Commissioning the LHCb VErtex LOcator (VELO)

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The LHCb VErtex LOcator (VELO) is designed to reconstruct primary and secondary vertices in b-hadron decays. It is a silicon microstrip detector situated closest to the interaction region. It provides fast tracking information to the trigger system. The design of the detector and the commissioning of its various sub-components are described here.

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1. Introduction

The LHCb experiment[1] is a single arm spectrometer designed to study heavy flavour physics in decays of B-mesons It will constrain the unitarity triangles of the CKM matrix[2] by measuring CP-violation and probe for physics beyond the Standard Model by studying rare decays.

The LHCb VErtex LOcator[3] (VELO) is required to reconstruct primary and secondary interactions close to the beam in an extreme radiation environment. It is the primary tracking detector of the experiment and provides fast reconstruction information to the trigger. An additional requirement placed on the VELO by the LHC is that the detector has to be 30mm from the interaction region during the injection of the beam.

2. Vertex Locator

The LHCb Vertex Locator is shown in figure 1 and consists of 42 modules arranged perpendicular to the beam around the interaction region. It is divided into two retractable halves contained in a secondary vacuum ($<10^{-4}$mbar) and is separated from the primary vacuum ($<10^{-8}$mbar) by a 300μm aluminium foil. The maximum allowed differential pressure is 5mbar. The shape of the foil is corrugated such that the halves partially overlap when the detector is in its closed position at a distance of 5mm from the interaction region.
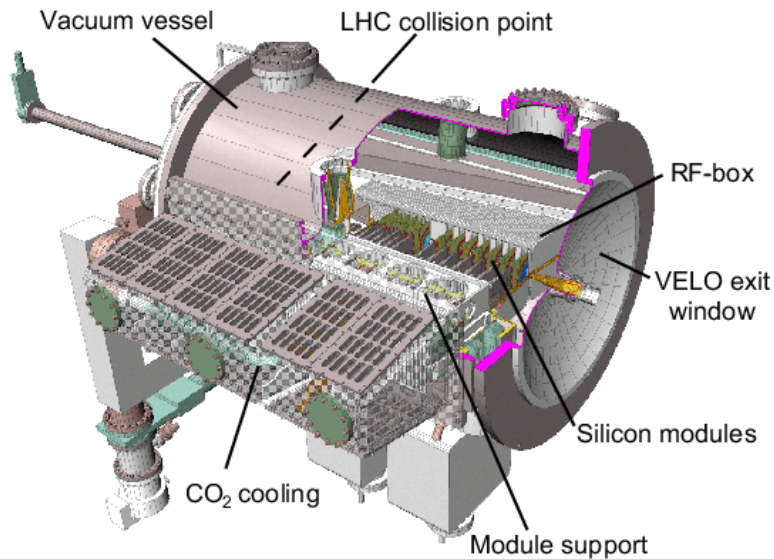

Figure 1: Overview of the VELO system.

A VELO module consists of two 300μm thick semi-circular silicon sensors with 2048 strips; one measures the radial co-ordinate, R, and the other measures the azimuthal angle, Φ. The sensors are n+-on-n oxygenated silicon which are optimised to operate in the non uniform radiation environment close to the LHC beams. The maximum fluence is expected to be $1.3.10^{14}$n$_{eq}$/cm^2 in the innermost region for a luminosity of 2fb^{-1}. This corresponds to one normal year of operation.

The R-sensor is segmented in $45°$ quadrants and has a pitch that increases linearly from 40μm at the inner radius (8.13mm) to 101.6μm at the outer radius (42mm). The Φ sensor has radial strips

with a small stereo angle split into 683 short inner strips and 1365 long outer strips. The pitch of the Φ sensors varies from 35 to 101μm and the strips in each region are skewed in opposite directions by $10°$ and $20°$.

The sensors are mounted on a double sided hybrid consisting of a substrate with a Thermal Pyrolytic Graphite (TPG) core cloaked in carbon fibre onto which a kapton circuit is laminated on each side. The 2048 strips are routed via a double metal layer on the sensor to the hybrid where there are 16 Beetle front-end chips[4]. The nominal power consumption of 20W is carried away from the front end chips by the TPG. A two-phase CO_2 system[5] keeps the sensors at $-7°$. The various components of a module are shown in figure 2.
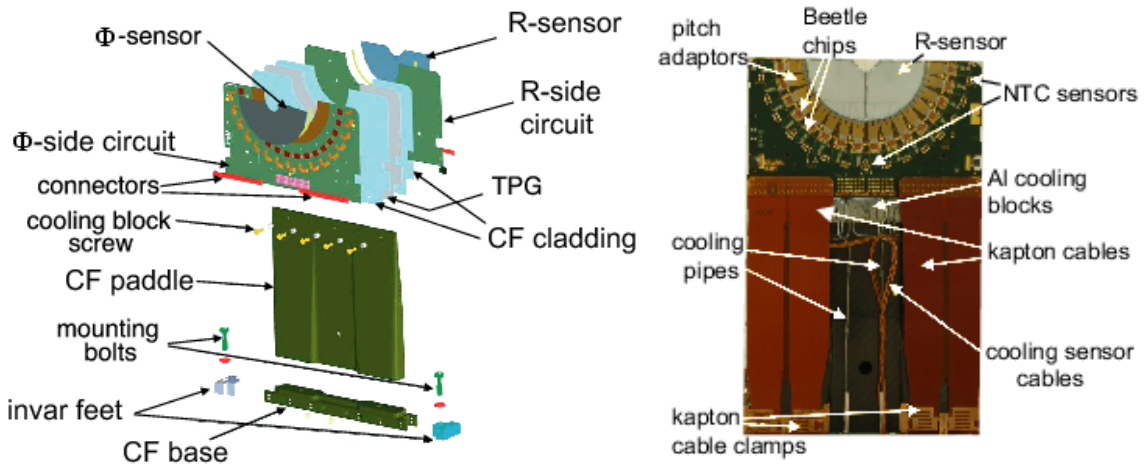
Figure 2: Principle components of a module (left) and a photograph of a mounted module (right). The temperature of the hybrid can be monitored at two different positions using NTC resistors.

The modules and mechanics were designed to minimise the amount of material in the geo-metrical acceptance. The average radiation length seen by particles passing through the VELO is shown in figure 3 (a) as a function of azimuthal angle and pseudo-rapidity. The average contribution to the total radiation length for each component of the VELO is shown in figure 3 (b). The average thickness of the VELO is 17.5% of a radiation length where the largest contribution comes from from the RF-foil. The shape of the foil was chosen to minimize the material between the interaction point and the first measuring plane.

## 3. Installation and Commissioning of Readout Electronics

The VELO electronics chain for one silicon sensor is shown in figure 4. A description of its various sub-components and the tests performed during installation are given in the following sections.

3.1 Repeater boards

Each sensor is connected via kapton cables to a repeater board located outside the vacuum tank. Each board contains four driver cards which send the analogue data signals across 60m
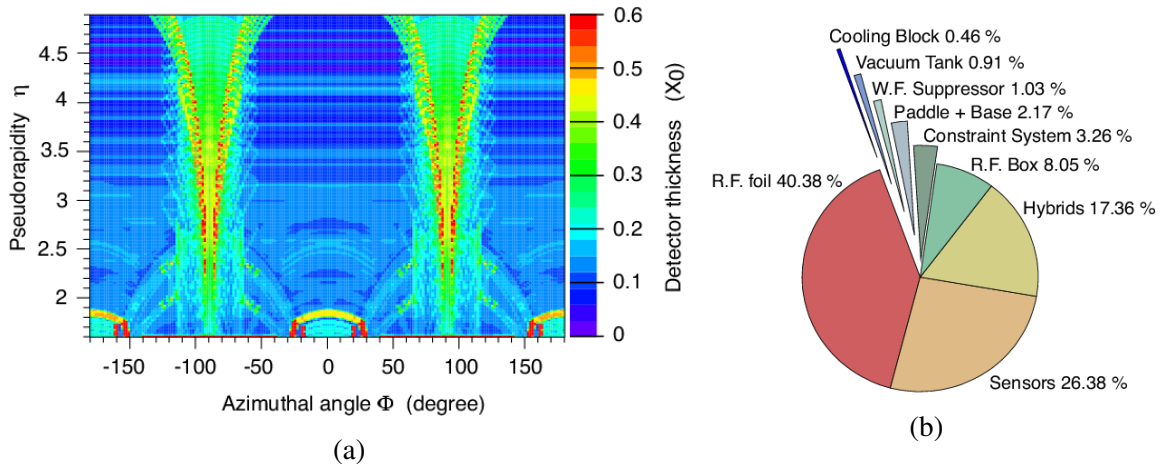
Figure 3: (a) The average radiation length seen by particles passing through the VELO as a function of azimuthal angle, ϕ, and pseudo-rapidity, η, with $1.6 < \eta < 4.9$. (b) The average contribution to the total radiation length from each component of the VELO.
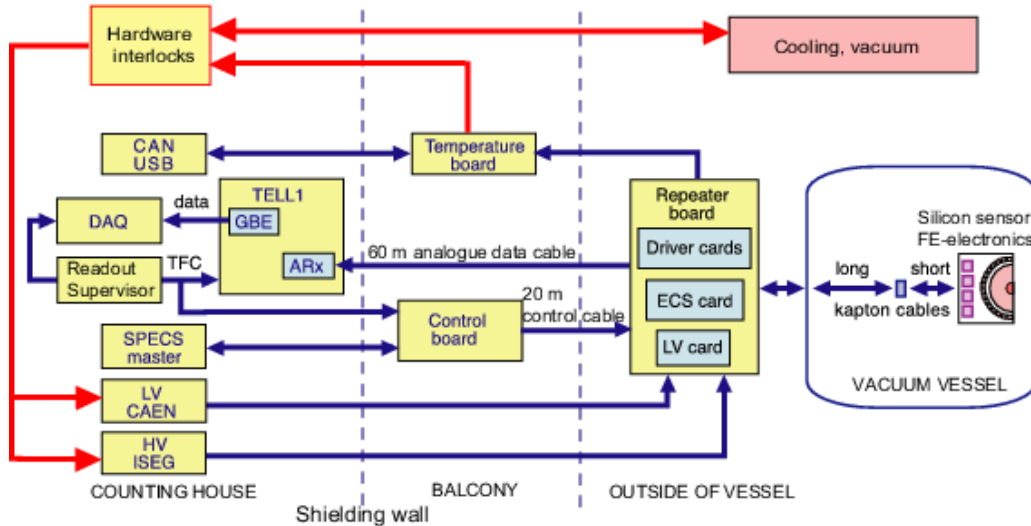
Figure 4: The VELO readout chain for one side of one module.

cables to the digitiser card; a low voltage card to power the driver cards and the Front End chips; and an Experimental Control System (ECS) card to communicate with the control boards (see next section). The repeater board receives and transmits differential signals, eg data, Timing and Fast control (TFC) and FE chip configuration, to the electronic circuits of the hybrid. Monitoring signals are also sent out to the detector control system.

3.2 Control Boards

The control board[9] distributes timing signals and fast commands from the Readout Supervisor to the L0 electronics. They distribute commands via I^{2}C from the Experimental Control System to Beetles chips on the hybrid and control the low voltage distribution for the repeater boards. Each control board supports six hybrids. The control boards are located on a platform in the cavern 25m

away from the vacuum tank.

3.3 Low Voltage (LV) System

The low voltage system provides the power to the LV card on the repeater board. This in turn provides the power to the front end chips, four analogue driver cards and an ECS card mounted on the repeater board. The LV system is a multi-channel power supply system based on the CAEN EASY3000 Embedded Assembly System[6]. The power to four repeater boards is provided by one A3009 12 channel 8V board. The boards are housed in crates in the counting room 60m away from the detector and each channel has a sensing circuit to compensate for the voltage drop across the cables.

The boards were tested to check the operation and linearity of the supplies before installation. The number of times an A3009 module had to be returned to the manufacturer under guarantee is shown in figure 5 (a).

(a)   (b)
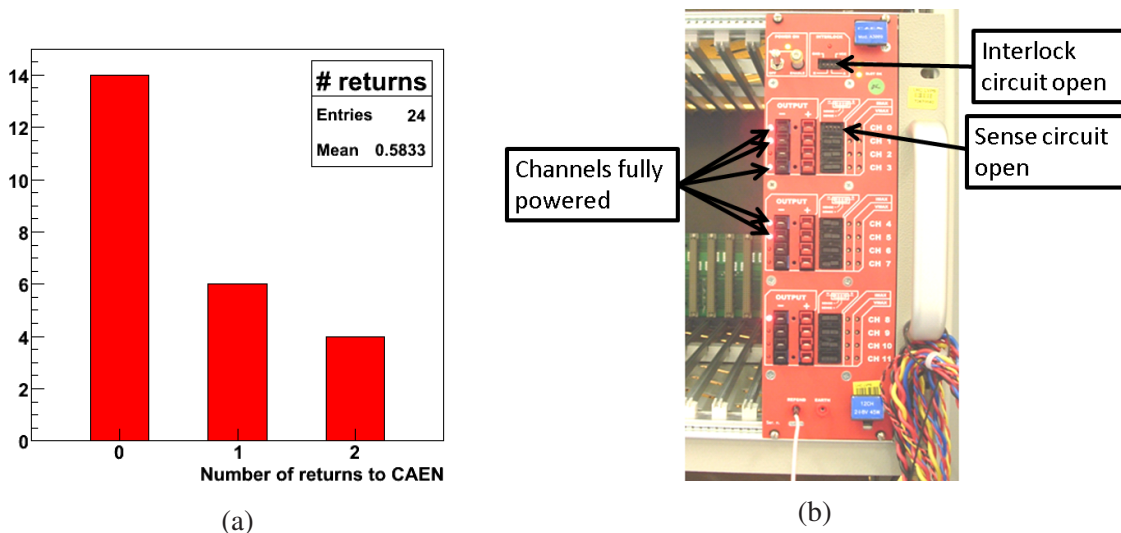
Figure 5: Problems encountered during testing of Low Voltage system. (a) shows the number of times a CAEN A3009 module was returned to the manufacturer under guarantee and (b) shows the CAEN module is powered when the interlock was fired.

Various safety tests were performed. A problem was discovered in the firmware of the power supply boards. It was found that the module could remain powered when communication between the board and the mainframe that controls it was lost. Figure 5 (b) shows one board powered with the interlock circuit open. This state could lead to rapid heating of the hybrid and a firmware fix was provided by the manufacturer.

3.4 High Voltage System

The high voltage system provides the bias voltage to the sensors. The system uses six ISeg EHQ F607 n-F modules[1] each of which can control up to 16 sensors. The modules are housed in

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[1]Manufactured by ISEG Spezialelektronik GmbH.

a non-interruptible power supply 60m from the detector. A detailed description of the system is available in [7].

The system was tested in four parts; normal operation of the high voltage system; verification of its stability under operation; discussion of its behaviour in failure modes; and details of operation at low voltage. The results are described in detail in [8]. An example problem found with the modules was that when a second channel in the module was started to ramp to its nominal voltage any other channel that was in the process of ramping jumped to its target voltage. The OPC server would crash and have to restarted at least once a week. These problems were fixed after 5 iterations of the OPC server.

3.5 TELL1 Boards

The TELL1 readout board[10] collects analogue data directly from the Beetle chips. The data from one sensor is digitised by four analogue receiver cards (A-Rx) on the board. One A-Rx card provides 16 channels of 10-bit ADCs which sample the analogue data from 4 Beetle chips at 40MHz. The TELL1 then performs data processing in four pre-processing FPGAs. The steps in the data processing are pedestal subtraction, removal of cross-talk, channel re-ordering, common mode noise suppression and clustering. The zero suppressed data are then sent to the trigger farm.

The power consumption and the output voltage of the A-Rx cards were tested before they were mounted on the TELL1. The digital performance of the A-Rx cards was tested when they were installed in the counting house. The sampling time for each channel of the A-Rx cards was adjusted using phase programmable clocks to compensate for different cable lengths.

The uniformity of the TELL1s was tested using a dummy module[2], a repeater board, a control board and a full set of cables. The noise spectra for each TELL1 was studied to find problematic links and broken TELL1s. There were 17 boards with problems which prevented data taking and were repaired. Some of the boards had a problem with the vias[3] which caused them to break when thermally cycled.

3.6 Readout Slice Tests

The electrical components of each module position, referred to as a readout slice, were connected to the dummy module. A series of tests were performed: the optimal sampling point for the ADCs on the TELL1 was set to account for differences in the length of the readout cables; the connections between the repeater boards and the TELL1 were checked by injecting known patterns into the detector readout; and problematic channels and links were found by looking at the noise and pedestal spectra of the data. The various tests used in the commissioning of the data acquisition are described in [13]. Problematic readout boards were exchanged and sent for repair.

4. Commissioning of VELO

The modules were assembled in Liverpool before being shipped to CERN where they were mounted on the base plates of each half. The 2 halves were installed in the vacuum tank in October

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[2]The dummy module was a fully populated hybrid with no silicon sensor attached.

[3]Connections between the different layers of the TELL1 printed circuit board.

2007. During the assembly process the modules had six visual inspections, six metrologies, seven electrical tests and 4 vacuum tests.

The geometry of the VELO is such that it would be extremely difficult to commission the detector using tracks from cosmic rays. Final commissioning can only be made when real beam collisions occur in the interaction region. A study of the expected performance of the dectector was made using a test beam and it is described in the section 4.1. The commissioning of the detector after installation is described in section 4.2 and was performed using sensor noise studies when operating single modules, detector halves and the full VELO system.

4.1 Alignment Challenge and Detector Commissioning in Beam Test

In November 2006, a partially equipped VELO half was tested in a 180 GeV pion beam at the CERN SPS. A total of 10 modules were installed, together with a small scale cooling system, and different combinations of 6 modules were read out using the final readout chain. The software for data acquisition; detector control; track and vertex reconstruction; and online monitoring of the data were tested. More than 50 million events were collected in various configurations which included data taken from targets displaced from the beam axis to investigate the tracking performance of the VELO in the open position. The data was used to study the performance of the VELO alignment algorithm[11].

The signal to noise ratio of the R (Φ) sensors was found to be 20-24 (24-29) depending on the sensor region. The sensor resolution was found to be $9.5 + 0.3 \times (\text{pitch} - 40)\mu$m for R and Φ sensors for normal incidence tracks. A detailed description of the experimental setup and the performance of the alignment algorithm is given in [12].

## 4.2 Detector Commissioning after Installation

After the installation of the detector halves, data was taken in two configurations: firstly, the vacuum vessel was filled with ultra-pure Neon and the modules in one half were powered up individually and collectively; secondly, the detector volume was evacuated to a pressure of 10^{-5}mbar and the modules in both halves of the detector were operated collectively. In all tests the sensors were biased to 100V.

4.2.1 Single Module Operation

The first VELO module was operated under a Neon atmosphere in March 2008 using its final electronic readout chain. This test was repeated for all module positions in one VELO half before being repeated for the all modules in the opposite half. A typical distribution of the raw noise for R and Phi sensors is shown in figures 6 (a) and (b) respectively.

4.2.2 System Tests

The A side of the VELO was operated under Neon atmosphere with 15 modules fully powered on the 15th May 2008. A reduced cooling capacity under the Neon atmosphere meant that the modules were operated at 25°C. The C side of the VELO was operated for the first time on the 10th June. Many problems were found with faulty TELL1 boards. The broken boards were replaced and their failure was found to be due to a problem in the manufacturing process (c.f. section 3.5).
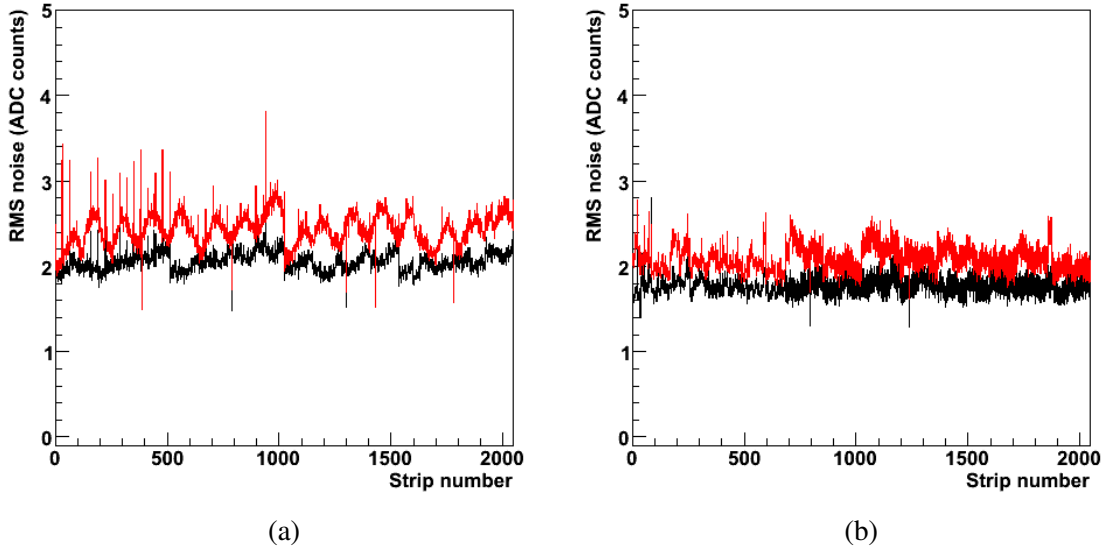
Figure 6: The raw noise (red) and noise after common mode subtraction (black) as a function of strip number for a typical (a) R sensor and (b) Φ sensor.

The VELO vacuum tank and the beam pipe were evacuated until a pressure of 10^{-5}mbar was reached in the secondary vacuum. The cooling was operated fully loaded at -25°C where the temperature of the modules was -5°C[4]. The full VELO system was operated under vacuum for the first time at 01:40 on the 28th June 2008.

An initial data sample of 300k non-zero suppressed events was taken. The number of fully operation channels was found to be 99.2%. A comparison of the noise for a single module when operated as part of the full system and standalone is shown in figure 7. There is a clear correlation between the noise values and only small variations were seen. The biggest difference in noise was found to be 0.045 ADC counts or 2.3%. No increase in noise was seen when all modules were powered simultaneously. The results from this study are described in [14].

5. Conclusions

The various components of the VELO were installed and extensively tested over the past year. There were problems with the delivery and the reliability of the Low Voltage modules. The High Voltage system suffered from instabilities in the OPC server which were fixed by the manufacturer. The TELL1 readout boards also suffered from problems in the manufacturing process and many boards had to be replaced and repaired. The full VELO system was operated successfully under vacuum for the first time. The number of channels which were fully operational was 99.2%. The VELO was ready for the first LHC beams.

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[4]The cooling was set to -5°C and the modules were operated at 14°C for all subsequent data taking to minimise the thermal cycling of modules during the commissioning.
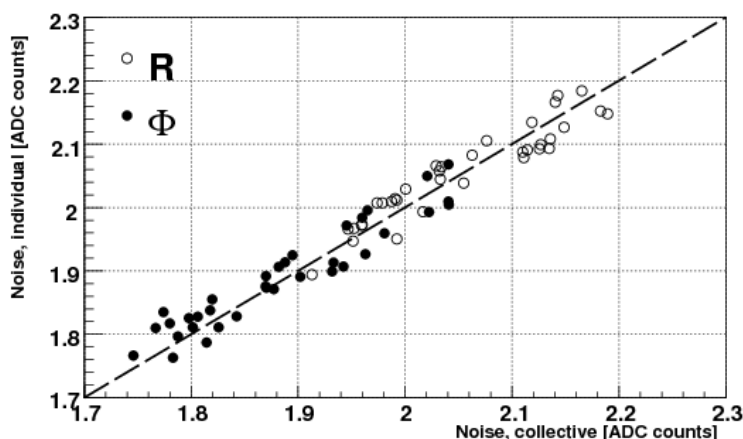
Figure 7: Comparison between the noise after common mode suppression for a module when operated standalone and as part of the full system.

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