# Simulation and analysis of the transverse spectrum in HIRFL-CSR*

LI Peng(李朋)[1,2;1)] YUAN You-Jin(原有进)[1] MAO Li-Jun(冒立军)[1]
YANG Jian-Cheng(杨建成)[1] LI Guo-Hong(李国宏)[1] YIN Da-Yu(殷达钰)[1,2]
LI Jie(李杰)[1,2] LI Xiao-Ni(李小妮)[1,2] CHAI Wei-Ping(柴伟平)[1,2] SHI Jian(石健)[1,2]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

**Abstract:** Particles in a storage ring oscillate in the longitudinal and transverse dimensions. Therefore, the signal that beam has generated can be analyzed in the frequency domain to extract many beam parameters, such as tune, momentum spread, emittance and their evolution with time and so on. In this paper, the transverse spectrum in HIRFL-CSR was simulated and analyzed under different conditions, including electron cooling, hollow electron beam, solenoid effect, the tune shift caused by power supply ripple and the misalignment between ion and electron beams. The result of the simulation shows that the longitudinal magnetic field of the electron cooling device should be compensated by a "compensation solenoid", and the power supply ripple must be controlled, otherwise the accumulation would be affected and the beam would be lost.

**Key words:** HIRFL-CSR, transverse spectrum, solenoid, electron beam, power supply ripple

**PACS:** 29.20.db **DOI:** 10.1088/1674-1137/35/2/015

## 1 Introduction

HIRFL-CSR is a new ion cooler-storage-ring system in China's IMP (Institute of Modern Physics); it consists of a main ring (CSRm) and an experimental ring (CSRe). The overall layout of the HIRFL-CSR can be seen in Ref. [1]. The heavy ion beams from HIRFL will be first injected into CSRm, with the accompanying accumulation, e-cooling and acceleration, and finally extracted to CSRe for many internal-target experiments [1]. Two electron coolers located in the long straight sections of CSRm and CSRe, respectively, are used for ion-beam accumulation and cooling. In order to obtain a high density beam, different cases involving accumulation must be analyzed. Spectral analysis is a powerful tool to complete this work. The basic concepts of the spectrum theory are given before describing the results of simulation.

## 2 Basic theories of the spectrum

### 2.1 Longitudinal spectrum

In a storage ring, a single particle of charge $Z$ circulating at a revolution frequency $f_k = 1/T$ induces a series of $\delta$ functions onto a short pick-up placed somewhere around the ring. With a passage time $t_k$ given by the initial conditions, the current created and its Fourier expansion are:

$$I(t) = Zef_k + 2Zef_k \sum_{k=1}^{\infty} \cos(n\omega_k(t-t_k)).$$

Here $n$ is the harmonic number, $Ze$ is the charge of the beam. The longitudinal spectrum consists of a DC part $I_{k0} = Zef_k$ which is the circulating beam current, and an infinite series of lines at all harmonics of $f_k$. Now assume a coasting beam consists of $N$ individual particles with random initial phases $\varphi_k$ and revolution frequency $f_k$, within a distribution $f_k \pm \Delta f/2$. Averaging $I_{k0}$ over $N$ particles gives the circulating beam current $I_k = N(Zef_k)$. Then each particle will contribute its own series of harmonic lines. It is important to note that in a coasting beam, the initial phase is completely random, only the DC term of the beam current is left if we directly sum all particles. However the r.m.s current per band is non-

Received 29 April 2009
* Supported by National Natural Science Foundation of China (10635090)
1) E-mail: lipeng@impcas.ac.cn

zero and in any single band the rms current is given by $I_{\rm rms}=2Zef_k\sqrt{N/2}$. The current distribution inside each band provides valuable information on the momentum profile of the beam $\Delta P/P=(1/\eta)(\Delta f/nf_k)$, where $\eta=|1/\gamma^2-1/\gamma_{\rm tr}^2|$ is the off momentum parameter of the machine, $\gamma$ is the relativistic energy factor and $\gamma_{\rm tr}$ is called transition-$\gamma$ [2].

### 2.2 Transverse spectrum

If the pick-up used to observe the longitudinal signal is made sensitive to the transverse position of the particle, then the betatron oscillation of the particle will be seen at the pick-up too. The betatron motion of the amplitude $a_0$ of the particle is described as $x(t)=a_0\cdot\cos(\omega Qt+\varphi_0)$. Then the signal extracted from the pick-up can be interpreted as the amplitude modulation of the longitudinal current:

$$d(t) = Zef_k\cdot a_0\left\{1+\sum_{n=1}^{\infty}[\cos(\omega_k(n+q)t) + \cos(\omega_k(n-q)t)]\right\},$$

where $q$ is the fractional part of the tune $Q$. The spectrum at a given harmonic n of the revolution frequency features two sidebands at $(n\pm q)f_k$. The power in each sideband is given by $I_{\rm rms}=Zef_k a_{\rm rms}\sqrt{N/2}$, where $a_{\rm rms}$ is the rms oscillation amplitude of all the particles, which is proportional to the square root of the transverse beam emittance. The widths of the sidebands at $(n\pm q)f_k$ are obtained by $\Delta f_{\pm}=[(n\pm q)\eta\pm Q\xi]\Delta P/P\cdot f_k$, where $\Delta Q/Q=\xi\Delta P/P$. Hence transverse spectrum provides a large set of fundamental beam parameters: the fractional part of the tune, the transverse emittance and so on [2, 3].

## 3 Simulation and analysis process

According to the theory of the spectrum mentioned above and the parameters of HIRFL-CSR, simulations were done to investigate how to get a higher intensity beam and avoid beam loss.

### 3.1 Ion beam initialization

First of all, a number of particles with certain distribution must be initialized. The parameters of ions and Twiss at the Cooler are assumed as the following: the type of ions is $^{12}C^{6+}$, energy is 7 MeV, the values of the betatron tunes are $v_x=3.62$ and $v_z=2.61$, the values of the betatron amplitude functions are $\beta_x=10.5$ and $\beta_y=16.6$, the emittances are $\varepsilon_x=150\ \pi$mm·mrad and $\varepsilon_y=25\ \pi$mm·mrad. According to the parameters mentioned above, the Gaussian distribution ion beams are adopted in the simulation.

### 3.2 Electron beam distribution

An electron gun equipped with a control electrode, located at the electron-cooling device of HIRFL-CSR, is capable of varying the transverse distribution of the electron beam and making a hollow beam [4]. So in the simulation, the hollow beam with different control voltages which affect the distribution is taken into account (Factor means control voltage). Profile of the electron beam under different factors can be seen in Fig. 1.

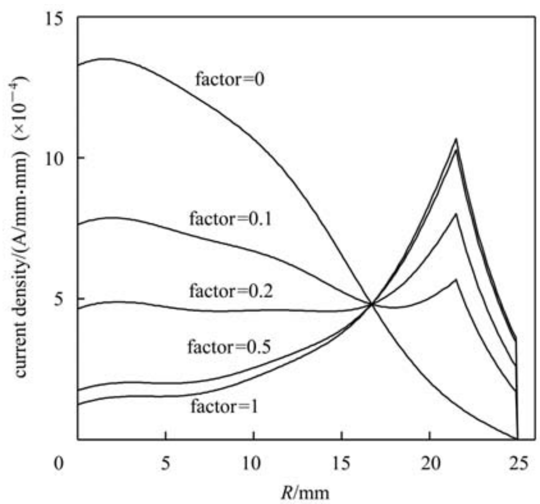


Fig. 1. 2D profile of the electron beam.

### 3.3 Ring matrix and different effect

In this paper, the transform matrix is calculated from its lattice parameters mentioned above. The betatron coordinates are transformed in accordance with the coefficients of the ring matrix. The electron cooling device is considered as a thin lens. In this case the ion angle variation is calculated as

$$\Delta\vartheta=\frac{F}{MC^2\beta^2\gamma}L_{\rm cool}N_{\rm turn},$$

here $F$ is the cooling force, $M$ is the ion mass, $L_{\rm cool}$ is the length of the electron cooling device and $N_{\rm turn}$ is the revolutions number. The ion coordinates are not changed inside the cooler. Some possibility may occur during the accumulation such as the non-compensated longitudinal magnetic field and misalignment between the ion and the electron beams. In addition, the level of power supply ripple is also an important factor that will affect the accumulation result. All those effects mentioned above are included in the next simulation.

## 4 Simulation result and discussion

### 4.1 Cooling time and FFT (Fast Fourier Transform) spectrum

In HIRFL-CSR, the electron cooling is a powerful tool for the accumulation, so the transverse cooling time is given in the simulation first. The initial angle of the electron beam is assumed as $5\times10^{-4}$ [5]. The calculation of the electron cooling effect is based upon the cooling force. According to the result, the vertical cooling time is about 0.3 s, and the horizontal cooling time is about 0.6 s (The cooling time was calculated as the time it took to cool the emittance value to its 1/e). Fig. 2 shows the transverse emittance decreased with the time. Meanwhile, we can take the particle coordinates as a discrete signal in the time domain and transform this signal into its frequency domain. Then the information about betatron motion of the beam can be analyzed. The fractional value of tune in two dimensions is 0.62 and 0.61, shown in Fig. 3.

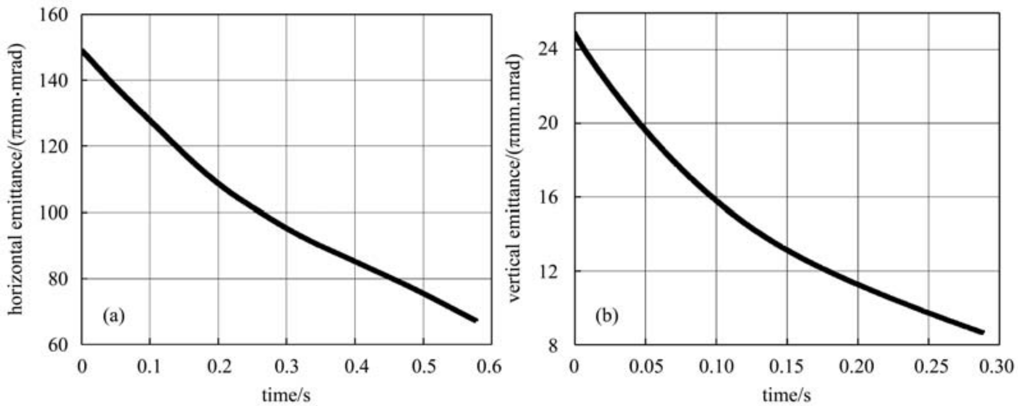


Fig. 2. (a) The horizontal emittance evolution. (b) The vertical emittance evolution.

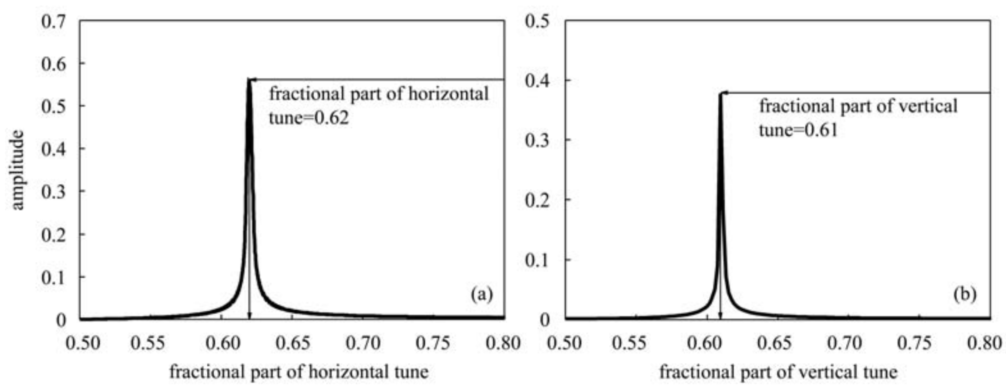


Fig. 3. (a) The fractional part of horizontal tune. (b) The fractional part of vertical tune.

### 4.2 Magnetic field compensation

In the electron cooling system, the longitudinal magnet field is used for the compensation deflection by the space charge of electron beam. Meanwhile, it must be compensated, otherwise transverse coupling will occur. During the operation of the machine under the parameters, the current of magnet field power is usually 48 A ($390\times10^{-4}$ T). If there is no other compensated solenoid, the horizontal tune shift is 0.00547 and the other one is 0.00867. Meanwhile we can see the coupling effect between the horizontal and the vertical directions from the FFT result, shown in Fig. 4. Fig. 5 is the tune shift result under different magnet fields. So in order to avoid beam loss, there

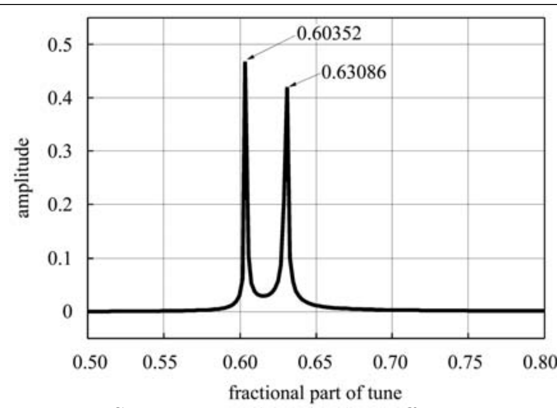


Fig. 4. Spectrum under coupling effect. 0.60352 is the fractional part of vertical tune, and 0.63086 is the fractional part of horizontal tune.

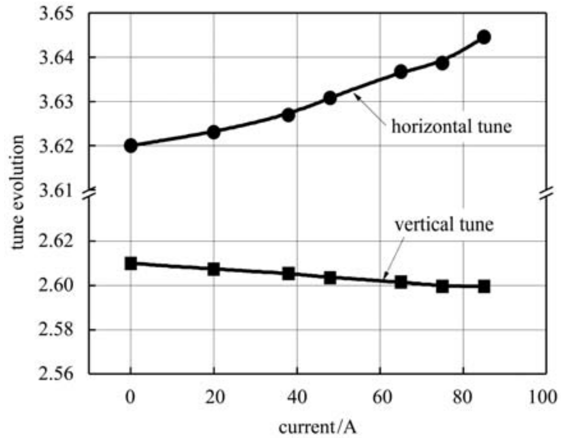


Fig. 5. Tune shift under different currents.

are “compensation solenoids” in HIRFL-CSR used to decrease the coupling [6].

### 4.3 Power supply ripple

In the storage ring, the causes of beam instability and “blow-up”, sudden total or partial loss of beam current, may be the power supply ripple. In this paper, a program was added to simulate this instability.

We assumed there is a cosine oscillation on a power supply. Its amplitude is 0.3 A and its frequency is 50 Hz. The transverse tune shift is 0.0075 under this modulation existence shown in Fig. 6. Fig. 7(a) shows the result that we take Fourier transform on the beam coordinates continuously. The horizontal axis corresponds to frequency. The vertical axis corresponds to time. The color displays the magnitude of the oscillation. It turns out that the sideband is not a line, it is a cosine oscillation. The tune shift will increase as long as the amplitude increases during the process, finally it may cause the beam loss. Fig. 7(b) is the spectrum result under modulation where the amplitude increases with time. So during the operation of the ring, the level of the power supply ripple must be controlled.

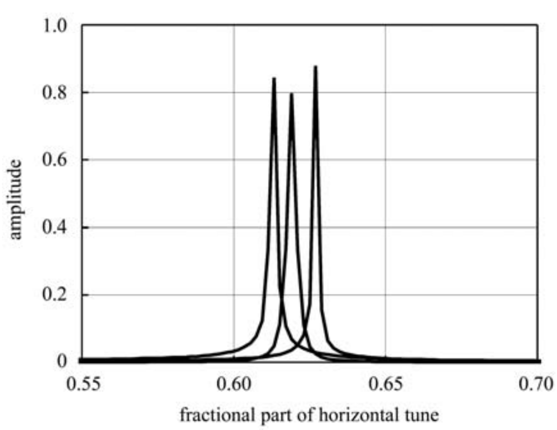


Fig. 6. Tune shift under amplitude modulation.

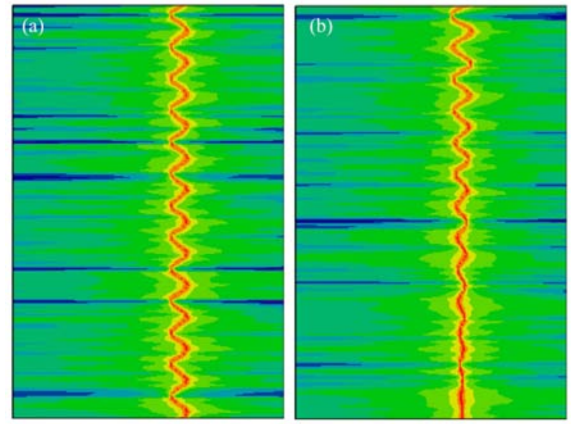


Fig. 7. (color online). The spectrum under modulation.

### 4.4 Misalignments between ion and electron beam

The simulation which involves the nonzero angle between the ion and the electron beams is also done [7, 8]. The electron cooling will be valid when the angle between two beams is too large. Assuming the angle is 4 mrad, we can see that at first the transverse emittance will increase with time under the electron cooling from Fig. 8. Because this angle is not large enough, the emittance finally decreases. But the

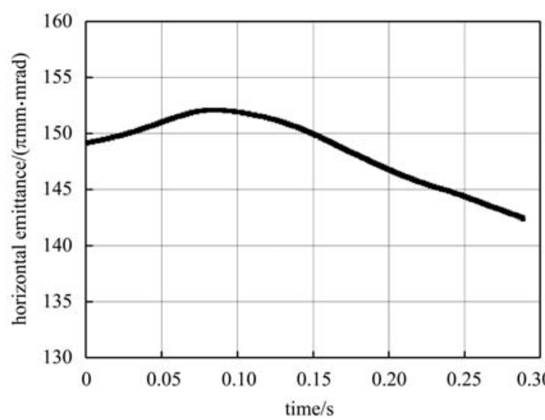


Fig. 8. Emittance evolutions with time.

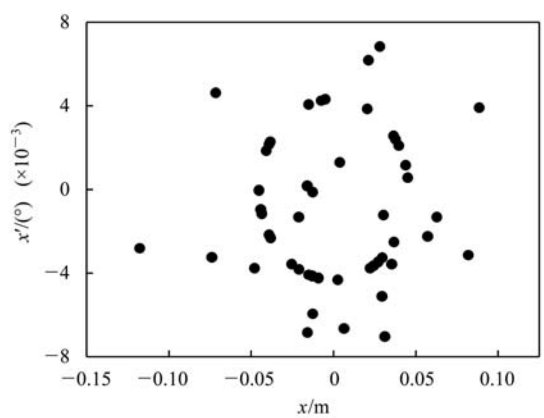


Fig. 9. Final distributions of ions.

cooling time will be long. In addition, the ion beams distribution shown in Fig. 9 will be different under this condition. This means that the ion beams will be hollow, most of the ions will distribute in the edge and this result may cause the beam loss.

## 5 Conclusions

Simulations under different conditions involving accumulation mentioned above have been given in this paper. Great attention must be paid to those issues in the operation to avoid beam loss. Information on the spectral behavior of beams helps us to analyze and solve the beam loss and instability problems at the time of beam accumulation as well as during various experiments. More simulations and analyses of the spectrum in the longitudinal and transverse dimensions will be done in the future.

---

### References


1 YUAN Y J, XIA J W, ZHAO H W et al. Present Status and Future Improvement of HIRFL-CSR. In: Proceeding of EPAC 2008. Genoa, Italy, 2008. 388–390

2 Tranquille G, Tan J. Beam Diagnostics with Schottky Noise in LEIR. In: Proceedings of EPAC 2006. Edinburgh, Scotland, 2006. 1214–1216

3 Peter Forck. Schottky Noise Analysis JUAS Archamps. http://www-bd.gsi.de/conf/juas/schottky_trans.pdf

4 Bubley A V et al. Nuclear Instruments and Methods in Physics Research A, 2004, **532**: 413–417

5 RAO Y N. HIRFL-CSR Electron Cooling. Dissertation of Doctor. Lanzhou: IMP CAS, 1997

6 ZHOU X M, XIA J W et al. HEP&NP, 2006, **30**(5): 462–465 (in Chinese)

7 Danared H, Kallberg A et al. Ordered Ion Beams in CRYRING. In: ION BEAM COOLING Toward the Crystalline Beam Proceedings of the Workshop. Kyoto, Japan, 2001. 43–55

8 MAO L J. Simulation and Experiments of Electron Cooling in HIRFL-CSR. Dissertation of Doctor. Lanzhou: IMP CAS, 2008