

A Beam Gas Vertex detector for beam size measurement in the LHC

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The Beam Gas Vertex (BGV) detector is foreseen as a possible non-invasive beam size measurement instrument for the LHC and its luminosity upgrade. This technique is based on the reconstruction of beam-gas interaction vertices, where the charged particles produced in inelastic beam-gas interactions are measured with high-precision tracking detectors. The design studies and overview expected performance of the currently developed BGV prototype will be presented with an given of the associated vacuum, detector and readout systems. A brief description will be given of the BGV Monte Carlo simulation application, which is based on the LHCb computing framework (Gaudi) and allows simulation studies to be performed and online event reconstruction algorithms to be developed.

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A BEAM GAS VERTEX DETECTOR FOR BEAM SIZE MEASUREMENT IN THE LHC

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The Beam Gas Vertex (BGV) detector is foreseen as a possible non-invasive beam size measurement instrument for the LHC and its luminosity upgrade. This technique is based on the reconstruction of beam-gas interaction vertices, where the charged particles produced in inelastic beam-gas interactions are measured with high-precision tracking detectors. The design studies and expected performance of the currently developed BGV prototype will be presented with an overview given of the associated vacuum, detector and readout systems. A brief description will be given of the BGV Monte Carlo simulation application, which is based on the LHCb computing framework (Gaudi) and allows simulation studies to be performed and online event reconstruction algorithms to be developed.

INTRODUCTION

The beam-gas vertexing technique [1] was pioneered and used at the LHCb experiment for the measurement of the geometrical properties of the LHC beams and for the determination of the absolute luminosity [2–5]. The charged particles produced in inelastic beam-gas interactions are detected with high-precision tracking detectors to determine the interaction (vertex) positions. The beam-gas interaction rate is controlled by injecting a small amount of gas into the primary beam volume (e.g. vacuum chamber). The beam-gas vertices reconstructed in a certain time interval are used to measure the two-dimensional transverse beam profile. This technique allows other beam properties to be measured as well: position, tilt, and relative bunch populations [4, 5]. One possible add-on, not in the baseline discussed here, is a timing detector which would allow longitudinal beam profile measurements to be performed as well.

The goal is to develop a transverse beam profile monitor capable of providing:

- Individual bunch width measurements with a 5 % resolution within 1 minute

- Average beam width measurement with an absolute accuracy of 2 % within 1 minute

These target accuracies and measurement durations would allow meaningful measurements to be performed along the LHC energy ramp and a direct calibration comparison to be made with other beam profile monitors. Combined with an independent determination of the β functions of the magnetic lattice, the BGV measurements will be used to provide precise values of the beam emittance (per bunch, or averaged over all bunches of one beam) throughout the LHC cycle.

The chosen strategy is to first demonstrate the potential of the beam-gas imaging technique for the LHC by installing and commissioning a prototype BGV system on one beam in the LHC by the end of 2015. A collaboration between CERN, EPFL Lausanne, and RWTH Aachen has been formed to design and develop this detector. The results and experience will be used to develop a more advanced BGV system which could be installed in the LHC during Long Shutdown 2 (2019).

BGV DEMONSTRATOR

The layout of the BGV Demonstrator is illustrated in Fig. 1. The tracking detector is external to the vacuum chamber and no movable parts are needed for the system operation. The main subsystems are: a gas target, a tracking detector, hardware and software triggers, and data readout and acquisition.

Design Considerations

The design study took into account the impact on the machine, the instrument performance, and the time available for its design, production and installation. It was considered essential to maintain the functionality of real-time bunch-by-bunch beam shape measurements with a resolution of about 5 %, while the target measurement intervals and absolute accuracy were increased to 5 minutes and 10 %, respectively.

The accuracy of the beam profile measurement is determined by the vertex resolution, i.e. by the accuracy of the vertex position measurements. Considering the simplified case of bunches with a Gaussian profile, one can extract the beam size σ_{beam} from the raw measurement σ_{raw} by subtracting the vertex resolution: $\sigma_{\text{beam}}^2 = \sigma_{\text{raw}}^2 - \sigma_{\text{vtx}}^2$. Denoting the error by δ and assuming negligible measurement

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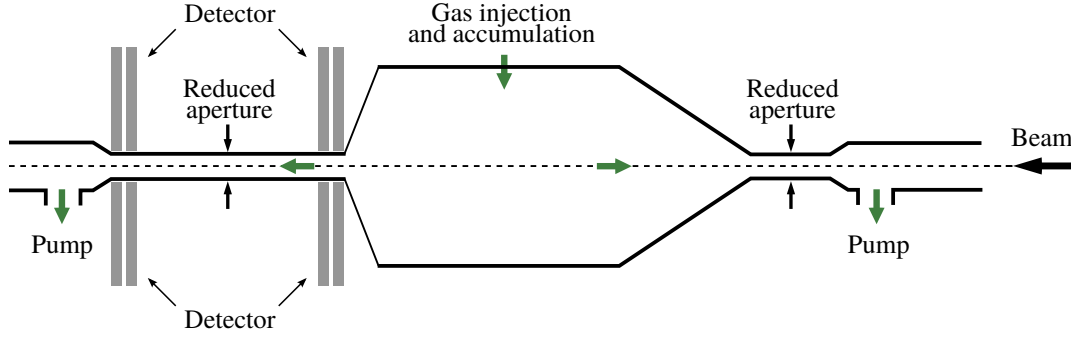


Figure 1: A sketch of the BGV Demonstrator layout. The two major components are shown: gas target (chamber for gas injection and accumulation, chambers with reduced aperture and pumping system) and tracking detector.

uncertainty ($\delta\sigma_{\text{raw}} \rightarrow 0$), one has:

$$\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} = \left(\frac{\sigma_{\text{vtx}}}{\sigma_{\text{beam}}} \right)^2 \frac{\delta\sigma_{\text{vtx}}}{\sigma_{\text{vtx}}} \quad (1)$$

Accurate beam width measurements can be performed when the vertex resolution is small compared to the beam size, and/or the vertex resolution is precisely known.

The vertex resolution is determined by the track reconstruction accuracy, quantified by the impact parameter resolution σ_{IP} (see Fig. 2), and the number of tracks used in the vertex reconstruction.

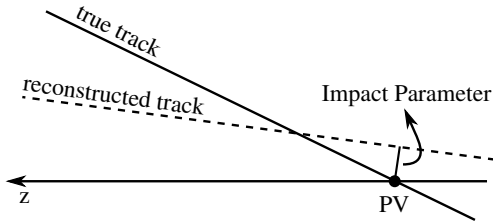


Figure 2: Definition of the track impact parameter.

A measurement setup featuring tracking detectors located near and far from the gas target (see Fig. 1) was considered in order to quantify the main effects contributing to the impact parameter resolution. The effects from multiple scattering and the extrapolation error of the hits measured in the tracking detectors are quantified as:

$$\begin{aligned} \sigma_{\text{IP}}^2 &= \sigma_{\text{MS}}^2 + \sigma_{\text{extrap}}^2 \\ \sigma_{\text{MS}} &\approx r_1 \frac{13.6 \text{ MeV}}{p_T} \sqrt{\frac{x}{X_0}} \\ \sigma_{\text{extrap}} &\approx \sqrt{\frac{z_1^2 + z_2^2}{(z_2 - z_1)^2}} \cdot \sigma_{\text{hit}} \end{aligned} \quad (2)$$

where the variables used have the following meaning:

- r_1 – transverse distance of approach of the detector modules to the beam
- $z_{1,2}$ – longitudinal position of the tracking detectors
- p_T – average transverse momentum of the tracks

- x/X_0 – radiation length traversed by the tracks
- σ_{hit} – detector hit resolution

The vertex resolution scales approximately as $1/\sqrt{N_{\text{Tr}}}$, where N_{Tr} is the number of tracks forming the vertex. One of the design goals was to maximize the detector acceptance in order to detect as many of the charged particles produced as possible.

The distance of approach of the detector to the beam is of primary importance for the performance of the monitor. Given a fixed polar acceptance angle, the reduction of r_1 leads to a reduction of the multiple scattering and the extrapolation error, see Eq. (2). At the LHC, the allowed minimal approach to the beam is determined as a function of the transverse beam size [6]. For this reason, the ratio of the minimal approach to the beam and the beam size is equally favourable everywhere in the LHC. Nevertheless, the optical configuration of the machine provided important input for choosing the installation location of the BGV Demonstrator. A place where the β functions have values of about 150 m implies that sensors with dimensions of a few tens of cm are sufficient to cover the predefined polar acceptance angle. In addition, the location of the BGV Demonstrator was chosen such that the beam sizes on the two axes are similar, thus avoiding the use of non-circular beam pipes.

With the beam-gas vertexing technique, real and simulated data can be used to independently parametrize the vertex resolution as function of the track multiplicity and the longitudinal position of the vertex. The comparison of the data- and simulation-based resolution models can be used to obtain an estimate of the accuracy of the vertex resolution parametrization $\delta\sigma_{\text{vtx}}/\sigma_{\text{vtx}}$, see Eq. (1). In the LHCb analyses, accuracy of about 5% was achieved [3,4]. Currently, no estimates are available for the BGV Demonstrator, and a value of 10% is assumed in the performance studies.

These considerations were used to define a baseline configuration for the BGV Demonstrator. Later, a simulation application was developed which used beam-gas interactions simulated with the LHCb Computing Framework as input. The HIJING Monte Carlo generator [7] was used. The performance of different detector configurations was studied in terms of acceptance, track impact parameter reso-

lution and vertex resolution. At 6.5 TeV beam energy, which corresponds to the most challenging conditions for the monitor, the expected relative uncertainty of the absolute bunch width is about 10 % for a normalised beam emittance of $3 \mu\text{m}$ (see [8] and the references therein).

Gas Target and Vacuum System

The gas target provides the inelastic beam-gas interactions required for this beam-gas detection method. The combination of performance and operational and maintenance considerations led to the choice of neon as the target gas. The operational pressure inside the gas injection chamber will be 6×10^{-8} mbar, which results in about 100 Hz of inelastic beam-gas interactions per nominal LHC bunch (1.15×10^{11} protons). In order to minimize the background to the BGV and the effect on the neighbouring LHC vacuum, the vacuum system was designed to provide limited conductance and a sharp pressure decrease outside the gas injection chamber.

One of the walls of the gas injection vacuum chamber serves as an exit window for the charged particles produced in beam-gas collisions (see Fig. 1). The material and the design of the gas injection chamber were optimized to reduce the effect of multiple scattering on the traversing particles.

Detector

The BGV Demonstrator will use scintillating fibre (SciFi) modules, read out by silicon photomultipliers (SiPM). The SciFi modules (see Fig. 3) are developed by EPFL, Lausanne and RWTH, Aachen, and are based on the same technology used in the other projects of these institutes, in particular, for the LHCb upgrade [9, 10].

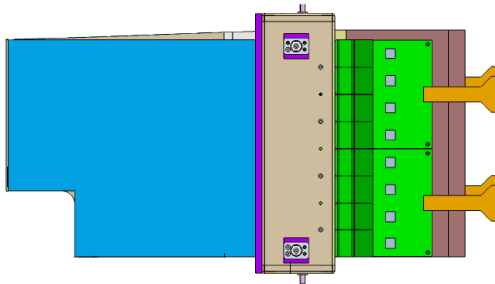


Figure 3: BGV scintillating fibre detector module. The dimensions of the active area (blue) are $260 \text{ mm} \times 340 \text{ mm}$. The corner cutout allows better acceptance to be achieved. The SiPMs are located in a cooling enclosure box (light brown).

Eight SciFi modules will be arranged around the beam pipe to form two tracking stations – near and far from the exit window of the gas injection chamber (see Fig. 4). The SciFi module contains two scintillating fibre mattresses with layers of $250 \mu\text{m}$ diameter fibres, each providing one-dimensional position measurement with a resolution of about $60 \mu\text{m}$ [9]. In order to facilitate the pattern recognition, the two fibre mattresses are rotated by a 2° “stereo angle” with respect to

each other. Each tracking station is comprised of two SciFi modules one behind the other and rotated by 90° with respect to each other, providing two x - y position measurements. The charged particle trajectories are determined by a linear fit to the positions measured in the far and near tracking stations.

Readout & Trigger

The BGV readout, data acquisition and online control and monitoring is based on the LHCb online system [11]. Beetle readout chips [12] and TELL1 acquisition boards [13] will be used. The average readout rate is limited to 1 MHz, with the possibility to acquire consecutive 25 ns bunch slots.

A hardware trigger made of scintillator plates will select beam-gas interactions for readout. Event reconstruction and filtering will be performed with a high-level trigger system based on commercially available networking and computing components.

Monte Carlo Simulations

The LHCb software framework (Gaudi) [14] is used for the detector simulation and for the development of offline and online reconstruction algorithms. In addition to the facilities provided by the framework, it is possible to re-use particular LHCb sub-detector and reconstruction algorithms.

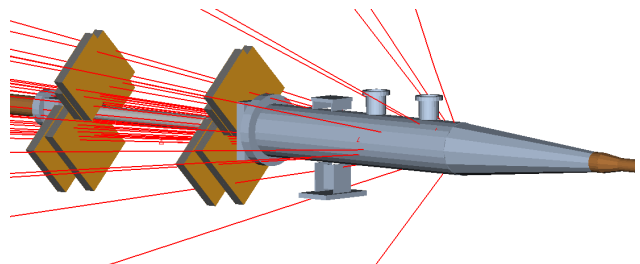


Figure 4: BGV simulation: visualization of the detector geometry and event data.

An initial version of the BGV geometry description is implemented (see Fig. 4). Algorithms exist that allow the simulated data to be represented in a format identical to the one used by the BGV data acquisition system. Ongoing developments concentrate on track reconstruction and detector-specific simulation (thermal noise, spillover, clusterization, etc.). The addition of a vertex fitting algorithm will allow performance and beam profile measurement studies to be made.

CONCLUSIONS

A transverse beam profile monitor using the beam-gas vertexing technique [1] is being developed for the LHC and its luminosity upgrade. A Demonstrator BGV system is being prepared for installation on one beam at the LHC before the end of 2014, with commissioning of the system planned for 2015. The results and experience from this prototype will be used for the development of a more advanced BGV system as part of the High Luminosity LHC upgrade project.

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