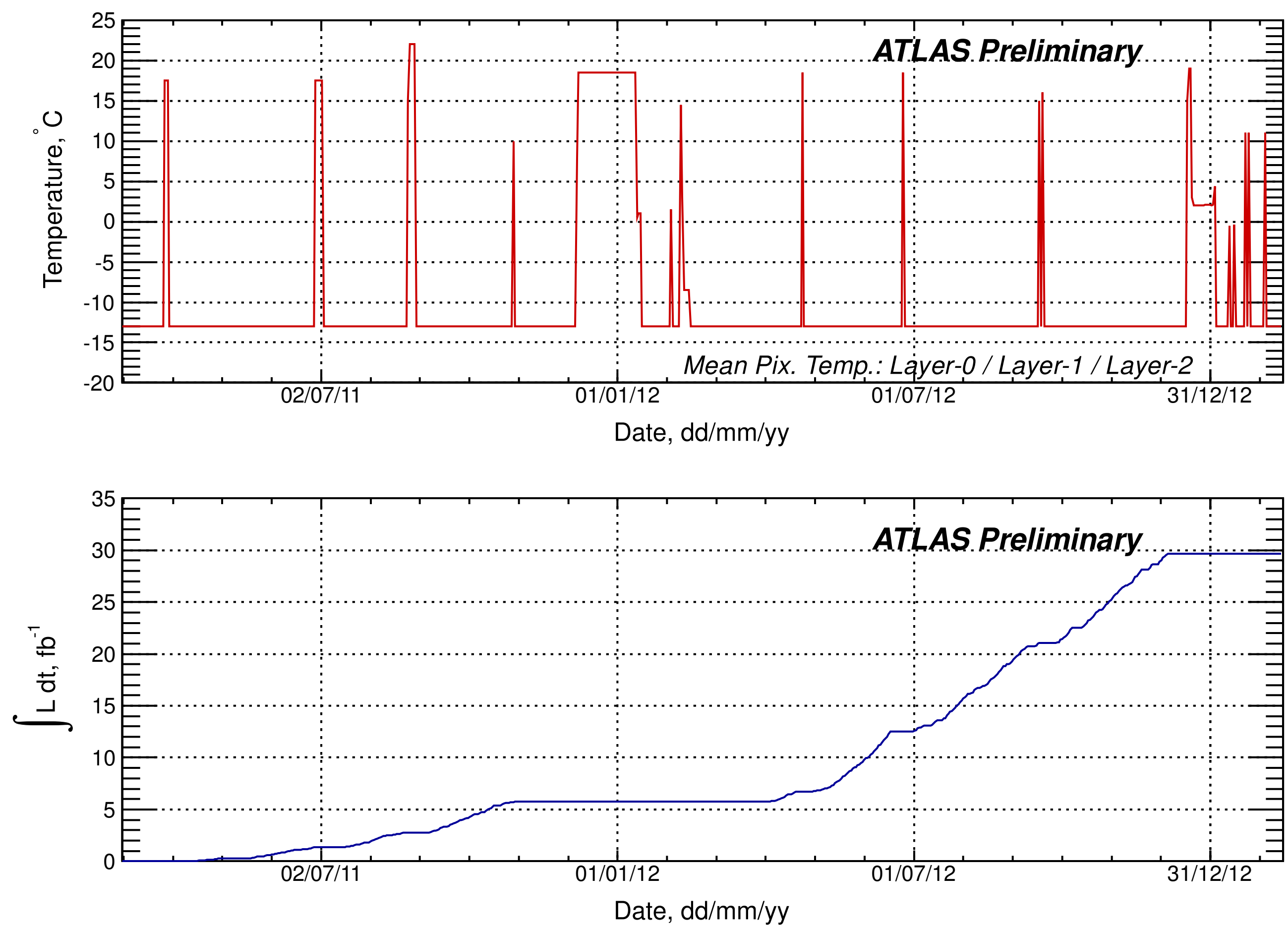
$$\int \mathcal{L}\,dt = \mathbf{5.61}\,\mathrm{fb}^{-\mathbf{1}}(\sqrt{s} = \mathbf{7}\,\mathrm{TeV})$$

$$+ \mathbf{23.3}\,\mathrm{fb}^{-\mathbf{1}}(\sqrt{s} = \mathbf{8}\,\mathrm{TeV}) \approx \mathbf{29}\,\mathrm{fb}^{-\mathbf{1}}$$

Temperature and Luminosity Profiles

Data from D. Münstermann and A. Schorlemmer (ATLAS/Geneva, Göttingen)

- Temperature per day 2011-2012 profile used in the analysis
- Operational $t = -13°C$, very stable
- Technical stops, winter shutdowns, cooling failures are the main causes of warm-ups
- Actually, use readings from temperature sensors mounted on pixel modules
- $\int \mathcal{L}\, dt$ per day, 2011-2012 profile

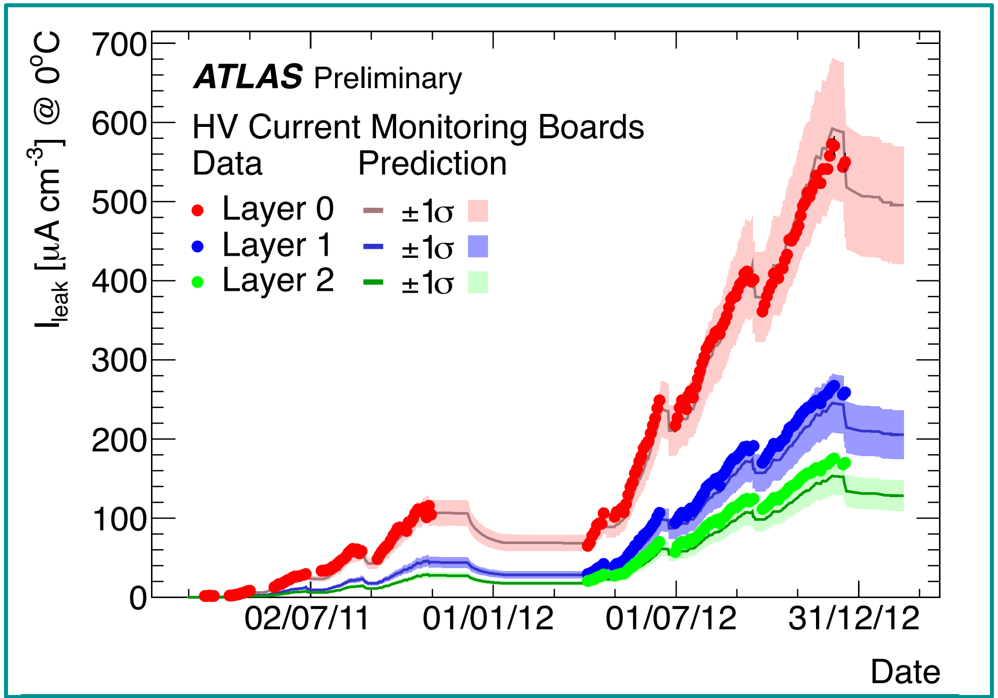


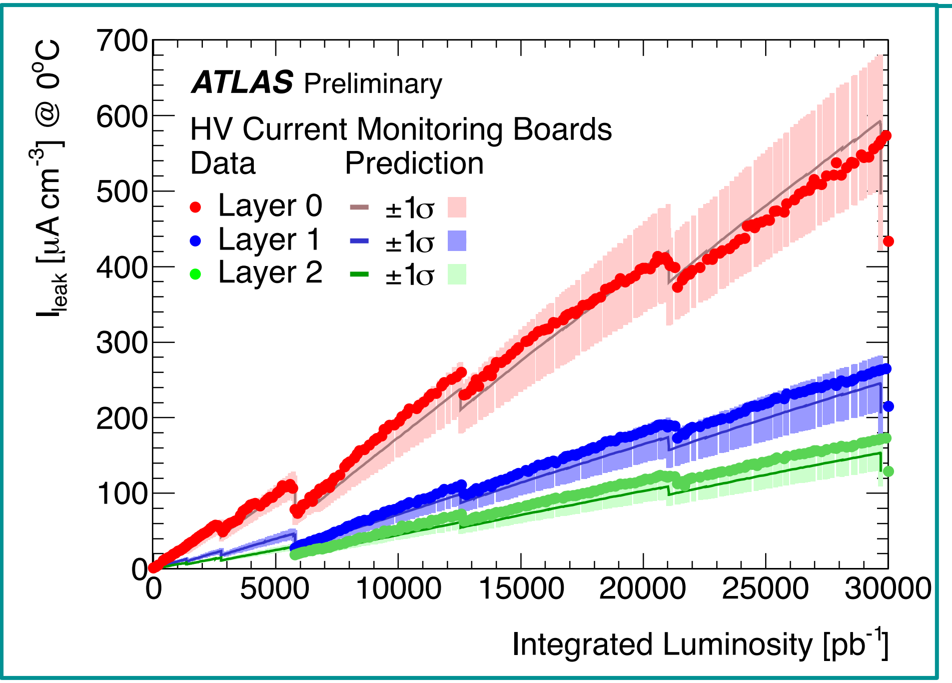
$$I(T) = I(T_R)/R(T),\ R(T) = (T_R/T)^2 \cdot \exp\left(-\frac{E_g}{2k_B}(1/T_R - 1/T)\right)$$

$$E_g = \mathbf{1.21}\,\text{eV},\ \mathbf{T_R}(°\text{K}) = \mathbf{0°C} + 273.15°$$

Leakage Current Data

- Exp data, (voltage, V) per chann. converted to (current, A) per chann.
  - most recent calibrations per channel made on surface (SR1)
  - cross-calibration with Iseg power supply current data
- Current values renormalized from $t_{\rm oper.} \approx -13°C$ to $t = 0°C$; per channel corr.
- Mean current value per Layer-0, Layer-1, Layer-2 are presented⇒
- $\Phi_{1MeV\,n} \propto \int \mathcal{L}\,dt$, using `Fluka+Phojet`
- Model predictions: O. Krasel, D. Münstermann, J. Weber A. Schorlemmer (ATLAS/ Dortmund,Geneva,Göttingen)



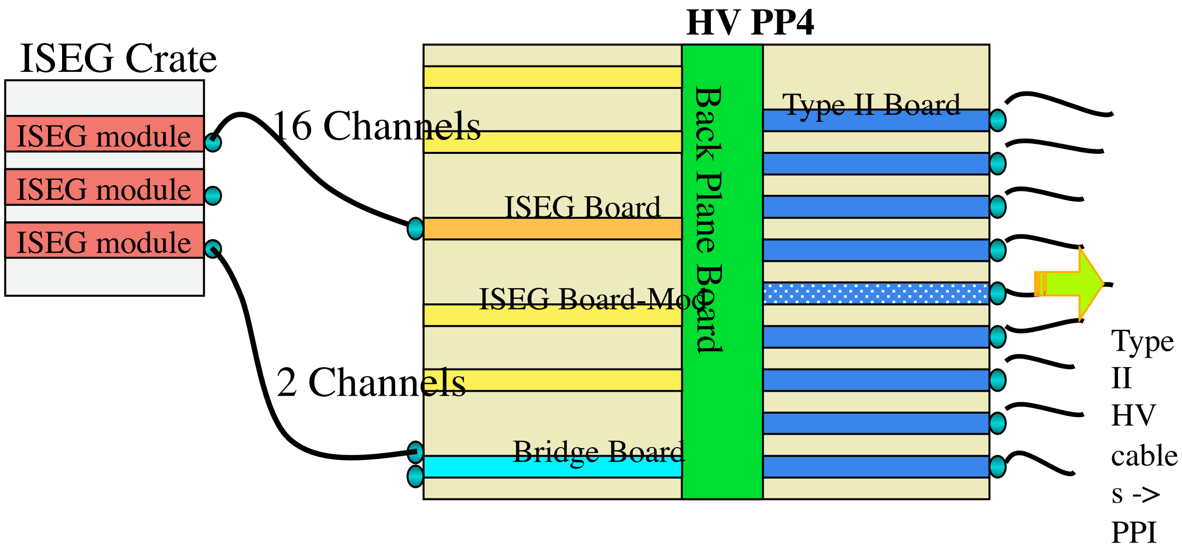


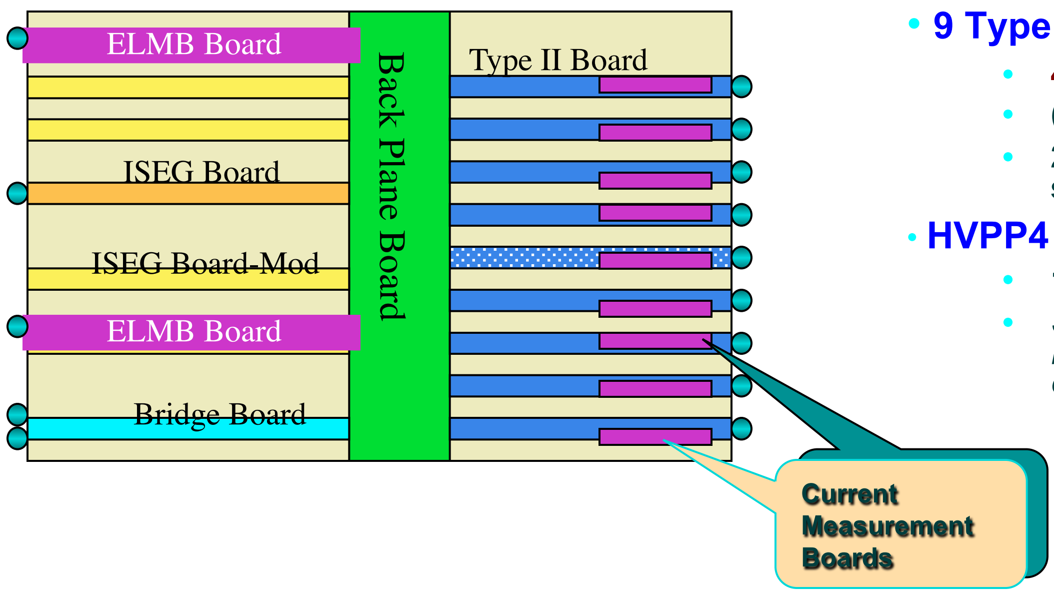
Summary

- A dedicated hardware to measure the leakage current in ATLAS pixel sensors has been implemented
  - available for the online monitoring
  - the stored data are used for the radiation damage analysis
- The radiation damage of the pixel sensor modules has been observed and measured for the 2011-2012 data taking period
  - the radiation damage data has been obtained in situ for the sensors of the ATLAS Pixel detector at its running conditions
- The measurements are compared with the model predictions made for the corresponding luminosity / fluence profile over 2011-2012
  - the data to model agreement is quite good within $\pm 1\sigma$

Back up slides …

Current Measurement Board (I)

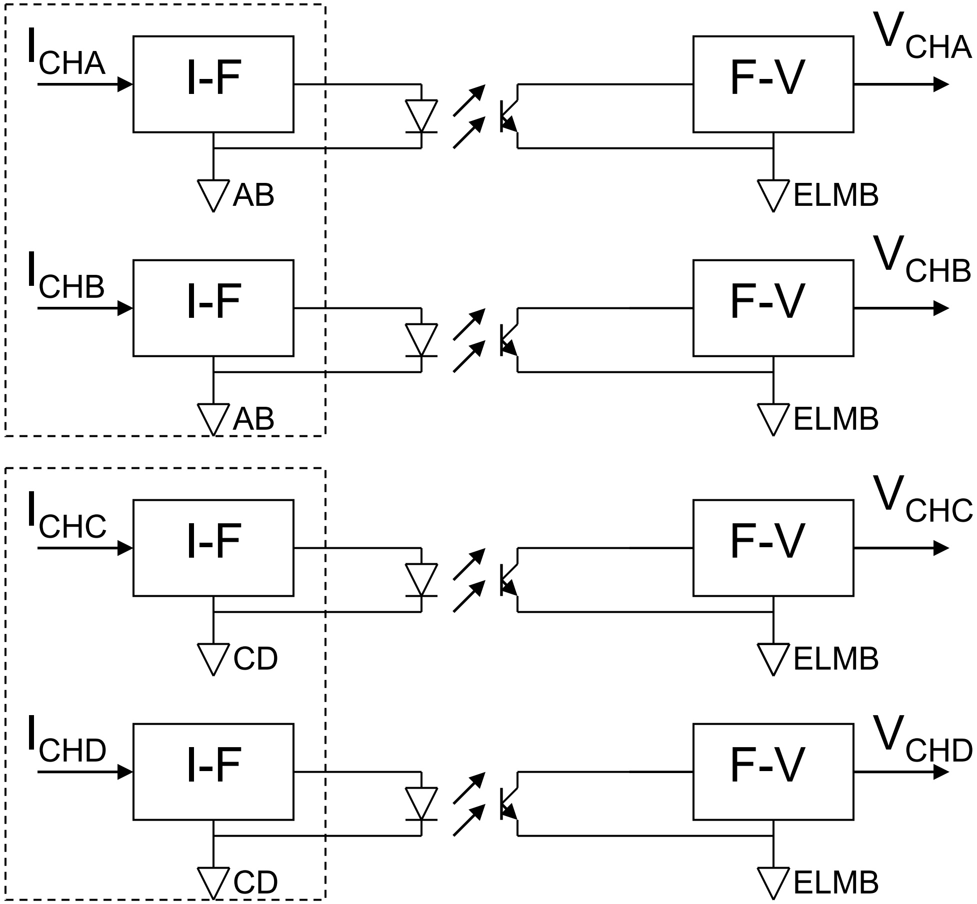




- **Present HVPP4 System:**
  - **Fan-out of the bias-voltages from ISEG power supply modules**
  - **1744 pixel modules**
- **New HVPP4 System: extended with:**
  - **Current Measurement Boards attached to the Type II boards**
  - **Analog-to-digital conversion ELMB boards**
- **9 Type II boards / VME crate**
  - **4 cha. / current meas. board**
  - **(< 9) × 4 cha. / crate**
  - **2 ELMB board to digitize and send data**
- **HVPP4 Total: 16 VME crates**
  - **16 × 9 × 4 = 576 channels**
  - ***Some amount of channels will not be used due to complicated mapping***

Current Measurement Board (III)

Current Monitor Scheme

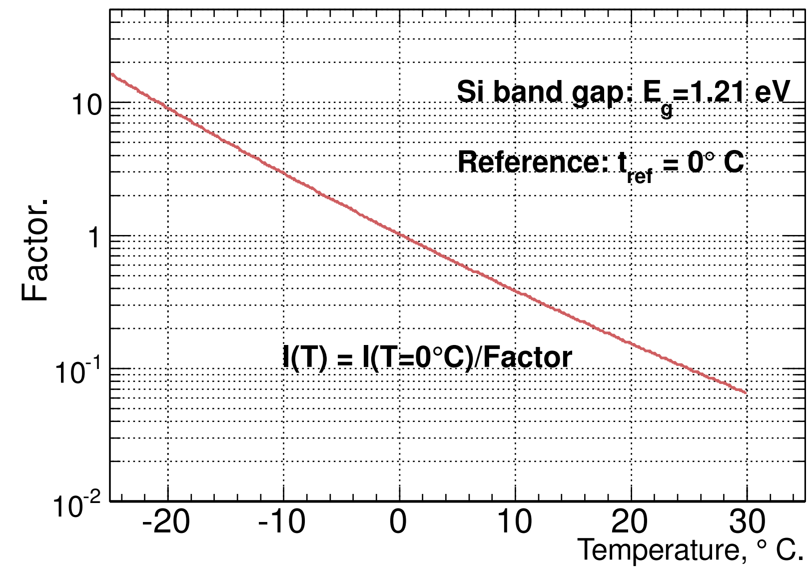


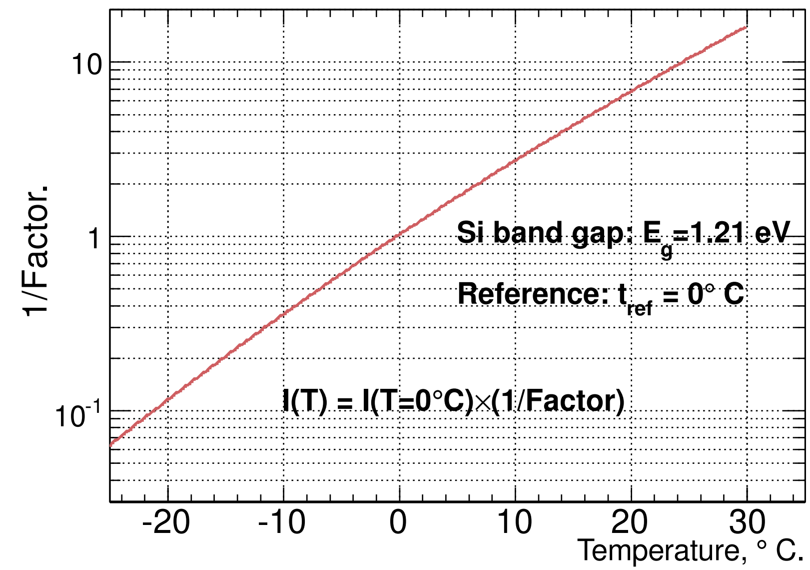
- **Circuit is a current-frequency converter**
- **Optically coupled to a freq-voltage converter.**
- **4 circuits per board**
- **Isolated in pairs of channels from each other and from the readout system**

Leakage Current (I)

- Current Measurements for every pixel module provide the powerful tool to monitor the status of every sensor and hence the quality of ATLAS Pixel Detector data
- Use current measurement data to estimate the fluence Φ [cm^{-2}]
- Every pixel module is equipped with temperature probe and the data are readout into PvssDb
- The current measurement data should be corrected by the temperature factors: ⇒
  - Corrections are made to
    $T_R = (273.15 + 0)^oK$
    $E_g = 1.21$ eV (per Chilingarov)

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

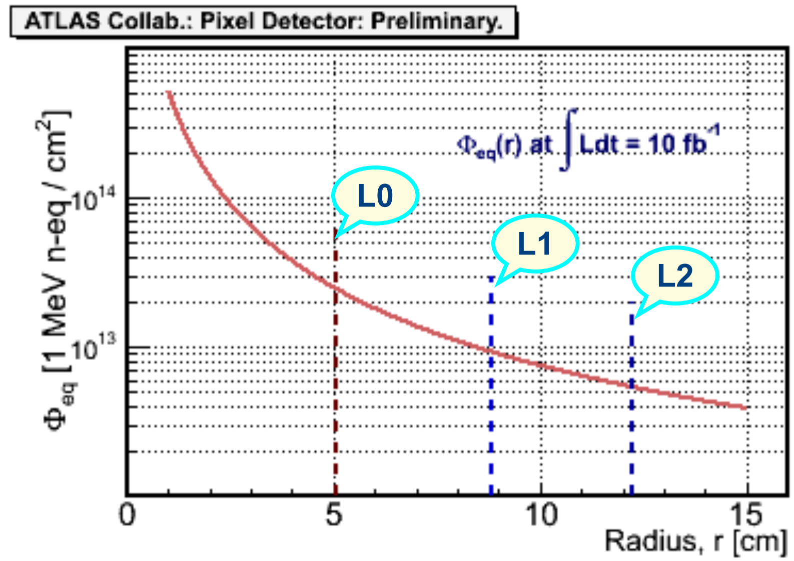


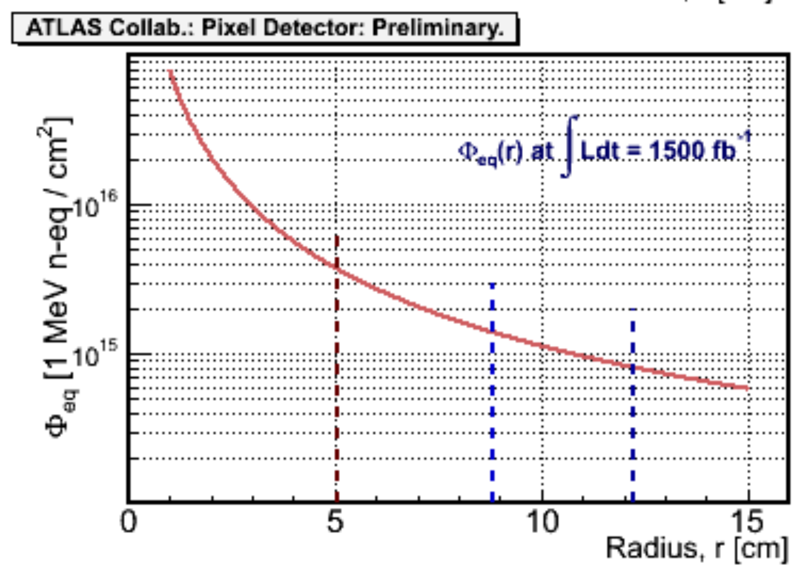


Leakage Current (III)

Fluences at Pixel Detector Area

- 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 $\Phi_{1MeV\text{-}eq}$ /1000fb^{-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%





$$\Phi_{1MeV} = (a_1 \cdot r^{-2} + a_2 \cdot r^{-1})/1000\,\mathrm{fb}^{-1},$$
$$\text{where } a_1 = 4.93 \cdot 10^{16},\ a_2 = 0.25 \cdot 10^{16}$$

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