The Progress of the HIRFL-CSR Project and the Commissioning of the Cluster Target

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Abstract. HIRFL-CSR, a new cooler-storage-ring project, is the post-acceleration system of the Heavy Ion Research Facility in Lanzhou (HIRFL) consisting of a main ring (CSRm) and an experimental ring (CSRe). The construction of the HIRFL-CSR complex is nearing completion. The stored beam in the CSRm has been observed. Recently, the stored beam was accelerated from 7 MeV/u to 30 MeV/u. The cluster target is located in one straight section of the CSRe providing cluster jet targets of inert gases and small molecular gases. The cluster target has been finished and the results of the test running are presented.

1. Introduction

HIRFL-CSR is a multi-purpose cooler-storage-ring system [1] including a main ring (CSRm), an experimental ring (CSRe), and a radioactive beam line (RIBLL2) connecting the two rings, as shown in figure 1. The two existing cyclotrons SFC (K=69) and SSC (K=450) of the HIRFL will be used as its injectors. Heavy ion beams in an energy range of 8–30 MeV/u from the HIRFL will be accumulated, cooled and accelerated to the energy of 1100 MeV/u (¹²C⁶⁺) and 500 MeV/u (²³⁸U⁷²⁺) in the main ring, and then extracted to produce secondary beams (radioactive ion beam or highly charged heavy ions). The secondary beams will be accepted by and stored in the experimental ring for internal-target experiments or for high-precision spectroscopy with beam cooling. The experimental ring CSRe can accept highly charged ions with energies up to 750 MeV/u (¹²C⁶⁺) and 500 MeV/u (²³⁸U⁷²⁺). On the other hand, these beams can also be used for different external-target experiments by using slow or fast extracted ions from the CSRm. The double-ring-system provides flexibility in the production of highly charged ions and of radioactive ion beams, thus offering opportunities for nuclear physics and atomic physics research. Construction and installation of the HIRFL-CSR storage ring complex is nearing completion. The first first-turn commissioning of the CSRm was successfully done at the beginning of 2005. The first stored beam in the CSRm was obtained on January 23, 2006 using 6.897 MeV/u C⁴⁺ as the injected beam in combination with stripping injection mode. A stored beam with a lifetime of more than 10 s was observed by means of Schottky spectroscopy (figure 2). Recently, the stored beam was accelerated from 7 MeV/u to 30 MeV/u.
The first phase experiments at the HIRFL-CSR include the internal target experiments in the CSRm, the external target experiments with RIBLL2 and the internal target experiments in the CSRe. The experiments cover a wide range of hadron physics, radioactive ion beam physics, highly charged atomic physics, high energy density physics, biological medical physics and so on.

There are two internal target devices, one is located in one straight section of the CSRm and another one is located in one straight section of the CSRe. The CSRm internal target is a pellet target [2, 3] which is used to provide a high-density target for hadron physics with a typical thickness of $10^{15} - 10^{16}$ atoms/cm$^2$. The pellet target is developed in collaboration with TLS, Uppsala, Sweden. A laser driven polarized H/D target [4] with an effective target thickness of $10^{14} - 10^{15}$ atoms/cm$^2$ and with a degree of target polarization of ~20%-40% is under consideration for the CSRm.

The CSRe internal target can operate either in an unpolarized mode or in a polarized mode [5]. The unpolarized target is a cluster-jet target and can provide gaseous targets of inert gases and small molecular gases with expected densities of $\geq 10^{12}$ atoms/cm$^2$. The HIRFL-CSR cluster target has been completed and installed to the due position of the ring. Test experiments have been carried out for H$_2$, N$_2$ and Ar gases.
2. Test results of the cluster target
The parameters and the structure of the cluster target have been described in details elsewhere [5]. Only brief description is given here. The cluster target consists of three parts: cluster source, interacting chamber, and the jet dump part. In the cluster source the clusters are produced during the expansion of the gas in the supersonic gas flow region of the nozzle. The cluster beam is formed while passing through a set of skimmers, giving an intense beam with a well bounded intensity profile. To get good clusterization it is necessary to keep the temperature of the nozzle in the range that corresponds to the saturation vapor pressure at given working pressure. The nozzle is therefore placed on the second stage of a cryohead. Its temperature can be varied from 20K to 300K by using a heater wrapped around the nozzle. The heavy ions interact with the gas jet in the interacting chamber. A set of conductance limiter is used along the ring to decrease the gas load produced by cluster evaporation during the ion-cluster collisions so that the vacuum in the ring is not affected considerably. The beam dump consists of three stages and is used to pump away the jet gas and to avoid significant back-streaming. To reduce the pressure in the scattering chamber and to keep the background vacuum of $5 \times 10^{-11}$ mbar of the ring to be nearly unaffected, an effective pumping system is needed. One turbo is served as the backing turbo of the next stage, i.e. the exhaust outlet of the 2nd stage turbo is connected with the 1st stage so the two turbos of the 1st stage can serve as the backing turbos of the 2nd stage. Similar connection way is used for other stages, as shown in figure 3.

Figure 3. Vacuum layout of the cluster target

PE: gauge   EV: electropneumatically valve   NV: needle valve
MP: mechanical pump   IP: ion pump   DRY: dry pump   RP: roots pump   TP: turbo pump
During the earliest test the running of the cluster target system was troubled with frequent blocking of the nozzle. A new gas delivery system including high purity gases (99.9999%), gas pipelines of electronic grade, metal valves, standard fittings, and an effective gas filtering were designed and installed. The blocked nozzle was replaced by one having a diameter of 0.12 mm. New tests of hydrogen and argon gases were carried out. The jet formation under different nozzle pressures was studied, and the running stability of the cluster source was tested both for hydrogen and argon.

2.1 Vacuum test
After the installation and alignment of the cluster target the vacuum test was done. The temperature of the scattering chamber was increased to 250°C at a rate of 0.5°C/min, kept at 250°C for 48 hours and finally decreased to room temperature again at a rate of 0.5°C/min. The source chamber and the beam dump chamber were not baked. The resulting pressures in the different stages are listed in Table 1. The pressure of the scattering chamber was found to be 9.0×10^{-12} mbar and 1.0×10^{-11} mbar without and with gas jet operation (99.99% N₂, 1013 mbar), respectively. Both values are better than the expected value of 5×10^{-11} mbar proving that the arrangement of the vacuum system is working well. The pressure in the scattering chamber goes up almost linearly in the range of 10^{-12}~10^{-11} mbar when the input gas pressure increases from 0 to 1013 mbar.

| Stages          | Pumping speed (l/s) | Pressure without gas in mbar | Pressure with gas in mbar |
|-----------------|---------------------|------------------------------|---------------------------|
| Cluster source  |                     |                              |                           |
| 1st stage       | 3200                | 10^{-7}                      | 10^{-3}                   |
| 2nd stage       | 1000                | 10^{-7}                      | 10^{-5}                   |
| 3rd stage       | 1000                | <2.0×10^{-9}                 | 10^{-7}                   |
| 4th stage       | 1000                | <2.0×10^{-9}                 | 10^{-7}                   |
| Chamber         |                     | 9.0×10^{-12}                 | 1.0×10^{-11}              |
| 1st tube        | 1000                | <2.0×10^{-9}                 | 10^{-7}                   |
| 2nd tube        | 1000                | 10^{-7}                      | 10^{-6}                   |
| 3rd tube        | 1000                | 10^{-7}                      | 10^{-6}                   |

2.2 The measurement of target density.
The target density can be obtained by [6]:

\[ n_t = \frac{I}{(\pi r^2 v)} \]

where \( r \) and \( v \) are the radius and velocity of the cluster jet, respectively.

The measurements were done for the lowest possible nozzle temperature when the nozzle heating supply was switched off. The maximum flux of the jet may be achieved at \( P_{\text{nozzle}}=350 \) mbar for H₂. Having considered that the pumping speed in the 4th chamber is about 2300 l/sec for H₂ [7,8], the jet intensity at a nozzle pressure of 350 mbar could be estimated from the products of the pressure change and pumping speed of the 4th stage for H₂:

\[ I = 1.3\times10^{-6} \text{ mbar}\times2300 \text{ l/sec} = 3\times10^{-3} \text{ mbar.l/sec} = 2\times7.35\times10^{16} \text{ atoms/sec} \]

Here 1.3×10^{-6} mbar is the pressure change in the 4th stage when the valve connecting the 4th chamber and the interaction chamber is opened. The density of the H₂ jet in the centre of the interaction chamber (interacting point) can be calculated as follows:

\[ n_t = \frac{I}{(\pi r^2 v)} = 2\times7.35\times10^{16} \text{ atoms/sec}/(0.1 \text{ cm}^2\times8.4\times10^4 \text{ cm/sec}) = 1.75\times10^{13} \text{ atoms/cm}^3 \]

Yielding a target thickness of:

\[ t = n_t \times d = 6.3\times10^{12} \text{ atoms/cm}^2 \]

where \( d \) is the diameter of the jet.
The test experiment for N₂ was done with the pressure in the nozzle $P_0=1013 \text{ mbar}$ and a temperature of the nozzle $T_n=100 \text{ K}$. The jet intensity is determined to be $I=3.0 \times 10^{16} \text{ atoms/s}$. The jet density can thus be calculated to be $1.2 \times 10^{13} \text{ atoms/cm}^2$. Similarly, the target density of Ar is determined to be $1 \times 10^{13} \text{ atoms/cm}^2$. The target density obtained above is similar to that of the GSI internal target [9, 10, 11].

### 2.3 Jet attenuation.

One of the reasons which can limit the intensity of the gas jet is the attenuation of the cluster beam by collisions with the background gas. To understand this situation the beam intensity was measured when the turbo pumps in the 2\textsuperscript{nd} chamber and in the 3\textsuperscript{rd} chamber were switched off, respectively. In this case the starting pressure in the chamber was high and later, when the pumps were switched on, the pressure decreased. The results of these measurements are shown in figures 4 and 5. Normal operational pressure in the 2\textsuperscript{nd} chamber is $4-6 \times 10^{-5} \text{ mbar}$, and normal operational pressure in the 3\textsuperscript{rd} chamber is $1 \times 10^{-6} \text{ mbar}$. From these two figures one can see that there is a considerable attenuation of the H₂ jet by collisions with the background gas.

Similar attenuation tests were done with Ar gas. Figure 6 presents the result of attenuation of the Ar cluster jet by a background gas in the 2\textsuperscript{nd} vacuum chambers with the nozzle temperature of 141 K.

![Figure 4](image1.png)  
**Figure 4.** Attenuation of the H₂ cluster jet by background gas in the 2\textsuperscript{nd} vacuum chamber.

Normal operational pressure in the 2\textsuperscript{nd} chamber is $5 \times 10^{-5} \text{ mbar}$. The Ar attenuation curve (see P4 pressure in figure 6) differs greatly from H₂ attenuation curve (see P4 pressure in figure 4). These measurements show that there is no attenuation of the Ar jet at the normal operation condition of the source, while the intensity of H₂ jet is limited due to attenuation of the beam by a background gas in the 2\textsuperscript{nd} and 3\textsuperscript{rd} vacuum chambers.

![Figure 5](image2.png)  
**Figure 5.** Attenuation of the H₂ cluster jet by background gas in the 3\textsuperscript{rd} vacuum chamber.

![Figure 6](image3.png)  
**Figure 6.** Attenuation of the Ar cluster jet by background gas in the 2\textsuperscript{nd} vacuum chamber.
2.4 Operation stability.

The long-time running stability of the cluster target was tested for 99.99% N₂. The result is shown in figure 7. The full circles represent the pressure in the nozzle and the full squares represent the copper resistance corresponding to the temperature of the nozzle. It can be clearly seen that the pressure in the nozzle was stable during the continuous running of 30 hours. The test results for Ar and H₂ gases are shown in figure 8 and figure 9. As one can see from these figures the results of long time running for Ar and H₂ cluster jets look promising. There is no essential change of the jet intensity during the test time. The test results suggest that the conditions for forming the cluster jet are stable and the cluster target can continuously run for a long time.

Conclusion

HIRFL-CSR, a new ion Cooler-Storage-Ring (CSR) project, is the upgrading project of the Heavy Ion Research Facility in Lanzhou (HIRFL). The construction of the HIRFL-CSR complex is nearing completion. The first stored beam in CSRm was observed using 6.897 MeV/u C⁺⁴ as the injected beam in the stripping injection mode. Recently, the stored beam was accelerated from 7 MeV/u to 30 MeV/u. The internal target is located in one straight section of CSRe which is designed to operate both in the unpolarized mode and in the polarized mode. Target thicknesses of 6.6×10¹² atoms/cm², 1.2×10¹³ atoms/cm² and 1.0×10¹³ atoms/cm² are obtained for H₂, N₂ and Ar gases, respectively. It is
found that the target density is limited due to the attenuation of the cluster jet by a background gas in the vacuum chambers of the source.

References

[1] Xia J W et al, 2002 Nucl. Instr. Meth. A 488 11
[2] Ekström C 1997 Nuclear Physics A 626 405c
[3] Ekström C et al 1996 Nucl. Instr. Meth. A 371 572
[4] Clasie B, Crawford C, Seely J, Xu W, Dutta D, Gao H, 2006 Phys. Rev. A 73 020703R
[5] Cai X et al 2005 Nucl. Instr. Meth. A 555 15
[6] Taiuti M et al 1990 Nucl. Instr. Meth. A 297 354
[7] Lu R, Master Degree Thesis 2005 Institute of Modern Physics, Chinese Academy of Sciences
[8] Lu R et al 2006 Journal of Atomic & Molecular Physics (in Chinese) 23 1
[9] Gruber A et al 1989 Nucl. Instr. Meth. A 282 87
[10] Reich H et al 1997 Nuclear Physics A 626 417c
[11] Krämer A et al 2001 Nucl. Instr. Meth. B 174 205