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EXPERIMENTS AND PRACTISE IN BEAM SHAKING

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Abstract Storage rings with negative particle beams suffer from neutralisation effects due to ions produced from the residual gas. For antiproton accumulators currently in service, these problems would be very serious were it not for the existence of efficient clearing systems to extract ions and feedback systems to stabilise the $\bar{p}$-beam. Similar problems exist for small electron storage rings, because clearing electrodes are often not sufficient to completely eliminate ions trapped in the beam potential well.

One antidote, recently further developed at CERN and Fermilab, consists in shaking the beam at a fixed frequency close to one of the betatron side bands of the main beam and close to the bounce frequency of trapped ions. This paper will describe the experience gained in applying this method on the CERN and the Fermilab Antiproton Accumulators, and on the CERN 600 MeV electron positron damping ring (EPA).

INTRODUCTION

Problems of residual beam neutralisation[1] have been observed in almost all high-intensity electron and antiproton storage rings. The situation in the Antiproton Accumulator (AA) at CERN may serve as an example. Adverse effects due to trapped ions were anticipated in the design of the AA[2]. Hence a number of measures to control these phenomena were taken during the construction and the later upgrading of the machine. First, the AA is equipped with a ultra-high-vacuum system[3] with high pumping speed to obtain an average pressure of less than 10^{-10} mbar. Second, a powerful clearing system[4] is operational with 45 electrodes nowadays, providing a vertical clearing field of several tens of V/cm. Individual electrodes are equipped with electrometers capable of measuring clearing currents down to 0.1 pA, thus providing a diagnostic tool to localise, e.g., regions of high outgassing. Third, screening of cavity-like objects was provided[4] by metallic sleeves to avoid neutralisation pockets caused by localised potential wells. Fourth, a feedback system[5] is used to damp coherent dipole mode instabilities.

In spite of these precautions, residual neutralisation remained a major cause of trouble leading to beam instabilities and emittance growth[6-11]. Over the years, the improvement of both stacking rate and peak density has been closely related to the amelioration of neutralisation effects.

BEAM SHAKING IN THE AA

An additional antidote introduced last year is beam shaking[12]. Transverse coherent oscillations of the $\bar{p}$-beam are driven by an rf-field applied on a pair of electrodes which act as a transverse kicker. A pure sinewave excitation is used. The kicker field is typically 10 V/cm and the length of the electrodes is 0.6 m. This leads to driven oscillations of the $\bar{p}$-beam with an amplitude of less than 0.01 mm, even when the shaking frequency is close to one of the betatron sideband frequencies $(n \pm Q)f_{rev}$. Surprisingly enough, even this small amplitude leads to a distinct improvement of the neutralisation behaviour when the shaking frequency is carefully chosen.

A number of frequencies in the range of 0.1-10 MHz were explored during machine study sessions. A very clear improvement was observed with vertical shaking near 490 kHz, which is about 10 kHz above the lowest $(0 + q)$ band, q being the fractional tune. Tuning the excitation still closer to this band tends to produce beam heating. The main effects observed were a reduction of the loss rate and an improvement of the equilibrium emittances with stochastic cooling. At intensities around 5×10^{11} $\bar{p}$, where most of the experiments were done, these improvements were of the order of 10%.

In addition, observations were made on a quadrupolar mode instability[10]. The threshold could be lowered by reducing the dc-clearing fields. It was found that with vertical shaking at 490 kHz a significantly larger reduction of the clearing field was possible before the instability started. Typical clearing voltages are 200 V in normal operation and 80 V and 40 V, respectively, for the onset of the instability of 5×10^{11} p without and with shaking.

We mention in passing that later in 1988 stability was much improved by raising the dc-voltage on a few strategic clearing electrodes and by tuning the working point very close to $Q_h = Q_v = 2.25$ where quadrupolar fast wave $(n + 2Q)$ and slow wave $(n - 2Q)$ frequencies coincide. This introduces stability by "fast-wave/slow-wave cancellation"[11] and probably also by coupling of the larger vertical frequency spread into the horizontal oscillation.

Since September 1988 vertical shaking at 490 kHz has been used routinely during operation. This, together with the improved dipolar mode stability, permitted intensities of 6×10^{11} to be exceeded without any significant increase of the loss rate up to 8.5×10^{12}. The improvement, with the standard shaking is clearly seen from Fig. 1. The design intensity of the AA, 10^{12} $\bar{p}$, after its upgrade in 1987/88, has recently been reached with an effective stacking rate of $\approx 8 \times 10^6$ $\bar{p}$/sec which is still more than half the value at low intensity.

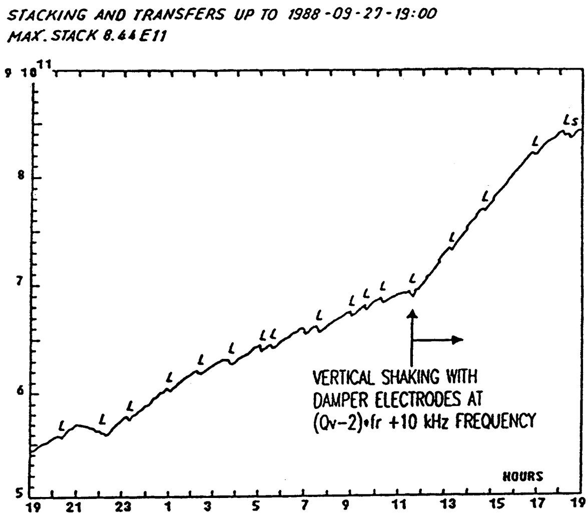

FIGURE 1 Stacking rate improvement in the CERN AA with shaking.

Beam excitation at other frequencies has been tried both independently of or in addition to the standard 490 kHz shaking. None of these tests has shown any significant (further) improvement.

Horizontal excitation even at 490 kHz or neighbouring frequencies showed no observable effect. Vertical excitation around 470 kHz, i.e. below the first bands, leads to an improvement much less pronounced than at 490 kHz. No observable effects were found at higher (vertical or horizontal) excitation frequencies close to other betatron sidebands, but a small improvement of equilibrium emittance --much smaller than with the standard shaking-- was observed on one occasion with vertical excitation near 400 kHz.

Other investigations were concerned with the amplitude of the driving field. Early this year, a new kicker and a stronger amplifier were installed permitting 10 to 20 times stronger excitation. It was found that at the standard frequency and for kicker fields above 10v/cm the effect was virtually independent of driving amplitude.

Using stronger fields, the frequency could be further removed from the (0 + q) band and shaking below this band became also effective, but results never exceeded those of the standard case (f = 490 kHz, E = 10 V/cm, ℓ = 60 cm) used in routine operation.

Most of these results can be explained --at least in a qualitative way-- by the theory[10-11] which assumes longitudinal motion of the ions leading to a lock on effect of the ions in the nonlinear ion-antiproton resonance. Shaking near a betatron sideband is efficient because the $\bar{p}$-beam responds resonantly. The theory also indicates that lock-on together with resonant response of the coupled $\bar{p}$-ion system is more efficient at frequencies just above an (n + q) band than just below the same band. The reverse is true for excitation near an (n - q) band.

Questions not fully understood concern the special role of the 490 kHz band and the ineffectiveness of horizontal shaking. The 490 kHz corresponds to the bounce frequency of singly charged ions of mass 25-30 (CO, etc.) in the long straight sections. As the beam size varies around the circumference, ions of different masses respond resonantly in other parts of the ring, but it seems that lighter ions (which respond at higher frequencies) are less important in the AA. The larger vertical sensitivity might be related to the fact that ions can move much easier vertically than horizontally in the bending magnets.

THE FERMILAB ANTIPROTON ACCUMULATOR (FNAL)

In March 1989, the experience gained on the CERN AA with transverse shaking helped to reduce ion neutralisation effects in the FNAL antiproton accumulator, a machine very similar to the AA but operating at 8 GeV/c and with 3 times less line charge density for similar antiproton beams. Transverse shaking was applied via the damper electrodes, with amplitudes also much less than 0.01 mm (typical integrated electric fields of 500 V·m /m) and with very similar positive results. Tuning the shaking frequency just above (+7 kHz) the fractional tune sideband at 400 kHz gave the best results in terms of improved stacking rate and reduced beam emittances (Fig. 2), the effect starting to be visible above 5×10^{11} particles.

Unlike the CERN AA, a limited amplitude coherent signal at $2-q_{v,h}$ (876 kHz) is usually present in both planes above stack intensities of 5×10^{11} particles in the FNAL accumulator. By applying vertical shaking below (-7 kHz) this ion-driven unstable mode, the instability could be suppressed. The fact that shaking above (+7 kHz) is less efficient, as can be seen in Fig. 3, is a demonstration of the asymmetry of shaking, as discussed in Ref. 10.

THE CERN ELECTRON POSITRON ACCUMULATOR (EPA)

The 600 MeV, 126 m circumference EPA of the LEP pre-injector chain at CERN stores electrons in 8 bunches for a few seconds, interleaved with positron cycles. This machine, too, is also plagued with ion neutralisation effects, despite its clearing electrode system[12]. With a nominal

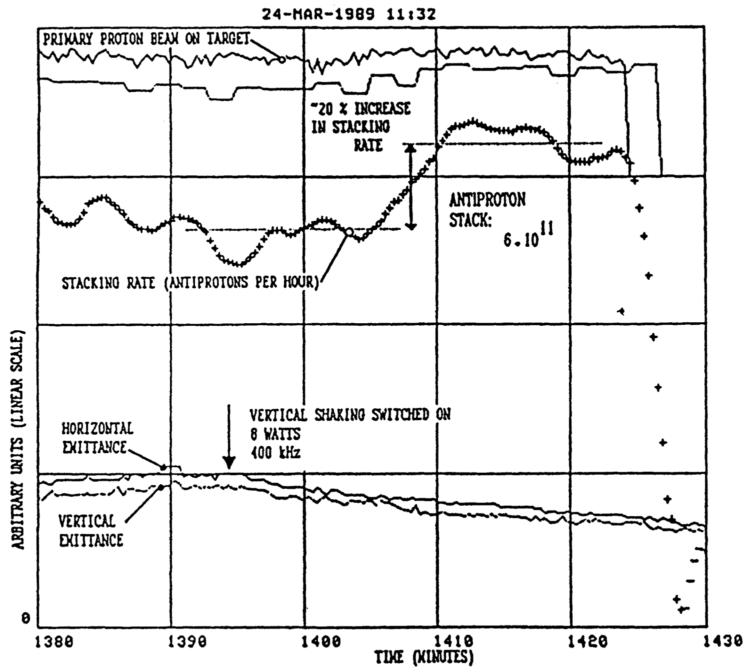

FIGURE 2 Stacking rate improvement with shaking, obtained in the FNAL Antiproton Accumulator.

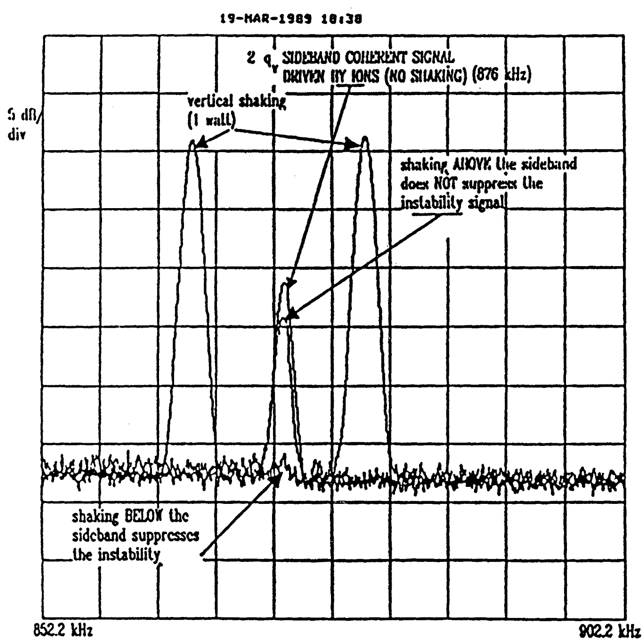

FIGURE 3 Suppression of an ion driven dipolar instability by vertical shaking in the FNAL accumulator.

transverse emittance of $8\pi\ 10^{-8}$ m.rad, and damping times of 60 ms, it is representative of many electron storage rings. Similar problems will also be important in B-factories, especially in designs where the e^+ and e^- orbits are separated over most of the circumference. Hence, beam shaking tests were conducted on EPA to further assess the effectiveness of curing ion effects in electron storage rings. The sine wave excitation voltage was fed via a 600 W rf amplifier onto one meter long transverse kicker electrodes used for tune measurements, resulting in beam amplitudes of typically a few hundredths of a millimeter. A whole set of transverse frequencies and rf power levels was tried, both horizontally and vertically, whilst monitoring the beam transverse emittances and tunes. Once again, it was found that large emittance reductions could be obtained by shaking vertically above the machine fractional tune (920 kHz). Shaking was found to work best within 30 kHz above this mode, with little dependence on rf power. No other mode frequency was found to be of any significant influence up to 20 MHz.

Figure 4 shows typical beam profiles as obtained on a synchrotron light monitor, without clearing electrodes (a), with clearing elec-

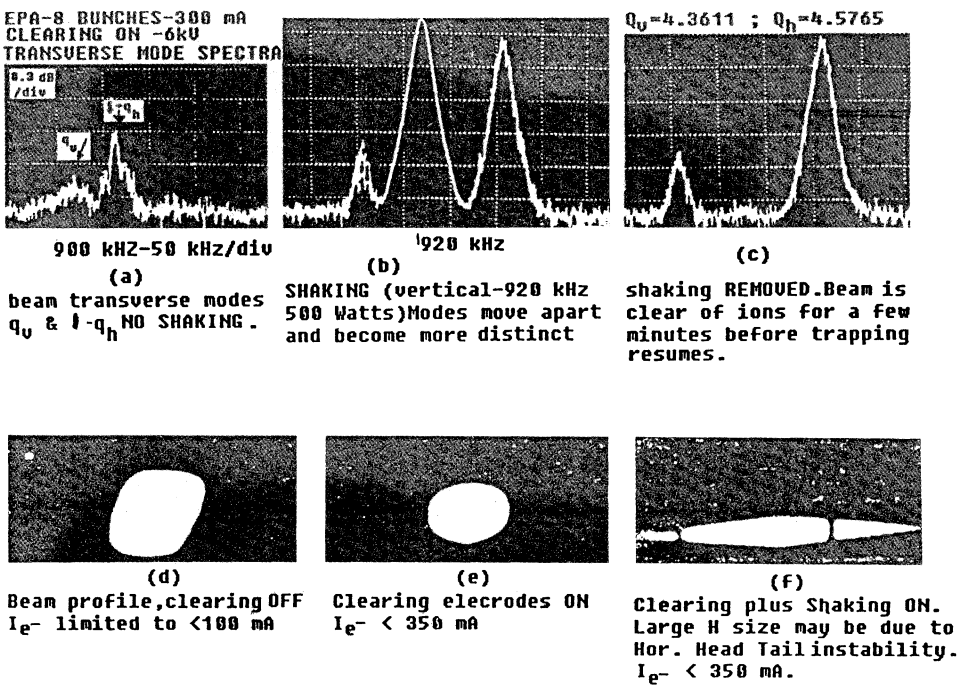

FIGURE 4 Beam profiles and transverse mode spectra with and without shaking on the CERN EPA machine.

trodes (b), and with clearing and shaking (c). Shaking was found to work best with clearing ON, as on the UVSOR. Figures 4a, 4b, 4c show the natural beam transverse mode envelopes (n=0) with and without shaking around 920 kHz. The tune shifts with shaking are consistent with a neutralisation of around 5% with no shaking. It was also found, though not always in a reproducible manner, that when the shaking was turned off, the beam would remain clear of ions (Fig. 4c), as if an ion trapping threshold had been passed. The beam image profile, however, would show on these occasions a large horizontal size, possibly resulting from a horizontal head-tail instability (Fig. 4f).

DISCUSSION OF RESULTS

Our experience shows that shaking has some influence only when the beam current is large enough. This means that in our cases rf transverse electrical fields used for shaking excite ions only indirectly, namely through transverse oscillations of the circulating beam. The beam excites ions at any point of the orbit through transverse oscillations of the potential well where ions are trapped.

We believe that when shaking is efficient, the shaking frequency is resonant with those ions which are responsible for harmful ions-on-beam influence. As a result the transverse distribution of ions becomes wider, and their density and their influence on the beam becomes smaller. The fact that the most efficient shaking frequencies always turned out to be close to some betatron sidebands (n+Q) or (n-Q) means that in all cases we have found the ions which are responsible for some mutual dipole beam-ion excitation. Although dipole excitations of the beam are partly suppressed by feedback loops in antiproton accumulators, and by synchrotron radiation in electron rings, the ions remain inside the beam and contribute to the excitation of high-order coherent resonances k(n+Q) or k(n-Q), $k > 1$. The shaking process suppresses or dilutes these ions.

The problem is that because of the variations of the beta-function along the ring, ion frequencies are also varying. Therefore, those ions which are responsible ONLY for high-order coherent beam-ion resonances (i.e., with frequencies or their harmonics close to (n+mQ) or (n-mQ), where n/m is NOT an integer) can be sitting in parts of the orbit which are different from the ones of the "dipole-ions" discussed above. Our shaking did not influence them. Such ions probably existed in EPA when shaking only improved emittances but did not extract ions. One case of the successful shaking in AA with 350 kHz shaking frequency (far from any sideband) perhaps also falls in this category. Unfortunately, we did not systematically investigate shaking frequencies close to non-dipolar resonances.

Our experience shows that it is possible to shake ions without significant excitation of the beam. The frequency of shaking must be close, but need not be too close to the corresponding sideband.

CONCLUSION

Our experiments and practical exploitation of shaking have confirmed that it is an effective method to remove or phase-space dilute the ions which are responsible for different mutual beam-ion excitations. For further improvements, it is necessary to investigate shaking near non-dipolar resonances and the efficiency of using several frequencies simultaneously. We never observed any effect when putting a second shaking frequency into operation and this is not fully understandable.

It is also necessary to develop numerical models that will take into account the mutual influences of coupled horizontal and vertical ion oscillations in the presence of shaking, the character of longitudinal movements of ions, and the influence of magnetic fields inside magnets of different types.

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