FIRST LHC TRANSVERSE BEAM SIZE MEASUREMENTS WITH THE BEAM GAS VERTEX DETECTOR*

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Abstract

The Beam Gas Vertex detector (BGV) is an innovative beam profile monitor based on the reconstruction of beam-gas interaction vertices which is being developed as part of the High Luminosity LHC project. Tracks are identified using several planes of scintillating fibres, located outside the beam vacuum chamber and perpendicular to the beam axis. The gas pressure in the interaction volume is adjusted such as to provide an adequate trigger rate, without disturbing the beam. A BGV demonstrator monitoring one of the two LHC beams was fully installed and commissioned in 2016. First data and beam size measurements show that the complete detector and data acquisition system is operating as expected. The BGV operating parameters are now being optimised and the reconstruction algorithms developed to produce accurate and fast reconstruction on a CPU farm in order to provide real time beam profile measurements to the LHC operators.

INTRODUCTION

The Beam Gas Vertex detector is a beam profile monitor being developed as part of the high luminosity LHC upgrade [1]. Beam profile measurement based on this method and detector was initially developed at the LHCb experiment [2]. A noble gas is injected in a modified vacuum chamber producing inelastic beam-gas interactions. The charged particles produced in the beam-gas collisions are measured with high precision tracking detectors used to measure the position of the interaction vertices. The BGV allows for non-invasive beam profile and position measurements to be made throughout the full LHC cycle, irrespective of beam energy or luminosity. The detector has been designed to estimate the average transverse beam profile with a precision of about 10% in approximately 5 minutes of integrated beam time [3]. Higher trigger rates and integration times should allow beam profile measurements on a bunch-by-bunch basis. Based on the beam width σ and given the β-function and dispersion of the magnetic lattice (measured independently), the emittance ϵ can be calculated. The detector can additionally be used for measurements of beam tilt, relative bunch populations and ghost charges (beam intensity in nominally empty bucket slots) [3,4]. Adding a timing detector would also allow one to measure the longitudinal beam profile.

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THE BGV DEMONSTRATOR

Detector Design

The BGV detector has been installed at Point 4 of the LHC on the beam 2 ring (Fig. 1). The detector consists of three main parts: the gas target volume, the tracking detector and the hardware trigger.

The target gas container consists of an aluminium (Al 2219) vacuum chamber of approximately 2 m length and 200 mm maximum diameter. The chamber allows for the injection of (neon) gas giving a local pressure bump of up to about 1×10^{-7} mbar. The BGV vacuum system was optimized to provide a sharp pressure decrease outside the vacuum chamber minimizing the diffusion of gas particles to the beam pipe. In order to reduce multiple scattering of particles produced by the beam-gas interactions, the thickness and density of the exit window towards the tracking detector has been minimized, ranging from 3.25 mm down to 1.15 mm close to the beam pipe. In addition, the beam pipe along the tracking detector has been modified to give a reduced diameter of 52 mm instead of 80 mm and minimum material so that the tracking modules can be as close as possible to the beam to increase the acceptance.

The tracking detector is situated behind the exit window. It is comprised of two stations ('near' and 'far') that are about 1 m apart. Each station has 4 scintillating fibre (SciFi) modules, one pair placed above the beam pipe and the other pair below. Within a pair, the modules have their fibres oriented perpendicular to each other to allow a 2-dimensional measurement.

Each SciFi module contains two fibre mats with 4 (near station) or 5 (far station) layers of scintillating fibres of 250 µm diameter [4]. The two mats are rotated by 2° with respect to each other in order to facilitate pattern recognition. A one-dimensional position measurement resolution of 32 µm has been achieved with a test beam setup [5]. The fibres are read out with silicon photo multipliers (SiPMs) which are cooled with liquid C_6F_{14}. Cooling is needed to improve the signal to noise ratio by reducing the SiPM dark count rate which increases with radiation dose. The radiation dose absorbed by the detector is monitored by a RadMon active

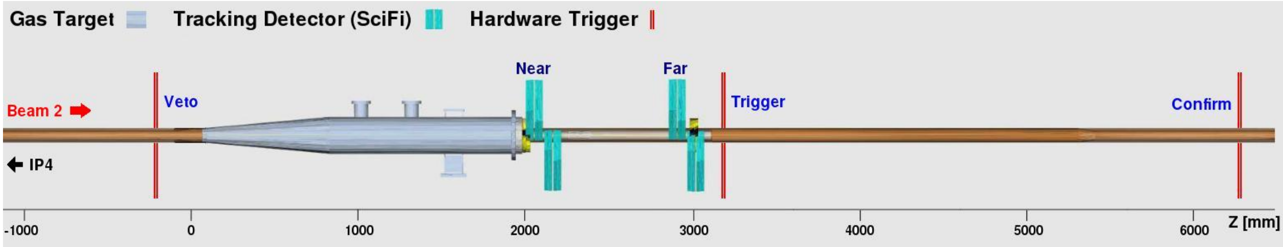

Figure 1: The BGV detector consists of three main parts: the gas target, the tracking detector & the hardware trigger.

detector [6], as well as 6 PIN diodes placed close to the SiPMs.

The BGV trigger consists of scintillator plates with dimensions $30 \times 30\,\mathrm{cm}^2$, arranged in 3 stations. A pair of scintillators is located before the gas target and is used to veto interactions occurring upstream of the target chamber. A second trigger plane is placed downstream of the SciFi stations and provides the trigger signal. A third trigger plane has recently been installed and will be commissioned during the LHC 2017 run. It will be used in coincidence with the second plane to reject background from the other beam and confirm a crossing particle produced in the gas volume by the correct beam.

Read-out & Timing Control

The read-out chain of the BGV is based on hardware from the LHCb experiment. Each SciFi module is read out by 16 128-channel SiPM arrays operated in Geiger-Müller mode. The Beetle front-end ASIC [7] receives the analogue signals from a SiPM. In order to match the Beetle chip's input current range, the signals are first attenuated by a factor of around 200-500 via an RC circuit. The Beetle has an analogue memory of a programmable maximum length of 160 stages with a serial read-out at the LHC bunch frequency of 40 MHz. Subsequently, the data are time-multiplexed on 4 output ports of 32 channels to form an analogue link (A-link) over which data are forwarded to the VELO repeater boards. At the repeater boards the signal data is amplified and sent over 60 m of cables to the TELL1 boards [8] for digitization.

The timing control of the data acquisition system is supervised by the ODIN board [9]. The board accepts the input from the hardware trigger and then sends a trigger to the Beetle chips to start transmission of the data. Timing studies of the coarse and the fine delays have been performed to ensure that the correct slot of the Beetle memory is retrieved [4].

BGV DATA

Several data taking campaigns were carried out after the commissioning of the detector during the 2016 LHC run, along with studies related to its proper operation and data acquisition.

Data corrections & clustering

The raw data have to be corrected for effects related to the SiPMs and the read-out electronics before being processed for the final estimation of the beam position and beam size. The corrections are applied in reverse order to how they are introduced in the read-out chain and include: pedestal subtraction, common mode noise suppression and channel correlation corrections. In the future, these steps will be implemented in the FPGAs of the TELL1 boards and performed in real-time. Further studies and analysis of these corrections can be found in [10, 11].

The energy deposited by a traversing particle is dispersed over several detector channels and must be assembled into a cluster. The clustering is performed by groups of 64 channels and uses a three threshold algorithm to suppress noise. Initially, a search is made for a signal over a given threshold. Clusters are formed by including neighbouring channels that themselves contain a significant amount of signal. Finally, the central position of the cluster is calculated as the weighted mean value of the signals inside the cluster [12, 13].

Analysis Method

Tracks are formed using clusters which are found in all 8 consecutive SciFi layers. For each track two parameters are calculated: the impact parameter d_{xy} which refers to the distance of closest approach of the reconstructed track to the z-axis; the azimuthal angle of the track ϕ is defined as the angle between the x-y projection of the track and the x-axis. These two parameters are related for a given position (x_0, y_0) of the primary vertex:

$$d_{xy} = x_0 \sin(\phi) - y_0 \cos(\phi) \tag{1}$$

The transverse beam width can be calculated using the impact parameter correlation (IPC) method. The event-by-event displacement due to the finite beam width affects all particles of a beam-gas interaction in the same way, thus a correlation is introduced. In the case of an untilted beam ellipse, and assuming the beam width at the BGV location to be $\sigma_x = \sigma_y = \sigma_{beam}$, this correlation can be described as [14, 15]:

$$\langle d_{xy}^{(1)} d_{xy}^{(2)} \rangle = \sigma_{beam}^2 \cos(\phi_1 - \phi_2) \tag{2}$$

where d_{xy} refers to the impact parameter of each track originating from the same vertex and ϕ to its azimuthal angle.

Results from the 2016 LHC Run

During the 2016 LHC run the detector was operated with a neon gas pressure of approximately 6×10^{-8} mbar which

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is assumed homogeneous inside the gas targets volume. The SiPMs were cooled to −25°C and the thresholds of the trigger system were set to very low values on the veto side so that the trigger becomes more selective. The results presented are based on non-zero-suppressed data sets taken during LHC fill 5570 over a time period of ∼5 minutes and with a rate of about 1 kHz.

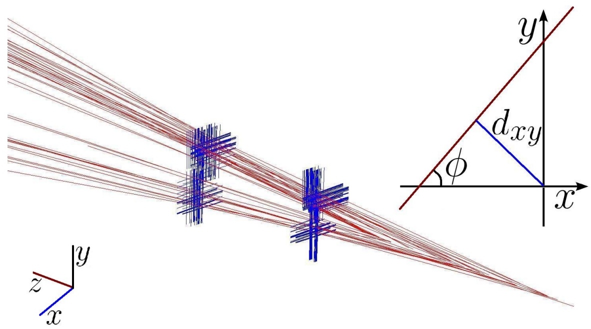

Figure 2: An event display at the BGV detector using the LHCb software *Panoramix*. A representation of the impact parameter d_{xy} and the azimuthal angle ϕ of the track is also displayed.

The distribution of the z-coordinates at which the impact parameter is minimized is displayed in Fig. 3. The measurements are well inside the limits of the gas target and are correlated with the expected gas pressure profile.

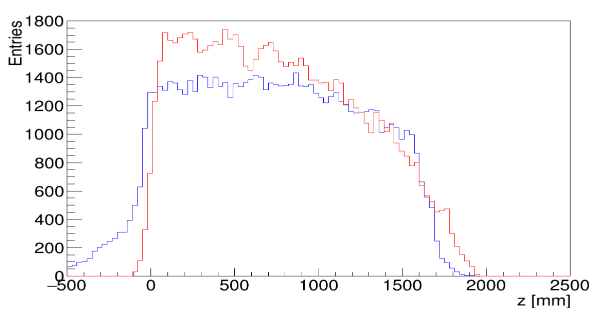

Figure 3: A comparison of the histograms of the points of closest approach to the z-axis between tracks from Monte Carlo (red) and the LHC data set (blue).

Plotting the d_0 against ϕ and using equation (1) the beam position can be estimated (Fig. 4), in this case giving $x = -0.75$ mm, $y = 0.29$ mm.

Using the IPC estimator (eq. 2) the σ^2_{beam} is expressed as the slope of the linear fit of the $\langle d^{(1)}_{xy} d^{(2)}_{xy} \rangle$ versus $\cos\Delta\phi$ (Fig. 5). The transverse beam width is measured as $\sigma_{beam} = (0.37 \pm 0.13(stat.))$ mm. Further refinement of the vertexing algorithm along with better event selection through improved triggering will be required to reduce this rather large statistical error and allow a full comparison with other LHC profile measurement devices.

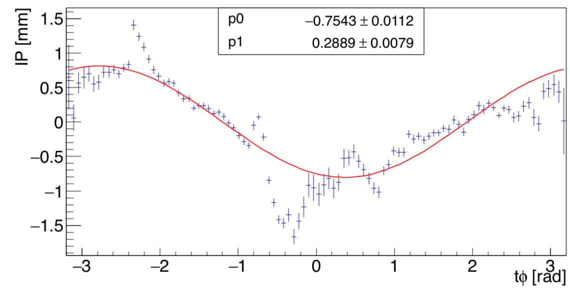

Figure 4: Beam position estimation using the the d_0 vs ϕ method. The fit (red curve) returns a beam position estimation of (−0.75 mm, 0.29 mm) relative to the detector frame.

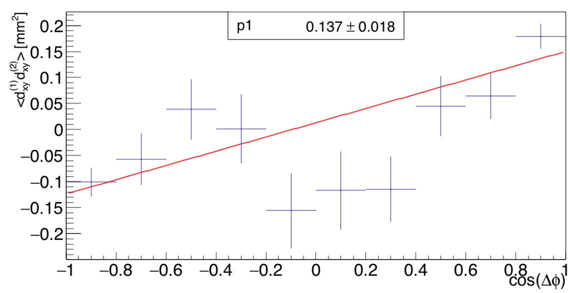

Figure 5: Using the IPC method the beam width is estimated to be $\sigma_{beam} = (0.37 \pm 0.13(stat.))$ mm.

SUMMARY & OUTLOOK

The BGV detector has successfully completed its first commissioning steps during the 2016 LHC run. The detector and acquisition system is fully operational and the first data have demonstrated the proper functioning of the complete BGV system. First test measurements result in a transverse beam size estimation with a 0.13 mm statistical error after 5 minutes at a trigger rate of 1 kHz. A larger rate of 100 kHz data will be achieved with the implementation of zero-suppressed acquisition, inserting the data corrections and the clustering in the FPGAs of the read-out electronics, and optimizing the track analysis for real-time execution in a CPU farm [16]. Adding the third plane of the hardware trigger will also drastically improve the selection of events. All of this is expected to reduce the statistical error by a factor of 10. A cross-calibration of the BGV to other instruments during special LHC runs will lead to the determination of any corrections needed. The first real-time beam width results from the BGV demonstrator are expected to be sent to the LHC control room during the 2017 run.

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