CHARGE STRIPPING SCHEME IN THE RIKEN RI-BEAM FACTORY

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Abstract

A charge stripping scheme in the RIKEN RI-beam factory is described. Four stripper sections in the RIKEN RI-beam factory at five typical kinds of energies for the intense heavy-ion beams are under investigation. An overview of these four stripper sections is presented. Charge-state distributions of ^{136}Xe stripped by carbon foils and polymer films measured at 11 MeV/nucleon and 39 MeV/nucleon are also presented.

INTRODUCTION

The RIKEN RI-beam factory (RIBF) is an accelerator complex for the acceleration of heavy-ion beams up to uranium to a final energy of 350 MeV/nucleon with an object of producing a great variety of RI-beam [1]. In such heavy-ion accelerators that form the RIBF, a charge stripper plays an essential role because high charge-states allow small machines that require low construction costs or allow extended application of existing accelerators.

In order to design accelerators or plan acceleration schemes, accurate predictions of charge-state distributions for heavy-ions behind the charge strippers are indispensable, because i) the design of magnets and RF systems depend wholly on the charge-state of the ion, ii) the beam current on target is roughly proportional to the product of the charge-state fractions behind the strippers, iii) the emittance superfluously blows up if we use unnecessarily thick stripper foils. A number of experiments to measure the equilibrium charge-states of various ions at various energies were performed for decades. By fitting these data several semi-empirical formulae were made (e.g., refs. [2-6]). Semi-empirical formulae, which provide equilibrium carbon foil or gas thicknesses, were also developed [7, 8]. In the last half decade of twentieth century, numerical calculation codes GLOBAL [9] and ETACHA [10] which calculate pre-equilibrium charge-state distributions were developed. However, the predictions of the formulae and the codes vary significantly.

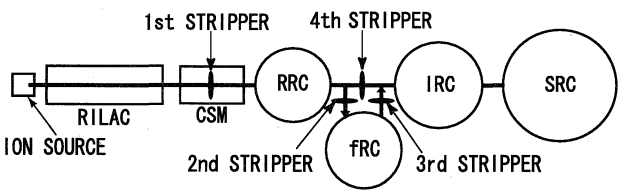

Figure 1: Schematic of RIBF.

Present plan for the charge-stripping scheme of the RIBF investigated using experimental data, semi-empirical formulae and calculation codes are presented. Some experimental data on pre-equilibrium charge-state distributions are also presented comparing with calculations.

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STRIPPING SCHEME

Figure 1 shows the schematic of the RIBF. In the RIBF, four stripper sections are under investigation at present. The first section is located between the accelerator and decelerator of the charge-state multiplier (CSM) [11]. The second section is located between the RIKEN ring cyclotron (RRC) and the fixed-frequency ring cyclotron (fRC). The third section is located between the fRC and the intermediate-stage ring cyclotron (IRC). The fourth section is located between the RRC and the IRC. Uranium and xenon beams at five kinds of energies are considered as typical beams that incident on strippers. Three energies out of five energies correspond to the case that the beam is accelerated by all the cyclotrons, the RRC, the fRC, the IRC and the superconducting ring cyclotron (SRC) to 350 MeV/nucleon using strippers at the first, second and third stripper sections. Remaining two energies correspond to the case that the beam is accelerated to 276 MeV/nucleon without the fRC using strippers at first and fourth stripper sections. The first stripper is not used when an ion source supplies a sufficiently intense ion beam at the required charge-state. In the following discussion, the incident beam currents on the strippers are estimated as to achieve a 1 pμA uranium beam and 1.5 pμA xenon beam at 350 MeV/nucleon, and a 0.2 pμA xenon beam at 276 MeV/nucleon on target. The beam loss caused by other sources than charge strippers are neglected here. The parameters of the strippers for the RIBF under consideration are tabulated in Table 1. An overview of these four stripper sections is presented in the following subsections.

First Stripper Section

The current of $^{238}U^{35+}$ beam behind the first stripper in the case with the fRC is expected to be 15 pμA in order to achieve 1 pμA at the exit of the SRC. The energy of the incident uranium beam is 0.9 MeV/nucleon. According to the table of equilibrium charge-state fractions in ref. [4], the incident beam current should be as high as 90 pμA. Similarly, the incident xenon beam current in the case without the fRC is 10 pμA. The distinctive features of the first stripper section are thus the high beam intensity and the low energies. Both features cause the short lifetime of carbon foils that are most commonly used charge strippers. Some semi-empirical formulae for carbon foil lifetime were made by fitting rather scattered experimental data [7, 12, 13]. For example, when a 90 pμA uranium beam at 0.9

Table 1: Parameters of the strippers for the RIBF.

		with the fRC					without the fRC	
Ion		^{238}U			^{136}Xe		^{136}Xe	
Stripper section		1st	2nd	3rd	2nd	3rd	1st	4th
Energy (MeV/nucleon)		0.9	11	46	11	46	2.9	39
Required charge-state		35+	72+	88+	42+	51+	38+	45+
Thickness (mg/cm^2)	C foil	0.025 [7]	0.5 [9]	14 [9]	0.15	20 [9]	0.061 [7]	0.3 [9]
Expecting charge-state	C foil	36+	72+	88+	44+	52+	38+	45+
Fraction	C foil	17% [4]	19% [9]	34% [9]	30%	52% [9]	9% [4]	26% [9]
Thickness (mg/cm^2)	N gas			0.09 [8], 14 [9]	0.03 [8]	0.09 [8]		0.08 [8]
Expecting charge-state	N gas			88+	43+	52+		51+
Fraction	N gas			2% [3], 30% [9]	20% [3]	30% [3]		28% [3]

MeV/nucleon is focused on a carbon foil with 5-mm-diameter circular shape, using Livingston's formula [12] it is predicted that the lifetime of the carbon foil is about 20 seconds. A rotating carbon foil may have a greater lifetime because it decreases the energy density deposited to the carbon foil by the beam. For example, when we bombard a 5-mm-diameter beam at the spot between 15 mm and 20 mm radiuses of the rotating carbon foil, the energy density deposited to the carbon foil by the beam is 1/28 of that of still carbon foil. Another possible method of improving the resistance to the beam for the xenon case is to use a liquid film stripper [14] because the temperature of the carbon foil is well below the evaporating temperature, thus breakage is not expected to be caused by the heat [15]. When a xenon beam is accelerated to 350 MeV/nucleon with the fRC, the first stripper is not required because a sufficiently intense xenon beam of the required charge-state is supplied from the ion source.

Second Stripper Section

Behind the second stripper section, 3 pμA $^{238}U^{72+}$ beam and $^{136}Xe^{42+}$ beam at 11 MeV/nucleon are expected. In the uranium case an experimental data [9] exists, that the equilibrium charge-state at 11.4 MeV/nucleon stripped by a 0.49 mg/cm^2 thick carbon foil is 73+ with a fraction of 19%. When a 15 pμA uranium beam is stripped by a 0.5 mg/cm^2 thick carbon foil, 1 kW power is deposited to the foil. Again, a rotating carbon foil is expected to facilitate the situation. We cannot use a gas stripper for uranium here in order to obtain a sufficiently high charge-state that can be accelerated by the fRC. On the other hand, a semi-empirical formula [3] predicts a 20% fraction of $^{136}Xe^{43+}$.

Third Stripper Section

Behind the third (and last) stripper section, 1 pμA $^{238}U^{88+}$ and 1.5 pμA $^{136}Xe^{51+}$ at 46 MeV/nucleon are expected as same as the currents at the exit of the SRC. The GLOBAL calculation predicts that 34% and 52% fractions of $^{238}U^{88+}$ and $^{136}Xe^{52+}$ can be obtained by 14 mg/cm^2 and 20 mg/cm^2 thick carbon plates, respectively. Such a thick stripper causes a serious energy loss of the ions. The fRC accelerate to a higher energy than the injection energy of the IRC taking the energy loss caused by the third stripper into consideration. About 8% of energies, 30 kW in the uranium case, are deposited to the carbon plate, so again a rotating stripper is indispensable. At the same time, a relatively large energy loss struggling and multiple scattering are caused by such a thick stripper. A rotating carbon disk stripper may cause another problem. If the thickness of the carbon disk varies 10%, the energy of the beam downstream oscillates about 0.8% in magnitude. The requirement to the uniformity of the carbon disk thickness is closely related to the running costs of the strippers at this section. A rotating carbon disk stripper is under development now.

The possibility to use other solid strippers thinner than carbon stripper foils was also examined by the GLOBAL calculation. According to the calculation, for example, we can obtain $^{238}U^{83+}$ at 46 MeV/nucleon with 18% fraction by a 1 mg/cm^2 thick tantalum foil receiving a lower amount of heat deposit than a 14 mg/cm^2 thick carbon plate. However, it is necessary to use another stripper before injecting into the SRC because the SRC requires 88+. Multiplying the fractions at the strippers downstream of the fRC and the IRC, we obtain one-sixth fraction of the case stripped by a 14 mg/cm^2 thick carbon plate downstream of the fRC, so we will not discuss the other materials further here.

The problem caused by the intense heat may be solved if we would use a gas stripper. We can obtain xenon ions at a sufficiently high charge-state using a gas stripper according to the semi-empirical formulae by Sayer and Schiwietz et al. However, it is a delicate situation in the uranium case. The predicted equilibrium charges are 86+ by Schiwietz's formula and 88+ by the GLOBAL calculation, but 84+ by Sayer's formula, so the fractions of 88+, the required charge-state by the SRC, are fifteen times different as 30% by the GLOBAL calculation compared with 2% by Sayer's formula. An experiment with a uranium beam will clarify the uncertainty, but we cannot obtain a uranium beam at present.

Fourth Stripper Section

At the fourth stripper section, a 0.2 pμA $^{136}Xe^{45+}$ beam at 39 MeV/nucleon is expected. The thickness of the stripper at the fourth section is required to be thin in order to avoid a large energy loss aiming at the incident energy range of the IRC. The thickness of the carbon stripper foil will be thus 0.3 mg/cm^2, at which thickness the fraction of xenon ions at 45+ is maximized (see Figure 3). The energy loss is about 0.2%. Another solution to obtain a

higher charge than 45+ without suffering a large energy loss is the use of a gas stripper.

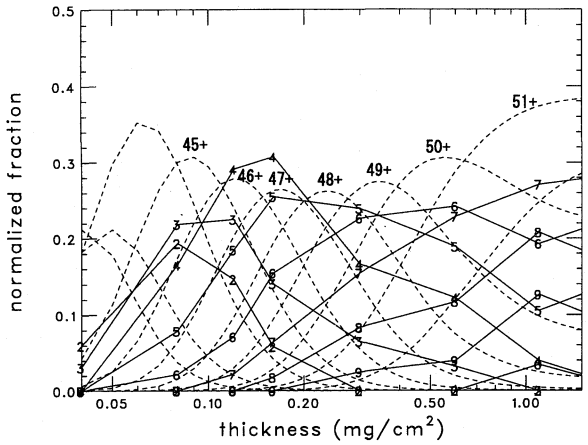

Figure 2: Charge-state fractions of ^{136}Xe at 11 MeV/nucleon stripped by carbon foils, aramid films, and a polyimide film. Horizontal and vertical axes indicate the thickness of the strippers and the charge-state fractions, respectively. Numbers joined with solid lines indicate the lowest digit of measured charge-state numbers between 42+ and 50+. The charge-state fractions are normalized by the area of the Gaussian fitted to the measured charge-state distribution. Dashed lines indicate the calculation by ETACHA.

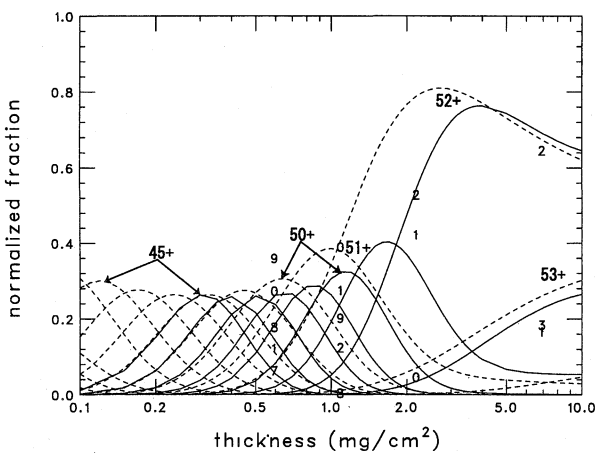

Figure 3: Charge-state fractions of ^{136}Xe at 39 MeV/nucleon stripped by carbon foils, aramid films, and a polyimide film. The definition of the axes is the same as Figure 2. Numbers without line indicate the lowest digit of measured charge-state numbers between 47+ and 53+. The charge-state fractions are normalized by the area of the Gaussian fitted to the measured charge-state distribution. Solid and dashed lines indicate the calculations by GLOBAL and ETACHA, respectively.

MEASUREMENT OF CHARGE-STATE DISTRIBUTIONS

The charge-state distributions of ^{136}Xe at 11 MeV/nucleon and 39 MeV/nucleon, which correspond to the incident energy of the second and fourth stripper sections respectively, were measured with strippers of various thicknesses. The xenon beam was bombarded on carbon foils, aramid films, and a polyimide film with thicknesses from 40 μg/cm^2 to 7 mg/cm^2. Figure 2 shows the charge-state fractions of ^{136}Xe at 11 MeV/nucleon. We can use, for example, a 0.15 mg/cm^2 thick foil to obtain ^{136}Xe^{44+} with 30% fraction. The ETACHA calculation is also drawn on the figure, however the calculation rather poorly reproduced the data. The GLOBAL code does not cover this energy range. Figure 3 shows the charge-state fractions of ^{136}Xe at 39 MeV/nucleon. Solid and dashed lines indicate the GLOBAL and ETACHA calculations, respectively. Comparing the calculations to the data, the GLOBAL calculation rather well reproduces the data than the ETACHA calculation. According to the GLOBAL calculation, we can get ^{136}Xe^{45+} by a 0.3 mg/cm^2 thick carbon foil with a 26% fraction.

CONCLUSION

A charge stripping scheme in the RIKEN RI-beam factory is investigated. Due to the highness of the beam intensity, rotating strippers are indispensable. It is likely to be effective to strip xenon ions by a gas stripper. Charge-state distributions of ^{136}Xe stripped by carbon foils and polymer films were measured at 11 MeV/nucleon and 39 MeV/nucleon.

REFERENCES

[1] Y. Yano et al., Proc. of the 13th Sympo. on Accelerator Science and Technology, Osaka, 20 (2001).
[2] H.D. Betz, Rev. of Mod. Phys. 44, 465 (1972).
[3] R.O. Sayer, Rev. Phys. Appl. 12, 1543 (1977).
[4] K. Shima et al., At. Data Nucl. Data Tables 51, 173 (1992).
[5] A. Leon et al., At. Data Nucl. Data Tables 69, 217 (1998).
[6] G. Schiwietz, P.L. Glande, Nucl. Instrum. Meth. B175-177, 125 (2001).
[7] E. Baron, IEEE Trans. Nucl. Sci. NS-26, 2411 (1979).
[8] M.A. McMahan, Handbook of Accelerator Physics and Engineering, ed. by A.W. Chao and M. Tigner (World Scientific, 1999).
[9] C. Scheidenberger et al., Nucl. Instrum. Methods B142, 441 (1998).
[10] J.P. Rozet et al., Nucl. Instrum. Methods B107, 67 (1996).
[11] O. Kamigaito et al., Proc. of the 12th Sympo. on Accelerator Science and Technology, Wako, 233 (1999).
[12] A.E. Livingston et al., Nucl. Instrum. Methods 148, 125 (1978).
[13] F. Nickel, Nucl. Instrum. Methods 195, 457 (1982).
[14] H. Akiyoshi et al., Proc. of the 13th Sympo. on Accelerator Science and Technology, Osaka, 331 (2001).
[15] G. Dollinger and P. Maier-Komor, Nucl. Instrum. Methods A282, 223 (1989).