Micromatter's Boron Containing Diamond-like Carbon Stripper Foils:

Why they do not develop pinholes and why they do not create an increased radiation burden

We have recently become aware of a competitor's statements published on their website and in their Product Information brochure that are aimed at discouraging the use of boron containing foils for beam stripping. They present their concerns as a reason why their company does not offer boron containing stripper foils.

In particular, the company claims that carbon-boron hybrid foils undergo spontaneous pinhole formation if exposed to certain elevated temperatures.

Furthermore, they cite radiation protection issues due to the additional activation of boron by proton beams of low energy, such as those typically produced in small medical cyclotrons, concluding that boron containing carbon foils should to be disposed of as radioactive waste, thus creating a perceived disadvantage compared to their own pure carbon products.

Micromatter disagrees with those statements. We wish to assure our customers that both claims are not applicable to Micromatter's boron containing foils for various reasons.

<u>Pinhole Issue</u>

Micromatter's boron containing foils are manufactured in a proprietary layering process using pulsed laser deposition, which results in a unique nano-crystalline structure that gives our foils excellent mechanical and physical properties. Typically, one or more thin boron layers are 'sandwiched' between diamond-like carbon layers, which, after annealing, guarantees optimum tensile strength and high flexibility. The usual boron content of the layered foils is ~5%.

The carbon-boron 'hybrid' foils our competitor refers to reportedly contained 20% boron and show pinhole formation at temperatures above 1800 K (Sugai et al., Nucl. Inst. Meth. A613 [2010] 457-461). These foils were manufactured by controlled DC arc discharge, which produces foils with comparatively large boron and carbon aggregates randomly distributed throughout the foil.

However, Sugai et al. report in Section 2.1, Foil preparation (ibid., p. 458): "The foils separated from the substrate, keeping a flat shape. Pinholes were observed in some parts of the annealed foils. For the beam test, we used foils without pinholes. The mechanism of pinhole formation is not yet understood, but this problem needs to be solved in the near future." Obviously, foils produced by arc discharge are prone to pinhole formation even during the manufacturing process. It is hence not surprising that pinholes also occur when the foils are irradiated and heated to high temperatures.

Layered boron containing foils, such as those produced by Micromatter, do not show this behavior. To date, there have not been any reports of unusual or spontaneous pinhole formation in our boron containing foils.

<u>Stripper Foil Activation</u>

In their Product Information brochure, our competitor states as follows:

"… beginning about in year 2010, longer-lived stripper foils were developed by incorporating boron in them. With boron in the range 15-25% by weight, foils' lifetimes in beam can be extended significantly. Such foils have been made experimentally by several investigators, and are now available commercially (but not from [competitor's company]!). The boron introduces an extra problem for radiation safety in the laboratory.

Natural boron has two stable isotopes, boron-10 and boron-11. Proton excitation of the boron-11 content of stripper foils produces little long-lived radioactivity. Proton excitation of the boron-10 content produces beryllium-7, a radioactive nucleus with a half-life of 53.2 days.

[A description of the nuclear reaction follows.]

"… This reaction's cross-section has most recently been reported …. and peaks near 0.1 barn (i.e., $1x10^{-25}$ cm^2) in the proton energy range 1 – 10 MeV. Because the cross-section is known, the radioactivity of a stripper foil due to beryllium-7 produced in it can be estimated. As an example, a current of 50 microamperes of protons through a 75-microgram/cm^2 foil that is 20% by weight of natural boron results in the production of $5.4x10^6$ beryllium-7 nuclei per second. These radioactive nuclei end up either in the foil, or on the foils frame, or on the foils surroundings, where they decay with a half-life of 53.2 days. The resulting radioactivity begins at zero for a fresh foil and rises toward 5.4 MBq (0.18 mCi) if the irradiation continues for several half lives.

"Technicians should therefore dispose of used stripper foils as radioactive materials, if they contain boron. Minimizing this problem can be done by using [competitor's company]'s carbon foils, which contain no boron."

These statements are based on a grave error in reasoning and a misunderstanding of the physics involved in beam stripping.

The above calculation is completely irrelevant for stripper foils in the low energy range as they are not irradiated with protons but H minus (hydride) ions, which do not cause nuclear reactions. This is in fact the main reason why modern isotope production cyclotrons are designed to accelerate H minus ions instead of protons: To virtually eliminate activation of components within the accelerator due to beam spills.

It is the actual purpose of the stripping foil to convert accelerated H minus ions into protons (by stripping electrons off the negative ion). The protons formed exit the stripper foil with nearly 100%

efficiency and are directed into a beamline or onto an isotope production target. There are virtually no nuclear reactions occurring within the foil, and hence no accumulation of radioactivity.

Over the years, Micromatter has supplied thousands of boron containing stripper foils to particle accelerators, in particular small medical cyclotrons, worldwide. We have never heard of any issues with long-lived radionuclides in spent stripper foils from medical cyclotrons.

As for high energy proton accelerators (GeV range) such as at J-PARC or CERN, which use tens of passes through a carbon foil to achieve complete stripping, all carbon foils naturally become radioactive, regardless of whether they contain a small amount of boron or not.