

# LHC Abort Gap Monitoring and Cleaning <sup>\* †</sup>

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## Abstract

Unbunched beam is a potentially serious issue in the LHC as it may quench the superconducting magnets during a beam abort. Unbunched particles, either not captured by the RF system at injection or leaking out of the RF bucket, will be removed by using the existing damper kickers to excite resonantly the particles in the abort gap. Following beam simulations, a strategy for cleaning the abort gap at different energies was proposed. The plans for the commissioning of the beam abort gap cleaning are described and first results from the beam commissioning are presented.

## INTRODUCTION

For all LHC filling schemes it is mandatory to keep an abort gap of at least  $3 \mu\text{s}$  to accommodate the beam abort kicker rise time. About 18 minutes are required in order to completely fill the two LHC rings with the nominal 2808 bunches. During this relatively long filling time, untrapped particles at injection as well as particles leaking out of the RF bucket will populate the abort gap and will be lost on the collimation system at the beginning of acceleration. During luminosity operation, particles diffusing out of the bucket will as well fill the abort gap and may quench the superconducting magnets during beam abort. Finally, it was calculated that failures of the RF system will result in filling the abort gap by the nominal beam in about 5 s at 450 GeV (LHC injection energy) and 20 s at 7 TeV [1]. In such a case, the beam must be dumped promptly.

The control of the abort gap population is a problem common to other high energy machines using superconducting magnets. Abort gap cleaning has been successfully applied at the Tevatron using an electron lens [2] and at RHIC [3] using stripline kickers and pulsed excitation.

We have studied the possibility of continuously removing the particles from the abort gap by using the kickers and the power system of the transverse feedback [4].

The thin lens MAD-X tracking module was modified [5] to allow turn-by-turn variation of parameters, e.g. the transverse damper kick. This tracking has been used to simulate the cleaning process for the LHC beam in presence of the measured magnet errors and their systematic and empirical corrections. In principle, modulating the damper kicker pulse at a frequency corresponding to one of the

transverse tunes will resonantly excite transverse oscillations and drive particles to larger and larger amplitudes, until they are intercepted by the betatron collimators. However, higher order chromaticity and dependence of tunes on amplitude introduced by non-linearities, may spoil the cleaning efficiency.

Previous studies [6] have shown that, if the systematic and empirical corrections of the magnet errors are applied, the tune dependence on amplitude is negligibly small within the range of betatron amplitudes allowed by the collimation system. The energy error of particles circulating in the ring is limited by the momentum collimator to about  $3.6 \times 10^{-3}$  at 450 GeV and  $1.7 \times 10^{-3}$  at 7 TeV. These values are respectively 4 and 5 times larger than the bucket height (8 MV and 16 MV). In this range of momenta, the variation of the tune is not negligible. However, simulations have shown that the cleaning efficiency is sufficient if the excitation frequency is changed in steps in order to cover the whole frequency spectrum of the unbunched beam. Cleaning of an already full abort gap using the transverse dampers should require no more than a few tens of ms.

## LHC TRANSVERSE DAMPER SYSTEM

LHC is equipped with a powerful transverse feedback system designed to stabilize the coupled bunch instabilities in the frequency range from 3 kHz to 20 MHz, as well as the injection oscillations. The system includes four horizontal and four vertical electrostatic kickers per beam, each providing a maximum kick of  $0.5 \times 450/\text{energy}[\text{GeV}] \mu\text{rad}$ . The wide band power amplifiers allow the simultaneous use of the kickers for cleaning the abort gap and for feedback purposes. The flat top of the kicker pulse within the abort gap may be modulated as desired. Details on the LHC damper system may be found in [7].

## ABORT GAP MONITORING

LHC is equipped with two synchrotron light telescopes providing the transverse profiles of the two beams [8]. At 7 TeV, each telescope will image visible light emitted in the superconducting dipole used to widen beam separation at the RF cavities. However the light emitted in the dipole at 450 GeV is not sufficient. Therefore a 2-period superconducting undulator [9] has been introduced at 1 m from the separation dipole. With a fixed field of 5 T, the spectrum for 450 GeV protons peaks in the visible light spectrum at 610 nm. Besides providing a non-invasive measurement of the bunch-by-bunch emittance, the system is used to moni-

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tor the abort gap population. 10% of the light is transmitted to the abort gap monitor (AGM). The gated photomultiplier allows to detect the small gap signal and to measure the quench threshold population to 5% accuracy over 100 ms. The gap is monitored in 30 bins of 100 ns. The full design details and commissioning of the AGM are described in [10].

## EXPERIMENTAL RESULTS

The first tests of the abort gap cleaning system were performed on December 15-16 2009, by using the vertical dampers on Beam 2, for which the undulator and the synchrotron light detector were being commissioned. The aim of the studies was to check the basic functionality of the dampers, to try cleaning the abort gap and to observe the effect on the stored beam. The energy spread (0.3 eVs emittance, 5 MV) at 450 GeV is  $2\sigma_p = 4.3 \times 10^{-4}$ , while the momentum collimator limited the maximum  $\delta p/p$  to about  $4 \times 10^{-3}$ .

Simulations have shown that the smaller the tune dependence on the momentum is, the higher is the cleaning efficiency. Lack of time did not allow a measurement of the non-linear chromaticity at that time, but a measurement has been done in March 2010 and indicated that the non-linear chromaticity may indeed be larger than theoretically assumed (see Fig. 1).

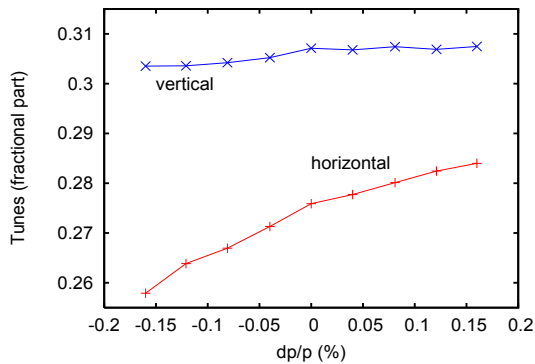


Figure 1: Measured tunes vs  $\delta p/p$  (March 2010 data).

### Cleaning of a bunched beam

A very first test consisted in cleaning a bunched beam. A pilot bunch was filled with  $5.8 \times 10^9$  protons. The beam tunes (fractional part) were  $Q_h = 0.295$  and  $Q_v = 0.266$ . The vertical dampers were set to kick at a *fixed* frequency, corresponding to  $q_{exc} = 1 - 0.266 = 0.734$ . The amplitude was  $V = 0.003 V_{max}$ .<sup>1</sup> The losses were mainly observed at the tightest vertical collimator, namely TCP.D6L7.B2, with a

<sup>1</sup>according to the 2009 calibrations,  $V_{max} = 0.169 \mu\text{rad}$ . The kick strength after full commissioning will be  $2 \mu\text{rad}$ .

large shower at the horizontal collimator downstream. The beam was lost within a few minutes<sup>2</sup>. The following programmed dump produced some losses indicating that not all particles had been kicked out.

The second test consisted in cleaning the bunched beam by using a *variable* frequency. The excitation tunes were varied from  $1 - 0.4 = 0.6$  to  $1 - 0.2 = 0.8$  in 10 steps each 100 turns long. As the kick amplitude was increased, the observed loss rates also increased.

### Effect on stored beam

An important requirement for the cleaning system is that the beam in the abort gap can be kicked out while the closest bunches are unaffected. This is crucial since the cleaning system must be kept working during the long runs for luminosity operation.

The so-called "trailing edge" effect was studied by injecting two bunches  $3 \mu\text{s}$  apart (simulating the abort gap length) and timing the damper kicks so as to cover the (empty) gap between the two bunches. The test was performed under the worst condition for the stored beam, namely kicking at the betatron frequency. Large losses of the downstream bunch were observed. During the 2009 tests, the only remedy was to reduce the kick amplitude and to shorten the pulse to roughly 1/3 to 1/4 of the abort gap length.

Following the 2009 tests, it has been identified that the trailing tail of the pulse is predominately caused by dispersion in the cable transmitting the signal from the surface to the LHC underground cavern UX45. A suitable filter has been installed in the shutdown 2009/2010 to correct for the attenuation and group delay variation of this cable with frequency. The new corrected pulse shape has yet to be tested with beam.

### Cleaning of a coasting beam

For this experiment,  $2.5 \times 10^{10}$  protons were injected in 4 bunches almost equally spaced along the machine. It has to be clarified that the abort gap is always in front of the first bunch (batch).

The RF was then switched off and after 5 minutes<sup>3</sup>, the cleaning of the abort gap started. The cleaning process was performed with  $V = 0.1 V_{max}$  and the frequency continuously ramped between  $1 - 0.8 = 0.2$  and  $1 - 0.7 = 0.3$  in 10 steps, each 100 turns long.

After 5 minutes of this procedure the beam was intentionally dumped. The BLM signals indicated that the procedure *failed* to clean the abort gap. This was confirmed by a later dump of an un-cleaned coasting beam, which showed exactly the same signature<sup>4</sup>.

<sup>2</sup>simulation suggests that it should have been lost in a few turns when the maximum kick is applied.

<sup>3</sup>5 minutes is the time a  $dp/p = 4.3 \times 10^{-4}$  proton, starting from the middle of the ring, needs to reach the abort gap at 450 GeV.

<sup>4</sup>the synchrotron light monitor was no longer available at this stage of the experiment.

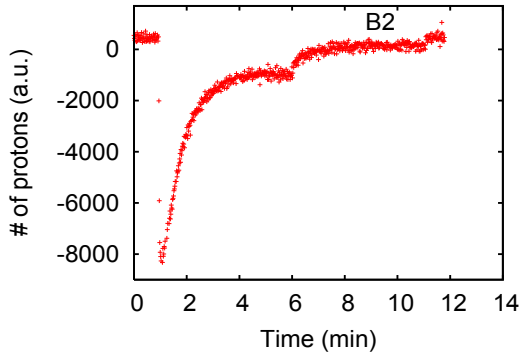


Figure 2: AGM signal during coasting beam cleaning experiment.

This test was repeated the following day with an excitation frequency program closer to the one adopted in the simulation of a successful abort gap cleaning. Here the excitation frequency was varied in 20  $\Delta q_{exc} = 0.001$  steps, each 700 turns long, around the measured vertical tune ( $Q_v = 0.310$ ). The kick duration covered about 1/3 of the abort gap and the amplitude was raised to  $V = 0.3 V_{max}$ .

Fig. 2 shows the (visible) synchrotron light, proportional to the total number of protons in the 3  $\mu s$  abort gap. The (negative) peak in the curve corresponds to the moment the RF is switched off. After about 5 minutes, the gap population reached an equilibrium and the light intensity settled to a constant level. At this moment, the cleaning started, and the synchrotron light production decreased proportionally to the gap population. But the last step of the curve, at 10 minutes, when the beam was dumped, shows that the gap had not been completely emptied. A low equilibrium gap population is expected, as protons outside the gap drift in and are removed by cleaning. But the larger population that remained here was the result of using a 1  $\mu s$  waveform to clean the 3  $\mu s$  gap.

Fig. 3, which plots the population of each of the 30 bins of 100 ns monitored by the AGM, confirms that the portion of the gap actually targeted was very quickly emptied. We see also that the leading edge of the cleaning waveform was sharp, but the ringing in the trailing edge noted earlier affected the following 500 ns. The new pulse-shaping filter should permit efficient cleaning of the entire gap.

## SUMMARY AND OUTLOOK

MAD-X has been used to simulate the LHC abort gap cleaning process, in presence of the measured magnet errors and their correction.

Simulation has shown the importance of the linearity of the machine. The linearity of the actual machine needs to be carefully checked experimentally and errors corrected to provide optimum conditions for the abort gap cleaning.

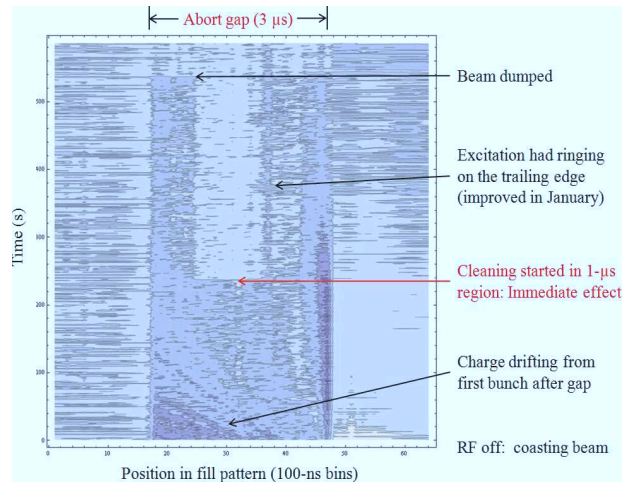


Figure 3: Population of each of the 30 bins of 100 ns monitored by the AGM

During 2009, the first abort gap cleaning tests were done with encouraging results. During the 2009-2010 LHC shutdown, modifications were implemented on the damper system to reduce the tail of the abort gap cleaning pulse and improve the shape of the pulse. The effect of these modifications has yet to be demonstrated with beam in the upcoming machine studies. Moreover a calibration of the damper kicks is being carried out so as to be able to quantitatively compare the experimental results with the simulations.

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