EMITTANCE EVOLUTION IN THE LHC: FROM INJECTION TO COLLISIONS

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Abstract

The emittance of the LHC beams when arriving in collisions is a key parameter for luminosity. Hence, the emittance of the beams from the injector complex needs to be preserved as well as possible throughout the cycle for maximum luminosity. Moreover, due to the V/H crossing scheme in IP1 and 5, non-round emittances yield different luminosities for ATLAS and CMS. Such a difference was e.g. observed in 2016 proton physics operation. This contribution analyzes the emittance evolution throughout the LHC nominal cycle in 2017. The emittance growth from injection to collisions is studied and the different emittance measurements are compared. Reproducible bunch patterns are shown and differences between the operational beam types (BCMS, 8b4e) are highlighted. Also, the roundness of the beams and the impact on the ATLAS to CMS luminosity ratio is assessed.

INTRODUCTION

Throughout 2017 operation, a broad range of different beam types was used in the LHC. Initially, “BCMS” type beams as introduced during 2016 operation [1] were used. After the vacuum issues in cell 16L2 became a blocking issue for operation [2], and the probability of 16L2 related dumps was found to be correlated to electron cloud, “8b4e” type beams [3] were used operationally. These beams were initially produced in the injector following the nominal LHC beam production scheme, yielding higher emittances compared to BCMS beams. To improve LHC performance, the production was later switched to a BCMS-like production scheme, dubbed “8b4e-BCS”.

These three different beam types showed significantly different initial emittances at injection as well as a different evolution throughout the cycle until reaching collisions. Comparing the observed emittance evolution to the expectation from intra-beam scattering and synchrotron radiation [4], considering the different properties of the three beam types, allows to pinpoint and to understand additional sources of emittance growth which limit the performance of the LHC.

Towards the end of the 2017 LHC run, an intermediate energy reference run at 2.51 TeV was carried out at the request of the experiments [5]. Comparing the evolution of emittances through this cycle to the emittance evolution in the nominal 6.5 TeV cycle gives an indication of how much emittance blow-up occurs (and could possibly be avoided) during the ramp.

During several periods over the year, the synchrotron light monitors (BSRT) used for operational emittance measurements showed a degradation of the image intensifiers [6] leading to wrong measurements, in particular for the small beam sizes at flat top energy. This was mitigated by moving the beam spot on the BSRT screen and re-calibrating the BSRT. Comparing the emittances from various sources allowed to spot and quantify the impact of this degradation.

INJECTED EMITTANCES

The BSRT automatically scans every newly injected bunch train in the LHC. In most fills, the Wire Scanners were also used to scan the first injected trains, up to the point where their intensity limit is reached [7]. As shown in Fig. 1, the measurements generally agree within ~10% in all planes,

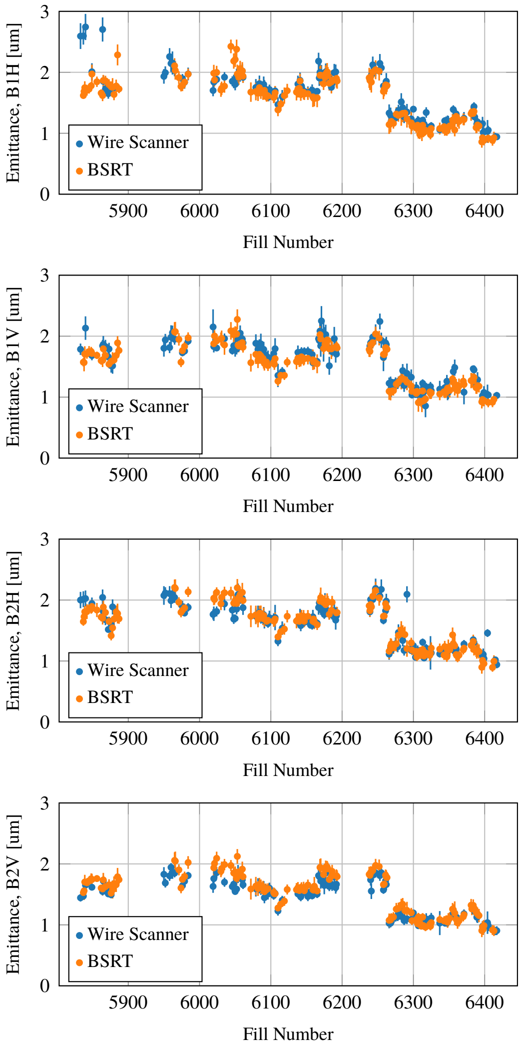

Figure 1: Injected Emittances in 2017 LHC operation.

Table 1: Injected Emittances per beam type.

[μm]	**BCMS**	**8b4e**	**8b4e-BCS**
B1H	1.71	1.91	1.22
B1V	1.64	1.87	1.20
B2H	1.74	1.95	1.14
B2V	1.62	1.87	1.10
convoluted	1.7	1.9	1.2

excluding a few fills very early in the year where the B1H wire scanners were still under commissioning, and the first period of BSRT degradation (around fill 6050, in particular in B1H).

BCMS-type beams were used until fill 6164 with an initial average emittance of ~1.9 μm; it is worth noting that as of fill 6065, the introduction of the "constant bucket area" technique [8] reduced the injected emittances to ~1.7 μm. This technique was then also applied to all further beam production schemes from the start.

To mitigate the 16L2 vacuum issues, 8b4e beams were introduced as of fill 6167. Since the beams were initially produced using the nominal (non-BCMS) LHC beam production with its intrinsic brightness limitations, injected emittances increased to ~1.9 μm. After Technical Stop 2, from fill 6360 onwards, the 8b4e beams were produced using the BCMS-like "BCS" technique; this reduced the injected emittances to ~1.2 μm. The measured injected emittances by plane are compiled in table 1. These values line up well with the predicted injector brightness [9].

EMITTANCE EVOLUTION AT 450 GeV

The evolution of emittance at flat-bottom energy can be measured from the difference of the first BSRT acquisition after a bunch was injected and the last BSRT acquisition before the ramp was started. At 450 GeV, emittance growth is dominated by intra-beam scattering (IBS), in particular in the horizontal plane. The measured emittance growth rates are compared to the model predictions in Fig. 2, and a compilation by beam type is given in table 2. In the vertical plane, the current version of the model predicts no growth from IBS, as it considers no linear coupling and no vertical dispersion.

It is worth noting that the extra emittance blow-up beyond the model in the horizontal plane depends significantly on the beam type. For BCMS-type beams, an extra blow-up of ~0.6 $\mu\mathrm{m}/h$ is observed, while for 8b4e-type beams it is ~0.2 $\mu\mathrm{m}/h$. This indicates that ~0.4 $\mu\mathrm{m}/h$ of the extra growth beyond the model may be linked to deterioration due to electron cloud. The bunch-by-bunch emittance growth pattern for BCMS and 8be4 beam types are compared in Fig. 3. A clear pattern resembling the build-up of e-cloud over the bunch trains is observed; note that for the BCMS beams, the bunches at the beginning of each SPS batch show a growth of ~0.5 $\mu\mathrm{m}/h$, which is at the same level as the 8b4e-type beams (which are not affected by e-cloud).

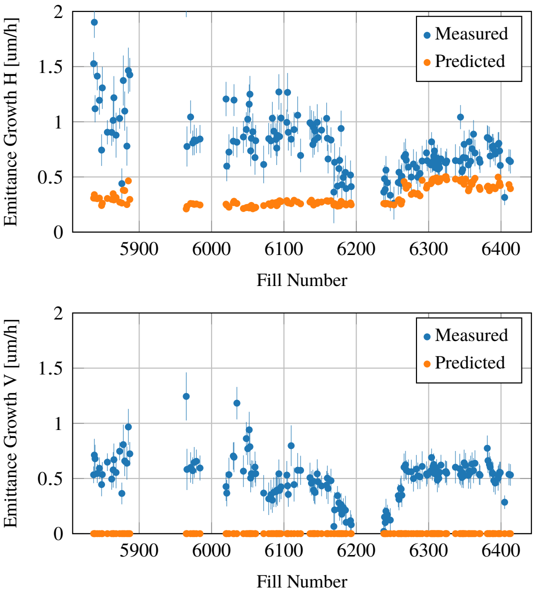

Figure 2: Emittance growth rates at 450 GeV.

Table 2: Emittance growth at 450 GeV per beam type.

[μm/h]	**BCMS**	**8b4e**	**8b4e-BCS**
H measured	0.90	0.47	0.65
H predicted	0.27	0.26	0.47
V measured	0.45	0.20	0.56

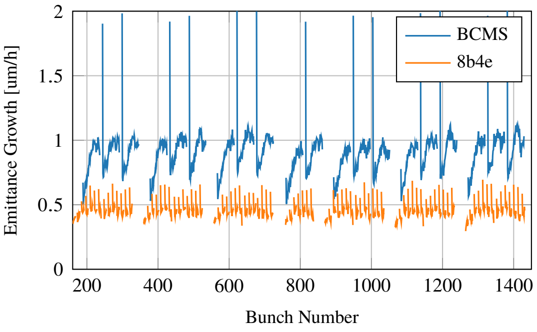

Figure 3: Bunch-by-bunch emittance growth rates, averaged per beam type.

EMITTANCE AT 6.5 TeV

Due to the strong synchrotron radiation damping at high energy, the emittance growth at 6.5 TeV is slow. In particular, the emittance growth at flat top until colliding and declaring Stable Beams is negligible, if present at all. For this reason, we can consider the emittance measured at the start of Stable Beams representative for the emittances just after the energy ramp. The long-term emittance evolution in Stable Beams is discussed in detail in another contribution [10].

Once in collisions, data from the experiments can be used for a complementary, independent measurement of the emittance. This is particularly important since the degradation effects of the BSRT image intensifier are more pronounced with the small physical beam sizes at high energy. In Fig. 4, we show emittance measurements from the following sources:

1. BSRT,
2. Emittance Scans [11] in IP5,
3. Luminous Region measurements [12] of ATLAS,
4. Emittances from absolute luminosity measurements of ATLAS and CMS, where the ratio of the two luminosities is used to derive the horizontal and the vertical beam size.

For fills where separation levelling was used (as of fill 6263), the measurements 2-4 are taken after the end of the levelling, and corrected for the expected emittance growth in Stable Beams [10].

In general, all emittance measurements agree within the expected systematic errors of 10-20% [7], with the exception of the periods with BSRT image intensifier degradation (around fills 6050, 6180 and 6300). There, the BSRT values differ significantly from the luminosity-based measurements, in particular in the vertical plane. This highlights the necessity of complementary measurements, even tough the BSRT provides a continuous, operational emittance measurement per beam and plane.

In 2016, the beams were not round at the start of collisions, which led to an ATLS/CMS luminosity difference of ~5% due to the vertical-horizontal alternating crossing scheme [13]. Such a behavior was not observed in 2017 operation; as shown in Fig. 5, the beams were round, and the measured luminosities of ATLAS and CMS agreed.

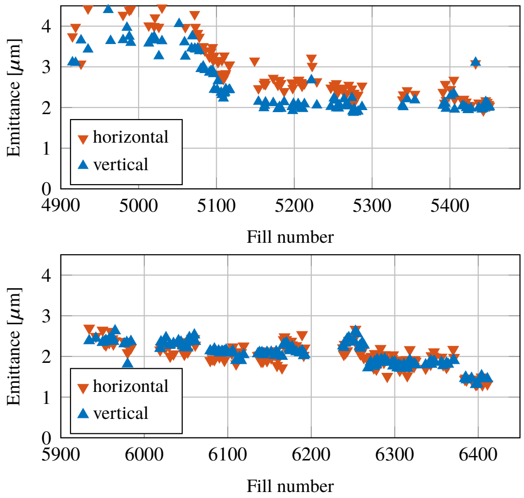

Figure 5: Beam Roundness at the start of collisions in 2016 and 2017.

EMITTANCE BLOW-UP IN THE RAMP

Fig. 6 shows the emittances at injection, before starting the ramp, and at the start of collisions. The emittance blow-up per part of the cycle and beam type is is aggregated in table 3. It is clear that in particular for the high-brightness 8b4e-BCS beams, a large part of the emittance blow-up occurs during the ramp. The BSRT data, where available, indicates that the blow-up is worse in beam 1 than in beam 2.

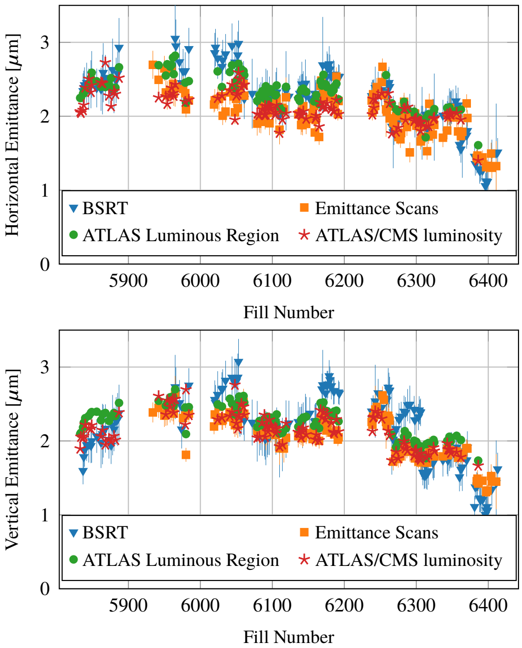

Figure 4: Emittances at the start of collisions in 2017.

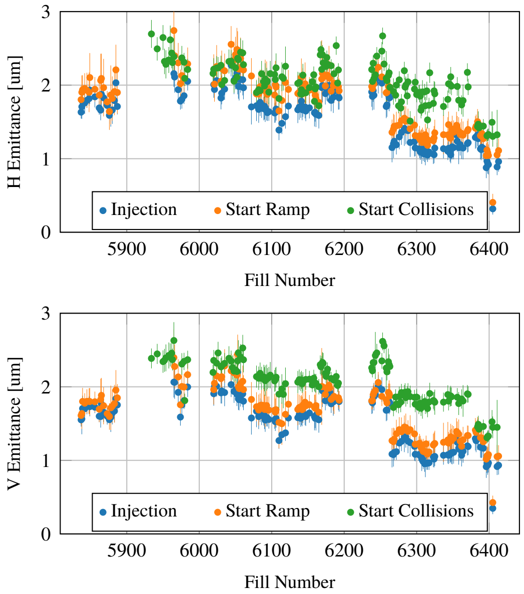

Figure 6: Emittance evolution through the cycle from injection to collisions in 2017.

Table 3: Emittance blow-up during the ramp.

[μm]	**horizontal**	**vertical**
BCMS	0.1 (5%)	0.4 (22%)
8b4e	0.3 (12%)	0.4 (20%)
8b4e-BCS	0.6 (43%)	0.6 (45%)
2.51 TeV	0.1 (8%)	0.1 (8%)

Due to the change of optics during the combined ramp and squeeze, and since there is no continuous beam size measurement available during the ramp for high-intensity beams, it is not straightforward to pinpoint the exact time in the ramp where this blow-up occurs. During 2018 operation, BSRT calibration fills (with beam intensities below the wire scanner limits) will be carried out more often, which will allow to monitor the beam sizes of single bunches through the ramp regularly using the wire scanners.

Towards the end of 2017 operation, a 2.51 TeV intermediate energy reference run was carried out. It used the same type of 8b4e-BCS beams used before for the 6.5 TeV run, but had a significantly shorter cycle. In particular, the energy ramp was ~3 times shorter (412 s instead of 1210 s) due to the lower flat-top energy and the usage of a PPLP instead of the established PELP scheme [14]. The emittance blow-up during this shorter ramp was only 8% (as opposed to 45% in the 6.5 TeV ramp with the same beam). A PPLP-type ramp will also be used in the 2018 LHC cycle [15]; the impact on the emittance preservation will be assessed.

CONCLUSIONS

The variety of beam types used in 2017 LHC operation allowed to study the emittance evolution through the cycle for different initial brightnesses, with or without the effect of e-cloud build-up.

At injection, BCMS-type beams had emittances of 1.7 μm on average; the 8b4e-BCS beams used towards the end of the year were significantly brighter with 1.2 μm average emittance.

A brightness-dependent emittance growth between 0.3 μm/h (BCMS) and 0.5 μm/h (8b4e-BCS) at injection energy is expected from intra-beam scattering. Comparing BCMS to 8b4e beams, e-cloud contributes up to 0.4 μm/h to the observed emittance growth for BCMS beams. A further 0.2 μm/h, which does not seem to be brightness dependent, is still to be tracked down to other sources (e.g. noise).

The most significant emittance blow-up was observed during the ramp, in particular for the high-brightness 8b4e-BCS beams, where it reached up to 0.6 μm or 45% over the course of the ramp. In the 2.51 TeV intermediate energy run, a blow-up of only 8% was observed for the same beams during the three times shorter ramp.

The emittances at the start of collisions were ~2.1 μm for the BCMS and ~1.8 μm for the 8b4e-BCS type beams. Unlike 2016, the beams were mostly round; the ATLAS and CMS luminosities were compatible.

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