Calibration and Performance Monitoring of the LHCb Vertex Locator

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Abstract. The LHCb experiment is dedicated to searching for New Physics effects in the heavy flavour sector, precise measurements of CP violation and rare heavy meson decays. Precise tracking and vertexing around the interaction point is crucial in achieving these physics goals. The LHCb VELO (VErtex LOcator) silicon micro-strip detector is the highest precision vertex detector at the LHC and is located at only 8.2 mm from the proton beams. The high spatial resolution (down to 4 microns single hit precision) is obtained by a complex chain of processing algorithms to suppress noise and reconstruct clusters. These are implemented in large FPGAs, with over one million parameters that need to be individually optimised. Previously [1], we presented a novel approach that has been developed to optimise the parameters and integrating their determination into the full software framework of the LHCb experiment. Presently we report on the experience gained from regular operation of the calibration and monitoring software with the collision data taken in 2011 by the LHCb experiment. Both the VELO performance and its impact on the physics results will be detailed.

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1. The LHCb Vertex Locator
The Large Hadron Collider Beauty detector [2] is a flavour physics detector, designed to detect decays of $b$- and $c$-hadrons for the study of CP violation and rare decays. In pp collisions at LHC [3] energies, $b\bar{b}$ production is primarily in the forward/backward direction. LHCb has been designed as a forward arm spectrometer, to exploit this fact.

The VELO consists of 42 modules placed along the beam direction, with the full length of the detector being approximately 1m. The mean interaction point is approximately 18cm from the first VELO module - the majority of modules sitting in the forward region. Figure 1(a) shows a cut-away view of the VELO. The modules can be seen in the centre of the tank, and in fig. 1(b) is a photograph of an individual module.

The VELO modules consist of two silicon sensors, R and $\phi$ (for radial and azimuthal measurements respectively), and 32 Beetle chips[4] bonded to a TPG (Thermal Pyrolytic Graphic) hybrid. This, in turn, is mounted onto a rigid carbon fibre pedestal. Kapton cables are used to connect the modules to the Repeater boards. A cooling block is attached to one side to cool the module to approximately $-10^\circ C$ when fully powered. Bi-phase CO$_2$ is used as the coolant. The modules are positioned to within 8.2mm of the beam and are retractable.
to protect the sensors, as the aperture of the LHC beams is a lot larger during injection and ramping.

The VELO is read out via a Beetle front-end ASIC [4]. The Beetle samples at the LHC bunch crossing frequency of 40MHz. For the VELO, the front-end of the Beetle is bonded to 128 silicon strips and the analogue readout is multiplexed onto 4 ports (also referred to as analogue links) of 32 channels/strips. The chip accepts trigger rates up to 1.1MHz. This analogue data is amplified via a set of repeater boards [5] situated on the outside of the VELO vacuum tank. From there the data is transmitted over 60m differential copper cables to the TELL1 data acquisition board for digitisation and zero-suppression.

2. The TELL1 data acquisition board

The TELL1 [6] is a multi-purpose readout board for LHCb (photograph: fig. 2(a)). It is equipped with a Credit-Card PC which communicates with the Experimental Control System, and a Gigabit Ethernet card for sending the data to the High Level Trigger farm. For the VELO, it consists of four analogue receiver (ARx) cards for analogue to digital conversion. The digitised signals are processed by FPGAs on the board which zero-suppress the data. Zero-suppression (ZS) involves a series of algorithms designed to extract particle hits in the data from background noise. The TELL1 can also output the raw non-zero-suppressed (NZS) data from the detector for the purposes of calibration and testing. The zero-suppression also serves to reduce the data rate to a manageable level. Normal activity in the VELO at 1MHz equates to an output data rate of approximately 700Mbps. On the other hand, NZS data would produce a rate greater than 20Gbps from a single TELL1, exceeding the limitations of both the TELL1 output rate (4Gbps), and other elements of the DAQ chain. The algorithms for zero-suppression in the current TELL1 firmware are as follows:

- **Pedestal calculation** equalises the baseline between channels.
- **Common ModeCorrection** subtracts any common mode noise shared across channels on the

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Figure 1: (a) VELO vacuum tank housing 42 VELO modules. A 300µm aluminium foil separates the VELO vacuum from the primary LHC vacuum. Each VELO half is moved out to 29mm from the beam line during injection. (b) Photograph of an individual VELO module.
same analogue link. There are two common mode correction algorithms - the first subtracts a mean value from all channels, and the latter performs a linear fit and subtracts the result.

- **Front-end cross-talk correction** compensates for effects of cross-talk due to the front-end ASIC.
- **Cable cross-talk correction** compensates for the effects of cross-talk between readout cables.
- **Channel Reordering** rearranges channels into their geometrical order on the sensor.
- **Clusterisation** determines for each channel if it passes the particle-hit thresholds. A cluster is generated for hits above a (high) seeding threshold. Neighbouring hits are added to the cluster if they pass a lower inclusion threshold, producing a multi-strip cluster up to four strips wide. The single hit resolution of multi-strip cluster is 1/8 of a strip pitch (compared to unity for a one-strip cluster).

3. **Vetra - TELL1 Calibration and Emulation**

In order to determine the accuracy and performance of the TELL1 data acquisition board, the algorithms encoded into the FPGA firmware running on the TELL1 were also coded in a software framework known as Vetra [7]. The initial goal of this project was to emulate each of the algorithms on the TELL1, although it has been extended substantially beyond its original design (cf. Sec. 4). Figure 2(b) shows a simplified schematic of the NZS and ZS data processing.
The default operation of the TELL1 is to read out physics-quality ZS data for further processing by the trigger farm.

To achieve “physics-quality” data, the TELL1 must first be calibrated and optimised. Vetra uses NZS data to determine the configuration constants that need to be uploaded to the TELL1. These constants include, for example, pedestals for each read-out channel, such that all the data from the detector is set to the same baseline. The effect of the pedestal subtraction algorithm after calibration is shown in fig. 3. The determined constants are stored in two distinct databases:

- **VELOCOND** - a collection of XML files stored in an SQLite database. This database is used by Vetra for offline data quality monitoring.
- **PVSS Recipe** - a database mapping constants to their memory registers on the TELL1. PVSS recipes are used by the LHCb Experimental Control System to apply the configuration constants to the detector hardware for data-taking.

Post-configuration, the NZS data from the TELL1 is passed through the Vetra TELL1 emulation chain. The same configuration parameters that have been applied to the TELL1 are also applied to Vetra via the VELOCOND database. Vetra produces an emulated ZS bank which is bit-wise compared to the (real) ZS bank from the TELL1 (outlined in fig. 2(b)). Any discrepancy indicates that the TELL1 firmware is not performing in the manner that is expected. In both Vetra, and on the TELL1, the various ZS algorithms can be activated or deactivated, allowing each step of the zero-suppression chain to be examined. In doing so, tracing the source of flaws in the firmware becomes a much more tractable problem.

3.1. Parameter tracking

Recent improvements have been made to the VELOCOND offline database - Intervals of Validity have been added to the database, meaning many parameter sets can be stored in the same database, and each are timestamped. For data analysis, the timestamp of the data determines which parameter set should be used. Versioning is also being added to the VELOCOND database and the PVSS TELL1 recipe used online, such that different parameter sets can be easily tracked. This is particularly useful for testing new TELL1 firmwares, and provides an instant check between the two separate databases. Software is being developed to read back
Figure 4: Screenshot of the VELO monitoring GUI used to regularly inspect plots to assess data quality. Primary Vertex distributions are shown in blue/solid. Small shifts can be seen with respect to the reference (black points), indicating a shift in the luminous region.

the configuration parameters directly from the TELL1 hardware and store them in the same VELOCOND database format. This allows for a cross-check that the parameters applied to the TELL1 match those in the databases produced in the calibration step.

4. Data Monitoring
Vetra has been extended to include an offline data monitoring suite. A series of monitoring tasks have been developed to analyse both ZS and NZS data from the detector. Critical parameters such as overall occupancy of the detector, number of error banks (which indicate a problem at the front-end, such as a desynchronisation of the Beetle chips), cluster distributions, etc., are matched to expected values/trends. Such values are monitored both online and offline to identify problems that may affect the quality of the data taken. A visual analysis of the data is performed for each fill. Figure 4 shows the VELO monitoring graphical user interface (GUI) which is used to regularly check for problems in the detector. Histograms of primary vertex (PV) positions are shown. The primary vertex position is determined from tracks reconstructed from hits in the VELO. The resulting histogram of many PVs is compared to a reference and deviations between the two are recorded for each LHC fill.

Special data sets are taken for calibration and monitoring on a regular basis, with specific analysis routines developed for each. IV scans (current versus voltage) are taken on a weekly basis to monitor the leakage currents of the sensors as they suffer more radiation damage due to the intense radiation environment of the LHC. Depletion voltages are monitored with monthly HV scans, where the overall noise in the sensors is monitored as a function of voltage. And lastly, charge collection efficiency scans are taken approximately three to four times per year to monitor the evolution of the performance of the detector as radiation damage accumulates.
5. Summary
Calibration and monitoring of the VELO detector is performed on a regular basis. The behaviour of the TELL1 firmware has been confirmed as well understood by the Vetra TELL1 Emulation software. New calibration monitoring allows tracking of different configuration parameters, and association of these parameters to respective data sets. Data monitoring in the Vetra software suite has provided invaluable information on the evolution of the performance of the VELO detector with accumulated radiation damage at the LHC.

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