EMITTANCE PRESERVATION

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Abstract

The preservation of the transverse emittance is crucial for luminosity performance. At the LHC design stage the total allowed emittance increase was set to 7 % throughout the LHC cycle. The injection process is particularly critical in this respect. Results of an analysis trying to quantify the emittance increase from injection to stable beams will be presented. The luminosity goals of the 2010 proton run could be achieved with fewer bunches than initially foreseen. This is due to the excellent performance of the injectors concerning the higher than nominal number of protons per bunch and also the smaller than nominal emittances. Recommendations for required instrumentation and emittance preservation goals for next year's run will be given.

INTRODUCTION

It is well-known from the formula for the luminosity, Eq. 1, that smaller beam sizes at the interaction point and hence smaller emittances are advantageous for luminosity performance.

$$L \approx \frac{f_{rev} \cdot n_b}{4 \cdot \pi} \cdot \frac{N_1 \cdot N_2}{\sigma_1 \cdot \sigma_2} \qquad (1)$$

with n_b the number of bunches, N_1 and N_2 the number of particles per bunch for the two beams and σ_1 and σ_2 the beam sizes of the beams. In proton machines, such as the LHC, without strong damping, preservation of the emittance throughout the different stages in the operational cycle is very important. The design values for allowed emittance increase from injection to collisions is $\varepsilon/\varepsilon_0 < 1.07$, allocating $\varepsilon/\varepsilon_0 < 1.05$ for injection. The obtained emittance increase values during the injection process are detailed in [1]. A summary of the findings will be given in this paper, that will also report on a first attempt at quantifying the emittance increase from injection to stable beams for the 150 ns proton period. Ions will be mentioned briefly towards the end when discussing possible explanations for the observed emittance growth during the period of collisions.

LIMITATIONS

At LHC injection currents reliable emittance measurements could be obtained with the wire scanners. They were systematically used up to an intensity of 2×10^{13}, above which a software interlock forbids their operation to avoid either wire damage (at 450 GeV) or quenching the downstream magnets (at 3.5 TeV). Unfortunately the synchrotron light monitors and ionisation gas monitors have not reached the operational state yet. Because of a lack of reliable, continuous emittance measurements for beam 1 and beam 2 and horizontal and vertical plane, emittances at flat-top were derived from the luminosity or the luminous region measurements. This approach has clear limitations. From the luminosity data no conclusion on the single beam behaviour can be drawn. Also, any possible offset between beam 1 and beam 2 at the IP is neglected in this paper for deriving the emittances. The results above injection and numbers for emittance growth from injection to collisions are therefore of a more qualitative nature.

In addition the nominal beta functions were assumed to convert beam sizes to emittances.

EMITTANCE PRESERVATION AT INJECTION

SPS and LHC wire scanner data for beam 1 and beam 2 and horizontal and vertical plane is plotted in Fig. 1 and Fig. 2.

Throughout this period, the SPS as the last machine of the LHC injectors delivered emittances well below nominal emittance of 3.5 μm. The SPS delivered about 2.5 μm until roughly fill 1400, and afterwards the injected emittances were even partly below 2 μm. These small emittances are a result of how the beam with the larger bunch spacing is produced. With 25 ns bunch spacing nominal emittances can be expected.

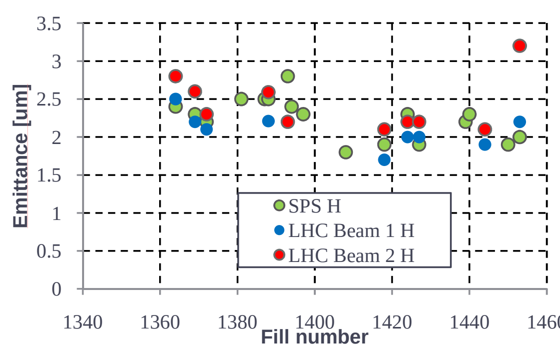

Figure 1: Horizontal emittances measured in the SPS at flat-top and in the LHC at injection for beam 1 and beam 2. The emittances for beam 2 are systematically larger than for beam 1.

The results in the LHC consistently indicate larger emittances for beam 2 in both planes, more pronounced however in the vertical plane. There are no shot-by-shot emittance measurements in the SPS. The emittances are measured as part of the preparation some time before the actual filling starts. This could be the reason why for beam 1 the wire scanners show partly even smaller emittances than measured in the SPS. To exclude nevertheless issues with cross-calibration between machines and LHC beams, cross-checks with other instruments (e.g. turn-by-turn screens) should be carried out in 2011.

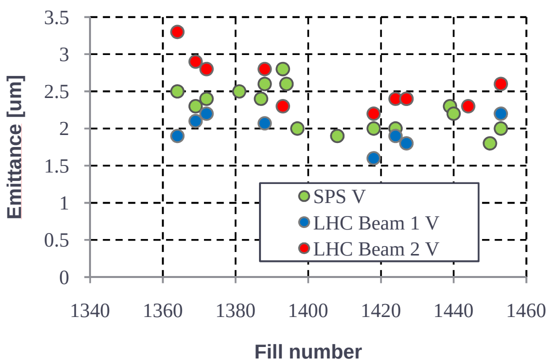

Figure 2: Vertical emittances measured in the SPS at flat-top and in the LHC at injection for beam 1 and beam 2. The emittances for beam 2 are systematically larger than for beam 1.

Also, the emittances in the LHC were not measured directly after injection, but rather either at the end of filling or after the first injections. Emittance growth from errors during the injection process can therefore not be easily disentangled from other effects like the hump. Taking nevertheless the values from Fig. 1 and 2 for beam 2, the difference on average between the LHC and the SPS values is 10 % in H and about 15 % in V. The emittance growth from the injection process itself is estimated to be lower by at least a factor 2, as described in the following.

Beam stability, kicker ripple, betatron, dispersion and coupling mismatch at the LHC injection point all lead to emittance increase at injection (details can found in [1]). The betatron mismatch to the nominal injection optics was evaluated during the transfer line setting up periods using the OTR screens. The measurements for TI 2 are shown in Fig. 3. The measured mismatch factors are λ = 1.05 to λ = 1.1, corresponding to an emittance increase in the order of 3 % for λ = 1.1 (the measured small beta beating in the LHC was not taken into account). More precise values will be obtainable with a turn-by-turn matching monitor in the LHC. Such an instrument might be available for 2011. The tools for the transfer line screen matching, as shown in Fig. 4, will have to be upgraded to also deal with the LHC matching monitor.

Due to the constraints of the transfer line collimators and the limited possibility to correct, we partly allowed for large injection oscillations. Amplitudes of 1.5 mm were tolerated. The LHC transverse feedback system took care of the emittance preservation. The excellent performance is demonstrated in Fig. 5 with a typical example of the damping times reached. Damping times were as low as 40 turns.

There is also a rotation angle between the reference frame of the transfer lines and the LHC. This 'tilt mismatch' leads to a phase dependant coupling, see [3], and emittance increase following

$$\frac{\varepsilon_x}{\varepsilon_{0x}} = 1 + \frac{1}{2}\cdot\left(\beta_x\gamma_y + \beta_y\gamma_x - 2\alpha_x\alpha_y - 2\right)\cdot\sin\theta^2 \quad (2)$$

The emittance increase due to this effect is 1.3 % for TI 8 (tilt angle of 54 mrad) and 0.3 % for TI 2 (tilt angle of 20 mrad) and is presently uncorrectable, although correction schemes using skew quadrupoles are under study.

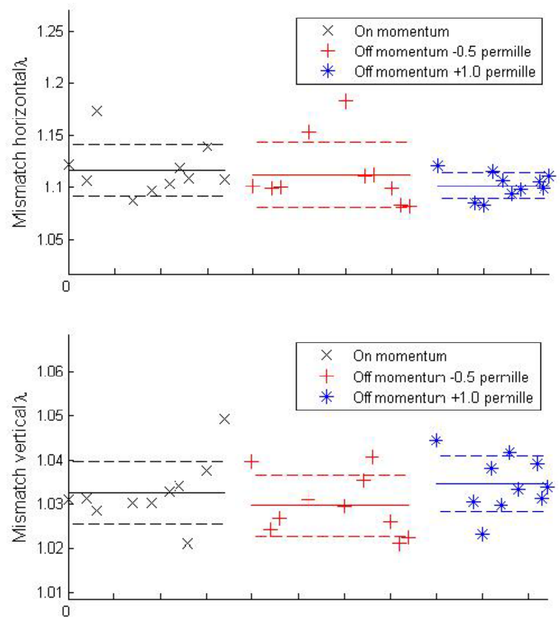

Figure 3: No measurable change of the betatron mismatch factor (to the nominal optics at the injection point) was measured for the transfer lines, also looking at possible momentum dependence. The betatron mismatch can be assumed to be in the order of 5 % for both lines. (The results in the horizontal plane show a larger mismatch due to using the nominal dispersion instead of the measured and not including the variation of the bunch length hence momentum spread). The LHC beta beating was found to be maximum 20 %, [4].

EMITTANCE INCREASE UNTIL COLLISION

Fig. 6 and 7 compare the emittances at injection for beam 1 and beam 2 with the data from the ATLAS luminous region at the moment of first collisions in the horizontal and vertical plane for all fills which made it into stable beams (wire scanner data does not exist for all analysed fills).

The achieved emittances at the moment of declaration of stable beams were still below nominal, with values on average below 2.5 μm at the beginning of the 150 ns period and below 2.5 μm for later fills.

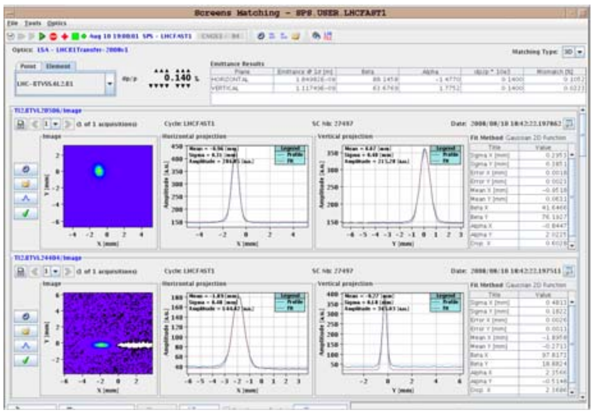

Figure 4: The screen matching application of the transfer line will have to be adapted for the LHC turn-by-turn matching screens. Instead of using several screens, several turns of one screen will be combined in the analysis.

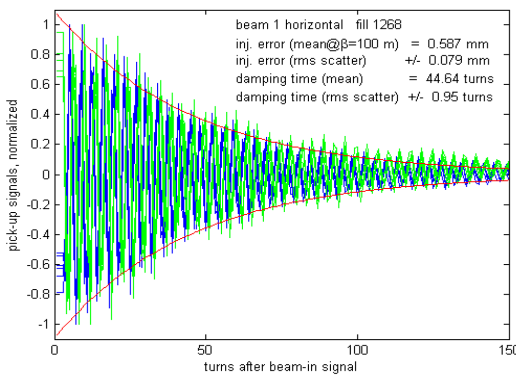

Figure 5: Horizontal injection oscillations of beam 1 for fill 1268, pick-ups Q7 (green) and Q9 (blue) as well as exponential fit from averages of the reconstructed data

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Because of the lack of consistent data throughout the LHC cycle, an indication of the emittance increase from injection to the start of collisions is derived from comparing the achievable beam size of the luminous region with the emittances at injection with the measured luminous region data from ATLAS. To calculate the convoluted beam sizes formula (3) was used.

$$\sigma_L = \left(\frac{1}{\sigma_1{}^2} + \frac{1}{\sigma_2{}^2}\right)^{-\frac{1}{2}} \qquad (3)$$

The results are shown in Fig. 8 and 9 indicating about 30 % emittance growth in both planes on average for the different fills, or about 15 % on average in convoluted beam size. Further studies are planned for 2011 with the aim of using the BSRT to disentangle contributions from beam 1 and beam 2.

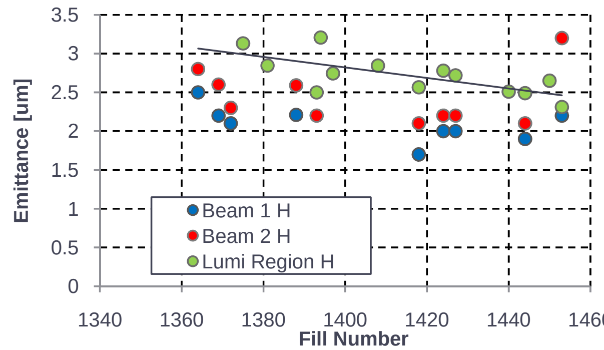

Figure 6: Horizontal emittances of beam 1 and beam 2 at injection and from the luminous region data from ATLAS at the beginning of physics for different fills.

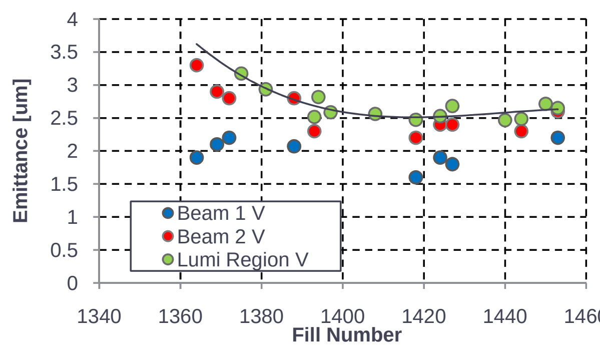

Figure 7: Vertical emittances of beam 1 and beam 2 at injection and from the luminous region data from ATLAS at the beginning of physics for different fills.

EMITTANCE INCREASE DURING PHYSICS

Fig. 10 shows the evolution of the luminosity during the 2010 record luminosity fill with a peak luminosity of 2.08×10^{32} $cm^{-2}s^{-1}$. The measured beam current data is used to plot the expected evolution of the luminosity assuming only current decay and the emittance as at the beginning of physics. The discrepancy between the expected and the real evolution of the luminosity is due to emittance growth during physics.

The emittance growth times were calculated by smoothing and differentiating the luminous region data using

$$\frac{\varepsilon}{\tau} = \frac{d\varepsilon}{dt} \qquad (4)$$

An example of the evolution of the growth time during fill 1440 is shown in Fig. 11.

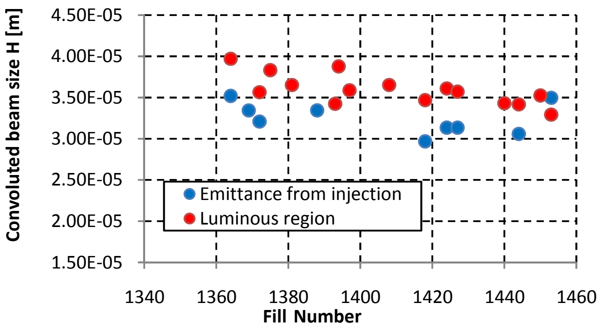

Figure 8: Horizontal convoluted beam size assuming the emittances at injection in blue and the beam size from the luminous region data of ATLAS in red. The beam sizes from the measured ATLAS are on average about 15 % larger.

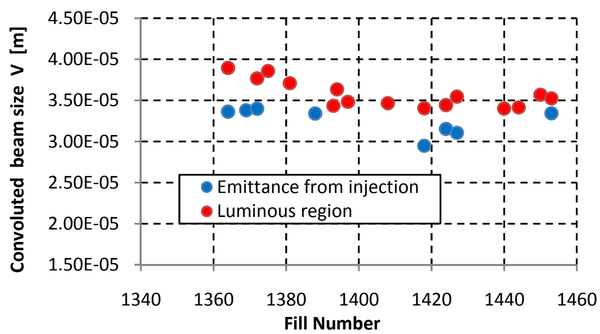

Figure 9: Vertical convoluted beam size assuming the emittances at injection in blue and the beam size from the luminous region data of ATLAS in red. The beam sizes from the measured ATLAS are on average about 15 % larger.

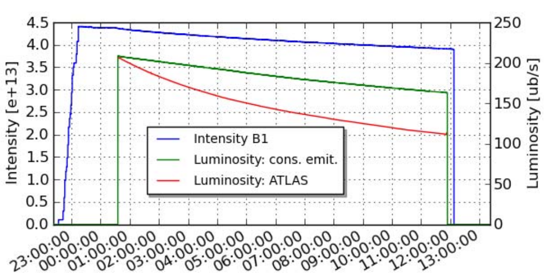

Figure 10: Evolution of the luminosity (data from ATLAS) during the record luminosity fill 1440 in red. The beam current during the duration of this fill is shown in blue. In green the expected evolution of the luminosity is plotted assuming no emittance increase, only beam current decay.

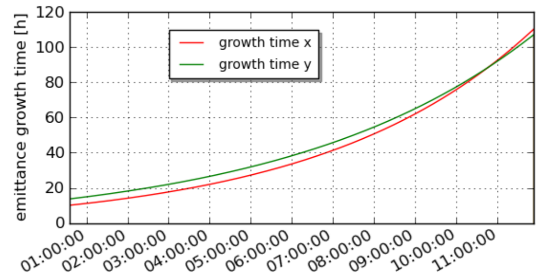

Figure 11: Emittance growth time in H and V by smoothing and differentiating the ATLAS luminous region data for fill 1440.

Fig. 12 shows the emittance growth times at the beginning of the physics period for different fills during the 150 ns run where data with sufficient quality was available. A trend to shorter growth times towards the end of the proton run from around 20 h to below 10 h is apparent.

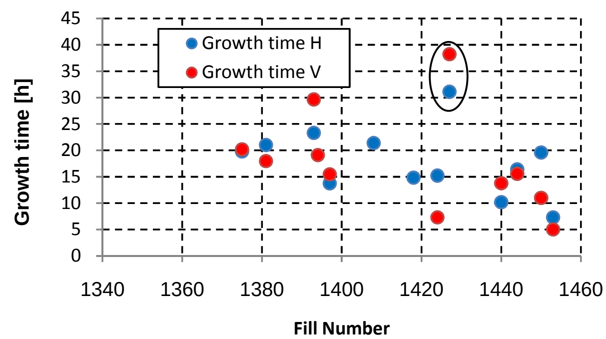

Figure 12: Emittance growth times for different fills during the 150 ns proton run period at the beginning of the collisions phase. Data quality did not allow to calculate growth times for all fills. The encircled data set corresponds to a fill with smaller bunch intensity.

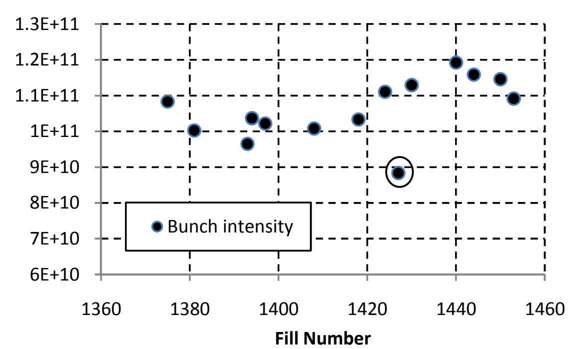

Figure 13: Towards the end of the 150 ns run period the bunch intensities were further and further increased from the injectors.

This coincides with the hunt for 50 pb^{-1} integrated luminosity where emittances were further and further reduced in the injectors and bunch intensities increased, see Fig. 13. One data set, fill 1427, does not follow the overall trend. This might be explained by the much reduced bunch intensity during this fill, see encircled data points in Fig. 12 and 13. The dependence of the emittance growth times on bunch intensity and initial emittance indicates beam-beam effects and IBS as main cause for the emittance increase. External noise such as the hump might be the driving source for the beam-beam related emittance growth. IBS alone does not explain the measured data. Whereas longitudinally the emittance growth times seem to show some agreement, transversely the predicted growth times do not fit the ones evaluated from the measured emittance increase. For the prediction of the IBS growth times, emittances from the ATLAS luminosity and luminous region data, as well as the used RF voltage and logged bunch length were used following the methodology developed in [5]. Full coupling between horizontal and vertical plane was assumed. Fig.14 and 15 show the IBS predictions and actual growth times for proton fill 1400. For ions the IBS predictions fit the observed values better, see Fig.16, 17 and 18 as an example.

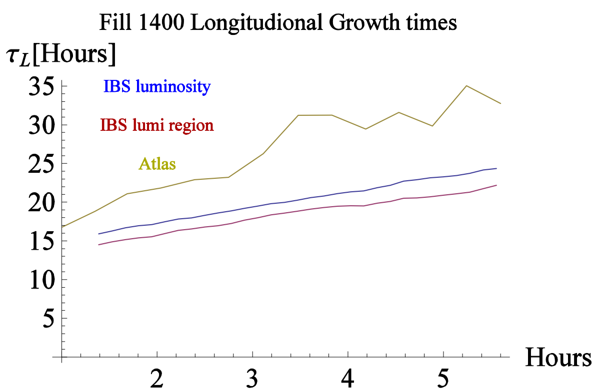

Figure 14: Proton fill 1400: Longitudinal growth times from the ATLAS luminous region and predictions for IBS using the luminous region data or luminosity from ATLAS.

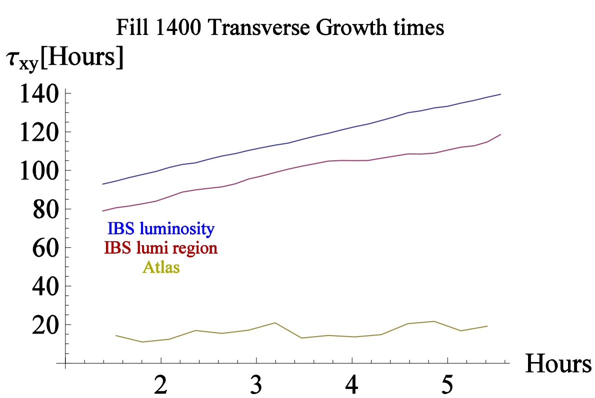

Figure 15: Proton fill 1400: Transverse growth times from the ATLAS luminous region and predictions for IBS using the luminous region data or luminosity from ATLAS.

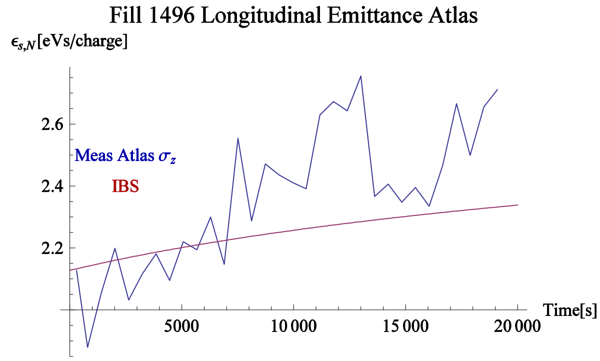

Figure 16: Ion fill 1496: Longitudinal emittance from the ATLAS luminous region and predictions for IBS using the luminous region data or luminosity from ATLAS.

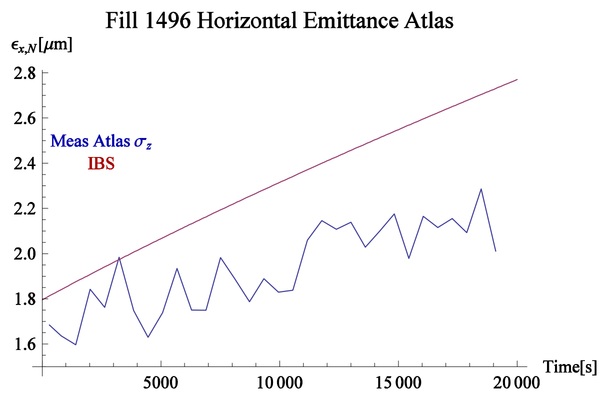

Figure 17: Ion fill 1496: Horizontal emittance from the ATLAS luminous region and predictions for IBS using the luminous region data from ATLAS.

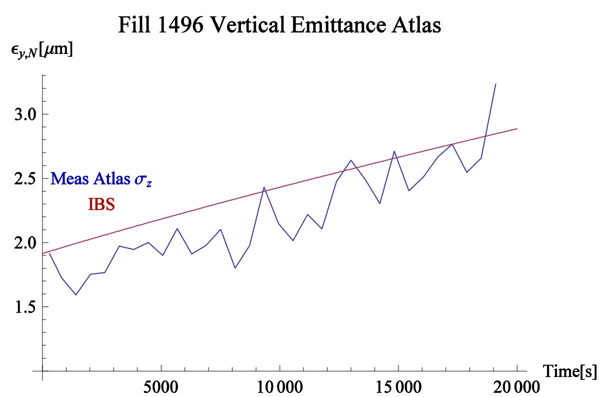

Figure 18: Ion fill 1496: Vertical emittance from the ATLAS luminous region and predictions for IBS using the luminous region data from ATLAS.

CONCLUSION AND OUTLOOK

The LHC 2010 run was a big success. The ambitious goal of 10^{32} $cm^{-2}s^{-1}$ peak luminosity was achieved, proving the extremely good performance of the LHC machine and also the injectors. The LHC injectors managed to consistently provide bunch intensities above nominal and emittances of down to 2 μm (the nominal emittance is 3.5 μm). Due to this extra margin for these critical parameters not much effort was spent to study emittance preservation and to set up reliable emittance measurements in 2010. This will become one of the priorities in 2011.

The LHC injections are well matched and the transverse damper is working well. Dedicated studies and new instrumentation in the form of the LHC turn-by-turn matching screens will be needed in 2011 to quantify the actual emittance blow-up at injection. Beam 2 seems to have systematically bigger emittances than beam 1, especially in the vertical plane. The hump is definitely a promising candidate to explain the differences. Nevertheless possible calibration errors for the different wire scanner systems will have to be excluded.

Significant emittance growth from the injection plateau until the moment of collisions was estimated from the 150 ns run data. Due to the lack of good quality continuous machine emittance measurements, data from the experiments for luminosity and luminous region was used at flattop to be compared to the injection wire scanner values. This gives an estimate of about 30 % emittance growth.

During collisions the emittances grow with typical growth times of 15-20 h at the beginning of physics. Values below 10 h were obtained towards the end of the 150 ns run period. For protons IBS does not seem to be the main driver for emittance growth. For Ions IBS predictions fit the observed emittance growth better.

The so far obtained values are all of preliminary nature due to the lack of good quality continuous data from the SPS to LHC beam dump for protons. In 2011 reliable emittance measurements throughout the fill, bunch-by-bunch and shot-by-shot for the SPS must become priority. Small emittances - smaller than nominal - and large bunch intensities are a promising solution for high luminosities with sufficient operational margin. This requires reliable emittance measurements.

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