LHCb: Lessons learned from operation of the VELO

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on behalf of the LHCb collaboration
The LHCb experiment

• LHCb is a dedicated heavy flavour experiment at the LHC

• Very precise vertex detector (VELO)
• One tracking stations before and three after a vertical dipole magnet
• Two ring imaging Cherenkov detectors
• Three layers of calorimetry
• Five of muon detectors interspersed with iron shielding walls
VELO parameters

- 42 modules with pairs of sensors all n-in-n
  - Except one n-in-p (module 0 in later plots)
- R/\phi geometry strip detector
  - Inner most strips are 8mm from the beam, outer most 42mm from the beam
- Designed to tolerate 5 years running at LHC: we’re above that now...

- Sufficiently radiation hard to be used without modification in a proton therapy beam at Clatterbridge Oncology centre

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LHCb data taking

Results are quoted on

<table>
<thead>
<tr>
<th>Year</th>
<th>√s (TeV)</th>
<th>Luminosity (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 &amp; 2011</td>
<td>7</td>
<td>1.1</td>
</tr>
<tr>
<td>2012</td>
<td>8</td>
<td>2.1</td>
</tr>
<tr>
<td>2015 - 2018</td>
<td>13</td>
<td>5.7</td>
</tr>
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LHCb uses luminosity levelling so we get less luminosity than ATLAS & CMS

LHCb Efficiency breakdown in 2018

Plus a small amount of beam-beam p-Pb, Pb-p, Pb-Pb collisions and also p-A where A is Helium or Argon for beam gas events

Radiation dose delivered

Fluence varies exponentially with radius and by x2 between stations

Effects of $\sqrt{s}$ are smaller, about 30% between Run I and Run II

x3 this for Run I total dose

x5.5 this for Run II dose so far

LHCb VELO (VErtex LOcator) : Technical Design Report
CERN-LHCC-2001-011
Operational temperature is about -8°C. Sensors at -30°C when the chips are unpowered.

Long periods between data taking due to LS1 and end of year shutdowns. Need to avoid annealing.

Currents measured at approx -8°C without beam and sensors at 150V. Typical increase was 1.9 µA per 100 pb⁻¹.
Deliberate annealing

Set the temperature to 20°C for 40 hours

Dropped average sensor currents from 190 μA to 150 μA at 150 V

Possible as the detectors only have to work to the end of the year and the excellent performance of the cyro-plant
HV changes are necessary

Major HV changes due to increasing effective depletion voltage (see later)
However IV curves for specific sensors must be monitored and adjusted to manage currents
Through out the data taking we have been able to fully deplete the sensors, even through now above design luminosity
Monitoring is critical

Occasional small effects in one sensor; such as current increase during a fill need to be caught and mitigated early.
Monitoring: both people and software are critical

The detector is checked daily during data taking on data taken and in the hardware status. Lot of effects seen, almost all corrected before any impact on data for physics.
Effective depletion voltage

An R sensor toward the end of the detector

HV increasing 20 – 250 V

Measure EDV during HV scans in data taking by looking at the charge collection efficiency vs Voltage curves
Effective depletion voltage in 2018

The detector can still be fully depleted so the charge collection efficiency is still excellent.
Predicting the EDV by the end of Run II

We expect to be able to fully deplete the sensors up to the end of Run II.

EDV is at ~80% of full depletion

Predictions of Hamburg model, last parameter correction in 2016

LHCb VELO Preliminary

LHCb VELO Preliminary – September 2018 CCE Scan

If run at 1.5°C warmer max HV lower by 15V

Modelling of 40 hours at 20°C
Hamburg model: consistent with LHCb VELO data
Signal to noise of the sensors

The MPV of the signals are 30-40 ADC counts after irradiation.

The noise is $\leq 2$ ADC count, and has been stable.

This huge Signal/Noise ratio means we have had no classical radiation damage induced inefficiency.

We set the clustering thresholds to get almost no noise in the detector: still have previous and next bunch spillover though.
Cluster finding (pseudo) efficiency

Note: these points are affected by fake tracks, reducing the apparent efficiency
Double metal effects

- R and phi sensors need two sets of metal lines
- One to capacitively couple to the strips, the other carrying the signal to the amplifiers over the outer strips
- Phi sensors (below) second metal routing is over the outer strips

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17
R sensors route across the outer strips

Guard rings

First Metal layer on top of strips

Outer edge of sensor

Bond pads for links to readout chips

Inner edge of sensor

Second metal layer running across the strips

Routing Line width ~ 11 um

Strip width ~ 11 um

Strip pitch 40 um

Routing Line width ~ 10 um

Strip width ~ 38 um

Strip pitch 101 um

Picture of the R sensor’s active area

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Coupling effects of signals in R sensors

- Before irradiation there was no visible coupling to between inner and outer strips
- When a signal passes between the 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

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Effects see during data taking

Cluster on inner R strips at very low ADC counts appearing

Predominately at the inner regions of the sensors, not where tracks crossed the sensors

Cluster size for R sensor clusters in ADC counts

Lower charge collected in R sensors than phi sensors

Wider distribution due to only some clusters losing charge

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Cluster finding efficiency 2D map for one R sensor, when new...

Cluster finding efficiency verse position on the sensor
After about 40 pb⁻¹
Second metal layer layout for R sensors

- Gaps in double metal coverage
- Gaps in 2nd metal layer
- Gaps in 2nd metal layer and a row of resistors
- Gaps in 2nd metal layer
Cluster finding efficiency 2D map for one R sensor, in the second year of data taking.

Cluster finding efficiency verse position on the sensor

After about 600 pb$^{-1}$

Gaps in double metal coverage

LHCb VELO preliminary

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Cluster finding efficiency 2D map for one R & phi sensor, September 2016

After about 5000 pb$^{-1}$

Different R sensor, so different pattern of dead strips

Inner to outer region
Simulation of the effects

To simulate the 2\textsuperscript{nd} metal effects we had to add the 2\textsuperscript{nd} metal to the detector description.

Real routing lines are complex to fit Micron's design criteria.

Need to correct charge sharing for the track position wrt the 1\textsuperscript{st} and 2\textsuperscript{nd} metal layers.

Use rate of production of fake clusters to tune simulation.
Measuring is easier than aligning

Measure the positions of your detector before installation!

Too many degrees of freedom lead to “unphysical” alignments and weak modes cannot be constrained.

Construction time R to Phi sensors alignments were taken with $\sim 4\mu m$ precision, these are still used as they cannot be bettered using alignment fits.

The VELO was measured in a metrology machine for over a week, which has significantly reduced the B decay lifetime systematics.
Conclusions

• LHCb VELO detectors do see radiation damage
• Hamburg model predicted IV evolution with luminosity
• Leakage currents rising linearly with luminosity
  • We try to always keep the detector cold to avoid unwanted annealing, but in the last year we can use beneficial annealing
• R sensors show coupling to second metal layer causing a small reduction in efficiency
• Tracking efficiencies are unchanged
• Every reason to believe that we will get to the end of Run II in good shape
  • We built a full spare VELO available just in case and we’ve started constructing the replacement for Run III this year: listen to Deepanwita Dutta’s talk tomorrow
Thank you for listening!

Any questions?