ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-WE3AB1

THE LHC BEAM GAS VERTEX DETECTOR - A NON-INVASIVE PROFILE MONITOR FOR HIGH ENERGY MACHINES*

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Abstract

The Beam Gas Vertex (BGV) monitor is being developed as part of the High Luminosity LHC project with the aim of providing measurements with less than 5% error on the beam size with an integration time of 5 minutes. It will be an instrument capable of non-invasive beam size measurements throughout the LHC acceleration cycle with high intensity physics beams. A prototype BGV monitor has been installed in the LHC since 2016. Particles emerging from beam-gas interactions are recorded by two tracking stations made of scintillating fibres. Based on vertex reconstruction of the detected tracks, this monitor allows for a non-invasive measurement of the beam profile with bunch-by-bunch resolution. A dedicated computer farm performs track reconstruction and event analysis online so that real-time beam profile measurements can be provided. Data taken in 2016 and 2017 will be presented that demonstrate the potential of this method.

INTRODUCTION

The LHC Beam Gas Vertex (BGV) detector is a non-invasive beam profile monitor being developed for use as part of the high luminosity LHC upgrade (HL-LHC) [1]. The BGV system reconstructs the transverse beam profile by detecting particles from inelastic beam-gas collisions [2]. A gas tank is installed in the path of each circulating beam so that noble gas (initially Ne) is injected in the beam's trajectory. Particles emerging from the beam-gas collisions are detected by several planes of scintillating fibre detectors (SciFi) to enable a precise track reconstruction. These tracks are in turn used to reconstruct the vertex of each collision building-up a picture of the transverse beam profile. This method, originally developed for the LHCb experiment [3], allows profile measurements in real time. The pressure in the gas volume can be tuned to accommodate a large range of accelerator luminosity and/or inelastic beam-gas cross-section (i.e. beam energy). Using five minutes of beam time data, the BGV system is intended to provide an absolute measurement of the transverse beam profile with less than 10% error [4]. The transverse profile of individual bunches may also be reconstructed. Based on the beam width and given the β-function and dispersion of the magnetic lattice (measured independently), the emittance ϵ can be calculated. With enough statistics the detector can in addition measure beam tilt. Furthermore, relative bunch populations and ghost charges (beam intensity in nominally empty RF buckets) can be quickly estimated by using the BGV trigger system as for these measurements no precise tracking or vertex reconstruction is needed.

The addition of a precise timing detector (with a resolution of approximately 50 ps) would allow also the measurement of the longitudinal beam profile.

One BGV demonstrator is currently installed at Point 4 of the LHC on the beam 2 ring. A location where β_x and β_y are similar was selected, giving similar profiles in both planes and allowing the use of a reduced diameter beam pipe around the main detector so that it can sit as close as possible to the beam line. At the BGV location the 7 TeV beam to be monitored is expected to have a transverse profile with $\sigma_{x,y} \approx 0.22$ mm. The BGV system is composed of three independent parts: The gas target where beam-gas interactions occur, the trigger system that selects interactions originating from the volume of interest and the precise tracking system used to reconstruct tracks and vertices (Fig. 1).

THE GAS TARGET SYSTEM

The gas target vacuum system was designed to have a minimal impact both on the passing beam and on the particles emerging from the beam-gas interactions. It is made of aluminium (Al 2219) and is approximately 2 metres long. It consists of three parts: a 0.75 m long conical tube at the beam entry (to minimise beam impedance) followed by the gas target itself, a 1.25 m long cylinder with a diameter of 200 mm, and ending with a thin exit window towards the trigger and tracking detectors. The exit window has a thickness ranging from 3.25 mm at its edges to 1.15 mm close to the beam pipe, in order to minimise the multiple scattering of the emerging particles. The beam pipe around the end of the conical section has been reduced to a diameter of 58 mm (instead of the nominal 80 mm) and around the tracking detectors to a diameter of 52 mm. This serves two purposes. First of all it allows the BGV tracking detectors to be as

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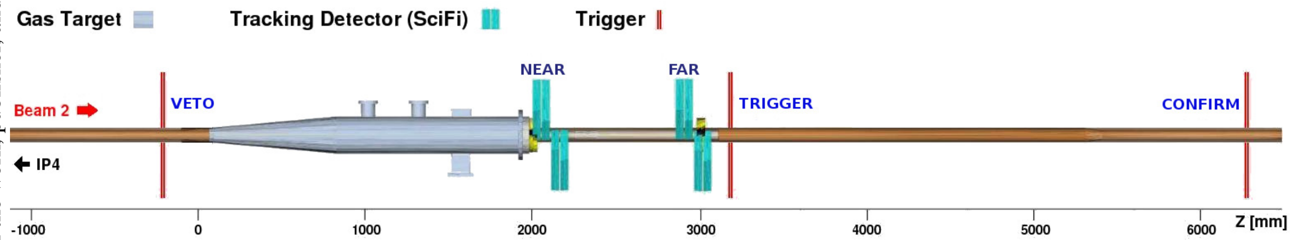

Figure 1: The BGV detector with its three main components: The gas target, the tracking detector and the trigger system.

close as possible to the beam pipe in order to increase the detector acceptance as most of the particles produced are in the very forward direction, and improve the track and vertex resolution by reducing the extrapolation distance. Secondly, the reduced beam pipe dimensions act as a gas flow restriction that allows the target gas pressure to reach $1 \cdot 10^{-7}$ mbar, while the pressure in the adjacent beam pipes can be kept at the nominal LHC vacuum pressure ($1 \cdot 10^{-11}$ mbar).

Neon is currently being used for the gas target in the BGV system. The expected beam-gas interaction rate R per bunch can be estimated by the following formula:

$$R = \int_{z_a}^{z_b} \rho(z) dz \, \sigma_{\mathrm{pA}}(E) N f_{\mathrm{rev}} \tag{1}$$

where $\rho(z)$ is the gas density, $\sigma_{\mathrm{pA}}(E)$ the proton-nucleus cross-section for proton energy E, N is the number of protons per bunch and f_{rev} the bunch revolution frequency (11.245 kHz). The integral boundaries z_a, z_b, represent the approximate detectors acceptance limits. Assuming a uniform gas distribution within the target region, Eq. 1 reduces to:

$$R(\mathrm{Hz}) = 2.5 \cdot 10^{-11} p(\mathrm{mbar}) \Delta z(\mathrm{cm}) \sigma_{\mathrm{pA}}(\mathrm{mb}) N f_{\mathrm{rev}}(\mathrm{Hz}) \tag{2}$$

Using $p = 10^{-7}$ mbar, $\Delta z = 100$ cm, $\sigma_{\mathrm{pA}} = 295$ mb (for 7 TeV protons and Ne gas target) and $N = 10^{11}$ p/bunch, one gets an expected rate of beam-gas inelastic events $R = 81$ Hz per bunch. It should be noted that as $\sigma_{\mathrm{pA}}(E) \approx \sigma_{\mathrm{pp}}(E) A^{2/3}$, a heavier gas would lead to an increased event rate.

THE TRIGGER SYSTEM

In order to identify beam-gas interactions the BGV detector is using a dedicated trigger system composed of three scintillator stations. The first (VETO) is upstream of the target region volume to reject particles not originating from the gas target. The second (TRIGGER) is just after the tracking detectors, while a third trigger station (CONFIRM) further downstream is used in coincidence with the TRIGGER station to identify particles passing through the whole BGV set-up. The trigger stations are placed outside the gas target to precision detector region so that no additional multiple scattering element is introduced into the system. Each trigger station is comprised of two $30 \times 30\,\mathrm{cm}^2$, 1 cm thick plastic scintillator plates placed above and below the beam line, connected to a photomultiplier and read out using a simple level discriminator. During normal LHC operation at a nominal bunch intensity of 10^{11} p/bunch and with nominal gas pressure at the BGV gas target volume this trigger system gives a rate of about 300 Hz per bunch.

By comparing the response time of the TRIGGER and the CONFIRM trigger stations for the same events, the time resolution of each station can be measured. Figure 2 shows the time difference distribution between these two scintillators. It has a width of 1.1 ns which implies a time resolution per station of 0.8 ns. This resolution is well in accordance with expectations given the time jitter generated by the scintillation process. In the near future the tails of the distribution will be further reduced by using constant fraction discriminators. This will also reduce the trigger rate as it will allow fine tuning of the trigger coincidence time windows. The

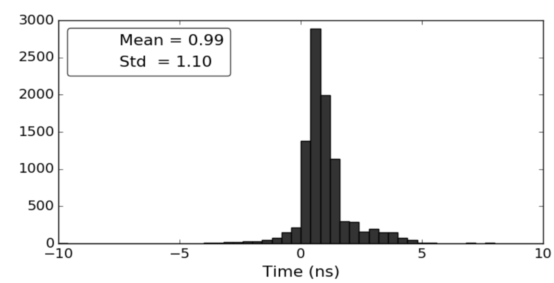

Figure 2: Time difference between signals at the TRIGGER and CONFIRM trigger stations.

excellent timing properties of the BGV trigger system allows it to be used independently for beam quality measurements as the exact beam bunch ID of each triggered event can be identified (LHC bunches are 25 ns apart). The relative bunch intensity and its time evolution can therefore be measured as well as the ghost charge fraction (the fraction of protons in RF buckets that are nominally empty). Figure 3 shows the full LHC bunch structure as measured by the BGV trigger system (and compared for reference with the measurements of the LHC Beam Current Transformer (BCT) system). From the data in Fig. 3 the ghost charge fraction for LHC fill 6053 is measured to be 2.9‰. By performing a similar measurement without injecting gas in the BGV gas target volume the systematic error of this measurement is estimated to be of the order of 0.3‰. The comparison of trigger rates with and without gas injected showed that the trigger background contamination is at the level of 10^{-4}.

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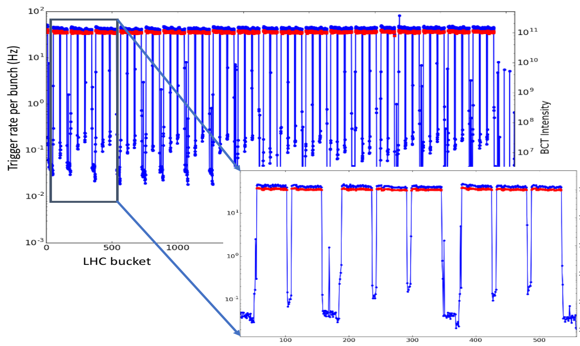

Figure 3: The LHC bunch structure as measured by the BGV trigger system (blue points). The insert is a zoom in an area of a few LHC bunches demonstrating the ability of the system to clearly identify individual bunches and their relative intensities. For comparison the intensity measurements from the Beam Current Transformer (BCT) are superimposed (red points). The BGV rate is not normalized to the absolute LHC beam intensity.

THE PRECISION TRACKING DETECTOR

The BGV precision tracking system consists of two tracking stations. One (the NEAR station) is situated just after the gas target exit window, and the other (the FAR station) one metre further downstream. For beam profile measurements the important parameter to be measured per track is its impact parameter (IP) (the distance of closest approach to the z-axis) and its error σ_{IP} (see the following section for more details). This error can be decomposed into two parts. One is due to the detector resolution and its impact on the track extrapolation to the point of closest approach. The other is due to multiple scattering introduced by material in the detected particle's path: $\sigma_{\text{IP}}^2 = \sigma_{\text{Extrap}}^2 + \sigma_{\text{MultScat}}^2$. If tracks are measured by two consecutive detector planes placed at positions z_1 and z_2 from the interaction point and each position measurement has an error σ_{hit} then:

$$\sigma_{\text{Extrap}} = \sqrt{\frac{z_1^2 + z_2^2}{(z_2 - z_1)^2}}\,\sigma_{\text{hit}} \qquad (3)$$

The multiple scattering error can, in a simplified approximation, be given by the following formula:

$$\sigma_{\text{MultScat}} = z_1 \frac{13.6\,\text{MeV}}{p}\sqrt{\frac{x}{X_0}} \qquad (4)$$

where p is the detected particle's momentum and x/X_0 the thickness of the material transversed in units of radiation lengths. For the material thickness calculation both the gas volume exit window and the first, upstream, tracking module should be taken into account. Given an expected hit resolution of σ_{hit} ~70 µm, the distance between the two tracking stations was selected such that σ_{Extrap} remains smaller than σ_{MultScat}, and the whole tracker was placed as close as possible to the BGV gas volume.

Each BGV tracking 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 [5]. The NEAR station has fewer layers in order to reduce multiple scattering effects. 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 [6] for well separated tracks in a low background environment. The fibres are read out with silicon photomultipliers (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 detector [7], as well as 6 PIN diodes placed close to the SiPMs.

The read-out chain of the BGV system uses hardware from the LHCb experiment. Each SciFi module is read-out by 16 128-channel SiPM arrays operated in Geiger-Müller mode. Beetle front-end ASICs [8] then receive the analogue signals from the SiPMs. The Beetle ASIC has an analogue input memory of 160 steps maximum length with an analogue, serial output at the LHC bunch frequency of 40 MHz. This serialized analogue output data is time-multiplexed on 4 ports of 32 channels to form an analogue link (A-link) over which data is forwarded to the VELO repeater boards situated a few metres away from the BGV detector inside the LHC tunnel. They amplify the signal data and send it over 60 m of cables to the service cavern where radiation levels are considerably lower. There the analogue signals are digitised by TELL1 boards [9].

The timing control of the data acquisition system is supervised by the LHCb ODIN board [10]. For every trigger signal received from the BGV trigger system it initiates and controls the front-end (Beetle) data transmission. Dedicated timing studies with real data have been performed to ensure that the correct slot of the Beetle memory is retrieved [5].

THE DATA ANALYSIS METHOD

In order to measure the transverse beam profile with the BGV data, one has first to process the raw data and transform SciFi hits to clusters induced by passing particles. These clusters then need to be analysed for tracks through an adequate pattern recognition method. With these tracks fitted the final relevant event parameters are found. Raw data has first to be corrected for effects related to the SiPMs and the read-out electronics. The corrections are applied in the 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 front-end FPGAs of the TELL1 boards and will be performed online. Fur-

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ther studies and analysis of these corrections can be found in [11, 12].

Energy deposited by particles transversing a SciFi plane is dispersed over several SiPM detector channels. A cluster has therefore to be formed using the amplitude information of all channels hit by a single particle. 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 (ADC Seed Threshold). Clusters are then formed by including neighbouring channels that themselves contain a significant amount of signal (ADC Neighbour Threshold). Finally only clusters with a considerable total energy deposited are retained (sum of amplitudes in a cluster above ADC Sum Threshold). For each cluster its central position is calculated as the weighted average of the signal amplitudes within it [13]. The SiPM hit read-out and clustering algorithm are shown in Fig.4.

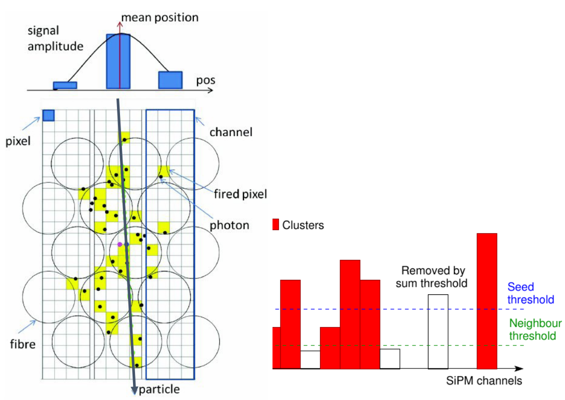

Figure 4: Left: Signal formation in a SciFi module. Scintillation photons are detected by several SciFi fibres. The sum of signals within a SiPM channel is read out. A weighted average is used to measure the exact coordinate of a hit. Right: Clustering algorithm and thresholds [11].

Using the clusters found per event a simple 3D pattern recognition method identifies clusters that belong to the same particle originated from the BGV gas volume. This starts from clusters at the furthest downstream SciFi plane and then searches the other planes using a search window that links the original clusters to the BGV gas target area. If clusters are found along this path (normally seven or eight are found) they are grouped together for a track fit. This is a simple straight line fit with the χ^2 method used to define the corresponding line parameters. A typical reconstructed BGV event is shown in Fig. 5.

Once tracks are found, and their parameters established, two methods allow the reconstruction of the beam profile. A vertex fit may be performed using all reconstructed tracks of each event. The vertex distribution on the (x, y) plane then provides a 2D image of the passing beam. Alternatively the beam width may be estimated using the beam impact parameter correlation (IPC) method.

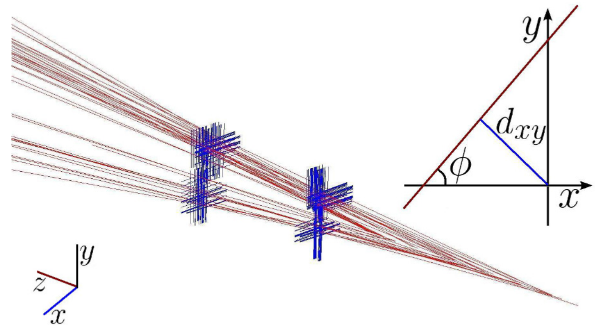

Figure 5: An event display at the BGV detector using the LHCb software *Panoramix*. Blue lines are the individual SciFi identified clusters. Red lines represent the tracks reconstructed for this event. The impact parameter d_{xy} and the azimuthal angle ϕ of the track are also defined in the insert.

For the IPC method two parameters are calculated per track: 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 , which is defined as the angle between the x-y projection of the track and the x-axis (for a visualisation of these two variables see Fig. 5). These two parameters are related for a given position (x_0, y_0) of the primary vertex by:

$$d_{xy} = x_0 \sin(\phi) - y_0 \cos(\phi) \quad (5)$$

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 have $\sigma_x = \sigma_y = \sigma_{\text{beam}}$, this correlation can be described as [14, 15]:

$$\langle d_{xy}^{(1)} d_{xy}^{(2)} \rangle = \sigma_{\text{beam}}^2 \cos(\phi_1 - \phi_2) \quad (6)$$

For the present study the IPC method was used as it provides directly the beam width irrespective of the vertex position and resolution. In the future however both methods will be used and their results will be compared to determine the optimal BGV analysis method.

FIRST BEAM PROFILE MEASUREMENTS

After installation in 2014–2015 and commissioning in 2016, several data taking campaigns with the BGV systems have taken place. Data collected was primarily used to develop and fine-tune all necessary algorithms and data analysis procedures. The results presented in this section were obtained during LHC fill 6082 (August 2017). The pressure in the gas target volume was $5 \cdot 10^{-8}$ mbar. The SiPMs were cooled to −10 °C. All SiPM channels were read out (more than 99% of the channels were active) and the corrections and clustering were performed offline. The BGV trigger rate

6th International Beam Instrumentation Conference IBIC2017, Grand Rapids, MI, USA JACoW Publishing
ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-WE3AB1

was about 1 kHz. The data sample presented corresponds to ~5 minutes of real-time data taking. The following selection criteria have been applied to the dataset used:

Cluster requirements:

1. ADC Seed Threshold = 40 (corresponding to approximately 6 SiPM photoelectrons),
2. ADC Neighbour Threshold = 30,
3. ADC Sum Threshold = 70.

Track requirements:

1. Tracks with clusters in all 8 consecutive SciFi planes,
2. χ^2/ndf of track fit < 0.5,
3. 0 m < z at point of closest approach < 2 m
4. 0 mm < d_{xy} < 1 mm

Event requirements:

1. 2 < total number of tracks found < 50,
2. matching BCID between selected events and LHC beam 2 fill pattern.

Figure 6 shows the distribution of the impact parameter of the reconstructed tracks along the z-axis. It compares well with Monte-Carlo simulation. This distribution is also a clear indication that, as expected, there is no significant residual gas pressure outside the BGV gas target volume and that the gas pressure is almost uniform within the volume.

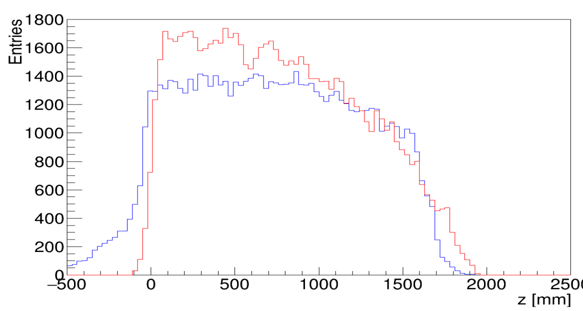

Figure 6: The distribution along the z-axis of the points of closest approach of the reconstructed tracks. Real data (blue) and Monte-Carlo simulation (red).

The distribution of the impact parameter d_0 as a function of the azimuthal angle ϕ is shown in Fig. 7. Fitting this data with the function of Eq. 5 the beam position is estimated to be $x = -0.60$ mm, $y = 0.26$ mm with respect to the (0,0) of the BGV detector's reference frame.

Once the beam offset with respect to the BGV reference frame is established all tracks are shifted accordingly so that they point around $(x, y) = (0, 0)$. In that way no systematic bias is introduced in the beam width analysis. Figure 8 shows the, corrected for the measured beam position, distribution of the correlation of the impact parameter of track pairs from the same event $\langle d^1_{xy} d^2_{xy} \rangle$ as a function of the cosine of their relative azimuthal angle ϕ ($\cos \Delta\phi$). A fit with the function in Eq. 6 yields the transverse beam width to be $\sigma_{\text{beam}} = 0.17 \pm 0.10(\text{stat.})$ mm. Further refinement of the

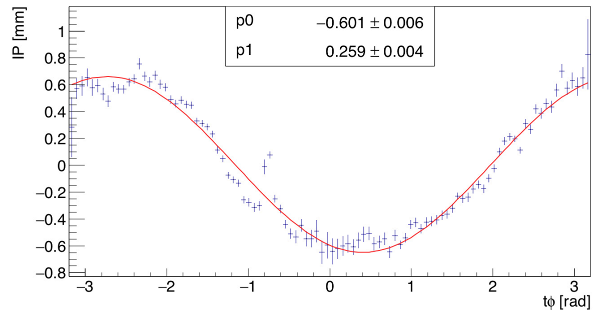

Figure 7: Beam position estimation using the the d_0 vs ϕ method. The impact parameter of reconstructed tracks is plotted as a function of their azimuthal angle ϕ. Fitting with the function of Eq. 5 (red curve) the beam position is estimated to be at $(x, y) = (-0.60\,\text{mm}, 0.26\,\text{mm})$ with respect to the detector's reference frame (0,0).

tracking algorithm along with better event selection through improved triggering will lead to a considerable improvement of the statistical error and allow a full comparison with other LHC beam profile measurement devices.

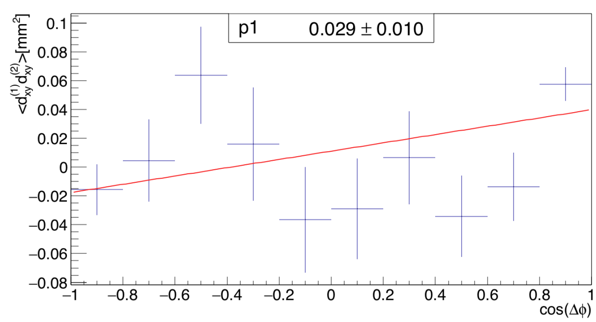

Figure 8: Beam width estimation using the IPC method. The impact parameter correlation is plotted as a function of the cosine of their relative azimuthal angle ϕ. Fitting with the function in Eq. 6 (red line) the transverse beam width is estimated to be $\sigma_{\text{beam}} = 0.17 \pm 0.10(\text{stat.})$ mm.

FUTURE UPGRADES FOR THE BGV SYSTEM

The current BGV system is beginning to demonstrate its ability to reconstruct beam profiles for the LHC. The final systems to be built for HL-LHC will implement a series of improvements as dictated by the current measurements.

Changing the target gas from Neon (20.2 atomic mass) to Argon (39.9 atomic mass) will increase the trigger rate by approximately 50%, with a similar increase expected in the number of tracks produced per beam-gas interaction. This simple upgrade would considerably shorten the integration time required to achieve similar resolution results.

Undoubtably, multiple scattering has a considerable impact on the track reconstruction accuracy and consequently on the beam width measurement resolution. The main source

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of multiple scattering in the BGV system is its aluminium gas target exit window. A redesign to achieve a thickness of approximately 1 mm over its full radius would lead to a 30% to 50% reduction in multiple scattering effects. A further factor of 2 reduction of these effects can be achieved by using an exit window made entirely of beryllium, but this brings with it other safety related issues.

Two options are also under investigation for upgrading the BGV precision tracking detector. One option is based on silicon-strip detectors and the other on micro pattern gas detectors (MicroMegas) [16]. The former has the advantage of using commercially available sensors, while the latter can be made with very thin sensors (about 100 µm thick compared to 250 µm for Si). They can both operate efficiently in the radiation field around the HL-LHC and have a measurement resolution of approximately 70 µm for a strip pitch (200 µm to 300 µm) that would keep the total number of read-out channels at reasonable levels. Further development of both technologies may allow the usage of double-sided sensors, further reducing their multiple scattering impact.

The BGV system can be upgraded to measure the longitudinal beam profile as well. At the LHC (or HL-LHC) proton bunches have a length of 9 cm which translates to a time spread of 300 ps. Therefore, in order to reconstruct the bunch longitudinal profile with at least 5-6 points, the arrival time at a given detector plane of beam-gas events would have to be registered with a time resolution of 50 ps. Under study for the BGV application is a version of a Micromegas plane detector that is based on measuring the Cherenkov radiation of particles crossing a thin radiator [17]. In this detector design, the UV photons produced travel only a few hundred μm. This allows time measurements with a resolution of 20 ps to 30 ps.

SUMMARY - OUTLOOK

The BGV beam profile monitor was successfully commissioned in 2016 and first measurements with 2017 data are already very encouraging. The gas injection system is very reliable and can, without any interference with the LHC operation, increase the pressure in the BGV gas volume up to $1 \cdot 10^{-7}$ mbar. The trigger system efficiently selects beam gas interactions, while the SciFi tracking detector has excellent resolution, is very reliable and has more than 99% of its channels operational. This allows for a very good reconstruction of tracks emerging from beam gas interactions. Preliminary results show that the BGV system measures the transverse beam width with a resolution of 0.13 mm (5 minutes integration time, 1 kHz read-out rate), a result that is for the moment limited by statistics. The zero suppression implementation in the front-end electronics will allow the read-out rate to reach 100 kHz. Together with the use of a CPU farm for real-time track reconstruction and profile measurement [18], this should allow beam profiles to be available in the LHC control room before the end of 2017. A cross-calibration of the BGV measurements with other existing beam profile monitors during special runs with well defined operational conditions will allow the determination of any systematic corrections needed.

In the near future improvements in the BGV trigger system (better time resolution and more stringent coincidence in time of the scintillator signals) will improve the purity of the BGV event sample. In that way the processing time of recorded data will be significantly reduced so that beam profile measurements may be provided faster in real time.

If the BGV demonstrator manages to achieve its goal of providing non-invasive, accurate, real-time, bunch-by-bunch beam profile measurements, then it could become the main beam profile monitor for the HL-LHC era, and would surely be a good candidate for both transverse and longitudinal beam size diagnostics in any future high energy hadron machines.

In addition there is no limitation that would exclude its use at future higher luminosity or energy machines.

ACKNOWLEDGMENTS

We would like to thank the LHCb Collaboration, in particular Clara Gaspar, Niko Neufeld and Markus Frank, for the support in the development of the BGV online control system. We wish to express our sorrow over the recent death of Bernd Dehning, a leading collaborator of the BGV project, and dedicate these first results to his memory.

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