

ORIGINS OF TRANSVERSE EMITTANCE BLOW-UP DURING THE LHC ENERGY RAMP

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Abstract

During LHC Run 1 about 30 % of the potential peak performance was lost due to transverse emittance blow-up through the LHC cycle. Measurements indicated that the majority of the blow-up occurred during the energy ramp. Until the end of LHC Run 1 this emittance blow-up could not be eliminated. In this paper the measurements and observations of emittance growth through the ramp are summarized. Simulation results for growth due to Intra Beam Scattering will be shown and compared to measurements. A summary of investigations of other possible sources will be given and backed up with simulations where possible. Requirements for commissioning the LHC with beam in 2015 after Long Shutdown 1 to understand and control emittance blow-up will be listed.

INTRODUCTION

In 2012 the LHC was operated with high brightness beams with beam parameters pushed to their limits for outstanding luminosity production. With a bunch spacing of 50 ns the LHC was filled for physics with 1374 bunches, containing up to 1.7×10^{11} protons per bunch (ppb) with transverse emittances as small as $1.5 \mu\text{m}$ at injection. However, high brightness could not be preserved during the LHC cycle. Measurement campaigns in 2012 revealed a transverse emittance blow-up of about 0.4 to $0.9 \mu\text{m}$ from injection into the LHC to the start of collisions, see Fig. 1. The emittance of the first 144 bunch batch in the LHC was measured with wire scanners at injection and compared to the calculated emittance from peak luminosity in ATLAS. Emittances from CMS luminosity show similar results.

EMITTANCE EVOLUTION THROUGH THE LHC CYCLE

Wire scanners are used to measure the emittance through the LHC cycle. Thus only low intensity fills (maximum 24 bunches) could be studied to avoid wire scanner breakage or excessive losses in the downstream superconducting magnets and beam dumps. An important ingredient for analysing the wire scanner data are reliable beta function measurements at locations of the profile monitors. The optics had been measured with the turn-by-turn phase advance method at 450 GeV injection energy, four discrete points during the energy ramp (at 1.33, 2.3, 3.0 and 3.8 TeV for beam 1, and at 1.29, 2.01, 2.62 and 3.66 TeV for beam 2) and 4 TeV flattop energy before and after the β^* squeeze [1].

Figure 2 shows the beam 1 horizontal emittance evolution through the cycle of two 6 bunch batches. The evolution

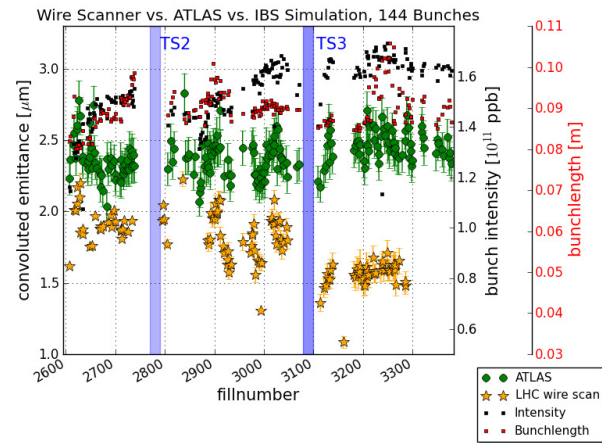


Figure 1: Convoluted average emittance of the first injected 144 bunch batch at injection (orange stars), measured with wire scanners and fitting the entire transverse profile, and at the start of collisions (green dots), calculated from ATLAS bunch luminosity using measured bunch length (red) and intensity (black).

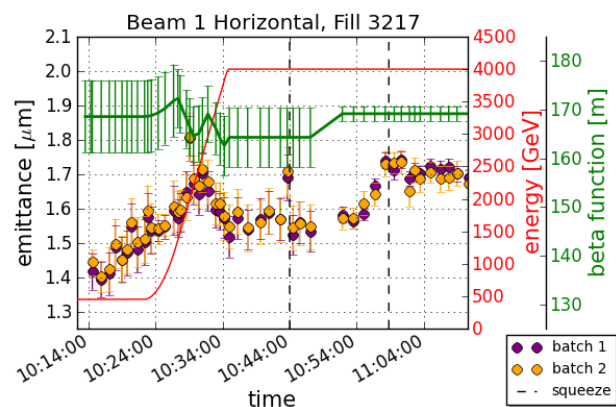


Figure 2: Average beam 1 horizontal emittances of 6 bunches per batch through the LHC cycle for Fill 3217 measured with wire scanner and compared to the beta function evolution. The core emittance is displayed. Vertical black dashed lines indicate the period of the squeeze.

of the energy and beta functions is also indicated. Linear interpolation is used between the different beta measurement points.

The growth during the injection plateau has been studied in detail in [2]. Intra Beam Scattering (IBS) and 50 Hz noise seem to be the main driver. The non-physical emittance evolution during the ramp is now believed to come from

insufficient knowledge of the beta function evolution during the ramp. Many more beta measurement points will be needed in the future. The dashed vertical lines in Fig. 2 indicate the period of the β^* squeeze. The emittance blow-up during the squeeze, which manifested itself mainly during the second half of 2012, is believed to be connected to the observed beam instabilities. Their origin is not understood to date.

During injection plateau and ramp, the emittance growth in the horizontal plane dominates. Vertical emittance growth occurs in case of large coupling during injection and ramp or with instabilities during the squeeze.

EFFECT OF IBS DURING THE RAMP

Understanding the emittance blow-up during the LHC ramp was one of the main objectives for emittance growth investigations in 2012, the last year of LHC Run 1. Only in 2014, after refined beta calculation algorithms to compute the beta functions at the profile monitors became available, progress in the understanding came. In spite of not changing the design optics between injection plateau and until the end of the ramp, the beta functions do not stay constant during the ramp due to various effects. The measurements of non-physical emittance evolution, e.g. shrinking emittances, can most probably be explained by non-monotonically changing beta functions and not enough beta measurement points during the ramp, see Fig. 3 for beam 1 vertical. The beta functions for beam 2 horizontal grow monotonously during the ramp and linear interpolation between two measurement points is justified, see Fig. 5.

IBS has been found to be the main source of growth in the horizontal plane during the injection plateau. The effect of IBS reduces with increasing energy but is not negligible for the LHC beam parameters during the ramp and flattop energy. Figure 4 compares emittance measurements corrected with the measured and interpolated betas during the ramp and predictions from IBS simulations. The simulations were

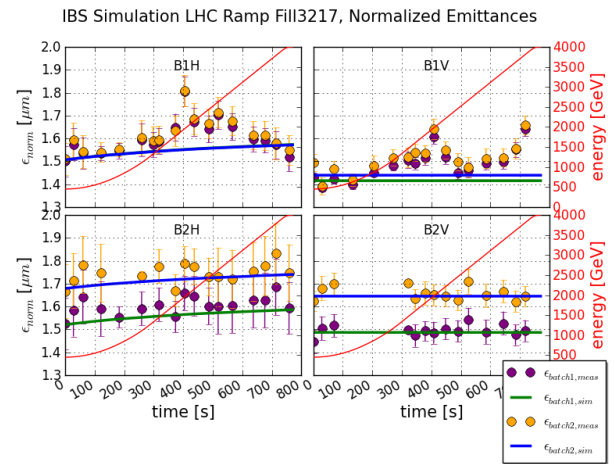


Figure 4: Average emittances of 6 bunches per batch during the LHC ramp for Fill 3217 measured with wire scanners and compared to IBS simulations with MADX.

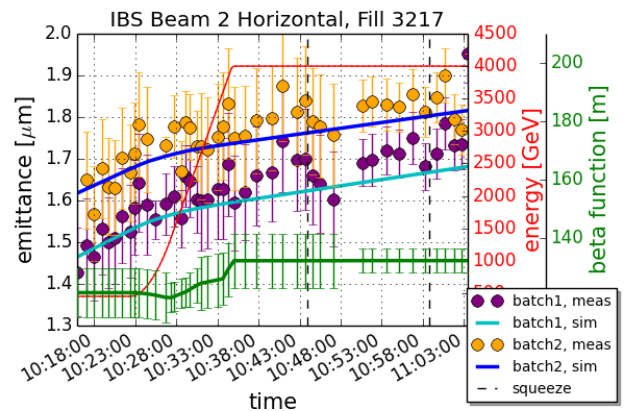


Figure 5: Average emittances of 6 bunches per batch during the LHC cycle for Fill 3217 beam 2 horizontal measured with wire scanner and compared to IBS simulations with MADX.

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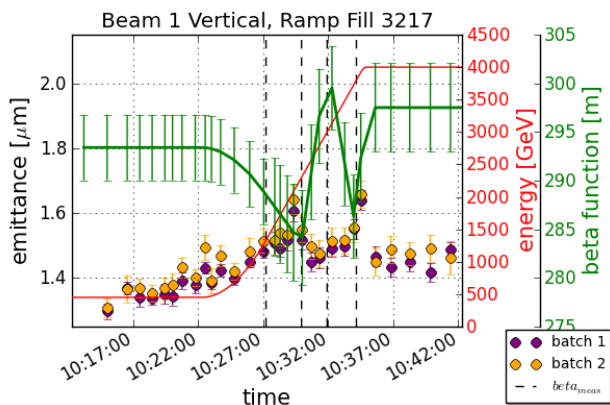


Figure 3: Average beam 1 vertical emittances of 6 bunches per batch during the LHC ramp for Fill 3217 measured with wire scanner and compared to the beta function evolution. Vertical dashed lines indicate a beta measurement.

performed with the IBS module of MADX [3] using nominal optics and the initial measured transverse emittances, bunch length and intensity as input parameters. The IBS module assumes no coupling or dispersion, therefore no growth in the vertical plane is predicted. To take the evolving emittances and therefore evolving IBS growth times into account, simulations were performed in an iterative way using intervals of 10 s. The updated emittances were then used for the next simulation. The total length of the ramp in 2012 was 13 minutes.

For beam 2 the simulated emittance evolution fits remarkably well with the measured one for the horizontal and vertical plane, see Fig. 4. Moreover, IBS seems to be the dominant source for emittance growth through the entire cycle for beam 2 horizontal, see Fig. 5.

IBS simulations for physics fills with typical 2012 beam parameters give an estimated total growth of about $0.4 \mu\text{m}$ in the horizontal plane for the very bright beams towards

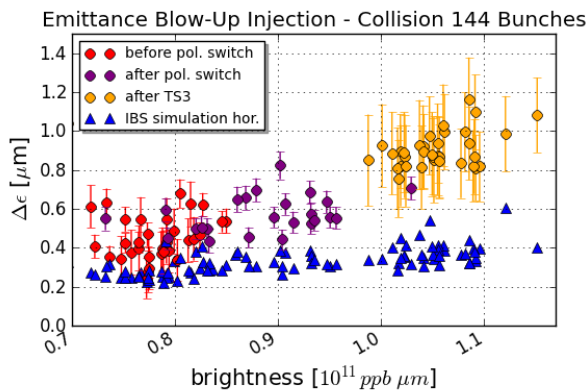


Figure 6: Average total blow-up of the first 144 bunch batch of the convoluted emittance (dots) from wire scans and ATLAS luminosity compared to simulated horizontal blow-up due to IBS (triangles). The colors indicate different LHC run configurations in 2012. After Fill 2926 the Landau octupole polarity was reversed (purple) and after TS3 bunches with even higher brightness were produced in the injectors (orange).

the end of 2012. However, growth in the order of $1 \mu\text{m}$ was measured.

Figure 6 shows the simulated emittance growth for IBS through the cycle in the horizontal plane versus brightness and compares it to the convoluted emittance growth obtained from injection wire scans and luminosity. The measured points are on a different slope than the IBS simulated ones. This is another indication that IBS is not the only source of emittance growth.

DISCREPANCY BETWEEN EMITTANCE FROM WIRE SCANS AND LUMINOSITY

The total growth measured through the LHC cycle with wire scanners for low intensity test fills at the end of the year is less than 50 % of what is measured with the emittance from luminosity for physics fills. The first conclusion after this observation was that low intensity fills are not representative for full intensity physics fills in terms of emittance growth. During test fills the beams were also put into collision and luminosity data was taken while the wire scans took place. Emittance results from wire scanners and the luminosities of ATLAS and CMS were obtained at exactly the same point in time. For the calculation of the emittance from luminosity all known effects and their uncertainties, such as measured β^* , crossing angle, measured bunch length and intensities, are taken into account. Nevertheless the convoluted emittances from luminosity are always about 30 - 50 % larger than the convoluted emittance from the wire scanners. An example measurement (Fill 3217) is shown in Table 1.

During another test fill (Fill 3160) beam profile data was also taken with the LHCb SMOG detector [4]. Compared to wire scanner results, LHCb delivers smaller or larger emittances,

depending on the beam and plane, with a difference of up to $0.6 \mu\text{m}$, which is still within the measurement uncertainty. For some cases the wire scanners measure even larger emittances. Mostly for this fill emittance values from LHCb are smaller than ATLAS and CMS values and larger than the wire scanner ones.

The discrepancy between wire scanner emittance values and those from luminosity and LHCb SMOG is not understood. With the results from LHCb we can preliminary conclude that the emittances from luminosity are overestimated. During LHC Run 2 wire scanner measurements and uncertainties on emittance extrapolations from luminosity will have to be characterized in detail.

Table 1: Comparison Convoluted Emittance from Wire Scans and Luminosity for Fill 3217 Batch 2

	Wire Scan	ATLAS	CMS
$\varepsilon_{\text{injection}}[\mu\text{m}]$	1.58 ± 0.06	Measurement not possible.	
$\varepsilon_{\text{collision}}[\mu\text{m}]$	1.84 ± 0.06	2.33 ± 0.12	2.63 ± 0.14
$\Delta\varepsilon[\mu\text{m}]$	0.25 ± 0.12 (16 %)	0.75 ± 0.18 (47 %)	1.05 ± 0.20 (66 %)

CONCLUSION

According to the LHC design parameters less than 10 % emittance growth through the cycle is allowed. During LHC Run 1 more than a factor 3 of this value was observed based on emittance derived from luminosity data. In this paper it was shown that IBS is one of the main sources of growth through the entire cycle including the 4 TeV flattop.

For the 25 ns high brightness beams in Run 2 (1.2 ns bunch length, 1.3×10^{11} ppb and $1.3 \mu\text{m}$ horizontal emittance at injection) IBS simulations suggest an average horizontal emittance blow-up during the cycle of about 20 %, assuming a 20 min ramp to 6.5 TeV and the same injection and flattop plateau length as in 2012.

Sudden emittance growth during the squeeze was also observed in 2012, probably associated with beam instabilities.

The discrepancy between emittance values from wire scans and luminosity is still not understood and has to be investigated thoroughly in 2015. Luminosity was the only means during LHC Run 1 to get emittance information for physics fills.

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