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The Upgrade of LHCb VELO

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ABSTRACT

LHCb physics achievements to date include some of the world's most precise flavour physics measurements, including the CKM phase γ and the discovery of *CP* violation in the charm sector. These achievements have been possible thanks to the enormous data samples collected and the performance of the subdetectors, with the efficiency and precision of the silicon vertex detector (VELO) being a major contributor to this success. The experiment has been upgraded to run at higher luminosity, requiring 40 MHz readout. The VELO Upgrade modules are composed of hybrid pixel detectors and electronics circuits glued onto a cooling substrate, made of thin silicon plates with embedded micro-channels, allowing for the circulation of evaporative CO_2. The detectors are located in vacuum, separated from the beam by a thin aluminium box. The upgraded VELO is composed of 52 modules placed along the beam axis divided into two retractable halves. The design, production, installation and commissioning of the VELO Upgrade system is presented together with test results.

1. LHCb detector

The LHCb experiment is a single arm forward spectrometer [1] whose searches are heavily focused towards physics of hadrons containing b- and c-quarks. These rely on the reconstruction of secondary and primary vertices of hadronic interaction, which in turn requires a precise tracking system. In this respect the VErtex LOcator (VELO) represents the core of the experiment tracking system, with its modules located in the near vicinity of the p–p collisions. The experiment is upgraded to run at 2×10^{33} $cm^2 s^{-1}$ of peak luminosity, with an entirely new tracking detector which has been installed in the experiment and is currently being commissioned for Run 3.

2. VELO Upgrade

The VELO Upgrade [2] is a brand new hybrid pixel silicon tracker made of 52 modules divided in two retractable halves that go as close as 5.1 mm to the interaction point when closed. On each module 4 sensors are attached, 2 per module side, and each sensor is bump bonded to 3 ASICs (to form a so called "tile"). The detector offers enhanced tracking, with $\sim$ 41 M readout channels (0.2 M strips for the Run1-2 VELO [3]), higher readout rate (40 MHz against 1 MHz) and higher radiation hardness, being able to withstand 8×10^{15} n_{eq} cm^{-2} compared to 4×10^{14} n_{eq} cm^{-2} of the old detector. The VELO Upgrade module (Fig. 1) sensors and electronics circuits are glued onto a cooling substrate, which is composed of 500 μm thin silicon plates with embedded micro-channels that allow the circulation of evaporative CO_2 [4].

2.1. Micro-channel silicon substrate

The micro-channel substrate offers both structural support and cooling via 19 micro-channels chemically etched in the substrate itself running at 140 μm and 240 μm of depth into the substrate. This cooling substrate gives excellent thermal efficiency, and improves physics performance due to the low and very uniform material budget. The tiles are glued directly onto the substrate as well as the Front End (FE) and Control hybrids.

2.2. Glue interface

The glue interface between the ASICs and the substrate is crucial for the heat dissipation and the mechanical soundness of the module. The adhesive layer is in fact the only interface for the dissipation of the 30 W produced by the ASICs in vacuum in operation conditions. The glue chosen for the VELO assembly is Stycast 2850FT with catalyst 23LV [5], an epoxy resin with alumina filler, cured with a catalyst. This glue has excellent thermal conductivity (1.1 W/mK), good radiation hardness and good match with the coefficient of thermal expansion (CTE) of silicon. The glue is dispensed in patterns on the ASICs, which are then attached to the micro-channel substrate. The patterns have to satisfy the following parameters optimised after an intense R&D campaign: thickness of 80 μm for good heat transfer and absorption of thermal stress; evenness below 40 μm for uniform heat dissipation; coverage of at least 70% of the ASIC surface; no air bubbles trapping during pressing down to avoid expansion of air pockets with vacuum and heat; avoid glue spillage in-between ASICs as a noise increase

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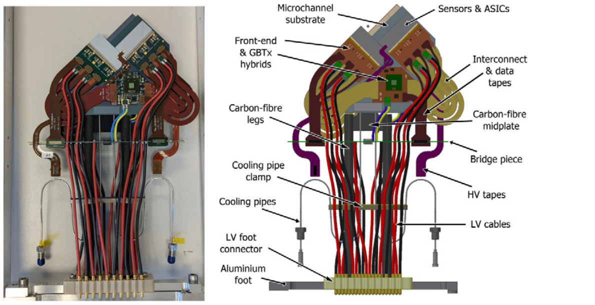

Fig. 1. Side view of a fully assembled VELO Upgrade module (left) and respective diagram (right) with highlighted components.

has been measured due to glue spillage in prototype modules. Once the layer parameters have been developed the glue pattern has been optimised to consistently meet the aforementioned parameters. The chosen solution is the "Double hourglass star" pattern (Fig. 2), where the star shape helps to avoid air trapping and the bowings on the perimeter reduce spillages in both directions.

3. VELO upgrade assembly

The VELO module assembly campaign has been carried out in two assembly sites: Nikhef in the Netherlands and The University of Manchester, UK. The assembly of the halves has been performed at Liverpool University, UK. Finally, the full detector commissioning is being carried out at CERN.

3.1. VELO upgrade module assembly

The assembly procedure can be divided into 4 main steps: the first one is the mechanical structure assembly, where the silicon substrate (with soldered cooling pipes and connector) is assembled with carbon-fibre legs and midplate and the aluminium foot (see Fig. 1). The second step is the tile gluing, described in Section 2.2. Hot air is applied to the patterns to remove humidity from the glue and tiles are pressed onto the micro-channel substrate. In the third step the 4 FE and 2 Control hybrids are glued to the silicon substrate. A silicone adhesive [6] is used in this step, which is deposited with the same robot dispenser. Finally, the interconnect, data and High Voltage (HV) tapes, Low Voltage (LV) cables, bridge piece (used to change the thickness of the cables to have thinner ones near the sensors), and LV foot connector are mounted on the module.

3.1.1. Metrology

After each assembly step careful metrology is performed to ensure every parameter is within specification. Grading is performed based on the adherence to the target parameters plus tolerances. Metrology includes substrate flatness measurement, tile flatness, glue thickness and tile alignment.

3.2. Modules validation

Completed modules are put in a vacuum tank and brought to −30° C to simulate operation conditions. They are tested for thermal and electrical performance before and after thermal cycling, and a grading is assigned to each test and to the overall module performance. The assigned grades are A, B, C, D or F; only A, B and C grades are detector quality, meaning their detection efficiency is > 99% and can be accepted for the experiment.

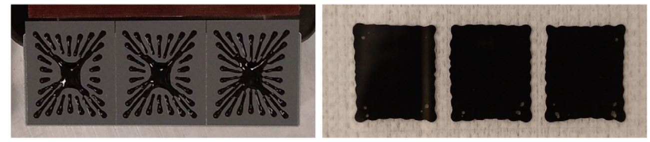

Fig. 2. Pictures of the optimised glue patterns before (on the left) and after being pressed down (on the right). Notice the square shape of the patterns after pressing.

3.3. Assembly campaign summary

The module assembly campaign has produced 61 modules at the moment of writing, 57 of which are detector grade (24 A-grade, 27 B-grade, 6 C-grade), 3 are D-grade and 1 is F-grade. The overall yield is > 93%. More spares modules are being assembled and qualified in Nikhef in case they are needed as replacement during the lifespan of the detector.

3.4. VELO assembly in Liverpool

The detector grade modules are shipped to Liverpool for the assembly in the detector halves. Each module is tested after reception and after installation into the VELO base. The electrical and thermal performance is assessed on each module individually while the cooling is applied to the full half. Leak tightness of the whole half is performed for the first time. Then, the measurement of the z position of the modules is performed both with and without cooling. This allows to infer the behaviour at cold temperature and check for potential twisting or warping.

3.5. Full detector commissioning at CERN

Complete halves are shipped to CERN for the installation in the experiment. Here each half is checked again for leak tightness and quick warm tests are run to check the electrical soundness of the modules: Bit Error Rate, high and low voltage test are performed at this stage. Metrology on all modules is performed again with a laser system. The halves are then lowered in the experiment. The detector has been successfully installed.

4. Conclusions

The new VELO Upgrade detector represents a significant leap forward from the previous VELO in terms of particle rate. The construction sites have produced 57 detector grade modules, a total of 52 modules have been successfully assembled in the two halves, installed in the experiment and are currently being commissioned.

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