New simulation of particle fluence for the LHCb VELO Upgrade

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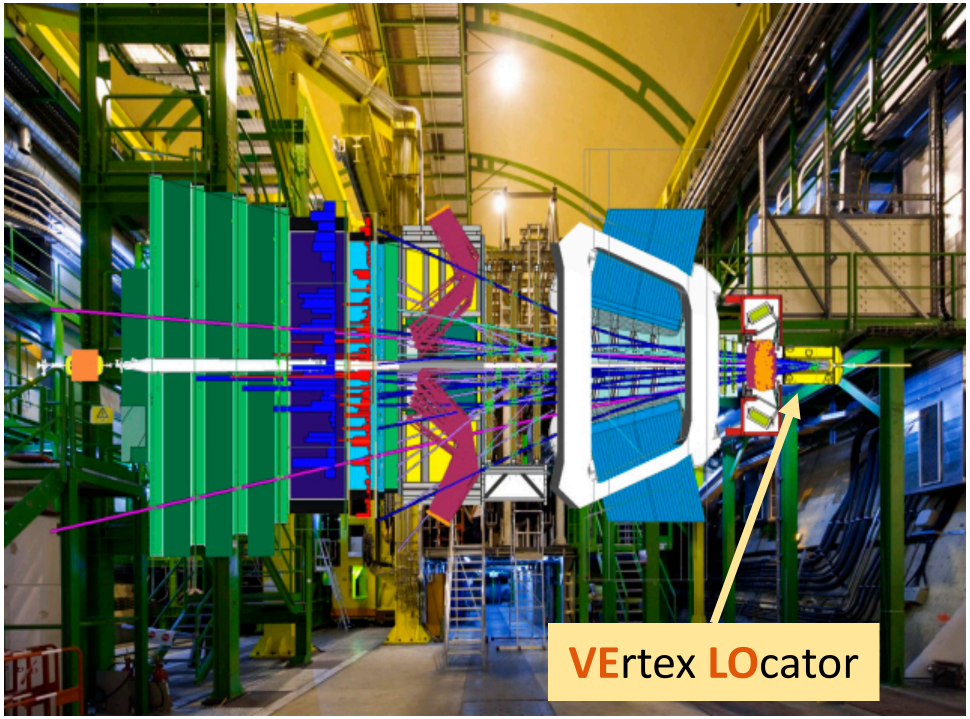
Plan

1. LHCb experiment and Vetex Locator
2. New simulation of fluence for VELO Run II condition.
3. Leakage current measurement.
4. Effective depletion voltage evolution in Run II.
5. Fluence for the Upgrade I.
6. Upgrade II.

LHCb experiment

The detector dedicated for studying flavour physics at LHC.
Especially CP violation and rare decays of beauty and charm mesons.



Physics program:

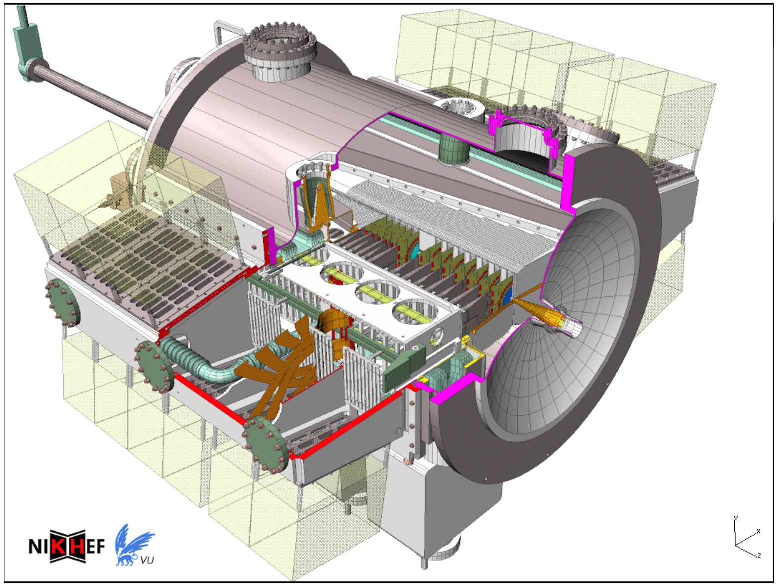
- CP Violation ,
- Rare B decays,
- B decays to charmonium and open charm,
- Charmless B decays,
- Semileptonic B decays,
- Charm physics,
- B hadron and quarkonia,
- QCD, electroweak, exotica …

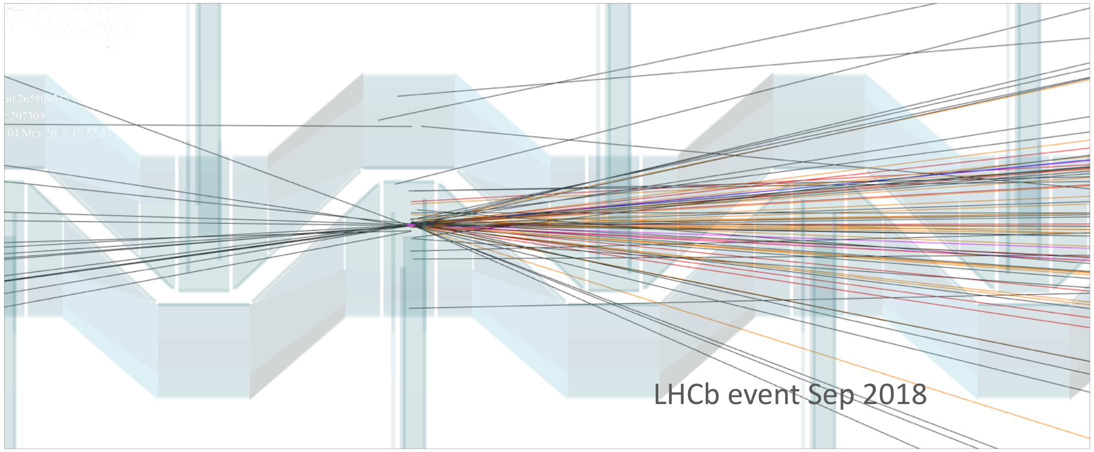
Excellent performance:

- 3 fb^{-1} accumulated in RUN I
- 3.26 fb^{-1} in Run II
- Excellent Vertex Resolution
- Precise tracking: $\delta p/p \sim 0.4 - 0.6\%$
- Hadronic identification 2-100 GeV/c

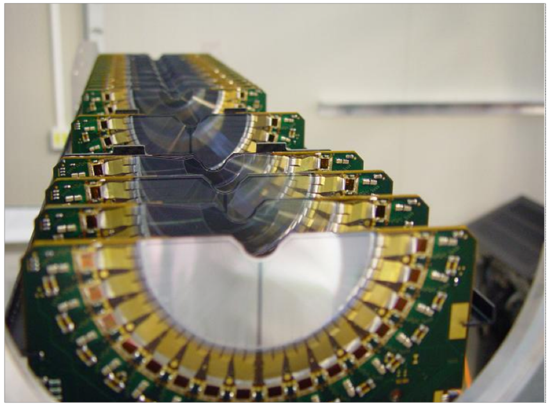
Vertex Locator (VELO)

- Silicon detector situated in close proximity of the beam-pipe.
- 42 modules with pairs of n-on-n (one is n-on-p) sensors.
- VELO halves were movable - the movement is steered by a precise system.
- When stable beams, the silicon edge was only 8 mm from the proton beam – sensors are in harsh particle fluence.
- Designed to tolerate integrated luminosity about 10 fb^{-1} .





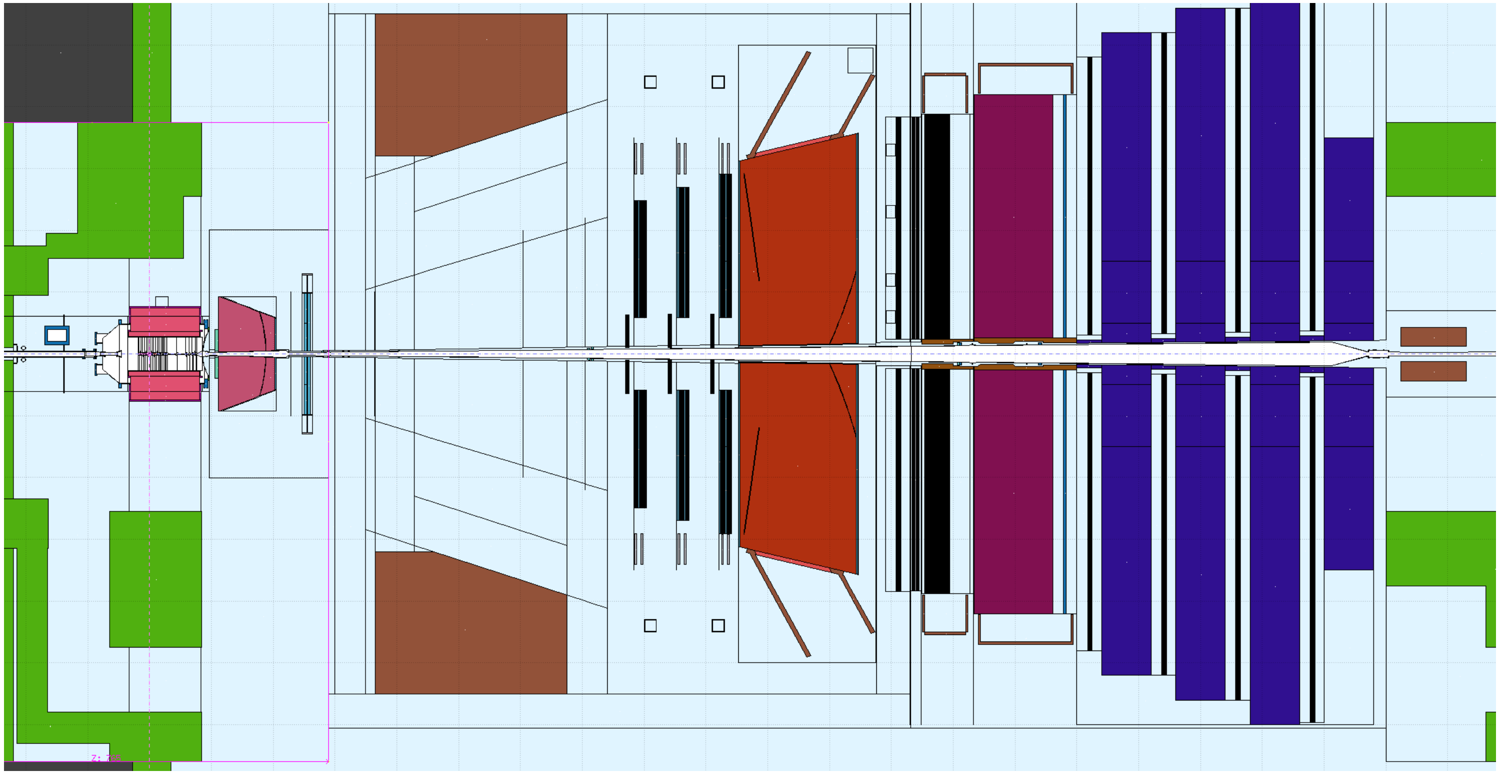
LHCb event Sep 2018



[Performance of the LHCb Vertex Locator](), [J. Instrum. 9 (2014) P09007]()

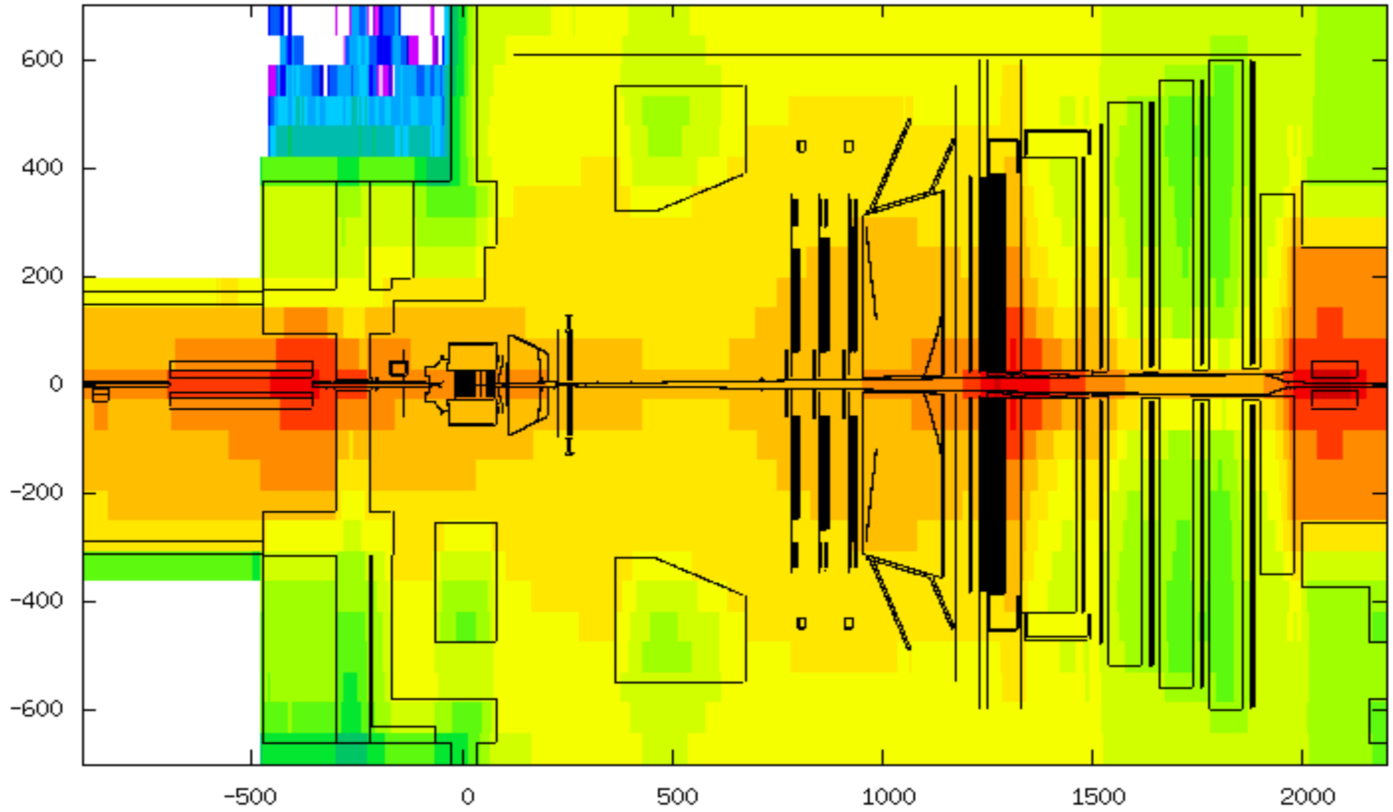
FLUKA simulaton of LHCb radiation

- Geometry description of the LHCb detector in Fluka comes from the Radiation Protection group.



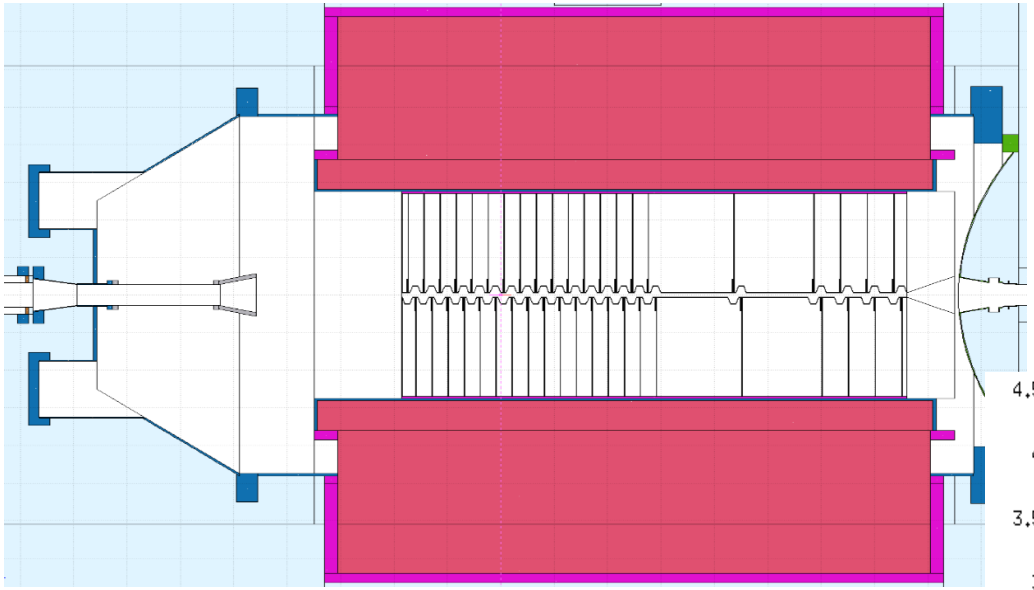
FLUKA simulaton of LHCb radiation

- Neutron equivalent fluence in the LHCb spectrometer

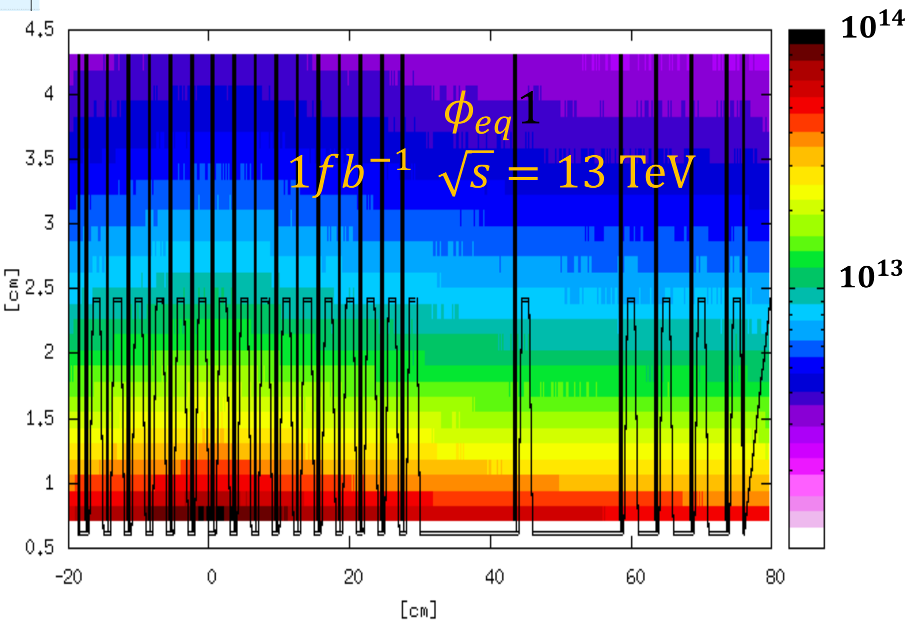


Fluence simulation for VELO

- LHCb operates luminosity $\mathcal{L} = 4.5 \cdot 10^{32} cm^{-2} s^{-1}$, ($\mathcal{L}_{int} = 9.6$ fb^{-1} in Run I and Run II) but the distance from the beam is only 8 mm.

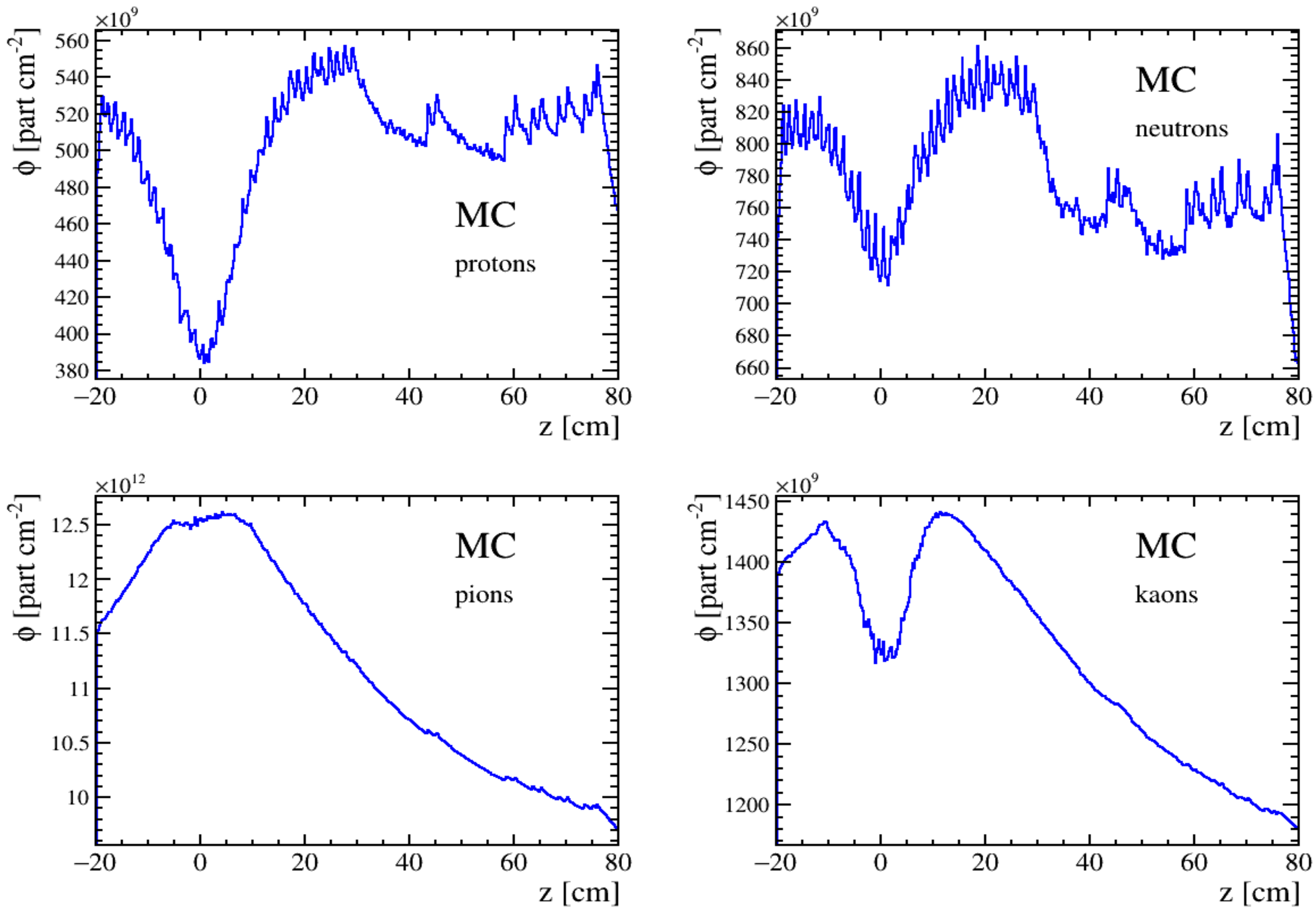


- In the VELO region the main components of flux originate from the primary proton-proton collision.



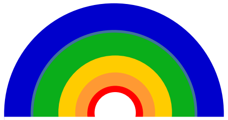
Fluka simulation Run II – particle fluence in VELO

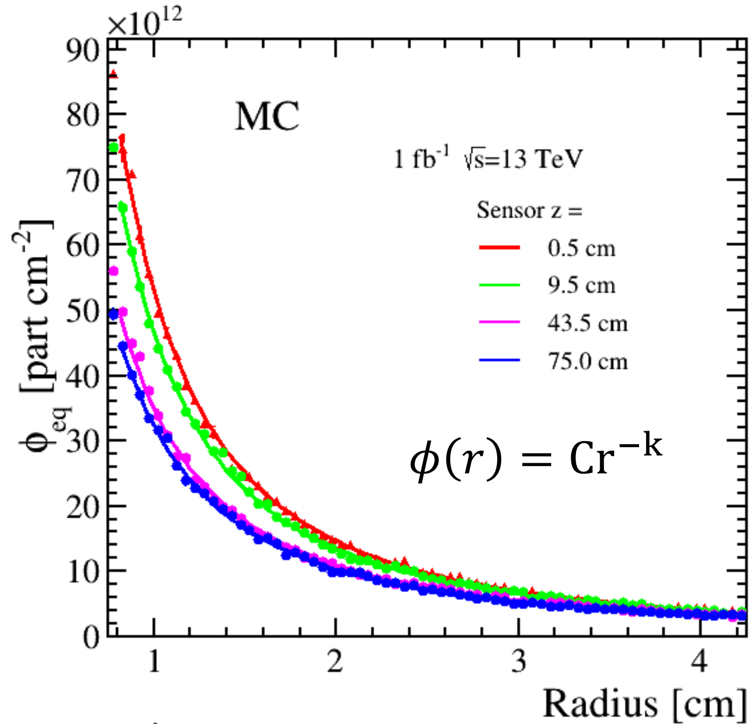
- The radiation field in the VELO region is non uniform and with strong dependence on the position along the beam line.
- The flux of particles is dominated by pions.

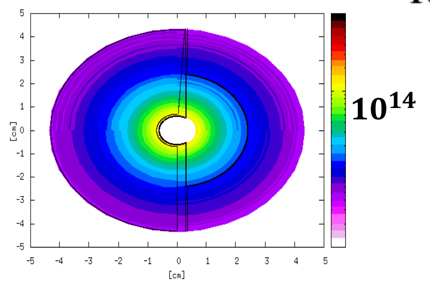


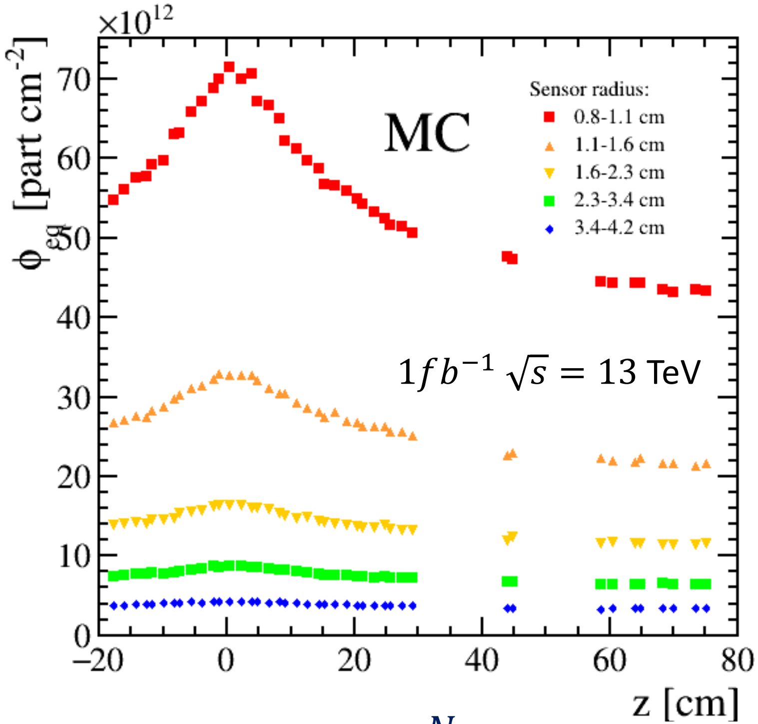
Fluka simulation – neutron equivalence fluence

- Radial dependency of neutron equivalence fluence showed that in sensor close to the IP the n_{eq} rises about order of magnitude.
- In more distant sensors the distribution is flatter.









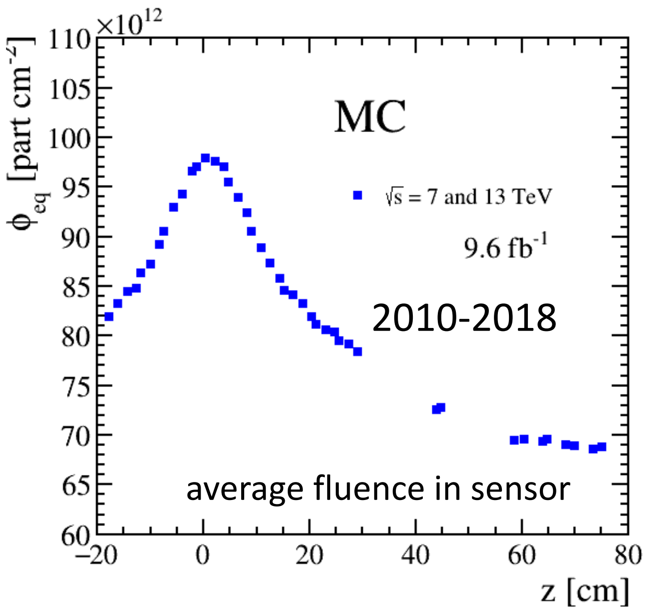
$$\phi_{reg} = \frac{N_{reg}}{S_{reg}}$$

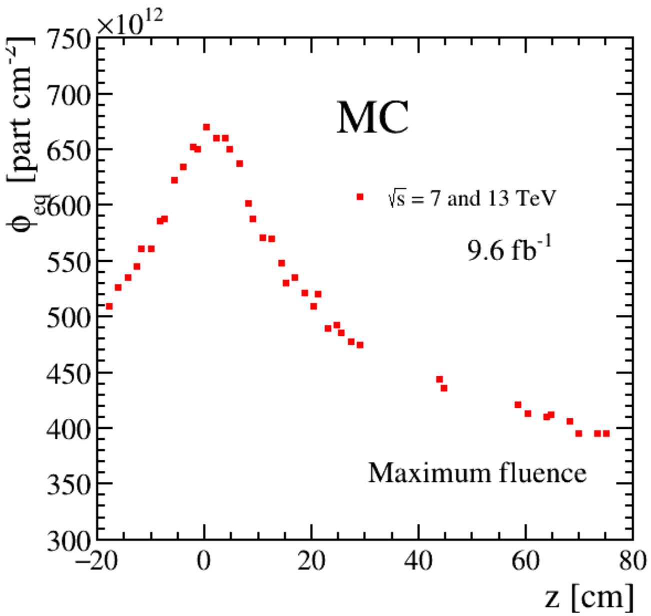
Simulation of n_{eq} fluence in each VELO sensor and in „standard" radial regions of a sensor.

Fluka simulation – neutron equivalence fluence

- Simulation for Run I and Run II:

$\sqrt{s}$	7 TeV	13 TeV
Delivered Lumi $[fb^{-1}]$	3.46	6.15
σ_{pp} $[mb]$	71	78
N_{pp} $/1fb^{-1}$	71×10^{12}	78×10^{12}





$\phi_{avg} = 0.98\times10^{14}\ \mathrm{n_{eq}/cm^2}$

$\phi_{max} = 6.5\times10^{14}\ \mathrm{n_{eq}/cm^2}$

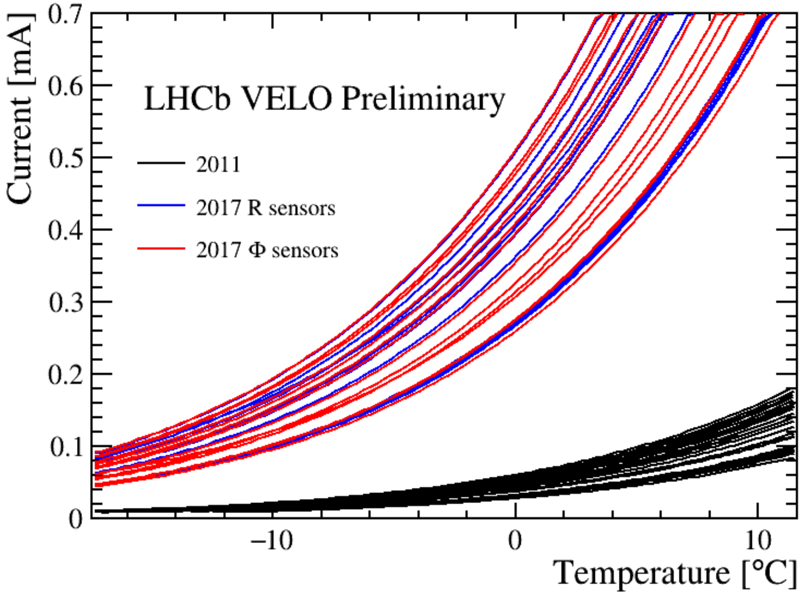
Leakage current – IT scans

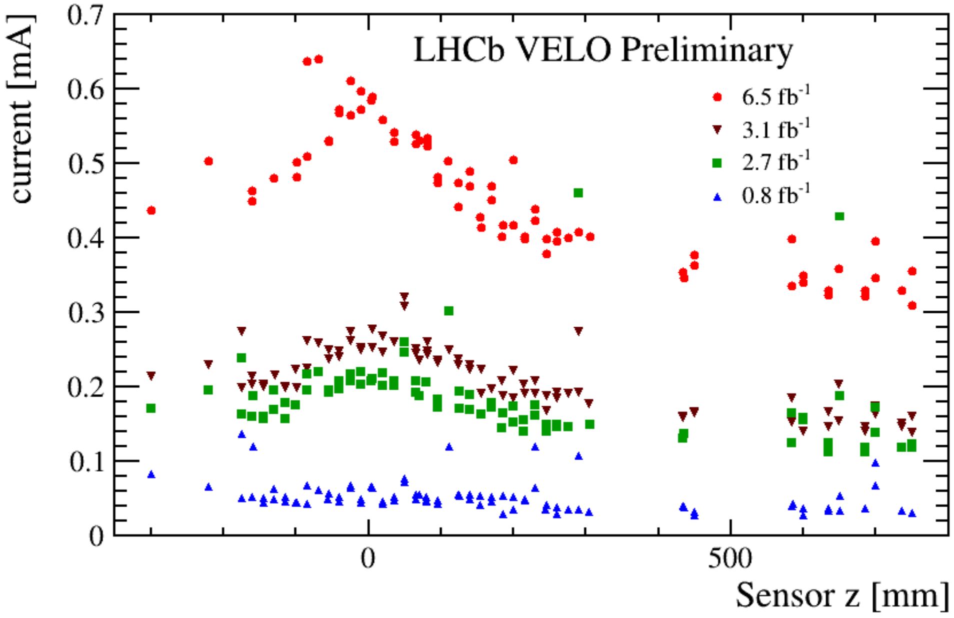
- The current-temperature characteristics (IT scans) were taken several times in breaks of data taking periods.

$$I(T) \propto T^2 e^{-\frac{E_{eff}}{2k_B T}}$$

Leakage currents @ 0°C

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



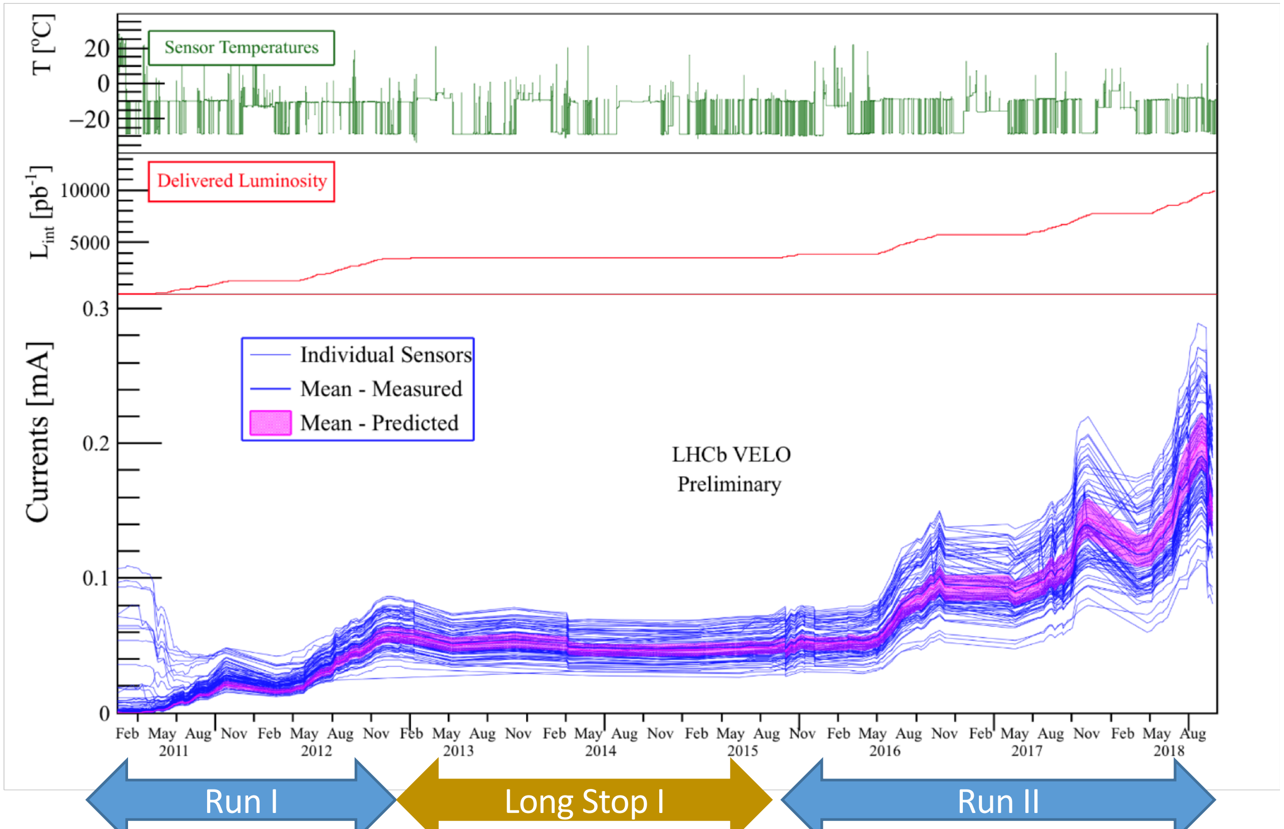


- The increase of the leakage current scales with fluence (and luminosity):

$$\Delta I = \alpha\, V_{ol}\, \phi_{eq}$$

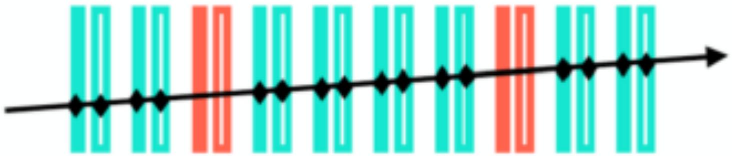
- Damage rate α is a function of the annealing temperature and evolves with time:

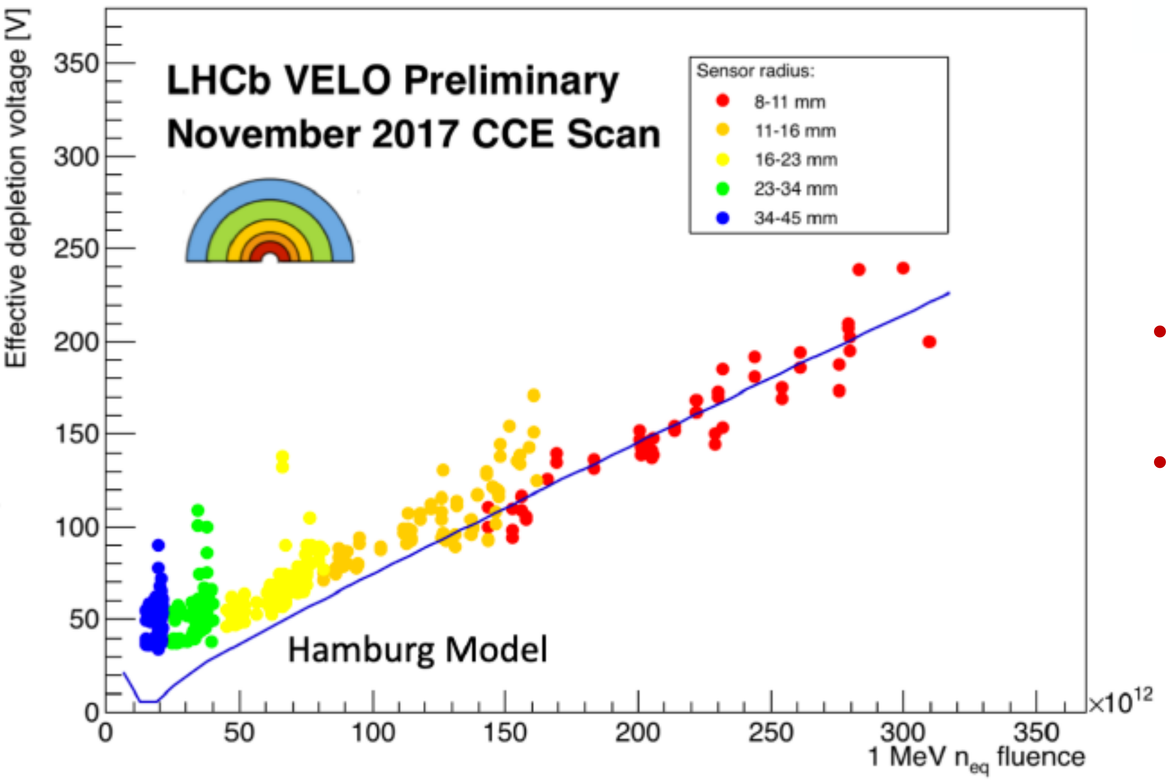
$$\alpha(t;T) = \alpha_1 \exp\left(-\frac{t}{\tau_1(T)}\right) + \left[\alpha_0(T) - \beta\, ln\left(\frac{t}{t_0}\right)\right]$$



Effective depletion voltage in Run II

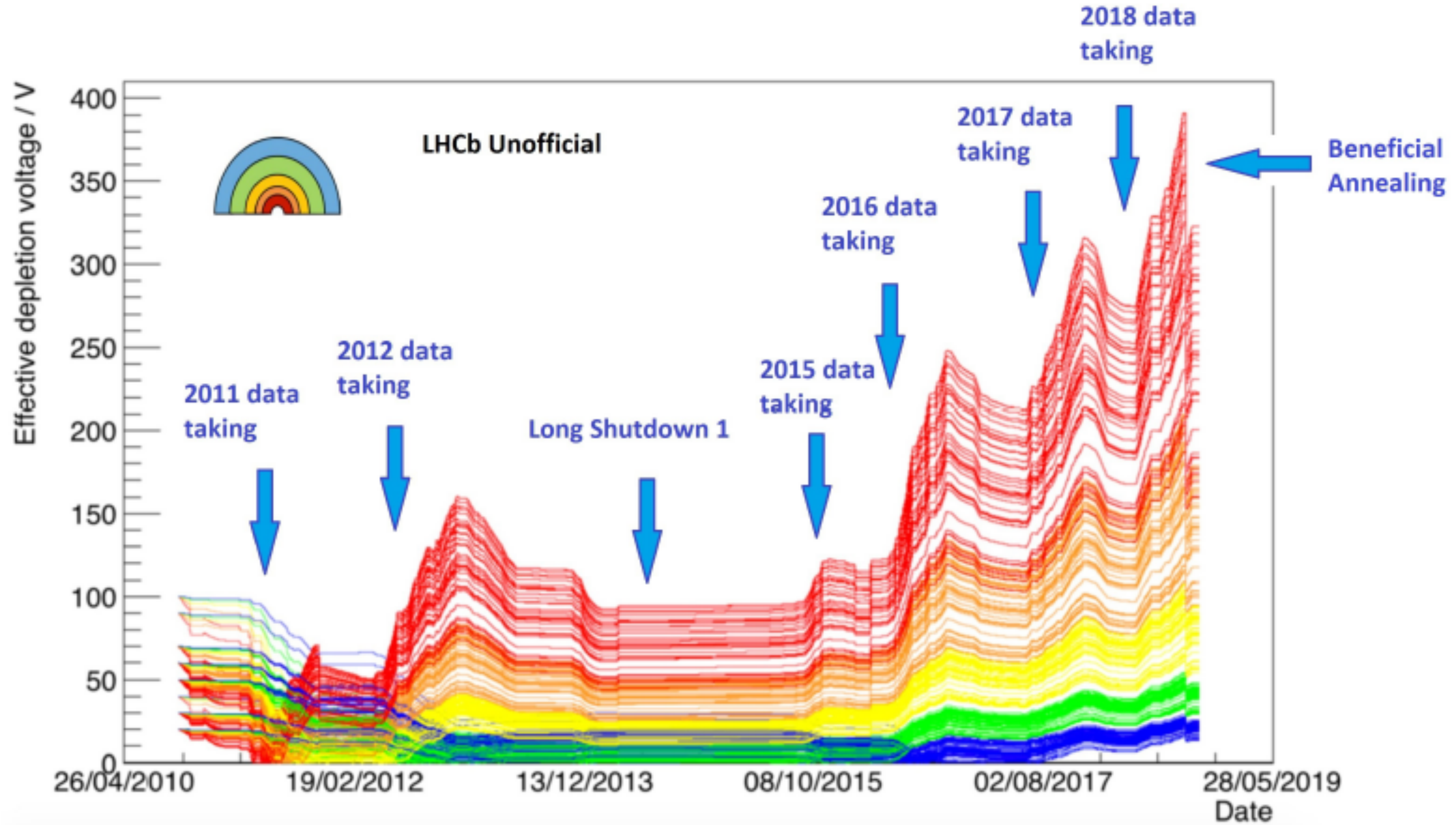
- Charge Collection scans were done regularly for VELO.
- Charge Collection Efficiency was determined and thus Effective Depletion Voltage (EDV).
- Each CCE scan was compared with Hamburg model.



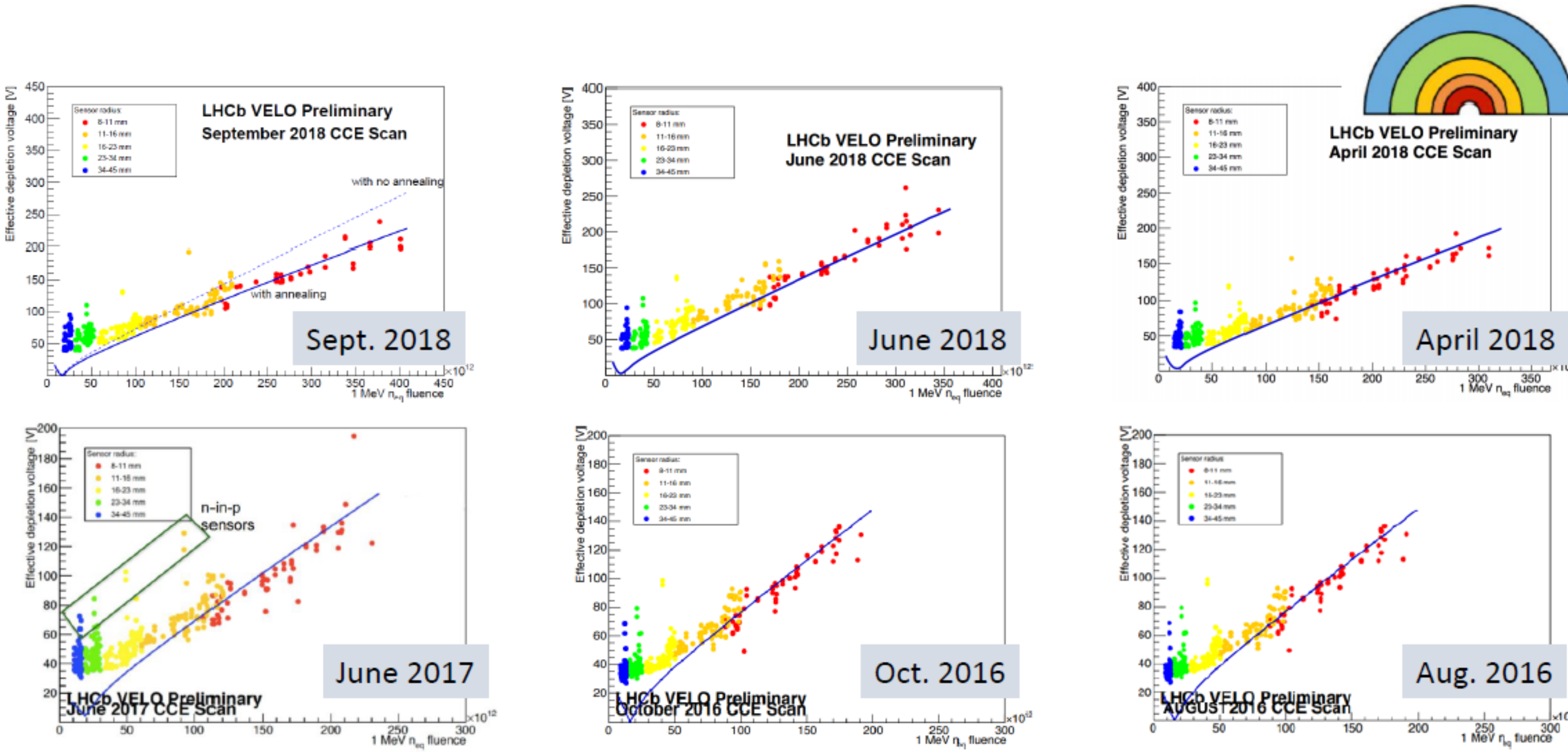


- Model and data were in agreement.
- It allowed to predict future evolution of RD.

Effective depletion voltage 2010-2018 (prediction)



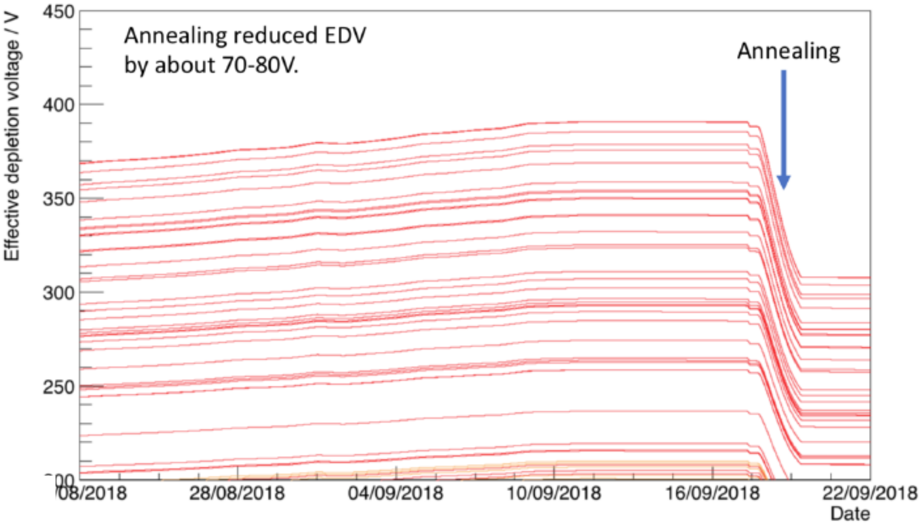
Effective depletion voltage 2016-2018 (measurements)

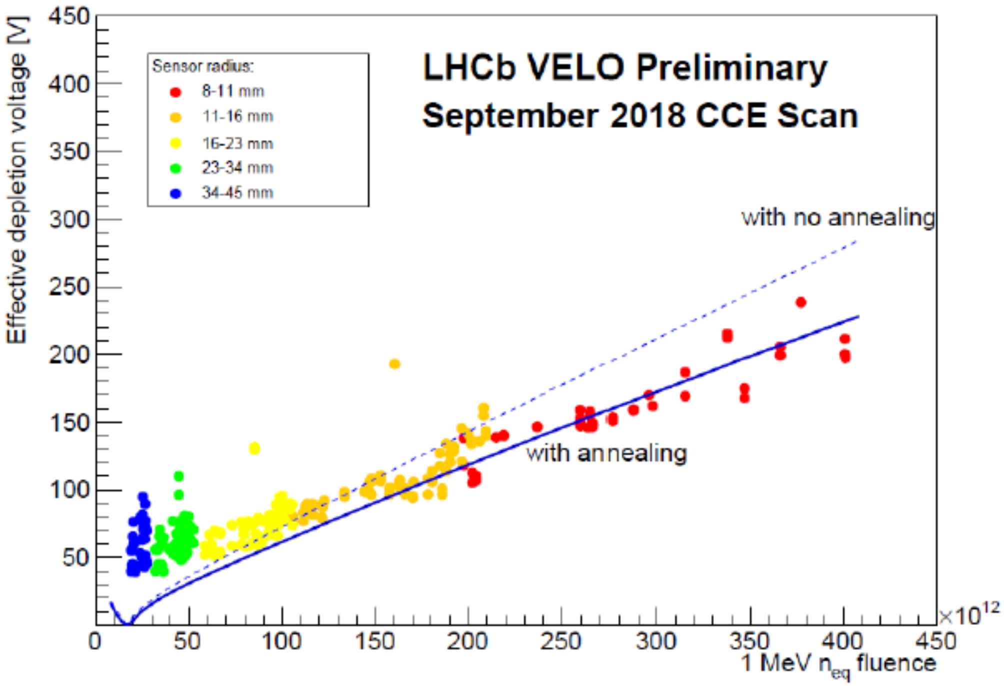


EDV evolution is consistent with Hamburg model

Beneficial annealing in VELO sensors in 2018

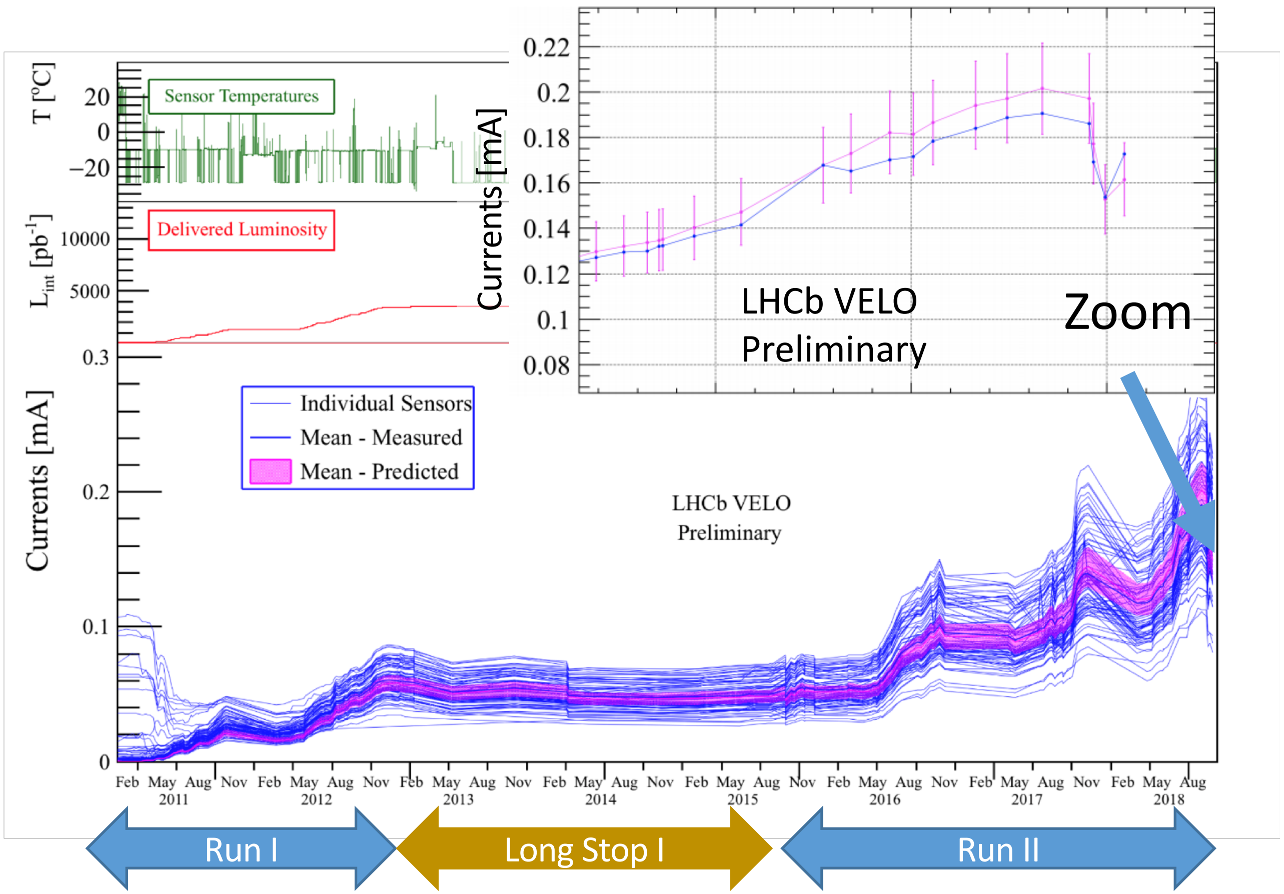
- Two months before the end of Run II, during TS, VELO sensors were kept in room temperature for two days (from -30 to +20°C).
- EDV reduced by 70-80 V.
- Hamburg model shows beneficial annealing.



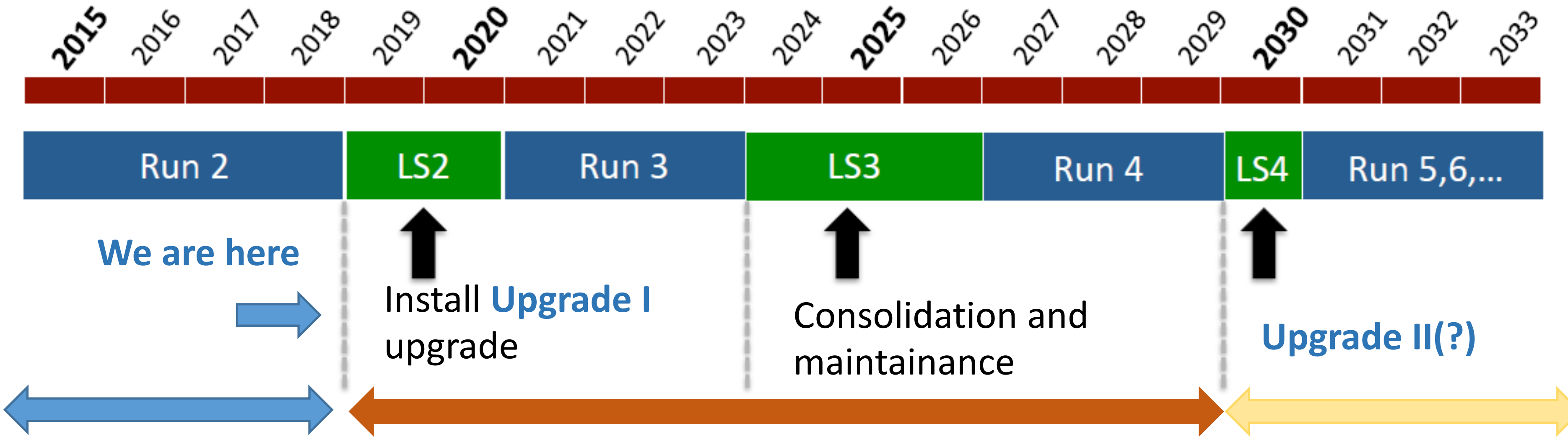


Deliberate annealing of VELO

The drop of about 25% (to 150 µA at 150V) in leakage currents was observed as well.



Upgrade after Upgrade



$\mathcal{L} = 4\times10^{32}\ cm^{-2}s^{-1}$
1.1 visible inteactions/crossing
9 fb^{-1} collected

$\mathcal{L} = 2\times10^{33}\ cm^{-2}s^{-1}$
5.5 visible inteactions/crossing
50 fb^{-1} collected

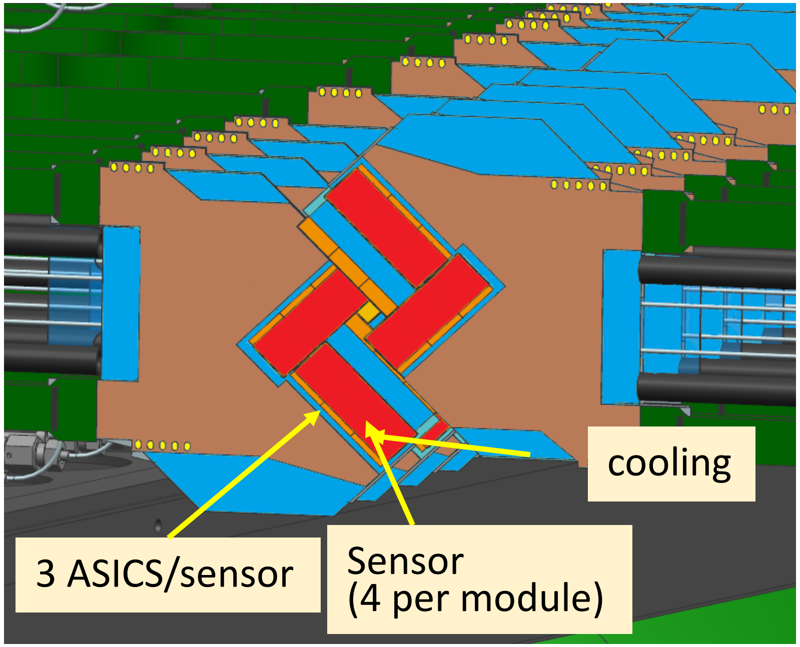
$\mathcal{L} = 2\times10^{34}\ cm^{-2}s^{-1}$
55 visible inteactions/crossing
300 fb^{-1} collected

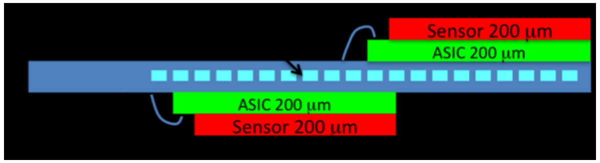
Detectors incompatible with higher luminosities must be re-designed

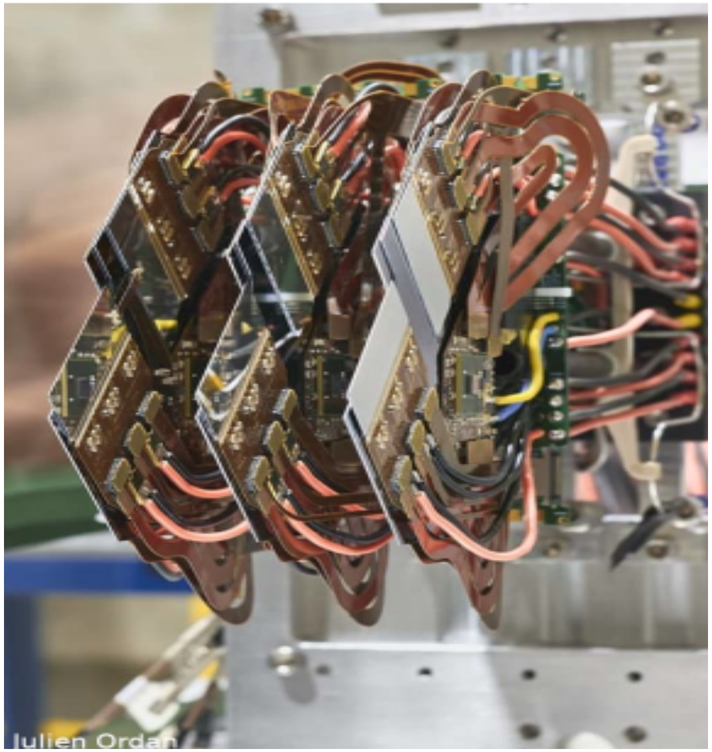
- The target peak luminosity of $\mathcal{L} = 2\times10^{33}\ cm^{-2}s^{-1}$, that is 10 times higher than the nominal and 5 times higher than the one we running at today
- Finer granularities and more radiation hardness.

VELO Upgrade I

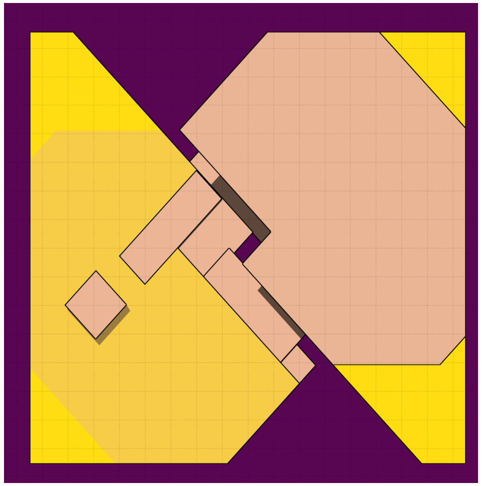
- Two retractable halves, separated by RF foil ($0.25\ mm$ thick) from LHC vacuum.
- 52 modules perpendicular to the proton beams.
- First active part $5.1\ mm$ from the beams.
- Four silicon pixel ($55 \times 55\ \mu m$) sensors per module, powered and readout via kapton cables and hybrid boards.

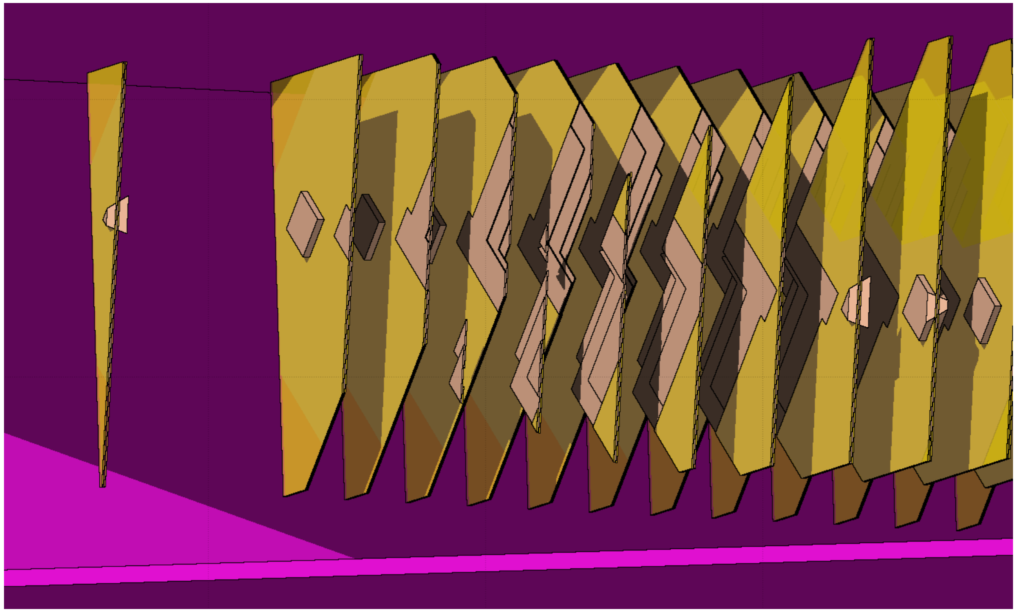


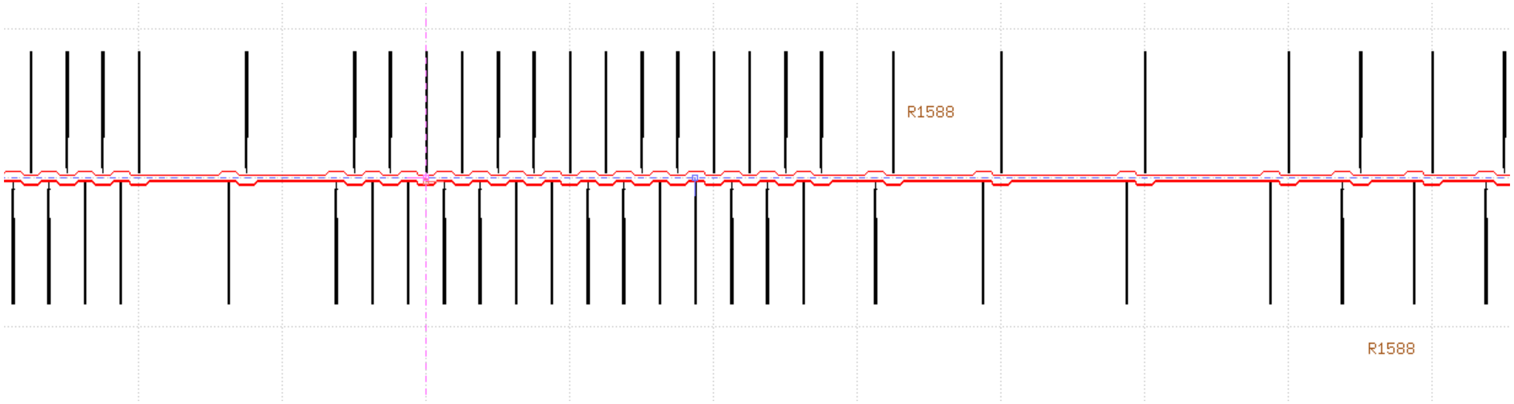




VELO pixel geometry was build in FLUKA (without other LHCb subdetectors)



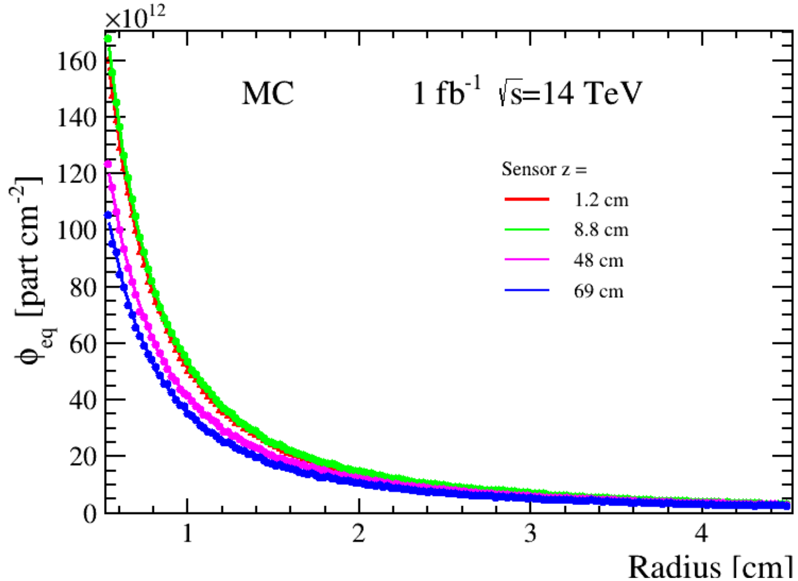


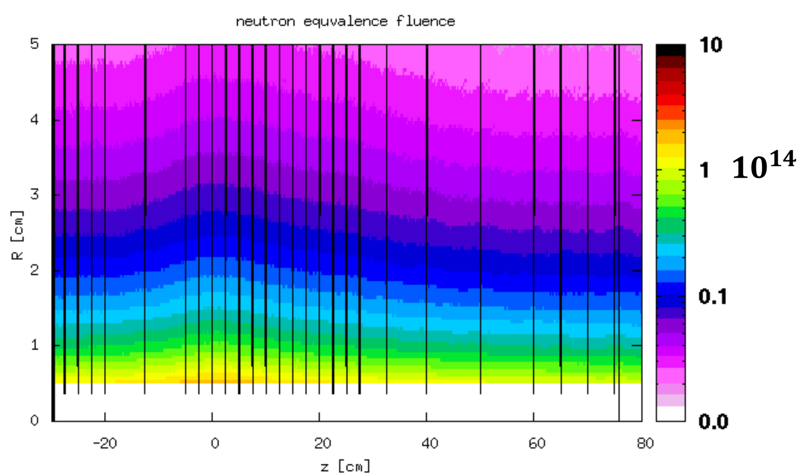


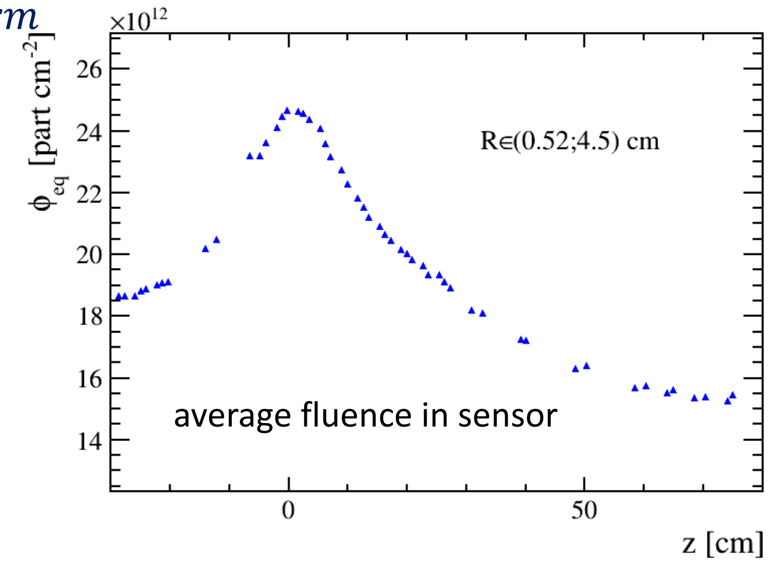
Simulation for the Upgrade I

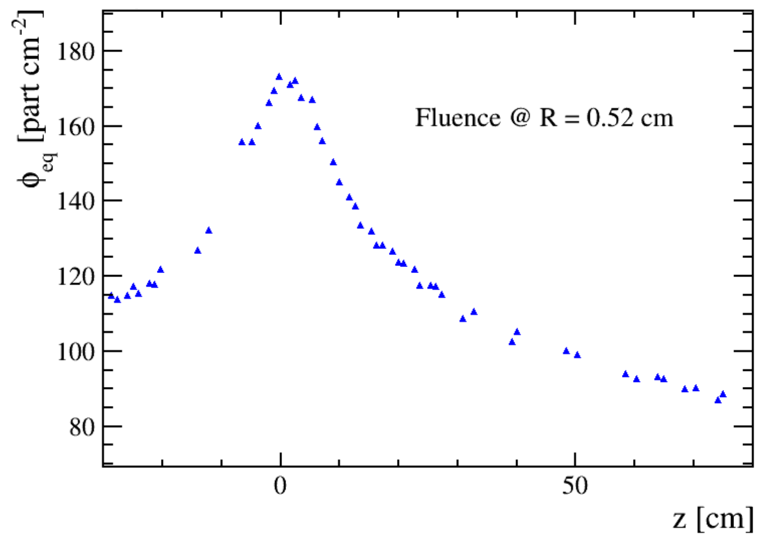
N_{eq} fluence reaches $\phi_{max} = 1.72{\times}10^{14}\ n_{eq}/cm^2$ at $R = 0.5\ cm$

(for $1fb^{-1}$, $\sigma_{pp} = 80\ mb$)









$\phi_{max,\,50fb} = 0.86{\times}10^{16}\ n_{eq}/cm^2$

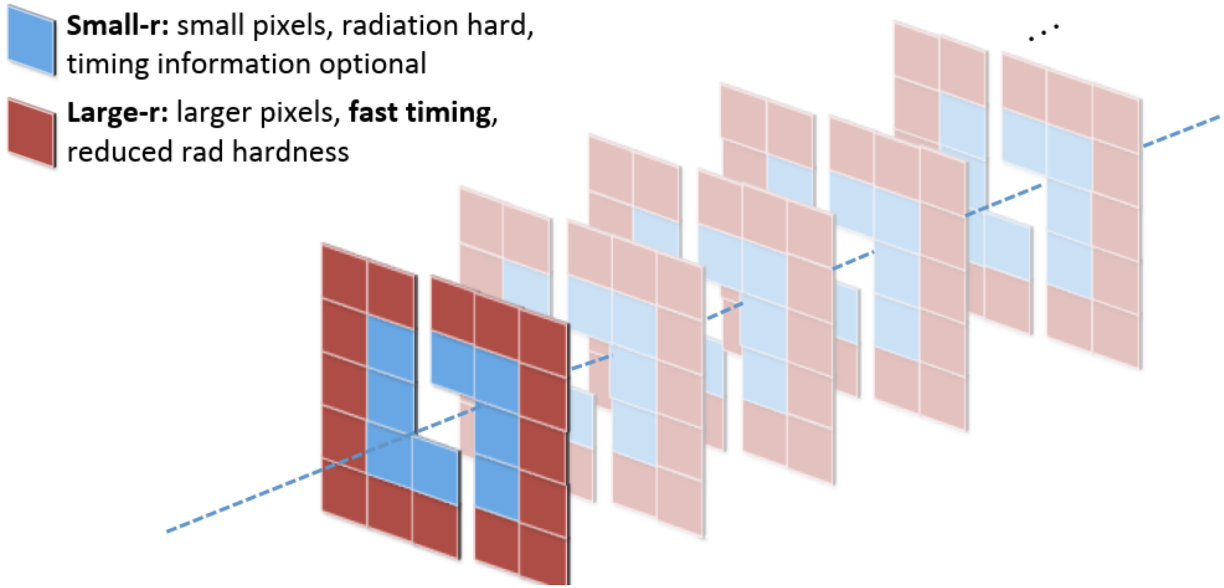
VELO Upgrade II (Phase II Upgrade)

Aim: better (or the same) physics performance as Upgrade I at 10x higher luminosity.

- 10x higher multiplicity,
- 10x more vertices,
- 10x higher fluence

https://cds.cern.ch/record/2320509

Radial dependence motivates a dual-technology design



Summary

1. A new simulation of fluence with Fluka program was done for VELO.
2. The maximum fluence in the inner tip of a sensor was $\phi_{max} = 6.5\times10^{14}\ \mathrm{n_{eq}/cm^2}$ (Run I-II with 9.6 fb^{-1}):
3. The increase of leakage currents and effective depletion voltage are in agreement with Hamburg model.
4. Unprecedented in HEP deliberate annealing improved the detector performance.
5. LHCb VELO behaved as (better than) planned to the end of Run II data taking period.

6. We designed the VELO pixel geometry in Fluka.
   a) The maximum fluence in the inner tip of one of the most irradiated sensor: $\phi_{max} = 1.72\times10^{14}\ \mathrm{n_{eq}/cm^2}$ for 1 fb^{-1}
   b) For the 50 fb^{-1} in Run III: $\phi_{max,\,50fb} = 0.86\times10^{16}\ \mathrm{n_{eq}/cm^2}$.

4. One year in Run III gives fluence equal the Run I + Run II data taking period.
5. Dual technology is considered in plans for the Upgrade II.

Backup

Damage functions - remarks

1. The particle flux is usually expressed in neutron equivalence units: $\phi_{eq} = \kappa \int \phi(E) dE.$
2. Any comparison with data should have about 30% of uncertainty assigned to the ϕ_{eq}, that comes from (see M. Huhtinen's talk at RD workshop):
   - The uncertainties from the 1 MeV neutron cross sections used for the normalisation (~20%).
   - The pion and proton hardness factors.
   - Unknown kaon damage.