TRANSVERSE EMITTANCE PRESERVATION THROUGH THE LHC CYCLE

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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 proton run in 2010 showed that the injectors can provide beams with smaller emittances than nominal and higher bunch intensities. The LHC parameters are well under control and the emittances are kept below nominal until physics. The LHC luminosity goals for the first year of running could therefore be achieved with fewer bunches than initially foreseen. This paper will report on the measured emittance growth at injection from the SPS and the evolution of the emittance through the entire LHC cycle. Sources and possible cures for the observed emittance growth will be discussed.

OBSERVATIONS

The current LHC parameters with 50 ns bunch spacing are summarized in Table 1. The maximum instantaneous luminosity so far achieved is 2.41×10^{33}cm^{-2}s^{-1}. The LHC injectors can produce brighter beams for 50 ns bunch spacing than with the nominal bunch spacing of 25 ns [1]. The normalised emittances prepared in the injectors have slowly been decreased during the summer months and are now below 1.5 µm.

Table 1: LHC run configuration since end of June 2011

Total number bunches for fill	1380
Max number bunches injected	144
Bunch spacing [ns]	50
Intensity/bunch	$1.1-1.4\times10^{11}$
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
Collision energy per beam	3.5 TeV
Max. luminosity achieved [cm^{-2}s^{-1}]	2.41×10^{33}

The emittances of about 60 fills from mid-July 2011 to August 2011 were analysed. The achieved peak luminosity from the experiments together with measured bunch intensities and bunch lengths were used to determine the emittance at the beginning of collisions. In Fig. 1 these emittances are compared with the emittances measured at the extraction flattop of the SPS. The blow-up from the SPS extraction flattop to beams in collision in the LHC is on average about 30 %, see Fig. 2.

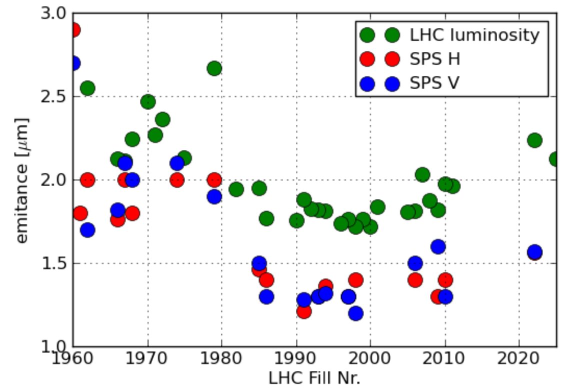

Figure 1: Normalised emittances as prepared in the SPS and the beginning of collisions in the LHC.

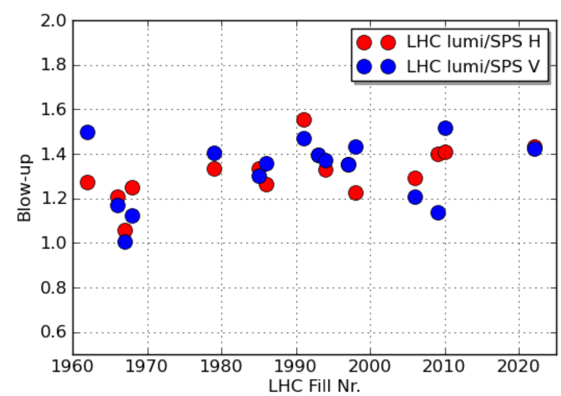

Figure 2: Blow-up between SPS and LHC at beginning of collisions.

For machine protection reasons, an intermediate intensity (12 bunches) is injected first, before the nominal batch filling starts [2]. The emittances of these 12 bunches are routinely measured with the wire scanners at injection, see Fig. 3. Beam 2 shows systematically larger emittance values than Beam 1. In the case of the analysed fills, the horizontal emittances of Beam 2 were larger by 20% on average and 28 % in the vertical plane.

The intermediate intensities and the nominal physics batches are prepared on different cycles in the injectors and cannot be directly compared. At rare occasions the emittances are also measured with wire scanners after the first nominal physics batch injection (144 bunches). In Fig. 4 the results of these measurements are compared with the emittances deduced from the luminosities. The vertical emittances of Beam 2 at injection are already similar to the emittance values calculated from the luminosity.

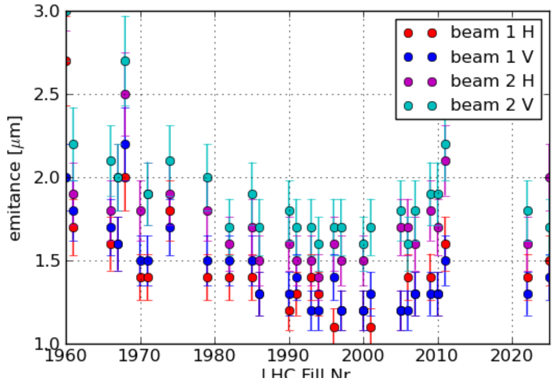

Figure 3: Wire scanner measurement results with 12 bunches for Beam 1 and Beam 2. Beam 2 is systematically larger in both planes. The error bars indicate 10 % measurement errors.

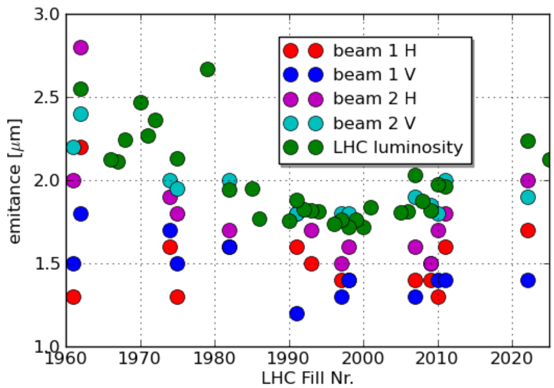

Figure 4: Wire scanner measurement results with 144 bunches for Beam 1 and Beam 2 where available and emittances from luminosity.

SYNCHOTRON LIGHT MONITORS

Two Synchrotron Light Monitors (BSRT) [3] are installed about 30 m downstream of the D3 cryostats hosting the D3 dipole and a superconducting undulator. The undulator has been built to provide enough synchrotron radiation at low beam energies. As the beam energy reaches 2.5-3 TeV, most of the useful light is generated by the D3. An extraction mirror deviates the light below the beam pipe where an optical system performs the imaging of the beam spot on CCD cameras. Two acquisition modes are available with the BSRT:

- Continuous (DC mode): each acquisition corresponds to the integration for 20 ms of all circulating bunches.
- Gated (PULSED mode): each acquisition corresponds to the integration over all the time windows (gates) programmed in 20 ms. The minimum gate length is 25 ns and the maximum repetition rate is 200 Hz.

There is no intensity limitation for proton beams. Continuous emittance measurements for Beam 1 and Beam 2, horizontal and vertical plane, throughout the LHC cycle are provided by the LHC BSRTs.

Limitations

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.

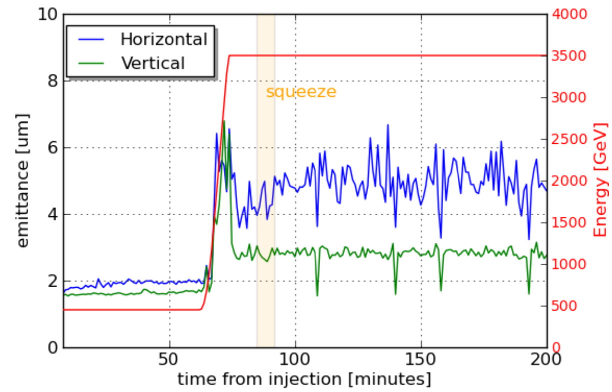

Figure 5: Emittances from BSRTs through LHC cycle for fill 2028, Beam 1. BSRTs were gated on bunch 39 only. The absolute emittance values are not reliable. The ramp values cannot be used.

Normally the BSRTs are used in pulsed mode for LHC physics runs. At least 1 s integration time per gate setting is required for good measurement quality. A scan through the full machine with 1380 bunches takes more than 20 minutes, about the same time as the LHC ramp. Measured emittance growth is therefore difficult to associate with a specific phase during the LHC cycle.

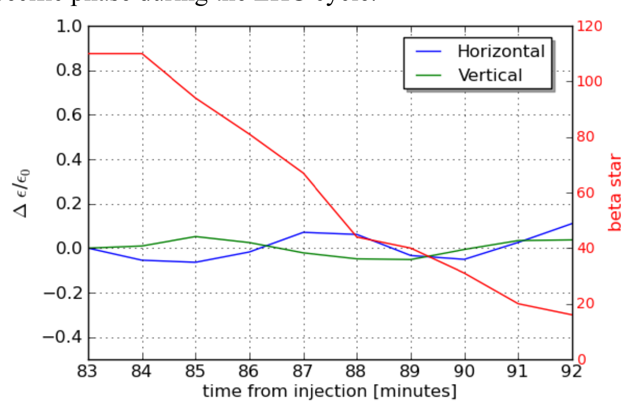

Figure 6: Beam 2, fill 2028. Emittance evolution before and during squeeze at 3.5 TeV. Considering the noise level, the data is consistent with no significant emittance growth during the squeeze.

At several occasions the gating was either set to a single bunch (fills 1897, 2013) or the first 12 bunches were kept for a long time at injection (fills 2028, 2029). These fills were used to follow the emittance evolution through the cycle or part of the cycle, see Fig. 5 as an example.

Emittance growth during collisions and the rare sudden blow-up at injection of singular batches are not discussed in this paper. Emittance growth during flattop is only treated briefly. Fig. 6 shows the evolution of the emittance before and during the squeeze at 3.5 TeV for Beam 2, fill 2028. The data is noisy on the 10 % growth level. This data is consistent with no significant growth at flattop before the beams are put into collision. Beam 1 behaves similarly.

EMITTANCE GROWTH AT 450 GeV

Figure 7 shows the evolution of the emittance from the BSRT during the injection plateau, fill 2028, Beam 1. The BSRT was gated on a single high intensity bunch (bunch slot 39). The horizontal emittance grew by 10 % in about 20 minutes for Beam 1. The results for Beam 2 are similar.

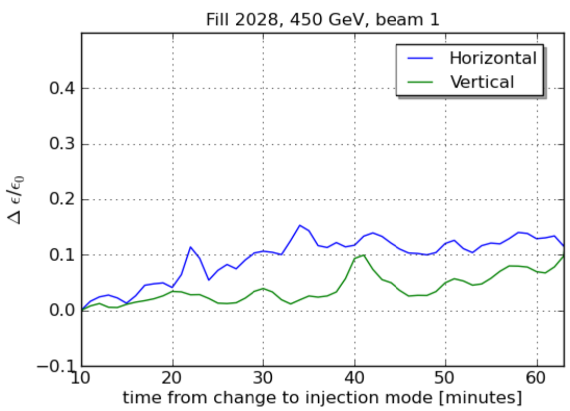

Figure 7: Beam 1, fill 2028. Emittance evolution at 450 GeV.

Emittance Growth and IBS

For fill 1897 12 bunches of Beam 1 were kept waiting at injection current for more than 1 hour before filling could be resumed.

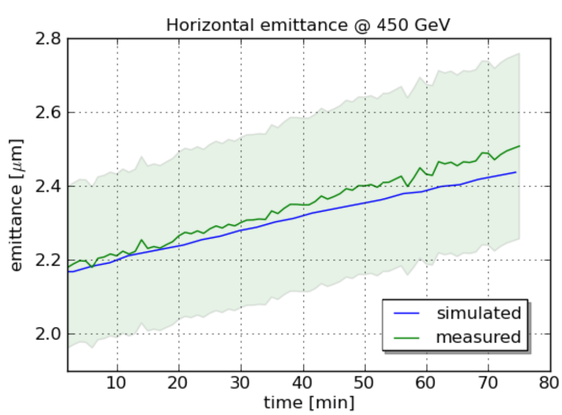

Figure 8: Evolution of emittance as measured (initial value from wire scanner and evolution according to BSRT) in green with 10 % error band. Simulation of emittance growth according to IBS using measured parameters of bunch length, emittance and bunch intensity in blue.

The measured bunch length and emittance growth is compared with simulation of intra beam scattering (IBS) at 450 GeV assuming no vertical dispersion (Nagaitsev algorithm [4]). Fig. 8 and 9 show the results. IBS explains a good fraction of the observed emittance growth. The sources for the nevertheless faster growth in H and the growth in V have not been identified yet.

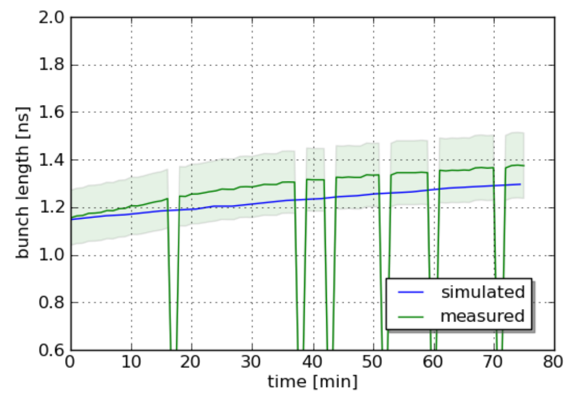

Figure 9: Evolution of bunch length as measured and simulated according to IBS. The discrepancy might be due to significant RF noise for Beam 1 as detected in August 2011 and needs further investigation.

CONCLUSION

The emittance blow-up from the SPS extraction flattop to LHC start of collisions is about 30 %. A reduction of this blow-up to about 10 % would increase the achievable peak luminosity by 20 %.

The beam 2 emittances are systematically larger by more than 20 % than Beam 1. Special instrumentation in the form of turn-by-turn screens and dedicated fills are necessary to investigate possible sources of this discrepancy. Most of the emittance growth probably either takes place during injection due to mismatch or the waiting time at the injection plateau due to IBS. Emittance growth due to possible transverse noise and its interplay with the transverse damper also need to be studied.

REFERENCES

[1] R. Steerenberg, "Performance Reach of the Injectors in 2011", Chamonix 2011 LHC Performance Workshop, Chamonix, France, 2011.

[2] V. Kain, "Injection – Issues and Potential Solutions", Chamonix 2011 LHC Performance Workshop, Chamonix, France, 2011

[3] T. Lefevre et al., "First Beam Measurements with the LHC Synchrotron Light Monitors", IPAC, Kyoto, Japan, 2010.

[4] T. Mertens, "Intra Beam Scattering in the LHC", CERN-THESIS-2011-042, CERN, Geneva, Switzerland, 2011.