THE STABILITY OF IONS IN A STORAGE RING IN THE PRESENCE OF SMALL GAP INSERTION DEVICES*

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1. INTRODUCTION

With more and more insertion devices in storage rings, where the vacuum chamber size can be suddenly different, ionization pockets may develop, thus ions may be trapped leading to beam blow up, beam instabilities or even beam loss.

One have to take a closer look at the stability conditions of the ions in these longitudinal potential wells. For equidistant bunches: are the ions above or below the Ac critical mass? For a bunch train followed by a gap: is the ion of mass A stable or unstable for a given current at a given azimuthal location in the ring? Are the ions longitudinally mobile and be able to get to an unstable region? If the ions proved to be stable in that region and if their longitudinal kinetic energy is less then the depth of the potential well, then they have to be statically cleared at that location.

We are going to investigate the question of ion stability in the NSLS X-ray ring with a .32 m long variable gap (4-18mm) undulator [1] and a .95 m long 27 mm gap undulator [2] in it. We will concentrate our attention to CO ions (A=28) since they are the most bothersome in the ring (H_2, being much lighter, they are always more unstable). We will show the effect of gap in the bunch train, the effect of nonlinearity in the beam kicks and the effect of restricted longitudinal mobility of ions. The methods used and the calculations performed are general enough to be applied to any other storage ring or accelerator, thus representing general interest.

2. BEAM POTENTIAL

The smaller the beam size or the larger the diameter of the vacuum chamber is, the deeper the beam potential will be at that location. This is easy to see for the simple case of round beam of radius a and round chamber of radius r_o, when the beam potential is $V = -(\lambda/2\pi\varepsilon_o)\ \ln(a/r_o)$, but it is also true in general (elliptic beam in elliptic chamber [3]). Therefore longitudinal potential wells will be found at either side of the small gap undulators, which will prevent ions (with longitudinal kinetic energy less then the depth of the well - which is the majority of the ions) entering the undulator from either direction. If the ions are stable in that regions, then ionization pocket occurs.

The beam in the X-ray ring is flat ($\sigma_x > \sigma_y$), therefore the vertical beam and vacuum chamber size is more critical than the horizontal. They are plotted together with the calculated beam potential at the center of the beam. The potential was calculated for I = 250 mA beam current. The figure shows, that the depth of the potential wells are ΔU =50 and 10 MeV for the two undulators, respectively.

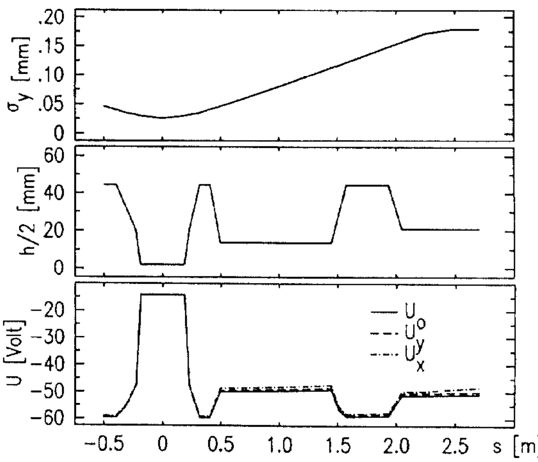

Fig. 1. Vertical beam size (σ_y), half height of the vacuum chamber (h/2) and beam potential at the center of the beam (U_o) in the 2 undulator region for I = 250 mA beam current.

3. CRITICAL MASS

In a simplified, linear model of ion trapping by a bunched electron beam the ions are "kicked" by the electron bunches and they drift freely between the kicks. (In this linear approximation the beam's electric field is assumed to be linear with the distance from the middle of the beam.) The effect of kick and drift can be described in the usual matrix formalism [4]. When the bunches are uniformly distributed, that is for equidistant bunches, then the stability condition imposed on the Trace of the matrix (Trace(M) $\le$ 2) yields a critical ion mass, above which the ion motion is stable:

$$A_c = \frac{C^2 r_p I}{2ecn_B^2}\ \frac{1}{\sigma_y\ (\sigma_x + \sigma_y)}$$

where r_p is the classical proton radius and I is the beam current.

The critical mass with 5, 15 or 30 equidistant bunches is plotted in one superperiod of the the ring for I = 250 mA on Figs. 2. The location of dipoles (-[ ]-), quadrupoles (- -) and undulators (-[ ]-) are also shown. One can see that with 5 bunches, practically all ions are instable anywhere in the ring. With 15 bunches only H_2 is unstable anywhere, CO and CO_2 is unstable only in the straight sections, where the undulators are. With all 30 buckets filled in the ring, even the H_2 ions are stable everywhere except in the straight sections and heavier ions are stable practically everywhere (except in a very small region around the middle of the straights).

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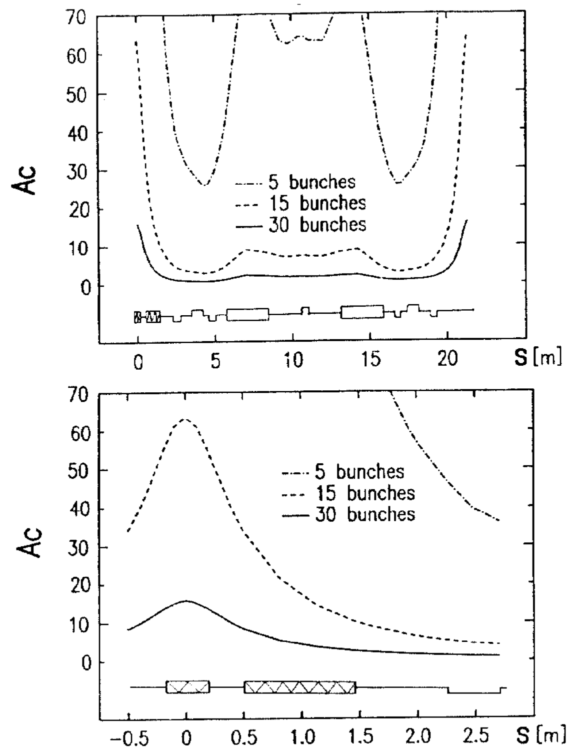

Fig. 2. Critical mass with 5, 15 or 30 equidistant bunches, for I = 250 mA shown in (a) one superperiod of the ring and (b) in the 2 undulator region.

4. NON EQUIDISTANT BUNCHES

In this section, we are still assuming linear beam-ion forces. When there are N uniformly distributed bunches

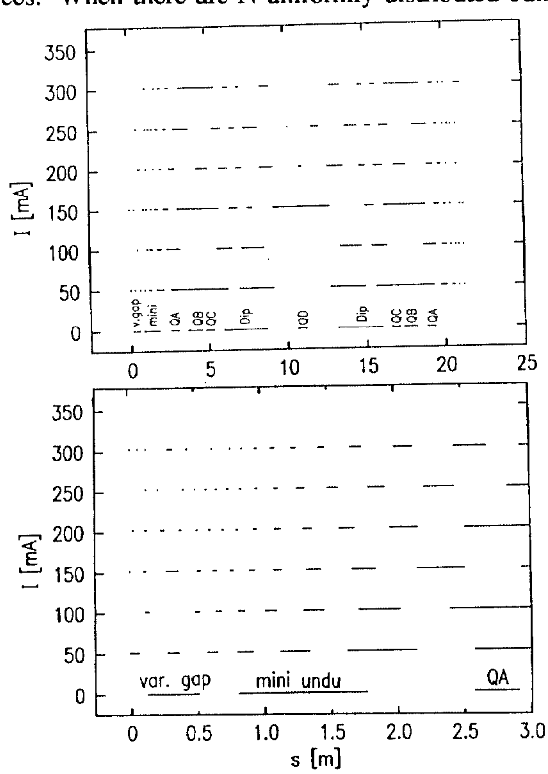

Fig. 3. Linearly stable regions of A=28 ions with 25 consecutive bunches are shown for different beam currents in (a) one superperiod (with ds=10 cm resolution) (b) the $0 \le s \le 2$ m undulators region (with ds=1 cm resolution)

(bunch train) followed by M empty bunches (gap) in the ring, then the stability condition imposed on the Trace of the matrix yields a N-th order nonlinear equation and instead of a critical mass, there are bands of stable regions of A for any given current and longitudinal location. This can be "mapped" into stable/unstable longitudinal (s) regions around the ring for a given ion, beam current and gap length.

We calculated the stable longitudinal regions for the CO ions with 25 consecutive bunches (M=5) in the ring at different beam currents and plotted them on Figs. 3. One can see, that even at I = 50 mA beam current, there are enough unstable regions in/around the undulator that the ions would not build up. This is also true around the ring.

5. NONLINEAR BEAM-ION FORCES

Let us now consider the nonlinear nature of the beam-ion force. We track ions [5] with different initial conditions for (x, y, s, v_x, v_y, v_s), and examine the relative number (%) of "living ions", that is ions still in and around the beam, as a function of the number of turns in the machine (time). 100 CO ions were tracked with initial Gaussian random distribution in (x, y, v_x, v_y, v_s) while the initial s_o was uniformly distributed in $0 \le s \le 2.0$ m (the region where the 2 undulators are) and $0 \le s \le 21$ m (one superperiod of the ring). In either case, linear and nonlinear tracking were performed with longitudinally mobile ions, as well as nonlinear tracking with longitudinally immobile ions. This latter is important to see, weather or not ions longitudinally confined in the potential wells around the undulators can escape from the beam. A=28 ions in 25 consecutive bunches for I=250 mA beam were used in the tracking.

The results are shown on Fig. 4. One can see that (a) nonlinearity of kicks makes the ions (initially) more stable but even so, ≈100 % of the ions created in the undulator region and ≈80 % of all ions will hit the vacuum chamber after only 250 turns, that is .14 msec, (b) ions created in the undulator region are slightly more unstable than those created anywhere else in the ring and (c) longitudinal ion mobility or lack of it does not influence the stability of ions. Consequently, with I=250 mA in 25 consecutive bunches, the ions do not build up around the undulators.

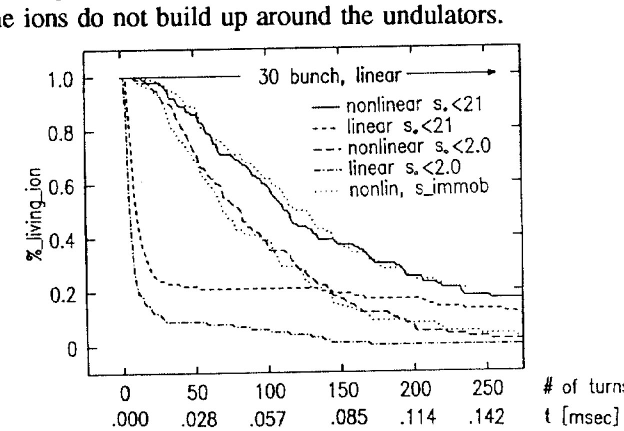

Fig. 4 % of living ions vs. number of turns with N = 25 consecutive bunches in the ring and A = 28, I =250 mA.

Next, we looked at the effect of increasing the number of consecutive bunches in the ring. Fig. 5a shows the % of living ions when 100 Gaussian random ions, created uniformly in the full superperiod, were tracked with linear beam-ion forces for N = 25 - 30, while Fig. 5b is for nonlinear beam-ion forces and N = 25 - 27. One can see, that even for linear forces, the ions are rapidly getting stable with increasing N, and with 30 bunches all ions are stable. In the realistic case of nonlinear forces all ions disappear after .17 msec when there are 25 bunches in the ring, but ≈40 % are still "alive" with 27 bunches.

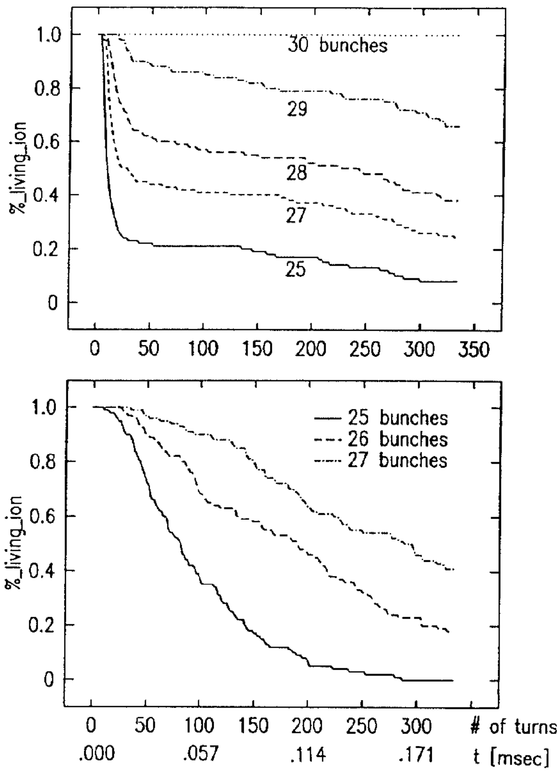

Fig. 5 Life-curve of A = 28 ions with I =250 mA and different number of consecutive bunches in the ring when assuming (a) linear and (b) nonlinear beam-ion forces.

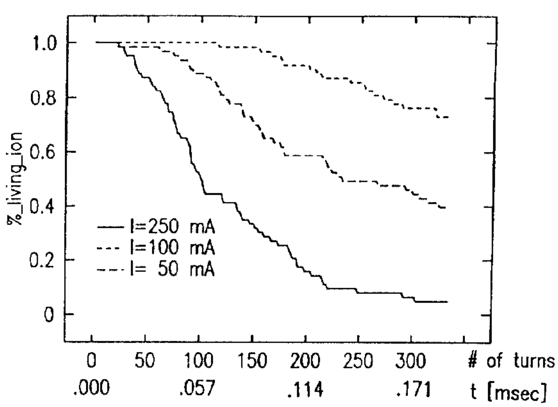

Fig. 6 % of living ions vs. number of turns with A = 28, I=50-250 mA and N = 25, assuming nonlinear beam-ion forces.

We already pointed out the current dependence of the critical mass and the linearly stable regions. The next figure shows the dependence of the nonlinear 'lifetime' of the ions on the beam current. The % of living ions is plotted on Fig. 6 when tracking was done with nonlinear beam-ion forces, N = 25 and I=50, 100 and 250 mA beam currents. The same 100 ions were tracked as for Figs. 5. The figure shows a strong dependence on current. Even with only 25 bunches in the ring, the ions are almost stable at I=50 mA.

6. EFFECT of POTENTIAL WELLs

We turn our attention now to the effect of the potential wells due to the narrowing vacuum chamber in the undulators and how do they effect the (un)stability of the ions.

Fig. 7 shows the "life-curve" of 100 CO ions in 25 consecutive bunches for I=250 mA beam assuming nonlinear beam-ion forces and under the following conditions. The ions were tracked with initial s_o uniformly distributed in $0 \le s_o \le .15$ m (before the variable gap undulator) with longitudinally mobile ions and (a) neglecting the effect of the potential well, (b) taking the effect of the potential well into consideration. 100 ions were tracked with initial s_o uniformly distributed in $0 \le s_o \le 2$ m (from before the variable gap undulator until after the mini undulator) with longitudinally mobile ions and (c) neglecting the effect of the potential well, (d) taking the effect of the potential well into consideration, as well as (e) with longitudinally immobile ions ($v_s = 0$ and no longitudinal kicks) and without the effect of the potential well. All ions were created Gaussian random in (x, y, v_x, v_y and v_s), except where $v_s = 0$ was assumed.

One can see that the potential well caused by the narrow vacuum pipe in the undulators have no considerable effect on the lifetime of ions (all 5 curves are identical), and that the ions are unstable in the two undulator region. The effect of the narrow cross section is that the ions will drift towards the deeper part of the potential well, away from the undulators. But since the whole area is unstable, the ions will get lost.

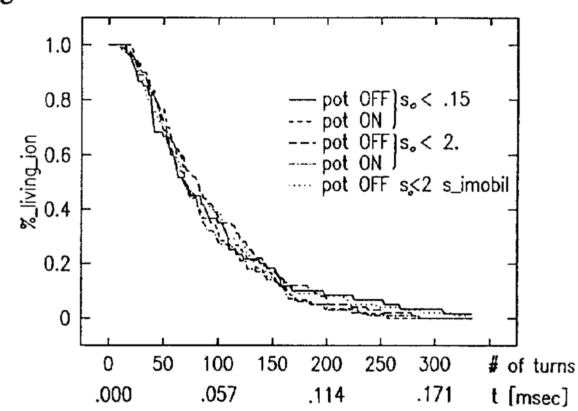

Fig. 7 % of living ions vs. number of turns with A = 28, I =250 mA and N = 25 assuming nonlinear beam-ion forces with and without the effect of beam potential.

Acknowledgement

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