THE HL-LHC BEAM GAS VERTEX MONITOR - SIMULATIONS FOR DESIGN OPTIMISATION AND PERFORMANCE STUDY

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Abstract

The Beam Gas Vertex (BGV) instrument is a non-invasive transverse beam profile monitor being designed as part of the High Luminosity Upgrade of the LHC (HL-LHC) at CERN. Its aim is to continuously measure bunch-by-bunch beam profiles, independent of beam intensity, throughout the entire LHC cycle. The primary components of the BGV monitor are a gas target and a forward tracking detector. Secondary particles emerging from inelastic beam-gas interactions are detected by the tracker. The beam profile is then inferred from the spatial distribution of reconstructed vertices of said interactions. Based on insights and conclusions acquired by a demonstrator device which was operated in the LHC during Run 2, a new design is being developed to fulfil the HL-LHC specifications. This contribution describes the status of the simulation studies being performed to evaluate the impact of design parameters on the instrument's performance and identify gas target and tracker requirements.

INTRODUCTION

The BGV device is a novel beam profile monitor that is currently under development for the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN. Its challenging goal is to provide a continuous measurement of the emittance and transverse beam profile throughout the entire LHC cycle in real time, which has not yet been achieved by any other single instrument in the machine. A conceptual drawing of the BGV can be seen in Fig. 1. The beam size and profile are determined by reconstructing secondary particles from inelastic beam-gas interactions that take place in a gas target chamber emplaced on the LHC ring. The particles emerging from the collisions are then observed downstream by a tracking detector. Track and vertex reconstructing methods are used to determine the interaction points with great precision and the beam profile is deduced from the spatial distribution of these points.

In the past, a BGV demonstrator device has been installed, commissioned and operated during LHC Run 2 [1]. While the BGV demonstrator was not able to reconstruct the beam profile due to its limited vertexing capabilities, it successfully measured the beam size and therefore demonstrated the feasibility of the method, and highlighted points that require improvement for a future device.

A new design is currently under development with the aim to overcome the shortcomings of the BGV demonstrator and successfully fulfil the specifications of: (1) measuring the beam size with an accuracy of < 5%, (2) bunch-by-bunch measurements of the beam size with a precision of around 1% and an integration time of around 1 minute and (3) measuring the transverse beam profile.

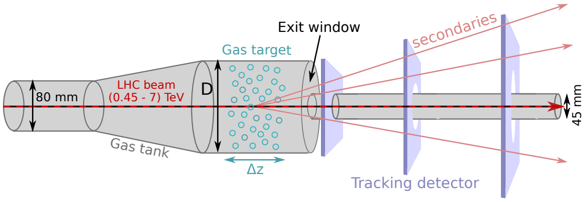

Figure 1: Sketch of the BGV setup.

The vertex resolution needed to resolve the smallest expected beam size of ≈ 200 µm at the foreseen BGV location has been estimated as follows. Assuming bunches with Gaussian transverse distributions with standard deviations of σ_b and a known vertex response with a width of σ_v i.e. the vertex resolution, the measured beam distribution can be assumed to be a convolution of the true beam distribution and the vertex response. Extracting the true beam distribution via deconvolution and using error propagation as well as assuming a negligible measurement uncertainty, yields the following relation for the beam size measurement error [2]: $\frac{\delta\sigma_b}{\sigma_b} = \frac{\sigma_v^2}{\sigma_b^2}\frac{\delta\sigma_v}{\sigma_v}$, where $\delta\sigma_v$ is the absolute vertex resolution uncertainty. This relation highlights the importance of a small σ_v relative to the beam size and precisely knowing the vertex resolution. Using the above listed specifications, we arrive at a lower limit for the vertex resolution of $\sigma_v \lesssim 140$ µm. The main influences on σ_v are: (1) the number of reconstructed secondary particles corresponding to the vertex; (2) the quality of the reconstructed tracks which depends on their momentum, the encountered material and the position resolution of the detector; (3) the distance between the vertex and the first detector plane which needs to be extrapolated and (4) the distances between the detector planes.

A complete simulation study is on-going to explore the large parameter space of the BGV and to study the impact of design parameters on its performance. The aim is to ascertain the requirements for the tracking detector and the gas target within the boundary conditions provided by the feasibility of integrating it into the LHC, budget and time scale. This contribution focuses on the simulation studies revolving around the BGV gas target system. Further studies on the detector choice will be reported elsewhere.

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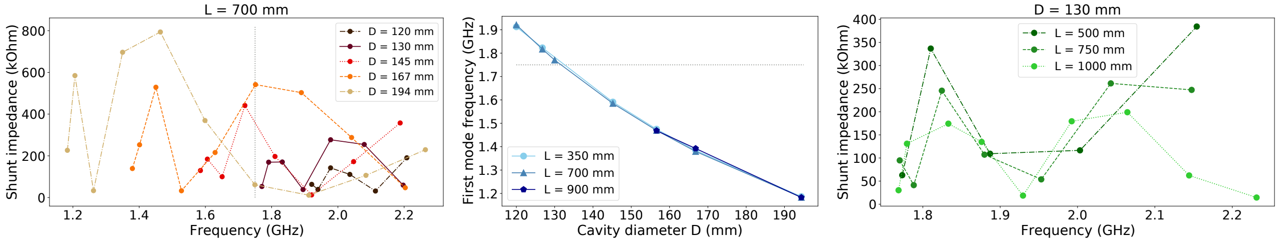

Figure 2: Main longitudinal electromagnetic modes that can be trapped in pillbox tank structures, with a standard LHC vacuum chamber on one side and a reduced aperture chamber on the other. Shunt impedance values are given in circuit convention. On left and right figures, the lines connecting the points help visualising which data belong to the same geometry.

GAS TARGET SYSTEM

Two possible technologies for the BGV gas target are under investigation. The first option is to create an extended vacuum pressure bump of 10^{-7} mbar extending over ≈ 2 m, as was already done for the demonstrator device, which leads to an inelastic interaction rate of ≈ 200 Hz per bunch [1]. A second option is to create a localised vacuum pressure bump extending over a few millimetres by means of a gas curtain, such as that developed for the BGC [3], which helps to identify tracks from the interaction vertex from other particle backgrounds.

The transverse homogeneity of the gas target within the volume the beam traverses during the integration time of 1 min is of importance for an unbiased beam profile measurement, since the measured profile is a convolution of the true beam profile and the gas density of the pressure bump. An inhomogeneous pressure profile would require in-situ monitoring of the gas density and would therefore increase the complexity of the instrument. Furthermore, σ_v is impacted by: (1) the gas species which influences the number of tracks and (2) the pressure which will determine the interaction rate and therefore the number of events with sufficient number of tracks within the given time interval. Related to the chamber housing the gas, the following parameters are of significance for the vertex resolution and are under investigation: (1) the diameter of the tank which will directly influence the size of the tracking detector and therefore the number of tracks in its acceptance; (2) the thickness of the exit window which the tracks need to traverse before reaching the detector and (3) the material of the exit window.

GAS TANK DESIGN

A re-design of the BGV gas chamber based on the demonstrator tank is currently on-going considering performance needs, mechanical stability and integration requirements. A dedicated simulation study using CST Particle Studio [4] is being performed to minimise the impedance of the device for the final HL-LHC design. The BGV gas tank will be connected upstream to a standard LHC vacuum chamber of 80 mm inner diameter, and downstream to a reduced aperture chamber, holding the tracking detectors, as shown on Fig. 1. The inner diameter of this chamber, 45 mm, has been chosen considering the minimum allowed aperture at the foreseen instrument's location in order to remain in the shadow of the collimators [5].

Figure 2 shows the longitudinal impedance results obtained from simulating pillbox shaped tank geometries, scanning their length and diameter. A first diameter scan (left) revealed that small diameter cavities only trap modes at high frequencies, where the beam spectrum has lower intensities, and with lower shunt impedance. Changing the cavity length doesn't affect the mode frequencies (center), however longer cavities show more possible trapped modes of smaller shunt impedance (right). From these first scans, it was concluded that the tank diameter should remain below 130 mm to avoid trapped modes with frequencies smaller than 1.7 GHz. Shunt impedance values are in the order of several hundreds of kΩ for the observed modes and for 70 cm long cavities without tapers, see Fig. 2. Adding a long upstream taper will help reduce these values. Scans of the taper angle are on-going in order for the tank shape to fit within the machine impedance budget. The transverse impedance will be estimated once the final shape will be known.

The exit window of the gas tank will be a significant contributor to the scattering of the secondary particles and will have a significant effect on the instrument performance. Studies are on-going to optimise the exit window design, in particular the material type, shape & thickness, in order to reach sufficient mechanical robustness while minimising the amount of material seen by the secondary particles.

BEAM-GAS INTERACTIONS

In order to determine the performance of the BGV, it is crucial to estimate the expected multiplicity of secondary emerging from the beam-gas interactions as well as their properties such as momentum and pseudo-rapidity. Several event generators were employed to model the inelastic hadronic proton-gas interactions. The models discussed here are HIJING 1.411 [6], which has been used by the BGV team in the past [7], and the two general purpose models DPMJET 3.06 [8] and EPOS LHC [9]. The latter two were accessed via the package CRMC (Cosmic Ray Monte Carlo) [10] which serves as an interface to event generators used for hadronic collisions. The Geant4 [11] models FRITIOF and QGS have not been included into the comparison here, because both models have an upper validity limit of ≈ 1 TeV [12].

Simulations have been performed for injection and flat top energy, i.e. 450 GeV and 7 TeV. The target gas species used for the presented results is Neon. The secondaries are assumed to emerge from a point source positioned at the origin. The particles within the detector acceptance are registered for further analysis. The detector acceptance is here assumed to cover the full extent of the exit window of a tank with the maximum diameter of 130 mm (cf. previous section). Initially, the distance between the source and the first detector plane (d_t) is scanned from 200 mm to 1000 mm in 50 mm steps, in order to determine the d_t at which the highest number of tracks is observed, see Fig. 3. As a measure of performance, the highest average number of charged pion tracks per event has been chosen, since the large majority of secondary particles are pions. The optimal d_t is defined as the distance showing the highest number of average tracks per event for injection energy, since those events show generally less tracks per event compared to 7 TeV events, ranges between 500 mm to 600 mm depending on the hadronic model. The data features a flat plateau in that region (cf. Fig. 3), therefore all results discussed below assume a d_t of 550 mm.

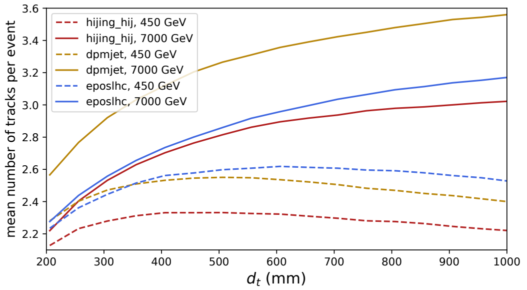

Figure 3: Mean number of tracks per event as a function of the distance between the gas target and the first detector plane. Dashed lines correspond to results with 450 GeV, solid lines to 7 TeV primary protons.

The charged pion multiplicity distributions within the detector acceptance can be seen in Fig. 4 (middle). The distributions exhibit some differences in the prediction of the models especially for low track numbers. However for the purpose of the BGV performance evaluation, the agreement between the models is sufficient. The pseudo-rapidity distributions of all emerging secondaries are shown in Fig. 4 (top), as well as the range covered by the detector. As expected, most tracks emerge in the forward direction. Figure 4 (bottom) displays the absolute momentum distributions of pions in the detector acceptance. As can be seen, most secondaries show relatively low momenta and are therefore prone to multiple scattering. It is therefore imperative to keep the amount of material that the tracks encounter low.

Future measurements with the BGV device of secondary properties of beam-gas interactions could yield valuable input to hadronic generators and help validate and tune those models.

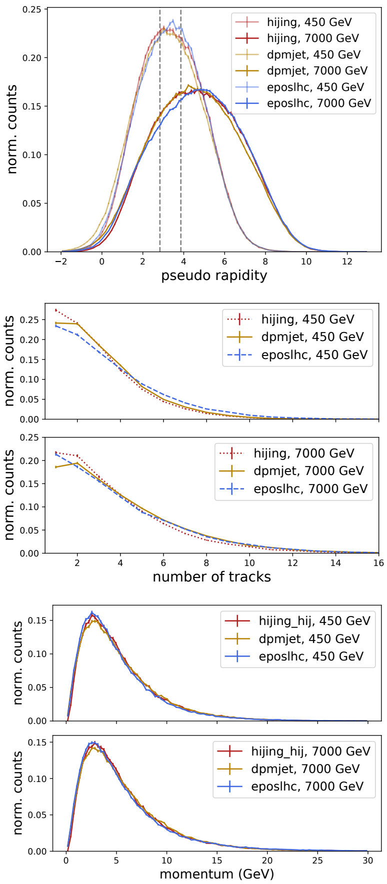

Figure 4: Distributions of secondary particle properties. Pseudo-rapidity distributions (top). Grey, vertical lines show the interval covered by the maximum detector coverage. Multiplicity distribution within the detector acceptance (middle). Momentum distributions (bottom). All distributions have been normalised. Error bars are calculated using Poisson errors.

SUMMARY AND OUTLOOK

A performance and design study of the future BGV is being carried out, based on the results and experiences of the demonstrator device. In addition to the simulations concerning the gas target system that have been discussed here, different detector technology options for the BGV forward tracker are under investigations. Those studies employ Geant4 to simulate the interaction of the particles with the materials of the BGV setup. The performance of different setups is evaluated by determining their corresponding vertex resolution via the track and vertex reconstruction tool-kit ACTS [13].

ACKNOWLEDGEMENTS

This research is supported by the CERN HL-LHC project, and the Royal Holloway University of London. We would like to thank M. Wendt and A. Miarnau for valuable discussions on the gas tank simulations and design, as well as R. De Maria for his input on aperture limitation. We would also like to thank R. Ulrich and T. Pierog for their help with CRMC.

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