COMPARISON OF TRANSVERSE EMITTANCE MEASUREMENTS IN THE LHC

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Abstract

Transverse emittance measurement in a collider is of crucial importance for understanding beam dynamics observations and evaluating the machine performance. Devices measuring the beam emittance face the challenge of dealing with considerable systematic errors that can compromise the quality of the measurement. Having different instruments or techniques that provide beam size estimations in order to compare the outcome and give an unbiased value of the emittance is very important in a collider. The comparison of the different results is as well very useful to identify possible problems in a given equipment which could remain unnoticed if such device is the only source of emittance reconstruction. In the LHC several of these instruments and techniques are available; wire scanners, synchrotron light monitors, emittance reconstruction from transverse convolved beam sizes extracted from luminosity scans at the LHC collision points and from beam-gas imaging in the vertex detector of the LHCb experiment. Those systems are briefly presented in this paper together with the comparison of the emittances reconstructed by each of them during physics production over the 2016 LHC run.

INTRODUCTION

In LHC there are, currently, two profile monitors able to measure the beam size in both planes and for both beams independently, the Wire Scanners (WS) and the Synchrotron Light Monitors (BSRT). Additional information about single-bunch sizes can be obtained from beam-gas imaging in the LHCb vertex detector, from the transverse convolved beam sizes extracted from luminosity scans at the collision points, and from the evolution of the luminous-region parameters as reconstructed by ATLAS and CMS inner tracker detectors during such scans. An attempt to cross-calibrate all those devices and techniques has been made in 2016 and it is documented in Ref. [1]. This paper focuses on the evolution of the transverse emittance in 2016 as measured by WS, BSRT, LHCb beam gas imaging and emittance reconstruction from luminosity scans.

BEAM INSTRUMENTATION

Wire Scanners

Wire Scanners are the reference devices to measure bunch-by-bunch transverse emittances for each beam and plane. The WS can measure the emittance throughout the full LHC machine cycle including the energy ramp, provided that the total intensity in the machine is limited to ~240 nominal bunches at 450 GeV and ~12 nominal bunches at 6.5 TeV.

The accuracy of the measurement is limited by the accuracy of the scale of the wire position measurement. In 2015, measurements of the WS length scale using closed orbit bumps and the beam position monitors (BPM) have shown discrepancies $< 5\%$ on the beam position, which is within the uncertainty on the BPM length scale [2].

The precision is limited by noise, both on the wire position and on the photomultiplier signal readings. In online measurements, a scan-to-scan spread of ~10% on the measured emittances has been observed [2]. When reprocessing the WS data offline, the position readings can be smoothed by applying a linear fit, while the noise on the signal can be reduced for isolated bunches by scanning and subtracting the noise in an empty bunch slot just before each bunch [2, 3].

BSRT

The Synchrotron Radiation Telescopes provide a continuous operational bunch-by-bunch measurement of transverse emittances by imaging the synchrotron radiation coming from a dedicated undulator at 450 GeV and from a bending dipole at energies > 2 TeV. The BSRT is calibrated against the WS during low-intensity fills. The BSRT measurements are very precise when averaging over several acquisitions. The accuracy is mainly limited by the calibration. In 2016, three calibrations were made:

- The first calibration was done during the initial commissioning in April 2016. The calibration covers emittances down to ~2.2 μm rad, as smaller bunches were not available at this point. The BSRT readings given by this calibration were found to agree with other emittance measurements and emittances derived from luminosity.
- A second calibration was done in August (as of LHC fill 5251), covering also lower emittances down to ~1 μm rad. While the readings of BSRT and WS were

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self-consistent during the calibration fill, this calibration was found to give unphysical low emittance readings, which was noticed due to the clear discrepancy with the emittance reconstructed from luminosity, transverse beam scans and LHCb beam gas imaging. This calibration will not be used in the following.

- The third calibration was done in October (as of LHC fill 5406) to overcome the problems of the second calibration. The new corrections can be back-propagated to the period of the second calibration, and the measured emittances were found to agree with other emittance measurements.

DATA FROM EXPERIMENTS

In collisions, additional data on the beam profiles can be gathered from the LHC experiments.

Emittance from Luminosity

The luminosity of a collider with Gaussian bunches and beams with equal size at the interaction point is given by [4]

$$L = \frac{f_{rev} N_1 N_2 n_b \gamma}{4\pi\beta^* \sqrt{\varepsilon_x \varepsilon_y}} G \qquad (1)$$

where $\varepsilon_{x,y}$ are the normalized transverse emittances, $N_{1,2}$ are the intensities per bunch, n_b is the number of colliding bunch pairs, f_{rev} is the revolution frequency, γ is the relativistic gamma, β^* is the beta function value at the interaction point and G is the geometric reduction factor due to bunches of a finite length σ_z crossing at an angle of α.

The convoluted effective emittance $\varepsilon_{eff} = \sqrt{\varepsilon_x \varepsilon_y}$ can be derived from the absolute luminosity in ATLAS and CMS by inverting Eq. 1 if the bunch intensities and the bunch lengths are known. Due to the geometric reduction factor, this calculation yields different results for ATLAS (vertical beam crossing) and CMS (horizontal beam crossing) if the beams are not round.

The accuracy depends on the accuracy of the absolute luminosity measurement from the experiments. The systematic errors on the 2016 data are 3.4 % for ATLAS and 2.5 % for CMS[1] [5].

Emittance Scans

Small beam separation scans ("emittance scans") were done throughout 2016 at the CMS experiment. From the luminosity measurement during the scan, the beam overlap area is measured, from which the transverse emittance can be derived [6]. The precision of these measurements is at the percent level, as the statistical uncertainty on the luminosity measurements from the experiments is essentially negligible at high luminosity.

In the CMS separation plane (vertical), the accuracy only depends on the linearity of the luminosity measurement, on the accuracy of the separation bump and on the β^* in CMS. The expected error on the emittance is ∼7%.

In the CMS crossing plane (horizontal), the longitudinal distribution is folded in due to the crossing angle. If the longitudinal profiles are measured, this effect can be compensated for [6], with an expected residual systematic error of ∼15%.

LHCb Beam-Gas Imaging and ATLAS/CMS Luminous Region Data

Using the Beam-Gas Imaging (BGI) method [7], a unique capability of the LHCb experiment, the beam width can be reconstructed and used to calculate the transverse emittance.

Each LHC beam is visible through the collision of protons in the beam with the residual gas molecules. The interaction vertices are reconstructed by the VErtex LOcator (VELO) subdetector placed around the interaction point. This allows the measurement of the beam shape, position and angle, the single bunch relative intensity and to measure charges outside of filled buckets. The individual beam shapes are the source of the transverse emittance measurements presented in this paper.

The accuracy of this method is limited by the sample size and the vertex position resolution of the VELO detector. The former can be improved by injecting gas inside the VELO vacuum chamber but this is not allowed during luminosity production fills. Therefore, long integration periods of the order of a few minutes are needed before a set of vertices is used to reconstruct the beam width. The reconstruction of interaction vertices is performed using standard LHCb algorithms [8,9]. The data presented here corresponds to the nominal LHC optics for which the β at the LHCb interaction point is 3 m, with the corresponding small beam sizes. The vertex resolution, therefore, dominates the accuracy of the measurement.

The observed vertex distribution is fitted with a convolution of a Gaussian true beam shape and the measured vertex position resolution of the VELO detector [10, 11]. Approximating the resolution with a Gaussian, the convolved beam width is given by

$$\sigma^2_{raw} = \sigma^2_{beam} + \sigma^2_{resolution} \,. \qquad (2)$$

An online analysis system for the LHCb beam-gas vertex reconstruction measurement was commissioned in 2016, which provides an online transverse emittance measurement for the bunches not colliding in LHCb. The emittance in both planes of both beams is measured at the same time. The uncertainty is dominated by the systematic component, which is expected to be approximately 10% to 20%, and which is in the process of being studied at the time of writing [1].

Additionally, data from the luminous region measurements from ATLAS and CMS could also give an indication of the beam size and hence the convoluted transverse emittances as well as the bunch length. However, the online data is not corrected for the vertex detector position resolution and the final offline-reconstructed data only becomes available after the run.

[1] All luminosity data used in this paper is courtesy of the ATLAS and CMS experiments and is based on quasi-online measurements. It is not based on a published luminosity analysis of the experiment collaborations, which is still ongoing.

EMITTANCES IN 2016

Convoluted Emittances

The convoluted transverse emittances at the start of collisions are compiled in Fig. 1. The convoluted emittance is obtained by averaging the emittances of both beams in a given plane. As of LHC fill 5079, the Batch Compression Merging and Splitting (BCMS) beam production scheme was used operationally in the LHC injectors to allow for lower transverse emittances. During a transition phase (until LHC fill 5105), the transverse emittances were decreased gradually in the injectors from ~2.7 μm rad to ~1.7 μm rad at LHC injection. At the beginning of collisions, the average emittances were (3.3 ± 0.5) μm rad before the transition and (2.1 ± 0.3) μm rad afterwards, averaged over all fills in the respective periods.

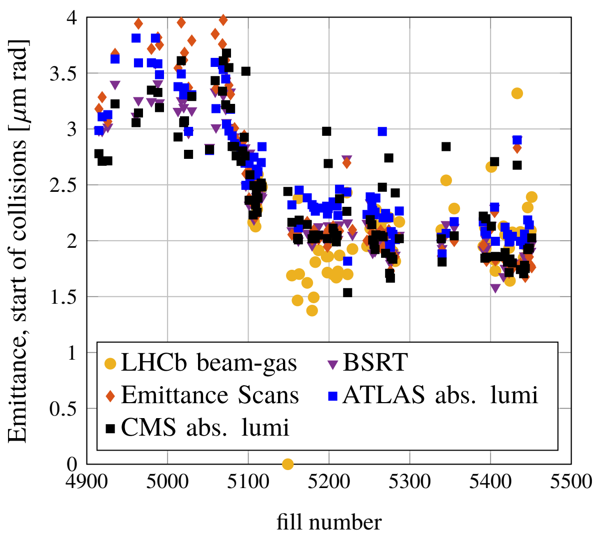

Figure 1: Average convoluted emittances at the start of collisions. The second (bad) BSRT calibration was retrospectively replaced by the first one.

Beam Roundness

Throughout 2016, it was observed that the CMS luminosity was consistently ~10% higher than the ATLAS luminosity at the start of collisions. A possible explanation for this, is a difference in the geometric reduction factors due to alternating crossing and non-round beams [5].

As shown in Fig. 2, a non-roundness of the beams was indeed observed on the BSRT, as well as on the LHCb beam-gas and the emittance scan data. The non-roundness is compatible with the luminosity difference for a large part of the run [12]. However for the last part of the year (after LHC fill 5416), the beams appear to be more round, which is in disagreement with the ATLAS to CMS luminosity ratio (indicating non-round beams). Also, the emittances measured by BSRT appear to be unphysically small for this period.

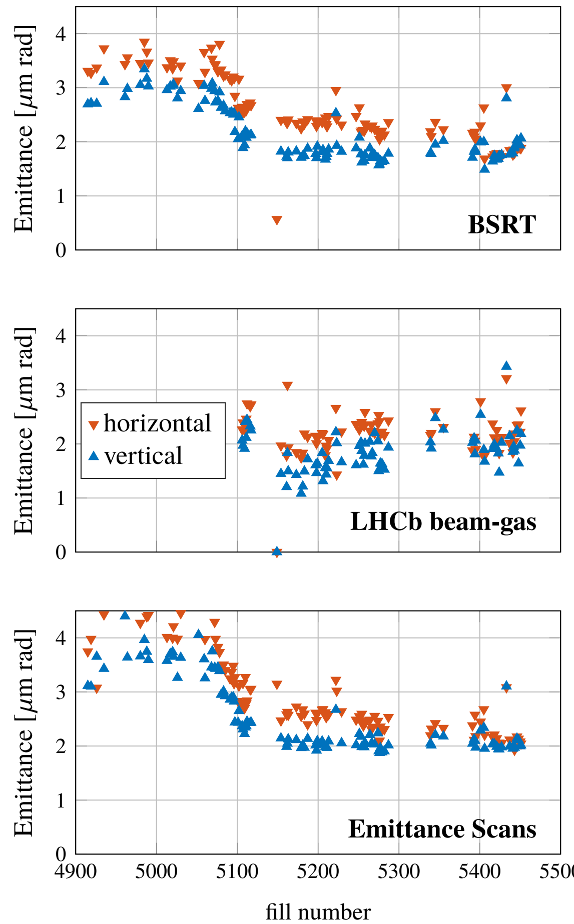

Figure 2: Average emittances by plane at the start of collisions. The second (bad) BSRT calibration was retrospectively replaced by the first one.

CONCLUSIONS

The operational transverse emittance measurement device was the BSRT, which is calibrated against the Wire Scanners. Also, small beam separation scans (emittance scans) were done regularly in CMS, and for the second part of the year, LHCb provided emittances from beam-gas vertex measurements. The emittance measurements have a typical systematic uncertainty of 10-20% on the scale, while the relative precision is much better.

As of June, the BCMS beam production scheme was used operationally in the injector complex. This lead to a decrease in transverse emittance from (3.3 ± 0.5) μm rad to (2.1 ± 0.3) μm rad at the start of collisions. The beams were not round for a large part of the year, leading to a difference in the luminosity delivered to ATLAS and CMS [5].

Thanks to the very different but complementary emittance measurements in LHC, in 2016 a very good understanding of the emittance in collisions could be achieved. The redundancy of the measurement, allowed to spot the calibration problem of the BSRT, that could have been unnoticed if this device would be the only source of emittance measurement in LHC.

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