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ION TRAPPING EFFECT OBSERVED IN NAR

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Abstract

The effect of trapped ions is shown to cause a serious problem in NTT normal-conducting accelerating ring (NAR), which adopted extremely low injection energy (15MeV). Although the large beam size at injection reduces the effect of ions, the ions seem to affect the beam more seriously than expected from the calculation. In this paper, ion trapping effect in NAR are examined both theoretically and experimentally.

1. Introduction

To reduce the size and cost of the injector LINAC, we adopted low injection energy (15 MeV) for NAR[1) 2)], which is used for SR applications at final energy (800 MeV). To remove ions, twelve sets of button type electrodes are placed in the ring of 52.8 m circumference and are always used. However, a couple of phenomena which seem to be caused by trapped ions are observed. Generally speaking, lower energy electrons are more liable to be affected from trapped ions but the evaluation is not so simple because the energy dependent electron beam size also has an important effect.

At 15 MeV, the large beam size at injection preserves over a long period because of the long radiation damping time. Therefore, the size of trapped ions is also large and the ion density is low. The larger beam size result in smaller effect on electron beam. On the contrary, the experiment shows that ion trapping problems are serious though the electron beam size is large at injection. Short life time and lack of appropriate monitors make the analysis more difficult.

According to the calculation of beam potential, the possibilities that the clearing electrodes are not placed properly and that ions are accumulated in the bending sections where the potential is deep are pointed out.

To avoid the effect of ions, we examined to adopt the partial fill operation which is a well known method to avoid ion trapping. The calculation and preliminary experiment showed that this method is not effective at injection whereas it is effective in storage.

In this paper, ion trapping effect observed in NAR is described. Outline of NAR and calculated result of the beam potential are presented in section 2 and the effect of trapped ions is numerically examined in section 3 and 4. Experimental result is shown in section 5. The effect of partial fill is tested in section 6. Ion trapping effect in NAR is compared to the effect in Super-ALIS in section 7.

2. Beam Potential

Lattice functions, beam size, and beam potential are calculated and shown in Fig. 1 for one fourth section of NAR.

Lattice functions are re-calculated assuming the conditions used in injection experiment.

Beam size at injection is computed from the following formula,

$$\sigma_x = \sqrt{\varepsilon_x \beta_x + (\sigma_\varepsilon \eta)^2} \qquad (1)$$

$$\sigma_y = \sqrt{\varepsilon_y \beta_y}$$

where ε_x and ε_y are the horizontal and vertical emittances, and ε_e is the energy spread. Whereas these emittances and energy spread during storage can be calculated theoretically, they depend on various conditions at injection. Therefore, two possible cases were examined. In case 1, $\varepsilon_x = 10\text{x}10^{-6}$ (πmrad), $\varepsilon_y = 1\text{x}10^{-6}$ (πmrad), $\varepsilon_e = 5\text{x}10^{-3}$ are assumed while ε_x is replaced by $2.5\text{x}10^{-6}$ in case 2. Horizontal emittance is large because electrons are injected by bumping closed orbit in horizontal plane.

Beam potential is computed against these two cases assuming elliptical (rectangular) vacuum chamber and beam[3)] (Fig. 1). The inner surface of vacuum ducts including the bending sections have nearly the same size except the section where RF cavity is located and RF knock out electrodes are placed. Then the size of vacuum duct is approximated to be constant rectangular shape of 120 x 58 mm^2. Beam current is assumed to be 100 mA.

To remove ions, button type electrodes are places at both ends of long straight sections (nearby QD) and in the middle of short straight sections (nearby QFc). The positions of these electrodes are also shown in Fig. 1.

As can be seen from Fig. 1, the beam potential in the bending sections is a few voltages deeper than that in the straight sections in case 1. This difference may produce the neutralization pocket. However, as the result strongly depends on the beam emittances which have not been confirmed experimentally, the existence of potential well cannot be proved from this calculation. Just a possibility is presented.

3. Neutralization Factor

Neutralization factor (h) is defined as n_i / n_e where n_i is the number of trapped ions and n_e is the number of electrons. The

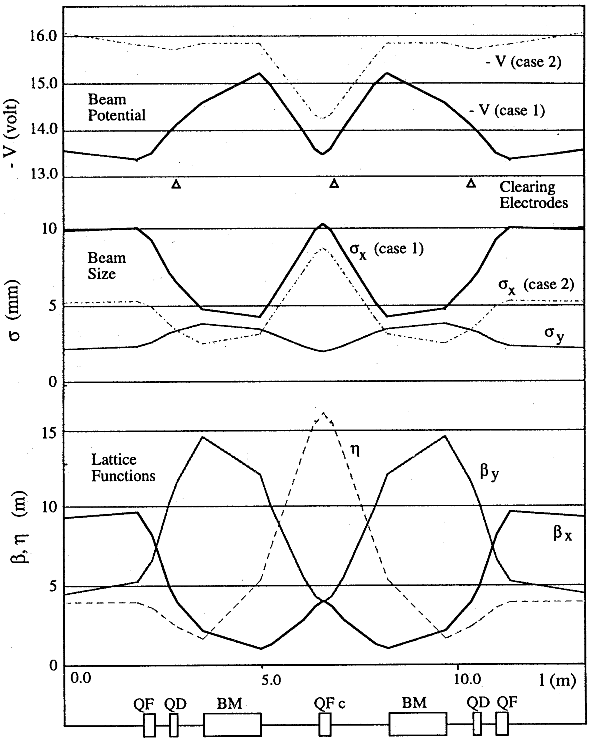

Fig. 1 Lattice functions, beam size, and beam potential

neutralization factor at injection is roughly estimated with ion clearing electrodes[4)]. Assuming that the residual gas molecules are CO, the ionization time (τ_{ionize}) which is the average time required for an electron to ionize a molecule is about one second. If there is no mechanism to clear ions, neutralization factor increases in proportional to elapsed time from injection and reaches as large as 100 % in one second. On the contrary, if a molecule ionized and trapped by the electron beam drifts along the electron beam with thermal velocity (a few hundreds meters per second) and is cleared at the electrodes which are placed in four to five meters intervals, an ionized molecule remains trapped for 10 msec. Therefore, the neutralization factor approaches to the equilibrium value of 1 % (= 10 msec / 1 sec) in about 10 msec. If H_2 molecules are assumed, the neutralization factor is estimated smaller because of the larger ionized cross section and the faster thermal velocity. As ions run faster in bending sections than in straight sections, the neutralization factor should be smaller.

In the following section, the effect of ions is estimated assuming the 1 % neutralization factor.

4. Numerical Evaluation of Ion Trapping Effect

In this section, the effect of trapped ions is numerically evaluated in terms of tune shift, pressure rise, and two beam instability.

The vertical tune shift due to trapped ions is expressed as[5)],

$$\Delta\nu_y = r_e \frac{1}{\gamma}\frac{R}{\nu_y}\frac{1}{2\pi\sigma_y(\sigma_x+\sigma_y)}\eta n_e \qquad (2)$$

where r_e is the classical electron radius, γ is the Lorentz factor, R is the mean radius of the ring, $\nu_{x,y}$ are the betatron tunes. Assuming that the beam size is σ_x = 5 mm and σ_y = 2 mm (this assumption is close to case 2 in section 2) and that the ions have the same size as that of electrons, tune shift at injection is estimated to be 0.0068 at 100 mA and 1 % neutralization factor. Tune shift is small compared to electron energy because the beam size is large at injection. As the electric fields produced by ions consist of large non-linear components, the same amount of tune spread is expected. Judging from this calculation, neither tune shift nor tune spread seems to be fatal as long as ions are removed efficiently at the clearing electrodes.

We tried to measure this tune shift experimentally but could not perform yet due to the difficulties of the precise tune measurement. The strength of RF knock out has to be controlled as small as possible so that it does not influence trapped ions. The tune have to be measured in a few tens milli-seconds because of the short life time at injection.

Pressure rise due to ions is estimated from[5)]

$$d_i = \frac{\eta n_e}{2\pi\sigma_x\sigma_y L} \qquad (3)$$

and we can derive 3.4×10^{11} $1/m^3$ at 15 MeV assuming the same size and the neutralization factor. As compared to the residual gas density, 3.5×10^{13} at 1×10^{-9} Torr, the pressure rise is very small.

In some condition, the electron oscillation and ion oscillation become coupled and the amplitudes of both oscillation grow rapidly[5)6)]. The threshold neutralization factors are calculated according to ref. 5. Supposing ν_y = 1.20, I = 100 mA, σ_x = 5 mm, and σ_y = 2 mm, the instability occurs when h is larger than 0.60 in case of H_2 molecules. The threshold is larger if heavier molecules are assumed. Therefore, this kinds of instability cannot happen with a few % neutralization whichever molecules are assumed.

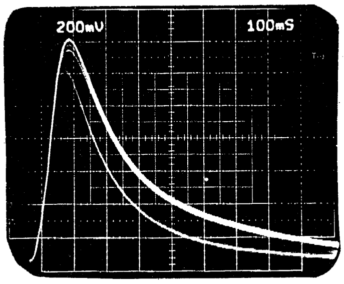

Fig. 2
Current decrease after injection
Upper line : ion clearing on
Lower line : ion clearing off
Horizontal : 100 msec / div
Vertical : 20 mA / div

5. Injection Experiment

In normal operation of NAR, an electron pulse from LINAC is injected in acceleration. To examine the injection condition, the experiment described in this section is performed with keeping the magnetization at constant injection level.

Current decrease after one pulse injection from LINAC is observed with DCCT at 15 MeV static level (Fig. 2). The difference with and without ion clearing electrodes can clearly be seen. However, considering the expected life time from vacuum pressure is longer than 10 seconds, the observed life time is still short even when the ion clearing electrodes are used.

The rising time of DCCT is about 100 msec which is too slow to observe the transition current just after injection. Then, the RF pick up signal of the electron beam is observed with spectrum analyzer which is set to measure RF acceleration frequency (125 MHz) with zero span mode (Fig. 3). The signal is thought to be in proportional to (the square of) the current. As the vertical axis in Fig. 3 is in logarithms scale, the current graph is expected to be straight as long as the beam current decreases with constant life. On the contrary, the slope gets steeper about 30 msec (without ion clearing) and 50 msec (with ion clearing) after injection.

This life time change is thought to be due to ion trapping effect from the following reasons. One is that the effect gets weaker if the ion clearing electrodes are used. Another reason is that the timing when the electron beam begin to be affected is consistent with the intervals required to produce ions of a few % neutralization. Estimated from the tune shift calculation in section 2, it is possible that the life shortens due to the tune shift induced by trapped ions of a few % neutralization.

Ion production rate at injection may be faster than the rate calculated in section 3 because much electrons which cannot be captured in RF bucket or have large emittances exist and ionize molecules, though these electrons are lost after a while and do not contribute to the beam current.

Even when the ion clearing electrodes are used, Fig. 3 (a) shows the similar shape as that of Fig. 3 (b) (without clearing). This indicates that ions cannot be removed well even if the clearing electrodes are used.

Therefore, the assumption that ions can drift along the electron orbit freely and clear at the electrodes does not seem valid. As expected from the calculation of case 1 in section 2, ions might be accumulated at neutralization pockets where beam potential is deep.

These interpretations are presumptions and are not proved yet. However, no other interpretation is presented thus far.

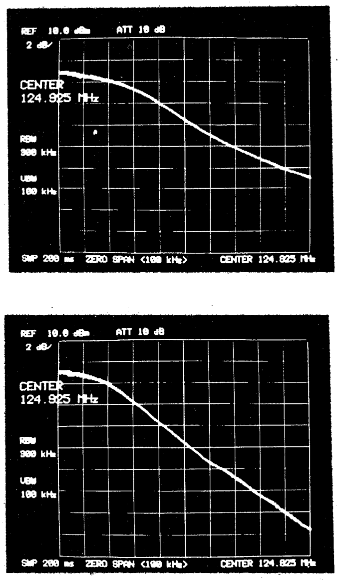

Fig. 3 RF pick-up signal of electron beam
(a) - upper - ion clearing on
(b) - lower - ion clearing off

6. Partial Fill Operation

It is well known that partial fill operation is an effective method to remove trapped ions. This method is examined as a measure to avoid ion trapping effect at injection. Partial fill operation in storage is also

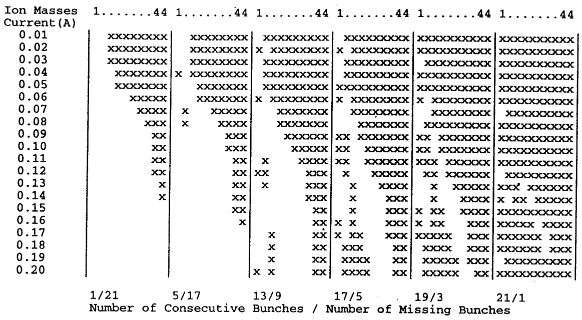

Fig. 4 Linear stability of ions of mass
= 1, 2, 12, 16, 18, 20, 22, 28, 40, 44
(x indicates stability for the given ions)

investigated for the purpose of confirming the effect of this operation.

First of all, the effect of partial fill is numerically estimated. Fig. 4 is a calculated result in storage (800 MeV). The partial fill operation can be effective to remove ionized light molecules such as H_2. At injection energy (15 MeV), ion motion always remains stable. The difference is caused by the difference in beam size. At 15 MeV, because of the large beam size, the focusing force per bunch is too weak for ions to escape the electron orbit while the ions are drifting between bunches.

The effect of partial fill operation is also examined experimentally. To perform partial fill operation in our system which adopt one pulse multi-turn injection, LINAC must be operated in a burst mode. That is, the electrons extracted from an electron gun are modulated by the radio frequency of NAR and partially removed in a period of the harmonic number of NAR. The partial fill operation functions well, however, the present injected current is about 30 - 50 mA, which is less than the normal operation (over 100 mA). RF pick up signal shows the bunch is filled as expected even if electrons are accelerated.

The effect of partial fill operation to avoid ion trapping with little current is examined by worsening vacuum pressure. Some of vacuum pumps are turned off to enhance ion trapping effect.

When more than three bunches omitted, beam profile observed with CCD camera is always stable even if the vacuum pressure is worsened. In full bunch operation, beam profile blinks if the vacuum pressure is worsened. Inferred from the calculation described above, this phenomenon seems to be due to two beam instability caused by light molecules such as H_2. Beam current was about 30 mA in this experiment.

We also compared the full bunch operation mode and 5 bunches omitted mode at 15 MeV injection. In both operation, the current increased with ion clearing electrodes on. This shows that ions are trapped without ion clearing electrodes.

Although this partial fill experiment is preliminary, partial fill operation is not shown to be effective to remove ions at 15 MeV. This result is consistent with the calculation.

7. Comparison to Super-ALIS

Maximum 200 mA beam current is performed in Super-ALIS, which also used 15 MeV injection energy. One of the differences from NAR is its circumference. That is, from eq. (2), tune shift is in proportional to the number of electrons stored as long as the other conditions, such as the beam size or neutralization factor, are the same. If the beam current is the same, the number of electrons is proportional to ring circumference. Therefore, tune shift in NAR of 52.8 m circumference is expected three times as large as that of Super-ALIS of 16.8m. The other deference is the places of ion clearing electrodes. Super-ALIS has clearing electrodes along the orbit in the bending sections as well as button type electrodes at the straight sections. In NAR, button type electrodes are located only in the straight sections.

8. Conclusion

In NAR, ion clearing electrodes are placed at twelve points and are always used. Even if the clearing electrodes are used, the life time at injection is very short due to the ion trapping effect. The possibility that ions are trapped in the bending sections where the beam potential is deep is presented. Partial fill operation mode is examined to remove trapped ions but is not shown to be effective at injection. Although ion trapping effect is not clearly analyzed, the elucidation and countermeasure of this problem are expected to improve NAR beam current.

Acknowledgment

The authors would like to express our appreciation to SR operators who cooperated in acquiring the experimental data.

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