Investigations on the radiation damage of the LHCb VELO: a full review

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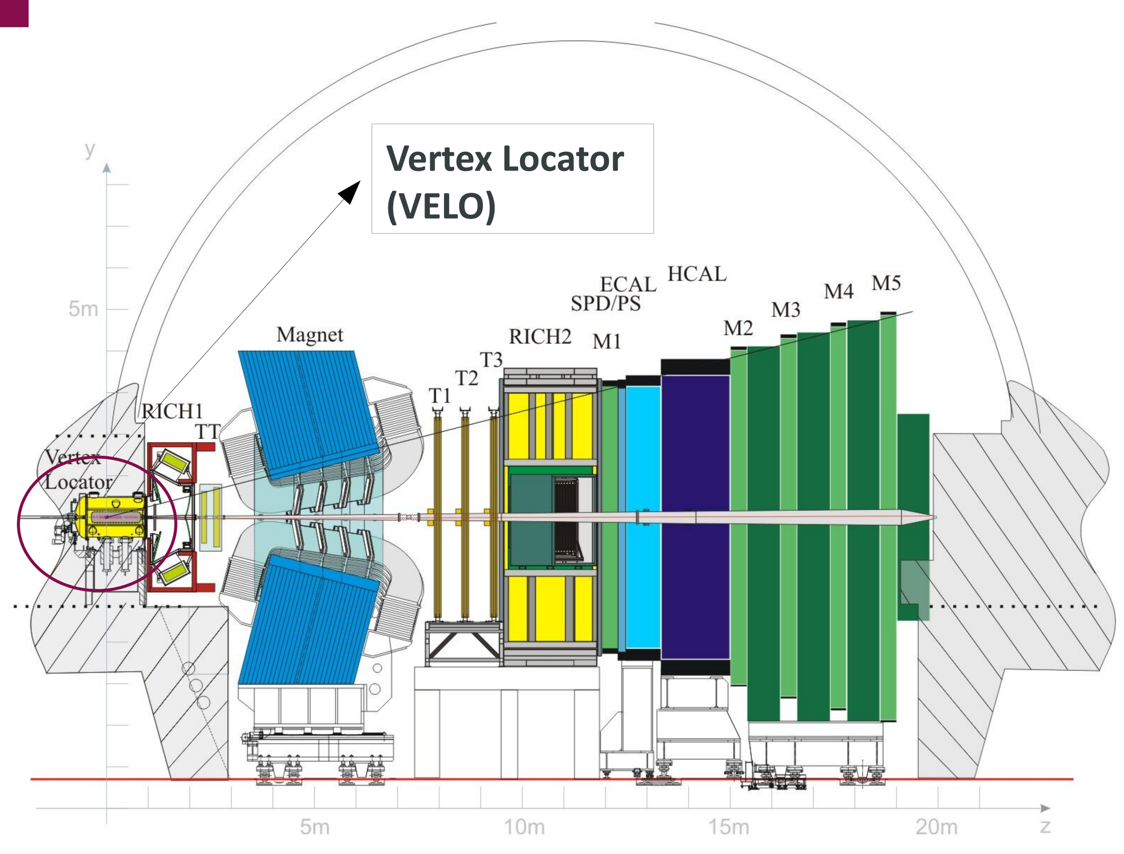
The LHCb Detector

The LHCb experiment and detector specification

- LHCb is a dedicated heavy flavour experiment at the LHC to searching for New Physics, by studying rare b- and c-quark decays.
- LHCb detector is the forward single-arm spectrometer with excellent vertex resolution.
- Detector upgrade 2019-2020 to triggerless read-out at 40 MHz.
- Consists of the Vertex Locator, one tracking station before the magnet (TT) and three after the magnet (T1-T3), two ring imaging Cherenkov detectors (RICH1, RICH2), three layers of calorimetry and five muon detectors (M1-M5).

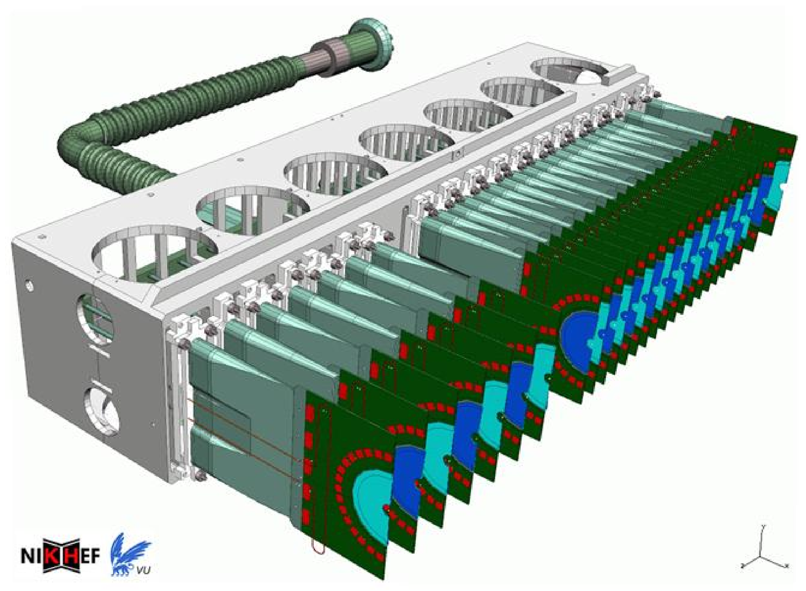


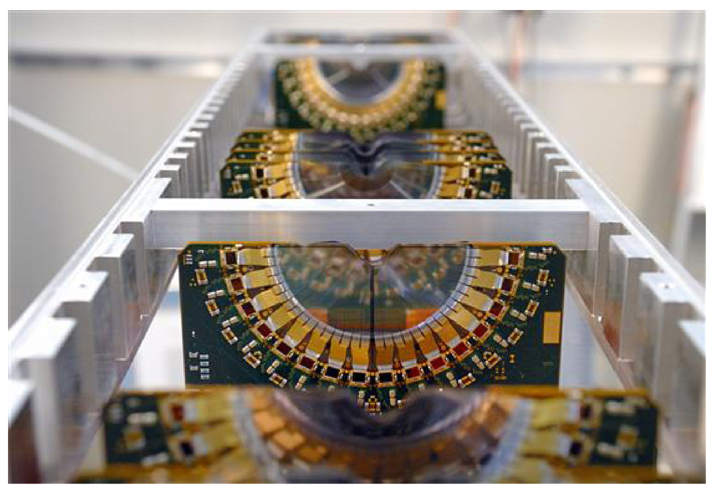
LHCb detector
CERN-LHCC-2011-001

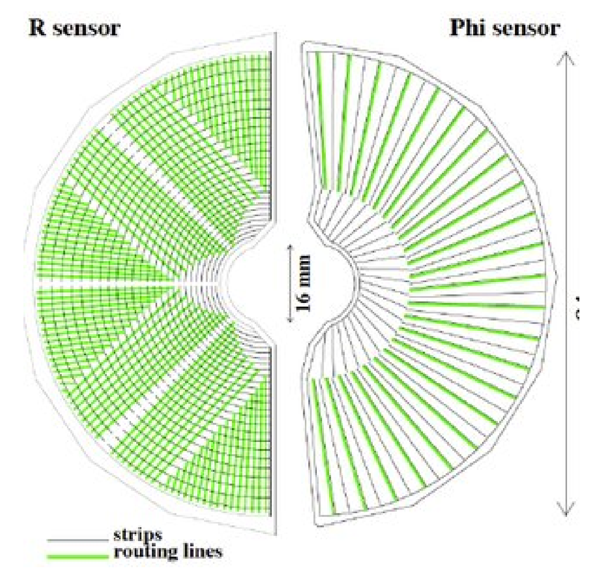
The Vertex Locator

Vertex Locator specification

- Vertex Locator (VELO) is a silicon micro-strip detector operating extremely close to the LHC proton beams, specialised in reconstructing primary and secondary vertices.
- VELO consists of 42 modules with pairs of semicircle sensors.
- Each station is build of one R and one Phi sensor, respectively with radial and circular geometry of silicon strips.
- Sensors survived 5 years running of LHCb detector, with innermost active strips up to 8mm to the beams.



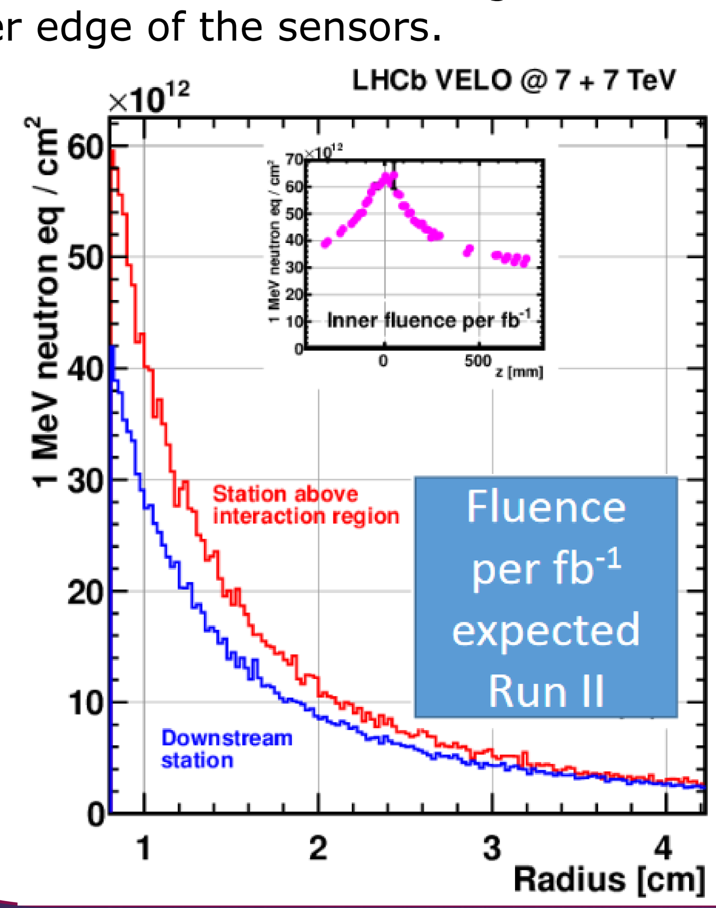




Radiation damage of VELO

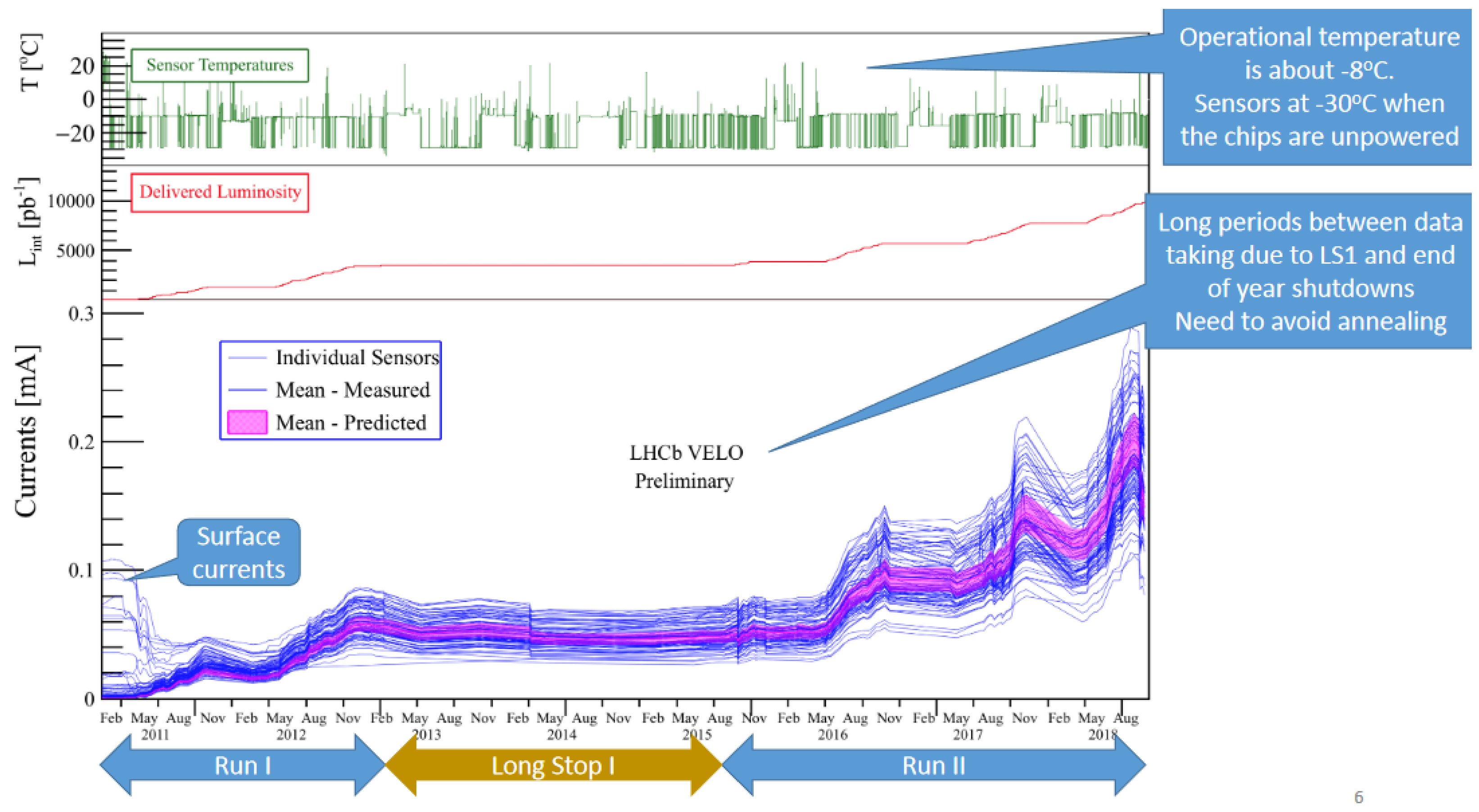
Radiation dose delivered

- Due to the sensors' circular shape, fluence varies exponentially with radius, as well as differs by the factor of 2 between most and least exposed stations.
- During experiment, sensor are not being irradiated uniformly. Fluence at the hottest points is even 10 times higher than at the outer edge of the sensors.



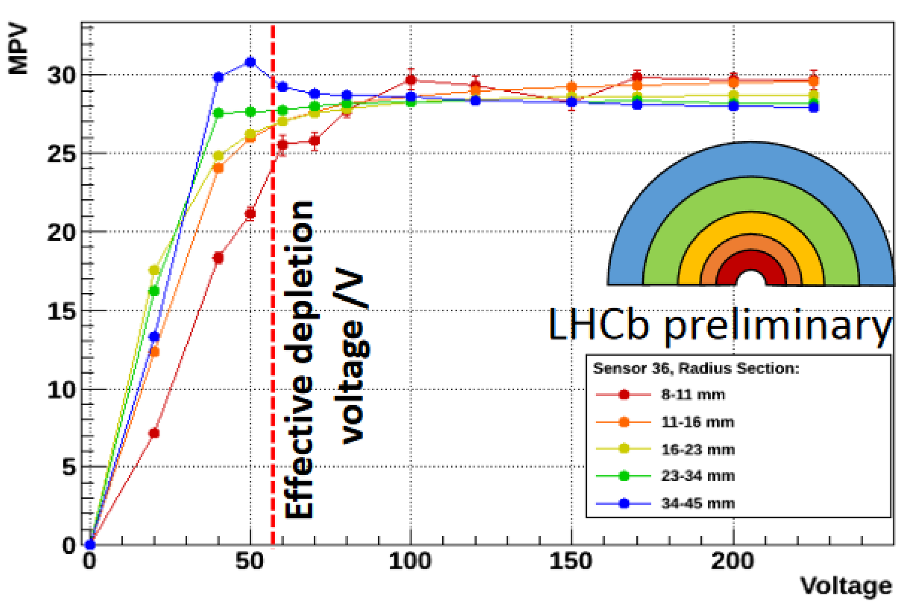
Leakage currents over the irradiation history

- Over 5 years of experiment (Run I and Run II) sensors were being irradiated and leakage currents were growing all the time.
- Leakage currents can be reduced through **annealing**, the procedure of heating the sensor to high temperature to recreate some properties of silicon crystal structure.
- Annealing operation lead to a great recovery of the sensors performance in November 2018, one month before shutting the Run II period.



Depletion region in VELO

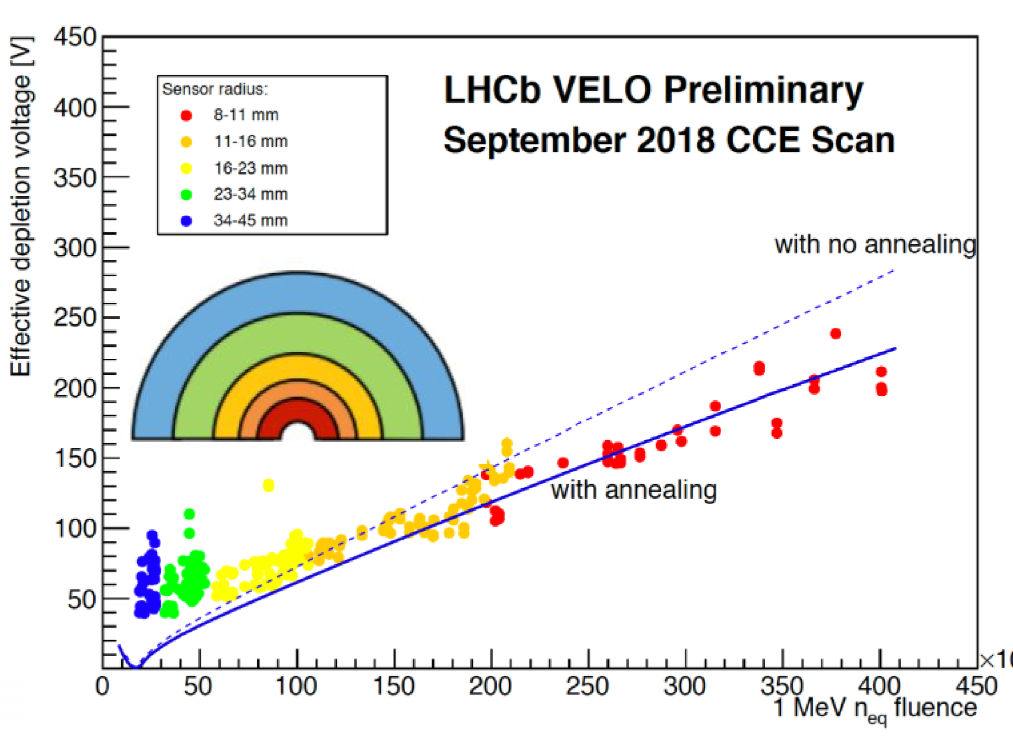
- Voltage needed to generate depletion zone across the whole sensor's active area is dependent on the irradiation.
- Crucial to charge collection efficiency is getting the full depleted detector.
- As the sensor is not irradiated uniformly, an **effective depletion voltage** was introduced.
- Effective depletion voltage is defined at 80% of the maximum MPV (most probable value of collected charge).

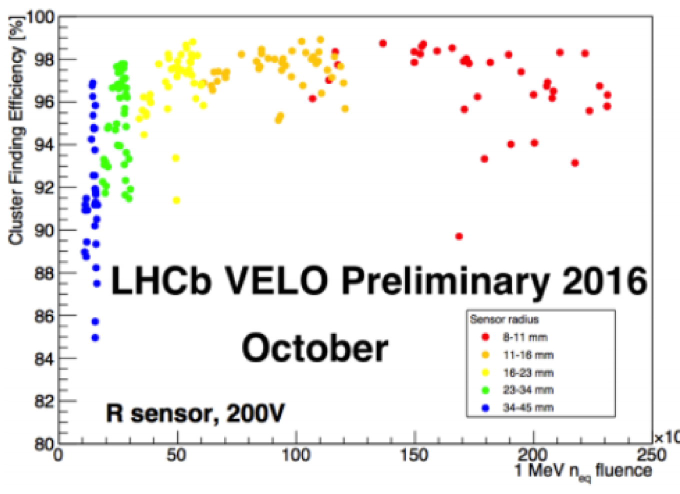


Cluster finding efficiency

Effective depletion voltage

- As the radiation damage is progressing, the voltage to get full depletion is increasing and obeys to Hamburg model, presented by blue line in the right picture.
- Due to limited signal integration time, there is no sensitivity below 30V.
- For the least irradiated area, voltage is high enough to invert the type of the sensor.





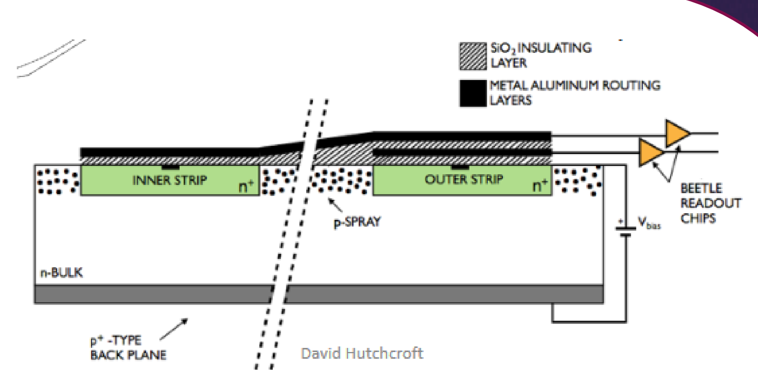
Cluster finding efficiency

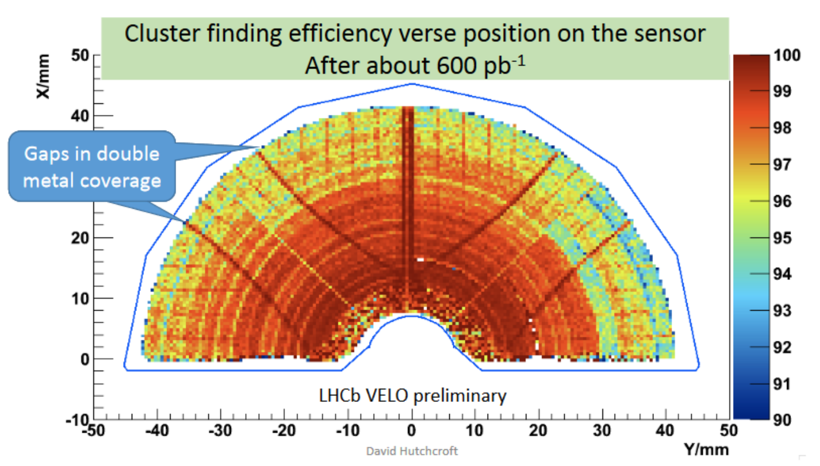
- At high irradiated parts of the sensor **cluster finding efficiency** naturally decreases, however its lowest is at the outer strips of the sensor, which is the least irradiated. This phenomena is caused by so called **double metal effects**.

Double metal effects

Reasons and characterization

- R and Phi sensors need two sets of metal routing lines, one to capacitively couple to the strips, the other carrying the signal to the amplifiers over the outer strips.
- Since routing lines of the circular R sensors are radial, routing lines have to cross perpendicularly, which leads to undesirable capacitive coupling effects.





Negative effects

- Before irradiation there were no effects visible. After irradiation, when a signal passes between strips, both layers of routing lines couple to the moving charge.
- Before irradiation free surface charges can act as a shield as does the 1st metal layer. After irradiation we see phantom signals in the inner strips.