# Developments in Radiation Hard Silicon for the LHCb VELO

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The LHCb experiment is a dedicated B-sector CP violation experiment for the LHC collider. The detector is a single arm spectrometer with an angular acceptance of 15 - 300 mrad. The detector contains two silicon tracking systems: the inner tracker and the VErtex LOcator (VELO). The tasks of the VELO include the reconstruction of the production and decay vertices of b-hadrons, necessary to distinguish between signals from b-hadron decays and background. Moreover the VELO has to reconstruct tracks covering the full angular acceptance of the downstream detectors and provide information to the second level trigger. The VELO makes heavy demands on the silicon performance, due to the participation of it in the trigger and the importance of making measurements in the rapidly oscillating $B_s$ channels.

The optimal impact parameter resolution requires short extrapolation distances to the vertex as well as a minimum of material before the first measured point. This is achieved by placing the sensors as close as possible to the LHC beam. Therefore, the VELO consists of 21 stations which are perpendicular to the LHC beam over a distance of 1 m around the interaction region, as shown in Fig. 1 (left). The first active silicon strip is only 8 mm from the LHC beam axis. This results in an extreme, non-uniform radiation environment of up to $1.3 \times 10^{14}$ $n_{eq}$/year , see Fig. 1 (right).

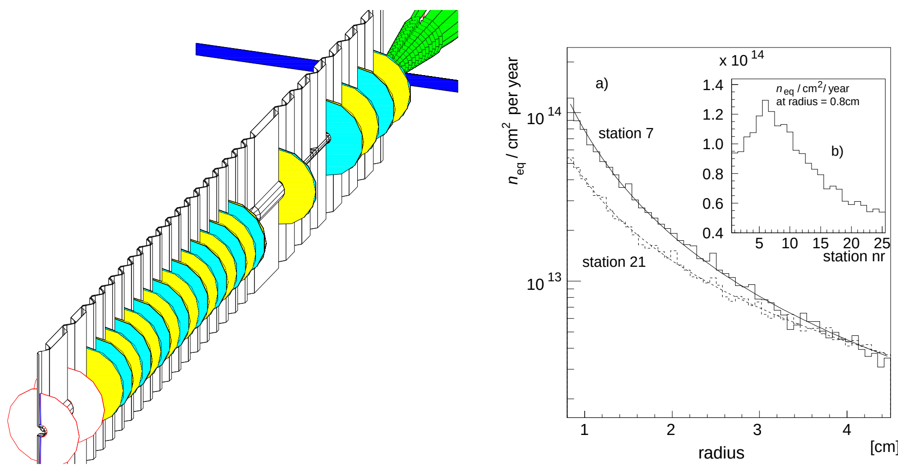


Figure 1: Left: The 21 semi-circular VELO silicon stations positioned around the LHC beam axis. The sensors are separated from the primary LHC vacuum by a thin RF foil. Right: The expected irradiation fluence per year as a function of the distance in cm from the beam axis. The first sensitive silicon strip is positioned at 8 mm.

A significant programme of research and development 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. 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 the comparison of identical layout $n^+$ - *on* - n and $p^+$ - *on* - n sensors. These studies [1], 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 outcome of the research efforts has resulted in the choice of a complex $n^+$ - *on* - n double metal layer oxygenated silicon solution.

In parallel to the development of the initial VELO detector we are continuing a research programme, in collaboration with the RD50 collaboration [2], to investigate radiation hard silicon for the future replacement VELO sensors. The silicon detectors which will be installed in 2007 will have to be replaced after about 3 years due to radiation damage. One such area of research is a study of the behaviour of Magnetic Czochralski silicon (MCz).

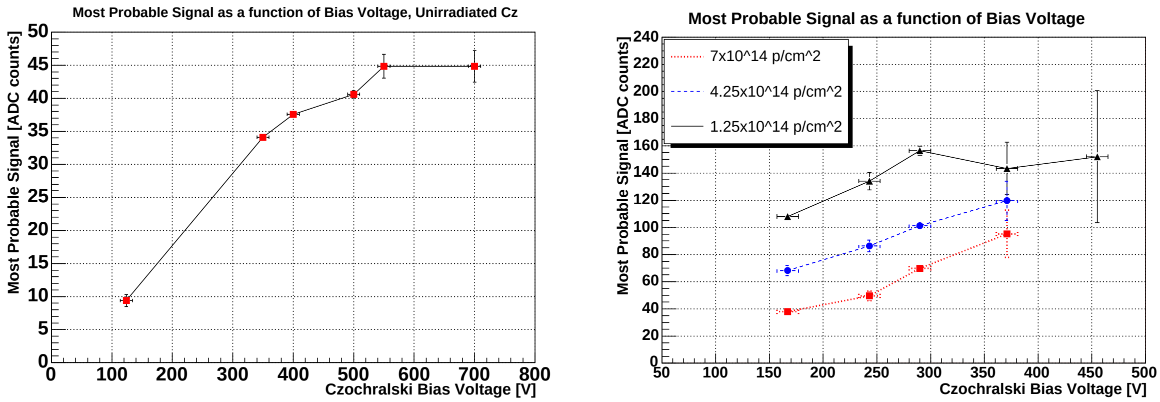


Figure 2: Unirradiated (left) and irradiated charge collection efficiency distributions for the magnetic Czochralski sensor. The radiation levels are quoted in 24 GeV protons/cm$^2$. The ADC values in unirradiated and the irradiated test beam periods can not be directly compared.

MCz 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 [3]. Recent technological advances have lead to the development of high resistivity MCz silicon. Furthermore, unlike Diffusion Oxygenated FZ, leading manufacturers are willing to process MCz grown silicon. Hence, it is worthwhile investigating this material as a candidate for use in the harsh readiation environments of the LHC.

The first charge collection efficiency and signal to noise studies on a large scale micro-strip 380 $\mu$m thick Czochralski silicon detector have been performed. The detector was read out with 40 MHz electronics with the primary aim of evaluating the performance for the VELO upgrade.

Before irradiation the 380 $\mu$m thick detector gave a peak signal to noise of 23.5 $\pm$ 2.5. This performance is easily comparable with that of the baseline LHCb VELO sensors. Afer irradiation, signal to noise values of 15, 11 and 7 were found for radiation regions equivalent to 0.5, 2 and 4 years, respectively, of the peak LHCb radiation environment.

The charge efficiency distribution as a function of voltage for the detector can be seen in Figure 2 (left). The MCz detector was then irradiated with 24 GeV protons and received a maximum fluence of 8 $\times$ 10 $^{14}$ protons/cm$^2$. The charge collection efficiency distribution as a function of voltage and irradiation levels can be seen in Figure 2 (right). Evidence for depletion in the lowest irradiation region can be seen in Figure 2 (right). Hence, these initial results show that this technology is a promising candidate for the replacement sensors of LHCb VELO and possible upgrades for LHC general purpose detectors.

Further studies are continuing on full scale detector proto-types. In collaboration with RD50, MCz pad diodes are also being examined using the Transient Current Technique to fully determine the properties of the material.

# References


[1] LHCb Collaboration, LHCb Vertex Locator Technical Report, CERN/LHCC/2001-011 (2001)

[2] RD50 Status Report 2002/2003, CERN/LHCC 2003-058

[3] Radiation Hard Silicon Detectors - Developments by the RD48 (ROSE) Collaboration, Nucl. Instr. & Meth. in Phys. Res. A 466, 308-326, 2001