TRANSVERSE DAMPING AND FAST INSTABILITIES

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Abstract

The characteristics of the LHC beams in the SPS, protons and ions, pose stringent requirements on the SPS damper (feedback system). The boundary conditions leading to the specification for the damper system are outlined. The status of the upgrade of the SPS damper in the framework of the SLI project is presented. A review of the MDs conducted in 1996–1998 for the damper summarises the experimental results. An outlook is given for the next stages of the upgrade program and the plans for 1999.

1 THE LHC BEAM IN THE SPS AND THE RESISTIVE WALL INSTABILITY

1.1 *Characteristics of the LHC beams in the SPS and specification for the damper*

The SPS damper combines the functions of a damper and transverse feedback. For the LHC beams in the SPS the system has to undergo a substantial upgrade program [1,2]. The main characteristics of the LHC beams in the SPS are:

- protons
  - 3 batches with gaps of 225 ns injected from PS
  - bunch spacing of 25 ns
  - 81 bunches of each 1×10^{11} protons per injected batch, confined in 1/11 of SPS circumference
- ions (Pb): bunch spacing and gaps between batches are 125 ns.

These characteristics together with assumptions on the injection errors and the beam properties lead to the following specification for the damper:

- a maximum kick strength of 3.4 μrad horizontal (at $\beta = 70$ m) and 7.4 μrad vertical (at $\beta = 55$ m) to stay within the set limits of allowed blow-up at injection
- a 5–95% risetime to full kick of 120 ns in order to cope with the gap between batches
- sufficient gain and a corrected phase over 20 MHz (half the bunch frequency) to provide feedback on all possible coupled bunch dipole modes.

1.2 *The resistive wall instability in the SPS*

Due to its stainless steel vacuum chamber the SPS has a high transverse impedance which gives rise to transverse coupled bunch instabilities (dipole modes) which must be cured by feedback for total intensities above approximately 5×10^{12} protons for the fixed target beam. The present feedback system, designed for this fixed target beam, ensures stability up to 6 MHz, while for higher frequencies Landau damping octupoles are used. For the very small LHC beams the damping effect of the octupoles will be marginal, hence the specification to cover all possible coupled bunch dipole modes with the feedback system.

The impedance of the vacuum chamber is estimated to be $\mathrm{Re}\{Z_{\perp,\mathsf{H}}\} = 120$ MΩ/m in the horizontal plane and $\mathrm{Re}\{Z_{\perp,\mathsf{V}}\} = 200$ MΩ/m in the vertical plane at the first betatron lines at 15–17 kHz [3]. Standard theory gives an instability risetime of horizontally 30 turns and vertically 18 turns for the ultimate LHC beam of 4×10^{13} protons total intensity at the injection energy of 26 GeV/c. However, model calculations with a resistive wall wake suggest that an increase in growth-rate should be observed when a *large* gap is left in the beam [4]. The instabilities that are then observed are batch type with weak coupling across the gap and resemble the beam break-up in linacs (see also [5]). For recent measurements of growth-rates see section 3.2.

1.3 *The maximum kick strength and the filamentation of injection errors*

While the specification of the overall bandwidth and the risetime are straightforward this is *not* the case for the maximum kick strength. The questions to ask are:

- How fast will an injection error convert into an emittance increase?
- How fast will an injection error grow when not damped?

Ultimately answers for the LHC beam will be given by experiments when this beam becomes available for MDs in the SPS with nominal parameters on a regular basis. To fix the maximum kick strength for the damper specification a conservative approach has been taken. The characteristic data are listed in Table 1.

- τ_R: For the instability risetime τ_R we have taken the numbers that standard theory gives for the SPS. There are *two* reasons why these numbers could be different for the injection scenario: *Firstly*, the risetime could be *shorter* because we squeeze the beam into 1/11 of the SPS and it may no longer be the total intensity that counts. *Secondly*, the *initial* risetime of an injection error may be *slower* than the calculations from coupled bunch modes show, for the following reason: The injection process is a *transient* phenomenon. The calculated coupled bunch modes and risetimes only represent a *steady state* solution. When the beam is injected there are no wake fields in the accelerator. For the resistive wall wake with contributions from many turns it will take *several turns* for the wake fields to build up coherently before the instability develops its full force and the risetime approaches its final value. The two described effects have the opposite direction. For this reason we believe that the assumptions for the risetime in Table 1 are reasonable also for the injection scenario.

- τ_F: The filamentation time τ_F quoted in Table 1 has been observed in the Sp$\bar{\text{p}}$S [6]. Although there is some dispute as to the origin of this fast filamentation a conservative design for the damper must assume the fastest filamentation imaginable.

- τ_D: Using a formula from [7] the damping times τ_D given in the Table lead then to the blow-up of 0.25 μm assuming an injection error of $0.8\ \sigma$.

The last columns in the Table show the injection error at the kicker in μrad and the required kick strength per turn.

A faster damping time reduces the blow-up for a given injection error. But it must be kept in mind that the relation is quadratic making it increasingly costly to buy a lower blow-up with damper power up to the point where it is not realistic. Before such an increase in damping power is demanded we need experimental data for the LHC beam for the risetime, the filamentation time and the resulting blow-up we observe for certain injection errors.

Table 1: Parameters for feedback specification

	inj. error	blowup allowed	τ_F	τ_D	τ_R	at kicker: inj. error	at kicker: x' req. μrad
H	0.8 σ	0.25 μm	50	50	30	31 μrad	3.4
V	0.8 σ	0.25 μm	20	20	18	35 μrad	7.4
			turns				

2 STATUS OF THE TRANSVERSE DAMPER UPGRADE

2.1 *Overall system and power amplifier*

There are presently two independent damper systems per plane. These are called H1 and H2 for the horizontal plane, and V3 and V4 for the vertical plane. In Fig. 1 the horizontal system H2, as used for the fixed target proton beam, is shown. A more detailed description can be found in [2]. Note that the Δ signals from the pick-ups used are proportional both to the intensity and the position of the beam. No normalisation is carried out. Consequently the damper gain is proportional to the intensity of the beam. This was intended in the original design of the damper, since the

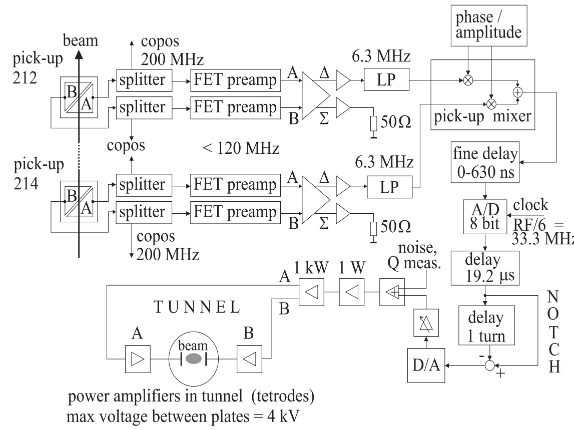

Figure 1: Block diagram of the present damper system (horizontal damper H2) installed in LSS2 [2].

driving force of the instability is also proportional to the intensity and without normalisation the Δ signal automatically maintains the correct feedback gain for stability at all intensities. However, it means that the gain for damping of injection errors of a low intensity beam is somewhat low, and this may have to be changed in future (LHC pilot beam).

To obtain damping the feedback signal has to be applied to the beam with the correct phase. For the phase adjustment the two pick up signals, approximately 90° apart in betatron phase, are multiplied by an adjustable constant and then added. The digital filter clocked at 33 MHz removes the closed orbit part of the signal. All the delays in the loop are adjusted to achieve the correct delay overall between pick-ups and kicker, within the bandwidth of the system.

In the tunnel a power amplifier with two tetrodes installed directly under the vacuum tank, drives the electrostatic deflector plates in push-pull mode (class AB). The 3 dB point and hence the risetime are given by the resistance in the anode circuit and the total capacitance, the largest part of the latter being due to the deflector plates themselves.

Measurements and calculations for the kicker [9] showed that a 20 MHz bandwidth is possible with this system and that little can be done to reduce the parasitic capacitance by improving the kicker design [10].

In order to achieve the desired risetime the power amplifier was completely re-designed. The anode resistance was lowered to 180 Ω to achieve the risetime. With the water cooled resistors it is now possible to completely shield the amplifier which is advised given the increased bandwidth and involved powers. The first prototype uses the tube TH561 from Thomson and a second amplifier, now under construction, uses the RS2048 CJ tube from Siemens. Both tubes can deliver 50-60 % more current than the original tube RS2012 CJ. The change of tube was necessary in order to preserve as much as possible the kick strength when reducing the impedance for the faster risetime. The new design is flexible allowing conversion of the amplifiers from one tube to another with a minimum of work. Construction of the remaining four power amplifiers, including the two spares, will start as soon as possible.

2.2 Infrastructure

The new power amplifiers require new power supplies for which specifications will be drafted in 1999. The water cooling system in the tunnel had to undergo substantial modifications in order to allow the new amplifier with the TH561 tubes to be tested. After testing of a prototype cooling installation for damper H1 in 1998, the conversion of the 3 other circuits will be completed during the present shutdown.

Radiation damaged cables are being changed this year in LSS2. This opportunity is being used to upgrade monitoring cables to low loss cables. It was found last year that these cables limit the bandwidth of observation of the kicker voltage to approximately 1 MHz. The new cables will allow a wide-band observation of the kicker action on the beam. Buffer amplifiers will provide special conditioned signals for the NAOS system in 1999. This system is presently being put in place by the operations group for the monitoring of important analogue signals of the equipment groups.

2.3 Low level electronics in 1998

A fiber optic link was established between the Faraday cage in BA3 and the damper racks in BA2. The 200 MHz RF and a revolution frequency signal are transmitted. These signals are used to locally generate bunch synchronous triggers for observation of the LHC beam. The trigger system was first used in December 1999. A third fiber was used during MDs to transmit important accelerator information from the CATV-network[1].

An active allpass was developed to linearise the phase response of the power amplifier up to 20 MHz. Contrary to the previously used filters with discrete passive elements, the active allpass filter can be more easily adapted to correct deviations from the theoretical one pole roll-off that it is intended to correct.

3 REVIEW OF MDS 1996–1998

3.1 Test of the new power amplifier in 1998

The new power amplifier was first tested with beam in June 1998 during a long MD with the fixed target beam. Fig. 2 shows the damping of an oscillation. In this experiment the beam was kicked with the Q-meter (5mm/2kV). The time base is 0.2 ms/div for the lower traces, 50 μs/div for the upper, expanded traces, and the vertical scale is 2 kV/div. It can clearly be seen that for the new damper H1 (a) the voltage is now limited to ± 3 kV while for the old damper the maximum voltage was ± 4 kV. In the expanded trace we can imagine that the risetime is actually faster for the new amplifier, but a better observation was not possible due to the cable limited bandwidth. The test of the power amplifier was successful, and it was used during two more test periods in August 1998 (during regular Physics) and in December for the LHC beam MD.

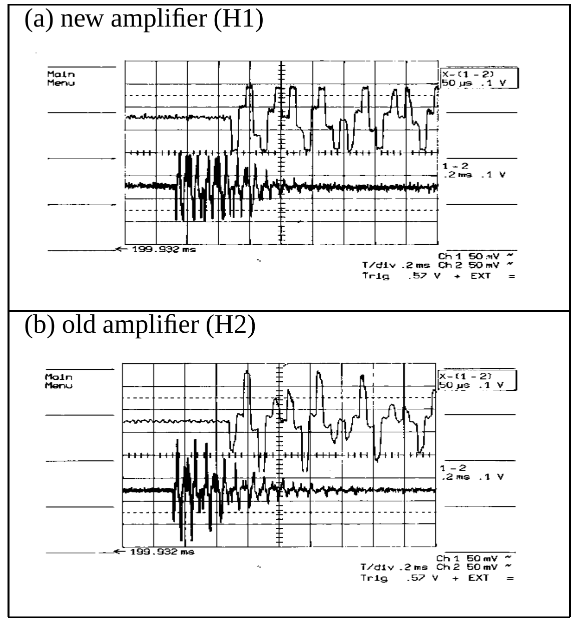

Figure 2: Comparison of new (a) and old (b) power amplifier in the horizontal plane.

3.2 Measurements of instability growth-rates with fractional filling at 14 GeV/c

On two occasions (September and November 1997) it was possible to study the transverse damping and stability of the fixed target proton beam with a bunch spacing of 5 ns and fractional filling of 1/11, 3/11 and 5/11 of the SPS. Detailed results of the September MD can be found in [11]. Fig. 3 shows the spectrum (2 MHz/div) of a transverse pick-up around the bunch frequency of 200 MHz with the horizontal damper on (a) and with the damper off (b) at 1×10^{12} protons total intensity and 1/11 of the SPS filled. At this low intensity the fixed target beam is usually stable without feedback. The picture clearly shows that within its bandwidth the damper suppresses the instabilities while outside the bandwidth (6 MHz) there is “activity” with damper on and off. Together with this spectrum, beam losses and emittance blow-up were observed [11]. Fig. 4 shows the time development of an instability on a single batch of $\simeq 2$ μs (1/11 of SPS). Starting at the end of the batch an instability develops at a frequency outside the damper bandwidth (dampers were on).

The aim of the second MD with these kind of beams in November 1997 was to actually measure growth-rates. This was done by looking with a spectrum analyser at the

[1] Note that BA2 is not connected to the CATV system and ST division only distributes a very limited number of channels to and inside BA2.

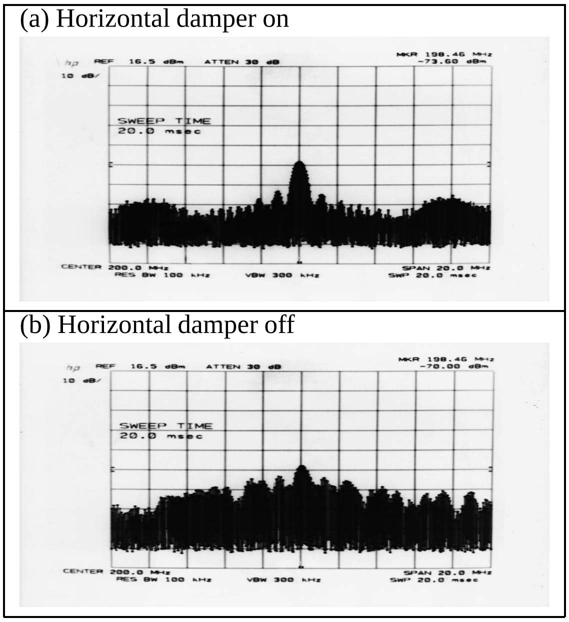

Figure 3: Spectrum of a wide-band transverse pick-up around bunch frequency of 200 MHz (2 MHz/div); 1×10^{12} protons in 1/11 of SPS circumference

time evolution of a single betatron line. Although the experiments were carried out at different frequencies it must be kept in mind that, due to the fractional filling patterns, any coupled bunch mode will appear at any betatron frequency. Hence independent of the line that we look at, we measure a mixture of modes, and in practice the fastest growth-rate. Therefore only the results for a frequency of 239-242 kHz will be presented in the following. This frequency is representative for the fast growing modes, rather independent of the filling pattern.

The horizontal growth-rates are summarised in Fig. 5 for the filling patterns of 1/11, 3/11, and 5/11. The octupoles were reduced to linearise the machine, and the chromaticity was corrected. The damper was switched off at a known instant and then for several ms the growth of the spectral signal was observed before the damper was switched on again in order not to lose the beam. The data clearly show that at 5×10^{12} we are very close to the threshold for the 5/11 filling pattern while for 1/11 and 3/11 the beam is already very unstable. At 1×10^{13} measurements with 1/11 filling were not possible due to the strong instabilities. The data for 3/11 and 5/11 are similar at this intensity which is not in contradiction with the model calculations in [4] where only a small difference between these filling patterns was observed.

Unfortunately no data are available for 1/11 in the vertical plane. Comparing Figs. 5 and 6 it can be seen that, as expected from the difference in impedance, the growth-rates are higher in the vertical plane than in the horizontal plane. Note that an impedance of 100 MΩ/m corresponds to a growth time of 1.85 ms or a growth-rate of 540 1/s at

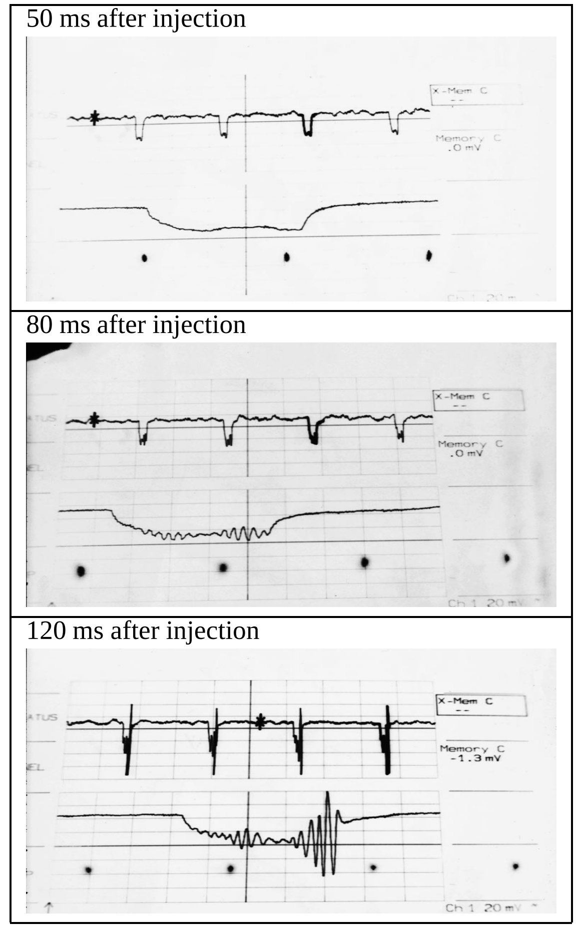

Figure 4: Horizontal instability developing from the end of the batch (scales: 100 μs/div total [upper traces], and 5 μs total for the lower, expanded traces); damper pick-up signals with dampers on, 3×10^{12} protons in 1/11.

14 GeV/c and 1×10^{13} assuming a $\beta_{\text{average}} = 50$ m.

In conclusion, a clear difference between the different filling patterns and a high growth-rate for the 1/11 pattern were observed. However, for a full comparison there is insufficient data, and more measurements should be done with the LHC beam and a different number of batches (1, 2 and 3 batches).

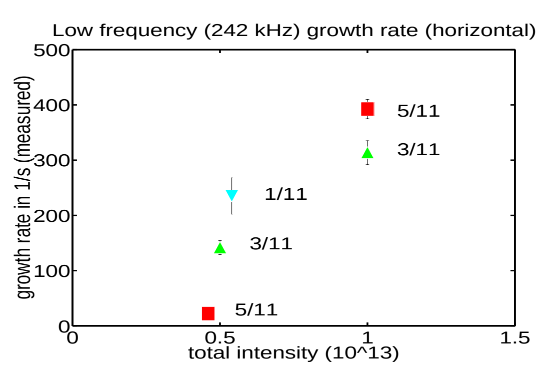

Figure 5: Horizontal growth-rates with fractional filling

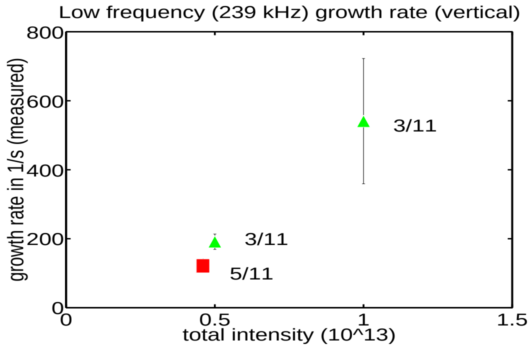

Figure 6: Vertical growth-rates with fractional filling

3.3 Bunch by bunch observation with 105 ns spaced bunches and emittance issues

Initially it was thought that transverse coupled bunch instabilities could be studied with a bunch by bunch BOSC system provided by SL-BI with a limited number of bunches (20 per 1/11 of the SPS) with a spacing of 105 ns, a beam which was available from the PS in 1996 and 1997 for the SPS MD-cycle. Due to the bunch spacing and the very long bunches (20 ns) this beam cannot be captured in the SPS, but we nevertheless thought that useful transverse studies are possible in a short time period following injection where the longitudinal motion could be considered "frozen". Results of the first MD with this kind of beam can be found in [12]. Typical beam parameters were:

- intensity: 1×10^{11} per bunch
- bunch length (4 σ) 25 ns
  longitudinal emittance 0.6 eVs
  $\Delta p/p = \pm 0.6 \times 10^{-3}$
- transverse emittances (TT10):
  $\epsilon_{\mathrm{H}}^{2\sigma} = 0.87\ \mu\mathrm{m} \quad \epsilon_{\mathrm{V}}^{2\sigma} = 0.59\ \mu\mathrm{m}$.

Subsequent MDs focused on understanding a horizontal beam size blow-up observed with this beam. In 1997 after measurements with different wire scanners at different values of dispersion it was clear that in fact the blow-up was a *longitudinal* blow-up increasing the momentum spread. The momentum spread increased 5 to 10-fold during debunching (RF off) in the first 100 ms after injection due to the longitudinal instabilities.

It is now clear that only limited transverse studies are possible with RF off and long bunches. Although most of the data were collected in the horizontal plane to track down the blow-up, the few vertical data on injection oscillations with corrected chromaticity and no octupoles support the fast filamentation observed by L. Vos [6].

3.4 Bunch by bunch observation on the LHC beam

With the arrival of the LHC beam with 25 ns bunch spacing in the SPS it became necessary to have a bunch by bunch observation and synchronous triggering for MD studies as well as for commissioning of new hardware for the damper. The system described in 2.3 will enable us to make bunch by bunch, and turn by turn observations on the LHC beam. The data are collected with a digital oscilloscope (Tektronix 784) and acquired locally by a Labview application running on a portable computer. The oscilloscope allows a re-arming of the trigger every turn of the SPS. A part of the beam can be measured over several turns with a high time resolution (e.g. one LHC batch). Data are acquired by the computer after completion of the data recording by the oscilloscope for the desired number of turns.

First tests of this system were done with the LHC beam at the "end of run" MD in December 1998. Fig. 7 shows as an example the transverse oscillations of 11 bunches from injection up to turn 47 (injection was at turn 4). Horizontal axis is the time within one turn and vertically subsequent turns are plotted. 500 points of data were acquired per turn with a spacing of 1 ns. The 25 ns spaced bunches appear longer than they actually are, because of the low pass characteristic of the pick-up electronics (100 MHz). The picture was taken with dampers off. We can see how, after a calm period of 10–15 turns after injection, the beam becomes unstable, and all bunches oscillate in phase. The gray scale represents the signal value (oscillation amplitude, normalised), where the centre part of the scale has been plotted white in order to make the bunches distinguishable from the background. An FFT of the movement of a bunch would give the tune for this bunch. In 1999 a dedicated oscilloscope will be available for expert use in BA2.

4 CONCLUSIONS

- The new power amplifier works OK with beam.
- The development for the phase compensation up to 20 MHz is well advanced.
- Results from 1,3,5 turn injection MDs: When 1/11 of the SPS is filled this leads to high growth-rates and a very unstable beam.
- The horizontal beam size blow up of long bunches, 105 ns spaced, with RF-off is understood (long. blow-up) and no further studies are required.
- On the LHC beam a bunch by bunch observation is possible with a digitising oscilloscope; the hardware is in place for future MDs.

5 1999 AND BEYOND

In 1999 the work will focus on the LHC beam. The aim is to extend the bandwidth of the damping system as far as possible during the year. The limitation in 1999 will come from the digital filter with its clock frequency of 33 MHz. We hope to raise the bandwidth of one horizontal and one vertical system to 1/3 of this frequency (meaning from the

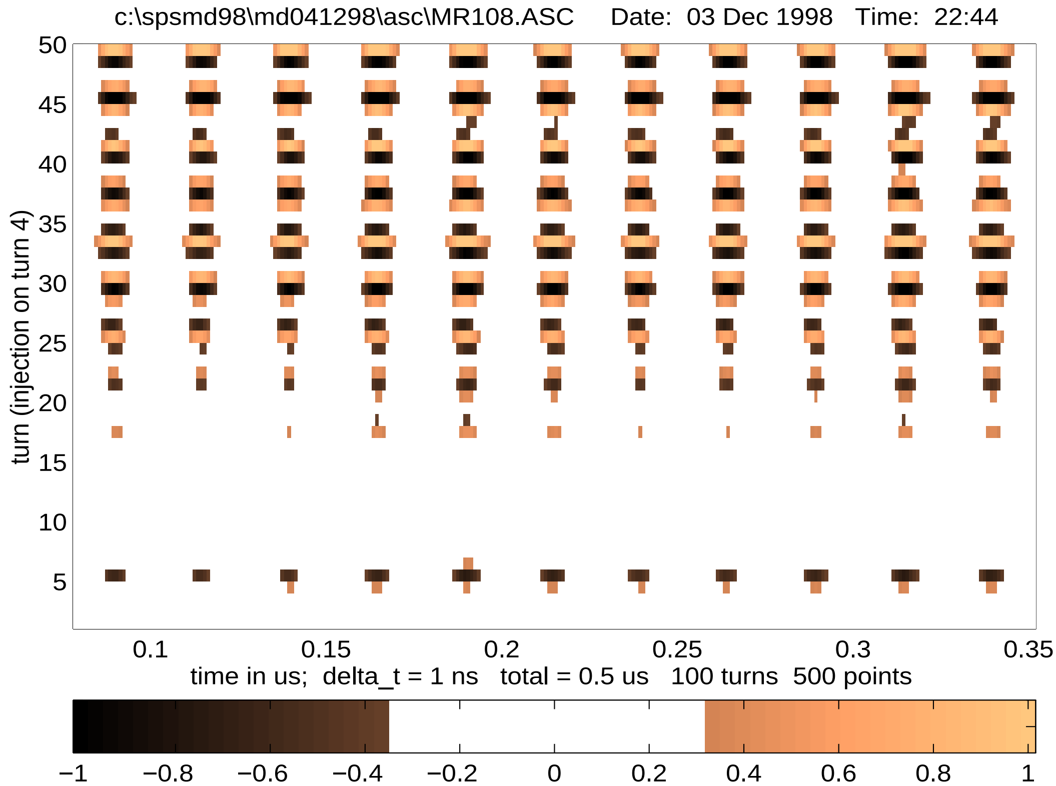

Figure 7: Horizontal oscillations of LHC bunches at injection

present 6 MHz to 11-12 MHz). In the RF group a development for the ADC and the DAC of the new digital filter was started last year. The sampling frequency maximally possible will be 60 MHz at 10 bits. The full bandwidth requires the new digital filter and is planned for the run in the year 2000. The upgrade project is expected to be completed in 2001.

6 ACKNOWLEDGEMENT

The work on the damper as presented, is a team work of many people inside our group and the division. We would like to acknowledge help and collaboration from our colleagues at the PS for providing the different beams for the MD studies, SL-OP, in particular G. Arduini for the help in MDs, SL-BI for help with the BOSC system in MDs, and ST-CV for the joint work on the water cooling system for the power amplifiers.

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