RESULTS FROM LANZHOU K450 HEAVY ION CYCLOTRON

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Abstract

The heavy ion research facility at Lanzhou (HIRFL) consists of a K69 sector focusing cyclotron SFC as the injector and a K450 separated sector cyclotron SSC as the main accelerator. Any ions from C to Ta can be accelerated and the maximum energies are ranged from 5 MeV/u to 125 MeV/u. As of May 1987 the injector SFC has been put into operation. The beam of C6+ was accelerated up to the outermost radius of SSC on December 8, 1988. The results from HIRFL are discussed in this report.

Introduction

The 1.5m conventional cyclotron designed by USSR was starting to be assembled in IMP in 1960 and put into operation in 1963. During 1960s, it was mainly used for fast neutron physics study and radioisotope production by using the extracted proton, deuterium and a-particle beams. Since IMP started to do researches on heavy ion nuclear physics at the beginning of 1970s, the experimental work has been done on this cyclotron modified to accelerate carbon, nitrogen and oxygen ions to energies of about 73, 105 and 85 MeV respectively. As the further development of heavy ion physics requires much modern facilities, the possibility of building a new heavy ion research facility in Lanzhou (HIRFL) was therefore surveyed. The idea of using the existing cyclotron converted to 1.7m sector focusing cyclotron (SFC) as the injector and constructing a new separated sector cyclotron (SSC) as the main accelerator was soon taking shape. The main goal of this project in set as follows:

- acceleration of ions from carbon to xenon with maximum energies of about 100 MeV/u for light ions (C-, N-, O-, Ne-) and 5 MeV/u for Xe-;
- beam intensity ranging from 10^12 pps for light ions to 10^10 pps for heavier ions;
- energy resolution being about 10^-3;
- beam emittance being about 4π mm mrad.

The results from HIRFL are discussed in this report.

By using the ECR ion source as an external ion source of SFC, the acceleration of ions can be expanded from Xe to Ta and the maximum energy can be reached up to 125 MeV/u.

As of May 1987 the injection SFC has been put into operation. The beam of C6+ was injected into SSC in June of 1988 and reached up to the outermost radius on December 8. We succeeded to extract the beam from SSC on Dec. 12, 1988.

HIRFL Scheme and Parameters

The HIRFL scheme and parameters have been described in previous publication[1], let me however recall the main points.

Figure 1 shows the general layout of HIRFL. It consists of following main parts:
- an injector SFC with energy constant K-69
- a main accelerator SSC with energy constant K-450
- 60m beam line from SFC to SSC
- experimental areas and concerning beam lines.

Table 1 gives the main parameters of HIRFL. The ion source of SFC is internal FLC type at present operation. An ECR ion source is now under testing in the cyclotron laboratory of IMP. It will be mounted in the basement under the SFC vault and used as an external ion source for SFC. The use of high change state heavy ion source will be able to expand the beam variety and energy range of HIRFL. Figure 2 gives the
Table 1: Main parameters of HIRFL

<table>
<thead>
<tr>
<th>Orbit parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection mean radius</td>
<td>1.00m</td>
</tr>
<tr>
<td>Extraction mean radius</td>
<td>1.21m</td>
</tr>
<tr>
<td>Radial betatron frequency</td>
<td>1.087-1.202</td>
</tr>
<tr>
<td>Vertical betatron frequency</td>
<td>0.742-0.864</td>
</tr>
<tr>
<td>Sector magnet</td>
<td></td>
</tr>
<tr>
<td>Number of sectors</td>
<td>4</td>
</tr>
<tr>
<td>Sector angle</td>
<td>52°</td>
</tr>
<tr>
<td>Magnet gap</td>
<td>10cm</td>
</tr>
<tr>
<td>Maximum field</td>
<td>16kG</td>
</tr>
<tr>
<td>Number of trim coil</td>
<td>36</td>
</tr>
<tr>
<td>Radio frequency</td>
<td></td>
</tr>
<tr>
<td>Frequency range</td>
<td>6.5-14MHz</td>
</tr>
<tr>
<td>Number of Dee</td>
<td>2</td>
</tr>
<tr>
<td>Dec angle</td>
<td>30°</td>
</tr>
<tr>
<td>Peak voltage</td>
<td>100-250kV</td>
</tr>
<tr>
<td>RF power</td>
<td>240kW</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>2-10</td>
</tr>
<tr>
<td>Accelerating aperture</td>
<td>5cm</td>
</tr>
<tr>
<td>Q-value</td>
<td>6000-10000</td>
</tr>
<tr>
<td>Coupling loop impedance</td>
<td>20-100kH</td>
</tr>
</tbody>
</table>

Vacuum:
- Volume of the vacuum chamber: 100 m³
- Operating pressure: 1.3×10⁻³ Pa
- Total gas load: 1.8×10⁻³ Pa m³ s⁻¹
- Effective pumping speed: 1.4×10² m³ s⁻¹

Buncher:
- Frequency range: 26-56MHz
- Harmonic number: 4
- Peak voltage: 70kV
- Number: 2

Injector SFC
- Number of sectors: 3
- Spiral angle: 33°
- Pole diameter: 170cm
- Extraction radius: 75cm
- Maximum mean magnetic field: 16kG
- Circular coil: 12 pairs
- Valley coil: 4x3 pairs
- Dee number: 1
- Dee angle: 180°
- Frequency range: 6×18MHz
- Peak voltage: 100kV
- RF power: 200kW
- Vacuum: 5×10⁻⁶ torr

Fig.2: The maximum energy vs. mass number of HIRFL.
I  SFC+PAC ion source
II SFC+SSC+PAC ion source
III SFC+ECR ion source
IV SFC+SSC+ECR ion source

maximum energy per nucleon vs mass number of HIRFL with and without ECR ion source. With an ECR ion source, HIRFL can accelerates, for example, tantalum ion to the energy of above Coulomb barrier for heavy ion nuclear collisions and light heavy ions, for example, carbon ion to the energy of 125 MeV/u.

The beam diagnostic system of HIRFL consists of diagnostic elements such as Faraday cups, slits, secondary emission multiwire chambers, centre phase probes, radial differential probes and position probes and measuring units such as beam energy measurements and beam emittance measurements act as an important role in the beam tuning and beam optimization.

The control system of HIRFL is based on CAMAC distributed intelligent control. The local control stations are designed according to HIRFL's subsystems such as injector, beam line, injection and extraction, magnet, vacuum, rf, diagnosis and measuring units. They are linked by CAMAC serial dataway and driven by master computer through CAMAC auxiliary crate controller then to realize CAMAC communication. In these stations, all the power supplies are controlled by microprocessors and the positioning devices are controlled by stepping motors or pneumatic units.

Two VAX-8350 computers, each having 12 MB memories and sharing 4×520 MB disk group and 2×300 MB removable disk mass storage cluster, with comfortable peripheral equipment have been installed on sites in the central control room of HIRFL. One of them is used as a master computer for HIRFL control system. Another one is used as a reserve computer when the former one is in fault. Additionally, it is also used for calculations and off-line data processing for the experiments carried out in the experimental areas.

The main console in the central control room consists of storage oscilloscope, signal observation and seven touch panels.
Paralleling to the main beam line from SFC to SSC, another two auxiliary experimental areas have been arranged and planned:

-first area: The beam extracted from SFC is guided into a 1 m diameter scattering chamber after going through about 10 m beam line. The experiments could be done in this area only in the case of no beam going through the main beam line.

-second area: After stripping, the beam with higher electric charge states can be guided into some experimental equipment. The useful beam for SSC acceleration with suitable electric charge states is still going through the main beam line. So that, both of the experiments could be done in this area and in the main experimental area at the same time.

A PDP11/44 computer with 4MB memories, 10MB and 456MB disks and comfortable peripherals is used for data acquisition for the experiments carried out in these two auxiliary areas. The counting room and PDP11/44 computer room are just behind the first area (see figure 1).

Main Experimental Area

The arrangement of the main experimental area of HIRFL including the post beam line is given in figure 1.

Experimental equipment

1. Isotope separator

The main parameters of the isotope separator is given as follows:

- Angle: 54.7°
- Curvature radius: 150 cm
- Magnetic field: 4 kG
- Gap: 6 cm
- Mass dispersion: 7.5 mm (for M=200)
- Maximum separation mass: 250
- Resolution: M/ΔM 1000
- High voltage: 50 kV
- Minimum lifetime: 100 mc

It will be used for short lifetime nuclide measurement on-line and long lifetime nuclide measurement off-line.

2. In beam γ-ray measuring devices

The in-beam γ-ray measuring devices consists of 8 sets of HPGe γ-ray detectors, 6 sets of BGO/NaI anticompton spectrometers and 14 pieces of hexagonal-shape BGO as a crystal ball used for γ-multiplicity filter. It will be used for nuclear structure and reaction mechanism research.

3. Heavy ion telescope

It is a combination system including a ΔE-E telescope and a time of flight apparatus. The resolutions of the heavy ion telescope is as follows:

- Δt: 200-300 ps
- ΔE/E: 0.01
- ΔE resolution: 0.05
- Z/ΔZ: 10-50
- A/ΔA: 60-80

4. Large area position sensitive ionization chamber

It includes PPAC plastic hodoscopes, ΔE-E detectors, γ-detectors and three kinds of ionization chambers. The ionization chamber will have the following resolutions:

<table>
<thead>
<tr>
<th>Window</th>
<th>140cm IC</th>
<th>80cm IC</th>
<th>35cm IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>40x20 cm²</td>
<td>40x20 cm²</td>
<td>25x5 cm²</td>
<td></td>
</tr>
<tr>
<td>ΔE/E</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Z/ΔZ</td>
<td>60</td>
<td>40-50</td>
<td>40</td>
</tr>
<tr>
<td>A/ΔA</td>
<td>2 mm</td>
<td>2 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>Δt</td>
<td>250ps</td>
<td>250ps</td>
<td>250ps</td>
</tr>
</tbody>
</table>

It is designed mainly for the intermediate energy heavy ion nuclear physics such as the inclusive experiments and the coincidence measurements between particle, γ-ray and fragments.

5. Cylindrical scattering chamber

It has following parameters:

- Diameter: 2.8 m
- Length: 8 m
- Minimum detectable angle: 1°
- Maximum flight distance: 6.5 m

Two kinds of detectors will be used in this chamber. One is fission fragment detector including the two dimension position sensitive PPAC and Brage curve ionization chambers. Another one is light particle detector using the one dimension position sensitive plastic scintillators.

6. Fast chemistry separation apparatus

It includes the liquid phase fast chemical separation device (1 second) and the gas phase fast chemical separation device with the He-jet transport system. It will be mainly used for the nuclear decay research of short lifetime nuclides and the syntheses of neutron deficient nuclides.

7. Equipment for atomic physics study

It consists of two parts. First part is a beam-foil spectroscopy used for the mean lifetime measurements of some atomic energy levels and the Rydberg state population probability. Second part is used for the studies of heavy ion atom collisions, mainly on the production mechanism of the inner shell vacancies during the collision.

8. Irradiation equipment

It consists of beam uniformity unit, beam monitor and irradiation chambers. A magnetic sweeping system has been designed to produce a beam size of 50x50 mm² with about 5% variation in uniformity. The irradiation temperature will
be controlled in the range of 4°K-800°K with an accuracy of 0.5°K. The chilling power is about 7 W at 10°K and 5 W at 20°K. It will be used for the studies of solid state physics, material science and biomedical irradiations.

Post beam line

The beam extracted from SSC going through a 66° D-magnet and the Q-magnets forms a double waist at the slit before guiding into the experimental hall. Regarding to it as starting point, the beam is delivered to each target position, where a beam spot size of 4 mm in diameter is available.

Two achromatic and double telescopic systems are employed as subsystem in the post beam line design. When beam goes through such a system, a waist in beam envelope at its beginning is reproduced as the same waist at its end both horizontally and vertically. Furthermore, the overfocusing effects are also avoided.

Operation of SFC

Figure 3 shows the schematic diagram of the injector SFC. It has been operated for more than one year. Table 2 gives the extracted ions and the concerning operating conditions. Three experiments title of the shadowing effect of emitted α-particles in the heavy ion reaction, the incomplete fusion fission reaction and the chemical research of complete and incomplete fusion reaction have been done.

The SFC's one year operation is quite satisfactory, however, as a part of the cyclotron components are too old, some renewal work has been planned. A pair of main coil of the cyclotron magnet together with the regulated rectifier DC power supply has been fabricated and tested and it will be put into operation on site this year.

Table 2: The operating parameters of SFC.

<table>
<thead>
<tr>
<th>Ion</th>
<th>12C⁴⁺</th>
<th>16O⁵⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>f(MHz)</td>
<td>7.1</td>
<td>7.1</td>
</tr>
<tr>
<td>B(kG)</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>V&lt;sub&gt;acc&lt;/sub&gt;(kV)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>V&lt;sub&gt;f₁&lt;/sub&gt;(kV)</td>
<td>56</td>
<td>58</td>
</tr>
<tr>
<td>V&lt;sub&gt;f₂&lt;/sub&gt;(kV)</td>
<td>60</td>
<td>63</td>
</tr>
<tr>
<td>I(eva)</td>
<td>1.1</td>
<td>1.4</td>
</tr>
<tr>
<td>E(MeV/u)</td>
<td>5.9</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Beam tuning of SSC

Figure 4 shows the schematic diagram of the main accelerator SSC. The main characteristics of the beam for beam tuning are summarized in table 3.

Table 3: The main characteristics of the beam for tuning.

<table>
<thead>
<tr>
<th>Ion</th>
<th>SFC</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass number A</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Charge state Z</td>
<td>4+</td>
<td>6+</td>
</tr>
<tr>
<td>Revolution frequency f&lt;sub&gt;rev&lt;/sub&gt;(MHz)</td>
<td>6.262</td>
<td>4.697</td>
</tr>
<tr>
<td>Radio frequency f&lt;sub&gt;r&lt;/sub&gt;(MHz)</td>
<td>6.262</td>
<td>9.394</td>
</tr>
<tr>
<td>Harmonic number h</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Maximum magnetic field B(kG)</td>
<td>12.270</td>
<td>10.735</td>
</tr>
<tr>
<td>Beam energy E (MeV/u)</td>
<td>4.5</td>
<td>50</td>
</tr>
<tr>
<td>Matching efficiency η (%)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Beam intensity I (na)</td>
<td>1000</td>
<td>30</td>
</tr>
</tbody>
</table>

Fig. 3: Schematic diagram of the injector SFC.

Fig. 4: The schematic diagram of the main accelerator SSC.
The extracted beam intensity from SFC is about lua. The preliminary result of the beam line tuning shows that the transmission efficiency from the exit of SFC to the entrance of SSC for C⁴⁺ beam (C⁶⁺ after stripping) is about 50%. That means that about 500nA of C⁵⁺ beam could be reached to the entrance of SSC. Then the C⁶⁺ beam was injected into the main accelerator SSC in June of 1988. Though we adjusted all of the electric parameters of the injection system including the steering magnet system, the injection efficiency was only about 10%. Furthermore, the beam always has a big initial amplitude of about 3 cm (upper) contributed to the axial Betatron oscillation. In such a case, we opened the vacuum chamber, adjusted the magnetic channel MS13 to produce a magnetic field of about 50G in the negative radial direction. After this collection we easily got an injection efficiency of about 50%. At that moment, the coupler between the south cavity and rf amplifier of SSC met some trouble and we had to stop for repairing and retesting. Finally, we extracted the 50 MeV/u C⁶⁺ beam from SSC in Dec. 12 of 1988. Figure 5 shows the beam pattern of SSC for the initial turns after injection measured by the radial differential beam probe. The extracted beam intensity from SSC is about 30nA.

Fig. 5: The beam pattern of SSC measured by radial differential probe.

Reference