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Radiation Damage Monitoring in the Upgraded VELO Detector

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The upgraded VELO (VErtex LOcator) is a lightweight hybrid pixel silicon detector surrounding the interaction region of the Large Hadron Collider beauty experiment. It enables precise reconstruction of primary and secondary vertices using silicon sensors that provide high spatial resolution, fast response, and high-rate capability. The intense radiation environment of the Large Hadron Collider, however, degrades silicon sensors through effects such as increased leakage current, charge trapping, and shifts in depletion voltage. Understanding and quantifying this damage is vital for optimizing detector performance and planning future upgrades. This work presents a data-driven study of radiation damage in the upgraded VELO. By correlating detector hits with predicted fluence, it refines predictive models of radiation effects and supports the development of long-term operational strategies for silicon vertex detectors.

topics: silicon vertex detector, hybrid pixel detector, radiation damage, particle fluence

1. Introduction

Silicon sensors play a central role in particle tracking due to their high spatial resolution, fast response times, and good radiation tolerance. At the Large Hadron Collider (LHC), however, prolonged radiation exposure degrades their performance, threatening detector longevity and data quality. Understanding this damage is crucial for designing and upgrading detectors. This work summarizes observed radiation damage and its effects on sensor performance, and discusses methods used to monitor and predict such damage. Simulation-based approaches (primarily using `FLUKA` and `Geant4`) and data-driven techniques based on VELO (VErtex LOcator) hit information are compared, highlighting how their combination improves fluence estimation and ensures reliable detector operation under high-luminosity conditions.

2. LHCb spectrometer and VELO detector

The Large Hadron Collider beauty (LHCb) detector is a single-arm forward spectrometer ($2 < \eta < 4.5$) [1], focused on heavy-flavor physics, including searches for new physics, charge-parity (CP) violation, and rare b- and c-hadron decays [2]. The Vertex Locator (VELO) situated near the interaction point provides precise vertex measurements [3]. Momentum is measured with a precision of 0.5–1.0% using tracking stations around a 4 Tm dipole magnet, and particle identification uses ring-imaging Cherenkov (RICH) detectors, calorimeters, and muon chambers. The schematic of the LHCb spectrometer is shown in Fig. 1a (see also [4]).

The upgraded VELO has 52 modules with 55 μm hybrid pixel sensors positioned 5.1 mm from the beam. Radiation-tolerant VeloPix ASICs (up to $\sim 8 \times 10^{15}$ $\mathrm{n_{eq}/cm^2}$) handle rates of 900 MHz per chip, producing 2.85 Tbit/s. Evaporative $\mathrm{CO_2}$ cooling in silicon microchannels removes up to 30 W per module, keeping sensors below -20°C while minimizing material budget [5]. Half of the VELO detector displaying the modules' front hybrid is shown in Fig. 1b (see also [6]).

3. Radiation damage in silicon sensors

In Run 2 (2015–2018), the innermost VELO silicon sensors were only 8.2 mm from the LHC beam, exposing them to intense, non-uniform radiation with fluences of up to $\sim 4 \times 10^{14}$ MeV $\mathrm{n_{eq}/cm^2}$. Radiation damage introduces lattice defects that increase leakage current, alter effective doping concentration, and reduce charge collection efficiency (CCE). These effects accumulate over time,

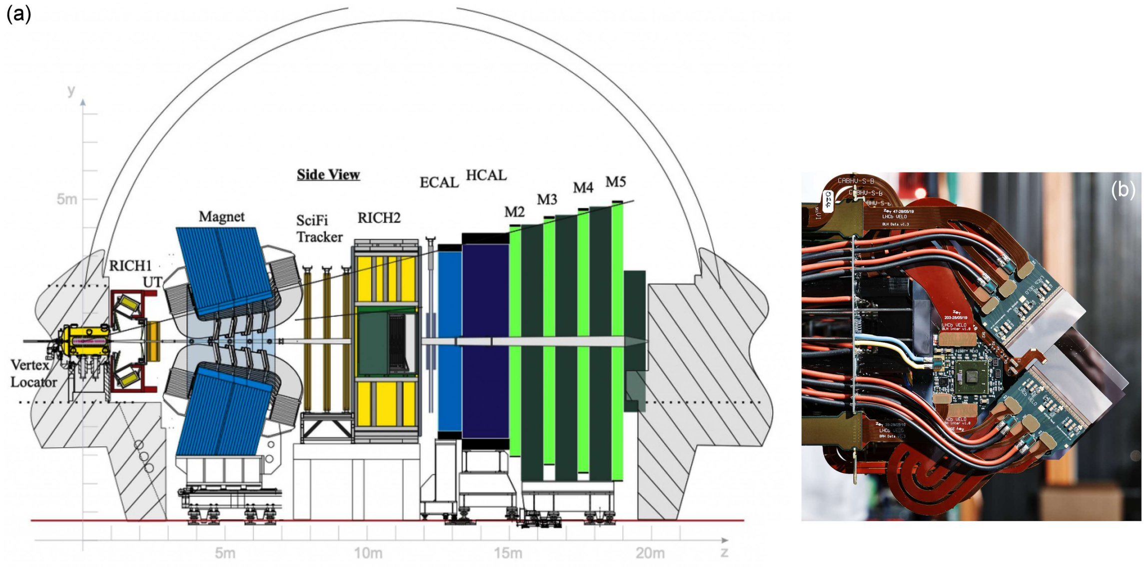

Fig. 1. (a) Schematic of LHCb for Run 3 [4] and (b) half of the VELO showing the front hybrid of the modules [6].

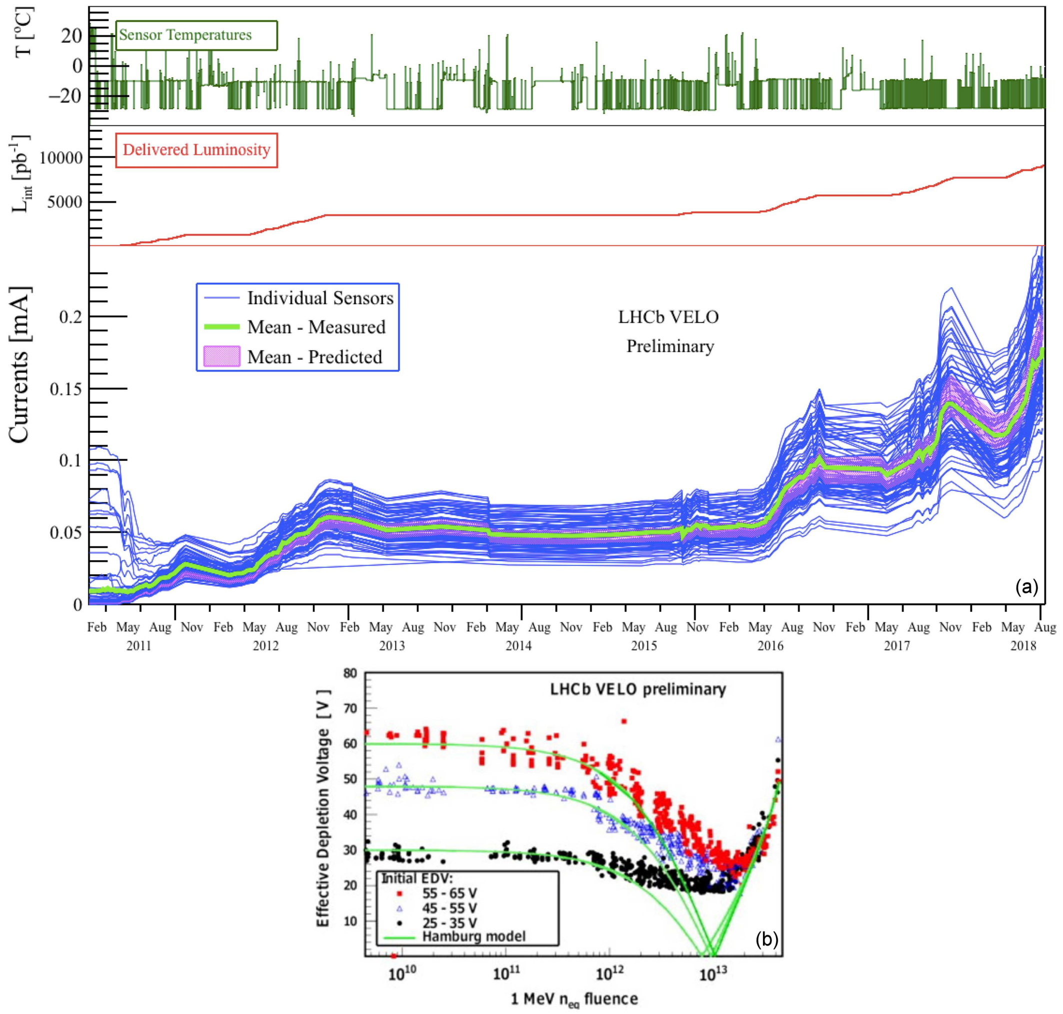

Fig. 2. (a) Time period vs leakage current, luminosity, and temperature [7] (from bottom to top, respectively). (b) Change in effective depletion voltage with the increase in neutron equivalent fluence (n_{eq}) [8].

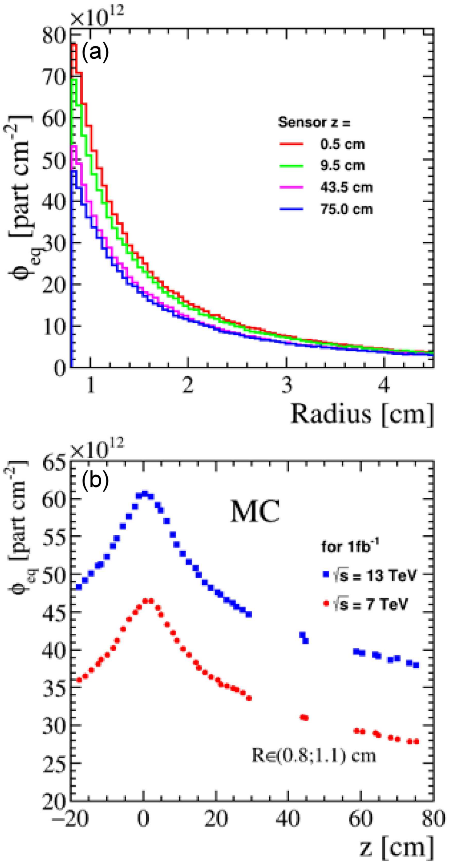

Fig. 3. FLUKA-simulated particle fluence in LHCb: (a) radial dependence with maximum at sensor tips per 1 fb^{-1} [7], (b) dependence on the z-position of the sensors for two collision energies, $\sqrt{s} = 7$ and 13 TeV, with an average radial position $R \in (0.8\text{–}1.1)$ cm.

requiring continuous monitoring and bias voltage adjustments. LHCb employs three complementary methods: current–voltage (I–V), current–temperature (I–T), and CCE scans, ensuring stable detector performance [7].

Leakage current rises approximately linearly with fluence and thus with delivered luminosity, while remaining stable during shutdowns, as shown in Fig. 2a (see also [7]). The effective depletion voltage (EDV) evolves with fluence, as shown in Fig. 2b (see also [8]). The n^{+}-on-n sensors first undergo type inversion, and EDV decreases before increasing roughly linearly due to radiation-induced defects. Results align well with the Hamburg model, which also accounts for annealing effects [8].

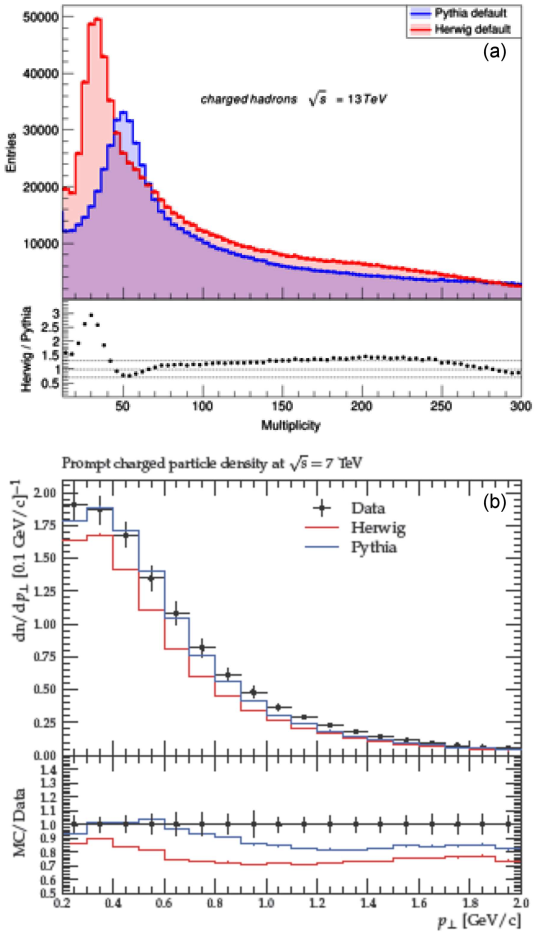

Fig. 4. Comparison of (a) Pythia and Herwig simulation results of charged particle multiplicity at $\sqrt{s} = 13$ TeV and (b) Pythia and Herwig simulation results and LHCb data of p_T distribution at $\sqrt{s} = 7$ TeV [9].

4. Predictions of radiation damage

Radiation damage in LHCb arises from prompt particles, secondary interactions, and radionuclide decay. Direct fluence measurements are limited by geometry and detector coverage, making simulations essential for estimating fluence and annealing strategies.

Both Geant4 and FLUKA are used, with FLUKA being preferred due to its validated low-energy neutron modeling, combinatorial geometry, and ongoing updates to include detailed LHCb detector configurations. Simulations indicate strong radial dependence of fluence, with sensors nearest the interaction receiving the most irradiation (Fig. 3a, see also [7]). During Run 2, the center-of-mass energy was increased to $\sqrt{s} = 13$ TeV, which caused an increase in the event multiplicity as well as fluence (see Fig. 3b).

5. Data-driven calculations

The FLUKA geometry for Runs 4–5 and later is not yet functional, as the detector geometry requires further update. In the meantime, one can compare

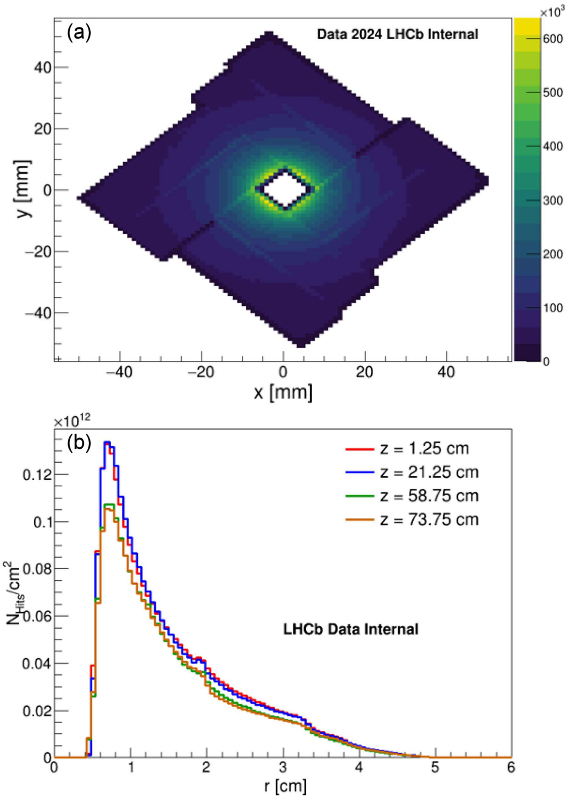

Fig. 5. (a) A 2D distribution of VELO hit density. (b) The radial hit density for different module positions per 1 fb^{-1}.

available tools for the simulation or develop a data-driven method for fluence evaluation. The first step of fluence simulation includes choosing the appropriate physics model for the estimation of the number of particles traversing silicon tracking stations. Figure 4a shows the results obtained by Pythia and Herwig simulations compared for multiplicity distributions. In Fig. 4b (see also [9]), the prompt charged particle density with respect to p_T is shown, and the results indicate that Pythia is in better agreement with LHCb data.

Since simulations clearly have their limitations, a data-driven method for fluence evaluation is proposed. The first method, based on reconstructed tracks, is not reliable due to the imperfect tracking algorithms. Instead, detector hits can be used. It can be assumed that every charged particle leaves a hit in a station, and the density of hits represents the flux of charged particles. A 2D VELO hit map is shown in Fig. 5a, illustrating that the highest flux occurs near the center of the sensor. According to the results in Fig. 5b, the modules positioned nearest the interaction point are subjected to the highest hit density. Two small discontinuities at approximately 1.9 cm and 3.3 cm in Fig. 5b likely correspond to sensor boundaries and geometry transitions affecting local hit efficiency. These are absent in the smoother FLUKA profile (Fig. 3a), which models the Run 2 VELO with simplified geometry. The inversion of the maximum flux from $z = 0.5$ cm in the Run 2 simulation to $z = 21.5$ cm in the Run 3 data-driven results likely arises from the upgraded detector geometry and different acceptance conditions in the new VELO design.

Combining simulations with hit-based data-driven methods is therefore crucial for accurately predicting radiation damage in the upgraded VELO.

6. Conclusions

The upgraded VELO faces significant radiation challenges, which affect leakage current and depletion voltage as the fluence increases. While FLUKA simulations offer valuable insights, their limitations render predictions uncertain, and direct fluence measurements are not feasible. Data-driven approaches, using detailed flux information and hit-based methods, complement simulations, providing more accurate radiation estimates. Combining both strategies is essential to predict damage, ensure stable operation, and maintain the detector's physics performance in LHCb. Data-driven extrapolations indicate that, at nominal luminosities of 2×10^{33} cm^{-2} s^{-1}, the innermost modules will experience a fluence of $\sim 1\times10^{15}$ $\text{n}_{\text{eq}}/\text{cm}^2$ per 10 fb^{-1}, with corresponding increases in leakage current and depletion voltage consistent with FLUKA predictions.

Acknowledgments

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