EXTRACTION BY STRIPPING OF HEAVY ION BEAMS FROM CYCLOTRONS

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Abstract

Accelerated heavy ions get a charge spectrum on passing a thin target. The charge dispersion and its maximum depend on the ion type, its energy, material, and the foil thickness. Change of the ion charge leads to change of the ion magnetic rigidity. Heavy ion beam extraction from the AVF cyclotrons by stripping in the thin targets is based on loss of the radial stability of the accelerated beam after its magnetic rigidity change. Property data of carbon foils used for the heavy ion beam extraction by stripping are given. Experience of using heavy ion beam extraction from the AVF cyclotrons of FLNR (Dubna) by stripping is considered.

INTRODUCTION

The method of heavy ion beam extraction from AVF cyclotrons was suggested in [1]. The sharp charge change of a heavy ion accelerated in the cyclotron when passing a thin target is the heart of this method. For that not completely stripped ions must be accelerated. As a result the charge and correspondingly magnetic rigidity of the ion change. And its orbit sharply differs from the closed one. Under correct radial and azimuthal position of the foil the ion orbit after the stripping can have a radial instability and the ion beam is extracted from the accelerator chamber practically freely. At FLNR the method of extraction of the accelerated heavy ions from AFV cyclotrons through the stripping foils is used as basic one in U200, U400, U400M cyclotrons.

The necessary thickness of the stripping foil is defined in the main by the accelerated ion velocity. The foil lifetime under low ion intensities depends on the dose density, ion type, and its energy. At very high power losses the foil lifetime is defined by thermal sublimation of the foil material. On the other hand, the stripping process has action upon the extracted beam.

The extraction efficiency of all charges after stripping almost always is close to 100%. The extraction efficiency of a separate charge from the spectrum amounts from 20 up to 100%.

The magnetic structure of AVF cyclotron affects on the possibility of the stripping method utilization. Evaluations of limits of the stripping method utilization for different magnetic structures are given below.

HEAVY ION EXTRACTION BY STRIPPING FROM AVF CYCLOTRONS OF FLNR

The method of heavy ion extraction from AVF cyclotrons suggested in [1] supposed placing the foil near the valley-hill border. After stripping the ion orbit is in the region of one period of the cyclotron magnetic structure, that is the high magnetic field level between the sectors and low magnetic field level in the valley. Because of this the reference particle orbit has a strong radial drift with a step (0.2 -0.3) R_{ext} and the beam is extracted out of the cyclotron chamber.

The extraction method by stripping with utilization of only one magnetic structure period we identify as the method 1 (M1). For the first time method M1 was used at FLNR in the cyclotron U200 for extraction of $^{2}D^{1+}$, $^{4}He^{1+}$, $^{12}C^{3+}$, $^{16}O^{4+}$ beams with the extraction efficiency about 100%. The cyclotron U200 has the structure of four 45^0 sectors without spiralling with flatter equal to 0.1.

The U400 cyclotron weighing about 2000 ton has the maximum energy factor of 625. It has the mean magnetic field of 1.9 – 2.1 T and the flatter of four sector magnetic structure without spiralling equal to 0.1.

The energy range of the accelerated and extracted ion beams is from 3 up to 20 MeV/amu. Extraction by the stripping method 1 is the basic one for this cyclotron. We name the ratio Z_2/Z_1 (the ion charge after and before stripping) as the stripping coefficient.

One uses only one, two and three-turn beam extraction with stripping coefficient from 2.5 up to 4.5. The beam tuning is carried on in the center of the horizontal correcting magnet at the beam line input.

The extraction efficiency for sum of all charges is close to 100%. The extraction efficiency of a single charge corresponds to the charge dispersion after stripping. Parameters of U400 cyclotron extraction system for some ion beams are given in Table 1.

Table 1. U400 Beam Parameters of some Accelerated and Extracted Ions

Ion	W MeV/Amu	Z_1	Z_2	Z_2/Z_1	EXT_{eff} %	I_{target} pμA
^{7}Li	8.6	1	3	3	100%	10
^{12}C	16.6	2	6	3	95%	6
^{40}Ar	5.1	4	16	4	50%	2
^{48}Ca	5.2	5	18	3,6	45%	1,5
^{136}Xe	5.3	15	42	2,8	25%	0,1

The example of two-turn extraction from U400 cyclotron for the ^{84}Kr ion beam spectrum is given in Fig. 1. One can see the angle and space dispersion of the beams at the accelerator output.

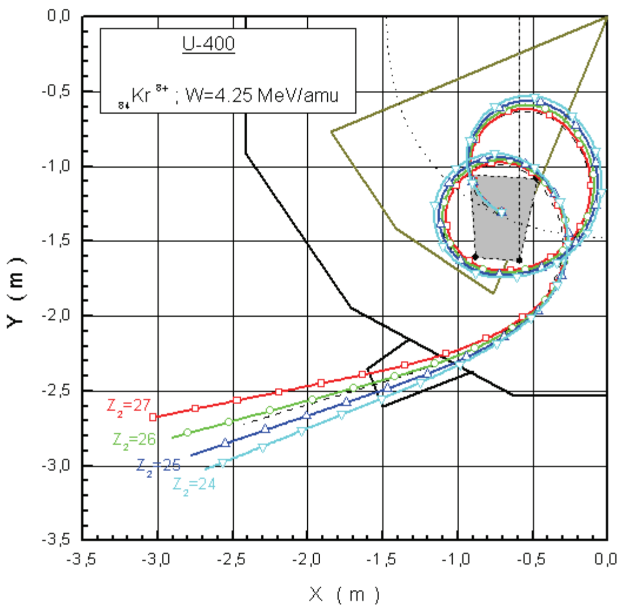

Figure 1: Two-turn extraction from U400 cyclotron.

This dispersion can be used for creation of a multichannel system for the ion beam lines or for irradiation of the large-format targets. The vertical dimension Δz of the extracted beam after stripping inside the cyclotron is less than 25 mm. The beam dimension at the distance of 1 m from the pole is $\Delta z \times \Delta x = 15 \times 50$ mm^2.

Utilization of one, two and three-turn extraction allows one to vary the energy of the extracted beams gradually with the step of about 30% not changing the mode of operation of U400 cyclotron itself. The energy microadjust is made within the limits of 10% by little radial and azimuthal movements of the foil.

U400M cyclotron weighing about 2300 tons and having the pole diameter of 4 m was designed for the ion acceleration with energies from 4 up to 100 MeV/amu. The magnetic structure has four sectors with spiralling of 42° and flatter from 0.08 up to 0.12. The maximum energy factor is equal to 550. The light ions $^{7}Li^{2+}$, $^{11}B^{3+}$, $^{15}N^{5+}$ having energies from 35 up to 50 MeV/amu are accelerated most frequently for production of secondary radioactive nuclei. The stripping method is also used for extraction of such accelerated beams. But the stripping coefficient of such ion type is from 1.35 up to 2. The orbits of such ions after stripping go around the center of U400M cyclotron. There is no evident explanation of the reason of the closed orbit radial instability after stripping. We name this extraction method by stripping as a method 2 (M2).

The reference particle trajectories of the ions extracted from U400M cyclotron are shown in Fig. 2. The reference particle trajectory tuning at the matching point is made by little radial and azimuthal movements of the foil. In order to compensate the defocusing action of the stray magnetic field one uses two passive magnetic channels.

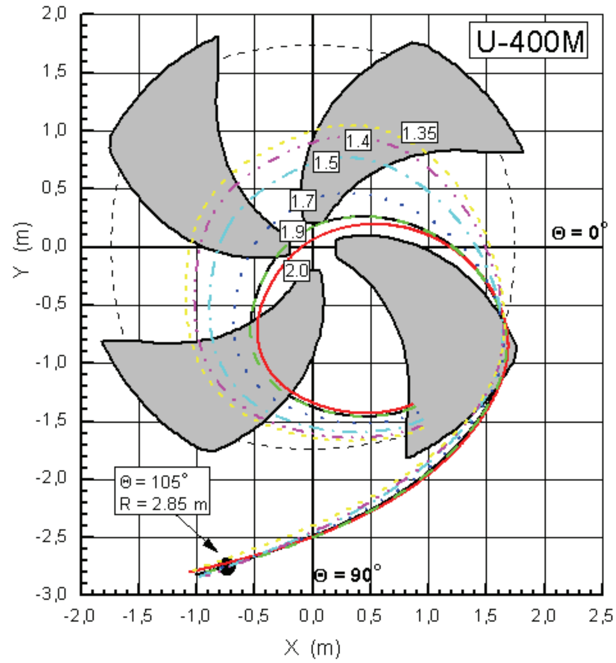

Figure 2: Reference particle trajectories of the ions extracted from U400M cyclotron by method 2.

The axial beam dimension Δz after stripping is less than 30 mm inside the accelerator.

Parameters of some ion beams extracted from U400M cyclotron by stripping method 2 are given in Table 2.

Table 2: U400M Beam Parameters of some Accelerated and Extracted Ions

Ion	W MeV/Amu	Z_1	Z_2	Z_2/Z_1	EXT_{eff} %	I_{target} pμA
^{7}Li	35	2	3	1.50	100	10
^{11}B	32	3	5	1.66	100	10
^{15}N	50	5	7	1.40	95	2
^{20}Ne	43	7	10	1.43	90	1.5
^{40}Ar	40	13	18	1.38	70	0.1

Trajectories of the low energy ion beams extracted from U400M cyclotron by method 1 are shown in Fig. 3. Tuning at the matching point (bending magnet) is carried out by changing the foil radius.

A combined extraction system for positive and negative ($^{1}H^{1-}$, $^{2}D^{1-}$) ions was created for DC72 cyclotron. The reference particle trajectories are shown in Fig. 4.

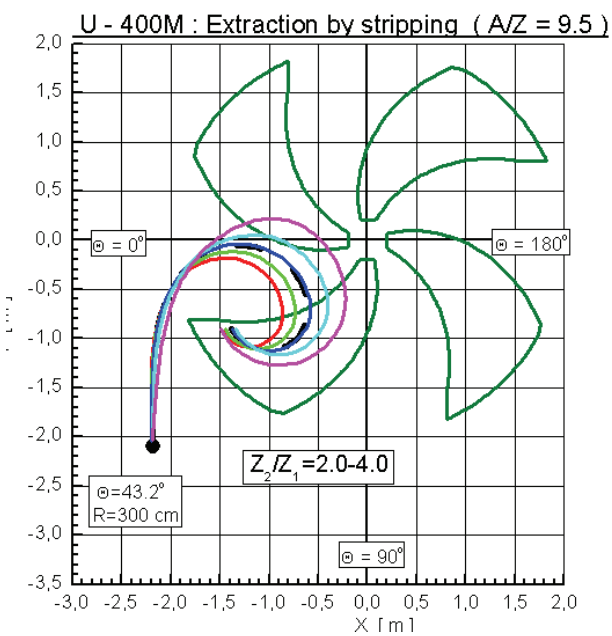

Figure 3: Trajectories of the low energy ion beams extracted from U400M cyclotron by method 1.

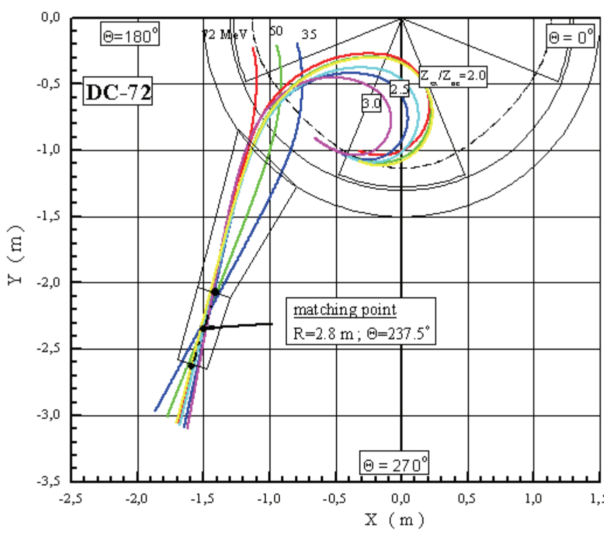

Figure 4: Reference particle trajectories of the ions extracted from DC72 cyclotron.

STRIPPING FOILS

The foils made of Be, C, Al, Al_2O_3, and mylar can be used as the stripping foils.

Choice of the foil material depends on its serviceability, lifetime, and limitation of the foil influence on the beam quality after its stripping. Beryllium would be the best material (maximum charge after stripping under smallest charge dispersion, additional angle scattering, and additional energy spread) but this material is toxic. It is convenient to work with Al and mylar but only when the beams have the high energies and small intensities. We have an experience of work with foils made of C, Al, Al_2O_3, and mylar. In practice the foils made of carbon have the best properties.

For every accelerated ion there is so called "equilibrium thickness" of the foil at which increasing the charge distribution does not change [2]. We use the following formula for evaluation of the foil equilibrium thickness in wide energy range

$$X_\infty\left[\mu g\cdot cm^{-2}\right]\approx 30\cdot W^{0,6}\left[MeV/_{amu}\right] \qquad (1)$$

Dependence of the ion stripping degree on the ion energy is shown in Fig. 5.

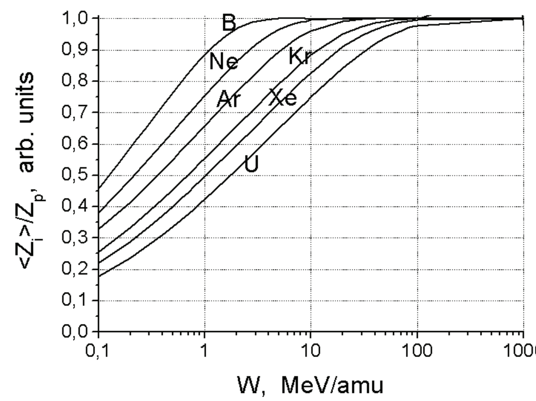

Figure 5: Dependence of the ion stripping degree on the ion energy.

The extraction efficiency by stripping of one charge from the spectrum is defined by the charge dispersion [3].

Dependence of the maximum efficiency of a single charge extraction by stripping versus the ion beam energy is shown in Fig. 6. Here I_{max} is the current of the ions with maximum charge and I_{in} is the common ion current.

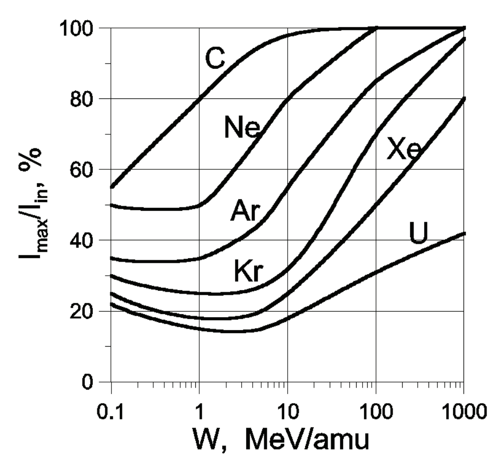

Figure 6: Maximum efficiency of a single charge extraction by stripping.

The ion scattering in the stripping foil causes the growth of the beam emittance (Fig. 7) [4].

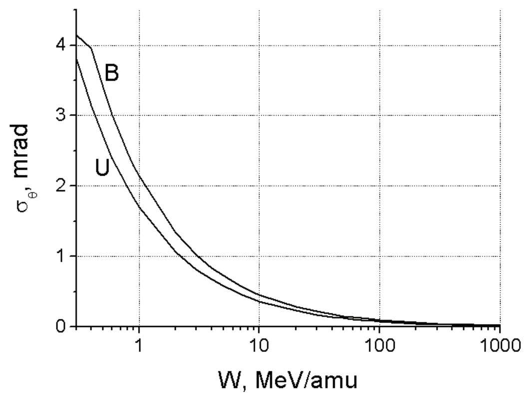

Figure 7: Dependence of the scattering angles for B and U in the carbon foils having the equilibrium thickness.

The stripping foil inserts an additional energy spread in the extracted beam (Fig. 8) [2].

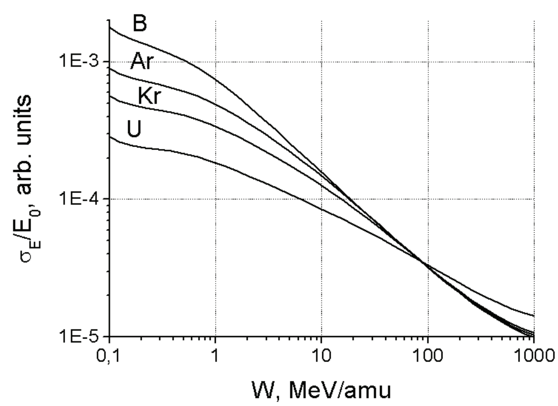

Figure 8: Dependence of the additional energy spread in the extracted beam.

The angle scattering and energy spread in a stripping foil may have a vital importance for cyclotrons with spectroscopic beams.

In evaluations of the carbon foil lifetime one should emphasize above all their radiation damage. Estimation of the foil lifetime is given below:

$$\mathrm{T[hours]} \approx (3 \div 6) \cdot 10^3 \, \frac{W\left[\dfrac{MeV}{amu}\right]}{Zp^2 \cdot j\left[p\mu A \Big/ cm^2\right]} \quad (2)$$

Here Z_p is the ion element number, W is the ion energy, and j is the beam current density. For B and U beams difference in the radiation lifetime of the foil amounts about 1000 under equal value of W and j.

The technology of foil production has a strong action on the foil lifetime. The pure amorphous or diamond-like foils are the best ones. Contamination, for example by hydrogen, drastically decreases the foil lifetime [5].

Usually the stripping foil intended for the beam extraction is glued on a small frame made of Al, C or Cu.

One internal edge of the foil is free. The frame with the foil is placed on the head of locked probe with radial and azimuthal movement of the head. The probe head may have water cooling, or temperature control or some control of the foil itself. Usually accuracy of the foil positioning is at the level of 0.1 mm.

The energy losses of ions in the foil to a certain degree do not affect on its lifetime. Dissipation of the delivered power occurs actually only owing to the thermal radiation temperature rise. The power losses of the ion beam stripping in a foil versus the energy and type of ions are shown in Fig. 9.

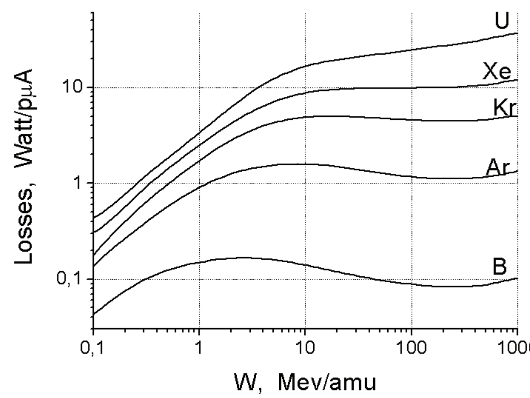

Figure 9: Power losses of the ion beam.

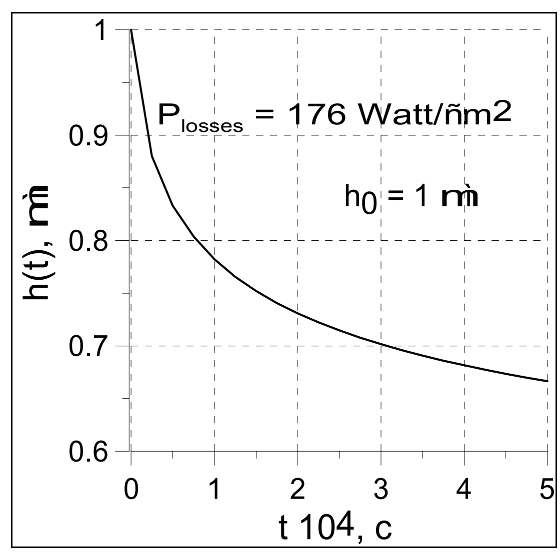

Figure 10: Evolutions of the carbon foil thickness.

In reality the beam density on the foil has some distribution. Evolution of the foil thickness by the beam having Gaussian distribution is shown in Fig. 11.

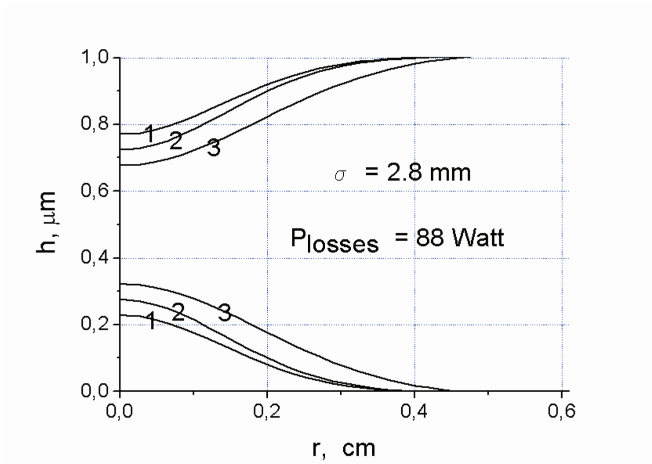

Figure 11: Curves 1, 2 and 3 correspond accordingly to the moment 100 c, 200 c and 2000 c after beginning of irradiation.

The power losses, foil temperature, and pressure of the carbon steam grow when the beam intensity increases. Sublimation of the carbon steam and decrease of the foil thickness intensively occurs. At that the foil thickness stabilizes at a new level (Fig. 10) [6].

As an additional result, the energy spread increases in the extracted beam. The radiation damages also bring to the same effect.

CONCLUSION

Extraction of the heavy ion beams by stripping from AVF cyclotrons is convenient in realization. The extraction efficiency of sum of the charges after stripping is about 100% and for a single charge it is from 20 up to 100% in dependence of the ion type and energy.

The stripping foil weekly affects on the extracting beam quality. The foil lifetime can be well estimated by the radiation damages. Under high power losses (> 150 W/cm^2) sublimation of carbon defines the foil lifetime.

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