PROCEEDINGS OF SCIENCE

Quality Assurance Tests of the LHCb VELO Modules

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The LHCb experiment has a dedicated vertex detector (VELO) to measure the particle's tracks close to the interaction point. This paper describes the main steps of the quality assurance tests performed during assembly, reception and installation of the LHCb VELO modules. Visual inspection, electrical tests, thermal tests and metrology measurements were made. A burn-in test of the modules was performed in a vacuum environment similar to that of the LHCb experiment. The signal to noise of the sensors was estimated to be $\sim$20.4±3.0 for R sensors and $\sim$22.4±3.0 for Φ sensors. The modules were tested up to 350 V and the leakage current of the modules did not exceed 20μA at any stage of the testing. Only 0.6% of channels were found to be noisy or not fully functional. The acceptable operating pressures of the modules in vacuum was also evaluated.

The 16th International Workshop on Vertex detectors
September 23-28 2007
Lake Placid, NY, USA

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1. Introduction

This article describes the LHCb VELO modules quality assurance tests. These tests were performed during the production, reception and installation of the modules. All the components were tested individually, during the module assembly and finally the complete modules were exercised under conditions similar to those expected in the LHCb experiment.

In section 2 the module production and the facilities used to test the modules are described. In section 3 the results of the quality assurance tests performed are presented and discussed. Section 4 reports the current status of the commissioning of the VELO. Section 5 concludes the report by providing an overview of the results of the tests performed and the other activities currently ongoing.

1.1 Vertex Locator

The LHCb VErtex LOcator (VELO) [1] will measure the position of the primary vertices with a resolution of 10μm in the transverse plane and 40μm in the beam direction. The VELO system is composed of a series of silicon detectors placed along the beam direction. There are two halves of the VELO detector. Each half contains 21 modules. The nominal distance of the sensors to the beam during operation will be 7mm. The halves can be retracted during LHC beam injection by 30 mm each side. Each module has two sensors back to back. The sensors are strip detectors with a half disk shape.

1.2 Module Description

The VELO module is composed of two silicon strip detectors attached on a hybrid which is glued to a carbon fibre support paddle. Figure 1 shows a production module. The LHCb VELO sensors are 300 μm n^+-on-n oxygenated silicon optimised for operation under the LHCb radiation environment. The maximum fluence was estimated to be $\sim 1.3 \times 10^{14}$ n_{eq}/cm^2 per year. The initial VELO modules will operate for a period of ~3 years at the nominal luminosity of 2×10^{32} $cm^{-2}s^{-1}$. The sensors come in two designs known as R and Φ. The strips on the R sensors have an annular shape, the strip length varies from 4.0 mm to 34.0 mm. The inter-strip pitch size varies from 40 μm to 92 μm. The strips on the Φ sensors have a radial geometry and are divided into inner and outer strips. The length of the inner and outer strips are 9.3 mm and 24.9 mm respectively. The pitch size on the Φ sensors varies between 37 μm and 98 μm.

The hybrid is a flexible kapton circuit which encapsulates a Thermal Pirolytic Graphite substrate wrapped by layers of carbon fibre to provide appropriate thermal conductivity allowing the removal of the heat from the front-end chips and sensors.

The electronic components are mounted and connected on the hybrid. The charge readout of each sensor is performed by 16 front-end ‘Beetle’ chips [2] whose location is indicated in Figure 1. The kapton cable connectors and temperature measurement points (NTCs) on the hybrid are also shown in Figure 1. The cooling interface, where the hybrid is glued to the paddle, has 5 captive screws to allow the cooling cookies to be attached. The paddle is a low mass carbon fibre piece attached to a base of the same material.

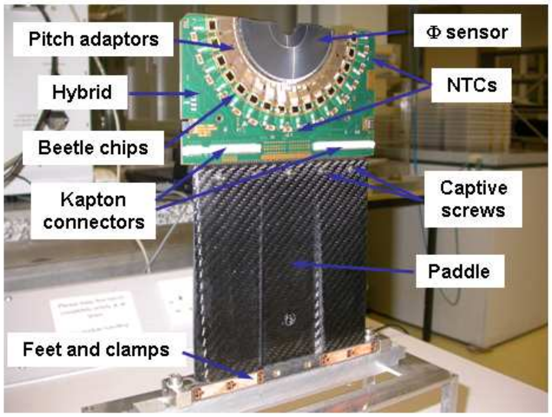

Figure 1: LHCb VELO module.

2. Module Production and Test Facilities

At each step of the production, reception and installation of the LHCb VELO module the components were carefully verified. The tests included quality checks of electronic components, metrology measurements of the hybrid and sensors and full visual inspection. The leakage current of the sensors was also measured in the different stages of the modules construction in order to verify their integrity. The production modules were electrically tested and fully operated. Kapton cables were also verified at different stages of the testing procedures.

The procedure of the VELO modules assembly started with the bare hybrids. Before the population of the hybrids with electrical components they were electrically tested, visual inspected and went for metrology measurements. The pitch adaptors and chips were then attached and a second visual inspection was performed. Then the back-end and front-end bonding of the chips was made, each bonding was followed by an electrical check.

After the chip bonding the silicon sensors were attached to the hybrids and a sensor-to-sensor metrology analysis was performed in order to spot any possible misalignment of one sensor with respect to the other. The sensors wire bonding was made and leakage currents measurements taken. To verify the connectivity of each bond a laser scan across the detector was performed with the module being readout. Combining the measurements of the electrical tests and the laser facility a list of bad channels was compiled for each module. Each of these bad channels were classified according to its problem. After the laser measurements a third visual inspection was done.

The pedestal and kapton cable attachments were the final steps to complete the modules production. Between the pedestal attachment, kapton attachment and vacuum test three sets of metrology measurements were performed in order to verify the integrity of the module after each one of these procedures. Once the modules production was complete they were operated in vacuum and noise data was acquired. A final visual inspection was also performed. The modules were then carefully packed and transported to the installation site.

To characterise the silicon sensors a set of facilities were used. A probe station was used to perform IC, IV and CV measurements on the bare sensors. A Smart-Scope metrology setup equipped with a camera and controlled via software was developed to measure the positions with $\sim 5\mu$m accuracy and check geometrical features such as the thickness and curvature of the sensors.

The Smart-Scope was also used to perform the metrology of the hybrids and measurements between the modules production steps. The precision of the relative positioning of the two sensors in the module was better than 10μm. The positioning of the centre of the R sensors with respect to its nominal position was performed with an accuracy smaller than 15μm in both x and y directions. A co-ordinate measuring machine survey of the module was performed after the module completion in order to check the placement.

An on-line database was used to keep all the information acquired during the tests at the module production site. This allowed fast access to the different measurement results by all members of the collaboration.

The final quality assurance of the modules was performed at the VELO system assembly site, prior to the installation of the modules on their base plate[3]. A reception, a microscopic visual inspection and a long-term burn-in procedure was performed. The reception procedure was intended to identify any visible damage that could have happened during shipment. The visual inspections were performed to verify the integrity of the modules before and after the burn-in procedure.

The burn-in setup was used to stress the modules, operating them in an environment similar to the LHCb experiment. The aim of the burn-in procedure was to uncover any possible weakness introduced in the modules or in its components during manufacturing. The modules were operated at pressure levels of the order of $\sim 10\times^{-5}$-$10\times^{-6}$ mbar for a period of around 24 hours. Temperature cycles between 30.0 °C to -30.0 °C were performed in vacuum. Measurements of noise and leakage current were taken before and after burn-in for comparison. The results obtained were compared to the measurements performed during the modules production[4].

Studies of vacuum operation of sensors were performed to identify the maximum bias voltages that can be applied as a function of pressure to the silicon sensors without risk of breakdown discharges occurring[5].

3. Quality Assurance Tests

All parts of the LHCb VELO modules were subject to a number of measurements to verify their quality and uncover any possible damage or failure. In this section the results of a selected subset of those measurements are presented. Some tests consisted of a single component evaluation and some were performed after the completion of the modules.

3.1 Sensors Testing

The silicon sensors characterisation measurements were performed. Electrical properties of the silicon such as the strip capacitance (with respect to the backplane) and depletion voltages were measured. The capacitance measurement was performed by applying high voltage to the backplane, all guard rings were left floating and the strip under test was close to 0V. Typical values for the strips capacitance vary between 20pF and 100pF. Figure 2 on the left-hand side shows the residuals distribution of the strips capacitance scaled by its rms value. The residuals capacitance are

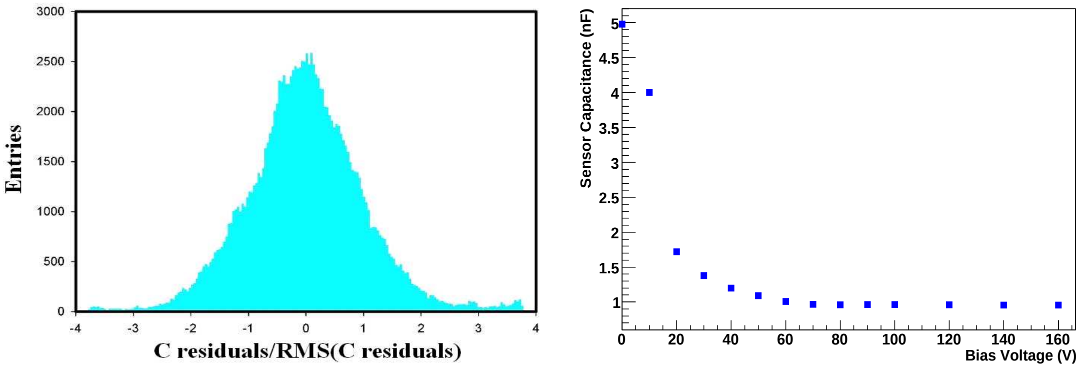

Figure 2: Pull distribution of strips capacitance (left) and sensor capacitance as function of voltage (right).

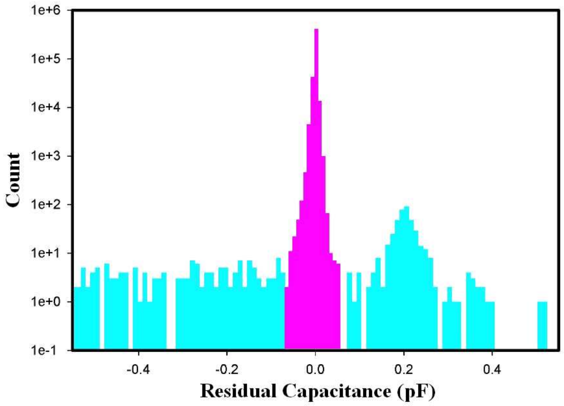

Figure 3: Pitch capacitance residuals.

defined as the difference between the measured capacitance and its expected value. The right-hand plot shows the total capacitance of a sensor as a function of the bias voltage applied.

3.2 Pitch Adaptors Testing

One specific example of a single electronic component quality check is that performed on the pitch adaptors, where a capacitance measurement was made to verify their integrity. A dedicated setup was build to probe each of the adaptors channels to check for good connectivity and look for possible breaks and shorts. Figure 3 shows the distribution of the residual capacitance indicating the components of the good channels, breaks and shorts. The residual capacitances are defined as the difference between the measured capacitance and the average calculated with all sensors. The residual capacitances for the breaks are distributed flat and most have negative values for the residuals. The capacitance behaviour of the shorted channels indicates an 50% increase on the capacitance resulting in a peak shifted to the right of the zero value of the distribution.

3.3 Visual Inspection

The aim of the inspection was to verify the physical integrity of the modules during their assembly and after transportation. This inspection consisted of a high resolution visual inspection over all the bonds, components and silicon on both sides of the module for any visual signs of damage. A few minor problems were found during the visual inspection of the final modules such as lifted bonds, pitch adaptor faults, silicon marks and surface debris.

3.4 Leakage Current Measurements

A dedicated analysis of the leakage current of the silicon sensors was performed. The aim of this analysis was to ensure the modules were produced with sensors with leakage current levels as low as possible and that the sensors were not damaged during the production steps. The leakage current of each sensor was measured at least 6 times. The first measurement was performed by the manufacturer of the sensors. Another measurement was performed with the bare silicon sensor, and it was measured again just after its attachment to the hybrid. Measurements were also performed before and after the burn-in procedure after the delivery of the modules in the reception site.

A long term high voltage test was performed with the bare sensors. The leakage current was measured before and after this procedure and an average increase of ∼6% was observed. Sensors with significantly worse performance were rejected. The leakage current was also compared before and after the long-term burn-in tests of the modules and an average increase of 30% was determined. This increase was expected since the modules had undergone thermal cycling stresses and long term operation. After all tests the leakage current of most modules did not exceeded 20 μA. Only one of the assembeled modules showed a significant increase of the leakage current, this was not installed in the detector but kept as a spare module.

3.5 Data Analysis

A full readout of the data from the module was taken at various stages of the modules testing to monitor the noise and compare between the different steps. Pedestal subtraction and common mode suppression algorithms were used to process the data. The typical value for the noise after applying these algorithms was ∼1.6-2.2 ADC units depending on the strip length.

These noise measurements were translated into equivalent signal-to-noise values. The magnitude of the header bits in the data had previously been calibrated in a test-beam to the signal observed in a test sensor. The header bits were then used in the burn-in data to determine the expected signal-to-noise values. The signal to noise ratio mean was found to be of the order of $20.4 \pm 0.03 \pm 3.0$ for the R sensors and $22.4 \pm 0.03 \pm 3.1$ for the Φ sensors. The first uncertainties are due the Gaussian fit and the second are due to the calibration uncertainties.

The noise data was combined with the visual inspection data and laser tests to characterise all the channels. The channels were classified as good, noisy, dead and shorted. Global cuts on the raw noise and common mode suppressed noise distributions were used to identify the dead and noisy channels. Noisy channels were also found when comparing the noise of a single channel with the average noise on the whole link of 32 channels (one output form a front-end chip). A percentage of 0.7% of bad channels were found for R sensors and 0.5% for Φ sensors. From these about 13% and 15% are shorted channels that can still be used.

3.6 Vacuum Studies

The operation of the LHCb VELO modules in vacuum was also investigated as a function of pressure. This allowed us to evaluate if there was a breakdown risk due to sparking in the gas during venting or pumping-down of the system.

A module was operated at different ranges of pressure and the bias voltage adjusted in order to measure the breakdown. As anticipated from Paschen's law, it was found that there is no risk of operating the modules at accessible voltages at he operating pressure levels or at atmospheric pressure. However, it was found that above 0.1 mbar breakdown was observed in air if the bias voltage applied is higher than 400-500V. Noise data was also taken and there was no evidence that the observed breakdown occurred over the sensors surface. As the VELO system will only be operated below 10^{-3}mbar no risk will occur to the system.

4. VELO Commissioning

The production and testing of the modules was completed and the LHCb VELO modules have been installed on their two VELO-half base plates in a clean room. During the installation of the modules similar tests were performed using the final system.

The electrical and thermal behaviour of the modules were very similar to those reported here. Metrology measurements were performed with the full halves and the modules positions were compared with the production measurements. No significant shift, deformation or damage to the modules and its components was observed.

The detector positioning system and cooling system were installed and commissioned in the experimental cavern. The VELO vacuum system was full exercised before the installation of the VELO halves in situ. The electronic readout boards were installed and all the low voltage and high voltage cabling completed.

The two VELO halves were recently transported to the pit and are being installed. Tests are currently being performed to commission the full electronic readout chain.

5. Summary

The LHCb VELO modules and its components were extensively tested. In this paper some of the testing procedures were described and results discussed. A total of 6 visual inspections, 6 metrology tests, 7 electrical tests including leakage current and noise data measurements, and 4 vacuum tests were performed in the production, reception and assembly of each module of the VELO system.

The LHCb VELO module performance has been found to match or exceed the expected quality in most parameters. The two VELO halves have been installed in the experimental cavern and the commissioning phase has now started. The VELO group is also undertaking development of replacement modules and technology studies for future upgrades.

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