HIRFL-CSR FACILITY*

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Abstract

CSR is a new ion cooler-storage-ring system at IMP (Institute of Modern Physics) in China Lanzhou. It consists of a main ring (CSRm) and an experimental ring (CSRe). The two existing cyclotrons SFC (K=69) and SSC (K=450) of the Heavy Ion Research Facility in Lanzhou (HIRFL) is used as its injector system. The heavy ion beams from the cyclotrons is injected first into CSRm for the accumulation with e-cooling. After the acceleration, beam is fast extracted to the CSRe for the internal-target experiments and mass measurements of radioactive ion beams (RIBs). Or it is extracted slowly for external-target experiments including cancer therapy application. In 2005 the CSR construction was completed, and the commissioning activities were performed from 2006 to 2008. The commissioning is successfully completed. For the carbon beam, 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 accelerating from 7MeV/u to 1000MeV/u with the RF harmonic-number changing at the mid-energy were performed. For the heavier ion beams such as Ar, Kr and Xe beams, the multiple multi-turn injection (MMI) and the beam accumulation with MMI and e-cooling for heavy-ion beams of Ar, Kr and Xe, the fast and slow extraction from CSRm were completed. In the commissioning of CSRe, the RIBs mass-measurement experiment with the isochronous mode with use of the time-of-flight method.

HIRFL-CSR DESCRIPTIONS[1]

CSR is a double cooler-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 of SFC+SSC is 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 are used for ion-beam accumulation and cooling.

The beam parameters and the major machine parameters of CSR are listed in Table 1.

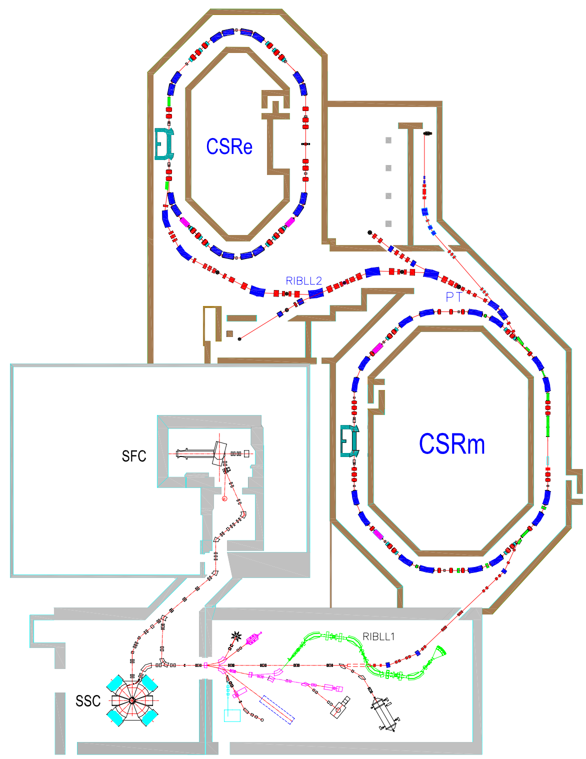

Figure 1: Overall layout of HIRFL-CSR.

Table 1: Major Parameters of the CSR

	CSRm	**CSRe**
Circumference (m)	161.00	128.80
Ion species	p -U	p - U
Max. energy (MeV/μ)	1100 (C^{6+})	500 (U^{90+})
$B\rho_{max}$ (Tm)	12.05	9.40
B_{max} (T)	1.6	1.6
Ramping rate (T/s)	0.1--0.4	0.1--0.2
E-cooler		
Ion energy (MeV/μ)	7--50	10--500
Length (m)	4.0	4.0
RF system	Accel.	Decel.
Harmonic number	1, 2, 4	1, 2
f_{min}/f_{max} (MHz)	0.24 / 1.81	0.4 / 2.0
Voltages ($n \times$ kV)	1×7.0	2×8.0
Vacuum pressure (mbar)	3.0×10^{-11}	3.0×10^{-11}

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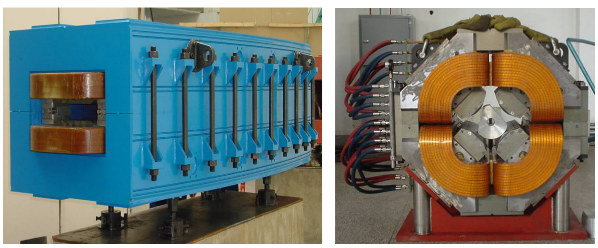
MAJOR SUBSYSTEM AND KEY DEVICE

Magnet

All magnet cores of CSR were laminated of 0.5mm-thick sheets of electro-technical steel with high induction and cold-rolled isotropy. Coils were made of T2 copper conductor insulated by polyimide stick hollow tape and vacuum epoxy resin impregnating. In order to reach to the requirement of field uniformity at the different levels of the range of 1000Gs~16000Gs, a so-called modified H-type dipole was designed for CSRm. In CSRe the C-type dipole with large useful aperture were adopt for physics experiments. Figure 2 shows the magnets of CSR.



a) Dipole of CSRm. b) Quadruple of CSRm.

Figure 2: The magnets of CSR.

Power Supply

The power supply of the ring magnets needs DC and pulse operation modes, accompanying with the high current stability of 10^{-4}/8h, low current ripple of 10^{-5}, good dynamic characteristic and small tracking error of 10^{-4} during ramping. Two types of supply, traditional multi-phase thyristor rectifier for dipoles and switching mode converter for quadruples, were adopted. Figure 3 shows the power supply system of CSRm.

Figure 3: The power supply system of CSRm.

Ultra-High Vacuum System

The vacuum system of CSR is divided into four parts, the two storage rings of CSRm and CSRe, and two beam lines. The pressure of 5×10^{-12} mbar (N2 equivalent) is required in CSRm and CSRe, and 1×10^{-9} mbar is necessary for the beam line. For CSR UHV system, the chambers and flanges were made of stainless steel of 304 or 316L and 316lN respectively. Titanium sublimation pump and sputter ion pump were chosen as the main pumps. The bake-out temperature is 250^0C, and all the components of the two rings will be equipped with permanent back-out jackets. The dipole and quadruple chambers were heated by coaxial heaters with an out-diameter of 2 mm. A special insulation material (Micro-herm) is used for these chambers to avoid thermal loss and protect the magnet coils from damage. This insulation layer will keep the outside temperature lower than 80^0C with the thickness of 3~5 mm. Figure 4 shows the UHV back-out jacket for the dipole chamber.

Figure 4: The UHV back-out jacket for dipole chamber.

Electron Cooler

Two e-coolers were equipped in CSRm and CSRe respectively. In CSRm e-cooling is used for the beam accumulation at the injection energy range of 7-25 MeV/u. In CSRe e-cooling is used to compensate the growth of beam emittance during internal-target experiments or to provide high-quality beams for the high-resolution mass measurements of nuclei. For the two e-coolers, the hollow e-beam can be obtained to partially solve the problem due to space charge effect and reduce the effect of recombination between the ions and the e-beam. Figure 5 shows the e-cooler of CSRm and the hollow e-beam.

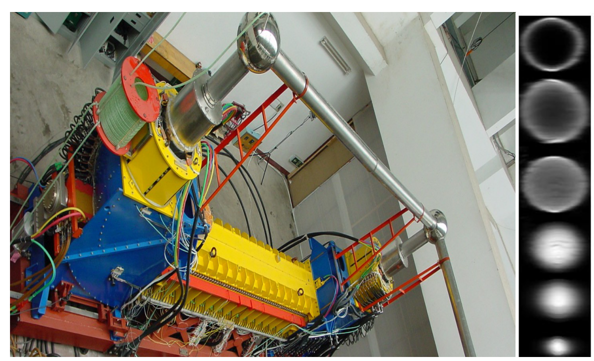


Figure 5: The e-cooler of CSRm and the hollow e-beam.

RF System

One RF cavity is used for the accelerating beam in CSRm. After beam accumulation, the heavy ion beams will be accelerated by the accelerating cavity from the low energy range of 7-25 MeV/u to the high-energy range of 100-1000MeV/u with the harmonic number of 1 or 2. In CSRe two identical RF cavities were installed in two drift sections, which will be used for beam capture, bunching, de-bunching and deceleration with harmonic number of 1 or 2. The three RF cavities are ferrite-loaded coaxial resonators, and the resonance frequency is controlled by tuning the magnetic biasing current of ferrite. Figure 6 displays the RF system of CSRm.

Figure 6: The RF system of CSRm.

Electric-Static Septum

3 electric-static septum (ES) are used in CSRm, one is for the multi-turn injection, and other two were used for the slow extraction. For those ES, the thickness of the septum is only 0.1mm, and was made of several hundreds of wolfram silks shown in Fig. 7. The high voltage can be reach to 160KV with the gap of 23mm.

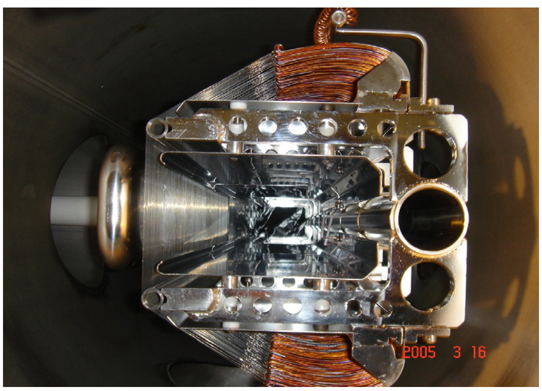


Figure 7: The electric-static septum of CSR.

Kicker

The fast-extraction from CSRm and single-turn injection to CSRe were realized by using two fast-pulse kickers with the rising time or falling time of 150ns and peak current of 2700A. Figure 8 shows the kicker of CSRm.

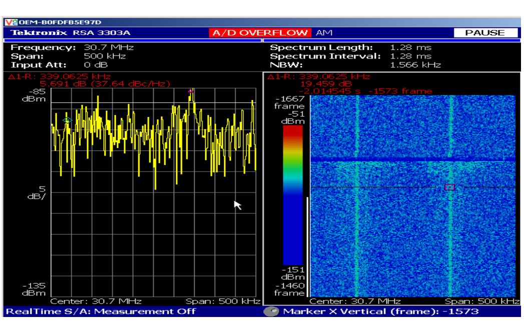
Figure 8: The fast-pulse kicker of CSRm.

COMMISSIONING OF CSRM

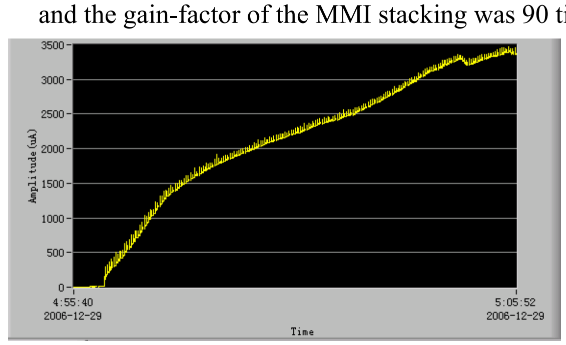
E-Cooling and Heavy Ion Accumulation

In the winter of 2006 the electron-cooling was started in CSRm, and the momentum spread of the C-beam with the energy of 7MeV/u was reduced from 10^{-3} to 10^{-4}. Figure 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 were accumulated to high intensity. Figure 9 (b) shows the intensity increase in CSRm during the cooling-stacking of C-beam in DCCT. The injection current from cyclotron SFC was 10.2μA, and after 8 minutes the C-beam intensity in CSRm was reached to 3.2mA, and the beam gain-factor for the accumulation was reached to 300 times.

In the spring of 2007 the multiple multi-turn injection (MMI) was successfully achieved for the beam of $^{36}Ar^{18+}$-22MeV/u with the hollow e-beam cooling in CSRm. Adopting the combination of MMI and e-cooling, Ar-beam was accumulated to high intensity. Figure 9 (c) shows the Ar-beam Schottky signal in the spectrum analyser during the MMI. The blue signal is the beam for one multi-turn injection, and yellow one is for the beam of MMI. Figure 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 eμA. After 2 minutes the Ar-beam intensity in CSRm was reached to 180 eμA, and the gain-factor of the MMI stacking was 90 times.

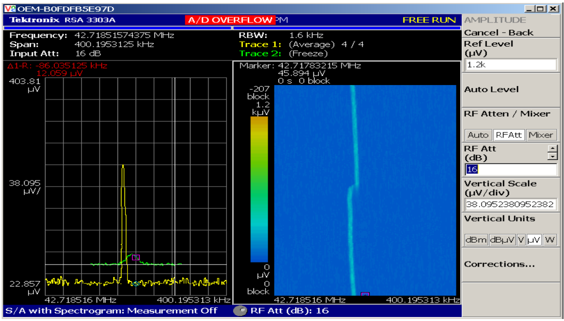


(a) C-beam Schottky signal with e-cooling.

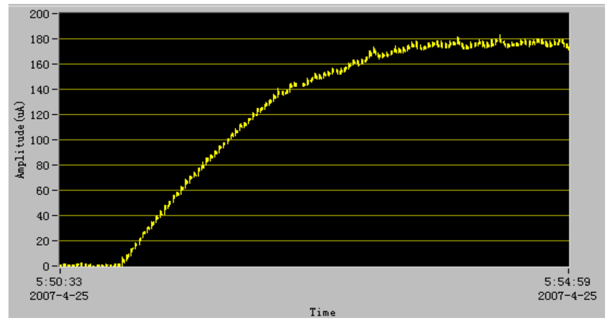


(b) C-beam accumulation with STI + e-cooling.

Figure 9 (a,b): The beam cooling and accumulation in CSRm.



(c) Ar-beam Schottky signal during MMI.

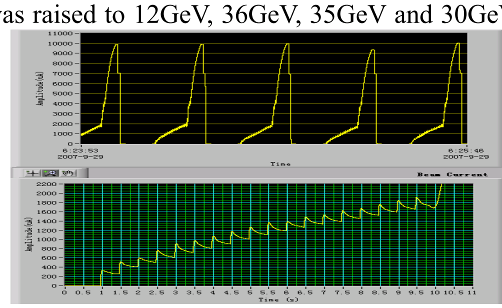


(d) Ar-beam accumulation with MMI + e-cooling.

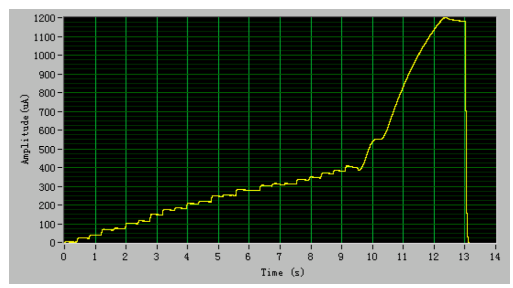
Figure 9 (c,d): The beam cooling and accumulation in CSRm.

Combination of Cooling-Stacking and Ramping

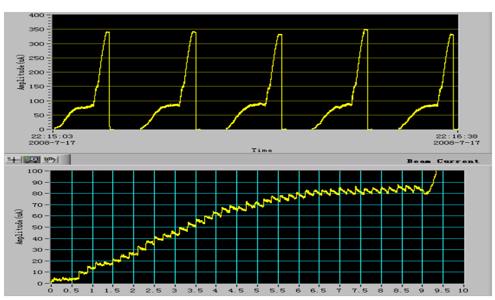
In 2007 based on the success of STI, e-cooling, MMI, varying-harmonic ramping and cooling stacking, the combination between cooling-stacking and synchrotron ramping for heavy ions was realized. With the wide energy-range accelerating by varying the RF harmonic-number at the mid-energy of 50MeV/u, the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



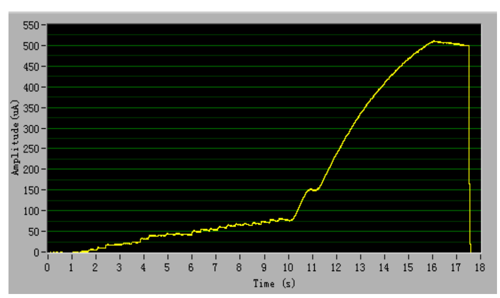
(a) C-beam current during STI + e-cooling and ramping.



(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.

Figure10: The heavy-ion beam accumulation and ramping in CSRm.

COMMISSIONING OF CSRE

Beam Cooling in CSRe

In the autumn of 2007, C-beam was fast extracted from CSRm and single-turn injected into CSRe. The stored C-beam reached to 15mA. In April of 2009, 200 MeV C-beam of 100 eμA was stored and cooled in CSRe. The momentum spread reduced from 9×10^{-4} to 7.5×10^{-5} after cooling. The longitudinal Schottky signal from spectrum analyzer was shown in Fig. 11.

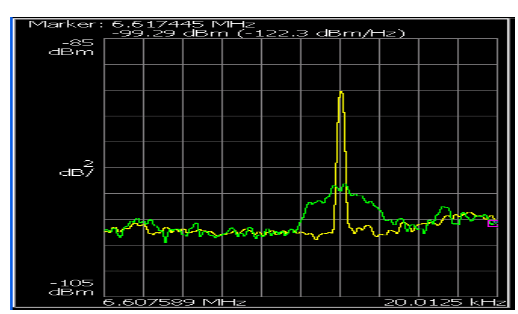


Figure11: Schottky signal of cooled C-beam in CSRe.

Isochronous Mode in CSRe

In 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 to the momentum spread of beam. Figure 12 shows the Ar-beam frequency spread with the energy of 368MeV/u at the CSRe isochronous mode, and the frequency spread $\Delta f/f$ reached to 8×10^{-7}.

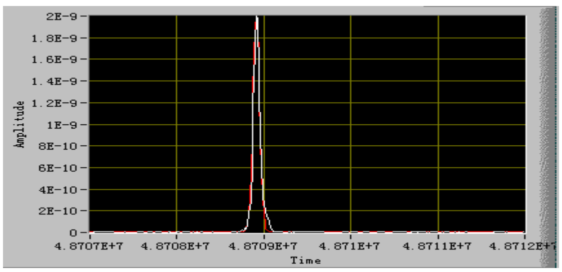


Figure 12: Δf/f of beam at the CSRe isochronous mode.

RIBs Mass Measurement Experiment in CSRe

In the end of 2008 and the beginning of 2009, a RIBs mass measurement experiment was made in CSRe. During this experiment, the primary beam of $^{78}Kr^{28+}$ was accelerated first to the energy of 481.88MeV/u in CSRm, and then extracted fast to the primary target in the beam line RIBLL2 in order to produce RIBs. Those secondary beams were accepted and stored by CSRe, and then detected by the time-of-flight method. Figure 13 shows the RIBs mass-measurement result in CSRe. For this experiment, the mass of the 3 drop-line nuclei of ^{63}Ge, ^{65}As and ^{67}Se with the life-time of nearly 100ms were measured, and the mass-resolution $\Delta m/m$ was reached to 10^{-6}.

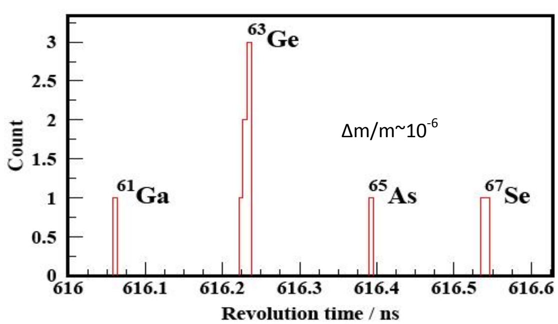


Figure 13: The RIBs mass-measurement result in CSRe.

SLOW EXTRACTION FROM CSRM

Slow Extraction of 1/3 Resonance

In the beginning of 2008 the slow extraction of 1/3 resonance from CSRm for the beam of $^{36}Ar^{18+}$-368MeV/u was realized, and the extraction beam-time was continued to 1.2 seconds for each pulse. In the summer of 2008 the intensity, stability and uniformity of the slow-extracted beam were improved. Figure 14 shows the slow-extraction signal for the beam of $^{12}C^{4+}$-300MeV/u from the scintillation crystal monitor (SCM), and the extraction beam-time was continued to 3 seconds. This result is the foundation of the heavy-ion cancer therapy by using CSRm.

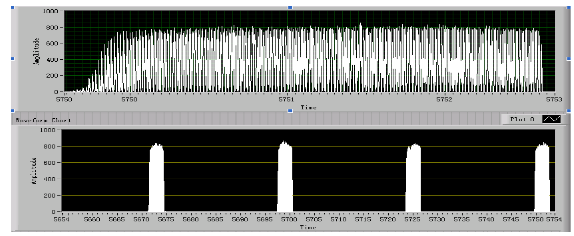
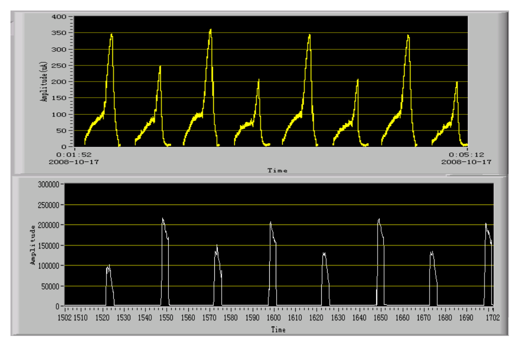


Figure14: The slow-extraction for the beam of $^{12}C^{4+}$.

Varying-Energy Slow Extraction

In the autumn of 2008, the varying-energy slow extraction was realized. During the resonance slow-extraction, the beam energy of each cycle can be changed. Figure 15 shows the slow-extraction signal of C^{4+}-beam with two energy of 150MeV/u and 300MeV/u. (a) is the DCCT beam signal in CSRm, and (b) is the slow-extraction beam signal from the scintillation crystal monitor. Figure 16 is the results of bragg-peaks test in water with 5 energy-values at the cancer therapy terminal.



(a)

(b)

Figure 15: The slow-extraction for two energy-values.

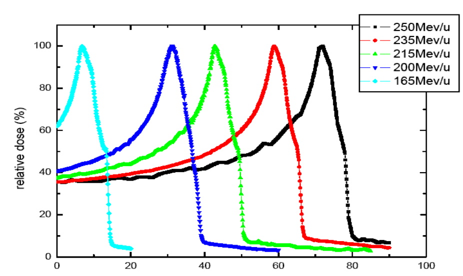


Figure16: The Bragg-peaks in water for 5 energy-values.

REFERENCES

[1] J.W.Xia, W.L.Zhan, B.W.Wei, et. al., The Heavy ion Cooler-Storage-Ring Project (HIRFL-CSR) at Lanzhou, NIM A 488(2002) 11-25.