The stripper design and test at HIRFL-CSR

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Abstract Charge stripping is employed to produce multi-charged ions for injecting the cooling storage ring. After penetrating through the carbon foil, the widened distribution of ion charge states poses a limit to the ion injection. Therefore, the carbon foil plays a key role in the charge stripping injection. In this paper, four strippers for Heavy Ion Research Facility at Lanzhou (HIRFL) and Cooling Storage Ring (CSR) are introduced. The charge state distribution of the stripped ions is measured and the stripping efficiency of the foils is investigated. The experimental results are consistent with the theoretical values.

Key words Heavy Ion Research Facility and Cooling Storage Ring at Lanzhou, Stripper section, Stripping efficiency, Charge state distribution, Charge Stripping injection.

1 Introduction

The HIRFL-CSR (Heavy Ion Research Facility and Cooling Storage Ring at Lanzhou) is an accelerator complex under construction. In 2006 a pilot test for beam acceleration in the CSRm (CSR main ring) was done successfully. As shown schematically in Fig. 1, the HIRFL-CSR consists of the SFC (sector focused cyclotron), SSC (separate sector cyclotron), CSRm and CSRe (CSR experiment ring). Four stripper sections (carbon foils) are placed in the SFC, SSC, CSRm and CSRe. Also, a carbon foil is installed in the CSRe for experiment of mass measurement. Therefore, a great number of carbon foils are prepared for these purposes.

Carbon foil based charge-stripping is used widely in particle accelerators. HIRFL-CSR is planned to accelerate diverse ion species from hydrogen to uranium. In the beam accumulation scheme of the CSRm, in addition to the MMI (multiple multi-turn injection), the charge stripping injection (CSI) is planned for accumulation of ions. The CSI is normally used to accumulate light ions (C~Ne) because in this method the light ions, such as carbon, can get a higher charge state, a higher energy with little energy loss, and a higher stripping efficiency[1].

In this work, the design of the four charge strippers was reviewed. Stripping efficiency of the carbon foils and the charge state distribution of stripped ions were measured, analyzed, and discussed.

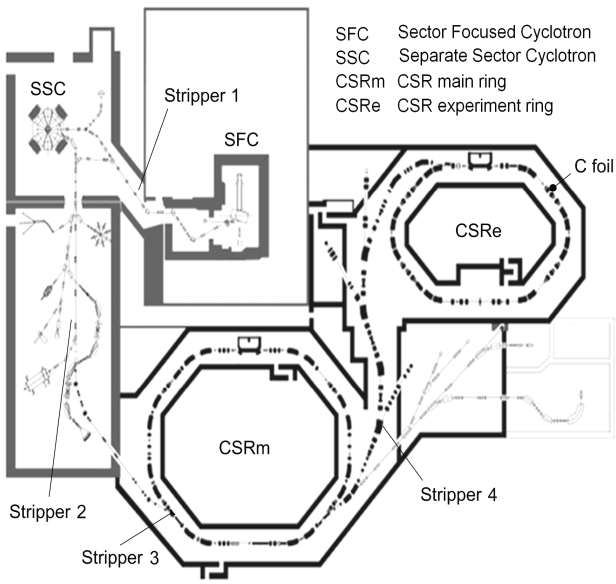

Fig.1 Schematic view of HIRFL-CSR.

Supported by Funds of the National Natural Science Foundation of China (Grant No: 10575120).

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Received date: 2009-11-19

2 Design of the charge strippers

The four strippers differ in terms of the beam energy and intensity. Strippers 1, 2 and 4 are mainly used to strip electrons from charged ions, so as to improve charge state of the ions, while Stripper 3 is mainly used for injecting the ions into the CSRm.

2.1 Stripper 1

This stripper section is mainly designed to strip electrons from diversified ions for providing highly-charged ions to SSC. Relatively, the beam energy is low but the beam intensity is high, so the carbon foil of Φ20 mm is in thickness of only 20–100 μg/cm^2. The target wheel has 18 openings for mounting a maximum total of 18 foils.

2.2 Stripper 2

Stripper 2 is designed to strip more electrons from the ion beams. The ions in this section have a higher energy and a lower intensity, hence the stripping foils in a little increased thickness. In a diameter of 12 mm, the thickest foil is about 510 μg/cm^2. The rotating target is capable of holding 20 stripper foils.

2.3 Stripper 3

After passing through the Stripper 2, the beam ions are further stripped by the stripping foils for injecting the CSRm. A carbon stripping foil is adhered to a U-shaped frame so as not to disturb the circulating ion beams in the CSRm. The foils are specially designed in structure, with stacked layers to increase the lifetime and improve uniformity of the stripper. The ion energy is about 7 MeV/u for $^{12}C^{4+}$ ions from the SFC or 22 MeV/u for $^{12}C^{4+}$ ions from the SSC. The optimum thickness of the stripper is about 15–100 μg/cm^2 [1].

The charge stripping injection is suitable for of light ions. The storage ring accepts a restricted range of beams with different charge ratios. The horizontal emittance of the injected beam is 20 π mm· mrad, and the accelerating beam acceptance is 80 π mm·mrad[1]. To achieve high injection efficiency and small accelerating beam emittance, it is important to match the phase space and dispersion of the ions.

The HIRFL-CSR ran the first beam of carbon ions in CSI mode at the end of 2006. The beam energy and intensity, and momentum spread of the beams, approached their design specifications. Ions of $^{12}C^{4+}$ were accelerated to 7 MeV/u by the SFC. The primary ions were stripped to $^{12}C^{6+}$ by a 15 μg/cm^2 carbon foil in Stripper 3, and were injected into the CSRm. The $^{12}C^{6+}$ ions were continuously accumulated for 12 times in the CSRm and were accelerated to 1GeV/u. The beam current in the CSRm measured by DCCT (DC Current Transformer) at that moment was 2700 μA, as shown in Fig. 2.

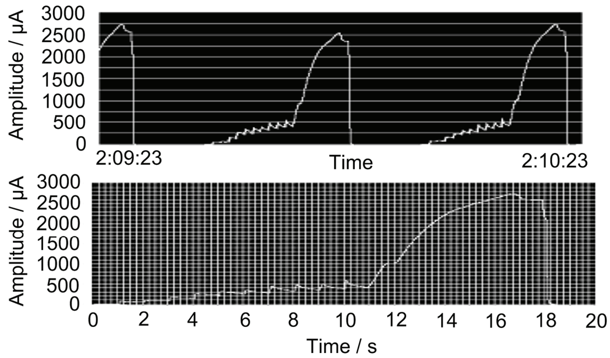

Fig.2 The beam current measured by DCCT.

2.4 Stripper 4

The heavy ion beam is extracted from the CSRm for performing atomic physics experiment on the CSRe. In order to increase energy acceptance of the CSRe, and as a further phase of development of the HIRFL-CSR, the heavy ions will be stripped to H-like or He-like ions in Stripper 4.

3 Stripping efficiency and charged state

A stripping foil increases the charge number of an ion. This reduces the total current requirement on the magnet, in other words, the foil increases the beam energy at a definite current of the magnet. The charge state distribution of the ion beam is dependent on thicknesses of the carbon foil and the beam energy[2,3]. Experimental measurements of the charge state distribution are crucial for determining the stripping efficiency and prediction of the location of beam loss in the charge selection[4,5].

The stripping efficiency of carbon foil was measured at the section of Stripper 2, with 22 MeV/u Ar^{8+} ions being stripped to Ar^{18+} ions by a 350 μg/cm^2

carbon foil. Fig.3 shows a schematic view of the experimental layout. The beam intensity of Ar^{8+} and Ar^{18+} ions were measured by FC01(Faraday Cup 01) and FC02, respectively. The 60° analyzer magnet is placed in between the stripping foil and the FC02. Different charged ions were chosen by using the analyzer magnet. The stripping efficiency can be calculated by,

$$\eta = 4I_2/(9I_1) \quad (1)$$

where, I_1 and I_2 are the beam intensity of Ar^{8+} and Ar^{18+}, respectively. Five independent measurements for the stripping efficiency were done. The average stripping efficiency is 63.4% (Table 1).

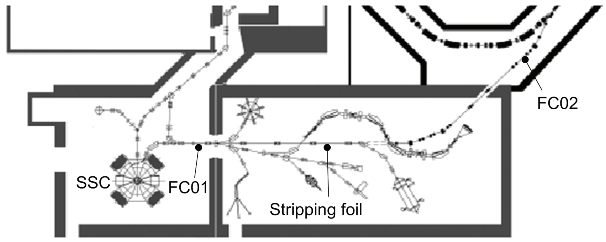

Fig.3 The experimental layout to measure the stripping efficiency.

Table 1 Measurement results of the stripping efficiency.

Ar^{8+} / nA	Ar^{18+} / nA	Stripping efficiency / %
482	666	61.4
500	713	63.4
475	660	61.7
414	620	66.6
500	720	64.0

Fig.4 shows the theoretical stripping efficiency of carbon foils of different thicknesses. It indicates that the stripping efficiency of 350 μg/cm^2 carbon foil is approximately 68.7%. The discrepancy between the experimental and the theoretical values is attributed to the beam transmission loss, scattering and uncertainty in foil thickness. It is observed that the stripping efficiency goes up with carbon foil thickness for Ar^{18+}, and drops down for Ar^{17+}.

The charge state of an ion moving through matter fluctuates as a result of electron loss and capture in collisions with the target atoms. When the ions have a sufficient number of collisions with the target atoms, an equilibrium distribution of charges is established, which is dependent on the atomic numbers, energy of the ions, and the target materials. During the ion collisions with the target atoms, various processes, such as electron capture, ionization, excitation, vacancy production and the consequent phenomena like energy loss stopping, are closely related to the projectile charge state evolution in the target. The knowledge of charge state distribution of ions after passing through a certain matter is important for not only the study of atomic collision, but also its application to accelerator design and understanding of the stripping efficiency.

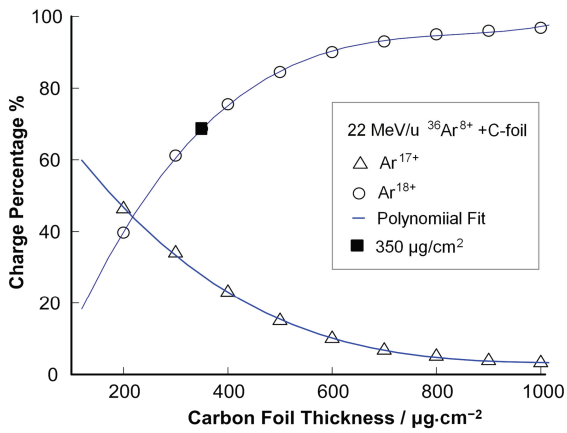

Fig.4 Theoretical stripping efficiency of carbon foil.

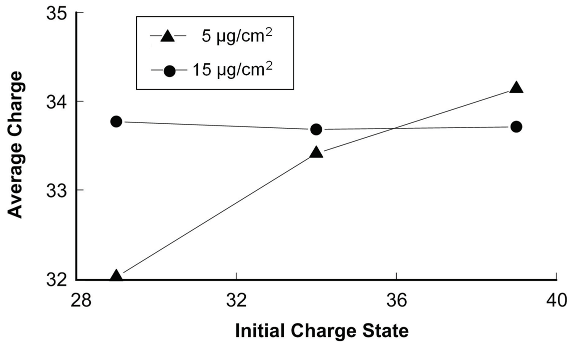

Fig.5 Average charge state of different carbon foil.

The charge state distributions were investigated for 0.8 MeV/u uranium ions passing through the carbon foil at RIBLL (the radioactive ion beam line in Lanzhou). Fig.5 shows the dependence of the mean charge state q_{ave} of the exited uranium ions on the initial charge states. The triangles denote the q_{ave} of $U^{29,34,39+}$ passing through 5 μg/cm^2 carbon foils, and the circles denote the q_{ave} of the same ions passing through 15 μg/cm^2 carbon foils. It is obvious that the

q_{ave} populated through 5 μg/cm^2 carbon foils goes up with the initial charge states, whereas the q_{ave} populated through 15 μg/cm^2 carbon foils is almost independent of the initial charge state. This finding implies that the charge states of the exited heavy ions have approached their equilibrium states after a 15 μg/cm^2 carbon foil, but not after a 5 μg/cm^2 carbon foil.

The ion effect on the charge state distribution will be further investigated with thinner stripping foils in the near future.

4 Conclusions

Four charge stripper sections have been planned in the HIRFL-CSR. A preliminary study of the strippers was made in CSI mode, and an exciting result had been achieved. The stripping efficiency and charge state distributions of ions after passing through the carbon foils are investigated in detail. We find that the measured values are consistent with theoretical value for the stripping efficiency. Moreover, it is observed that the q_{ave} of no equilibrium goes up with the initial charge states. The charge state fractions of beam ions could be estimated by some empirical formula[6] and compared with the experimental measurements.

Continuous improvements have been made for CSI. To determine the stripping efficiency accurately, especially for low-energy beam ions and thin carbon foils, more experimental measurements is planned in the future.

References

1 Yuan Y J. 2001 Annual Report IMP & HIREL, 2001, 120.
2 Wittkower A B, Ryding G. Phys Rev, 1971, **A4:** 226–232.
3 Wang Y Y, Zhao Y Z, Xiao G Q, *et al.* Acta Phys Sin, 2006, **55:** 673–676.(in Chinese)
4 Ryuto H, Inabe N, Fukunishi N, *et al.* Proc 17th international conference on cyclotrons and their applications, Tokyo, Japan, 2004, 307–309.
5 Chou W, Kostin M, Tang Z. 23rd World conference of international nuclear target development society (INTDS), Tsukuba, Japan, 2006, 425–448.
6 Schiwietz G, Grande P L. Nucl Instrum Meth B, 2001, **175:** 125–131.