TRANSVERSE EMITTANCE THROUGH THE LHC CYCLE - AN UPDATE

M. Kuhn[1,2], G. Arduini[1], V. Kain[1], A. Langner[1,2], Y. Papaphilippou[1], G. Papotti[1], M. Schaumann[1], R. Tomas[1], [1]CERN, Geneva, Switzerland, [2]University of Hamburg, Hamburg, Germany

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 injection plateau and the energy ramp probably due to Intra Beam Scattering (IBS). IBS Simulation results will be shown and compared to measurements also considering emittance growth during collisions. Requirements for commissioning the LHC with beam in 2015 after Long Shutdown 1 to understand and control emittance blow-up will be listed. A first estimate of emittance measurement accuracy for LHC Run 2 will also be given.

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 μm 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 μm 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. At the end of the 2012 LHC proton run it was found that wire scanner gain and filters have an influence on the obtained beam sizes. It was not possible to obtain optimum wire scanner settings and thus optimum beam size values during LHC Run 1 [1].

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 [2].

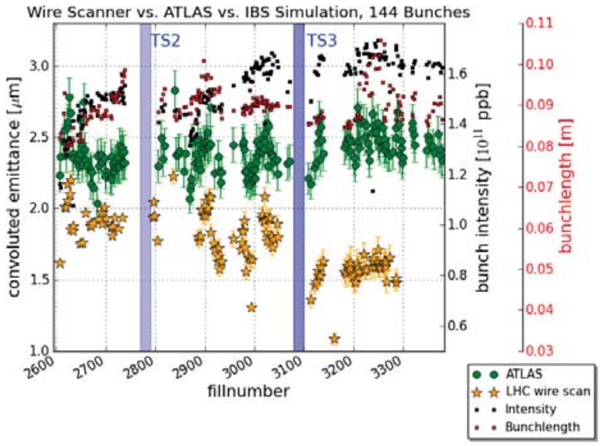

Figure 1: Convoluted average emittance of the first injected 144 bunch batch at injection (orange stars), measured with wire scanners and fitting the entire transverse profile, and at the start of collisions (green dots), calculated from ATLAS bunch luminosity using measured bunch length (red) and intensity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

Figure 2 shows the beam 1 horizontal emittance evolution through the cycle of two 6 bunch batches during test Fill 3217 (October 2012). The evolution of the energy and beta functions is also indicated. Linear interpolation is used between the different beta measurement points. The injected bunches had an intensity of 1.6×10^{11} ppb, a bunch length of 1.2 ns and a transverse emittance of 1.3 - 1.6 μm.

The growth during the injection plateau has been studied in detail in [1]. Intra Beam Scattering (IBS) and 50 Hz noise

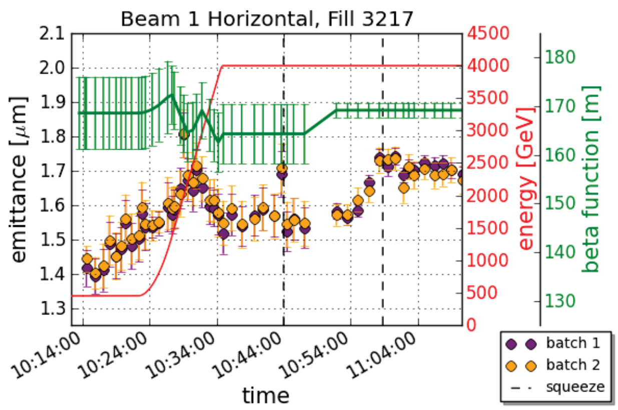

Figure 2: Average beam 1 horizontal emittances of 6 bunches per batch through the LHC cycle for Fill 3217 measured with wire scanner. The core emittance is displayed. Vertical black dashed lines indicate the period of the squeeze.

seem to be the main driver. The non-physical emittance evolution during the ramp is now believed to come from insufficient knowledge of 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.

Non-Physical Emittance Evolution during 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 proton physics 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.

EFFECT OF IBS DURING THE CYCLE

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 en-

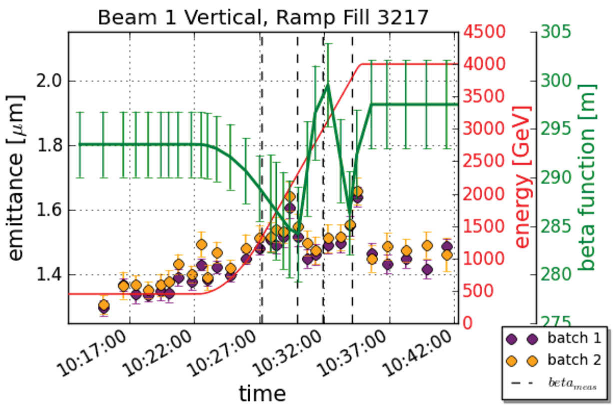

Figure 3: Average beam 1 vertical emittances of 6 bunches per batch during the LHC ramp for Fill 3217 measured with wire scanner and compared to the beta function evolution. Vertical dashed lines indicate a beta measurement.

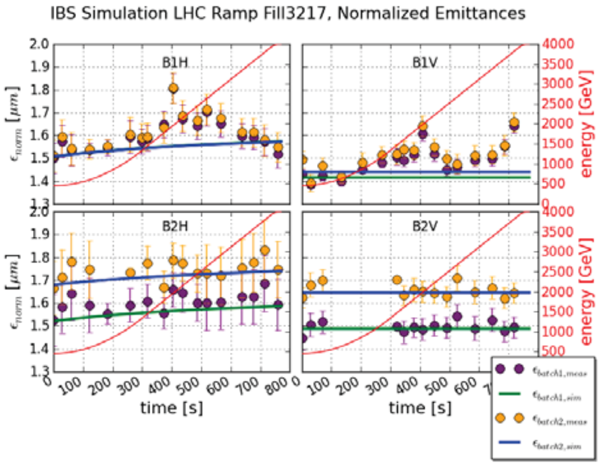

Figure 4: Average emittances of 6 bunches per batch during the LHC ramp for Fill 3217 measured with wire scanners and compared to IBS simulations with MADX.

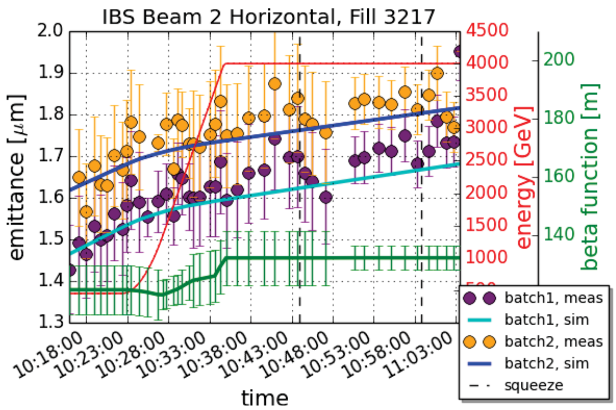

Figure 5: Average emittances of 6 bunches per batch during the LHC cycle for Fill 3217 beam 2 horizontal measured with wire scanner and compared to IBS simulations with MADX. The beta function evolution is also shown.

ergy. Figure 4 compares emittance measurements corrected with the measured and interpolated betas during the ramp and predictions from IBS simulations. The simulations were performed with the IBS module of MADX [3] using the initial measured emittance, bunch length and intensity as input parameters. 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 during the ramp 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 μm in the horizontal plane for the very bright beams towards the end of 2012. However, growth in the order of 1 μm was measured.

EFFECT OF IBS DURING COLLISIONS

To be able to compare emittances of physics beams during collisions calculated from luminosity to IBS simulations one has to assume equal transverse beam sizes. Therefore the real value of the horizontal emittance at the start of collisions is uncertain. To get meaningful simulation results, long, high performance fills from 2011 and 2012 were chosen and data cleaned if necessary (e.g. removal of unstable bunches). A comparison of emittances from luminosity and simulation during collisions in the LHC is shown in Fig. 6. IBS simulations where performed with MADX and the Collider Time Evolution program (CTE) [4] taking the measured bunch intensity and bunch length evolution into account.

Note that for fills later in 2012 the emittance at the start of collisions is larger (~ 2.4 μm) and the slope of emittance evolution is steeper at the beginning of collisions and overall more parabolic than for fills earlier in 2012 and in 2011 (emittance at start of collisions ~ 2.2 μm). The simulated growth, however, looks similar for all fills. The absolute measured emittance growth is about 1 μm in 8 hours for all fills. For fills at the end of 2012 the emittance blow-up calculated from luminosity is almost twice as large as the simulated horizontal emittance growth.

During a low intensity test fill in 2012 emittances were measured with wire scanners while beams were colliding (Fill 3160). Here a direct measurement of the horizontal emittance can be compared to IBS simulations (MADX), see Fig. 7. Measurements were performed only during 2 hours in collisions and the bunches had a very short bunch length and small emittances, thus emittances blew up by ~ 40 %. Yet,

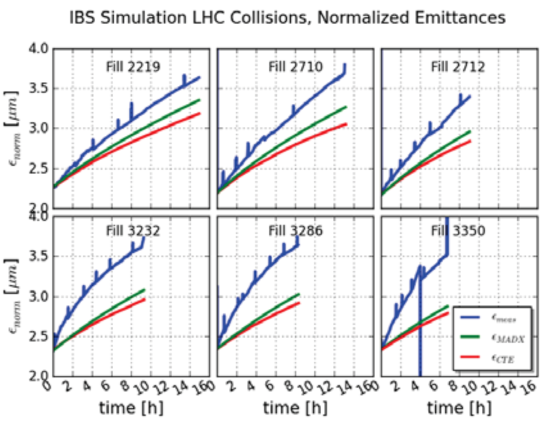

Figure 6: Convoluted emittance evolution during LHC collisions calculated from luminosity (blue) for fills in 2011 (Fill 2219), beginning of 2012 (Fill 2710, 2712) and end of 2012 (Fill 3232, 3286, 3350) and compared to simulated horizontal emittance growth from MADX (green) and CTE (red). The spikes in the blue curve correspond to luminosity optimization scans.

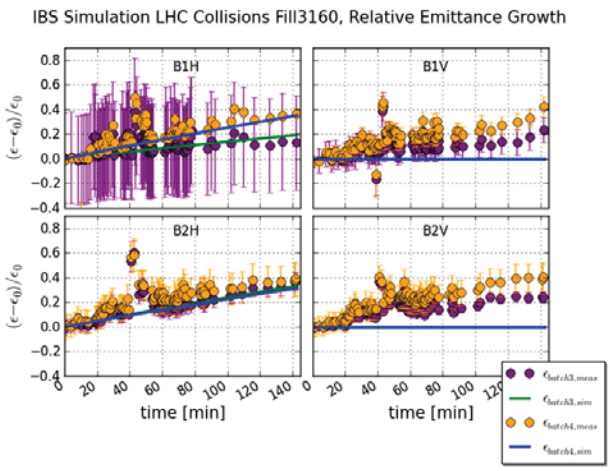

Figure 7: Average relative emittance growth of 6 bunches per batch during LHC collisions for Fill 3160 measured with wire scanners and compared to IBS simulations with MADX. Batch 3 bunches are non colliding. Bunches of batch 4 are colliding in ATLAS and CMS.

the simulation matches the measurement in the horizontal plane.

Figure 7 also shows almost the same measured emittance blow-up in the vertical plane as in the horizontal plane. So far no explanation could be found.

IBS Emittance Growth for Beams In Run 2

At the start of Run 2 the LHC will be running with nominal beams meeting the LHC design parameters (standard scheme [5]. Later in the run the beam parameters can be pushed to higher brightness with a Batch Compression, bunch Merging and Splitting scheme in the LHC injectors (BCMS scheme [6]). Assuming that injection and flattop plateau length are the same as in 2012 and a 20 min ramp to 6.5 TeV, estimates for the horizontal emittance blow-up during the LHC cycle and collisions from IBS can be given, see Table 1 (RF voltage from 6 MV at injection to 12 MV at 6.5 TeV, 1.25 ns bunch length, 1.3 $\times 10^{11}$ ppb at injection and 95 % transmission through the cycle). Based on previous physics fills about 20 % intensity losses during 8 hours in collisions are predicted and included in the simulations. Similar as in 2012, the high brightness beams will suffer severely from IBS.

Table 1: Simulated Horizontal Emittance Growth from IBS for LHC Run 2 Beam Parameters.

Scheme	Standard	BCMS
$\varepsilon_{injection}$ [μm]	2.4	1.3
$\Delta\varepsilon_H$ cycle	5 % ($\leq$ 0.15 μm)	20 % ($\leq$ 0.3 μm)
$\varepsilon_{collision}$ [μm]	2.7	1.7
$\Delta\varepsilon_H$ 8 h collisions	13 % ($\leq$ 0.35 μm)	35 % ($\leq$ 0.6 μm)

EMITTANCE MEASUREMENT PUZZLE

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 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 2.

During another test fill (Fill 3160) beam profile data was also taken with the LHCb SMOG detector [7]. 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 μm, 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 2: Comparison Convoluted Emittance from Wire Scans and Luminosity for Fill 3217 Batch 2.

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

NEW LHC POINT 4 OPTICS

In 2015, at 6.5 TeV LHC collision energy, the transverse beam sizes of the high brightness beams will be very small. This affects the measurement accuracy. It will not be possible to get reasonable emittance results for beam sizes smaller than 200 μm. A solution would be to increase the beta function at the transverse profile monitors to increase the local beam size. Table 3 shows the expected beam size improvements with overall new ATS-compatible optics in LHC point 4 [8, 9] assuming 1.7 μm emittance at flattop energy.

Increased beta functions at the wire scanners and BSRT leads to a better beam size measurement accuracy and meaningful emittance results. Also the BGI might be applicable during LHC Run 2 for beam size measurements with the new optics. (It was not possible to calibrate the BGI correctly for the LHC proton run in 2012.)

Table 3: Expected Beam Size Improvements at the Transverse Profile Monitors with New LHC Point 4 Optics (ATS) at 6.5 TeV with 1.7 μm emittance with respect to design optics (nom).

$\sigma[\mu m]$	**B1H**		**B1V**		**B2H**		**B2V**	
	ATS	nom	ATS	nom	ATS	nom	ATS	nom
Wire Scanner	201	217	266	289	174	213	315	320
D3 (BSRT)	206	222	230	271	177	219	287	297
BGI	277	282	153	229	259	279	228	251

CONCLUSION AND PLANS FOR LHC RUN 2

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.

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.

The emittance measurement accuracy LHC Run 2 could be improved with new optics in point 4 that increase the beta functions at the transverse profile monitors.

To understand and control emittance blow-up after Long Shutdown 1, early optics measurements with the turn-by-turn phase advance measurement and with k-modulation are essential. All transverse profile monitors need to be calibrated at the start of Run 2. This includes quantifying wire scanner photomultiplier saturation.

Van der Meer scans at the beginning of Run 2 can be used to compare wire scanner measurements to emittance results from ATLAS and CMS luminosity as well as beam sizes from the LHCb SMOG detector. Measurements with few bunches during the entire cycle including collisions are requested to compare emittances measured with wire scanners, BSRT, BGI and BGV if possible. Finally, lumi scans at the end of physics fills might help to understand emittance blow-up during collisions.

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