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# Characterization of graphene stripper foils in 11-MeV cyclotrons

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**Abstract**

An experimental study of the use of graphene as an extractor (stripper) foil in the 11-MeV Siemens Eclipse Cyclotron is discussed in this paper. The main advantage of graphene is its high thermal conductivity compared to that of amorphous carbon films. Graphene also has significant mechanical strength. The lifetime of the graphene foils under proton bombardment exceeded 16,000 µAh. Graphene-based stripper foils demonstrated a significant increase in the transmission factor (defined as the ratio of the beam current on the target to the beam current on the stripper foil), which was approximately 90%. Fabrication of the graphene-based foils is discussed. The pros and cons of using the graphene material as a stripper foil in cyclotrons are analyzed.


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*Keywords:* Stripper foil; graphene, cyclotron, eclipse, extractor foil

## 1. 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 (see Papash *et al.* 2008). The 11-MeV Eclipse Cyclotron uses this approach for the production of medical isotopes. The standard stripper foils are based on carbon foil materials. The discovery of graphene and the unique properties of graphene have created significant interest in this material as a stripper foil and compare it to the standard graphite and amorphous carbon foils. The main difference in these materials is the thermal conductivity of graphene, which is much higher than that of polycrystalline graphite. This motivated our interest for the application of graphene as a stripper foil in accelerators of charged particles, especially in commercial cyclotrons such as the Eclipse Cyclotron. Preliminary tests of graphene-based foils from Applied Nanotech in charge stripping applications demonstrated a few key advantages of this material in comparison with standard carbon and graphite foils (Pavlovsky and

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Fink, 2012). The main focus of this study was to assess the lifetime of stripper foils and to understand any cyclotron operating performance improvements. Another goal of this effort was to characterize the radiation damage of graphene under irradiation by negative hydrogen ions with a kinetic energy of 11 MeV and currents up to 100μA.

## 2. Fabrication of graphene-based foils

The technology for the fabrication of graphene foils is described in more detail in Pavlovsky and Fink (2012). The foil fabrication method is based on the controlled reduction of graphene oxide by hydrazine with addition of ammonia in 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 out 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 foils. The described process can be adapted to fabricate foils with a wide range of thickness and different isotopes of carbon.

## 3. Experiment

### *3.1. Design*

The experiments with graphene foils with a thickness of approximately 3μm (0.5mg/cm$^2$) were conducted on four Siemens Eclipse cyclotrons. The graphene foils were installed on the cyclotron carousels. A photograph and an SEM cross-section of the graphene material are shown in Fig. 1. The SEM analysis was performed at Cerium Labs (Austin, TX) using a Hitachi S4800 field emission scanning electron microscope. The edge view was created after mechanically cutting the foil.

a) b)

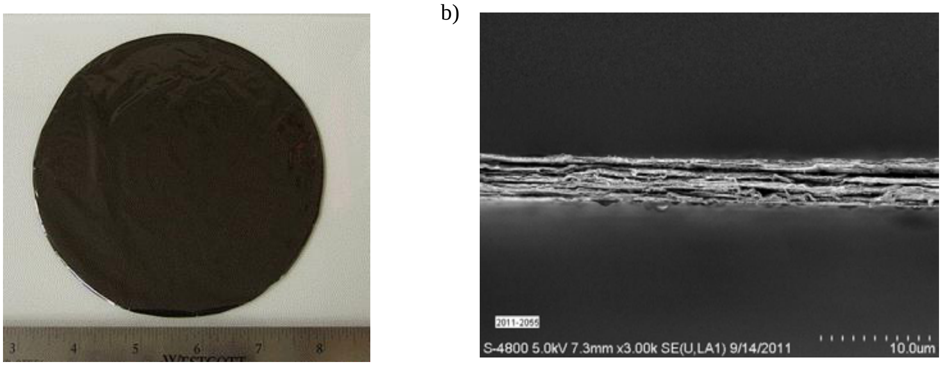


Fig. 1. Images of graphene foils: a) a photograph of a fabricated foil, scale in inches; b) SEM of graphene foil cross section (scale on image). The dimensions of a graphene stripper foil on the carousel of Eclipse cyclotrons is 10mm x 10mm.

Experiments were conducted on the Siemens Eclipse Cyclotron (see Fig. 2).

The beam parameters used in the experiments were the following:

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

Fig. 2. The general view of the Eclipse Cyclotron

### *3.2. Results*

The experimental data were collected from the four Eclipse cyclotrons. The summary of the transmission factor measurements data is provided in Table 1. The experimental study on high current mode with dual proton beam of 80 µA on each target demonstrated a decreasing level of the ion source (arc) current (see Fig. 3). The bias current level was also found to decrease during the experiments. The main result of experimental testing with graphene stripper foils is a higher transmission factor that leads to a decrease of ion source current. Decreasing foil thickness combined with high thermal conductivity of the foil permits us to work with lower ion source currents. This results in an increase of the lifetime of the ion source.

Table 1. Experimental data

| Cyclotron | Proton beam current (µA) | Transmission factor for regular and graphene stripper foils (%) | Ion source current for cyclotron with regular and graphene stripper foils (mA) |
|---|---|---|---|
| Cyclotron #1 | 2x55 | 75/86; 78/92 | 230/192 |
| Cyclotron #2 | 2x25 | 80/81; 88/89 | 120/90 |
| Cyclotron #3 | 2x60 | 75/88; 89/90 | 340/250 |
| | 2x75 | 70/72; 87/92 | 500/300 |
| Cyclotron #4 | 2x60 | 73/82; 82/90 | 320/220 |
| | 2x80 | 70/85; 82/93 | 600/450 |


Fig. 3. Experimental log plot

### *3.3. Lifetime of graphene-based foils*

The lifetime of the stripper foils was determined based on the observed radiation defects and sublimation [Koptelov *et al.* (1987) and Gikal *et al.*]. The experiments with graphene foils on the Eclipse cyclotron demonstrated that both the radiation defects and sublimation took place. The lifetime of graphene foils was determined by beam losses of the transmission factor and the mechanical destruction of graphene foil. The main contribution to limitation of the lifetime is high foil temperature due to dissipation of beam energy. Considering that the dissipated power of the beam in the stripper being typically 1%, we have a total dissipated power for beam in the Eclipse cyclotron of about 10 W for a 90 µA beam current (for production of dual beam 2x80 µA). A temperature distribution in a graphene foil calculated using Comsol Multiphysics FEA package is summarized in Table 2.

The lifetime test of the graphene foils performed on one of the Eclipse Cyclotrons has demonstrated a lifetime of 16,000 µA*hrs, which is 60% higher than the existing specification lifetime. Figure 4 shows a picture of a damaged graphene foil taken at the end of this lifetime test.

Table 2. Simulation of temperature distribution for different foil materials

| Beam power dissipation | Tmin graphene | Tmax graphene | Tmin graphite | Tmax graphite |
|---|---|---|---|---|
| 10 Watts | 355°C | 552°C | 251°C | 706°C |

Fig. 4. Picture of damaged graphene foil.

### *3.4. Discussion*

The main advantages and disadvantages of graphene as a stripper foil material compared with the standard stripper foils are provided in Table 3.

Table 3. Comparison of foil materials

| Type of stripper foil | Pros | Cons |
|---|---|---|
| Carbon foil | • Low cost | • Short lifetime<br>• Poor thermal conductivity<br>• High ablation rate |
| Diamond-like carbon | • Good lifetime<br>• Small thickness | • High cost<br>• Fabrication method |
| Polycrystalline graphite foil | • Low cost | • Lifetime<br>• Thermal conductivity<br>• Ablation of foil |
| Graphene-based foils | • High thermal conductivity<br>• Small thickness<br>• Excellent lifetime | • Technology of fabrication<br>• Small number of suppliers |

## 4. Recommendations

The graphene-based foils compete well against other carbon foils that are used as stripper foils, such as a DLC or polycrystalline graphite. Our investigations show the benefits of using the graphene-based stripper foils. Continued improvement of the foil properties, such as uniformity and impurity levels, is expected.

## 5. Conclusions

In conclusion, graphene-based stripper foils have a future that will require additional testing on different types of accelerators with stripper foils to understand the potential breadth of future use. The main advantage of the graphene stripper foils is their unique properties, such as a high thermal conductivity and higher beam transmission factor compared to amorphous carbon and graphite-type foils as well as extended lifetime.

## 6. Acknowledgements

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