ABORT GAP CLEANING USING THE TRANSVERSE FEEDBACK SYSTEM: SIMULATION AND MEASUREMENTS IN THE SPS FOR THE LHC BEAM DUMP SYSTEM

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Abstract

The critical and delicate process of dumping the beams of the LHC requires very low particle densities within the 3 μs of the dump kicker rising edge. High beam population in this so-called 'abort gap' might cause magnet quenches or even damage. Constant refilling due to diffusion processes is expected which will be counter-acted by an active abort gap cleaning system employing the transverse feedback kickers. In order to assess the feasibility and performance of such an abort gap cleaning system, simulations and measurements with beam in the SPS have been performed. Here we report on the results of these studies.

INTRODUCTION

Abort gap cleaning has been successfully applied at the Tevatron using an electron lens [1] and at RHIC [2,3] using kick pulses applied to stripline kickers.

Also for the LHC beam dump system (LBDS) [4] a so-called beam *abort gap* is needed, a particle-free gap in the bunch filling scheme which can accommodate the field rise time of the beam dump kicker system, see Fig.1.

Particles filling this abort gap would see a sweeping kicker field (3 μs rise time) and may be lost at various positions in the machine, possibly causing magnet quenches or damage. Hence one important aspect is to keep the particle density below a critical level defined by the quench limit. Non-negligible intensities can be accumulated in the otherwise particle-free abort gap by re-filling due to longitudinal diffusion processes (eg. by intra-beam scattering or RF noise) [5].

Therefore an active *abort gap cleaning* system has been foreseen for the LHC [6]. A gated signal on the transverse feedback kickers will be used to resonantly excite the particles in the abort gap to large amplitudes and intercept them in a controlled way on the LHC collimators.

Previous SPS studies demonstrated a proof of principle [7]. In the present study in the SPS, we performed quantitative measurements of the cleaning time dependent on different beam parameters in order to benchmark simulations. Since the LHC is a non-linear machine, particular interest was put on the dependence on chromaticity ξ and detuning arising from non-linearities in the machine.

In a linear machine the performance of an abort gap cleaning system can be roughly estimated by the average time τ_{clean} needed to dispose of particles from the abort gap

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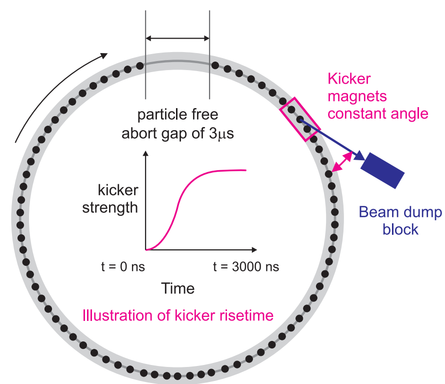

Figure 1: Illustration of the LHC *abort gap*.

$$\frac{\tau_{\text{clean}}}{T_0} \simeq \frac{1}{\pi\,|q-\nu|}\cdot\arcsin\left[\frac{2\,h_{\text{coll.}}}{\hat{\theta}\,\sqrt{\beta_{\text{coll.}}\,\beta_{\text{kick.}}}}\,\pi\,|q-\nu|\right]. \quad (1)$$

$\hat{\theta}$ is the peak kick angle applied by the cleaning pulses, $\beta_{\text{kick.}}, \beta_{\text{coll.}}$ are the β-functions at the kicker and collimator position, T_0 the revolution time, $q < 1$ is the tune line closest to the excitation frequency and $h_{\text{coll.}}$ is the collimator half gap. The cleaning pulses are modulated with a frequency $f = \nu/T_0$ which should be close to the (fractional) tune of these particles or the corresponding image frequency line. The factor 2 accounts for the fact that the average effective angle applied $\sqrt{\langle\theta^2\rangle}$ is only half the peak kick $\hat{\theta}$. In the case the excitation is exactly at the tune frequency line, $\nu = q$, the oscillation amplitude will grow linearly and the collimator is reached after $2\,h_{\text{coll.}}/(\hat{\theta}\sqrt{\beta_{\text{coll.}}\beta_{\text{kick.}}})$ turns. Eq.(1) assumes a sinusoidal beating of the excitation with the particle betatron oscillation.

In a non-linear machine however, one has to resort to particle tracking simulations to get an estimate for τ_{clean}. Using the SPS as LHC test bed, we carried out a measurement and simulation campaign in order to verify the significance of the simulations results.

SIMULATION SETUP

In order to reproduce the actual processes of the real machine a full 6D tracking code has to be used. We have chosen the latest MADX version as it allows *6D*, *element-by-element* tracking with *aperture* and the machine description of the SPS (and LHC) is readily available in form of *sequence files*, *strength files* and *aperture definitions*. Optics parameters can be varied and changed easily via `match` and `twiss` commands.

For the purpose of modelling the feedback system, the MADX code was upgraded by implementing time (ie. turn by turn) *varying* parameters in the tracking module. A typical simulation run then comprises the following steps:

1. Set optics and beam parameters (eg. nominal SPS optics, LHC beam & working point);
2. Set ξ chromaticity;
3. Set k_3 octupole strength (non-linearities);
4. Set transverse damper excitation program;
5. Generate particle distribution (according to given beam parameters);
6. Track particles over x turns (with **time-varying** kicks from the feedback kicker) and record *loss rate*, *integrated loss* and *loss pattern*.

No magnetic field errors or misalignment errors were treated in this study, since we are primarily interested in the first order (dominant) effects.

Given the simple estimation in Eq.(1) the expected 'linear' cleaning time in the SPS is around 250 turns, assuming a peak kick angle per turn of $\hat{\theta} = 2.89\,\mu$rad, $\beta_{\text{kicker}} = 39$ m, $\beta_{\text{coll.}} = 81$ m and the tune is $Q_{\text{V}} = 26.18$. The aperture limit is the TIDV with a half gap size of $h_{\text{coll.}} = 20.4$ mm. Simulation results reproduce this behaviour for this linear case.

MEASUREMENT SETUP

Beam conditions We used an LHC type beam in the SPS, single bunch (captured) with an intensity of 5.0×10^{10} protons, at a momentum of 26 GeV with the following measured characteristics:

Long. emittance:	$\varepsilon_{\text{n, long.}} = 0.26$ eVs,
	4σ bunch length $= 2.0$ ns (3MV);
Trans. emittance:	$\varepsilon_{\text{n, trans.}} = 1.0\,\mu$m;
Tunes:	$Q_{\text{H}} = 26.13,\ Q_{\text{V}} = 26.18$;
Chromaticity:	$\xi_{\text{H}} = +0.02,\ \xi_{\text{V}} = +0.03$ (nominal);
Coupling:	no coupling effects (via tune meas.).

An orbit bump of -8 mm at the TIDV was used to concentrate losses at this location.

Tests with up to 4×12 bunches at 25 ns bunch spacing were also carried out and show an increased cleaning efficiency compared to [7] due to the optimized excitation programs used.

Beam instrumentation Knowledge of the beam conditions is of vital importance in order to compare measurement with simulation. During the experiments tune, orbit (BPM), intensity (BCT, FastBCT) and loss (BLM) data were taken. Additionally wirescanner and wallcurrent monitor data for measuring transverse emittance and bunch length were stored. A special beam loss monitor (LHC type), installed on the TIDV, was capable to provide loss data with a $40\,\mu$s resolution over a period of 1.7 s in post-mortem operation. A trigger signal from the transverse damper system synchronized the start of the BLM acquisition with the start of the damper excitation signal with a precision of one machine turn.

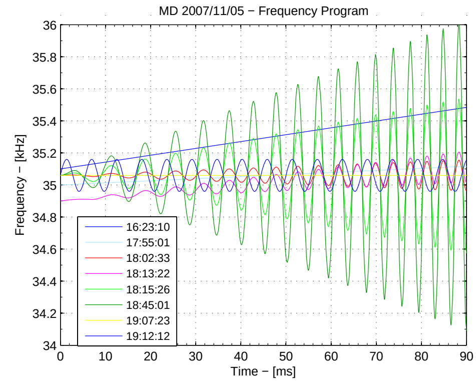

Figure 2: Illustration of the excitation programs used.

Excitation signal Measurements were done in the vertical plane. Only one vertical damper V1 (BDV 214.55) was used, providing a maximum kick angle of $2.89\,\mu$rad per turn. A programmable arbitrary waveform generator (Agilent 33250A) was used to provide the excitation signal, which was always applied around $(1-q) \times f_{\text{rev}}$, ie. 35 kHz with the fractional tune of $q = 0.18$ and the revolution frequency $f_{\text{rev}} = 43.3$ kHz at 26 GeV.

Different frequency programs were explored, Fig.2:

- Fixed frequency;
- Swept frequency;
- Modulated frequency (FM);
- FM on a carrier that is itself swept.

The maximum frequency deviation and variation for the swept and modulated cases was adjusted to provide optimum cleaning efficiency, and relates directly to the frequency spread of the particles in the beam.

A swept frequency should be the optimum when the tune depends on the oscillation amplitude, where the excitation follows the change of average tune of the particle distribution as the oscillation amplitude increases. Therefore modulated programs were introduced to provide optimum excitation in synchronization with the longitudinal motion. The transverse tune changes with momentum during the synchrotron motion, and the synchrotron frequency decreases with increasing momentum, hence the idea of sweeping the modulation frequency.

A different approach is to use band-limited noise with a width matched to the tune spread of the particle distribution. This method was not tried in the experiments. It is expected to provide slower but more regular cleaning in a diffusion-like process. A combination of coherent excitation alternated with band limited noise has the potential of combining the advantages of both types of excitation.

SPS MEASUREMENTS

We measured the cleaning time (= loss time) and cleaning efficiency (= intensity drop) while varying the vertical chromaticity ξ_{V} from $+0.03$ to $+0.93$ and the octupoles strengths k_3 of both families (LOD, LOF) in the range of 0 to $+50$ units, see also Figs.3–4.

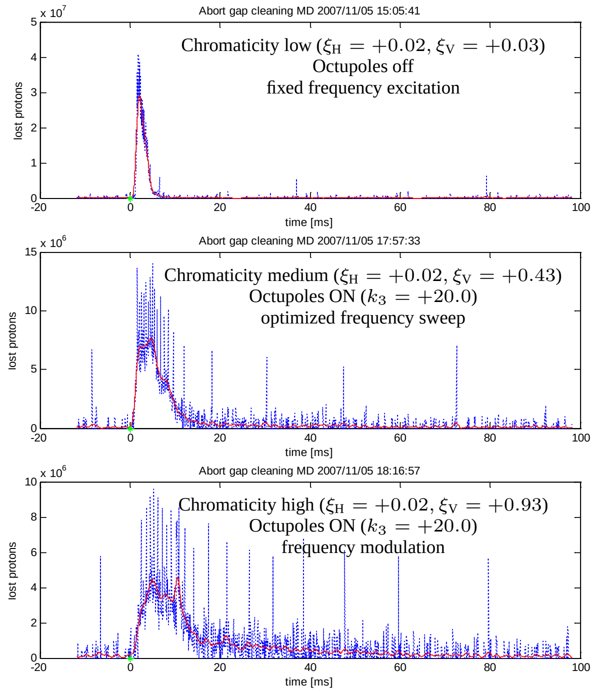

Figure 3: Measured loss rates at TIDV.

For an optimized fixed frequency excitation and negligible chromaticity ($\xi_V = +0.03$), octupoles switched off, we find a cleaning time of 5 ms (220 turns) which corresponds again very well to the estimate made with Eq.(1). The maximum cleaning efficiency that we could achieve was 97.3 %. When switching on octupole families as nonlinearities the cleaning efficiency drops significantly, while the cleaning time is roughly doubled.

At medium chromaticity settings of $\xi_V = +0.43$ and with non-linearities ($k_3 = +20$) no cleaning can be achieved with a fixed frequency excitation. With a sweep program we can however achieve 99.9 % efficiency. The cleaning time increases to about 40 ms (1740 turns).

We used a frequency modulation program to clean the very stable beam at a chromaticity setting of $\xi_V = +0.93$, octupoles still powered at $k_3 = +20$ units. A cleaning efficiency of 99.7 % was achievable, with the cleaning time in the order of 80 ms (3500 turns).

Little dependence of cleaning efficiency and time on the non-linearity settings (k_3, octupoles) was observed, but considerable influence from chromaticity settings.

The loss pattern around the SPS machine showed significant losses also in other places than the TIDV, but which from the time structure clearly result from the cleaning efforts. Modelling the actual orbit and aperture conditions in a simulation is beyond the scope of the present study not possible, as the orbit from the SPS is not known with high enough precision.

SPS SIMULATION

Using the same optics setting, beam parameters as measured and excitation programs as in the SPS experiments, we ran the MADX simulations. Within an error limit of 10–20 % we can reproduce the measured quantities of cleaning time and efficiency very well. Only the loss pattern cannot be reproduced due to aforementioned insufficient knowledge of actual orbit and aperture (misalignment) in the machine.

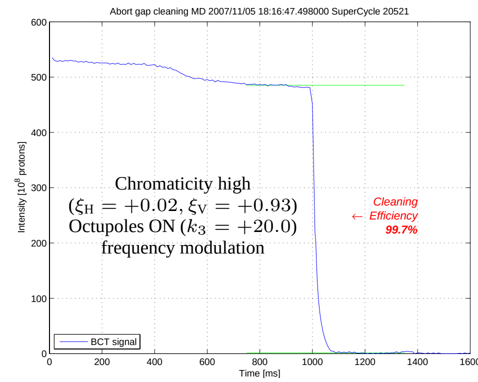

Figure 4: Measured cleaning efficiency.

It is interesting to note that simulations done before the experiments predicted a dominant influence of the chromaticity on the cleaning efforts and less so the nonlinearities from octupoles, which was entirely confirmed by the measurements.

CONCLUSION AND OUTLOOK

Using the transverse feedback kickers to actively clean the abort gap has once more shown to be working well in the SPS. It should be stressed however, that the measurements were done with captured beam and in particular the tune was known very well in order to excite the particles at the right betatron frequency.

In the LHC and especially with uncaptured beam the situation has more unknown variables and the optimization of the excitation program will be more difficult. Therefore it is of vital importance to have an abort gap monitor working, to enable a precise measurement of the particle intensity in the abort gap, their longitudinal distribution and their susceptibility to the cleaning excitation program.

The simulations have shown to give very good agreement with the SPS measurement results, hence they are a major tool now for optimizing the abort gap cleaning system for LHC.

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