Nuclear Instruments and Methods in Physics Research A 765 (2014) 35–40

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The LHCb VELO: Performance and radiation damage

H.L. Snoek

Nikhef, P.O. Box 41882, 1009 DB Amsterdam, The Netherlands

On behalf of the LHCb VELO group

ARTICLE INFO

Available online 11 June 2014

Keywords:
LHCb
VELO
Silicon radiation damage
Detector performance
Silicon detector

ABSTRACT

LHCb is a forward spectrometer experiment dedicated to the search for New Physics in the decays of beauty and charm hadrons produced by the proton–proton interactions at the Large Hadron Collider (LHC) at CERN. The measurement of the flight distance of these hadrons is critical for the physics program. The VErtex LOcator (VELO) is the silicon detector surrounding the LHCb interaction point and provides excellent resolution of charged tracks and vertex positions. The VELO has been run successfully since installation. The sensors have the first sensitive strips at a radius of 8.2 mm and are exposed to maximum radiation doses of $\sim 0.6 \times 10^{14}$1 MeV n_{eq}/cm^2 per fb^{-1} delivered integrated luminosity. The performance of the VELO during the first LHC run is described, together with methods to monitor radiation damage. Results from the radiation damage studies are presented showing interesting features, such as an unexpected charge coupling to the second metal layer routing lines after irradiation. The radiation damage has so far no impact on the track reconstruction performance.

1. Introduction

The LHCb detector [1] is a single-arm forward spectrometer that studies beauty- and charm-flavoured hadron decays at the LHC to search for New Physics phenomena beyond the Standard Model. The analysis of these decays relies on excellent vertex and momentum resolution and particle identification. The silicon VErtex LOcator (VELO) is an LHCb sub-detector positioned around the proton–proton interaction point and extends from 30 cm upstream to 75 cm downstream with respect to the interaction point. It provides excellent vertex and impact parameter resolution with excellent efficiency. Additionally it provides fast pattern recognition for triggering purposes through the identification of displaced vertices that are identifiers for beauty and charm decays. The good performance of the VELO is vital for the LHCb experiment.

The LHC has started its proton–proton collisions in Fall 2009 and currently is undergoing its first long shutdown for planned maintenance. The first data run has been very successful. In this period LHCb has received an integrated luminosity of 3.4 fb^{-1} with increasing beam energies up to 4 TeV. It is planned to resume operations in 2015.

2. The VELO detector

The VELO consists of two detector halves, each containing 21 modules with half-disc shaped sensors. A module consists of two, 300 μm thick, silicon strip sensors, one which measures the radial distance (R-type) from the beam and the other, the azimuthal angle (ϕ-type). The inner radius of the sensors is 7 mm away from the beam axis with the sensitive area between 8.2 and 42 mm radius. All sensors are n^+-on-n type with the exception of a module with n^+-on-p type sensors placed most upstream, to test this technology in an operation environment for future upgrade projects. Each sensor contains 2048 strips, with pitches ranging from 38 to 102 μm. Each strip implant is capacitively coupled to a first metal layer that is following the implant along its full length. The first metal layer is connected to a routing line in a second metal layer that carries the signals to one of the 16 Beetle chips [2] located at the outer radius of the sensors. The chips sample the signal at 40 MHz and provide analogue information.

The module produces about 20 W and is cooled with a bi-phase CO_2 cooling system [3,4]. During normal operations, the silicon sensors are cooled to −7 °C, when the electronics are powered off to about −30 °C, and there are exceptional periods at room temperature when interventions are made to the cooling system.

The sensors are operated in a secondary vacuum separated from the primary beam vacuum by a 300 μm thick foil. The foil is corrugated to allow the sensors of the two detector halves to overlap for alignment and efficiency purposes.

E-mail address: hella.snoek@nikhef.nl

http://dx.doi.org/10.1016/j.nima.2014.06.009

The two detector halves are retracted by 3 cm to prevent damage from the proton beams during injection and non-stable beam operations. Once the proton beams are declared stable, there is a fully automated procedure to close the detector safely and efficiently. During the procedure, the proton–proton interaction positions are individually reconstructed by the two detector halves. The information of these calculations is used to centre the detector around the beams, both vertically and horizontally. The closing of the detector takes 210 s at the start of each LHC fill.

3. Performance

The VELO has operated stably and reliably throughout the first run period of the LHC.

The hit resolution has been measured as a function of the local strip pitch and for different projected track angles, see Fig. 1, by measuring the residuals between the reconstructed hit positions and the track projection on the sensor [5]. There is a clear benefit in the resolution from charge sharing over multiple readout strips which can be seen by comparing the hit resolution for different impact angles. For the most favourable conditions (inner sensor region and higher impact angle), the hit resolution obtained is 4 μm, which is a clear manifestation of the excellent performance, tuning and alignment of the VELO.

The precise reconstruction of the primary vertex (PV) position, and separating it from secondary vertices in the subsequent decay of particles, is a crucial component of many of the LHCb physics analysis performed. Fig. 2 shows the resolution of the reconstructed PV along the beam axis ($\hat{z}$) versus the number of tracks associated to that PV. The vertex resolution has been measured by splitting the track sample associated to a single PV arbitrarily in two, and measuring the difference between the primary vertices reconstructed from the two subsamples [5]. For a typical PV with 25 associated tracks the measured resolution is $\sigma_{x,y} \approx 13$ μm perpendicular to the beam axis in the horizontal ($\hat{x}$) and vertical ($\hat{y}$) directions, and $\sigma_z \approx 90$ μm along the beam axis. This shows the good performance of the VELO.

The impact parameter (IP) is the distance of closest approach of a track to the PV and is widely used in signal selections and the LHCb trigger. The main contributions to the IP resolution are the single hit resolution and the amount of multiple scattering before the first hit measurement. Fig. 3 shows the momentum dependent $\mathrm{IP_x}$ resolution. It has been measured to be $11.6+23.4/p_{\mathrm{T}}$ μm, this is a clear demonstration of the capabilities of the VELO.

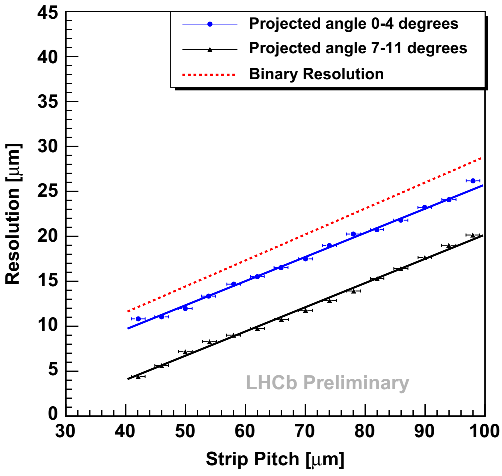

Fig. 1. Hit resolution for an R-type sensor versus the local strip pitch for two categories of projected impact angles. The dashed line indicates the binary resolution where no charge sharing information is available.

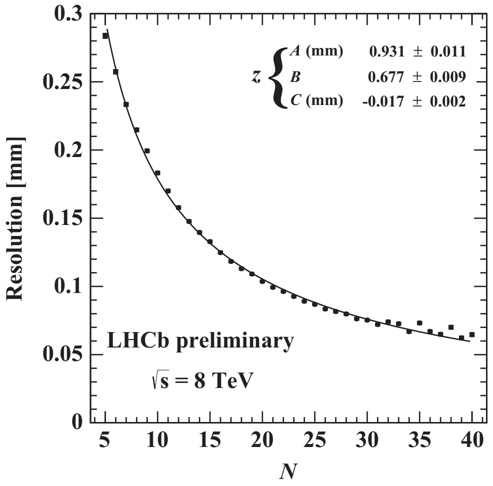

Fig. 2. Resolution along the beam axis (z) of the reconstructed primary vertex versus the number of tracks used in the reconstruction. The measured data points have been fitted with a function in terms of the track multiplicity: $\sigma_{PV} = A/N^B + C$.

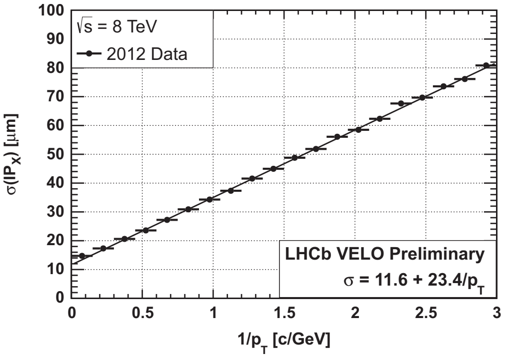

Fig. 3. Resolution along the x coordinate of the track impact parameter versus the $1/p_{\mathrm{T}}$ of the used tracks.

4. Radiation damage

The VELO is subjected to severe radiation due to its close proximity to the LHC beams, leading to damage of the silicon bulk. The radiation fluence scales roughly as $1/r^2$ with the radial distance to the beam line. This implies a strongly non-uniform irradiation over the area of a single sensor, with the fluence received by the inner and the outer radius differing by over an order of magnitude. Also the location of the sensor with respect to the beam interaction point influences the received radiation dose. Fig. 4 shows the fluences predicted from simulations as a function of sensor position and radial distance from the beam axis. Up to 5×10^{13} 1 MeV $\mathrm{n_{eq}/cm^2}$ per delivered fb^{-1} is expected in the hottest regions of the VELO detector, with an assigned error of 8%, for more details see Ref. [6].

Several methods are in place to monitor the radiation damage in the VELO. We will briefly summarise them here, more detailed information can be found in Ref. [6].

4.1. Current–temperature scans

In the relevant temperature range the bulk current is expected to scale according to $I(T) \propto T^2 \exp(-E_g/2kT)$, where T is the temperature in Kelvin, k is the Boltzmann constant and E_g is the band-gap energy with an expected effective value of 1.21 eV [7]. Fig. 5 shows the current versus temperature behaviour for two sensors (one in each plot) before and after (some) irradiation. Before irradiation one of the sensors has a surface dominated