Developing Radiation Hard Silicon for the LHCb Vertex Locator

C. Parkes on behalf of the LHCb VELO group

Department of Physics and Astronomy
Kelvin Building
University Avenue
Glasgow G12 8QQ
UK
E-mail: c.parkes@cern.ch

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 $\times$ $10^{14}$ 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.

Key words: Silicon Micro-strip, Vertex Detector, Radiation Hardness
PACS: 29.40.Gx

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 mrad. The detector has recently undergone a re-optimisation to reduce the material in the detector and optimise the trigger strategy (1). The LHCb Collaboration expects to start data taking at the time of the first LHC collisions in spring 2007. The collaboration has finalised the design and entered the
Fig. 1. Layout of the left-hand half of the LHCb VELO. The silicon sensors, hybrids, modules and mounting supports are shown.

construction, testing and assembly phase. The detector contains two silicon tracking systems: the trigger tracker and inner tracker, and the vertex locator (VELO) which is 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 $1.3 \times 10^{14}$ 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. The base-line $n^+ - o n - n$ silicon sensors are semi-circular in shape and have an active area from 8 to 40 mm. Two sensor layouts are produced: a sensor with pseudo-radial strips and a sensor with semi-circular strips.

In both sensors the inter-strip pitch varies as a function of radius, with a minimum pitch of 40 $\mu$m. The detectors are produced on either 200 $\mu$m or 300 $\mu$m 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 .25 $\mu$m CMOS process.

Recent test-beam results show that a signal/noise ratio of 18:1 is obtained for a 300 $\mu$m R-sensor and that the measured pulse reduces to 30% of it peak value in 25 ns. This device satisfies the requirements (2) of the experiment: good signal discrimination is made for the current event; and the number of fake hits observed in the next event, due to the pulse-shape decay, is sufficiently small.

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. Good spatial precision (currently the system has a best hit resolution of 4 $\mu$m), low material budget (the current system has achieved 19%$X_0$ by keeping the
Fig. 2. CCE for a full-scale MCz silicon sensor equipped with LHC speed electronics. The radiation levels are quoted for 24 GeV protons/cm².

electronics and cooling largely outside the acceptance of the experiment) and extreme radiation tolerance (> 1 × 10¹⁵ 1 MeV neutrons / cm²) would be required for any future upgrade. Possible replacement technologies include 3D sensors and n-on-p technology. One area of this research is a study of the behaviour of magnetic Czochralski (MCz) silicon.

High resistivity MCz silicon wafers are now available. The material has an oxygen content one-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 (3). A first full scale (6.1 cm × 1.9 cm) detector prototype was irradiated and operated with LHC speed (40 MHz) SCT128A front-end electronics in a VELO group test-beam in autumn 2003 (4). 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) and had an initial depletion voltage of 420 V.

The sensor was irradiated with 24 GeV protons and received a maximum fluence of 8 × 10¹⁴ protons/ cm². Using the eight sensor VELO test-beam telescope, tracks were fitted and extrapolated to the cooled MCz test detector. The unirradiated sensor was fully depleted and operated at upto 700 V, a signal/noise ratio of greater 23:1 was measured. As shown in figure 2 the charge collection efficiency (CCE) was measured against voltage. Unfortunately limitations in the experimental setup prevented us from fully depleting the sensor at the highest irradiation levels but significant CCE was still observed even
after $7 \times 10^{14}$ protons / cm$^2$

5 Summary of Velo status

The design of the initial VELO is now completed, the front-end chips have been manufactured and sensors of the final design are currently being delivered. First modules incorporating the final sensor, hybrid and front-end chips are currently being tested.

In parallel the group is researching radiation hard silicon technologies for future sensor replacement. Promising results have been obtained from operating in a testbeam 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.

References