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Developing Radiation Hard Silicon for the LHCb Vertex Locator

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Abstract

LHCb is a dedicated experiment at the LHC to study CP Violation. The vertex locator is a silicon detector designed to provide precise information on the production and decay vertices of b-hadrons both off-line and for the second level trigger. The active silicon is positioned only 8 mm from the LHC beam and will operate in an extreme radiation environment (up to 1.3×10^{14} 1 MeV neutron equivalents / cm^2 / year). A report is presented on the sensor design and the related radiation hard silicon research, including promising new results on Czochralski silicon.

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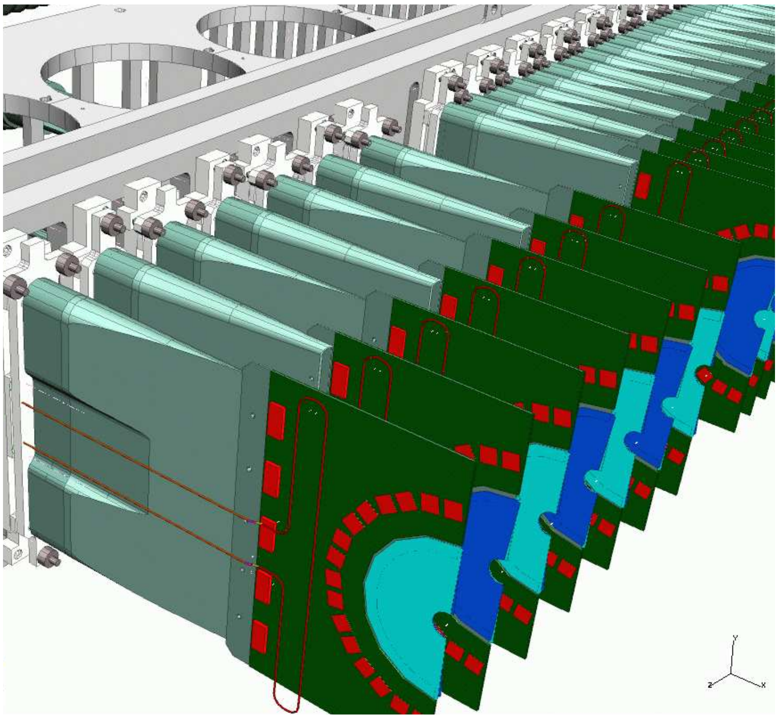

Figure 1: Layout of the left-hand half of the LHCb VELO. The silicon sensors, hybrids, modules and mounting supports are shown.

1 Introduction

LHCb is a dedicated B-sector CP violation experiment for the LHC collider. The B production cross-section at the LHC will be a factor 10,000 larger than at the B-factories and the full range of B baryons will be accessible. This will facilitate the measurement of all angles and sides of both measurable CKM triangles and hence a full test of the standard model mechanism of CP violation.

The detector is a single arm spectrometer with an angular acceptance of 15 - 300 mrads. The detector has recently undergone a re-optimisation to reduce the material in the detector and optimise the trigger strategy [1]. The detector expects to start data taking at the time of the first LHC collisions in spring 2007. The experiment is currently finalising the design and entering the construction, testing and assembly phase. The detector contains two silicon tracking systems: the trigger tracker and inner tracker, which are discussed elsewhere in these proceedings [2], and the vertex locator (VELO) discussed here.

The reconstruction of vertices is a fundamental requirement for the LHCb experiment as this permits the separation of b-hadron decays from background. The LHCb Vertex Locator (VELO) has been designed to provide the precise measurements necessary to reconstruct and resolve the vertices in b-hadron events which, at the LHC, are produced predominantly at small angles to the beam axis. In addition, the VELO is both the primary standalone tracking device of the experiment and the basis of the second level displaced vertex trigger.

2 VELO Design and Radiation Environment

The VELO consists of 84 semi-circular silicon sensors positioned perpendicular to the LHC beam axis and arranged over a distance of 1 m around the LHCb collision point as shown in Figure 1. In order to obtain the optimal impact parameter resolution the sensors should be located as close as possible to the LHC beam. In the VELO this is achieved by placing the sensors in a retractable housing, separated from the primary vacuum of the LHC by only a thin 250 μm aluminium foil. The shape of the foil has been designed to minimise the amount of material traversed before the first hit in the silicon. The first active silicon strip is only 8 mm from the LHC beam axis.

Inevitably, this proximity to the LHC beam will result in an extreme radiation environment with the inner strips receiving a fluence, comprised predominantly of charged particles, of up to 1.3×10^{14} 1 MeV neutron equivalent particles per cm^2 per year. A significant programme of R&D has been performed to develop a sensor that is capable of providing a good signal/noise performance for several years of LHCb running, after which replacement of the sensors is foreseen.

3 Sensor Prototypes

Prototype silicon sensors have been manufactured and studied in the laboratory and test-beam environments. Amongst the significant results that have emerged from these studies is a comparison of identical layout $n^+ - on - n$ and $p^+ - on - n$ sensors. These studies [3], identified a number of significant disadvantages of the $p^+ - on - n$ sensors, particularly when it is necessary to operate the sensors below full depletion. The irradiated $p^+ - on - n$ sensors show a sharp degradation in charge collection efficiency when operated under full depletion. Furthermore, the sensor charge is then also spread and hence the resolution affected. Charge losses to the second metal routing line layer of up to 25% were also observed on the $p^+ - on - n$ sensors. These effects are all more damaging in the $p^+ - on - n$ design as, after irradiation, depletion occurs from the n-side of these devices.

The base-line $n^+ - on - n$ silicon sensors are semi-circular in shape and have an active area from 8 to 40 mm. Two sensor layouts, shown in Figure 2, are produced : a sensor with pseudo-radial strips and a sensor with semi-circular strips.

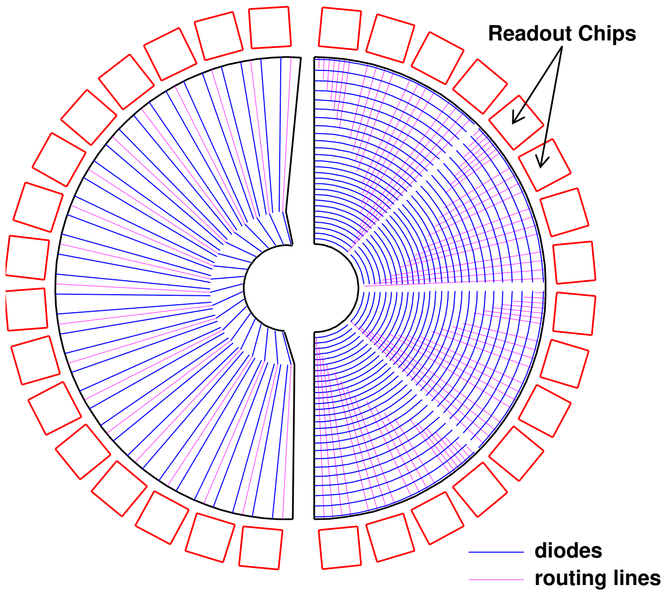

Figure 2: Schematic diagram of the VELO sensor layouts, left: ϕ-measuring sensor, right: R-measuring sensor.

In both sensors the inter-strip pitch varies as a function of radius, with a minimum pitch of 40 μm. The detectors are produced on 220 μm thick diffusion oxygenated float-zone silicon. The read-out electronics is largely located outside the LHCb acceptance around the outer edge of the sensors, with the signals from the inner sections of the sensor being routed over a second metal layer.

In order to obtain optimal resolution and monitor the sensor performance as a function of irradiation analogue readout is used. A 40 MHz radiation hard front-end chip has been developed for the VELO in the .25μm CMOS process.

4 Czochralski Silicon

In parallel to the development of the initial VELO detector we are continuing a research programme, in collaboration with the RD50 collaboration, to investigate radiation hard silicon for the future replacement VELO sensors. One area of this research is a study of the behaviour of magnetic Czochralski (Cz) silicon.

In the past year high resistivity Cz silicon wafers have become available. The material has an oxygen content two orders of magnitude higher than in float-zone material. The ROSE collaboration showed that increasing the oxygen concentration by diffusion increased the radiation hardness of sensors to charge particle irradiation [4]. A first full scale detector prototype was irradiated and operated with LHC speed (40 MHz) SCT128A front-end electronics in a VELO group test-beam in summer 2003. The 50 μm pitch $p^+ - on - n$ sensor was fabricated on 380 μm thick 900 Ω cm magnetic Czochralski silicon at the Helsinki Institute of Physics [5].

The sensor was irradiated with 24 GeV protons and received a maximum fluence of 8×10^{14} protons/ cm^2. Using the eight sensor VELO test-beam telescope, tracks were fitted and extrapolated to the cooled Cz test detector. The charge deposited on the strips neighbouring the track extrapolation point was taken. From this data, Landau distributions were produced as a function of the irradiation dose received on the areas of the sensor. The Landau distributions were fitted and the most probable value obtained as a function of voltage. Preliminary results from this direct determination of the sensor depletion voltage indicate a full depletion voltage of around 500 V at the maximum fluence. This is to be compared with a simulation of an equivalent sensor fabricated from float zone silicon where the anticipated depletion voltage would be approximately 1400 V. The full results of this study will be provided in a forthcoming paper.

5 Summary of Velo Status

The design of the initial VELO is now close to completion, in particular the sensor design has been finalised and front-end chips manufactured. Prototypes consisting of sensor, hybrid and front-end chips have been successfully tested.

The baseline design is $n^+ - on - n$ diffusion oxygenated float zone silicon sensors. The sensors are still fully efficient at only 60% depletion and micro-discharge problems have not been observed running at bias voltages of up to 500 V. After an equivalent radiation dose of 3 LHCb years a signal to noise of 21:1 was obtained on a 300 μm thick ϕ-measuring sensor.

In parallel the group is still researching radiation hard silicon, for future sensor replacement, and have obtained promising results from operating at LHC speed the first irradiated silicon strip detector fabricated from magnetic Czochralski silicon.

A systems test of the complete VELO will be performed in early 2006, following which the detector will then be installed in the experiment. LHCb looks forward to recording our first physics events in April 2007.

6 Acknowledgments

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