AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE
AGH UNIVERSITY OF KRAKOW

Leakage current evolution in LHCb VELO sensors during Run 1-2 LHC data taking period

Maria Pycior (corr. author), Agnieszka Obłąkowska-Mucha, Tomasz Szumlak

LHCb spectrometer Run 1-2 (2010-2018)

Forward General-Purpose Detector at the LHC ($2 < \eta < 5$)

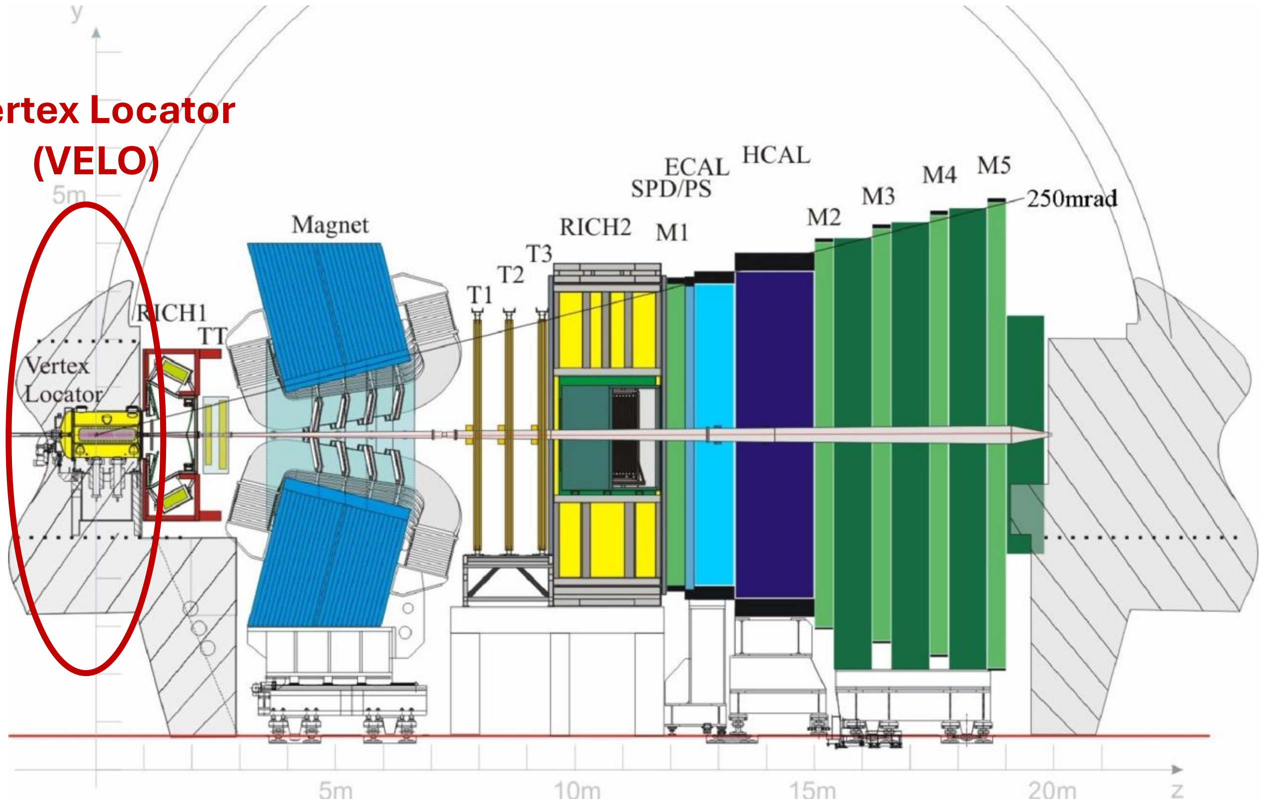
Physics programme:

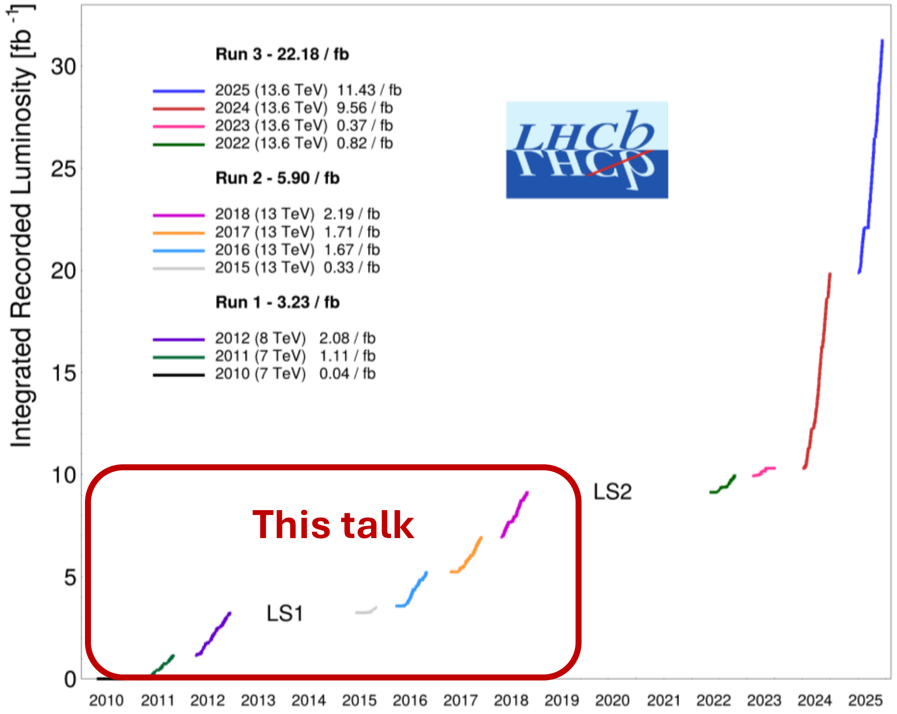
- CP Violation and rare decays of beauty and charm meson
- …
- …
- QCD, electroweak, exotica, Dark Matter …

Silicon micro-scrip detectors:

- **Vertex Locator (VELO)**
- Tracker Turicensis (TT)
- Inner Tracker (IT)

Vertex Locator (VELO)





LHCb spectrometer Run 3 (2022-2025)

Forward General-Purpose Detector at the LHC ($2 < \eta < 5$)

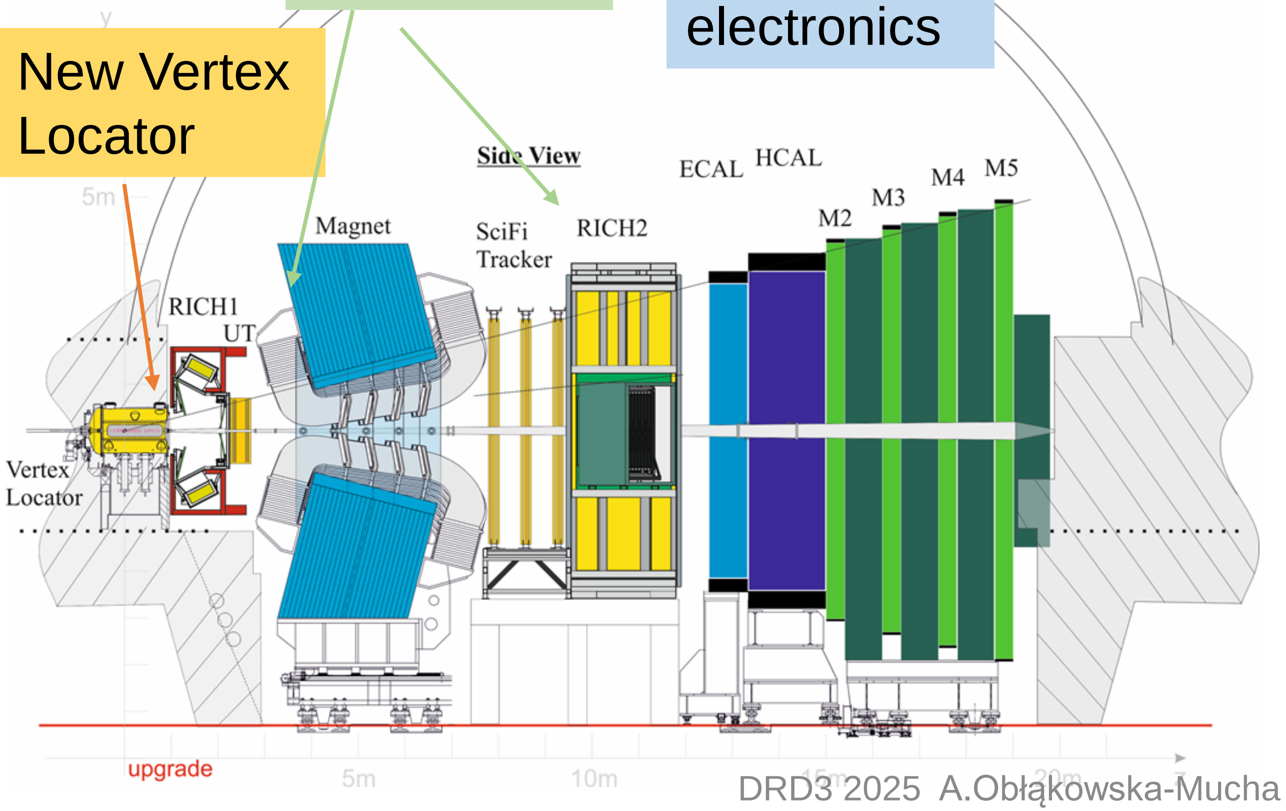
More data, higher precision

New software trigger (triger-less readout)

New Tracking System

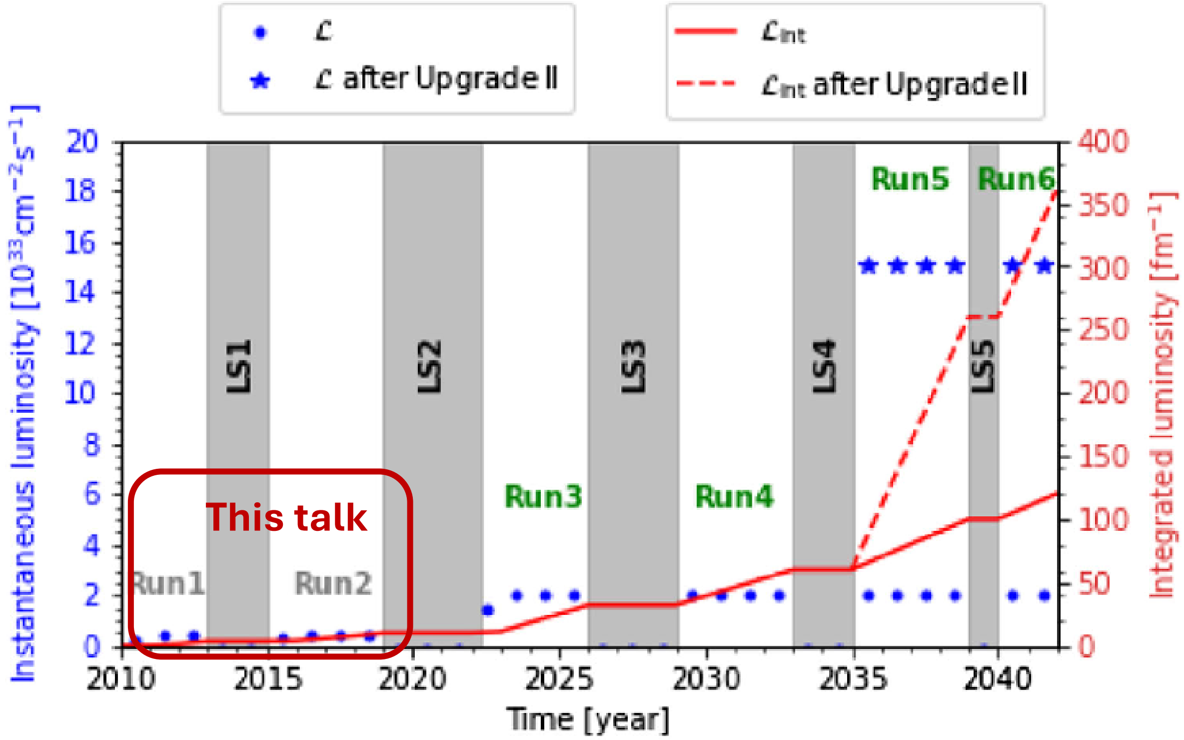
New detectors, electronics

New Vertex Locator



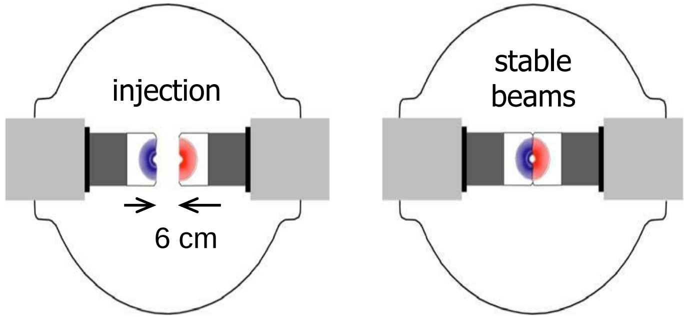
Silicon detectors:

- **Vertex Locator (VELO) - pixel**
- Uprtream Tracker (UT) - microstrip

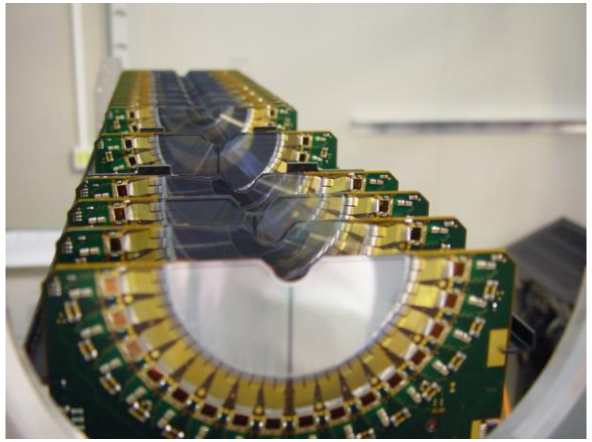


LHCb Vertex Locator (VELO) Run 1-2

- Close proximity of the beam-pipe (8 mm).

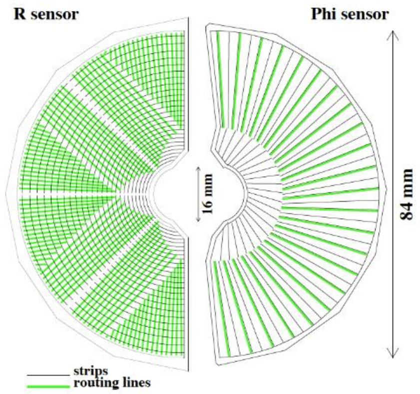


- VELO halves are movable- the movement is steered by a precise system (accuracy of 10 μm),
- When stable beams, the silicon edge is only 8 mm from the proton beam – sensors are in harsh and non-uniform particle fluence .
- Operated in a secondary vacuum, separated from the LHC vacuum by 300 μm thick aluminium foil.



Sensors

- VELO consisted of 42 modules (two halves).
- Modules have two (R and Phi) microstrip silicon oxygenated n^+-on-n sensors (two sensors are n^+-on-p).
- Sensors are 300 μm thick, strip pitches: 40-100 μm.
- Evaporative CO_2 cooling system keeps sensors at -7^{o}C.



Leakage current – radiation damage

- The level of leakage current reveals the amount of the radiation damage.
- The increase in leakage current is proportional to the accumulated fluence (time, delivered luminosity) :

$\Delta I = \alpha \cdot \phi_{eq} \cdot V$, typically 2 μA per 100 pb^{-1}

annealing constant $\alpha(20℃) = (3.99 \pm 0.03) \cdot 10^{-17}$ A/cm

- The currents of the sensors are measured as a function of time while operating at nominal conditions (depletion voltage, temperature)
- In the presented analysis, **the simulation of leakage current growth was obtained and compared with measurements**, using:
  - ✓ fluence simulation,
  - ✓ delivered luminosity
  - ✓ temperature of sensors recorded during detector lifetime

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VERTEX LOCATOR

Hamburg model in a nushell

- Increase in leakage current is expected to be **proportional to fluence:**

$$\Delta I = \alpha \cdot \phi_{eq} \cdot V$$

- Some damage vanishes over time - **annealing**
- Evolution of current-related damage coefficient α:

$$\alpha(t;T) = \alpha_1 \exp\left(-\frac{t}{\tau_1(T)}\right) + \left[\alpha_0(T) - \beta \ ln\left(\frac{t}{t_0}\right)\right]$$

- Leakage current formula with time-scaling functions Θ and τ:

$$I_{leak} = \sum_{i=1}^{n} V \cdot \Phi_{eq,i} \cdot \left[\alpha_I \exp\left(-\sum_{j=i}^{n} \frac{t_j}{\tau(T_j)}\right) + \alpha_0^* - \beta \log\left(\sum_{j=i}^{n} \frac{\Theta(T_j) \cdot t_j}{t_0}\right)\right]$$

$$\Theta(T) = exp\left[-\frac{E_I^*}{k_B}\left(\frac{1}{T} - \frac{1}{T_R}\right)\right]$$

- Model parameters were obtained experimentally in 1999

T_a [°C]	α_I [10^{-17} A/cm]	τ_I [min]	α_0 [10^{-17} A/cm]	β [10^{-18} A/cm]	t_0 [min]
21	1.23	1.4×10^4	7.07	3.29	1
49	1.28	260	5.36	3.11	1
60	1.26	94	4.87	3.16	1
80	1.13	9	4.23	2.83	1
106	–	–	3.38	2.97	1

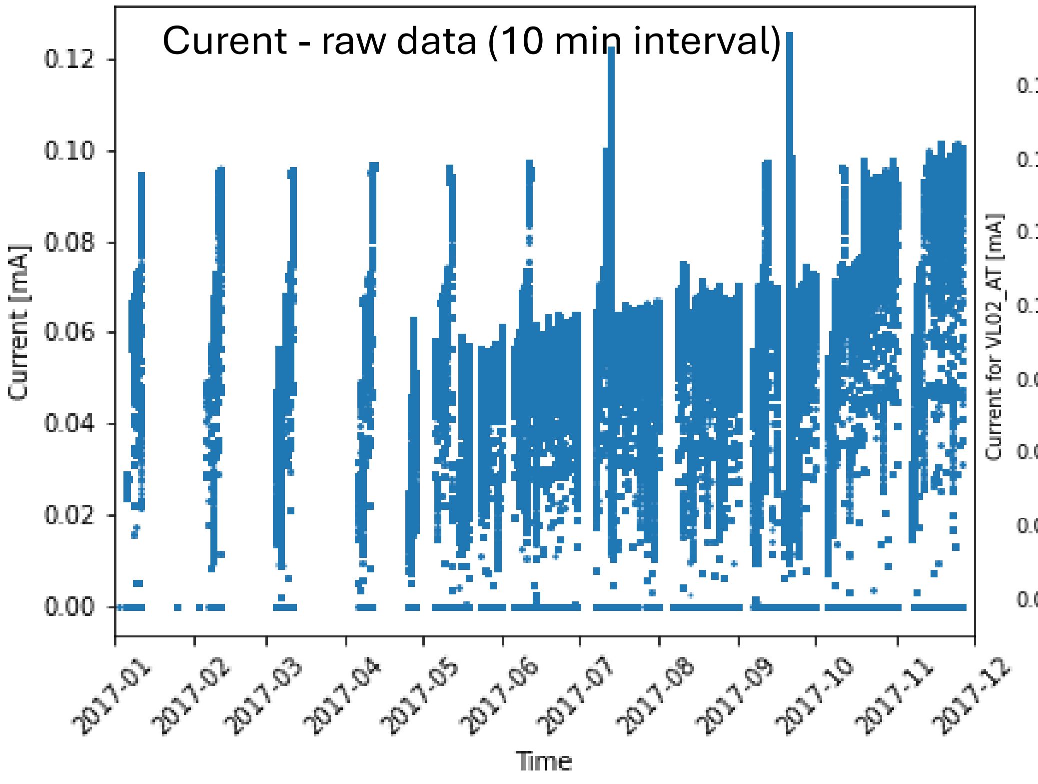
$$\frac{1}{\tau_{a,Y}} = \frac{1}{\tau_{0a,Y}} \exp\left(-\frac{E_a}{k_B T}\right)$$

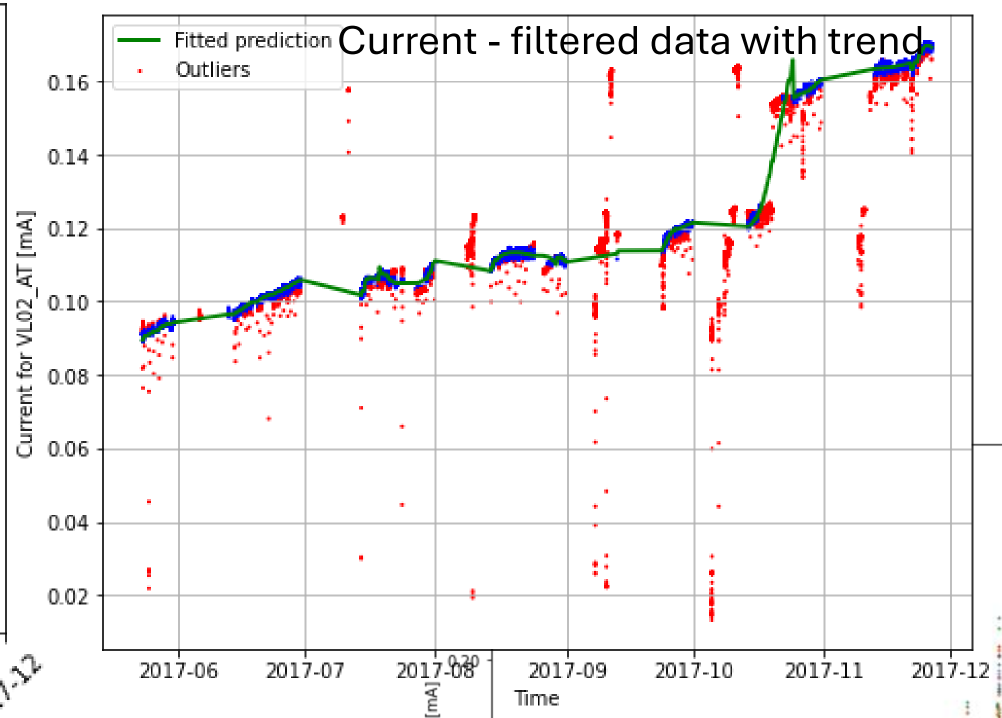
Simulation are valid only for chosen T_{ref}, and must be rescaled to match measurement T:

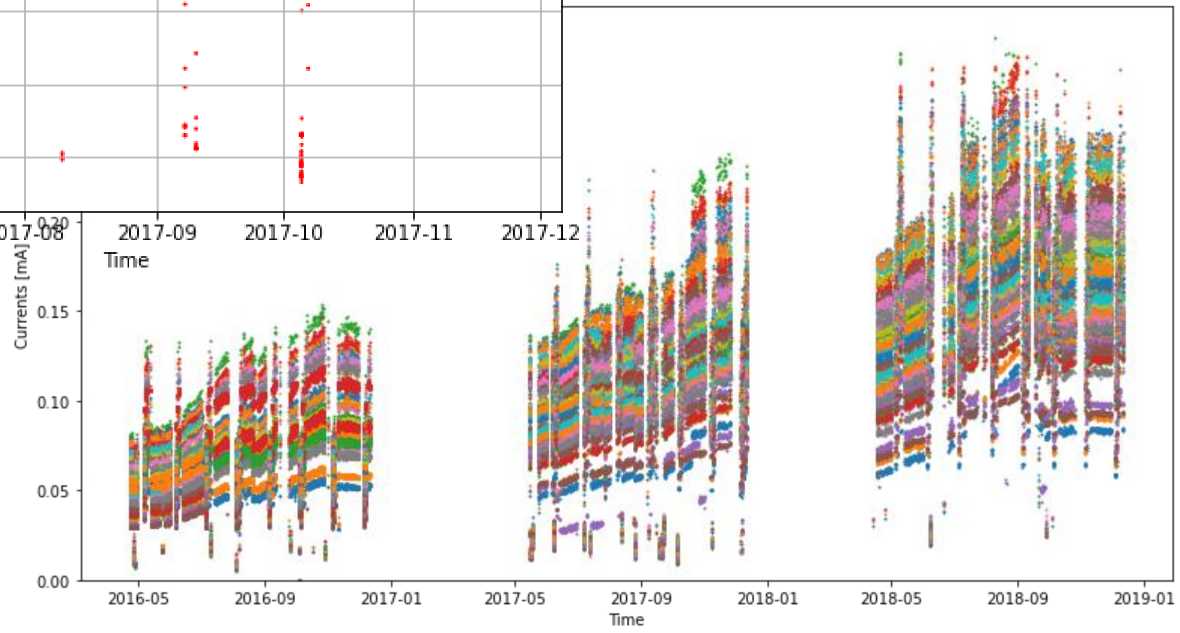
$$\frac{I(T_R)}{I(T)} = \left(\frac{T_R}{T}\right)^2 exp\left[-\frac{E_g}{2k_B}\left(\frac{1}{T_R} - \frac{1}{T}\right)\right]$$

Data extraction and filtering

- Current, HV and temperature are read out by three different systems.
- A new filtering algorithm was developed to get rid of jumps and artefacts and to speed up calculations.







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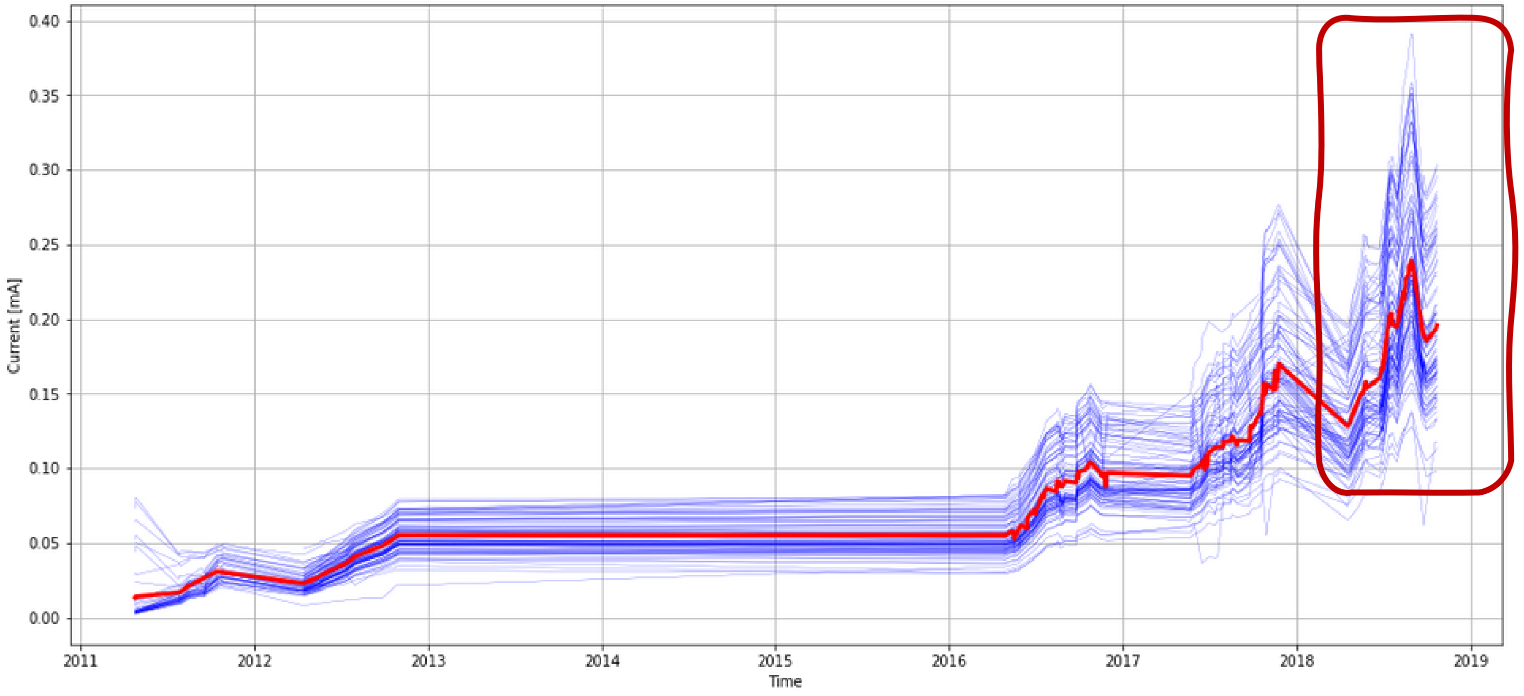
Leakage current - results

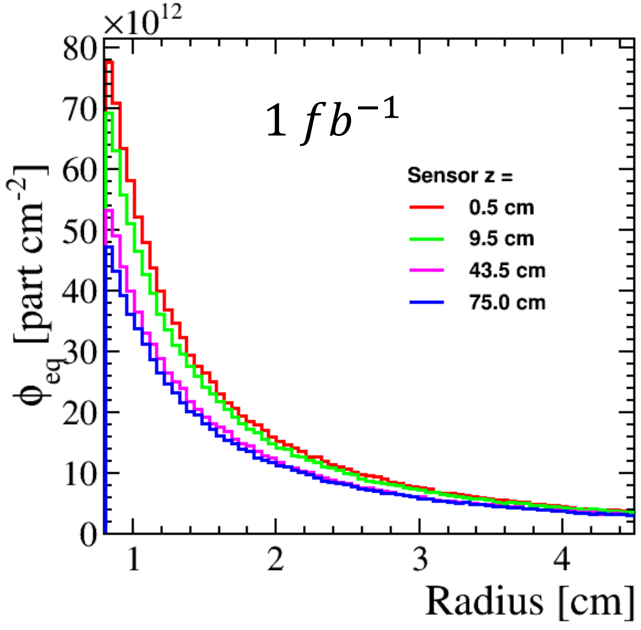
- Leakage current evolution in VELO sensors during Run 1-2, new analysis.



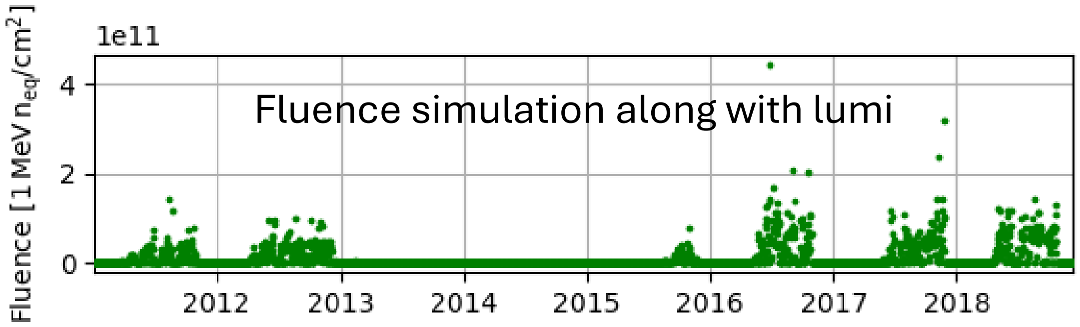
end of VELO life-time: deliberate warming to room temp

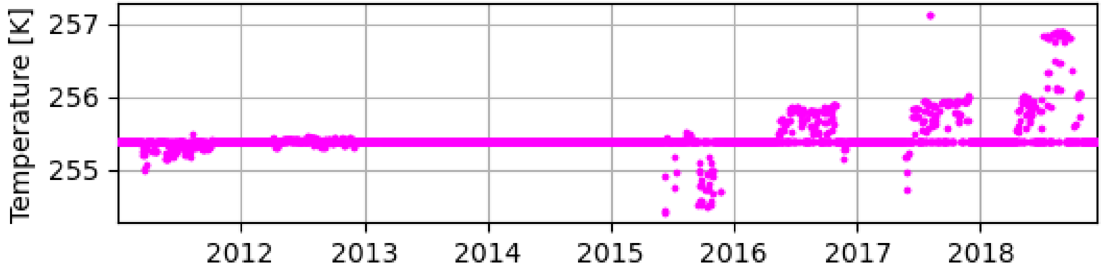
Fluence simulation

- Fluence has strong radial dependence:



- Leakage currents depends on contributions from all previous irradiations, requiring knowledge of **temperature and fluence** binned in time
- Data collected from 2011 to 2018 was used:
  1) Unfiltered sensors temperature (for HM simulation)
  2) Filtered leakage current (for comparison)
- Neutron-equivalent fluence from FLUKA simulation + integrated luminosity from LHCb database



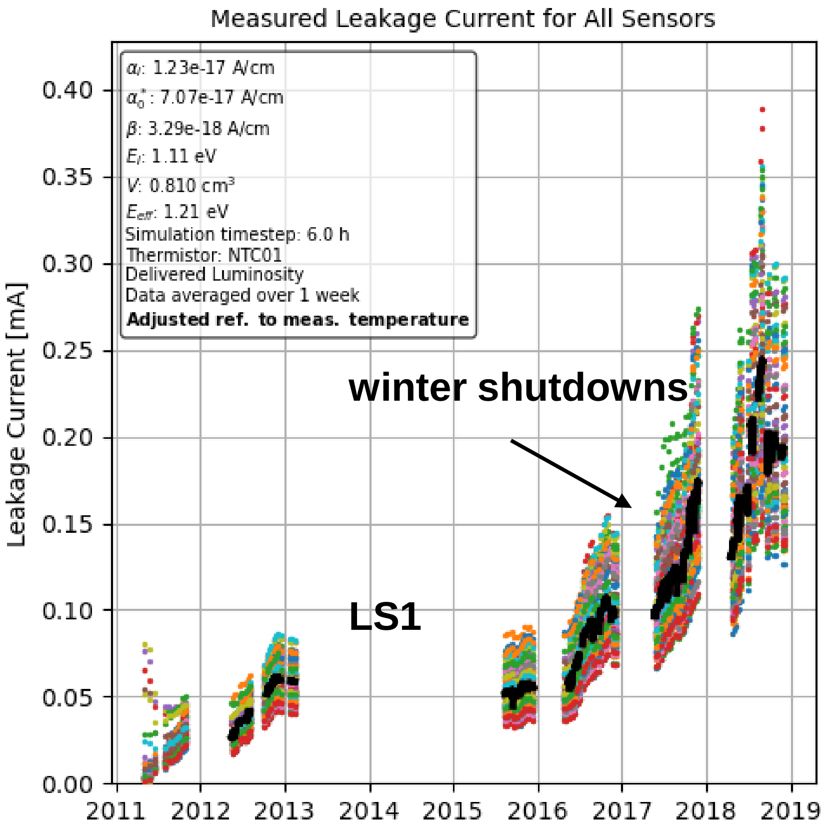


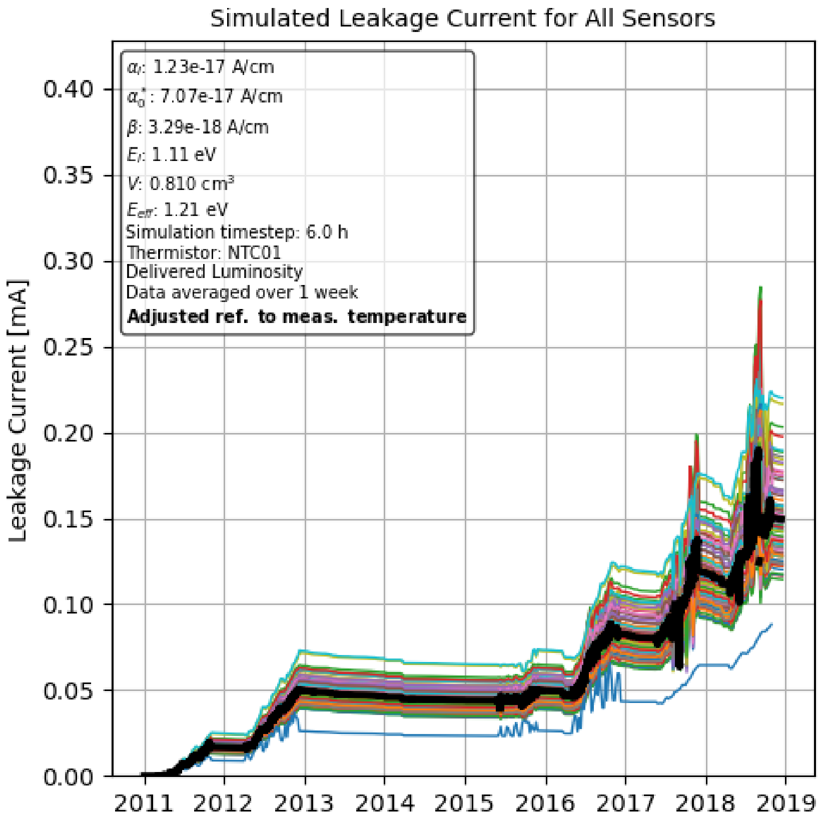
Leakage current – measurement vs simulation

- Combining the HM with Lumi and ϕ_{eq} simulation:

$$I_{leak} = (\Phi_{\mathrm{eq}}/L_{\mathrm{int}}) \times V \cdot \sum_{i=1}^{n} L_{\mathrm{int},i} \cdot \left[\alpha_{\mathrm{I}} \exp\left(-\sum_{j=i}^{n} \frac{t_j}{\tau(T_j)} \right) + \alpha_0^* - \beta \log\left(\sum_{j=i}^{n} \frac{\Theta(T_j) \cdot t_j}{t_0} \right) \right]$$

Parameter	Value	Unit
k_B	8.617×10^{-5}	eV/K
T_{ref}	294.15	K
E_I^*	1.30	eV
α_I	1.23×10^{-17}	A/cm
α_0^*	7.07×10^{-17}	A/cm
β	3.29×10^{-18}	A/cm
E_I	1.11	eV
K_{0I}	1.2×10^{13}	s^{-1}
t_0	1.0	min
V	0.810	cm^3
E_{eff}	1.21	eV





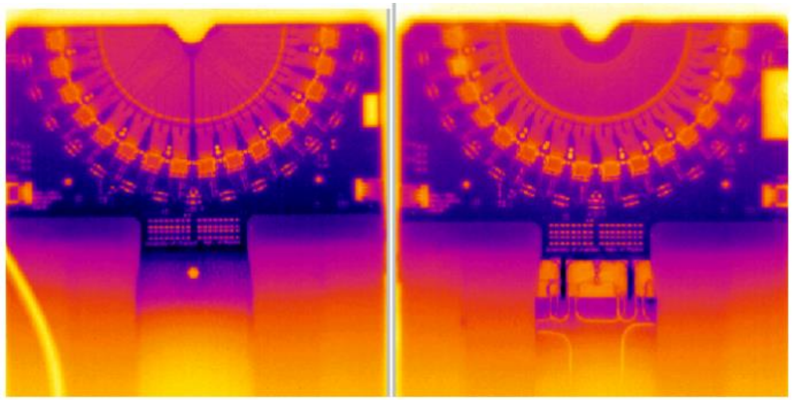
Temeperature correction

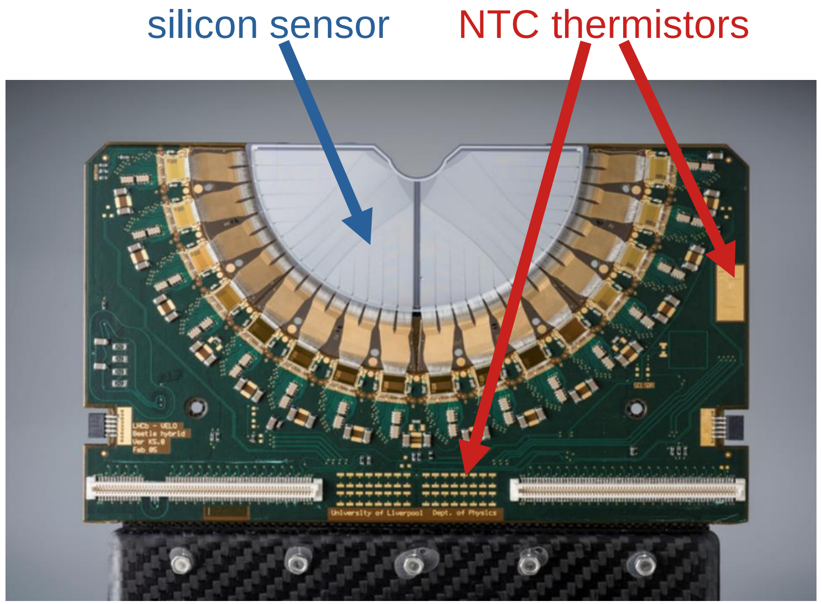
- **Leakage current is highly dependent on silicon temperature**
- During data-taking periods, when sensors are powered, the temperature across the module is non-uniform
- Difference between T_{NTC} and (warmer) T_{Si} was found to be **3.2 ± 1.6 °C** (vacuum tank test, 2008*)
- This is one of many potential sources of uncertainty: NIEL damage curves**, cross-sections, Hamburg model parameters…

** G. Casse et al., "VELO Module Production: Vacuum Tank Tests", LHCb-2007-082. CERN-LHCb-2007-082, March 2008*

*** M. Huhtinem, M. Manousos On the uncertainties of silicon hardness factors, LHC Radiation Damage Workshop presentation, 2019*

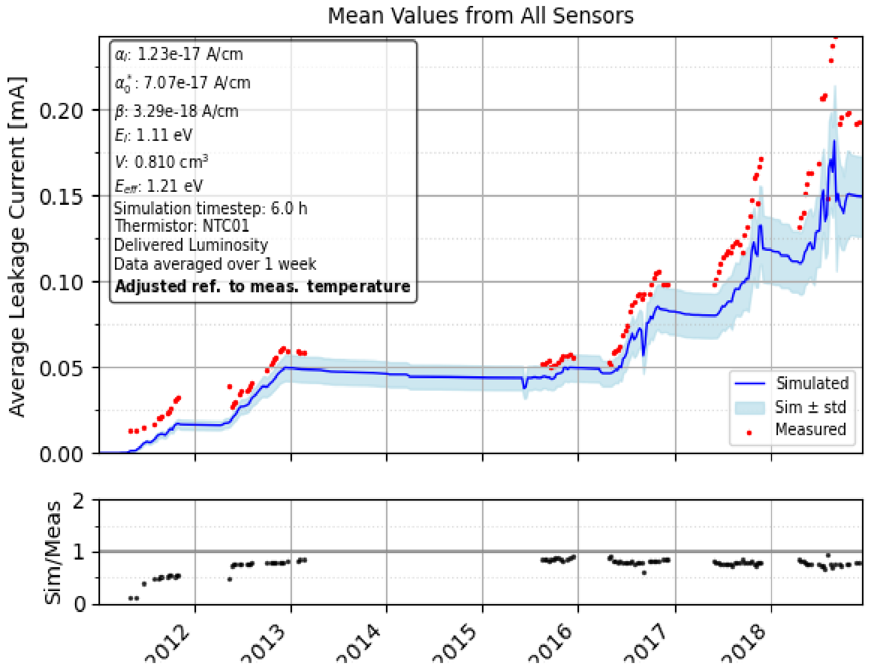
Temperature gradient on the hybrid

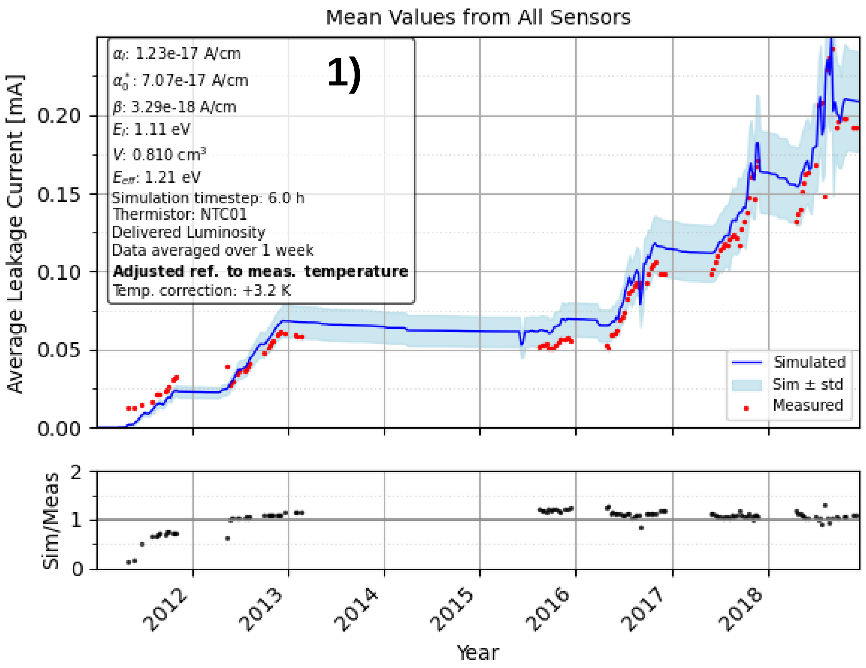


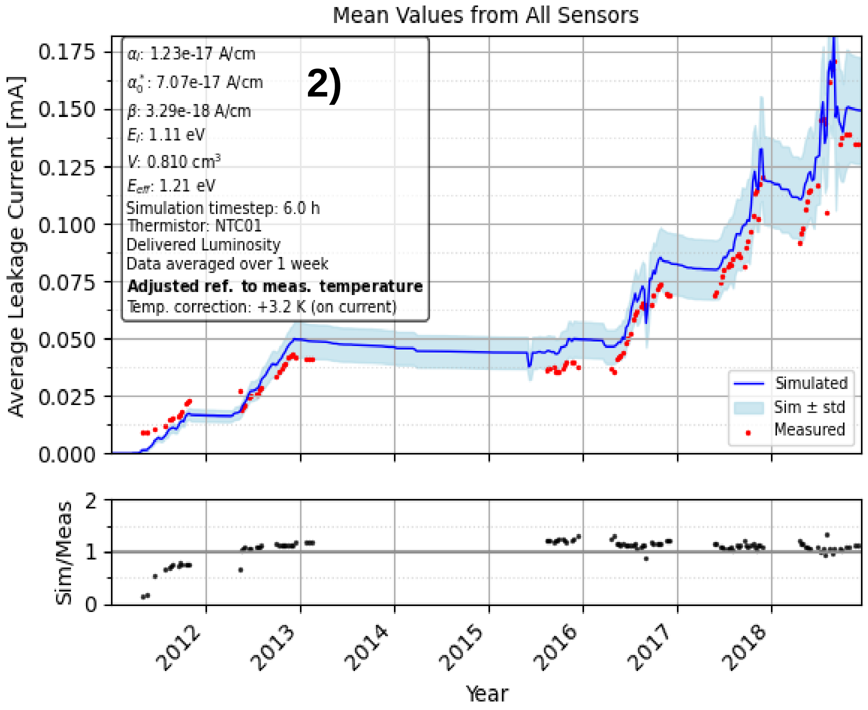


Temeperature correction

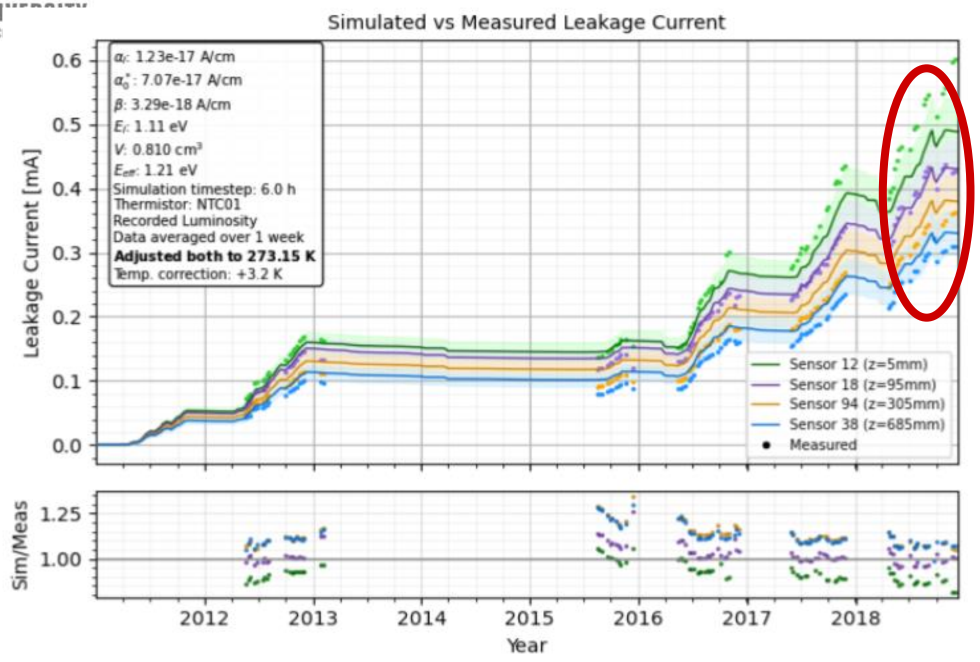
- Before applying corrections, <u>simulation results were lower than the measurements</u>
- **3.2°C** adjustment was applied:
    1) to simulation input data
    2) to measured leakage current
- Both methods gave consistent results

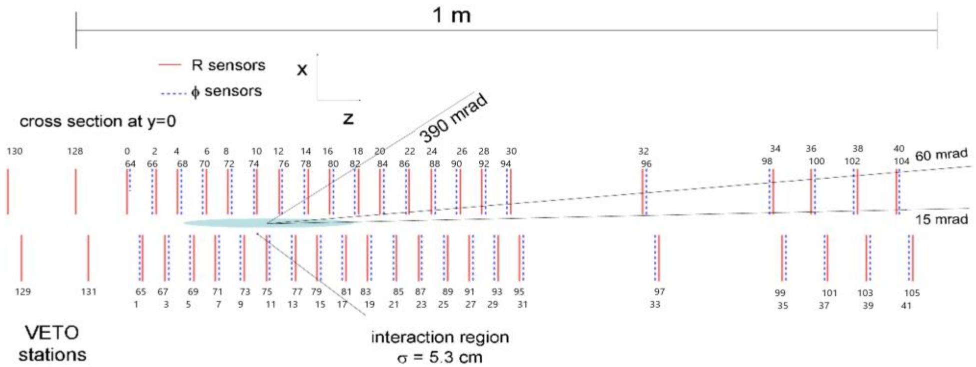


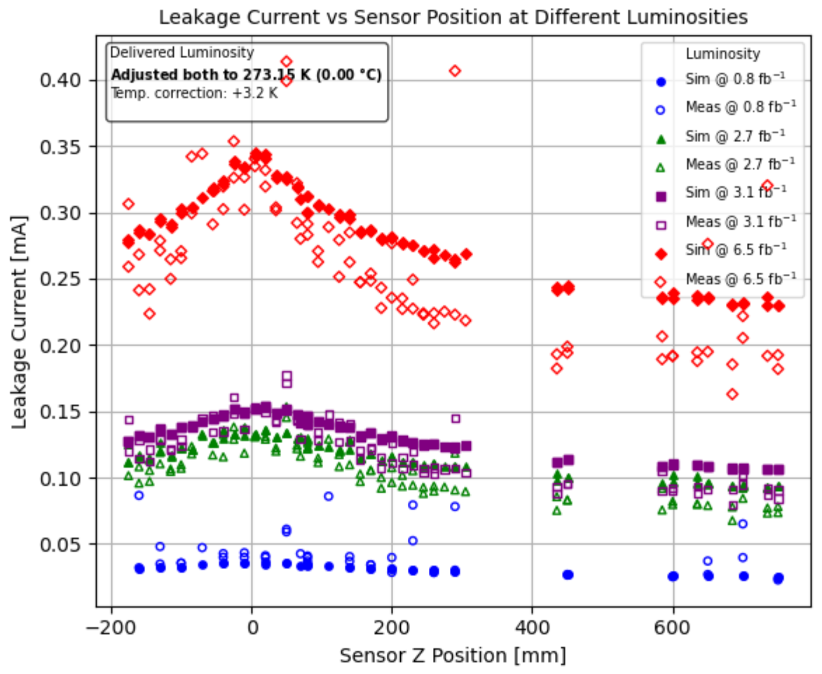




Dependence on sensor position (z coordinate)







- Simulation shows weaker dependence on sensor distance from IP
- Overestimated or underestimated values
- Possible fluence discrepancy
- Observation appears consistent with ATLAS fluence-to-luminosity conversion factor studies:

T. Lari on behalf of the ATLAS Collaboration, Modeling radiation damage in the pixel sensors of the ATLAS detector, INFN Milan, 2020

Summary

- The operation of the VELO microstrip detector in Run 1-2 delivered a large dataset, enabling test of the Hamburg model and simulations.
- Hamburg model simulation predicted the increase in leakage current and enabled further testing
- For more accurate results, temperature correction may be required and might need to be investigated further
- The simulation does not accurately reproduce the position dependence, as has been observed in other experiment.