EMITTANCE GROWTH AT LHC INJECTION FROM SPS AND LHC KICKER RIPPLE

G.Kotzian, B.Goddard, M.Barnes, L.Ducimetière, W.Höfle, CERN, Geneva, Switzerland.

Abstract

Fast pulsed kicker magnets are used to extract beams from the SPS and inject them into the LHC. The kickers exhibit time-varying structure in the pulse shape which translates into small offsets with respect to the closed orbit at LHC injection. The LHC damper systems will be used to damp out the resulting betatron oscillations, to keep the growth in the transverse emittance within specification. This paper describes the results of the measurements of the kicker ripple for the two systems, both in the laboratory and with beam, and presents the simulated performance of the transverse damper in terms of beam emittance growth. The implications for LHC operation are discussed.

INTRODUCTION

The preservation of the transverse emittance of the proton beam at injection into the LHC is crucial for luminosity performance. The transfer and injection process is important in this respect, and injection offsets are a well-known source of error. The ripple in the kicker waveforms is an effect which can only be countered with the transverse damper: for a damped injection error the emittance growth is conventionally assumed to be:

$$\frac{\varepsilon}{\varepsilon_0}=1+\frac{1}{2}\frac{\Delta x^2+\left(\beta\Delta x'+\alpha\Delta x\right)^2}{\beta\varepsilon_0}\left(\frac{1}{1+\tau_{DC}/\tau_d}\right)^2$$

where α and β are the conventional Twiss parameters at the injection point, Δx and $\Delta x'$ the injection error in position and angle, and τ_{DC} and τ_d are the filamentation time (67 ms) and damping time (5 ms) respectively. The above equation represents an approximation, valid for small injection errors and assuming that the phenomena leading to the filamentation can be described well by a simple exponential decay function. Moreover, it is assumed that the damping time τ_d by active feedback is much shorter than the filamentation time $\tau_{DC.}$ Calculation of the emittance growth in absence of active damping requires for large injection errors more elaborate simulations taking into account the actual nature of the different contributions to the filamentation. This is discussed in detail in the section on simulations below.

For the original specification of the LHC transverse feedback system [1] it was assumed that the decoherence time is 67 ms [2] and that the feedback needed to achieve a damping time of 3.6 ms in a linear regime with a peak injection error of 4 mm at 185 m β, corresponding to 3 σ. The resulting emittance blow-up (with an increase of the damping time to ~ 4 ms due to the adverse effects of the resistive wall instability) was estimated at 1.9 %.

The importance of transverse emittance preservation led to a very tight specification for the injection kicker ripple. The maximum allowed injection error into the LHC was specified as 1.5 σ in either plane [1], which resulted in a specification of the maximum ripple of the SPS extraction and LHC injection kickers of ±0.5 %.

KICKER RIPPLE

The ripple of the SPS extraction kickers was measured accurately with the LHC-type single bunch pilot beam, by varying the kick delay of the extracted bunch and recording the position on BTV displays. With the known transfer function between the kick and the display, the variation in the kick strength could be directly deduced. The results are shown in Figs 1 and 2 for the beam 1 and beam 2 extractions respectively. Measurements have also been made in the laboratory on individual magnets – for the LSS6 system which operates in short circuit: this is complicated by the lack of terminating resistors to allow interpretation of capacitor pick-up voltage [3].

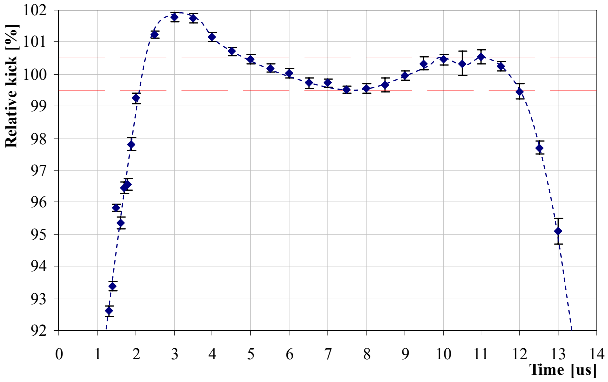

Figure 1: Ripple of SPS LSS6 extraction kickers (LHC beam 1) measured with beam.

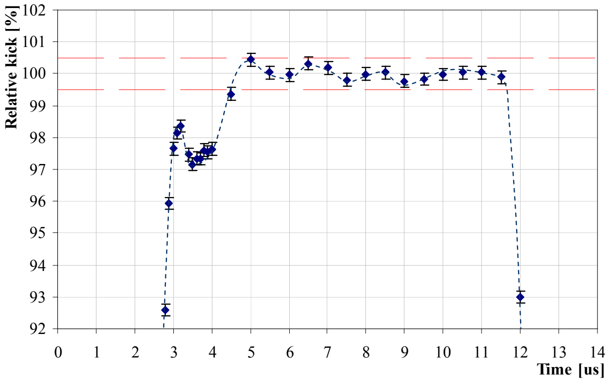

Figure 2: Ripple of SPS LSS4 extraction kickers (LHC beam 2) measured with beam.

The LHC extracted beam length is 7.8 µs, and the kicker timing can be adjusted to optimise the part of the waveform used. The kick length in the SPS LSS4 extraction can also be increased to a maximum of 14 µs, whereas in LSS6 the length is fixed and defined by the Pulse-Forming Network (PFN). From the above the ripple in the LSS6 system is about ±0.75 %, which is out of tolerance – this is presently the object of an upgrade [3].

The ripple of the LHC injection kickers was measured with an inductive probe, for different magnet kick lengths, Fig. 3. The high-frequency ripple at the start of the pulse is seen on both MKI magnets that were measured. However it is not yet proven whether the high frequency ripple is real or introduced by the measurement system. Assuming it is real, it was feared that this would cause problems for the transverse damper since the frequency content is in a range were the maximum possible kick strength of the damper already rolls off – hence the rapid oscillation of adjacent bunches with very different injection kicker deflections will be damped much slower. This feature prompted the present study.

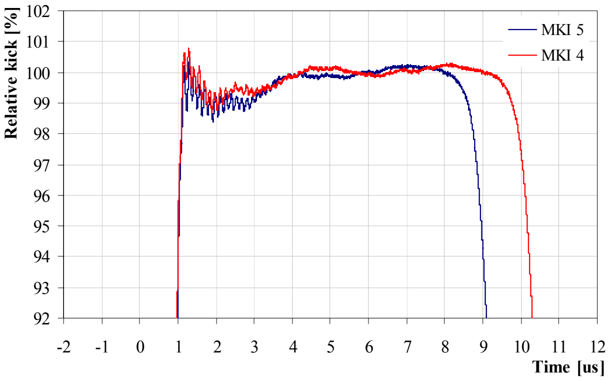

Figure 3: Measured LHC MKI injection kicker waveform, for different magnets and different pulse lengths.

LHC INJECTION DAMPER

A powerful transverse damper has been installed in LHC to damp injection oscillations as well as to provide feedback to stabilise coupled bunch dipole modes of oscillations [4,5]. The largest part of the injection error covers a frequency range defined by the gap of 1 µs between injected batches. The system in the LHC is similar to the SPS damper system with tetrode amplifiers installed directly under the damper-kicker structure in the accelerator tunnel. The damper-kicker plates deflect the beam with the electrical field only. Two tetrodes connected to the two damper-kicker plates operate in counter phase on a high impedance of 1 kΩ allowing a large kick strength at low frequency where it is needed for injection damping. At higher frequency the impedance is shunted by the damper-kicker capacitance leading to a loss of kick strength and consequently a slower damping of the higher frequency content of the MKI kicker ripple. The gain at higher frequency can be enhanced by signal processing, however the maximum kick strength is limited by the available tetrode current [6].

SIMULATIONS

Methodology

A simplified approach has been used in the past to estimate the effect of the kicker ripple at the extraction of the SPS for the CNGS beam [7]. This simplified approach was based on the approximate formula assuming exponential decay of the coherent oscillations. A detailed discussion of the derivation of this approximation can be found in [8] together with an extension to non-linear feedback systems. A more accurate description for large injection errors needs to take into account the nature of the filamentation process. Different physical processes contribute to filamentation - nonlinearities in the lattice modifying the transverse tune of a single particle, as well as collective effects modifying the spread of tune within a bunch. Analytical formulas have been derived for the combined case of filamentation due to a quadratic tune change with amplitude (octupoles) and linear tune change with momentum via chromaticity [9]. For the present study we take into account both chromaticity and octupolar effects and add the effect of damping by the feedback on a turn-by-turn basis. Instabilities and collective effects changing the tune of the particles are neglected. 1000 particles per bunch were tracked in the simulation [10].

Results

We assume at injection a target chromaticity of Q'=2 units giving an rms tune spread of ΔQ_{rms} = Q' $(\Delta p/p)_{rms}$ for an rms momentum spread of $(\Delta p/p)_{rms}=0.44\times10^{-3}$ [3] with a Gaussian distribution. The detuning with amplitude due to an octupolar field is assumed to be $\Delta Q = 10^{-4}\ (a/\sigma)^2$ for an oscillation amplitude of a. In the numerical simulation the longitudinal motion is taken into account, the synchrotron tune is $Q_s=5.5\times10^{-3}$. In the case without damper and octupoles re-coherence occurs after one synchrotron period. In practice the re-coherence will not be complete as the synchrotron frequency is not the same for all particles.

The design parameters for the feedback system were to damp low frequency components of the injection error up to 1 MHz within 40 turns starting from an initial maximum injection error of 3.3σ corresponding to 4 mm at β=185 m. Fig. 4 shows the kick voltage necessary on the dampers as a function of the turn number and the exponential decay of the oscillation amplitude. The necessary feedback gain is 0.05 and the damping time 3.6 ms or 40 turns.

Fig. 5 shows the result of the simulation taking the measurements on an MKI kicker as an input waveform. These show a very high frequency ripple and pose a potential difficulty to the damper as the gain drops off at higher frequency. A nominal batch of 288 bunches was injected and tracked over 500 turns together with a train of 72 bunches already circulating from the previous injection.

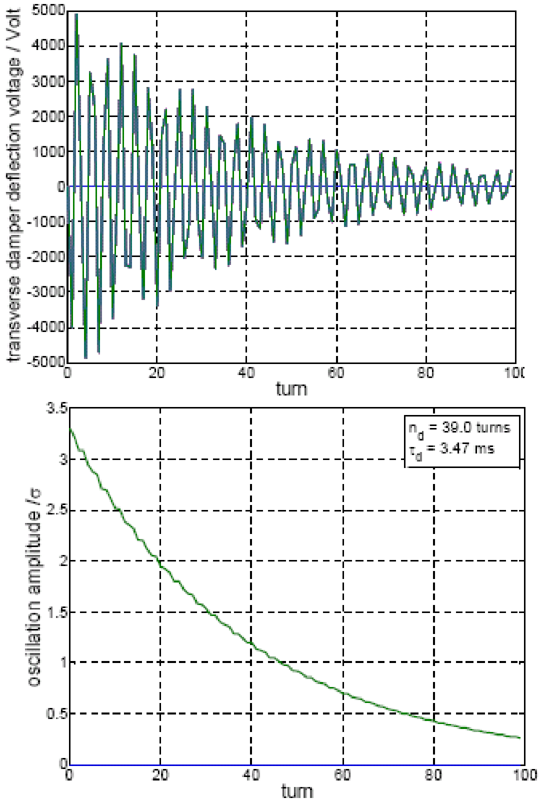

Figure 4: Damper kicker voltage (top) and exponential decay (bottom) of injection oscillation for a fixed 3.3σ injection error applied to all bunches.

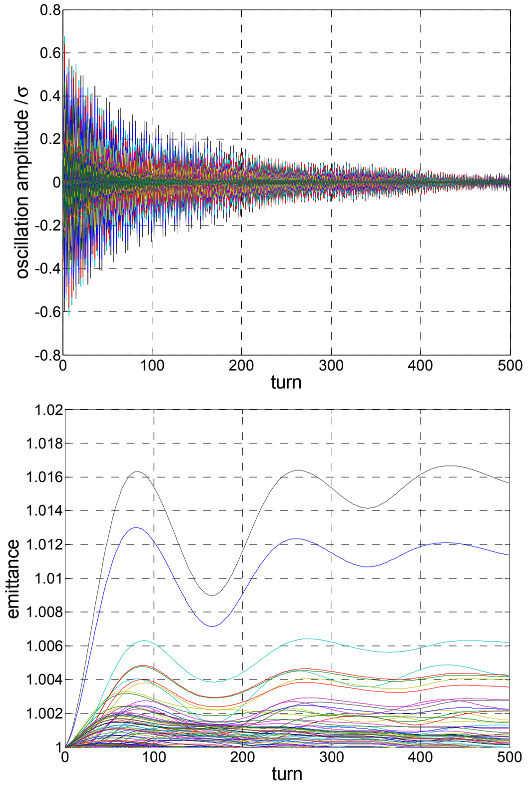

Figure 5: Evolution of single bunch oscillation amplitudes (top) and emittance increases (bottom) as a function of time after injection, using the measured MKI kick.

The top figure shows the evolution of the oscillation amplitude of all these 360 bunches. The bottom picture shows the evolution of the individual emittances of all the bunches normalised to the injected emittance. The oscillatory behaviour of the emittance values is due to the decoherence - recoherence phenomenon and occurs at a period of 182 turns, i.e. the synchrotron period. Damping by the feedback is much faster than the decoherence and as expected the emittance blow-up stays well below the specified 2.5%. The most critical bunches were found to be the third and forth bunches of the injected batch, but some of the details depend on the exact firing moment of the kicker. It should be noted that due to the relatively small peak error of 0.7 σ, less than 20% of the peak damper kick strength is required to damp the ripple, leaving a comfortable margin in kick strength to cope with damping of additional steering errors.

The SPS MKE kicker ripple leads to horizontal injection errors into LHC. Although these are larger in amplitude than the ripple of the LHC MKI they occur at a much lower frequency where there is sufficient kick strength to damp them sufficiently fast: if the amplitude of the MKE kicker ripple is within the specification the emittance blow-up from the MKE kickers will be of the order of 0.5% and can therefore can be considered as acceptable.

CONCLUSION

It has been shown that the LHC transverse feedback system can efficiently damp the high frequency injection oscillations of the MKI kicker ripple from the LHC injection kickers. The residual emittance increase is very small, with only two of the 272 injected bunches having increases above 1%. The measured MKE kick waveforms do not show the same high frequencies in the regions of interest, and so will pose even fewer problems for the horizontal damper.

REFERENCES

[1] L. Vos, EPAC '98, Stockholm 1998, CERN LHC Project Report 193, CERN 1998.
[2] O. Brüning et.al (Ed.). LHC Design Report, CERN-2004-003, CERN, Geneva, 2004.
[3] M. Barnes et al., TUPD003, These procedings.
[4] W. Höfle et.al., THPC121, These proceedings
[5] E. Gorbachev et.al., PAC'01, June 2001, Chicago, p. 1237.
[6] G. Kotzian et.al., THPC122, These proceedings.
[7] E. Vogel, W. Höfle, CERN-AB-2005-010, 2005
[8] V.M. Zhabitsky, Physics of Particles and Nuclei Letters, JINR, Dubna, 2008, vol. 5, No. 1 (143), 2008, p 49.
[9] M. G. Minty, A. W. Chao, W. L. Spence, PAC '95, Dallas, TX, USA, May 1995, SLAC-PUB-95-6815, 1995.
[10] G. Kotzian et.al., THPP114, These Proceedings.