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TACKLING TRANSVERSE COHERENT INSTABILITIES OF CO- AND COUNTER-ROTATING BEAMS IN THE CERN ANTIPROTON ACCUMULATOR

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Summary

In the CERN Antiproton Accumulator, transverse instabilities set in at circulating intensities as low as 10^{10} p($\bar{p}$), mainly because of the unusually small variation of Q vs. momentum. The bunched p "test" beam is lost due to head-tail instabilities, and vertical coasting beam modes of the $\bar{p}$ stack lead to an intolerable emittance growth. Based on estimated AA transverse impedances, a fairly simple feedback system was built. Particular features are (i) low power requirements (10 W); (ii) housing the electronics outside the tunnel; (iii) a "double damper" arrangement enabling the system to tackle simultaneously the $\bar{p}$ stack and the counter-rotating p test beam; (iv) the system's use for controlled beam blow-up to determine machine apertures. Whereas the measured growth rates match the resistive wall impedance, significantly higher damping rates are required to eliminate all coasting beam modes, for yet unknown reasons.

System's Characteristics

Initially, the system was designed for damping coasting beam instabilities[1] in the high density $\bar{p}$ stack, and possibly head-tail instabilities of a $\bar{p}$ bunch circulating on the ejection orbit. Two fairly simple systems, acting on horizontal and vertical modes respectively, and tailored to the particularities of the AA machine, were proposed[2]. Their task is to compensate the AA transverse coupling impedance Z_t by an "equivalent coupling impedance" Z_{tD}

$$\mathrm{Re}(Z_{tD}) = -\frac{G}{\beta^2 c}\,\frac{2}{C}\,\frac{\ell_{PU}}{w_{PU}}\,\frac{\ell_D}{w_D}\sqrt{\frac{\beta_{PU}}{\beta_D}}\,(1+\beta)\,\sin\Phi \qquad (1)$$

where G is the electronic gain, $\beta = v/c$, C the beam position monitor (Pick-Up electrode) capacitance, ℓ_{PU}, w_{PU}, β_{PU}, ℓ_D, w_D, β_D length, width of and betatron amplitude function at the PU and deflector, Φ the betatron phase shift between PU and deflector.

Initial Hardware Layout. The beam oscillations in both planes are sensed in a dispersion-free location by a standard electrostatic position monitor (PU). Horizontal and vertical signals, treated separately, are sent to the Equipment Room outside the tunnel, properly delayed and pre-amplified. For each plane, two signals, 180^0 out of phase, are generated by a splitter and fed into 10 W amplifiers, which in turn drive the transmission line deflector in push-pull mode. PU and deflectors (one per plane) are only a few meters apart; the delay available is thus slightly in excess of a full machine revolution, enabling the electronics to be installed outside the tunnel (see Table 1).

Closed Orbit and Amplifier Power. Accommodating PU and deflectors in a dispersion-free straight section cuts down the power requirement because (i) the deflector dimension can be kept small (w_D in Eq. 1)); (ii) the closed orbit signal of the bunched beam does not saturate the 10 W amplifiers, even without special circuitry suppressing harmonics of the revolution frequency[3].

Bandwidth: Coasting Beam[4]. For stack stability, the system has to provide

$$-\mathrm{Re}(Z_{tD}) > \mathrm{Re}(Z_t) \qquad (2)$$

at betatron line frequencies

$$f_\beta = (n-Q)f_o, \quad n \text{ any integer} > Q \qquad (3)$$

(n < Q lines intrinsically stable), up to a frequency where the betatron frequency spread

$$\Delta f_\beta = \left[(n-Q)\eta + \xi Q\right] f_o \left(\frac{\Delta p}{p}\right) \qquad (4)$$

(with $\eta = -\frac{df_o}{f_o} / \frac{dp}{p}$ and $\xi = \frac{dQ}{Q} / \frac{dp}{p}$)

provides sufficient Landau damping. The transverse coupling impedance, dominated by the resistive wall, has been computed[5]

$$Z_t \sim 6.4\times10^4 - i\ 3\times10^7\ \Omega/\mathrm{m} \text{ around } 1\ \mathrm{MHz}.$$

The highest unstable mode number n is determined by drawing the stability diagram of the final $\bar{p}$ stack intensity vs. momentum distribution. Modes are unstable for $3 \leq n \leq 12$, suggesting a bandwidth of $0.5 \leq f \leq 25$ MHz, including some margin.

Bandwidth: Bunched Beams[6]. In contrast to coasting beams, modes n are coupled to each other and thus easier to damp. On the other hand, the appearance of head-tail modes higher than m = 4 (m = number of nodes within a bunch) requires in principle a large bandwidth. However, these modes grow slowly and are thus rather harmless for the resistive wall-type impedance and small chromaticity ξ (see Fig. 1).

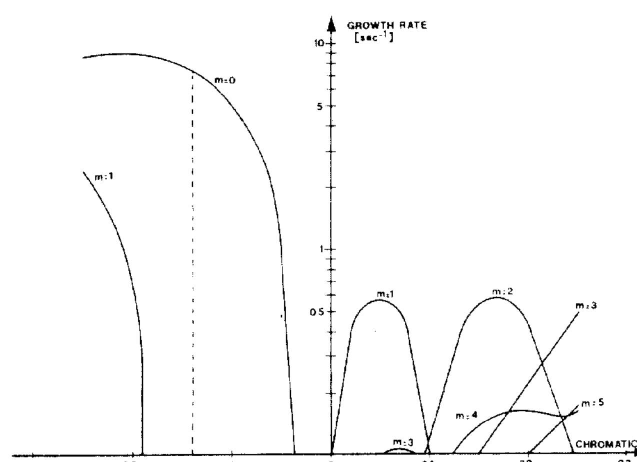

Fig. 1: Growth rate vs. chromaticity for a bunch of 10^{11} p, with the AA resistive wall impedance $\mathrm{Re}(Z_t) = 63000/\sqrt{f(\mathrm{MHz})}\ \Omega/\mathrm{m}$ for small values of chromaticity. m = head-tail mode number.

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Table 1: Damper Parameters

	horiz.		vert.	
Position PU electrode	horiz.		vert.	
length ℓ_{PU}		0.22		m
width w_{PU}	0.12		0.09	m
capacitance C		70		pF
amplitude function β_{PU}	17.4		11.1	m
Deflectors				
length ℓ_D		0.42		m
width w_D	0.076		0.064	m
amplitude function β_D	10		7.3	m
betatron phase shift Φ-2×360				
clockwise ($\bar{p}$)	120		117	DEG
counter-clockwise (p)	66		84	DEG
characteristic impedance (push-pull mode)		50		Ω
Electronic chain				
total electronic gain G	67		63	dB
out of which power amplifier		50		dB
attenuator (computer-controlled)		-6 ÷ -17		dB
maximum betatron phase error (up to 30 MHz)		± 30		DEG
power amplifier rating		10		W
noise		- 32		dBm
electronic delay:				
clockwise ($\bar{p}$)	561		555	nsec
counter-clockwise (p)	523		532	nsec

Double Damper

Aim. The system was initially designed for clockwise circulating beams: (i) the $\bar{p}$ stack; (ii) the $\bar{p}$ bunch on the ejection orbit. There are, however, more types of unstable beams, rotating ccw: (i) the p test beam on the ejection orbit; (ii) debunched p beams for machine experiments. Test p bunches are injected into the AA in reverse direction prior to $\bar{p}$ transfer for checking the beam line, thus the unstable $\bar{p}$ stack may be in the presence of a counter-rotating p bunch (the latter proves unstable on certain orbits, with intensities as low as 2×10^{10}p).

Changing Sense of Beam Rotation. PU and deflectors are only a few meters apart. With the nominal machine tune Q ∿ 2.27 in both planes, the non-integer part of the betatron phase shift is fairly near to the optimum value of 90^0 (Eq. (1)) for both beam directions (Table 1). Nevertheless, the electronic delay as well as the deflector connections need changing when the sense of beam rotation is to be reversed. In actual operation, this proves quite cumbersome as it requires stopping the beam, and does not help to damp counter-rotating beams simultaneously.

Separation of Damper Electrodes. Instead of building a second loop for the p test beam, a solution using existing equipment and thus saving precious straight-section space is applied: rather than operated in push-pull mode, the two electrodes of the transmission line deflector are driven by independent electronic chains, one with the connections and electronic delay appropriate for clockwise rotating particles ($\bar{p}$), one for anti-clockwise circulating beams. As the effect of a signal on the beam is proportional to 1 ± β (- for the deflector electrode connected in the sense of beam rotation, + for the opposite), and β = 0.97, the effect of the $\bar{p}$ electrode on p, and vice versa, is small.

Potential Drawbacks. (i) The transmission line deflector has ∿ 50 Ω in push-pull operation, matched to the amplifier output impedance. Separation of the electrodes influences the characteristic impedance, but the mismatch proved ∿ 10 % and the reflected signal thus acceptable. (ii) The loop gain is lowered by 6 dB which has to be compensated. (iii) The position PU is non-directional, thus there is no way of avoiding, for instance, a signal due to the p test beam entering the $\bar{p}$ stack stabilizing loop. Yet, no adverse effects due to this have been observed so far.

A block diagram of the system, with the double damper arrangement, is given in Fig. 2.

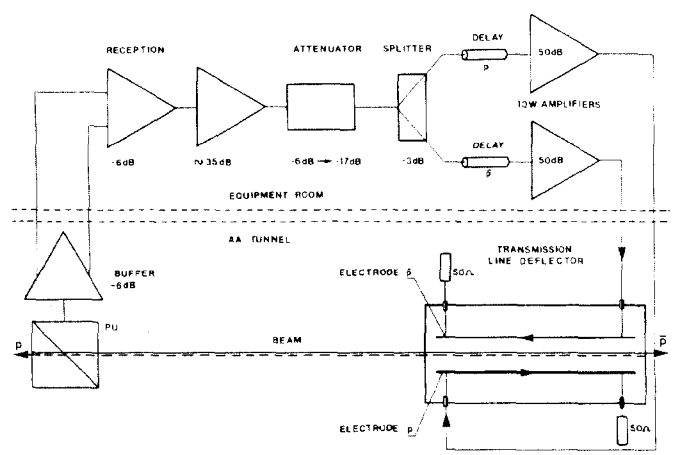

Fig. 2: The AA transverse feedback system in "double damper" connection (one system per plane).

Beam Experiments[7]

Delay Adjustment. The beam transfer function is measured with a network analyzer by exciting a test beam. The loop delay is adjusted such that the maximum of beam response coincides with phase ≈ 0 (± 30^0 up to 30 MHz). The effective damping rate is derived from the inverse transfer function (stability diagram).

Stack instabilities. A series of experiments performed on a cooled stack of ∿ 7×10^{11} p (rotating clockwise) revealed the following features (feedback loops open): (i) Fairly random appearance of vertical betatron lines on a Schottky PU signal, peaked around 18 MHz $[(12-Q_V)\cdot f_0]$ and yielding enlarged vertical emittances rather than leading to beam loss. (ii) Fastest growth rate 0.5/sec, much slower than what one would expect with the resistive wall impedance, provided the entire stack oscillates (∿ 60/sec). (iii) All horizontal lines are stable. (iv) Eliminating ∿ 1 % of the beam by vertical shavers completely removed the betatron lines. This latter observation suggests that in the stack, only a small fraction of the beam is unstable: The high mode numbers n are generated by local tune vs. frequency variations within the stack (the "macroscopic" AA chromaticity is much too small to explain the observed mode pattern), and growth rates would then become compatible with $\mathrm{Re}(Z_t) \sim 10^5\ \Omega/\mathrm{m}$. However, with the loops closed, a seemingly excessive gain increase of 30 dB over the one which would just cancel the growth rate, is required to completely eliminate all stack instabilities, for yet unknown reasons (see Fig. 3, damping rate $\sim$ 30 times faster than the growth rate).

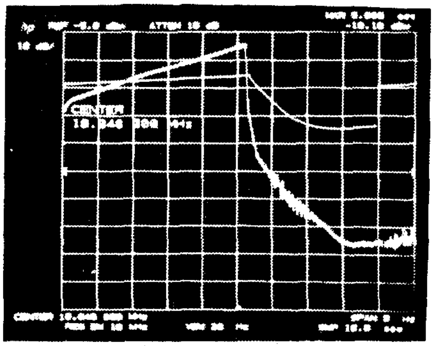

Fig. 3: Two shots of vertical coasting beam mode $(12-Q)f_o$ before and after closing the feedback loop. 10 dB/div., 1 ms/div.

Bunched Beams. Their transverse stability appears intimately linked to local Q variations in the AA momentum range, as sudden coherent blow-up occurs at distinct revolution frequencies. For instance, a horizontal head-tail mode m = 0 (head-tail phase shift $\sim$ 5 rad with a local chromaticity $\xi = -.14$) destroyed a test beam of 2×10^{10} p with a growth rate of 2 sec^{-1}; this is in good agreement with what one would expect from the resistive wall impedance (Fig. 1, to be scaled from 10^{11} to 2×10^{10} p). Bunched beam modes are readily damped by the system, $\sim$ 100 times faster than the instability growth rate.

Cross-talk Between Beams. A $\bar{p}$ stack and a $\bar{p}$ bunch being extracted from the stack and brought onto the ejection orbit co-rotate. The damping loop has the appropriate delay for both beams, thus providing stabilization for each of them. A cross-talk effect may, however, be generated by a coupling impedance which changes strongly over the AA momentum range (aperture). Another critical situation may arise when the $\bar{p}$ stack "feels" the signal of an (unstable) counter-rotating p test bunch as the PU electrode is non-directional. Apart from local wiggles, the betatron tune is constant within 0.005 over the momentum range, thus the betatron bands of a beam on the injection/ejection orbit do not coincide with those of the stack. Instabilities involving both beams cannot be generated in this situation; they may, however, be provoked in machines with stronger tune variations. While these beam configurations occur regularly in AA operation, none of the cross-talk effects have been observed since the feedback systems have been run in the double damper arrangement.

Controlled Blow-up. The AA apertures are explored by exciting the beam on the lowest betatron sideband ($\sim$ 1.3 MHz) until the first beam losses occur, and subsequent measurement of beam dimension[8]. The excitation signal is FM modulated around 1.3 MHz (carrier deviation ± 40 kHz, modulation rate 15 Hz). Higher modulation frequencies are much less effective, probably because then spectral lines are too far apart to blow up all particles. It has been shown[9] that a random noise signal of equivalent bandwidth and power fits the emittance growth rate (a few minutes with 8 W power) observed with 15 Hz modulation.

Outlook. Stabilizing substantially higher $\bar{p}$ intensities should not require more electronic gain (Eq. (1)), unless the AA coupling impedance Z_t is significantly changed. A possible complication may arise from the closed orbit signal due to bunches of more than 10^{11} $\bar{p}$; it can be coped with by increasing the amplifier power.

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