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A Development of Faraday Cup for the Application to the SNU Tandem Accelerator Beam Line

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Abstract

Typical Faraday cup was designed and developed for practical use in Seoul National University (SNU) Tandem accelerator beam line. In order to make it use in the beam line, several conditions were taken into considerations such as physical dimensions, cup materials, its heat load caused by proton energy, the reaction of proton with cup material, and material activation following its nuclear reaction. In this paper, the requirements of the Faraday cup design were studied and discussed.

1. Introduction

There are many kinds of way in detecting or monitoring a beam itself and its uniformity or characteristics corresponding to beam-applied energy range, flux, and dimension, etc. For instances, a scintillating fiber detector has been developed and applied for monitoring an intense beam.[1] High-sensitivity diamond-based beam monitors that have very high radiation hardness have been also developed and usefully used in case where a monitoring must be performed in intense radiation fields.[2] Compared with the above detectors, Faraday cup is relatively simple device as a beam monitor. Since the cup was originally constructed about thirty-five years ago, its design has been changed several times step by step in order to modernize and improve the reliability of the key system of the cup. As a result the Faraday cup (FC) has been come up to the development of a micro-Faraday array-typed monitor for probing uniformity of ion beam.[3]

In this work, we present studies on the several requirements of the Faraday cup, and ultimately determined the cup design to run adequately in Seoul National University Tandem accelerator beam line. This beam line will be utilized to variable research fields such as semiconductor irradiation process, flowering plants as well as basic research. So it would be indispensable to understand the beam characteristics fundamentally.

As physical properties of the SNU Tandem accelerator beam line, it has a maximum energy with 6 MeV, beam current with 6 μA, and beam diameter with 2 mm. Based on the beam conditions, Faraday cup was designed to consider as follows.

2. Design Considerations

a. Physical dimensions

An important characteristic of Faraday cups is its performance in trapping incident ion, or protons in our case, without allowing the proton to backscatter out of the cup, sputter away material from the cup, or emit secondary electrons back out of the cup, because both cases could change the collected charge state of the cup. Such problems can be settled by several ways that is well known. One of the ways is dimensional structure, that is, the ratio of diameter to the length of the cup become making it about 1/5. A schematic of the Faraday cup is shown in Figure 1. In the figure 1, the aperture size is 10 mm, and full length is about 67 mm. The housing of the cup was designed to attach to a moving-up and down plate.

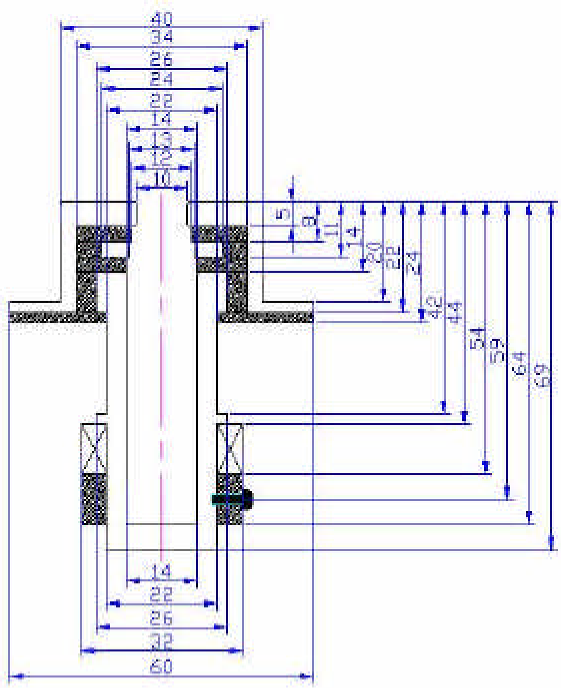

Figure 1. Drawing view of the Faraday cup.

For suppressing secondary electrons, we have employed two methods, that is, one is to suppress it by magnetic field using of permanent magnets, and the other is to do by electric filed using voltage-applied ring. Magnetic field B of the magnet is determined by the calculation of the equation (1) for the relationship between the magnetic field and secondary electron energy, provided that the energy range of secondary electrons emitted from the cup surface is limited as below ~1 keV.

$$r = \frac{m_e \cdot v}{qB\sin q} = k\frac{\sqrt{T_E}}{B} \cong 3.37\frac{\sqrt{T(eV)}}{B(mT)} \text{ [mm]} \tag{1}$$

Where $k_{\min} = \frac{\sqrt{2m_e}}{q\sin q} \cong \frac{\sqrt{2\times 9.109\times 10^{-31}}}{1.6\times 10^{-19}\times \sin q} \cong 3.37$

The bending radius r is fixed with a value of 5 mm since the inlet aperture diameter of the Faraday cup is 10 mm. Referring to the constrained condition of the bending radius, the estimation of the magnet filed corresponding to the secondary electron energy is presented in Table 1.

Table 1. A Magnetic field corresponding to the secondary electron energy

Radius	Electron Energy	B (θ=0.44π)		B (θ=π/2)		Average B	
(mm)	Max (keV)	(mT)	gauss	(mT)	gauss	(mT)	gauss
	0.5	76.9	769.2	15.1	150.7	46.0	460.0
	0.6	84.3	842.6	16.5	165.1	50.4	503.9
	0.7	91.0	910.1	17.8	178.3	54.4	544.2
	0.8	97.3	973.0	19.1	190.6	58.2	581.8
	0.9	103.2	1032.0	20.2	202.2	61.7	617.1
5	1	108.8	1087.8	21.3	213.1	65.0	650.5
	1.1	114.1	1140.9	22.4	223.5	68.2	682.2
	1.2	119.2	1191.7	23.3	233.5	71.3	712.6
	1.3	124.0	1240.3	24.3	243.0	74.2	741.7
	1.4	128.7	1287.1	25.2	252.2	77.0	769.7
	1.6	137.6	1376.0	27.0	269.6	82.3	822.8

As shown in equation (1), the k value contributes to the bending radius and depends on the incident angle of the electron to the direction of magnetic field B. The angle has a range of $\sin\frac{d}{\sqrt{l^2+d^2}} \cong 0.196 \le \sin q \le 1$, where l denotes the length of Faraday cup, and d is diameter. Table 1 shows magnetic field values for maximum and minimum together with average in case that θ has a maximum and minimum value. Referring the results, the magnetic field for suppression could be enough to be 700 gauss at the center of magnet. The magnets are arranged near to the bottom of the cup for early bending paths of the secondary electrons. In addition to that, the suppression ring was also mounted on the cup as a spare suppressor.

Permanent magnets equipped in the Faraday cup are shaped in truncated cylindrical style with a thickness of 10 mm and consisted of two pieces. Magnetic pole of one of the two magnets is configured to be S pole at inner side and N pole at out side or vice versa. By the hand, the pole configuration of another piece of magnet is contrary to the coupled one.

In the selection of materials of the Faraday cup, radiations, heat road, and machinable hardness were considered. Aluminum has been known to minimize activation. So, that material was applied to the cup, which is consisted of two parts, i.e., inner part made of pure aluminum about 99.9% and housing part made of aluminum alloy. Macor, a machinable glass ceramic as an insulator was inserted for electric insulating between the housing and the inner cup[4].

b. Nuclear reaction

Activation by the reaction of proton with material may give rise to radiation. By taking it into consideration, the Faraday cup was made by pure aluminum as remarked above, and the housing is done by hard aluminum for easy in machining and strength.

When a proton with energy of 1 to 6 MeV reacts with aluminum, it produces a neutron and ^{21}Si daughter nuclei. We have calculated neutron flux caused by the reaction (p, n). Figure 2 shows microscopic cross-section with respect to proton energy.

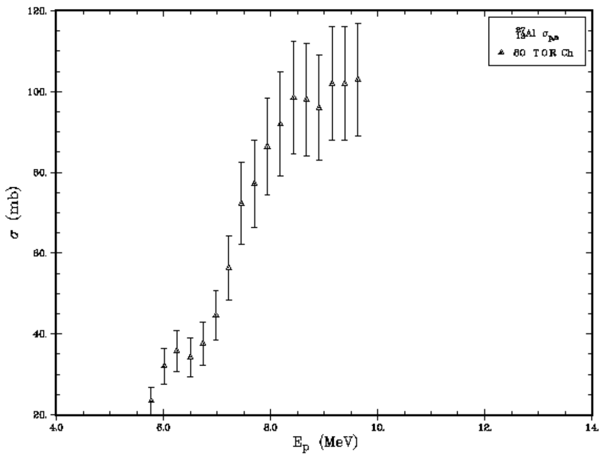

Figure 2. A graph of cross-section verses proton energy.[5]

When reaction equation is expressed in equation (2), reaction rate R_R, and transmission rate R_T of proton can be defined respectively as equations of (3) and (4). Once we use the above cross-section data, the two reaction rates can be easily obtained.

$$F = F_0 e^{-s_m \cdot x} = 1.194\times10^{15} e^{-0.0259 \cdot s_m} \quad (2)$$

where $s_m = N \cdot s = r \dfrac{N_A}{A_{Al}} \cdot s = 6.024\times10^{22} \cdot s$

$$R_T(\%) = \frac{F}{F_0} \times 100 \quad (3)$$

$$R_R(\%) = 100 - R_T = 100 - (\frac{F}{F_0} \times 100) \quad (4)$$

where F_0 is initial flux of positron, and F is a flux passing through aluminum with a thickness x, σ_m denotes macroscopic cross-section defined as above. N_A denotes Avogadro's constant, ρ is a density of aluminum, and A is an atomic weight of aluminum. TRIMM code was used to calculate x value for the proton energy of 6 MeV. Figure 3 shows the result of stopping power. The ion range of proton in aluminum from the simulation result is substituted in the equation (2) as x value.

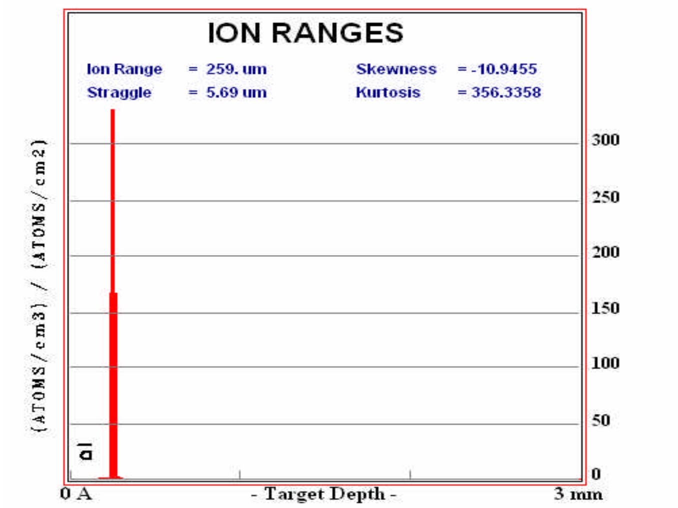

Figure 3. Proton range in pure aluminum target with a maximum energy of 6MeV.

Table 2. Neutron flux and transmission flux and its ratio respect to proton energy

Energy (MeV)	σ (mb)	Transmission Flux $\times10^{13}(cm^{-3}s^{-1})$	Reaction Ratio R_R (%)	Neutron flux $\times10^{10}(cm^{-2}s^{-1})$
5.77	23.4	119.423	0.004	4.209
6.01	32	119.421	0.005	5.756
6.25	35.8	119.420	0.005	6.439
6.5	34.3	119.421	0.005	6.169
6.74	37.6	119.420	0.006	6.763
6.98	44.6	119.419	0.007	8.022
7.702*	70.082	119.414	0.011	12.605

The rate, R_R and R_T respect to the proton energy are summarized in Table 2. Neutron flux generated from the (p, n) reaction is considered more or less over estimated, because other reactions were neglected. The Faraday cup will be installed in the irradiation chamber. So, it could be expected that the neutron flux be decreased more or less. End line in the table 2 represents average values respect to average proton energy. Considering the chamber shielding effect with its thickness of 1.5 cm and shielding distance, resultant flux is a order about ~10^4 $cm^{-1}s^{-1}$ But the flux is still not a low value. In the further, shielding problems would be taken into considerations some more.

c. Heat load calculation

An important requirement to make Faraday cup is also relative to the heat load to the cup material delivered by the proton energy. We have investigated the heat load. It was simulated by the use of ANSYS code. For the heat interpretation, the material characteristic data was applied to the simulation code. Table 3 shows the material characteristic data.

Table 3. Characteristic data for the ANSYS simulation

	K [watt/mm.K]	Cp [J/Kg.K]	ρ [Kg/mm^3]
Pure Al	0.237	903	2.702E-6
Al alloy (2024-T6)	0.177	875	2.77E-6
Pure Copper	0.401	385	8.933E-6
Macor	1.46E-3	800	2.52E-6

In simulating the heat load, the boundary condition is adopted as follows; the beam is assumed to flows like a heat flux, the heat flux is calculated based on the our beam properties as mentioned early, and finally applied to the simulation conditions as 9.55 watt/mm^2. Initial temperature gets started in 20°C. The heat load interpretation was performed to use a solid tetragonal-shaped element having ten node points. The simulation was done in two cases, that is, the thickness of aluminum has 3mm and 5 mm. Maximum allowable temperature change was obtained with respect to beam irradiation time when the aluminum surface is irradiated. The results are shown in table 4 and in Figure 4.

Table 4. Temperature increasing relative to the irradiation time in case of 3 mm thickness.

Irradiation time	10sec	60sec	120sec	180sec
Temperature (Max.)	91.5℃	174.8℃	272.5℃	369.9℃

In case of 3mm thickness, it realized that the maximum irradiation time is limited in about 3~ 5 minutes, considering that the melting point of aluminum is about ~680°C provided that the material is not cooled. The result of the thickness of 5 mm is also presented in table 5 and in figure 5. In the figures, gray scale level represents the temperature degree.

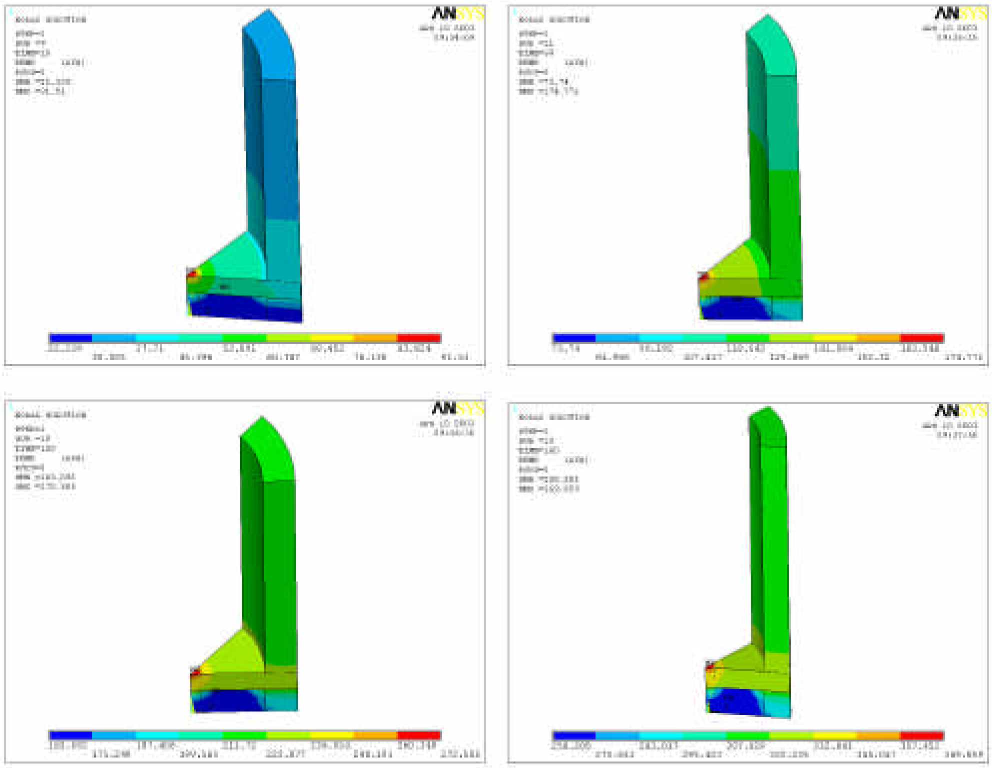

Figure 4. Simulation results for the 3mm thickness pure aluminum with time variations.

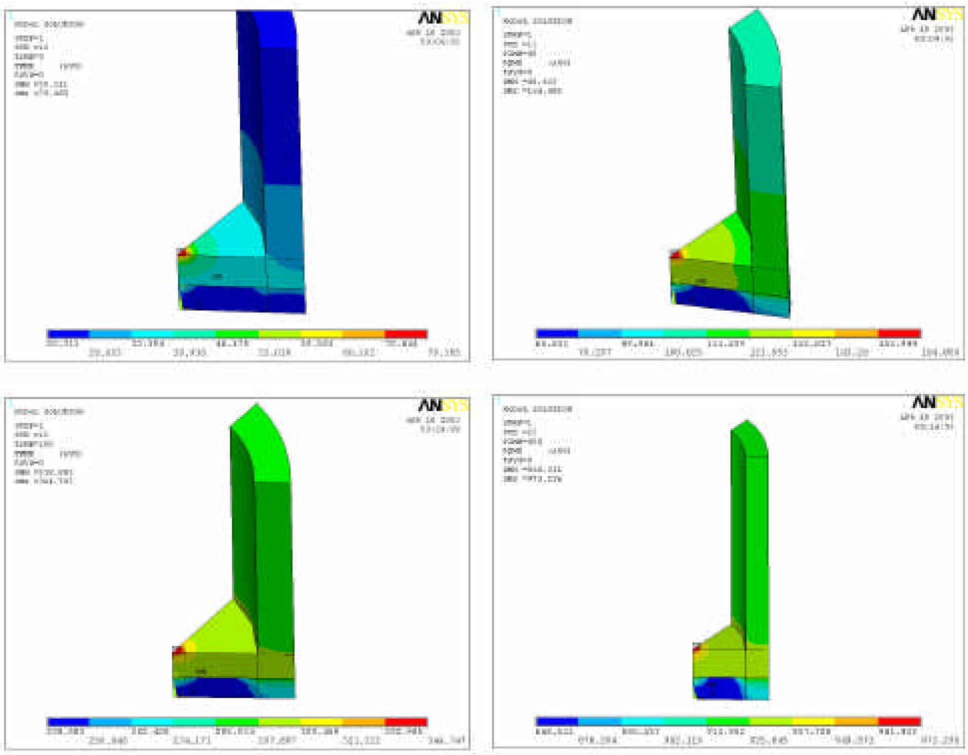

Figure 5. Simulation results for the 5mm thickness pure aluminum with time variations.

Table 5. Temperature increasing relative to the irradiation time in case of 5 mm thickness

Thick=5mm	5sec	60sec	180sec	600sec
Temperature (Max)	79.2℃	164.6℃	344.8℃	973.3℃

Referring to the data in table 5, we can look forward that the irradiation time can be extended to nine minutes. According to the results, the thickness of the bottom part in Faraday cup was adopted to use as thickness of 5 mm.

3. Future Plans

Those requirements for the development of Faraday cup are very important because it will be usefully basic information for the enhancement of the system. The Faraday cup will be applied directly to the beam line for beam monitoring and detecting. Soon or later, such developed Faraday cup will be tested in 6 MeV SNU Tandem accelerator beam line as well as in other several ion beam stages and then, according to the test results, it will be supplemented if necessary. We have a plane that the Faraday-typed monitor system will get more advanced to array-typed cup on the assumption that the developed system become to be successful. Based on these requirements and conditions for the development of Faraday cup including with test results, many experiences and data will be reflected and applied to new arrange-typed Faraday cup to be developed.

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