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RESONANCE STOP-BANDS COMPENSATION AT BOOSTER RING OF HIAF*

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Abstract

Booster Ring (BRing) of the new approved High Intensity heavy-ion Accelerator Facility (HIAF) in China is designed to stack 0.3-1.0·10^{11} number of $^{238}U^{35+}$ ions by painting injection and deliver over such intensity beam in extraction. However, depressed tune spread caused by space charge effect crosses the low-order resonance stop-bands after bunching the storage beam. To keep a low beam loss during crossing, stop-band compensation scheme is proposed covering the whole process of RF capture and early acceleration.

INTRODUCTION

Facility Layout

The High Intensity heavy-ion Accelerator Facility (HIAF) is a new heavy ion accelerator complex under detailed design by Institute of Modern Physics of Chinese Academy of Sciences [1]. Two typical particles of $^{238}U^{35+}$ and proton are considered in its design. The 34 Tm booster ring (BRing) is planed to stack beam intensity up to space charge limit at the injection energy 17MeV/u and deliver over such intensity beam through HIAF FRagment Separator (HFRS) and further to Spectrometer Ring (SRing) at 800 MeV/u.

The particles derive from a Superconducting Electron Cyclotron Resonance (SECR) ion source or an intense H_2^+ source, and are accelerated by an ion linear accelerator (iLinac) and an booster ring (BRing). The iLinac can accelerate $^{238}U^{35+}$ to 17 MeV/u and H_2^+ to 48 MeV at entrancing of the BRing. The beam will be injected with multi-turn two-plane painting scheme together with stacking in the BRing and extracted with fast kicker or resonant sextuples after being accelerated to 0.8 GeV/u. Following the extraction, $^{238}U^{35+}$ is stripped to bare ion at HFRS or bombing targets to generate secondary beams that will also be separated by HFRS. Finally, the selected ions is guided to external target or injected into the SRing for high-precision experimental measurement. In addition, five external target stations of T1 - T5 is arranged at HIAF for nuclear and atomic experimental researches with energy range 5.8-800 MeV/u for uranium beam.

The BRing has a three-folding symmetry lattice around its circumference of 569.1 m. Each super-period consists of an eight-FODO-like arc and an over 70 m long dispersion-free straight section reserved for two-plane painting injection, Extraction and RF cavities respectively. Figure 1 shows layout of the BRing lattice of one super-period.

The BRing operates at three modes of normal, slow extraction, and proton. Ions like $^{238}U^{35+}$ beam will operate

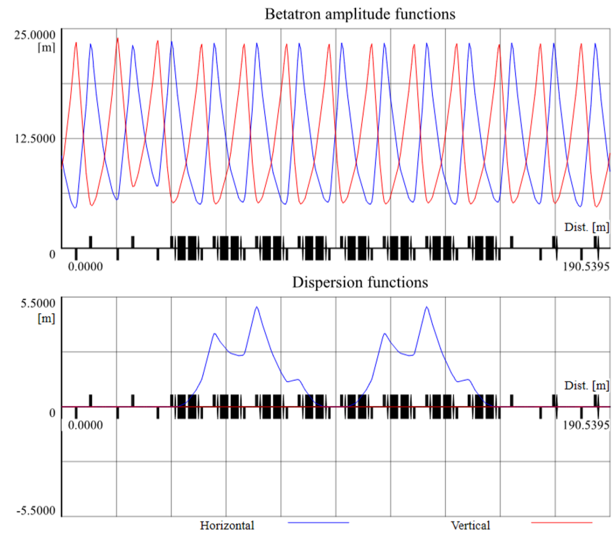

Figure 1: BRing lattice for one super-period.

at the first mode and finish painting injection within 150 revolution turns. Main parameters of the BRing are listed in Table 1.

Table 1: Main Parameters of $^{238}U^{35+}$ at the BRing

Circumference	569.1 m
Max. magnetic rigidity	34 Tm
Periodicity	3
Injection energy	17 MeV/u
Betatron tune	(9.47,9.43)
Acceptance ($H/V, \delta p/p$)	$200/100\pi mmmrad$, ±5.0 ‰

RESONANCE AND STOP-BANDS

Space Charge Effects and Betatron Resonances

The space charge effect of intensive highly charged particle beam creates depressed spread in tune space. This spread width grows several times when the beam gets bunched during RF cavity capture.

Figure 2 shows the space charge effect deduced tune spread by bunched $^{238}U^{35+}$ beam at intensity of 1.0·10^{11} ion number. The BRing nominal working point (9.47, 9.43) seats next to the linear coupling difference resonance of $\nu_x - \nu_y = 0$. The only low-order systematic or structure resonance appeared in the figure is $2\nu_x - \nu_y = 9$ shown as blue solid line while the betatron ones as dot lines. The $4^{th}-$order resonances are ignored due to weak effect.

The 1.0·10^{11} ions produces a vertical spread about 0.15 after injection by two-plane painting methods. In the calculation [2], the uranium beam has a uniform distribution in transverse phase space and longitudinal Gaussian one,

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the emittances $200/100\pi mmmrad$ that equals to the synchrotron acceptance, a momentum spread $\pm$ 2.5‰, and a bunching factor 0.4 after dual RF capture. The figure also shows an overlap of tune spread with two 3^{rd}-order betatron resonances.

As a conventional experience in synchrotron operation, the maximum transverse emittance is usually smaller than the acceptance. This will result in a larger spread and consequently more low-order resonance crossing at the same intensity of storage beam. Resonance will cause emittance growth or beam loss when the tune of particle sits just upon low-order resonance stop-bands.

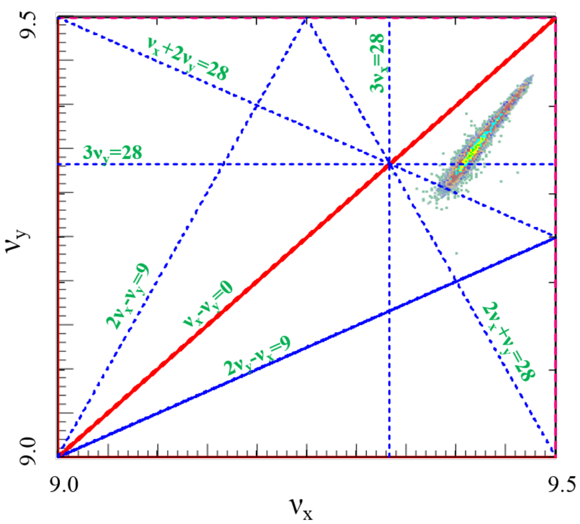

Figure 2: Tune spread of $^{238}U^{35+}$ beam and low-order resonances in tune diagram i.e., linear difference coupling (red dotted line), 3^{rd}-order betatron (blue dotted line) and structure or systematic (blue solid line), and two half-integer resonances; The nominal working point at injection plateau is (9.47, 9.43).

To enlarge valid space for expanded tune at high intensity, multipole magnetic fields compensation or correction are proposed to decrease stop-bands that are mainly derived from magnets misalignment or magnetic field imperfections. Compensation of the following low-order betatron resonances are considered at the injection plateau and early stage of $^{238}U^{35+}$ beam acceleration at the BRing.

Stop-bands and Sources

Resonances stop-bands concerned with the BRing and their main sources are listed as:

(a) Stop-bands from half-integer resonances of $2\nu_x = 19$ and $2\nu_y = 19$

derived from quadruple fields imperfection and high-order field component of magnets and to be compensated with normal quadruple fields

(b) Linear coupling difference resonance $\nu_x - \nu_y = 0$

derives from longitudinal magnetic fields like solenoid, rotation of quadruples, magnets offset, and high order field component; to be compensated with skew quadruple fields

(c) The 3^{rd}-order betatron resonances $3\nu_x = 28$ and $\nu_x + 2\nu_y = 28$, and systematic resonance $2\nu_y - \nu_x = 9$

derives from high-order components of magnets and sextuple alignment; to be compensated with normal sextuple field

(d) The 3^{rd}-order resonances $3\nu_y = 28$ and $2\nu_x + \nu_y = 28$

derives from high-order components of magnets and sextuple alignment; to be compensated with skew sextuple fields

Table 2 lists the mainly concerned magnet misalignment details at the BRing. We included all misalignment into the BRing lattice for tacking [3]. Figure 3 gives the tracking result where κ represents the normalized resonance strength or beam loss rate. The figure inidcates a obvious resonances ridge of linear coupling $\nu_x - \nu_y = 0$ and 3^{rd}-order systematic $2\nu_y - \nu_x = 9$. Among all the magnet misalignment effect on stop-bands strength, transverse tilt at horizontal x and vertical y planes contribute the most, transverse offset the second, and rotation around the longitudinal axis s do the least.

Table 2: Magnet Misalignments

Type	Dipole	Quadruple	Sextuple
Offset x,y (mm)	0.2	0.15	0.15
Tilt x,y (mrad)	0.2	0.2	0.5
Rotation (mrad)	0.2	0.2	0.5
Offset s (mm)	0.2	0.2	0.2

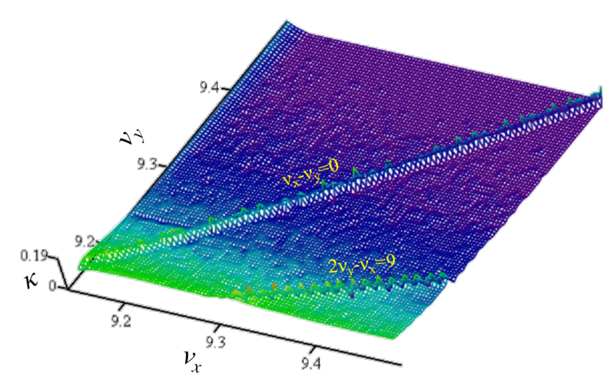

Figure 3: Resonances stop-bands from all the contributed misalignment of main magnets.

Another stop-bands contribution source is the non-zero betatron amplitude of stored particles. Because of large transverse emittance at the BRing, the two stop-bands ridges shown in Fig. 3 is also appeared in Fig. 4 even without all the concerned misalignment in tracking. But this contribution

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has a weaker effect on the stop-band strength than that by misalignment. In additional, the ridges grow when the tune get close to the integer-resonances.

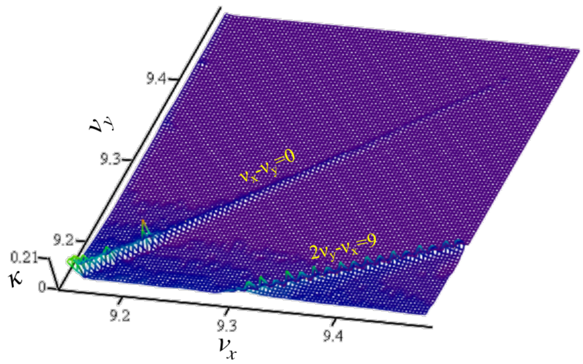

Figure 4: Resonances stop-bands contributed from particle betatron amplitude at the BRing.

Tune Spread Dependence on Energy

The BRing repetition rate is about 2 Hz. One cycle consists of 20 ms for ramping up to the injection plateau, 2 ms for painting injection, 50 ms for RF capture, and over 110 ms of acceleration, and 100 ms on the top plateau, and ramping down in 200 ms. If we take 0.4 as the maximum valid vertical tune spread for storage beam, then it will shrink to 0.1 when the synchrotron ramps up to 200 MeV/u according to spread calculation. Then, the effect of low-order resonance can be eliminated after acceleration due to not overlapping with the stop-bands any more. Thus, the compensation is needed only below 200 MeV/u at the BRing.

COMPENSATION SCHEME

According to misalignment parameters listed in Table 2 and magnetic field disturbance imperfections, we compensated the concerned stop-bands with special multipole magnetic fields. The phase advance $\Delta\phi$ between compensating elements obeys the following relationship:

$$\frac{\Delta\phi}{Q_{x,y}} \cdot M \rightarrow (n + \frac{1}{2})\pi \qquad (1)$$

where $Q_{x,y}$ is the horizontal or vertical working point, M is the resonance number of $j\nu_x + k\nu_y = M$, and j, k, n, are any integers. Meanwhile, a large ratio between the two transverse betatron functions at the position of compensation elements is helpful to release the field strength requirement.

Half-integer Resonance

The compensation of half-integer resonance is reserved for shifting working points above half-integer $2\nu_y = 19$. The imperfections bring a stop-band width of 0.002. We use two trim coils combined with the existed quadruples at straight section to make compensation. The designed strength is 0.004 m^{-2} and 1.5% strength of the standard quadruple at injection plateau.

Linear Difference Coupling

Four skew quadruple field elements by adding cores and additional windings upon orbit correctors are proposed to make compensation. This type corrector has four magnet cores with two opposite ones providing steering field and all the four ones produce skew quadruple field. They have the same length of 0.3 m and design strength of 0.025 m^{-2}.

To check the linear coupling stop-band compensation effect under the misalignment listed in Table 2, we scan the tune space and give the tracking result in Fig. 5. It shows that most part of the linear coupling stop-band is compensated by the skew quadruple fields. However, the compensation also excites two betatron third-order resonances $3\nu_y = 28$ and $2\nu_x + \nu_y = 9$, among them $2\nu_x + \nu_y = 9$ shows the strongest ridge in tune space of Fig. 5.

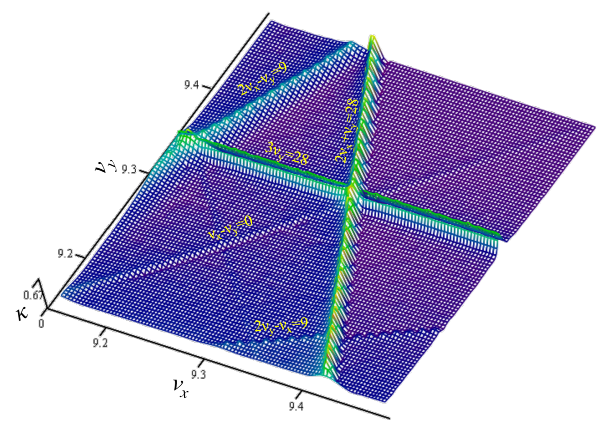

Figure 5: Compensation effect of linear coupling stop-bands with mangets misalignment.

We also adjust the BRing working point to (4.7, 4.7) just upon the linear coupling difference resonance stopbands. The misalignment is also amplified by double the maximum tilt of the main magnets for contrast. This produces 0.01 width stop-bands. The tracking shows that the remained intensity is decreased to 78% after 350 turns, while the loss rate is only 2% for the case of compensation with skew quadruple fields. The details are shown by Fig. 6.

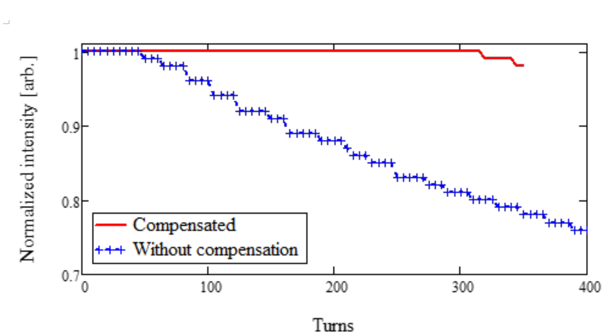

Figure 6: Compensation checking through intensity evolution under enhanced tilt misalignment

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3^{rd}-order Resonance

The imperfections around the synchrotron create a stop-band width 0.001 for $\nu_x + 2\nu_y = 28$ and 0.0007 for $3\nu_x = 28$ at injection energy. Following the principle in formula (1), four trim sextuples used for chromaticity correction at the arc section are considered to produce normal sextuple field for compensation with a strength of 0.05 m^{-3}. The misalignment and error also induced a stop-band of 0.006 for $2\nu_y - \nu_x = 9$, that will been corrected by four trim sextuple for chromaticity correction at the arc section with a strength of 0.2 m^{-3} and length of 0.3 m.

The stop-band width is 0.002 for $2\nu_x + \nu_y = 28$ and $3\nu_y = 28$ at injection energy. We introduce four new skew sextuples to make compensation with strength of 0.2 m^{-3}. They locate at the straight sections but separated by the arc section.

CONCLUSION

Space charge effect of high intensity uranium ions stacking at the BRing induces depressed tune spread and low-order stop-bands crossing. Their compensation details are discussed. The compensation results are checked by tracking as well.

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