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The LHCb VELO Upgrade

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The LHCb experiment is dedicated to study CP violation and other rare phenomena in the decays of beauty and charm particles at the LHC. The detector readout and trigger are optimized to run at nominal instantaneous luminosity ~2×10^{32} $cm^{-2}s^{-1}$. An upgrade which will enhance the experiment's sensitivity by at least an order of magnitude is critical to the completion of LHCb's physics program. This will be achieved by being able to cope with luminosity up to 2×10^{33} $cm^{-2}s^{-1}$, and by an improvement of the hadron trigger. In order to achieve these goals, all detector elements will need new front end electronics featuring 40 MHz readout. In addition a new design of the vertex detector (VELO) is critical to the upgrade, suitable to fast and efficient pattern recognition and capable of withstanding the radiation fluence corresponding to 100 fb^{-1} data taking. The VELO upgrade investigations have focused on pixel solution with readout ASICs that will be developed based on the Timepix readout chip. Other solutions are also under investigation. We summarize a conceptual design of the upgraded vertex detector for LHCb and some of the planned R&D activities.

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1. Introduction

On November 23, 2009 the LHC had its first successful pp collision. This event signals the start of a new era in the history of particle physics. The LHC provides vast opportunities for discovery of new physics. LHCb, one of the four experiments at the LHC, is dedicated to study CP violation and other rare phenomena in the decays of beauty and charm particles and probe physics beyond the Standard Model [1].

LHCb plans to run at a nominal instantaneous luminosity ~2×10^{32} cm^{-2}s^{-1} for ~5 years and collect 10 fb^{-1} data. As new physics manifestations in charm and beauty decays may be subtle, a LHCb upgrade is planned, with the goal of enhancing the data rates and the sensitivity to B decays to hadronic final states [2]. The experiment is planning to be able to cope with a luminosity of 2×10^{33} cm^{-2}s^{-1}, which is within the capability of the current LHC. Thus the LHCb upgrade is independent of the super LHC upgrade. In order to sustain the increased data rates, LHCb plans to read out the data from all subdetectors at 40 MHz. VELO, the vertex locator, is one of the key elements of the LHCb detector. As it is very close to the beam, radiation hardness is a crucial quality required. Moreover, at the higher luminosity, fast and efficient pattern recognition with high suppression of spurious tracks is a key to the success of the experiment. Thus, alternative pixel-based detector solutions are being explored.

2. Running at High Luminosity

The LHC delivers two opposite direction proton beams in bunches at a rate of 40.08 MHz. At the LHCb site (P8) 2622 out of total 3564 possible bunch slots have actual crossings, giving a maximum interaction rate of ~30 MHz. At instantaneous luminosity ~2×10^{32} cm^{-2}s^{-1} most of the bunch crossings (~70%) are empty as shown in Figure 1.a. The interesting bb events occur at a rate of ~100 kHz, ~100 lower than the minimum bias interaction rate.

The current LHCb data acquisition system is capable of reading out events at 1 MHz trigger frequency. To reduce the rate from 30 MHz bunch crossing to 1 MHz while maintaining high efficiency for the interesting b events, LHCb relies on a hardware-based Level 0 trigger. The L0 trigger selects events with large transverse momentum (P_t) particles: hadron, μ, e and γ. The events are further selected at higher level trigger (HLT) performed on a CPU farm. At higher luminosity, the b event rate increases. However, the L0 criteria have to be tightened so that the overall event rate stays below 1 MHz. While the yield from the L0 trigger based on high P_t μ scales linearly with the luminosity, there is no net gain in hadron channels, as shown in Figure 1.b [3].

At luminosity ~2×10^{32} cm^{-2}s^{-1} the non-empty events contain 1 interaction predominantly, as shown in red dots in Figure 1.a. The events are clean and relatively easy to reconstruct. At luminosity ~10^{33} cm^{-2}s^{-1} the most probable number of interactions per crossing is either 1 or 2. The luminosity of 2×10^{33} cm^{-2}s^{-1} makes the events much complex. The dominant number of interactions per event becomes ~4. It requires significant increase of CPU time to perform pattern recognition due to large combinatorics. The upgraded VELO needs higher granularity, especially near beam where the hit density is very large.

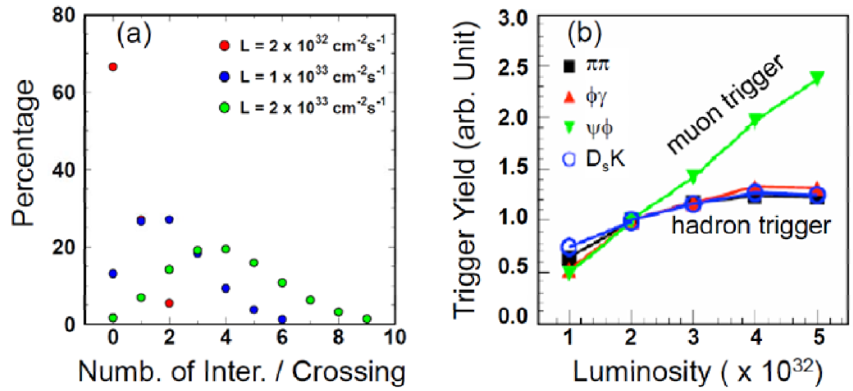

Figure 1. a) Number of interactions per beam crossing for instantaneous luminosity of 2×10^{32}, 10^{33}, and 2×10^{33} $cm^{-2}s^{-1}$ in red, blue, and green solid dots respectively. b) Trigger yields of different channels as functions of luminosity.

The LHCb upgrade is designed to cope with a luminosity of 2×10^{33} $cm^{-2}s^{-1}$ for 5 years and accumulate 100 fb^{-1} data. The L0 trigger will be removed, and the data will be transmitted at 40 MHz to a CPU farm which will perform event reconstruction and filtering. A luminosity increase by a factor of 10, coupled by a twofold increase in the sensitivity of the hadron trigger channels will increase the statistical accuracy by ~20 for hadronic channels and ~10 for leptonic channels.

3. The Present VELO Detector

The VELO is one of the key sub-detectors at LHCb. It is used to reconstruct the event topology, identifying primary vertices and detached vertices consistent with charm and beauty lifetimes, and is part of the tracking system. It provides crucial information in HLT to select interesting b events [4].

The present VELO detector consists of 21 stations along the beam direction. The stations are perpendicular to the beam axis, with distance between stations in interaction region ~30 mm, and wider separation further downstream as shown in Figure 2.a. A station has two modules each covering half the acceptance. The whole detector comprises two halves. During beam injection the two halves can be retracted by 30 mm to protect the detector from unnecessary radiation damage. VELO modules are double-sided with half circular R-sensor and Φ-sensor attached to readout hybrid. The micro-strip silicon sensors have 2048 strips each in concentric or axial direction as shown in Figure 2.b to measure either radial (R) or azimuthal (Φ) coordinates [4]. The strips of the Φ-sensor are tilted at angles. They are flipped for alternative stations to provide stereo measurements. The strip configuration are optimized for tracking of particles originating from beam-beam interactions and to provide fast online 2D (R-Z) tracking and offline 3D tracking in two steps [5].

The VELO sensors are fabricated with n^+-on-n sensor with p-spray inter-strip isolation. The sensors are 300 μm thick. The strip pitches are between 40-100 μm. The innermost region of the sensor is ~8 mm away from the beam axis, and is exposed to ~1.3×10^{14} n_{eq}/cm^2 particle fluence per year at current nominal luminosity.

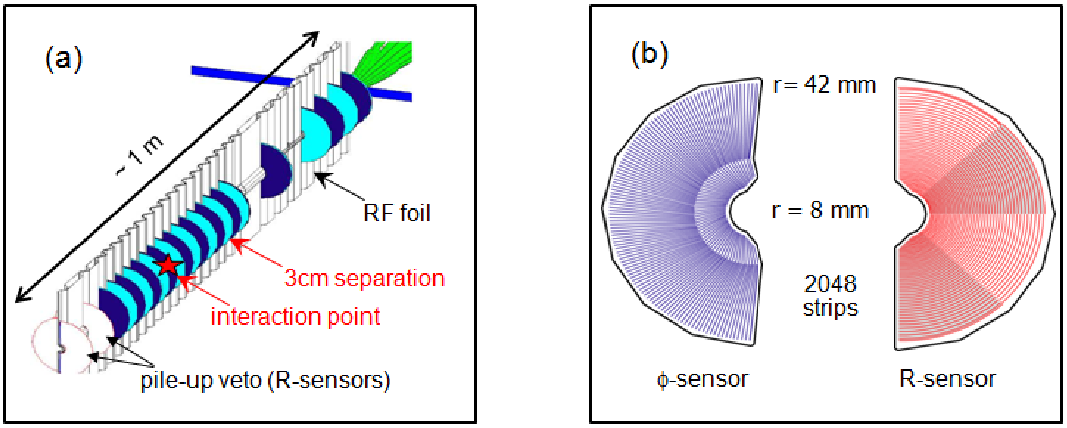

Figure 2. The VELO detector a) configuration of stations, and b) strip layout of R-sensor and Φ-sensor.

Charge signals from strips are processed by 16 Beetle ASICs for each sensor [6]. A Beetle ASIC has 128 low noise fast analog processors. Analog signals are stored in 4 μs pipelines and shipped out through 4 pairs of LVDS lines. Signals from 32 channels and 4-bit header information are sent out serially through one pair of LVDS lines upon receiving the L0 trigger signal. It takes ~900 ns to read out all 36 analog signals, which limits the data rate to ~1 MHz. More details on the status of the current VELO are described elsewhere [7].

4. The VELO Upgrade Plan and R&D Activities

The VELO upgrade encompasses R&D activities to identify the optimal sensor, electronics, and module design to cope with the requirements dictated by the higher radiation exposure and increased event complexity. In addition, a synergy with the trigger design is critical to achieve optimum performance. The VELO detector needs to have fast and robust pattern recognition. The readout electronics and sensor need to be radiation hard. The material of VELO detector and material before VELO need to be minimized to reduce multiple scattering effects.

LHCb has compared different upgrade options starting from modification of the current VELO. At 40 MHz rate analog readout of event, like in the current detector, is unrealistic. Signals have to be digitized at the front end. Data need to be sparsified and pushed to storage buffer in real time. The size of the sensor can be reduced to ease the difficulty of cooling at the inner most part. With strip option, the R-Φ structure will be kept thus the pattern recognition algorithm is similar to the current one.

An approach of hybrid pixel sensor bump bonded to a custom made front end electronics has also been explored [8]. The electronics will withstand the same radiation environment as the sensor. The total ionizing dose (TID) reaches ~400 Mrad in the highest region for 100 fb^{-1} data. The electronics need to be more radiation hard than for the strip option. The bump bonded ASICs also contribute to the total radiation length. The sensor and electronics need to be thinned after bump bonding to reduce the material. On the other hand, sensors with pixel size of ~50 μm × 50 μm are well developed technology. One pixel sensor measures precisely in both directions and provides a space point, in comparison to the strip option that hits in R and Φ sensors need to be matched to provide space point. Thus pixel option benefits significantly the pattern recognition.

The VELO detector operates in vacuum. Heat generated by readout electronics and leakage current under sensor bias voltage needs to be evacuated. After irradiation the leakage current increases, the bias voltage may also need to be increased to maintain high charge collection efficiency. Silicon sensor need to be operated at low temperature to minimize radiation induced effects. Combination of all these requirements makes cooling a challenge.

After evaluating different requirements, LHCb decided to focus on a pixel solution based on Velopix ASIC, an adaptation to our needs of the Timepix readout chip, which best satisfies the upgrade requirements.

4.1 VELO Modules

The overall layout of the upgraded VELO detector along the beam will be similar to the current one. There are about 21 stations. Each station has detection area ~7 cm × 7 cm, with two modules each covering half the acceptance. The number of stations, distance between adjacent stations, and the size of the stations need to be further optimized.

The current Timepix ASIC [9] has 256 × 256 pixel cells of size 55 μm × 55 μm, total pixel matrix area ~14.1 mm × 14.1 mm. The adaptation to LHCb needs requires ~14.1 mm × 0.8 mm space for digital periphery. Based on these sizes a conceptual design of the upgraded VELO module is illustrated in Figure 3. The pixel sensor of each module consists of either 2 pieces of 30.9 mm × 15.1 mm and 1 piece of roughly 37.4 mm × 43.5 mm silicon sensors, or one big piece that covers the whole area, with 0.5 mm wide guard rings. There is a cut-out of ~13.0 mm × 6.5 mm at small radius for beam. The silicon sensors are bump bonded to 10 Velopix ASICs. A diamond thermal plane is then glued to ASICs and mounted to supporting structure and with cooling channels attached.

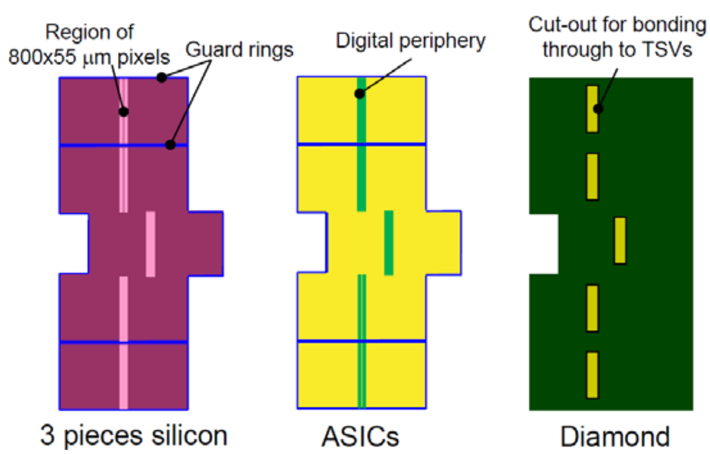

Figure 3. A conceptual layout of an upgraded VELO module.

The cross section of the VELO module zoomed near the digital periphery is shown in Figure 4 [10]. The sensor and electronics are thinned to 150 μm thick each. Under the periphery the pixel size is larger to reduce inefficiency. A 50 μm thick ground plane is aluminized on the 200 μm thick diamond thermal plane. Through-silicon-via (TSV) technology will be used, allowing vertical connection of electronics signal and power through the ASIC dices. Windows are cut on the diamond plane immediately above the TSVs allowing wire bonding connections of TSVs to power tape and metallization traces on the surface of the diamond plane.

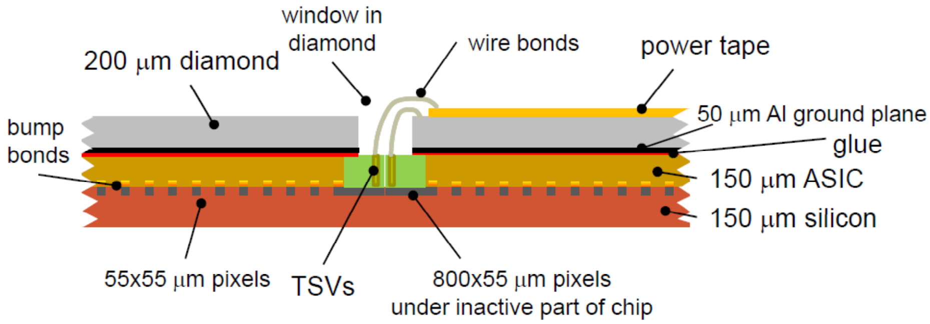

Figure 4. Cross section of an upgraded VELO module zoomed near TSVs.

4.2 Readout Electronics

Velopix, the front end readout chip, will be developed based on the Timepix ASIC, which in turn was derived from Medipix2 chip [9]. Each Timepix chip has 256 × 256 pixel cells of size 55 μm × 55 μm. The preamplifier of each cell has a fast rising edge ~90 ns, and a slow (~500-2500 ns) constant-current-return to zero. Using reference clock up to 100 MHz the time-over-threshold (ToT) can be measured, which is proportional to the total charge collected. In ToT mode Timepix provides better than 6-bit equivalent ADC resolution.

Hybrid pixel modules with Timepix readout have been tested in a 120 GeV π beam at CERN in the summer of 2009. A telescope was constructed with 4 Timepix and 2 Medipix2 detectors for tracking. The Timepix detector under test is placed in the telescope and rotated at different angles. Preliminary results are promising as shown in Figure 5. There is more charge sharing when tracks are at larger angle. The spatial resolution reaches ~5 μm at 10 degree. More details on Timepix and the testbeam can be found in [11].

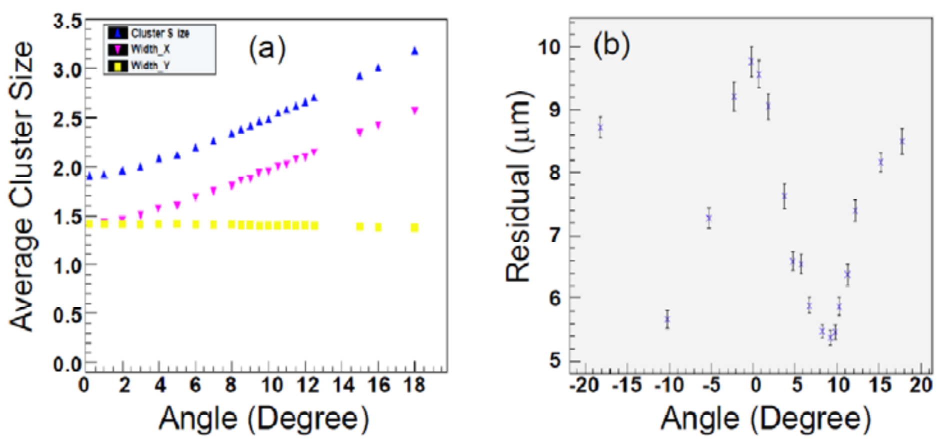

Figure 5. Preliminary results from Timepix testbeam: a) Average cluster size vs track angle with tilt angle in X direction: blue triangles are the total number of pixels, magenta triangles are number of pixels in X direction, and yellow squares are number of pixels in Y direction. b) Spatial resolution vs track angle where tracking error ~2.5 μm is not removed.

The Timepix ASIC does not have a continuous or synchronous readout. It operates much like a camera with a shutter signal. Events recorded happened within a time interval, on the order of ms. Faster electronics, event time tagging, faster readout architecture are required to meet LHCb requirements, and are currently under investigation.

The Velopix readout chip is 3-side buttable. The space to accommodate IO periphery, DAC and connection pads are expected to fit within a 0.8 mm × 14.1 mm area. And through-silicon-via (TSV) bonding allows implementation of the U-shape geometry shown in Figure 3, eliminating the dead area required for wire-bonding to the control and bias lines.

The ASICs need to maintain stable operation for accumulated ~400 Mrad TID. A Medipix3 chip implemented with 130 nm CMOS technology has been irradiated in X-rays up to 400 Mrad TID. The Chip has remained operational for full dose. This test needs to be followed up by hadron irradiation. The Velopix ASIC will be implemented in 130 or 90 nm technology, which may reduce power consumption, allow higher density of logic and be radiation hard.

4.3 Sensors

Requirements for sensor upgrade are: radiation hardness, low leakage current and heat dissipation, high granularity, and minimizing material. The VELO group is exploring sensors of various types: the current n^+-on-n strip sensor (n-type), n^+-on-p strip sensors (p-type) for next replacement, 3D detector, and Chemical-Vapor-Deposition (CVD) synthetic diamond.

The VELO detector currently employs n-type sensors, which will be replaced by p-type sensors after a few years running. A pair of n-type and p-type R-sensors were differentially irradiated. The maximum irradiation particle fluence is ~0.86×10^{15} n_{eq}/cm^2, about 6 years running at the current nominal luminosity ~2×10^{32} $cm^{-2}s^{-1}$ in the inner most region of the sensor. In April 2009 the irradiated sensors were tested in a 120 GeV proton beam at Fermilab. The sensors are stored at -20°C and operated at ~ -10°C. A 5-station FPIX2 pixel telescope of aperture ~35 mm × 35 mm was constructed to provide tracking in collaboration with Dr David Christian of Fermilab [12]. The projection on the VELO sensors has precision ~4-8 μm. The VELO sensors were tested at different angles and under different bias voltages. Preliminary result shows that the charge collection efficiency of the n-type sensor drops by ~25% with bias HV of 500 V after 6 years running as shown in Figure 6. More results on irradiated sensors are coming soon.

Besides of charge collection efficiency, cooling is another big concern. The leakage current of irradiated silicon sensor increases. Moreover, the sensor needs to be biased at higher voltage after large irradiation to have enough charge collected. The combination of these two properties makes cooling a big challenge, especially at the inner most part. The group has been comparing pixel sensors implemented on various silicon substrates (p-type, n-type both in float zone and magnetic Czochralski) within collaboration of RD50 [13]. Single chip pixel sensors with layout matching the FPIX2 chip have been fabricated by Micron Semiconductor [8]. The sensors were tested in bench setting before irradiated with various dose. The irradiated sensors are being examined.

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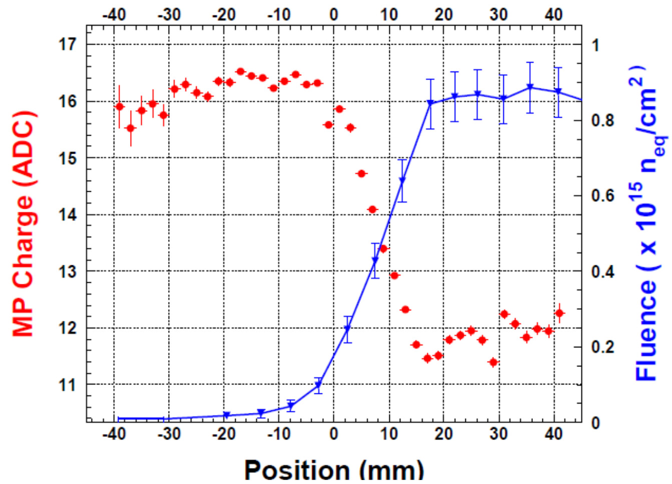

Figure 6. Charge collection efficiency of an n-type sensor and irradiation profile: in red dots the most probable charge vs. hit position of the sensor, in blue triangles the particle fluence.

Another approach that can significantly reduce the cooling difficulty is the novel “3D” detector [14]. This technology was proposed originally by S. Parker, and is rather challenging because it is constructed with Micro-Electro-Mechanical-Systems (MEMS) processing. This is an innovative approach to segmented solid state detectors, where narrow holes and trenches are etched through silicon wafer and the back filled with conductive polysilicon (n and p doped). The depletion region is achieved with lateral bias, from electrodes as close as 50 μm, thus requiring moderate high voltage. Now this process is pursued in a broader community. In particular, the Glasgow group, in collaboration of CNM (Centro Nacional de Microelectronica), has been developing double sided 3D sensor [15]. Prototype 3D sensors have been bump bonded to Timepix/Medipix2 readout chips, tested in Diamond X-ray light source and exhibit promising quality [16].

Another interesting option being explored is CVD sensors. The work is done in the framework of RD42 [17]. Polycrystalline and single crystal CVD diamond detector can withstand fluence up to 1.8×10^{16} n_{eq}/cm^2. The material has very low dielectric constant hence low capacitance and intrinsic noise. The signal to noise ratio achieves ~20 for diamond pixel detector. Diamond sensor needs no guard ring thus can be edgeless. The leakage current is extremely low at all levels of irradiation, well below nA instead of typically μA for silicon sensors. The detector can be operated at room temperature. The diamond material itself has very high thermal conductivity. Thus the cooling system is less a big challenge than that for silicon detectors. It is ideal for VELO upgrade especially at low radius area where particle flux is high. The cost of diamond solution, however, is a concern.

All the sensor technologies considered will be tested in the laboratory and with beams in order to choose the best solution.

4.4 Mechanical and Cooling

The RF shield is an important issue needs to be addressed for VELO upgrade. It shields VELO detector against RF pickup from the beam, protects the LHC vacuum from detector outgassing. Its material, however, is a major contribution to the total radiation length of the VELO, and it happens before the first position measurement. In current system the RF shield is constructed of 300 μm AlMg3 alloy coated with insulator and getter. For the VELO upgrade cutting down its total radiation length contribution benefits tracks and vertex reconstruction. LHCb is exploring alternative low mass implementations of the RF foil, for example replacing AlMg3 with carbon fiber composites.

The inner most region of the vertex detector experiences much higher particle fluence. If a silicon-based telescope is constructed, the increased leakage current could induce thermal runaway, if the cooling is not sufficient. Thus in design of the upgrade detector cooling of the system is very carefully simulated to ensure stable operation. In the current VELO system evaporative CO_2 cooling is used [18]. An alternative method, studied for the BTeV experiment baseline design, would involve mounting the modules on TPG (Thermal Pyrolytic Graphite) or other high conductivity substrates, coupled to liquid nitrogen heat sink [19].

Summary

The exciting LHCb physics program has started. Interesting results are forthcoming and will enrich our understanding of heavy flavour phenomenology, and perhaps produce some glimpses into new physics. To achieve much higher physics sensitivity the LHCb plans to upgrade the detector and run at ~10 times higher instantaneous luminosity. Critical requirements affecting the design of a new vertex detector for the LHCb upgrade are radiation hardness, applicability to fast and reliable hadron trigger, vertex resolution and efficiency. Currently, hybrid pixel modules read-out with an adaptation of the Timepix ASIC represents our baseline solution. Different silicon sensor technologies are being explored to find radiation hard sensor that best satisfies the LHCb upgrade requirements. In high radiation area near beam CVD diamond sensor is a possible solution. A multiprong R&D effort is addressing all the design issues which satisfy the requirements of the more challenging regime of operation of the upgraded detector.

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