POSSIBILITY OF ROUND BEAM FORMATION IN RIBF CYCLOTRONS

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Abstract

Since 1997 RIKEN Nishina center has been constructing a next-generation exotic beam facility, RI beam factory (RIBF), based on a powerful heavy ion driver accelerator. Its accelerator complex was successfully commissioned at the end of 2006 and started supplying heavy ion beams in 2007. The four ring cyclotrons (RRC, fRC, IRC and SRC) connected in series accelerate the energy of the heavy ion beams up to 400 MeV/u for the lighter ions such as argon and 345 MeV/u for heavier ions such as uranium. Intensity upgrade plans are under way, including the construction of a new 28 GHz superconducting ECR ion source. The new ECR will take all the succeeding accelerators and beam transport lines to a space charge dominant regime, which should be carefully reconsidered to avoid emittance growth due to space charge forces. Beam dynamics in the low energy cyclotron, RRC was studied with OPAL-cycl a flavor of the OPAL. The simulation results clearly show vortex motions in the isochronous field, resulting in round beam formation within the first 10 turns after the injection.

INTRODUCTION

RIKEN Nishina center has undertaken construction of an RI Beam Factory (RIBF) [1] since April 1997 aiming to realize a next generation facility that is capable of providing the world's most intense RI beams at energies of several hundred MeV/nucleon over the whole range of atomic masses. The RIBF requires an accelerator complex which would accelerate the full mass range of ions and deliver ~80 kW of uranium beam at energy of 345 MeV/nucleon. Figure 1 shows a bird's eye view of RIBF. The left part is the old facility completed in 1990. Using the four-sector K540-MeV ring cyclotron (RRC), many experiments were carried with RI beams of light ions because RRC can accelerate relatively light ions up to 100 MeV/u, which is the lower limit for the RI-beam production as shown in Fig. 2. At first, the two ring cyclotrons, Intermediate Ring Cyclotron (IRC). Superconducting Ring Cyclotron (SRC) were designed as energy boosters for the RRC in order to expand the

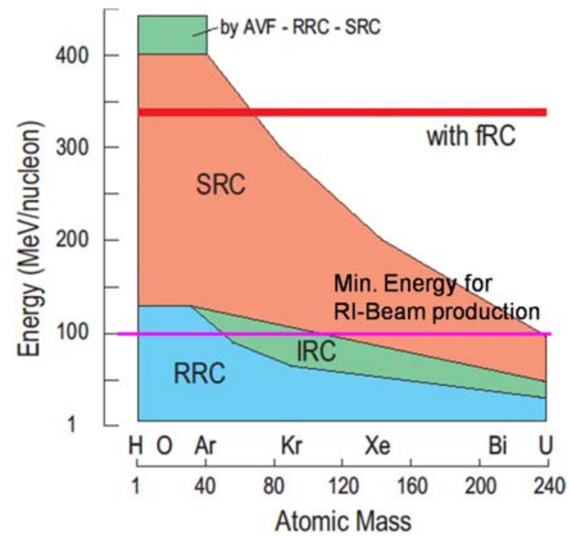

Figure 2: Performance of the RIBF accelerator complex.

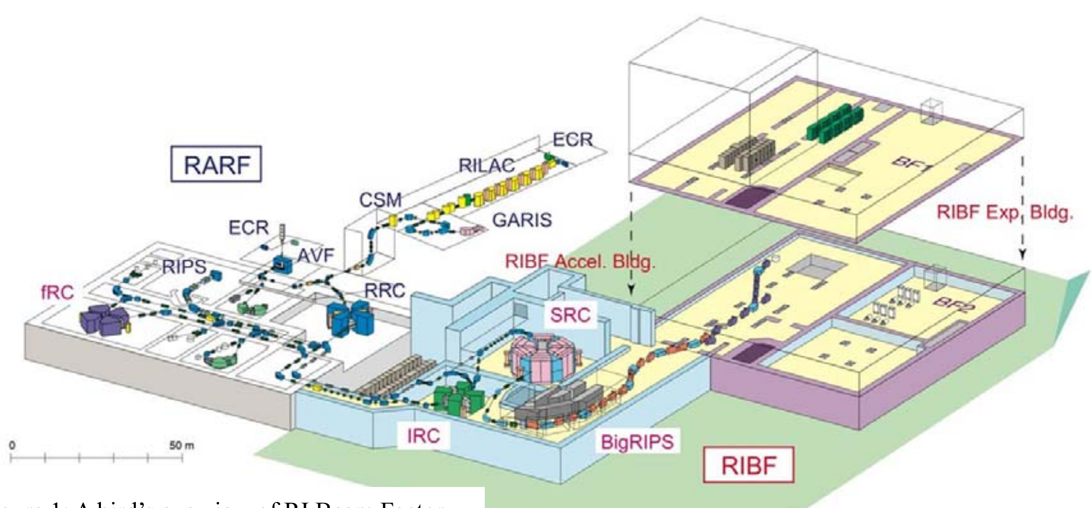

Figure 1: A bird's eye view of RI Beam Factory.

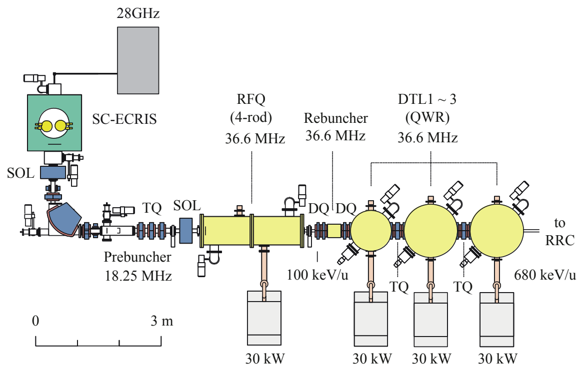

Figure 3: A plan of the new injector.

mass range where RI beams can be produced as shown in Fig. 2. In 2000, after the appearance of the RIA project in the US , we realized that all the ion beams including uranium can be accelerated up to the maximum energy of 345MeV/u by adding another cyclotron, a fixed-frequency ring cyclotron (fRC), before the IRC. In this way, we are now able to generate a wide variety of RI beams from hydrogen to uranium. The intensity of the goal is more than 1 pμA (6.0 x 10^{12} pps).

The RIBF accelerator complex was successfully commissioned at the end of 2006 and started supplying heavy ion beams in 2007. In 2008 intensity of Ca beam extracted from SRC reached 170 pμA (1.1 x 10^{12} pps) which is close to the goal intensity. Uranium beam of 0.4 pμA (2.5 x 10^{9} pps) could be accelerated up to 345 MeV/u in November 2008. [2] This intensity is a value of the world's top level, but far from our goal.

Key issues to increase the intensity of uranium ion beams can be clearly pointed out as follows. First, we need more beams from the ion source. A new 28GHz superconducting ECR ion source has been constructing. [3] This ion source is designed to have as large plasma volume as 1100 cm^3 and expected to produce U^{35+} ions at an intensity of more than 15 pμA, which is necessary to obtain 1 pμA beams from the SRC. Beam tests started form the last May with 18 GHz rf power source and operation with a 28 GHz source will start from the next year. Next, we need a new injector which efficiently accelerates ion beams from the new powerful ion source in order to avoid the emittance growths due to their space charge forces. Figure 3 shows a plan for the new injector which is designed to accelerate ions with a mass-to-charge ratio of 7, aiming at heavy ions such as $^{84}Kr^{13+}$, $^{136}Xe^{20+}$ and $^{238}U^{35+}$, up to energy of 680 keV/nucleon. [4] It consists mainly of the SC-ECR, an RFQ linac based on the four rod structure and three drift-tube linac (DTL) based on the quarter-wavelength resonator (QWR). A four-rod structure RFQ denoted by Kyoto University will be recycled for this purpose after some modifications to change the resonance frequency by about 10 %. The new injector linac will be commissioned from the autumn of 2010. The following section of this paper will describe the space charge effects in the succeeding cyclotrons which may be taken to space charge dominant by the intensity upgrade program for uranium beam.

PSI Inj. 2	RRC	fRC	IRC	SRC
1	0.644	0.096	0.031	0.016

Table 1: List the value of the parameter of (1) in the text.

MOTIVATION

The intensity upgrade of uranium beam described in the previous section motivated us to study the vortex motions in the RIBF cyclotrons. Longitudinal space charge force causes additional acceleration for head particles and deceleration for tail particles. The accelerated or decelerated particles move to higher or lower radii due to isochronous condition in cyclotron, causing rotation of the bunch. The nonlinearity of space charge force produces spiral shaped halo, finally rotating sphere. These vortex motion phenomena were theoretically studied as shown in [5-9] and experimentally verified at the PSI Injector II.

Pozdeyev described in his thesis [8] that the effects of the space charge force for bunches of similar lengths approximately scale as:

$$\frac{qI}{\gamma^5 mh\omega^3} \qquad (1)$$

where I is the total beam current, h is the harmonic number and the momentum is $p= m\gamma R\omega$. Table 1 lists the values of the parameter in the case of Injector II, RRC, fRC, IRC and SRC, indicating that RRC is approximately equivalent to the Injector II from the point of view of space charge force effects, while the effects in the other three cyclotrons are small. Therefore our beam dynamics study focused on the RRC, low energy cyclotron.

Item	Value
K value	540
Number of magnet sector	4
Sector Angle	50 deg
Inj. and ext. radius	0.39 and 3.56 m
Number of Cavity	2 (double gap)

Table 2: Main specification for RRC.

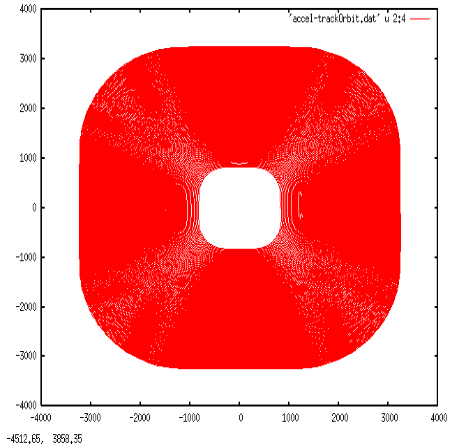

Figure 4: Top view of single-particle tracking of the reference particle up to the final turn in RRC.

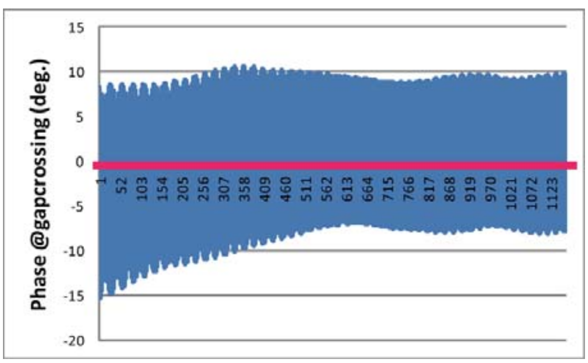

Figure 5: Phase slip at the gap crossing in RRC.

SIMULATIONS USING OPAL

OPAL-cycl [10] is one of the flavours of the Object Oriented Parallel Accelerator Library (OPAL) framework. It is a new 3D PIC based self-consistent numerical simulation code covering neighbouring bunch effects. Self consistency is to be understood in the electrostatic approximation. A more detailed description of the OPAL framework and OPAL-cycl code can be found in the User's Reference Guide [11].

Table 2 shows the main parameters of RRC which consists of the four-sector magnets and two double-gap

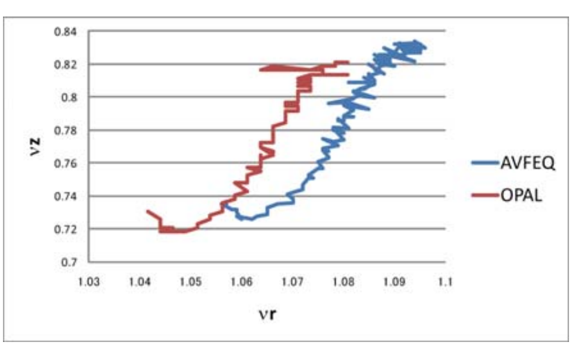

Figure 6: Tune diagram for RRC.

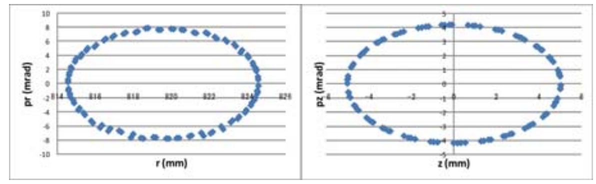

Figure 7: Eigen-ellipses at the first turn of RRC in the radial and vertical directions.

rf resonators. Simulations using OPAL-cycl need realistic isochronous field map and radial distribution of rf voltage at the gaps. The field map for isochronous field was calculated by ANSYS with high accuracy. [12] Radial distribution of rf voltage was assumed to be constant since the resonator of RRC shows almost constant radial distribution in the case of 18.25 MHz.

Single-particle tracking and tune calculation

OPAL-cycl prepares single-particle tracking and tune calculation which are important to check isochronism of the field map, validity of the initial condition and matching phase ellipse before multi-particle tracking including space charge forces. Figure 4 shows the top view of the acceleration up to the final turn. It took about 296 turns for the particle to reach the final energy of the cyclotron. Phase slip at the rf gap crossing is shown in Fig 5, showing that the used field map is sufficiently isochronous. Betatron frequencies in the radial and vertical direction were calculated using the tune calculation mode of OPAL-cycl, as shown in Fig. 6. The result from AVFEQ [13] and OPAL-cycl shows good agreements even though different numerical algorithms are used, however we are in the process understanding the visible differences. Single-particle tracking was carried out with initial offsets of r (z) = 5.0 mm, pr (pz) =0.0 mrad from the static equilibrium orbit at the injection energy, in order to get eigen-ellipses in the radial and vertical directions. The results in Fig. 7 shows that the ratios between the semi major axis and semi minor axis are 5.0/4.2 and 5.0/2.5 mm/mrad in the radial and vertical direction, respectively. These ellipses were used as the initial conditions for multi-particle tracking described in the next subsection.

Multi-particle tracking including space charge force effects

Multi-particle tracking including space charge forces was carried out at the beam current of 0.5 mA after obtaining the initial conditions from the single-particle tracking studies. The first 10 turns after injection were simulated with acceleration because we are mainly interested in the behaviour of bunches just after the beam injection. Initial transversal rms emittance was assumed to be 2.5 mm mrad from the operational experiences. Initial rms bunch length was assumed to be 2 or 4 degree in order to study how the bunch length impacts on the vortex motion. Figure 8 shows the results for the simulations. The results for both cases of 2.0 and

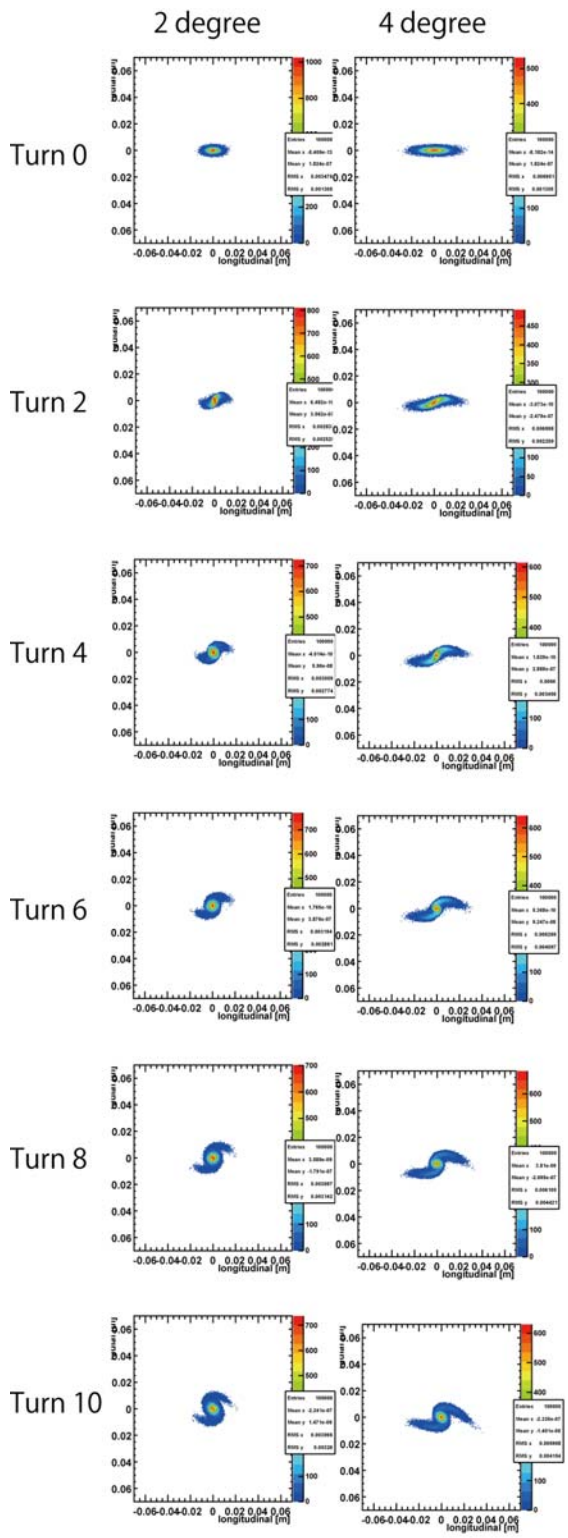

Figure 8: Result for multi-particle tracking. Turn numbers are shown in the left side of the contour plots. Rms of the initial bunch length is shown in the top of the contours.

4.0 degree clearly show the vortex motions of bunches toward stationary round distributions. The bunch in the case of 2.0 degree has smaller tails and rotates faster than that in the case of 4.0 degree. More detailed simulations up to the final turns including space charge effects from neighbouring turns are in progress.

SUMMARY AND FUTURE WORKS

The intensity upgrade of uranium beam is under way in the RIBF accelerator complex. This may be based on the vortex motions in the low energy cyclotron RRC from Pozdeyev's scaling law, which motivated us to simulate the beam dynamics in RRC using OPAL-cycl. After obtaining the initial conditions using single-particle tracking, as a first step we simulated the first 10 turn of the RRC. The results show the clear signs of vortex motions, motivating us to carry out a more detailed simulation campaign up to the final energy, including neighbouring turns.

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