Radiation Damage of LHCb's Silicon Detector Systems

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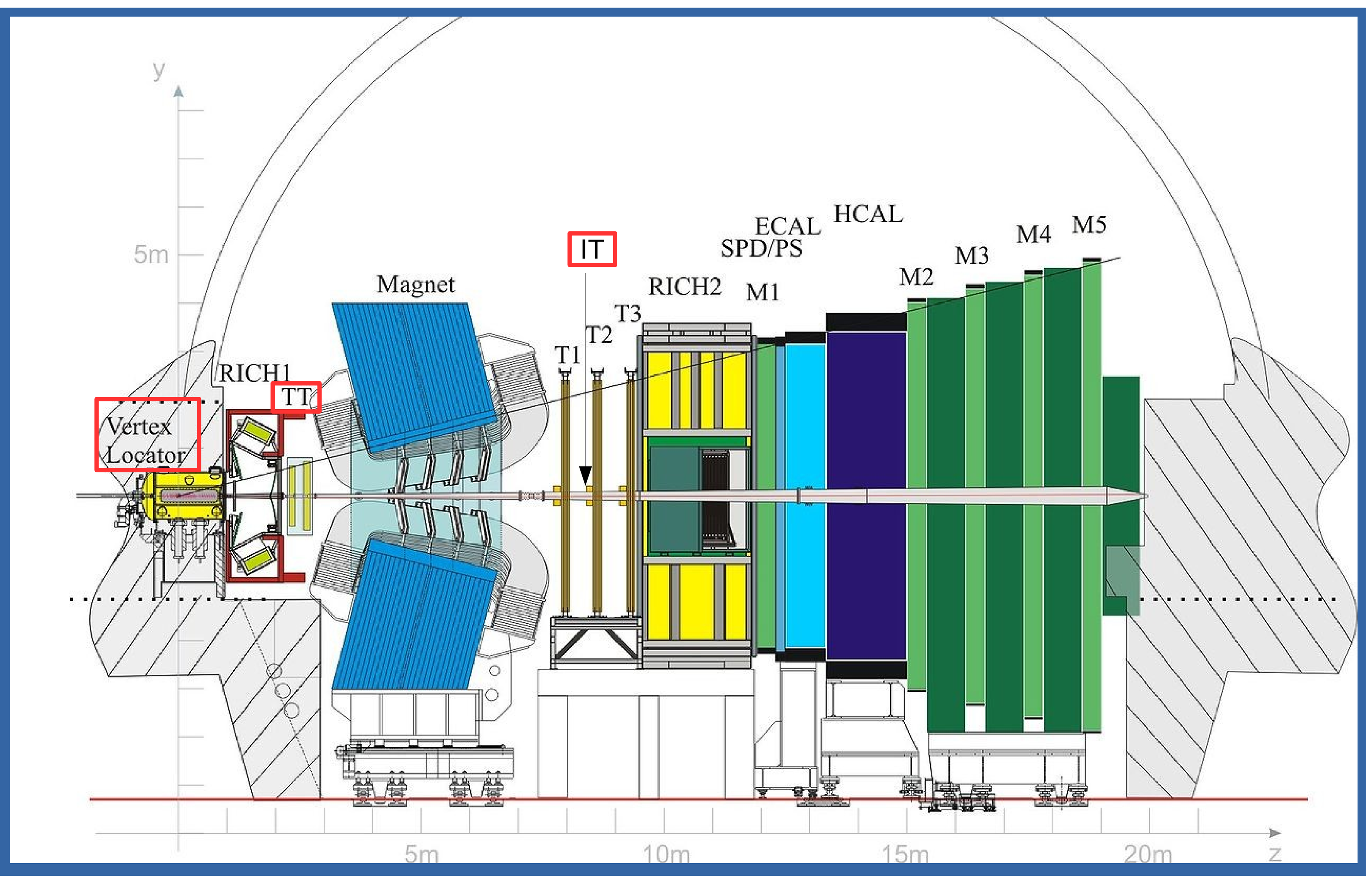
Abstract

The LHCb is a successful experiment taking data at the LHC since 2009. Vertex and track reconstruction in the regions with highest particle occupancies are performed with a set of micro silicon-strip detectors, consisting of the VErtex LOcator (VELO) and the Silicon Tracker (ST). The detectors have performed very well throughout Run 1 of the LHC, but face new operational challenges in the LHC Run 2 environment with the reduced bunch separation of 25 ns and higher particle multiplicities. The cumulative radiation damage poses challenges in reaching full depletion in the most irradiated zones of the detectors, which have highly non-uniform exposure, reaching fluences of 0.01-4×10^{14} 1-MeV neq/cm^2 in the same sensor. The overall damage is monitored through regular measurements of the leakage current and charge collection efficiency (CCE) as function of the bias voltage. The radiation damage has been shown to decrease the collection of signal by the strip implants due to charge accumulation in the SiO_2 layer, reducing the shielding effect to the routing lines in the sensors with 2-metal layer readout. A TCAD simulation was implemented using the Perugia n-type bulk model and the Peltola surface damage model concluding that up to 60% of the charge is collected by the routing lines. Studies of radiation damage throughout runs 1 and 2 of the VELO and ST will be presented.

Silicon Detectors at LHCb

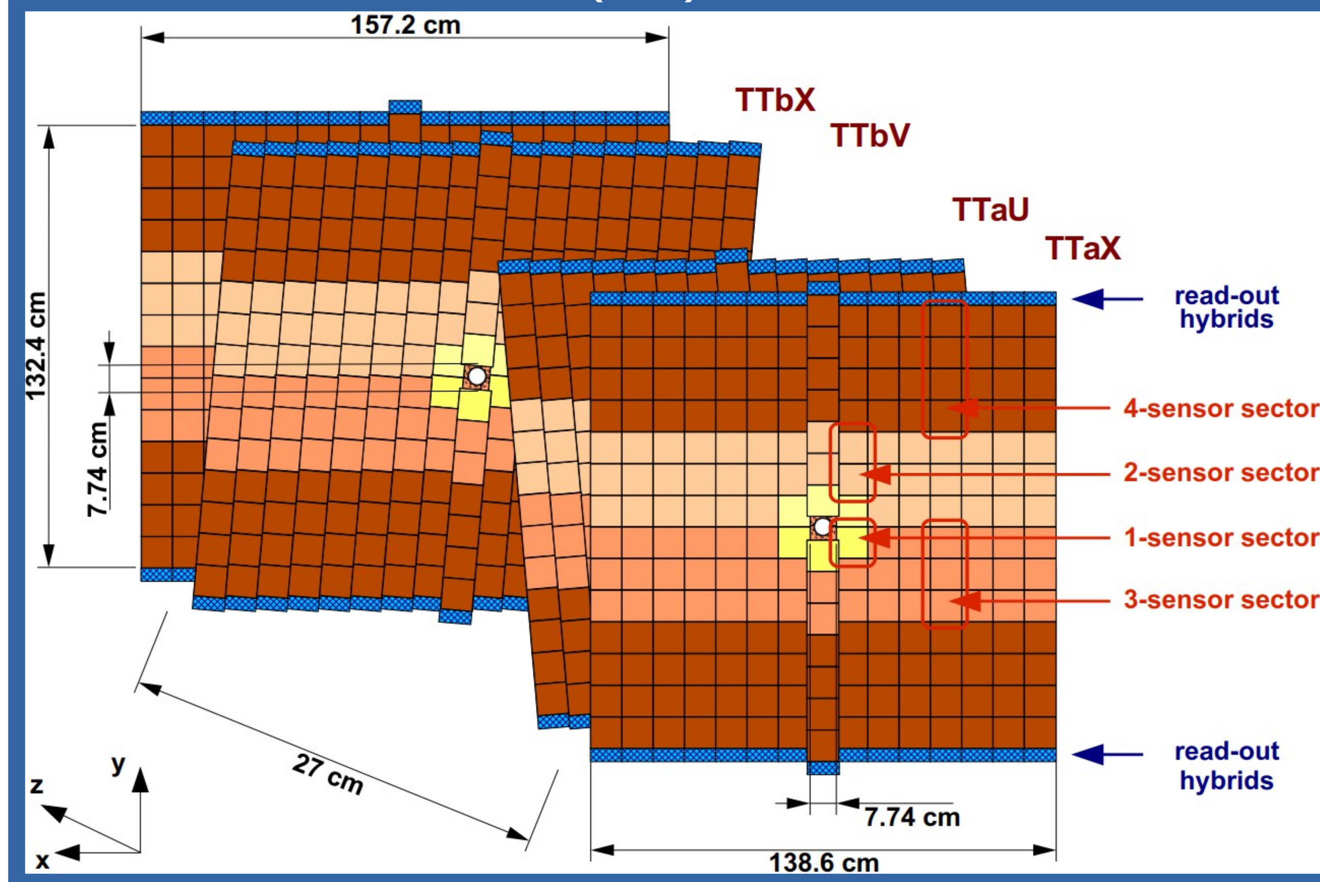
LHCb counts with 3 silicon sensor based detectors:

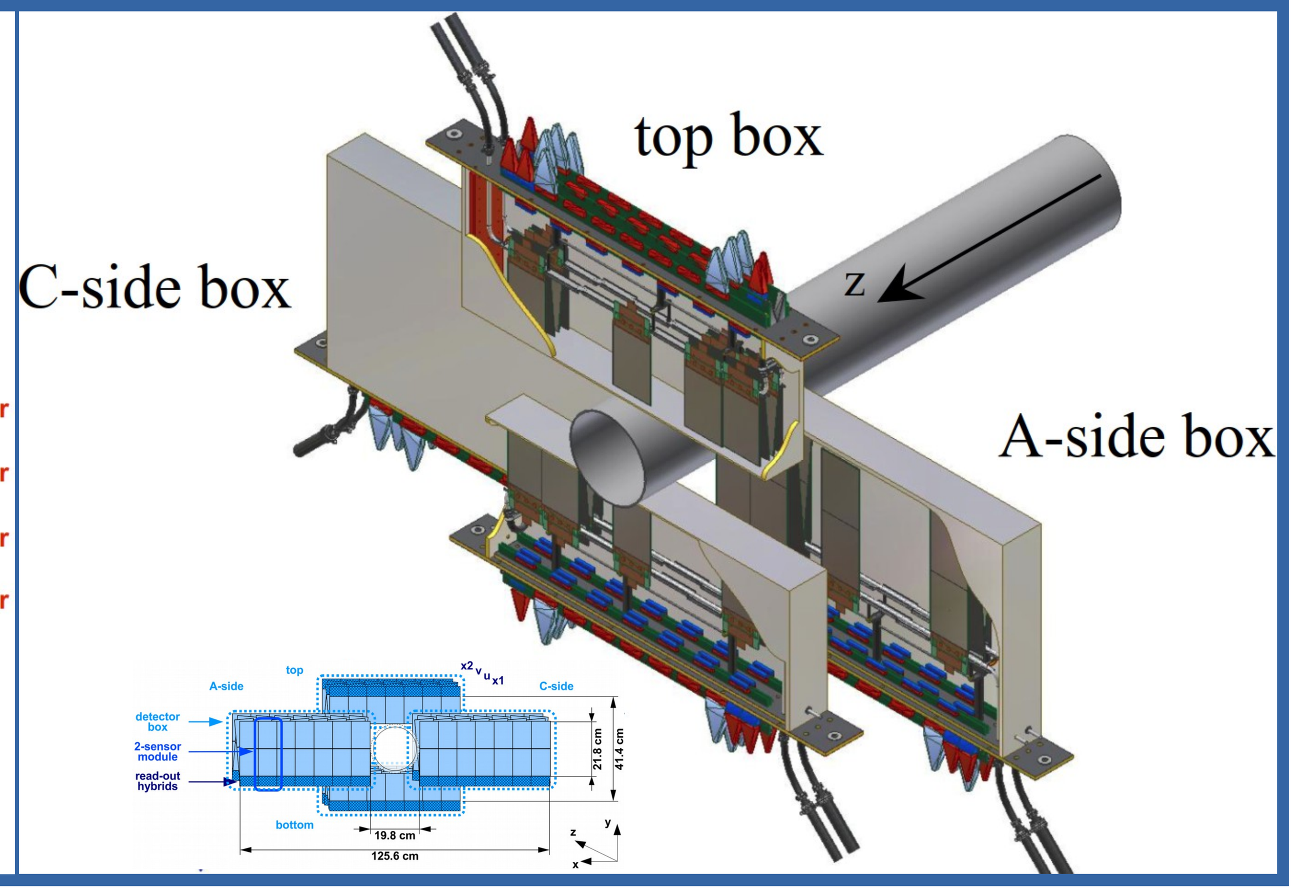
- VErtex LOcator: Reconstructs primary & secondary vertices
  - 42 double sided modules
    - 1 side R and 1 side ϕ
    - 300 µm thick Micron n$^+$-on-n silicon sensor
      - Pitches vary from 35.5 to 101.6 µm depending on position
    - 2048 strips per sensor
- Tracker Turicensis: Position before the magnet
  - 4 planes of sensor tiles
    - Tilted at 0º, +5º, -5º, 0º
    - 500 µm thick HPK p+-on-n silicon sensor
      - Pitch of 183 µm
    - Sensors grouped in longer or shorter sectors depending on the position with respect to the beam
- Inner Tracker: Position after the magnet
  - Three stations in Z (one in each T1, T2, T3 tracking plane)
  - Each station hosts 4 detector planes
    - Tilted at 0º, +5º, -5º, 0º
    - 198 µm pitched HPK p+-on-n silicon sensor
      - 410 µm thick in lateral boxes, 320 µm thick in top and bottom
      - 2x11 cm long sensors on lateral boxes
      - 1x11 cm long sensors on top and bottom boxes
  - The ensemble of TT and IT is called ST (Silicon Tracker)



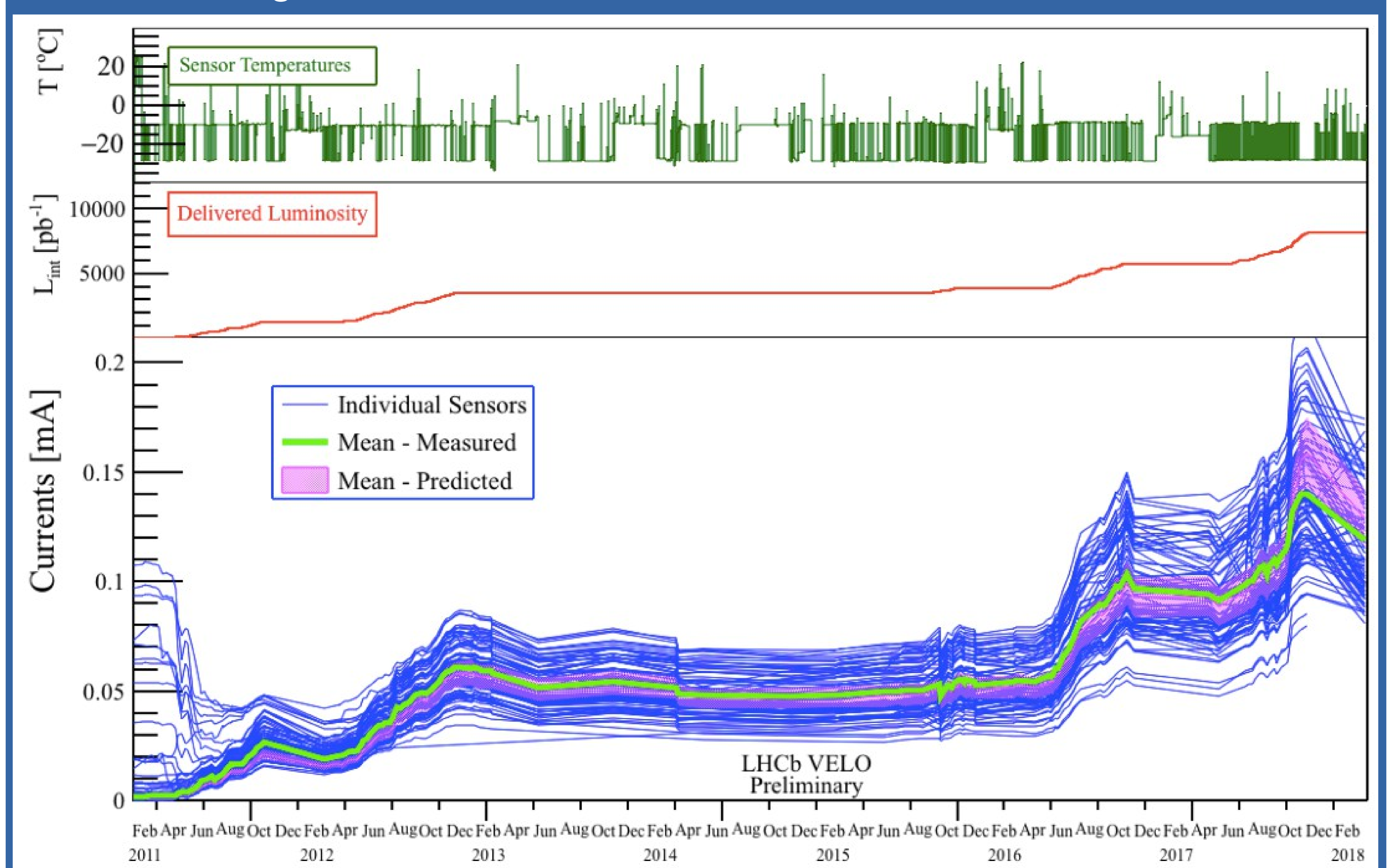
The VErtex LOcator (VELO)

The Silicon Tracker (ST)



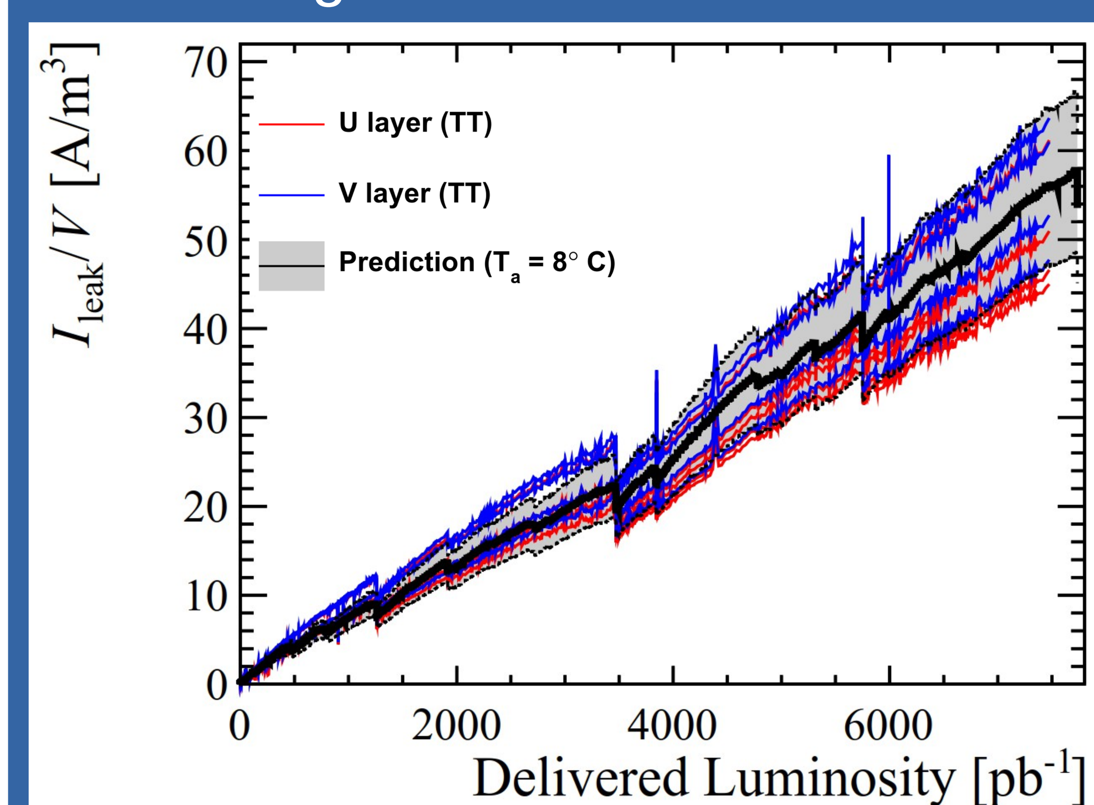


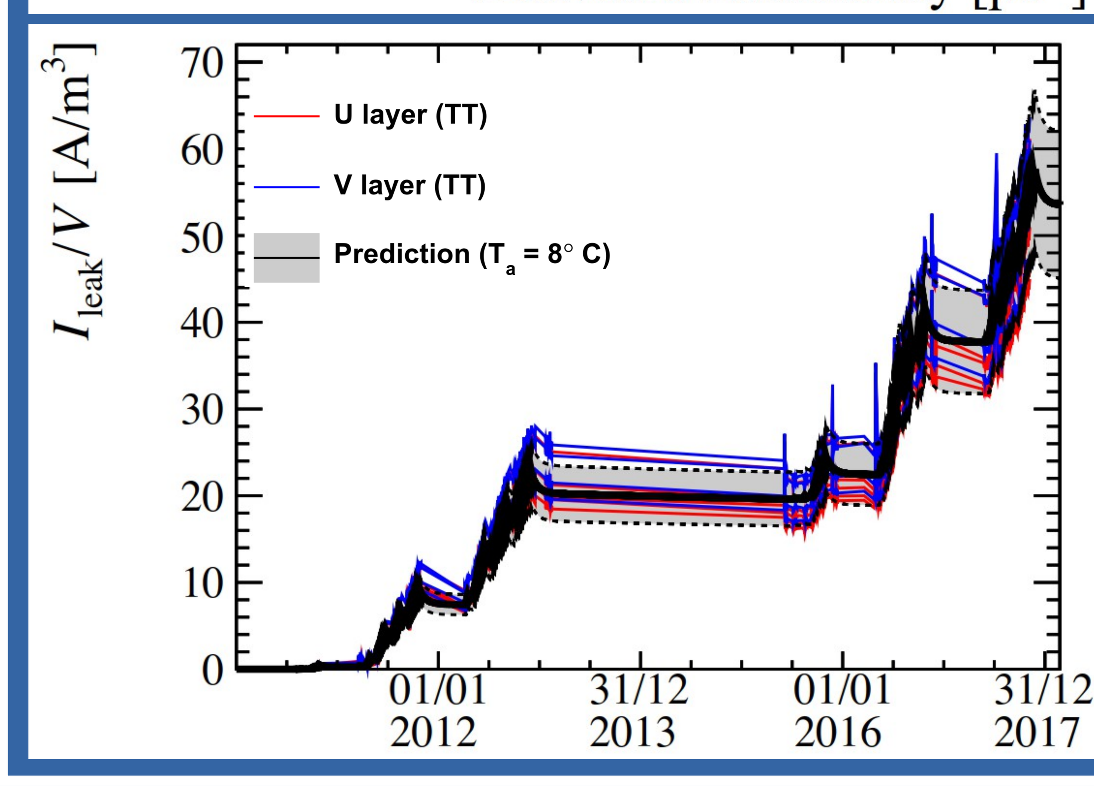
VELO Leakage Current evolution



The above figure shows the temperature, accumulated luminosity and the current monitoring over time. After calibrating for temperature the measured changes in bulk current due to accumulated radiation damage is in good agreement with the prediction. This allows for validation of the predicted fluence which is important for VELO as it feeds into the projection of the bias voltages that are periodically updated.

ST Leakage Current evolution





The ST group monitors leakage current and operating temperature at all times as a measure of the detector health and to ensure a well understood predictable behaviour.

This is one of the few observables for radiation damage in the silicon.

Measurements are then compared to theoretical predictions for the estimated delivered luminosity.

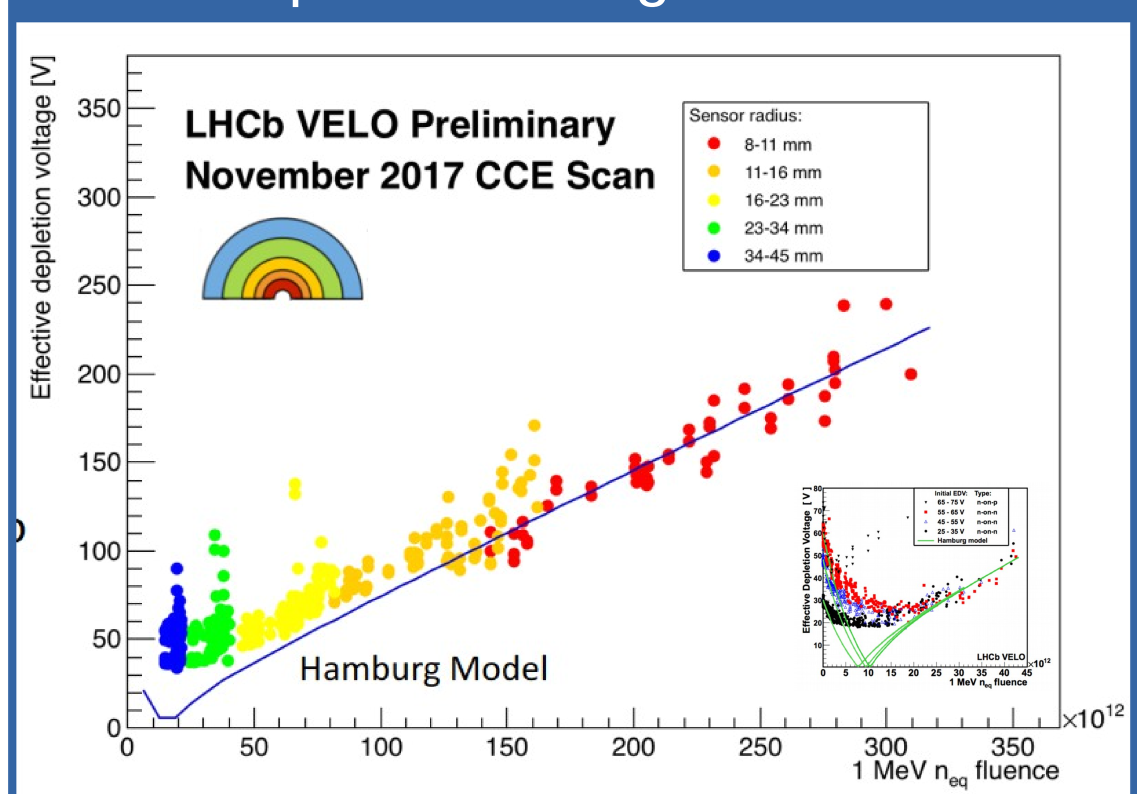
Current consumption changes during the particle fill, so the current is defined to be the maximum observed at a given partition for a given fill. The delivered luminosity is the one after the fill has ended and it is compensated for the position of each sensor.

The top left plot shows the leakage current for TT in very good agreement with theoretical calculations.

Because it is closer to the interaction point radiation damage is more pronounced in this detector so we show a worst case scenario.

The bottom left plot shows the same leakage current, but as a function of time. There it is possible to observe the annealing during periods without data taking. This effect is masked as vertical lines in the delivered luminosity plot.

VELO Depletion Voltage evolution

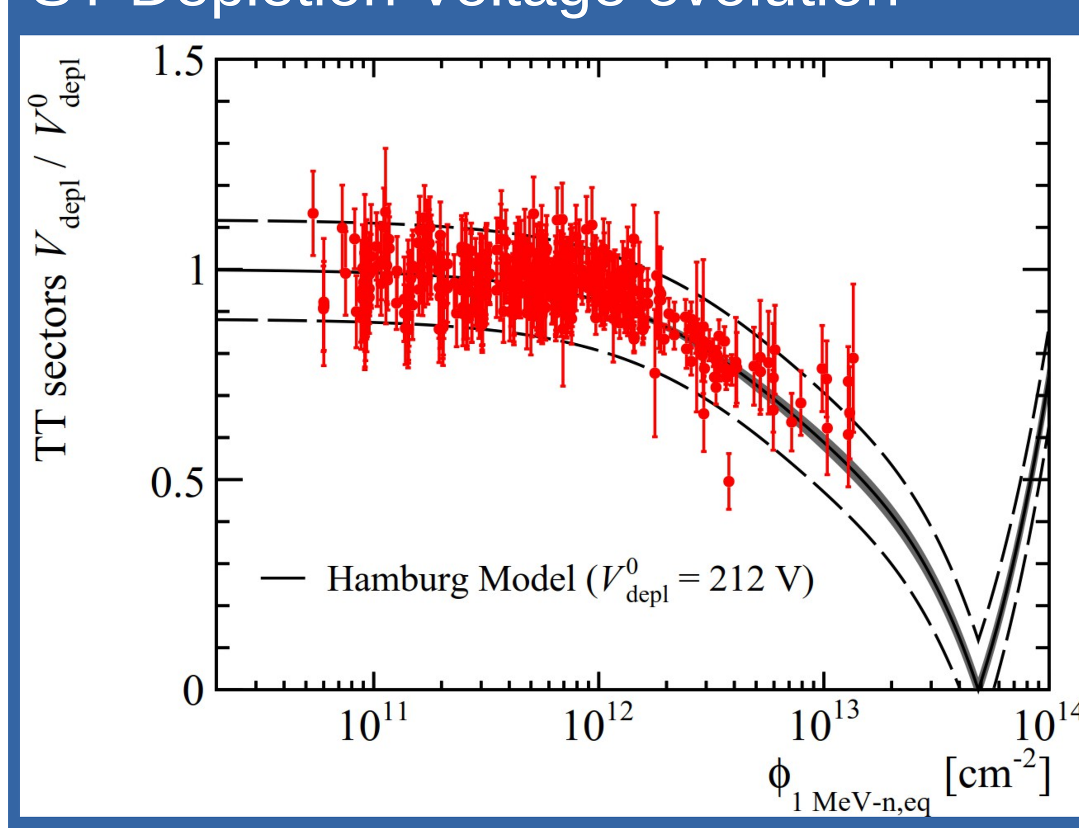


The VELO group monitors the depletion voltage of their sensors periodically using CCE scans (charge collection efficiency).

This is later compared to calculated values based on the Hamburg model.

Type inversion was reached already in run 1, so now the depletion voltage needs to be continuously raised to keep up with the damages caused by radiation. The good agreement shown in the plot is important because it shows the predicted bias voltage is reliable.

ST Depletion Voltage evolution



The ST group periodically performs charge collection efficiency (CCE) scans. This operation consists in scanning several sensor bias voltages and observing when the integrated charge saturates. This is the depletion voltage, another observable of radiation damage effects.

Results are then compared to FLUKA simulated irradiation maps for the various beam energies that the sensor has seen in its work life, with its measured temperature and the luminosity delivered by LHCb.

The left plot shows a good match between simulation and measurement.

It also shows that even in the worst case (TT) the sensors are not foreseen to receive enough radiation damage to reach the point of type inversion.