CARBON STRIPPER FOILS FOR HEAVY-ION ACCELERATORS

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Summary

Carbon stripper foils have for many years been successfully used with accelerators because they yield higher average charge states than gas strippers. However, with the development of heavy ion accelerators and the resulting use of heavier ions, the carbon stripper foil lifetimes are greatly reduced. Even when using the new foils changer systems, which typically contain two hundred foils or more, it becomes necessary to have frequent accelerator shutdowns for foil reloading. The rate of experiment interruption makes it clear a new approach is necessary to increase foil lifetimes. Several techniques have been tried with varying degrees of success to strengthen these foils so that they will last longer; the most successful one reported a lifetime increase on the order of a factor of 30 over foils produced in the conventional manner. Methods of producing various types of foils will be presented, a discussion will be given on the order for foil breakage, and some new ideas will be introduced for further increasing foil lifetimes.

Introduction

It has long been recognized that carbon stripper foils play an important role in the successful operation of a tandem accelerator. Their location in the machine is shown in Fig. 1. The introduction of

heavy ion acceleration has greatly reduced the lifetimes of these foils and considerable time and effort has been spent to better understand the reasons for this reduction as well as to find ways to increase their lifetimes or discover new types which last longer. Vattena¹⁾ presented a review in which he discussed such topics as charge states, multiple scattering and energy straggling of heavy ions. The chief advantage of using foils for heavy ion acceleration is that they yield higher average charge states than does the method of gas stripping. As a result the energy of the beam emerging from the accelerator can be substantially higher than that from gas stripping. Also, one avoids some of the operational difficulties that would be expected from the use of gas strippers.

The first approach to solving the short lifetime of the stripper foils in heavy ion accelerators was to greatly increase the number of foils in the accelerator. Several schemes have been devised to use foil changers containing two hundred or more foils. The problems associated with using larger and larger foil loadings become very complex, such as space limitations and increased time necessary for foil mountings. In addition, it is quite a hindrance to the experiment to have the beam interrupted for frequent foil changes

Figure 1. Location of carbon stripper foils to be used with FN tandem-superconducting linac booster system at Argonne National Laboratory.

and to restabilize the machine.

Heating and Rotating Foils During Bombardment

With the oncoming development of the superconducting linac booster system to be used with the FN tandem accelerator at Argonne National Laboratory, it was apparent that longer-lived carbon stripper foils would be needed. This system was proposed to accelerate ions up to $\sim$ mass 120.

Yntema^{2,3,4)} performed a series of experiments using foils produced by a carbon arc in which he observed a significant increase in carbon foil lifetimes by either heating or rotating the foils or both. In these experiments a 3-3.5 MeV Krypton beam from the Argonne Dynamitron was used and the foils were heated to $450 \pm 150^\circ\text{C}$. Later work by Thomas et al.⁵⁾ confirmed the earlier work of Yntema (see Table I).

Mode	Number of Foils	Dynamitron Voltage (MV)	J (pA mm ⁻²)	Lifetime to 75% Original Intensity -2 (pA min mm ⁻²)
Stationary Room Temp. Series I	2	3.5	0.2	0.4
Stationary Room Temp. Series II	8	3.0	0.125	0.5
Stationary Heated	4	3.5	0.2	1.6
Rotated	6	3.0	0.125	1.2
Rotated and Heated	3	3.0	0.125	2.6

In another experiment⁶⁾ a rotating target system was used having eight separate carbon foils ($5 \mu\text{g}/\text{cm}^2$) mounted over elongated slots near the periphery of a 10 cm dia. aluminum wheel rotating at 1400 rpm. This arrangement has a foil lifetime approximately equivalent to 100 single foils. Heating or rotating foils in these ways does increase their lifetime but the difficulty in finding a place in the accelerator to mount such a large system at this time may not seem to justify the foil lifetime increase that would be achieved.

Various explanations have been offered for the lifetime increase produced by heating the foils. Since radiation damage can be annealed out of graphite, it was thought that this would also apply to the foils. It is possible that radiation damage caused by the beam changes the structure of the carbon or causes the atoms to migrate to the area of the beam. This might explain the dark spot seen on the foil, followed by a gradual tightening of this area and the eventual rupture of the foil from the subsequent stresses produced in it. The beam may also cause the carbon to graphitize (acquire a crystalline structure), re-ordering the beam atoms and compacting them - thus reducing the area. Residual carbon in the beam tube could also contribute to the mass of the beam spot.

Foils Made by Cracking Ethylene Gas in a Glow Discharge

The conventional technique for manufacturing carbon foils has been by vacuum deposition from a carbon arc or, less frequently, from electron beam heating. A new approach to producing carbon stripper foils has been taken by Whitmel et al.⁷⁾ which consists of

cracking ethylene gas in a glow discharge. The method of cracking ethylene gas to produce carbon was first described by König and Helwig⁸⁾. The intent of depositing the film by this method was to produce material which although amorphous would be more resistive to radiation damage than conventional carbon arc foils. Their system for producing these films is shown in Figure 2.

Figure 2. System used by König and Helwig⁸⁾ for cracking ethylene gas to produce pure carbon

NaCl is first evaporated onto a glass or metal plate and then the plate is clamped onto a shielded cathode in the system, making sure that there are no sharp edges on the plate. A negative voltage of 2-6 kV is applied using $\sim$ 0.1 torr pressure of argon. The argon is then replaced with ethylene or a mixture of ethylene - 10% argon and the discharge continued until the desired thickness is obtained. The Daresbury-Harwell⁹⁾ group has demonstrated that foils made at 1.5 kV or less break as soon as the beam is applied. They have shown that these foils contain very large amounts of hydrogen. As higher voltages are applied the percentage of hydrogen in the foils decreases, indicating that possibly the cracking is more complete under these conditions.

A further increase in foil lifetime has been obtained by Armitage et al.¹⁰⁾ by "slackening" the foils. It was observed that during irradiation by heavy ions radial stress lines appeared outside the irradiation area, tightening the foil and then breaking it. By mounting the foils on a suitable ring and then reducing the ring diameter the foil becomes slack or floppy. This procedure does significantly increase the lifetime of the foil but care must be taken when using these foils to insure that the irregularities in them does not produce an undesirable degradation of the beam resolution. Den Hartog et al.¹¹⁾ have made straggling measurements with slackened foils using the Argonne FN tandem-superconducting linac booster system and a 500 na ^{58}Ni beam. In most experiments the resulting increase in beam energy spread will not be significant. Their lifetime increase for slackened foils is consistent with that reported by other experimenters.

It is not the purpose of this paper to give a detailed description of all the advances in this field but we would mention that significant contributions have been reported by Tait et al.¹²⁾, Armitage et al.¹³⁾, Gallant et al.¹⁴⁾, Auble et al.¹⁵⁾, and others. Table II shows the increase in foil lifetime using a 1.2

MeV argon beam with a 10 mm² spot, the lifetime being the point at which the foil split or until a significant hole appeared. The lifetime is increased by about a factor of 30-40 by using slackened foils made by glow discharge over that obtained for standard foils made by the carbon arc method. Using heavier ions, the foil lifetimes are greatly reduced but the clear advantage to using slackened glow discharge foils is still evident.

Table II

Foil lifetimes for glow discharge (gd) stripper foils made in 90% ethylene, 10% argon and for foils made by evaporation from a carbon arc (ca). A 1.2 MeV argon beam with a beam spot of 10 mm² was used.

Foil Type		Areal Density ($\mu\text{g}/\text{cm}^2$)	Number	Lifetime ($\mu\text{s. min.}$)
gd	unslackened	5-10	15	23 ± 4
	slackened	5-10	6	91 ± 24
	unslackened	15-30	14	71 ± 9
	slackened	15-30	6	127 ± 20
ca	unslackened	3-10	17	3.2 ± 0.4

Graphitized Carbon Stripper Foils

As stated earlier, the principal mechanism which causes the stripper foil to rupture during ion bombardment is not well understood. One possibility is that heat deposited in the foil due to the loss of energy by a heavy ion may cause the originally amorphous carbon to be graphitized in the area of the beam. The local mass density is increased due to the rearrangement of the atoms. Stress lines then occur in the area of the non-irradiated foil, causing it to break. Also, these heavy energetic ions traversing the foil may further damage its structure in a way which we do not understand.

Maier-Komor¹⁶) suggested that foils be treated such that they would exhibit a non-amorphous crystalline structure before they are exposed to the beam, thus preventing stress between the irradiated and non-irradiated areas. Sander and Bukow¹⁷) were able to graphitize foils by flushing argon over them while in an oven in temperatures up to 1300°K. Maier-Komor and Ramzinger¹⁸) heated foils by electron bombardment in a high vacuum system up to 2200°K. The beam was held constant or swept over an area of 100 mm² and the bombardment lasted only a few seconds. This method produced an increase in foil lifetime over standard foils of about a factor of four.

Ramzinger et al.¹⁹) recently have done experiments to graphitize carbon foils using a 100 w beam from a Nd:YAG laser. It was estimated that a temperature of 2800°K was achieved. These foils were tested using ³²S-ions from the Munich MP tandem with a terminal voltage of 10.6 MV. They were compared with foils pre-treated by both thermal heating and electron bombardment. All foils were made by the same technique (using a Pierce-type electron beam gun). In their results foil lifetime was defined as the time for the intensity of the analyzed beam to reach one half of its original intensity. The laser-heated foils of 5 $\mu\text{g}/\text{cm}^2$ thickness were the best performers, showing an average lifetime increase of a factor of ten over that for standard stripper foils.

Discussion

Several techniques have been used to increase carbon stripper foil lifetimes when exposed to heavy ion beams. Some of them are:

1. Heating the foils to anneal them during use.
2. Rotating the foils in the beam.
3. Slackening the foils.
4. Producing carbon stripper foils by glow discharge.
5. Graphitizing the foils before use by thermal, electron bombardment, or laser heating.

It is difficult to quantitatively compare each type of foil since different methods were used to prepare the standard foils, the beams used were not the same and each experimenter had his own criteria for deciding when a foil was no longer useful. As a result we have made no direct comparisons for the lifetimes of each type of foil. However, it appears that the longest lived foils are produced by either glow discharge or those graphitized by a laser beam.

There is much more interesting work to be done. At present, we may be able to produce foils with acceptable lifetimes. However, in the future with the acceleration of still heavier ions, further improvements in foil lifetime will be needed.

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