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Nuclear Instruments and Methods in Physics Research A 590 (2008) 18–21
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Multilayer carbon foils for cyclotron beam extraction

Stefan K. Zeisler*, Vinder Jaggi

TRIUMF, Applied Technology Group, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3

Available online 2 March 2008

Abstract

The TRIUMF Applied Technology Group operates high-power industrial cyclotrons for commercial radioisotope production. Two of these cyclotrons, TR30-1 and TR30-2, are capable of accelerating H^- ions to an energy of 30 MeV and beam currents in excess of 1000 μA. For many years, amorphous carbon foils of approximately 2.0 μm thickness have been utilized to extract proton beams from these accelerators.

Novel multilayer foils consisting of layers of amorphous and diamond-like carbon (DLC) of 2.0 ± 0.2 μm thickness were manufactured in-house by carbon arc and pulsed laser deposition, respectively. In the TR30 cyclotrons, the new composite foils with 25% DLC content show a three times longer lifetime than the purely amorphous foils, while maintaining their excellent physical and mechanical characteristics during irradiation.

PACS: 81.05.Uw; 81.15.Fg; 68.65.Ac; 68.55.Jk

Keywords: Carbon stripper foils; Multilayer foils; Laser deposition; Stripper lifetime

1. Introduction

Carbon foils are used in particle accelerators as electron strippers for negative ions. Many commercially available cyclotrons for the large-scale production of medical radioisotopes accelerate H^- ions to 12–30 MeV and can achieve extracted beam currents up to ~1.2 mA. High-power cyclotrons operating in an industrial environment require stripper foils of optimum quality to provide excellent beam shape and stability during irradiation. The lifetime of the foils should be as long as possible to keep production downtime and radiation exposure to maintenance staff to a minimum.

The durability of carbon stripper foils in a cyclotron depends on several parameters, such as type of foil material (amorphous, microcrystalline or nanocrystalline carbon structures), mounting method, handling of the foil before and during the mounting process, and eventually ion beam density and beam distribution. During regular operation, the characteristics of an ion beam circulating in a cyclotron are virtually constant. Obviously, much attention needs to be given to the careful handling and mounting of the stripper foils to ensure that they do not suffer mechanical damage before they are irradiated. Additionally, the foils should be mounted in a way that allows shrinkage or expansion when exposed to high temperatures by beam heating [1].

Standard stripper foils for high-current cyclotrons are usually 1.0–3.0 μm (~200–600 μg/cm^2) thick and can easily be produced by carbon arc deposition [2–10]. This process yields carbon films of amorphous or microcrystalline structure depending e.g. on the deposition rate. Other procedures for manufacturing of stripper foils have been described in the literature, such as controlled AC–DC or AC arc discharge [11–13], ion beam sputtering [14], plasma enhanced sputtering [15] and laser ablation [16,17]. A comprehensive compilation of production methods for carbon stripper foils can be found in Ref. [18].

Many lifetime studies on stripper foils made from different carbon species have been performed. For example, diamond foils or films of diamond-like carbon (DLC) have been found most favorable for heavy ion stripping since they can be manufactured in very low thicknesses and

*Corresponding author. Tel.: +1 604 222 7364; fax: +1 604 221 0436.
E-mail address: Zeisler@triumf.ca (S.K. Zeisler).

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doi:10.1016/j.nima.2008.02.057

show high mechanical strength. However, diamond and DLC films are rather transparent and can only cool by radiating at higher temperatures than other forms of carbon, which may limit their use at high-power density. All deposition processes for DLC films have been reported to be comparatively slow, thus making this method only suitable for thin films. Furthermore, techniques such as physical vapor deposition (PVD) often require high temperatures, which may not be feasible for particular substrates.

We were interested in investigating the fabrication of self-supporting multilayer foils consisting of amorphous (or microcrystalline) carbon (aC) produced by carbon arc deposition and at least one DLC layer of comparable thickness, thus combining the outstanding mechanical characteristics of DLC with the favorable heat-transfer properties of the readily producible amorphous carbon (aC). While the fundamental concept of layered stripper foils involving different carbon species has been presented before [19], the publication by Kabiraj et al. describes only very thin strippers for tandem accelerators ($5\,\mu g/cm^2$), which consisted of a $1\,\mu g/cm^2$ layer of C_{60} molecules enclosed between two carbon layers produced by electron beam evaporation. Their method involves an intricate deposition of volatile fullerene and apparently does not lend itself to scaling for foils of 200–400 $\mu g/cm^2$ thickness.

The most promising process for the fabrication of DLC films, in our opinion, is the laser ablation as described by Maier-Komor and co-workers [20,21]. Based on our previous experience with this method and in view of our goal to be able to manufacture DLC layers of at least 1 μm, we purchased a customized pulsed laser deposition (PLD) apparatus that affords the rapid fabrication of DLC films in a wide thickness range.

In the following, the technical details of the laser deposition system, the procedure for producing multilayer carbon foils as well as results from several months of testing in the TRIUMF TR30 cyclotrons are presented.

2. Pulsed laser deposition system

A customized PLD system was purchased from UHV Technologies, Inc. (Ft. Worth TX, USA) (Fig. 1). It consists of five major component groups: (1) Spectron Nd:YAG infrared laser as specified in Table 1, with dedicated power supply; (2) 48 cm diameter stainless steel bell jar containing a movable graphite sputter target, four substrate holders on a planetary gear, optical components for directing and focusing of the laser beam, and a quartz crystal deposition monitor, as shown in the schematic below; (3) high vacuum system based on a CTI-8 cryogenic pump; (4) GE Fanuc 90-30 PLC (programmable logic controller), operated through LabVIEW™ controls software on a standard PC; (5) frame with racks for power supplies, PLC, services, valves, display screens, etc.

A sketch drawing of the vacuum chamber and its components is shown in Fig. 2. In summary, the laser beam (1) enters the vacuum chamber through a glass window in the upper part of the bell jar and is defocused by two adjustable concave lenses (2,3) before impinging on a 45° laser mirror (4). Subsequently, the laser beam passes through a condenser lens (5) and is focused on the sputter target (6) to evaporate carbon particles, which deposit on the substrates mounted onto the substrate holders (7). The thickness of the deposited layers is estimated using an Inficon quartz thickness monitor (8).

Fig. 1. TRIUMF Carbon Foil Laboratory with pulsed laser deposition system (left) and carbon arc deposition system (right).

Table 1
Characteristics of the Spectron Nd:YAG laser ($\lambda = 1064$ nm)

Energy per pulse	$\leqslant 3000$ mJ
Pulse width, FWHM	10 ns
Maximum peak pulse power	3×10^8 W
Repetition rate	$\leqslant 30$ Hz
Laser beam diameter	12.5 mm
Typical applied power density on target	$\sim 3\times10^{10}$ W/cm^2

The initial defocusing of the laser beam reduces the beam power density in this section by a factor of four, thus helping to extend the lifetime of the expensive mirror. During the deposition, both the target disk and the substrate holders are constantly moved. The target disk, glued onto a circular support table, is rotated by means of a small motor mounted underneath the table, while the entire target assembly is moved back and forth in longitudinal direction using guide rails and a gear drive. This mechanism ensures smooth ablation of the target disk.

The substrate holders form the satellites of a planetary gear set. The planetary subassembly is rotated by a chain and sprocket drive (not shown) located on the periphery of the large holding ring onto which the planets are mounted. Since a typical deposition process takes between one and several hours, the substrate holders orbit the target many times, while simultaneously revolving around their centers. As result, the deposited carbon films have excellent homogeneity.

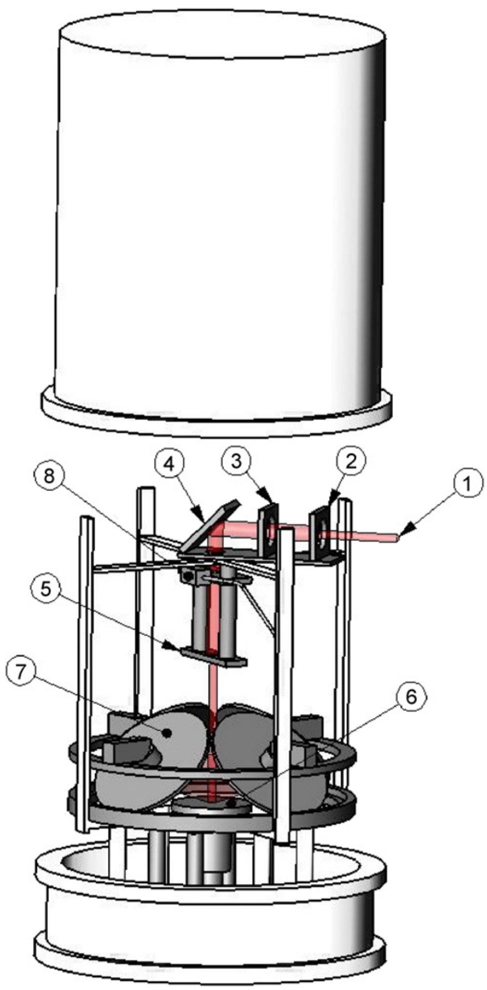

Fig. 2. Schematic drawing of the vacuum chamber of the PLD system—(1) laser beam; (2, 3) concave lenses; (4) 45° laser mirror; (5) condenser lens; (6) graphite target; (7) substrate holders; (8) crystal thickness monitor.

The system permits either manual or automatic operation. In automatic mode, the controls can be programmed to end the deposition when the required thickness has been achieved, or it is terminated after a preset deposition time.

3. Production of multilayer foils for the TRIUMF TR30 cyclotrons

A typical 2.0 μm multilayer foil for the TR30 cyclotrons consists of one DLC layer (0.5 μm) sandwiched between two layers of aC (0.75 μm each).

The procedure starts with cleaning the glass substrates with suitable solvents and coating them with a parting agent, such as betain–sugar solution [22]. The slides are then mounted into the carbon arc deposition system, and the first layer of aC is deposited on the substrates. Very fine grain and microcrystalline structures can be obtained by using a pulse method with long cooling periods, as previously described [23]. This step takes about 6 h.

Once a thickness of 0.75 μm has been reached, the substrates are transferred to the pulsed laser deposition system and coated with 0.5 μm of DLC in approximately 1–2 h. Eventually, the substrates are remounted into the carbon arc system and the third layer, i.e. 0.75 μm of aC is deposited on top of the DLC layer.

The films are then heated in a vacuum oven at temperatures between 150 and 200 °C for an extended period. The foils are separated from the substrates by immersion in warm water (‘‘floating’’) and are left to dry at ambient temperature.

4. Results and discussion

The multilayer foils thus fabricated show excellent smoothness and homogeneity. The thickness variation across the foils, as measured with a Dektac stylus, is rather insignificant ($<1\%$). The foils are light-tight, virtually flat and of considerable hardness and stiffness. Handling and mounting into the extractor carousels can be performed with ease.

As for practical considerations, 36 slides can be simultaneously coated in the carbon arc system, whereas the laser deposition system can produce 48 slides per batch. It has been suggested to equip the carbon arc system with the same type of planetary gear as the PLD system to facilitate the transfer of the substrates from one system to another and also to provide the capability to manufacture a larger number of multilayer foils per process cycle.

Obviously, the multilayer method can be extended from two layers to virtually any number of layers, and theoretically to any desired thickness. To date, we have manufactured very robust self-supporting multilayer foils of up to 4 μm thickness and 50 mm × 70 mm size. Furthermore, the ratio between aC and DLC may be varied according to specific requirements of the intended application. In our experimental assessment, which included irradiations of multilayer stripper foils with high intensity H^- beams, foils with higher DLC content (up to 50%) generally performed better and lasted longer than foils with lower DLC content. Foils with less than ~15–20% DLC content showed no significant improvement over pure aC foils.

Detailed performance data from the TRIUMF TR30 cyclotrons were collected between January and October 2006. Both accelerators have virtually identical characteristics (energy, typical beam currents, beam shape); therefore, the data from both cyclotrons were combined for evaluation. Typical proton beam currents through the stripper foils ranged from 200 μA to 550 μA at 29 MeV. Foil lifetime was measured in units of integrated electrical charge (μAh). A foil was considered spent when two conditions were met: (a) beam spills along the beamline or on the target collimators reached the warning or trip level; (b) beam spills could not be reduced by retuning the available steering and focusing devices.

The standard aC foils of 2.0 ± 0.2 μm thickness had a lifetime of 12856 ± 2883 μAh (mean ± s.d.; $n = 47$). In comparison, the multilayer foils of the same thickness including 0.5 μm DLC withstood 40,323 ± 13,399 μAh (mean ± s.d.; $n = 48$), which constitutes a threefold improvement over the standard foils.

5. Conclusion

For the first time, self-supporting stripper foils consisting of alternating layers of aC and DLC have been produced. These multilayer foils can be manufactured in a wide range of thicknesses and show superior performance in high-power cyclotrons. Experiments are currently in progress to evaluate their performance in heavy ion applications and in particle storage rings.

Acknowledgments

The authors wish to thank TRIUMF and MDS Nordion, Inc. for financial support and Dr. Nalin Kumar, UHV Technologies, Inc. for many helpful discussions.

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