

TRANSVERSE EMITTANCE MEASUREMENTS USING LHCb'S BEAM-GAS INTERACTIONS

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Abstract

Measurements of the transverse beam emittance are of great importance at particle accelerators such as the LHC in order to monitor, understand and improve the performance of the machine. A number of profile monitors at the LHC are capable of measuring the transverse emittance from a range of different processes including wire scanners and beam synchrotron light monitors, each having advantages and shortcomings. It is possible additionally to measure the beam profiles using interaction vertices reconstructed in LHCb's VERteX LOcator (VELO). Interactions between colliding beam particles and between beam particles and residual gas nuclei are used to build up a picture of the beam profiles. To guarantee the reliability and quality of the different emittance measurements, a dedicated cross-calibration was performed during a Machine Development period in October 2016. The results obtained with the LHCb VELO during this cross-calibration are presented here.

INTRODUCTION

At the LHC there are a number of different methods capable of measuring the transverse beam sizes in both planes and for both beams [1]. Using the Beam-Gas Imaging (BGI) method [2], the LHCb experiment has the unique capability of providing measurements of the beam width, which can be used to calculate the transverse emittance. During 2016 the evolution of these measurements were monitored and compared to the existing profile monitors. This culminated in a dedicated cross-calibration Machine Development period in October 2016 in which a small number of bunches with a range of emittances were measured to help understand the relationship between the different profile monitors.

THE LHCb DETECTOR

The LHCb detector is designed to study the decays of b and c quarks produced during proton-proton collisions [3]. The relatively long lifetimes of the hadrons produced necessitates a high-precision tracker around the interaction point to reconstruct the displaced vertices that are characteristic of these decays. However, simultaneously, the LHCb VELO is capable of reconstructing collisions between the bunches of protons and residual gas nuclei, allowing a picture of the beam profile to be built up. These beam-gas interactions are used to produce measurements of the transverse beam properties in real-time during operation. Offline, the analysis can be repeated allowing the full available dataset to be

used, as only a fraction can currently be processed online. A schematic of the whole LHCb detector is illustrated in Fig. 1 along with a 3D model of the VELO sub-detector with a number of tracks originating from a collision.

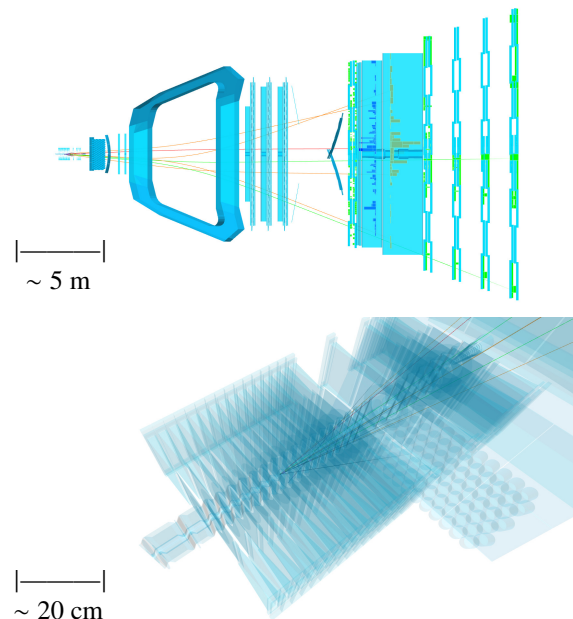


Figure 1: Schematic of the LHCb detector from above with the VELO on the far left (top) and a 3D model of the VELO (bottom).

ONLINE AND OFFLINE ANALYSIS

During data-taking, monitoring of the beam properties involves the collection of suitable reconstructed beam-gas interaction vertices, and the periodic publication of the measured values once sufficient statistics have been accumulated. The beam-gas interactions can be isolated by analysing bunch crossings in which only one of the two beams passed through LHCb. Typical distributions of reconstructed vertices in the horizontal and vertical planes are shown in Fig. 2. The two beams collide at an angle in the horizontal plane as illustrated in this Figure. Currently, due to bandwidth and CPU constraints, only a fraction of bunch crossings are available to process in real time. Offline, the analysis can be repeated using the full available statistics.

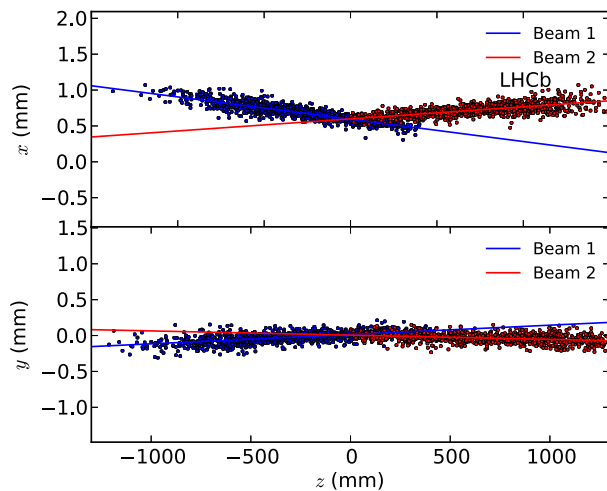


Figure 2: Example distributions of beam-gas vertices within the LHCb VELO in the horizontal (top) and vertical (bottom) planes. Taken from Ref. [4].

Reconstruction

Vertices are reconstructed from tracks originating in the VELO detector. This is performed using standard reconstruction algorithms designed to reconstruct primary interactions within LHCb [5]. Vertices with a minimum of 5 tracks are processed if the position falls within the longitudinal range of the VELO (± 1500 mm) and within a radius of 4 mm to the centre of the VELO. This is to remove vertices resulting from interactions with the material around the beam pipe. Additionally it is required that for Beam 1 (Beam 2) all tracks are in the forward (backward) direction, where forward is defined to be to the right in Fig. 1. This helps to remove vertices from other sources such as smaller satellite bunches that can collide with the main bunch.

Measured Quantities

The first quantity that must be determined from the vertices is the slope of each beam such that the width can be correctly calculated. Each vertex is projected along the slope on to a plane at $z = 0$. The resulting profile is fitted with a single Gaussian distribution. The mean and width of this distribution corresponds to the raw position and width of the beams that are then published. The shape of the beam profile has been studied and found to have a double Gaussian nature. However, for the ease of comparison with the other measurement methods, a single Gaussian shape has been used here.

Bunch-Averaged and Bunch-By-Bunch Measurements

For real-time feedback it is useful to have updates that are both high statistics, to ensure precision, and relatively frequent. Average measurements are produced that contain all bunches present in the respective beams. The values are published when a threshold number of vertices have

been collected, which corresponds to an update every 5-10 minutes during normal operation.

Measurements are also made of the individual bunch properties. The same analysis method is used, but only vertices from a specific bunch are used in the calculations. The update rate of these measurements is typically much slower as it takes longer for a given bunch to accumulate the required statistics to produce measurements. Real-time feedback is transmitted by LHCb to the LHC using the DIP exchange protocol within the LHCb framework for data exchange with the LHC [6].

DETECTOR RESOLUTION

The measurements of the beam widths made with the LHCb detector must be corrected to account for the finite resolution of the apparatus. The measured beam width will be a convolution of the true beam with the vertex resolution function of the VELO. For a Gaussian beam profile and Gaussian resolution function the measured beam width ($\sigma_{measured}$) is given by

$$\sigma_{measured}^2 = \sigma_{beam}^2 + \sigma_{resolution}^2 \quad (1)$$

where σ_{beam} represents the true beam width and $\sigma_{resolution}$ is the width of the resolution Gaussian.

Previous studies [4, 7] have found that the resolution depends strongly on the number of tracks used to create a vertex, as well as the longitudinal position in the VELO. During online operation tabulated values of the resolution are accessed as a function of these parameters, such that a value can be found for each vertex. The average of these values is then used as $\sigma_{resolution}$ when fitting a single Gaussian whose width is given by Eq. (1). The tabulated resolution values are obtained from samples of Beam-Gas interactions. To determine these values the tracks for each vertex are split into two random sets. The vertex reconstruction algorithm is then run on the two individual sets, and the separation between the two split-vertices is used as an estimation of the detector resolution. These measurements are periodically updated to ensure the samples of Beam-Gas interactions are representative of the data they are being applied to. The data presented here uses resolution values determined from the same sample of Beam-Gas vertices.

CROSS-CALIBRATION

During October 2016 a joint measurement between the LHC profile monitors and individual experiments was undertaken to cross-calibrate the different beam profile monitors [8]. This involved a small number of bunches with a variety of different sizes to compare the methods over a range of emittances. During this fill the value of β^* at the LHCb interaction point was large (~ 25 m). This meant that the beam widths were significantly larger than the detector resolution, reducing the effect of any uncertainty in the resolution determination. However, during nominal physics fills the beam widths and resolution values are of a comparable scale. Typical values for the resolution are around $\sim 40 \mu\text{m}$.

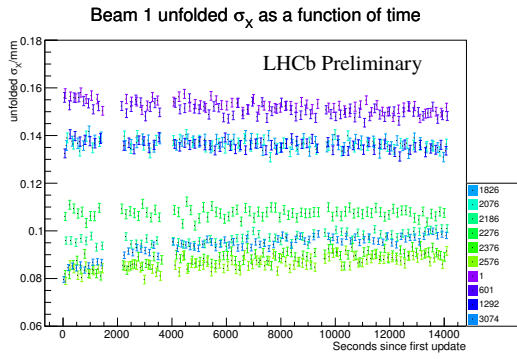


Figure 3: Resolution unfolded beam widths for Beam 1 in the Horizontal plane as a function of time. The range of sizes between the different bunches is illustrated.

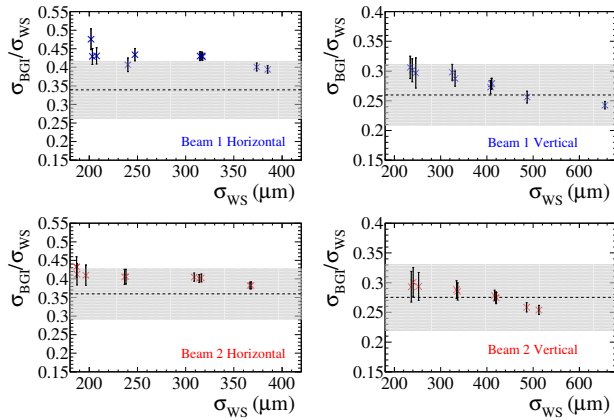


Figure 4: Ratio of the beam widths as measured by LHCb Beam-Gas measurements vs. wire scanners. Each point corresponds to a different bunch, with all values averaged over the fill. The measured β^* values have been used to calculate the expected sigma ratios and their associated errors represented by the grey bands.

In order to increase the statistics of beam-gas interactions helium gas was injected inside the VELO vacuum chamber (pressure $p \approx 10^{-7}$ mbar). This led to a larger sample of Beam-Gas interaction vertices as the extra gas increased collision rate. Although there were fewer bunches present than during a nominal physics fill, the additional gas meant the overall collision rate was similar.

An example of the resolution-unfolded beam widths during the Machine Development fill is illustrated in Fig. 3. The range of different bunch sizes is clearly illustrated in this Figure, as well as the variation in size over time.

These values are compared to the beam widths as calculated using wire scanners. In order to do this, all vertices taken during stable beams are averaged for each bunch. The ratios of the two measurements are shown in Fig. 4 as a function of the width measured by the wire scanners. The values of β^* tabulated in Ref. [8] have been used to calculate the expected sigma ratios using the equation $\sigma_{BGI}/\sigma_{WS} = \sqrt{\beta_{BGI}^*/\beta_{WS}^*}$. The errors on these values have been propagated and are also shown in the Figure as a

band. The largest discrepancy is observed in the horizontal plane for beam 1. Studies have been performed to cross-check any possible sources of uncertainty in the Beam-Gas interaction measurements. This includes looking for any variation in the beam widths as a function of the longitudinal position in the VELO, as this would point towards problems with the resolution unfolding. The unfolded beam widths for each beam and plane are shown in Fig. 5. Additionally, the beam slopes and cross-section per bunch have also been studied, none of which can account for the discrepancy observed. The measured cross-section is found to be stable within a few percent across bunches and over time. Currently the source of the discrepancy is not known. It is possible that the differences are a result of the large uncertainty on the measurement of β^* at LHCb. To determine if this is the case it is important to repeat the cross-calibration with sufficiently different beam optics.

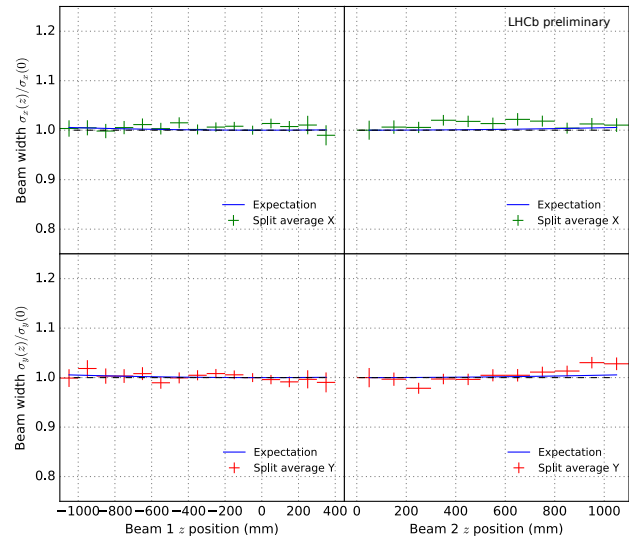


Figure 5: A crosscheck performed to investigate sources of discrepancies between BGI and WS measurements. The resolution unfolded width measurements are not found to vary significantly as a function of longitudinal VELO position.

CONCLUSIONS

Many different devices are capable of making emittance measurements at the LHC including measurements from Beam-Gas interactions at LHCb. During 2016 measurements were made in real-time during physics fills throughout the year. The cross-calibration Machine Development period was of great importance to understand the relationship between the measurements made by LHCb and the other profile monitors. Discrepancies exist between these measurements and as yet the source of these has not been found. It is hoped the cross-calibration can be repeated with different optics to provide further information into the source of the discrepancies.

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