Studies of Radiation Damage in the LHCb Vertex Locator after Run I

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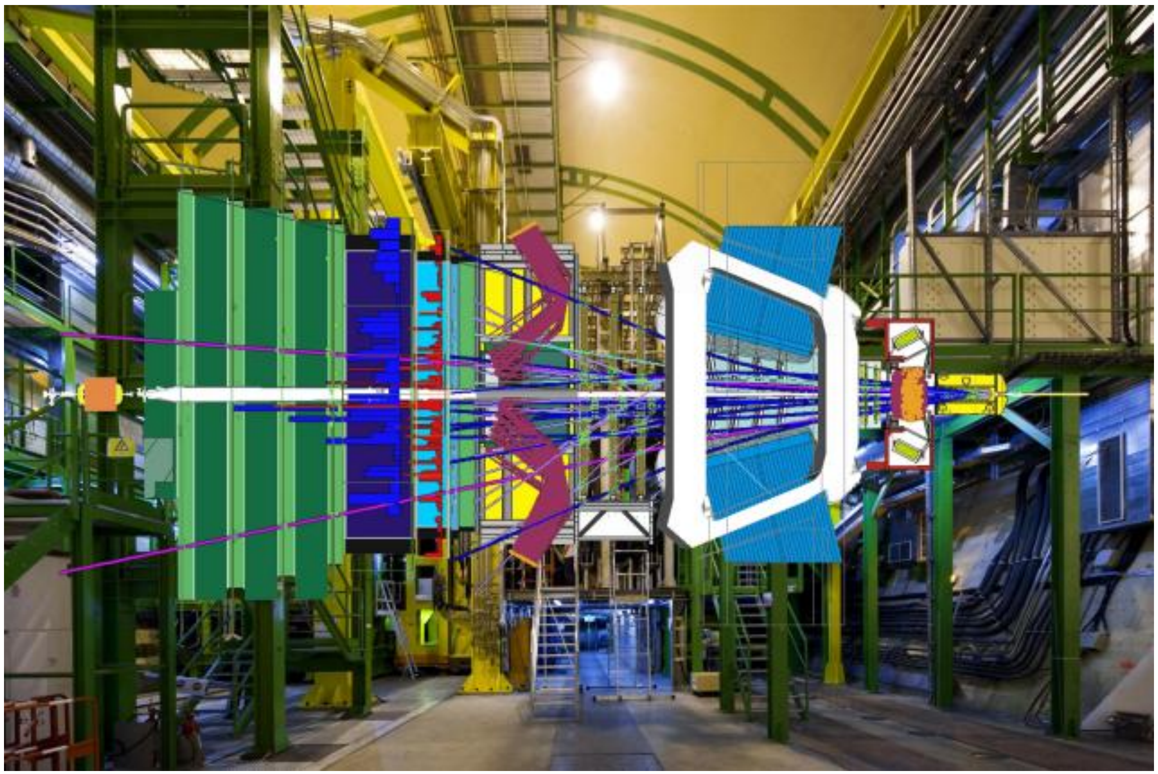
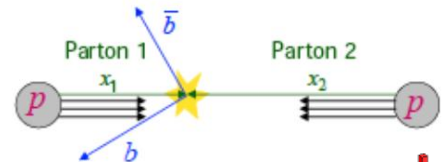
on behalf of LHCb VELO Group

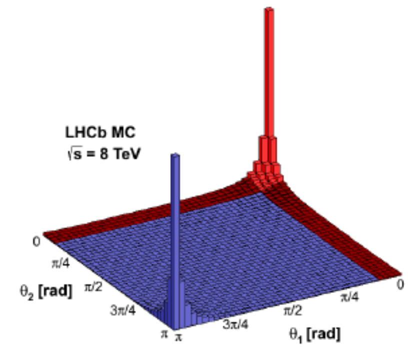
LHCb spectrometer

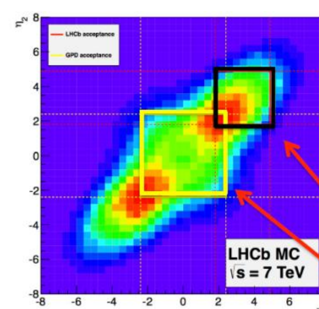
The detector dedicated for studying **flavour physics** at LHC.
Especially **CP violation** and **rare decays** of beauty and charm mesons.



$$\sigma_{b\bar{b}} = (75.3 \pm 14.1)\ \mu b$$
$$\sigma_{c\bar{c}} = (1419 \pm 133)\ \mu b$$







LHCb 2<η<5

ATLAS,CMS: |η|<2.5

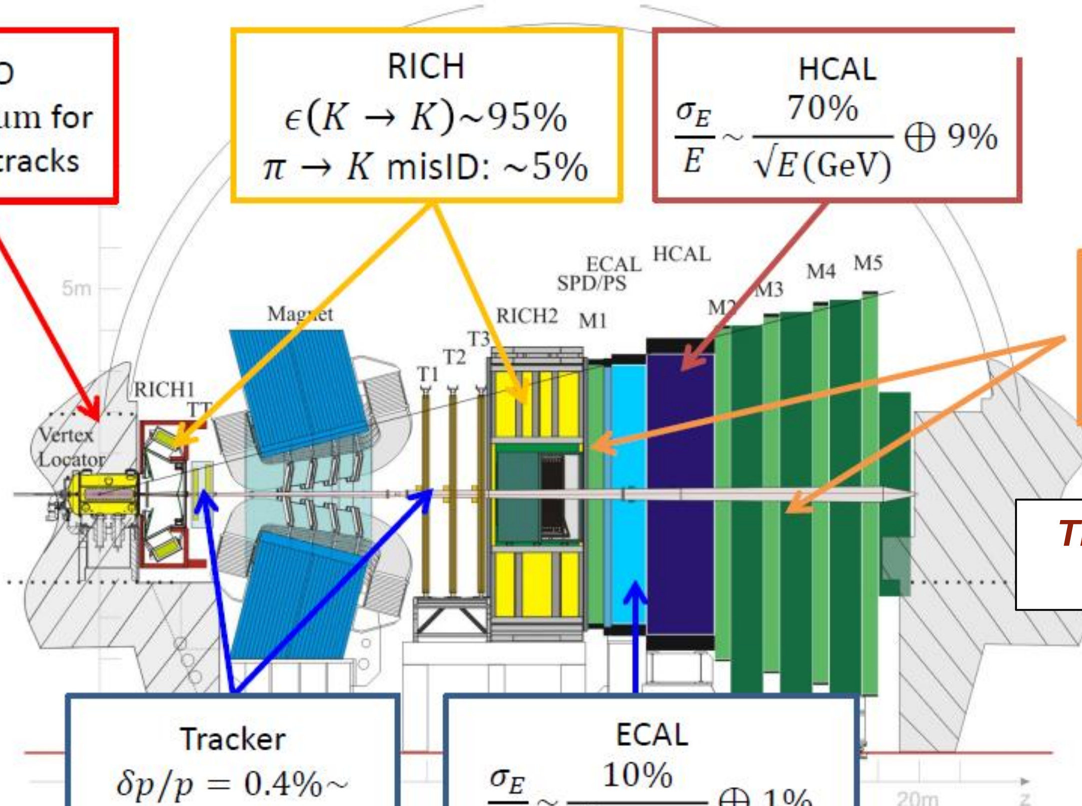
LHCb spectrometer

VELO
$\sigma_{IP} \sim 20\mu m$ for high p_T tracks

RICH
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ misID: ~5%

HCAL
$\frac{\sigma_E}{E} \sim \frac{70\%}{\sqrt{E(\mathrm{GeV})}} \oplus 9\%$

Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ misID: $1-3\%$



The LHCb detector at LHC
(JINST 3 2008 S08005)

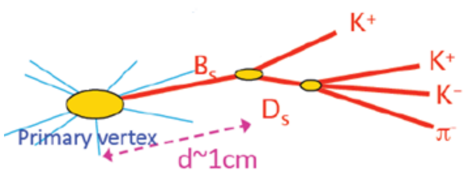
Tracker
$\delta p/p = 0.4\% \sim 0.6\%$

ECAL
$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E(\mathrm{GeV})}} \oplus 1\%$

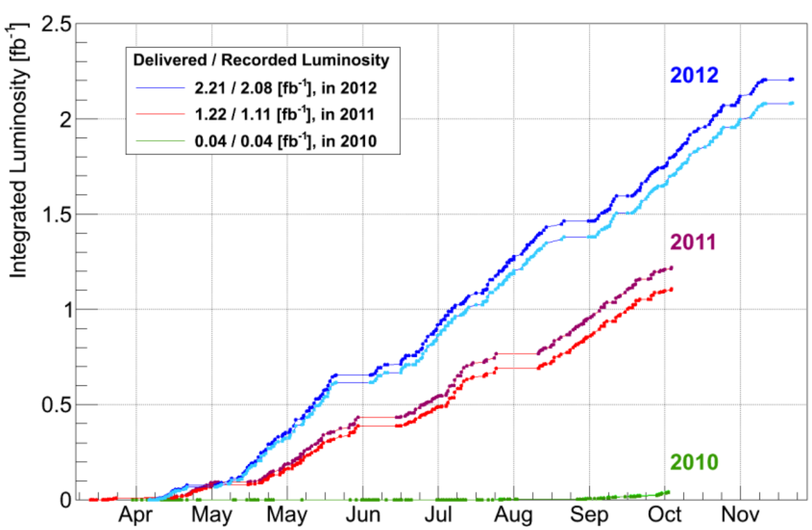
Run I data taking
6×10^{12} $c\bar{c}$ quark pairs
3×10^{11} $b\bar{b}$ quark pairs
~180 published articles

LHCb operation during Run I

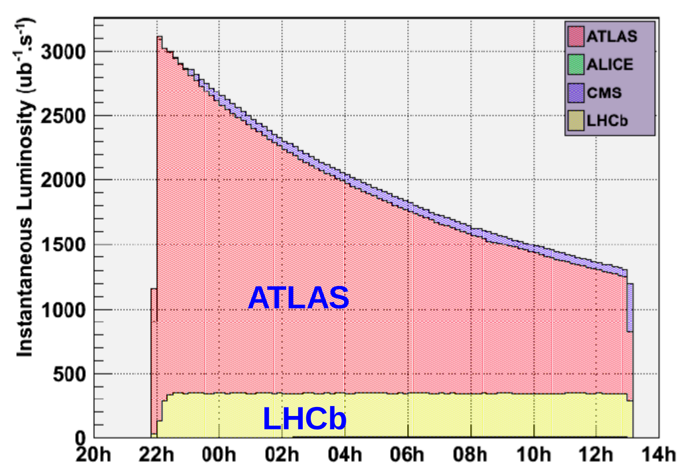
Beam energy: 2011- 3.5 TeV, 2012 - 4TeV



- delivered luminosity 2010-2012 L= **3.4** fb^{-1}
- LHCb stably operated at L_{inst} = **4.0 x 10^{32}** $cm^{-2}s^{-1}$ (nominal **2.0 x 10^{32}**)
- Average number of visible interactions per x-ing μ = **1.4-1.6** (nominal 0.4)
- Data taking efficiency ~**90 %** with **99 %** of operational channels
- HLT (High Level Trigger) input ~ **0.85 MHz**, output ~ **3 kHz**



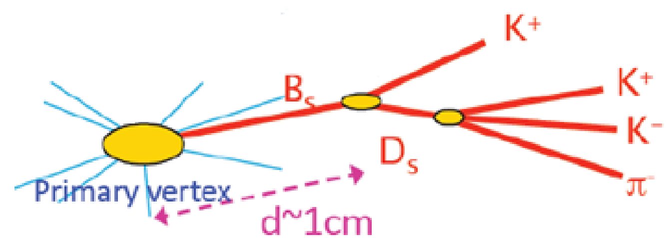
Luminosity levelling through vertical beam displacements

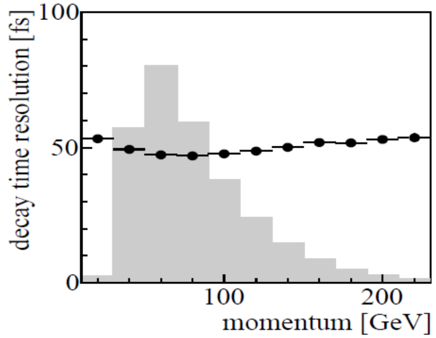


LHCb performance

Experiment optimized for B physics requires:

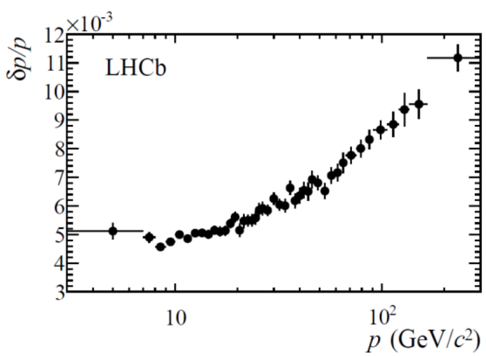
- Precision tracking and vertexing (mass, proper time)
- Excellent particle identification: e, γ, μ, π, K, p
- Efficient trigger for hadronic and leptonic modes

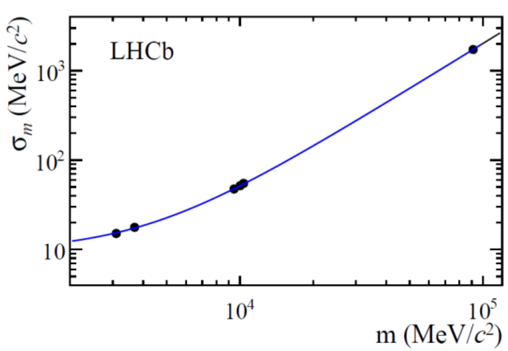


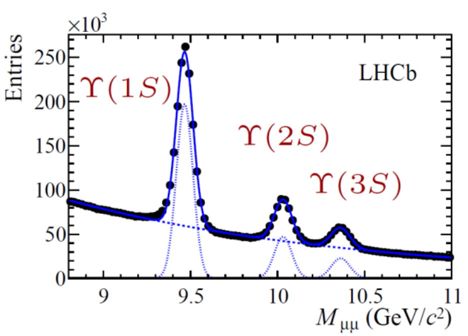


LHCb performance:

- Decay time resolution Δt: 30-50 fs,
- $\Delta p/p$ = 0.35-0.55%, 1<p<100 GeV/c,
- Δm=10-20 MeV/c^2
- Id muon: 95%, RICH ID π/K 95%

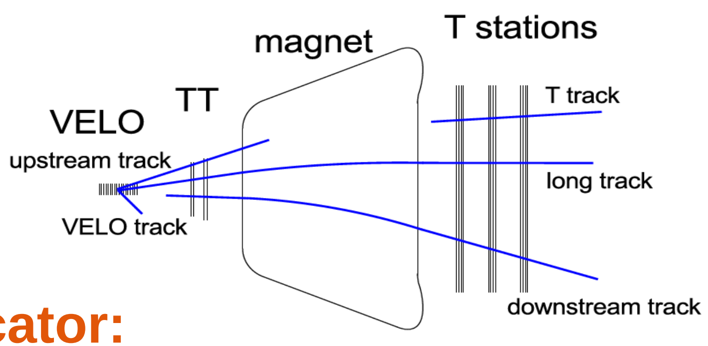






LHCb physics program

- Study CP violation and rare decays with beauty and charm hadrons.
- Search for new physics using heavy flavour mesons

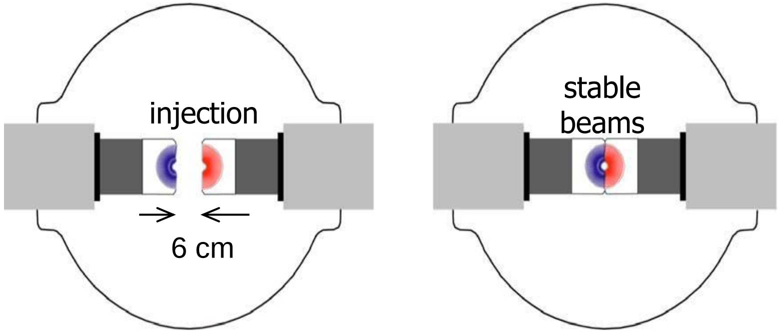


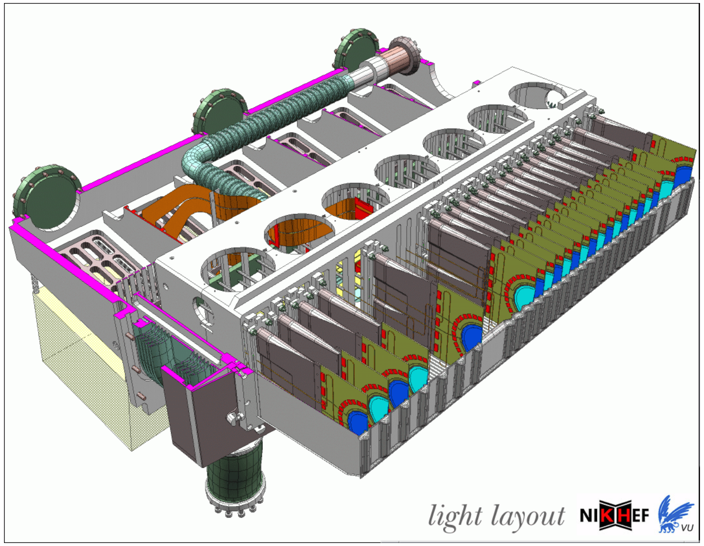
starts with the Vertex Locator:

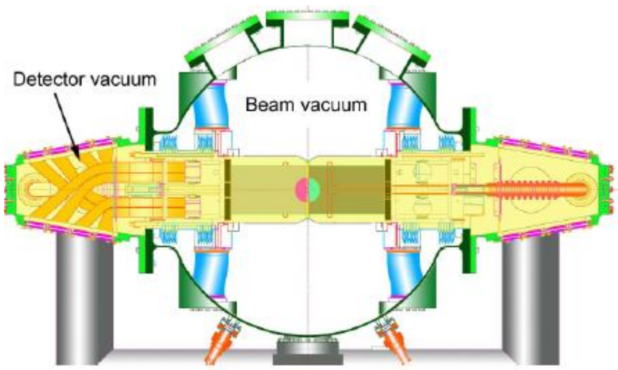
- The angular acceptance of VELO is only 1.8% of solid angle but 27% production for $b\bar{b}$ pair have tracks which cross at least three VELO stations,
- VELO tracks are useful for the primary vertex reconstruction,
- Displaced secondary vertices are used for High Lever Topological Trigger,
- VELO hits are the first part of LHCb tracking and play the crucial role both in efficient pattern recognition and fake track rejection,
    - tracking efficiency (for long tracks) is about 98%,
    - impact parameter resolution of 12 μm for high p_T tracks is the best value in LHC
- Proper decay time is achieved from measurements of mesons' flight distance.

LHCb Vertex Locator

- The closest to the proton beam detector of all LHC detectors.
- VELO halves are movable,
- The movement is steered by a precise system (accuracy of 10 μm),
- When stable beams, the silicon edge is only 7mm from the proton beam.
- Operated in a secondary vacuum, separated from the LHC vacuum by 300 μm thick aluminium foil.
- Designed to withstand 5 years running at LHC



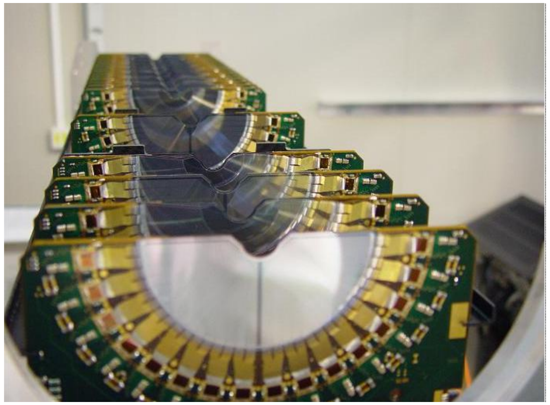


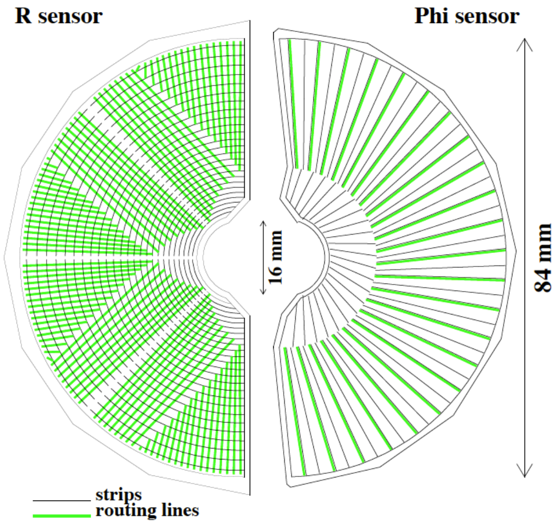


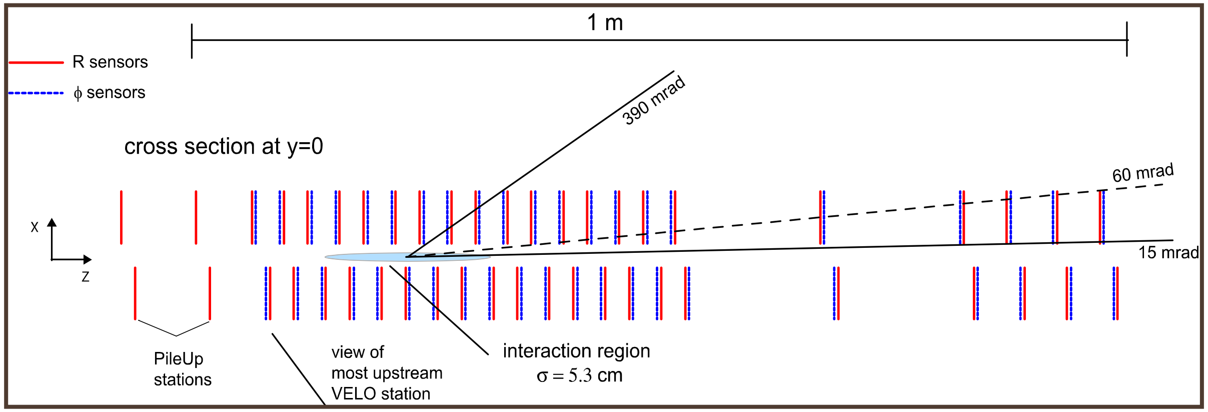
Performance of the LHCb Vertex Locator
arXiv:1405.7808

VELO - modules

- VELO consist of 42 modules (two halves)
- Modules have two (R and Φ) 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 to keep sensors in -7°C







Radiation damage - effects

The main macroscopic effects caused by the radiation:

- **Increase in leakage current**, caused by creation of generation and recombination centres.
- **Change** of the effective doping concentration with significant influence on operating **voltage** needed for total **depletion**.
- **Loss of charge collection efficiency** due to charge carrier trapping.

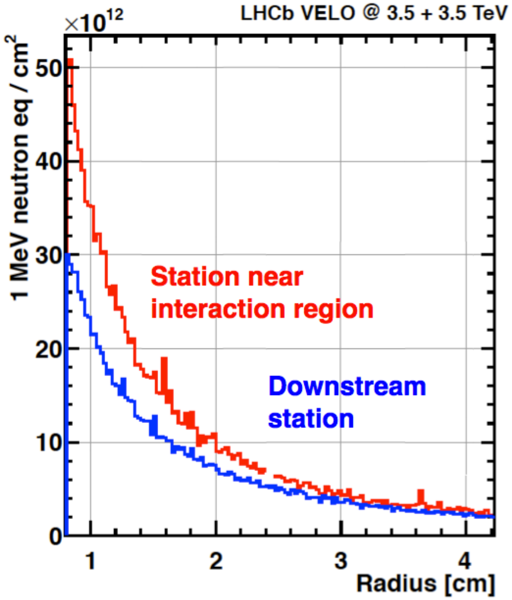
Selected methods to monitor radiation influence on VELO:

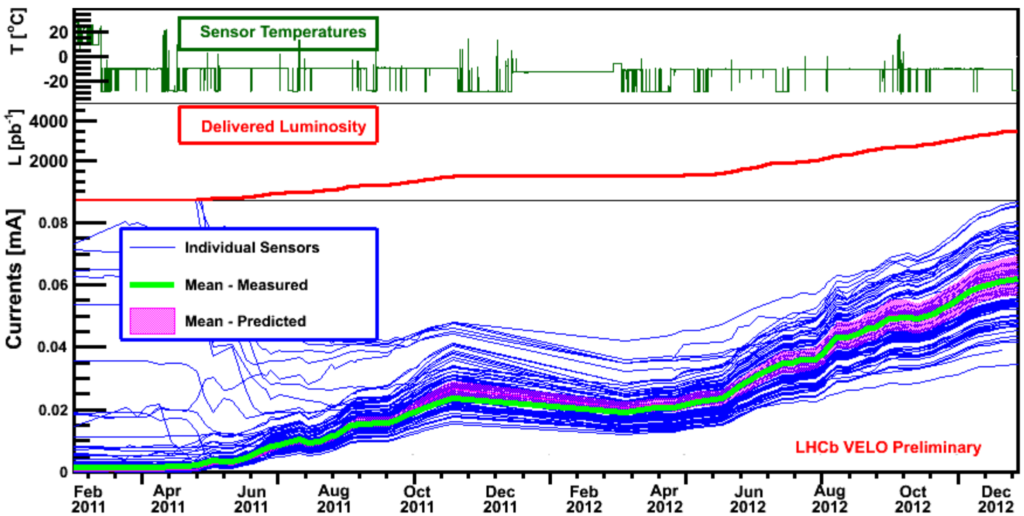
- Current-Temperature scans (IT)
- Charge Collection Efficiency scan (CCE)

Radiation damage in the LHCb Vertex Locator
JINST 8 (2013) P08002

Radiation damage

- VELO is currently the **most exposed** detector in the LHC- fluence up to 50×10^{12} 1MeV n_{eq}/cm^2,
- LHCb has collected more than 3 fb^{-1} in 2009-13, VELO designed to cope with ~6-10 fb^{-1}



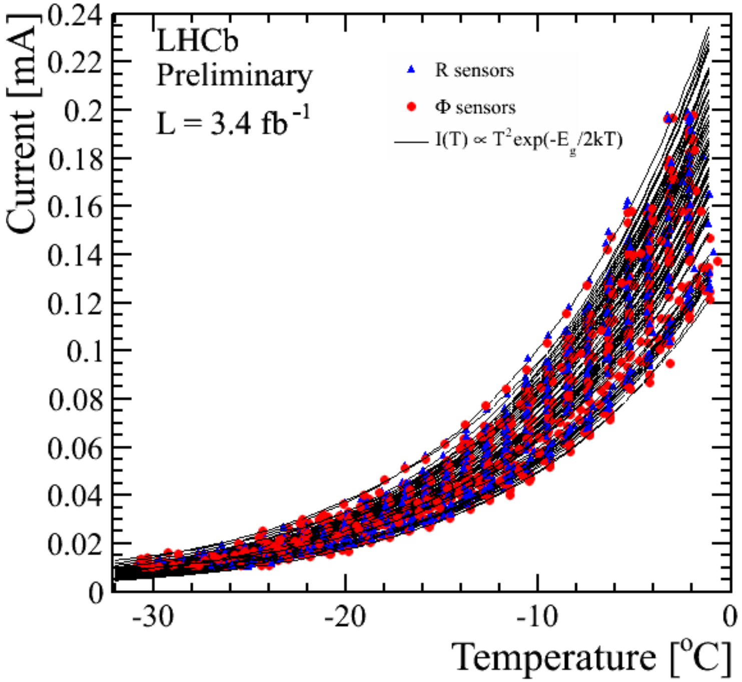


- Leakage currents as a function of time - increase with fluence, proportional to the delivered luminosity, typically 2 μA per 100 pb^{-1}.
- Periods of annealing

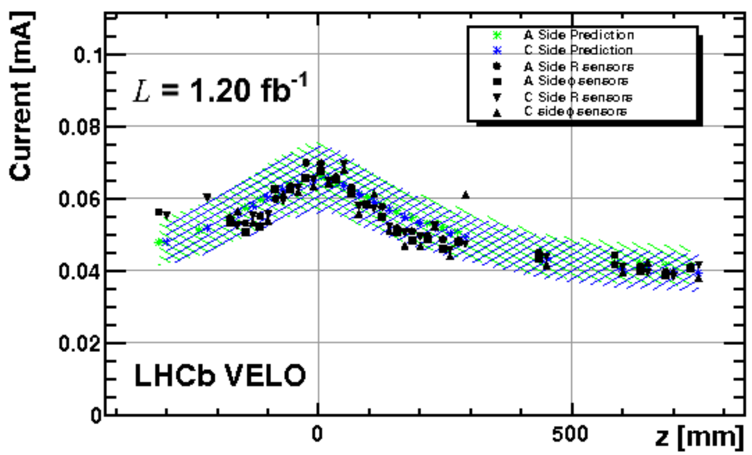
Radiation damage – leakage current monitoring

- Measurement of current as a function of temperature (**IT scans**) for each sensor,
- **Effective band gap** from exponential fit:

E_{eff}=1.16 ± 0.06 eV



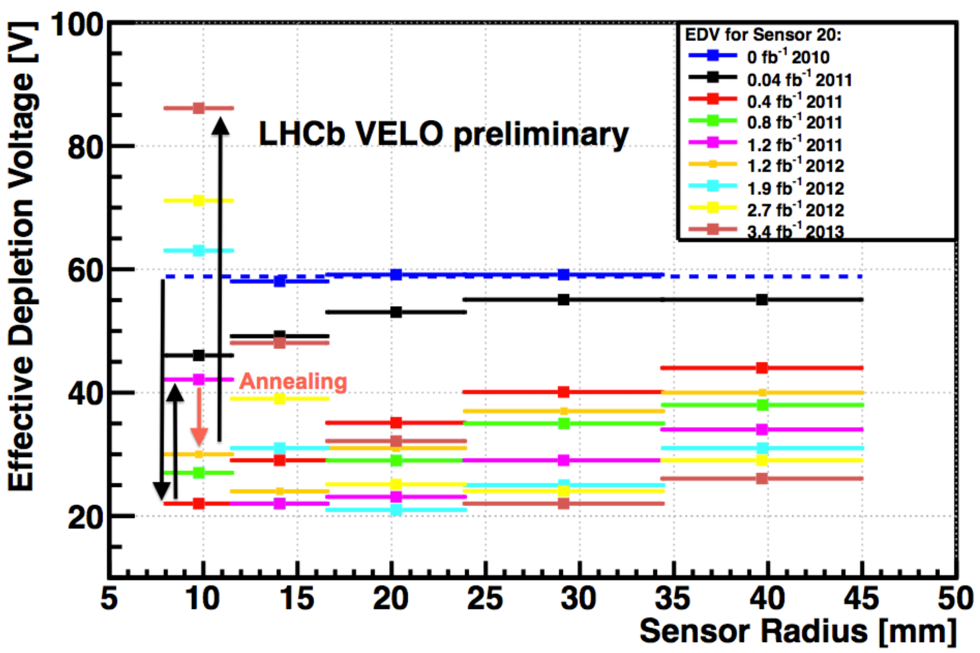
- Current scaled to 0°C - good agreement with simulation (z dependence).



- After irradiation bulk current dominates over surface current

Radiation damage – Effective Depletion Voltage

- Charge collection efficiency versus HV bias scans were performed regularly during data taking’
- A charge collection efficiency vs voltage is determined.

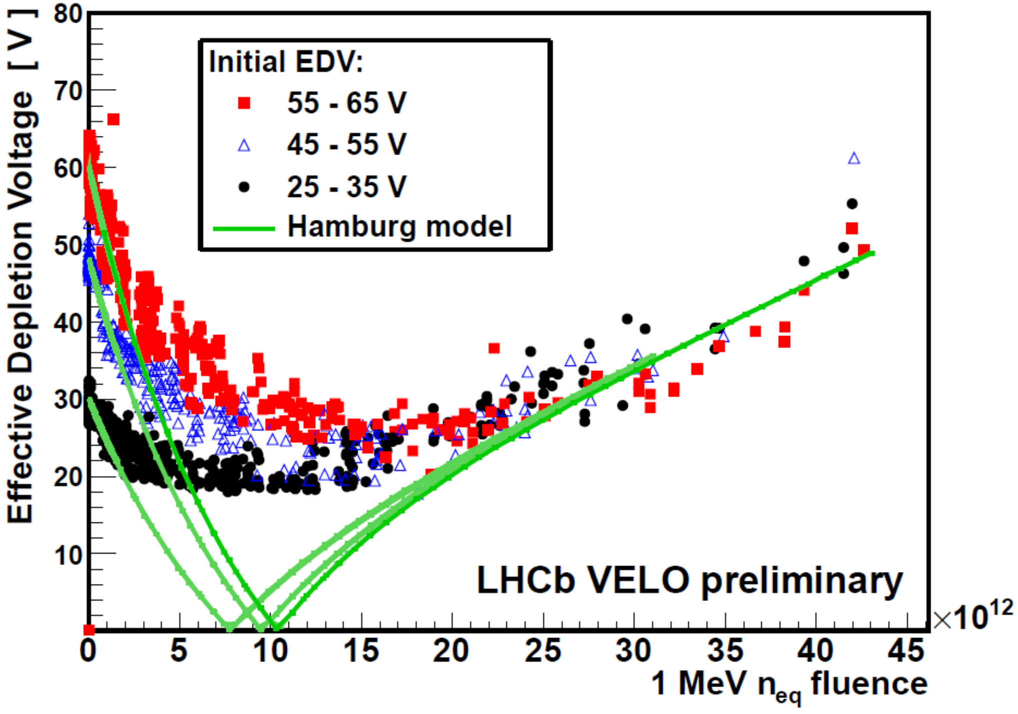


- EDV for example sensor close to interaction point, at different delivered luminosities.
- Type inversion of n-bulk to p-bulk at inner radius – EDV increased after 2.7 fb^{-1}

Radiation damage – effective depletion voltage

- At the production, initial depletion voltage was ~25-70 V.
- Sensors in 2011-12 were biased at 150 V (can be operated up to 500V)

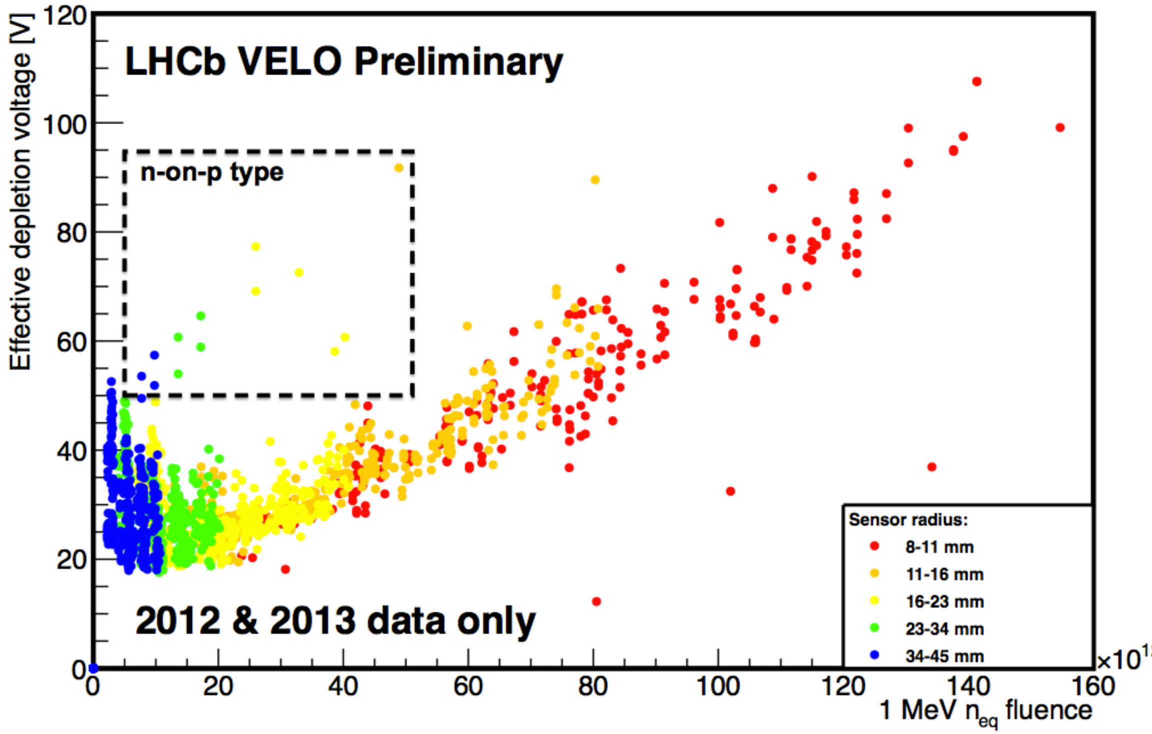
- **Type inversion** occurred at (10-15)×10^{12} 1MeV n_{eq}/cm^2, inversion started at inner radius.
- Good agreement with **Hamburg model** (except the EDV minimum – need a sufficient electric field to collect the charge)

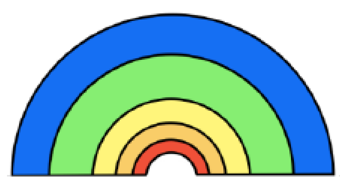


Radiation damage – EDV – radial dependency

the recent data with division into radial regions

- **type inversion** starts at inner radial region,
- The two n-in-p sensors show a drop then rise in the EDV with fluence

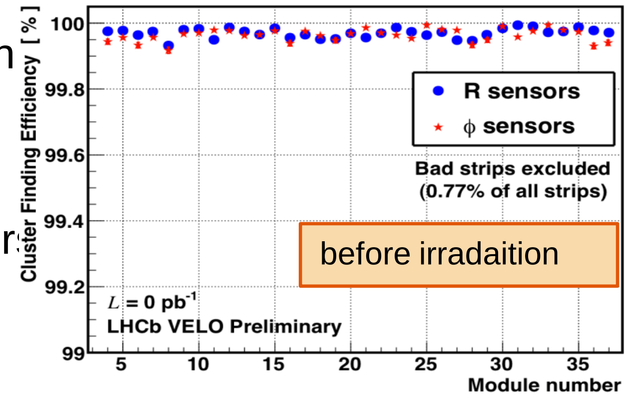


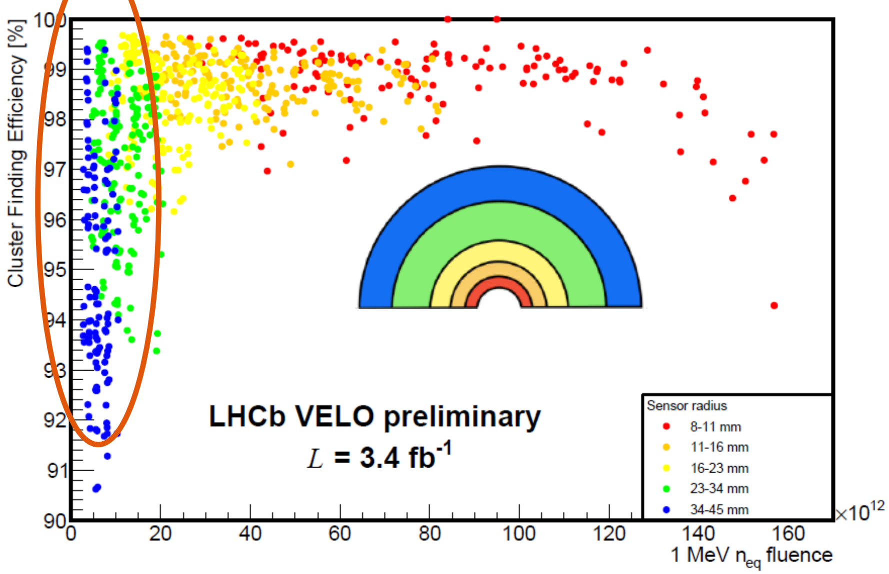


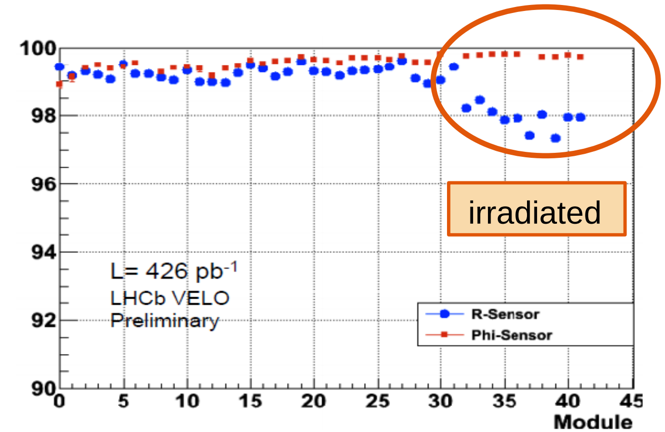
Radiation damage – Cluster Finding Efficiency (CFE)

Cluster Finding Efficiency (CFE) – a percentage of clusters obtained at the extrapolation point

- > 99% before irradiation,
- noticeable reduction for downstream R-type sensors observed during 2011,
- no effect in tracking



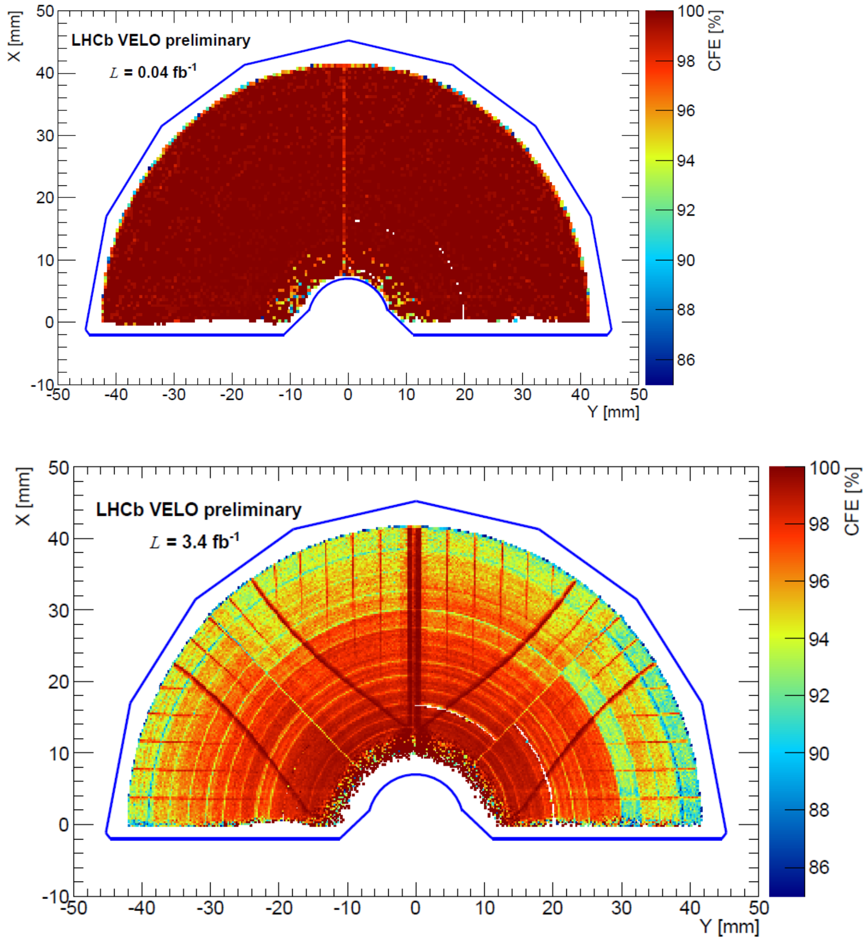


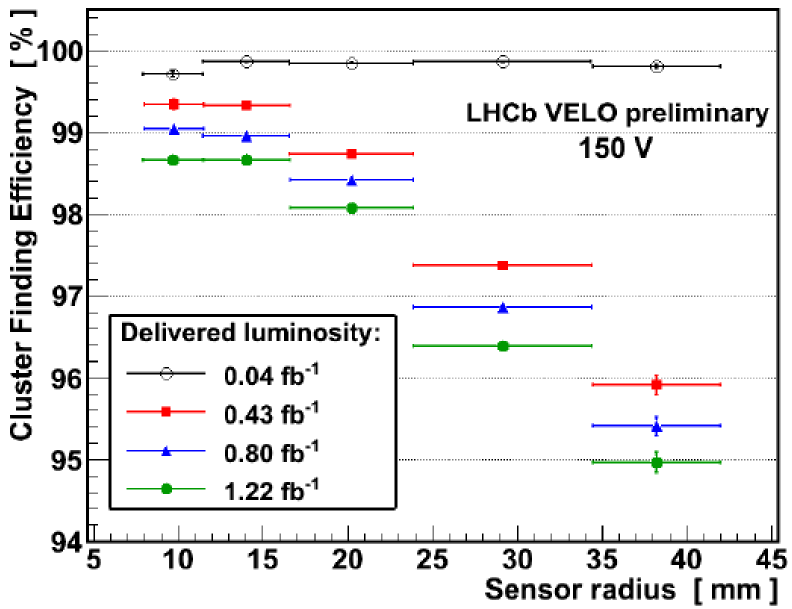


Effect visible in the R, forward sensors.

Radiation damage – CFE – a closer look

- Decrease in CFE more rapid with delivered luminosity and bias voltage and at large radius

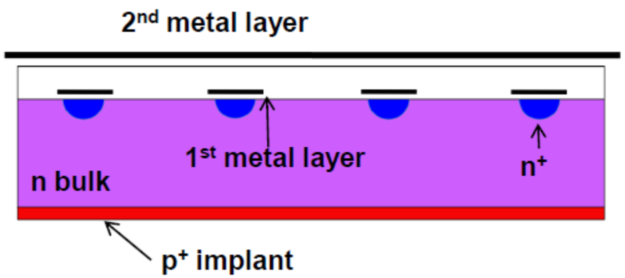




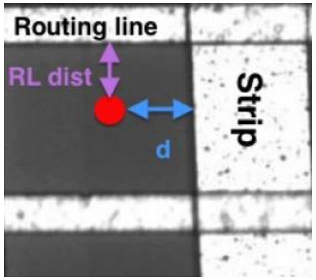
Radiation damage – CFE – second metal layer

An explanation lies in sensor design

n⁺-on-n type (82 sensors)

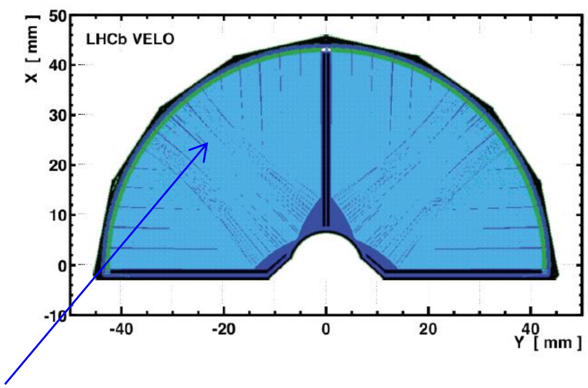


- 2nd metal layer carries signal to read-out electronics
- Routing lines in R-sensors are perpendicular to strips

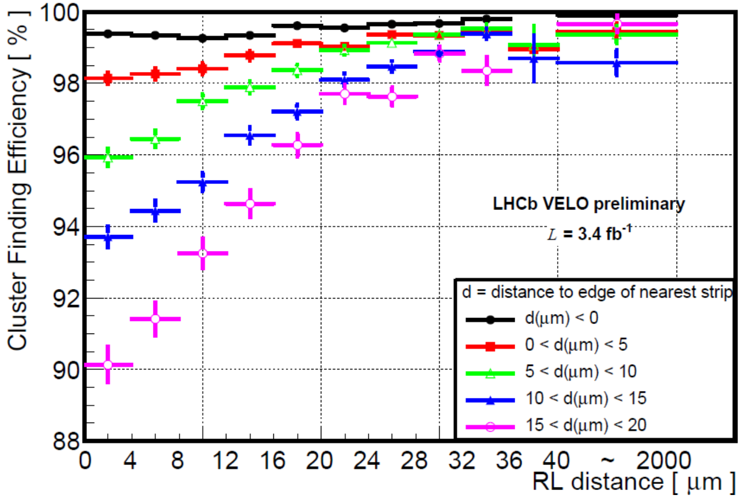


- Charge is deposited also on routing lines
- Effect visible when distance to routing lines is less than to strip (outer region)

Routing lines map for R-type sensor



Gaps in double metal



No measurable effect on tracking efficiency

SUMMARY

- LHCb is an experiment for beauty and charm hadrons, CP violation, rare decays and search for New Physics.
- The programme requires excellent vertex reconstruction precision, tracking and particle identification.
- VELO performed very well, according to the expected assumptions, during Run I data taking period
- VELO has been exposed to severe radiation conditions.
- Its state is monitored on regular basis by especially dedicated scans.
- Change of the depletion voltage and leakage currents agree with expectations.
- Currently no significant physics performance degradation effects observed - we expect to be able to operate to 2018 without any degradation in physics performance.