

## 7 - 21 Development of Beam Dynamics

Shen Guodong, Liu Jie, Cai fucheng, Hou Lingxiao, Guo Cheng, Chai Weiping, Ruan Shuang, Wang Geng, Mao Lijun and Yang Jiancheng

The HIAF High Intensity heavy Ion Accelerator Facility is under construction in Huizhou City, Guangdong, China<sup>[1]</sup>. To fulfill the demand of frontier research in nuclear physics, astrophysics, atomic physics, and high energy density physics, HIAF aims to provide the ambitious beam intensity of pulsed heavy ions with the energy range of several hundred MeV/u up to GeV. To research more detailed high intensity beam dynamics process a high-performance simulation platform CISP-GPU is developed. With CISP-GPU the high-order resonance is simulated and analyzed. Then a delicate compensation multipole scheme is designed and optimized to mitigate the undesired beam loss. The acceleration of proton is complicated and challenging during the transition energy crossing. The longitudinal dynamics without transition energy crossing is investigated under a high  $\gamma_t$  lattice design. The dynamic magnetic field induced by rapid cycling results in serious magnetic field deviation. Dual magnetic field correction schemes have also been developed and demonstrated with SESRI facility successfully.

### 1. Development of High-performance Beam Dynamics Simulation Platform

In last year, the high-performance beam dynamics simulation platform for complex heavy ion accelerator facilities, named CISP-GPU, has been developed based on CISP<sup>[2]</sup> to fulfill the requirements of analyzing the coupling effects of nonlinear fields, space charge fields, wake fields, and complex beam manipulations like injection, bunch merging, and so on. This software platform makes it possible for the first time to cover all vital effects of heavy ion accelerators in a single high-precision element-by-element simulation with the help of its high performance guaranteed by fully modifying all beam dynamics modules into a highly parallel style which is 100 times faster than the CPU version. The CISP-GPU has been successfully applied to design and test all beam dynamics in the BRing of HIAF project, a major national science and technology infrastructure, including optimization of two plane painting injection based on tilted electrostatic septum, analysis and correction of resonances driven by nonlinear fields and space charge fields, simulation and stabilizing of conventional collective instabilities driven by coupling impedances, and discovering of new instabilities like asymmetric bunch coupling instability in the bunch merging, quite different effects between ultra-short wake fields and ultra-long bunches during the transition energy crossing, and so on. Some of these simulations are shown in the Fig. 1. Now, the CISP-GPU is shared internationally via a website <https://cisp.acsoftware.cn> temporarily. In the future, with the high performance of CISP-GPU, it will be embedded into the control system to provide the online simulation capability which will change the way we research and operate an accelerator facility and largely improve the efficiency of beam commissioning and operation.

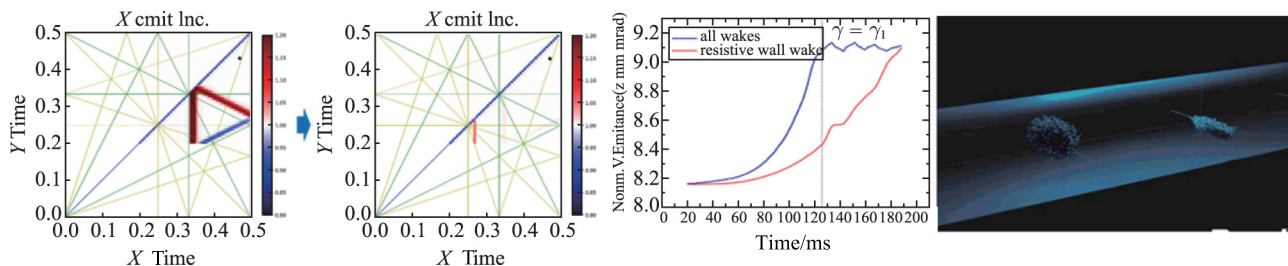


Fig. 1 (color online) Left: correction of resonances, middle: effects between ultra-short wake fields and ultra-long bunches during the transition energy crossing, right: asymmetric bunch coupling instability in the bunch merging.

### 2. Resonance Corrections

Resonance driven by imperfect magnet is a serious source of beam loss for high intensity synchrotron. The tune spread of HIAF-BRing will cross five third-order resonance lines:  $3Q_y = 28$ ,  $Q_x + 2Q_y = 28$ ,  $Q_x - 2Q_y = -9$ ,  $2Q_x + Q_y = 28$ ,  $3Q_x = 28$ . Among them, three resonance lines ( $3Q_x = 28$ ,  $Q_x + 2Q_y = 28$ ,  $Q_x - 2Q_y = -9$ ) are excited by normal sextupole fields, and two resonance lines ( $3Q_y = 28$ ,  $2Q_x + Q_y = 28$ ) are excited by skew sextupole fields. Therefore, two normal sextupoles are installed in the zero-dispersion region at the center of each arc section, and four skew sextupoles are installed in the straight sections of the first and second quadrants. This scheme ensures that these compensation sextupole fields can perform resonance compensation without affecting the chromaticity. The method of setting errors is to randomly select a vector direction and calculate the vector direction of the sextupole field errors of all dipole and quadrupole magnets in the ring. The errors that are consistent with the

selected vector direction are set to positive values, and the errors that are opposite to the selected vector direction are set to negative values, in order to obtain the largest possible error effect. Figure 2 shows the beam loss under the conditions of no error, only error, and error + compensation.

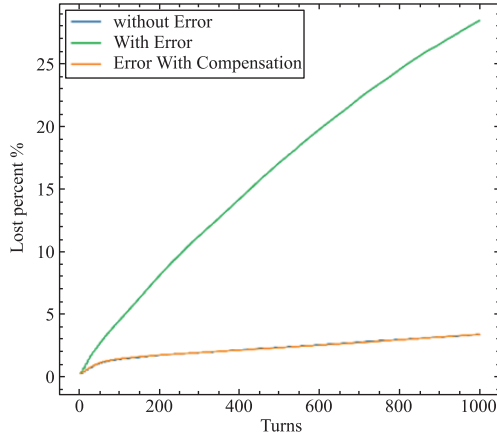


Fig. 2 (color online) Beam loss simulation of imperfect resonance.

Figure 3 shows the beam momentum spread of schemes with different  $\gamma_t$  (Left) and longitudinal beam phase space at extraction stage with  $\gamma_t = 13.28955$  (Right). The oscillation of momentum spread near extraction is  $(1.01 \pm 0.23) \times 10^{-3}$  with  $\gamma_t = 13.28955$ , which is acceptable. The extraction timing should be optimized to obtain beams with momentum spread smaller than  $\pm 0.001$ . The wake voltage induced by beam loading effect reaches 69 kV at the end of acceleration stage and extraction stage, which should be compensated very carefully to avoid severe bunch distortion and even beam loss. More simulations are being done to study other collective effects during the whole acceleration process with  $\gamma_t = 13.28955$ .

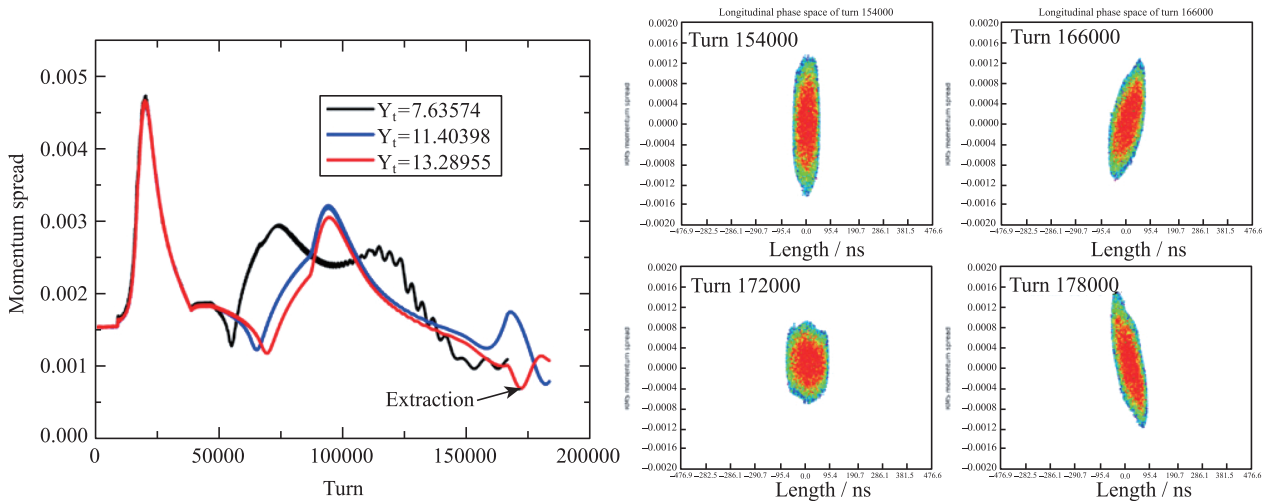


Fig. 3 (color online) Left: Beam momentum spread of schemes different  $\gamma_t$ . Right: Longitudinal beam phase space at extraction stage with  $\gamma_t = 13.28955$ .

### 4. High Precision Dynamic Magnetic Field Correction

The dynamic magnetic field impose a challenge to rapid cycling synchrotron concerning the precise synchronization demand between magnet and RF. The BRing dipoles rise in a maximum velocity of 12 T/s which induces a dynamic magnetic field of more than 100 Gs<sup>[4]</sup>. All of the particles will lose at positions of large dispersion  $Dx$  in the initial acceleration stage. To mitigate the beam loss an offline dynamic magnetic field correction method and an online method are developed. Preliminary demonstration is performed on SESRI facility with beam experiment successfully.

The offline dynamic magnetic field correction is based on careful measurement of the SESRI synchrotron dipoles and quadrupoles in the thermostatic laboratory before the magnets were installed online. Based on the offline

### 3. Proton Beam Acceleration Scenario Without Transition Energy Crossing

Transition energy crossing is a special dynamic process for proton acceleration when longitudinal motion slow down and beam loss occurs<sup>[3]</sup>. The lattice of HIAF/BRing for heavy ion beams ( $\gamma_{t1}=7.63574$ ) was also proposed for proton beam. The  $\gamma_t$  jump scheme was designed to reduce the growth of momentum spread and influence of collective effects near transition energy. To obtain a height of  $\gamma$  jump  $\Delta\gamma = 2$ , the current of the power supplies of the fast quadrupoles should decrease from 600 A to  $-600$  A within 0.5 ms, which poses a huge challenge to the design of power supplies and magnets. Thus, lattices with higher  $\gamma_t$  larger than 11 have been proposed to avoid transition energy crossing. The bunches are merged to one bunch at 500 MeV/u, which can save much time compared to merging at extraction stage with small phase slip factor.

measurements, computation of the correction power supply waveform is performed for all patterns of magnetic field curve. Under this procedure, magnetic field deviation was corrected to less than 8 Gs.

The online dynamic magnetic field correction is based on the online measurement of the SESRI synchrotron dipoles. The measurement elements include PCB (Printed Circuit Board) induced coils and Hall probes placed in two reference synchrotron dipoles. The combination of the magnetic field signals collected by measurement elements allows the real-time integrated magnetic field to be obtained during the synchrotron operating. With iteration of the online magnetic field correction, magnetic field error was reduced to within 0.2 Gs (Fig. 4).

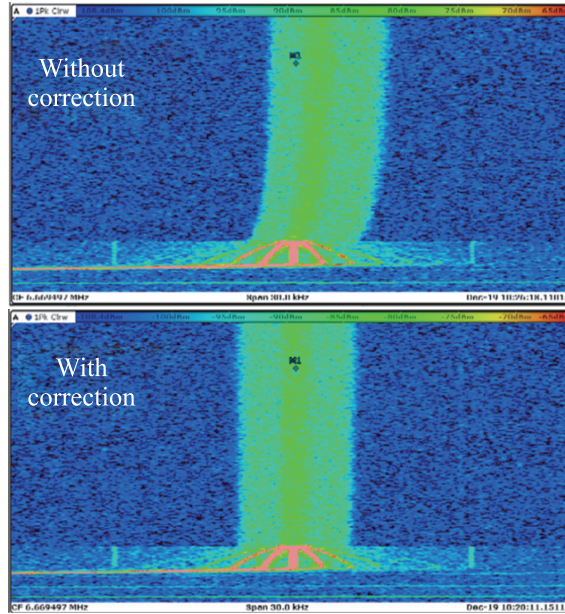


Fig. 4 (color online) The Schottky signal on the extraction flattop in online dynamic magnetic field correction experiment.

## References

- [1] J. C. Yang, J. W. Xia, G. Q. Xiao, et al., Nucl. Instrum. Meth. B, 317(2013)263.
- [2] J. Liu, J. C. Yang, J. W. Xia, et al., Nucl. Instrum. Meth. A, 881(2018)36.
- [3] F. C. Cai, J. C. Yang, J. W. Xia, et al., Phys. Rev. Accel. Beams, 23(2020)064402.
- [4] X. Q. Chen, J. C. Yang, J. W. Xia, et al., Nucl. Instrum. Meth. A, 920(2019)37.