**Impact of Radiation on the LHCb VELO Sensors**

Thank you for your comments. I have responded to all below in red.

A general comment: VELO rules mean I have to show the plots as they were approved for the conference at which they were presented. This requires them to have “LHCb VELO Preliminary” on them. I cannot change this.

Abstract

line 3-4: I suggest to write "the VELO sensors were exposed to radiation with levels  up to about 45 X10(12) 1 MeV neutron equivalent (1 Meq)". - done

Line 6: I suggest to change at the end of the sentence " obtained after sensor irradiation" - done

Line 7: in the line you have used twice the verb "observed", please rephrase. - done

Line 8: please rephrase " The only…" – We feel it is true and worthwhile to point out that these are the only n-on-p type sensors in operation at the LHC. I cannot think of another way of phrasing this.

Line 10: in the line you have used twice "following”, change the first one in "up to a fluence ….". Change the second in " After this point…." – I have left the first “following” in, changed the second one. Now only one “following” in absract.

Line 12: I suggest not writing "unexpected effect".  With the VELO sensors geometry should have been expected, and I believe that the design has been made minimizing the effect. So please rephrase the full sentence. – The significance of the effect was unexpected to everyone working on the velo… Over 10 decreases in CFE in places. I have changed it anyway.

1.Introduction

Line 3 : please change  "vertexing"   better to use "vertex reconstruction"  - done

Line 4 : "particles fluence"  - I think you mean “high particle fluences” - done

Line 5 : do not use "essential", I  suggest  "necessary" - rephrased

Caption Figure 1. line 2: instead of "photograph" use "detail" (END figure caption)

- I disagree. Detail is vague. This is a real photo of a VELO sensor. I think the following description is useful for understanding the strip and routing line orientations (especially useful for understanding section 4). I have left as it was.

Line 6 : I suggest to change "During LHC beam operation injection and energy rump, the VELO…." – This is purely stylistic, I prefer it as it was.

Line 10 : I suggest to write " ) in order to improve…" - done

Line 13 - 16: should be interesting to write the crystal orientation and resistivity, both play a role in the radiation damage. – I’m afraid we don’t know the crystal orientation. Regarding initial resistivity, I’m not sure, though we could probably find out by digging through the old notes... As far as I am aware, the initial resistivity plays a role in the intial depletion voltages, which we measure and show in Fig. 7.

Line 17 : I suggest not to name "aluminum track" a pattern that is usually named as the AC metal side of a strip capacitor, through which the charge is readout. - done

Line 19: seems to me that the "second metal layer" is connected to the AC metal, and not to the silicon "strip". – clarified.

2.Sensor currents

Line 2 : I suggest to remove the figure 2 left, belongs not to VELO  research, you should put a reference rephrasing. - done

Line 3-6 : Why " A single current "  I propose to write " The current of each VELO sensors is monitored and raw data as a function LHC run time is shown in figure 2" – simplified as suggested.

Figure 2:  I suggest removing the figure (left). Figure (right) The x-axis scale of plot at right is not understandable.  Why are you showing half of the picture referred to a LHC non-operation time? Should be interesting to explain the spread of the values, i.e. is a function of distance from beam? you are also referring to simulation, bulk and surface current, concept that are discussed later I suggest to remove this.    Also the line of "mean" is not visible.

Figure should be "approved" by experiments and not "preliminary"

- x-axis is time. The part during shutdown shows we experienced sensor annealing during shutdown.

- spread in values is now mentioned.

- Have re-shuffled this section as you request in later comment.

Figure 3. Figure should be "approved" by experiments and not "preliminary" – see comment at top of this document

Line 13:  I suggest to explain better "anneals with fluence". Before irradiation (figure 3 right) the surface current is predominant, after irradiation is the other way around. Relative Sign of currents is? They sum up or compensate? Can you explain which figure (3 left or right) is more representative for the VELO sensors?

* I have clarified statement "anneals with fluence".
* Surface and bulk currents will add. I’m afraid it is beyond the scope of this note to go into the details of this much more than I have shown (struggling to keep within 10 pages already). I have referenced the detailed and public studies of sensor currents.

line 14 : temperature of interest ? can you explain ?

- range is that which the VELO is operated and can be heated up to during shutdown (i.e. that of Fig. 3). Clarifying statement has been added.

Line 15: remove the value of the Boltzmann constant - done

Line 19:  put a reference for the 1.21 eV measured after radiation damage. - done

Line 19-23: check reference. – changed to updated ref, where Chilingarov notes have been made public

Line 24-30: I suggest to move this part + figure 4 after line 6. You can explain better  Figure 2  that show simulation results.  – done

line 29:  change "following"  with "after" - done

Figure 4: explain the "dashed area"  Figure should be "approved" by experiments and not "preliminary" - this was explained in the caption. Have changed “shaded”-> “dashed” to make more clear.

3. Depletion Voltage

line 5: I suggest to remove "further" - done

Line 10: EDV is not a property but the method by which you can estimate in operational conditions the Depletion Voltage. –I feel this is open to debate. The EDV is the voltage required to obtain 80% of the total charge, as stated. We define the 80% so the two properties match initially. After significant irradiation this may not be the case (due to charge trapping defects etc…). Then the EDV will be more a measure of charge collection efficiency than the depletion voltage.

Line 12: Special data have been collected in which every fifth module (test sensor) is …. - done

Line 14: remove " (those operated at various voltages) " - done

Line 15-16 : here is relevant to have an evaluation of the extrapolation error, or provide a reference. – added a comment on this. Although it is worth mentioning, if the strips with the corresponding charge are not found due to poor extrapolation, this will not influence the EDV, which is determined with a fit to the ADC distribution (i.e. if the charge is not found, an entry at ~0ADCs is simply added which doesn’t effect the gauss-landau ADC fit).

Lines 18-21:  please add here a reference or demonstrate with a picture that the 80%  cut is effective. – I do not have room for a picture on this, and there is no reference for this (other than my thesis (which is not yet public). However, we do say:
“The threshold of 80% was chosen as it gives closest agreement with depletion voltages determined from pre-irradiation CV measurements, with differences between the two methods below 10V for all sensors.” – which indicates the accuracy of the comparison between the two variables.

Line 19 : change "demonstrated" with "showed" – This figure is a demonstration of the method, as I have shown an example of how the EDV is determined. I prefer to leave as it is.

Figure 5.  left: Y-axis " Relative number of tracks", can you explain/label it better? – arbitrary unit. I have changed the label.

Line 23-25: please explain better how the regions are selected. I suppose you have used simulation. – yes simulation, the accuracy of which has been verified in studies of sensor currents (i.e. section 2). I have clarified this statement.

Line 24: seems contradictory that fluence increases moving at higher distance from the beam. – true, this is a mistake. Changed “increases”->“decreases”.

Line 28: contradicts line 24. – see above

Line 31: please change "observed by others" with a more formal sentence, as "reported in the literature" - done

Figure 6  Y-axis label  , use EDV.Figure should be "approved" by experiments and not "preliminary" – done (changed to “EDV”).

Figure 6 caption.

Line 2-3 : rephrase the part of the sentence in (….) i.e. "data not collected at all radii before irradiation". Line 3: change "later" with "last"  (END figure caption) – this was meant to say “latter”. Has been changed. (It is not “last”, as it is seen in the last two scans.)

Line 32-37:  effects of non-0 Neff of theoretical inversion point is also see in literature using Capacitance-Voltage measurement. Papers report it as the Double Junction effects. Can you disentangle this effect in your devices ? The 18 V can be evaluated independently?  - We have not made attempts to disentangle double-junction effects. I thought that although CV measurements measure non-0 Neff, they find the depletion voltage is still much less than 18V (a few volts at a guess?).

Figure 7  Y-axis label  , use EDV. Figure should be "approved" by experiments and not "preliminary" - done

Line 40 and Line 43: suggest removing "further" - done

Figure 8: I suggest to show only one version Lin or Log. Figure should be "approved" by experiments and not "preliminary", Use EDV in the Y-axis – done. Am using only Lin.

Line 57 :  " a decrease of the sensor noise" - done

Line 60: your conclusion is not 100% correct; you forget to consider here the effect of the leakage current to the noise. This may play a role also for the following conclusion you have made. – I am not 100% sure of your meaning. I have softened the statement:

“In this situation the strips are immediately isolated at the application of a bias voltage and the relationship between noise and voltage cannot be exploited as effectively to extract information related to the depletion voltage.”

Figure 9 shows n-n and n-p detectors. Can you write a conclusive sentence also for these last detectors? Can you please explain the legend in the figure 9 right? It is difficult to accept that noise is not independent from the sampling time, why this change?

- added a statement on n-on-p lineshapes. i.e. lineshape shows little dependence on voltage, as expected for reasons already described.

- Regarding noise offset, this is caused by a very LHCb specific technical issue, which shifts all noise values. Common noise to all strips in a sensor (known as common mode noise) is subtracted. A timing issue in the ADC sampling time of the first strip causes a shift in the common mode noise subtraction, which shifts the whole distribution. This was considered too technical to describe in this note, given the page constraint.

You have used Ref [11] in order to demonstrate behavior of inter-strip resistance. I'm not able to find within the reference this result. Can you please check it? – I made a mistake. This was a follow up paper to the reference I meant to give. I have replaced it with the correct one. You can find it at: http://www.sciencedirect.com/science/article/pii/S0168900211009600

4.Charge loss of the second metal layer

line 2 : remove "instead" - done

Line 5-6: can you please quote the decrease in CFE? Can you please explain why the larger loss is at high voltage?

* first question: The decrease in CFE is different in each sensor, as it depends on fluence, and the angle of the incident tracks. So this is difficult to give. I have added that the CFE decrease is around 5% in the worst effected radial regions.
* Second question: I am afraid not. He we simply report the dependence. We are releasing a paper in JINST shortly with more information on this.

Figure 10: refers to a radiation-damaged detector? Can you please add to the caption ?  Write CFE in the y-axis. Is the color scale in common for the two plots?

Use approved data from LHCb not Preliminary.

Please report on the text the extrapolation precision

* It does say 1.15fb on the plot, but I have added to caption to make clearer.
* Extrapolation error is not relevant for what this plot is showing: i.e. that the CFE is better in regions with no routing lines.
* The left plot does not have a colour scale. It shows the routing line layout (dark blue are routing lines, light blue/cyan is where there are no routing lines).

Line21-23: can be the case that you are not able to see inefficiency in phi-strips because they are irradiated to varying dose along the radial distance? – no, we are able to measure CFE in very precise regions of the sensors, as shown by fig 10b. The phi sensors do not experience the same CFE loss. We have done many checks of this.

Figure 11: Use CFE in Y-axis (left) , use arbitrary units or A.U. in Y-axis right. - done

Lines 24-28 I have a few comments. First, are you sure that the peak is not only noise? Seems the tail of a Gaussian curve.

Please comment the figure at left as it is: shows the CFE and not the noise induced clusters as you report in lines 26-28.

* Yes, this was a little confused. I have re-phrased.
* We are confident the low ADC noise peak is associated to the second metal layer effect. It shows similar dependence to the CFE on the distance to a routing line and strip. Also, it has grown with fluence, and isn’t seen in phi sensors.

Figure 12:  (left) you refer to two luminosity, one of this is 0 fb-1  can you please rephrase the caption.

Caption: "various amount of luminosity” change in " different integrated luminosity" - done

Lines 32-33: are you sure that is the effect of second metal layer only? There is no trapping effect? Can you explain better? – yes we are sure. This is actually how we first discovered the CFE effect. The decrease in MPV with voltage depends on the sensor radius, distance to strip, and distance to routing line in the same way as the CFE. Also, we don’t see this in phi type sensors. Any charge trapping effect is small in comparison. I have added a brief line, but space is tight to stay within 10 pages…

Reference [13] : I do not think that the charge loss measured in the pixel and due to the bias grid can be compared to the effect of your second metal layer. Please check it. – I think a very similar effect is reports. See the bottom-left column of page 1155 in Ref[13], continuing onto the top-right column.