First Results from the LHCb Vertex Locator

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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 the silicon detector surrounding the interaction point and will be located only 7 mm from the LHC beam during normal operation. The beauty and charm hadrons are identified through their flight distance in the VELO, and hence the detector is critical for both the trigger and offline physics analyses. The VELO has been commissioned and successfully operated during the initial running period of the LHC. The detector has been time aligned to the LHC beam, and spatially aligned. Preliminary operational results show a signal to noise ratio of 20:1, a cluster finding efficiency of 99.6%, and a best single hit precision of 4 μm.

Key words: Vertex Detector, Silicon, LHC
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1. Introduction

LHCb [1] is a dedicated experiment to study new physics through the investigation of CP violation and rare decays in the decays of beauty and charm hadrons at the Large Hadron Collider (LHC) at CERN. At a nominal luminosity of 2×10^{32} cm^{-2}s^{-1} and collisions at a centre-of-mass energy of 14 TeV, about 10^{12} $b\bar{b}$ pairs will be produced per year. LHCb is a single arm spectrometer covering the angular region from 15-300 mrads around the beam direction, since the b-hadrons are produced highly forward boosted.

The vertexing and track reconstruction around the interaction point is performed by the silicon microstrip Vertex Locator (VELO). The first results from this detector during operation with LHC collisions are reported in this paper. The remaining tracking system consists of a a silicon microstrip detector in front of the spectrometer magnet, and three tracking stations behind the magnet. These three stations consist of silicon microstrips in the region close to the beam pipe and straw tube drift cells for the outer parts. The particle identification in LHCb is achieved using two ring imaging Cherenkov counters; a calorimeter system composed of a scintillator pad detector and preshower, an electromagnetic, and a hadronic calorimeter; and a muon detector system.

Synchronisation tests of the LHC occurred in the summer of 2008, as part of these a single proton bunch beam was collided on a beam absorber in the transfer line between the CERN Super Proton Synchrotron (SPS) and the LHC. The first fully reconstructed beam-induced tracks at the LHC were observed in the LHCb VELO [2]. In September 2008 the first beams were circulated in the LHC, but LHC operations were halted by an incident during commissioning, requiring twelve months of repairs and the development of additional safety systems. The first collisions at the LHC were obtained in November and December 2009, with centre-of-mass energies of 900 GeV and 2.36 TeV. This paper describes the VELO system, and the preliminary results obtained with this initial data sample.

2. LHCb VELO

LHCb identifies b- (and c) hadrons through their flight distance. The VELO surrounds the collision point and is responsible for reconstructing this flight distance from the primary vertex and b-decay vertices. The detector is used for displaced vertex triggering in the second level of triggering, and is readout at 1MHz. The detector is also a primary component of the tracking system of the experiment.

The VELO consists of two detector halves, one of which is shown in figure 1. Each half contains 21 modules, with each module containing two semi-circular silicon sensors perpendicular to the beam-axis. One sensor is R-measuring with circular arc strips, the other Φ-measuring with pseudo-radial strips. Each sensor has 2048 strips and a strip pitch varying from approximately 40 to 100 μm. The sensors are readout with a double metal layer to a hybrid mounted on a carbon fibre encased thermo-pyrolitic graphite support. This is attached to a carbon fibre paddle.

The detectors are operated in vacuum to reduce to a minimum the amount of material particles have to traverse before reaching the sensitive devices. The LHC beam vacuum is separated from the detector vacuum by 300 μm thick aluminium RF foils mounted on each side.

The two VELO halves are moved according to the aperture required by the operation of the LHC machine. During physics collisions the sensors are only 7 mm from the beam. However,

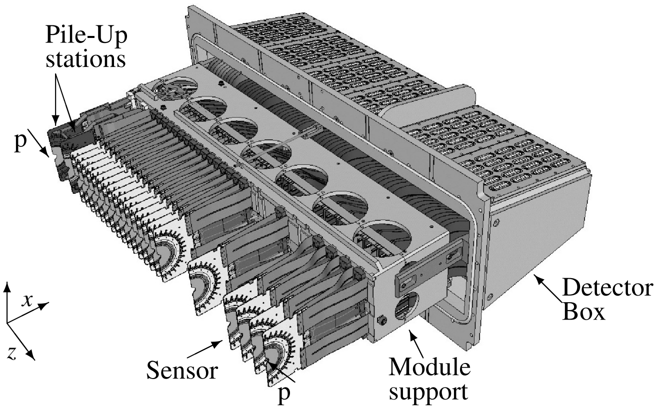

Figure 1: Overview of the VELO left half box. The sensors, module supports and detector box are indicated.

they are retracted by 30 mm from the beam axis during injection. This close distance to the beam results will result in a particle fluence of 1.4×10^{14} 1 MeV neutron equivalents/cm^2 per nominal 2 fb^{-1} operational year at the inner radius of the detector. The radiation dose is highly non-uniform, falling with an approximately $1/r^2$ distribution across the sensor.

The VELO sensors are readout with a .25 μm analogue front-end chip [3]. The signals are transmitted to FPGA readout boards responsible for the digitisation and processing of the analogue data [4]. The clusters obtained are then sent to the experiment's trigger CPU farm.

The detailed system design studies started in 1997, and installation of all components of the VELO system was completed in October 2007. The full system VELO comprises the silicon sensors, modules and front-end electronics; the readout electronics and FPGA processing boards; the vacuum, motion and cooling systems; the sensor bias high voltage and electronics low voltage supply system; the control and safety interlock systems; the data acquisition system; the simulation, reconstruction, and monitoring algorithms. The complete system has been operated since June 2008.

3. First Results

The results obtained from the data sample collected from proton collisions with a beam absorber, during the LHC synchronisation tests, are reported in [5]. Two key areas were identified where the data quality would be improved in early LHC collision operation: the data processing algorithm tuning and the non-optimised timing set-up.

The analogue data from the detector is digitised and processed in a sequence of algorithms implemented in FPGAs. These algorithms perform pedestal subtraction, cross-talk removal, common mode subtraction and clusterisation. The performance of the algorithms is controlled by over one million parameters. Automatic procedures were developed to tune these parameters for each individual channel of the detector, and put in place for 2009 operation. A novel approach was taken in which raw data is processed through a bit-perfect emulation of the FPGA algorithms implemented inside the full reconstruction framework of the experiment [6], hence allowing the optimisation of the algorithms and parameters for the overall detector performance.

The timing set-up included the optimisation of the front-end chip sampling time with respect to the LHC beam-crossing clock. The signal in the LHCb front-end has rise and fall times of the order of 25 ns (the LHC clock speed). Data was taken at a number of different sampling times and fits to the pulse shape obtained. This has allowed the sampling time for all sensors to be adjusted to within 2 ns of the optimal point, as shown in figure 2.

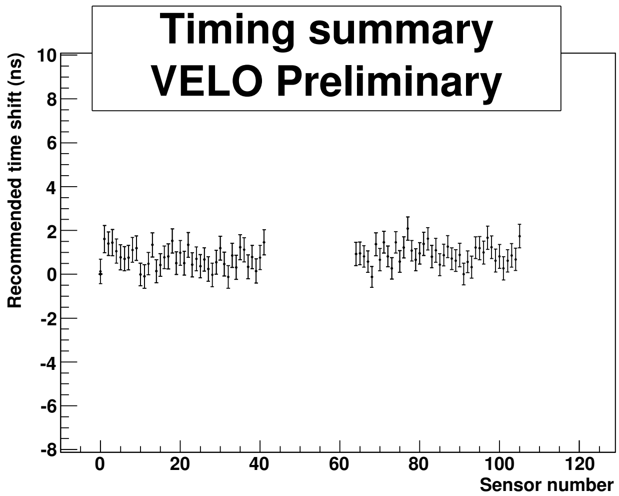

Figure 2: Optimisation of the front-end chip sampling time of the VELO sensors. The R-measuring sensors have the lower range of sensor numbers, the Φ-measuring sensors the higher numbers.

The observed cluster ADC distribution was fitted for each sensor with a Gaussian convoluted with a Landau distribution, and the most probable value extracted. A good uniformity was obtained, demonstrating that the gains in the system had been correctly equalised. The ADC gain calibration procedure utilises the headers and test injection system signals from the front-end chip. The single channel noise of the system, after common mode correction, was measured in runs without beam. Signal to noise values of around 20:1 were measured for all sensors in the system using the first collision data.

The cluster finding efficiency was evaluated. Each sensor was excluded in turn from the pattern recognition and tracking algorithms, and the tracks were extrapolated to the sensor being examined. A cluster was then checked for within ±4 strips of the extrapolated track crossing point on the sensor. The preliminary result is shown in figure 3, and shows a cluster finding efficiency of 99.6%. Only one front-end chip in the full system is not functioning, the corresponding efficiency drop is clearly seen in the figure for that sensor. The number of dead and noisy channels in the system has also been monitored from the noise distributions, a preliminary value of 0.6% of channels was determined. The distribution of detector occupancy during collisions is in good agreement with the expectation at all closing positions at which data was taken.

The VELO was first spatially aligned with the LHC synchro-

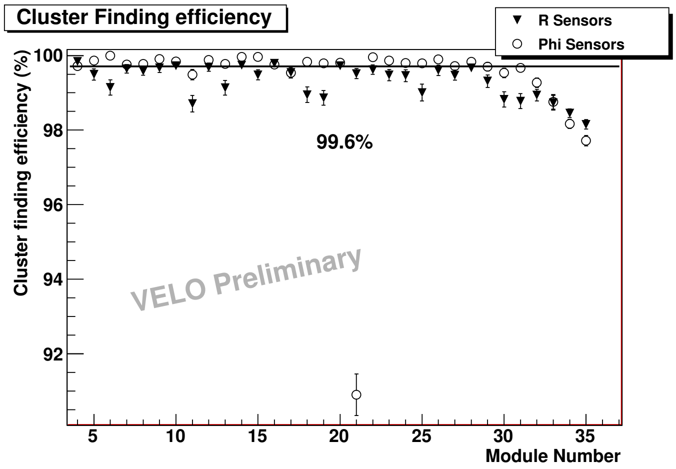

Figure 3: Cluster finding efficiency, obtained by extrapolating tracks to the sensor under investigation, as a function of the module number.

nisation test data in which the beam was collided with an absorber [5]. The alignment method primarily relies on a non-iterative matrix inversion technique [7]. The method is split into three stages: the relative alignment of the sensors in the modules; the relative alignment of the modules; and the relative alignment of the two velo halves. The alignment is assessed using the residual distributions between the cluster position and the extrapolated track position, a preliminary alignment precision of 4 μm in the plane transverse to the beam was measured. As a result of running the system at two different temperatures during the beam and absorber collision data the thermal expansion of the carbon fibre bases of the modules was observed and measured.

Using this alignment, the first measurement of the single hit resolution performance was obtained. The result for an example R-measuring sensor is shown in figure 4 as a function of the pitch on the sensor. The pitch of the sensor increases with increasing radius across the sensor. The result shown is for tracks of angles to the beam in the range $6-12°$. The cluster position is reconstructed performing a weighted strip average using the analogue signal pulse-height information from each strip. The resolution is found to be considerably better than binary, due to the sharing of the deposited charge of the traversing tracks between the strips on the R-measuring sensor. For the optimal track angle (approximately 10°) and minimal strip pitch (40 μm) a single hit resolution of 4 μm was obtained.

The reconstruction of the primary vertices in the VELO is critical for the physics performance. An example event display picture showing hits and reconstructed tracks resulting from a collision is given as figure 5. The primary vertex position is also required to be monitored on-line to allow the two halves of the VELO to be safely closed around the beam, and to ensure the safety of the detector throughout the physics fill. The two halves can be positioned separately to be closed around the beam position, and can be moved together in the perpendicular direction in the plane transverse to the beam. During the first collision data period in November and December 2009, the VELO halves were inserted to a distance of ±15 mm from their

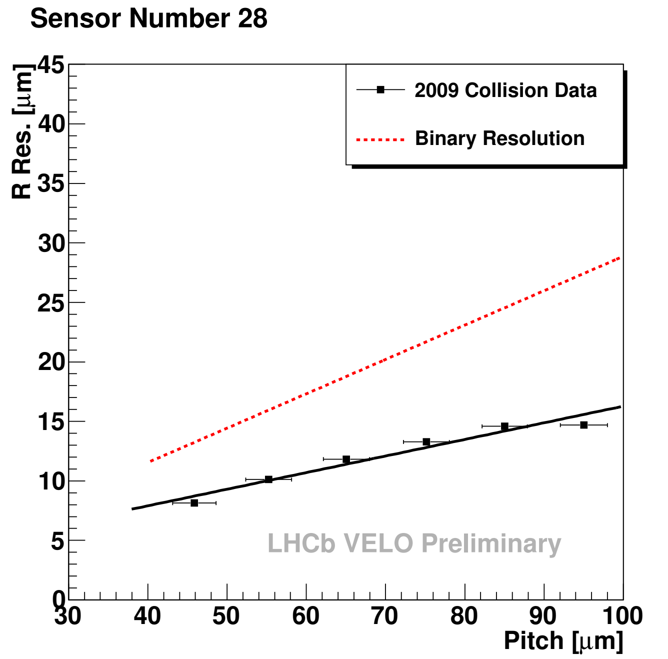

Figure 4: Resolution of an example R-measuring sensor as a function of the inter-strip pitch on the sensor. The tracks used in this plot have polar angles to the beam direction of $6-12°$.

nominal closed operational point. The full insertion can safely occur once the beam energy rises above 2 TeV. The distance of closest approach of tracks to the primary vertex is known as the 3D impact parameter, and is a critical element of all physics selections. The impact parameter distribution has been reconstructed and found to already be in reasonable agreement with the simulation over the primary momentum range of interest for b-decays.

The statistical power of the precision vertexing of the system has been demonstrated in reconstructing the mass distributions of K_s from $\pi^+\pi^-$ decays and Λ decays from $p^{+/-}\pi^{-/+}$. Even with the VELO only partially inserted, at ± 15 mm, the mass resolution improves by a factor of two when including the VELO in the tracking system. The mass values obtained from LHCb are in good agreement with the particle data group averages.

4. Conclusions

The LHCb VELO has been commissioned and successfully operated during the initial running period of the LHC, and preliminary results shown. A signal to noise ratio of 20:1 was obtained, and a cluster finding efficiency of 99.6%. The system has been aligned and a best signal hit precision of 4 μm obtained so far. The system has been used to reconstruct primary and secondary vertices and in conjunction with the other elements of the tracking system the masses of long-lived particles have been reconstructed. Further improvements are expected as the system is studied and refined in the coming months.

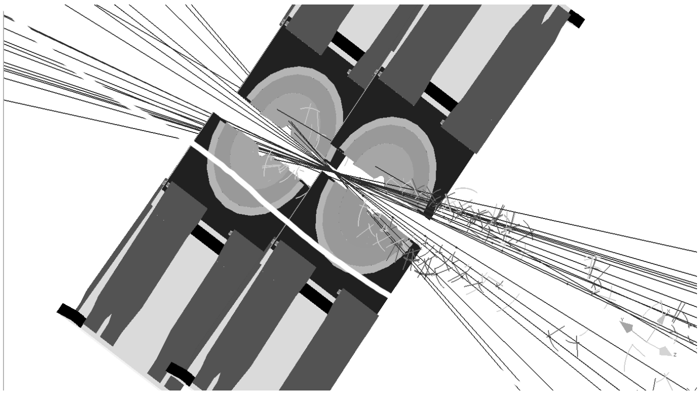

Figure 5: Event display image of a proton-proton collision event from December 2009. Hits and reconstructed tracks in the VELO are shown. Images of two modules in each VELO half are included.

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