The LHCb upgrade

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Abstract

The physics programme of LHCb, the dedicated B-physics experiment at the LHC, could be significantly enhanced by the collection of increased statistics. A future upgrade to the detector is proposed that will allow the experiment to run at significantly higher instantaneous luminosities (around $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$). Significant changes to the detector which are under consideration include the development of a silicon vertex locator capable of withstanding a fluence in excess of $10^{15}$ 1 MeV neutron equivalent particles per cm$^2$ and the introduction of an FPGA based displaced vertex trigger.

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1. Introduction

LHCb [1] is a dedicated B-physics experiment for the LHC that will start data taking in summer 2007.

The initial LHCb detector has been designed to operate at an average instantaneous luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, which is expected to be obtained shortly after the start of LHC operation. This luminosity is a factor of 50 reduced from the full LHC design luminosity that will be utilised by the general purpose detectors. It is planned that the LHC beams will be defocussed at the LHCb interaction point to maintain this reduced luminosity throughout operation of the initial LHCb experiment. Despite the previously unprecedented B-hadron statistics of approximately $10^{12}$ $b\bar{b}$ pairs that will be produced per year, the LHCb physics programme will remain statistically limited in key measurements in both of its main areas of interest: CP violation and rare $b$-decays.

The reduced luminosity at LHCb has been selected as it has two key advantages for LHCb operation:

- The radiation damage to the experiment is limited.
- The collected events will be dominated by single proton–proton (pp) interactions per beam crossing permitting effective triggering on these interactions with existing technology.

However, emerging technologies will allow us to address both of these topics in the early part of the next decade.

2. Physics programme

An increase in statistics could be obtained from higher luminosity running and improved trigger efficiencies (see below). This would benefit the physics programme of the experiment in both the areas of standard model measurements and new physics constraints. For example:

- A very high precision measurement of the angle $\gamma$ of the unitarity triangle of the CKM matrix is potentially feasible for an upgraded experiment since the theoretical errors from the Atwood–Dunietz–Soni [2] extraction method, using channels like $B^+ \rightarrow D^0 K^+$, are as low as 0.1%.
- The $B_s \rightarrow J/\psi \phi$ channel holds interesting prospects for the initial experiment in searching for physics beyond the standard model but without an upgrade five years of data will only yield a 3 sigma measurement of the $B_s$ oscillation weak mixing phase $\phi_s$ at the standard model value [1].
• The increase in statistics from an upgrade will allow access to probing new physics modified values of $\phi_s$ in $B_s \rightarrow \phi\phi$.

Rare decay studies will also benefit from the higher event yield of the upgraded experiment. For example, in $B_d \rightarrow K^+\mu^+\mu^-$ decays only the muon forward–backward asymmetry has currently been considered but many other angular correlations are also sensitive probes of new physics models. However, it will only be possible to explore these correlations with the much higher statistics that the upgraded experiment will bring. CP violation searches in this channel (and related decays like $B_s \rightarrow \phi\mu^+\mu^-$) will also benefit from this proposal.

3. Trigger

At its nominal luminosity LHCb is primarily aimed at the reconstruction of single pp interactions per beam crossing. However, at a luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$ the detector, and particularly the trigger system, will have to cope with up to four interactions per beam crossing.

The LHCb trigger [3] relies upon an initial hardware trigger based upon high $p_t$ muons and calorimeter clusters. This trigger level reduces the data from the 40 MHz LHC beam crossings to a 1 MHz rate and operates with a 4 $\mu$s latency.

The trigger has an efficiency of around 90% for physics processes containing muons. The performance of the muon trigger level has been studied for a typical process ($B_s \rightarrow J/\psi\phi$) and shown to scale with luminosity: it has been demonstrated that by dedicating five time the bandwidth to the muon trigger the event yield can increase by a factor of five when moving to five times higher luminosity. Hence the experiment can perform an enhanced programme for channels containing muons without requiring a trigger upgrade: four out of ten of the initial benchmark LHCb channels have $\mu^+\mu^-$ in the final state.

However, the same performance is not obtained for channels containing hadrons: the full bandwidth of the 1 MHz trigger is quickly saturated so that the yield does not track the luminosity increase. Channels such as $B^+ \rightarrow D^0K^+$, $B_s \rightarrow \phi\phi$ that were discussed above would not gain from a luminosity upgrade without trigger improvements. Furthermore, the first level trigger efficiency for these hadron processes is typically only 40–50%, so it may be possible to increase event yields even at the nominal luminosity. As the high transverse energy trigger is not sufficient, the option of exploiting the finite lifetime of the $B$-mesons by introducing a displaced vertex trigger into the initial trigger level has to be considered. The trigger would benefit further from the addition of track momentum information. If the replacement of the majority of the LHCb front-end electronics is to be avoided the processing time available for this algorithm will be around 2 $\mu$s. The feasibility of implementing this algorithm in this time budget using modern FPGA processing remains to be studied, but the system does have some precedents in other proposed systems.

• Currently a first level pile-up veto trigger is being implemented in LHCb. This algorithm searches for events containing two primary vertices in a beam crossing, and these events are currently vetoed. This system reads out two planes of sensors in the VELO at 40 MHz and FPGA processing is performed.

• A displaced vertex trigger is performed at the second level of triggering in LHCb. This algorithm finds the primary interaction vertex and the secondary decay vertex of the B-hadron and is implemented in a CPU farm but with an average execution time of 1 ms not 2 $\mu$s.

• A displaced vertex trigger was proposed for the BTeV experiment using a pixel based vertex detector. While the trigger architecture for BTeV would have differed significantly from that implemented in LHCb, and the Tevatron beam crossing rate is 132 ns, not 25 ns, this does provide a detailed feasibility study.

4. Radiation hard vertex locator

The VELO [4] consists of 84 semi-circular silicon sensors positioned perpendicular to the LHC beam axis and arranged over a distance of 1 m around the LHCb collision point. The first active silicon strip is only 8 mm from the LHC beam axis. This proximity to the LHC beam results in an extreme radiation environment with the inner strips receiving a fluence, comprised predominantly of charged particles, of up to $1.3 \times 10^{14} \text{MeV neutron equivalent (n}_{eq})$ particles per cm$^2$ per year calculated for a nominal LHC operational year of $10^7$ s at a luminosity of $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$. The sensors are made with n-on-n processing and include p-spray implant isolation. The detector components have been specified up to 500 V and simulations, lab-tests and test-beam results demonstrate that an acceptable signal-to-noise performance will be obtained at 300 V after three nominal years of operation (6 fb$^{-1}$ of data).

However, at a luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$ a radiation fluence of $6.6 \times 10^{14} \text{MeV n}_{eq}\text{cm}^2$ per year will be obtained, higher than the expected radiation tolerance of the current device.

Furthermore, in order to obtain the optimal impact parameter resolution the sensors should be located as close as possible to the LHC beam. Moving the sensors to an inner radius of 5 mm, the current LHC accelerator group limit for the VELO would increase the fluence by a further factor of 2.6. Hence, a future VELO Superior Performance Apparatus (VESPA) would require a radiation tolerance in excess of $10^{15} \text{1 MeV n}_{eq}\text{cm}^2$.

A number of radiation hard technologies are being investigated by the RD50 collaboration and are potential candidates, notably:
- **Magnetic Czochralski Silicon (MCz)** [5]. Results from the Transient Current Technique have demonstrated that, unlike Float Zone (FZ) and Diffusion Oxygenated Float Zone, MCz does not undergo space charge sign inversion. Hence, simple single sided p-on-n processing can be used. Furthermore, at high fluxes the evolution of the depletion voltage with fluence for MCz has been shown to have a lower gradient than in FZ silicon. MCz devices have already been successfully tested in a test-beam with LHC speed electronics.

- **n-on-p** detectors start with a p-type substrate and hence also do not undergo type inversion. By controlling the p-spray isolation technique detectors have been run at very high voltages (900 V) and significant charge collection efficiency obtained after doses of $7.5 \times 10^{15}$ $1 \text{MeV neq cm}^{-2}$ [6]. Again, only simple single-sided processing of devices is required.

- **3D Detectors** [7] overcome the intrinsic material limits by adopting an alternative geometry. The close implant spacing in these devices results in short signal collection times and a high intrinsic radiation hardness but at the expense of complex device processing.

The current LHCb VELO sensors are produced in two types: (i) R sensors that contain strips running circumferentially and (ii) Phi sensors that have strips running radially. This R/Phi geometry is of benefit to the trigger where the displaced vertex tracking is performed first in the R–Z plane with Phi information only being added to candidates of interest. Furthermore, the sensors have an implant pitch that varies from a 37 $\mu$m minimum at the 8 mm inner radius to 102 $\mu$m at the 42 mm outside radius of each sensor. This arrangement naturally matches the occupancy of the sensors (approximately 1% at nominal luminosity) which varies with the distance from the LHC beam.

However, for the higher occupancy environment of the LHCb upgrade, pixel detectors should also be evaluated. Pixels would provide low occupancy 3D space-points and, in terms of signal to noise performance, their small size provides the highest radiation tolerance for a given material. A pixel dimension of 50 $\mu$m or less would be required to achieve a resolution approaching that of the inner strips on the current detector. A pixel detector could potentially require less layers of devices that the current VELO layout, since both R and Phi silicon sensors are not required. However, once the detector, its bump bonded chip, support structure and cooling services are considered this could not be expected to significantly reduce the material budget of the experiment.

The material budget of the current VELO has an average value of 19% $X_0$ over the LHCb acceptance. The largest single contribution is that of the RF-foil: a 250 $\mu$m thick aluminium structure that separates the sensors from the primary vacuum of the LHC machine and provides wakefield suppression. The design of this foil should be re-evaluated for the upgrade in the light of initial experience with LHC running, with replacement by a thinner foil or wires being a possibility if the separation of the detector from the LHC primary vacuum is no longer demanded.

The current sensors have a guard ring design that uses 1 mm of space on the sensors. Studies show that utilising edgeless technologies would already yield a 10% improvement in the impact parameter performance of the sensor. If the RF-foil is removed and the inner sensor radius moved to 5 mm this becomes a 35% improvement, as shown in Fig. 1. The impact parameter performance is particularly important for $B_s$ meson studies that are heavily dependent on the proper-time reconstruction abilities of the experiment.

### 5. Summary

An upgrade of the LHCb experiment is being discussed to produce a detector capable of fully utilising the B-physics potential of the LHC. This high luminosity upgrade will occur early in the next decade and does not require any modifications to the LHC accelerator system. The two primary elements of the upgrade would be a vertex detector with further enhanced radiation hardness and a displaced vertex trigger. The physics programme, for both the key objectives of CP violation and rare B decays, of the experiment can be significantly enhanced at a cost that is relatively modest compared with the existing accelerator infrastructure.

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