Injection method of barrier bucket supported by misaligned electron cooling for CRing*

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Abstract: A new accelerator complex HIAF (the High Intensity Heavy Ion Accelerator Facility) is approved in China. It is designed to provide intense primary and radioactive ion beams for researches in high energy density physics, nuclear physics, atomic physics as well as other applications. In order to achieve a high intensity up to 5×10^{11} ppp $^{238}U^{34+}$, CRing needs to stack more than 5 bunches transferred from BRing. However, the normal bucket to bucket injection scheme can only achieve an intensity gain of 2, so an injection method, fixed barrier bucket (BB) supported by electron cooling, is proposed. To suppress the severe space charge effect during the stacking process, misalignment is adopted in the cooler to control the transverse emittance. In this paper the simulation and optimization with BETACOOL program are presented.

Key words: barrier bucket, misaligned electron cooling, BETACOOL, HIAF

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1 Introduction

HIAF is a new accelerator facility under design at the Institute of Modern Physics (IMP) to provide high intensity heavy ion beams for a wide range of experiments in high energy density physics, nuclear physics, atomic physics and other applications [1]. It consists of two Superconducting Electron-Cyclotron-Resonance ion source (SECR) and a high intensity H_{+}^{2} ion source (LIPS), a 17MeV/u superconducting Ion Linac (iLinac), a 34Tm Booster Ring (BRing), a 43Tm multifunctional Compression Ring (CRing), a high precision Spectrometer Ring (SRing), an electron machine based on Energy Recovery Linac (ERL), and several experimental terminals. Its schematic layout is shown in Fig. 1.

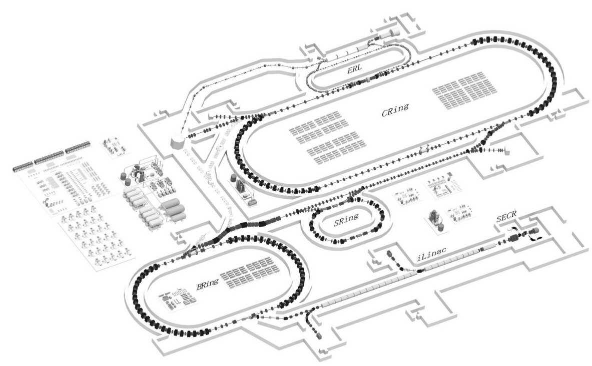

Fig. 1. Overview of the HIAF facility.

Generally the beam stacking between synchrotrons is performed by bucket to bucket scheme. To avoid dilution in longitudinal phase space, the circumferences of the two synchrotrons have an integer ratio and the RF systems operate at the same frequency. Thus injected bunches match buckets well and filamentation phenomenon can be suppressed effectively [2]. However this scheme is followed by a restriction that the intensity gain cannot exceed the circumference ratio. The injection method, fixed barrier bucket supported by electron cooling, can exploit the longitudinal phase space signif-

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icantly. The barrier bucket RF system can build spaces along the beam direction time and again, enabling injection of much more bunches [3]. The electron cooling is essential to shrink the momentum deviations and make the barrier bucket stacking more efficient [4]. In stacking process, overcooling of transverse emittance can lead to a severe space charge effect. Particles will suffer instability and get lost when their tunes are pushed near resonance lines. So a small angle between electron beam and ion orbit, namely misalignment, is introduced to control overcooling [5]. In this paper, the conceptual design of the stacking scheme and the simulation result are reported.

2 Stacking scheme

The fixed barrier bucket RF system generates two isolated quasi-sin shape pulses with opposite voltages in one revolution. A local potential well is formed in longitudinal phase space. The cooled particles stay in the bottom of the hollow and leave the flat-top empty. The next bunch can be injected here [6–8]. The depth of the potential well, also known as barrier height, is defined as [9]

$$\left(\frac{dp}{p}\right)_{height} = \frac{1}{\beta}\sqrt{\frac{ZeV_{peak}}{\eta\gamma Am_0c^2}\frac{\Delta\varphi}{\pi}}. \quad (1)$$

where Z is charge state, V_{peak} is the peak barrier voltage, β and γ are relative parameters, m_0 is average nucleon mass in rest frame, c is velocity of light, η is slip factor and $\Delta\varphi$ is barrier phase width. The longitudinal phase space is divided into two parts, stable area and unstable area which correspond to well and flat-top respectively. The stable area is used for storage of particles with small momentum deviations while the unstable area is for injection.

The schematic procedure of CRing stacking (as shown in Fig. 2) can be described in 3 steps:

1. The bunch extracted from BRing propagates through the transfer line HFRS and gets to the unstable area. In the next several thousand turns, particles spread immediately to all over the longitudinal dimension. In stable area momentum deviations become larger and particles shift faster while otherwise in unstable area.

2. Momentum deviations decrease due to the interaction between ion beam and electron beam. Particles fall into the potential well one after another. The shrink of the transverse phase space shown in Fig. 2(2) indicates that the transverse Courant-Snyder (CS) invariants move towards a nonzero balance.

3. As shown in Fig. 2(3) most of the particles are restricted in stable area after sufficient cooling. The transverse CS invariants are concentrated in a narrow area. At this time the empty unstable area is ready to accept the next injection.

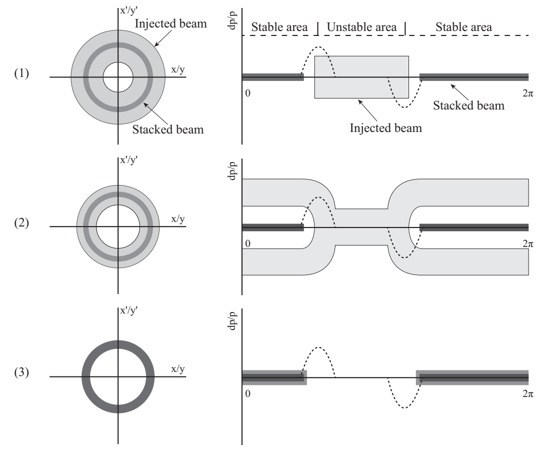

Fig. 2. Evolution of transverse phase space (left) and longitudinal (right) phase space during CRing Stacking.

3 Misaligned electron cooling

Electron cooling is critical to cool longitudinal phase space down. However, it acts on transverse dimension simultaneously due to its intrinsic characteristics [10]. The transverse emittance can be overcooled before being captured by BB, which gives rise to a grave space charge problem [11].

Different from normal cooler, misaligned electron cooling sets a small crossing angle between electron beam and ion orbit. So particle gets an extra heating friction effect, which is described as a Hopf bifurcation phenomenon [12]. The final emittance is a balance between heating and cooling. To lower the space charge effectively, misalignment is set equal in horizontal and vertical directions. Fig. 3 shows the relationship between crossing angle and final emittance. The emittance is seen to grow rapidly below 0.4mrad because of bifurcation and grow slowly above 0.6mrad due to the increasing relative velocity between ions and electrons.

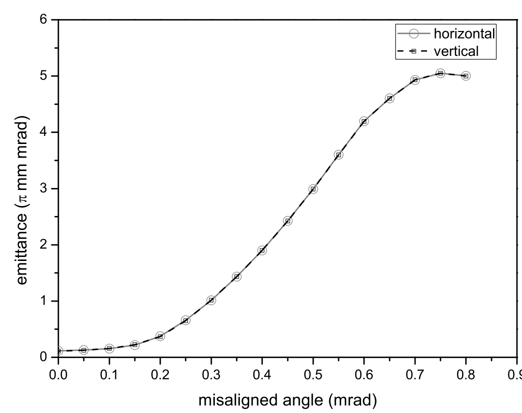

Fig. 3. The balanced transverse emittance under different misalignments.

4 Stacking study and optimization

The simulation is performed by BETACOOL program which takes account of several effects, including barrier bucket dynamics, misaligned electron cooling, IBS effect and beam loss resulted from electron capture, acceptance and injection KICKER [13, 14]. It should be noted that space charge effect is not included in the simulation process. The Laslett tune shift is calculated according to the particle distribution in the end of simulation.

The 15m electron cooler provides electron beams with a wide energy range from 100 keV to 800 keV to match most of ions from BRing and SRing. The electron gun can provide an electron current of 3A with a round cross-section and uniform distribution. The main parameters are listed in Table 1. The cooling force calculation is based on Parkhomchuk semi-empirical formula, which is in quite reasonable agreement with available experimental results [15, 16]:

$$\vec{F} = -4\pi Z^2 n_e r_e^2 m_e c^2 L_P \frac{\vec{V}}{(V^2+\Delta_{e,eff}^2)^{3/2}}. \qquad (2)$$

where all the variables are in PRF, n_e is density of electron beam, r_e is classical electron radius, c is the speed of light, L_P is Coulomb logarithm related to electron beam temperature, V is the ion velocity, and $\Delta_{e,eff}$ is the effective electron velocity.

Table 1. The main parameters of the cooler.

Parameter	Value
Cooling section length	15m
Longitudinal magnetic field	0.2T
β_x/β_y	20m/20m
α_x/α_y	0/0
Transverse temperature	0.5eV
Longitudinal temperature	1meV
Effective temperature	1meV
Electron beam radius	1.8cm
Electron beam current	<3A
Neutralisation	20%

As the cycle of BRing is 6s, 6 injections are performed in 36s to achieve the stacking goal.The following parts will focus on the investigations of relative parameters.

4.1 Cooling current

Electron cooling improves the beam quality through Coulomb collision between ions and electrons, so the higher electron current brings a higher collision probability and a faster cooling. However the space charge effect inside the electron beam gives rise to energy spread, which increases the velocity deviation relative to ions. According to Eq. (2), the cooling force decreases. Fig. 4 shows the stacking efficiency under different electron beam currents. The space charge effect dominates the cooling when the current exceeds 1A. Then the stacking efficiency increases slowly and even begins to drop.

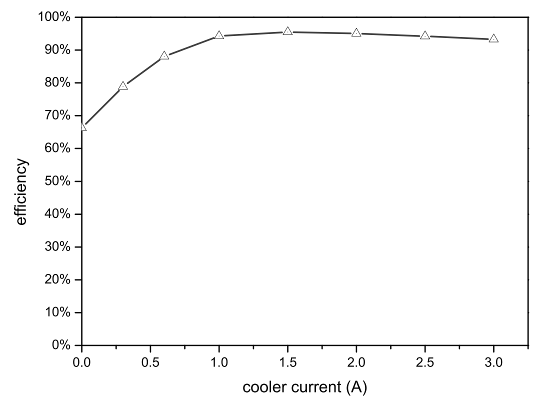

Fig. 4. The relationship between stacking efficiency and cooling current.

4.2 Misaligned angle

Fig. 5 shows how stacking efficiency varies with the misaligned angle increasing. The misalignment can increase the transverse emittance and lower the longitudinal heating due to IBS effect. Meanwhile, following the increase of emittance the cooling force decrease owing to the transverse velocity deviation. As the balance between electron cooling and IBS effect[17–19], 0.55mrad is the best choice.

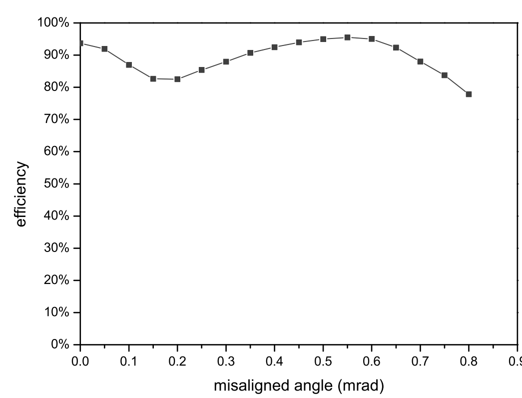

Fig. 5. The relationship between stacking efficiency and misaligned angle.

4.3 BB voltage

For the stored beam, the deeper of the potential well the better, because less particles can escape and be killed by the injection KICKER. However, the injected particles get additional momentum deviations corresponding to depth of the potential well. This problem adds extra burden on electron cooling. Fig. 6 indicates that 1000V corresponding to a potential well of 2.47×10^{-4} is enough.

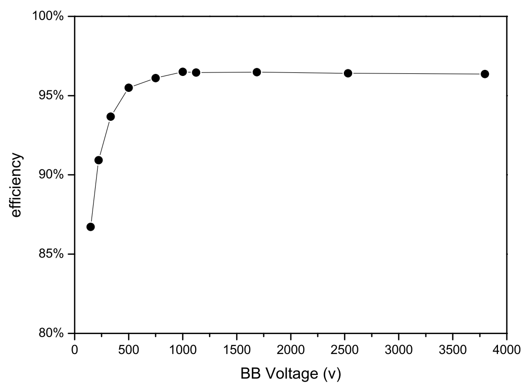

Fig. 6. The relationship between stacking efficiency and BB voltage.

4.4 Laslett tune shift

Laslett tune shift is the maximum shift of working point due to the space charge effect. According to the experience, particle may cross the resonance line and get lost when the Laslett tune shift is smaller than -0.1 [20]. Misalignment can increase the transverse emittance to lower space charge effect, as shown in Fig. 7. To keep the beam safe, the misaligned angle should be larger than 0.5mrad.

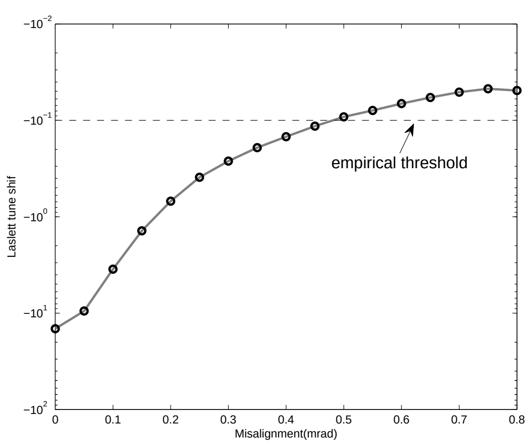

Fig. 7. The relationship between Laslett tune shift and misaligned angle.

4.5 Optimization

The parameters are optimized with the aim of maximizing the number of retained particles. The optimized parameters are listed in Table 2. All of the results below are based on them. The optics parameters at the reference point are $\beta_x=\beta_y=10m$, $\alpha_x=\alpha_y=0$. Fig. 8 shows the particle distribution in horizontal phase space. All of the particles are concentrated on a narrow ellipse. Fig. 9 shows the beam distribution in transverse real space. Fig. 10 shows the distribution of momentum spread.

Table 2. The optimized parameters.

Parameter	Value
Misaligned angle	0.55mrad
Cooling current	1.5A
BB voltage	1000V
retained particles	5.79×10^{11}
stacking efficiency	96.5%
Laslett tune shift	-0.078

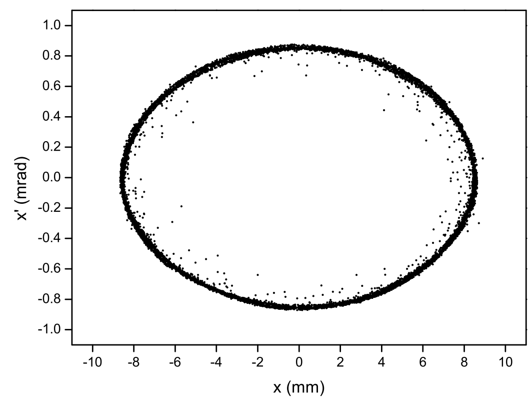

Fig. 8. Particle distribution in horizontal phase space.

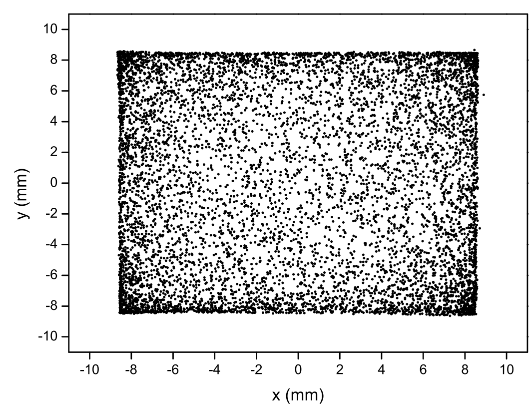

Fig. 9. Particle distribution in transverse real space.

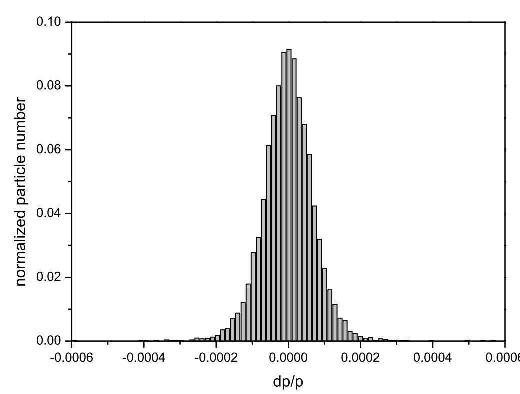

Fig. 10. The distribution of momentum deviations.

5 Conclusion

The simulation and optimization of BB stacking in CRing are performed. The relations between stacking parameters and efficiency are researched based on the simulation code BETACOOL. The results demonstrate that BB stacking is an effective way to achieve the intensity gain. With the misaligned electron cooling, the space charge effect is restricted remarkably in high intensity case. The retained particles after 6 injections reach 5.79×10^{11} ppp, corresponding to a stacking efficiency of 96.5%. In future, the space charge effect in stacking process will be further investigated.

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