OPERATION OF THE TRANSVERSE FEEDBACK SYSTEM AT THE CERN SPS

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Abstract

To prevent transverse instabilities at high beam intensity in the SPS, the transverse feedback system for damping the betatron oscillations has been upgraded for larger damping decrements and for increased system's bandwidth. The feedback loop now contains a digital delay line cancellor, so that the damper works with a velocity feedback Δx/Δt, unaffected by the closed orbit position x at the pick-up station. The digital processing of the feedback signal facilitates nonlinear feedback techniques such as antidamping and "bang-bang" feedback. The "bang-bang" feedback provides the maximum possible damping rate of the injection oscillations in the SPS-collider, in order to minimize the emittance increase caused by filamentation. The antidamping nonlinearity provides small continuous beam oscillations of 50 μm amplitude for tracking the machine tune Q with a phase locked loop.

Tasks of Damper

The damper of the SPS is an active feedback loop, which senses transverse beam oscillations, amplifies the voltage signal of the position monitor, and feeds back a deflection voltage to the beam in order to reduce the amplitude of the betatron oscillation.

The old damper of the SPS [1] has been replaced in 1980 by a new design with more deflection force and larger frequency bandwidth. A new active feedback system with selective beam monitors, with digital signal processing and powerful beam deflectors was required in order to damp the horizontal and vertical injection oscillations of antiproton bunches at 26 GeV/c in the presence of proton bunches 100 times more intense.

For fixed target operation with 1 to 4×10^{13} ppp (present maximum 3.5×10^{13} ppp), the new damper must damp the injection oscillations and stabilize the increased growth rate of horizontal and vertical beam instabilities caused by the resistivity of the vacuum chamber wall. The block diagram of the damper for fixed target operation is shown in fig.1 .

Since 1983 the beam deflector of the damper is also used as a pulse train kicker for the Multi-Q tune measurement during the acceleration cycle both in collider and fixed target operation [2]. This method is the most suitable for a fast adjustment of the machine. If reasonably good operating conditions are established with a small enough tune spread in the beam, a more precise method can be applied : through antidamping on a short azimuthal beam segment, the damper can excite small continuous betatron oscillations for on-line tracking of the machine tune with a phase-locked loop [1] (photo 1).

The beam deflector of the damper has also served to measure the transverse beam transfer function and the relative betatronic function near to the low beta insertions of the collider lattice [3].

The SPS accelerates electrons and positrons for LEP as from 1987. As for protons and antiprotons, the feedback system will damp the injection oscillations. It would also be capable of fighting the transverse mode coupling instability provided the oscillations induced by this phenomenon have a sufficient component at low frequency. Due to the long lepton bunches of 1 ns this is not considered to be likely in the case of the SPS at 3.5 GeV/c.

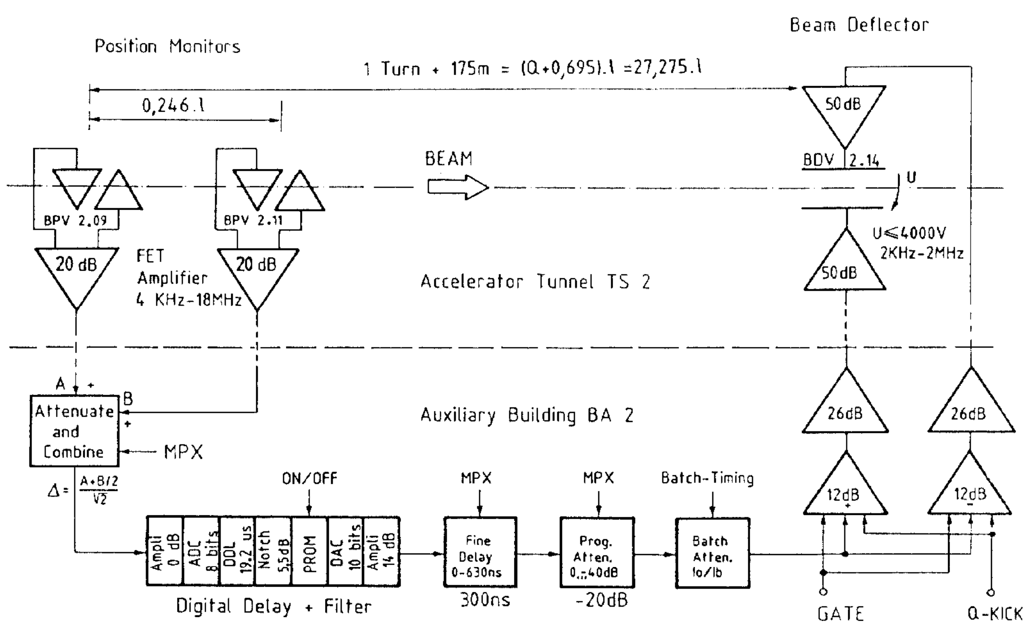

FIG.1 Blockdiagram of Vertical Damper Feedback

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Deflection Momentum of Electrostatic Beam Deflector

In collider operation, the single bunches of protons and antiprotons are injected into the SPS with injection errors of 1 to 4 mm, which need to be damped within a fraction of the coherence time τ_c in order to avoid blow-up of the beam emittance. Because of the fast damping rate required at p_z=26 GeV/c, the damper system comprises two horizontal and two vertical pairs of beam deflecting electrodes.

The two electrodes of the electrostatic deflector are driven by two power tetrodes providing a maximum deflection voltage of 4000 V over a frequency range 1 KHz - 2 MHz (-3 dB). The horizontal deflector electrodes are 2.4 m long, have 142 mm horizontal aperture, and develop a transverse beam momentum p_x of up to 68 KeV/c. The vertical deflector electrodes are 1.6 m long, have an aperture of 38 mm, and give the beam a vertical momentum p_y of up to 168 KeV/c.

The effective bandwidth of the damper is larger than that of the power amplifiers, which provide still sufficient gain to damp beam instabilities up to 5 MHz (photo 2). At frequencies above 7 MHz, the strength of the instability decays rapidly (photo 3) and can be damped by the Landau damping octupoles.

Proportional and Bang-Bang Feedback of Injection Oscillations at 26 GeV/c

The feedback system when working in its linear range provides a deflection voltage proportional to the beam oscillation. Taking into account the betatron amplitude β_o=100 m at the beam monitors, the betatron amplitudes β_x, β_y at the beam deflectors and the phase angle μ of the feedback loop, the beam oscillations observed at β_o are damped by a single proportional deflection at a maximum rate $\dot{x}$, $\dot{y}$:

$$\dot{x}_{max} = \frac{f_o \cdot p_x}{2 \cdot p_z}\sqrt{\beta_x \cdot \beta_o} = 4.5 \text{ mm/ms}$$

$$\dot{y}_{max} = \frac{f_o \cdot p_y}{2 \cdot p_z}\sqrt{\beta_y \cdot \beta_o} = 9.1 \text{ mm/ms}$$

for f_o=43.3 KHz (beam revolution frequency), sin μ=1.

In the case of proportional feedback, the beam oscillations are damped exponentially with an e-folding time T which depends on the beam position $\hat{x}$ at which the beam deflector gets saturated : $T = \hat{x}/\dot{x}$.

Important energy differences have been observed at injection between proton and antiproton bunches resulting in an offset of the closed orbit of antiprotons, which was larger than the injection oscillations (fig. 2) and which saturated the power amplifiers of the beam deflector. In addition, electrostatically, the closed orbits of p and pbar are separated horizontally by ±5 mm at injection in order to avoid beam-beam collisions. These large position offsets are removed from the feedback signal by means of a digital notch filter, and only the signal of the beam oscillation is transmitted to the beam deflector.

Faster damping speed of the injection oscillations can be obtained by nonlinear feedback. If the amplitude of the beam oscillations is larger than about 0.3 mm (β_o=100 m), the deflector kicks the beam with maximum voltage at every turn. In this régime, called bang-bang, the beam oscillation decays linearly with a constant damping rate $\dot{x}=(4/\pi)\dot{x}_{max}$. If the beam oscillation is smaller than 0.3 mm, the feedback works in the proportional régime in order to avoid hunting of the nonlinear system in a limit cycle.

For injection errors a_o smaller than the rms size of the beam, the beam size σ increases after the damping of the injection oscillations to [4]

$$\sigma^2 \simeq \sigma_o^2 + \frac{a_o^2\,\tau^2}{2\,\tau_c^2} \text{ , wherein}$$

τ_c = 1 to 2 ms is the coherence time of the injection oscillations without damper, and τ is the e-folding time of the oscillations with damper.

For bang-bang feedback, $a_o\tau = \pi a_o^2/(4\dot{x}_{max})$, and large horizontal errors a_o can cause an appreciable blow-up of the beam size :

$$\sigma^2 = \sigma_o^2 + a_o^4/150 \text{ mm}^2 \ (p_z\text{=26 GeV/c, } \tau_c\text{=1.5 ms}).$$

In order to avoid filamentation of large injection oscillations, it is most important to reduce the Q-spread so that τ_c>1.5 ms.

The energy difference between antiprotons and protons in fig. 2 has been measured by a monitor at α_p = 2.8 m : Δp/p = 2.7 mm/α_p = 10^{-3}. The beating of the injection oscillations in fig. 2 has a period of 30 turns and is caused by a longitudinal oscillation.

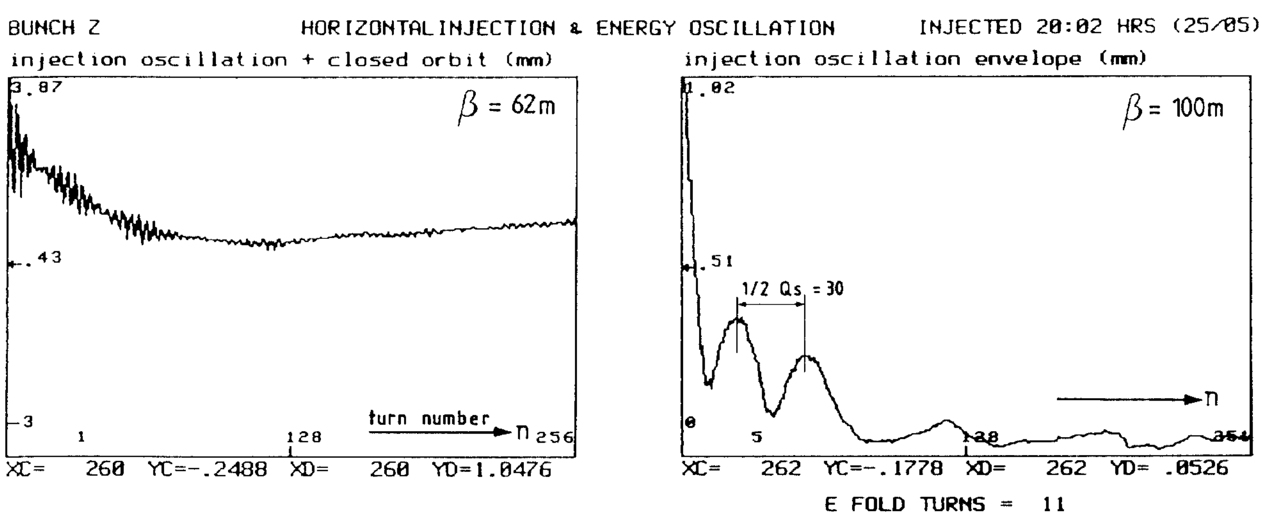

Fig.2 Injection oscillation of a pbar bunch

Digital Processing and Phase of Feedback Signals

As in most damper systems of existing accelerators, the position signal of the beam is delayed and fed back to the beam deflector after one or several beam revolutions. The stability of a feedback system with a delay time in the loop depends on the gain and the phase linearity of the open loop. In order to obtain the best possible linearity of phase even beyond the bandwidth of the system, a digital delay has been chosen. The measurements of the beam position are digitized by a 8 bit ADC with a clock rate of 33 MHz and stored into a RAM memory (DDL in fig. 1), from where the data are retrieved after 19.2 μs.

During acceleration the beam velocity increases and the digital delay is reduced by the same amount, since the clock frequency is derived from the RF-frequency of the beam. The linear phase error of the ADC and DAC of the digital processor is less than ±3° for signal frequencies 0-10 MHz.

Subsequent to the digital delay, the position signal of the beam is processed by a digital notch filter which rejects the closed orbit information from the feedback signal. The digital notch filter employs another digital delay of T_o=23.1 μs corresponding exactly to one beam revolution period (fig. 3).

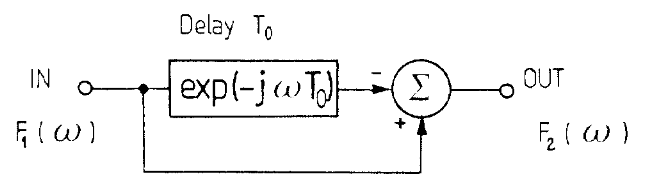

Fig.3 Blockdiagram of notch filter
$H(w) = F_2/F_1 = 1-\exp(-jwT_o)$

The digital filter has a perfectly linear phase φ versus angular frequency w and a constant group delay T_g :

$$\varphi(w) = \arctan \frac{\sin(wT_o)}{1-\cos(wT_o)} = \frac{\pi - wT_o}{2}$$

$$T_g = d\varphi/dw = -T_o/2.$$

The notch filter provides the position difference between two successive turns, which means differential or velocity feedback instead of position feedback. The system's gain γ of the feedback with a notch filter amounts to :

$$\gamma = \sin(\mu_o+2\pi Q) - \sin(\mu_o+4\pi Q) = -2\sin(\pi Q)\cos(\mu_o+3\pi Q)$$

The nature of the feedback system is changed and the phase of the velocity feedback must be a multiple of π :

$$\mu_o + 3\pi Q = n\pi, \text{ n=integer, wherein}$$

Q is the machine tune and μ_o is the betatron phase between the beam monitor and the beam deflector.

The digital form of the feedback signal at the output of the notch filter allows easy implementation of nonlinear feedback techniques [1,5] by a 9-bit PROM. The PROM provides different functions such as linear transfer, bang-bang for damping the injection oscillations larger than 0.3 mm and antidamping of beam oscillations smaller than 0.1 mm (photo 1).

References

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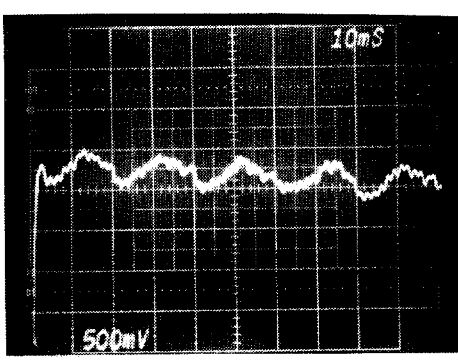

Photo 1 Vertical Q-tracking Q (t) 100-200 ms after first injection Q_o at center line : Q_o=26.58
Q-variation : ΔQ=0.01/0.5V=0.01/div
Note Q-ripple 50 Hz + 600 Hz.

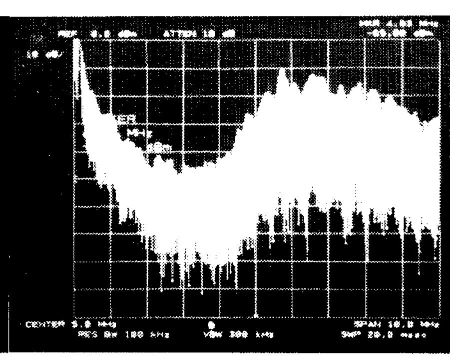

Photo 2 Spectrum of vertical instabilities 0-10 MHz with damper. Octupoles set to zero.
10 dB/div, 1 MHz/div, VBW 300 KHz first batch 1.5×10^{13} ppb sweeped 100-120 ms after injection.

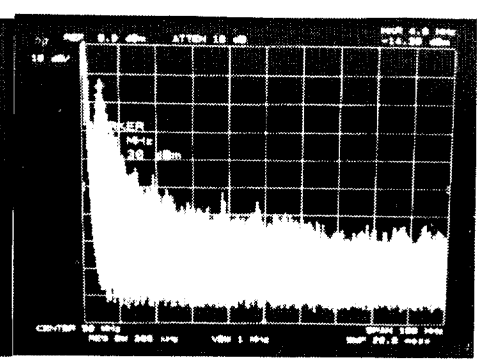

Photo 3 Spectrum of vertical instabilities 0-100 MHz with damper. Octupoles set to zero.
10 dB/div, 10 MHz/div, VBW 1 MHz first batch 1.5×10^{13} ppb sweeped 100-120 ms after injection.