Particle Accelerators, 1997, Vol. 58, pp. 269–279
Reprints available directly from the publisher
Photocopying permitted by license only

TOWARDS A TRANSVERSE FEEDBACK SYSTEM AND DAMPER FOR THE SPS IN THE LHC ERA

WOLFGANG HÖEFLE *

CERN, SL Division, 1211 Geneva 23, Switzerland

(Received 10 January 1997; In final form 3 March 1997)

The SPS will serve as injector for the LHC, accelerating up to 4×10^{13} protons per cycle from 26 to 450 GeV/c. The transverse feedback system (damper) is essential for keeping the transverse emittance blowup within the limits fixed for the LHC injector chain. The fast filamentation requires rapid damping of any injection errors. Injection errors are the combined result of steering errors and ripples on the magnet power supplies in the transfer line as well as from the PS extraction kicker and the SPS injection kicker. Besides damping injection oscillations the damper will also provide transverse feedback to stabilise the beam against the resistive wall coupled bunch instability. The required bandwidth, kick strength and power bandwidth (rise time) were discussed during the 1996 Montreux *Workshop on High Brightness Beams for Large Hadron Colliders* in the working group on *Active Emittance Control*. In the present report the requirements for the damper are summarised and the development of a system to meet these specifications, based on the existing hardware, is described.

Keywords: Proton synchrotron; Transverse feedback; Damper; Injection oscillations

1 INTRODUCTION

The present SPS damper[1] combines the functions of a *damper* (damping injection oscillations) and *feedback* (stabilisation against transverse coupled bunch instability). Today the SPS accelerates a high-intensity proton beam and a low-intensity Pb-ion beam for fixed target physics, and also serves as injector for the LEP electron–positron collider. For all the particle types the damper system may serve to damp the

---

* Tel.: +41 22 767 5175. Fax: +41 22 767 9185. E-mail:Wolfgang.Hoefle@cern.ch.

injection oscillations, while the feedback mode all along the accelerating cycle is only used with the high-intensity proton fixed target beam. This beam is unstable without feedback because of the high resistive wall impedance, which causes a transverse coupled bunch instability in both planes.

In the LHC era, the SPS will serve as injector for LHC and will have to accelerate a large number (243) of dense bunches with up to 1.7×10^{11} protons per bunch. The SPS has successfully operated with a few bunches of this intensity as $p\bar{p}$ collider and for fixed target physics accelerates the same *total intensity* as is required for the LHC beam, on a regular basis. In choosing the LHC beam parameters, both of these achievements of the SPS have been combined. In addition, the LHC beam will be confined to 3/11 of the SPS circumference. Together with the tight emittance budget for the LHC beam this poses challenging problems for the damper system. In particular, a bunch by bunch damper will be needed to stabilise all possible coupled bunch dipole modes. In the following sections the requirements for the damper are summarised, the present damper system is described and prototyping towards a bunch by bunch damper reported.

2 BASIC REQUIREMENTS FOR THE DAMPER WITH THE LHC BEAM IN THE SPS

2.1 Kick Strength

The maximum kick strength required is determined by the injection error, the speed with which this injection error converts into an emittance increase, the allowed emittance blowup, and the rise time of the transverse resistive wall instability. These numbers are still being discussed. The state of knowledge is that the kick strength of the present damper is sufficient, but given the uncertainty of the input parameters there is not much margin. Increasing the kick strength could be achieved by moving the damper into a region with higher β values or by installing more units. It is evident that there is no engineering problem associated with such an upgrade except possibly the restricted space in the SPS.

2.2 Power Bandwidth – Rise Time

A large part of the horizontal injection error will be dynamic, and vary along the injected batch with a frequency of 5–6 MHz. These oscillations on the batch, which are caused by the injection kicker of the SPS and the extraction kicker of the PS, must be damped quickly to keep the emittance within the design limits. The amplitude of this dynamic part of the horizontal injection error is about 50% of the total injection error. Although the PS extraction and the SPS injection is in the horizontal plane and there will be no rotation of planes in the transfer, part of the high-frequency ripple will couple to the vertical plane. Hence a good choice is to fix the 3 dB cut-off frequency for all dampers at 6 MHz. We will call this bandwidth the "power bandwidth".

A second dynamic requirement comes from the gap left between adjacent batches, which will be 220 ns for proton batches, and as small as 125 ns between Pb ion batches injected from the PS[†]. Within this 125 ns the damper voltage has to rise from zero to the maximum voltage to within a certain tolerance. This requires approximately the same power bandwidth as found above, and this is not by coincidence: the ripple frequency of 5–6 MHz of the kickers is characteristic for the rise time of 125 ns that these devices must achieve.

2.3 Total Bandwidth for Bunch by Bunch Operation

A minimum bandwidth of half the bunch frequency is required to stabilise the beam against all possible transverse coupled bunch dipole modes. For the 25 ns spaced bunches of the LHC beam this is 20 MHz. In practice one needs slightly more to accommodate the finite cut off of all the filters and signal processing involved. While the feedback gain may roll off towards 20 MHz, the phase has to be tailored to achieve damping beyond 20 MHz. The principle of "phase correction" by group delay equalisation in the feedback loop is explained in Section 4.4.

[†] The LHC is also designed to accelerate lead ions.

3 THE PRESENT SPS DAMPER

3.1 Principle and Feedback Loop

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 Figure 1 the horizontal system H1, as used for the fixed target proton beam, is shown. There are two pickups per system. These are the standard electrostatic pickups of the SPS installed at one end of all quadrupoles. A passive resonant splitter provides a 200 MHz signal for the orbit measurement and a base band signal for the transverse damper. There are wide band preamplifiers with high input impedance installed in the tunnel close to the pickups. These transform the high internal impedance of the pickup to a lower impedance acceptable for driving the following circuitry. From the two signals of the electrostatic pickup A and B the sum $\Sigma = A + B$ and difference $\Delta = A - B$ signals are generated with operational amplifiers.

The Σ signal is available for observation in the service building on the surface some 150 m away from the pickups. The low-pass filter

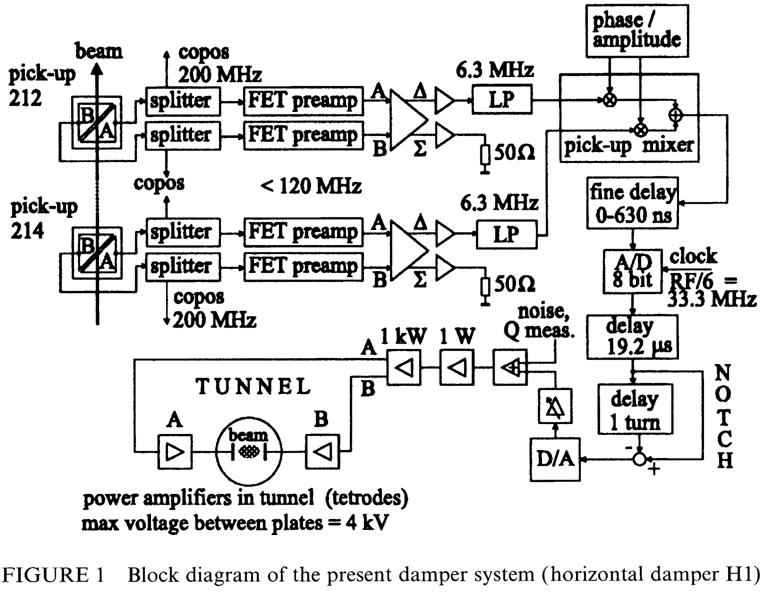

FIGURE 1 Block diagram of the present damper system (horizontal damper H1).

with cut-off at 6.3 MHz limits the Δ signal to the operational band of the damper loop. Note that the Δ signal is proportional both to the intensity and the position of the beam. No normalisation is carried out. Consequently, the damper gain will be proportional to the intensity of the beam. This is intended, since the 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.

To obtain overall damping, the feedback signal has to be applied to the beam with the correct phase. For the phase adjustment the two pickup signals, approximately 90° apart in betatron phase, are multiplied by an adjustable constant and then added. The signal then appears to come from a virtual pickup sitting at the desired betatron phase with respect to the deflector.

Continuing in the feedback loop we have the fine delay which is very important to ensure that we apply the kicks to the correct part of the beam. The signal is then digitised at a sampling rate of exactly 1/6 of the main SPS RF (200 MHz). This 33.3 MHz frequency signal, generated in the main RF control room, changes in frequency during the acceleration of the beam. The total delay in our feedback loop must be 1 turn + the time required for the beam to travel between pickup and deflector. The delay of 19.2 μs in the digital part complements the cable delay, the electronic delay, and the fine delay to make up the total delay required. It should be noted that the 19.2 μs delay changes with the revolution frequency, while all the other delays do *not*. A small delay error is introduced depending on the momentum of the beam. For the present damper this does not pose a problem, but when we extend the bandwidth of the damper system this may become important for the high-frequency components of the feedback signal.

In the digital part of the signal processing a digital notch filter removes the closed orbit contents of the signal (revolution frequency lines in the frequency domain). After the notch filter there is an adjustable gain (attenuation). The driver amplifiers and a gate, where the feedback loop can be opened by a timing signal, follow. There is also a summing point to inject signals for special purposes such as the continuous tune measurement,[2] or to blow up the beam intentionally. There is a 1 kW (50 Ω) transistorised driver amplifier in the surface building.

TABLE I Characteristics of the present damper system (26 GeV/c)

Plane	β	l (length)	d (gap)	Voltage	x'	$f_{\max}$
H	76 m	2.396 m	142 mm	4 kV	2.6 μrad	6.3 MHz
V	45 m	1.536 m	38 mm	4 kV	6.2 μrad	6.3 MHz

In the tunnel a power amplifier with two tetrodes (Siemens RS 2012 CJ), installed directly under the vacuum tank, drives the deflector plates in push–pull mode (class AB). Presently, the supply voltage and the operating point is chosen to give a maximum voltage excursion of + 3 kV, while the voltage of the opposite plate at that instant is −1 kV. The total deflecting voltage seen by the beam is therefore 4 kV. Table I summarises the characteristics of the present damper system. The 3 dB cut-off frequency of 1.3 MHz is given by the RC constant of the anode resistor ($R = 560\,\Omega$) and the total capacity (deflector and parasitic, 210 pF) seen by the tube.

4 TOWARDS AN AMPLIFIER AND DEFLECTOR WITH 20 MHz BANDWIDTH AND 6 MHz POWER BANDWIDTH

The advantage of an electrostatic system operating in the base band is its flexibility: It can be used for any bunching structure, and independent of the direction of the beam. Keeping in mind the history of the SPS as a multiparticle-type accelerator it is wise to preserve these features. The experience gained with this system over the years and the possibility of reusing most of the design and also part of the hardware make it an economic solution, too.

4.1 The Deflectors

The deflectors flat electrodes are 100 mm wide and their spacing and length for the two planes were given in Table I. The electrodes are housed in a tank of diameter 340 mm, and are connected at the centre. Theoretically, the vertical deflector becomes resonant at 98 MHz and the horizontal deflector at 63 MHz (length = 2 × $\lambda/4$). For the vertical deflector the resonance frequency has been measured and found to be slightly smaller than the theoretical value. These resonance frequencies are much higher than the required frequency of 20 MHz for the bunch by bunch operation and thus the deflectors can be reused for the future damper. However, the deflecting field seen by the beam could be increased somewhat by giving the electrodes a different shape. It is worth investigating this possibility for the horizontal deflector where the separation of the electrodes is larger than their width.

4.2 Achieving 20 MHz Bandwidth – Experimental Results

A vertical damper unit with deflector is available in a test stand for measurements. Initial measurements revealed that there are parasitic resonances above 10 MHz which have been found to be caused by the inductances of the connections together with the deflector, the tube and the anode resistor capacitance. The parasitic inductances could be reduced by replacing the wires by closely spaced wide metal strips for the connections inside the tank and for the connections from the feed-throughs to the anodes of the tubes.

For the measurement of the transfer function a network analyser was employed. The source signal was split and the two power amplifiers were driven with opposite phase. High-voltage dividers connected to the ends of the deflector plates provided the signals to the *A* and *B* inputs of the network analyser. The voltage difference between the plates was measured and normalised with a reference signal from the network analyser source. Moreover, the response of the voltage dividers, cables and splitters can be removed by normalising with a reference measurement (voltage dividers connected to the output of the drivers). Figure 2 shows the transfer function measured by the method described up to 60 MHz. It has a smooth roll off, and is resonance free up to 30 MHz.

4.3 Increasing the Power Bandwidth

The 3 dB cut-off frequency

$$f_{3\,\mathrm{dB}} = \frac{1}{2\pi RC} \tag{1}$$

can be increased by reducing the time constant *RC*. The first choice would be to reduce the capacitance *C* seen by the tetrode. However,

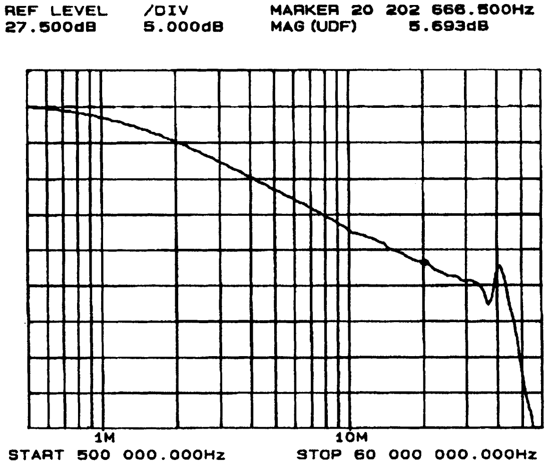

FIGURE 2 Measured transfer function of the power amplifier and vertical deflector.

the transverse dimensions of the deflectors are given by the maximum beam size and cannot be changed. The length of the electrodes could be reduced, but this would also reduce the maximum kick available. The parasitic capacitance (tube, resistors and connections) cannot be further reduced. Hence the only way to reduce the time constant *RC* is to change for a smaller anode resistor. Preliminary estimates suggest that reducing this resistor from 560 to 180 Ω is a good choice. This would increase the 3 dB cut-off frequency to 4 MHz, but we would have to pay for it by a higher current for the same voltage. Tests with such a reduced anode resistor are being prepared.

Another route to achieve a fast response is by compensation. This can be done in the power amplifier or by using a filter in the low-level part of the feedback loop. For the same maximum voltage, a compensated amplifier will draw more (peak) current. It is likely that the final choice is a combination of all the different measures discussed here. The problem can be stated in the following form: What is the optimum anode resistor value and tube operating point for maximum voltage at 6 MHz, when the maximum voltage at high frequency is only required for a short period of time (1 ms). Part of the solution is to modify the input circuit of the power amplifier to allow for the maximum tube current to be supplied.

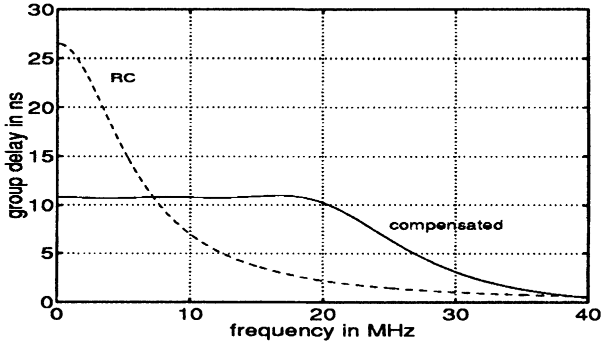

FIGURE 3 Group delay of *RC* model ($f_{3\,\mathrm{dB}} = 6\,\mathrm{MHz}$) and the compensated system (filter plus *RC* model).

4.4 Compensating the Phase Response

For simplicity we assume for the following discussion that our power amplifier transfer function (normalised) is

$$F = \frac{1}{1 + \mathrm{j}\omega RC} \tag{2}$$

and that the 3 dB cut-off is at 6 MHz. The phase at low frequency is 0 (resistive) and approaches −90° at high frequency (capacitive).

Such a transfer function would yield damping of beam oscillations at low frequency but due to the phase lag damping would be lost at high frequencies. It is practically not possible to compensate for a constant phase 0.

However, we can design a filter to *linearise* the phase in the frequency range up to 20 MHz. The group delay of the combined system (power amplifier and filter) will then be constant. Figure 3 shows the group delay of (2) and the equalised delay typically achieved with filtering. The filter changes the frequency response, but the excess gain introduced at high frequency can be removed by a low-pass filter with flat group delay.

5 DAMPER STUDIES WITH BEAM

During the development and commissioning of a *bunch by bunch* damper, tests with beam are very important and in particular a

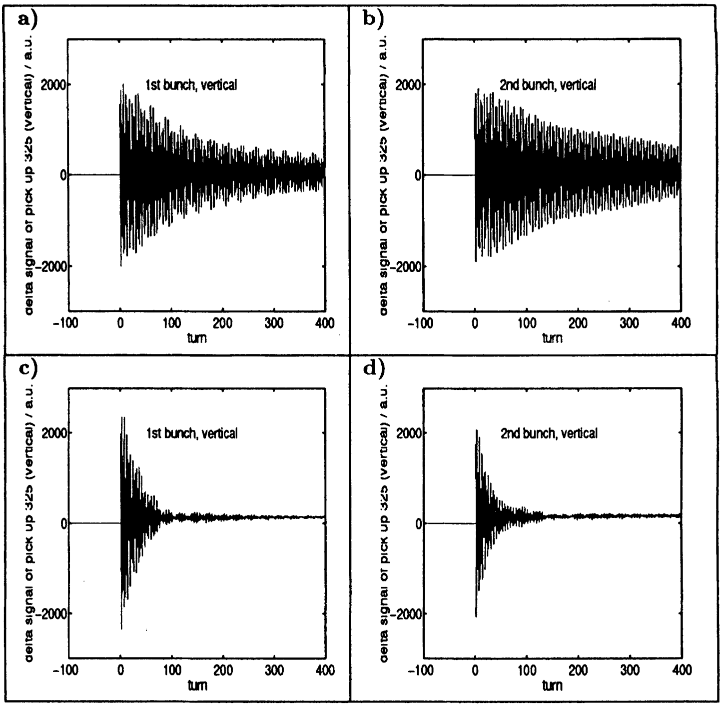

FIGURE 4 Vertical injection oscillations of the first two bunches of a train of 20 bunches, measured turn by turn with damper OFF (top; (a) and (b)) and ON (bottom; (c) and (d)) (1×10^{11} protons per bunch, 4σ bunch length 25 ns, bunch spacing 105 ns, RF OFF).

bunch by bunch observation of the beam oscillations is highly desirable. Injection studies with a bunch spacing of 105 ns and bunch by bunch observation have been performed in 1996 and will continue in 1997.[3] Figure 4 shows as an example the vertical oscillation of the first two bunches *turn by turn* with damper ON and OFF. The studies were done without capturing the beam (no RF) because trains of short bunches with the nominal LHC intensity and correct spacing are not available yet.

6 CONCLUSIONS

The transverse damper (feedback) for the proton LHC beam must cover a bandwidth of more than 20 MHz and the rise time to maximum kick voltage must be fast enough to cope with the gaps between the injected batches as well as the high-frequency component of the injection error caused by the kickers. It has been shown that a 20 MHz bandwidth is feasible with the present system and the way to increasing the power bandwidth has been discussed. It is thought that the requirements can be met by upgrading the present damper system and prototyping work in this direction has started. Studies with beam and the present damper have started as well, and will intensify once the LHC beam with 25 ns bunch spacing and a prototype bunch by bunch damper become available during the next few years.

Acknowledgements

Many thanks to the participants of the working group on *Active emittance control* at the 1996 Montreux *Workshop on High Brightness Beams for Large Hadron Colliders*. Special thanks to the chairman G. Lambertson (LBL) and the working group secretary P. Baudrenghien (CERN). I would like to thank R. Louwerse for the prototyping work and measurements. Thanks to T. Linnecar and L. Vos for discussions and valuable input, and also to W. Sinclair and J. F. Malo for assistance in the measurements.

References

[1] L. Vos, CERN SL/91-40 (BI), CERN, Geneva 1991.
[2] C. Boccard *et al.*, *Proc. 5th EPAC*, 1600–1603, Barcelona 1996.
[3] G. Arduini *et al.*, SL-MD Note 225, CERN, Geneva 1996.