HOW WELL DO WE KNOW OUR BEAMS?

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Abstract

Intensity, transverse emittance and bunch length are key parameters defining the LHC luminosity reach. This paper gives an overview of the available beam instrumentation to measure these parameters, and estimates how well they can be measured. The evolution of these parameters during 2016 proton physics operation is also presented and the impact of the machine configuration and bunch production schemes are highlighted.

INTRODUCTION

Following e.g. [1], the luminosity of a collider with Gaussian bunches is given by

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

where $\varepsilon_{x,y}$ are the normalized transverse emittances[1], $N_{1,2}$ are the intensities per bunch, n_b is the number of colliding bunch pairs and G is the geometric reduction factor due to bunches of a finite length σ_z crossing at an angle of α in the interaction point, where ε_{xing} is the transverse emittance in the crossing plane.

$$G = \left(1 + \sqrt{\frac{\gamma}{\varepsilon_{xing}\beta}} \sigma_z \frac{\alpha}{2}\right)^{-0.5} \tag{2}$$

From Eqn. 1, 2 it is clear that for a given machine configuration (energy, β^*, crossing angle, number of bunches), the key beam parameters defining the luminosity are the intensity, the transverse emittance, and the bunch length. In the following, we will provide an overview of the available measurements of these quantities at the LHC and their evolution during 2016 proton physics operation.

INTENSITY

Intensity Measurements

The reference intensity measurement at the LHC is given by the DC Beam Current Transformer (DCCT or DCBCT). It provides a measurement of the total number of charges per beam (summed over all circulating bunches) with an uncertainty of ~0.5% for high-intensity fills [2].

The bunch-by-bunch intensity sharing is measured by the Fast Beam Current Transformer (FBCT). The total of the FBCT is calibrated against the DCBCT measurement. In order to assess the long-term behaviour and stability of the FBCT calibration, the FBCT for Beam 2 has not been recalibrated for extended periods throughout 2016, while the FBCT on Beam 1 was recalibrated regularly [3]. As shown in Fig. 1, the error on the Beam 1 intensity (with respect to the DCBCT measurement) is typically below 0.5%, while the error on Beam 2 is 1-2%.

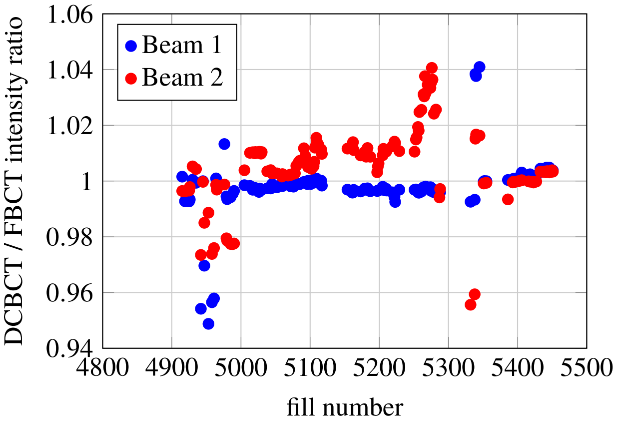

Figure 1: Ratio of the intensities seen by the DCBCT and the FBCT at the start of collisions.

Additionally, the relative distribution of charges in either beam is also measured by the longitudinal profile monitors: the LHC Beam Quality Monitor (BQM) and the longitudinal synchrotron light monitor (BSRL). These data can be combined with the total intensity measurement from the DCBCT to derive bunch-by-bunch intensities.

Intensities in 2016

In Fig. 2, the evolution of the average bunch intensity throughout 2016 is shown. After the initial intensity ramp-up, the bunch intensity at the start of collisions was first pushed to $\sim 1.2 \cdot 10^{11}$ protons per bunch. In the second part of the run, the operational limit was $\sim 1.1 \cdot 10^{11}$ protons per bunch due to the interlocked vacuum conditions at the injection kicker magnet for LHC beam 2 (MKI8) [4].

TRANSVERSE EMITTANCE

Beam Instrumentation

Wire Scanners The Wire Scanners (WS) 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.

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[1] In the following, the normalized transverse emittance will be referred to as “emittance”.

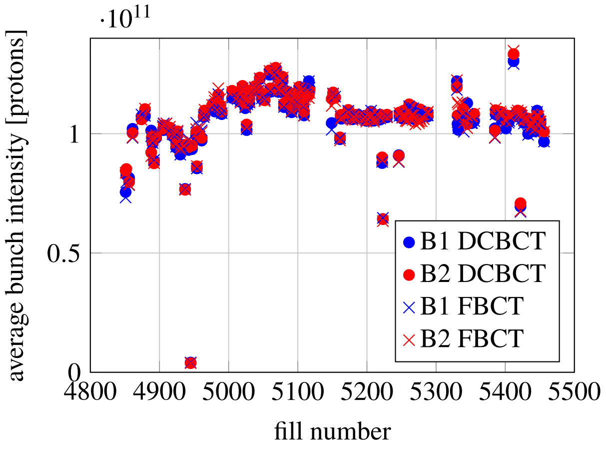

Figure 2: The average bunch intensity at the start of collisions in 2016.

The accuracy of the wire scanner 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 [6].

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. 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 empty bunch slot just before each bunch [6] [5].

BSRT The Synchrotron Radiation Telescopes (BSRT) 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 accuracy of 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 um, 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 um. While the readings of BSRT and WS were self-consistent during the calibration fill, this calibration was found to give unphysically low emittance readings. 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 convoluted effective emittance can be derived from the absolute luminosity in ATLAS and CMS by inverting Eqn. 1 if the bunch intensities and the bunch lengths are known. It is to be noted that due to the geometric reduction factor, this calculation yields different results for ATLAS (vertical crossing) and CMS (horizontal crossing) if the beams are not round. The accuracy depends on the accuracy of the absolute luminosity measurements from the experiments, which is typically $< 5\%$ for offline data.

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 [7]. The precision of these measurements is at the percent level, as the statistic 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 IP5. 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, but in the 2016 no continuous operational measurement of longitudinal profiles was available. Hence the 2016 data was compensated for a reference profile acquired by an on-demand measurement in August 2016, with a residual systematic uncertainty of ~20%.

LHCb Beam-Gas Imaging and ATLAS/CMS Luminous Region Data 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 IP8. This method measures the emittance in both planes of both beams a the same time. The uncertainty is dominated by systematics which are in the process of being studied at the time of writing. However, a realistic estimation could be ~20%.

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

Emittances in 2016

Convoluted Emittances The convoluted transverse emittances at the start of collisions are compiled in Fig. 3. 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 um to ~1.7 um at LHC injection. At the beginning of collisions, the average emittances were 3.27 ± 0.47 um before the transition and 2.05 ± 0.26 um afterwards.

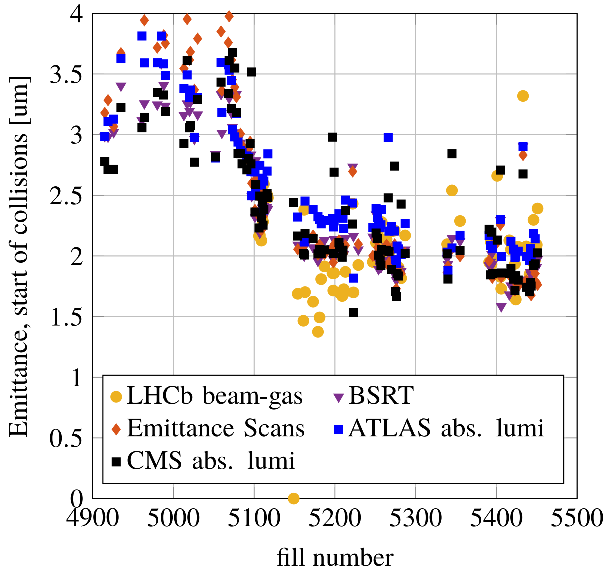

Figure 3: The average convoluted emittances at the start of collisions. The second (bad) BSRT calibration was retrospectively replaced by the first one.

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 G (Eqn. 2) due to alternating crossing and non-round beams. If the beams are larger in the horizontal plane than in the vertical one, the experiment crossing in horizontal (CMS) is privileged by a larger G with respect the experiment crossing in vertical (ATLAS).

As shown in Fig. 4, 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 [8]. However for the last part of the year (after LHC fill 5406), the beams appear to be more round, which is in disagreement with the ATLAS to CMS luminosity ratio (indicating non-round beams).

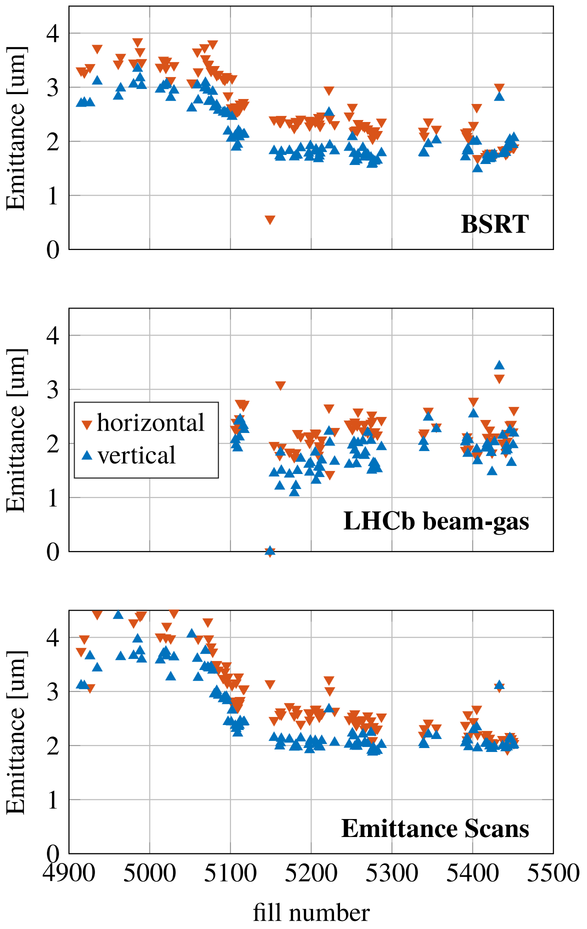

Figure 4: The average emittances by plane at the start of collisions. The second (bad) BSRT calibration was retrospectively replaced by the first one.

LONGITUDINAL DISTRIBUTION AND BUNCH LENGTH

Measurements

The bunch length is operationally measured by the LHC Beam Quality Monitor (BQM). It uses a wall current monitor pick-up with an 8 GS/s ADC to acquire the longitudinal profiles. The full-width half-maximum of the waveform is then measured and converted to a bunch length assuming a Gaussian longitudinal distribution [9]. While this measurement is precise, the measured bunch length only accurately represents the r.m.s. width provided that the longitudinal distribution is Gaussian.

Additionally, the longitudinal synchrotron radiation monitor (BSRL) continuously measures the longitudinal distribution of charges in the beams. It uses the same synchrotron light source as the BSRT, but it measures the temporal distribution of the incoming light. A histogram of 50 ps bins is filled over 5 minutes. The long integration time allows to reach a dynamic range of several orders of magnitude. While the BSRL is already used operationally for monitoring ghost charges and satellite bunches in the LHC, the longitudinal profile measurement is still under development.

For on-demand measurements and diagnostics, two 40 GS/s scopes connected to wall current monitor pickups are installed in SR4. The transfer functions of the pickups and cables were measured and are available for deconvolution [10]. The scopes can acquire a longitudinal profile of either beam over a full LHC turn.

Longitudinal Distribution in collisions

To avoid instabilities due to the loss of Landau damping the bunches in the LHC are blown up longitudinally during the energy ramp by injecting phase noise [11]. This leads to a longitudinal distribution which is significantly non-Gaussian at the start of collisions. A change in longitudinal distribution is also observed when the longitudinal bunch flattening in collisions introduced in 2016 [10] is used.

When untouched over the course of several hours in collisions, the longitudinal distribution becomes Gaussian again (Fig. 5).

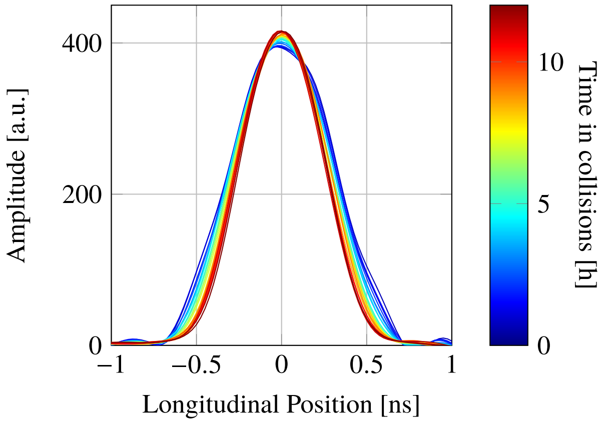

Figure 5: Evolution of the longitudinal bunch profile in LHC fill 4964, measured using the 40 GS/s scopes in SR4, one acquisition per 30 min.

Bunch Length in 2016

The bunch lengths as measured by the BQM at the start of collisions are compiled in Fig. 6. After the longitudinal bunch flattening in collisions was operational, the bunch length target for the blow-up during the ramp was gradually reduced from 1.25 ns to 1.1 ns (as of LHC fill 5038). This lead to a decrease of the bunch length at the start of collisions from 1.2 ± 0.01 ns to 1.06 ± 0.01 ns.

CONCLUSIONS

We reviewed the instrumentation and measurement techniques used in 2016 proton physics operation to measure the key beam parameters determining the luminosity performance for a given machine configuration: intensity, transverse emittance and bunch length.

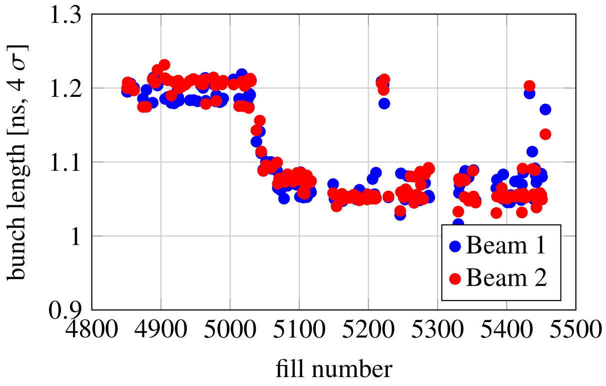

Figure 6: BQM bunch length at the start of collisions.

The intensity is operationally measured by the DC-BCT and the FBCT. The uncertainty was typically lower than 1% for Beam 1 and 1-2% for Beam 2. The average bunch intensity was $1.08 \pm 0.12 \cdot 10^{11}$ ppb and the total beam intensity $2.4 \pm 0.15 \cdot 10^{14}$, limited by the MKI8 vacuum interlock.

The operational transverse emittance measurement 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 3.27 ± 0.47 um to 2.05 ± 0.26 um at the start of collisions. The beams were not round for a large part of the year, leading to a difference in the geometric luminosity reduction factors in ATLAS and CMS, and thus a difference in the delivered luminosity.

The bunch length is measured by the BQM using a full width half maximum algorithm. The longitudinal distribution differs significantly from a Gaussian at the start of collisions, while over the course of several hours in collisions it becomes Gaussian shape. This behaviour will be taken into account in a future version of the LHC luminosity model.

The bunch length was 1.2±0.01 ns at the start of collisions in early 2016, and 1.06 ± 0.01 ns in June after the change of the target for the longitudinal blow-up during the ramp.

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