Radiation Damage Monitoring of the ATLAS Pixel Detector

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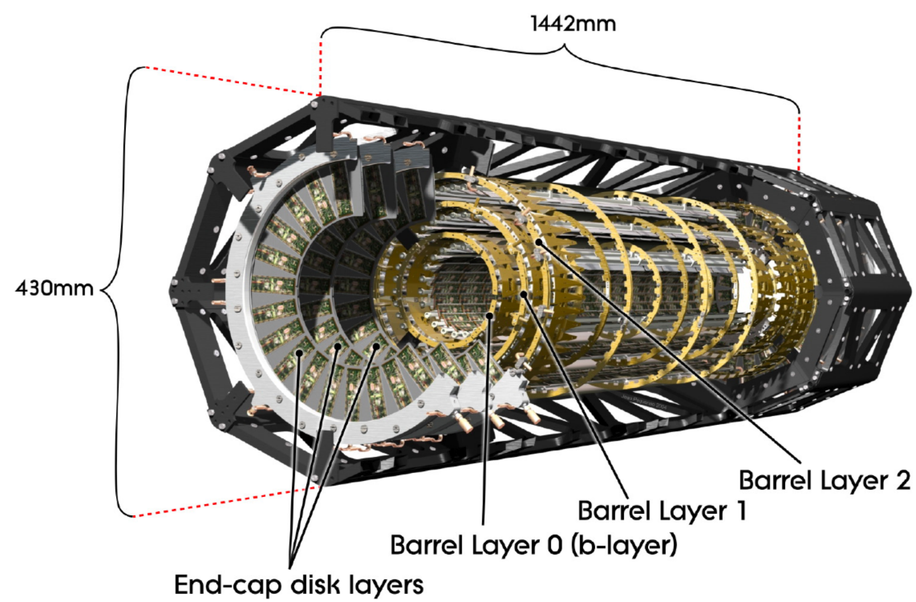
Outline

ATLAS Run 1 Pixel Detector

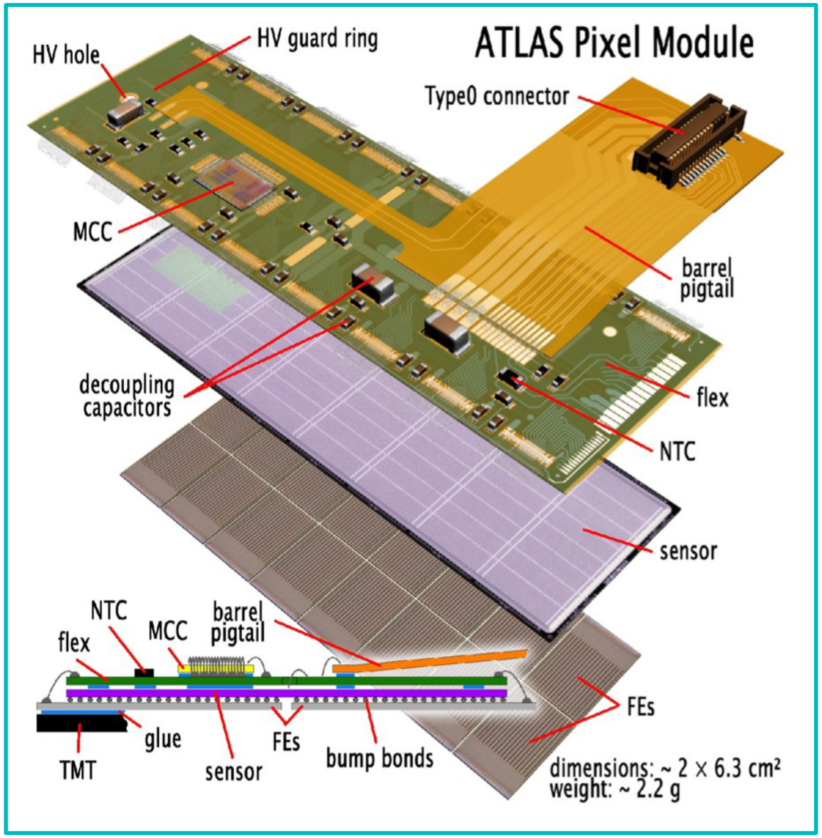
- **Introduction**
- **Radiation Damage Effects**
- **Annealing**
- **Pixel Leakage Current Measurements**
  - Data and model predictions
- **Current Measurements from HV lines**
  - Technical Solutions
  - Current Measurement Board
  - Data and model predictions
- **Summary for the Run 1 Pixel Detector and Outlook for Run 2**



Introduction (I)

ATLAS Run 1 Pixel Detector: Geometry

- Planar n^+-on-n sensors on 256 ± 3μm thick 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
    - Detector systems have been tested at bias HV ≤1kV



Introduction (II)

ATLAS Run 1 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

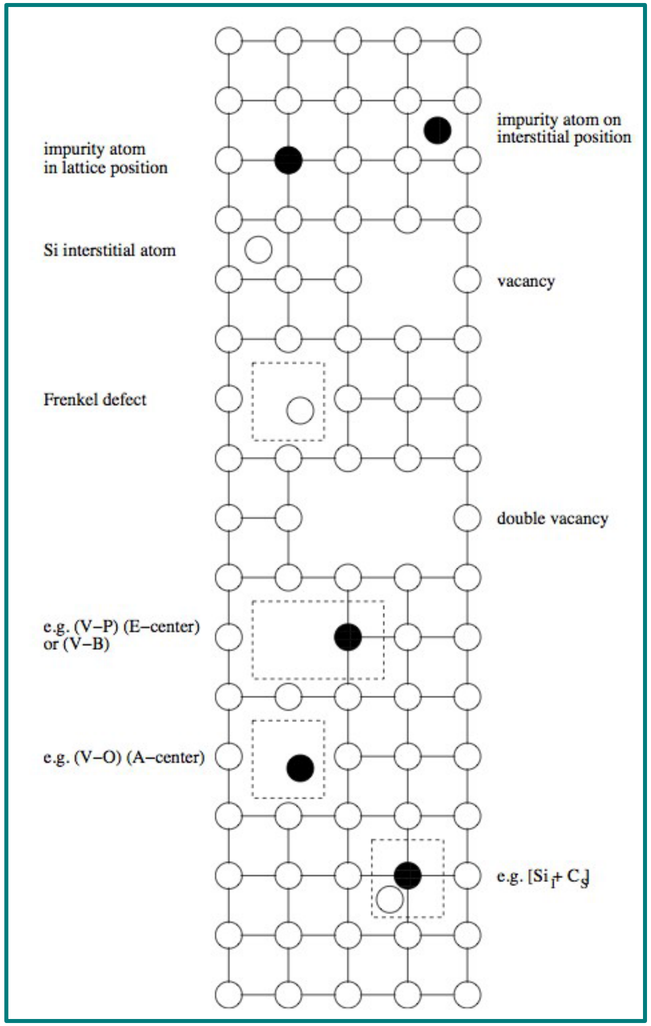
End Cap Region of ATLAS Pixel Detector

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 chip with 2880 pixels**
  - **pixel pitch size: 50μm (along ϕ) × 400μm (z, barrel or r, disks)**
- **Each module sensor with 2880 × 16 = 46,080 channels**
  - **module size: 60.8mm × 16.4mm × 0.250mm**
  - **sensors include guard ring structure**
- **In total: 67,092,480 (barrel) + 2×6,635,520 (disks) = 80,363,520 channels**
- **Total instrumented area: ~1.7m^2**

Radiation Damage Effects

- Dominant radiation damage
  - Displacement defects in the bulk
  - Due to Non-Ionizing Energy Loss (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 at defect centers increases the leakage current, degrading signal/ noise and requiring more cooling (-13°C)
  - Change of N_{eff} concentration and voltage V_{dep}
    - effectively inverts to p-type
    - increases V_{dep}
    - requires higher bias voltages
    - effect should be visible at $\Phi < 1 \times 10^{15}\ n_{eq}/cm^2$



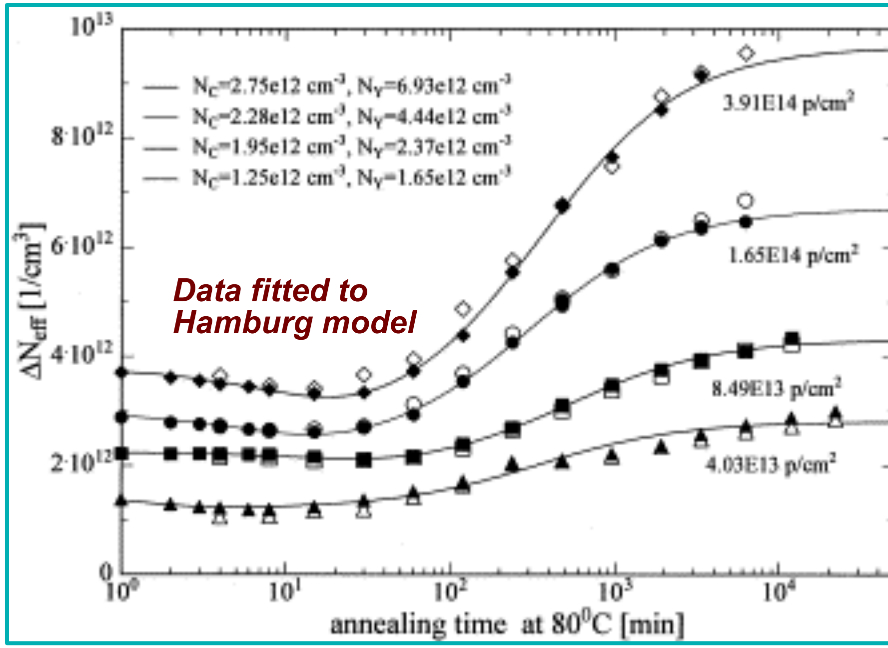
Annealing (I)

- **Defects in the crystal bulk can anneal**
  - **Diffusion: defects migrate until gettering at sinks; form new complex defects.**
    - **examples: interstitials and vacancies mobile at room temperature**
  - **Dissociation**
  - **Strongly temperature dependent**
  - **Have different activation energies depending on the defect type**
- **Trapping: beneficial annealing**
  - **the electron trapping times increase, resulting in higher signal yield**

Depletion voltage V_{dep} ($|N_{eff}|$) time-dependence is subject to both beneficial, N_A and reverse annealing, N_Y terms.

Hamburg Model:

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

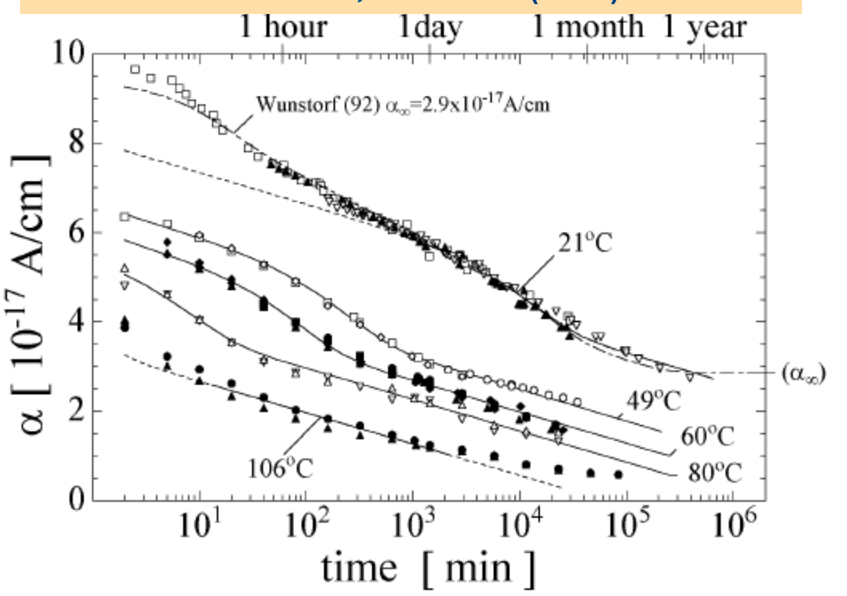


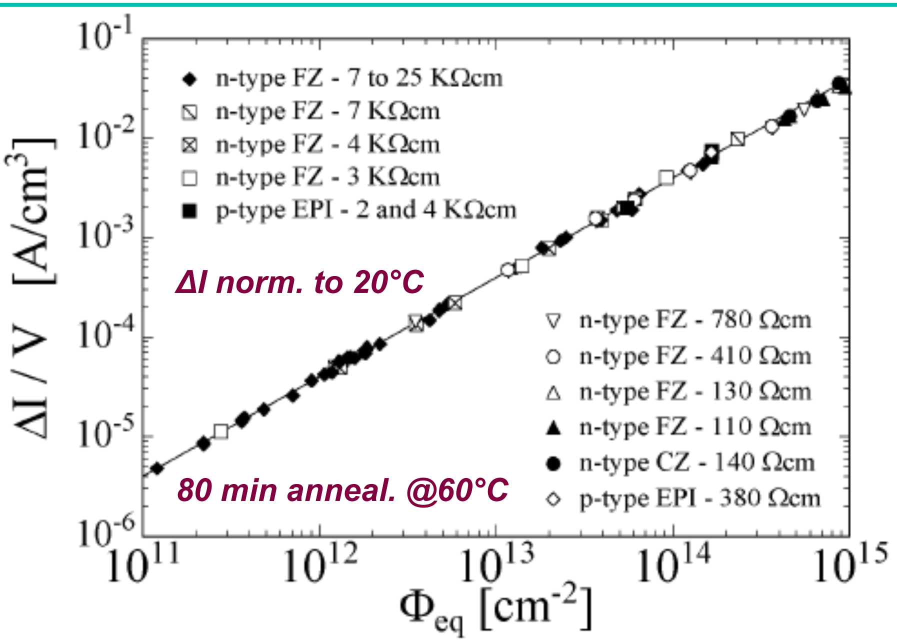
$$
\begin{aligned}
\Delta N_{eff}\left(\Phi_{eq},\, t(T_a)\right) &= N_{eff,0} \\
&- N_{eff}\left(\Phi_{eq},\, t(\tau_a)\right) \\
\Delta N_{eff}\left(\Phi_{eq},\, t(T_a)\right) &= N_C(\Phi_{eq}) \\
&+ g_A \cdot \Phi_{eq} \cdot \exp(-t/\tau_a) \\
&+ g_Y \cdot \Phi_{eq} \cdot (1 - \exp(-t/\tau_Y))
\end{aligned}
$$

Annealing (II)

- **Leakage current: beneficial annealing**
  - leakage current reduced; typically factor of 2 can be annealed
  - then operation at cool temperatures
- **Leakage current: linear behavior versus fluence**
  - due to creation of recombination / generation centers
  - proportional increase with $\Phi_{n\text{-}eq}$
  - use of guard ring

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





$$\alpha(\mathbf{t}) = \alpha_\mathbf{I} \cdot \exp(-\mathbf{t}/\tau_\mathbf{I}) + \alpha_\mathbf{0} - \beta \cdot \ln(\mathbf{t}/\tau_\mathbf{0})$$

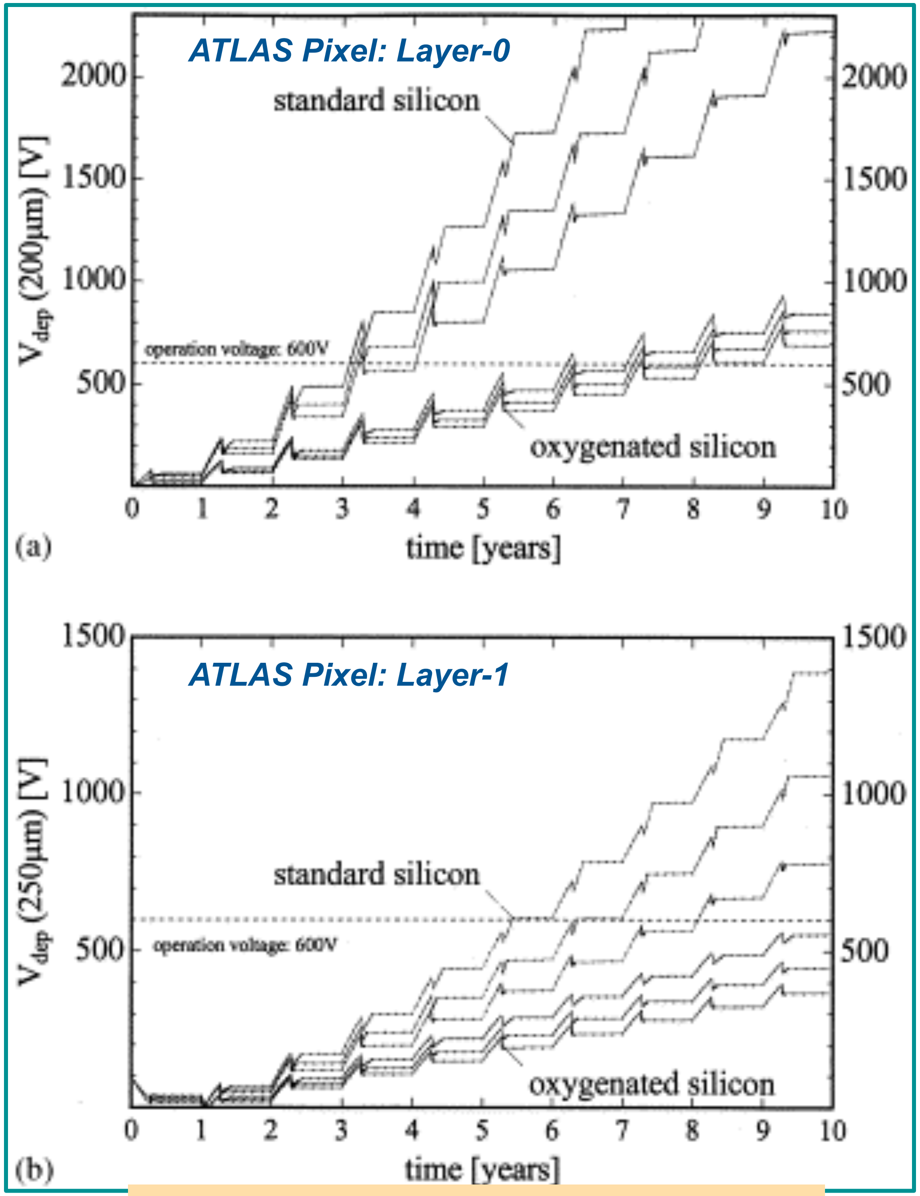
$$\Delta I = \alpha \cdot \Phi_{eq} \cdot V$$
$$\alpha(20°C) = (3.99 \pm 0.03) \cdot 10^{-17}\ \mathrm{A/cm}$$

Annealing (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

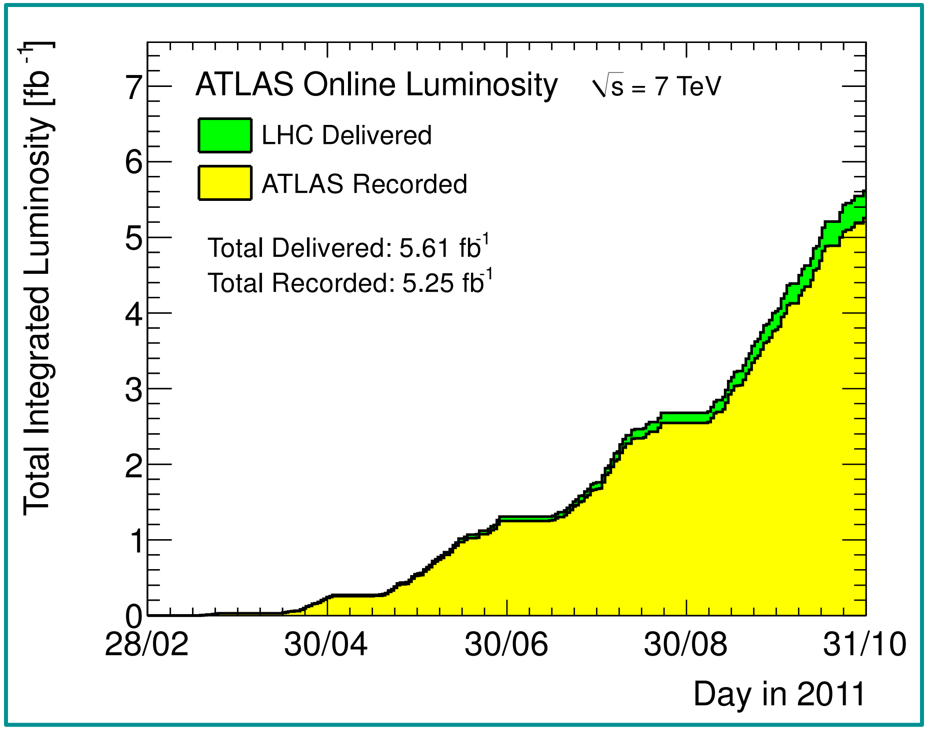
  V_{dep} ≤ 600V (ATLAS Pixel spec.)

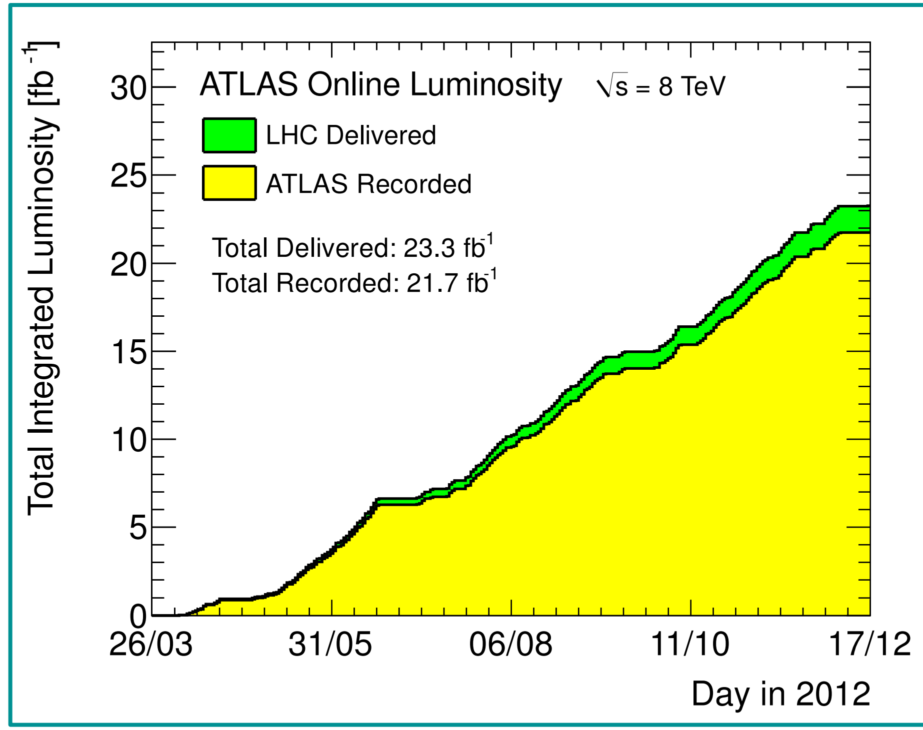
  the reverse annealing should be suppressed:
    - the pixel detector modules must be kept cold when *beams are OFF* except during the maintenance periods



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

Luminosity Collected: 2011-2012



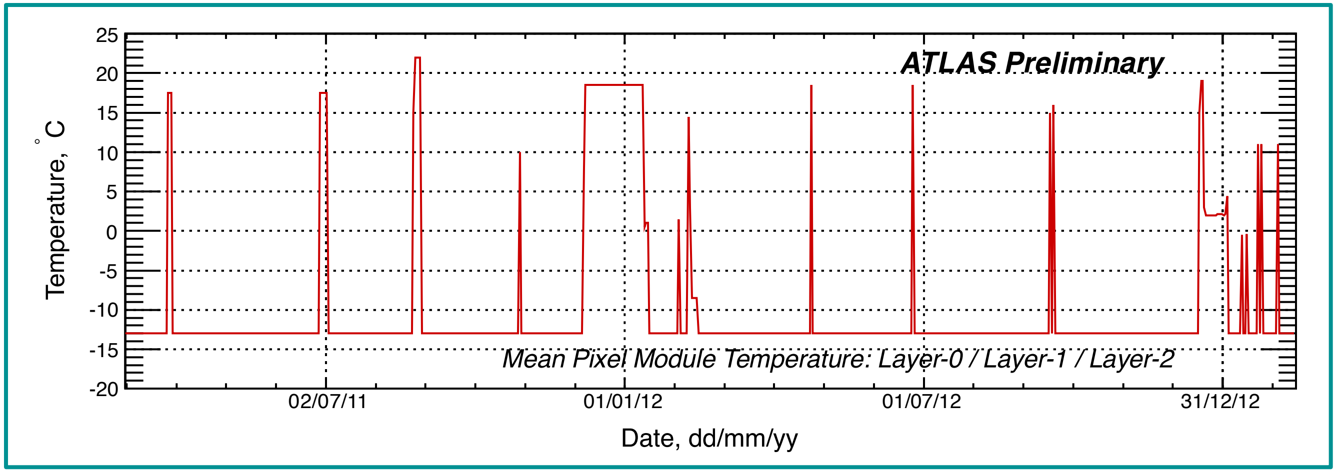


$$\int \mathcal{L}\, dt = \mathbf{5.61\,fb}^{-1}(\sqrt{s} = \mathbf{7}\,\mathrm{TeV})$$
$$+ \mathbf{23.3\,fb}^{-1}(\sqrt{s} = \mathbf{8}\,\mathrm{TeV}) \approx \mathbf{29\,fb}^{-1}$$
$$\int \mathcal{L}\, dt \propto \mathbf{\Phi_{eq}}$$

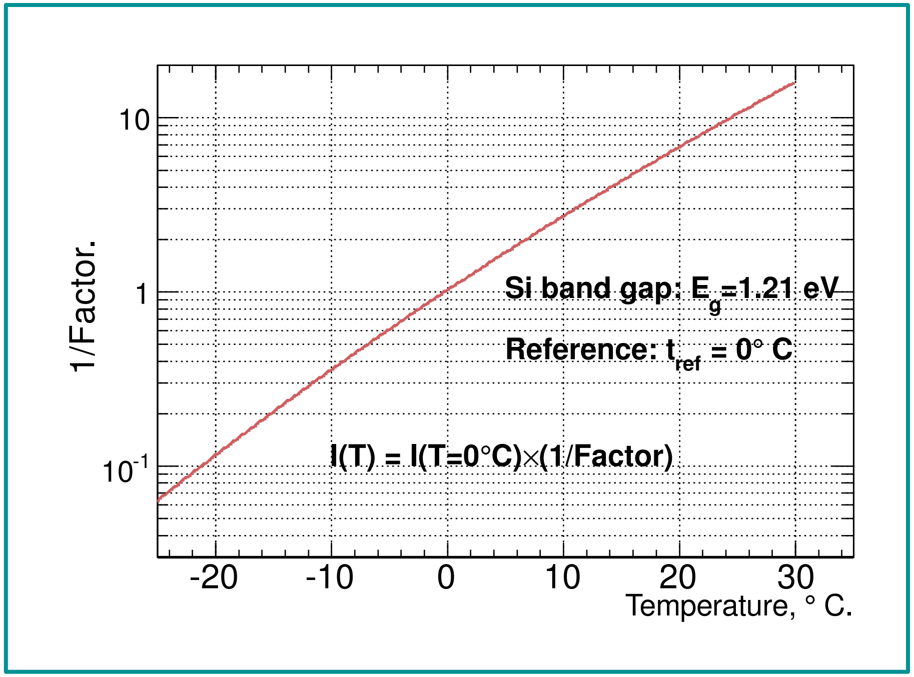
hadron flow : FLUKA calculations

Temperature Profile Data and Corrections

- Use $t°C$ readings from temperature sensors mounted on pixel modules
- Shown $t°C$ per day 2011-2012 profile; averaged over the pixel modules
- Operational $\mathrm{t} = -13°\mathrm{C}$, very stable
- Technical stops, winter shutdowns, cooling failures are the main causes of warm-ups



$$
\begin{aligned}
I(T) &= I(T_R)/R(T), \\
R(T) &= (T_R/T)^2 \cdot \exp\left(-\frac{E_g}{2k_B}(1/T_R - 1/T)\right) \\
E_g &= 1.21\,\mathrm{eV}, \text{(per Chilingarov)} \\
T_R(°\mathrm{K}) &= 0°C + 273.15°
\end{aligned}
$$

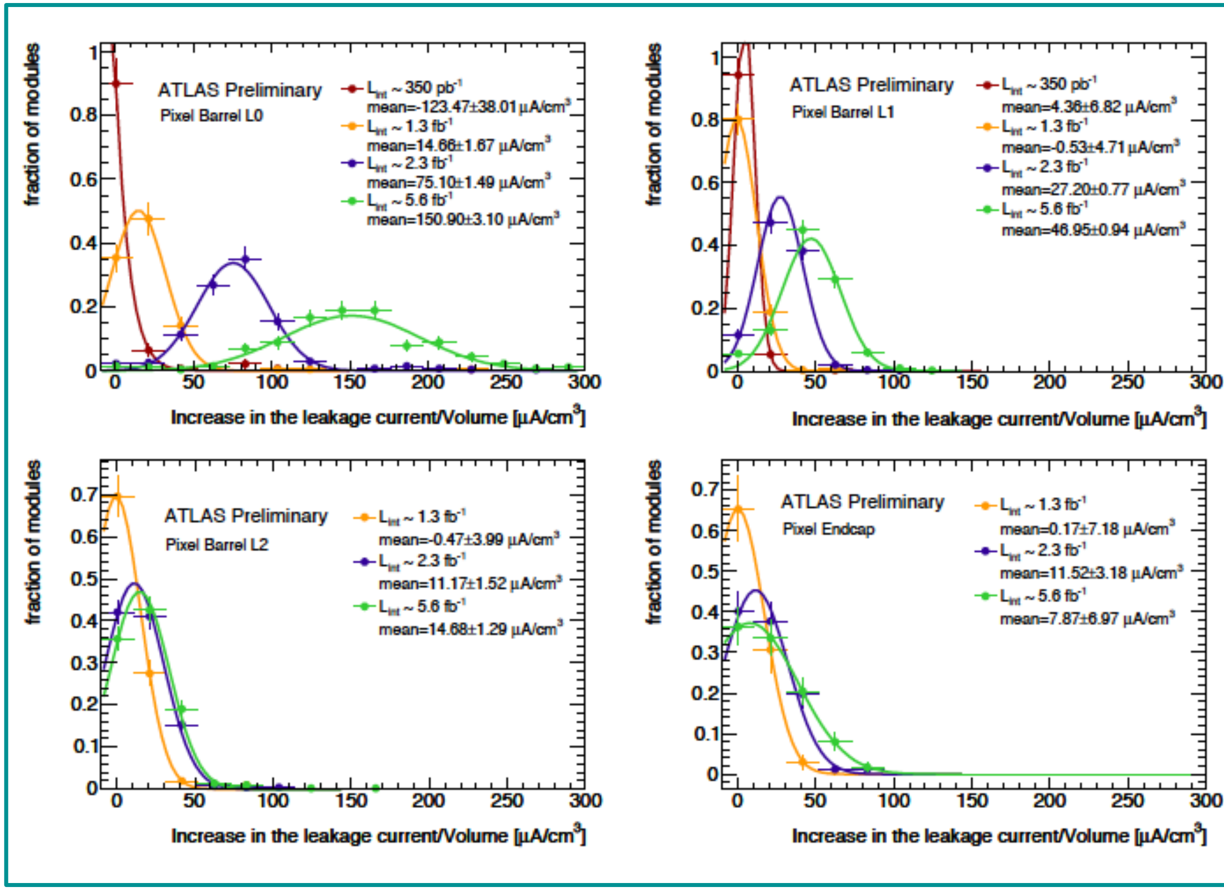


Pixel Leakage Current Measurement: Scans with Pixel Readout Chip

- **Leakage current measurements done at the level of the FE-I3 readout chip**
- **use special function of FE-I3 chip**
  - **one ADC channel per FE chip**
  - **only one pixel per FE chip digitized**
  - **special runs with calibration scans required**
- **current range of** $I_{\rm pixel} = (0.125,\ 128\,{\rm nA})$ **per pixel**
  - $(0,\ 1023)$ **of 10-bit ADC**
  - $LSB = 0.125\,{\rm nA}$
- **current range for a module of** 46080 **pixels**
  - $I_{\rm module} = (5.8\,\mu{\rm A},\ 5.9\,{\rm mA})$
  - **wide dynamical range of** 10^3

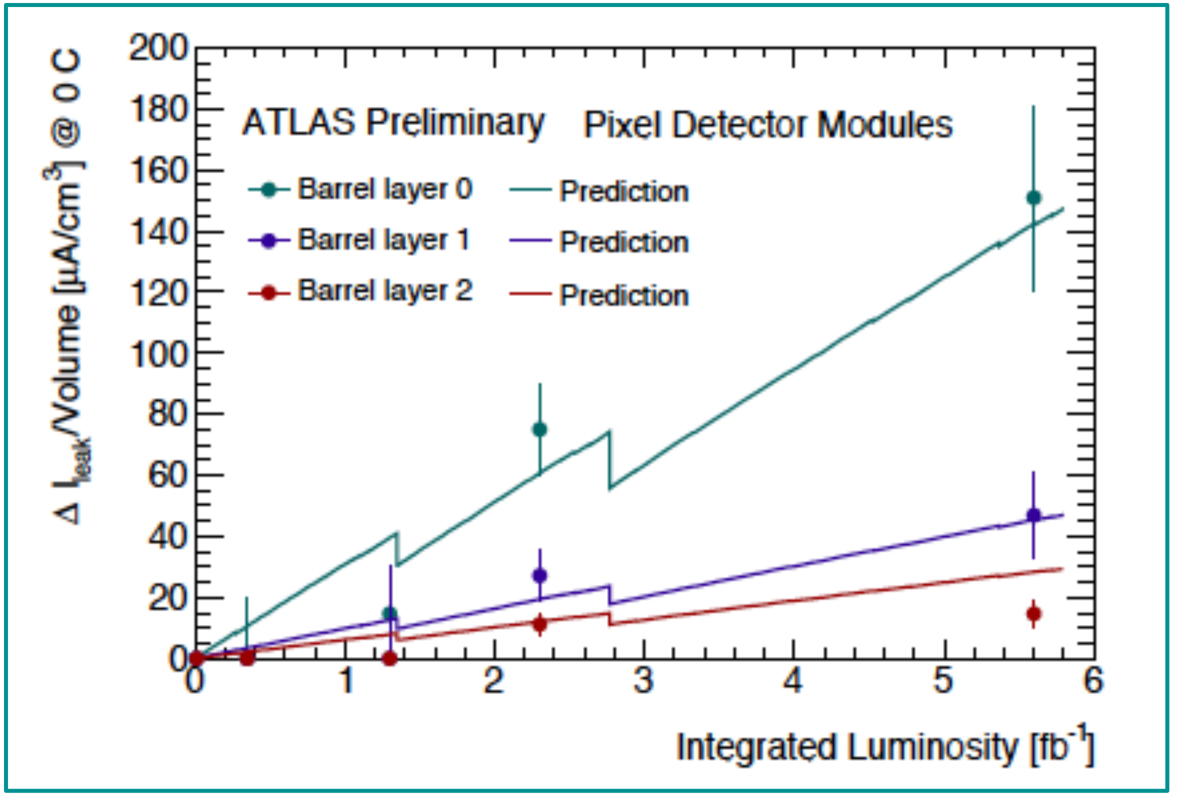
Leakage Current with Pixel Scans (I)

- **Average increase of the leakage current per module**
- **Averages over Layer-0, Layer-1, Layer-2**
- **The calibration scans done at several values of $\int \mathcal{L}\,dt = (0.350,\,1.3,\,2.3,\,5.6)$ fb^{-1}**
- **the increase in the total current of module pixels: $\Delta I_{module}/V_{module}$**
- **the distributions are fitted with a Gaussian function**



Leakage Current with Pixel Scans (II)

- **Average increase of the leakage current per module, as a function of $\int \mathcal{L}\, dt$ for $\sqrt{s} = 7\,\mathrm{TeV}$ data taking period**
- **Shown for Layer-0, Layer-1, Layer-2**
- **for innermost Layer-0 $\Delta I_{leak}/V_{module} \approx 150\,\mu\mathrm{A}$ at $\int \mathcal{L}\, dt = 5.6\,\mathbf{fb}^{-1}$**
- **for Layer-2 $\Delta I_{leak}/V_{module} \approx 40\,\mu\mathrm{A}$ at $\int \mathcal{L}\, dt = 5.6\,\mathbf{fb}^{-1}$**
- **for endcap disks, integrated over radius $\Delta I_{module}/V_{module}$ is negligible and below the threshold sensitivity of this method**



- **the $I_{leak}(t°C \sim -13°C)$ per pixel sensor module renormalized to $I_{leak}(t°C = 0°C)$ (slide # 10)**
- **the model (slide # 7) describing the linear behavior, $\Delta I_{leak}/V_{module} = \alpha(t) \cdot \Phi_{eq}$ with the beneficial annealing $\alpha(t)$ is applied**
- **the data are in an agreement with the model predictions**

Module Leakage Current: Measurements from HV lines

- Monitoring of ATLAS pixel sensors with leakage current measurements done in situ and in real time
  - *no special runs required*
  - *pixel sensor modules are measured*
  - *i.e. the total bulk leakage current of 46080 pixels*
- 4 modules out of 6/7 per half-stave are measured
  - *with staves instrumented evenly per Layer-0, 1, 2*
- The currents are monitored over long periods
  - wide dynamical range
  - $\Phi_{1MeV\,eq} \leq 1.0 \times 10^{+15}\ \mathrm{cm}^{-2}$
- 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
  - *use the model to project the depletion voltage development in time for various LHC / ATLAS data-taking scenarios*

Technical Solution: Current Measurement Boards (I)

- Main system unit: Current Measurement Board (or *CMB*)
  - ***Direct measurement of an individual pixel sensor module's 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 the corresponding HV fan-out board of the *HVPP4*
- Power Supply (*Iseg*) current measurements
  - the power is delivered per half-stave comprising 6 or 7 modules
  - ***the measurements are made of leakage current drawn by ganged groups of 6 or 7 modules***
- The measured current values are digitized and transmitted via data bus to the detector slow control by a CERN-developed digital board (ELMB)
  - 64 digital channels
  - served by 16 bit ADC
  - digitizing voltages fed by *CMB*
  - current data from Iseg power supply channels
- The slow control software reads out the data from *digital* boards and downloads the data to the database
- Physics analysis on the radiation damage proceeds offline using data accessed from DB

Current Measurement Board (II)

- $(0.05\,\mu\mathrm{A}\,,\,2\,\mathrm{mA})$, 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

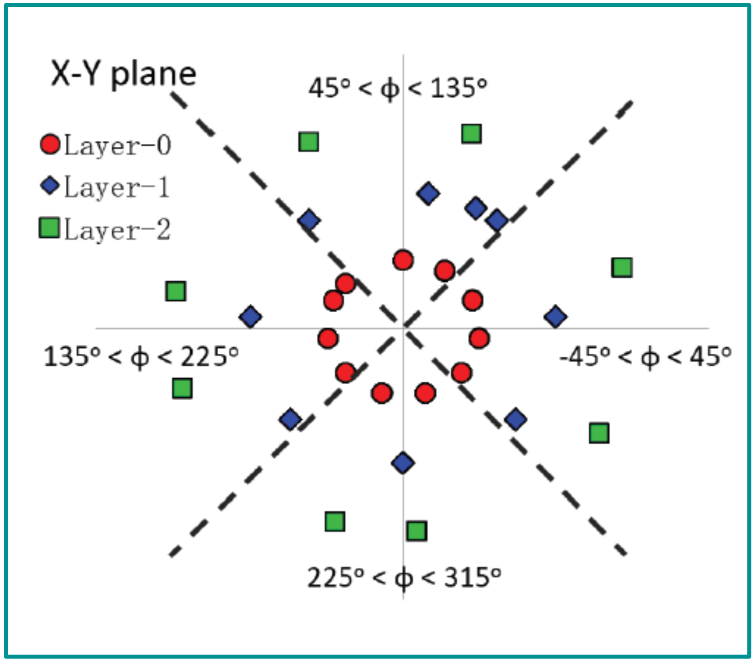
NO in situ calibration system is available.

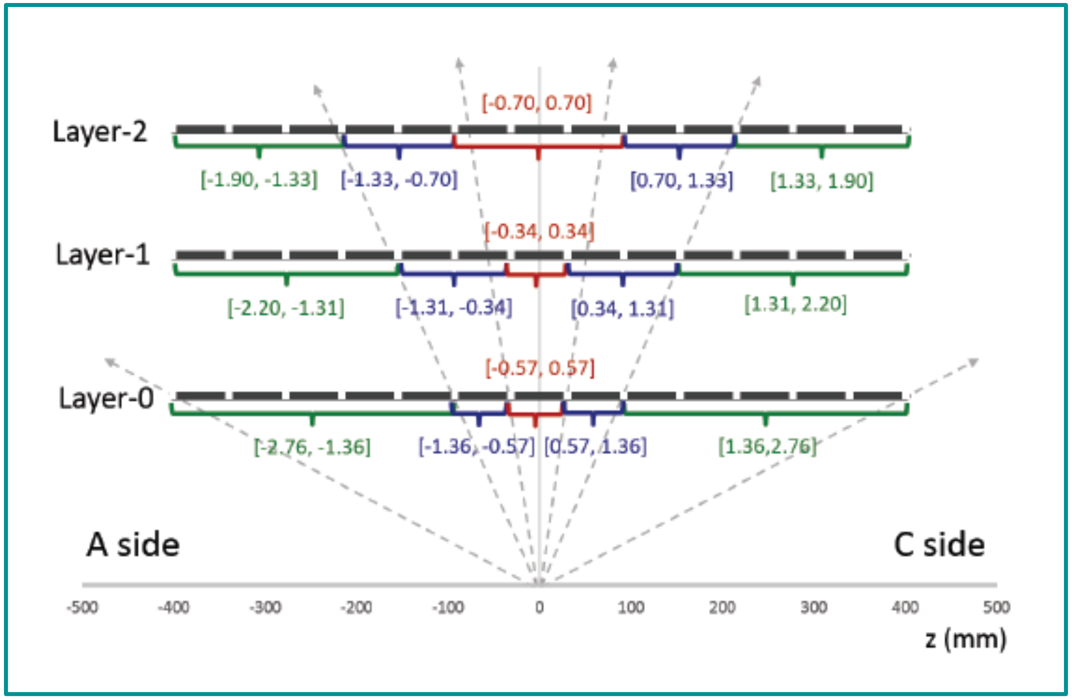
- realistic voltage range (present setting) for ADC: $(0.0,\,1.0)\,\mathrm{V}$
  - $(0,\,65535)$ of 16-bit
  - high gain: $LSB = 15.3\,\mu\mathrm{V} \approx 0.5\,\mathrm{nA}$
  - low gain: $LSB = 15.3\,\mu\mathrm{V} \approx 18\,\mathrm{nA}$

Current Measurement Boards: Status in Run 1

- 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

Leakage Current Data (I)



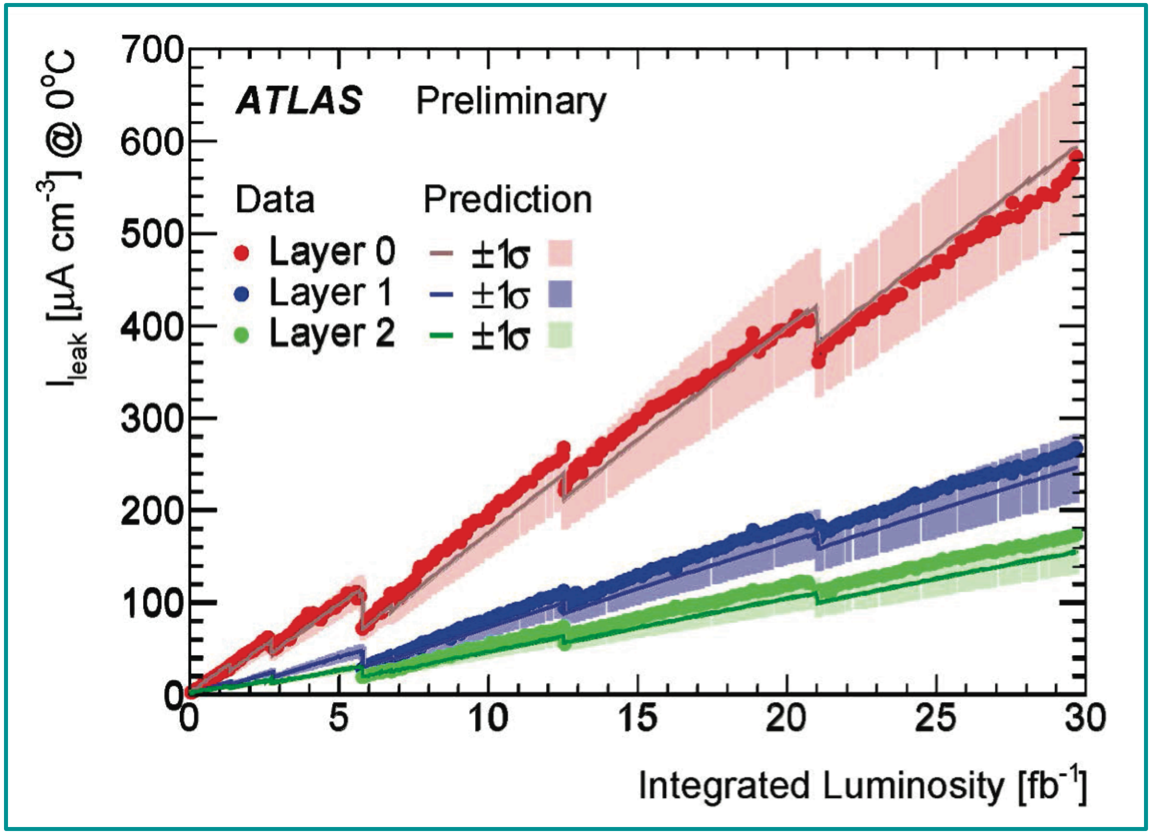


- **modules instrumented:**
  projection onto the transverse plane
- ***Φ* ranges to be analyzed**

- **modules instrumented:**
  projection along the beam line
- ***η* ranges to be analyzed**

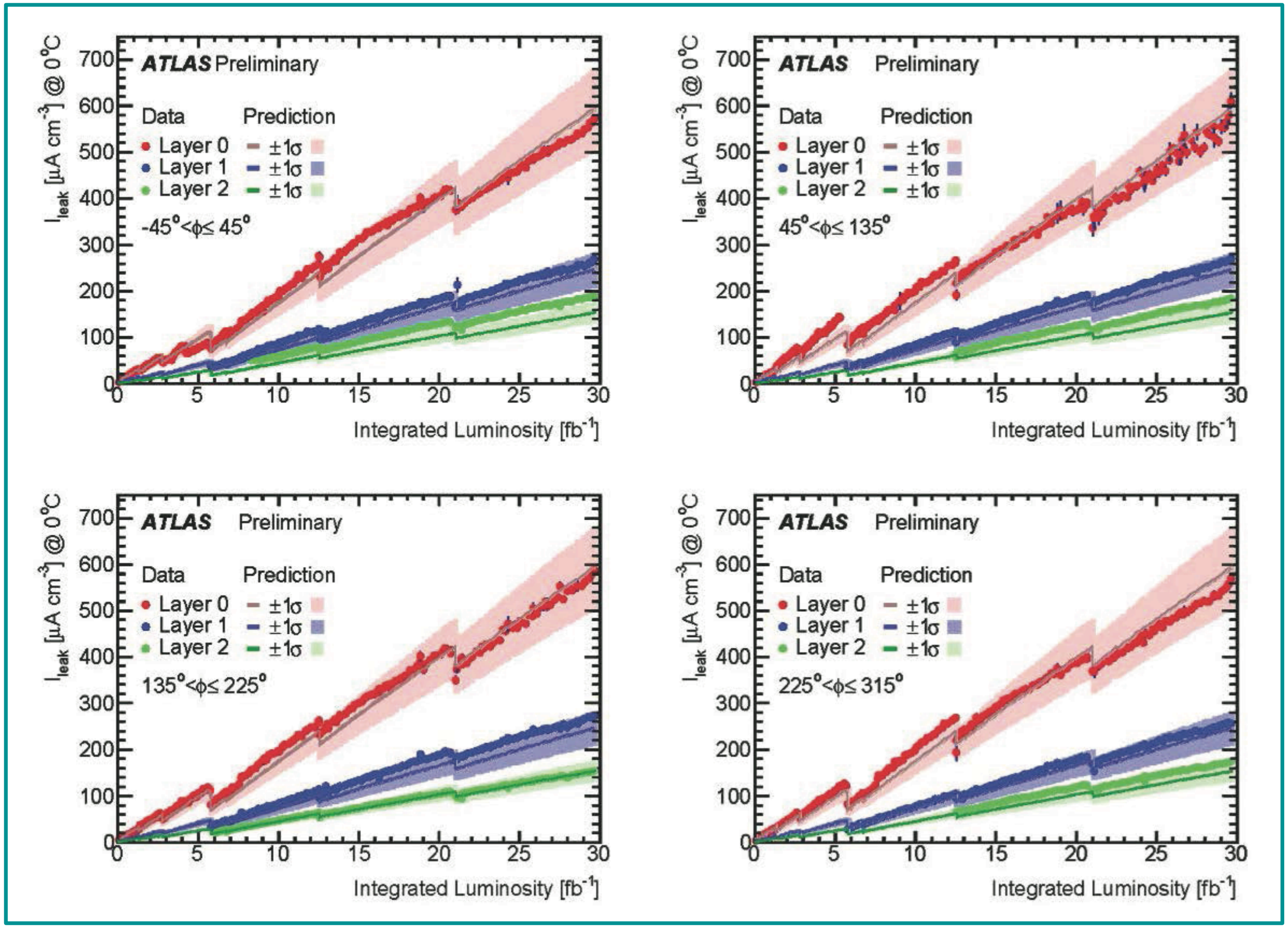
Leakage Current Data (II)

- $\Delta I_{leak}/V_{module}$ vs. Int-lumi as recorded by CMB system
- corrected to t = 0°C
- 2011-2012 data-taking period is shown
- I_{leak} readings are averaged over instrumented modules in Layers 0, 1, and 2
- Some Layer 1 and 2 data are missing from the early part of the run, instrumented later
- The data are in agreement with the predictions within ±1σ
- The annealing periods due to cooling stops appear as discontinuities in the linear behavior
- The predictions were made according to the model of Slide #7

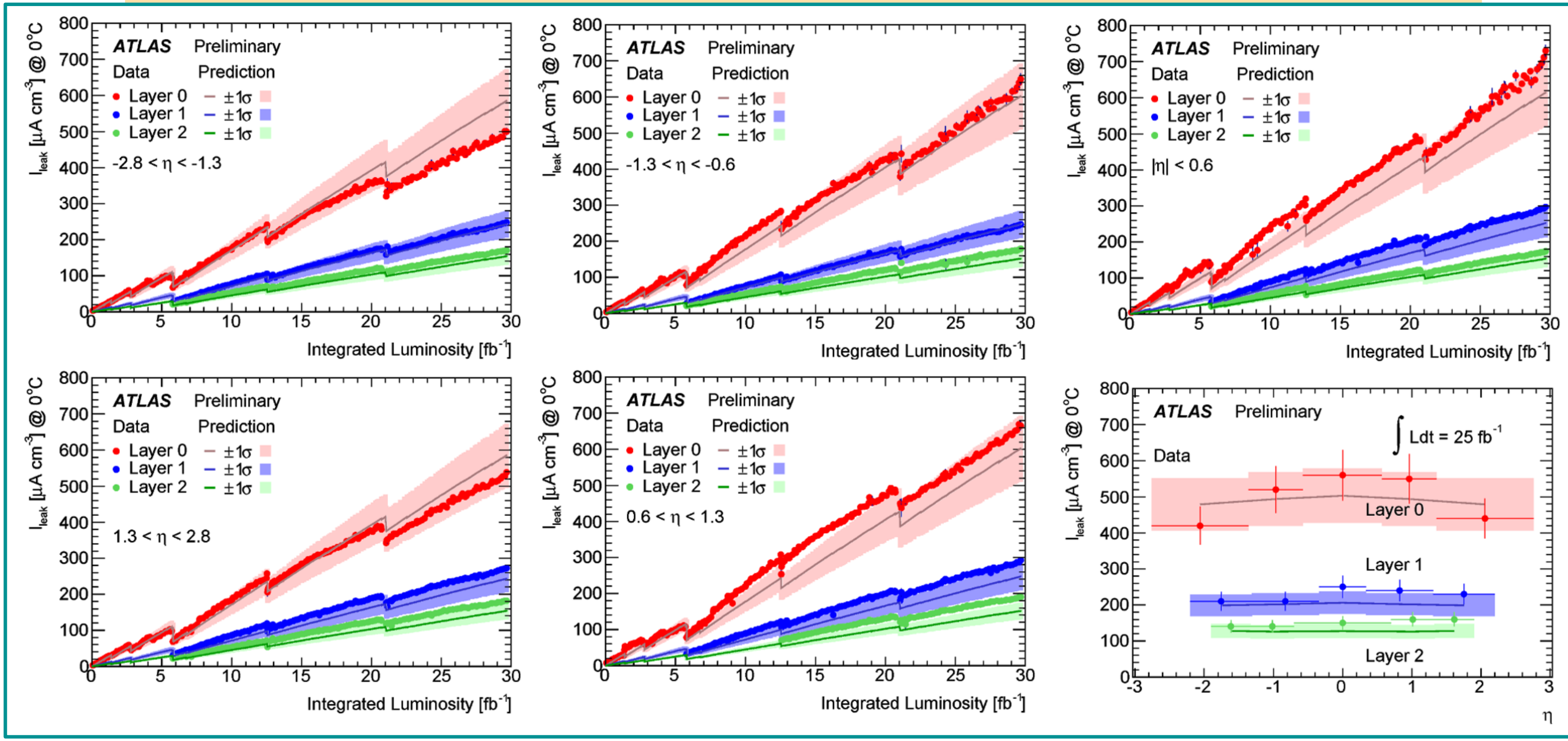


Leakage Current Data (III)

- $\Delta I_{leak}/V_{module}$ vs. Int-lumi is analyzed in four bins (quadrants) in azimuthal angle Φ (slide #18)
- I_{leak} readings are averaged over instrumented modules in Layers 0, 1, and 2 per each Φ bin.



Leakage Current Data (IV)



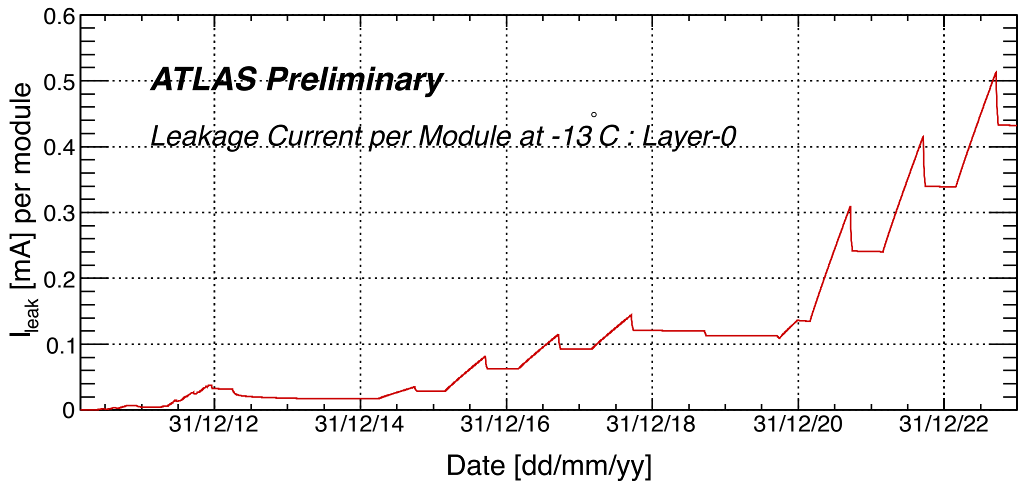
- $\Delta i_{leak}/V_{module}$ vs. Int-lumi in five bins in pseudorapidity η (slide #18)
- I_{leak} averaged over Layer-0, -1, -2 per each η bin
- Graph 6: Graphs 1-5 are projected at Int-lumi = 25 fb^{-1}
- The predictions are made according to the model of Slide #7

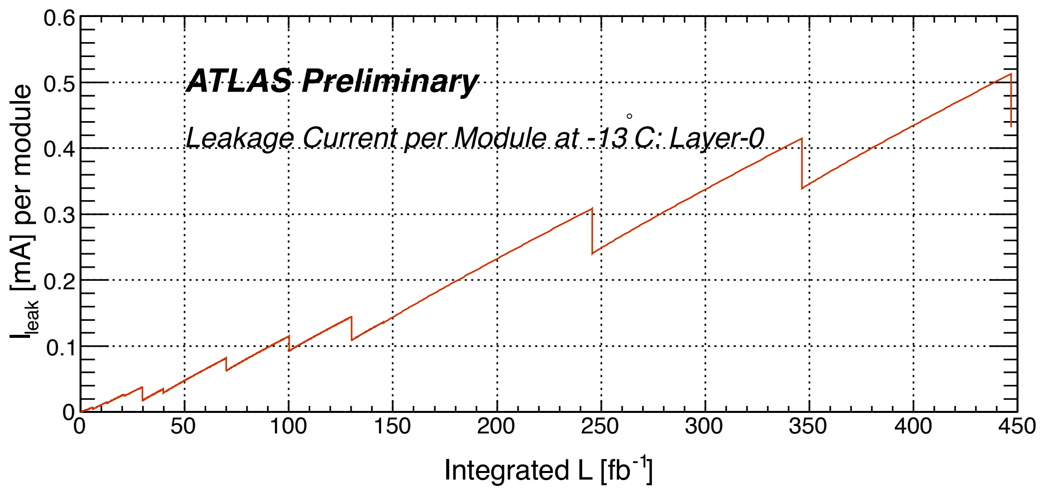
- $\Delta i_{leak}/V_{module}$ at Int-lumi = 25 fb^{-1}, vs. η
- Consistent with the expected Φ_{eq} profile

Leakage Current: Extrapolation

Data-taking scenario

- **Use the Hamburg model, which describes the collected data well**
- **Assume: in future years, pixel modules will undergo:**
  - **10 days of cooling maintenance at t = 20°C**
  - **otherwise they will operate at t = -13°C**
- **Specification: I_{Iseg}(chann.) ≤ 4000μA**
- **Prediction: $I_{module\text{-}leakage}$ (year 2024) × 2 ≤ 1000μA**





Summary for Run 1 and Outlook for Run 2

- The leakage current of individual pixels is measured using ad-hoc capabilities of the readout FE-I3 chip
    - the data are available through special calibration runs
- Dedicated hardware to measure the leakage current from the HV lines of ATLAS pixel sensor modules has been implemented
    - available for online monitoring
    - the stored data are used for radiation damage analysis
- The radiation damage-induced leakage current in the pixel sensor modules has been measured for the 2011-2012 data-taking period using both methods
    - the radiation damage data have been obtained in situ for the sensors of the ATLAS Pixel detector under its running conditions
- The measurements are compared with Hamburg Model predictions made for the corresponding luminosity / fluence profile over 2011-2012
    - the data to model agreement is good: within $\pm 1\sigma$

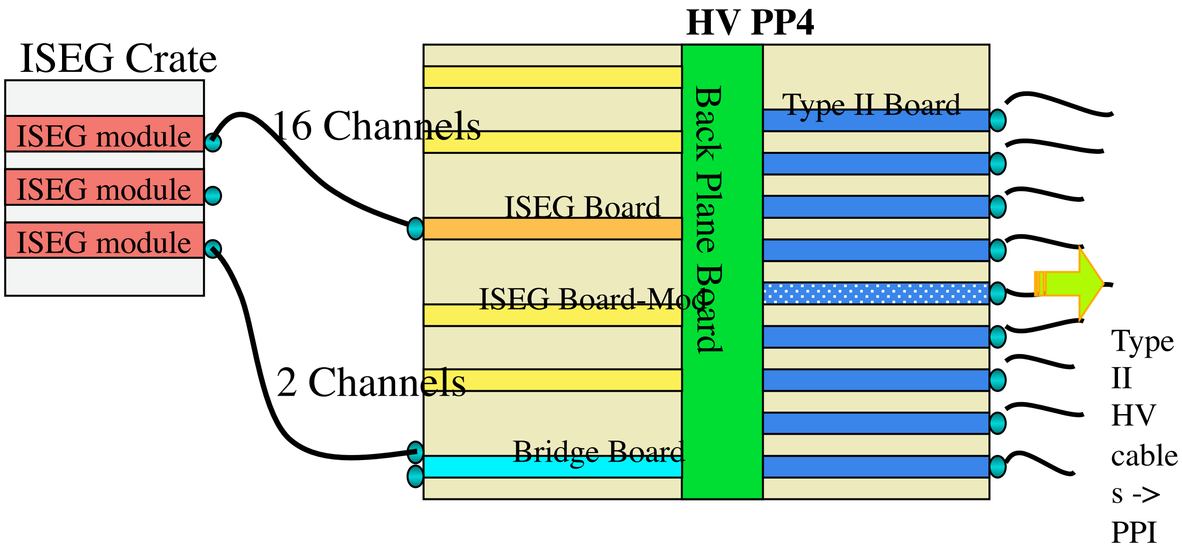
- In January 2015, the dedicated system was extended to the Pixel disks.
- Further details are available at ATL-INDET-PUB-2014-004.

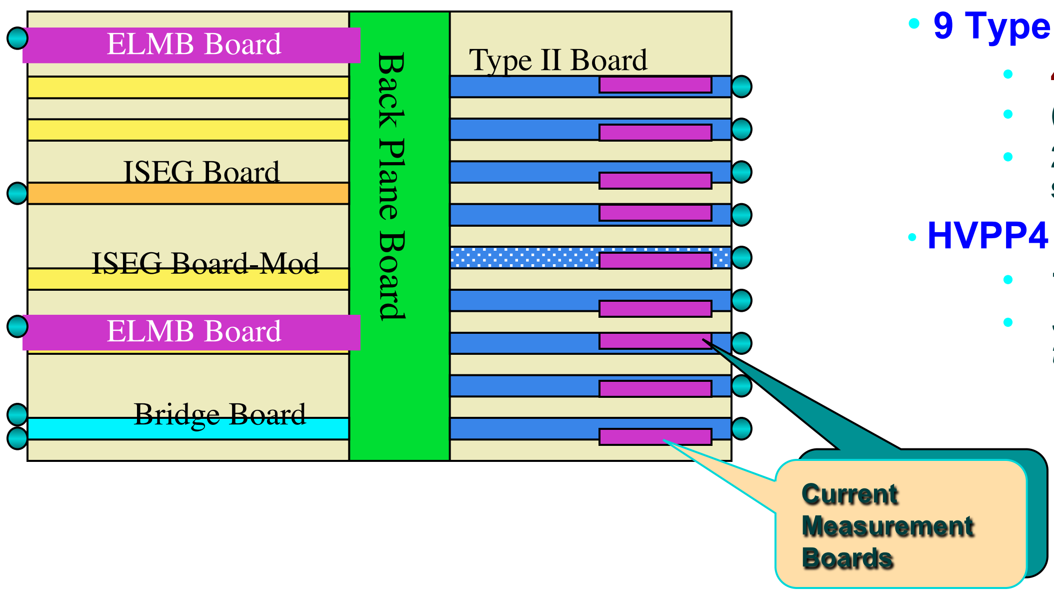
Acknowledgement

- The Pixel Current Monitoring Board project is primarily the work of University of New Mexico ATLAS members Martin Hoeferkamp, Igor Gorelov, Konstantin Toms, and Rui Wang. Daniel Muenstermann has kindly provided the Hamburg Model predictions.

Back up slides

Current Measurement Board (I)

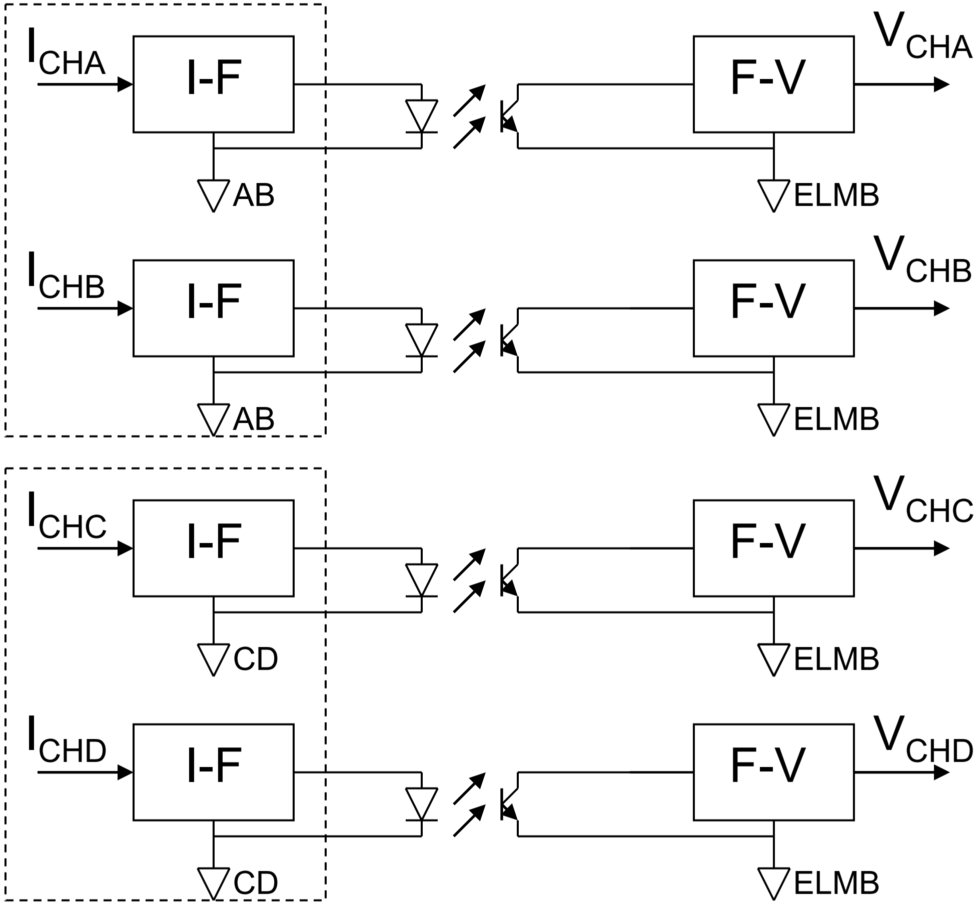




- **Present HVPP4 System:**
  - Fan-out of the bias-voltages from ISEG power supply modules
  - 1744 pixel modules
- **New HVPP4 System: extended with:**
  - Current Measurement Boards attached to the Type II boards
  - Analog-to-digital conversion ELMB boards
- **9 Type II boards / VME crate**
  - 4 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 channels not used due to complicated mapping*

Current Measurement Board (II)

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**