POSSIBLE PARAMETERS FOR BUNCH COMPRESSION IN A RING IN FUTURE RIKEN PROJECTS

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Abstract

Possible beam parameters are investigated for bunch compression in a storage ring, TARN II. Fast rotation scheme is carried out for the generation of high current beam after ion stacking with beam cooling method. From the viewpoint of the magnetic rigidity and tune shift, allowable beam parameters during the beam stacking in the ring are estimated analytically. Beam dynamics during the bunch compression is studied by the envelope equations. Particle-in-cell simulations are also carried out for the study of beam dynamics, and the results are compared with the envelope calculations.

INTRODUCTION

At RIKEN, facilities are being upgraded with new superconducting ring cyclotrons (SRC) intended primarily for radioactive beam research in nuclear physics [1]. In this radioisotope beam factory (RIBF), the SRC can be used to fill beams of rare unstable radioisotope to storage rings for internal target experiments and mass measurements [2]. Not only the radioisotopes, also stable heavy ions can be extracted from the SRC. The site facilities including buildings for future rings are presently under construction. Parts of storage ring TARN II [3] are being moved to RIKEN, and it may be possible to rebuild this ring as the bunch accumulation ring for nuclear physics of rare unstable radioisotope and High Energy Density Physics (HEDP) applications [4]. In this project, the rebuilt TARN II ring will be filled from the SRC using rf stacking and beam cooling schemes.

In inertial confinement fusion using intense heavy ion beams (HIF), space-charge-dominated beam physics is crucial for the effective target pellet implosion [5, 6]. For this reason, we are planning the beam physics experiments in the rebuilt TARN II in RIBF at RIKEN. In this paper, the possible parameters for stacked ion beam are estimated, and after the stacking the bunch compression in the ring by fast rotation scheme [7] is considered using the envelope model and multiparticle simulations.

RECONSTRUCTION OF TARN II RING

It is proposed that TARN II ring is installed into the building in RIBF at RIKEN. Figure 1 and Table 1 show the configuration and parameters of the TARN II ring [3]. TARN II has an rf cavity and an electron cooler, because of the ring was designed as a cooler synchrotron. The focusing structure of the magnet system is a focusing-bending-defocusing-bending-focusing-drift (FBDBFO) lattice. The tunes and machine acceptance depend on the operation modes, and the large acceptance of 400 πmm-mrad can be allowable in the acceleration mode.

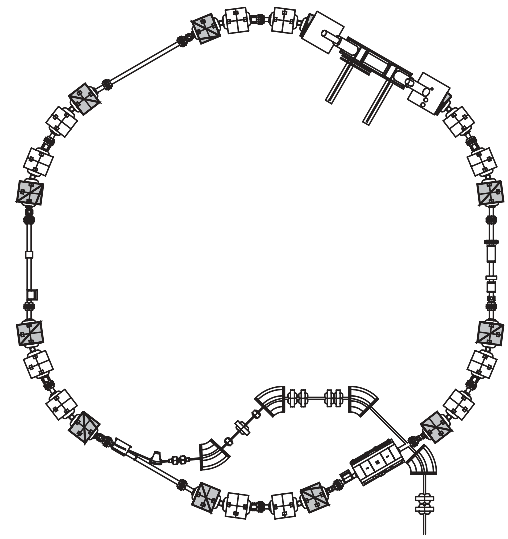

Figure 1: TARN II ring.

The circumference of TARN II is allowable for the reconstruction in RIBF from the viewpoint of the site limitation. The ring at longer straight section has advantage for nuclear experiments and spaces for the rf cavity and electron cooler, since the extension of the straight section may be considered in the future work.

Table 1: TARN II parameters

Circumference [m]	77.76
Length of Straight Section [m]	4.2
Superperiodicity	6
Horizontal / Vertical Tunes	1.67 / 1.73
Horizontal Aperture Radii [mm]	100
Vertical Aperture Radii [mm]	20
Max. Magnetic Rigidity [Tm]	6.1
Max. Horizontal Beta Function [m]	11.361473
Max. Vertical Beta Function [m]	18.358040
Max. Dispersion Function [m]	5.278943
Transition Gamma	1.793402

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BEAM STACKING IN TARN II RING

The magnetic rigidity $B\rho$ is given by [5]

$$B\rho = \frac{\gamma A m_u \beta c}{qe}, \quad (1)$$

where γ is the relativistic factor of the beam, A is the atomic mass number, m_u is the atomic mass unit, β is the beam velocity divided by speed of light c in vacuum, q is the charge state of the beam ion, and e is the elementary charge, respectively. Due to the limitation from the magnetic rigidity, the particle energy per atomic mass number of the ion is restricted as 200 MeV/u at $^{238}U^{92+}$ ion beam in TARN II ring. However the lower particle energy ($<$ 50 MeV/u) is favorable for HIF. For this reason, the limitation due to the magnetic rigidity of TARN II ring is not important in this purpose.

The beam at large tune shift may cause the instability during the bunch revolution in the ring. The stacked ion number is restricted by the tune shift value. The particle number N_b of a beam bunch is estimated by [8, 9, 10]

$$N_b = \frac{\pi|\Delta Q_{sc}|B_f\beta^2\gamma^3}{r_i F_{sc}}\epsilon_y\left(1+\sqrt{\frac{\epsilon_x Q_y}{\epsilon_y Q_x}}\right), \quad (2)$$

where $|\Delta Q_{sc}|$ is the absolute value of space-charge (Laslett) tune shift, ϵ_x and ϵ_y are the unnormalized horizontal and vertical emittances, Q_x and Q_y are the horizontal and vertical tunes, $r_i (= q^2e^2/4\pi\epsilon_0 A m_u c^2)$ is the classical ion radius with permittivity ϵ_0 of free space, F_{sc} is the factor depended on the particle distribution, and B_f is the bunching factor, respectively. For Gaussian distribution on the transverse direction of the beam, $F_{sc} = 1$ is approximated. If the coasting beam is assumed, $B_f = 1$.

Electron cooling is carried out after the accumulation and the prospects for this are under investigation. By the beam cooling and rf voltage at harmonic number $h = 1$, the bunch length is shortened until half length (i.e., $B_f = 0.5$) of the circumference of the ring. After the manipulations, fast rotation of the longitudinal phase-space using rf technology is carried out.

BEAM DYNAMICS DURING BUNCH COMPRESSION IN RING

Using the beam envelope model and multiparticle calculation, we estimate the beam dynamics during bunch compression in TARN II ring. The initial beam parameters are assumed as Table 2. These parameters satisfy the restriction from Eqs. (1) and (2) for $B_f = 0.5$ and $|\Delta Q_{sc}| = 0.25$.

The fast rotation scheme, which was proposed for the fast bunch compression in the ring [7], is used after the beam cooling in this study. The rf voltage for the beam bunching of 65.266 kV at $h = 1$ is applied from the head to the tail of the bunch in TARN II ring. As a result, the longitudinal beam envelope is rapidly rotated by the rf voltage, and the exchange between the small momentum spread at the initial condition and the bunch length is occurred by the longitudinal rotation in the phase space. If the initial momentum spread is small enough, the bunch length will be shortened after the longitudinal rotation.

At first, we calculate the longitudinal beam dynamics by the envelope equations [7, 11]. Figure 2 shows the longi-

Table 2: Beam parameters for bunch compression in ring

Ion Species	$^{238}U^{92+}$
Particle Energy [MeV/u]	50
Number of Beam Ions	1×10^9
Horizontal Emittance [πmm-mrad]	2
Vertical Emittance [πmm-mrad]	4
Momentum Spread [%]	0.01

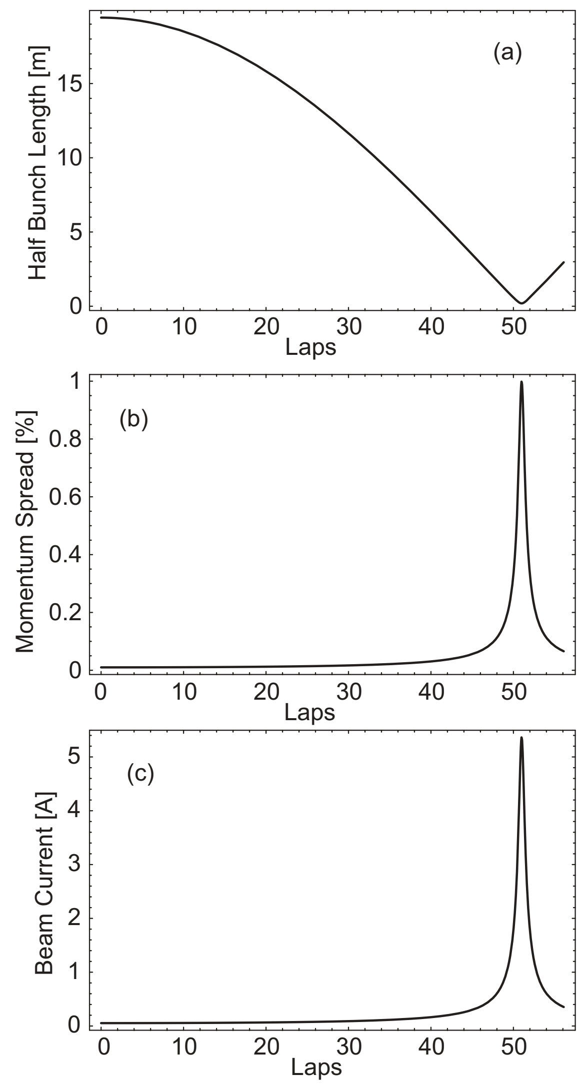

Figure 2: Longitudinal beam behavior as a function of revolution laps during bunch compression in ring, (a) half bunch length, (b) (incoherent) momentum spread, and (c) beam current, respectively.

tudinal beam dynamics during the bunch compression in TARN II ring. The acceptance of the momentum spread in TARN II ring is 1%, so that the bunch can be compressed until the limitation of momentum spread. In this case, the beam current is increased from initial 0.05 to 5.372 A at the peak due to the bunch compression using the fast rotation as shown in Fig. 2. The transverse beam dynamics given by

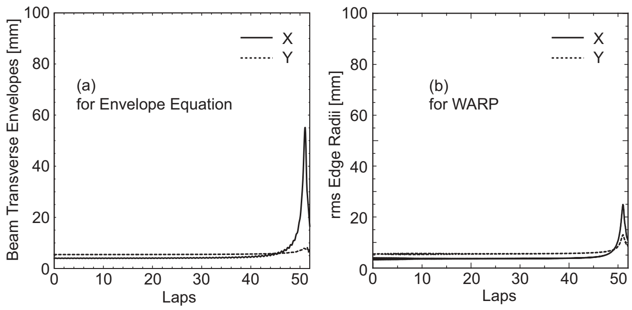

Figure 3: Transverse beam behavior as a function of revolution laps during bunch compression in ring, (a) envelope calculation results and (b) PIC results by WARP code, respectively.

the envelope model is shown in Fig. 3 (a). Also, we employ more detailed particle-in-cell (PIC) simulations as shown in Fig. 3 (b). The PIC simulations are carried out using the WARP code [12] originally developed to study strong space-charge effects in HIF. As shown in Fig. 3, the PIC result predicts the strong coupling between the transverse directions of the beam at the peak compression, rather than the envelope result. In these results, the transverse beam radii are smaller than the ring apertures, so that the transverse expansion of the beam can be allowed even in the peak compression state.

CONCLUSION

For the study of space-charge-dominated beam, the bunch compression in the rebuilt TARN II ring using the fast rotation scheme was investigated by the envelope model and PIC simulations. The initial beam parameters were restricted by the magnetic rigidity and space-charge tune shift. The calculation results indicated that the beam current of the order of ampere can be expected by the bunch compression in the rebuilt TARN II ring.

Interaction experiments between the beam and plasma or solid target may be possible using the high current beams generated from TARN II ring. The bunch is compressed longitudinally in the ring to about 1% momentum spread, and is kicked out of the ring near peak compression into an extraction line for the final transport and focusing onto a target. This fast compression scheme in the ring requires the control of space-charge and dispersive effects to achieve maximum performance at the target. Not only physics of space-charge-dominated beams, also the interaction experiments using the heavy ion beam will be considered in our future works.

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