MEASURING BEAM SIZE WITH THE LHC BEAM GAS VERTEX DETECTOR*

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Abstract

The Beam Gas Vertex detector (BGV) is an innovative beam profile monitor being developed as part of the High Luminosity LHC (HL-LHC) project at CERN. The goal is to continually measure the transverse beam size by reconstructing tracks originating from beam-gas interactions using high precision tracking detectors. To confirm the feasibility of such a device, a demonstrator based on eight modules of scintillating fibre detectors has been constructed, installed in the LHC and operated for the past 3 years. It will be shown that using the BGV the average transverse beam size can be obtained with a statistical accuracy better than 5 µm (assuming a Gaussian beam with a sigma of ~200 µm). This precision is obtained with an integration time of less than one minute. In addition, the BGV measures the size of individual bunches with a statistical accuracy of better than 5 % within 5 minutes. Results obtained from data acquired in 2018 will be presented and compared to measurements from other beam profile monitors.

INTRODUCTION

The LHC Beam Gas Vertex (BGV) demonstrator is a non-invasive transverse beam size monitor developed as part of the high luminosity upgrade of the LHC (HL-LHC). It uses two tracking stations to reconstruct inelastic beam-gas interactions to measure the transverse beam size in both the horizontal and vertical plane simultaneously. A dedicated gas chamber was installed to provide a uniform target for the beam to interact with, which included a thin exit window for the secondary particles to escape with minimal scattering. High-precision scintillating fibre (SciFi) detectors placed in two stations behind this exit window record the very forward collisions and enable high precision track reconstruction. A dedicated pattern recognition algorithm was developed using the correlation of the impact parameter (IP) of the recognised tracks to calculate the beam size. This method was first developed and tested by the LHCb experiment [1–3]. The BGV demonstrator was installed in point 4 of the LHC and successively commissioned in 2016 and 2017, before running in a near fully operational mode in 2018.

LAYOUT

The BGV setup consists of three main components: a gas target chamber, a precision tracking detector and a trigger system as shown in Fig. 1. For a complete description of the whole setup please refer to [4].

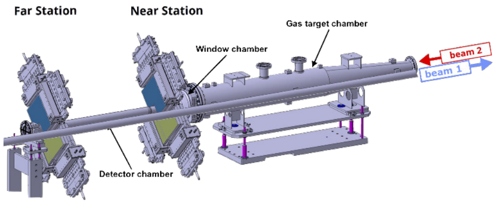

Figure 1: Layout of the BGV detector as installed in the LHC.

ANALYSIS

The BGV analysis consists of reconstructing tracks from the recorded clusters, using the tracks from the same event to calculate the correlation values and then combining the values from many events to calculate the beam size from the correlations. The pattern recognition algorithm for associating clusters with tracks was developed for the special geometry of the demonstrator, utilising the specific layout and properties of the modules to narrow down the large number of possible cluster combinations to those physically possible. The beam size calculation is based on correlating tracks originating from the same vertex, using the Distance Of Closest Approach (DOCA) of each track as previously applied in [5, 6]. Due to the limited geometrical coverage of the SciFi planes the measured beam size differs from the actual beam size, requiring a correction estimated by simulating various beam profiles and comparing the measured and generated size.

RESULTS

All results presented in this section have been recorded using the full BGV detector, and are corrected using the procedure described in [4].

Precision

The distributions of successive BGV beam size measurements over periods of several minutes during stable LHC

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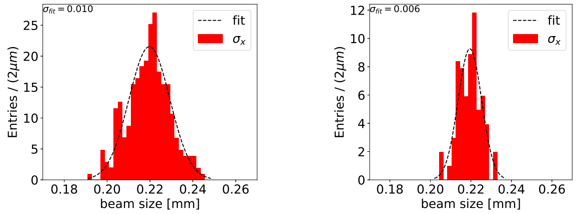
operation conditions (stable beams) are shown in Figs. 2, 4 and 5. These distributions can be approximated by Gaussian functions and hence the error of the BGV measurement can be defined as the width of the associated Gaussian fit. The resulting error scales, as expected, with the inverse square root of the integration time as shown in Fig. 2. As the plots show the number of measurements taken within a fixed time period, the number of entries is reduced accordingly when going from a 5s integration time to a 20s integration time. This, however, has no impact on the error as that is given by the number of events acquired within one integration period. Consequently we can calculate the precision of a measurement given the integration time as shown in Fig. 3. The average beam size is ~0.8 mm at 450 GeV and ~0.2 mm at 6.5 TeV, meaning that an integration time of 6 s and 23 s is required for 2 % precision at injection and top energy respectively.



(a) 5s integration time (b) 20s integration time

Figure 2: Precision based on integration time over a period of 22 minutes for the LHC proton Fill 7329 at 6.5 TeV. Note the change in the sigma of the Gaussian fit denoted in the graph.

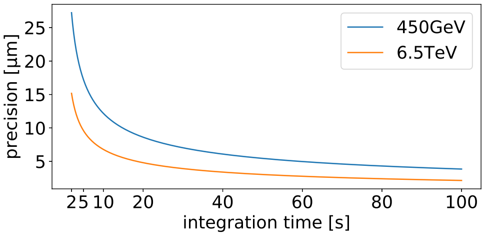


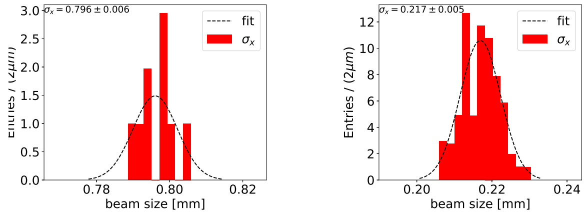
Figure 3: Precision of measurements based on the integration time with 6 kHz read-out rate.

Measurements of Proton Beam

During standard operation the LHC accelerates up to 2556 bunches with 1.1×10^{11} protons per bunch. Fig. 4 compares the measurements obtained at injection energy with those at top energy. Despite the fact that there are fewer events at injection energy the relative error on the beam size is smaller due to the larger overall beam size.

Measurements of Ion Beam

The LHC usually accelerates and collides lead ion beams for one month per year. Due to the lower intensity of the ion beam (1.9×10^{10} ions/bunch vs 1.1×10^{11} protons/bunch) as well as the lower number of circulating bunches (733 vs 2556) the BGV trigger rate is reduced, resulting in the need for an increased integration time to equal the precision obtained with the more intense proton beams.



(a) 450 GeV (b) 6.5 TeV

Figure 4: Size histogram for injection and flat top energies for Fill 7320 with an integration time of 20s per measurement for data acquisition durations of 3 min and 23 min for injection and top energies respectively.

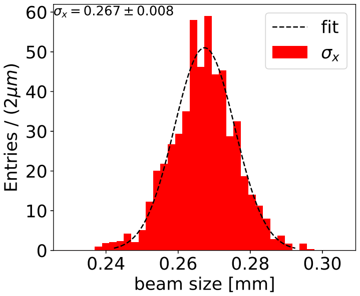


Figure 5: Beam size average over all 733 bunches of ion Fill 7467 at flat top energy (6.3 TeV) with an integration time of 20s per measurement over almost 4 hours.

Measurements of Individual Bunches

The possible read-out and trigger rates of more than 1 MHz allow the BGV to measure the beam size on a bunch-by-bunch basis. With the current demonstrator setup, the processing rate is limited to around 6 kHz, constrained by the amount of computation power installed in the tunnel. A measurement of more than around 30 nominal bunches at the same time therefore reduces the per bunch acquisition rate, with the acquisition rate for a nominal LHC fill with 2556 bunches falling to only 2.3 Hz per bunch. Since the precision of a measurement depends on the number of events used much longer integration times are required for bunch-by-bunch measurements to achieve the equivalent precision as for the average beam size.

To achieve maximum precision for a few selected bunches they can be defined in advance in the acquisition software to dedicate them the full processing bandwidth (Fig. 7).

Measurements During the Energy Ramp

The BGV can measure the beam size at any point during the acceleration cycle from injection to collision energy. The expected change in beam size, assuming a constant

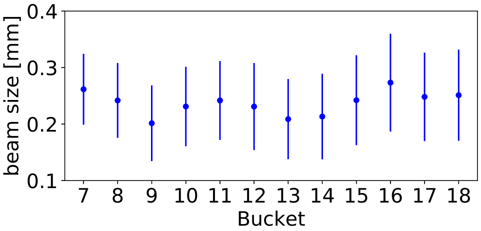


Figure 6: Selection of 12 bunches out of 2556 from a standard measurement performed during Fill 7334 with 150 s of integration time per measurement per bunch.

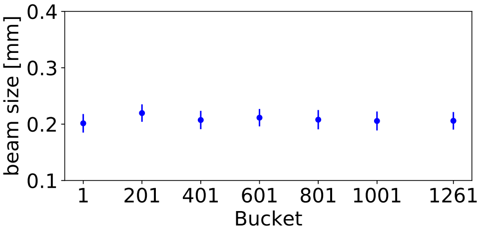


Figure 7: Measurement of 7 bunches during Machine Development Fill 7376 with an event rate of ~50 Hz per bunch. Due to the lower bunch intensity at the time, an integration time of 150 s was again required.

normalized emittance, is given by

$$\sigma(E) = \sigma_{\text{inj}}\sqrt{E_{\text{inj}}/E}. \tag{1}$$

As can be seen in Fig. 8 the BGV measurements follow this trend quite nicely.

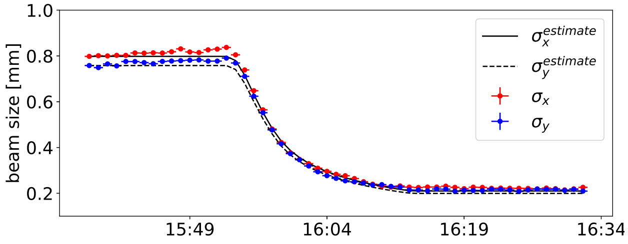


Figure 8: Change of average beam size at the location of the BGV from injection to top energy for LHC Fill 7334 with a 60s integration time. The lines show the expected beam size evolution as given by Eq.1.

Emittance Evolution During Energy Ramp

Using this data the BGV can be used to study the emittance evolution during the LHC acceleration cycle. The normalised emittance is given by

$$\varepsilon_n = \gamma_L \frac{v}{c}\varepsilon = \gamma_L \beta_r \frac{1}{\beta}\left[\sigma^2 - \left(D\frac{dp}{p}\right)^2\right] \tag{2}$$

with $\gamma_L = E/(m_0 c^2)$ and $\beta_r = v/c$, β the optical beta function and D the dispersion.

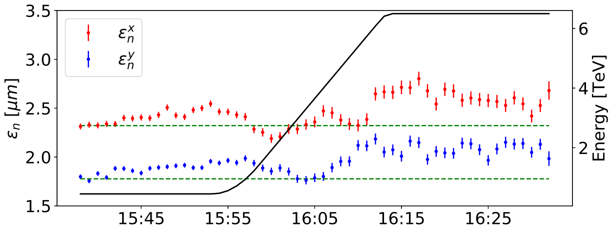


Figure 9: Emittance evolution of proton LHC Fill 7334. The black line denotes the energy of the particle beam and the dashed line the initial emittance.

The proton beam emittance is seen to increase by about 20 % during the energy ramp in both horizontal and vertical planes (Fig. 9). The source of this emittance increase is still unclear, but having an instrument capable of regular measurements throughout the cycle will clearly help to understand this in the future. The unphysical shrinking of emittance observed at various stages in the energy ramp comes from an imprecise knowledge of the optical β function.

For ions the expected decrease of the vertical emittance due to dampening was observed (Fig. 10).

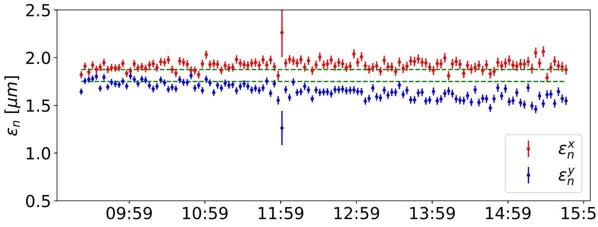


Figure 10: Shows the decrease of the vertical emittance at flat top energy (6.3 TeV) of lead ion LHC Fill 7486 during six hours of data acquisition with 180 s of integration time per measurement. The dashed line denotes the expected constant emittance extrapolated from the first five measurements.

OUTLOOK

The BGV prototype has demonstrated the ability to continuously measure the average transverse beam size with a statistical precision reaching 5 µm with a 20s integration time. Following this success, efforts are currently ongoing to implement a fully-fledged instrument for continuous beam size measurements for the High Luminosity era of the LHC [7].

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