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SIMULATION OF BEAM INTENSITY LIMITATIONS UNDER SPACE CHARGE EFFECTS AT BRing OF HIAF *

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Abstract

The booster ring (BRing) of the new approved High Intensity heavy-ion Accelerator Facility (HIAF) in China is designed to stack $^{238}U^{35+}$ ions at the injection energy of 17MeV/u and deliver $1.0{\cdot}10^{11}$ of uranium ions at 800MeV/u. Two injection modes, with or without the electron cooling, are introduced. The transverse emittance evolution and beam lifetime are investigated by simulation of RF capture process for the fast cycle mode.

INTRODUCTION

HIAF Layout

The High Intensity heavy-ion Accelerator Facility (HIAF) is a new heavy ion accelerator complex under detailed design by Institute of Modern Physics [1]. Two typical particles of uranium and proton is considered in the design. The beam is generated by a Superconducting Electron Cyclotron Resonance (SECR) ion source or an intense proton source, and accelerated mainly by an ion linear accelerator (iLinac) and an booster ring (BRing). The iLinac is designed to deliver H_2^+ at 48 MeV and $^{238}U^{35+}$ at 17 MeV/u. Before entrancing into the BRing, H_2^+ is stripped to proton, then accumulated by two-plane painting and accelerated to 9.3 GeV. The $^{238}U^{35+}$ is injected by multi-turn two-plane painting scheme, after accumulation or cooling by an electron cooler at the BRing, then accelerated to 0.2-0.8 GeV/u for extraction. After being stripped at the HIAF FRagment Separator (HFRS), the secondary beam like $^{238}U^{92+}$ is injected to the Spectrometer Ring (SRing) for the high precision physics experiments. Besides, five external target stations of T1 - T5 is planned for nuclear and atomic experimental researches covering the energy range from 5.8-800 MeV/u for uranium beam. The global layout of the HIAF complex is illustrated in Fig. 1.

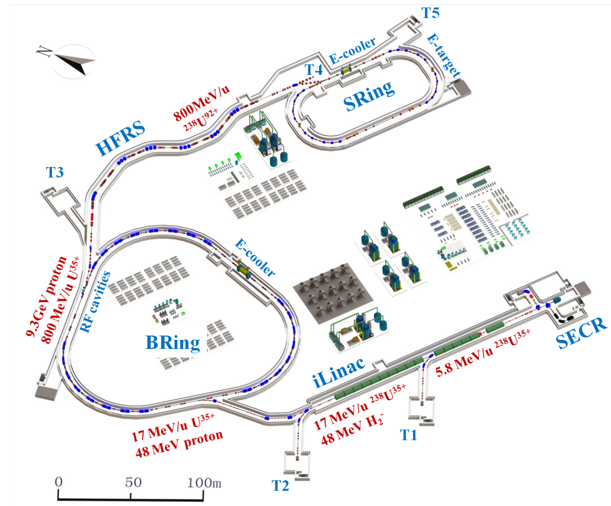

Figure 1: General layout of the HIAF complex.

Overview of the BRing

The BRing is designed to accumulate beam intensity up to the space charge limit at injection energy and deliver over $1.0 \cdot 10^{11}$ $^{238}U^{35+}$ ions or $1.0 \cdot 10^{12}$ protons in extraction. Two operation modes of fast and slow are considered. The fast mode feathers multi-turn two-plane painting injection within around 120 revolution turns whereas the slow one by over 10 s injection time for electron cooling helped accumulation. Main parameters of the BRing are listed in Table 1. The BRing has a three-folding symmetry lattice around its circumference of 549.45 m. Each super-period consists of an eight-FODO-like arc and an over 70 m long dispersion-free straight section featured with length of 15.7 m drift reserved for electron cooler, two-plane painting injection, or RF cavities. Lattice layout of the BRing for one super-period is shown in Fig. 2.

Table 1: Main Parameters of the BRing

Parameter	Proton	$^{238}U^{35+}$
Injection energy	48 MeV	17 MeV/u
Injection mode	EX [a]+PT [b]	PT, PT+EC[c]
Betatron tune	-	(8.45,8.43)
Circumference	549.45 m	
Max. magnetic rigidity	34 Tm	
Super-periodicity	3	
Bunching factor	0.2~0.4	
Acceptance ($H/V, \delta p/p$)	$200/100\pi mmmrad$, ±5.0‰	

[a] Charge exchange.
[b] Two-plane painting.
[c] Electron cooling.

Factors Concerning to Space Charge Effect

Space charge effect induced resonances dominate the limit on beam intensity and density especially at low energy heavy-ion synchrotron. Factors concerning to this effect at the BRing are list below.

Painting Injection Two-plane painting multi-turn injection scheme is adopted to accumulate high intensity beam. The injected storage beam has a momentum spread ±2.0‰, and horizontal emittance 200 πmmmrad and vertical one of 100 πmmmrad with a quasi-uniform or Gaussian distribution in transverse phase space according to the simulation [2, 3].

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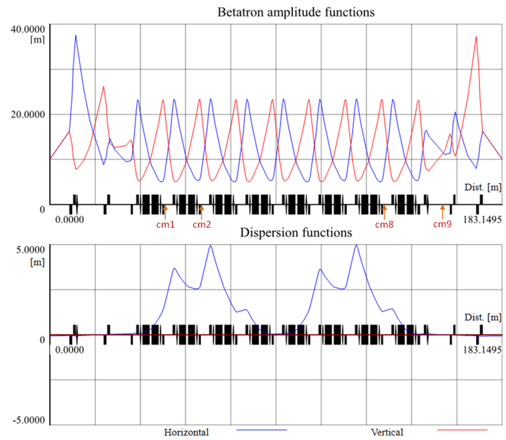

Figure 2: BRing lattice for one super-period.

RF System An intermediate plateau is planed within acceleration from injection to extraction energy. The capture and first stage of acceleration works at a harmonic number of three for $^{238}U^{35+}$, and harmonic number of two for proton at a ramping speed of 12 T/s. To depress the space charge effect, a dual harmonic RF system is considered to increase the bunching factor up to 0.4 whereas it's about 0.2 in the case of a single harmonic.

Electron Cooling To obtain intense beam at injection energy and short bunch at middle acceleration plateau, the magnetized electron cooling is adopted for accumulation at 17 MeV/u and cools bunched beam at 200 MeV/u. It is expected that the injected uranium beam will be cooled to a emittance less than 50 $\pi mmmrad$ and a momentum spread less than $3.0 \cdot 10^{-4}$ at the injection energy [4].

Collimation System To keep the vacuum condition ~ $1.0{\cdot}10^{-11}$ mbar, each super-period is placed eight collimators ($cm1 \ldots cm8$) just behind each defocusing quadruple at arc section and one more ($cm9$) at the position between the first focusing and defocusing quadruple at straight section. The total number of collimator is 27 around the ring.

Stop-bands Compensation Stop-bands correction system is proposed to depress the main resonance for a larger space for tune spread by high intensity beam. Compensation of linear coupling and the 3^{rd}-order stop-bands are considered at the nominate working point (8.45,8.43) for uranium beam. The valid tune space after compensation is expected to reach ~ 0.4.

RESONANCES AND TUNE SPREAD

Resonances

The charged particle beam produces repulsive force and resulting in depressed distribution in tune space. During the injection and accumulation process of $^{238}U^{35+}$ beam at BRing, the nominal working point is set as (8.45, 8.43) with safety distance from dangerous low-order structure resonances shown in Fig.3 as the blue solid lines, i.e. 3^{rd}-order $2Q_y - Q_x = 9$ and $2Q_x - Q_y = 9$. Whereas it sits next to the linear coupling difference resonance $Q_x - Q_y = 0$ and about 0.1 above the 3^{rd}-order betatron resonances $3Q_y = 25$, $Q_x + 2Q_y = 25$, $3Q_x = 25$, $2Q_x + Q_y = 25$ shown as dotted lines. Thus the valid vertical space is 0.1 without any stop-bands compensation and a little larger than 0.4 after compensating the linear coupling resonance and 3^{rd}-order ones above the integer resonance of $Q_y = 8$. They are indicated in Fig. 3 by short heavy diagonal line and long double line respectively. The 4^{th}-order resonances indicated as pink lines in figure are ignored due to weak effect considering operation experiences.

For operation at the design intensity of $1.0 \cdot 10^{11}$, the linear coupling will be compensated by skew quadruple field which is produced by additional windings on steering magnets at the straight lattice section. The 3^{rd}-order stop-bands is planned to be compensated by sextuple fields produced by windings on existed normal and new skew sextuple magnets.

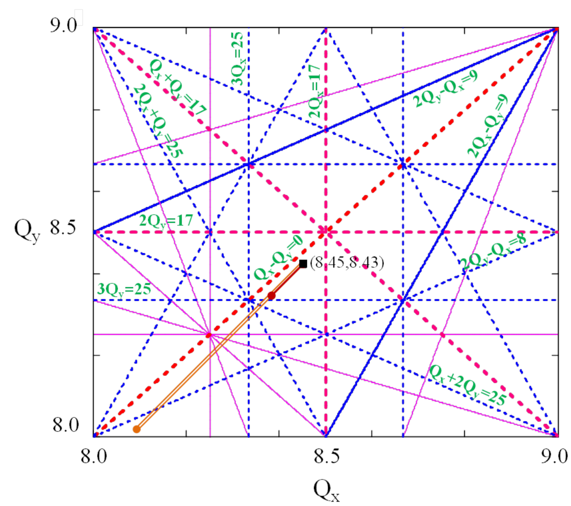

Figure 3: Resonances in tune diagram at the BRing: half-integer and linear difference coupling (red dotted line), 3^{rd}-order structure (blue solid line), 3^{rd}order betatron (blue solid line), and 4^{th}-order structure (pink solid line). The nominal working point (■) for $^{238}U^{35+}$ injection is set as (8.45, 8.43).

Tune Spread

The maximum allowed intensity of storage beam at BRing is limited by transverse space charge effect through valid space for tune spread that can been evaluated by:

$$\Delta Q_{y\_inc} = -\frac{N_i r_i}{\beta\gamma^2}\frac{G_t}{B_f \epsilon_{y\_n}}\left(1 + \sqrt{\frac{\epsilon_{y\_n} Q_h}{\epsilon_{x\_n} Q_v}}\right) \qquad (1)$$

in which ΔQ_{y_inc} is incoherent tune spread, N_i is particle number, β and γ are relativistic factors, $r_i = 7.93 \cdot 10^{-18} m$ is the classical radius of $^{238}U^{35+}$, ϵ_{x_n} and ϵ_{y_n} are the normalized transverse beam emittance. G_t is transversal distribution factor and equals to 2 for Gaussian distribution

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in real space, B_f longitudinal bunching factor and equals to 1.0 for coasting beam and reaches 0.4 here in the case of dual harmonic RF system, Q_h and Q_v are the nominal horizontal and vertical working points. Table 2 lists the calculation result of beam intensity limitation by transverse space charge at injection energy and vertical incoherent tune spread at design intensity when the emittance comes up to the designed acceptance.

Table 2: Intensity Limitation and Tune Spread at the BRing

Parameters	**Proton**	$^{238}U^{35+}$
ΔQ_{y_inj} [a]	0.09	0.14
ΔQ_{y_mid} [b]	-	0.01
Intensity limitation [c]	$4.38{\cdot}10^{12}$	$2.87{\cdot}10^{11}$
Bunching factor	549.45 m	
Max. magnetic rigidity	34 Tm	
Valid tune space	0.4	
RF bunching factor	0.4	
Normalized emittance (H/V)	$38.4/19.2\pi mmmrad$	

[a] Tune spread at injection energy with design intensity.
[b] Tune spread at middle platform with design intensity.
[c] RF bunched beam at injection plateau.

Figure 4 shows the simulation for $^{238}U^{35+}$ when the beam emittance equals to the transverse acceptance and momentum spread of ±2.0%¸ at its design intensity of $1.0{\cdot}10^{11}$ and is bunched after RF capture with a bunching factor of 0.4. The simulation result indicates a vertical tune spread width about 0.16 that is bigger than 0.14 by calculation. The difference of tune spread can been explained by ions with larger betatron amplitude. Moreover, the spread crosses four 3^{rd}-order betatron resonances and the linear coupling difference resonance. Compensation or correction of these resonances is considered for normal operation.

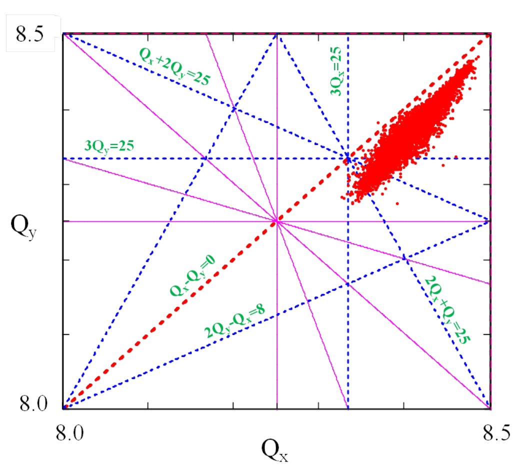

Figure 4: Tune spread of $^{220}U^{35+}$ beam at the design intensity $1.0{\cdot}10^{11}$ at the BRing, and resonances of linear coupling (red dotted diagonal), 3^{rd}-order betatron (blue dotted lines), 4^{th}-order structure (pink solid lines).

EMITTANCE EVOLUTION UNDER SPACE CHARGE EFFECT

To observe the transverse beam emittance change and beam survival of $^{238}U^{35+}$ at its designed intensity of $1.0{\cdot}10^{11}$, ten thousands of macro particles is tracked about 5000 turns during the RF capture process from initial coasting beam after injection. We applied adiabatic RF voltage variation from zero to 23.4 kV [5], zero phase and three number of harmonic frequency upon one of six cavities at the injection energy. The simulation is performed by modified pyORBIT code under 2.5D space charge model [6]. We symmetrically set three elliptical aperture limits at the positions of straight section collimator ($cm9$). The aperture limit is set as 50 mm larger than the beam envelope size (129 mm, 64 mm) at the case of designed beam acceptance. The lost ions will been collected when their betatron amplitude exceeds the aperture limit at the three places and get their related message recorded in simulation. Figure 5 shows the dependences of relative or normalized emittance and beam intensity on revolution turns in logarithmic coordinate.

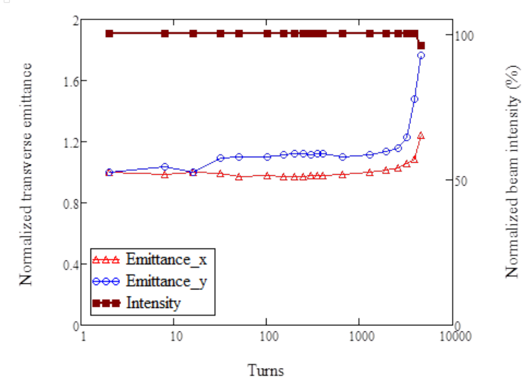

Figure 5: Evolution of normalized horizontal (△) and vertical (○) emittance and survived beam intensity (■) during the RF capture process from initial coasting beam.

The simulation indicates emittance exchange between the horizontal and vertical planes in the first 1000 turns and a gradually accelerating growth of emittance variation. The exchange is explained by tune spread overlapping with the stop-band of linear difference coupling, while a slow emittance variation by beam rotation in longitudinal phase space during the early RF bunching process. The emittance growth is caused by spread staying on the 3^{rd}-order resonances with longer time when the preliminary bunch is formed.

CONCLUSION

We list factors concerning to space charge effect for high intensity at beginning. Then the resonances and tune spread at BRing are discussed. The emittance evolution under space charge effect suggests to compensate the linear coupling resonance stop-bands and the one of 3^{rd}-order at the BRing.

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