FERMILAB-CONF-09-189-APC

LHC Abort Gap Cleaning with the Transverse Damper*

E. Gianfelice-Wendt (Fermilab, Batavia), B. Goddard, W. Höfle,
V. Kain, M. Meddahi, E. Shaposhnikova (CERN, Geneva), A. Koschik (ETH, Zurich)

Abstract

In the Large Hadron Collider, LHC, particles not captured by the RF system at injection or leaking out of the RF bucket may quench the superconducting magnets during beam abort. The problem, common to other superconducting machines, is particularly serious for the LHC due to the very large stored energy in the beam. For the LHC a way of removing the unbunched beam has been studied and it uses the existing damper kickers to excite resonantly the particles travelling along the abort gap. In this paper we describe the results of simulations performed with MAD-X for various LHC optics configurations, including the estimated multipolar errors.

INTRODUCTION

Various filling schemes have been proposed for the LHC. In all schemes it is foreseen to keep an at least 3 μs long abort gap to accommodate the abort kicker rise time.

To completely fill the two rings of LHC with the nominal pattern, 2808 bunches, requires about 18 minutes. Untrapped particles at injection as well as particles leaking out of the RF bucket during the relatively long filling time will populate the abort gap and will be lost in an uncontrolled way during acceleration.

During luminosity operation as well, particles diffusing out of the bucket will fill the abort gap and may quench the superconducting magnets during beam abort.

Failures of the RF system will fill the abort gap in about 5 s at 450 GeV and 20 s at 7 TeV [1]. In such a case the beam must be promptly dumped.

Abort gap cleaning has been successfully applied at the Tevatron using an electron lens [2] and at RHIC [3] using the stripline kickers and pulsed excitation.

We have studied the possibility of continuously removing the particles from the abort gap by using the kickers and power system of the transverse feedback [4]. Studies have been undertaken in the SPS to show the feasibility and efficiency [4, 5].

In LHC there are four horizontal and four vertical dampers, each providing a maximum kick of 0.5×450/energy[GeV] μrad. The voltage can be raised within the abort gap quickly enough in order to give a strong transverse kick to the beam present in the abort gap, while leaving the beam outside untouched. The flat top of the kicker pulse within the abort gap may be modulated as desired. Modulating for instance at a frequency corresponding to one of the transverse tunes will resonantly excite transverse oscillations rapidly, driving particles to large amplitudes. Non-linearities introduce higher order chromaticity and dependence of tunes on amplitude making this simple scheme less efficient, in particular for the untrapped beam.

The thin lens MAD-X tracking module has been modified [6] to allow turn by turn variation of parameters, namely the damper kick. This tracking has been used to simulate the cleaning process for the LHC beam in presence of the measured magnet errors. Only the clockwise rotating beam 1 has been considered under the assumption that differences between the non-linearities actually seen by the two beams are not relevant for this study.

INJECTION OPTICS

The bucket area at injection energy, 450 GeV, is 1.4 eVs for an RF voltage of 8 MV. For an emittance of 1 eVs of the injected beam the expected energy spread is $\sigma_{\rm p}$= 4.3×10^{-4} and the rms bunch length is 0.45 ns. The normalized beam transverse emittance is $\epsilon_{\rm N} = 3.5$ μm.

2000 particles have been tracked with coordinates randomly extracted from a 6D gaussian distribution. At injection, the momentum collimator, TCP.6L3.B1, limits the maximum relative energy offset for a particle circulating in the ring to 3.6×10^{-3}, about 8 times larger than $\sigma_{\rm p}$. The momentum spread has been therefore artificially increased by a factor 3 in order to populate also the energy range outside the bucket (blue crosses in Fig. 1). With the full kick available at 450 GeV, all particles are kicked out within the first 50 turns (4.4 ms), by the vertical dampers, while 1.9 % of the particles survive an excitation with the horizontal dampers. In both cases only vertical or horizontal dampers were used and the pulse was modulated with the *nominal* betatron frequency. The linear chromaticity is adjusted to its nominal value at injection, 2 units. Considering the successfull cleaning over the entire longitudinal acceptance within 50 turns, abort gap cleaning using the transverse damper seems straightforward at injection energy.

Nevertheless, to gain some experience on which excitation would be more efficient, the maximum kick has been *reduced* by a factor 10 and some different excitation algorithms have been tried, while leaving the collimators at their nominal injection position. By exciting the particles over 700 turns by using the vertical dampers, 54% of the particles are lost. Fig. 1 shows the initial distribution in the longitudinal phase space. In red are denoted the starting coordinates for those particles which will be *lost*. The particles with very large $\Delta p/p$ are immediately lost at the momentum collimator, while the *core* is lost between the first 200 and 500 turns at the collimator TCP.D6L7.B1

* Work partly supported by Fermilab, operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy

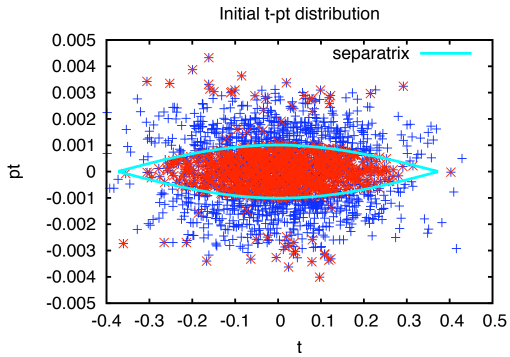

Figure 1: Initial longitudinal particle distribution for the injection energy case; in red are particles which will be lost when kicking at the nominal vertical betatron frequency and maximum kick reduced by a factor 10 together with the separatrix (cyan).

which is the vertical collimator closest to the beam (5.7 $\sigma_{\rm y}$). The particles with intermediate momenta are still circulating after 700 turns excitation. A longer excitation does not help (see Fig. 2). The starting transverse coordinates of the lost particles are in contrast to the longitudinal case uniformly distributed. Fig. 3 shows the tune variation

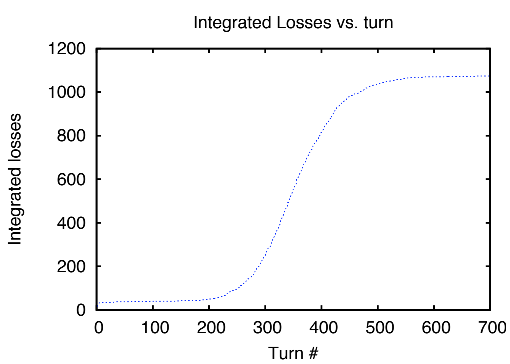

Figure 2: Integrated losses vs. turn number for the injection case with reduced vertical kick.

with amplitude. The largest dependence on amplitude is in the horizontal plane: for a particle with 240 nm emittance, or Courant-Snyder invariant, (larger emittance particles are intercepted by the collimators) the shift in tune is $\Delta Q_x \simeq 5\times10^{-4}$. Chromaticity versus momentum is shown in Fig. 4. The largest dependence on momentum is in the horizontal plane, where ΔQ_x varies between 8×10^{-4} for $\Delta p/p = \sigma_{\rm p}$ and 0.1 for $\Delta p/p = 8\ \sigma_{\rm p}$. To clean out the remaining particles we have changed the kicking frequency in *steps*, each 700 turns long, so as to cover the whole range of particle tunes. Fig. 5 shows the number of particles extracted vs. damper excitation frequency, on the left by using the horizontal dampers, on the right by using the vertical ones. Losses are more *broader* distributed when the beam is excited horizontally. This is in agreement with the stronger dependence on momentum of the horizontal tune.

We have tried a *swept frequency* excitation as well as

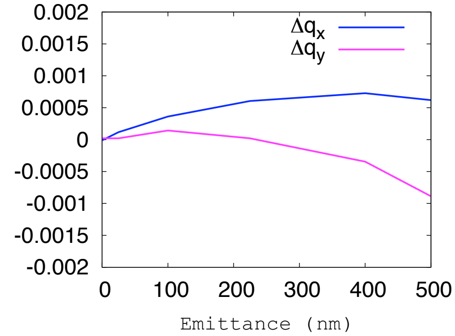

Figure 3: Tune variation vs. particle emittance (by FFT of Turn-By-Turn data, injection optics with errors).

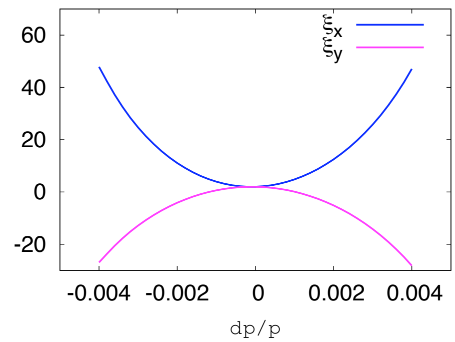

Figure 4: Chromaticities vs. momentum (MAD-X, injection optics with errors).

noise *bandlimited* around the betatron frequency. They were both not more efficient. What counts finally is that each frequency of the spectrum of the abort gap population is excited long enough so that the corresponding particle amplitude can build up until one of the collimators is reached. Fig. 5 thus is a guide for how large the frequency range and step size should be.

Kicking out all particles with horizontal dampers, for instance, required 35000 turns, i.e. 3 s (with the damper strength *reduced* by a factor 10 for testing purposes). As the time scale for abort gap filling ranges between 5 s and 25 s [1], this procedure seems feasible.

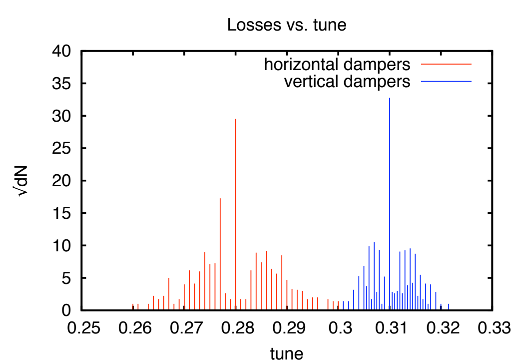

Figure 5: Number (sqrt) of lost particles vs. excitation frequency

LUMINOSITY OPTICS AT 7 TEV

During luminosity operation the collimators closest to the beam are at 6σ, that is, at 7 TeV, they are physically a factor $\simeq$4 closer to the beam, while the dampers are a factor $\simeq$15 weaker than at injection energy.

With 16 MV total RF voltage, the bucket area at 7 TeV is 2.5 eVs and the bucket height is 3.58×10^{-4}. The maximum energy spread is $\sigma_{\rm p} = 1.1\times10^{-4}$ and the rms bunch length is 0.27 ns.

At 7 TeV synchrotron radiation is not negligible; one can expect the abort gap to be filled by particles with negative $\Delta p/p$ [1] only, the momentum collimator limiting the maximum $|\Delta p/p|$ to 1.7×10^{-3}.

Fig. 6 shows the tune variation with amplitude for the luminosity optics including the measured magnet errors (triplet error/correction not included). The collimators limit the maximum particle Courant-Snyder transverse invariant to about 16 nm. Within this range the tunes, especially the vertical one, are quite constant.

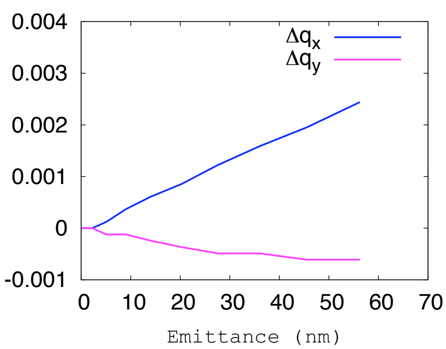

Figure 6: Tune variation vs. particle emittance (by FFT of Turn-By-Turn data, luminosity optics with errors).

Fig. 7 shows the dependence of the chromaticities on momentum. The nominal chromaticities have been set to +2 in both planes. For $\Delta p/p = -1.7\times10^{-3}$ the shifts in tune are $\Delta Q_{\rm x} = -0.0087$ and $\Delta Q_y = -0.021$. We extracted the coordinates of 2000 particles from the 6D gaussian distribution with $\sigma_{\rm p}$ increased by a factor 6. We have kept only particles outside the separatrix and with $\Delta p/p <$ 0 to fill the momentum aperture; as mentioned above, this is the scenario expected during luminosity operation.

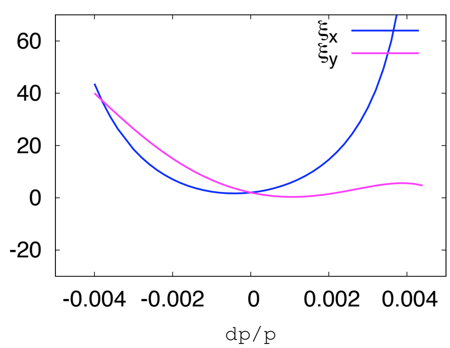

Figure 7: Chromaticities vs. momentum error (MAD-X, luminosity optics with errors).

By kicking, with full strength (0.032 μrad per damper), at a frequency corresponding to the nominal vertical tune, namely 0.32, 72% of the particles are kicked out within 250 turns. The remaining particles could be removed in four steps, covering the range 0.315-0.319, within the first 250-300 turns.

If the horizontal dampers are used instead and modulated with a frequency corresponding to the nominal horizontal tune (0.31 at luminosity) all particles are kicked out within the first 250 turns. The horizontal dampers are in this case more efficient. This is due to the very small horizontal chromaticity for negative $\Delta p/p$ within the momentum aperture $|\Delta p/p| < 1.7 \times 10^{-3}$, see Fig. 7.

SUMMARY AND OUTLOOK

MAD-X has been used for simulating the abort gap cleaning process of the LHC in presence of measured magnet errors. By resonantly exciting the particles at the nominal betatron frequency, the cleaning of an already full abort gap will require a few tens of ms.

Simulation results strongly depend on the relative linearity of the machine. The non-linearity of the actual machine needs to be carefully experimentally checked and errors corrected to provide optimum conditions for cleaning.

In case of unpleasant surprises, the results shown here for the injection case with reduced kick suggest that by using a few *bursts* of kicks at fixed frequencies around the nominal one will clean the abort gap in an acceptable period of time.

ACKNOWLEDGMENTS

The authors would like to thank M. Giovannozzi for providing them with the MAD-X input files, T. Risselada for helpful discussions and T. Weiler for assisting with the collimators data.

REFERENCES

[1] E. Shaposhnikova, S. Fartoukh, B. Jeanneret, Proceedings of EPAC04, Luzern, July 2004, p. 611 (2004)

[2] X.-L. Zhang et al., PRST Accel. Beams 11:051002 (2008)

[3] A. Drees et al., Proceedings of EPAC04, Luzern, July 2004, p. 908 (2004)

[4] W. Höfle, Proceedings of EPAC04, Luzern, July 2004, p. 575 (2004)

[5] A. Koschik, B. Goddard, W. Höfle, G. Kotzian, D. Kramer, T. Kramer, Proceedings of EPAC08, Genoa, June 2008, p. 2656 (2008)

[6] A. Koschik, Private Communication.