LANZHOU COOLER STORAGE RING COMMISSIONING*

J.W. Xia#, Y.J. Yuan, J.C. Yang, Y. Liu, L.J. Mao, R.S. Mao and CSR group
Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS)
P.O. Box 31, Lanzhou, 730000, P.R. China

Abstract
HIRFL-CSR is a new series-accelerator complex with two cyclotrons and two cooler-storage-rings at IMP. It has recently made significant progress in commissioning a variety of light to heavy ion in the cooler ring system. Also, carbon therapy was successfully carried out. A significant operation is the energy modulation slow extraction realizing tumor patient treatment.

HIRFL-CSR DESCRIPTIONS

As shown in Fig.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.

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 CSRe for 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 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. Fig.2 and Fig3 are the tunnels of CSRm and CSRe.

Table 1 Major parameters of the CSR

<table>
<thead>
<tr>
<th></th>
<th>CSRm</th>
<th>CSRe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>161.00</td>
<td>128.80</td>
</tr>
<tr>
<td>Ion species</td>
<td>p -U</td>
<td>p – U</td>
</tr>
<tr>
<td>Max. energy (MeV/μ)</td>
<td>1100 (C⁶⁺)</td>
<td>500 (U⁹⁰⁺)</td>
</tr>
<tr>
<td>Bp max (Tm)</td>
<td>12.05</td>
<td>9.40</td>
</tr>
<tr>
<td>Bmax (T)</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Ramping rate (T/s)</td>
<td>0.1–0.4</td>
<td>0.1–0.2</td>
</tr>
</tbody>
</table>

E-cooler

<table>
<thead>
<tr>
<th></th>
<th>Acceleration</th>
<th>Deceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion energy (MeV/μ)</td>
<td>7–50</td>
<td>10–500</td>
</tr>
<tr>
<td>Length (m)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>1, 2, 4</td>
<td>1, 2</td>
</tr>
<tr>
<td>fmin/fmax (MHz)</td>
<td>0.24 / 1.81</td>
<td>0.4 / 2.0</td>
</tr>
<tr>
<td>Voltages (n × kV)</td>
<td>1 × 7.0</td>
<td>2 × 8.0</td>
</tr>
<tr>
<td>Vacuum pressure (mbar)</td>
<td>3.0 × 10⁻¹¹</td>
<td>3.0 × 10⁻¹¹</td>
</tr>
</tbody>
</table>

COMMISSIONING OF CSRM

E-cooling and heavy ion accumulation

The commissioning of CSR was started in the spring of 2006. In that winter the electron-cooling was began to the working in CSRm, and the momentum spread of the C-beam with the energy of 7MeV/u was reduced from 10⁻³ to 10⁻⁴. Fig. 4 (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 was accumulated to high intensity. Fig. 4 (b) shows the intensity increase in CSRm during the cooling-stacking for 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.

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#xiajw@impcas.ac.cn
In the spring of 2007 the multiple multi-turn injections (MMI) was successfully achieved for the beam of 36Ar\textsuperscript{18}\textsuperscript{+}-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. Fig 4 (c) shows the Ar-beam Schottky signal in the spectrum analyser during the MMI. The blue signal is the beam for once of multi-turn injection, and yellow one is for the beam of MMI. Fig. 4 (d) is the DCCT beam signal of the cooling-stacking for Ar-beam, the injection current from the two cyclotrons SFC+SSC was 2 \( \mu \text{A} \). After 2 minutes the Ar-beam intensity in CSRm was reached to 180 \( \mu \text{A} \), 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.

(c) Ar-beam Schottky signal during MMI.

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

Figure 4: 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, 0.8mA and 0.5mA respectively by the stacking of MMI + e-cooling. Fig. 5 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$^{27+}$.

![Figure 5: The heavy-ion beam accumulation and ramping in CSRm.](image)

COMMISSIONING OF CSRE

Beam stored in CSRe

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 150ns and peak current of 2500A. At 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 660MeV/u was stacked further by using the multiple single-turn injection in CSRe, and the C-beam current was reached to 15mA, shown in Fig. 6.

![Figure 6: C-beam was stacked to 15mA in CSRe.](image)

Beam cooling in CSRe

In April of 2009, the C-beam of 400 MeV/u with the current of 1000 eμA was stored and cooled in CSRe. The momentum spread reduced from ±1.6×10^{-4} to ±1.5×10^{-5} after e-cooling. The longitudinal Schottky signal from spectrum analyzer was shown in Fig. 7, and the Schottky signal width of beam became narrow during the cooling.

![Figure 7: Beam Schottky signal during e-cooling.](image)
Fig. 8 is the momentum spread and the beam size of C-beam before and after cooling. After the cooling the beam size became very small. Considering with the beta-function of 8m in the measurement point, the beam emittance was cooled down to 0.03π mm-mrad.

![Momentum spread and beam size comparison](image1.png)

**Figure 8-a):** Momentum spread before and after cooling.

**Figure 8-b):** Beam size before and after cooling.

**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 equal to the energy γ of beam. In this case the revolution frequency of ions is independent to the momentum spread of beam. Fig. 9 shows the Ar-beam frequency spread with the energy of 368MeV/u at the CSRe isochronous mode, and the frequency spread Δf/f reached to 8×10^{-7}.

![Isochronous mode diagram](image2.png)

**Figure 9: Δf/f of beam at the CSRe isochronous mode.**

**EXPERIMENTS IN CSR**

**RIBs mass measurement experiment in CSR**

In the 2008 and 2009, the RIBs mass measurement experiments were 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. The experiment layout was shown in Fig.10, and Fig. 11 shows the RIBs mass-measurement result in the range of A=2Z-1. For this experiment, the mass of the 9 drop-line nuclei of $^{43}$V, $^{49}$Fe, $^{52}$Ni, $^{56}$Co, $^{63}$Cu, $^{65}$As, $^{67}$Se and $^{71}$Kr with the life-time of nearly 100ms were measured, and the mass-resolution Δm/m was reached to the range of 3×10^{-6}~1×10^{-7}.

![RIBs experiment layout](image3.png)

**Figure 10: The RIBs experiment layout in CSR.**

![RIBs massmeasurement result](image4.png)

**Figure 11: The RIBs mass-measurement result in CSRe.**

**Atomic physics experiment with internal target**

In the beginning of 2010, an experiment on radioactive electron capture (REC) was done with the internal target in CSRe. During this experiment Xe$^{27+}$-beam was first accelerated to 200MeV/u in CSRm, and then fast
extracted to be stripped to Xe$^{54+}$, finally injected to CSRe. In CSRe the Xe$^{54+}$-beam with the energy of 197MeV/u crossed with the N$_2$-jet produced by the internal target. Fig.12 is the angle-distribution of x-ray emitted during the REC.

**CANCER THERAPY WITH C-BEAM**

*Slow extraction of 1/3 resonance*

In the beginning of 2008 the slow extraction of 1/3 resonance from CSRm was realized. Fig. 13 shows the slow-extraction signal for the beam of $^{12}$C$^{6+}$-200MeV/u from the DCCT in CSRm and the anode-stripped ionization chamber (AIC) in the therapy terminal. The extraction beam-time was continued to 1~5 seconds for each pulse.

*Uniform scanning and point scanning*

During the beam acts on tumour, two scanning modes are used. The first mode is the uniform scanning, the slow-extraction C-beam was first sent to the cancer therapy terminal to focus a 3mm-spot, then scan the beam at the xy-plan with a uniform distribution. Fig.14 shows the beam distribution for the uniform scanning. The second one is the point scanning. For this mode the beam spot can first stop at one point of tumour, once the dose reach to the calculation value, then move the beam-spot to next tumour point. Fig.15 is the dose distributions in 2D and 3D for the point scanning on the terminal.

From 2008 to 2009, the treatments for 8 patients were done, and up to now, the 90% of those tumours have been vanished.

*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. Fig.16 is the results of bragg-peaks test in water with 5 energy-values at the cancer therapy terminal.

**REFERENCES**