

# New methods for testing cyclotron carbon stripper foils

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## Abstract

Carbon foils are used in cyclotrons and other accelerators to strip electrons from fast ions, enabling the extraction or further acceleration of those ions. Lifetimes of stripper foils (extractor foils) need to be as long as possible to maximize the efficiency of accelerator use and minimize radiation exposure of maintenance personnel. A foil's useful lifetime is determined in part by operating temperatures, manufacturing method, and mounting method. We used two methods to test foils in a simulated accelerator environment. These methods involve the heating in vacuum to temperature ranges 500–1750 and 500–4000 K. Either kind of testing can be done in a few minutes instead of the days or weeks typically needed in a cyclotron. Such tests show clearly that foils manufactured by different methods have different responses to elevated temperatures. Because of this fact, optimum mounting techniques depend on the foil type. Results to date are summarized.

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## 1. Introduction

Many experiments use carbon stripper foils. Stripper foils range in thickness from a few nm for start/stop detectors operating with ions of a few keV, to several  $\times 10 \mu\text{m}$  for beams at particle energies of hundreds of MeV. Foils in intense beams ultimately break because of particle bombardment. In order to maximize the efficiency of accelerator use and minimize the radiation exposure of maintenance personnel, the lifetimes of foils should be as long as possible, consistent with the other requirements of beam production. Lifetimes of foils depend on the form of carbon used, the method of mounting, and their operating conditions. In the present work, testing by heat treatment of carbon foils used as extractor foils in cyclotrons is used to simulate some of the effects of their bombardment by ions. The two most common types of foils used in medical cyclotrons, composed of arc-evaporated carbon and of graphite, are studied. Two different temperature regimes are used: 500–1750 and 500–4000 K, using two specially

constructed apparatus. Foils' dimensional changes when heated are used to explain in part their breakage under bombardment by ion beams. Table 1 indicates typical properties of these stripper foils and the cyclotron beams with which the foils are used.

### 1.1. Stability and deterioration of carbon foils

The stable equilibrium form of pure carbon at room temperature is a compact graphite crystal. Typical carbon foils having a relatively large ratio of area to volume are metastable in air; their relaxation rate toward equilibrium surface/volume ratio is imperceptible at room temperature. The production of arc-evaporated foils and graphite foils from bulk material introduces impurities and lattice defects, besides creating the large surface/volume ratio characteristic of a foil. The relaxation rates of foils toward equilibrium have not yet been intensively studied.

A region of a carbon foil that is placed in an ion beam in vacuum reaches a temperature  $T$  above room temperature. That temperature can be estimated moderately well by assuming that the loss of heat (primarily by radiation) balances the input heat deposited via the energy losses of

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Table 1  
Typical cyclotron beam and foil parameters

Ion	H <sup>-</sup>
Ion energy	5–30 MeV
Ion current	50–1000 $\mu$ A
Foil material	Carbon, arc-evaporated or graphite
Foil's areal density	50–5000 $\mu$ g/cm <sup>2</sup>
Foil temperatures	<1000–>3500 K
Stripping reaction in foil	H <sup>-</sup> $\rightarrow$ p <sup>+</sup> + 2e <sup>-</sup>

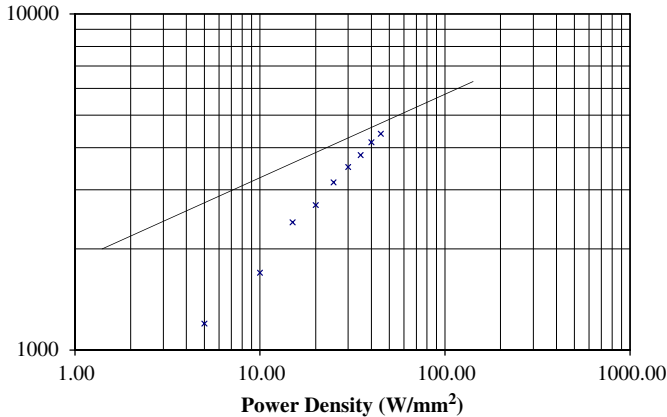


Fig. 1. Calculated temperatures of opaque carbon foils vs. incident power density. The solid line is calculated using Eq. (1), assuming that the foil's surroundings are at 0 K, the foil is at thermal equilibrium, heat is lost by the foil only via radiation, and foils are thick enough that their total emissivity is 0.8 [2] (see also Ref. [17]) at all temperatures and wavelengths. The discrete points are taken from the graph in Ref. [2], using peak powers of ion beams pulsed at 60 Hz with pulses having 1 ms duration. The differences between the two curves are attributed to the (calculated) fact that the foil cannot reach thermal equilibrium during a 1 ms pulse.

the ions and electrons incident upon the foil. Assuming negligible radiation from the surroundings to the foil,  $T$  is then given by

$$T = [(P/A)/(2e\sigma)]^{1/4} \quad (1)$$

where  $P/A$  is the power per unit area absorbed by the foil,  $e$  is its emissivity, and  $\sigma$  is the Stefan–Boltzmann constant. The factor of 2 accounts for the emission from both faces of the foil. More-complex calculations have been done, making various assumptions concerning the stopping powers and emissivities of carbon foils, heat losses via conduction, etc. [1–4]. Fig. 1 shows the dependence of foil temperature on incident power density for an opaque carbon foil, calculated using Eq. (1) and also as calculated by Liaw et al. [2] for a pulsed beam at the spallation neutron source (SNS).

Diamond stripper foils have been studied by several authors with mixed results [1,3–6]. Diamond is a mechanically strong material, but it is transparent over the wavelength range 0.27–2.6  $\mu$ m [7] and cannot radiate in this region. Arc-evaporated and graphite foils are absorbing and can radiate in this region. Diamond foils must cool by radiating outside this wavelength region, hence must

reach temperatures higher than the other forms of carbon. Above 1800 K, graphitization of diamond foils is expected to occur [1,8]. The resulting dimensional changes with accompanying stresses may limit the utility of diamond foils; diamond foils are not considered further in this work.

If heated sufficiently, carbon foils begin to evaporate. The vapor pressure of carbon is moderately well known as a function of temperature [9–14], and from it, the evaporation rate can be calculated [9], and the lifetimes of carbon foils estimated at high temperatures. For the present work, a linear fit to the graph given by Liu et al. [11] was used to find vapor pressures of carbon [see Eq. (2a)]; evaporation rates of carbon are taken from [9] [Eq. (2b)]

$$\text{Log}_{10}(P_{\text{atm}}) = (-37.3)(1000 K/T) + 8.16 \quad (2a)$$

$$\text{Log}_{10}(dm/dt) = \text{Log}_{10}(P_{\text{atm}}) - (1/2)\text{Log}_{10}(T/K) - 2.187 \quad (2b)$$

where  $P_{\text{atm}}$  is the vapor pressure in atmospheres,  $T$  is the absolute temperature, and  $dm/dt$  is the evaporation rate in g/cm<sup>2</sup> s.

The vapor pressure curve Eq. (2a) lies approximately midway between the data from Refs. [9,14]. Data taken from Refs. [10,13] (reported in Ref. [12]) lie somewhat above the curve presented by Liu et al. [11]. The spread of these data suggests an uncertainty of roughly a factor of three in both vapor pressure and evaporation rate.

Power deposited in foils via stripping of H<sup>-</sup> ions includes energy losses by the proton and by the accompanying two electrons. These losses have been calculated when needed, using the NIST programs PSTAR [15] and ESTAR [16]. Ignoring uncertainties in stopping powers and vapor pressures, Table 2 shows some typical calculated operating temperatures of foils from Eq. (1) and temperatures of phase changes and crystallographic changes in carbon.

## 1.2. Isolation of parameters affecting lifetimes of stripper foils

Lifetimes of foils are determined by manufacturing method, mounting method, and operating conditions (including accidents and mistakes in handling). Manufacturing methods to date include at least 41 techniques [20] and result in at least 41 different kinds of carbon foils. Most kinds have not been tested as stripper foils. Foils that have been tested either initially expand permanently upon heating, contract permanently upon heating, or do not change dimensions significantly upon heating. All foils shrink with sufficient irradiation. Best mounting methods for the three types are considered separately [21]. Details of foils' operating conditions vary considerably among users and facilities, and are not considered here. The present work focuses on the observed dimensional changes of foils upon heating, and implications of these changes.

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