INVESTIGATIONS OF THE LHC EMITTANCE BLOW-UP DURING THE 2012 PROTON RUN

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Abstract

About 30 % of the potential luminosity performance is lost through the different phases of the LHC cycle, mainly due to transverse emittance blow-up. Measuring the emittance growth is a difficult task with high intensity beams and changing energies. Improvements of the LHC transverse profile instrumentation helped to study various effects. A breakdown of the growth through the different phases of the LHC cycle is given as well as a comparison with the data from the LHC experiments for transverse beam size. In 2012 a number of possible sources and remedies have been studied. Among these are intra beam scattering, 50 Hz noise and the effect of the transverse damper gain. The results of the investigations are summarized in this paper. Requirements for transverse profile instrumentation for post LHC long shutdown operation to finally tackle the emittance growth are given as well.

INTRODUCTION

Measurement campaigns during the 2012 proton run revealed substantial transverse emittance blow-up through the LHC cycle. Figure 1 shows the evolution of the emittances in 2012 in collision, obtained through luminosity measurements (green), and after injection, wire scans of the first 144 bunch batch injection (yellow). 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 in the LHC were, however, blown up by up to 40 % until collision. The uncertainties on emittances from luminosity assume 15 % error on β^* and 5 % error on the crossing angle. The main parameters of the 2012 run are summarized in [1].

In 2013 a few proton fills were carried out with reduced collision energy of 1.38 TeV and thus shorter ramp of 5 min instead of 13 min for the nominal 4 TeV ramp. The total average emittance blow-up through the cycle for these fills was 0.1 – 0.2 μm, convoluted emittance. The emittance growth for the same bunch intensities (1.2×10^{11} ppb) from injection to collision for the 4 TeV run was 0.5 – 0.6 μm in 2012. From these measurements the predicted average emittance blow-up for the 6.5 TeV LHC cycle after LS1 with bunch intensities not larger than 1.5×10^{11} ppb would therefore be substantial: 0.8 – 1 μm, assuming the same filling time, but a longer energy ramp (21 min for 6.5 TeV [2]).

BLOW-UP THROUGH THE LHC CYCLE

Low intensity test cycles were used in 2012 to measure the emittances through the cycle with wire scanners. The emittance values were calculated with beta functions measured with k-modulation at injection, end of ramp and after the squeeze. For measurements through the ramp, a linear interpolation between injection and end of ramp beta values was used. The emittance error includes beta function error, fitting error and error from averaging.

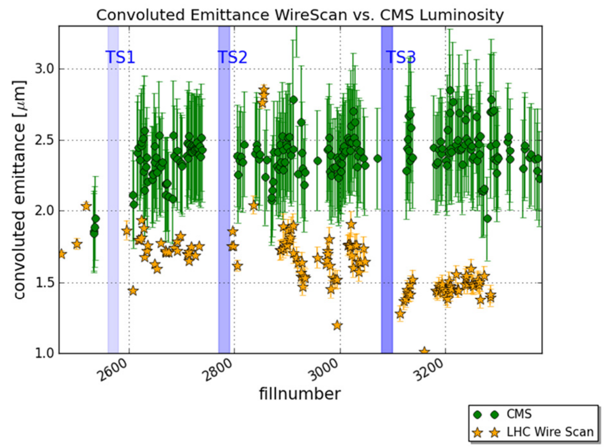

Figure 1: Convoluted, average emittance of the first 144 bunch batch measured with wire scanners at LHC injection (yellow stars) compared to the convoluted emittance calculated from CMS peak luminosity (green dots) of physics fills with 1368 proton bunches colliding in ATLAS&CMS at 4 TeV collision energy and 50 ns bunch spacing. The periods of the technical stops are marked with TS. With the introduction of the Q20 optics in the SPS [3] (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.

Figure 2 shows the emittance evolution through the cycle for beam 1, horizontal plane, measured with wire scanners during Fill 3217 with 6 + 6 50 ns bunches and bunch intensities of about 1.6×10^{11} ppb as an example. 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. The emittance blow-up in the vertical planes is smaller. The total emittance growth for this fill from LHC injection to start of collisions was about 0.48 ± 0.06 μm (35 %), convoluted emittance.

In 2012 many dedicated fills were studied with wire scanners and BSRT measurements to identify emittance growth during the various phases of the LHC cycle with the following results (details can be found in [1]):

- *The LHC injection process:* emittances in the vertical and horizontal plane are conserved within measurement precision of ± 10 % from SPS extraction to LHC injection

- *The LHC injection plateau:* The emittance growth in the horizontal plane is well predicted with IBS (8 % in 20 min), but slightly faster than the simulation (10 % in 20 min). A possible explanation is 50 Hz noise, see later. Through coupling the vertical plane can be affected as well at low damper gain.
- *The LHC ramp:* All beams and planes show an emittance blow-up through the ramp. Generally it is larger in the horizontal plane (15 – 30 %) than the vertical plane (~ 5 %) and more pronounced for beam 2 than for beam 1 in 2012.
- *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. Emittances in the vertical planes and beam 2 horizontal were conserved.

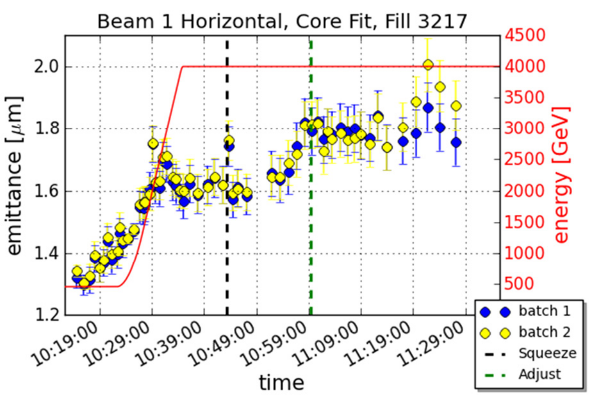

Figure 2: Average emittance of 6 bunches per batch through the entire LHC cycle for beam 1 horizontal measured with wire scanner, Fill 3217. Batch 1 is colliding at LHCb, batch 2 in ATLAS and CMS.

Comparison with Data from LHC Experiments

For MD Fill 3160, 6 nominal (1.3×10^{11} ppb) 50 ns bunches were colliding head on in ATLAS and CMS. Wire scanner measurements were taken and could be compared to bunch-by-bunch data from luminosity and luminous region as well as beam sizes measured with the LHCb SMOG experiment [4], see Fig. 3. For the emittance from the experiments the nominal beta functions were used ($\beta^*_{IP1\&5}$ = 0.6 m, β^*_{IP8} = 3 m). The error on emittance from SMOG data and ATLAS luminous region include statistical errors and also systematic errors in case of the SMOG experiment. There is a large discrepancy between the different values from wire scanners and experiments. In addition, there is a systematic difference between SMOG data and emittances from ATLAS. In general the wire scan measurements always showed smaller emittances than obtained by the experiments. An explanation could be photomultiplier saturation of the wire scanner [1]. Another indication of a potential wire scanner issue is that in 2012 emittances were partly shrinking with energy, see Fig. 2. Nevertheless the LHC wire scans at injection can be trusted as wire scans at SPS extraction give similar results. Thus the comparison between LHC injection wire scan values and emittances from luminosity holds.

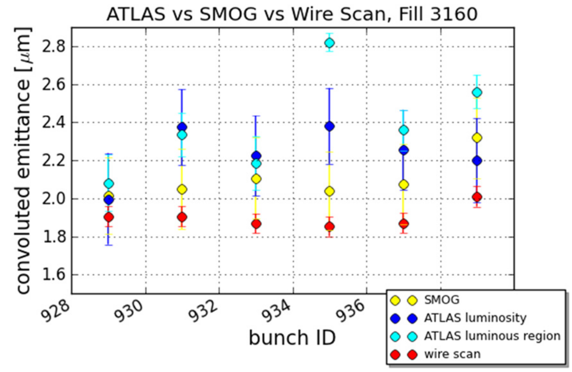

Figure 3: Convoluted emittance per bunch measured with SMOG and wire scanners and calculated from ATLAS luminosity and luminous region for Fill 3160.

POSSIBLE SOURCES AND REMEDIES

IBS at the LHC Injection Plateau

As a solution for the effects from IBS the longitudinal RF batch-by-batch blow-up was tested at 450 GeV [5]. For MD Fill 2556 wire scans of 12 bunch batches were frequently taken. In Fig. 4 the relative emittance evolution of beam 2 horizontal for batches, blown up longitudinally in the first minute following injection, and batches left to natural blow-up is plotted. The batches that are not artificially blown up suffer more from emittance blow-up. Their emittance growth is about 20 % in 20 min. For the longitudinally blown up batches the growth is only about 10 % in 20 min. The effects of IBS are clearly reduced.

Another source of emittance growth at 450 GeV is 50 Hz noise.

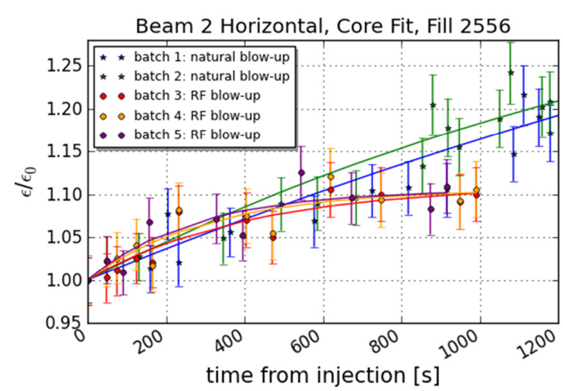

Figure 4: RF batch-by-batch blow-up test with 5 batches of 12 bunches. Batches 1 and 2 are left to natural blow-up. Batches 3, 4 and 5 are longitudinally blown up from a bunch length of 1.1 ns after capture to a target of 1.6 ns. An exponential fit (line) is applied to the relative emittance growth measured with wire scanner (dots). ε_0 is the emittance at injection into the LHC.

Influence of 50 Hz Noise 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. Figure 5 shows the influence of the 50 Hz noise on the

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emittances of 6 nominal (1.3 x 10^{11} ppb) 50 ns bunches measured with wire scanners at the 450 GeV injection plateau. The horizontal tune was altered in intervals of 10 min from the fractional nominal tune (0.28) to a fractional tune of 0.283, away from 50 Hz noise, and 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 vertical plane the blow-up almost vanished with a tune far away from the 50 Hz line. In the horizontal plane the effect is less visible because IBS dominates.

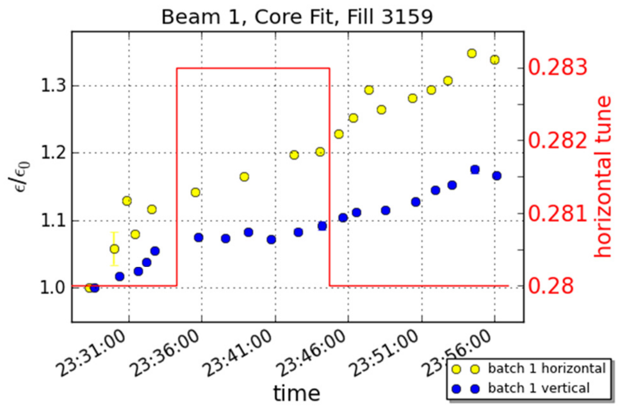

Figure 5: Relative average emittance growth of 6 bunches at injection energy for beam 1 horizontal and vertical measured with wire scanners, Fill 3159, with changing horizontal fractional tune (red line).

Effect of Higher ADT Gain during the Ramp

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 for the ramp [6]. To improve specific luminosity and minimize emittance blow-up a higher damper gain during the ramp was tested. In Fig. 6 the specific luminosity of physics fills with low and high ramp gain are compared. The higher transverse damper gain for the ramp has no visible effect on the specific bunch-by-bunch luminosity.

REQUIREMENTS FOR POST 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.

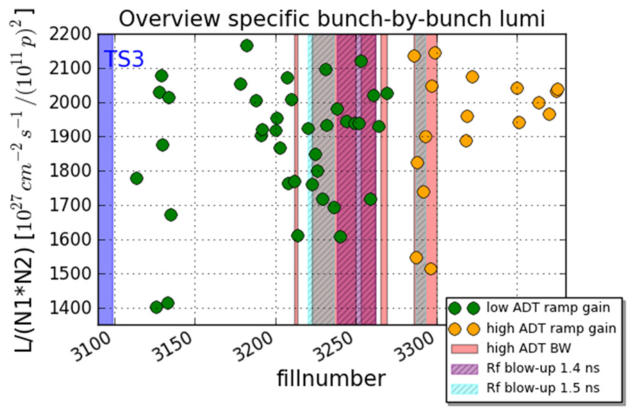

Figure 6: Most-probable average specific bunch-by-bunch luminosity for fills after Technical Stop 3 in 2012. Measures such as high bandwidth transverse damper (high ADT BW) and RF batch-by-batch blow with target bunch lengths of 1.4 and 1.5 ns are also displayed.

CONCLUSIONS

At the end of LHC run 1, it is still very difficult to measure emittances and emittance blow-up. The wire scanners measure rather too small beam sizes. The emittances from luminosity still give the most trustable result. In 2012 most of the emittance blow-up though the LHC cycle occurred 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 unclear. 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 has not led to significant improvement of the emittance blow-up for physics beams. It is possible that these measures reduced the emittance blow-up after all, but bunches at the end of the cycle became partly unstable and ended up with higher emittances at the start of collision.

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