EXPERIENCE GAINED IN THE SPS FOR THE FUTURE LHC ABORT GAP CLEANING

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Abstract

Abort gap cleaning using a transverse damper (feedback) has been previously shown in the RHIC accelerator [1]. We report on experimental results in the SPS [2], where the transverse damper was used to excite transverse oscillations on part of an LHC test beam and, by the induced losses, to create a practically particle free zone. It is proposed to use the same principle for abort gap cleaning in the LHC.

For the LHC accelerator, abort gap cleaning may be required at injection energy, during the ramp and at top energy [3]. The transverse excitation can be optimized taking into account the actual bandwidth of the damper systems and the possibility to fully modulate their input signal to match the beam betatron tune distribution.

MOTIVATION FOR ABORT GAP CLEANING IN LHC

Various filling schemes have been proposed for the LHC [4]. The nominal bunch spacing is 25 ns, with options for 75 ns for initial running-in, in order to overcome problems with the electron cloud effect, as well as filling schemes with fewer bunches for the TOTEM experiment and early Physics during commissioning. To completely fill the LHC with the nominal pattern (2808 bunches), injection of 12 SPS batches is required for each ring of the LHC. This leaves the LHC idling on the injection plateau of 450 GeV for about 18 minutes. In all filling schemes it is foreseen to have an abort gap of at least 3 μs to accommodate the abort kicker rise time (119 missing bunches for the case of 25 ns bunch spacing).

Capture losses at injection and particles lost from the buckets during the relatively long flat bottom plateau at 450 GeV will give rise to beam filling the abort gap. Time scales for the processes involved have been estimated and range from ~5 s for abort gap filling at 450 GeV with RF off, to 25 s at 7 TeV with RF on [3,5,6].

SPS EXPERIMENTS

We carried out pilot experiments in the SPS accelerator in order to show that abort gap cleaning with the transverse damper will be feasible in the LHC.

SPS transverse damper

In the SPS there are two horizontal dampers, H1 and H2, and two vertical dampers V1 and V2 [7]. The two vertical systems are installed with a betatron phase shift of 60 degrees in between at different locations in the ring. This makes excitation of coherent oscillations cumbersome as we would have to take into account the phase shift and the correct delay when applying the input signals to the two different systems. These are the reasons why, for the practical experiment in the SPS, the two horizontal damper systems were used. These are installed next to each other with only 2 degrees of phase advance in between. Identical input signals can be used.

Beam conditions and excitation signal

The beam conditions for the experiment were:

- one batch of 72 bunches spaced by 25 ns
- 3 x 10^{10} p / bunch
- momentum: 26 GeV/c, stored beam
- tunes: Q_H=26.176, Q_V=26.151

Both horizontal dampers were used to excite betatron oscillations. The dampers were used at about 65% of their maximum kick strength providing a total deflection at 26 GeV/c of 2.5 μrad at a β=68 m. As excitation a gated (width chosen was 500 ns) 35.67 kHz signal corresponding to an excitation at the horizontal tune was applied (f_{rev}=43.3 kHz, excitation at $(1-q_{frac})f_{rev}$). The excitation was repeatedly switched on for about 4000 turns (85 ms) every 16.8 s (time frame fixed by the SPS timing system which still continues to cycle in storage mode). Fig. 1 shows the excitation function with gating.

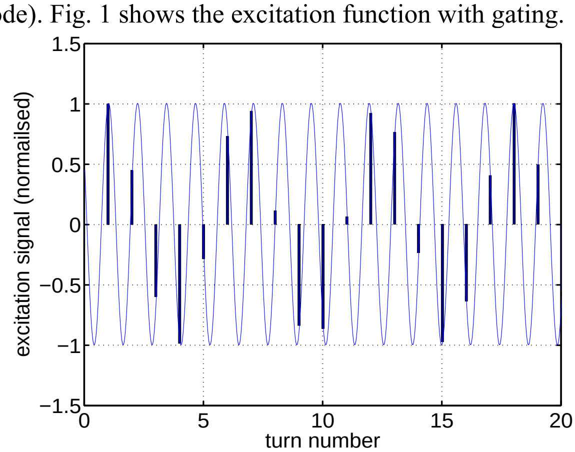

Fig. 1: Pulsed (gated) excitation signal turn by turn with the generating envelope of 35.67 kHz.

Observation of cleaning in SPS

In order to observe the cleaning effect the excitation was first centred *inside* the 72 bunch batch. Fig. 2 shows the batch structure seen on a wide band pick-up (AES) before, and Fig. 3 after, the excitation signal has been applied for approximately two minutes corresponding to 6 excitation bursts. We can clearly see that in the centre close to 95% of the beam has been removed. Bunches at the edges of the 500 ns window have been partially removed. This is due to the limited rise time (bandwidth) of about 100 ns of the SPS damper system.

Cleaning was then also applied outside the batch. Small amounts of uncaptured and captured beam were present outside the batch. The cleaning effect could be observed by monitoring higher bunch frequency harmonics, namely

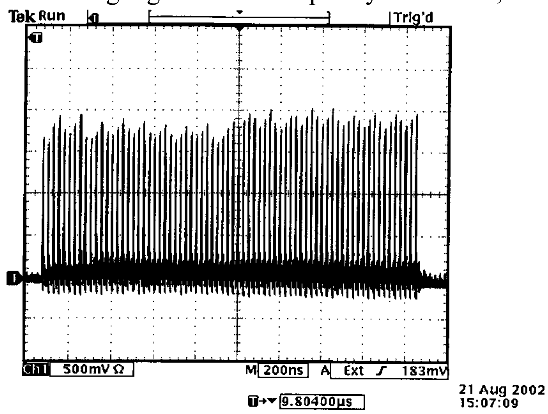

Fig 2: Batch of 72 bunches spaced by 25 ns at the beginning of the coast.

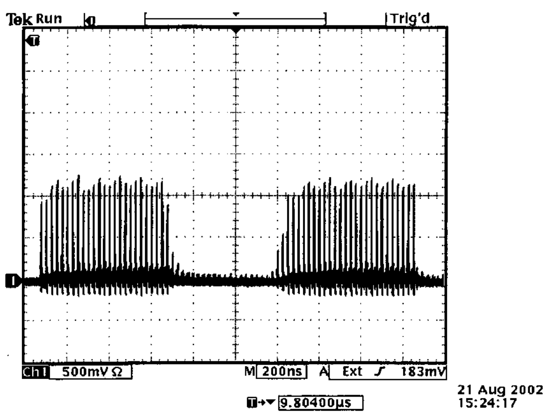

Figure 3: Demonstrated effect of beam cleaning on LHC batch: 6 cleaning bursts of 85 ms length (picture taken 17 minutes after Fig. 2).

the 200 MHz component (the RF frequency) and the 400 MHz components [2]. When cleaning is applied a rapid change of these components was observed.

The cleaning experiment was carried out without the use of collimators, hence the beam was uniformly lost at aperture limitations in the SPS. The aperture of the SPS is rather large in the horizontal plane, ~120 mm at about β=100 m. The peak kick of 2.5 μrad applied at β=68 m corresponds to ~0.2 mm at β=100 m. Neglecting the amplitude dependence of the tune, particles would reach the aperture limit after 1200 turns, if the excitation is done exactly at the true tune value. Note that due to the modulation the rms kick is only half the peak kick.

In practice the tune will depend on the amplitude of oscillation and through the chromaticity also on the momentum. It is therefore not possible to keep the excitation in phase with the oscillation over a very long time. This is why we chose to switch off the excitation after about 4000 turns. During the burst of excitation particles at large betatron amplitudes will be lost and the remaining beam emittance will increase. Eventually all particles will be lost after sufficient bursts.

A better cleaning should be achievable by sweeping the frequency slowly or by applying subsequent bursts at slightly different frequencies. In order to optimise the excitation more information is needed on the dependence of betatron tune with amplitude. This dependence was not precisely known for the conditions of our experiment. Improvement is expected in future experiments with the use of collimators which will restrict the aperture leading to faster losses. Moreover, with a restricted aperture non-linearities will be better known (can be measured) and the excitation bursts can be accordingly matched to quickly drive particles out of the centre into the collimator(s).

ABORT GAP CLEANING IN LHC

Capabilities of LHC damper

The capabilities of the LHC damper at injection energy are summarised in Table 1 [8]:

Table 1: LHC damper capabilities (kick/turn) at 450 GeV

Damper	**nominal performance (β=100m)**	**actual performance (optics 6.4)**
Beam 1 (hor)	0.23 σ	0.36 σ
Beam 2 (hor)	0.23 σ	0.33 σ
Beam 1 (ver)	0.23 σ	0.36 σ
Beam 2 (ver)	0.23 σ	0.38 σ

The nominal performance assumes a beta function of 100 m at the location of the feedback kickers, while the actual performance takes into account the true values of the beta functions for the LHC optics version 6.4. In pulsed mode an even higher kick strength is possible, approaching 0.5 σ. It follows that an oscillation of 1 σ can be easily built up in ~4 turns. At top energy (7 TeV) it would take more turns to reach the same amplitude (in mm), but as the bunch size reduces during acceleration 1 σ could be reached at top energy after ~30 turns.

The frequency up to which the power amplifiers can deliver the full kick strength is 1 MHz [8]. Beyond this frequency its gain is limited by a 1-pole roll-off. In practice this means that the cleaning pulse can be ramped-up and down within 1 μs as shown in Fig. 4. From the curve it is also visible that particles *captured* in buckets next to the edges *cannot* be cleaned by this method. However, *uncaptured* beam will travel along the bunch trains and eventually, if not intercepted beforehand by the momentum cleaning, arrive in the middle part of the abort gap where it can be efficiently removed by transverse excitation with the damper and betatron cleaning.

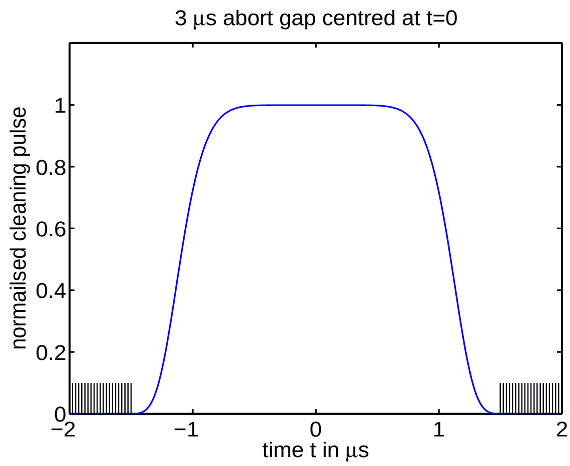

Fig. 4: Normalised wave form of damper pulse during abort gap with bunches of adjacent batches.

Collimation system and time scales

The primary collimators of the LHC collimation system will intercept the beam at 6 σ at top energy and 6-7 σ at injection energy [8]. Neglecting non-linearities we can reach the required amplitudes for cleaning after ~50 turns at injection energy and after ~200 turns at 7 TeV. The time scales for cleaning at injection energy are therefore <5 ms, at top energy <20 ms.

Optimum excitation signal for cleaning

For the nominal working point the LHC tunes are 64.28 in the horizontal plane and 59.31 in the vertical plane at injection, and 64.31 and 59.32 at top energy [8]. The expected tune variations with betatron amplitude, and via chromaticity (~2 units) and non-linear chromaticity (for a relative momentum deviation of +/- 0.1%), are limited to $+/-7x10^{-3}$ at injection energy [9]. Assuming a peak kick strength corresponding to 0.33 σ (see Table 1) and an excitation $7x10^{-3}$ off in tune, gives a turn by turn time function as depicted in Fig. 5. After about 55 turns the primary collimator is reached at 7 σ. So even if the tune varies (with amplitude!) during the excitation Fig. 5 still describes an upper estimate for the time needed to reach the collimator. If the excitation is closer in tune the linear regime would extend further leading to more rapidly growing oscillations.

At top energy (7 TeV) the effect of the transverse damper is smaller by a factor 15.6 (7 TeV/450 GeV), but collimators will be moved in, to intercept the beam at 6 σ, the beam size being smaller at top energy by a factor four. With the reduced relative kick strength of the damper it would now take ~4 times longer to reach the collimators. Assuming a tune offset similar to injection, part of the beam would no longer reach the collimators as the excitation signal will become out of phase with the built-up oscillation. In this case it is better to switch off the excitation after ~100 turns, and change the frequency or apply a new burst with slightly different frequency a few ms later. In practice one can also optimise the excitation knowing that the beam entering the abort gap will always have a negative momentum offset [5], hence with a positive chromaticity the excitation frequency should always be slightly lower than that corresponding to the nominal tune. In addition the expected tune spread due to non-linearities will be smaller, only +/- 0.0025 at collision energy [9]. Neglecting tune spread by beam-beam effects, which still may effect the beam in the abort gap, the decoherence time at top energy is three times longer than at injection and it may still be possible to clean out all of the beam in a single burst.

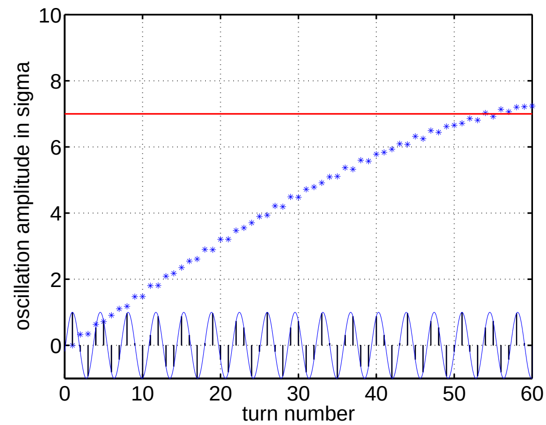

Fig. 5: Normalised excitation signal pulses and resulting betatron oscillation for a tune difference of 0.007: 7 σ (assumed collimator setting) is reached after ~55 turns using a peak kick of ~0.33 σ at injection energy of 450 GeV).

REFERENCES

[1] A. Drees, L. Ahrens, R. Fliller III, D. Gassner, G.T. McIntyre, R. Michnoff, D. Trobojevic, "Abort Gap Cleaning in RHIC", EPAC'02, Paris, p. 1873.

[2] T. Bohl, W. Hofle, T. Linnecar, E. Shaposhnikova, J. Tuckmantel, "Observation of Parasitic Beam and Cleaning with Transverse Damper", AB-Note-2003-021 MD, CERN, Geneva, 2003.

[3] E. Shaposhnikova, "Abort Gap Cleaning and the RF System", LHC Performance Workshop – Chamonix XII, 2003, CERN AB-2003-008, p. 182, Geneva, 2003.

[4] P. Collier, "Baseline Proton Filling Schemes", LHC Project Workshop –Chamonix XIII, CERN-AB-2004-014, p. 30, Geneva, 2004.

[5] E. Shaposhnikova, S. Fartoukh, B. Jeanneret, "LHC Abort Gap Filling by Proton Beam", these Proc.

[6] E. Shaposhnikova, "Longitudinal motion of uncaptured particles in the LHC at 7 TeV", LHC Project Note 338, CERN, Geneva, 2004.

[7] W. Hofle, "Progress with the SPS Damper", LHC Workshop Chamonix XI, 2001, CERN SL-2001-003 DI, 117-124, Geneva, 2001.

[8] The LHC Design Report, CERN-2004-003, vol. I, Geneva, 2004

[9] S. Fartoukh, O. Bruning, "Field Quality Specification for the LHC Main Dipole Magnets", LHC Project Report 501, CERN, Geneva, 2001.