PROCEEDINGS OF SCIENCE

Operational experience of current vertex detector at the LHCb experiment

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The experience of the LHCb Vertex Locator from first LHC collisions to the final weeks of operation in 2018 are presented. The radiation damage and effects on the operations, including the operational changes made to ensure the optimized physics performance, are discussed.

The 27th International Workshop on Vertex Detectors - VERTEX2018
22-26 October 2018
MGM Beach Resorts, Muttukadu, Chennai, India

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1. Introduction

The LHCb VELO detector [1] was designed to be a precise tracking detector surrounding the LHC beam to determine the trajectories of the particles produced in proton-proton collisions at up to $\sqrt{s} = 14\,\text{TeV}$. To achieve the required resolution the inner edges of the sensors were very close to the LHC beams. This required that they were operated in a very stringent radiation environment; the effects of the irradiation were monitored and where appropriate the operating conditions were adjusted.

2. LHCb Experiment

The LHCb detector [2] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles produced close to one of the proton beams. The detector elements that are particularly relevant to this analysis are: a silicon-strip vertex locator (VELO) surrounding the pp interaction region that allows c- and b-hadrons to be identified from their characteristically long flight distance. The LHCb detector has a vertically oriented dipole magnetic field and detectors after the magnets, which determine the momentum of particles, while the VELO determines their trajectory close to their production vertex.

The VELO is comprised of 88 silicon sensors, arranged as shown in Fig. 1 surrounding the interaction region. These strip sensors have a sensitive area from 8 to 42 mm from the interaction region, with 2048 strips on each. The two types of sensor measure the radial position and azimuth for all charged particles crossing them. Each detector half is retracted by 3 cm before each LHC injection to avoid the larger beam spread before acceleration to the collision energies, then closed around the luminous region each fill. The detector was designed to tolerate five years of operation at the nominal LHC luminosity; which they have more than experienced, having been in operation since 2009. The detector is being replaced with an upgraded version [3] during the two years of LHC shutdown starting in 2019.

3. VELO sensors

The 86 of the VELO sensors are n-in-n silicon, with a p-implant on the back to create the n-p junction diode which is reverse biased by the applied HV supply. The remaining two sensors are n-in-p sensors, to evaluate the operation of that technology choice. A p-spray implant is inserted between each n type readout strip, to improve the charge isolation between strips. Each strip is connected to a channel on the front end ASIC, the ASICs sit outside the sensors. To connect the ASICs to the strips two layers of aluminum traces provide the signal routing, allowing the electrons arriving after the passage of a charged particle to be detected. The first metal layer is along the center line of each strip, the second runs between the strip and the ASIC.

4. Effects of the radiation

The Large Hadron Collider (LHC) has operated in proton-proton mode delivering $1.1\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$, $2.1\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$ and $5.7\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$ to LHCb between 2009 and 2018.

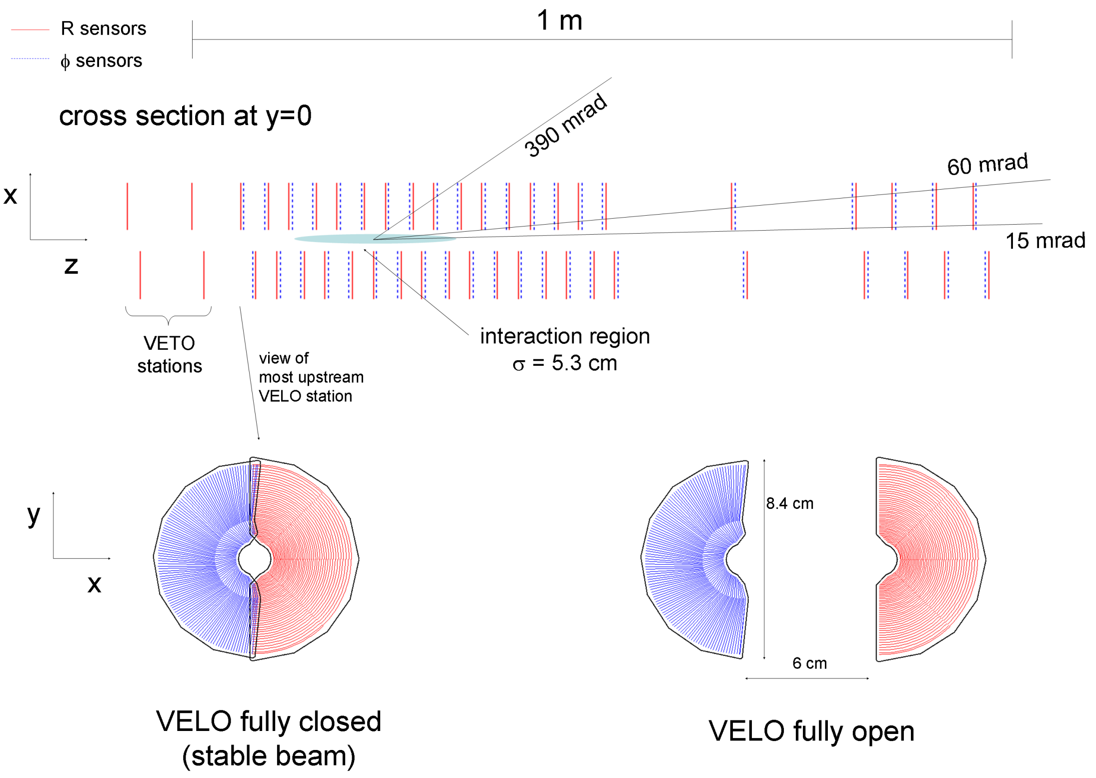

Figure 1: Layout of the VELO sensors along the beam line (top) and the sensor positions around the beam in operation and injection settings (bottom).

Small amounts of proton-ion and ion-ion data were also collected in dedicated data taking periods. The radiation dose delivered to the sensors varies exponentially from $(2-60)\times 10^{12}$ 1 MeV neutron equivalent per cm^2 as a function of radius and by a factor of two as the z position of the sensor changes [1]. The effects of the radiation damage [4] are thus very concentrated at the inner radius of the sensors. One effect seen is the increase in leakage current with time, see Fig. 2, which shows the current at a fixed voltage increasing due to the damage to the silicon.

Before significant irradiation there were a few sensors with significant surface currents, which rapidly reduced, then all of the sensors' currents evolved with the delivered luminosity. The occasional dips in current were due to beneficial annealing, as the cryogenics plant, which provides the liquid CO_2 to cool the sensors, was undergoing maintenance. The final dip on the plot in Fig. 2 on the right hand edge was a deliberately induced annealing at 20°C for 40 hours; using the remaining beneficial annealing before the final data taking later in 2018. The average sensor current dropped from $190\,\mu A$ to $150\,\mu A$ at 150 V, which was consistent with the prediction from the Hamburg model [5].

At installation the sensors were all fully depleted at the operational bias of 150 V, later as the inner edges of the sensors underwent type inversion the effective depletion voltage (EDV) increased and the sensors were operated at up to 400 V. The EDV definition adopted is the voltage

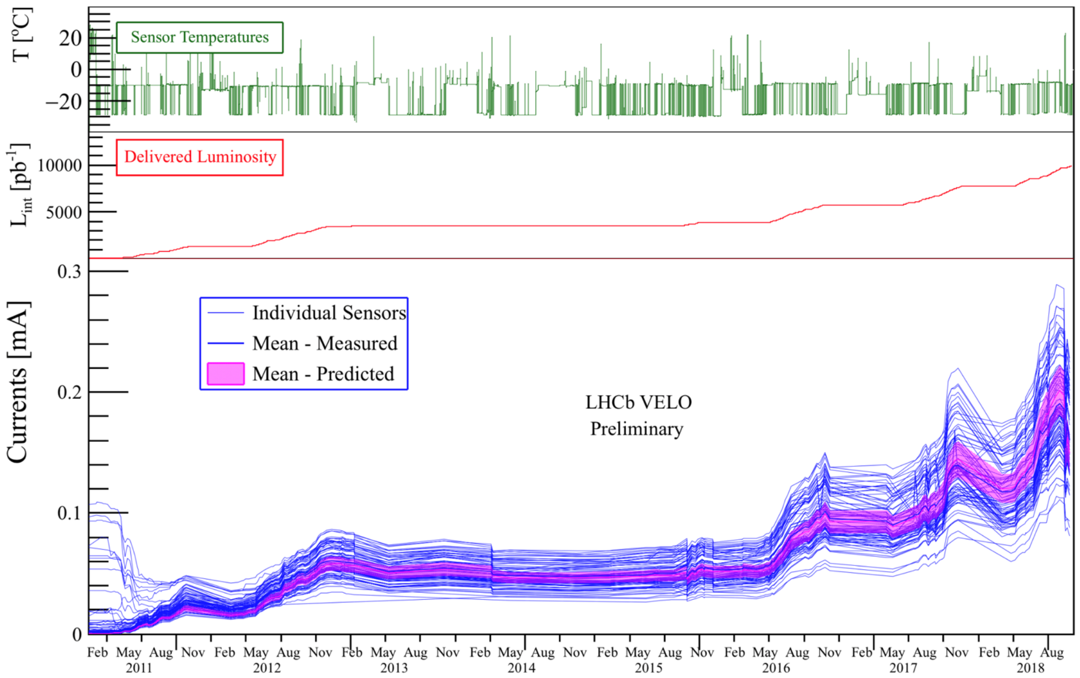

Figure 2: The operational temperature of the VELO (top), the delivered Luminosity (middle) and the leakage currents for all sensors and the average (bottom), verse the date. The pattern in the temperatures is that the sensors are at -8°C when powered and -30°C when quiescent, the liquid CO_2 cryogenics plant was run nearly continuously once the sensors had been first irradiated. In the period from spring 2013 to spring 2016 the LHC underwent a two year stop for accelerator upgrades and maintenance, the constant VELO leakage currents during the stop reflect the lack of irradiation during that period. After the restart the instantaneous luminosity delivered was increased over the following two years, as the LHC operation improved. The more rapid rise in currents from 2016 onward reflect the higher delivered irradiation.

which gives 80% of the charge collected for a fully depleted sensor. The EDV was monitored every few months, by short dedicated runs where the HV on sets of sensors was scanned and the collected charge evaluated using tracks extrapolated from the fully depleted sensors. Fig. 3 shows the state of the detector in September 2018, after the deliberate annealing. This is compared with the predictions from the Hamburg model [5] with and without annealing, the extrapolation in the Hamburg model was from a calibrated point in early 2016. Using the EDV scans the HV was adjusted on a per sensor basis to ensure full deletion across the full surface area. The deliberate annealing made sure that in the final year of running none of the sensors would require more than 450V to deplete, lower than the design HV of 500V. The prediction of the Hamburg model was that the deliberate annealing would reduce the maximum EDV from around 400V to 300V at the time of the annealing.

The VELO sensors have excellent signal to noise ratios, with noise averaging ~ 2 ADC counts or less for all strips, and the most probable values of the signal distributions are between 28 and 35 ADC counts for all sensors in 2018. So the global cluster finding efficiency (CFE) was excellent, contributing to the impressive physics performance. However, there were some anomalies in the CFE, with lower efficiencies in some areas. These effects were traced to effects of having the

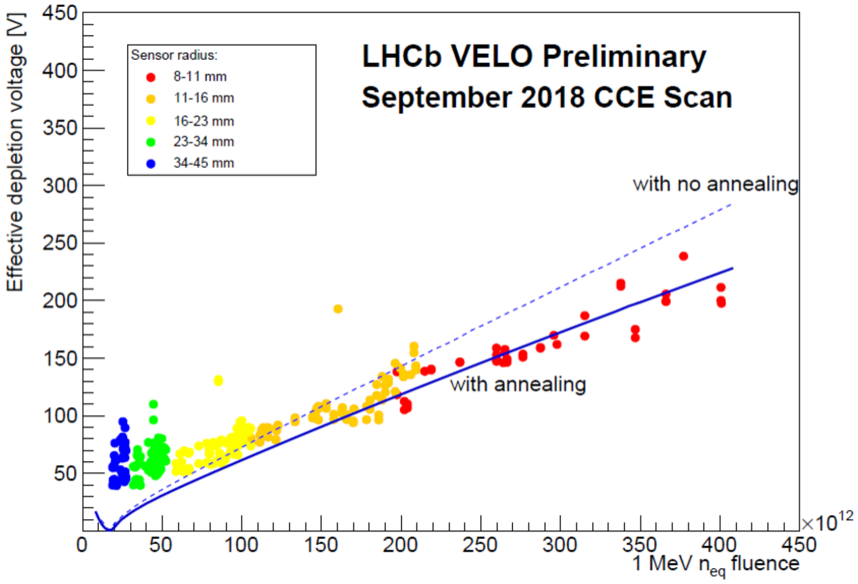

Figure 3: The effective depletion voltage verse fluence in bands of sensor radius The prediction of the Hamburg model with and without an annealing period is also plotted. The Hamburg model prediction line assumes that there are no surface current paths and a constant type inversion across the band, which underestimates the leakage current at low irradiation. The two n-in-p sensors have measured EDV higher than the n-in-n sensors for the same radiation delivered.

second metal layer readout lines crossing the strips in the R sensors. The effects were that signals were induced in the readout lines producing small phantom clusters in the low radius strips and also loss of charge from the main clusters at larger radius strips. The ϕ sensor geometries mean the inner strip routing lines could be routed on top of the outer strip readout lines; so did not experience these effects. As the outer part of the R sensors is crossed by more routing lines the effect was more significant there, and caused efficiencies issues only for near perpendicular tracks.

The effect was not seen initially in irradiated sensors, but appeared after more than a year of low luminosity data taking. It was then stable, has been added to the simulation and actively monitored. The effects on the tracks were small and corrected using the normal corrections between data and MC. The overall VELO performance was well monitored with the tracking efficiency and track resolution as expected from the detector design [6].

5. Conclusion

LHCb had an excellent data taking period between 2009 and 2018, with the VELO providing the precise tracking required for the physics program. It also demonstrated the effects of irradiation delivered over nine years, with the effects of very occasional annealing. The detector had some unexpected features but has still delivered the tracking performance required for the LHCb physics program. The spare detector built in case of an LHC beam loss damaging the installed detector has remained a display piece, and a replacement pixel detector is currently in construction for the LHCb upgrade.

6. Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); ANR, Labex P2IO and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom); Laboratory Directed Research and Development program of LANL (USA).

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