

SPACE CHARGE EFFECTS IN RIKEN CYCLOTRONS

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Abstract

The RI Beam Factory is under construction at RIKEN. The new accelerator system consists of three cascade cyclotrons, and Experimental Storage rings. Space charge effects on the beams are the subjects to be studied. Acceleration of the ions $^{16}\text{O}^{8+}$ and $^{238}\text{U}^{88+}$ was considered in the Superconducting Ring Cyclotron (SRC). The flattop (FT) compensation of the longitudinal space charge (LSC) was attempted. In the AVF cyclotron the simulation of the energy spread suppression by FT was fulfilled.

1 INTRODUCTION

The RI Beam Factory is under construction at RIKEN[1]. The new accelerator system consists of three cascade cyclotrons (fRC, IRC and SRC) and Multi-Use Experimental Storage rings (MUSES) [2]. A beam from the RIKEN Ring Cyclotron (RRC) is injected into the system. Nuclei up to Uranium are accelerated with the highest intensity ≈ 1 particle- μA (μA). High peak current, such as $100\mu\text{A}$, ion beam acceleration is required in the cyclotron injector.

Several authors have investigated the space charge effects in cyclotrons [3-6]. A special attention should be paid to the LSC effects, since isochronous cyclotrons do not have the property of longitudinal focusing. Adjusting the phase of the flattop harmonic with respect to the accelerating RF voltage can compensate the linear part of the bunch broadening. The turns remain separated as long as the space charge induced energy spread is smaller than the energy gain per turn at the extraction radius.

Because the space-charge electric fields are severely non-linear, practical investigation must be preceded by numerical methods. A particle-in-cell code "PICS" [5] was used for the LSC effect calculations in the RIKEN SRC and AVF cyclotrons. The three-dimensional multi-particle code "NAJO" [7] was also used for simulation of AVF beam dynamics characteristics.

2 INPUT PARAMETERS

The SRC parameters from [1], [8], [9] were used in calculations (Table 1). The radial dependence of the energy gain per turn for 4 single-gap cavities (harmonic number = 6) had the maximum value of 2.4MV. The gap value of 90mm [1] was used to apply a reduction factor to the Coulomb force. The FT voltage per turn (the 3rd harmonic) was assumed to be 1/9 of the main one.

Table 1:SRC selected list of parameters

Particle	$^{16}\text{O}^{8+}$	$^{238}\text{U}^{88+}$
Initial energy, MeV/u	126.7	115
Min. number of turns	~ 260	~ 300
Final energy, MeV/u	400	350
RF frequency, MHz	38.114	36.669

The charge density distribution versus RF-phase was given by:

$$I(\varphi) = [1 - (\frac{\varphi}{\varphi_{\text{lim}}})^2]^{xm}. \quad (1)$$

The maximum phase extension of the bunch φ_{lim} was derived from the effective bunch width $\Delta\varphi$ (full width) multiplied by some extension factor. The choice of the parameters $xm=7.5$ and $\Delta\varphi=10^\circ$ provided a realistic charge distribution in the bunch, corresponding to the measurements of the RRC beam characteristics [8].

An effective radial half-width of the bunch was assumed to be $R_{\text{beam}} = 2\text{mm}$. The total radial width of the beam was composed of this parameter and the width component $DY = 1.5\text{mm}$, which corresponded to the momentum spread $= \pm 2.5 \cdot 10^{-4}$ in the bunch.

The beam was represented with dots (quasi-particles). The total number of dots was taken to be 4623 with 11 dots per vertical row.

The minimum number of turns was taken in the simulation, neglecting the phase excursion during acceleration. Everything below is related to the $^{16}\text{O}^{8+}$ beam acceleration in the SRC unless $^{238}\text{U}^{88}$ is not mentioned explicitly.

3 ANALYTICAL ESTIMATION

Assuming that the total LSC energy spread is equal to half of the energy gain per turn, the average LSC beam intensity limit for separated turns is defined by [4]

$$\langle I \rangle = \frac{0.5}{f_n} \cdot \frac{U_f}{2.8k\Omega} \cdot \frac{\Delta\varphi}{2\pi} \cdot \frac{\beta_{\text{fin}}}{n^3}, \quad (2)$$

with $\beta_{\text{fin}} = v_{\text{fin}}/c$ - final velocity, n - total number of turns, $U_f = (W_{\text{fin}} - W_{\text{inj}})/Ze$ - total voltage gain during acceleration, $W_{\text{inj}}, W_{\text{fin}}$ - kinetic particle energy at injection and at extraction, Ze - particle charge, $f_n = 0.25$ - non-linear fraction of the LSC voltage spread. According to this formula for $^{16}\text{O}^{8+}$ beam the LSC intensity limit in the SRC will be $14\mu\text{A}$ and $55\mu\text{A}$ after FT compensation. Since the formula takes into account the turn radial gain by acceleration only, the computer simulations are needed for the real SRC situation.

4 BUNCH PHASE WIDTH VARIATION

In the program “PICS” the longitudinal and radial profiles with the corresponding $2 \times \text{rms}$ width values ($2 \times l$) and ($2 \times r$) are both projections from the 2D radial-azimuthal charge density distribution of the beam bunch. The radial profile can therefore give a hint on the radial width of the simulated beam, and by knowing the radial gain per turn at extraction some hint on extraction losses might eventually be possible. Such conclusions have, however, to take into account that the sphere model, implemented in the code, is highly simplified approximation to the real beam behaviour in a cyclotron with space charges [10].

Assuming that up to ~98% of the equivalent Gaussian charge distributions of two neighboring bunches would not overlap, we have to require that the effective radial width of the bunch $D_{beam} = (2.88 \times 2 \times r)$ should be less than the turn radial gain at extraction ($= 12.5\text{mm}$ due to acceleration and beam off-centering) to get clearly separated turns in the region.

At the maximum beam current of $100\mu\text{A}$ in the $\Delta\varphi = 12^\circ - 20^\circ$ range the radial beam size decreases for smaller phase width due to dependence of the particle energy gain on its phase position (Figure 1). No LSC effects are visible yet in this region.

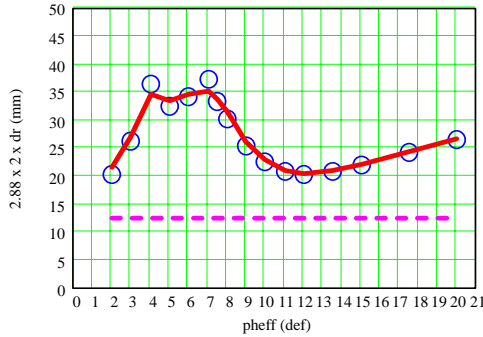


Figure 1. Final effective radial width of the beam versus $\Delta\varphi$. Dash line: radial gain per turn.

In the $\Delta\varphi = 7^\circ - 12^\circ$ range the synchrotron oscillations start to constitute a type of vortex motion [3] due to the LSC effects. As a result the broadening of the radial beam size takes place (Figures 1 and 2).

In the $\Delta\varphi = 2^\circ - 7^\circ$ range the non-monotonous behaviour of the curve in Figure 1 could be explained by the structure change of the charge distribution (Figure 2). Decreasing the “tails” in the initial phase charge distribution emphasizes the process, increasing R_{beam} makes it less pronounced and increasing DY leads to larger rotation angle of the charge distribution.

At $\Delta\varphi = 2^\circ$ the round beam formation [5] manifested itself (Figure 2), allowing attempts for the particle acceleration beyond the longitudinal space charge limit[6].

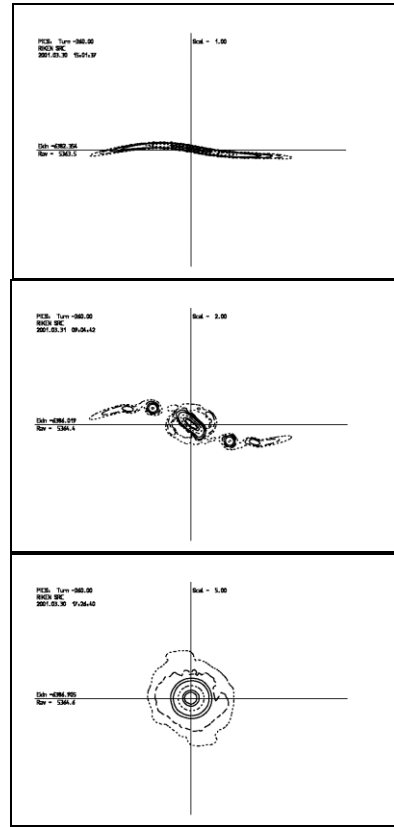


Figure 2. Final beam charge distribution for $\Delta\varphi = 10^\circ$ (upper frame), $\Delta\varphi = 5^\circ$ (middle frame) and $\Delta\varphi = 2^\circ$ (lower frame). The contour lines represent 2%, 5%, 10%, 20%, 50%, 80% and 90% of the maximum charge density at extraction.

5 THE LSC INTENSITY LIMIT

The LSC intensity limit, defined as the beam current, for which the effective bunch width is equal to the radial gain per turn, is $\approx 25\mu\text{A}$ when the FT is not used (Figure 3). To accelerate the beam with higher than that value the compensation of the linear part of the LSC was attempted by using the FT. The optimal FT phase shift to get a minimum radial broadening of the beam was taken in the range $180^\circ - 185^\circ$. As a result the LSC intensity limit became $\approx 75\mu\text{A}$. Above this current the non-linear

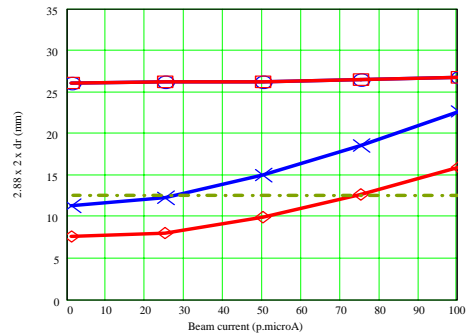


Figure 3. Final bunch radial width versus beam current. Cross: no FT, diamond: FT, box: $\Delta\varphi = 20^\circ$ and no FT and dash-dot line: radial gain per turn.

part of the LSC defined the beam dimension increase with intensity. But such high beam current is required only for MUSES [2], which implies a pulse operation of the cyclotrons keeping the average dissipated beam power below the tolerable level.

For $\Delta\phi = 20^\circ$ it was still difficult to get a clean turn separation at extraction even with the FT system. The worsening of the beam quality to $R_{beam} = 4\text{mm}$ and $DY = 3\text{mm}$ led to overlapping turns at extraction.

The $\Delta\phi = 10^\circ$, $R_{beam} = 2\text{mm}$ and $DY = 1.5\text{mm}$ case was taken in the simulations for $^{238}\text{U}^{88}$. The analytical model showed that the LSC intensity limit was $\approx 1\mu\text{A}$ without FT and $\approx 4\mu\text{A}$ after FT compensation. The “PICS” simulation gave the LSC current limit to be $\approx 2.5\mu\text{A}$ without FT and $\approx 6\mu\text{A}$ with FT.

6 AVF SIMULATIONS

In the AVF cyclotron the energy spread suppression by the FT system in order to improve the turn resolution at the extraction was simulated by “PICS”. Calculation conditions were as follows: reference particle $^{14}\text{N}^{5+}$, beam current = $0.2\mu\text{A}$, $20\mu\text{A}$ and $100\mu\text{A}$ (available from the ion source), bunch phase width = 20° , betatron amplitudes = 2.5mm , momentum spread = $5 \cdot 10^{-3}$, energy gain per turn = 200kV , number of turns = 100 and final energy = 7MeV/u .

For currents less than $20\mu\text{A}$ the “PICS” simulations showed that the bunch curvature was defined by the energy spread in the beam due to different particle phase position.

For the beam intensity of $100\mu\text{A}$ the part of the energy spread could be suppressed by the FT system with the phase shift $\approx 10^\circ$. Furthermore, an asymmetry in the charge distribution due to the LSC was eliminated.

Since the radial turn gain at extraction is $\approx 4\text{mm}$ there is no turn separation in the AVF cyclotron at final radius even for low beam intensity (Figure 4).

“NAJO” simulations showed that for the beam current up to $20\mu\text{A}$ there was rather weak LSC impact on the radial beam dimension, which agreed with the “PICS” results. For $100\mu\text{A}$ case the LSC effects still did not appear to be so strong as in “PICS” calculations. This

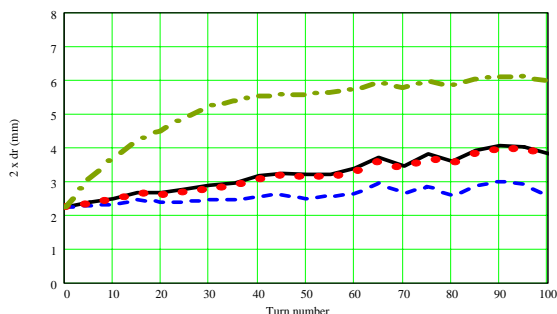


Figure 4. Beam radial dimension ($2 \times r$) versus turn number. Dot line: $0.2\mu\text{A}$, solid line: $20\mu\text{A}$ and FT compensation, dash-dot line: $100\mu\text{A}$.

could be probably explained by neglecting the details of the charge distribution in “NAJO” code.

Concluding, it could be suggested that an increase of the particle extraction efficiency might be obtained by installation of the FT system along with increase of the energy gain per turn and/or controlled beam radial off centering.

As expected the transverse space charge effects leads to increase of the axial beam size on $\approx 30\%$ at lower energy range for the beam current of $100\mu\text{A}$. For the bunch intensities below $20\mu\text{A}$ there was practically no change in the axial beam size due to space charge forces.

7 CONCLUSIONS

- In the SRC an injected beam phase width has a strong impact on the beam intensity limit due to the LSC effects.
- Beam quality should be good enough to provide clearly separated turns at extraction in the SRC.
- In the AVF the LSC effects are hardly noticeable at the beam intensity below $20\mu\text{A}$. They start to be visible at $100\mu\text{A}$.
- Use of the FT gives a noticeable reduction of the radial spread at final radius in the AVF cyclotron.

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