ACTIVE FEEDBACK FOR CURING THE TRANSVERSE RESISTIVE WALL INSTABILITY IN THE SPS

W. Höfle

Abstract

The resistive wall impedance in the SPS causes transverse coupled bunch instabilities, that have to be cured by active feedback. The status of the upgrade program for the feedback system (damper) will be reviewed. Results of machine development sessions of 1999 will be presented with emphasis on the performance with LHC type beam. Plans for the year 2000 run are outlined.

1 INTRODUCTION

The SPS accelerator requires a transverse feedback system to damp injection errors and to provide beam stability. Total intensities above a few 10^{12} protons are unstable. Due to the stainless steel vacuum chamber with its high transverse broadband impedance many coupled bunch dipole modes become unstable and have to be damped with active feedback. Requirements for the LHC beam are more challenging than for the present fixed target physics beam, and an upgrade program was set-up to meet them. A comprehensive summary can be found in [1].

For the upgrade most of the power hardware and practically all the low level hardware has to be rebuilt. At the same time it will only be possible to remove equipment dedicated to leptons after the year 2000 run. The challenge of the upgrade is to do all the work *in situ* on a system that is mandatory for the fixed target program. During the upgrade a high degree of flexibility is required in order to react fast to new situations as they were encountered with the electron cloud phenomenon.

In the following the performance of the damper system with the LHC beam will be reviewed, as well as the status and the plans for the upgrade. The investigations of the electron cloud effect on the damper pick-ups led to some interesting results for the impedance of the electrostatic pick-ups in the SPS and these are presented in section 7.

2 PERFORMANCE OF DAMPER WITH LHC BEAM

2.1 Electron cloud effect

The electron cloud effect on the damper pick-ups, seen with the LHC beam, severely limited the performance of the transverse feedback system during the run 1999 [2]. As far as the damper is concerned the effect is discussed in detail in [3]. The solution adopted for the year 2000 run is presented in section 5.

2.2 Performance with 3 LHC batches

Solenoids around the damper pick-ups provided a temporary remedy for operating the damper in presence of the electron cloud phenomenon. This worked up to an intensity of about 5.5×10^{12} protons per batch of 80 bunches of LHC beam [3]. The performance of the damper with solenoids on is best illustrated by looking at the beam losses along a cycle. Fig. 1 shows the results of a test of the horizontal damper H2 with the vertical damper V4 on. Beam intensities are plotted as a function of time during an LHC cycle with 3 batch injection and acceleration. Two curves are shown, one with damper H2 on, the other with damper H2 off. With damper H2 off about 25 % of the injected beam is lost rapidly after the first injected batch. Of the second injected batch 30 % are lost and slow losses continue. After the third injection losses are due to acceleration.

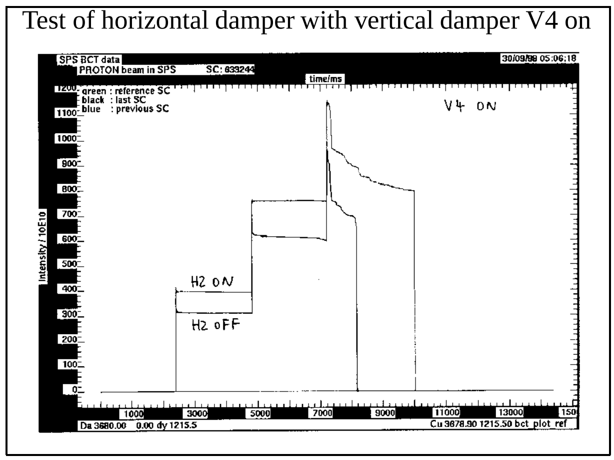

Figure 1: Effect on beam losses of switching off the horizontal damper H2 (vertical damper V4 was left on).

For the vertical damper the situation is shown in Fig. 2. There are practically no losses after the first injection, even with the vertical damper off. After the second injection losses are fast without damper, as well as after the third injection.

In conclusion: Horizontally there are rapid losses at injection, one batch 3×10^{12} is stable, and two batches are (almost) stable, while vertically there are very little or no injection losses, but 4×10^{12} total intensity seems to be an intensity limit, at which the beam becomes unstable without damper.

2.3 Injection kicker spikes

During tests with the LHC beam we often noticed large transverse excursions of the injected beam. These spikes

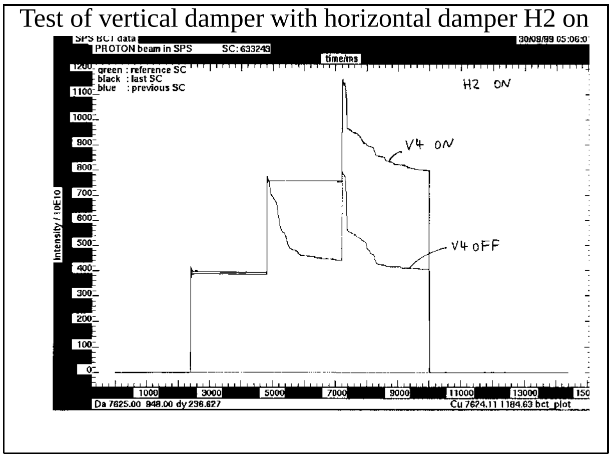

Figure 2: Effect on beam losses of switching off the vertical damper V4 (horizontal damper H2 was left on).

originate from the kicker rise times in the PS and SPS. About 4–6 bunches are incorrectly kicked and some of these end-up in the SPS with large oscillating amplitudes. Fig. 3 shows the Δ-signal of a pick-up with the third LHC

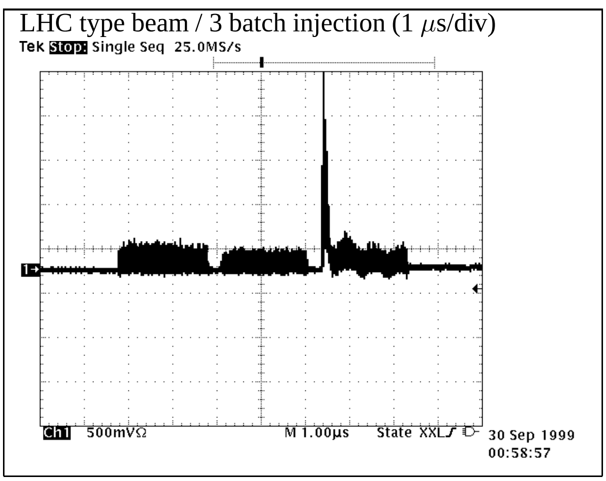

Figure 3: Horizontal Δ-signal of a pick-up with the third injection on the first turn; shows the effect of kicker rise time (spike).

batch being injected. Shown is the first turn after injection with the spike visible. It was observed that the damper struggles to damp the oscillation, and often the oscillation propagates into the batch. Part of this behaviour is due to the limited bandwidth of the damper system which tends to spread out fast spikes during the initial damping phase. In addition transients were observed in the matching transformers of the driver which distort the signals under these conditions. It is expected that this limitation will disappear with new drivers. We also consider gating the signal so that the damper does not act on these 3 bunches which in any case should not be injected. As another approach one would foresee a *feed-forward* that already raises the damper voltage in the beam gap, in preparation of the spike. With the creation of a proper kicker gap in the PS, as foreseen, part of this problem will eventually disappear.

3 STATUS OF DAMPER UPGRADE

3.1 List of hardware

A short list of hardware in development and production is given, with controls and LHC pick-up signal processing being treated in sections 4 and 5. The main hardware developments are:

- power amplifiers
- drivers
- digital filter
- miscellaneous electronics

3.2 Power amplifiers and kickers

During the last year a second upgraded power amplifier (on damper V3) was successfully commissioned and installed in the tunnel. The production of the remaining 4 amplifiers, 2 for the ring, and 2 spares has started. A third amplifier will be ready for the start-up, and the fourth will come early in 2000, pending delivery of the tetrodes. The two spares will also be completed during 2000. The running scenarios with these amplifiers and the available power supplies is discussed in section 6. Presently it is thought that no modifications to the kickers are required for the 20 MHz bandwidth upgrade.

3.3 Drivers and cabling

A driver prototype will be tested in the start-up period and after evaluation with beam a decision on the series production will be made. The required wide-band driver is not available on the market, but is essential in order to use the full bandwidth of the power amplifiers. The upgrade of cables started in the last shutdown 1998/1999, and will be finished this shutdown with the installation of 7/8" low loss cables for the drivers.

3.4 Digital Filter

Another strong limitation for the bandwidth comes from the present 33 MHz, 8 bit digital notch filter that is used to remove the closed orbit offset in the pick-up signals. After initial tests in 1999 with existing 10 bit hardware it was decided — in view of the requirements for the LHC damper — to go directly to a 12 bit solution. An ADC/DAC combination was tested in the lab and in BA2 with real beam signals. The dynamic range was found to be excellent over a large range of clock frequencies [5]. For operation a clock rate of 80 MHz has been chosen, with a comfortable safety margin. The notch filter and the 1-turn delay will be implemented with 12 bits on a single chip [5]. The hardware

(2 systems, horizontal and vertical) are planned to be completed this year.

3.5 Miscellaneous hardware

A number of smaller developments for low level controls have to be completed in order to make the system work up to 20 MHz. The crucial components are the digital filter and the driver described in the two proceeding paragraphs. Set-up of the system requires MD time in 2000 with careful tuning of the phases in the overall feedback loop taking into account all distortions by cables and electronics.

4 PLANS FOR TIMING AND CONTROLS

Future multi-cycling operation requires a new hardware and software for controls. The part of the controls system that directly interfaces with the damper hardware will be developed in the controls section of the SL-LRF group. A first step towards multi-cycling was made in 1999 with the commissioning of a "new" timing system for the damper. This timing system is now compatible with all other SL-HRF timing hardware of the SPS. The software to be used allows a high degree of flexibility, but being rather a specialist tool, must be complemented by an applications software suitable for standard operation from the control room.

During the workshop it was emphasised that in the future a better control of the damper parameters is required. This is in particular true for the loop gain. For multi-batch injection the gain should be switched between different injections. Presently this is not possible. The gain control is a typical example of a "real time" controls application. We will distinguish three *very* different cases:

- **modulation at the revolution frequency:** This might be required to stabilise short 2 μs batches with the transverse feedback system. After having observed that the tail of bunch trains starts to become unstable before the head, MDs are recommended to see whether increasing the gain along the batch can help to cure this type of instability. Moreover, to profit from the fast rise- and fall time of the damper system after the upgrade one might have to "fill in" information into the beam gaps. It will be investigated to what extent this could be incorporated digitally in a special filter. All these types of modulations are *"at the revolution frequency"* and have to be built into the hardware, maybe with some parameters being controlled online.

- **changing parameters continuously over the cycle:** For changing parameters *continuously* during the cycle at a ms rate, the ROCS system is the right hard- and software choice. 2 channels are already used for the damper system to program the excitation of the continuous Q system along a cycle. Four more channels have been requested for the damper control. These could be used to tune the gain along a cycle. After MDs it will be decided in which form this will be made an operational tool.

- **step-wise change of parameters in a cycle:** The third case of controls is to change parameters a few times per cycle, or on a cycle to cycle basis. Here a multi-cycling compatible hardware is being developed in SL-LRF [6]. Fig. 4 shows a sketch of the system that will be tested in 2000. Data transmission from the damper ECA ("*E*quipment *C*ontrol *A*ssembly") to the equipment crates is via a serial link. Data can be loaded into user modules synchronously with the ms clock. Dead time between loading is < 0.4 ms. A prototype set-up was tested in the lab. The new ECA will replace the existing controls during the year 2000 run. High level application software must be developed to make it a user friendly system.

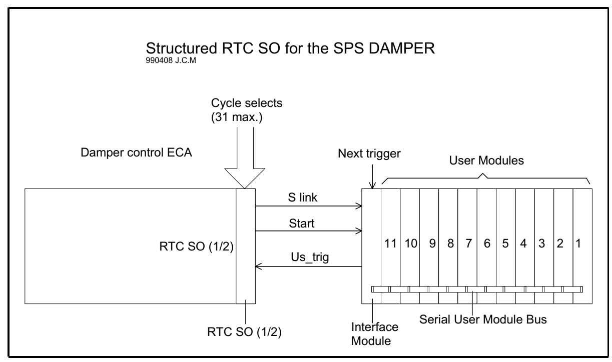

Figure 4: Real time control for damper [6].

5 NEW PICK-UP ELECTRONICS FOR LHC BEAM

To cope with the electron cloud effect new pick-up electronics is required for the LHC type beam with 25 ns bunch spacing [3]. To this end, a set of pick-ups, horizontally PU 2.04 and 2.06, and vertically PU 2.05 and 2.07 will be shared with the MOPOS system. Fig. 5 shows a sketch of the LHC-beam front-end for the damper. Wide band hybrids installed in the tunnel will be used to generate sum and difference signals from the two pick-up plates. The pick-ups must be matched to 50 Ω for both frequency bands, at 200 MHz for the MOPOS system and at 120 MHz for the LHC damper front-end. Hybrids on the surface will split the signal. The Δ-signal will be band-pass filtered at 120 MHz (± 20 MHz) and mixed with an RF-reference at 120 MHz, derived from the beam synchronous 200 MHz generated in the Faraday Cage in BA3. During acceleration the 200 MHz reference changes frequency and due to the signal delay from BA3 to BA2 (the damper location) there will be a phase slip. This phase slip converts into an amplitude modulation after mixing. It is planned to compensate for the dephasing by a phase shifter on the 200 MHz signal sent from the Faraday Cage, driven by the SPS frequency program.

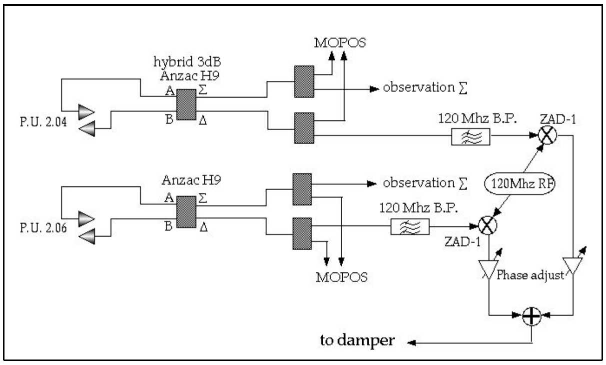

Figure 5: LHC-beam front-end electronics planned for year 2000 run.

6 YEAR 2000 RUN

Following questions at the workshop the start-up strategy with new hardware will be outlined.

- **Power amplifiers and power supplies:** Initially, dampers H1 and H2 will run on separate power supplies, and damper V3 and V4 will run on a common supply. Damper H1 and the damper pair V3 and V4 will be operated with the "old software", while damper H2 will be controlled from the start-up by a new ECA and new software. After delivery of new power supplies all dampers will run on separate power supplies controlled by the new ECA and new software. Dampers H1 and H2 will be equipped with amplifiers with TH561 tubes which are slightly more powerful than the alternative tube RS2048 CJ. Damper V3 will run with a RS2048 CJ tetrode, and V4 for the start-up with an old amplifier, pending supply of new tetrodes. The default running configuration is then with dampers H1, H2, and V3. In the vertical plane one damper should be sufficient, V4 acting as hot spare (disabled by timing). Tripping of a horizontal damper might cause instability problems at injection, limiting the beam intensity.
- **Cables and LHC front-end:** The loop delay must be adjusted very well, and cable delays from the new pick-ups for the LHC front-end must be adjusted. Most of the work can be done during the start-up using the positron beam. Some commissioning time with a high intensity proton beam, including the LHC type beam is required.
- **Driver:** A new driver with more bandwidth will be tested on damper H1. A decision about the series production can be made only after these tests.
- **Digital filter:** The new digital filter will be commissioned during start-up, but may require set-up time with a cycling magnetic field on the p^{+1} cycle, and test beam on this cycle.

7 IMPEDANCE OF ELECTROSTATIC PICK-UPS

During the search for the cause of the disturbed signals on the damper pick-ups with LHC beam, RF multi-pacting in the pick-up was considered a possible cause. A series of measurements on a horizontal electrostatic pick-up were performed. In the set-up the bellows and a cavity like structure similarly to the vacuum pumping ports were shielded. A bar was placed inside the pick-up to simulate the beam excitation. The bar diameter was adjusted for a line impedance (formed by the bar and the rectangular chamber) of 50 Ω. The quality of the adaptation to the networkanalyzer port cables was checked with a reflectometer. It was 50 Ω within a few Ohms, despite the fact that no special transition pieces were used. However, due to the vertical end plates in the set-up, standing waves were observed, but these could be clearly identified in a reference measurement.

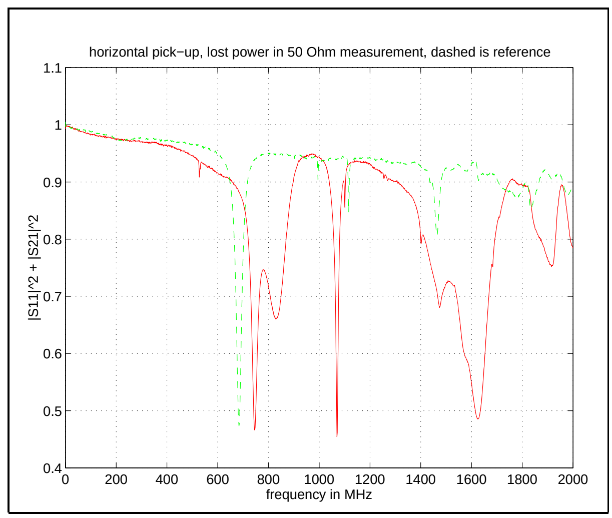

Figure 6: Raw data of impedance measurement. Shown is a measure of the power lost in the set-up, pick-up measurement (solid line) and reference measurement with shielded pick-up slots (dashed).

Fig. 6 shows the raw data of a measurement. S_{11} is the reflected wave amplitude and S_{21} the transmitted wave amplitude through the pick-up with the 50 Ω bar in place. The plotted quantity $\eta = |S_{11}|^2 + |S_{21}|^2$ is a measure of the power not lost in the structure, i.e. $1 - \eta$ is the fraction of power dissipated in the set-up. The dashed line is a reference measurement, where the 2 mm wide slots surrounding the triangular pick-up electrodes were closed with conducting tape. It is evident that the resonances at 1060 MHz and at higher frequencies which *do not* appear in the reference measurements must be due to the electrodes and their coupling to the coaxial volume screened in the reference measurement. Those peaks that also appear in the reference measurement are due to standing waves in the set-up, and do not represent an impedance seen by the beam. They can be clearly distinguished from the peaks representing beam impedance.

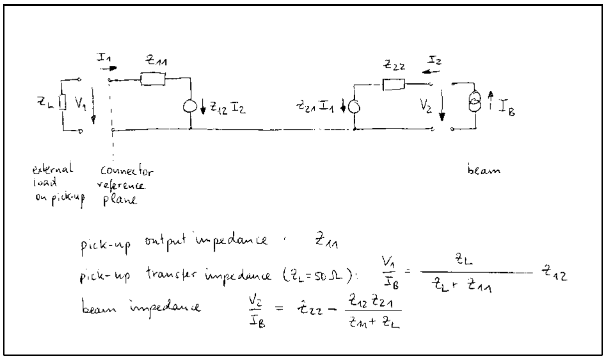

Figure 7: Equivalent circuit of pick-up.

The pick-up can be modelled using an impedance matrix $[Z]$ as used in network theory. Fig. 7 shows the equivalent circuit with beam current I_B, the reference plane of the connector, and an external loading Z_L. The other electrode is assumed to be loaded with $50\ \Omega$ in this model. Z_{11} is the output impedance of the pick-up, Z_{12} the *open circuit* transfer impedance and Z_{22} a beam impedance, for the case that the pick-up is *not* terminated. The beam impedance *with* termination is given by the equation in Fig. 7 and depends on all elements of the impedance matrix $[Z]$ *and* the external loading Z_L. Also given in the Figure is the equation defining the usual transfer impedance referenced to $50\ \Omega$ loading. The elements of the impedance matrix

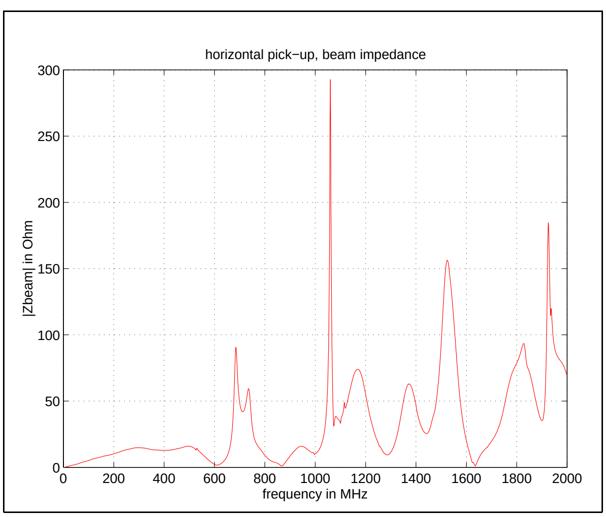

Figure 8: Impedance of horizontal electrostatic SPS pick-up calculated from S-parameters.

were calculated from the S-parameters. Z_{11} and Z_{12} are in good agreement with the known characteristics of the pick-up (58 pF at low frequency, and $j9\ \Omega$ at 200 MHz for Z_{11} and about $4\ \Omega$ for Z_{12}). The beam impedance includes an additive $50\ \Omega$ from the line impedance of the set-up. After subtracting $50\ \Omega$ we are left with an absolute value of the beam impedance for the pick-up as plotted in Fig. 8. We recognise a sharp peak at 1060 MHz, and additional peaks at 1525 MHz and at 1925 MHz. The peaks around 700 MHz and some of the background are due to standing waves in the imperfect measurement set-up. From the 1060 MHz resonance we estimate an R/Q of this resonance of $1.25\ \Omega$. Assuming 5 such resonances (higher frequencies) gives an estimated $Z/n = 0.3\ \mathrm{m}\Omega$ *per* pick-up. Assuming that vertical and horizontal pick-ups are similar, the total contribution of the more than 216 pick-ups is estimated at $Z/n = 0.06\ \Omega$. This is ten times more than the value quoted in [7]. Still it is a small value when compared with the total Z/n of the SPS machine.

In summary, the pick-ups do not have a dramatically high Z/n, however, they exhibit resonances at higher frequencies. This should be followed-up by more accurate measurements, and compared with results from beam spectral scans.

8 CONCLUSIONS

For the LHC beam the damper system is essential for stabilising the beam. The upgrade program is advancing and difficulties encountered with the LHC beam in the 1999 run due to the electron cloud effect are expected to be overcome in 2000. For the bandwidth upgrade to 20 MHz many new hardware components will be commissioned in 2000, requiring MD time. Measurements on the SPS electrostatic pick-ups revealed some resonances which should be examined more detailed. However, the impedance contribution to Z/n was found to be small, in agreement with previous assumptions.

9 ACKNOWLEDGEMENTS

For the hardware developments many people have contributed from the SL-HRF group, beam control section, and the SL-LRF group, digital control/software section. Their contributions are acknowledged. For valuable input and discussions I would like to thank T. Linnecar, and J. Tückmantel.

10 REFERENCES

[1] W. Höfle, Proceedings of the Workshop on LEP-SPS performance — Chamonix IX, Chamonix, 1999, 86–91.

[2] T. Linnecar, Presentation 1.5, these Proceedings.

[3] W. Höfle, Presentation 4.2, these Proceedings.

[4] P. Collier (Ed.), CERN SL-97-007 (DI), 1997.

[5] V. Rossi, private communication.

[6] J. Molendijk, private communication.

[7] L. Vos, CERN SPS/86-21 (MS), 1986.