EFFECTS OF IONS IN THE SINCROTRONE TRIESTE

C.J.Bocchetta and A.Wrulich
Sincrotrone Trieste, Padriciano 99, 34012 Trieste, Italy

Abstract

We describe the stability of trapped ions in the Sincrotrone Trieste and how they may be removed. The influence of a gap in the electron bunch train is examined. We study the consequences of the nonlinear electron bunch field and the use of static and oscillating electric clearing fields.

Introduction

The residual gas resident in the vacuum chamber is detrimental to the performance of an electron storage ring. Positive ions are produced by collisions between the circulating electrons and the gas molecules. The electron bunches act as focusing elements and under certain circumstances ions are trapped. The effects of ion trapping are manyfold and can be observed via: The effective neutralization of the electron beam in a time scale of seconds for pressures in the range 1 to 10 nTorr, a shift and spread in the electron tune, coupling of horizontal and vertical electron motion, emittance blowup, instabilities (electron-bunch ion-cloud oscillations) and a enhancement of elastic and inelastic electron-gas collisions. These problems can be avoided by using positrons instead of electrons or alleviated through the use of clearing electrodes. The former is a rather expensive solution. We investigate here candidate methods to clear trapped ions in the Trieste synchrotron.

Linear Theory [1]

Treating the *equidistant* electron bunches as thin focusing elements and the space between bunches as drift spaces we can describe the transverse motion of the ion in terms of transport matrices, in a manner analogous to the linear optics used in accelerator physics. Thus, $\mathbf{X_1} = \mathbf{MX_0}$, with $\mathbf{X}$ a column vector containing the position and momentum of the ion at position $\mathbf{0(1)}$, and $\mathbf{M}$ is given by,

$$M = \begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -a & 1 \end{pmatrix}$$

With a the kick parameter and τ the bunch to bunch drift time. For stable motion it is required that $-2 \leq \mathrm{Tr}\mathbf{M} \leq 2$. This relation yields a critical ion to proton mass ratio, A_c, such that all ions with mass $A \geq A_c$ have stable motion. A_c is given by,

$$A_c = \frac{r_p C_r N}{2b^2 \sigma_{x,y}(\sigma_x + \sigma_y)}$$

where r_p is the classical proton radius, C_r the machine circumference, N the total number of electrons in the machine, b the number of equidistant bunches and σ_x, σ_y the horizontal and vertical r.m.s. beam dimensions. From this expression we see that large electron currents and small beam dimensions favour high critical masses, however, A_c is inversely proportional to the square of the number of bunches.

Evaluating the above expression for the Trieste synchrotron "ELETTRA", with a natural emittance of 7.4×10^{-9} (m-rad), C_r = 259.2 (m), emittance coupling ($\varepsilon_y/\varepsilon_x$) of 0.1, considering both planes and choosing a point in the lattice giving the largest value of A_c yields: For a single bunch current of 8 mA a vertical A_c=378, whereas with a current of 200 mA and all RF buckets filled (b=432), A_c=0.05. Thus no ions are trapped in the single bunch mode, but all ions are trapped in the multi-bunch mode.

With the introduction of a gap in the bunch train the symmetry of the focusing structure is broken and the width of the 1/2-integer resonance of the ion motion is increased, similar to the half-integer resonances in the linear theory of magnetic quadrupoles. The matrix $\mathbf{M}$ is now given by,

$$M = \left[\begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -a & 1 \end{pmatrix}\right]^{b}\begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix}^{h-b}$$

with h the harmonic number. Numerically solving the trace of this matrix reveals stable mass bands [2], which depend on the size of the gap. Figure 1 shows the total number of stable ions (out of fifty contiguous integer ion masses) as a function of gap and beam current. The accumulation of heavy ions is the most damaging because they may neutralize the electron beam to such an extent that ions with smaller masses become stable, i.e., an ion ladder is built up.

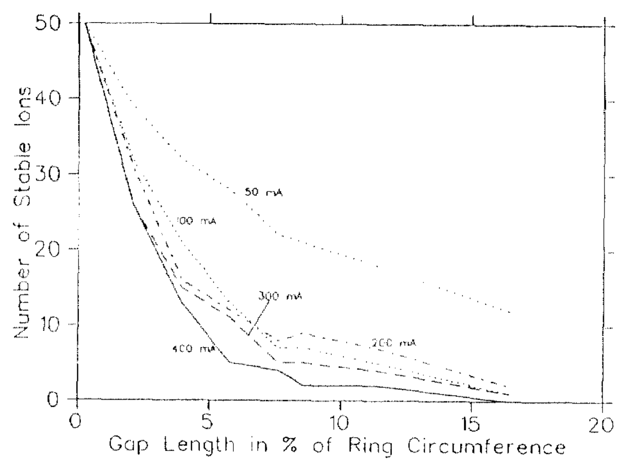

Fig. 1. Number of stable ions as a function of gap and beam current.

Nonlinear electron bunch field

The transverse kick an ion receives from a two-dimensional Gaussian distribution of electrons can be described in terms of the complex error function [3]. Linear theory is only applicable to motion which is bounded to approximately two r.m.s. of the transverse beam dimensions. Ion oscillations outside these bounds feel higher order restoring forces, and effects will now be seen which depend on the oscillation amplitude. The change in the ion momentum caused by the passing of an electron bunch can be written as,

$$\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = N_b r_p \sqrt{\frac{2\pi}{\Delta\sigma^2}} \begin{pmatrix} \mathrm{Im} \\ \mathrm{Re} \end{pmatrix} \left(w\left[\frac{x+iy}{\sqrt{2\Delta\sigma^2}}\right] - \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right] w\left[\frac{x\frac{\sigma_y}{\sigma_x} + iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2\Delta\sigma^2}}\right] \right)$$

With $\Delta\sigma^2 = \sigma_x^2 - \sigma_y^2$. The magnitude of the kick as a function of position in the transverse plane is shown in figure 2. Note the rapid decrease towards the centre of the bunch. we see that the restoring force is strongly determined by the position of the ion in transverse space. For a given electron bunch pattern and current we have numerically tracked an ion mass which is stable by linear theory. For all subsequent calculations reported here we examine ion mass 40, using 416 electron bunches (i.e. a gap 16 bunches) and a current of 400 mA. The tracking is done with different initial starting amplitudes and a threshold amplitude is found beyond which the ion motion becomes unstable. The threshold depends on where in the transverse plane the ion is created, smaller thresholds are found for ions starting in the vertical plane.

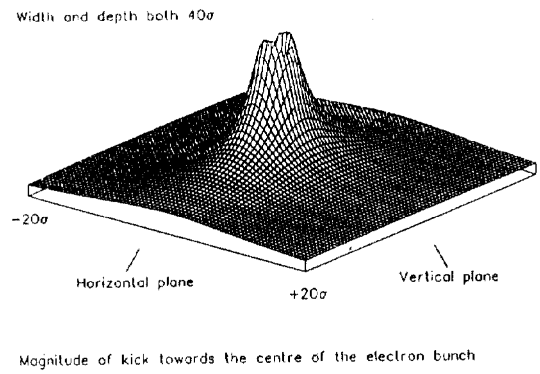

Fig. 2. Restoring force of a 2D Gaussian distribution of electrons.

Figures 3 and 4 show the behaviour of ion motion when the ion is created purely in the vertical or horizontal plane, with reference to the centre of the electron bunch. We note that for the vertical plane the ion is created at $0.5\sigma_y$ (σ_y=0.09 mm) and is lost after 80 turns, whereas in the horizontal plane the ion was created at $1\sigma_x$ (σ_x=0.15 mm) and is not lost after 100 turns, but executes large amplitude oscillations of up to 80 beam dimensions. The vacuum chamber dimensions are 40x80 mm^2. The step like behaviour in the small amplitude oscillations is due to the gap in the bunch train.

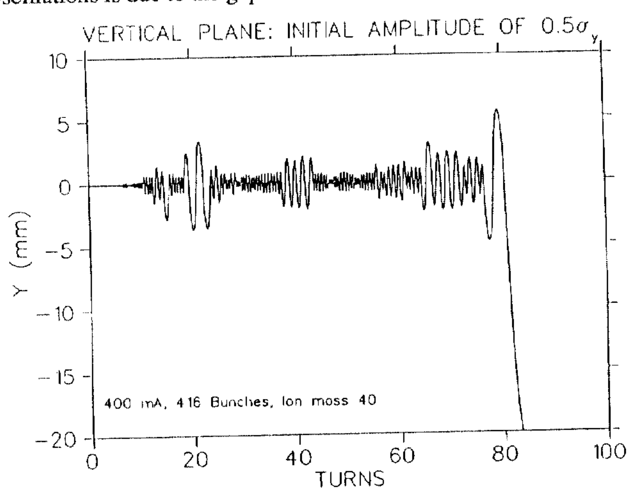

Fig. 3. Vertical component of ion motion in a nonlinear electron field.

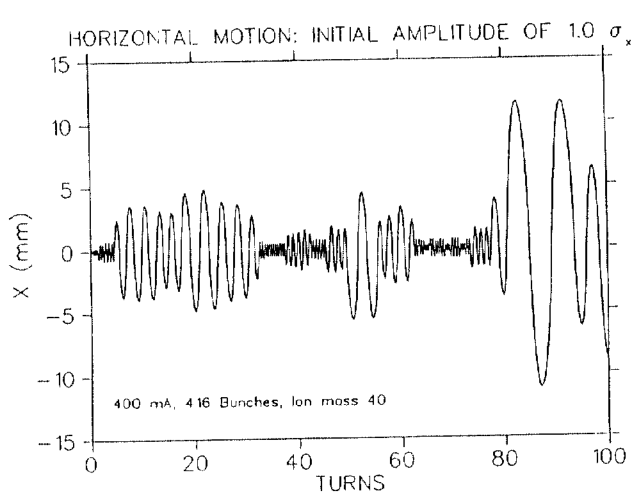

Fig. 4. As fig.3 but for the horizontal component.

Static clearing fields

The thresholds suggest that we may remove trapped ions by perturbing their motion into the nonlinear region of the electron bunch field. This can be done by applying a static electric clearing field, which is comparable in strength to the linear kick an electron bunch gives to an ion. The action of an external electric field will affect both electrons and ions. The electron effect is small due to the large gamma factor (~4000 at 2 GeV). We consider here the stationary case after equilibrium has been reached. This will occur in a time scale of milleseconds (radiation damping). The most difficult ion to remove is the one which describes the closed orbit of the ion motion. This ion is at the centre of a phase ellipse containing all the other ions, which execute betatron oscillations about it. With no external field the closed orbit goes longitudinally through the centre of the electron bunches, when a field is applied the closed orbit is dragged away from the centre. In the time domain all the ions rotate about this orbit, occasionally sampling the nonlinear regions of the electron bunch field and here they may be lost. By shifting the closed orbit sufficiently far away from the linear region of the electron bunch field all ions can be effectively removed. For a given external field gradient the closed orbit of the ion motion can be calculated using an iterative procedure. The calculations reported here use linear homogeneous external fields. Cases which used an accurate nonlinear external field were also computed (not shown here), the results of which showed no essential differences with the linear case.

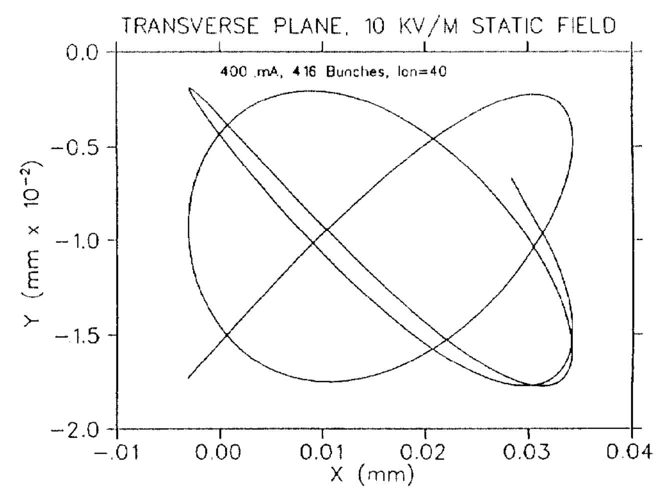

Fig. 5 Closed orbit of ion in transverse space using a static field.

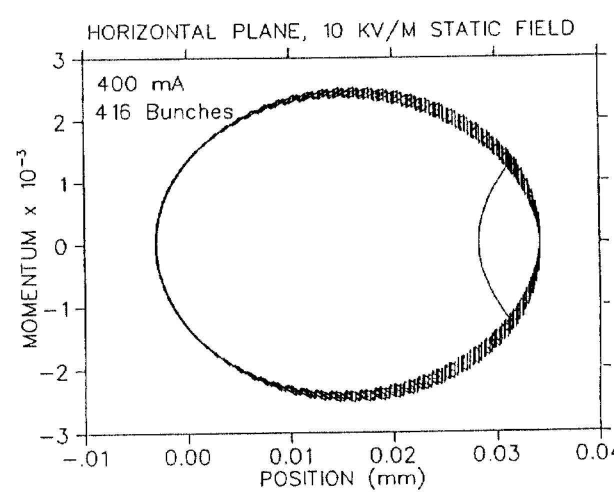

Fig. 6 As fig.5 but for horizontal phase space.

Figure 5 shows the closed orbit in transverse space of the test ion under the influence of a constant field with 10 kV/m components in both planes. The stable orbit lies within the linear region of the electron bunch field. The orbit has near two-fold symmetry (the ion being created very near the centre of the electron bunch train) starting at ~(-0.004,-0.0175) . Figure 6 gives the horizontal phase space motion, the curve within the ellipse is due to the gap. The external field attracts in the positive x direction, and the broading of the ellipse away from the origin results from the stronger bunch kicks (see fig. 2).

Oscillating clearing field

The static field works well for small beam currents and large gaps, for larger currents and smaller gaps stronger fields are necessary (e.g., 10 kV/m for the above mentioned case). Linear theory defines both vertical and horizontal ion tunes, $Q_{x,y}$. The tunes are unique for a given position in the storage ring. We can define the ion frequency as $\omega_{x,y}=2\pi f_0 Q_{x,y}$, where f_0 is the revolution frequency (1.16 MHz).

An ion located at the centre of an electron bunch when driven at its characteristic frequency will have a growth in amplitude which is linear in time, until the amplitude samples the nonlinear region of the bunch. At this point a frequency shift will occur (to lower frequencies) and a modulation of the amplitude will be seen. The magnitude of the amplitude is a function of the magnitude of the external driving field and the frequency shift. Once the ion is in the nonlinear region we can expect the ion to be lost. Figure 7 shows the vertical component of motion for the test ion having zero initial displacement, under the action of a sinusoidal field oscillating in both planes at the characteristic ion frequency. The field strength was chosen as 100V/m for each direction. The ion is lost after 80 turns. A static field of the same magnitude would produce a very small shift of the closed orbit. In calculating the motion both the electrons and ion were affected by the field. The electrons received impulsive kicks from an electrode 15 cm long, this perturbation was then propagated around the ring using a transport matrix.

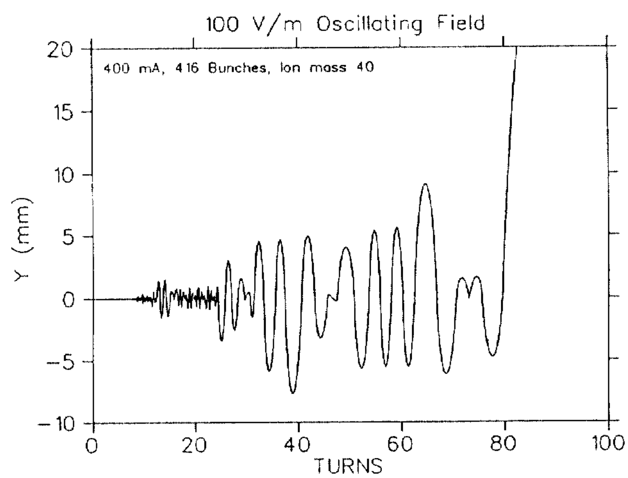

Fig. 7 Vertical component of ion motion in an oscillating external field with 100 V/m components. The driving frequency is equal to the ion frequency.

The above case was for zero initial displacements and momenta. In general ions that are trapped will tend to have small amplitudes otherwise they will be *eventually* lost in the nonlinear region of the electron bunch. These ions execute oscillations which are determined by the phase of the external oscillatory field. This phase condition results in a modulation of the amplitude. For high field strengths we expect large oscillations. Figure 8 shows the horizontal component of the ion motion when the driving frequency is 10% greater than the natural ion frequency. Here a 1kV/m field in each direction is used and the ion is lost after 280 turns. Once in the nonlinear region the ion is more susceptible to static clearing fields, the result of this is shown in figure 9.

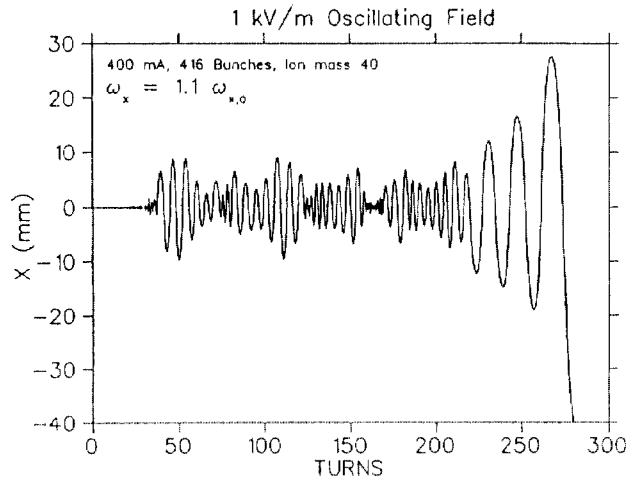

Fig. 8 As in fig. 7 but with a frequency 10% greater and 1 kV/m field.

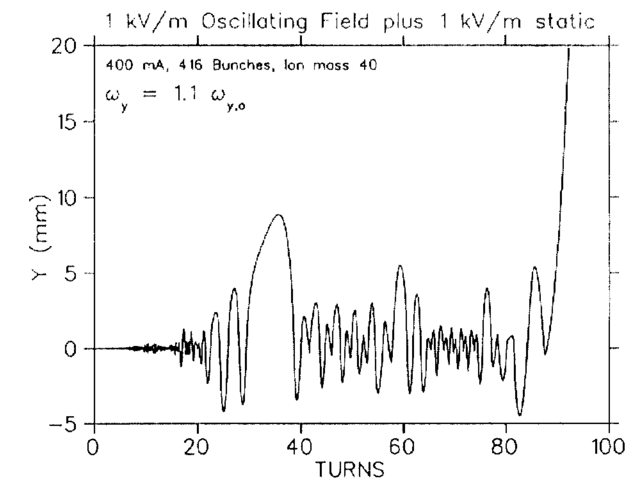

Fig. 9 As in fig. 8 but with the addition of a static field.

Conclusions

The results presented above suggest that a powerful technique for ion clearing would be to use low voltage oscillating electric fields with a static backgound field and a gap in the bunch train. Ions, however have longitudinal velocities given by thermal motion and motion due to the time averaged longitudinal potential well of the beam. The potential well will have a minimum at low beta values and ions will drift there and an equilibrium between the thermal motion will be reached.The effects of a clearing electrode must be felt on a time scale comparable to the time spent in the vicinity of the electrode. These effects have not been taken into consideration, nevertheless, for the results presented here, in all cases, the ion was lost in less than 300 turns (~ 0.3 ms). With an average thermal velocity of ~420 m/s, ion mass 40 travels ~12 cm during this time, and this is still within the field of the electrode used in the calculations.

References

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