# Box 6: Carbon Stripper Foils – Preparation and Quality

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## Introduction

Foil strippers of carbon are commonly employed in electrostatic accelerators for electron stripping of ion beams. Carbon foils have the advantage of being stable in vacuum at high temperatures, in combination with good electrical and thermal conductivity. Carbon has the further advantage of being the material with the lowest $Z$ that can be fabricated into a very thin foil to minimize multiple scattering and energy straggling of the transmitted ions. In many energy ranges, lower-$Z$ materials also can lead to higher average charge states compared with higher-$Z$ materials [1]. However, the significant disadvantage of foil strippers is their limited lifetime due to irradiation effects, for example the thickening and shrinkage observed in carbon foils (see for example [2] and references therein. These effects both deteriorate the stripper quality, especially under heavy-ion beams, and lead eventually to the rupture of the stripper foil, with the lifetime being strongly dependent on ion mass, energy, beam density, and the vacuum environment in the terminal as well.

## Preparation of Carbon Stripper Foils

### Carbon Stripper Requirements

A good stripper foil should have a constant and satisfactory ion yield during the experiment. In more detail, carbon stripper foil requirements can be summarized as follows:

1. optimum thickness from the point of view of ion yield and transmission through the acceleration tube,
2. long irradiation lifetime,
3. high mechanical strength,
4. amenability to mass fabrication.

It is clear that these requirements are all related somehow to the foil thickness and preparation technique. As reported in [3, 4], the optimum thickness of a carbon stripper foil for maximal transmission at a terminal voltage of 5–10 MV is about $10\,\mu g/cm^2$ for light ions ($Z \leq 6$), several $\mu g/cm^2$ for medium-heavy ions, and less than 2 μg/cm$^2$ for heavy ions ($Z > 16$). However, standard commercial foils with a thickness of several μg/cm$^2$ may appear impractical for terminal stripping, since they typically break in minutes when irradiated with heavy ($Z \geq 16$) ions [1,5] under normal accelerator conditions. A significant improvement in the foil stripper quality can be achieved by (a) slackening foils, and (b) preparing them by the proper technique for the optimum structure. If successful, a combination of the two methods can produce more than one order of magnitude increase in the lifetime compared with standard foils. A brief description of various preparation methods is given below for carbon strippers in the thickness range of 2–10 μg/cm$^2$, together with some comparative data.

## Procedure

The majority of preparation methods for carbon stripper foils are based on deposition of the material onto a glass slide, coated with a water-soluble parting agent. The resultant film is floated off the slide and mounted on a suitable frame. The thickness of the foils (areal density) is usually measured by a light transmission method at suitable wavelengths [6]. A variety of parting agents are known from the literature [7, 8]. The parting agent may influence not only the yield of usable foils but also their stripping efficiency and lifetime [9]. Most target laboratories use detergent-like parting agents, for example Teepol 610, RBS 25 Creme-Cotec, or potassium oleate ($C_{18}H_{33}O_2K$). Another large group of commonly used parting agents is the halides [9], in most cases chlorides. These have the advantage of being much more thermally stable than organic parting agents. The third group of parting agents in use are sugars, for example betaine-sucrose [10]. An important advantage of betaine-sucrose is that carbon foils produced on such a parting agent are very flexible and have a very high mechanical strength. This is due to the highly corrugated structure of the foil, which obviously replicates the significant surface roughness of the parting agent. A drawback of betaine-sucrose as a parting agent is that the covering process must be done in a humidity of near 40% to keep the proper crystallite structure of the layer [11]. Also, the nonhomogeneity of the stripper foil caused by this parting agent should not be neglected for certain experiments requiring high energy and time resolution. Free-standing carbon stripper foils of 2–5 μg/cm$^2$ are usually reinforced, prior to picking up in a suitable frame, by means of collodion (cellulose nitrate) or formvar films. The plastic coatings will evaporate in a short time when exposed to the beam.

## Evaporation–Condensation Methods

The thermal evaporation of carbon in vacuum is carried out by three different techniques: (i) resistance heating of carbon filaments, (ii) arc evaporation, and (iii) electron beam heating. Since the first application of carbon stripper foils in tandem accelerators in the 1960s [5], the arc-evaporation method has become standard, mainly because of its amenability to mass-production of inexpensive and relatively strong carbon foils in a wide thickness range [7,12]. However, carbon stripper foils made by conventional thermal evaporation methods, especially by resistance and electron beam heating, suffer from irradiation damage that limits their use in heavy-ion tandem accelerators [9]. These foils have the shortest lifetimes. Recently, a significant improvement has been reported in the preparation procedure of carbon strippers by arc deposition called "controlled DC arc discharge"(CDAD) [13]. The major point of the CDAD method is a strictly controlled ratio of carbon clusters emitted by the anode and cathode during the DC arc discharge. The average lifetimes of very thin optimized CDAD foils were measured to be at least three times longer than those of similar standard foils.

### Cracking of Ethylene Gas

Preparation of stripper foils by the DC glow-discharge cracking of ethylene gas offers improvements in lifetime by factors of 5 to 10 compared with standard carbon foils under heavy-ion bombardment, owing to the much higher resistance of ethylene-cracked foils against irradiation shrinkage [14]. The extensive development efforts since the end of the 1970s have finally resulted in the routine use of such foils for the stripping of heavy ions with $Z > 60$ in many tandem accelerators [15]. Detailed descriptions of the modifications of the ethylene-cracked foil technique are given in [5,8,14]. Carbon films prepared by cracking of ethylene are brittle, and the whole procedure requires experienced personnel to facilitate a reasonable foil-production yield. Also, some features of the glow discharge cracking process limit the minimal possible thickness of the foil to about $3\,\mu\text{g/cm}^2$ [14]. Stripper foils prepared by cracking of ethylene have medium lifetimes [5,8,15].

### Ion Sputtering

Ion sputtering seems attractive for the preparation of long-lived carbon stripper foils, owing to the much higher impact energy of sputtered particles compared with that in the evaporation process. This has been confirmed by using heavy-ion beam sputtering (HIBS) and ion beam sputtering with reactive-nitrogen (IBSRN) methods [13,16]. Foils prepared using $\text{Xe}^+$ and $\text{Kr}^+$ sputtering at 3, 5, 10, and 15 keV have demonstrated significantly longer lifetimes compared with those of thermally evaporated foils under heavy-ion irradiation, and outlast even cracked ethylene foils [16]. Unfortunately, the suitability of ion-beam-sputtered foils for heavy-ion tandem accelerators seems rather problematic so far, since the minimal possible thickness of such foils is about $10\,\mu\text{g/cm}^2$. In order to overcome this difficulty, magnetron sputtering can be utilized [17].

### Laser Plasma Ablation

A laser plasma ablation–deposition technique to produce long-lived stripper foils has been developed at the Technical University of Munich on the basis of comprehensive investigations of the destruction mechanisms in carbon foils under heavy-ion bombardment (see for example [18] and references therein). According to the accepted theory, only carbon foils with a structure of randomly oriented nanocrystals can exhibit the longest possible lifetimes. To create such a structure, the energy of the deposited particles should be at least one order of magnitude higher than that in evaporation–condensation techniques. In order to fulfill these requirements, a high-power pulsed Nd:YAG laser (400 mJ, 10 ns) was used to shoot onto carbon targets in ultrahigh vacuum. As a result, carbon foils with the desired structure are being produced in the thickness range of 4–20 $\mu g/cm^2$. Today, stripper foils made by laser plasma deposition have been demonstrated to have the longest lifetimes of all foils. In addition, laser plasma ablation (LPA) foils have a unique mechanical strength so that, unlike any other foils, even 4 $\mu g/cm^2$ LPA foils do not need any plastic support for safe handling and mounting. However, this very successful method is extremely complicated and relatively expensive. It is also difficult to produce very thin carbon strippers by this technique. Sputter diamond-like carbon (DLC) foils, described below, have no such limitations.

### Sputter Deposition of Diamond-Like Carbon Foils

The significant improvements with laser ablation stripper foils confirmed considerations that a higher energy of the deposited particles may result in an increased lifetime. This point has attracted considerable attention to diamond-like carbon films, since they are being grown using fast particles, having an energy about 30–50 times higher than that for thermally evaporated foils. Developed in the Kurchatov Institute, DLC stripper foils are produced by special-purpose DC glow discharge sputter deposition of energetic (30 eV) carbon atoms onto glass substrates cooled to liquid-nitrogen temperature. Strong and flexible DLC foils, in the thickness range from 0.6 to 20 $\mu g/cm^2$, can easily be produced by this method. The preparation and comparative testing of DLC foils under heavy-ion irradiation have been described in [19, 20] and references therein. It was observed that DLC stripper foils last more than 10 times longer than similar standard carbon foils and compare favorably with LPA foils.

## Conclusions

1. A variety of advanced stripper foil preparation techniques are currently capable of fulfilling the requirements of modern tandem accelerators, although not all variables of the irradiation effects can be explained so far, and further investigations are necessary.

2. Laser plasma ablation foils and DLC foils seem to be the longest-lived stripper foils for tandem accelerators up to now.
3. In view of the necessity for thicker and long-lived strippers for higher-energy ion beams, new forms of carbon, for example fullerene (randomly oriented substitutes) and nanotubes (exceedingly high tensile strength) show promise as candidate materials.

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