Impact of Radiation on VELO Sensors

Adam Webber, on behalf of LHCb
The VELO

- Located near to interaction point (~8mm at closest point).
- Retractable detector halves.
- Key properties:
  - n+-on-n (mostly)
  - Oxygenated
  - 300 μm silicon
  - Double metal layer
  - Radiation hard: (~5yrs operation at LHC)
The Sensors

- 82 of the 84 VELO sensors are n⁺-on-n:
  - n bulk
  - 1st metal layer
  - n⁺ - diode
  - p⁺ implant
  - 2nd metal layer

- 2 of the 84 VELO sensors are n⁺-on-p:
  - p bulk
  - 1st metal layer
  - n⁺ - diode
  - p⁺ implant
  - 2nd metal layer

Depletion region grows from opposite sides for different sensor types.
Radiation Damage Studies

For monitoring radiation damage in the LHCb VELO we pursue several independent studies:

- Current vs Voltage (IV)
- Current vs Temperature (IT)
- Evolution of Depletion Voltage
- Cluster Finding Efficiency
Radiation Damage Studies

- Current vs Voltage (IV)
- Current vs Temperature (IT)
- Evolution of Depletion Voltage
- Cluster Finding Efficiency
For each sensor we measure a single current, with contributions from two sources:

1. Bulk current — related to defects in the silicon bulk
2. Surface current — scratches, guard rings, process errors, etc

Bulk current saturates with voltage, but is strongly dependent on temperature:

\[ I(T) \propto T^2 \exp\left(\frac{-E_g}{2kT}\right) \]

Surface current varies with voltage in ‘Ohmic’ way, with little temperature dependence.

\[ I(V) \propto V \]
Examples of individual sensors:

Bulk dominated before
Bulk dominated after

Surface dominated before
Bulk dominated after

\[ I(T) \propto T^2 \exp\left(\frac{-E_g}{2kT}\right) \]

Ref [1]
Accurate measurement of the effective bandgap energy:

\[ I(T) \propto T^2 \exp\left(-\frac{E_g}{2kT}\right) \]

Bulk/Bulk current dominated before/after

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Luminosity</th>
<th>Preliminary</th>
<th>&quot;effective band gap E_g&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>100V</td>
<td>480 pb(^{-1})</td>
<td>1.12 ± 0.06 eV</td>
<td></td>
</tr>
<tr>
<td>150V</td>
<td>480 pb(^{-1})</td>
<td>1.11 ± 0.07 eV</td>
<td></td>
</tr>
<tr>
<td>150V</td>
<td>821 pb(^{-1})</td>
<td>1.10 ± 0.04 eV</td>
<td></td>
</tr>
<tr>
<td>150V</td>
<td>1204 pb(^{-1})</td>
<td>1.14 ± 0.04 eV</td>
<td></td>
</tr>
</tbody>
</table>

Literature: \( E_g = 1.21 \text{ eV} \)

Ref [2]
MC Fluences

- MC studies show the expected radiation as a function of sensor position (z is along beam-pipe) and radial distance from the beam-pipe.

MC study accounts for:
- Different particle damage factors
- Particle angle of incidence
- Sensor geometry
- Annealing factors

- NIEL scaling hypothesis
- MC uses GEANT4 (not FLUKA)

LHCb VELO Preliminary

LHCb VELO @ 3.5 + 3.5 TeV

Per fb⁻¹
Comparing measurements to the predictions from MC gives:

- Good agreement shows an understanding of the particle fluences our detector receives. Validates following plots for which MC predicted fluences are used.

![Graph showing fluence prediction comparison]

- Normalised to 21°C
- 821 pb-1
- Mean measurement within 7% of prediction

LHCb VELO Preliminary
Bulk current show an increase with fluence in line with delivered luminosity.

Trend of all sensors at 150V and -8° C:

LHCb VELO
Preliminary

~ 1.9 μA per 100 pb⁻¹ at -8°C
Radiation Damage Studies

• Current vs Voltage (IV)
  Current vs Temperature (IT)

• Evolution of Depletion Voltage

• Cluster Finding Efficiency
For $n^{+}$-on-$n$ sensors we expect type-inversion (see right):

For $n^{+}$-on-$p$ we expect competing initial mechanisms (more on this later).

Standard measurement method uses C-V scans:

After installation we need to use an alternative method.

Ref [5]
Charge Collection Efficiency

Principle: Reconstruct unbiased tracks:

- Extrapolate the track to a strip on the test sensor and record amount of charge in this area.

- Vary the voltage of the test sensors between 0 and 150V.
Data is collected for each sensor at each voltage scanned:

- Fit the MPV of the distribution and plot vs bias voltage.

- Define the Effective Depletion Voltage (EDV) as the voltage at which the MPV is 80% of maximum.
For a specific sensors, the EDV vs sensor radius for several CCE scans:

- Decrease in EDV with luminosity
- Type-inverted in low radius regions
- Min EDV ~20V
For a n⁺-on-p type sensor, the EDV vs sensor radius for several CCE scans:

- Decrease in EDV with luminosity
- Min EDV ~40V
- Oxygen induced removal of Boron acceptors Ref [6,7]
For all VELO sensors:

1. EDV decreases with fluence - reaches minimum of ~18V before increasing again.

2. Inversion point is \(~10\text{-}15\times10^{12}\text{ MeV } n_{\text{eq}}\)

3. After type-inversion, \(n^+\)-on-\(n\) increase at a similar rate to \(n^+\)-on-\(p\).
For all VELO sensors:

At current rate, $n^+$-on-$p$ will hit voltage limit of system having received approximately $35 \times 10^{12}$ $1\text{ MeV}$ $n_{eq}$ less fluence than an equivalent $n^+$-on-$n$ sensor.
EDV vs DV

- EDV compared to Hambbug model prediction of DV:
  
  - Good agreement at low and high fluences.
  - Divergent around type-inversion due to operational constraint on charge collection time.
Noise scans do not require beam, and so can be collected frequently. The idea:

- Under-depleted sensor has higher capacitance and therefore higher noise.
- Depleted sensor has lower capacitance and so has lower noise.

“Noise Effective Depletion Voltage” (NEDV) – defined as voltage at which \((1/\text{noise})\) reaches 80% of difference between 10V and 150V.
Similar plot to CCE method can be made:

- When NEDV reaches 10V sensor is type-inverted.

Good agreement with CCE method has been observed.

(bands at 20V and 10V due to insensitivity of method for low DVs)
Radiation Damage Studies

- Current vs Voltage (IV)
- Current vs Temperature (IT)
- Evolution of Depletion Voltage
- Cluster Finding Efficiency
The cluster finding efficiency for all modules:

- Particularly bad for downstream R-type modules.
Second Metal Layer

- 1\textsuperscript{st} metal layer to capacitively couple to the strips.
- 2\textsuperscript{nd} metal layer to carry signal to read-out electronics.
- For R-type, routing lines are perpendicular to strips:
  - Phi-type sensor routing lines are parallel to and above strips.
  - 3.8 ± 0.3 \mu m SiO\textsubscript{2} insulation between metal layers.
The second metal layer routing lines in R-type sensors:

- Gaps in 2\textsuperscript{nd} metal layer
- No 2\textsuperscript{nd} metal layer routing lines
The cluster finding efficiency in R-type sensors:

- Gaps in 2\textsuperscript{nd} metal layer
- No 2\textsuperscript{nd} metal layer routing lines
The cluster finding efficiency in R-type sensors:

- Gaps in 2\textsuperscript{nd} metal layer
- No 2\textsuperscript{nd} metal layer routing lines
The cluster finding efficiency in R-type sensors:

- **1st metal layer**
- **2nd metal layer**
- **RL dist** = distance to nearest routing line
- **d** = distance to nearest strip edge
- **Track intercept**
The cluster finding efficiency in R-type sensors:

- **RL dist** = distance to nearest routing line
- **d** = distance to nearest strip edge

Preliminary
Not only is charge reduced at particle location, but noise clusters are induced.

Clusters are at inner sensor regions at low ADC values.

Similar dependence on distance to a routing line and strip.
The CFE of $n^+$-on-$n$ type sensors show a dependence on reverse bias voltage.

This is not observed for $n^+$-on-$p$ type.

Voltage dependence is removed after type inversion.
Variety of analysis techniques give us excellent understanding of the health of our detectors.

Second metal layer CFE decrease is as much at ~10% in worst effected regions. But there has been no significant decrease in tracking efficiencies (within 0.3% errors)

Some excellent agreement with predictions, some less expected observations, all very interesting!

Ref [1]: LHCb-PUB-2011-021, “Use of IT (current vs temperature) scans to study radiation damage in the LHCb VELO”  
Ref [3]: LHCb-PUB-2011-020, “Use of IV (current vs voltage) scans to track radiation damage in the LHCb VELO”  
Current Mapping

- Using the measured currents and MC predicted simulation of fluence as a function of radius:

\[
\begin{align*}
Z &= 0 \text{ mm} \\
Z &= 750 \text{ mm}
\end{align*}
\]

- From this we can map the expected current increase per volume of silicon at any distance from the radiation source.
For a n\textsuperscript{+}-on-p type sensor, the EDV vs sensor radius:

- **n\textsuperscript{+}-on-p (sensor 64)**

- **RD-2 1993** (thanks to Steve Watts)

- Acceptors in p-type bulk (Boron interstitials) are removed by oxygen. Neff and (therefore DV) decreases.
EDV vs fluence

With points connected (black points are n-on-p sensors):
For a particular radius region of the sensor, the picture is clearer:

- 34 – 45 mm
- 16 – 23 mm

Only R-sensors displayed for plot clarity.
➢ For a particular radius region of the sensor, the picture is clearer:

![Graph showing EDV vs fluence]

➢ Only R-sensors displayed for plot clarity
EDV vs fluence

- n\textsuperscript{+}-on-p compared to n\textsuperscript{+}-on-n type sensors:

1. Initial drop in EDV of approximately 20 V.

2. After initial decrease the EDV increases in similar way to inverted n\textsuperscript{+}-on-n type.

Would we lose a years worth of operation with the n\textsuperscript{+}-on-p?
The rate of charge collection efficiency with bias voltage:

- Small increase maximum collected charge of ~3% after small fluence \(<1\times10^{12} \text{ 1 MeV } n_{\text{eq}}\)

- After a further \(40\times10^{12} \text{ 1 MeV } n_{\text{eq}}\) of fluence the max charge of \(\phi\)-type sensors is reduced by ~4%.

An additional source of charge reduction for R-type:
- 8% decrease in inner regions (~40x10^{12} 1 MeV \(n_{\text{eq}}\))
-12% in outer regions, explained shortly…
CFE comparison between sensor types:
CFE in vs Lumi and Voltage

- CFE vs voltage and lumi
Voltage Dependence

- Voltage dependence removed after type-inversion

Table 4: The CFE change, $\Delta CFE_v = CFE_{V=150} - CFE_{V=80}$, averaged over all R-type sensors.

<table>
<thead>
<tr>
<th>Delivered Luminosity</th>
<th>8-11mm</th>
<th>11-16mm</th>
<th>16-23mm</th>
<th>23-34mm</th>
<th>34-42mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.426 fb$^{-1}$</td>
<td>$-0.09 \pm 0.09$</td>
<td>$-0.19 \pm 0.02$</td>
<td>$-0.30 \pm 0.01$</td>
<td>$-0.76 \pm 0.03$</td>
<td>$-1.84 \pm 0.19$</td>
</tr>
<tr>
<td>1.220 fb$^{-1}$</td>
<td>$-0.03 \pm 0.28$</td>
<td>$-0.06 \pm 0.02$</td>
<td>$-0.21 \pm 0.02$</td>
<td>$-0.57 \pm 0.04$</td>
<td>$-1.15 \pm 0.40$</td>
</tr>
<tr>
<td>1.912 fb$^{-1}$</td>
<td>$0.12 \pm 0.11$</td>
<td>$0.15 \pm 0.06$</td>
<td>$-0.15 \pm 0.05$</td>
<td>$-0.85 \pm 0.11$</td>
<td>$-1.49 \pm 0.34$</td>
</tr>
</tbody>
</table>