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THE SPACE CHARGE EFFECTS ON THE SLOW EXTRACTION PROCESS

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ABSTRACT

The calculation of the slow extraction which includes the space charge effects has been performed for the Compressor/Stretcher Ring (CSR) of the proposed Japanese Hadron Project. We have investigated the slow extraction of 1GeV proton beam with an average current of 100μA. Calculation shows not only the emittance growth of the extracted beam but also decrease of the extraction efficiency and discontinuity of beam spill.

INTRODUCTION

The Japanese Hadron Project consists of three experimental facilities, 1GeV linac and CSR. The CSR aims at compressing the long beam pulses from the linac to two short pulses and providing them to two experimental facilities called Neutron and Meson Arenas. The long linac pulse of 400μs is compressed into short pulses of 200ns in the CSR. The repetition rate of the linac and CSR is 50Hz. Each Arena requires an averaged current of 100μA. The circulating current becomes 6A. The Meson Arena requires slow-extracted beam pulse which has a long duration of nearly 20ms for using the high intensity π beam.

The fundamental lattice of the CSR is a FODB cell and whole ring has 16 superperiods, as shown in Fig.1. In order to reduce the beam loss during the extraction process, it is necessary to attain a reasonably large turn separation, comparing with the effective thickness of the first septum. It is also required to keep the angle of the extracted beam fixed at the septum for the reduction of the emittance of the extracted beam as well as for the reduction of the effective thickness. For this reason, a scheme to overlap outgoing

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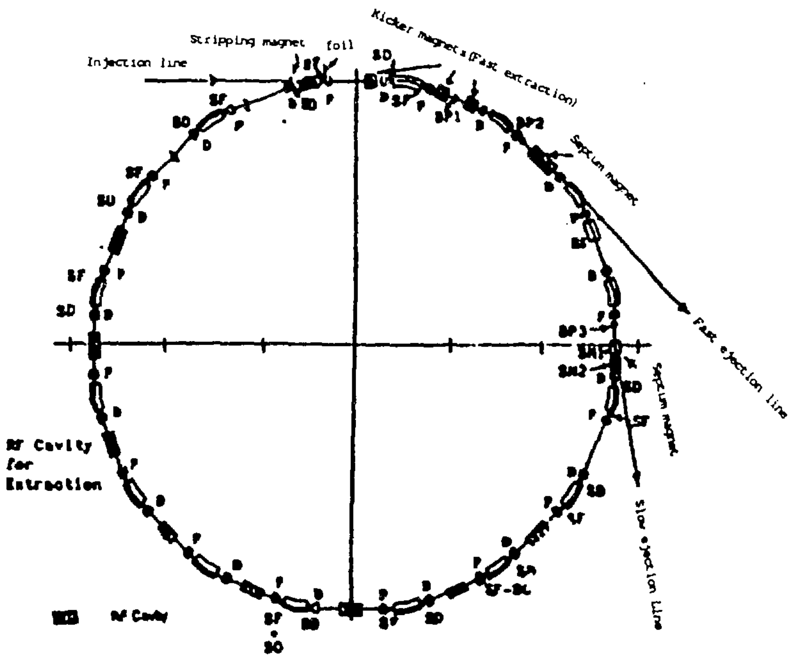

Fig. 1. Layout of the CSR and its equipment for slow extraction. ES and SM1,2 are electric and magnetic septums, respectively. SF and SD are the sextupole magnets for the chromaticity correction. SO and -SO are resonance exciters.

separatrices at every instant by using the third order resonance extraction has been proposed[1]. Beam tracking calculations without space charge have been performed[2,3]. The calculation shows the extraction efficiency is more than 99%. The emittance of the extracted beam is 0.8πmm·mrad. The calculation also shows that a flat and long beam spill can be made as shown in Fig.2.

However, these calculations don't include the space charge effects. When the circulating current is 6A, the space charge tune shift in the ring becomes 0.075 derived by Laslett tune shift formula. The tune shift value is larger than the tune variation by the acceleration of 0.005. The aim of this work is to study the space charge effect on the slow extraction process.

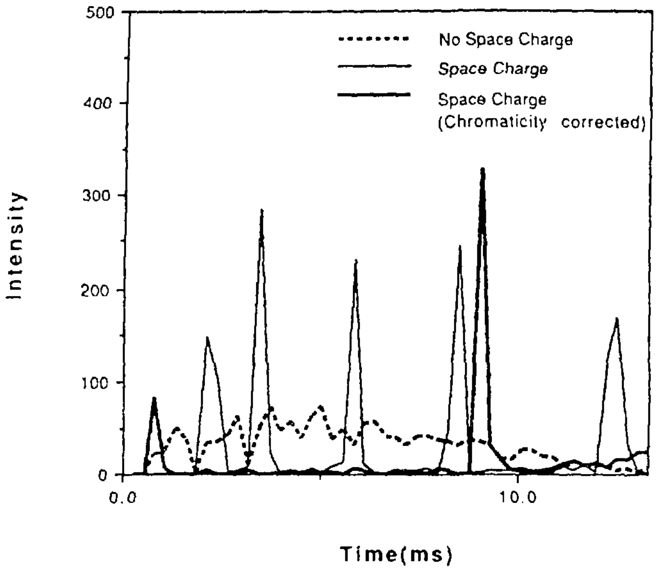

Fig.2. Calculated time structures of the beam spill. Dashed, dotted and solid lines mean the no space charge case, the case satisfies the overlapping condition and includes the space charge, and the case includes the space charge and has a large chromaticity, respectively.

FORMULATION OF SIMULATION

The simple matrix formula is used as the basic program structure. The effects of the sextupole field is taken into account by the thin lens approximation. The effect of RF acceleration and motion in the longitudinal phase space are also taken into account. As the space charge kick depends on the beam intensity, it will become small according to decrease of the circulating current by the slow extraction. We assume the horizontal emittance is proportional to the beam intensity i.e. the number of macro particles. The motion in vertical phase space is neglected. We assume that all tracked particles are on the median plane and the vertical beam size is derived from the vertical beta function and constant emittance. Two or four thousand macro particles are generated and tracked during 20,000turns for the accuracy of calculation[4]. As the revolution frequency is 1.5MHz, this turn number corresponds to 13.3ms. The particle distribution in the horizontal and longitudinal phase space is assumed to be uniform since the phase space painting will be used at the beam injection. The whole ring is divided into 304(=16*19) sections and a space charge kick is inserted between sections. The horizontal kick is derived by

$$d(p_x c)=\frac{e}{\gamma^2}\lambda(s)\frac{\partial\Phi(x,y)}{\partial x}cdt$$

$$\Phi(x,y)=\frac{e}{4\pi\varepsilon_0}\begin{cases}\displaystyle\int_0^\infty dt\frac{x^2/(a^2+t)+y^2/(b^2+t)}{\sqrt{(a^2+t)(b^2+t)}}, & \dfrac{x^2}{a^2}+\dfrac{y^2}{b^2}<1\\[2ex] \displaystyle\int_0^{t_0} dt\frac{1}{\sqrt{(a^2+t)(b^2+t)}}+\int_{t_0}^\infty dt\frac{x^2/(a^2+t)+y^2/(b^2+t)}{\sqrt{(a^2+t)(b^2+t)}}, & \dfrac{x^2}{a^2}+\dfrac{y^2}{b^2}>1\end{cases}$$

where t_0 is the value given by,

$$\frac{x^2}{a^2+t_0}+\frac{y^2}{b^2+t_0}=1\quad.$$

a and b are the lengths of the ellipses along x-axis and y-axis, respectively. The particle distributions in the transverse phase spaces are uniform as the phase space painting method is used at the injection. In this calculation, we assumed that the beam density in the horizontal phase space is constant and the distribution will keep to be uniform during the extraction. By the assumption, b is proportional to the square root of the beta function. a and b are given by

$$a=\sqrt{\varepsilon\beta}+\eta\frac{\Delta p}{p}=\sqrt{\varepsilon_0\beta\frac{I_b}{I_0}}+\eta\frac{\Delta p}{p}$$

where ε, ε_0, I_b and I_0 are the beam emittance, initial beam eimittance, beam current and initial beam current, respectively.

RESULTS

The horizontal space charge tune shift of 0.06 is given by simulation. The tune value is derived by the Fourier transformation of betatron oscillation and the rotation angle in the phase space, independently. Both tune values of no space charge case are consistent with the value given by the computer code MAGIC. The tune shift value is also consistent with the values of 0.075 derived by the Laslett formula and 0.05 derived by the computer code SPACEX[5]. The code can calculate the tune shift when the distribution is KV-type.

Firstly, the slow extraction calculation satisfying the overlapping condition described before was performed. The operation point for the slow extraction is chosen to be 4.40 and the horizontal tune becomes 4.34 by the space charge tune shift. In this case, the horizontal chromaticity is corrected to be small negative value by the sextupole magnets. The operating point will be shifted by 0.005 by the acceleration which is the optimum value for the extraction in the no space charge case. The slow extraction begins after beginning of the acceleration as shown in Fig. 2. However, the extraction stops after 4% of the circulating particles were extracted. The tune distribution of the circulating particles shows that the horizontal tune can not stay at the point near the resonance after a part of the beam was extracted since the space charge tune shift is relaxed by decrease of circulating beam current(see Fig. 3). The horizontal tune goes away from the resonance point and the extraction is stopped until the tune will go to the point near the resonance again. The tune variation of 0.005 by the acceleration is too small to extract the beam efficiently. By this effect, the extraction efficiency becomes 30%.

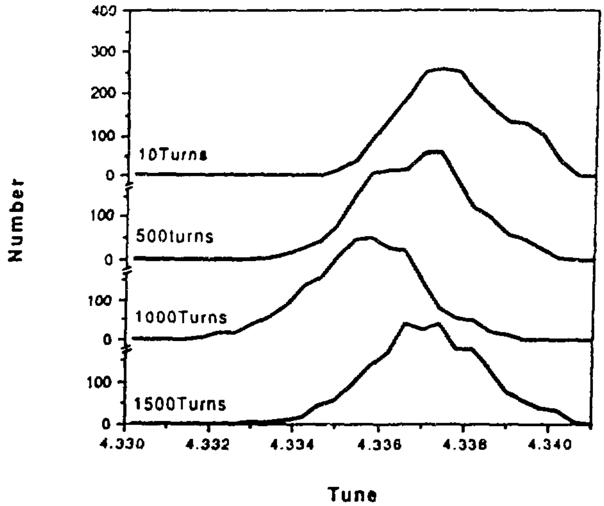

Fig. 3. Horizontal tune distribution of circulating beam. The horizontal tune value shifts to the resonance by the acceleration. Eight percent of the circular particle are extracted immediately after 1000turns and the tune goes away from the resonance by the relaxation of the space charge.

In order to extract all circulating particles, the variation of the horizontal tune should be as large as the space charge tune shift. It is necessary for the large tune variation to make the chromaticity large since the momentum aperture of the CSR is limited. We calculated on the large chromaticity case in which the variation of the horizontal tune is as large as the space charge tune shift. It shows the extraction efficiency become larger than 90%. However, such a large chromaticity can not satisfy the overlapping condition. The beam emittance of the extracted beam becomes too large. The beam spill is not continuous as shown in Fig 2. It shows that the variation of tune by the acceleration, extraction of a part of beam and tune shift by the relaxation of the space charge are repeated.

The discontinuity of the beam spill also appears when we change the tune value by the lattice quadrupole magnets. It is possible to get the extraction efficiency more than 90%. In this case, the beam emittance of the extracted beam is about 10πmm·mrad. It is very large emittance comparing with that when the overlapping condition were satisfied.

DISCUSSIONS

In order to extract the high intensity beam by the slow extraction, the beam emittance of the extracted beam should be small and the extraction efficiency has to be almost 100% to avoid the large beam loss which causes the radio-activation of the accelerator. The multi-particle tracking calculation shows the difficulty of the slow extraction of the high beam current from the designed CSR. That is, if we extract the circulating particles with high efficiency the emittance of the extracted beam becomes much large since the overlapping condition can not be satisfied.

The racetrack type ring may satisfy both requirement, that is, the small beam emittance of the extracted beam and high extraction efficiency. As it is possible to make a high beta function at the slow extraction septum, the beam emittance of the extracted beam can be minimized although there is the large space charge effect. The racetrack lattice for the CSR has investigated[8] for decreasing the beam loss on the slow extraction and direct H^- injection. The space charge effect on the slow extraction from the racetrack-type CSR will be investigated.

The discontinuity of the beam spill makes the experiment inefficient as the duty factor decreases. For the experiment using the high intensity π beam, the beam spill should be continuous and flat. The control of the beam spill has to be investigated. The calculation which includes the feedback system of the beam spill should be performed.

CONCLUSIONS

The space charge effects on the slow extraction process are investigated by the multi-particle tracking calculation by means of the vector computer. The calculation shows the decrease of the extraction efficiency, emittance growth and discontinuity of the beam spill. These effects will make the slow extraction of the high current beam difficult.

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