Radiation Damage in the LHCb VELO

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Abstract

LHCb is a dedicated experiment to study new physics in the decays of beauty and charm hadrons at the Large Hadron Collider (LHC) at CERN. The Vertex Locator (VELO) is a silicon micro-strip detector which surrounds the LHCb interaction point and provides µm resolution of charged tracks and vertex positions. The tip of the VELO sensors is predicted to receive a dose of 0.5×10^{13} 1 MeV n_{eq} cm^2 per fb of data. The highest fluence of any silicon tracker at the four major LHC experiments. Radiation damage studies have been carried out during the first two years of data taking at LHCb for all 88 sensors of the VELO. Radiation damage has been observed in all sensors, with those sensors in the highest fluence regions showing evidence of type inversion. Radiation induced charge loss due to the second metal layer on the sensors is also observed.

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1. Introduction

LHCb is a single arm spectrometer designed to take advantage of the production of $b\bar{b}$ and $c\bar{c}$ pairs at small angles to the beam axis[1]. Much of the LHCb physics program requires measurement of the decay length of these beauty and charm particles, therefore precise determination of the primary vertex (PV) and secondary decay vertex positions are required. The vertex measurement at LHCb is performed by the Vertex Locator (VELO) sub-detector, which is positioned around the interaction region of LHCb.

The VELO is a silicon micro-strip detector made up of two detector halves, each containing 44 semi-circular silicon strip sensor planes. When the LHCb is recording collision data, the active area of the sensors is positioned only 8 mm from the beamline and extends out to 42 mm. Here the sensors are exposed to instantaneous luminosities greater than 10^{31} cm^{-2} sec^{-1}. For protection during the proton injection of the LHC the VELO halves can retract by 3 cm. The VELO sensors come in two types, one which measures the radial distance from the beamline, R, and one which measures the azimuthal angle, ϕ. These sensors are arranged in 42 pairs, 21 on each side, along the beamline (called modules) allowing measurement of both co-ordinates at the z-position of each module. There are also 4 pile-up veto sensors located upstream of the interaction region which contain only an R sensor. The majority of the sensor planes are made from 300 µm n-on-n silicon containing 2048 strips with pitch varying between 40 µm and 100 µm. Two oxygenated n-on-p silicon sensors are installed in the VELO, as a test of a LHC silicon upgrade candidate.

2. Expectation and Mesurement Method

The depletion voltage of the silicon is a good measure of the sensor performance and its evolution with particle fluence. According to the Hamburg model [2] we expect an initial reduction in the depletion voltage with increasing particle fluence for n-on-n silicon. The n-type bulk is then expected to type invert to p-type. After this, further irradiation leads to an increase in the depletion voltage until it is larger than the electrical breakdown of the silicon.

The depletion voltage of the sensors was measured during production by measurement of the capacitance and bias voltage [3]. This is not possible to measure now that the VELO is assembled, so another property similar to the depletion voltage is measured instead. A property known as the Effective Depletion Voltage (EDV) is found using the following technique.

Several test sensors were removed from the VELO reconstruction algorithms and were allowed to vary in applied voltage. A most probable value (MPV) for the number of ADC counts at a set voltage is found by fitting the ADC distribution. The VELO has a nominal operating bias of 150V. As shown in Fig. 1 The MPV tends to rise with increasing bias until reaching a plateau, generally at bias values less than 100V. The EDV is defined as the voltage at which the MPV reaches 80% of the maximum MPV.

3. Results

3.1. Bulk Radiation Damage

Fig. 2 shows the measured EDV, for different radii ranges, as a function of the received fluence. There is a common type inversion point at $\sim 10^{13}$ 1 MeV n_{eq} fluence, though the EDV does not reach 0V before this occurs as in the Hamburg model [2]. The highest fluence regions, above 25×10^{13} 1 MeV n_{eq}, have type inverted. The points not conforming to the overall

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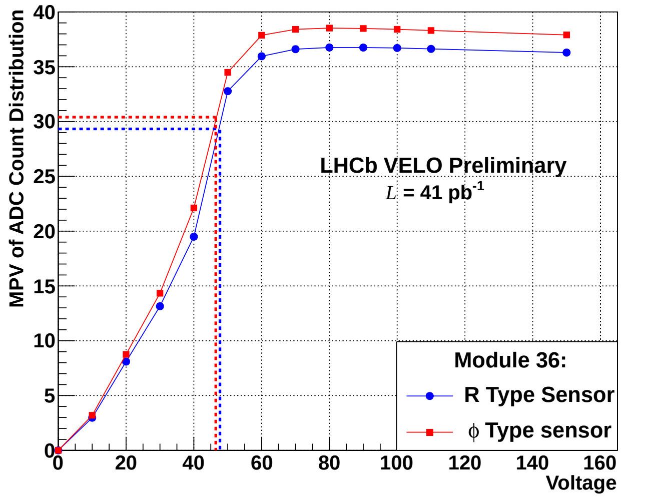

Figure 1: The MPV against the bias voltage for module 36. The dashed lines indicate the corresponding EDV.

pattern in the top left of Fig. 2 are from the n-on-p sensors. These also see a drop in EDV, before increasing at a much lower fluence than the n-on-n sensors. If this gradient continues for the n-on-p sensors, the operational lifetime will be much lower, questioning the suitability for the LHCb upgrade.

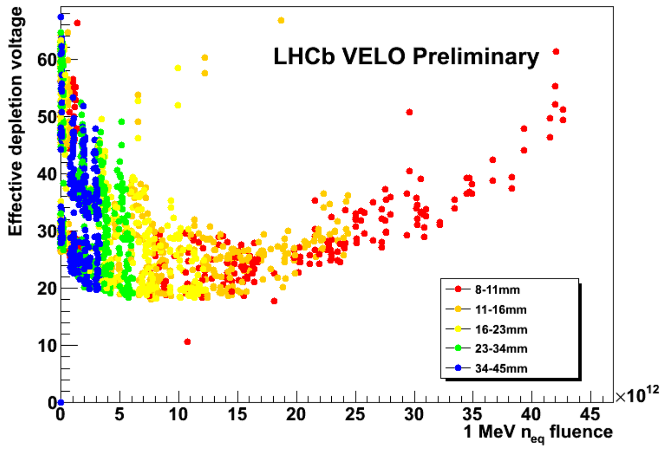

Figure 2: The EDV against the fluence for all VELO sensors at different radii.

3.2. Cluster Finding Efficiency

A cluster in the VELO is defined as multiple adjacent strips which have deposited charge above a threshold value. The Cluster Finding Efficiency (CFE) was measured using the same data samples as in Section 3.1. It is defined as the fraction of tracks that have a cluster at the reconstructed track intercept on the test sensor. Before irradiation the CFE was measured to be greater than 99%, however in Fig. 3 the efficiencies are often less than 95% in certain areas of the sensor. In the VELO, to bring the signal from the strips to the processing electronics at the periphery of the sensor, a second metal layer is used. This second layer is isolated from the first by a 3 μm thick SiO_2 layer. The organisation of these metal routing lines correspond to areas on the sensor with lower CFE, and areas without routing lines have higher CFE. This suggests that coupling between the strips and the metal routing lines is causing a reduction in the collected charge and thus a reduction in the CFE. This effect is not seen in the ϕ sensors due to an intentional reduction in pickup of the lines made possible by the ϕ sensor strip orientation [4].

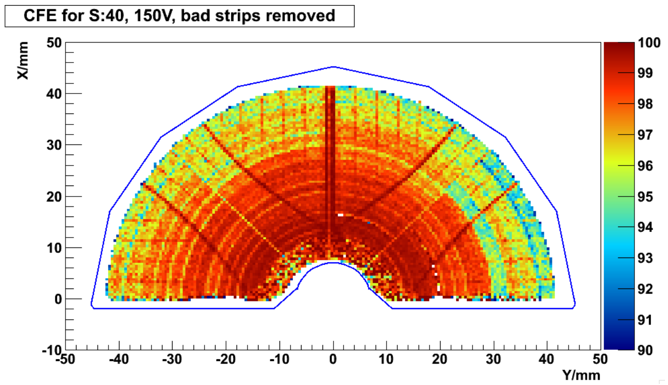

Figure 3: A CFE map of sensor 40 using 150V bias voltage, after ∼ 750 pb of delivered luminosity.

4. Summary

Radiation damage has been measured and observed in all of the LHCb VELO sensors. The highest fluence areas of the sensors have already type inverted as expected. The n-on-p sensors will require further measurement over the coming months, to quantify their suitability for the LHCb upgrade. A reduction in CFE has been observed and explained. No significant impact on track reconstruction efficiency has yet been observed.

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