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RESONANCE STOP-BANDS COMPENSATION FOR THE BOOSTER RING AT 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 $1.0{\cdot}10^{11}$ number of $^{238}U^{35+}$ ions at the injection energy of 17MeV/u and deliver over such intensity beam to SRing (Spectrometer Ring) at 800MeV/u. However such intensity beam causes low-order resonances crossing during RF bunching. To keep a low beam loss, resonance stop-band compensation scheme is proposed covering the process from RF capture to the first stage of acceleration below 200 MeV/u.

INTRODUCTION

Layout of the HIAF

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 $^{238}U^{35+}$ 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 the BRing, H_2^+ is stripped to proton, and 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 a 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 with the energy range from 5.8-800 MeV/u for uranium beam.

Overview of the BRing

The BRing is designed to accumulate beam intensity up to space charge limit at the injection energy and deliver over $1.0\cdot10^{11}$ $^{238}U^{35+}$ ions or $1.0\cdot10^{12}$ proton to SRing in extraction. Two operation modes of fast and slow are considered. 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 a 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. 1.

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

Circumference	549.45 m
Max. magnetic rigidity	34 Tm
Periodicity	3
Injection energy	17 MeV/u
Betatron tune	(8.45,8.43)
Acceptance ($H/V, \delta p/p$)	$200/100\pi mmmrad$, ±5.0‰

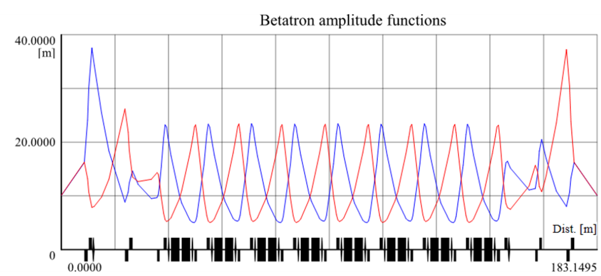

Figure 1: BRing lattice for one super-period.

RESONANCE AND STOP-BANDS

Betatron Resonances

The charged particle beam produces repulsive force and results in depressed tune distribution in tune diagram. During the injection and accumulation process of $^{238}U^{35+}$ beam at the BRing, the nominal working point is set as (8.45, 8.43) with safety distance from dangerous low order structure resonances e.g., $2Q_y - Q_x = 9$ and $2Q_x - Q_y = 9$. The only structure resonances appear in Fig. 2 are four $4th$-order ones shown as pink lines. They will be ignored due to weak effect considering the operation experiences. Thus, no structure resonances will be considered at our case.

The tune spread of $^{238}U^{35+}$ at the design intensity of $1.0{\cdot}10^{11}$ is shown in Fig. 2 as the blue dots when the transverse emittance equals to acceptance. The red dots give the spread information of cooled beam when the emittance is decreased to $50/50\pi mmmrad$ [2]. For the two cases above, the uranium beam has a momentum spread of ±2.0‰ and bunching factor of 0.4 after RF capture. The design intensity produces a vertical tune spread about 0.16 for $200/100\pi mmmrad$ and 0.33 for the cooled beam. The figure also indicates an overlapping of tune spread with four 3^{rd}-order betatron resonances and a linear coupling difference resonance at the both situation. The overlapping of tune

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spread with these resonances will induce emittance variation and even beam loss.

To enlarge valid tune space for beam accumulation, new correction fields are introduced to counteract with stop-bands derived from the magnets imperfection and unwanted multi-pole fields. Correction or compensation of the following low-order betatron resonance stop-bands is considered for intensive $^{238}U^{35+}$ beam operation at the BRing.

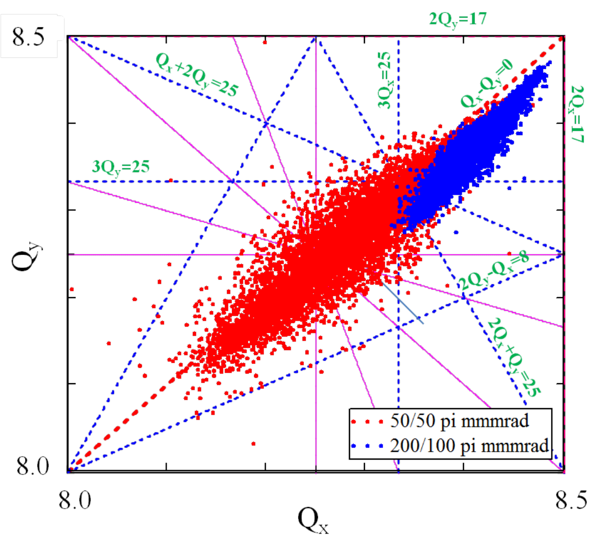

Figure 2: Resonances in tune diagram at the BRing i.e., linear difference coupling (red dotted line), 3^{rd}-order betatron (blue dotted line), 4^{th}-order structure (pink solid line), and two half-integer resonances; The nominal working point for $^{238}U^{35+}$ injection is set as (8.45, 8.43).

Stop-bands Compensation

Resonance causes emittance growth or beam loss when the tune of ion sits on the stop-bands. The main sources of related resonance stop-bands at the BRing are listed as below:

(a) Half-integer ones of $2Q_x = 17$ and $2Q_y = 17$

derives from quadruple fields imperfection and high order field component of magnets; to be compensated with normal quadrupole field

(b) Linear coupling difference of $Q_x - Q_y = 0$

derives from longitudinal fields by solenoid, rotation of quadruples, vertical offset of sextuple, and high order field component; to be compensated with skew quadrupole fields

(c) 3^{rd}-order of $3Q_x = 25$, $Q_x + 2Q_y = 25$, and $2Q_y - Q_x = 8$

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

(d) 3^{rd}-order of $3Q_y = 25$, $2Q_x + Q_y = 25$

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

where Q_x and Q_y is the betatron tune values.

Tune Spread Dependence on Energy

The time length for one fast cycle is about 3 s that consists of 20 ms for ramping up to the injection plateau, 2 ms for painting injection, 60 ms for RF capture, 73 ms at the 1^{st} stage of acceleration, 90 ms for RF debunching, 120 ms for the 2^{nd} stage of RF capture, 973 ms for the 2^{nd} stage of acceleration, 40 ms at top plateau, and ramping down in 1580 ms. If we take 0.4 as the maximum valid vertical tune space for the spread of stored beam, then it will shrink to 0.093 when the synchrotron ramps up to the middle plateau of 200 MeV/u according calculation of tune spread [3]. That means the effect of low order resonance will be eliminated due to not overlapping any more low-order resonances. Therefore, the compensation becomes necessary only below 200 MeV/u for the current nominal working point at the BRing. The dependence of maximum allowed tune spread upon energy is shown in Fig. 3.

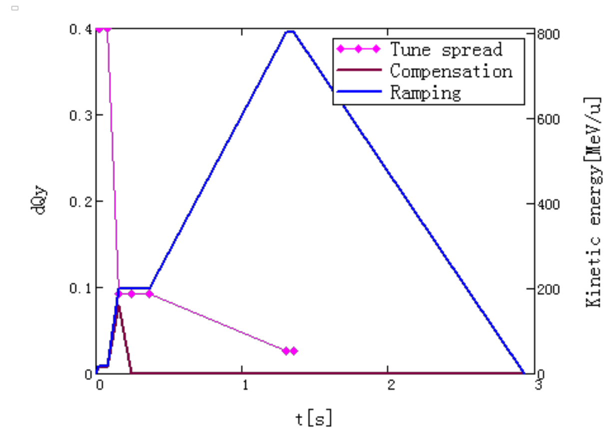

Figure 3: Dependence of allowed tune spread upon kinetic energy at the BRing at the fast cycle mode.

COMPENSATION SCHEME

We assume that the misalignment errors of dipole, quadruple, and sextuple magnets have a random distribution with transverse offset $\delta x = 0.2$ mm, $\delta x = 0.2$ mm, rotation $\delta\phi_t = 0.2$ mrad, and longitudinal offset $\delta s = 0.2$ mm and rotation $\delta\phi_s = 0.2$ mrad, and multi-pole field error $\delta B/B = 3 \cdot 10^{-4}$. For the case of applying the electron cooling, at the straight section for electron cooler, a longitudinal magnetic field is introduced by cooling section solenoid and two toroids with an equivalent length of 9.6 m and a strength of 0.08 T.

For stop-band compensation, the phase advance $\Delta\phi$ between compensating elements demands the following rela-

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tionship:

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

where $Q_{x,y}$ the horizontal or vertical working point and M is the resonance number of $jQ_x + kQ_y = M$. And j, k, n, are any integers. Meanwhile, A large ratio between the two transverse betatron functions of the compensation elements is demanded because it can release the strength requirement for compensation magnet.

Half-integer Resonance

The compensation of half-integer resonance is reserved for setting new working points out range of the tune area shown in Fig. 1. The misalignment and multi-pole field errors list above bring a resonance stop-band width of 0.003 for $2Q_x = 17$, and 0.004 for $2Q_y = 17$ at the injection energy. According to the phase advance and betatron function, we use two group of trim coils added upon existed quadruples of QFS2K and QFSK, QDSK and QD1 within the same straight section to make the horizontal and vertical compensation separately. The designed strength is $0.0015\,\mathrm{m}^{-2}$ or about 0.6% of that for the standard quadrupole at injection energy.

Linear Difference Coupling

According to the calculation of stop-band width of linear difference coupling resonance of $Q_x - Q_y = 0$, the contribution to resonance excitation from the longitudinal fields introduced by switching on electron cooler is six times larger than that by misalignment and field errors that corresponds a stop-band width of 0.025 and 0.004 respectively

Four group of skew quadruple field families are considered for horizontal compensation with SQH01 and SQH02, and for the vertical one with SQV01 and SQV02. In each family, the two skew quadruple elements locates at the straight section but separated by the arc section. The skew field is generated by winding additional coils upon the close orbit dipole corrector. This type of corrector is designed with four magnet cores with two opposite ones providing dipole field and all the four ones produce skew quadruple field through additional windings. To release the strength of skew field in the case of compensation longitudinal field by cooler., eight skew quadruple element is considered with a strength of $0.025\,\mathrm{m}^{-2}$. They have the same length of 0.3 m as dipole correctors.

3^{rd}-order Resonance

The misalignment and field errors around the synchrotron create a stop-band width of 0.0002 for $Q_x + 2Q_y = 25$ and 0.001 for $3Q_x = 25$ at injection energy. According to formula (1), four trim sextuples used for chromaticity correction at the arc section are considered to generate normal sextuple field for the compensation with a strength of $0.02\,\mathrm{m}^{-3}$. That's a strength of 0.1% of the standard sextuple magnet. The misalignment and error also induced a stop-band of 0.0006 for $2Q_y - Q_x = 8$, that will been corrected by four trim sextuple for chromaticity correction at the arc section with a strength of $0.01m^{-3}$ and length of 0.4 m .

The stop-band width produced by the errors listed above is 0.0002 for $2Q_x + Q_y = 25$ and 0.0006 for $3Q_y = 25$ at injection energy. Four new skew sextuples with strength of $0.02\,\mathrm{m}^{-3}$ are planned to compensate the two resonances. They locates the straight section but separated by the arc section.

CONCLUSION

Accumulation of uranium beam to its design intensity at the BRing induces an overlapping between tune spread and several low-order resonances. Compensation of these resonances below 200 MeV/u are considered. The preliminary compensation scheme is introduced for the resonances concerned.

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