ION SHAKING in the 200 MeV XLS-RING*.

Eva Bozoki and S.L. Kramer
Brookhaven National Laboratory, Upton, N.Y.

Abstract

It has been shown [10-15] that ions, trapped inside the beam's potential, can be removed by the clearing electrodes when the amplitude of the ion oscillation is increased by vertically shaking the ions. We will report on a similar experiment in the 200 Mev XLS ring. The design of the ion clearing system for the ring and the first results obtained, were already reported [3,4]. In the present series of experiments, RF voltage was applied on a pair of vertical striplines. The frequency was scanned in the range of the ion (from H_2 to CO_2) bounce frequencies in the ring (1-10 MHz). The response of the beam size, vertical betatron tune and lifetime was studied.

1. INTRODUCTION

The transverse electric field of the beam will cause ionized gas atoms to oscillate around the beam centroid with a frequency (in the linear approximation [1,2]):

$$f_{ion} = \frac{\omega}{2\pi} = \frac{1}{2\pi}\left[\frac{2\, r_p\, c^2\, N_e}{A\, L\, \sigma_{x,y}\, (\sigma_x+\sigma_y)}\right]^{1/2} ,$$

where L=circumference of the ring, N_e=number of electrons in the beam, A=mass of ion and $\sigma_{x,y}$=horizontal and vertical beam size. Depending on the circumstances, the ions can be stable or unstable. In the **linear theory** of ion trapping with **uniformly distributed bunches** an ion is trapped if its mass is less then the critical mass (A_c), which is proportional to the number of electrons per bunch and inversely proportional to the beam size [3]. A similar linear analysis in the case of a **bunch train** followed by a gap of empty bunches yields (instead of one critical mass) regions of stable and unstable ion masses depending on beam current and beam size [5].

Nonlinearities in the beam-ion force (in some cases coupled with a gap in the bunch train) can produce destabilizing resonances in the ion's oscillatory motion at certain regions of the lattice. If the ions are longitudinally mobile, they can be lost for the electron beam by passage between a stable and unstable region of the lattice. Consequently, only ions inside some core remain stable [7].

Stable ions with amplitudes outside the beam can be cleaned with static voltage (clearing electrodes). For small amplitudes the ions accumulate and an ion cloud is produced in/around the the beam which partially or totally neutralizes it. Due to the focussing effect of the fields produced by the ions on the beam, this can lead to instabilities and beam loss [8].

The amplitude of the ion oscillations can be increased by applying RF frequency **shaking**. The clearing electrodes then can remove the "shaken out" ions. Several methods have been tried to couple energy into the oscillatory modes of the ion motion [9]. In the **resonant mode**, shaking the beam near one of the betatron sidebands causes the beam displacement to grow resonantly and the ions, oscillating near this frequency are effected. In this case small RF voltage is enough to remove the ions. For the AA and EPA at CERN for the AA at Fermilab as well as an experiment at UVSOR this method yielded excellent results [10-13]. When the f_{ion}'s are far away from these sidebands, the **rigid mode** shaking of the beam at f_{ion} can still drive the ions to large amplitudes, although less efficiently. This was tried successfully at both UVSOR [14] and TERRAS [15].

Calculations were done [14,16] for the expected effect with **frequency modulation** shaking, where as a result of the nonlinearity of the beam space charge the ion oscillation amplitude "locks on" to large values when the shaking frequency is swept from above to below the ion bounce frequency.

Finally, **cyclotron resonant** shaking [17] is horizontal shaking to clear ions inside dipole magnets, where the magnetic field leads to cyclotron motion in the horizontal plane, at the cyclotron frequency instead of the ion bounce frequency.

2. EXPERIMENTAL SETUP

Throughout the experiments clearing electrodes (CE) at both ends of each dipole, where the potential wells are, and in the two straight sections (see [3,4]) were used. The same voltage was applied on all CE's

For part of the experiments **vertical shaking** was applied. The 1-10 MHz region was scanned and each time the "most effective" frequency, the one which had the greatest effect on the beam size, was determined by monitoring the beam profile signal. The shaking frequency was split into two signals 180° apart in phase and used to differentially drive two pair of vertical plates of a quadrupole stripline kicker. Each stripline consisted of a 30 cm long, 50Ω stripline, terminated in a 50Ω load and driven by a 100 Watt broadband amplifier. The voltage response of the amplifier and the coupling to the beam varied with frequency but yielded an rms vertical displacement of $y_{rms} < 5\mu m$ at 4.5 MHz.

---

* Work performed under the auspices of the U.S. Department of Energy and funded by the U.S. Department of Defense.

The calculated f_{ion} for A = 2 - 44 is shown in Fig.1 as a function of beam current in six uniformly spaced bunches. Since no ions have f_{ion} close to any of the sidebands $f=(n \pm m\nu_y)f_o$ (where ν_y=.415, f_o=35.3 MHz), the beam will not respond resonantly amplifying the beam displacement to larger amplitudes. However, even the small displacements provided here are expected to induce resonant ion motion provided the frequency spread around the lattice is not too large. The influence of the ion trapping on the stored beam was measured using three beam properties: vertical beam size, beam current lifetime and betatron tune shift and shape.

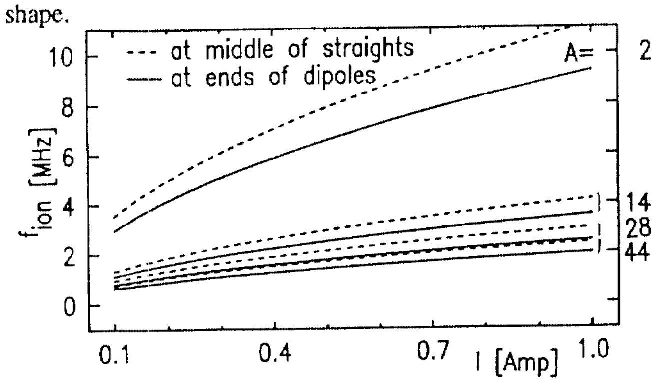

Figure 1. Ion bounce frequency (calculated in the linear approximation) for 6 uniformly spaced bunches in the ring.

Beam size measurements were performed using a synchrotron radiation monitor at the end of one of the dipoles. This consisted of light collection optics and apertures in a non-reflective tube that provided an image of the beam on a CCD camera with a magnification of 0.53. The video signal was captured by a digital frame grabber (DFG) interfaced to the XLS control system. The digital analysis of the video signal yielded horizontal and vertical beam size and position information. Later, a Spiricon Laserbeam Analyzer (SLA) was used to provide greater speed of response and flexibility of the analysis (e.g. multi-frame averaging and correlated elliptical beam fitting) of this video signal. Data taken with the SLA was typically averaged over 2 to 4 frames in order to reduce beam motion effects. Both systems gave similar measurements of the beam size and had variable gain and blacklevel offset, in order to optimize the dynamic range of the digital signal, as the intensity varied.

The **beam life time** was measured by detecting the rf frequency component of the beam signal from the sum of the signal of a pair of wide plate striplines. A spectrum analyzer with a 300 kHz bandwidth measured the signal intensity as a function of time. A least squares fit to this data gave the exponential lifetime to a resolution of 0.2 min for a period of 15 seconds. The striplines provided large charge collection and their signal was quite insensitive to position changes in the orbit but had systematic shifts resulting from synchrotron oscillations (≈200kHz).

The **tune** measurements used a network analyzer to drive a horizontal coherent betatron oscillation using the same amplifiers and stripline kickers used for beam shaking but at a frequency of 195 MHz. The coherent dipole beam signal was obtained from the vertical difference of the signals from the stripline pair used for lifetime measurements (described above). Sufficient coupling between the horizontal drive and the vertical dipole signal was available to allow simultaneous measurement of both betatron tunes. With the large coupling of the striplines at the frequencies being excited, the drive power could be kept quite small in order to avoid disturbing the ions by the scanned measurement. Typically the tunes were measured with a resolution of ±0.00035.

3. MEASUREMENT RESULTS

Beam size measurements using only static clearing voltage were carried out earlier [4]. The measurements showed a vertical beam size growth without clearing, which increased with the beam current, limiting the maximum injected current. Applying and increasing the clearing voltage up to a value (V_c), equal to the maximum of the beam's potential, caused σ_y to decrease. Increasing the clearing voltage beyond V_c had no effect.

Fig.2 shows the influence of rf ion shaking at the "most effective" frequency (typically 2.8 to 4.5 MHz) on the vertical beam size. These data were taken at different occasions over a period of about one year. In each measurement the rf shaking was repetitively turned ON (●) and OFF (o) during the decay of the beam. There were 6 bunches in the ring and the clearing voltages varied between 100 - 500 volts. One can see that the vertical beam size is significantly and systematically lower with shaking then without it.

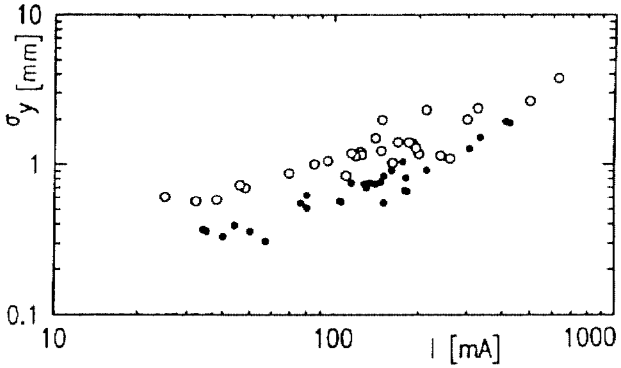

Figure 2. Vertical beam size as a function of the stored beam current with shaking turned ON (●) and OFF (o). Clearing voltage was 1 - 500 V.

On several occasions, σ_y was measured with rf shaking on but without clearing voltage, and they always showed that shaking alone had no effect. This is consistent with the model for rf ion shaking as being an enhancement to the effectiveness of the dc clearing voltage (or vice versa) for extracting trapped ions from the beam's potential well [6,14]. It is also consistent with previous experimental findings [12-14].

On other occasions, beam was injected with the rf shaking on allowing injection above previous limits set with only the dc clearing voltage on. However, instabilities would set in at higher current values, sometimes with a beam dump.

Varying the shaking frequency showed that once the beam size was reduced at the "most effective" frequency, it could be lowered (not raised) and the beam size would remain small at frequencies which previously had no significant effect on the beam size. The above observations are consistent with the "lock-on" effect discussed earlier.

Since the CCD camera integrates the beam image over a time interval of 1/30 sec, any beam motion during this time would appear as a shape and width change. In order to verify the beam size changes described above were not due to beam motion the beam **lifetime** was measured as a function of current and ion clearing conditions. Since the XLS lifetime is dominated by Touschek scattering, this property of the beam should vary inversely as the particle density in the bunch. Fig.3 shows the measured lifetime with (•) and without (o) ion shaking applied. Although the lifetime data showed large fluctuations due to beam instability, a clear reduction of more than a factor of 2 is observed below 150 mA. Above this current beam instabilities made lifetime measurements difficult. Typically, measurements were made by switching the rf shaking off and on. In each case, the lifetime would take up to a minute to stabilize to its new value, possibly the result of the ion production and clearing rates. One point (◊) at 15 mA shows the large increase in lifetime resulting from a measurement with no clearing and no rf shaking on. This indicates the influence of the ion fields on the beam size when trapping by the beam is not countered by these two methods.

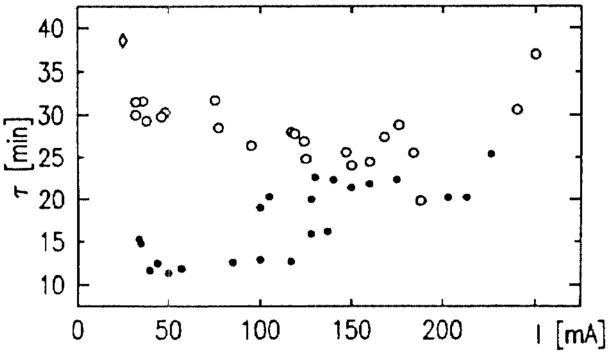

Figure 3. Beam lifetime with shaking ON (•) and OFF (o). Clearing voltage was 1 - 500 V. One point (◊) corresponds to no shaking and no clearing.

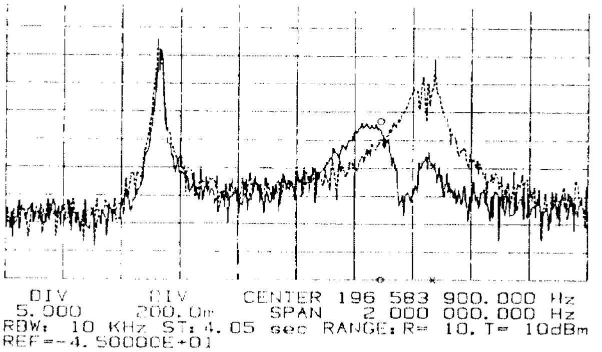

Figure 4. Tune signal with shaking ON (solid line) and OFF (dotted line). Clearing voltage was 300 V.

Tune measurement showed very distinctive effects of the ions. With only DC clearing voltage applied the vertical tune signal showed a broad peak with a shoulder toward higher tune values. The width increased with current and the average value of the signal peak moved toward higher values as the current increased, consistent with the focusing effect due to ion trapping. When the rf shaking was added the tune decreased and showed a narrower peak only at low currents. As the current increased, the tune signal shifted toward higher values and split into two peaks when the rf shaking was turned on, as shown in Fig.4. This phenomenon is not consistent with any of the present models for the effect of rf shaking and will be the subject of further study.

4. CONCLUSIONS

There are frequencies (between 2.8 and 4.5 MHz, not always the same, somewhere around hydrogen or somewhat heavier), where slowly scanning the shaking frequency from higher to lower, the beam size suddenly changes from round or rather vertically larger beam to a much flatter (vertically smaller) beam. This change is rather convincing. However, at higher current the effect was not found with such clarity. At higher current the beam size is big enough that the ion amplitude with 100 watt fixed frequency shaking is still inside the beam. Since the beam's potential well is proportional with the beam current the ions need more kinetic energy to get out of it.

Shaking together with dc clearing is better then clearing alone. Shaking alone has no effect.

The effect of trapped ions on the betatron tune shows a dependence consistent with models at low currents or with only dc clearing. The influence of the rf ion shaking at higher currents is considerably different than the behavior predicted by these models and will be the subject of future study.

5. REFERENCES

[1] A.Poncet, CERN/MT/90-1 (ES), 1989.
[2] Y. Miyahara et all., NIM, A270, p.217-225, 1988.
[3] Eva Bozoki and H. Halama, NIM A307, p.156-166, 1991.
[4] H. Halama and Eva Bozoki, PAC, San Francisco, 1991.
[5] M.Barton, NIM A243, p.278-80, 1986.
[6] C.J.Bocchetta and A.Wrulich, ST/M-88-26, 1988.
[7] D.Sagan and Y.Orlov, Proc. of PAC, p.1839 San Francisco, 1991.
[8] R.D.Kohaupt, DESI H1-71/2, 1971.
[9] R.Alves-Pires, Proc. of the Fermilab III instabilities workshop, 1990.
[10] J.Marriner, A.Poncet, FNAL $\bar{p}$ note 481, 1989.
[11] A.Poncet, Y.Orlov, PS/ML/Note 98-1.
[12] J.Marriner et all., CERN/PS/89-48 (AR).
[13] T.Kasuga et all., Jap.Journ. of Appl.Phys. V24, p.1212, 1985.
[14] T.Kasuga, Jap.Journ. of Appl.Phys. V25, p.1711, 1986.
[15] S.Sugiyama et all., 6-th Symp. on Accelerator. Sci. and Tech., Tokio, 1987.
[16] R.Alves-Pires and R.Dilao, IST-DF-6/91 (Portugal)
[17] P.Zhou, J.B.Rosenzweig, Proc. of PAC, p.1776 San Francisco, 1991.
[18] R.Nawrocky, NSLS Tech. Note #436, 1991.
[19] S.Kramer, R.Rose, NSLS Tech. Note #447, 1992.