CHAPTER 14

THE SPS DAMPER

14.1 RE-ENGINEERING THE SPS DAMPER FOR THE LHC BEAM

The SPS transverse feedback system, also called the "transverse damper" combines three principal functions:

- damping of transverse injection errors
- feedback: curing transverse coupled bunch instabilities (dipole modes)
- excitation of transverse oscillations for beam measurements, see for example [7,15]

Since its inception in the late 1970's the SPS transverse feedback system [1] has undergone several major upgrades to cope with the increasing beam intensity and different beams [2,4,5]. In the framework of the project for the upgrade of the SPS as LHC injector [6,8,9,11], the transverse damper system has again been upgraded and re-engineered.

14.1.1 SPS Damper in 1996

In 1996 the SPS damper consisted of four electrostatic kickers, two per plane, with power amplifiers employing two tetrodes and installed directly under the kickers. All four kickers were installed in the dispersion suppressor left of LSS2 in a half period with missing MBA dipoles. The bandwidth of the system was about 6 MHz in feedback mode, with a 3 dB point at around 1.5 MHz and a maximum kick voltage of +/- 4 kV. With the fixed target beam at a bunch spacing of 5 ns, higher frequency coupled bunch dipole modes were cured by octupoles [4]. Digital signal processing was employed with a notch filter and a 1-turn delay, the hardware to perform the signal processing dating from the 1980's, and was clocked at 33 MHz [3].

14.1.2 Goals of the Upgrade for the LHC Beam

The aim of the upgrade, which was started in 1997, was to increase the total bandwidth of the feedback system to 20 MHz, half the LHC bunch frequency of 40 MHz. This was necessary in order to provide feedback for all possible coupled bunch dipole modes of the LHC beam with 25 ns bunch spacing. Moreover, the 3 dB bandwidth needed to be increased in order to achieve a rise-time compatible with the gap of eight missing bunches between the individual batches injected from the PS accelerator into the SPS. An increase of this 3 dB frequency from 1.5 MHz to 4.5 MHz was achieved by lowering the impedance (anode resistance) and rebuilding the power amplifiers with a more powerful tube giving a higher peak current. The higher current is needed in order to change the voltage on the kicker plates in the short time of 225 ns between the injected batches. As part of the upgrade all the electronics, the 100 W driver amplifiers and the power amplifiers were rebuilt, the infrastructure was upgraded, new power converters procured and software and controls re-engineered in a way that is compatible with the general SPS RF controls system. Fig. 14.1 shows the SPS tunnel with the horizontal damper H1, (BDH214.37). The kicker tank can be seen with the power amplifier installed below.

14.2 HARDWARE PARAMETERS AND ELEMENTS OF THE TRANSVERSE DAMPER

Fig. 14.2 shows a block diagram of the two vertical systems after the upgrade. The system V2 was moved in the shutdown 2000/2001 from the original position upstream of LSS2 to a new position downstream of LSS2. This position change was required in order to cure an instability that develops when too much feedback gain is applied at tunes close to the integer, or half integer (see Sec. 14.4). The horizontal systems H1 and H2 were left in place upstream of LSS2. Tab. 14.1 shows the optics parameters for the four systems. The global performance at 26 GeV/c (the injection momentum of the LHC beam) is given in Tab. 14.2. The horizontal systems use amplifiers with TH561 tetrodes, the vertical system uses RS2048 CJ tetrodes which have a lower performance. The requirements for the feedback system are summarised in Chap. 15. In the following, the design and implementation of the individual building blocks of the damper system are described.

Figure 14.1: The SPS damper H1 (BDH214.37) with its power amplifier installed below the kicker tank.

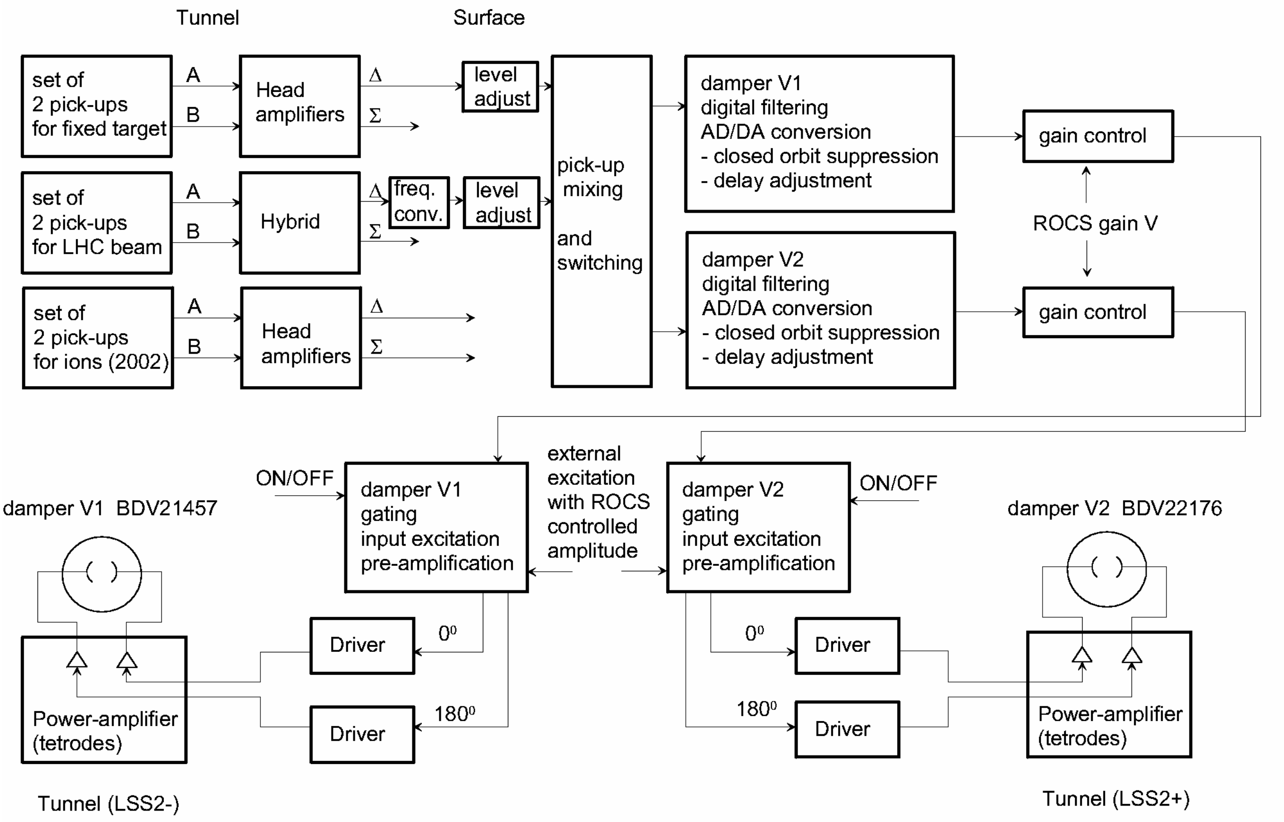


Figure 14.2: Block diagram of the two vertical damper systems V1 (BDV214.57) and V2 (BDV221.76).

Both the kickers and their associated power amplifiers are installed in the accelerator tunnel. The rest of the feedback system, including the 100 W driver amplifiers and all HV power converters, interlocks and control electronics is installed on the surface. The low-level part of the feedback system consists of front end signal processing for the pickup signals (different schemes and pickups are used for the large variety of beams). This is followed by a digital part working at a clock frequency of 80 MHz [16] and finally an amplification system. Feedback gain can be adjusted before and after the digital processing in order to make best use of the dynamic range available from the 12-bit ADC. A summing point is provided at the end of the low-level part which is used operationally in order to inject signals onto the damper. This facility is used principally for continuous tune measurements. In addition, use has been made of injected signals during machine development sessions for controlled beam blow-up. The damper signals are clipped and amplified before being sent to the power part of the equipment.

Table 14.1: Optics parameters and machine position of damper systems

System	Name in layout (position)	Beta function [m]
H1	BDH 214.37	77
H2	BDH 214.51	67
V1	BDV 214.55	39
V2	BDV 221.76	45

Table 14.2: Hardware performance of SPS damper systems:

Plane	number of systems	length mm	gap mm	voltage kV	kick strength µrad per system (at 26 GeV/c)
H	2	2396	142	2.9	1.9
V	2	1536	38	2.7	4.2

14.2.1 Kickers and Power Amplifiers

The electrostatic kickers represent a small capacitive load at low frequency to the power amplifiers. At higher frequencies, towards 20 MHz, a detailed analysis has to take into account the transmission line properties of the structure [10]. The connection to the power amplifier is made in the centre of the kicker. The vertical kicker has its $\lambda/4$ resonance frequency at about 100 MHz, while for the horizontal kicker the equivalent resonance is at 60 MHz. Both these are sufficiently far from the maximum operating frequency of 20 MHz to not pose any serious problems. The 3 dB roll-off frequency of 4.5 MHz is determined by the total capacitive loading and the anode resistance [10]. Between the low frequency and high frequency domains the RC roll-off introduces a phase lag of $\pi/2$. At the 3 dB frequency the phase lag is $\pi/4$. This phase lag is compensated by two second order all-pass filters in the low level part of the feedback loop. This introduces an additional frequency dependent phase shift, such that the total phase lag is linear with frequency up to 20 MHz. This linear phase shift corresponds to a constant group delay which can be absorbed into the overall 1-turn delay of the system. The total transfer function of power amplifier and compensating all-pass filters can be expressed as ($s=j\omega$):

$$F(s) = \frac{1}{1+\tau \cdot s} \cdot \frac{s^2 - \frac{\omega_1}{Q_1} s + \omega_1^2}{s^2 + \frac{\omega_1}{Q_1} s + \omega_1^2} \cdot \frac{s^2 - \frac{\omega_2}{Q_2} s + \omega_2^2}{s^2 + \frac{\omega_2}{Q_2} s + \omega_2^2}$$

with τ = 35.4 ns, Q_1=1.840, Q_2=0.874, $\omega_1/(2\pi)$ = 20.853 MHz, and $\omega_2/(2\pi)$ = 11.511 MHz.

In theory the phase of the overall transfer function deviates less than 2° from the linear case (= constant group delay) up to 25 MHz. In practice, with the analogue active filters used, a non linearity of better than 5°

has been achieved with a gain flatness of the all-pass part of +/- 0.4 dB. In the future it is envisaged to improve the phase compensation further by incorporating it in the digital part of the feedback loop.

14.3 PEFORMANCE WITH LHC BEAM

14.3.1 Injection Damping

The performance of the injection damping is illustrated in Fig. 14.3. It shows the horizontal (upper trace) and the vertical damping (lower trace) for an LHC batch of nominal intensity. The damping time is approximately 0.5 ms. Operation at and beyond the electron cloud instability threshold requires careful monitoring and setting up of the damper.

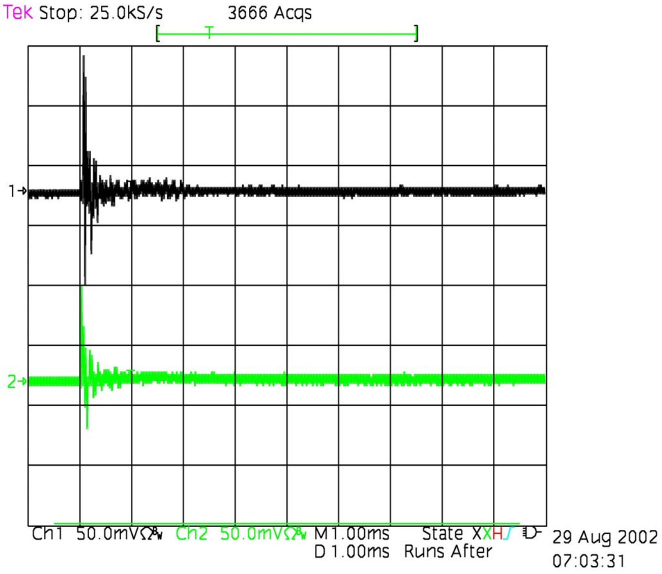
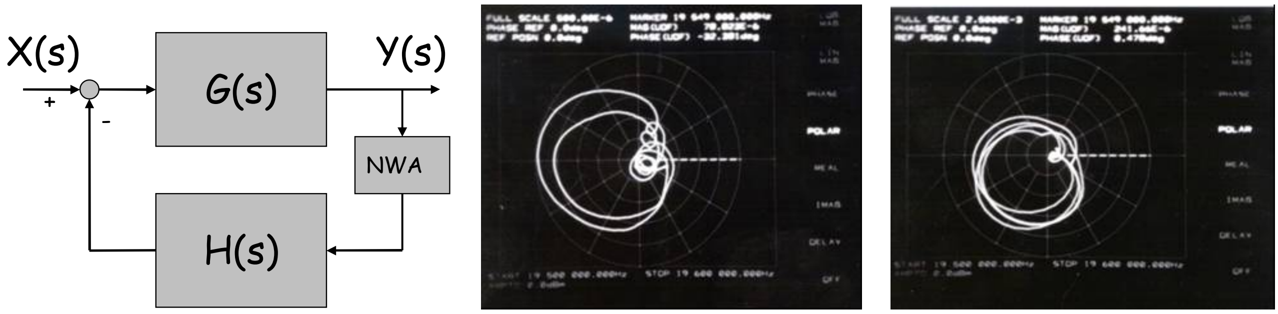


Figure 14.3: Horizontal (upper trace) and Vertical (lower trace) injection damping for the LHC type beam with 72 bunches at 10^{11} protons per bunch

14.3.2 Stability

Stability and damping for individual betatron lines can be checked at low frequency where the beam is stable without feedback, by inserting a network analyzer in the feedback path as shown in Fig. 14.4. The polar plots show a measurement of the open loop transfer function of beam and feedback system for the horizontal system H1 and the vertical system V1. The measurement is usually done at different frequencies to verify and adjust feedback phase and the overall “one-turn” delay in the loop. The circles in the polar plot represent the combined open loop transfer function of beam G(s) and feedback H(s); orientation of G(s)H(s) towards the negative half plane indicates stability of the closed loop transfer function (for betatron lines at 20 MHz in this example).



horizontal G(s)H(s) @ 20 MHz vertical G(s)H(s) @ 20 MHz

Figure 4: Results of beam transfer function measurement with feedback.

14.4 UNFORESEEN ELEMENTS DURING THE UPGRADE AND FUTURE EVOLUTION

14.4.1 The Electron Cloud Effect

The two principal consequences of the electron cloud effect and instability for the transverse damper systems and its upgrade were:

- The signals from the standard electrostatic pickups with high impedance electronics were disturbed and a new system with synchronous detection had to be put into place [12].
- There was an increase in the growth rates of horizontal coupled bunch instabilities and consequently the strength of the horizontal feedback systems may limit the damper performance with ultimate intensity.

The electron cloud effect and its cures are described in more detail in Chap. 15.6. In between the passage of two bunches, electrons, transversely accelerated by the electric fields of the passing bunches, will hit the chamber wall and the pick-up plates. Since the bunches are relatively short (<5 ns at injection, <2 ns at top energy) the beam spectrum extends to high frequencies, well beyond 200 MHz. The electrons of the electron cloud have a large energy spread and will hit the chamber wall during a time slot considerably longer than a bunch (>5 ns), but still shorter than the 25 ns bunch spacing. The spectrum of the electron cloud signal will therefore cut-off at a lower frequency than the true beam signal.

With the original wide band, high impedance pick-up electronics both the electron cloud signal from impinging electrons and the beam signal were measured. As a result of the high impedance loading of the pick-up, a quasi static signal persisted after the passage of a bunch and the electrons of the cloud. This signal seriously perturbed the feedback system to the extent that damping was impossible. The solution for the damper has been to move the processing to a higher multiple of the 40 MHz bunch frequency, allowing the pick-up to be matched to 50 Ω. In this case, electrons hitting the pick-up are quickly removed and therefore no longer accumulate on the pick-up electrodes. The damper shares the four pickups (BPH 204.09, BPH 206.09, BPV 205.09 and BPV 207.05) with the SPS closed orbit system and a compatible solution had to be found. A frequency band at 120 MHz, i.e. three times the bunch frequency of 40 MHz, was chosen for the processing. This frequency is high enough in order not to be disturbed too much by the electron cloud effect. On the other hand, 120 MHz is reasonably close to the 200 MHz working frequency of the SPS orbit system.

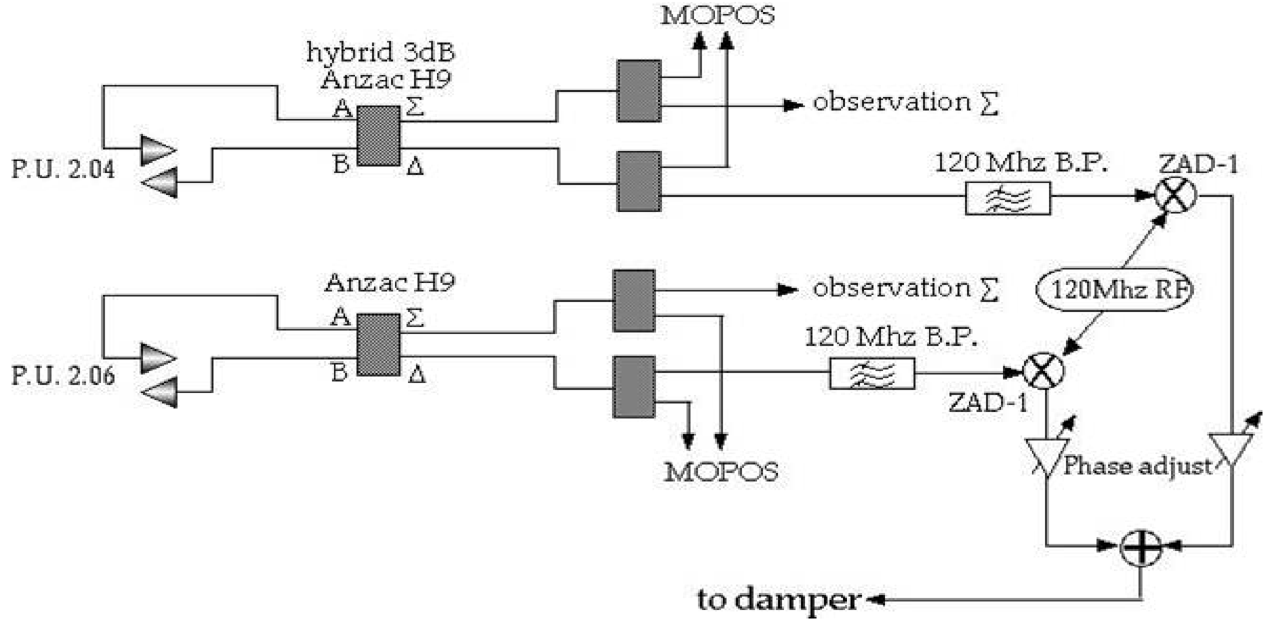
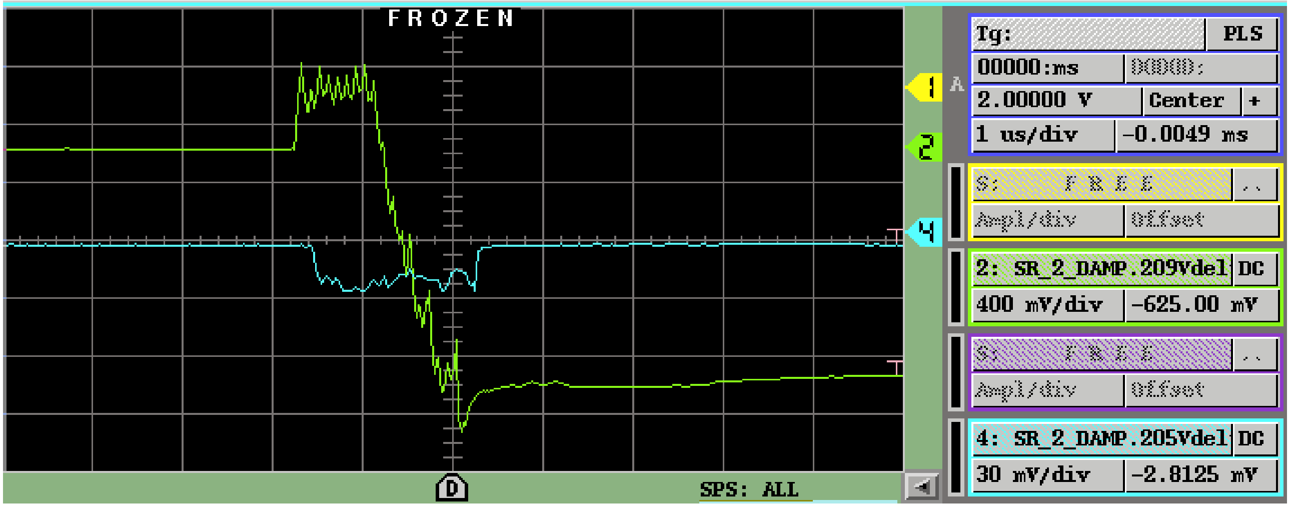


Figure 14.5: Principle of pick-up signal processing at 120 MHz (horizontal dampers). The betatron phase adjustment is done by combing the two orthogonal signals from pickups 2.04 and 2.06 with correct ratio and sign [13].

Pickups are matched to 50 Ω by a wide band matching circuit, covering the range 40-240 MHz. The sum and difference signal are produced by hybrids. Fig. 14.5 shows the principle layout of the system that was used during the run during 2000 and with which the adverse effects of the electron cloud were overcome. Mixing was done with the 120 MHz frequency derived from the main 200 MHz RF frequency together with the revolution frequency. These reference signals are transmitted from the RF Faraday cage in BA3 to the damper installation in BA2, a distance of more than 1 km. Because of the distance, the phase of the 200 MHz signal shifts during acceleration. This effect is compensated by a phase shifter driven by the frequency program of the SPS.

Fig. 14.6 shows a pickup signal perturbed by the electron cloud (trace 2). This signal was produced using the high impedance electronics and base-band processing. For comparison an unperturbed signal (trace 4) is also shown. This was mixed down from 120 MHz. Both signals were taken with an LHC batch of 72 nominal intensity bunches [12].



Tg: PLS
00000:ms
2.00000 V Center +
1 us/div -0.0049 ms
2: SR_2_DAMP.209Vdel DC
400 mV/div -625.00 mV
4: SR_2_DAMP.205Vdel DC
30 mV/div -2.8125 mV

Figure 14.6: Pickup signals: Trace 2 -perturbed by the electron cloud effect and Trace 4 - unperturbed.

The present solution does not completely suppress the effect of the electron cloud. Depending on the beam parameters this could become significant in the future, especially in the case of very short bunches and high intensities. If the energy spread of the electron cloud impinging on the pickup becomes smaller, the pulse generated in the pickup will be shorter and hence influence more the signal at the pickup processing frequency of 120 MHz. If this should become a problem in the future, it may be necessary to move the processing away from the 120 MHz sideband, to a higher multiple of 40 MHz. This is likely to be incompatible with the current sharing of the pick-ups between beam orbit observation and the transverse damper. Separate pick-ups would therefore be needed. This would require installation of dedicated pick-ups, which is not planned at present. An alternative is under investigation. This makes use of a Hilbert filter and a single pick-up (such as the existing couplers BPCR 214.34, and BPCR 214.35) for the phase adjustment. The Hilbert filter has already been tested successfully with beam [16,17]. In addition, the smaller diameter of the BPCR pick-ups would make it easier to apply an external magnetic solenoid field which can completely suppress the electron cloud effect.

14.4.2 Instability at Half Integer and Integer Tunes

With very high gains it can be shown that the feedback system becomes unstable when the tune approaches a half integer or integer value [14]. This occurred in the vertical plane where the standard tune in the SPS has been 26.58. The problem can be cured by installing the two damper systems at different betatron phases, the optimum being at orthogonal positions (π/2 phase shift in between the two systems). In practice after the relocation during the 2000-2001 shutdown there is a phase advance of about 60° between the two vertical systems. In the meantime the working point for the LHC beam has also changed which would have in any case cured the feedback instability. However, for fixed-target beam operation the original working point is still used and this justifies the modifications made.

14.4.3 Future Evolution and Use of the Damper within the Framework of the I-LHC Project

Currently there are no further upgrades needed for the operation of the SPS damper with the LHC proton beam. For operation with ions the use of the SPS damper is presently restricted to injection damping. Feedback along the ramp will not be provided. The present ion beams for fixed target physics do not require such a feedback. However, the intensity of the LHC ion beams to be accelerated in the SPS will approach the limit of the resistive wall instability threshold. The use of the SPS damper for ions along the ramp will require a modification of the digital signal processing in order to account for the large swing in frequency during acceleration. In addition, a re-design of the pickup electronics to optimise for the intensity per bunch and the bunch spacing might be necessary. These modifications may be implemented once studies have been made in the SPS with LHC ion beams.

The issue of the revolution frequency swing is illustrated in the following by comparing the situation for the proton LHC beam with the ion beam. The transverse feedback system as implemented is a "one turn delay" feedback: The signals acquired by the pickups are transmitted from the tunnel to the surface where they are delayed for "one turn" before being re-applied to the beam. If the pick-ups and kickers were installed at exactly the same location in the tunnel, the total delay required τ_1 would equal the machine revolution time T, which in turn is a function of the revolution frequency and hence beam energy. In practice the total delay τ_1 is slightly different from T, as the pickups are not installed exactly at the place of the kickers. A large fraction of the electronic delay is realised in digital form, clocked at a frequency locked to the revolution frequency. This part correctly keeps track of the increasing velocity of the beam during acceleration. A smaller fraction of the delay comes from cable and electronic delay, which is fixed and does not change with beam energy. As a result there will be a small phase error in the feedback loop. If the feedback is perfectly adjusted at injection (26 GeV/c), the phase error at top energy (450 GeV/c) for the proton LHC beam amounts to between 17° and 18° at the highest frequency of the feedback system, i.e. 20 MHz [18]. This small phase error can be neglected. For the LHC ion beam the maximum feedback bandwidth must be 5 MHz (100 ns bunch spacing). Using the parameters of the present ion beam, together with the 5 MHz bandwidth leads to a large phase error, i.e. approximately 80°. Although the LHC ions will be injected at a higher energy than the present fixed-target ion beam, this effect needs to be taken into account. The phase error can be minimised by an appropriate choice of pickups (minimisation of fixed delay in cables). The residual phase errors will depend on the type of ions used and their injection energy. Analogue and digital methods exist to compensate for the phase error. These will be considered after 2006, should it be necessary.

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