Particle Accelerators, 1990, Vol. 28, pp. 113–118
Reprints available directly from the publisher
Photocopying permitted by license only

EXPERIMENTAL AND THEORETICAL STUDIES ON THE LONGITUDINAL MOTION OF TRAPPED IONS IN AN ELECTRON STORAGE RING

YOSHIKAZU MIYAHARA
Synchrotron Radiation Laboratory
University of Tokyo
3-2-1, Midori-cho, Tanashi, Tokyo 188, Japan

Abstract Longitudinal motion of trapped ions in an electron storage ring was studied by observing γ-ray intensity responding to a pulsed voltage applied to a clearing electrode. In addition theoretical analysis was mode on the motion under the $\bar{E}x\bar{B}$ force due to the electric field of electron beam and the magnetic field of bending magnet particularly in the fringe field region.

INTRODUCTION

In electron storage rings residual gases are ionized by the collision of electron beam and additionally by the interaction with synchrotron radiation. The positively charged ions are trapped in circulating electron beam and induce harmful effects such as tune shift, broadening of electron beam and decrease of beam lifetime. Thus it is desired to eliminate the trapped ions to a sufficiently small extent. This has been done with a considerable success by RF knock out,[2] clearing electrode[2] and partial fill of beam bunchs in RF buckets.[3] In order to eliminate the trapped ions sufficiently, it is useful to know the properties of trapped ions.

So far longitudinal motion of trapped ions has slightly been understood. We have investigated this property experimentally in SOR-RING by the method of clearing electrode,[4,5] and found that longitudinal average velocity of trapped ions is about 950 m/s. This is considerably faster than the thermal velocity 290 m/s of CO gas. It has been known theoretically that the trapped ions are accelerated by the $\bar{E}x\bar{B}$ force,[6] where $\bar{E}$ is the transverse electric field in the electron beam and $\bar{B}$ is the vertical bending field. Thus the faster exmerimental velocity is consistent with this acceleration. We have made a further analysis of the $\bar{E}x\bar{B}$ force taking into account the fringe field of bending magnet, and found that the trapped ions are reflected by the fringe field or transmitted through the bending field depending on the initial condition of trapped ions.

EXPERIMENTAL RESULTS

We have applied a dc voltage on a disk-shaped position monitor, being used as a clearing electrode in the present experiment, and observed γ-ray intensity at first with a γ-ray survey meter at a position downstream. The γ-rays are emitted by the collision of electron beam with residual gases and trapped ions as well as by the collision of outgoing electrons with the vacuum chamber of the storage ring. When a pulsed voltage was applied to the electrode, the γ-ray intensity is reduced substantially as shown in Fig.1. The reduction is caused by the elimination of trapped ions, and implies that the trapped ions travel very fast longitudinally in the electron beam. When the voltage is turned off, the γ-ray intensity recovers to the former level quickly, which is due to a fast production of trapped ions. The reduction saturates above an applied voltage of 1 kV for vertical disk gap of 13 cm, which is approximately in accord with the estimated maximum electric field of 100 V/cm in the electron beam.

The γ-ray intensity was monitored at several positions around the ring. Figure 1 shows the dependence of γ-ray reduction on the distance from the clearing electrode. The reduction decreases symmetrically for upstream and downstream. This implies that the trapped ions travel in the same ways in both directions upstream and downstream.

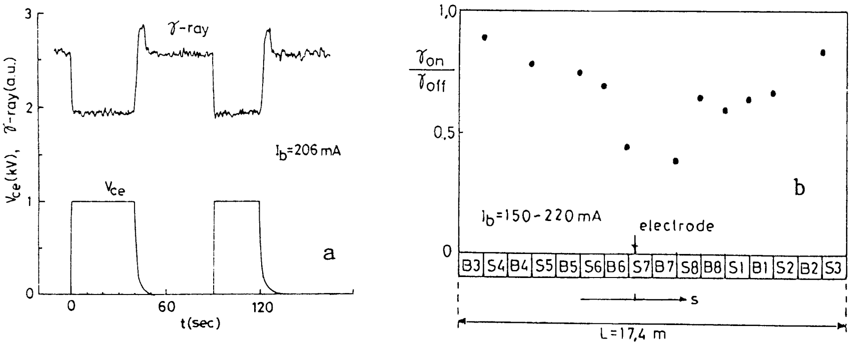

FIGURE 1 Response of γ-ray intensity to a pulsed voltage applied to a clearing electrode. (a)

Dependence of γ-ray reduction on the distance s from clearing electrode. (b)

Next in order to see the velocity of trapped ions we have applied a sharp pulsed voltage with a rise and fall time less than 10 μs, and monitored the γ-ray intensity with a NaI synchilator. The photo-pulses from the synchilator were accumulated in a multi-channel analyzer. The pulsed voltage with a width of 80 ms was repeated every 400 ms, with which the anlyzer was triggered. Figure 2 shows the examples of the accumulated photo-counts monitored at several positions against the time delay from the trigger.

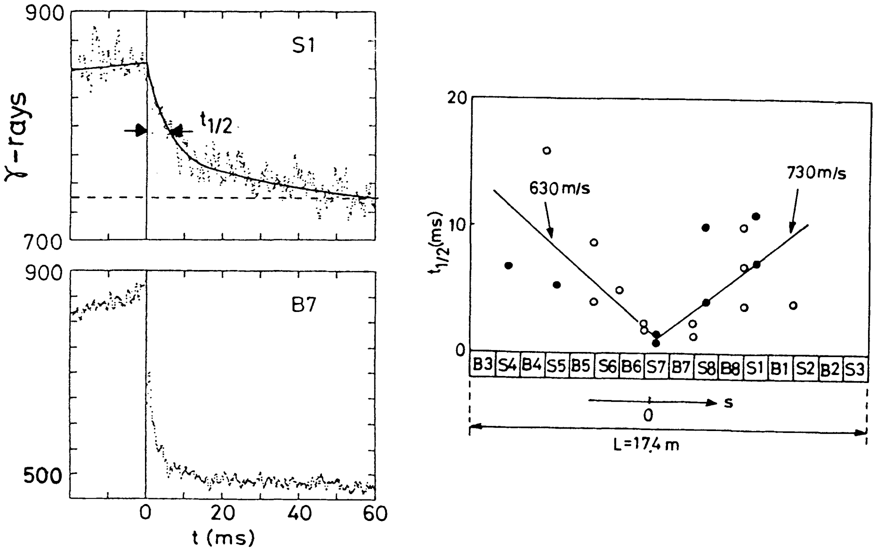

FIGURE 2 Fast response of γ-ray intensity to a sharp pulsed voltage (a), and half decay time $t_{1/2}$ against the distance s (b).

The half decay time $t_{1/2}$ of the photo-counts or γ-ray intensity is plotted in Fig.2 against the distance. By the root mean square fit we find that the velocity of trapped ions corresponding to the half decay time is 630 m/s for upstream and 730 m/s for downstream, which are the same within experimental errors. Assuming a Gaussian distribution of velocities of trapped ions we can reproduce the decay curves of γ-ray intensity at a given distance. This results in an average velocity about 950 m/s.

The trapped ions related to the present experiment is thought to be CO^+ because the production rate and emission rate of γ-rays, both of which being proportinal to atomic number, are much larger for CO^+ than for H_2^+. At the instance when CO molecule is ionized, the initial velocity of CO^+ is thought to be the same as the thermal velocity of CO gas because the reduction of γ-ray intensity and velocity of trapped ions are symmetric for upstream and downstream.

THEORETICAL RESULTS

As mentioned before the trapped ions are accelerated by the $\overline{E}x\overline{B}$ force in the bending magnet. The drift velocity by the force is expressed as

$$v_d = (x_0\omega_c + v_0)\frac{\omega_x^2}{\omega_x^2 + \omega_c^2} \tag{1}$$

where ω_x is the oscillation frequency due to the electric field, ω_c the cyclotron frequency due to the bending field and x_0 and v_0 are initial horizontal position and longitudinal velocity of trapped ions. Since the ions are produced by the collision of electron beam, the initial position of trapped ions is thought to distribute in the same way as the electron beam. Then substituting numerical values for the parameters in Eq.(1) we find the average drift velocity $\langle v_d \rangle \cong 3000$ m/s.

In Eq.(1), $x_0\omega_c$ is much larger than v_0, so that it is supposed that at the entrance of bending magnet, half of the trapped ions are reflected by the bending field and the other half are transmitted through the bending field. But in realty the fringe field of bending magnet changes gradually, so that the reflection and transmission of trapped ions are affected to some extent by the fringe field. We have made a theoretical analysis of the motion of trapped ions in the fringe

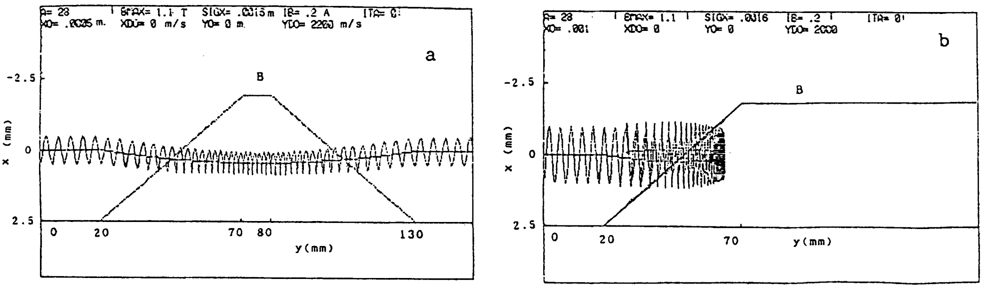

FIGURE 3 Simulation of the motion of trapped ion under the $\overline{E}x\overline{B}$ force. (a) and (b) represent the motion of a trapped ion with a small and large initial position x_0.

field. It was found that the ions are reflected under the following condition

$$\left| v_o / x_o \right| < \omega_c (B_{max}) / \sqrt{2} \qquad (2)$$

where $\omega_c(B_{max})$ is the cyclotron frequency at the maximum bending field. Figure 3 shows examples of numerical simulation of the motion of trapped ions in the free space and bending field including fringe field. Ions with a small initial amplitude are transmitted through the bending field, while the ions with a larger initial amplitude are reflected by the fringe field, and the reflected ions are again reflected by the fringe field in the opposite site. Thus the fringe field works as a potential barriar for the longitudinal motion of trapped ions.

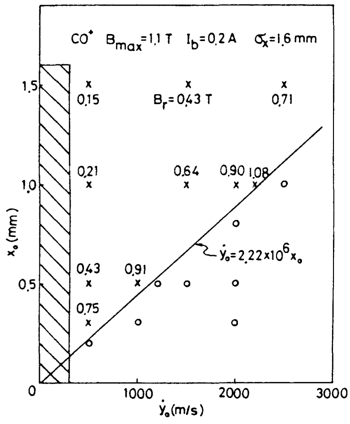

FIGURE 4 Map of reflection and transmission of trapped ions with respect to the initial condition x_o and $v_o(=\dot{y}_o)$.

Figure 4 shows the map of reflection and transmission with respect to the initial condition of x_o and $v_o(=\dot{y}_o)$.The boundary of the reflection and transmission in the same figure is close to the condition (2). In the same figure the shaded region represents the initial condition of trapped ions in the storage ring. Thus, almost all trapped ions produced in the free space are reflected by the fringe field, and consequently such ions are bounded in the free space. On the other hand the trapped ions produced in the bending magnet travelthrough the bending field and free space, and therefore circulate around the ring. According to the simulation the velocity in the free space is 1.7 times faster than the drift velocity in the bending field. Taking into account the length of bending field (8x0.86 m) and free space (8x1.81 m) we find an average velocity 4400 m/s of trapped ions for the circulation. This is much faster than the experimental velocity of 950 m/s. The reason of this difference is not known yet. The amounts of the bounded ions in the free space and the circulating ions around the ring are proportional to the production rate of ions in the free spaces and bending magnets, respectively,which are approximately proportional to the length of free space and bending magnets. Therefore about 30 % of trapped ions are expected to circulate around the ring. The circulating ions are related to the reduction of γ-rays when the pulsed volateg is applied to the clearing electrode.

It is known that the electric potential produced by the electron beam is deeper in the region of larger vacuum chamber, and that the ions produced in such a region are bounded there. The present analysis indicates that even if the chamber size is almost the same all around the ring, the trapped ions produced in the free space are bounded there. Accordingly it is necessary to install clearing electrode in all free spaces to eliminate the trapped ions sufficiently.

In multipole wigglers and undulators the bending field varies sinusoidary. The ions produced in weaker field regions of such insertion devices are bounded there. The ratio of bounded ions in an undulator with a peak field of 0.4 T and period length of 6 cm, for instance, is about 35 %. To eliminate them it may be necessary to install a strip line type of clearing electrode.

REFERENCES

1. Y.Miyahara, Jpn.J.Appl.Phys. 26 1544 (1987).
2. T.Kasuga etal, Jpn.J.Appl.Phys. 24 1212 (1985).
3. M.Q.Barton, Nucl.Instr.Methods, A 243 278 (1986).
4. Y.Miyahara, J.Vac.Sci.Tech. A 5 2927 (1987).
5. K.Watanabe etal, Jpn.J.Appl.Phys. 26 L1964 (1987).
6. R.D.Kohaupt, Internal Bericht, DESY H1-71/2(1971).
7. Y.Miyahara etal, Nucl.Instr.Methods A 270 217 (1988).