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BEAM-GAS IMAGING MEASUREMENTS AT LHCb

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Abstract

The LHCb detector is one of the four large particle physics experiments situated around the LHC ring. The excellent spatial resolution of the experiment's vertex locator (VELO) and tracking system allows the accurate reconstruction of interactions between the LHC beam and either residual or injected gas molecules. These reconstructed beam-gas interactions gives LHCb the ability, unique among experiments, to measure the shape and the longitudinal distribution of the beams. Analysis methods were originally developed for the purpose of absolute luminosity calibration, achieving an unprecedented precision of 1.2% in Run I. They have since been extended and applied for online beam-profile monitoring that is continuously published to the LHC, for dedicated cross-calibration with other LHC beam profile monitors and for studies of the dynamic vacuum effects due to the proximity of the VELO subdetector to the beam. In this paper, we give an overview of the LHCb experience with beam-gas imaging techniques, we present recent results on the outlined topics and we summarise the developments that are being pursued for the ultimate understanding of the Run II measurements.

INTRODUCTION

The Beam-Gas Imaging technique in use at LHCb is unique among particle physics experiments in allowing the independent measurement of charged particle beam profiles of colliding beams. Its principal application is to provide measurements for the precise luminosity calibrations necessary for absolute cross-section determination [1] but it also permits a variety of additional beam diagnostic measurements. This technique was first developed and put to use during Run I of the LHC (from 2009–2013) when a record precision for the luminosity measurement at a bunched beam hadron collider was achieved [2]. This paper presents the technique's current use at LHCb and a set of additional applications developed during Run II.

THE LHCb DETECTOR

LHCb is a flavour physics experiment designed to observe the decays of b and c quarks produced in the high energy hadronic collisions taking place at the LHC [3]. The relatively long lifetimes of the decay products produced by these interactions necessitate a precise measurement of both primary and secondary decay vertices. This is achievable due to the excellent spatial resolution of the detector's tracking system, most notably the VELO subdetector. A schematic diagram of the full detector layout, including the various subdetectors, can be seen in Fig. 1.

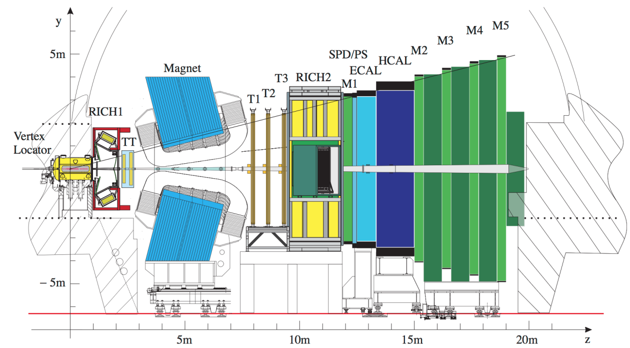

Figure 1: A side view of the LHCb detector showing the various subdetectors that make up the full experiment. The VELO is shown on the far left and the downstream tracking system is made up of the Trigger Tracker (TT), located before the magnet, and the tracking stations T1–T3, located after the magnet [3].

BEAM-GAS IMAGING

The VELO subdetector can also be used for the precise reconstruction of inelastic interactions between the high-energy proton beam and gas molecules within the LHCb interaction region. These reconstructed beam-gas vertices can then be used to measure the properties of the colliding beams such as their profiles, sizes or crossing angle.

Reconstruction

The reconstruction of these vertices uses hits in the VELO's 21 silicon strip r-ϕ sensor modules to form tracks which are then combined to find vertices using LHCb's pattern-matching algorithms [4]. A selection based on the vertex track multiplicity and spatial coordinates is applied in order to enhance the sample of beam-gas vertices. Vertices are required to have at least five constituent tracks and to fall within the longitudinal range of the VELO acceptance (±1500 mm). There is an additional radial cut of 4 mm to exclude any secondary interactions with the detector material. The directionality of the constituent tracks is then used to assign vertices to a given beam with a requirement that vertices assigned to beam 1(2) have all tracks in the forward(backward) direction. Forward tracks are defined as those tracks moving from the interaction point towards the LHCb magnet, i.e. from left to right in Fig. 1.

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Gas Injection

While beam-gas interactions do take place during the nominal running of the LHC their rate is very low. In order to obtain enough vertices for a precise profile measurement in a reasonable period of time a gas injection system was developed to temporarily increase the gas pressure in the beam pipe near LHCb. Noble gas species are used for the injection to avoid damaging the NEG coating of the LHC beam pipe, with helium, neon and argon having been employed to date. This gas injection technique increases the beam-gas interaction rate by more than an order of magnitude, as can be seen from Fig. 2. The full description of this system is detailed in [2].

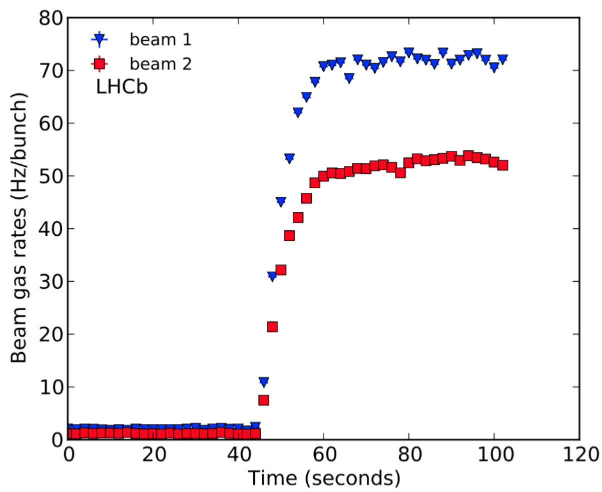

Figure 2: The effect of neon gas injection on the beam-gas interaction rate observed by LHCb during one fill of the LHC [1].

Beam Profile Measurements

In order to accurately estimate the transverse beam profile, it is first necessary to measure the trajectory of the beam, typically coming at an angle, and subsequently correct the observed vertex distributions. The beam slopes and positions are calculated from a linear fit to the observed distributions of each beam in the zx and zy planes. An example of such a fit is shown in Fig. 3. The corrected profile can then be fitted with an appropriate model. For beam width measurements that are used to compare with other LHC instrumentation a simple Gaussian shape is used for consistency. To achieve the ultimate precision for luminosity calibrations, luminous region vertex distributions are added in global fit and the beam shape is modelled with a sum of Gaussian functions, as detailed in [2].

Detector Resolution

Another quantity that must be corrected for when determining the beam profile is the finite resolution of the detector as the observed vertex position distribution is a convolution of the true beam distribution with the resolution function.

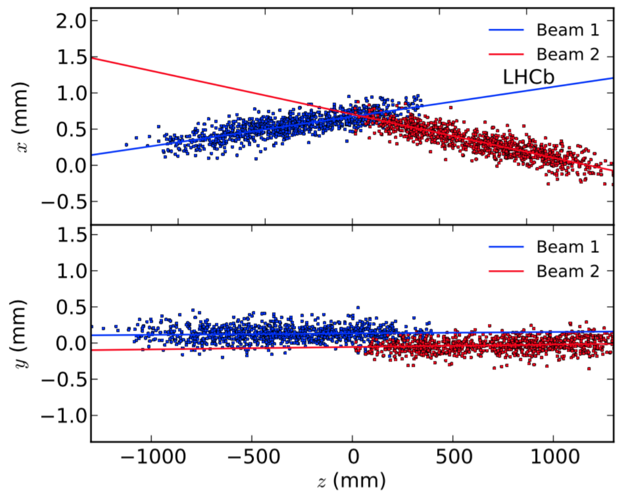

Figure 3: Positions of beam gas vertices in the zx and zy planes with the lines showing the fits to the slopes of the two beams. The offset between the two beams in y is also clearly visible. Figure taken from [1].

A data-driven method of measuring the resolution is used where the tracks used to reconstruct each vertex are divided up randomly into two nearly equal groups and then a new vertex is refitted from each group. The distribution of the difference in spatial position between the two resultant vertices is taken as an estimate of the resolution function. The transverse position resolution for beam-gas vertices is found to be of the order 20 µm to 80 µm, depending on the vertex track multiplicity and longitudinal position, while the nominal beam size at LHCb is about 30 µm. For dedicated luminosity calibration data taking the beam size is increased in order to reduce the relative importance of the resolution.

Cross-Calibration

In October 2016 a machine development (MD) session was dedicated to the cross-calibration of the various emittance measuring devices around the LHC ring. Bunches of markedly different emittances were injected into the LHC and their emittances measured by each piece of instrumentation. This allowed an in depth study of possible systematic biases in the beam-gas imaging measurement. This effort was detailed thoroughly in references [5, 6].

GHOST AND SATELLITE CHARGES

The term ghost charge refers to any charge found outside the nominally filled 25 ns bunch slots around the LHC ring. Satellite charges are those charges sitting within a filled bunch slot but outside the central 2.5 ns RF bucket of that slot. Both sets of charges are picked up by the LHC direct current current transformers (DCCTs) but do not contribute to the collisions seen by the LHC experiments. It is thus necessary to measure the fraction of these charges in order to correct the precise total charge from the DCCTs, which is used for normalisation in luminosity calibrations. The size

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of this correction varies from the percent (typical with ion beams) to the per mille level (typical during nominal proton physics) in Run II.

LHCb can measure the fraction of ghost charges by counting the number of beam-gas interactions observed during empty-empty crossings, where both slots are nominally empty. Counts are normalised to absolute charge using data from beam-empty crossings, where one of the two beams contains a nominally filled bunch with a known intensity. Both satellite and ghost charges are visible to the LHC longitudinal density monitor (BSRL), which makes use of the synchrotron light emitted by the circulating particles in a dedicated undulator to measure the longitudinal charge distribution [7, 8].

The importance of having an independent measurement to cross-check the BSRL results was demonstrated in November 2017 during the 2.5 TeV low-energy run of the LHC. As can be seen in Fig. 4 the BSRL measurement of the ghost charge fraction appears to decrease throughout the fill while the LHCb measurement increases. This is suspected to be caused by de-bunching of the LHC beam, as also seen in another low energy fill in 2015 [9]. This causes charges to be pushed outside the buckets defined by the LHC RF system. This de-bunched charge is seen as a background by the BSRL and subtracted from its measurement as part of a baseline correction. From the LHCb point of view, however, these charges still produce beam-gas interactions and thus add to the total ghost charge fraction. The difference between the DCCT and FBCT total charge values confirms the trend seen by LHCb. This provides a cross-check as any circulating de-bunched beam will be seen by the DCCT direct current measurement but not by the time-gated FBCT measurement. The uncorrected BSRL data also show an upward trend throughout the fill and their absolute offset was confirmed to be in agreement with the standby signal from the detector in the absence of beam.

Time Profile

In order to investigate this suspected de-bunching of the beam a new technique was implemented to produce the first LHCb measurement of the time profile within a 25 ns bunch slot. This technique makes use of drift time measurements from LHCb's Outer Tracker (OT) to assign time coordinates to reconstructed vertices. Due to the asymmetric geometry of the LHCb detector it is only possible to make measurements for LHC beam 1.

The OT is a gaseous detector forming the outer section of the three downstream tracking stations T1–T3. These stations contain just under 100 modules with each module made up of two staggered layers of drift tubes. The arrival times of ionization clusters produced by charged particles are measured with respect to the beam crossing time (from the LHC clock) and then digitised for each 25 ns slot. This digitised value value is given in units of 0.4 ns, as the 25 ns window is encoded with 6 bits. As of Run II these time values are now calibrated in real-time as described in Ref. [10]. The improved drift-time resolution of the OT hits in Run II allows

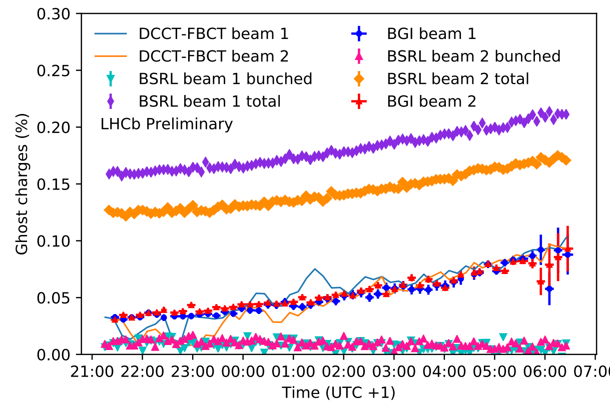

Figure 4: The evolution of the ghost charge fraction throughout LHC fill no. 6380 as measured with the LHCb BGI method and the LHC BSRL instrument. The BSRL values are shown with (bunched) and without (total) the background subtraction. The difference between the DCCT and FBCT total charge measurements, normalised to the earliest LHCb data points for each beam, is shown as a cross-check.

timing information to be assigned to tracks and vertices. Drift time residuals are calculated as the difference between the measured hit drift time and the prediction from the fitted track position. The time value for a single track can then be defined as the weighted average of the drift time residuals from the hits making up the track. The time value for a vertex is finally calculated as the weighted average of the track times of all tracks associated with that vertex.

The standard LHCb reconstruction expects interactions to occur within the narrow window of the luminous region time distribution with a spread of 0.25 ns. Therefore, the observation of the larger time deviations across the 25 ns slot, associated with ghost charges, requires a modification of the reconstruction chain, where various windows related to OT hit timing are relaxed. In addition, the fitted track trajectory, and hence the drift time residuals, is biased by the assumed zero time origin of the interaction, which in turn leads to a bias in the measured track time. To overcome this, multiple reconstructions of each event are performed, each time shifting all OT hit times by a constant in steps of 2.5 ns covering the full 25 ns slot. The reconstructed event with the best global fit quality of all tracks containing OT hits is retained. The value of the applied shift is then summed with the measured residual to give the time value. Using beam-gas interactions from beam-empty crossings, which have a narrow, centred time distribution, we find a vertex time resolution on the order of 0.5 ns.

The first such measurement can be seen in Fig. 5, presenting data from two distinct time periods during the 2017 LHC 2.5 TeV calibration session. The vertex time values relative to the central bucket are shown integrated across all empty-empty crossings for the two time periods. The data from the later time period shows an increase in the ghost charge across all buckets and the 2.5 ns spacing observed

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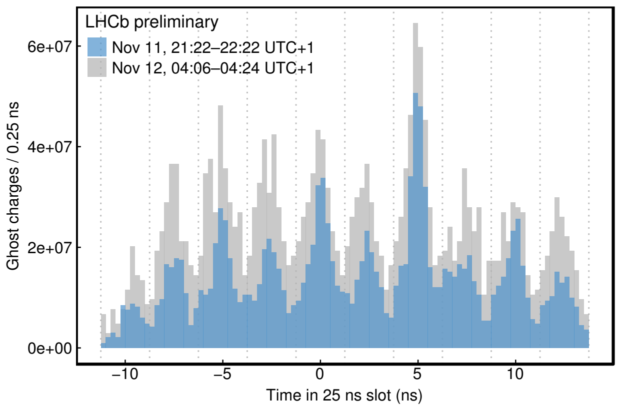

Figure 5: Distribution of measured vertex time for interactions of beam 1 with the gas in the range −11.25 ns to 13.75 ns, integrated over all empty-empty crossings, for two time periods during LHC fill no. 6380.

between peaks in each case gives a hint of the de-bunching taking place during this fill. Under nominal LHC operation, at 6.5 TeV, the 200 MHz RF structure of SPS is preserved and the bunch trains provided by the injector chain to the LHC show peaks in their longitudinal charge distribution every 5 ns [11]. However, due to suboptimal RF set up during 2.5 TeV operation, charge seems to leak out of this 5 ns structure and collect in the stable 2.5 ns buckets of the LHC's 400 MHz RF. Our present understanding of the time resolution limits our ability to distinguish potential de-bunched charge sitting between RF buckets from a simple overlap of adjacent peaks. We also need to understand to what extent the trigger and reconstruction efficiency of these measurements reduces at the trailing and leading edges of the bunch slot where the detector timing is not optimal.

DYNAMIC VACUUM EFFECTS

Beam-induced dynamic vacuum effects are well documented at LHCb with a five fold increase in the vacuum pressure observed under the influence of 1380 bunches of $2{\times}10^{14}$ protons [12]. It has been proposed that this effect could be enhanced by the movement of the RF foil that isolates the VELO detector modules, which approaches to within 5 mm of the collision point after the declaration of stable beams. If this is the case the effect could become more important in the context of the new VELO design for the LHCb upgrade [13] and as the LHC moves to High Luminosity conditions.

In order to investigate a possible effect, the change in the observed rate of beam-gas interactions inside and outside the volume between the two RF boxes, before and after the VELO closing was measured. To achieve this without biasing the measurement through the change in geometric acceptance due to movement of the VELO, it is necessary to make use of LHCb's downstream tracking system for the vertex reconstruction (see Fig. 1). These tracking stations are normally used in conjunction with the VELO tracks to form what are known as long tracks. Here, however, we reconstruct beam-gas vertices using only the downstream stations, achieving a transverse resolution of 1.9 mm in x, 1.3 mm in y and a longitudinal resolution of $\sigma_z = 11$ cm.

This proposed effect would cause a beam-intensity dependent pressure differential between the residual gas inside and outside the VELO. Vertices are classified as inside or outside the VELO based on the position of the VELO edges as measured in Ref. [14]. Margins of $\pm 2\sigma_z$ are used to avoid cross-feed between the samples, resulting in $[-13, 53]$ cm ($[-200, -57] \cup [97, 200]$ cm) for the inside (outside) range. A radial cut of 4 mm is applied in order to limit contamination from material interactions. The longitudinal variation of the vertex reconstruction efficiency, ρ, is estimated when the VELO is open as the ratio of the rates of beam-gas vertices in the two fiducial regions, $R_{\text{in|open}}/R_{\text{out|open}}$. Finally, after the VELO is closed the beam-gas vertex rates are used to estimate the pressure inside relative to outside, $p_{\text{in}}/p_{\text{out}} = R_{\text{in|closed}}/R_{\text{out|closed}}/\rho$, thus avoiding the need of a precise baseline pressure measurement.

The outlined method is applied in two separate LHC fills of differing beam intensities. At a lower intensity data come from LHC fill no. 6012 with 57 bunches per beam and at the higher intensity from LHC fill no. 6245 with 1916 bunches per beam. Under high intensity conditions only vertices from bunches crossing the opposing beam's abort gap are used in order to eliminate contamination from ghost charge p-p collisions. The data at low intensity is used as a control sample, assuming the effect there is small with respect to a potential effect at high intensity.

The longitudinal variation of the reconstruction efficiency, ρ, is measured with the data from the two fills and the difference of 8% is conservatively taken as a systematic uncertainty. Varying the boundaries of the fiducial volumes has a negligible impact on the result. A preliminary relative pressure change, $p_{\text{in}}/p_{\text{out}}$, of $1.21 \pm 0.02 \pm 0.08$ ($1.04 \pm 0.04 \pm 0.08$) is observed at high (low) intensity, where the first uncertainty is statistical and the second is systematic, indicating a measurable pressure increase with closed VELO at high beam intensity.

CONCLUSIONS

The BGI technique continues to be a powerful tool for beam diagnostic measurements at the LHC. A set of new applications of this technique developed during Run II are described along with their first results. LHCb's ability to measure the temporal charge distribution of an LHC beam at the nanosecond scale is demonstrated and a first study of dynamic vacuum effects caused by the VELO RF foil is presented.

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REFERENCES

[1] LHCb collaboration, R. Aaij *et al.*, "Precision luminosity measurements at LHCb", JINST 9, P12005, 2014.

[2] C. Barschel, "Precision luminosity measurements at LHCb with beam-gas imaging", Ph.D. thesis, RWTH Aachen University, 2014.

[3] LHCb collaboration, A. A. Alves Jr. *et al.*, "The LHCb detector at the LHC", JINST 3, S08005, 2008.

[4] M. Kucharczyk, P. Morawski, and M. Witek, "Primary Vertex Reconstruction at LHCb", LHCb-PUB-2014-044.

[5] T. Hadavizadeh *et al.*, "Transverse Emittance Measurements Using LHCb's Beam-Gas Interactions", Proceedings of IPAC2017, Copenhagen, Denmark

[6] R. Alemany-Fernandez *et al.*, "Comparison of Transverse Emittance Measurements in the LHC", Proceedings of IPAC2017, Copenhagen, Denmark

[7] A. Alici *et al.*, "Study of the LHC ghost charge and satellite bunches for luminosity calibration", CERN-ATS-Note-2012-029 PERF, BCNWG Note 4, 2012

[8] M. Palm *et al.*, "Near-Saturation Single-Photon Avalanche Diode Afterpulse and Sensitivity Correction Scheme for the LHC Longitudinal Density Monitor", 3rd International Beam Instrumentation Conference, Monterey, California, 2014

[9] M. Rihl, "Development of a non-destructive beam-profile monitor based on scintillating fibre planes and SIPMs" Ph.D. thesis, Vienna Technical University, 2018

[10] P. d'Argent *et al.*, "Improved performance of the LHCb Outer Tracker in LHC Run 2", JINST 12, P11016, 2018

[11] A. Boccardi *et al.*, "LHC Luminosity calibration using the Longitudinal Density Monitor", CERN-ATS-Note-2013-034 TECH, 2013

[12] R. Aaij *et al.*, "Performance of the LHCb Vertex Locator", JINST 9, P09007, 2014

[13] LHCb Collaboration, "LHCb VELO Upgrade Technical Design Report", CERN-LHCC-2013-021, 2013

[14] M. Alexander *et al.*, "Mapping the material in the LHCb vertex locator using secondary hadronic interactions", JINST 13, P06008, 2018