EMITTANCE PRESERVATION IN THE LHC

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Abstract

Emittance measurements during the LHC proton run 2011 indicated a blow-up of 20 % to 30 % from LHC injection to collisions. This presentation will show the emittance preservation throughout the different parts of the LHC cycle and discuss the current limitations on emittance determination. An overview of emittance preservation through the injector complex as function of bunch intensity will also be given. Possible sources for the observed blow-up and required tests in 2012 will be presented. Possible improvements of emittance diagnostics and analysis tools for 2012 will be shown.

INTRODUCTION

One reason of the remarkable performance of the LHC in 2011 was the extraordinary performance of the LHC injectors. Bunch intensities of 1.5 × 10^{11} protons with emittances of 1.9 µm were produced for the 50 ns beams. The evolution of the emittances versus bunch intensities through the different injectors is shown in Fig. 1. The total blow-up through the chain is below 0.5 µm.

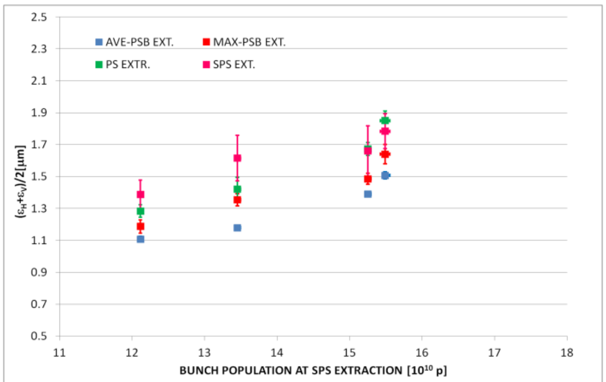

Figure 1: Emittance versus bunch intensity through the injector chain for 50 ns. The total blow-up through the chain is less than 0.5 µm.

This paper analyses emittance preservation from SPS extraction to start of LHC collisions. The focus is on the blow-up under nominal 2011 run conditions, see Table 1. The analysis is based on data from SPS and LHC wire scan measurements (SPS wire scanners at positions 416 and 519), the LHC synchrotron light monitor and the luminosities of ATLAS and CMS.

Table 1: LHC run configuration after June 2011

Total number bunches for fill	1380
Max number bunches injected	144
Bunch spacing [ns]	50
Intensity/bunch	1.1 –1.4 ×10^{11}
Intermediate intensity [bunches]	12
Number of injections per fill and beam	12 (+1 pilot)
Filling time	~ 20 min
Number collisions (ATLAS+CMS/ALICE/LHCb)	1318/39/1296, 1331/0/1320
Collision energy per beam	3.5 TeV
Max. luminosity achieved [$cm^{-2}s^{-1}$]	3.6 × 10^{33}

Limitations

The emittances of LHC 50 ns beams are routinely measured at the SPS flattop for the intermediate intensity of 12 bunches, which is injected first into the LHC, and 144 bunches, the full 50 ns SPS batch, before an LHC fill starts. There are however no routine measurements for the LHC transfers. Comparisons of SPS and LHC emittances at injection are thus not necessarily comparing emittances of the same beam.

Especially in the injectors the required wire scanner settings for the PM and filters depend strongly on various parameters of the beam and need to be adjusted carefully. The fit quality also needs to be scrutinized before trusting the results. As a consequence fairly large shot-by-shot variations on the measured emittance results are observed which do not seem to correspond to physical variations. An extreme example is shown in Fig. 2.

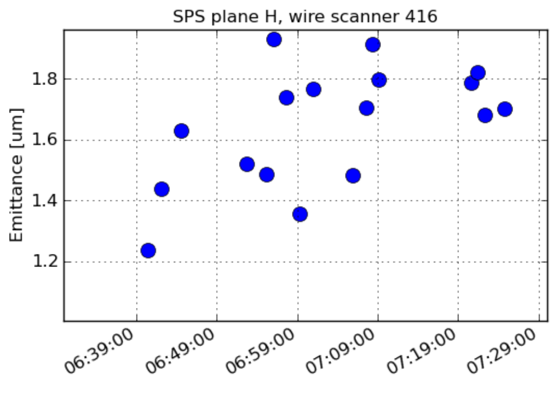

Figure 2: Emittance measurements in the SPS with 144 bunches, horizontal plane. Preparation of fill 2240. The spread of the obtained values is larger than 50 %.

For every fill the emittances of the first 12 bunch batch are measured with the LHC wire scanners. The first 144 bunch batch however is only rarely measured. Wire scans beyond an intensity of 2.5 ×10^{13} p+ are not allowed, to protect the wires and avoid quenches. There are no LHC wire scan measurements for physics beams at 3.5 TeV.

The LHC synchrotron light monitor (BSRT) continuously measures bunch-by-bunch emittances. In 2011, integration times of 3 s per bunch were required for good quality data. Measuring the emittance of every bunch once for 1380 bunches took therefore 69 minutes. Obviously the scan time was too long to follow the emittance evolution of a single bunch through the cycle and associate growth with specific parts of the cycle. For example the LHC ramp in 2011 took 17 minutes. Dedicated fills with a limited number of bunches or the BSRTs gated over a few bunches were hence used to study emittance evolution with these devices.

Another issue with the beam size values obtained from synchrotron light monitors is the absolute calibration. The BSRTs are calibrated using lamps and calibration targets. Nevertheless energy dependent effects like aberration and diffraction make an absolute calibration difficult. Wire scanners are used to calculate calibration factors at a given energy. For the time being the BSRTs are mainly used for relative comparisons at constant energy. An example of the obtainable data during the LHC cycle is shown in Fig. 3.

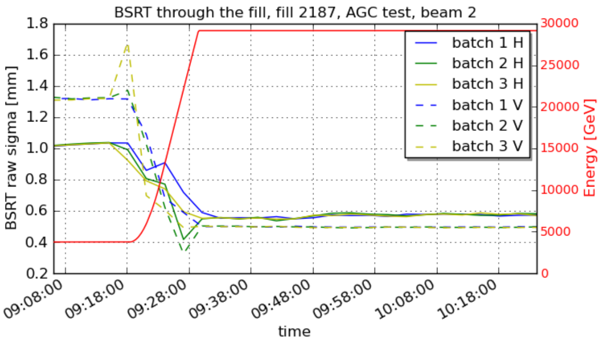

Figure 3: If gated on a few bunches only the BSRTs can be used to study the evolution of the emittance through the cycle. The data during the ramp cannot be used.

An indication of the emittance at the end of the LHC cycle, the start of collisions, can be obtained from the peak luminosity published by the experiments CMS and ATLAS. The resulting emittance value is a convolution of the horizontal and vertical emittances for the two beams. This approach is based on several assumptions and uncertainties. The experiments must be fully optimized and the published luminosity values correct. Both conditions were not always fulfilled in 2011. Another assumption is that the transverse intensity distribution is Gaussian. Measurements indicate that the population of the bunch tails might be larger than for truly Gaussian beams [1].

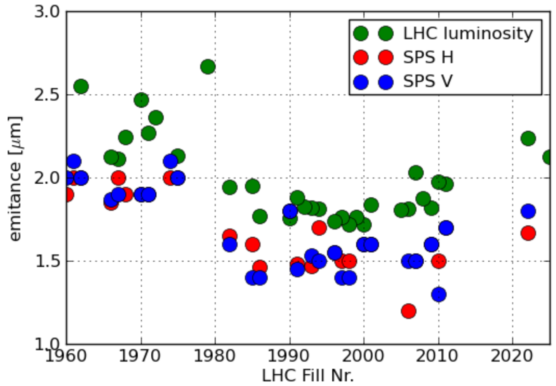

Figure 4: Comparison of the wire scan emittances of 144 bunch batches at the SPS flattop (blue, red) with emittances calculated from the LHC luminosity. Period: mid of July to mid of August 2011

CURRENT UNDERSTANDING OF LHC EMITTANCE PRESERVATION

60 LHC fills between mid July and mid August 2011 were analysed in [2]. The emitances from SPS wire scans with 144 bunches were compared with the emittances from LHC luminosity, see Fig. 4. A blow-up of 20 to 30 % on average between SPS flattop and LHC collisions is apparent, Fig. 5.

In the following the contribution to emittance blow-up from the different phases of the LHC cycle will be analyzed.

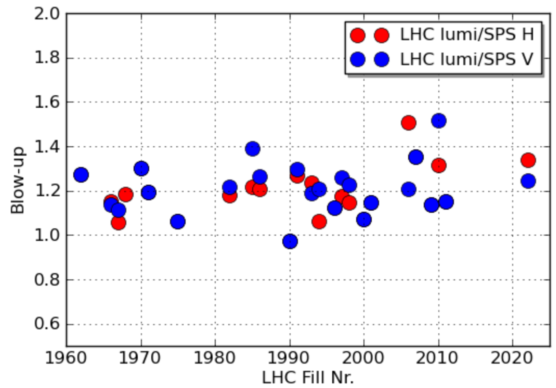

Figure 5: Blow-up between emittances of 144 bunch batches in the SPS and emittances from collision from Fig.4. Period: mid of July to mid of August 2011.

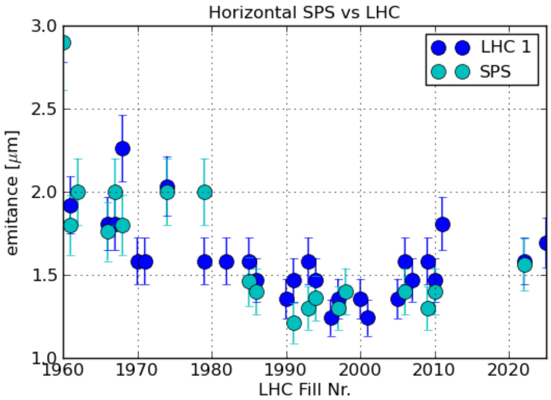

Figure 6: Comparison of horizontal wire scans of 12 bunches in the SPS and LHC.

MISMATCH AT INJECTION?

For the same 60 fills as above the wire scanner data for 12 bunch batches at the SPS flattop was compared with the 12 bunch wire scan data in the LHC. Fig. 6 and Fig. 7 show the results of the measurements for the horizontal and vertical plane of beam 1. Within the measurement accuracy, the emittance values are the same, see results in Table 2. No significant growth can therefore be attributed to the injection process.

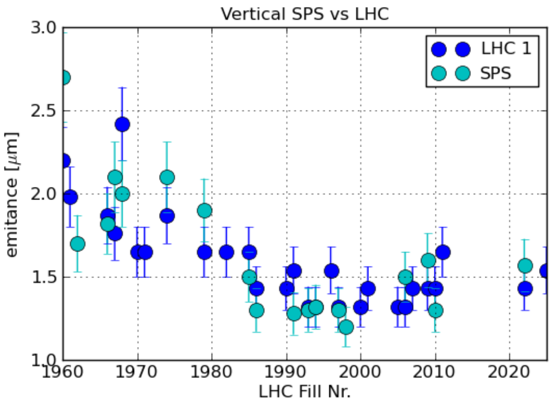

Figure 7: Comparison of vertical wire scans of 12 bunches in the SPS and LHC.

Fig. 8 and Fig. 9 compare the 12 bunch wire scan data of beam 1 and beam 2 at injection. Using the measured beta functions at the wire scanners beam 1 and beam 2 emittances are the same within the measurement accuracy. The results can also be found in Table 2.

Table 2: Results of comparison of 12 bunch wire scans between SPS extraction and LHC injection for beam 1 and comparison of LHC beam 1 and beam 2.

Horizontal LHC/SPS	1.07 ± 0.11
Vertical LHC/SPS	0.99 ± 0.12
Horizontal LHC 1/LHC 2	0.96 ± 0.08
Vertical LHC 1/LHC 2	1.06 ± 0.08

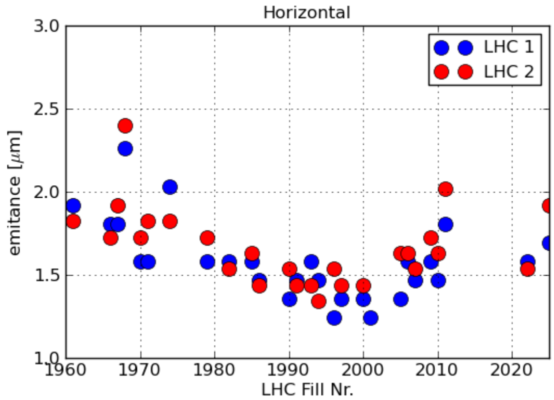

Figure 8: Comparison of horizontal wire scans of 12 bunches for beam 1 and beam 2.

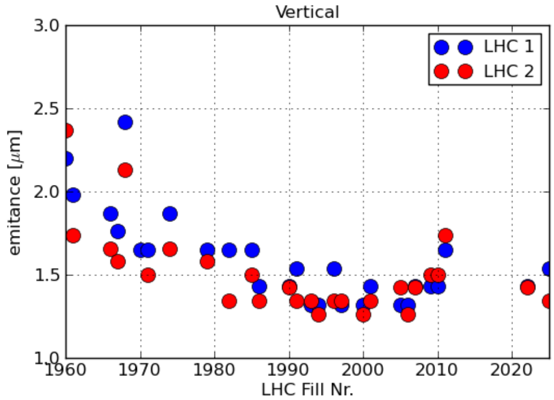

Figure 9: Comparison of vertical wire scans of 12 bunches for beam 1 and beam 2.

EMITTANCE GROWTH @ 450 GEV

The emittance evolution at 450 GeV was studied using the BSRTs gated on a single bunch or a few bunches only while waiting at injection of long periods (> 60 minutes). An example is shown in Fig. 10, Fill 2028. In this case the data was obtained while gating over a single bunch only. It is hence relatively noisy. The emittance in the horizontal plane grows by about 10 % in 20 minutes. The growth thereafter slows down as is typical for IBS Simulations were carried out to find the origin of the emittance blow-up. In Fig. 11, IBS simulation results are compared with emittance measurements for Fill 1897. The BSRT had been gated over 12 bunches for this occasion. The horizontal emittance growth is reasonably consistent with the growth predicted by IBS. The simulations used measured parameters of initial emittance (wire scanner), emittance evolution (BSRT), bunch length (LHC BQM), bunch intensity (LHC FBCTs) and RF total voltage as input. Method and code are described in [3].

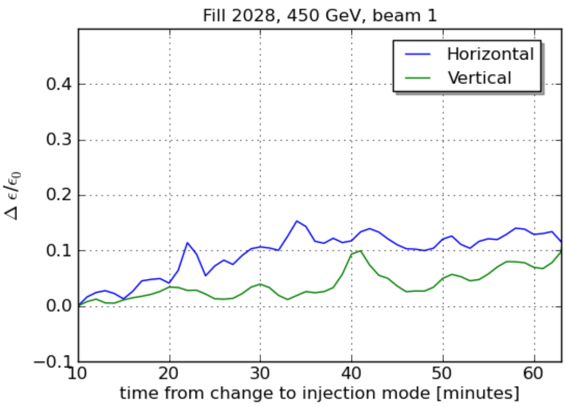

Figure 10: For fill 2028 the BSRT was gated over a single bunch. The measurement is noisy, nevertheless a growth in the horizontal plane of about 10 % in 20 minutes is apparent.

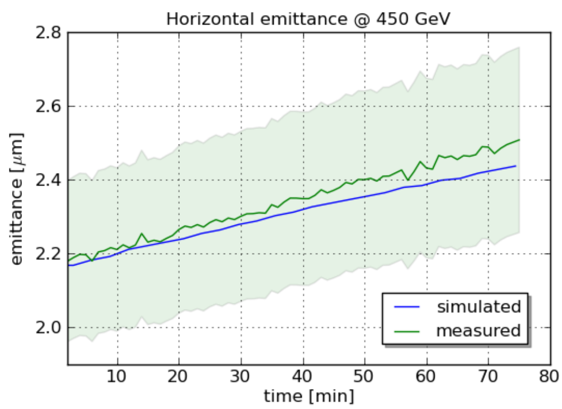

Figure 11: Comparison of measured horizontal emittance evolution at injection, green curve, with simulation of IBS (uncoupled), blue curve.

More studies will have to be carried out in 2012 to understand the nonetheless slightly faster growth in H than predicted by IBS and also the discrepancy between simulation and measurement of the bunch length evolution as shown in Fig. 12 for the same Fill 1897.

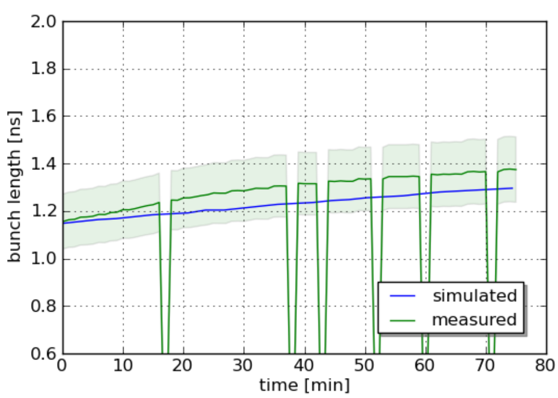

Figure 12: Comparison of evolution of measured bunch length with simulation of IBS. The discrepancy still needs to be understood.

The LHC filling (excluding the injection of the intermediate batch) takes about 30 minutes. This should be long enough to develop significant differences between the emittances of the first injected batch and the last injected one according to the growth rates seen in Fill 2028, Fig. 10. These differences should be visible in the specific bunch-by-bunch luminosity. And this is indeed the case as shown in Fig. 13. The difference in specific luminosity between the first and the last injected batches is about 10 %.

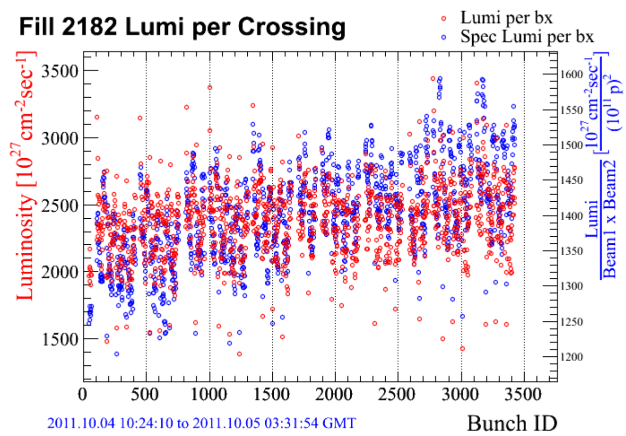

Figure 13: Bunch-by-bunch luminosity and specific bunch-by-bunch luminosity for fill 2182 at beginning of fill. There is a 10 % difference in specific luminosity for the first batches compared to the last injected batches. *Courtesy A. Ryd, CMS*

EMITTANCE GROWTH DURING THE RAMP

As the LHC BSRTs do not produce useful data during the energy ramp and the Beam-gas Ionization Profile Monitors (BGI) were not commissioned, other methods had to be thought of to study emittance evolution during the ramp. In the end the wire scans were triggered several times during the ramp for dedicated fills with a low enough number of bunches.

Fill 2187 was an appropriate fill with only 36 bunches per ring in groups of 12 bunches spaced by 50 ns. The purpose of this fill was to study abort gap cleaning at flattop. The initial emittances from the wire scanners at 450 GeV for this fill are summarized in Table 3.

Table 3: Initial normalized emittances for abort gap cleaning test fill, Fill 2187.

ε_{1H}	[μm]	1.6
ε_{1V}	[μm]	1.3
ε_{2H}	[μm]	1.6
ε_{2V}	[μm]	1.4

All wire scan measurements during the ramp were re-fitted offline and the measured beta functions at the wire scanners were used to calculate the emittance. Beta measurements are available at 450 GeV and 3.5 TeV. Linear interpolation for the beta function was used for any energy in between. Fig. 14 and Fig. 15 show the results of the emittance growth for beam 1 and beam 2. The measurements indicated an emittance blow-up of about 20 % for both beams and both planes during the ramp.

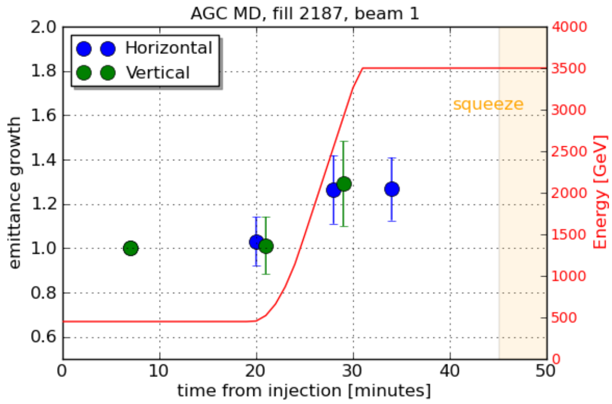

Figure 14: Emittance growth during fill 2187 measured with wire scanners for beam 1. 36 bunches per ring.

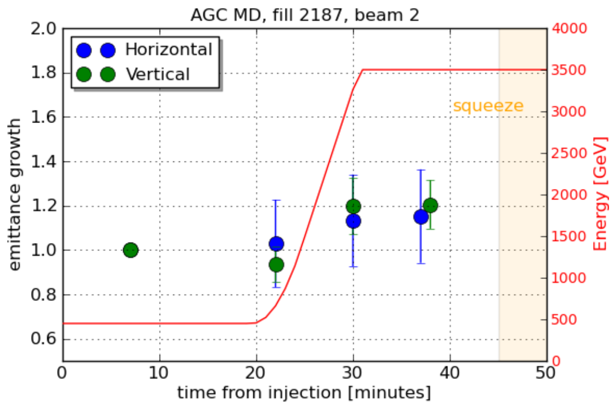

Figure 15: Emittance growth during fill 2187 measured with wire scanners for beam 2. 36 bunches per ring.

There was also another occasion where wire scans could be carried out during the ramp. During the BI MD of the last MD block in 2011, 4 bunches per ring were ramped with different emittances. 2 bunches had large emittances (> 3.5 µm) and 2 bunches small emittances (~ 1.5 µm). The larger emittances had been obtained by inserting screens in the SPS injection line. Unfortunately only data for beam 2 could be recorded. The beam 1 wire scanner had a timing issue. The results for beam 2 are shown in Fig. 16 and Fig. 17. Interestingly the relative growth for the different emittances is significantly different, however in absolute the emittances grow by the same amount. In the horizontal plane the emittances grew by about $\Delta\varepsilon \approx 1$ µm and in the vertical plane the emittance grew by about $\Delta\varepsilon \approx 0.7$ µm during the ramp.

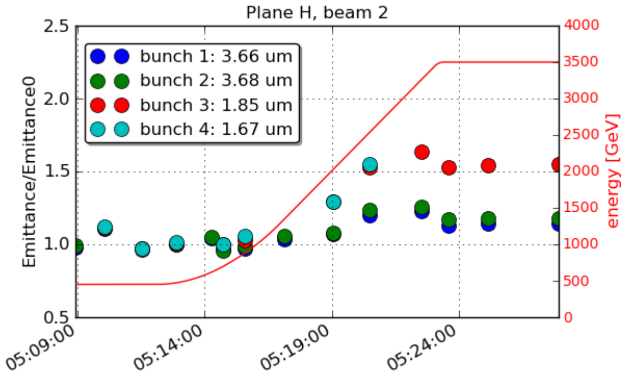

Figure 16: Relative emittance growth for different initial emittances for BI MD test ramp, beam 2 H.

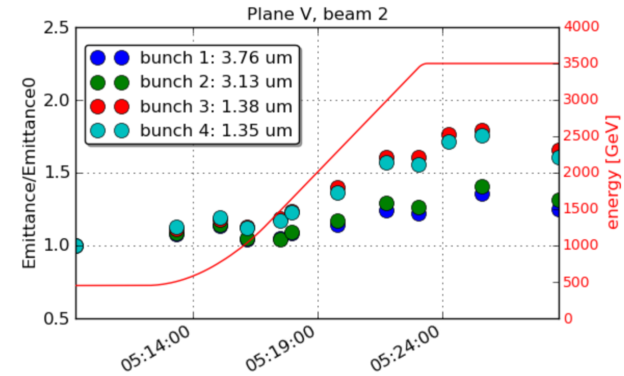

Figure 17: Relative emittance growth for different initial emittances for BI MD test ramp, beam 2 V.

POSSIBLE SOURCES FOR EMITTANCE GROWTH DURING RAMP

One of the parameters which were not fully optimized during the ramp commissioning of 2011 was the gain of the transverse feedback. No systematic scan of damper gain versus transmission or tune signal were carried out. It has to be reduced during the ramp to allow the operation of the BBQ based tune feedback [4]. The reduction of the gain takes place before the ramp starts, and is clearly visible as increase of the BBQ amplitudes, see Fig. 18. The larger oscillations measured by the BBQ could potentially lead to emittance blow-up.

The effect of the damper gain change at 450 GeV on emittance growth was checked for Fill 2236. The evolution of the emittance and the damper gain is shown in Fig. 19 and 20. The data from the BSRT gated on a single bunch is noisy and the time spent with lower damper gain before starting the ramp is insufficient to conclude on the effect of the damper. A special test will have to be carried out in 2012 with longer waiting times.

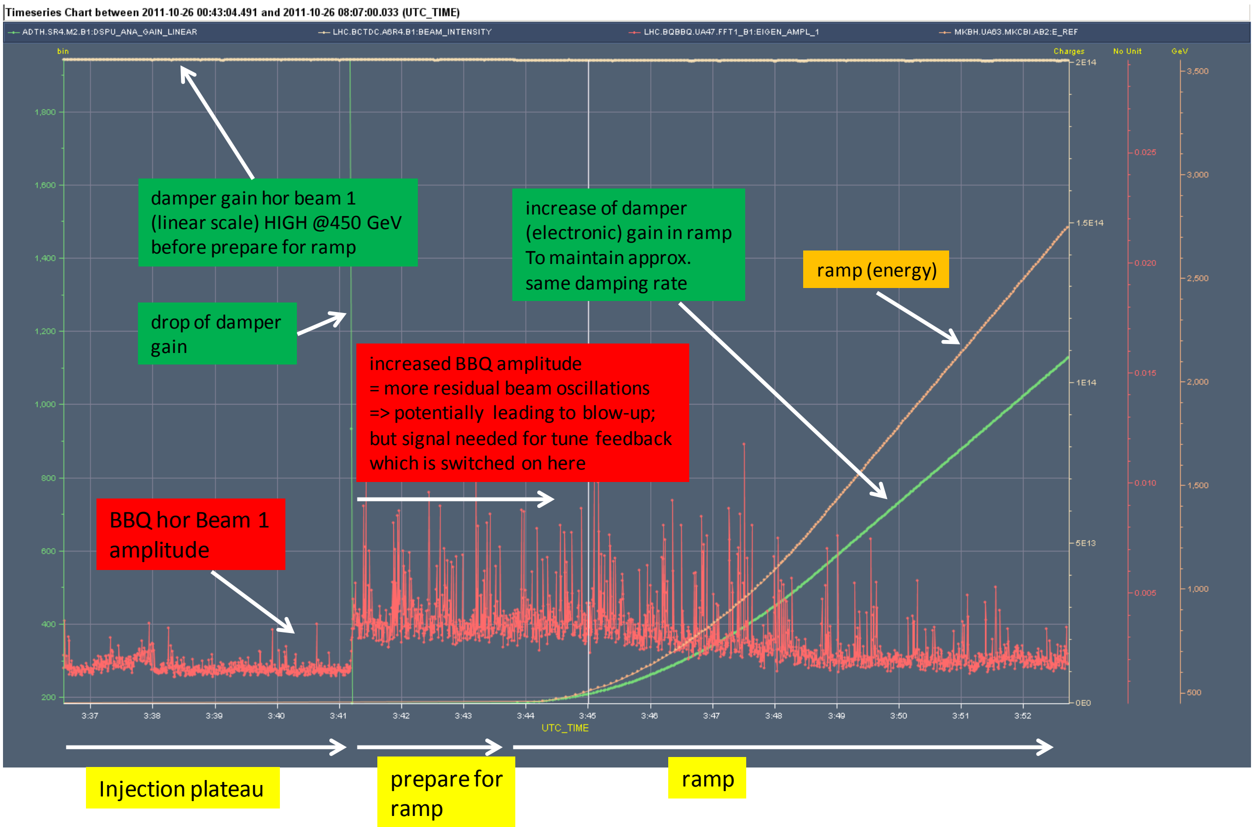

Figure 18: Plot of the logged parameters of BBQ amplitudes (red) and damper gain (green) and beam energy (pink). At the moment of the reduction of damper gain in preparation of the energy ramp the BBQ amplitudes increase. *Courtesy W. Hofle*

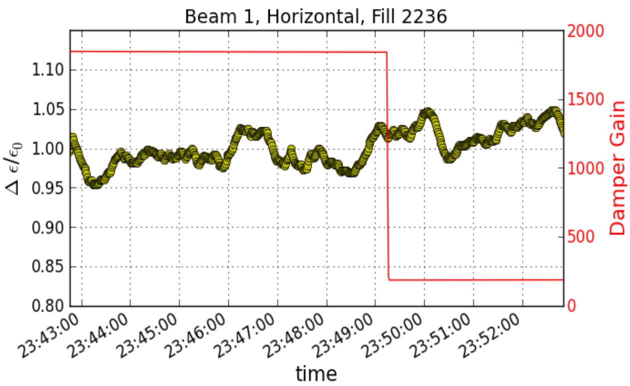

Figure 19: Emittance and damper gain evolution at 450 GeV from BSRT gated over single bunch in horizontal plane, beam 1, for Fill 2236. Effect of damper gain change is not clear. Data is inadequate. More time after gain change is necessary.

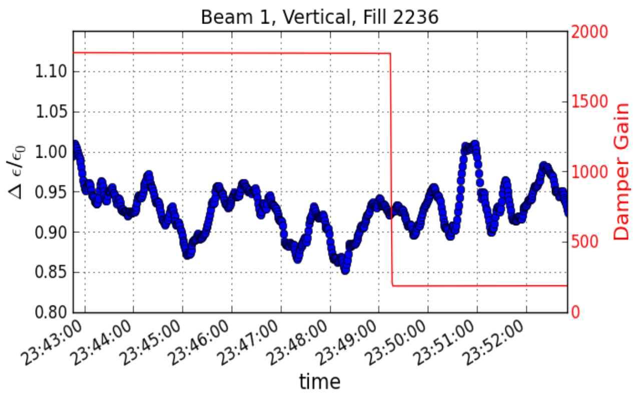

Figure 20: Emittance and damper gain evolution at 450 GeV from BSRT gated over single bunch in vertical plane, beam 1, for Fill 2236. Effect of damper gain change is not clear. Data is inadequate. More time after gain change is necessary.

EMITTANCE GROWTH AT FLATTOP

At flattop with constant energy, the BSRT is the obvious device to study the emittance evolution. Off-line the data of the abort gap test fill, Fill 2187, was averaged per batch (average over 12 bunches). The evolution of the average emittances per batch for beam 1 and beam 2 is shown in Fig. 21 and Fig. 22.

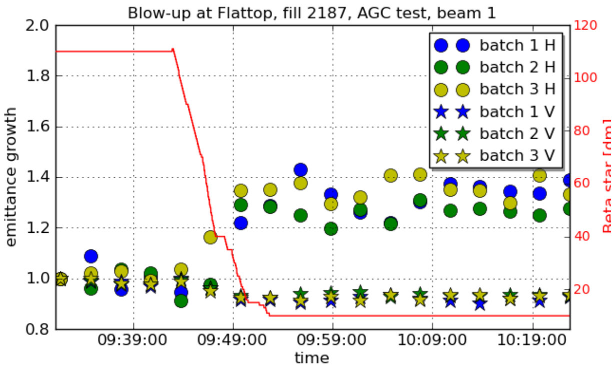

Figure 21: Relative emittance growth for different batches after ramp and during squeeze for Fill 2187, beam 1.

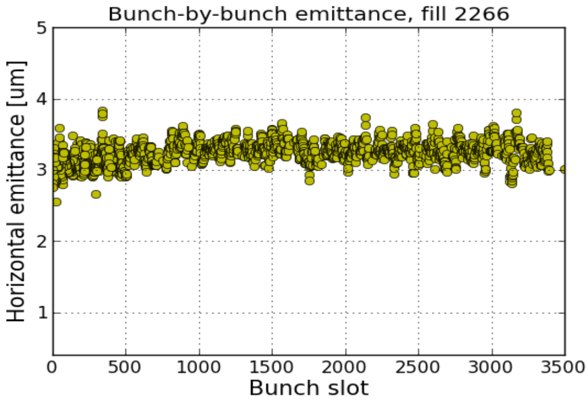

Figure 23: Bunch-by-bunch emitance in horizontal plane, beam 1, for Fill 2266 1 h into stable beams. The emittances of the different bunches are similar.

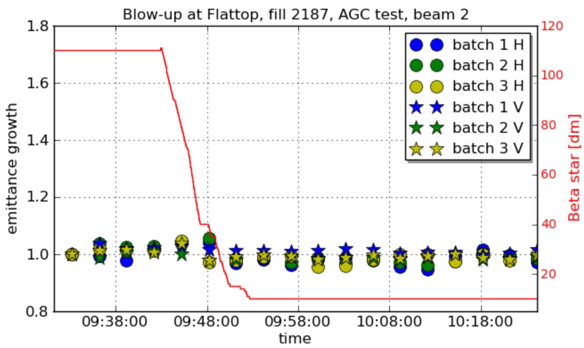

Figure 22: Relative emittance growth for different batches after ramp and during squeeze for Fill 2187, beam 2.

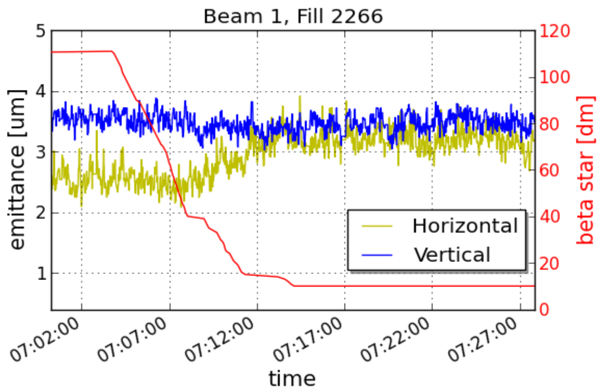

Figure 24: The evolution of emittance versus time for beam 1 for Fill 2266 through the squeeze. The evolution was obtained from the BSRT bunch-by-bunch scan. The bunches have similar emittances, see Fig. 23.

Whereas for beam 2, both planes, and beam 1, the vertical plane, the emittances remain constant within measurement accuracy after the ramp and during the squeeze, the horizontal beam 1 emittances show blow-up starting after 5 m β*, see Fig. 21 and Fig. 22. The measured betas at the D3 were taken into account where available: at flattop, 3.5 m and 1 m β*. The question remained whether the emittances of beam 1 H systematically blow up during the squeeze or whether Fill 2187 was exceptional. The evolution of the emittance of several physics fills was analysed as a consequence. No special set up of the BSRT scan was used under these conditions. If all bunches have similar emittances, the emittances of the different bunches scanned by the BSRT can be used as approximate evolution of the emittance in time. All analysed fills show the same behaviour, the emittances of beam 1 H blow up between 5 m and 1.5 m β*. The example of physics Fill 2266 is shown in Fig. 23 and Fig. 24.

DEPENDENCE ON BUNCH INTENSITY

The blow-up from the SPS to LHC collisions as function of bunch intensity was obtained by combining data from the summer period and October 2011, see Fig. 25. SPS wire scanner data with 144 bunches and emittance values from the luminosity data were used. Interestingly again the absolute value of emittance growth between SPS and LHC stays approximately constant for different bunch intensities.

IONS

IBS has a much larger impact for ions at injection [3], and they also experience emittance blow-up during the ramp. As for protons, wire scans during the ramp for physics beams are not possible due to the intensity limitations. Wire scans during the ramp were carried out during the quench test fill on 7 December 2011. A single bunch was analyzed. The measured blow-up during the ramp is about 20 %, see Fig. 26.

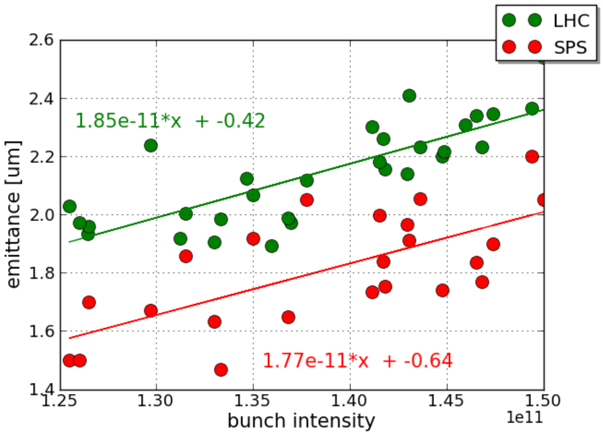

Figure 25: Comparison of emittance from LHC luminosity and emittance of 144 bunch wire scans in the SPS as function of bunch intensity. The absolute growth between SPS extraction and LHC start of collisions seems to be independent of bunch intensity.

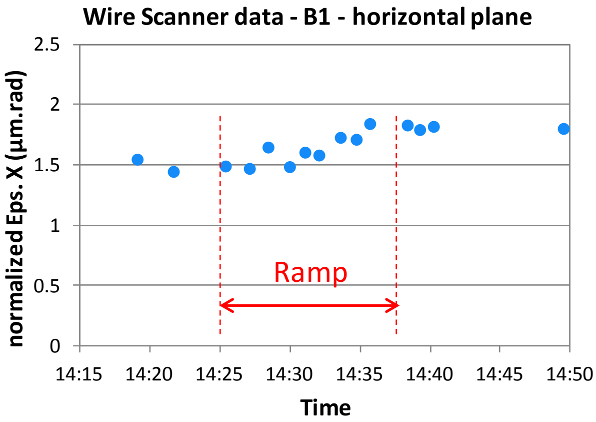

Figure 26: Emittance evolution during ramp for ions. The emittances grow by about 20 %.

PLANS FOR 2012

Many more studies are required to get a clear picture of the apparently additive source of emittance growth during the ramp. Several MDs are planned. Bunches with different intensities and same emittances and different emittances will be studied to check the effect on IBS at injection and the effect on emittance blow-up during the ramp. Also, the effect of different damper gains and working points (e.g. to avoid 50 Hz lines) will be investigated.

Planned Improvements for Diagnostics

A number of improvements for transverse profile diagnostics and analysis methods are planned for 2012:

- Faster and better calibrated BSRTs
- BGI commissioned for protons
- Pre-prepared wire scanner settings as function of intensity
- Bunch-by-bunch wire scans in the SPS
- Automatic wire scans through the ramp
- Synchronous measurements across the accelerator complex
- Use measured betas in the different analysis tools instead of nominal
- More reliable fits
- Write fit results into logging database.

CONCLUSIONS

The LHC transverse emittances grow by about 20 to 30 % from SPS extraction to the start of collisions in the LHC. The collected data is consistent with no emittance growth from the injection process into the LHC. The emittances grow at the injection plateau (~ 10% in 20 minutes for the horizontal plane), reasonably consistent with IBS. Effort should therefore be put on minimizing the time spent at injection and dedicated LHC filling cycles could be re-investigated.

Wire scanner data indicates an emittance blow-up during the ramp. Measurements so far show a blow-up of more than 20 % for 50 ns trains in H and V, even more for single bunches. The emittances seem to grow by the same amount independently of the bunch intensity or initial emittance indicating an additive growth source like for example external noise.

The emittances of beam 1 H further increase by more than 20 % through the squeeze between 5 m to 1.5 m β^*. This was consistently measured during a test fill and physics fills.

The goal for 2012 is to understand and possibly correct the blow-up through the LHC cycle. Improvements for diagnostics, applications and analysis are planned. The data of dedicated fills and physics fills will be combined to get the full picture of LHC emittance preservation.

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