THE NEW DAMPER OF THE TRANSVERSE INSTABILITIES
OF THE SPS AT HIGH INTENSITIES

R. Bossart, J.P. Moëns and H. Rossi

ABSTRACT

A new active feedback system has been installed in the SPS in order to damp the horizontal and vertical instabilities caused by the resistive wall effect of the vacuum chamber. The new equipment was necessary because the growth rate of the coherent transverse instabilities has increased proportionally with the higher beam intensity of the SPS. The new damper has been designed for a maximum beam intensity of $5 \times 10^{13}$ ppp, maximum beam oscillations of $\pm 4$ mm, and a bandwidth of 1.5 MHz. Four new electrostatic deflectors, each driven by a 50 kW amplifier, have been installed in the accelerator tunnel. The four electrostatic deflectors have a total electrode length of 8 m, and the power amplifiers provide a maximum deflection voltage of 4000 V. The growth rates of the instability, the gain, bandwidth, and stability of the feedback system have been analysed and compared with beam measurements.
1. **INTRODUCTION**

The old damper, designed in 1974, was for a maximum beam intensity of $10^{13}$ ppp, a bandwidth of 500 kHz, and a deflection voltage of 1000 V$_{ptp}$. In parallel with the increasing beam intensity of the SPS, the old damper was continuously improved and, in 1978, the power amplifiers reached a bandwidth of 1 MHz and a deflection voltage of 2000 V$_{ptp}$.

Measurements carried out with the beam and the old damper have shown that the growth rates of the transverse instabilities, in the frequency range 15 kHz to 3 MHz, are in good agreement with the theory of the resistive wall effect. The gain of the old damper feedback loop was perfectly adequate for suppressing transverse beam instabilities in the frequency range 10 kHz to 1 MHz for beam intensities up to $1.5 \times 10^{13}$ ppp, but at higher beam intensities the deflection voltage was not sufficient for injection oscillations and closed-orbit deformations exceeding 2 mm.

At injection, the power amplifiers of the electrostatic deflectors became saturated if the beam oscillations exceeded a certain limit, depending on beam intensity. Since the deflection voltage is proportional to beam position and beam intensity, the saturation limit decreases inversely with increasing beam intensity, and came down to 1.0 mm at $3 \times 10^{13}$ ppp for the old damper. During routine physics operation, injection oscillations of ±8 mm for part of the beam have been measured both in the horizontal and vertical planes. It should be noted that these errors cannot be corrected by the steering of TT 10.

The large amplitude of part of the horizontal injection oscillation is caused by the injection kicker of the SPS, when the second batch is injected and the tail of the kicker pulse kicks the first batch again. The peak amplitude of part of the vertical injection oscillation is caused by the staircase generator of the continuous extraction in the CPS over several turns, which have different positions at the input to TT 10. Since there is a phase-plane exchange in TT 10, the horizontal position errors of the CPS extraction show up in the vertical plane of the SPS.

The new damper has been designed to work without saturation for beam oscillations up to 4 mm horizontally and vertically at $5 \times 10^{13}$ ppp. For this purpose the number and length of the electrostatic deflectors have been increased. There are now two vertical deflectors of 1600 mm electrode length each, and two horizontal deflectors of 2400 mm length each (see Table 1). Four new 50 kW twin power amplifiers have been built with a maximum deflection voltage of 4000 V$_{ptp}$ between electrodes.
Table 1

Characteristics of electrostatic deflector

<table>
<thead>
<tr>
<th></th>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
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<tbody>
<tr>
<td>Location</td>
<td>BAPV 31455 + BAPV 31457</td>
<td>BAPH 31437 + BAPH 31451</td>
</tr>
<tr>
<td>Length of electrode, l</td>
<td>1600 mm</td>
<td>2400 mm</td>
</tr>
<tr>
<td>Distance between electrodes, d</td>
<td>38 mm</td>
<td>142 mm</td>
</tr>
<tr>
<td>Width of electrode, w</td>
<td>100 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>Inner diameter of vacuum tank, D</td>
<td>354 mm</td>
<td>354 mm</td>
</tr>
<tr>
<td>Ground capacitance, C₀</td>
<td>39 pF</td>
<td>98 pF</td>
</tr>
<tr>
<td>Inter-electrode capacitance, C₁₂</td>
<td>45 pF</td>
<td>18 pF</td>
</tr>
<tr>
<td>Amplifier stray capacitance, Cₐ</td>
<td>120 pF</td>
<td>120 pF</td>
</tr>
<tr>
<td>Max. inter-electrode voltage, Uₘ₉</td>
<td>4000 V</td>
<td>4000 V</td>
</tr>
<tr>
<td>Anode resistance, R</td>
<td>560 Ω/8 kW</td>
<td>560 Ω/8 kW</td>
</tr>
</tbody>
</table>

The four electrostatic deflectors of the new damper have been installed downstream of QF 314, so that they can be used for p̅p operation in order to damp the injection oscillations. The time interval between successive p and p̅ bunches at the new deflectors amounts to 0.9 µs. The electrostatic deflectors of the old damper were installed downstream of QD 319 close to the crossing point of the p and p̅ beams. Since the location of the old damper is incompatible with p̅p operation, the old deflectors BAMH/V were removed from the tunnel during the long shutdown in the summer of 1980.

2. SPECIFICATION OF ACTIVE FEEDBACK

Active feedback systems of transverse beam oscillations are in use since 1965, when the first feedback system was built for the Zero Gradient Synchrotron (ZGS) at Argonne2). Since then, many other accelerators have been equipped with active damping systems3-5).

The purpose of the active feedback is to reduce the transverse beam oscillations by an angular deflection opposite and proportional to the oscillation amplitude (Fig. 1). For a stable beam the damping rate of the oscillation must be stronger than the growth rate of the instability, which is caused by the skin effect of the vacuum chamber. Unstable transverse beam oscillations arise at the betatron frequencies6):
\[ f(m) = (m + 27 - Q) f_{\text{rev}} \]

\( f(m) \): betatron frequency of mode \( m \)
\( f_{\text{rev}} \): beam revolution frequency, \( f_{\text{rev}} = 43.3 \text{ kHz} \)
\( m \): mode number, \( m = 0, 1, 2, 3, \text{ etc.} \)
\( Q \): betatron wave number, \( 26 < Q < 27 \).

The resistivity of the vacuum chamber increases with frequency because of the skin effect, so the growth time of the instability also increases at higher frequencies. The strongest instability with the shortest growth time is mode 0 at frequencies between 16 and 19 kHz (\( Q = 26.57 \ldots 26.62 \)). Measurements with the old damper\(^1\) have shown that the time constant \( \tau_g \) for the undamped exponential growth of mode 0 at \( 10^{13} \) ppp and 10 GeV amounts to

\[ \tau_V = 1.0 - 1.4 \text{ ms in the vertical plane} \]
\[ \tau_H = 1.8 - 2.5 \text{ ms in the horizontal plane} . \]

Since the forces of the coherent resistive wall instability are proportional to the mean beam intensity, the growth times of the instability become inversely shorter with higher intensity. The expected growth times for \( 5 \times 10^{13} \) ppp at 10 GeV are

\[ \tau_V = 200 \mu\text{s in the vertical plane} \]
\[ \tau_H = 400 \mu\text{s in the horizontal plane} . \]

If we choose an e-folding time \( \tau \) of the injection oscillation equal to the time constant \( \tau_g \) of the instability, the damper gain must be twice as strong as required for suppressing only the resistive wall effect at injection. Some gain margin is also required during the front porch and transition when transverse instabilities may suddenly set in. For these reasons, the time constant \( \tau_d \) of the damper system should be about half the growth time constant \( \tau_g \) of the resistive wall instability at injection:

\[ e^{-t/\tau} = e^{-t/\tau_d} \times e^{+t/\tau_g} \]
\[ 1/\tau = 1/\tau_d - 1/\tau_g \]
\[ \tau_d = \tau_g/2 = \tau/2 . \]

The damping time constant \( \tau_d \) defines the feedback gain. The damping time \( \tau_d \) means that the oscillation would be damped to 1/e of the original amplitude after \( N \) beam revolutions, if there were no resistive wall effect (\( \tau_g = \infty \)):

\[ N = \tau_d f_{\text{rev}} = 0.5 \tau_g f_{\text{rev}} . \]
The feedback gain $G$ of the damper is defined as the ratio between the deflection angle $\delta$ of the beam provided by the electrostatic deflector and the beam position $x$ measured by the electrostatic pick-up. The damper gain is given by

$$G = \frac{\delta}{x} = \frac{2}{N \beta_1 \beta_2 \sin \mu_{12}} = \frac{4}{\tau_g f_{\text{rev}} \beta_1 \beta_2 \sin \mu_{12}} \quad (\text{mrad/mm}),$$

where

$x$ : beam position

$\delta$ : deflection angle

$G$ : damper gain

$N$ : number of beam revolutions needed to reduce the amplitude by $1/e$ ($\tau_g = \infty$).

$\tau_g$ : growth time constant of instability

$f_{\text{rev}}$ : beam revolution frequency

$\beta_1$ : betatron function of position monitor

$\beta_2$ : betatron function of electrostatic deflector

$\mu_{12}$ : betatron phase angle between monitor and deflector.

<table>
<thead>
<tr>
<th>Location of deflector</th>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of pick-up</td>
<td>42 m</td>
<td>97 m</td>
</tr>
<tr>
<td>Beta function of pick-up, $\beta_1$</td>
<td>BPV 31309</td>
<td>BPH 31409</td>
</tr>
<tr>
<td>Beta function of deflector, $\beta_2$</td>
<td>42 m</td>
<td>62 m</td>
</tr>
<tr>
<td>Phase angle between pick-up and deflector, $\mu_{12}$</td>
<td>26.77 $\times$ $2\pi$</td>
<td>26.64 $\times$ $2\pi$</td>
</tr>
<tr>
<td>$\sin \mu_{12}$</td>
<td>-0.99</td>
<td>-0.77</td>
</tr>
</tbody>
</table>

For the optimum system gain required for beam stability, the distance between the position monitor and the deflector in the ring should be an odd multiple of a quarter betatron wavelength: $\sin \mu_{12} = 1$. For $5 \times 10^{13}$ ppp at 10 GeV, the damper gain $G$ amounts to

$$G_V = 7.3 \ \mu\text{rad/mm in the vertical plane}$$

$$G_H = 3.9 \ \mu\text{rad/mm in the horizontal plane}.$$ 

The deflection angle $\delta$ of the electrostatic deflector is given by

$$\delta = \frac{U_2}{Ed} \quad \text{(rad)},$$

where
U: deflection voltage between electrodes of deflector
L: length of the electrostatic deflector
d: distance between the electrodes of the deflector
E: acceleration voltage of the beam, $E = 10^{16}$ V at 10 GeV.

The dimensions of the electrostatic deflectors are indicated in Table 1. The maximum deflection voltage provided by the power tetrode RS 2012 CJ amounts to $U = 4000 \, V_{\text{ppp}}$, which limits the maximum deflection angle provided by two electrostatic deflectors at 10 GeV:

$$
\delta_v \leq 34 \, \mu\text{rad in the vertical plane}
\delta_h \leq 14 \, \mu\text{rad in the horizontal plane}.
$$

For a beam intensity of $5 \times 10^{13}$ ppp, the maximum admissible oscillation amplitudes are:

$$
\gamma = \frac{\delta_v}{G_v} = \pm 4.5 \, \text{mm in the vertical plane}
\zeta = \frac{\delta_h}{G_h} = \pm 3.5 \, \text{mm in the horizontal plane}.
$$

If the injection oscillations exceed these limits, the power amplifiers of the electrostatic deflectors become saturated, and higher instability modes are no longer damped. If the injection oscillations exceed the saturation limits by a factor of 2, the beam is definitely unstable at the fundamental mode.

The same amplitude limits are valid at any beam energy, since both the damper gain and the growth rate $1/\tau_g$ decrease inversely with beam energy.

Operating the damper at a lower systems gain, say only 3 dB instead of 6 dB above beam instability, improves the saturation limit of the beam oscillations by a factor of $\sqrt{2}$. However, the limit of beam stability will still be the same, namely $\pm 9 \, \text{mm vertically and } \pm 7 \, \text{mm horizontally at } 5 \times 10^{13} \, \text{ppp}$. This limit can be only improved by increasing the deflection voltage of the power amplifiers.

The bandwidth of the feedback system must be sufficient to damp not only the fundamental mode of the injection oscillation but also the higher frequencies inherent to the continuous transfer of the CPS. The bandwidth of the damper should cover at least the revolution frequency of the CPS up to its third harmonic, which is still very strong. Therefore the damper should have a bandwidth of 1.4 MHz. Of course, a higher bandwidth would be desirable to prevent beam instabilities of the higher modes, but these instabilities can be cured by octupoles.

3. DESCRIPTION OF THE EQUIPMENT

The various pieces of equipment of the damper feedback system are shown in the block diagram of Fig. 1. The active feedback loop consists of a beam position
monitor, an amplifier chain in auxiliary building BA3, and an electrostatic beam deflector downstream of quadrupole QF 314. The beam position monitor provides the beam position signal ∆ from two electrostatic pick-up electrodes, and senses beam oscillations as small as 0.01 mm at 10^{13} ppp. The beam monitor is chosen from amongst the pick-ups located in straight sections 311 to 316. In BA3 the feedback signal ∆ is amplified and delayed by the time the beam takes for one revolution from the beam monitor to the deflector. The amplification factor of the feedback loop from the pick-up electrodes to the deflector electrodes amounts to 103 dB for operation with one single vertical deflector, and 113 dB for one horizontal deflector. The amplification factor of the feedback loops is the sum of the electrical gains of the following equipment (Fig. 1):

<table>
<thead>
<tr>
<th></th>
<th>Vertical (dB)</th>
<th>Horizontal (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Programmable FET amplifiers (standard settings)</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Attenuator</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>Gater</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Ampli. &quot;Nuclétudes&quot;</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Power amplifier</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>Deflector (push-pull)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Amplification factor (standard setting)</td>
<td>103</td>
<td>113</td>
</tr>
</tbody>
</table>

3.1 Beam position monitor

The beam position is sensed by a pair of triangular split electrodes. The beam induces a signal on the electrodes which is proportional to beam intensity and position. The low-frequency response of the beam position monitor is preserved by a pair of FET amplifiers located in a pit underneath the monitor. At the input of the FET amplifiers, low-pass filters of the Bessel type, with a cut-off frequency of 5 MHz, prevent the amplifier from being saturated by single bunches of high local density. At the output of the Bessel filter the pulse width is about 90 ns FWHM for single bunches, and the peak amplitude is reduced by a factor of 100 for bunches of 1 ns pulse width.

The voltage \( U \) induced by a beam of intensity \( I \) in the centre position depends on the electrode length \( \ell = 125 \text{ mm} \) and the total capacitance \( C = 430 \text{ pF} \) of the electrode and the FET amplifier\(^8\):

\[
U = \frac{Q}{C} = \frac{I\ell}{2Cc}, \quad c = 3 \times 10^8 \text{ m/s}.
\]
The transfer impedance \( Z_t \) of the beam position monitors with RF/LF adapters amounts to
\[
Z_t = \frac{U}{I} = \frac{V}{2C} = 0.5 \, \Omega.
\]

The difference voltage \( \Delta \) between the two electrodes is proportional to the beam intensity \( I \) and beam position \( y \). The sensitivity \( S \) of the beam position monitor is expressed by
\[
S = \frac{\Delta}{yI} = \frac{2Z_t}{r} = \frac{V}{C} c r,
\]
\( r \) being the distance of the electrode measured from the centre along the direction of the beam position measurement:

- **BPH:** \( r = 78 \, \text{mm} \), \( S_H = 13 \, \mu\text{V/mm} \cdot \text{mA} \)
- **BPV:** \( r = 42 \, \text{mm} \), \( S_V = 24 \, \mu\text{V/mm} \cdot \text{mA} \).

These values agree perfectly with the signals measured for a beam intensity of 140 mA.

The sum and difference of the electrode signals are provided by a hybrid transformer at the input of the FET amplifier in the electronic pit. The signals \( \Delta \) and \( \Sigma \) are amplified by a programmable multistage amplifier (Fig. 2). The gain of the \( \Sigma \)-channel is fixed to 20 dB, whereas the gain of the \( \Delta \)-channel can be programmed to 20-30-40 dB according to the gain needed in the feedback loop. The gain of the programmable amplifier can be set manually by the gain control unit in BA3, or remote controlled from MCR by the multiplex module "A". The difference signal at the input of the FET amplifier is adjusted to zero by varicap diodes, so that small closed-orbit positions of ±1 mm can be compensated for.

The preamplified sum and difference signals are transmitted from the tunnel to BA3, where they pass through the gain control unit for impedance matching of the symmetric cables TWC 95 (\( \Delta \)-channel) and QUAD (\( \Sigma \)-channel). The difference signal \( \Delta \) can be attenuated in the gain control unit by 3, 6, or 9 dB locally, or remote controlled for fine adjustment of the damper feedback gain.

The bandwidth of the programmable FET amplifier with two 5 MHz Bessel filters at the input amounts to 3 kHz to 4 MHz (-3 dB limit). The low-frequency limit 3 kHz is given by the hybrid transformer and the output transformers which produce a phase lead \( \phi \) at frequencies \( f \) below 50 kHz:
\[
\phi = \frac{320^\circ}{f/\text{kHz}}.
\]

At high frequencies, \( f = 500 \, \text{kHz} \) to 5 MHz, the phase delay is fairly constant due to the Bessel filter. The programmable FET amplifier alone has a higher bandwidth
of 8 MHz. The delay time of the Bessel filter and programmable FET amplifier amounts to 150 ns, and the non-linear phase distortion is less than ±6° for 100 kHz to 5 MHz.

3.2 Signal processing in BA3

The signal processing in BA3 comprises three major operations: The closed-orbit component of the beam position signal Δ is suppressed by the plug-in unit called "closed-orbit clipper" or "beam-hole blanker". Then the feedback signal is delayed by about 19-20 μs to wait for one beam revolution. Finally, the gated driver opens and closes the feedback loop when required by the MCR via the timing generator TG2.

Closed-orbit positions larger than 4 mm at 2.5 × 10^{13} ppp overload the power amplifiers in the tunnel if one single deflector is used per plane. It is therefore necessary to clip the signal of the closed-orbit position, otherwise the power amplifiers are saturated by a short pulse caused by the missing bunches of the beam. For two-batch injection there are two beam holes of 1 μs duration each. After fast extraction other beam holes appear. The amplitude of the beam-hole pulses is proportional to beam intensity and closed-orbit position at the pick-up station of the damper. The beam-hole pulses are suppressed by a FET switch which short-circuits the feedback signal during the duration of the hole (Fig. 3). The clipping switches Q₁ and Q₂ are activated by the sum signal Σ when it reaches about 50% of the negative peak value. The switching transients of the feedback signal are very short and do not saturate the power amplifiers because of the limited bandwidth. The feedback signal Δ is delayed by about 150 ns in front of the closed-orbit clipper in order to synchronize the sum and difference signals for proper signal clipping.

The feedback signal is further delayed by about 19.6 μs, so that it acts, at the deflector, on the same portion of beam where the beam position was picked up from a beam revolution before. The delay line consists of a fixed delay, 19.4 μs, and a fine delay, 10-630 ns, which can be adjusted from the MCR via the multiplex system in steps of 10 ns. The delay box 19.4 μs is made of a magnetic-core delay cable HH-2000 which has a characteristic impedance of 2000 Ω and a delay of 0.36 μs/m. At the output of the delay box an amplifier drives the 50 Ω load and compensates the phase distortion of the delay cable. The rise-time tᵣ at the output of the 19.4 μs delay is improved by active compensation by a factor of 3 and amounts to tᵣ = 120 ns. It is the 19.4 μs delay box which has the lowest bandwidth, f_{3dB} = 3 MHz, of all signal processing equipment in BA3. However, the 19.4 μs delay box does not cause phase errors larger than ±15° for frequencies 4 kHz to 5 MHz.
The fine delay is made of pieces of coaxial cable RG-58 which are connected in series by remote-controlled coaxial RF relais. The rise-time of a 160 ns long RG-58 cable amounts to $t_r = 50$ ns and does not require active compensation.

The plug-in unit "gated driver" (Fig. 4) opens or closes the feedback loop during the acceleration cycle according to the timing selected in the MCR. The gated driver has two outputs of opposite polarity to drive the two electrodes of the deflector in push-pull mode. The amplification factor of the gated driver is 12 dB and the bandwidth amounts to 7 MHz ($t_r = 50$ ns). The pair of opposite feedback signals is transmitted to the double power amplifier in the tunnel by a pair of 50 W amplifiers constructed by Nuclétudes. These amplifiers have a gain of 26 dB and a bandwidth 1 kHz to 10 MHz.

3.3 Power amplifiers and beam deflectors

The power amplifiers in the tunnel provide a deflection voltage of 4000 $V_{ptp}$ over a bandwidth 1 kHz to 1.25 MHz. The two electrodes of the beam deflector are driven in push-pull mode by a double power amplifier (Fig. 5). Since the deflection electrodes represent a high impedance load at these frequencies, a tube amplifier has been chosen and installed in the tunnel just underneath the deflector tank (see photo 1). Modern power tetrodes are very reliable, even in the radioactive environment of the accelerator. All eight power tetrodes of the old damper have worked without failure during 20,000 hours, each tetrode accumulating a radiation dose of about $5 \times 10^6$ rad.

The power tetrode RS 2012 CJ is operated in class A, is water-cooled, and has a maximum anode dissipation of 18 kW. Of course, class B operation would reduce the power dissipation, as is normally done for radio transmitters. But the damper requires a good linearity for very small signals and a large bandwidth for small and large signals, two characteristics which are best met by class A amplifiers. The power tetrode RS 2012 CJ has a high emission current of the cathode, which assures a long lifetime for the tube under pulsed and saturated operation when, for example, the closed-orbit position is not corrected.

The anode resistance of the power tetrode consists of 10 power resistors put in parallel and cooled by air ventilators. The power resistors are bifilar wire-wound and have a very low self-inductance. The anode resistance $R_2 = 560 \ \Omega$ defines the voltage gain and high-frequency cut-off of the deflector. Because of the large size of the anode resistors, the stray capacitance of the amplifier output is about the same as the deflector capacitance. The power tetrode has a voltage gain $G_2 = 34$ and a cut-off frequency $f_2 = 1.2$ MHz:
\[ G_2 = S_2 R_2 = 60 \text{ (mA/V)} \times 560 \Omega = 34 \]
\[ f_2 = 1/(2\pi R_2 C_2) = 1/(2\pi \times 560 \Omega \times 250 \text{ pF}) = 1.2 \text{ MHz} \]

The anode signal of every power tetrode can be observed on the oscilloscope in BA3 by means of the monitor output of the high-voltage divider 20,000:1.

The power tetrode is driven by another tube amplifier consisting of two pentodes RS 1003. The pentodes have a relatively high transconductance \( S_1 = 25 \text{ mA/V} \) that is necessary to drive the grid capacitance of the power tetrode. The voltage gain \( G_1 \) and bandwidth \( f_1 \) of the driver amount to

\[ G_1 = 2S_1 R_1 = 2 \times 25 \text{ (mA/V)} \times 250 \Omega = 12 \]
\[ f_1 = 1/(2\pi R_1 C_1) = 1/(2\pi \times 250 \Omega \times 250 \text{ pF}) = 2.5 \text{ MHz} \]

The total voltage gain of the power amplifier in the tunnel is 52 dB, i.e. 400 X. The bandwidth 1 kHz to 1.25 MHz (3 dB) of the power amplifier limits the high-frequency response of the damper. Special care has been taken to keep a constant delay time \( t_d = 150 \text{ ns} \) of the power amplifiers up to 3.5 MHz. Owing to the graduated cut-off frequencies of the power tetrode (1.25 MHz) and the driver (2.5 MHz), the non-linear phase error is smaller than \( \pm 20^\circ \) up to 3.5 MHz.

The deflector electrodes have been designed for an homogeneous electric field distribution in the centre area occupied by the beam. For this reason both the horizontal and vertical electrodes are 100 mm wide. The gap height between electrodes is dictated by the aperture of the SPS, which shall not be restricted by the damper, see Table 1. The horizontal deflection electrodes are longer than the vertical electrodes in order to compensate for the electric field strength, which is much weaker for the same deflection voltage.

Despite the large diameter of the deflector tank \( D = 354 \text{ mm} \), the electrodes have a large ground capacitance \( C_0 \). For push-pull operation of the electrodes, the inter-electrode capacitance is doubled, because the median plane between the two electrodes stays at ground potential. The total electrode capacitance \( C_3 \) seen by the power amplifier amounts to:

\[ C_3 = C_0 + 2C_{12} = 130 \text{ pF} \ (\text{see Table 1}) \]

For beam intensities of \( 3 \times 10^{13} \text{ ppp} \) the deflection of one single tank is sufficient to stabilize beam oscillations of about 6 mm amplitude. As long as the beam intensity does not exceed \( 3 \times 10^{13} \text{ ppp} \), the damper can be run with one single tank per plane, and the second tank can be used as standby for verification of the correct operation of the damper and for machine developments.
3.4 High-voltage supplies and interlocks in BA3

The power amplifiers in the tunnel are powered from the high-voltage power supplies installed in BA3. There are two voltage-stabilized supplies, Philips 8000 V/16 A, for the horizontal and vertical dampers. The high power rating 128 kW of each supply made it necessary to install these large supplies at some distance from the low-level electronics. Only a chassis for remote control, and containing the regulation circuits of the thyristor-controlled rectifiers, is housed in the same electronic racks in BA3 as the auxiliary supplies and interlocks, which together fill four complete racks, one rack for every deflector tank (see Fig. 6). There are several auxiliary voltage supplies for every double power amplifier, e.g.:

1 screen supply for 2 power tetrodes, FHG 1250 V/0.5 A
2 separate grid supplies for each power tetrode, Kepco 525 V/0.5 A
2 anode supplies for 4 driver pentodes, Witmer 2 × 300 V/1 A
1 screen supply for 4 driver pentodes, Kepco 525 V/0.5 A.

The switching-on of the high-voltage supplies must be done in a determined sequence (see Fig. 6), otherwise the tubes can be damaged. An analogous switching-off procedure must be followed for setting down the damper. By no means should the screen voltage be on if the anode voltage is off, otherwise the screen grid takes all the cathode current and is destroyed.

A comprehensive safety and interlock system has been built to protect the power amplifiers from destruction by component failures or operation mistakes. The interlocks' chassis of each power amplifier signals the water-cooling of the tetrodes, the heating of the cathodes, the ventilation and over temperature of the anode resistors, and the presence of the grid and screen voltages of the driver and power tetrode. All these interlocks are summarized for every power amplifier, and if one single interlock is signalling a fault, the corresponding high voltage power supply Philips 8000 V/16 A is immediately switched off. The status of the individual interlocks of all four double power amplifiers can be read by the computer system.

There is also a chain of interlocks in every high-voltage power supply, summarizing personnel safety, over temperature, over voltage, over current, mains on, phase failure, and external interlock from the amplifiers. All these interlocks, as well as the commands on/off, reset, remote/local control, can be acquired and transmitted by the computer system.

3.5 Computer control of damper

The new damper can be entirely remote controlled from the MCR. The equipment of the four damper tanks is controlled by the data module subroutine "Damper".
The programs (222)NWDAH and (222)NWDAV connected to the program tree of the MCR give access to the horizontal and vertical dampers. These programs control the power amplifiers in the tunnel, the high-voltage power supplies, the gain and fine delay of the feedback loops, and its start and stop times.

The power amplifiers in the tunnel can be switched on and off from the MCR. Before the high voltages are applied to the tubes, an automatic setting-up procedure starts by heating the filaments. Several high voltages of every power amplifier can be acquired by the MPX system, such as the anode supply voltage, screen voltage, and control grid voltage of the power tetrodes, but also the anode supply and screen voltage of the driver pentodes.

The status of the damper system can be read in the MCR by the programs (202)NWHDST and (202)NWVDST. The most important parameters displayed are the gain, fine delay, and timing of the damper feedback loop. The status program displays also the anode supply and screen voltage of the power tetrodes, and the main interlocks of the power amplifiers and high-voltage supply.

The program (202)NEW_DA calculates the betatron phase between the beam-position monitors and the damper as a function of the betatron wave number Q of the machine. This program indicates which monitors provide the best damping.

4. **BANDWIDTH AND STABILITY OF FEEDBACK LOOP**

In any feedback system, the amplitude and phase response of the open loop determine the stability of the feedback system. Both characteristics, amplitude and phase response versus frequency, are linked together. Since the damper works with a feedback delay of 19.4 μs, the linear phase delay of the amplifier chain can be compensated by the delay line. The gain of the feedback loop can be reduced at higher frequencies, because the forces of the resistive wall instability become weaker with increasing frequency. Therefore, the active feedback loop has been designed for optimum phase linearity up to 5 MHz and for a constant amplitude response up to 1 MHz.

In this section we shall investigate the conditions for the active feedback components, so that they do not cause beam instability at frequencies above the bandwidth of the damper. Any transverse instabilities of the beam itself above the bandwidth of the damper must be cured by octupoles.

A complete analysis of beam stability with active feedback comprises the measurement of phase and amplitude between the beam position monitor and the beam deflector, and also the measurement of the beam response to transverse excitation. The latter measurement is not yet available, and a model is used instead.
The beam is considered as a resonator with distinct resonance frequencies 
\((n \pm Q)f_{\text{rev}}\), which have a narrow resonance width of

\[
\frac{\Delta Q}{Q} f_{\text{rev}} \quad (Q = 26.6; \quad f_{\text{rev}} = 43.3 \text{ kHz}; \quad n = 27, 28, 29, \ldots).
\]

Crossing a betatron resonance produces a phase change of 180° of the beam response\(^3\). Furthermore, the theory of the resistive wall effect predicts that the forces of the instability are proportional to the beam intensity and that they decrease at high frequency \(f > 100 \text{ kHz}\) as \(1/\sqrt{f}\) \(^6\). Only the slow waves \((n - Q)f_{\text{rev}}\) of the resistive wall current can cause beam instability.

The stability of systems with delayed feedback can be analysed by means of the equivalent circuit, which has no propagation delays. The equivalent loop has the same amplitude response and phase distortion versus frequency as the open loop with delayed feedback. A necessary condition, in order that the delayed feedback be stable, is the stability of the equivalent system\(^1\). It can be shown for the damper that this condition is also sufficient for system stability. If the feedback delay is adjusted correctly, so that it is exactly equal to the propagation delay of the beam from the position monitor to the deflector, then the Nyquist diagram of the equivalent system is equal to that of the delayed feedback system. It must be noted that only the linear phase delay of the amplifier chain can be compensated by the delay line, and that the non-linear phase distortion of the amplifiers, delay lines, and cables must be taken into account in the stability analysis of the equivalent system.

The amplitude and phase response of the different pieces of equipment of the damper have been measured individually. The power amplifiers of the beam deflectors have the lowest bandwidth of the loop. At present the bandwidth for constant amplitude response \((-3 \text{ dB})\) is limited by the power dissipation of the anode resistors of the power tetrode. It is not possible to extend the bandwidth of the power amplifiers by frequency correction networks without increasing the phase distortion. In order to get a linear phase response of the loop above 1 MHz, the other amplifiers must roll off at 5–10 MHz. Part of the phase lead of the power amplifier at 1–5 MHz can be compensated by the phase lag of the FET amplifier with Bessel filters. Above 5 MHz the delay line HH-2000 causes important phase distortions, which limit the bandwidth of the loop for linear phase response.

The gain and the phase distortion of the active feedback from the beam position monitor to the beam deflector are shown in Fig. 7. The active feedback gain reduces by \(-3 \text{ dB} at 700 \text{ kHz}\) because of the insertion loss of the coaxial cables \((-4 \text{ dB at } 1 \text{ MHz})\) between the tunnel and BA3. The gain decreases rapidly above 2 MHz because of the power amplifier, but is still sufficient to stabilize the
resistive wall effect up to 4 MHz. The gain limit in Fig. 7 has been measured in the SPS for the fundamental mode n = 27, and has been extrapolated for higher frequencies from the theory of the resistive wall effect (see Ref. 6).

Slight changes in the delay time cause important phase errors at 4 MHz (30 ns ± 45°), which affect the stability of the feedback system. Between injection at 10 GeV and transition, the revolution time of the beam changes by 100 ns. At present a new delay line is being developed, which changes its delay during the acceleration cycle as the beam velocity changes.

The gain and phase margin of the damper feedback loop have been measured with a beam intensity of $3.3 \times 10^{13}$ ppp. The minimum feedback gain at which the beam is still stable agrees perfectly with the design values of the damper given in Section 2. The lower limit of the gain of the new vertical damper for operation with one deflector tank alone has been measured: $A_V \geq 100 \pm 1$ dB. In the horizontal plane the measured lower limit amounts to $A_H \geq 109 \pm 1$ dB. These amplification factors A between the beam position monitors and one single beam deflector correspond to a minimum system gain G of the damper at injection:

$$G_V \geq 2.3 \ \mu rad/mm \$$
$$G_H \geq 1.4 \ \mu rad/mm \$$

from minimum gain measured

at $3.3 \times 10^{13}$ ppp, 10 GeV/c.

The minimum systems gain G calculated from the growth rate $\tau_g$ of the instability (see Section 2) amounts at injection to

$$G_V \geq 2.4 \ \mu rad/mm \$$
$$G_H \geq 1.3 \ \mu rad/mm \$$

calculated for $3.3 \times 10^{13}$ ppp,

10 GeV, $\tau_{gV} = 0.3 \ \mu s$, $\tau_{gH} = 0.6 \ \mu s$.

For safe operation of the damper, the feedback gain must be sufficiently higher than the minimum value. But the gain shall not be too high, otherwise the feedback system becomes unstable at high frequencies. The gain and phase margin of the damper have been measured with a beam intensity of $3 \times 10^{13}$ ppp (see Fig. 8). The limit values of the feedback gain and delay time depend very much on the Landau damping octupoles, whose field gradient L is changing during the acceleration cycle. The Landau damping octupoles (Refs. 6 and 11) stabilize the resistive wall and other transverse instabilities of the beam above the bandwidth of the damper.

5. CONCLUSIONS

For beam intensities up to $3 \times 10^{13}$ ppp, the damper should be operated with only one deflector for the vertical and horizontal plane. The second deflector should be used as a standby facility in case of beam instabilities.
The damper gain of one deflector is sufficient to suppress resistive wall instabilities below 3-4 MHz (Fig. 7). Other stronger instabilities, which may be caused by parasitic resonators in the machine\textsuperscript{12}, cannot be cured. If the damper gain is increased because of other instabilities such as stopband resonances, the phase margin and delay margin for system stability are reduced (Fig. 8), and the beam stability becomes marginal. The non-linear phase errors of the amplifier chain can cause beam instabilities at 2-5 MHz if the feedback delay is not correctly adjusted.

Transverse instabilities above the bandwidth of the damper must be suppressed by the Landau damping octupoles. Transverse beam oscillations which have their driving force above the frequency bandwidth of the damper can cause sideband frequencies appearing on the damper feedback signal much below the frequency of beam oscillation. The sideband frequencies are generated by the intermodulation between the pulsing beam intensity signal and the transverse beam oscillation.

In order to improve the adjustment of the feedback delay with the beam revolution period during acceleration, a new delay line is being developed which reduces the delay time as the beam gets faster.

For $\bar{p}$ operation, the beam-position monitors must be chosen such that the feedback system is stable both for $p$ and $\bar{p}$ beams. This will not be possible for any betatron wave number $Q$, and a bunch selector will separate $p$ and $\bar{p}$ signals.

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12) Y. Miyara and K. Takata, Coherent transverse instability of a bunched beam induced by interaction with a kicker magnet, Particle Accelerators 10 (1980) 125.
Photo 1  The four beam deflectors with double power amplifiers below the deflector tank
FIG 1 - BLOCK DIAGRAM OF DAMPER LOOP.
NOTE: Set for $V = -100 \text{ mV}$ at point A after 1/4 h of warm up.
FIG. 5: DOUBLE POWER AMPLIFIER 400 x, 0 - 4000 V ptp, 1 KHz - 1,25 MHz.
SETTING-UP

1. SWITCH ON +48 VDC
   POWER SUPPLY IN RACK 0328-42

2. SWITCH ON POWER (LEFT) OF AUXILIARY
   POWER SUPPLIES AND 50 W AMPLIFIERS

3. SWITCH ON MAINS CONTROLLER ON
   THE INTERLOCKS CHASSIS.
   FOLLOWING STATUS MUST BE OK (GREEN):
   POWER A+B, PLUG, VENTIL., WATER,
   TEMP A+B AND AFTER ~30 s HEATER A+B

4. SWITCH ON DC (RIGHT) OF BIAS A
   AND BIAS B POWER SUPPLIES.
   STANDARD SETTING: ~-80 V

5. SWITCH ON DC (RIGHT) OF SCREENS DRIVER POWER SUPPLY.
   CHECK DRIVER POWER SUPPLIES.
   STANDARD SETTING ANODES ~340 V - 800 mA
   SCREENS ~300 V < 100 mA

6. CHECK THE HV-CABLES IN 8 KV PHILIPS POWER SUPPLIES:
   BAPH 31457 AMPLI 1
   1A No. 56625
   1B No. 56626
   BAPH 31451 AMPLI 2
   2A No. 56641
   2B No. 56642
   BAPV 31655 AMPLI 3
   3A No. 56657
   3B No. 56658
   BAPV 31657 AMPLI 4
   4A No. 56673
   4B No. 56674

7. SWITCH ON 380 V MAINS AND MANUAL CONTROLLER ON
   PHILIPS POWER SUPPLY REQUIRED (see fig. 7)
   PHILIPS No. 1
   RS 1876
   PHILIPS No. 2
   RS 1876
   380 V 220/02
   PHILIPS No. 3
   RS 1876
   380 V 220/02

8. CHECK THE SETTING OF PHILIPS CONTROL UNIT:
   CHARGING CURRENT ~ 12 A
   OVERCURRENT ~ 12 A
   OVERVOLTAGE ~ 7 KV
   TOGGLE SWITCHES ~ LOCAL + DC
   THUMBSWHEELS ~ 850

9. UNBOLT THE KEY (IN - ON)
   PRESS THE INTERLOCKS RESET
   PRESS THE BLACK PUSH-BUTTON
   UPDATING THE DAC

10. PRESS THE GREEN PUSH-BUTTON FOR
    SWITCHING ON THE HIGH VOLTAGE.
    AFTER A FEW SECONDS CHECK:
    STANDARD SETTING: ANODES POWER 5 KV - 6A
    (* FOR 1 POWER AMP)
    SCREENS POWER 900 V ~120 mA
    (* WITHOUT SIGNALS)
    THE CURRENT LIMITATION OF SCREENS POWER
    SUPPLY (Fig) MUST BE SET AT 400 mA (Pos. 8.0)

11. SET THE TOGGLE SWITCH
    TO REMOTE POSITION

POWER SUPPLIES INTERLOCKS

WATER HEATER
TEMP. A
VENTIL.

ANODES
POWER

SCREENS
POWER

BIAS A

BIAS B

FIG. 6 SPS DAMPER
SETTING-UP POWER AMPS
SPS - ABM 24 May 1988

SETTING-DOWN

12. SWITCH OFF HV ANODES SUPPLY BY RED PUSH-BUTTON
    OF THE PHILIPS POWER SUPPLY.

13. AFTER 3 MINUTES SWITCH OFF MAINS
    CONTROLLER OF THE INTERLOCKS BOX.
    SWITCH OFF 380 V MAINS OF THE
    PHILIPS POWER SUPPLY.
FIG 7 GAIN AND PHASE DISTORTION VS. FREQUENCY OF HORIZONTAL FEEDBACK LOOP.
FIG. 8. NEW DAMPER LIMITS ON 18-4-80
beam intensity 25 \ldots 33 \times 10^{12} \text{ ppp at injection}
Landau octupole gradient = L