Radiation damage effects in the LHCb Vertex Locator

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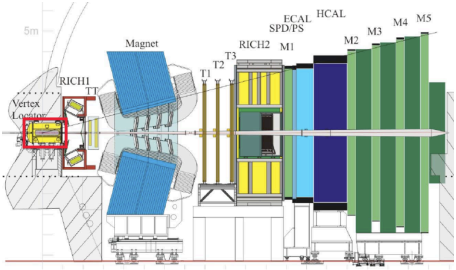
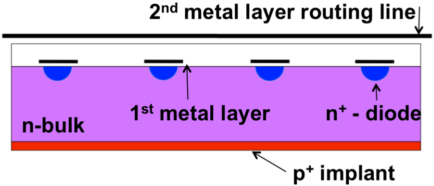
The LHCb Vertex Locator

- The LHCb Vertex Locator (VELO) is the closest sub detector to the beam at the LHC → 8 mm at closest point
- Two retractable halves
- 84 sensors, of which 82 are n^+-on-n and 2 are n^+-on-p
- 42 R sensors and 42 ϕ sensors

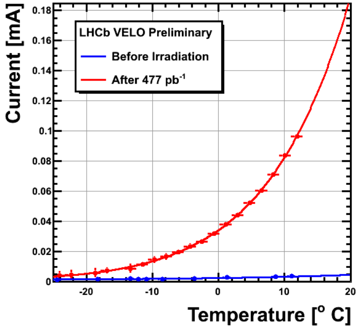




- 300 μm silicon at -8°C
- Oxygenated
- Double metal layer
- Designed to cope with LHC radiation environment
  $\sim$6 fb^{-1} delivered luminosity

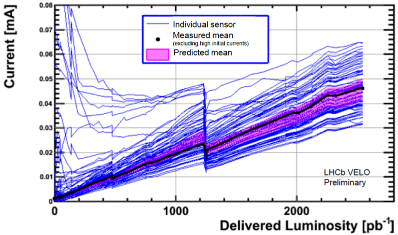
Effective bandgap and current increase

- Measure the effective band gap from exponential fit to leakage currents:



$E_g = 1.16 \pm 0.06$ (eV) at 2.7 fb^{-1}
c.f. 1.21 eV from A. Chilingarov

- Increase in bulk current with fluence proportional to delivered integrated luminosity:

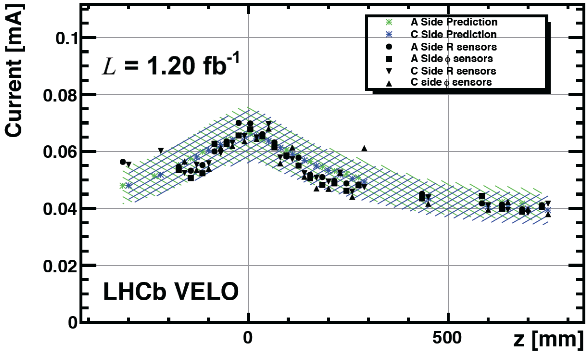


All sensors at 150 V and -8° C

- Good agreement with MC predictions
  $\rightarrow$ also seen in 2012 at 8 TeV

Fluence predictions

- Compare current measurements to MC predictions sensor by sensor:



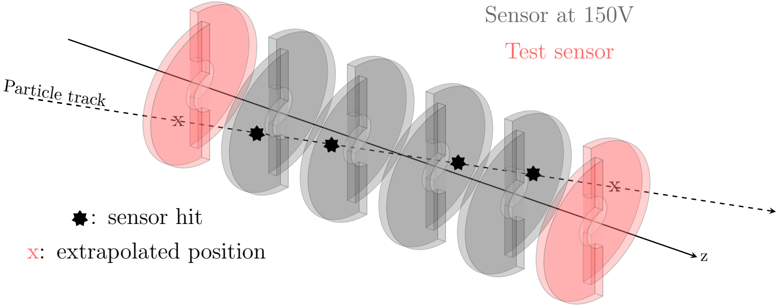
Good agreement further justifies our understanding of the fluences received by the VELO

→ use MC predicted fluences in several of the following studies

Effective Depletion Voltage

Effective depletion voltage 1

- Depletion voltage of sensors measured during assembly using C-V scans
- Cannot be repeated after installation so use dedicated data taking periods every 3-4 months



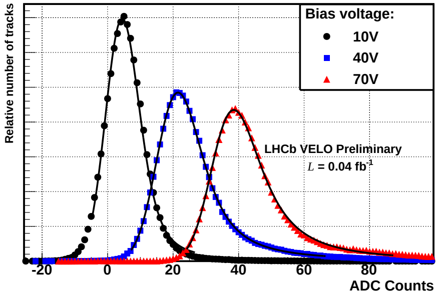
Method: extrapolate tracks to test sensor and determine amount of charge collected

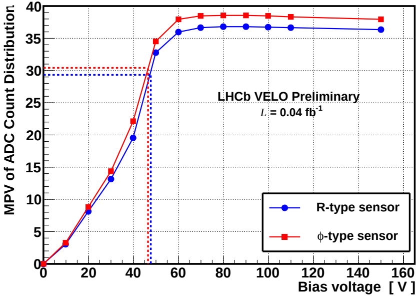
Effective depletion voltage 2

- Pattern varied to collect data at each sensor across a range of voltages

Fit MPV of ADC distribution...

...and plot vs voltage

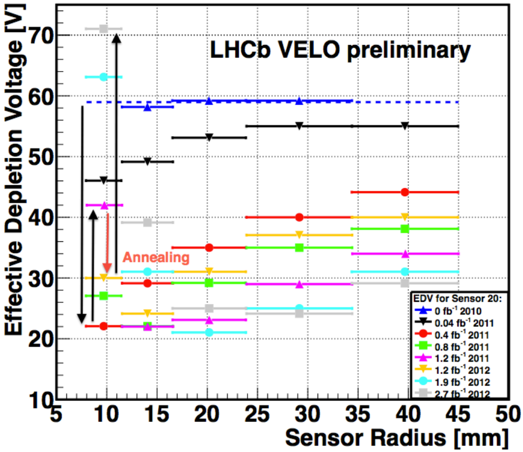




- Effective Depletion Voltage (EDV) is defined as the voltage at which the MPV is 80% of the maximum

EDV vs fluence 1

Plot change in EDV for a single n^+-on-n sensor in bins of radius for different delivered luminosities:

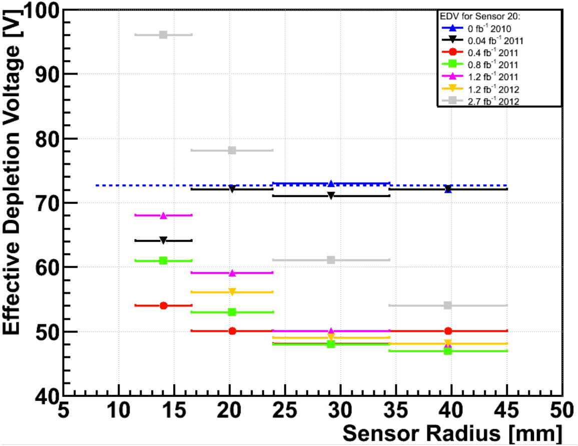


Conclusions:

- EDV decreases with fluence before type-inversion
- EDV increases with fluence after type-inversion
- Type-inversion starts in inner radial regions

EDV vs fluence 2

Change in EDV for a single n$^+$-on-p sensor in bins of radius for different delivered luminosities:

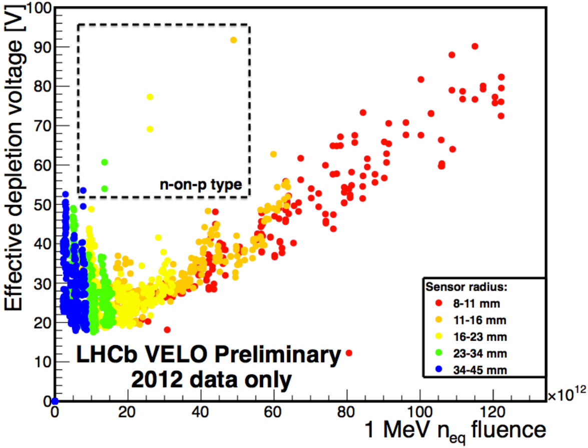


Conclusions:

- EDV decreases with fluence initially as in n$^+$-on-n type
- EDV then increases with fluence rapidly
- Minimum EDV point is much higher ∼45V

EDV vs fluence 3

Plot change in EDV versus fluence for all sensors:



Conclusions:

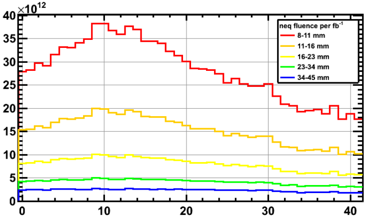
- Minimum observed EDV of $\sim$ 18 V before type-inversion
- Type-inversion occurs at $\sim 15 \times 10^{12}$ MeV n_{eq}
- n^+-on-p sensors appear to have a shorter lifetime before type-inversion

EDV extrapolations: sensor by sensor

- Fit to EDV vs fluence plot and extrapolate results to 3.6 fb^{-1}

Sensor	Max EDV at 3.5ifb
0	241
4	122
5	128
6	127
7	131
8	134
9	145
10	145
11	140
12	138
13	143
14	141
15	132
16	132
17	130
18	125
19	122

120-129V, 130-139V, 140-149V



Predicted fluence vs sensor number

- Highest EDVs are centred around the interaction point
- EDV approaching current operating voltage (150 V) $\rightarrow$ change before the end of the year

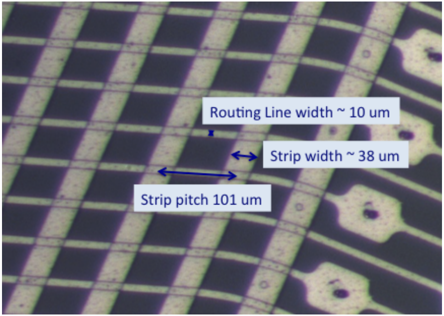
Cluster Finding Efficiency

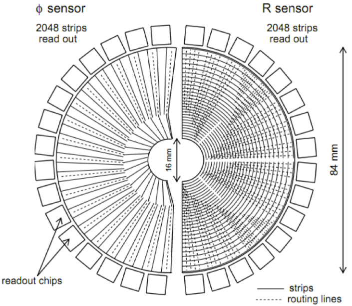
Cluster Finding Efficiency

- A key aspect of VELO physics performance is the ability to efficiently find and reconstruct clusters
- A cluster is defined as one or more adjacent silicon strips with charge above a particular threshold
- Cluster Finding Efficiency (CFE) is therefore the percentage of tracks at a particular point in the sensor where a cluster is obtained at the track extrapolation point
- Typically measured using regular dedicated scans, but can also be derived from physics data

Second metal layer

- 1^{st} metal layer capacitively couples to strips
  2^{nd} metal layer carries signal to read-out electronics

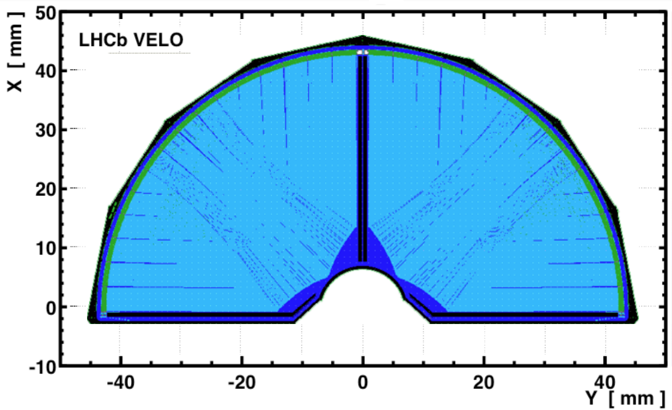




- Routing lines are perpendicular to strips in R-sensors and parallel to strips in ϕ-sensors
- Charge capacitively couples to routing lines in R-sensors and reduces CFE

2D CFE plots

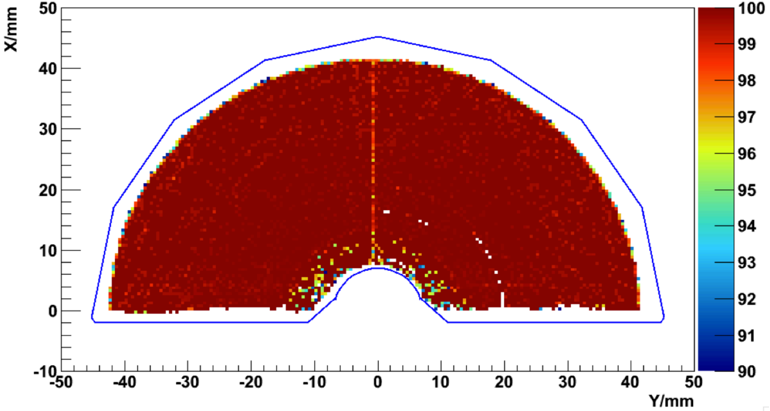
- Map of routing lines in an R-type sensor:



- Light parts indicate absence of routing lines

2D CFE plots

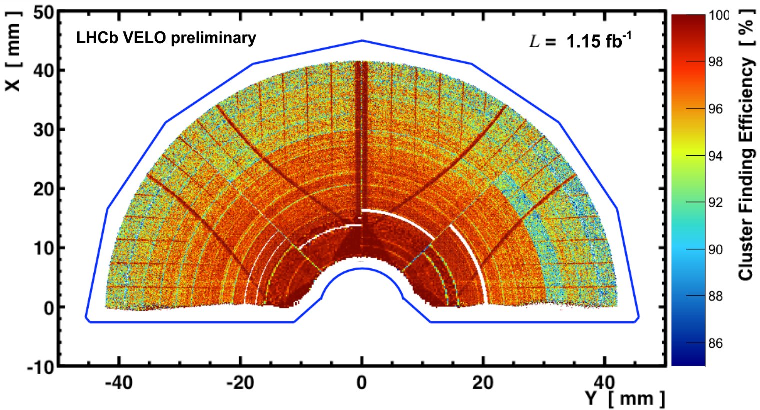
- Plot CFE in *x* and *y* bins:



- Early March 2011, after 40 pb^{-1}
  $\rightarrow$ CFE is $\sim$ 100% in all regions of sensor

2D CFE plots

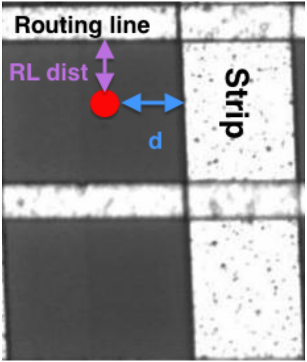
- Repeat after 1.15 fb^{-1} (Oct 2011) delivered integrated luminosity:

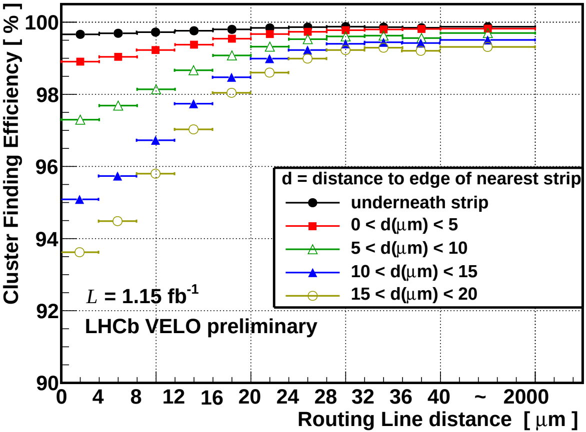


- CFE drops with fluence, especially in outer radial regions
- High efficiency in absence of routing lines

Routing line and strip distance dependence

- CFE is worst in regions far away from strips and close to routing lines (shown here for 2011 data - known to be the same in 2012):



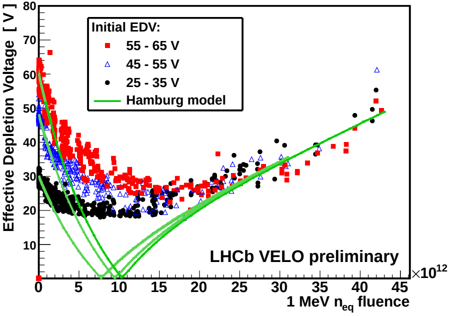


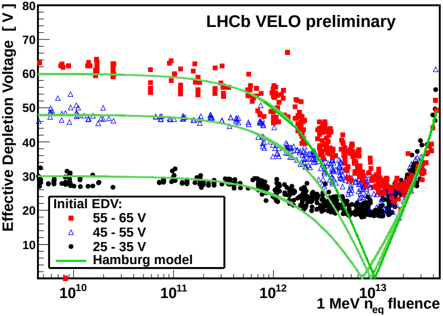
- No measurable effect on tracking efficiency

Other studies

Hamburg Model comparison

- Compare results to Hamburg Model (for 2011 data only):

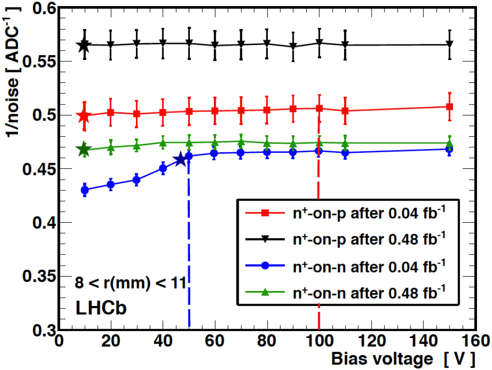




- Good agreement at low and high fluences
- Discrepancy around type-inversion point due to finite charge collection time
- Important to predict evolution of depletion voltage for future operations

Noise vs Voltage 1

Can also take regular noise scans without requiring beam

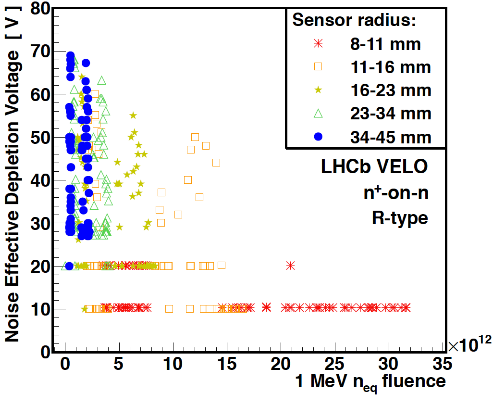


- Under-depleted sensors have higher capacitance
- Depleted sensors have lower capacitance due to depleted region
- Noise proportional to capacitance
  → noise decreases as sensor approaches type inversion point

- Not applicable for n^+-on-p and type-inverted sensors due to direction of growth of depleted region
- Dashed lines represent initial depletion voltage

Noise vs Voltage 2

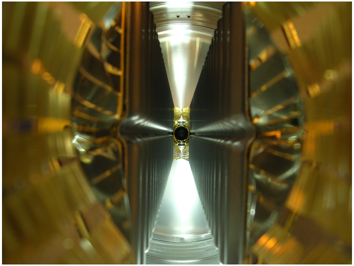
Define Noise Effective Depletion Voltage (NEDV) as voltage at which 1/noise is 80% of maximum

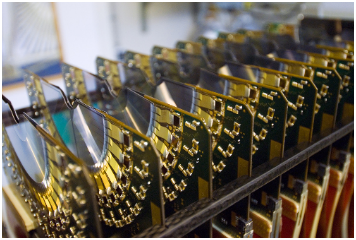


- Plot vs fluence for all sensors, similarly to EDV
- Sensitive to lower voltages than the EDV method
- Excellent agreement with EDV in predicting regions which have type-inverted

NEDV indicated by stars on previous slide for illustration
$\rightarrow$ good agreement with initial depletion voltage

Summary

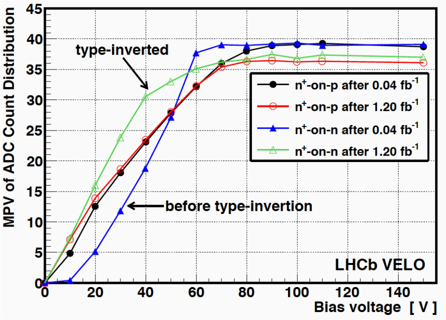




- Radiation damage effects are studied with several methods
- Change of depletion voltage with fluence agrees well with expectations
- Large CFE decrease due to second metal layer effect observed in some regions of R-sensors
- Currently no significant effect on physics performance
- Studies ongoing and in the process of moving towards publication

BACKUP

MPV vs voltage



- For n^{+}-on-n depletion region grows from the back plane of the sensor
- For n^{+}-on-p depletion and n^{+}-on-n after depletion region grows from the strip side of the sensor
- Accounts for the different shape of the curves

Minimum EDV

- Observe a minimum EDV of $\sim$ 18 V
- Due to the slow drift of the charge in the low electric field combined with the fast shaping of the Beetle chip
- Electron drift speed: $\sim$ 9 µm/ns at 18 V, Beetle shaping time: $\sim$ 20ns
  $\rightarrow$ within shaping time only 60% of electrons reach electrode (+ a small amount from other contributions)
- Require 80% of signal to measure EDV

Further information on effective band gap

- Follow up article on E_g from: A. Chilingarov 2
- Do not expect a direct comparison between E_g quoted within and the experimentally determined value

CFE vs voltage

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

Delivered Luminosity	$\Delta CFE_v = CFE_{V=150} - CFE_{V=80}$ (%)				
	8-11mm	11-16mm	16-23mm	23-34mm	34-42mm
0.426 fb^{-1}	-0.09 ± 0.09	-0.19 ± 0.02	-0.30 ± 0.01	-0.76 ± 0.03	-1.84 ± 0.19
1.220 fb^{-1}	-0.03 ± 0.28	-0.06 ± 0.02	-0.21 ± 0.02	-0.57 ± 0.04	-1.15 ± 0.40
1.912 fb^{-1}	0.12 ± 0.11	0.15 ± 0.06	-0.15 ± 0.05	-0.85 ± 0.11	-1.49 ± 0.34

- CFE decrease has been found to depend on voltage
- Therefore any increase to account for increasing depletion voltages should be carefully considered
- However dependence appears to disappear for n^{+}-on-p sensors and n^{+}-on-n sensors after type-inversion