INVESTIGATION OF CYCLOTRON CARBON FOIL LIFETIME IN RELATION TO ITS THICKNESS*

J.H. Kim#, S.G. Hong, J.W. Kim,
Rare Isotope Science Project (RISP), Institute for Basic Science (IBS), Daejeon, Korea
Y.G. Choi and Y.S. Kim,
Nuclear & Energy Engineering Department, Dongguk University, Gyeongju, Korea

Abstract

Thin carbon foils are used as positive-ion extractors in negative-ion accelerators by stripping two electrons. Power deposited in foils via stripping H^- ions and accompanying two electrons generates heat. The energy loss of protons and electrons in carbon foil can be estimated by the multiplication of stopping power (dE/dz) and its thickness. The stopping powers are estimated as the values of 8.51 and 7.25 MeV/(g/cm^2) for the proton and electron, respectively. In cyclotron the stripper is located in a strong magnetic field of ~1.7 Tesla, which makes electrons circular motion around the foil and eventually stops by it. In this study, three carbon foils (200, 400, and 800 μg/cm^2) are tested to investigate the correlation of foil temperature and its lifetime at 1-mA proton extraction. Lifetimes of stripping foils are needed to be as long as possible before replacement of broken foils. Effective lifetimes of carbon foils are investigated as a function of a foil peak temperature, using 38-keV DC electron beam with 2~3 mm diameter.

INTRODUCTION

In negative-ion accelerating cyclotrons a thin carbon foil is usually used to stripe two electrons from the negative ions shown in Fig. 1. Each negative hydrogen (H^-) ion consists of one proton and two electrons, which travel together during accelerating up to 70 MeV in cyclotron. Therefore the kinetic energy of electron is 38.13 keV at the moment of stripping. Power deposited in foils via stripping H^- ions includes energy losses by the proton and also by accompanying electrons. These energy losses of protons and electrons have been calculated by using PSTAR [1] and ESTAR [2] programs. When ions (protons and electrons) pass through a carbon foil, heat is generated mainly through the ionization loss and transferred by the radiation emission. After a time the foil is at thermal equilibrium, heat is emitted by thermal radiation, which is dominant because typical carbon foils have a relatively large ratio of area to volume. It is desirable to have foils running as long as possible before replacement, in order to minimize cyclotron downtime. However, an ion-induced damage, removal of atoms from the foil via elastic and inelastic collision is not considered. In this study, three carbon foils with different thicknesses (100, 200, 400, and 800 μg/cm^2) are investigated in order to find long-lived stripper foils for proton at the extracted energy of 70 MeV. The lifetime of the foil is defined as when the downstream beam is reduced by 10% of its initial value as shown in Fig. 1 (right side). Stripper foils have tested in order to estimate their lifetimes with energetic electron beams corresponding to the practical operating condition.

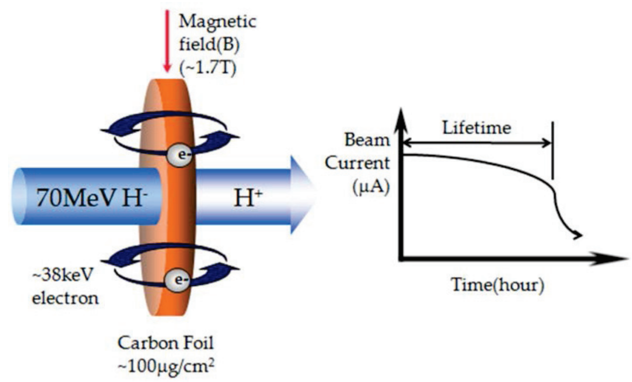

Figure 1: Schematic diagram of stripping two electrons from a negative ion by a carbon foil. As the foil is rupturing, the extracted beam current is decreasing. Since the electrons are travelling with 70-MeV protons together the kinetic energy of electron is 38.13 keV at the moment of stripping.

THEORY

A simplified adiabatic model could be used for an estimation of thermal distribution on the foil. Deposited power densities through the carbon foil by 70-MeV negative hydrogen ions with 1-mA current and by accompanying electrons are estimated by using PSTAR and ESTAR programs, respectively. The density of carbon foil is used as a value of 2.0 g/cm^3 [3].

Stopping Power for Protons

The energy loss of accelerated protons in matter is primarily due to ionization and atomic excitation as shown in Fig. 2. An electronic stopping power, average rate of energy loss per unit path length due to Coulomb collision is the main contribution for generating heat in matter. A nuclear stopping, energy loss per unit length due to the transfer of energy to recoiling is less effective when the ion's energy becomes high.

ISBN 978-3-95450-128-1

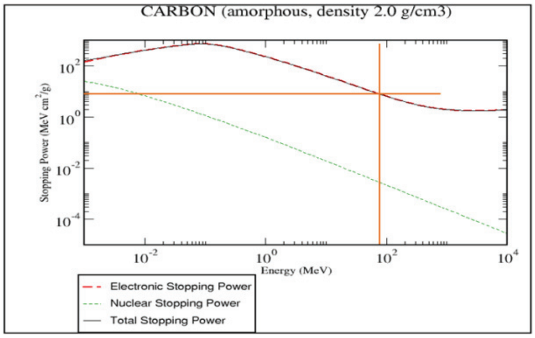

Figure 2: Stopping power and range tables [1] for proton at carbon foil. Line is indicated to corresponding at 70-MeV proton energy and the stopping power is estimated as a value of 8.51 MeV/(g/cm^2).

Stopping Power for Electrons

For electrons, the collision stopping power is dominant to generating heat at ~keV kinetic energy region. A radiative stopping power, average rate of energy loss per unit path length due to collisions with atoms and atomic electrons in which bremsstrahlung quanta are emitted is effective to hundreds MeV or higher energies (Fig. 3).

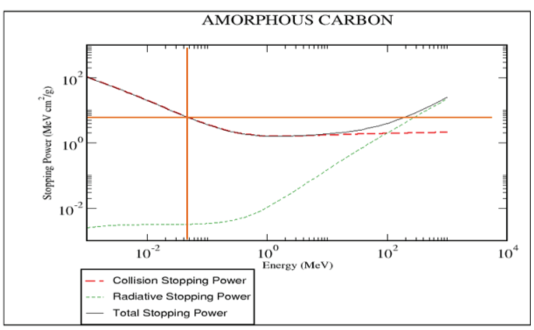

Figure 3: Stopping power and range tables for electron [2] at carbon foil. Line is shown at about 38.13-keV electron energy and the stopping power is corresponding to 7.25 MeV/(g/cm^2).

Total Power Deposited on Carbon Foils

Table 1 summarized the estimated powers deposited by protons and electrons on the carbon foils. The protons pass through the thin carbon foils release more energy as travelling a path longer. However, the electrons dissipate all their kinetic energies into the foils regardless their thicknesses due to stopping on the foil by strong magnetic fields.

Table 1: Summary of estimated powers deposited by protons and accompanying electrons. Total power is dominated by the power deposited from accompanying electrons.

Thickness (μg/cm^2)	100	200	400	800
By Protons (W)	0.85	1.70	3.40	6.80
By Electrons (W)	76.26	76.26	76.26	76.26
Total Power (W)	77.11	77.96	79.66	83.06

EXPERIMENTAL SETUP

Figure 4 shows a schematic diagram of experimental setup for measuring temperatures of carbon foils (made by Arizona Carbon Foil Co., Inc. [4]) whose thicknesses are 200, 400, and 800 μg/cm^2. The apparatus for this measurement has a small electron gun with a resistively heated W-filament as the source of electron. Electrons emitted by the filament are accelerated toward a grounded copper plate and passed through the carbon foils being tested with less than 3-mm diameter. An IR camera is used to measure foil temperatures through a window. All the measurements are carried in the vacuum below 3.2x10^{-7} Torr during the irradiation while the base pressure is 2.7x10^{-8} Torr.

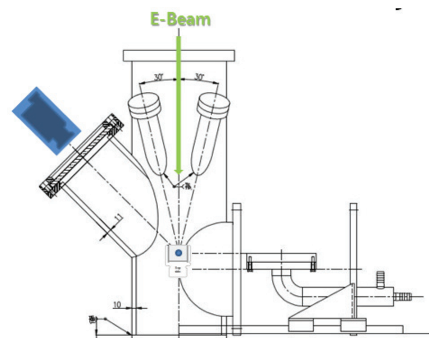

Figure 4: A schematic diagram for generating electron beam, measuring temperature on carbon foils.

RESULT AND DISCUSSION

Estimation of Temperature and Lifetime

Temperature can be estimated (see Eq. 1) assuming that the loss of heat through radiation balances the input heat deposited via the energy losses of the ions and electrons incident upon the foil [5].

$$T = \left[\frac{\left(\frac{P}{A}\right)}{(2e\sigma)}\right]^{1/4} \quad (1)$$

Where P/A is the power per unit area absorbed by the foil, e is its emissivity (= 0.8), and σ is the Stefan-Boltzmann (5.67x10^{-8} w/m^{2}T^4) constant. The factor 2 accounts for the emission from both faces of the foil. Using the beam parameters at cyclotron operating condition, the maximum temperatures on the carbon foils are 2,200 K, 1,800 K, 1,500 K, and 1,200 K for 100, 200, 400, and 800 μg/cm^2 thicknesses, respectively.

Above 1,800 K, an evaporation is expected to occur [6], resulting the thickness changes with accompanying stresses. The vapor pressure of carbon is moderately well defined as a function of temperature [7]. From the calculation of the evaporation rate at elevated temperatures, the lifetimes of carbon foil can be estimated. The lifetime was defined as the time required to evaporating the 10% mass of its original thickness. Table 2 summaries the dependence of carbon foil lifetime on its temperature with an incident power density, calculated using Eq. 1.

Table 2: Summary of deposited power, evaporation rate, and lifetime.

Thickness ($\mu g/cm^2$)	100	200	400	800
Deposited power (W)	77.11	77.96	79.66	83.06
Power Density (MW/m^3)	$1.97x10^6$	$9.99x10^5$	$5.07x10^5$	$2.65x10^5$
Estimated Temp (K)	2,200	1,800	1,500	1,200
Evaporation rate($g/cm^2/sec$)	$7.9x10^{-8}$	$7.6x10^{-11}$	$3.6x10^{-14}$	$3.6x10^{-19}$
Lifetime(Day)	0.014	30	$1.2x10^5$	$25x10^{10}$

For the measurement the electron gun provides current < 10 mA in a spot with diameter of 2 mm, and has been used to provide comparisons between foils of different thickness at elevated temperatures. Figure 5 shows the comparison of the foils before and after electron beam irradiation. Three carbon foils with a dimension of 17 mm x 17 mm, is mounted on an Al-frame in a vacuum chamber. All foils are shown to be shrunken with a sufficient irradiation. The shrinkage may be a first step cause of breakage seen at the foils of 200- and 400-$\mu g/cm^2$ thicknesses. A hot spot on the foil is produced by electron beams.

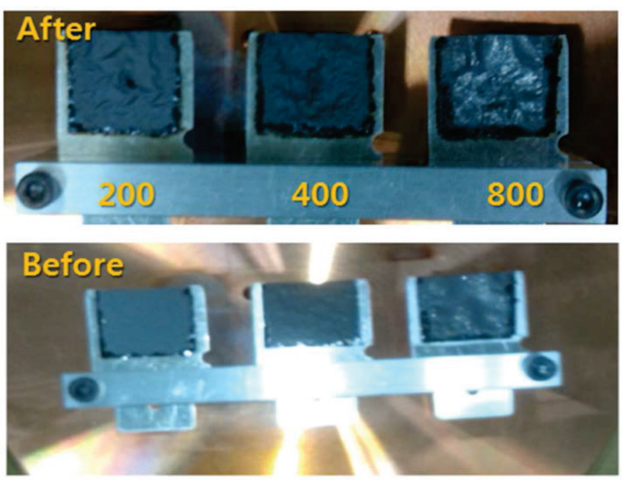

Figure 5: A photo of the carbon foils mounted on Al-frame in vacuum chamber (top) after and (bottom) before electron beam irradiation. The irradiated electron beam size is measured with a 2-mm diameter.

Temperature on foils is measured by an IR thermometer (Chino) while an electron-beam irradiation (see Fig. 6). It is shown that the foil temperature elevates as the current increases up to 7 mA. However, at 10 mA the temperature falls and remains below 1,700 K that may be caused by a hole appeared on foil as shown in Fig. 5. To make this testing more quantitative, an effect of secondary electron and hot spots must be minimized. Another test will be carried.

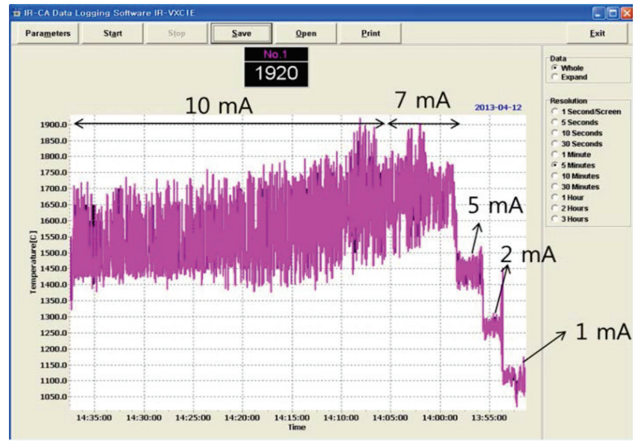

Figure 6: Variations of temperature from 200-$\mu g/cm^2$ carbon foils with an electron beam irradiation. The large fluctuation may be due to transmitted and secondary electrons.

The conclusion is the lifetime of the carbon foil will be short for thinner foils with higher beam currents. The lifetime of a carbon stripping foil would decrease sharply when the foil temperature exceeds 2,000 K.

Discussion

Lifetime of the stripping foil carbon foils primarily depends on the factors of beam current density, foil thickness, and so on. Due to the scattering of the H^- and electron the carbon foil produces a high temperature. When the foil temperature is low, the foil fails mainly due to the radiation damage and the foil temperature is high the sputtering effect becomes more dominated and consequently would become more shorten the foil lifetime significantly. For achieving an effective foil's lifetime longer, a thicker one is prefer. But the thicker foil would result in severe beam emittance due to multiple Coulomb scattering.

REFERENCES

[1] Stopping power and range table for proton (PSTAR), http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html
[2] Stopping power and range table for electron (ESTAR), http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
[3] J.O. Stoner Jr., Nucl. Instr. and Meth. A 303 (1991) 94.
[4] Arizona Carbon Foil Co., Inc., Tucson, AZ.
[5] S. A. Miller, C. S. Jolivert, and J. O. Stone, Nucl. Inst. and Meth. in Phy. Res. A 590 (2008) 57.
[6] I. Sugai, Y. Takeda, M. Oyaizu, H. Kawakami, Y. Irie, Y. Arakida, K. Hara, H. Hattori, K. Kawasaki, J. Kamiya M. Kinsho, and K. Kuramochi, Nucl. Instr. and Meth. A 561 (2006) 16.
[7] A. L. Marshall, and F. J. Norton, J. Am. Chem. Soc. 72 (1950) 2166.

ISBN 978-3-95450-128-1