LHC EMITTANCE PRESERVATION DURING THE 2012 RUN

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Abstract

Emittance measurements through the 2012 LHC proton cycle examined possible major sources for the large blow-up through the LHC cycle already seen in 2011. The behavior of single bunch and 50 ns beams from LHC injection to collisions has been investigated. Accuracy and limitations of the LHC transverse profile monitors will be discussed. The effect of 50 Hz noise on the emittance growth and the influence of different transverse damper gains are presented. Intra beam scattering is one of the major sources of blow-up in the horizontal plane at injection. RF batch-by-batch blow-up has been put into operation towards the end of the year to counteract this effect. The impact of these measures on specific luminosity will be presented. The creation of tails through the LHC cycle will also be briefly discussed and an outlook for future LHC upgrade scenarios with low emittance beams will be given.

INTRODUCTION

Measurement campaigns during the 2011 proton run revealed substantial transverse emittance blow-up through the LHC cycle. The emittances at collision - typically 2.5 μm for 1.5×10^{11} ppb - were still below the LHC design values of 3.5 μm, but about 30 % larger than at the end of LHC injector chain. The blow-up during the different phases in the LHC cycle was evaluated with the following main results [1]:

- No measurable blow-up from injection into the LHC
- Blow-up during injection plateau: consistent with Intra-Beam Scattering (IBS), causes batch-by-batch differences, 0 - 10 % blow-up depending on injection time of batch
- Significant blow-up during the ramp: more than 20 % for 1.6 μm emittances
- Beam 1, horizontal plane, blow-up by about 20 % during the squeeze
- Absolute emittance growth seems to be independent of bunch intensity and initial emittance: $\Delta\varepsilon \sim 0.5 - 0.6$ μm, convolution of beam 1 and beam 2.

In 2012 the protons were ramped to 4 TeV instead of 3.5 TeV as in 2011 and β* was squeezed down to 0.6 m in point 1 and point 5 instead of 1 m as in 2011. The main parameters of the 2012 run are summarized in Table 1. Fig. 1 shows the evolution of the emittances in collision (green) and after injection (yellow) throughout the 2012 proton run. The emittances from the high performing injectors were as small as 1.5 μm for bunch intensities of up to 1.7×10^{11} ppb. The emittances of the beams were, however, blown up by up to 40 % in the LHC until collision during the 2012 high intensity proton run.

Table 1: LHC proton run configuration in 2012

Total number bunches for fill	1374
Max number bunches injected	144
Bunch spacing [ns]	50
Intensity/bunch	1.1 –1.7 $\times10^{11}$
Intermediate intensity [bunches]	12
Number of injections per fill and beam	12 (+1 pilot)
Filling time	~ 30 min
Number collisions (ATLAS+CMS/ALICE/LHCb)	1368/0/1262
Collision energy per beam	4 TeV
Max. luminosity achieved [$cm^{-2}s^{-1}$]	7.7×10^{33}

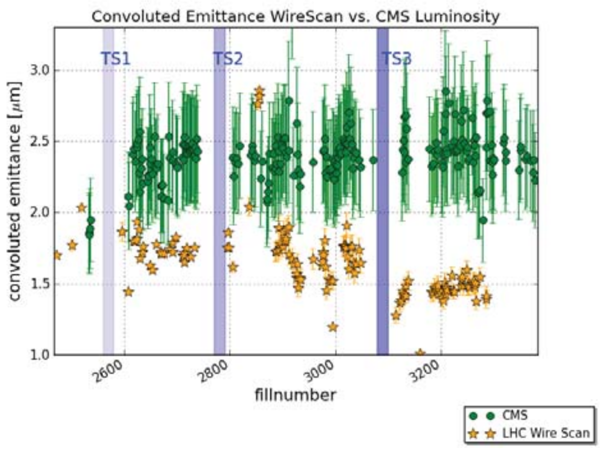

Figure 1: Convoluted, average emittance of the first 144 bunch batch measured with wire scanners at LHC injection (yellow stars) compared to the convoluted emittance calculated from CMS peak luminosity (green dots). The periods of the technical stops are marked with TS. With the introduction of the Q20 optics in the SPS [2] (after TS3) the emittances from the injectors were even smaller (improvement from 1.8 to 1.5 μm), but the emittance at collision in the LHC stayed the same.

EMITTANCE MEASUREMENT

Three types of instruments are installed in the LHC to measure the transverse beam size: the wire scanner, the Beam Synchrotron Radiation Telescope (BSRT) and the Beam-Gas Ionization Monitor (BGI). Still none of the instruments could be used to measure the high intensity physics beams throughout the whole cycle due to the systems limitations. For physics beams the emittances were measured at two points of the cycle: wire scans were performed after the first 144 bunch batch injection and indirect measurements of the convoluted emittance were obtained through luminosity and luminous region measurements at the end of the cycle, see Eq. 1.

$$\varepsilon_{conv} = \sqrt{\varepsilon_{1x} + \varepsilon_{2x}}\sqrt{\varepsilon_{1y} + \varepsilon_{2y}} \qquad (1)$$

The uncertainties on emittances from luminosity presented in this paper assume 15 % error on β* and 5 % error on the crossing angle.

Low intensity test cycles were used to measure the emittances through the cycle with wire scanners. The cores of the transverse profiles of in and out scans were fitted with Gauss Functions to obtain beam sizes. All emittance values from wire scanners in this paper were calculated with beta functions measured with k-modulation. K-modulation values for 2012 are available at injection, end of ramp and after the squeeze. For measurements through the ramp, the beta functions were obtained through linear interpolation between the beta value at injection and at flattop.

Towards the end of the proton run, the wire scanners became partly unavailable. Issues occurred with the maximum number of measurement cycles and robustness of the wires. During technical stop (TS) 3 all wires were switched to the spare system and the maximum allowed intensity for scans was even further reduced due to the still thicker wires. The wire scanner intensity limit at 4 TeV flattop energy was decreased from 30 to 20 nominal bunches. After a wire had broken with beam no more scans were done with physics beam at injection (from Fill 3287 onwards). Another issue with the wire scanners in 2012 concerned the accuracy of the beam size measurement. This topic will be treated in more detail later on in this paper.

The LHC BSRTs became the workhorse for physics beam measurements during the injection plateau and at 4 TeV. Due to the improved speed of the scans (3 to 4 bunches per second) since May 2012 the bunch-by-bunch emittance evolution during injection and squeeze can be studied with sufficient statistics for the full machine. However, only the beam 1 system was available from August 2012 due to a damaged mirror on the beam 2 systems.

The BGI - the only system which is able to measure physics beams through the ramp – could not be used in 2012. Only the beam 2 system was operational, but the energy dependent calibration was not satisfying. There are signs of beam space charge driven distortion of the beam profile in the BGI.

EMITTANCE EVOLUTION THROUGH THE CYCLE

Fig. 2 shows the emittance evolution through the cycle for beam 1, horizontal plane, measured with wire scanners during a test fill with 6 + 6 bunches per ring, 50 ns bunch spacing and bunch intensities of about 1.6×10^{11} ppb (Fill 3217). Beam 2 horizontal looks qualitatively similar: the emittances grow mainly during the injection plateau and the ramp. Some growth is also seen towards the end of the squeeze, especially for fills later in the 2012 run.

The total emittance growth measured by wire scanners for the fill in Fig. 2 is about 0.48 ± 0.06 μm (35 %), convoluted emittance. Yet the peak luminosity for ATLAS and CMS measured at the end of the cycle corresponded to a growth of the convoluted emittance of about 0.72 ± 0.34 μm (50 %). This discrepancy between wire scanner measurements and emittance from luminosity were seen throughout the 2012 run. More details on this topic will be discussed later in the paper. In the following the emittance growth of the different parts of the LHC cycle will be presented.

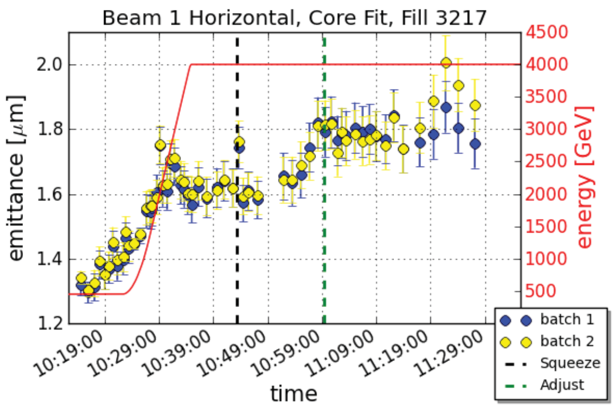

Figure 2: Average emittance of 6 bunches per batch through the whole LHC cycle for beam 1 horizontal measured with wire scanner, Fill 3217. Batch 1 is colliding at LHCb, batch 2 in ATLAS and CMS.

The LHC injection process

As was already the case in 2011, the emittances in the vertical and horizontal plane are conserved within the measurement precision at injection from the SPS into the LHC (measurement precision ± 10 %). The LHC matching monitors are not operational yet. Wire scans at SPS flattop and right after LHC injection are used instead. Fig. 3 shows an example of measurements in the SPS and in the LHC. The measurements in the LHC are bunch-by-bunch, whereas in the SPS an average for all bunches is given. The wire scanners in the SPS are at locations with small beta functions and the wire speed cannot be reduced due to issues with saturation. Only a few points are available per scan to obtain the Gaussian fit. Overlaying profiles of several scans increases the accuracy significantly, see Fig. 4. This method was used to obtain the SPS numbers in Fig. 3 and 4.

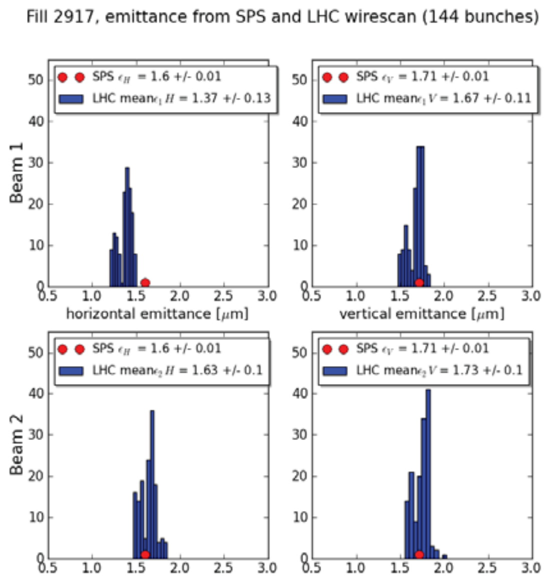

Figure 3: Emittances at SPS and LHC. Wire scan histograms of bunch-by-bunch emittances at LHC injection (blue bars) compared to average emittances of 144 bunches at SPS extraction (red dot).

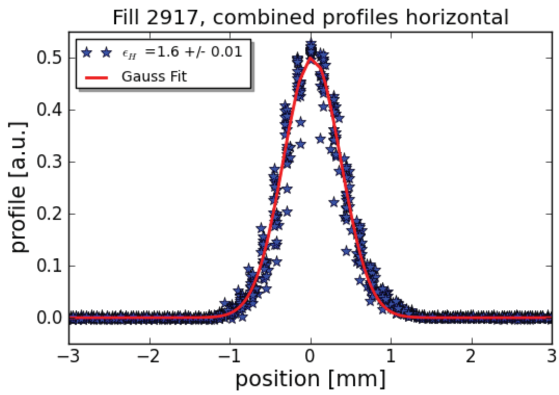

Figure 4: SPS combined profiles from wire scans of 144 bunches in the horizontal plane at SPS extraction energy of 450 GeV.

The LHC injection plateau

In 2012 many dedicated fills at injection energy were compared to IBS simulations. Fig. 5 and 6 show 6 nominal (1.6 x 10^{11} ppb) 50 ns bunches measured with wire scanners and the matching IBS simulations for every bunch of beam 1 horizontal and vertical. The emittance growth in the horizontal plane is well predicted with IBS, but slightly faster than the simulation. A possible explanation is 50 Hz noise. The results were cross checked with measurements from BSRT and also different initial emittances, which give similar agreement. As a solution for the effects from IBS the longitudinal RF batch-by-batch blow-up was tested. The effects at injection introduce batch-by-batch differences in the specific luminosity. Batches that stay longer at injection have a larger emittance blow-up and therefore their specific luminosity is smaller than batches that spend less

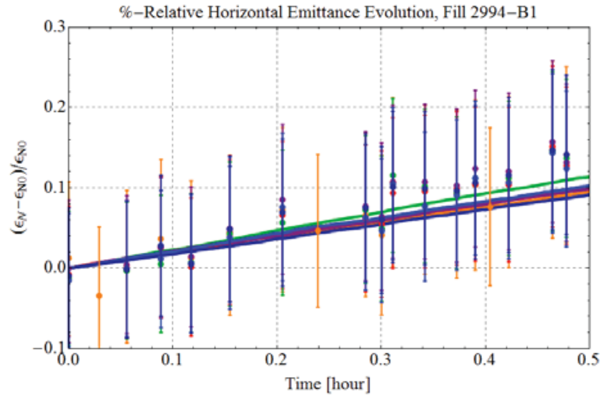

Figure 5: Relative emittance growth at the injection plateau for 6 bunches of beam 1 horizontal measured with wire scanner (dots) and compared to IBS simulations with same initial conditions (lines), Fill 2994.

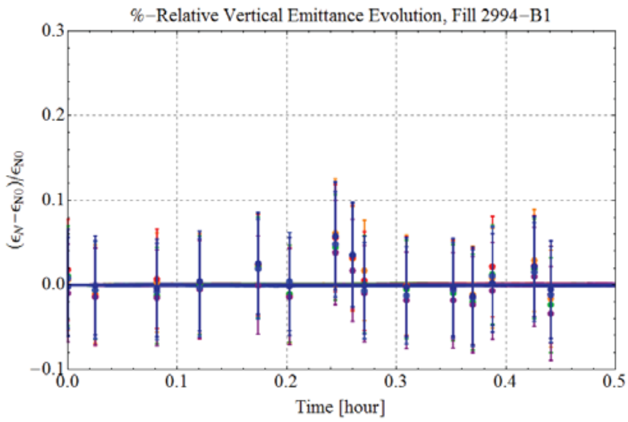

Figure 6: Relative emittance growth at the injection plateau for 6 bunches of beam 1 vertical measured with wire scanner (dots) and compared to IBS simulations with same initial conditions (lines), Fill 2994.

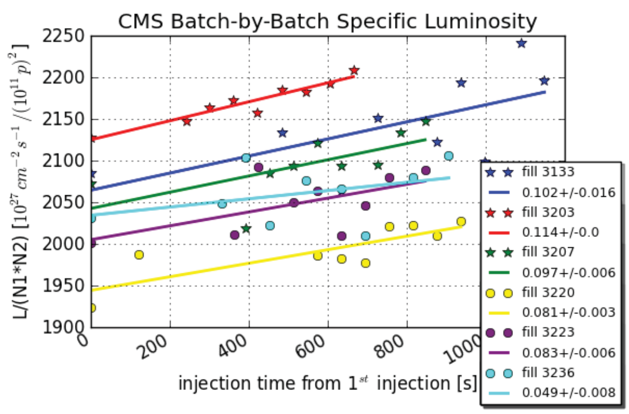

Figure 7: Specific CMS luminosity calculated from CMS peak luminosity and bunch intensity at collision, averaged per batch and plotted as a function of injection time from the first injection for fills with (dots) and without RF batch-by-batch blow-up (stars). A linear interpolation is displayed. The fitted slopes can be found in the legend.

time at the injection plateau. Fig. 7 shows the specific luminosity for the different batches as function of the injection time for fills with and without RF batch-by-batch blow-up. Fills 3133, 3203 and 3207 are left to natural blow-up. Fills 3220, 3223 and 3236 are longitudinally blown up to a target bunch length of 1.4 ns. The data points are fitted linearly. The average slope is slightly smaller for fills with longer bunches but there is no clear improvement. Another source of the batch-by-batch differences could be 50 Hz noise.

Noise Studies at 450 GeV

The LHC horizontal injection tune sits on top of a 50 Hz line and the beam is slightly excited by this noise. Fig. 8 shows the influence of the 50 Hz noise on the emittances of 6 nominal (1.3 x 10^{11} ppb) 50 ns bunches measured with wire scanners. The bunches were injected and kept at the nominal fractional tune of 0.28 for a period of 10 min. Then the horizontal tune was moved to 0.283 to avoid the 50 Hz noise. After 10 min the tune was moved back to nominal. Changing the horizontal tune clearly had an effect on the emittances in both planes. The effect coupled into the vertical plane as the betatron coupling was about a factor 2 above the typical physics fill values for this fill. In the horizontal plane IBS and 50 Hz noise cause emittance growth and the effect of the tune changes was only a small change of the slope of the emittance growth. The effect was, however, more visible in the vertical plane where the blow-up almost vanished with a tune far away from the 50 Hz line and then increased again when changing back to the nominal tune.

In view of these results a test ramp was carried out with a horizontal tune off the 50 Hz line. No evident improvement of the emittances at the end of the ramp was measured. The test ramp will have to be repeated under controlled conditions.

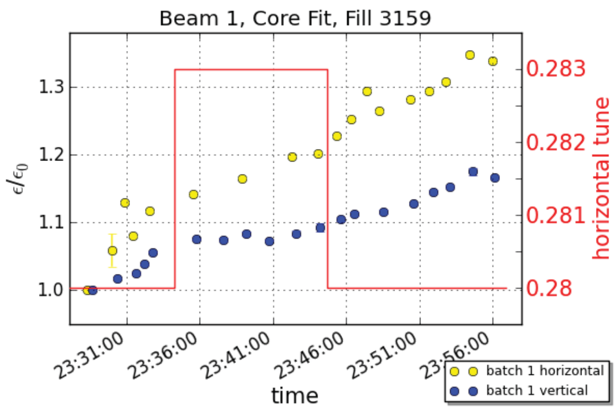

Figure 8: Relative average emittance growth of 6 bunches at injection energy for beam 1 horizontal and vertical measured with wire scanners, Fill 3159. ε_0 is the emittance at injection into the LHC. The horizontal fractional tune during the measurement period is displayed as well.

Transverse Damper Gain at 450 GeV

At injection, the LHC transverse damper is operated with a very high gain to keep emittances small after injection due to injection oscillations and possible other effects. At the start of the ramp the gain is reduced to allow for a sufficient tune signal to switch on the tune feedback during the ramp [3]. The tune measurement of the feedback system comes from the LHC Base-Band-Tune (BBQ) monitors. Fig. 9 and 10 display BSRT emittance measurements at injection energy with varying transverse damper gain in both planes for beam 1. One nominal bunch with an intensity of 1.4 x 10^{11} protons was injected with high injection gain. Then the gain was reduced to the original 2012 low ramp gain and after 10 min back to high gain. The slope of the fit for the vertical plane clearly increases when moving to lower damper gain. The higher damper gain reduces or even removes the emittance growth. In the horizontal plane the blow-up mainly originates from IBS, on which the damper has no effect and the slope of the growth only changes slightly between the different gains.

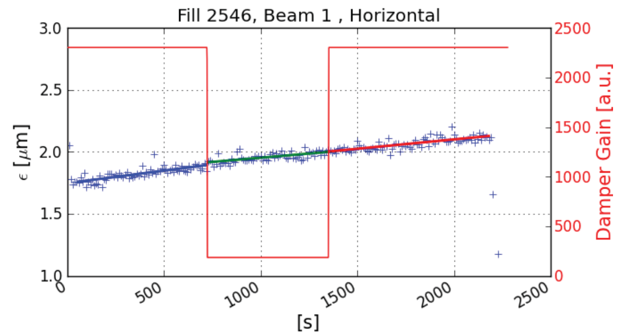

Figure 9: BSRT measurements on 1 nominal bunch for beam 1 horizontal at injection energy with changing horizontal ADT gain from nominal high injection gain to low ramp gain and back to high gain. The emittance growth in the different segments is fitted linearly, Fill 2546.

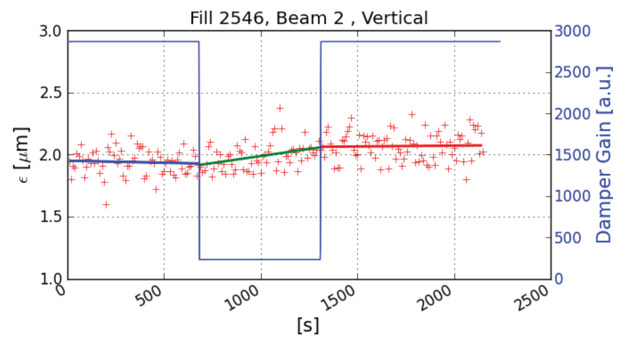

Figure 10: BSRT measurements on 1 nominal bunch for beam 2 vertical at injection energy with changing vertical ADT gain from nominal high injection gain to low ramp gain and back to high gain. The emittance growth in the different segments is fitted linearly, Fill 2546.

The LHC ramp

All beams and planes show an emittance blow-up through the ramp. Generally it is larger in the horizontal plane than the vertical plane and more pronounced for beam 2 than for beam 1 in 2012. In Fig. 11 a test ramp measured with wire scanner for beam 1 horizontal is shown. For Fill 3217 the total average emittance growth during the ramp is about 20 % for beam 2 horizontal, about 15 % for beam 1 horizontal, and approximately 5 % in the vertical plane for both beams. The ramp has been studied thoroughly. The observed growth is unlikely to be a measurement artifact. The measured beta functions are used at injection and flattop and a linear interpolation between these values for energies during the ramp is applied. Dispersion is not taken into account as it has been measured to be small (< 10 cm at injection, < 30 cm at flattop). The absolute emittance blow-up through the ramp is roughly the same, independent of the emittance value at the start of the ramp.

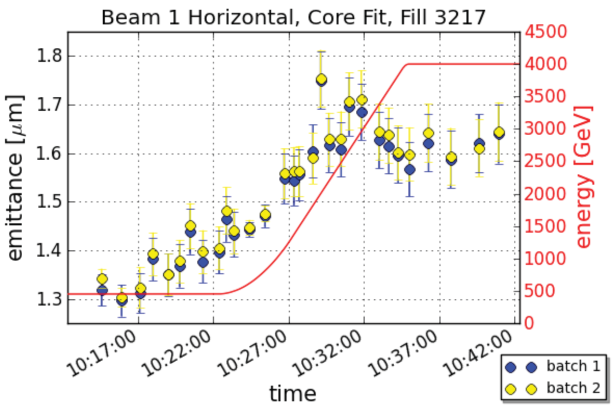

Figure 11: Wire scans of beam 1 horizontal during the ramp with emittances averaged over 6 bunches in one batch, Fill 3217.

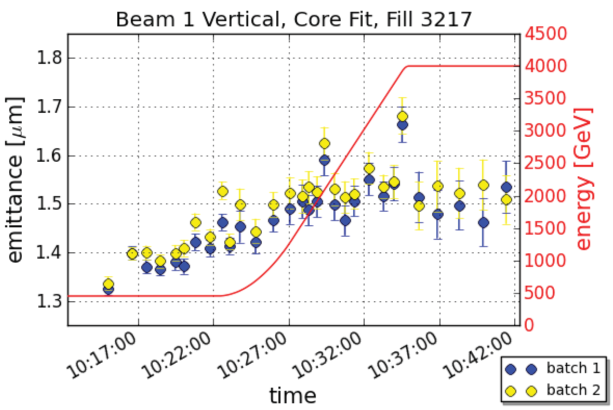

Figure 12: Wire scans of beam 1 vertical during the ramp with emittances averaged over 6 bunches in one batch, Fill 3217.

Transverse Damper Gain during the Ramp

The encouraging results on emittance growth from increased damper gain during the injection plateau triggered a test with increased damper gain during the ramp. To be able to compare batches with and without increased gain, the damper gain was modulated around the LHC circumference. Fig. 13 and Table 2 summarize the ADT gain modulation for the 4 batches used during the test. Each batch contained 6 nominal (1.3 x 10^{11} ppb) 50 ns bunches. The emittance measurement results of the different batches are shown in Fig. 14 and 15. The emittance growth in the vertical plane is small, see Fig. 15. Table 3 summarizes the emittance growth of the different batches of beam 1, horizontal. For all batches the growth during the ramp was about 0.26 ± 0.07 μm (25 %). There was no significant difference of blow-up for different transverse damper gains.

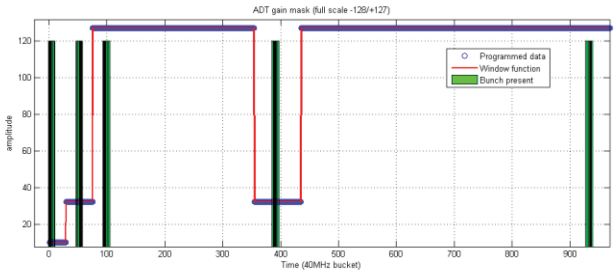

Figure 13: ADT ramp gain modulation for Fill 3160, beam 1. Batch number 4 was not injected. The function was applied before starting the ramp.

Table 2: ADT ramp gain modulation for Fill 3160

Batch 1	Very low gain bunches, sacrificial (lower than operational gains)
Batch 2	Low gain bunches (~ nominal low prepare ramp gain)
Batch 3 Batch 4	Very high transverse damper gain (~ nominal injection gain)

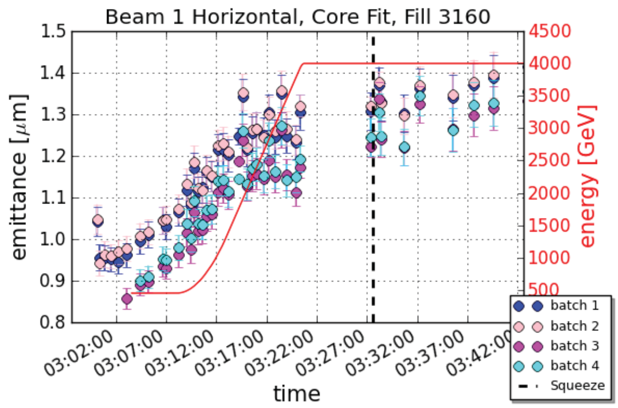

Figure 14: Average emittance of 6 bunches per batch through the ramp and the squeeze for beam 1 horizontal measured with wire scanner, Fill 3160. The bunches have different transverse damper gains at the start of the ramp, see Table 2.

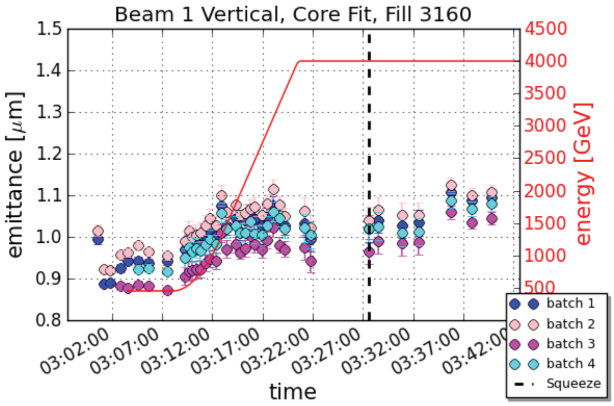

Figure 15: Average emittance of 6 bunches per batch through the ramp and the squeeze for beam 1 vertical measured with wire scanner, Fill 3160. The bunches have different transverse damper gains at the start of the ramp, see Table 2.

Table 3: Emittance growth of beam 1 horizontal, Fill 3160

	Growth during ramp [μm]
Batch 1	0.24 ± 0.08 (23 %)
Batch 2	0.25 ± 0.06 (23 %)
Batch 3	0.26 ± 0.05 (27 %)
Batch 4	0.27 ± 0.07 (27 %)

The LHC squeeze

Towards the end of the 2012 proton run a small blow-up at the end of the squeeze for beam 1 horizontal was observed, but not always by the same amount. The emittances in the vertical planes and beam 2 horizontal were conserved (caveat: beam 2 was only measured with wire scanners for low intensity fills). Examples are given in Fig. 16 - 19.

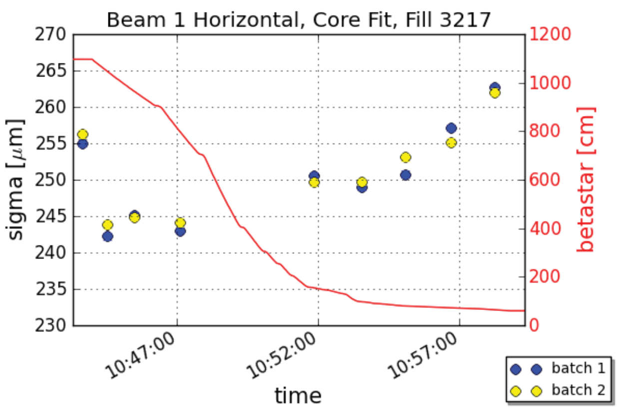

Figure 16: Beam sizes averaged over 6 bunches in one batch for beam 1 horizontal during the squeeze of Fill 3217 measured with wire scanner.

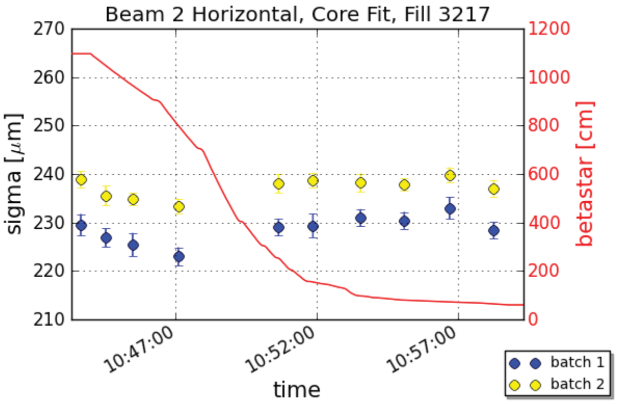

Figure 17: Beam sizes averaged over 6 bunches in one batch for beam 2 horizontal during the squeeze of Fill 3217 measured with wire scanner.

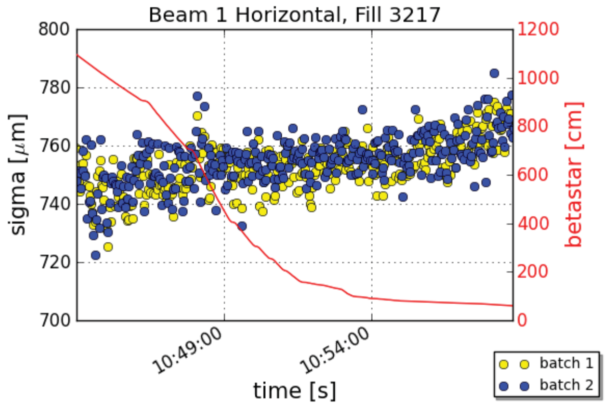

Figure 18: Beam sizes for beam 1 horizontal during the squeeze of Fill 3217 measured with BSRT. Beam sizes are averaged over 6 bunches in one batch.

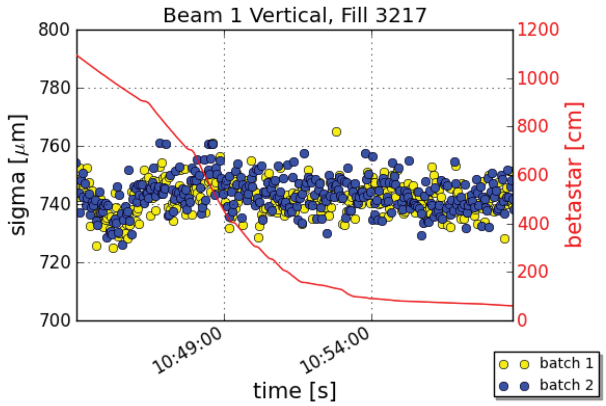

Figure 19: Beam sizes for beam 1 vertical during the squeeze of Fill 3217 measured with BSRT. Beam sizes are averaged over 6 bunches in one batch.

MEASURES AGAINST EMITTANCE GROWTH

After Technical Stop 3 (TS3) several potential measures against emittance growth during the LHC cycle became operational. A summary can be found in Fig. 20. Since Fill 3220 the RF batch-by-batch blow-up was used for physics fills. Because the gated BBQ system became operational after Fill 3286 it was possible to have fills with higher ADT gain for the ramp. Also higher ADT bandwidth was used from flattop to the start of stable beams. Fig. 20 shows the influence of the different measures on the emittance at LHC collision. The emittances at injection are plotted as well for comparison. The emittances from peak luminosity vary slightly but within the error bars they are constant.

There is a short period around Fill 3280 where the emittances at collision were reduced when only the high ADT bandwidth was used. Due to the small number of fills during this period it is, however, not clear whether this is not just a statistical fluctuation. In conclusion, there is no obvious improvement of the average emittance at collision for any measures taken so far. But it seems the peak bunch-by-bunch specific luminosity can be increased with higher transverse damper gain during the ramp [4].

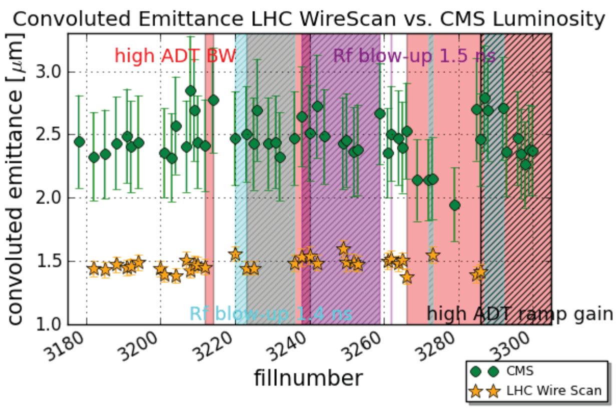

Figure 20: Convoluted averaged emittance of the first 144 bunch batch measured with wire scanners at injection in the LHC and compared to the convoluted emittance obtained from peak luminosity at CMS. Periods with different measures as RF batch-by-batch blow-up, high ADT bandwidth (BW) and high ADT ramp gain are highlighted.

COMPARISON OF EMITTANCE FROM EXPERIMENTS AND WIRE SCANNERS

For MD Fill 3160, 6 nominal (1.3 x 10^{11} ppb) 50 ns bunches were colliding head on in ATLAS and CMS. Wire scan measurements were taken and could be compared to bunch-by-bunch data from luminosity and luminous region. Also the LHCb SMOG experiment was taking beam size data. In Fig. 21 and 22 the convoluted bunch emittances from ATLAS luminosity, luminous region, wire scanner and SMOG are shown at two different timestamps. For the emittance from the experiments the nominal beta functions were used (IP1&IP5 $\beta^* = 0.6$ m, IP8 $\beta^* = 3$ m). The error on emittance from SMOG data and ATLAS luminous region also include statistical errors and systematic errors in case of the SMOG experiment.

There is a large discrepancy between the different values from wire scanners and experiments, sometimes more pronounced (Fig. 21) and sometimes less (Fig. 22). There is also a systematic difference between SMOG data and emittances from ATLAS/CMS. In general the wire scan measurements always showed smaller emittances than obtained by the experiments.

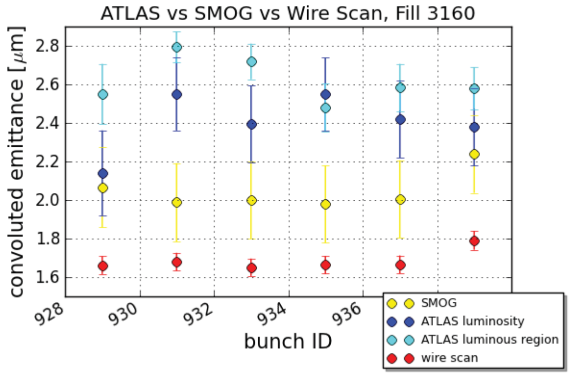

Figure 21: Convoluted emittance per bunch measured with SMOG and wire scanners and calculated from ATLAS luminosity and luminous region. Timestamp 12/10/2012 04:42, Fill 3160.

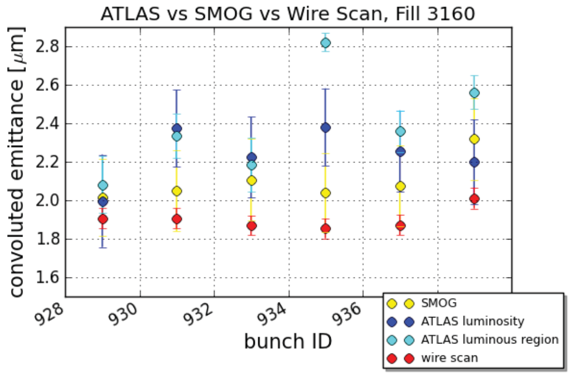

Figure 22: Convoluted emittance per bunch measured with SMOG and wire scanners and calculated from ATLAS luminosity and luminous region. Timestamp 12/10/2012 5:04, Fill 3160.

Accuracy of the Wire Scanners

The findings presented in the previous section led to investigations of the optimum wire scanner settings. For this purpose the beam size was measured with the wire scanners for different settings of photomultiplier voltage and transmission filter. Fig. 23 shows an example of the measurements at injection energy for beam 1 horizontal. Scans were performed for all beams and planes at injection and flattop energy and the results look all similar. The constant linear emittance growth in the plot is due to IBS at injection energy but clearly gain and filter change have a significant influence on the beam size. This is not ADC saturation, since all profiles still look Gaussian. The photomultipliers are saturating at certain settings and it is not clear which settings give the real beam size. The resulting uncertainty on the beam size measurement therefore has to be increased from originally 0.1 μm to 0.5 μm at 450 GeV and to 0.8 μm at 4 TeV. The optimum working point of the wire scanners needs further investigation.

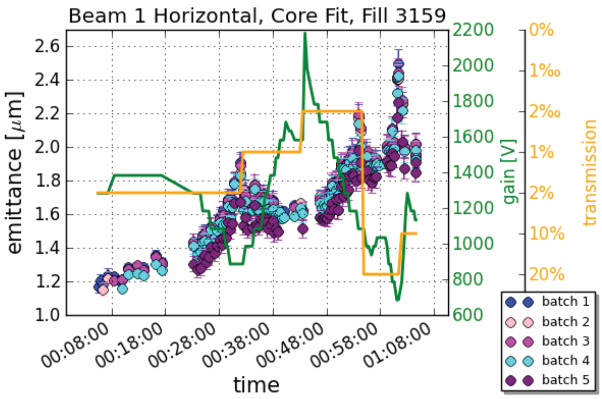

Figure 23: Average emittance of 6 bunches per batch during the injection plateau measured with wire scanner. Variations of wire scanner filter and voltage are displayed for beam 1 horizontal, Fill 3159.

EMITTANCE BLOW-UP VERSUS BUNCH INTENSITY

Fig. 24 shows the emittance blow-up from LHC injection to collision for all physics fills during the 2012 proton run as a function of the average bunch intensity. The intensity was obtained with the Fast Beam Current Transformer (FBCT) at peak luminosity. The high brightness test fills [5] (Fill 2994 and Fill 3372) are marked in green. Up to a bunch intensity of 1.5 x 10^{11} ppb the emittance blow-up is almost constant - about 0.7 μm. For bunch intensities beyond 1.5 x 10^{11} ppb the growth increases with bunch intensity. Whereas for the high brightness Fill 2994 the overall growth is similar as surrounding points in the plot, the growth for Fill 3372 is below 0.5 μm. Fill 3372, where the Batch Compression, Merging and Splitting (BCMS) [5] scheme in the PS was used, fell in a period where the higher damper gain during the ramp was already operational, which could be an explanation for the lower growth.

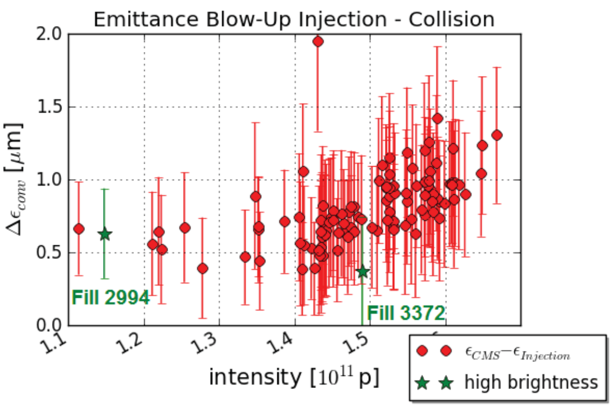

Figure 24: Convoluted average emittance growth from injection to collision as a function of average bunch intensity at collision. Δε is calculated from emittance from CMS peak luminosity and convoluted average emittance of the first 144 bunch batch measured with wire scanners at LHC injection. The high brightness fills (stars) are highlighted.

TAILS: CAN WE MEASURE THEM?

The evolution of transverse tails through the cycle has not been studied in 2012, but a way to indicate tails was found. The difference between the measurement signal and the Gauss fit of the transverse profile, see Fig. 25, was used to give an estimate of the tail population. In Fig. 26 the evolution of this difference is plotted for the wire sans at injection of beam 2 horizontal, for the period after TS2. Problems with tails right after TS2 are clearly visible.

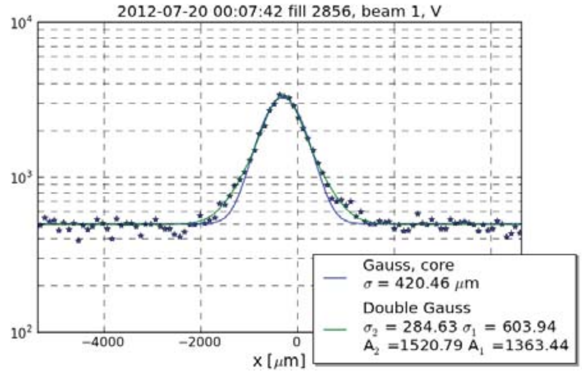

Figure 25: Transverse beam profile measured with wire scanner (dots). The core of the profile is fitted with a Gauss (blue line). Also a double Gauss fit is shown (green line). The corresponding beam sizes are given in the legend.

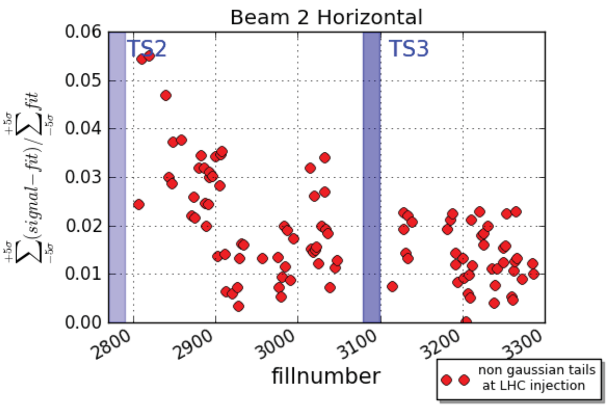

Figure 26: Tails calculated from the Gaussian fit of the transverse profiles measured with wire scanner and averaged over the first 144 bunch batch at LHC injection for the 2012 run after TS2.

INSTRUMENTATION WISH LIST FOR AFTER LS1

After the first long LHC shutdown (LS1) reliable emittance measurements through the whole cycle will be essential. The LHC wire scanners will have to be able to measure 288 bunches at injection. More time will have to be dedicated to understanding the wire scanner systematics to reliably calibrate the other instruments. Measurements through the cycle with physics beams would be highly desirable. For this the BSRT would need to be complemented with an operational BGI during the ramp. The installation of a Beam-Gas Imaging Vertex

Detector (BGV) following the principle of LHCb SMOG is under discussion. This device would greatly enhance the possibilities for understanding the LHC emittance evolution with physics beams.

CONCLUSIONS

At the end of LHC run 1, it is still very difficult to measure emittances and emittance blow-up. The wire scanner beam size measurements have large systematic errors due to issues with photomultiplier saturation. The emittances from luminosity still give the most trustable result. Emittance blow-up through the cycle in 2012 is similar to 2011. Most of the blow-up occurs during injection and ramp, occasionally also at the end of the squeeze. The sources of emittance growth at 450 GeV have been identified as IBS and 50 Hz noise. The cause for the blow-up during the ramp is still a mystery. The absolute emittance growth through the cycle is about 0.7 – 1 μm using the convoluted averaged emittance from luminosity. Any potential mitigation like RF batch-by-batch blow-up against IBS and higher transverse damper gain during the ramp have not lead to significant improvement of the emittance blow-up.

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REFERENCES

[1] V. Kain et al., “Emittance Preservation”, LHC Operations Workshop, Evian, France 2011.

[2] H. Bartosik et al., Optics Considerations for Lowering Transition Energy in the SPS, IPAC 2011, San Sebastian, Spain, September 2011.

[3] R. Steinhagen, “Real-Time Beam Control at the LHC”, PAC 2011, New York, USA, March 2011.

[4] M. Kuhn, “Emittance Preservation at the LHC”, Master Thesis, University of Hamburg/CERN, Geneva, Switzerland 2012.

[5] H. Damerau et al., “Performance Potential of the Injectors after LS1”, LHC Performance Workshop, Chamonix, France 2012.