SPACE CHARGE EFFECTS OF HIGH INTENSITY BEAMS AT BRING*

J. Li#, J.C. Yang, IMP CAS, Lanzhou, 730000, China

Abstract

Space charge effects perform one of the main intensity limitations for low energy synchrotron. Large tune spread and crossing resonance stop-bands can hardly be avoided for intensive heavy ion beam at high intensity. Several subjects like Betatron and structure resonance, and tune spread are discussed. Simulations are carried out for $^{238}U^{34+}$ focusing on emittance and intensity change during RF capture at the injection energy at the booster ring of the High Intensity heavy ion Accelerator Facility (HIAF).

INTRODUCTION

The HIAF [1] is a new heavy ion accelerator complex under feasibility study for construction by Institute of Modern Physics (IMP). It consists of two accelerators: a linear accelerator – iLinac (17 MeV/u for $^{238}U^{34+}$, 48 MeV for proton) and a booster ring – BRing (0.2~0.8 GeV/u for $^{238}U^{34+}$, 9.3 GeV for proton). Schematic layout of the HIAF complex is illustrated in Fig. 1. The figure also shows a superconducting ECR ion source and an intense proton source LIPS, a high precision spectrometer ring – SRing (0.2~0.8 GeV/u for $^{238}U^{92+}$), a merging ring – MRing (0.2~0.8 GeV/u for $^{238}U^{92+}$), a radioactive beam transfer line – HFRS and five experimental terminals – T1~T5. Considering heavy-ion feature of the HIAF, we focus our study on $^{238}U^{34+}$ in this report.

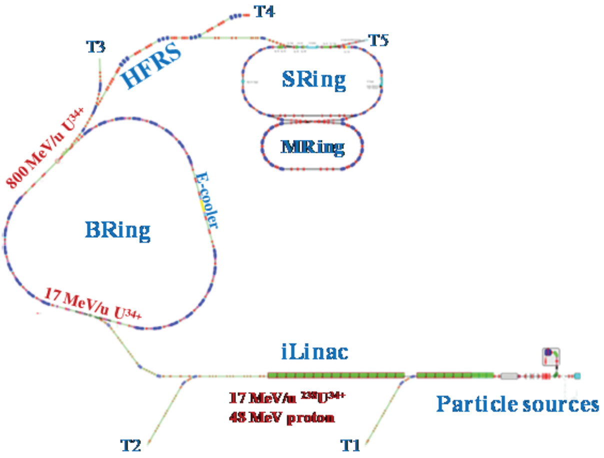

Figure 1: Layout of the HIAF complex.

OVERVIEW OF THE BRING

The BRing performs the step to increase beam intensity up to space charge limit at the injection energy and to accelerate storage beam to extraction energy, i.e. to accelerate $1 \cdot 10^{11}$ ions from 17 MeV/u to 0.2~0.8 GeV/u for $^{238}U^{34+}$. It operates under fast cycle mode with 1ms injection plateau for two-plane painting and slow mode with almost additional 10s reserved for electron cooling. Main parameters of the BRing are summarized in Table 1.

Table 1: Main parameters of the BRing

Circumference	492.53 m	
Super-periodicity	3	
Bunching factor	0.35~0.4	
Acceptance (x/y,δp/p)	200/100 πmmmrad, ±0.5%	
Particle type	proton	$^{238}U^{34+}$
Injection energy	48 MeV	17 MeV/u
Cycle mode	EX+PT (fast)	PT (fast) PT+EC (slow)
Betatron tune	(11.45,11.42)	(8.45,8.42)

*EX: Charge exchange, PT: painting, EC: electron cooling, fast: fast cycle mode, slow: slow cycle mode.

Lattice of the BRing is three-fold symmetrical with each super-period consists of an eight-FODO-like arc and an about 60 m long dispersion-free straight section featured with the length of 16 m drift reserved for either electron cooler, painting injection, or six RF acceleration cavities. Fig. 2 shows a layout of the BRing Twiss parameters and horizontal beam envelope for one super-period.

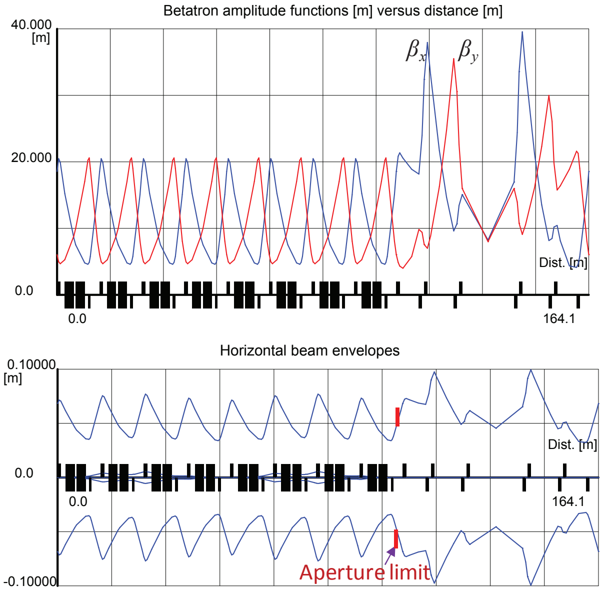

Figure 2: The BRing Twiss parameters and horizontal beam envelope for one super-period.

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#lijie@impcas.ac.cn

RESONANCES IN TUNE SPACE

The BRing is a three-fold symmetry synchrotron. Both Betatron resonance and structure or systematic resonance need to considere for high intensity operation, of which the later is more severe.

Structure Resonances

For the BRing operation of $^{238}U^{34+}$ at injection energy, we set working point as (8.45, 8.42) with safe distance from dangerous low order structure resonances indicated in the tune space of Fig. 3, e. g. the third-order structure resonances Q_x-$2Q_y$=9 and Q_y-$2Q_x$=9. The linear coupling resonance Q_x-Q_y=0, however, is next to the setting working point. For the BRing operation at high intensity, they should be compensated by skew quadruple field and sextuple fields. Considering experiences from other complex [2], it's suggested to adopt auxiliary winds on quadruples and sextuples. The fourth-order resonances shown as pink lines in Fig. 3 are weak and ignored.

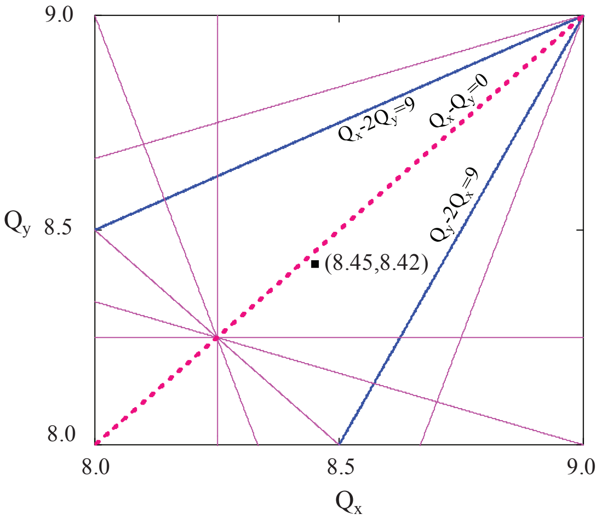

Figure 3: Structure resonances at BRing: 3rd order (blue solid), 4th order (pink solid); linear coupling (red dash).

Betatron Resonances

The nominal working point locates just next to two half-integer resonances referring the operation experience from JPARC [3]. Fig. 4 shows the Betatron resonances in tune diagram.

The charged particle beam produces repulsive force and resulting in depressed spread in tune space. The tune spread likely crosses the close-by low-order resonance stop-bands shown as dashed lines in Fig. 4 when the spread expands. Considering operation at high intensity, it seems necessary to compensate below second and third order of resonance stop-bands with multiple fields.

Second order (by skew quadruple fields):

Q_x-Q_y=0

Third order (by sextuple fields):

$3Q_x$=25, Q_x+$2Q_y$=25 $2Q_y$-Q_x=8

Third order (by skew sextuple fields):

$3Q_y$=25, $2Q_x$+Q_y=25

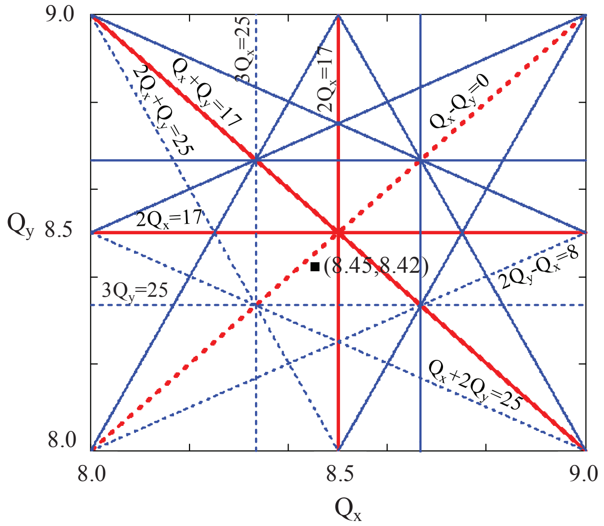

Figure 4: Betatron resonances in tune diagram at BRing: 2nd order (red solid line), 3rd order (blue solid line); resonance stop-bands to be compensated (dash line). The nominal working point ("■") for $^{238}U^{34+}$ operation is set as (8.45, 8.42) at injection energy.

CALCULATION OF TUNE SPREAD

Particles number or incoherent tune spread under space charge limit can be estimated roughly through formula (1) below,

$$N_i = \frac{\Delta Q_{y\_inc}\cdot\beta^2\gamma^3}{-r_i}\cdot\frac{B_f\cdot\varepsilon_y}{g_f\cdot\pi}\left(1+\sqrt{\frac{\varepsilon_x\cdot Q_y}{\varepsilon_y\cdot Q_x}}\right) \quad (1)$$

where, ΔQ_{y_inc} is incoherent tune shift, β and γ are relativistic factors, and r_i=7.5·10^{-18}m is classical radius of $^{238}U^{34+}$. $\varepsilon_{x,y}$ corresponds to full transverse beam emittance. g_f is transversal forming factor and equals to 1 for transverse K-V beam distribution. Longitudinal bunch factor B_f is 1 for coasting beam and can reach 0.35~0.4 when dual harmonic RF system is adopted.

Table 2: Tune Spread at Design Intensity for the BRing

Particle type	proton	$^{238}U^{34+}$	
Injection energy	48 MeV	17 MeV/u	
Design intensity	1.0·10^{12}	1.0·10^{11}	
$\varepsilon_x/\varepsilon_y$ (πmmmrad)	200/100	200/100	50/50
Beam distribution	K-V	K-V	K-V
$\Delta Q_{y\_inc\_coasting}$	-0.06	-0.08	-0.2
$\Delta Q_{y\_inc\_bunched}(B_f=0.35)$	-0.16	-0.24	-0.57
$\Delta Q_{y\_inc\_bunched}(B_f=0.4)$	-0.14	-0.21	-0.5
Time at inj. energy	~1 ms	~1 ms	10 s
Cycle mode	Fast	Fast	Slow

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Either after two-plane painting injection at fast cycle mode or additional electron cooling at slow mode, the transversal distribution of stored beam in the BRing is approximate uniform. So we make a K-V distribution approximation in calculation and simulation. With design intensity at BRing, we derived the incoherent tune spreads by formula (1) with assuming transverse acceptance of the BRing is fully occupied after painting injection, and the beam is electron-cooled down to 50 πmmmrad at the two transverse planes. The calculation results listed in Table 2 shows an acceptable tune spread at design beam intensity for fast cycling mode, but a large spread of -0.5 for cooled beam.

SIMULATION OF TUNE SPREAD

BRing operates at two cycle modes. They feature time length difference at injection energy, e. g. about 1ms at slow mode for filling up the transverse acceptance by painting injection and 10 s for cooling. During the whole process of painting and cooling, the stored beam is coasting due to absence of RF voltage. Thereafter, the RF system is switched on and longitudinally captures the stored beam with a bunching factor of 0.35~0.4. In tune spread simulation below, we assume this factor is 0.35 and the initial beam distributions are K-V at transverse planes. Table 3 lists the main parameters in simulation.

Table 3: Main Parameters in Simulation for the BRing

Particle type	$^{238}U^{34+}$	
Injection energy	17 MeV/u	
Beam intensity	$1.0\cdot10^{11}$	
$\varepsilon_x/\varepsilon_y$ (πmmmrad)	200/100	50/50
Initial distribution	K-V	K-V
Time at injection energy	~1ms	10 s

Spread at Filling up Transverse Acceptance

After filling up transverse acceptance by painting within about 100 revolution periods, the horizontal and vertical beam emittances are 200 πmmmrad and 100πmmmrad respectively. RF capture condenses the circulating beam longitudinally and increase tune spread according to formula (1). Fig. 5 plots the simulation result at the situation.

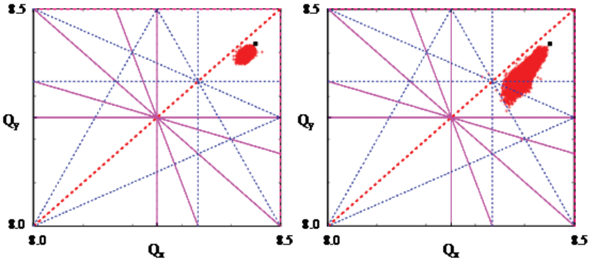

Figure 5: Tune spread of coasting (left) and bunched (right) U^{34+} beam after filling up the transverse acceptance. The dot "■" marks the nominal working point at the BRing.

Tune spread by simulation gives almost a half width of that by calculation in Table 2. It also shows that the spread of bunched beam crosses third-order Betatron resonances but not for coasting beam.

Spread of Cooled Beam at 50/50πmmmrad

The magnetization electron cooling is used at the BRing for intensive ion beam. In this operation mode, 10s is reserved for cooling down large emittance U^{34+} beam after the acceptance is occupied up by painting injection. The RF system is not applied in cooling process until acceleration. Fig. 6 plots the tune spread of coasting and bunched beam with 50 πmmmrad emittance at both transverse planes.

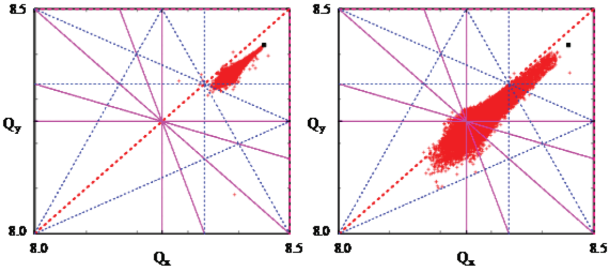

Figure 6: Tune spread of coasting (left) and bunched (right) U^{34+} beam with emittances of 50/50 πmmmrad.

The simulation result also indicates nearly a half width of tune spread comparing to calculation. Moreover, the spread touches the third-order resonance for coasting beam and crosses four third-order Betatron resonances and the linear coupling difference resonance for bunched beam. The compensation of coupling resonance is suggested for slow cycle mode. The fourth-order structure resonances are weak and ignored.

SIMULATION OF THE EMITTANCE

To observe the transverse beam emittance change and survival beam intensity at the designed intensity – $1.0\cdot10^{11}$ number of U^{34+} ions, ten thousands of macro particles is tracked 40000 turns or 0.35 s for study the RF bunching process from initial coasting beam,. We applied constant RF voltage of 4 kV with zero synchronous phase angles on two RF cavities at the second harmonic number. The simulation tracks the whole capturing process from coasting beam at the case of either filling up transverse acceptance or cooling down to 50 πmmmrad at fixed injection energy of 17 MeV/u.

The simulation is performed by pyORBIT code under 2.5D space charge model [4].We set aperture limit just after the last defocusing quadruple at the end of FODO-like arc section, which collects lost particles that oscillates out of transverse acceptance of the BRing. Its position is marked as "Aperture limit" in Fig. 2. The aperture is elliptical with 41 mm semi-minor-axis at the horizontal limit and 50 mm semi-major-axis at the vertical plane. The aperture limit records all the lost particles messages in simulation.

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Emittance at Filling up Transverse Acceptance

After filling up transverse acceptance, the circulating beam is affected by both resonances and RF bunching. Fig. 7 shows the emittance change and survival intensity in simulation. The relative emittance in the figure is defined as the ratio of instant emittance to its initial value – 200 πmmmrad at horizontal and 100 πmmmrad at vertical. The normalized survival intensity is defined as the ratio of beam intensity to its initial value – 10000 macro particles or $1.0\cdot10^{11}$ $^{238}U^{34+}$. The horizontal axis marks the turn number where one revolution period is 8.7 µs at injection energy.

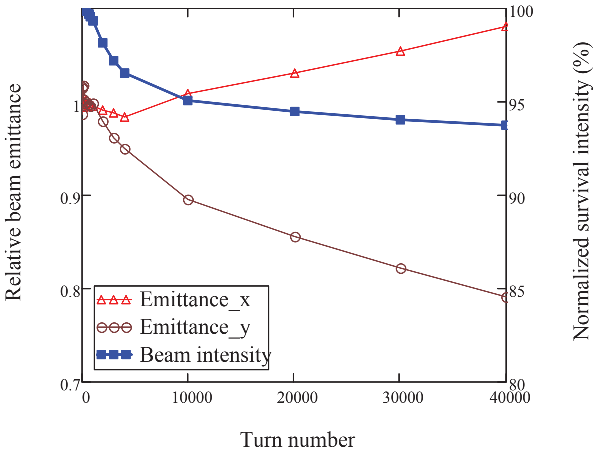

Figure 7: Simulation of relative emittance at horizontal (red "△") and vertical (brown "○") planes after filling up the transverse acceptance, and normalized survival beam intensity (blue "■") during RF capture process from initial coasting beam.

Simulation results in Figure 7 indicates that the vertical emittance starts growth from about 1000 turns or 8.7 ms while the horizontal one decreases simultaneously. The phenomenon means that the linear coupling resonance causes emittance exchange at the two transverse planes which then induced beam loss under the vertical aperture limit. The beam loss reaches 6% after 40000 turns. To reduce the loss, compensation of the linear coupling resonance is suggested.

Emittance of Cooled Beam at 50/50πmmmrad

The simulation begins from the time of storage beam being cooled down to 50/50 πmmmrad. In other words, the RF capturing simulation below proceeds without electron cooling. Fig. 8 shows the dependences of emittance and beam intensity on turn number in logarithmic coordinate. According to the simulation result, a fast emittance growth of 15% at horizontal and 25% at the vertical occurs within 100 turns during RF capturing. Similar phenomenon of emittance exchange through linear coupling also occurs but 15% slower than the case of filling up transverse acceptance of the BRing. The storage beam loss only 0.4% after 40000 turns of simulation. That's much less than the former case.

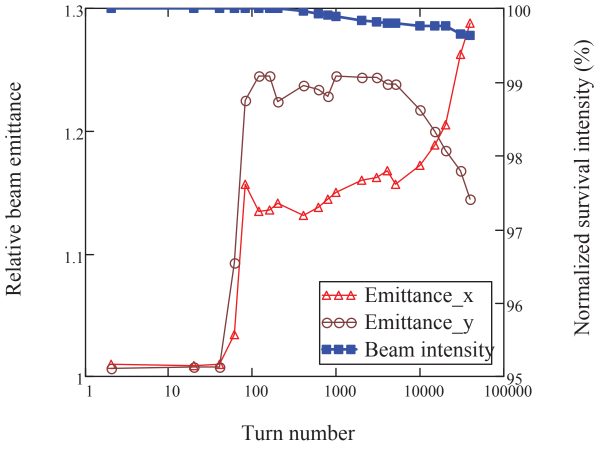

Figure 8: Simulation of relative emittance at horizontal (red "△") and vertical (brown "○") planes with 50/50 πmmmrad emittance, and normalized survival beam intensity (blue "■") during RF cavity capture process from initial coasting beam to bunch.

We attribute the beam loss larger at the former case to close proximity with emittance and acceptance, and less loss at 50/50 πmmmrad to shrinked transverse emittance under linear coupling.

CONCLUSION

The structure and Betatron resonances are discussed for the nominal working point at injection energy at the BRing. Tune spreads of two cases at the design intensity are evaluated by calculation but twice the width comparing to simulation. Transverse emittance exchange occurs from about turn 1000 in RF bunching tracking at the two operation cycle modes. Shrinkage of transverse emittance by electron cooling is helpful for reducing beam loss when linear coupling resonance is involved.

OUTLOOK

Further study is considered for the BRing with near actual transverse and longitudinal distribution, and field errors at the injection energy. Compensation of resonances is suggested but more details for technical design are required.

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