HIRFL-CSR commissioning in 2006 and 2007*

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Abstract HIRFL-CSR, a new heavy ion cooler-storage-ring system at IMP, had been in commissioning since the beginning of 2006. In the two years of 2006 and 2007 the CSR commissioning was finished, including the stripping injection (STI), electron-cooling with hollow electron beam, C-beam stacking with the combination of STI and e-cooling, the wide energy-range synchrotron ramping from 7 MeV/u to 1000 MeV/u by changing the RF harmonic-number at mid-energy, the multiple multi-turn injection (MMI), the beam accumulation with MMI and e-cooling for heavy-ion beams of Ar, Kr and Xe, the fast extraction from CSRm and single-turn injection to CSRe, beam stacking in CSRe and the RIBs mass-spectrometer test with the isochronous mode in CSRe by using the time-of-flight method.

Key words CSR, commissioning, heavy ion, e-cooling, accumulation

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1 Introduction

From 1996 to 1998, an ion accelerator plan[1] was proposed to upgrade the HIRFL[2] system with a multi-functional cooler-storage-ring (CSR) forming an HIRFL-CSR accelerator system shown in Fig. 1. In July 1998, this proposal was approved by the Chinese central government, and an December 10, 1999, the CSR project was started. The period from the beginning of 2000 to the summer of 2001 was the stage of the building construction, design optimization and prototype experiments. The machine fabrication was from 2001 to 2003, 2004 and 2005 were used for the installation and subsystem tests, and the period from 2006 to 2007 was the commissioning stage.

2 HIRFL-CSR descriptions[3]

CSR is a double cooling-storage-ring system with a main ring (CSRm), an experimental ring (CSRe), and a radioactive beam line (RIBLL2) to connect the two rings, shown in Fig. 1. The heavy ion beams with the energy range of 7—25 MeV/u from the cyclotron SFC or the cyclotron complex SFC+SSC will be injected, accumulated, cooled and accelerated to the high energy range of 100—500 MeV/u in the main ring CSRm, and then extracted fast to produce radioactive ion beams (RIBs) or highly charged heavy ions (high-Z beams). Those secondary beams will be accepted and stored or decelerated by the experimental ring CSRe for many internal-target experiments or high precision spectroscopy with e-cooling. On the other hand, the beams with the energy range of 100—1000MeV/u will also be extracted from CSRm by using slow extraction for many external-target experiments or cancer therapy.

Two electron coolers located in the long straight sections of CSRm and CSRe respectively, will be used

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for ion-beam accumulation and cooling.

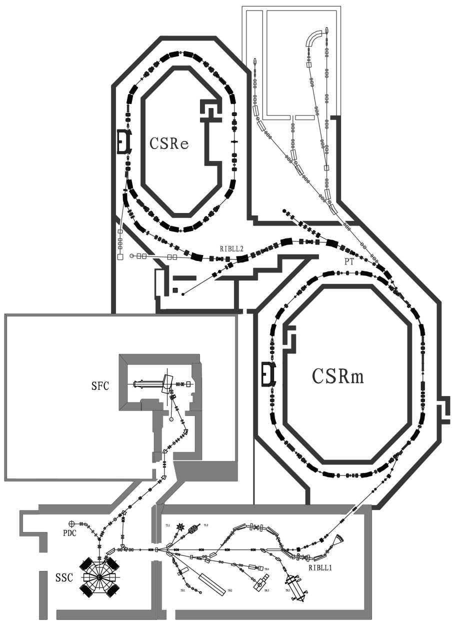


Fig. 1. Overall layout of HIRFL-CSR.

3 Initial commissioning of CSRm

3.1 First beam storage in CSRm

In the beginning of 2006, the main ring CSRm was under preliminary commissioning. on January 18, 2006, the beam of C^{6+}-6.89MeV/u for the single-turn stripping injection was stored successfully in CSRm with bumping orbit. Fig. 2 is the stored beam signal from a BPM. In this case the RF system of CSRm was switched off, thus the bunched beam from the cyclotron SFC became a costing beam gradually after the single-turn injection, and the beam signal from BPM also became weak turn by turn.

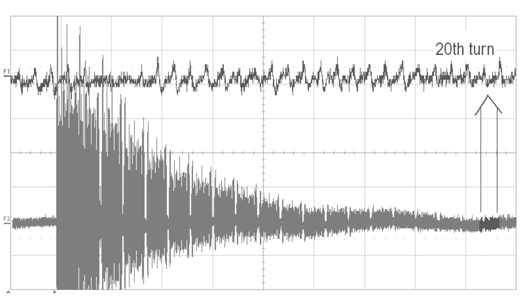


Fig. 2. The stored beam signal from BPM.

From the result of Fig. 2, we can see that the beam signal of the 20^{th} turn has already become very weak.

Based on the single-turn beam storage, on January 23, 2006, the beam of C^{6+}-6.89 MeV/u for the multi-turn stripping injection was stored successfully in CSRm with bumping orbit. Fig. 3 is the stored beam signal from the spectrum analyser connected with a BPM in the zero-span mode.

In order to observe the stored beam signal from BPM for a long time, the stored costing beam should be re-bunched by the RF system of CSRm with the harmonic number of 4 and the RF voltage of 1.3 kV. With the RF modulating, the stored beam signal can be obtained from the spectrum analyser connected with a BPM in the zero-span mode. As shown in Fig. 3, after the multi-turn stripping injection, the stored beam was modulated by RF five times in 10 seconds. The first modulating period was 1 second, and after that every period was 0.5 seconds. According to Fig. 3, the $1/e$ life-time of stored beam was about 10 seconds.

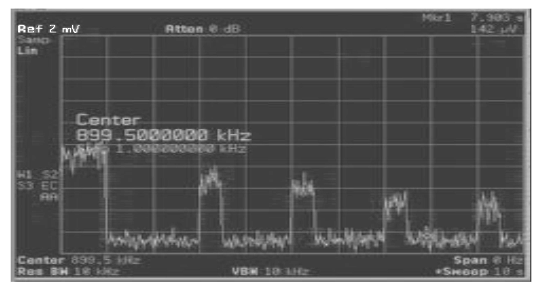


Fig. 3. The first stored beam signal from the spectrum analyser.

3.2 Preliminary beam accumulation

In the spring of 2006, the new controller DSP developed by ourselves was used in the power supply control system of dipole, quadruple, bump and RF system. By using this new DSP, the synchronous time between the dynamic bumping orbit which is used to cross the stripper, the period of injection beam and the RF system can be controlled accurately. Fig. 4 is the synchronous signal between RF, bumping orbit and injection beam.

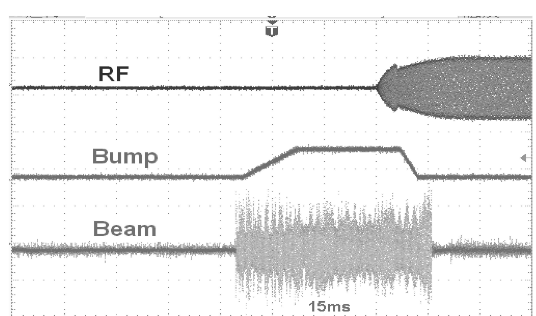


Fig. 4. Signals between RF, bump and injected beam.

In the summer of 2006, the new DCCT device was used to measure the beam current in CSRm. With this powerful diagnosis, the adjustment of the injection match orbit and the preliminary closed orbit correction can be done carefully. on June 29, 2006, the accumulated beam current first exceeded 200 μA for the beam of C^{6+}-7 MeV/u. Fig. 5. is the DCCT current signal for the stored C-beam in CSRm.

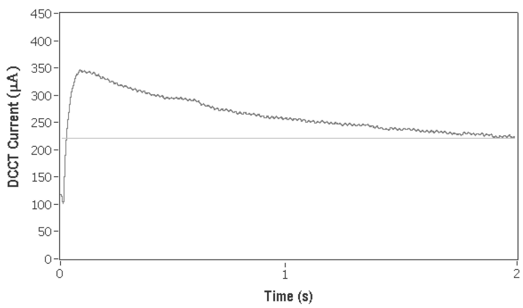


Fig. 5. DCCT current of the stored C-beam in CSRm.

3.3 Tune measurement and modification

In the autumn of 2006, the tune value of the machine can be measured first, and the initial tune (Q_x/Q_y) of CSRm is 3.44/2.75 that is far from the design value of 3.64/2.61. According to the analysis, this large tune shift was caused by the hysteresis of quadruple fields. After modifying the quadruple-field data, the machine tune was adjusted to the original design value, and the 1/e beam life-time in the first 3 seconds became longer from 4 s to 15 s. Fig. 6. shows the stored beam with the tune value of 3.610/2.637.

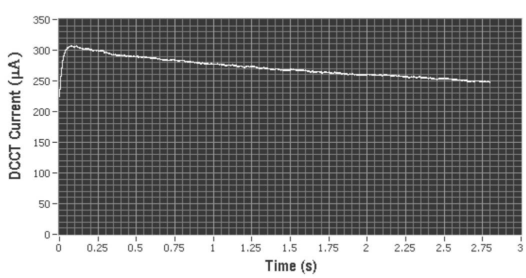


Fig. 6. The stored beam with the tune of 3.610/2.637 in CSRm.

3.4 First varying-harmonic synchrotron ramping

After the modification of tune value, the high energy acceleration test from 7 MeV/u to 1000 MeV/u for C^{6+} ions was done. Fig. 7 is the energy curve, the curves of RF voltage and frequency, and the exciting currents of dipole and quadruples during the ramping period.

During the synchrotron ramping, the C^{6+} beam, which was injected by stripping injection from the small cyclotron SFC, was accelerated from 7 MeV/u to 1 GeV/u, the magnetic rigidity of beam was changed from 0.76 T.m to 11.3 T.m, the dipole field was increased from 0.1 T to 1.5 T accompanied with the exciting current of power supply from 160 A to 2500 A, and the exciting currents of the 30 quadruples were raised from nearly 20 A to about 600 A respectively.

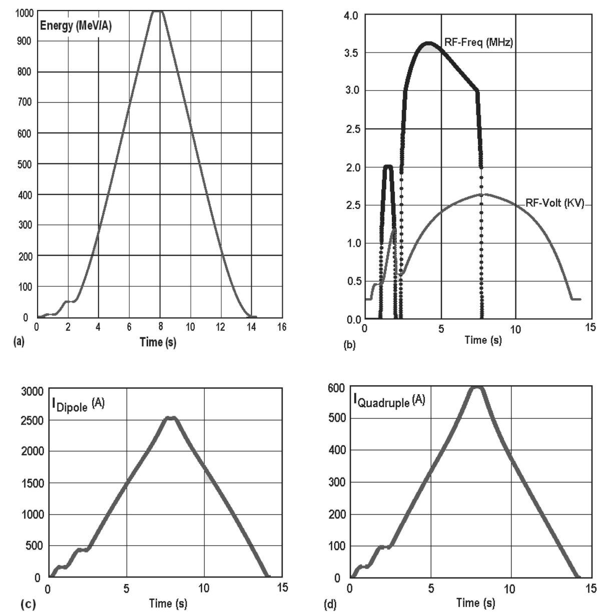


Fig. 7. Curves of energy, RF and exciting currents for ramping.

For the 1 GeV/u ramping, the RF harmonic number of frequency should be changed from 2 to 1 at the energy of 50 MeV/u. Because the frequency region of the CSRm RF system is 0.25—1.7 MHz, but the revolution frequency of the beam at the injection energy of 7 MeV/u is only 0.227 MHz, this can't reach to the low limit of the RF frequency region. So, in the low energy section of the ramping, the harmonic number of RF is adopted as 2, and the start frequency is 0.454 MHz. After 50 MeV/u the revolution frequency is more than 0.586 MHz, then the harmonic number can be changed to 1 until the final energy of 1 GeV/u. Fig. 8 shows the beam current during the 1 GeV/u ramping.

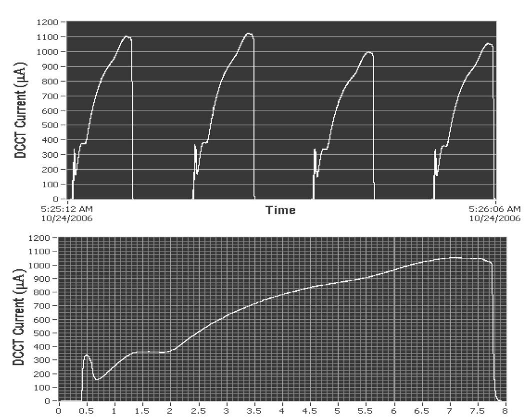


Fig. 8. The beam current during the 1 GeV/u ramping.

For the 1 GeV/u acceleration, the ramping circle is about 8 s, including 200 ms for the stripping injection, 200 ms for the harmonic number change, and 200 ms for the 1 GeV/u top. The acceleration efficiency of the beam is more than 90%, and on the final 1GeV/u top, the beam current can reach to 1 mA, namely the particle number of the C^{6+} ions with the energy of 1 GeV/u is 5×10^8 in CSRm.

4 Commissioning of CSRm

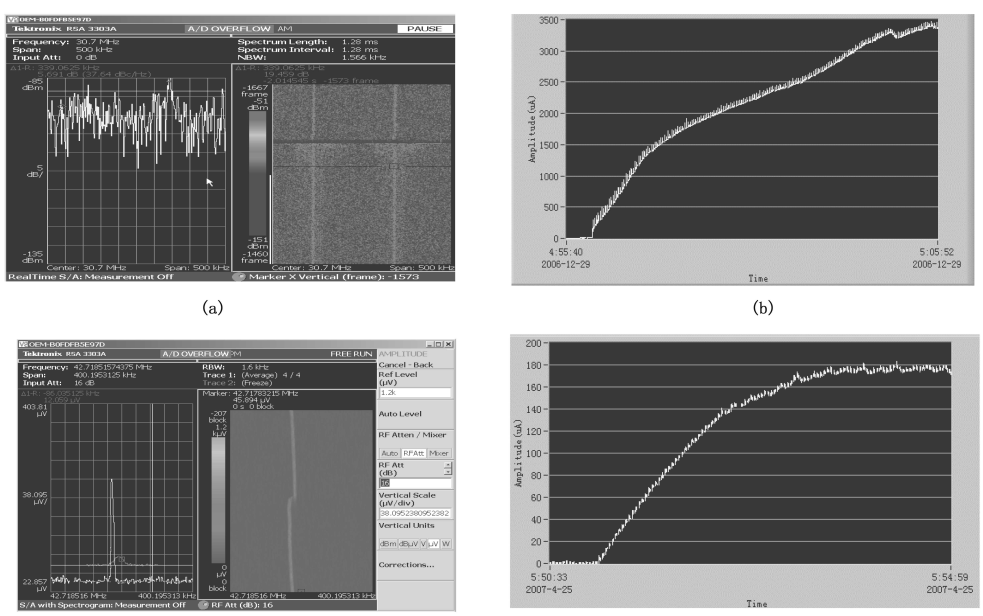
4.1 E-cooling and heavy ion accumulation

In the winter of 2006 the electron-cooling was started in CSRm, and the momentum spread of the C-beam with the energy of 7 MeV/u was reduced from 10^{-3} to 10^{-4}. Fig. 9(a) is the C-beam schottky signal in a spectrum analyser during the e-cooling. By using of the stripping injection (STI) and the hollow e-beam cooling, C-beam can be accumulated to high intensity. Fig. 9(b) shows the cooling-stacking of C-beam in DCCT, the injection current from cyclotron SFC was 10.2 μA, after 8 minutes the C-beam intensity in CSRm reached 3.2 mA, and the beam gain-factor for the accumulation reached 300 times the former value.

In the spring of 2007 the multiple multi-turn injection (MMI) was successful for the beam of $^{36}Ar^{18+}$-22 MeV/u with the hollow e-beam cooling in CSRm. Adopting the combination of MMI and e-cooling, Ar-beam also can be accumulated to high intensity. Fig. 9(c) shows the Ar-beam schottky signal in the spectrum analyser during the MMI. The blue signal is the beam for one time of multi-turn injection, and the yellow one for the beam of MMI. Fig. 9(d) is the DCCT beam signal of the cooling-stacking for Ar-beam, the injection current from the two cyclotrons SFC+SSC was 2 μA, after 2 minutes the Ar-beam intensity in CSRm reached to 180 μA, and the gain-factor of the MMI stacking was 90 times the former value.

4.2 Combination of cooling-stacking and ramping

In 2007 based on the success of STI, e-cooling, MMI, varying-harmonic ramping and cooling stacking, the combination between cooling-stacking and synchrotron ramping for heavy ions was realized. With the wide energy-range acceleration by varying the RF harmonic-number at the mid-energy of 50 MeV/u, the total ion energy was raised to 12 GeV, 36 GeV, 35 GeV and 30 GeV for C, Ar, Kr and Xe ions respectively. On the ramping-top the C-beam current reached to 10 mA by the stacking of STI + e-cooling, and for the heavy-ion beams of Ar, Kr and Xe, the ramping-top currents reached to 1.2 mA, 0.35 mA and 0.5mA respectively. Fig. 10. shows the beam accumulation and ramping in CSRm for the heavy ions of $^{12}C^{6+}$, $^{36}Ar^{18+}$, $^{78}Kr^{28+}$ and $^{129}Xe^{27+}$.



(a) (b) (c) (d)

Fig. 9. Beam cooling and accumulation in CSRm. (a) C-beam schottky signal with e-cooling; (b) C-beam accumulation with STI + e-cooling; (c) Ar-beam schottky signal during MMI; (d) Ar-beam accumulation with MMI + e-cooling.

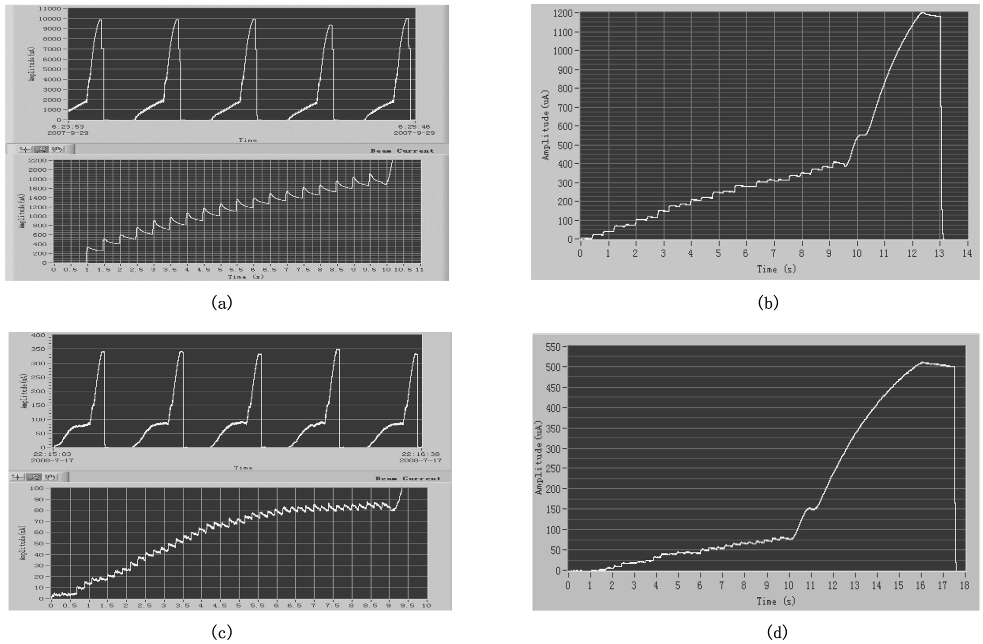


Fig. 10. Heavy-ion beam accumulation and ramping in CSRm. (a) C-beam current during STI + e-cooling and ramping; (b) Ar-beam current during MMI + e-cooling and ramping; (c) Kr-beam current during MMI + e-cooling and ramping; (d) Xe-beam current during MMI + e-cooling and ramping.

5 Commissioning of CSRe

5.1 Beam stacking with double rings

In the autumn of 2007 C-beam fast-extraction from CSRm and single-turn injection to CSRe were realized by using the kicker of the rising time or falling time of 150 ns and peak current of 2500 A. On October 6 the experiment ring CSRe got the fist stored C-beam.

Based on the first-stage accumulation with e-cooling in CSRm, the C-beam with the energy of 660 MeV/u was stacked further by using the multiple single-turn injection in CSRe, and the C-beam current reached to 15 mA, shown in Fig. 11.

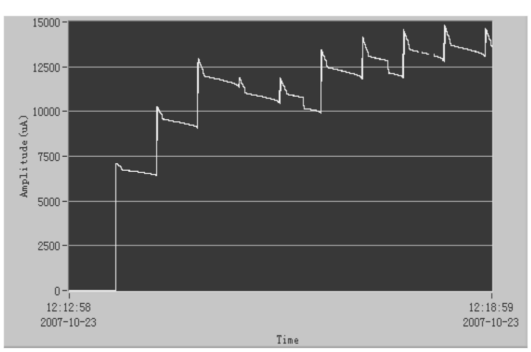


Fig. 11. C-beam was stacked to 15 mA in CSRe.

5.2 Isochronous mode in CSRe

At the end of 2007 the commissioning for the complex of SFC + SSC + CSRm + CSRe was successful with Ar-beam. And in CSRe the isochronous mode was realized with the machine transition γ_t equal to the energy γ of beam. In this case the revolution frequency of ions is independent of the momentum spread of beam. Fig. 12. Shows the Ar-beam frequency spread with the energy of 368 MeV/u in the CSRe isochronous mode, and the frequency spread $\Delta f/f$ reached to 8×10^{-7}.

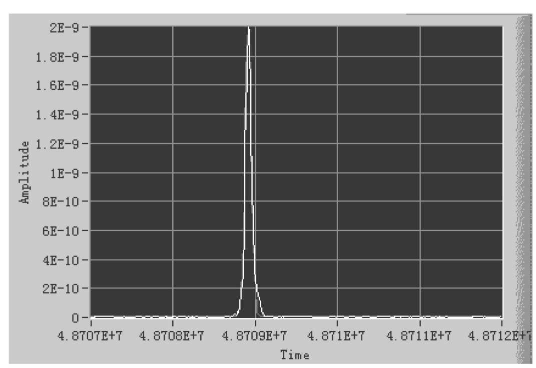


Fig. 12. Beam frequency spread in CSRe isochronous mode.

5.3 RIBs mass measurement in CSRe

Based on the isochronous mode of CSRe, the mass-measurement of the RIBs produced in the beam line was realized in CSRe with the time-of-flight (ToF) method, and the mass resolution reached to 4×10^{-6}. Fig. 13. is the first RIBs mass-measurement result in CSRe. In this experiment, RIBs were produced at the primary target in the beam line RIBLL2 with the primary beam of $^{36}Ar^{18+}$-368 MeV/u extracted fast from CSRm. Those secondary beams were accepted and stored in CSRe, and then detected by ToF method.

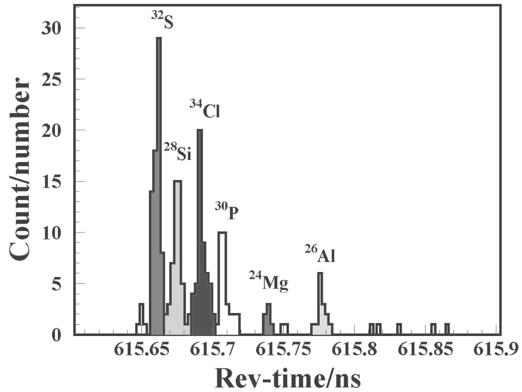


Fig. 13. First RIBs mass-measurement results in CSRe.

During the RIBs mass-measurement experiment, each turn signal of the single ion can be detected by the C-foil target of ToF system shown in Fig. 14.

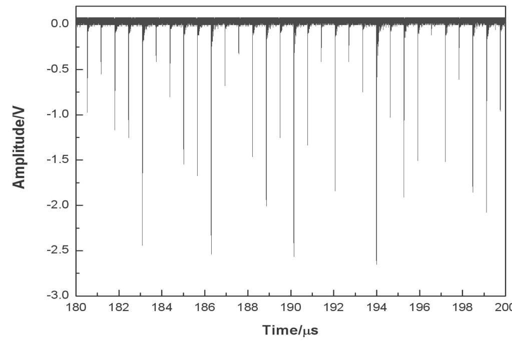


Fig. 14. Single ion signal in CSRe from the ToF target.

6 Summary

With two years commissioning of HIRFL-CSR, it proves that the complex of two cyclotrons and a double cooling-ring synchrotron system is successful. And for this combination many functions have been realized, including, STI, e-cooling with hollow e-beam, MMI, cooling stacking, synchrotron ramping by the varying-harmonic, fast extraction, single-turn injection, isochronous lattice mode and RIBs mass measurement.

References

1 XIA J W, RAO Y N, YUAN Y J et al. HIRFL-CSR PLAN. In: The 6th China-Japan Joint Symposium on Accelerators for Nuclear Science and Their Applications. Chengdu: Academic Press, 1996. 24—27

2 WEI B W. IEEE, 1989, Particle Accelerator Conference: 29—33

3 XIA J W, ZHAN W L, WEI B W et al. NIM A, 2002, **488**: 11—25