THE USE OF GRAPHENE AS STRIPPER FOILS IN SIEMENS ECLIPSE CYCLOTRONS

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Abstract

This paper presents the results of an experimental study for the use of graphene foils as an extractor (stripper) foil in the 11-MeV Siemens Eclipse Cyclotron. The main advantage of graphene foils compared with carbon is very high thermal conductivity. The graphene also has significant mechanical strength for atomically thin carbon layers. The life time of these foils is more than 16,000 μA*H. The graphene foils showed a significant increase in the transmission factor (the ratio of the beam current on the stripper foil to the current on the target), which was approximately more 90%. The technology in fabricating these graphene foils is shown. The pros and cons of using the graphene material as a stripper foil in cyclotrons are analysed.

INTRODUCTION

The use of stripper foils in the cyclotrons with negative hydrogen ions allows for easy output of the proton beam from the cyclotron into the target [1]. The 11-MeV Eclipse Cyclotron [2] uses this approach for the production of medical isotopes. The standard stripper foils based on carbon materials are widely used for these goals. The discovery of graphene [3] and the unique properties of graphene have created a large interest in this material as a stripper foil compared to the standard graphite and carbon foils. The main difference is the thermal conductivity of graphene which is up to 20 times higher than that of polycrystalline graphite. This gave interest for the application of graphene as a stripper foil in accelerators of charged particles and especially in commercial cyclotrons, such as the Eclipse cyclotron. The preliminary application of graphene foils from Applied Nanotech [4] as a stripper foil shows the main advantages of this material in comparison with the standard carbon and graphite foils. The main focus of this study was to determine the lifetime of stripper foils and to understand any cyclotron operating performance improvements. One the main questions was to characterize the radiation damage of graphene under irradiation by negative hydrogen ions with a kinetic energy of 11 MeV and current up to 100μA.

THE TECHNOLOGY OF FABRICATION FOR GRAPHENE FOILS

The technology for the fabrication of graphene foils is described in more detail in [5]. The foil fabrication method is based on the controlled reduction of graphene oxide by hydrazine with addition of ammonia in an aqueous dispersion. The dispersion of graphene oxide with loading of 0.5% wt. in water was obtained from Angstron Materials. The dispersion was reduced for 4 hours at 95°C and then cooled down to room temperature. The thickness of graphene foils was controlled by using a calculated volume of graphene dispersion knowing the loading of graphene. A commercially available stainless steel filter holder was used to make graphene foils by pressure filtration. The diameter of the fabricated foils was 13 cm. The filter holder allowed increasing the differential pressure across the filter. A compressed air line with a pressure regulator was connected to the filter holder to pressurize the air space above the graphene dispersion. Pressure up to 300 kPa was used to filter the dispersion. Commercially available polymer filter membranes with a diameter of 142 mm were used for the filtration. After filtration, graphene foils still on the filter membrane were removed from the filter holder and peeled off the filter membrane to obtain free-standing graphene foils. The described process can be adapted to fabricate foils with a wide range of foil thickness and using different isotopes of carbon.

EXPERIMENT

The experiments with graphene foils with a thickness of about 3μm (0.5mg/cm^2) were conducted on four Siemens Eclipse cyclotrons. The graphene foils were installed on the carousels of the Eclipse cyclotron. The general picture of the graphene material is shown in Figure 1.

a) **b)**

Figure 1: General view of graphene foils: a) fabricated foil; b) graphene cross section.

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The dimension of graphene stripper on the carousel of Eclipse cyclotrons is 10mm x 10mm.

Experiments were conducted on the Siemens Eclipse Cyclotron [2], an example of is shown in Figure 2.

Figure 2: View of the Eclipse cyclotron.

The main experiments were conducted with main parameters of Eclipse cyclotrons:

1 Energy of negative hydrogen ions is 11 MeV.
2. Beam current on the foils ranged from 30 to 100 µA.
3. Beam current on the Faraday Cups (target) ranged from 25 to 80 µA.
4. Beam diameter of negative hydrogen ions is about 10 mm.

EXPERIMENTAL DATA

The experimental data was collected from four Eclipse cyclotrons. The summary of data for the transmission factor measurements is given in Table 1. The experimental study of high current mode of Eclipse cyclotrons with dual proton beam 80 µA on each target showed a decreasing level of the ion source current (arc current); see the plot in Figure 3. The bias current level was also observed to decrease during the experiments. The main experimental result of testing of cyclotron with graphene stripper foils is high transmission factor allowing the decreasing of ion source current. The good experimental correlation is decreasing of thickness with high thermal conductivity and ion source current permits us to work with a relative low current ion source. This in turn increases the life time of ion source.

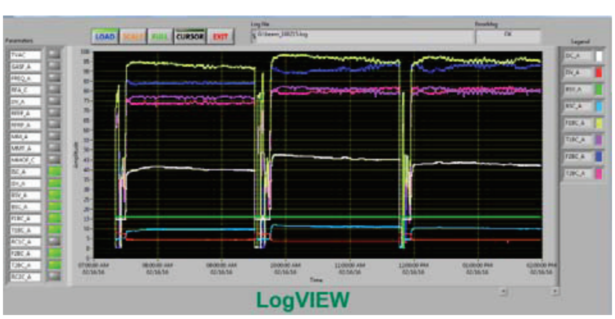

Figure 3: The log file display.

Table 1: Experimental Data

Cyclotron	Proton Beam Current (µA)	Transmission Factor (*) (%) Reg/Gr		Ion Source Current (*) (mA) Reg/Gr
1	2 x 55	86/75	92/78	230/192
2	2 x 25	80/81	88/89	120/90
3	2 x 60	75/88	89/90	340/250
	2 x 75	70/72	87/92	500/300
4	2 x 60	73/82	82/90	320/220
	2 x 80	70/85	82/93	600/450

(*) for Regular/Graphene stripper foils

LIFE TIME OF GRAPHENE FOILS

The lifetime of stripper foils is determined by 2 main mechanisms: radiation defects and sublimation [6, 7]. The experiments with graphene foils on the Eclipse cyclotron showed the radiation defects and sublimation have place. The lifetime of graphene foils determined by beam losses of the transmission factor and the mechanical destruction of graphene foil. The main contribution to lifetime is temperature from dissipation of beam energy. Typically considering dissipated power of the beam in the stripper is 1%, we have total dissipated power for beam in the Eclipse cyclotron of about 10 W for a 90 µA beam into the foil (for production of dual beam 2x80 µA). The distribution of temperature in graphene foil using Comsol Multiphysics package is shown in Table 2.

The lifetime test of the graphene foils on one of the Eclipse Cyclotrons was tested and resulted in a lifetime of 16,000 µA*Hours, which is 60% higher than the existing specification.

Table 2: Temperature Distribution in Stripper Soil

Dissipation Beam Power (W)	T_{min} Graphene (°C)	T_{max} Graphene (°C)	T_{min} Graphite (°C)	T_{max} Graphite (°C)
10	355	552	251	706

Figure 4 shows a picture of damaged graphene foil as observed at the end of this lifetime test.

Figure 4: A damaged graphene foil.

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DISCUSSION ABOUT USING OF GRAPHENE AS A STRIPPER FOILS

The use of Graphene as a stripper foil shows benefits in comparison to the regular polycrystalline graphite foils. The main pros and cons of graphene compared with the standard stripper foils are provided in Table 3.

Table 3: Comparison of Strippers

Stripper Foil Type	Pros	Cons
Carbon	Low cost	Lifetime Thermal conductivity Foil ablation
DLC	Lifetime Small thickness	High cost Fabrication technology
Polycrystalline graphite	Low cost	Lifetime Thermal conductivity Foil ablation
Graphene	High thermal conductivity Small thickness Lifetime	Fabrication technology Limited suppliers

RECOMMENDATIONS

The graphene foils can be competitors to other carbon foils that are used as stripper foils, such as a DLC or polycrystalline graphite. Our investigations showed the benefits of using the graphene stipper foils. The question remains as to whether the technology to fabricate the graphene foils will continue to develop as well as the resulting cost.

CONCLUSIONS

In conclusion we can say that graphene stripper foils have a future that will require additional testing on diffrenet types of accelerators with stripper foils. The main advantuge of the graphene stripper foils is their unique properties, such as a high thermal conductivity and high mechanical strength compared to the standard carbon and graphite type foils.

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