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Study of Cyclotron Carbon Foil Thickness for Lifetime Extension

J.H. Kim[a], S.K. Hong[a], J.W. Kim[a], Y.K. Choi[b], Y.S. Kim[b]
[a]*Rare Isotope Science Project (RISP), Institute for Basic Sciences (IBS),*
70 Yuseong-daero 1689-gil, Yusung-gu, Daejeon, Korea 305-811
E-mail:jhkim68@ibs.re.kr
[b]*Department of Nuclear & Energy System Engineering, Dongguk University*
707, Seokjang-dong, Gyeongju 780-714
E-mail:unison@dongguk.ac.kr

1. Introduction

For extracting positive hydrogen atoms from accelerated negative ones, a thin carbon foil is usually used to stripe two electrons from the negative atom shown in Fig. 1. Each negative hydrogen (H^-) consists of one proton and two electrons, which travel together during accelerating up to 70MeV. Therefore the kinetic energy of electron is 38.13keV at the moment of stripping. The energy loss of protons and electrons in carbon foil could be estimated by the multiplication of stopping power (dE/dz) and the foil thickness. The stopping powers were estimated with 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 ~1.5 Tesla, which makes electrons circular motion around the foil depositing all their kinetic energies into it. In this study, several different carbon foil thicknesses (100, 200, 400, and 800 μg/cm^2) were investigated the correlation of foil temperature and their lifetime for the case of 1mA proton extraction. Lifetime of a stripper foil has to be sustained as long as at least two weeks for irradiating protons onto an ISOL target.

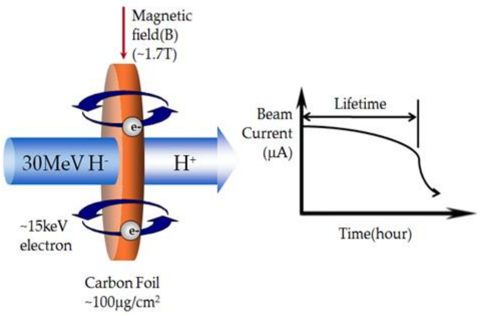

Fig. 1. Schematic diagram of stripping two electrons from a negative ion by a carbon foil. When the foil is rupture, the beam current starts to decrease. Stripping reaction in foil is followed as $H^- \rightarrow p^+ + 2e^-$.

2. Theory

When ions (protons and electrons) pass through a carbon foil, heat is generated mainly through the ionization loss and transferred by the radiation emission. A simplified adiabatic model could be used for an estimation of thermal distribution on the target. Deposited power densities through the carbon foil by 70MeV negative hydrogen ions with 1mA current were estimated by PSTAR [1] and ESTAR [2] programs, respectively. The density of carbon foil is used as 2.0g/cm^3.

2.1. 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.

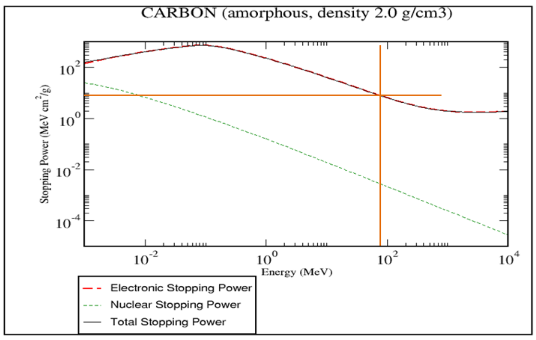

Fig. 2. Stopping power and range tables for proton at carbon foil. Line is located at 70MeV energy.

2.2. Stopping power for electrons

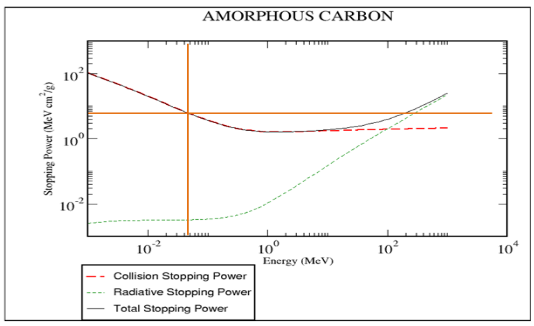

Fig. 3. Stopping power and range tables for electron at carbon foil. Line is located at about 38.13keV energy.

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.

2.3. Total deposited power to carbon foils

Table 1 summarized the deposited powers by protons and electrons on the carbon foils whose thickness varies from 100 to 800μg/cm². The protons pass through the thin carbon foils release more energy when they are travel longer path. However, the electrons dissipate all their kinetic energies into the foils regardless their thicknesses due to the trap by magnetic field.

Table 1: Deposited powers by protons and electrons

Thickness (μg/cm²)	100	200	400	800
Protons(W)	0.85	1.70	3.40	6.80
Electrons(W)	76.26	76.26	76.26	76.26
Total(W)	77.11	77.96	79.66	83.06

3. Experimental Setup

Fig. 4 shows a schematic diagram for measuring temperatures of carbon foils whose thicknesses vary from 100 to 800μg/cm². An electron beam having 3mm diameter is irradiated vertically from the top of the chamber. A camera will measure their temperatures through a window. A base pressure is kept at ~10^{-6} Torr during the measurements.

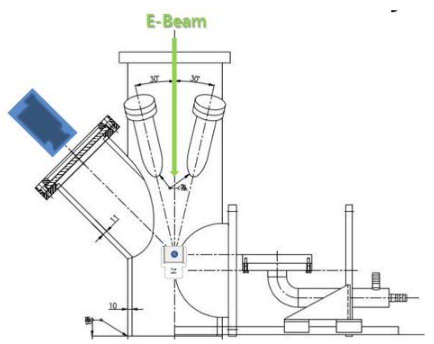

Fig. 4. A schematic diagram for measuring temperature from carbon foils with an electron beam.

4. Result and Discussion

4.1. Estimation of temperature and lifetime

Temperature could be estimated by a well-known equation (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 [3].

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

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 (5.67×10^{-8} w/m^2T^4) constant. The factor 2 accounts for the emission from both faces of the foil.

From the calculation of the evaporation rate at elevated temperatures, the lifetimes of carbon foil could be estimated [4]. The lifetime was defined as the time required to evaporating the 10% mass of its original thickness.

Table 2: Deposited powers by protons and electrons

Thickness (μg/cm²)	100	200	400	800
Deposited power (W)	77.11	77.96	79.66	83.06
Power Density (MW/m^3)	1.97×10^{6}	9.99×10^{5}	5.07×10^{5}	2.65×10^{5}
Estimated Temp (K)	2,200	1,800	1,500	1,200
Evaporation rate(g/cm²/sec)	7.9×10^{-8}	7.6×10^{-11}	3.6×10^{-14}	3.6×10^{-19}
Lifetime(Day)	0.014	30	1.2×10^{5}	25×10^{10}

4.2. Discussion

For an effective longer lifetime of foils, thicker one is prefer for a long operation. But the thicker foil would result in severe beam emittance due to multiple Coulomb scattering.

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