

# ALTERNATIVE FABRICATION PROCESS FOR CARBON STRIPPER FOILS USED IN PARTICLE ACCELERATORS

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## Abstract

Carbon foils are widely used in particle accelerators to produce ion beams with high charge states. These stripper foils are primarily deposited on a soluble substrate, (e.g. NaCl or betaine-sucrose) that is subsequently dissolved to provide a free-standing foil. For use in accelerators, the free-standing foils need then to be mounted on a metallic frame, a delicate and time consuming operation. In this paper, we propose an alternative fabrication process, where the foils are deposited directly onto a metallic supporting frame. The process involves the surface preparation of plain copper plates, in-situ Ar-H<sub>2</sub> plasma treatment to enhance adhesion, deposition of the carbon film by magnetron sputtering, and removal of the copper from the central part of the supporting plate by chemical etching, to create an aperture for the passing ion beam. We describe the different fabrication steps, the quality control approach used to assess the carbon areal density, the thermal outgassing rate, and the porosity of the foils. The first beam test results using CERN-produced carbon stripper foils, obtained with Pb54+ ion beams at 4.2 MeV/u at LINAC 3, are presented.

## PREPARATION OF THE FOILS

The fabrication process involves three main steps: (1) preparation of the supporting frames, (2) carbon coating, and (3) chemical etching of the copper in the central window of the frame. The areal density of the carbon film is determined by weighing the frame before and after coating. After completion of the etching step, the porosity is evaluated by optical microscopy, and the outgassing rate is measured after 24 h of pump-down. The three steps are detailed in the following subsections.

### Preparation of the Supporting Frames

The supporting frames consist of ETP copper rectangles (15.1 × 25.1 × 1 mm), with a central pocket (depth: 0.9 mm, diameter: 25 mm), as shown in Fig. 1. The surfaces of the frames must be free of scratches, as these can act as initiation sites for cracking and subsequent mechanical failure of the foil.

Surface preparation includes degreasing in an ultrasonic bath, followed by chemical etching using a solution of Ammonium persulphate (200 g/mol) and Sulfuric acid (8 ml/l) to remove surface defects and induce controlled roughness (~0.7 Ra), thereby reducing residual stress in the deposited films (approximately 30 μm of material is removed from the surface). The frames are then passivated in a chromic acid solution and rinsed with demineralized water.

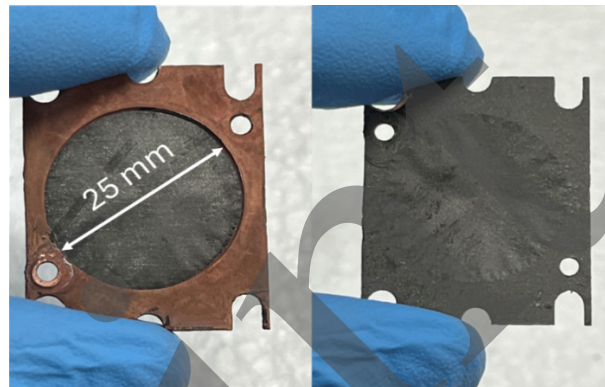


Figure 1: Copper frames with carbon foil.

### Coating Process

Four frames are coated simultaneously in each deposition run. Prior to mounting on the sample holder, the mass of each frame ( $m_0$ ) is measured using a precision balance (Mettler AE240, resolution: 0.01 mg, accuracy ~3%). To minimize contamination-induced defects (porosity), the frames are assembled in an ISO-5 cleanroom environment and transported to the coating system in a hermetically sealed container. During transfer into the vacuum chamber, the frames are exposed to ambient air for approximately 15 minutes before pump-down.

The system is baked at 120 °C for 8 h. The base pressure prior to deposition is in the 10<sup>-6</sup> mbar range. To enhance adhesion, the copper frames are exposed to an Ar (98%)–H<sub>2</sub> (2%) plasma generated by a remote plasma source (GV10x UHV DS Asher, IBSS Inc., USA), reducing surface oxides. The low ion energy (<45 eV) minimizes sputtering, and the associated mass loss is negligible.

Table 1: Distribution of CERN and GSI (Reference) Samples in the Arms of the LINAC Beam Stripper

Arm-Sample	Foil 1 μg/cm <sup>2</sup>	Foil 2 μg/cm <sup>2</sup>	Foil 3 μg/cm <sup>2</sup>	Foil 4 μg/cm <sup>2</sup>
1-GSI_150	151	151	151	149
2-GSI_120	120	121	122	149
3-CERN_130	128	131	131	118
4-GSI_100_A	98	98	97	96

High-purity argon (quality 60) is then introduced to a pressure of 8 × 10<sup>-4</sup> mbar, and carbon deposition is initiated. Carbon is sputtered from a high-purity graphite target using a planar magnetron (Gencoa) operated in DC mode at 160 W (630 V, 0.26 A). The target-to-substrate distance is 185 mm, and the deposition rate is 13 μg/cm<sup>2</sup>/h. During

deposition, the substrate temperature is not actively controlled and stabilizes at approximately 120 °C. After coating, the final mass ( $m_{\text{final}}$ ) is measured, and the areal density is calculated. Assuming a volumetric density of  $\sim 1.9 \text{ g/cm}^3$ , an areal density of  $130 \mu\text{g/cm}^2$  corresponds to a film thickness of approximately 700 nm. The areal densities of the produced foils are summarized in Table 1.

### Copper Etching

To protect the carbon layer during etching, a photoresist (HiPR 6512, Fujifilm) is applied on top of the coating. The frames are mounted on a motorized holder allowing controlled immersion and withdrawal from the chemical bath. The etching is performed at room temperature (20 to 24 °C) in a solution of ammonia persulphate in water, at a concentration of 200 g/l, and lasts for 6 hours. After etching, the protective photoresist is removed using acetone.

### Quality Control

The areal density is calculated as:

$$\text{areal density} = \frac{m_{\text{final}} - m_0}{A} \quad (1)$$

Where  $m_0$  and  $m_{\text{final}}$  are the masses of the frame before and after coating, and  $A$  is the coated area of the frame. The measurement uncertainty is estimated to be  $\pm 5\%$ .

Film porosity is analyzed by optical microscopy using back-illumination. High-resolution images are acquired at  $200\times$  magnification, and a custom image analysis algorithm is used to determine the pore size distribution. Fig. 2 shows the porosity measurements for foils produced at CERN and reference foils from GSI, the Helmholtzzentrum für Schwerionenforschung[1].

The outgassing rate of each foil is measured under ultra-high vacuum conditions after 24 h of pump-down, yielding values in the range of  $1 \times 10^{-7}$  to  $8 \times 10^{-7}$  mbar·l/s, depending on air exposure time.

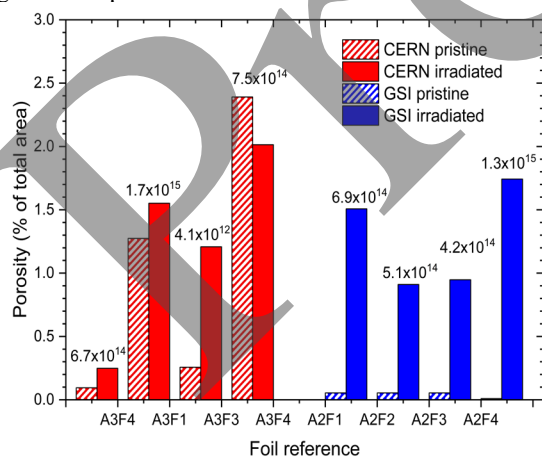


Figure 2: Foils porosity before and after irradiation (in percentage of total area of the foil). For GSI, the values presented for the pristine foils were taken on equivalent foils (not the ones irradiated). The labels indicate the quantity of  $\text{Pb}^{54+}$  produced through stripping.

### IRRADIATION IN THE LINAC 3

The performance of the foils was evaluated using 4.2 MeV/u  $\text{Pb}^{29+}$  ion beams, ( $5 \times 10^9$  ions per pulse of 300  $\mu\text{s}$  on a  $2 \times 2 \text{ mm}^2$  spot), measuring the production yield of the outgoing  $\text{Pb}^{54+}$  ions and the momentum spread  $\sigma = \Delta p / p$  as a function of the quantity of ions produced. Ageing effects were investigated at different beam repetition rates: accelerated ageing (4.2 Hz), worst-case operation (2.2 Hz), and standard operation ( $< 2.2$  Hz). Reference foils from GSI were tested in parallel.

The beam stripper unit consists of four arms, each holding four foils. A naming convention is adopted where, for example, A2F4 refers to Arm 2, Foil 4. The distribution of foils and their areal densities is given in Table 1. GSI foils in arms 1 and 2 underwent one annealing cycle; GSI foils in arm 4 two annealing cycles and CERN foils are not annealed.

Figures 3 and 4 show representative foil images before and after irradiation, and the initial  $\text{Pb}^{54+}$  yields, respectively. The evolution of the momentum spread  $\sigma$  with accumulated irradiation is presented in Fig. 5.

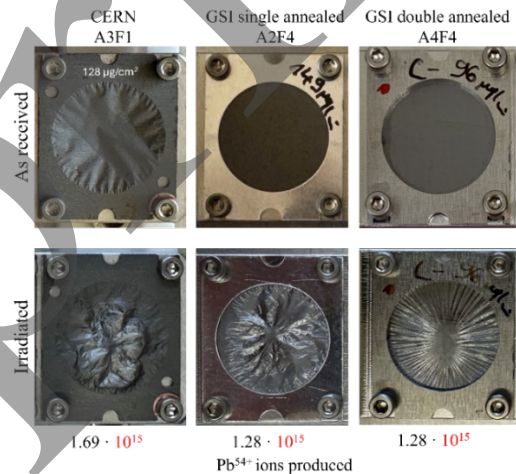


Figure 3: Pictures of representative CERN and GSI foils before and after irradiation.

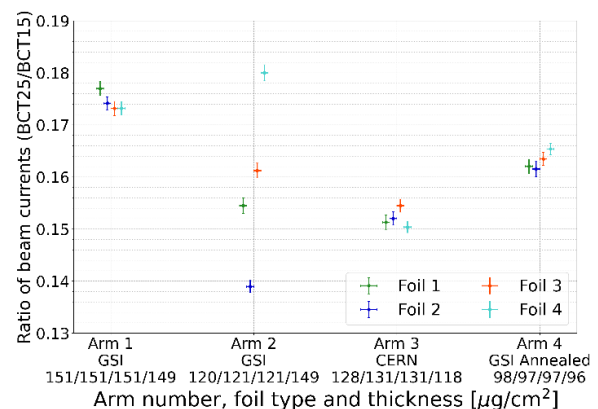


Figure 4: Initial yields of  $\text{Pb}^{54+}$  production, calculated based on the signal from the beam current transformers before (BCT15) and after (BCT25) stripping.

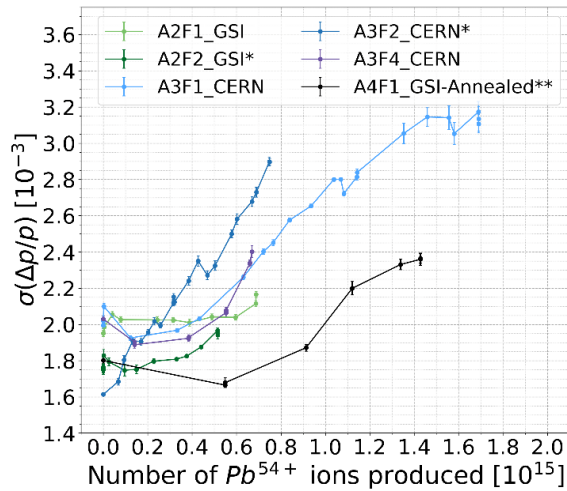


Figure 5: Evolution of the momentum spread  $\sigma$  with the dose of  $Pb^{54+}$  ions produced. Samples aged at 4.2 Hz, or (\*) at 2.2 Hz or (\*\*) under nominal operation (< 2.2 Hz).

## DISCUSSION

Figure 3 shows representative foils before and after irradiation. The observed deformations are attributed to structural changes in the carbon film caused by elevated temperatures during irradiation (>650 °C) [2]. CERN foils exhibit the largest deformation, followed by GSI foils subjected to single (arms 1 and 2) and double (arm 4) annealing cycles at 100 oC and 130 oC respectively (as part of the production process [1]). This indicates that low temperature thermal treatment improves structural stability.

Initial  $Pb^{54+}$  yields of CERN foils are comparable to those of GSI foils (Fig. 4), although approximately 5% lower than those of 100  $\mu\text{g}/\text{cm}^2$  GSI foils. This difference can be attributed to the higher initial porosity observed in CERN foils (Fig. 2), which is likely to be due to residual dust contamination prior to deposition.

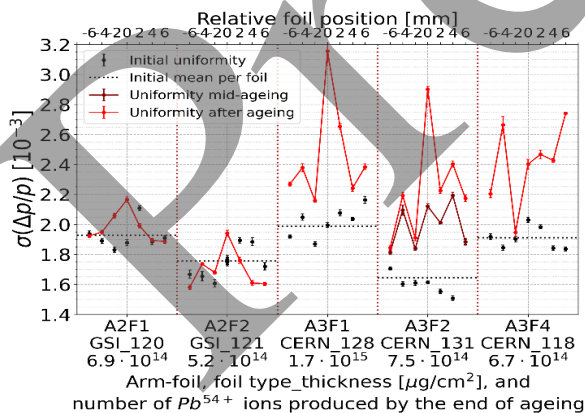


Figure 6: Momentum spread of the beam measured along the diameter of the stripping foil: at the initial stages of the bombardment (black dots), and at the end of the ageing (red dots). The total number of ions produced by each foil is shown in red below the abscissa axis.

Porosity generally increases with irradiation due to thermally induced structural changes [3]. The only exception

is foil A3F4. In this case, the apparent decrease in measured porosity is likely to be due to the severe morphological changes affecting optical transmission during the measurement.

The initial momentum spread  $\sigma$  is similar for CERN and GSI foils; however, CERN foils show a faster degradation with irradiation (Fig. 5). This is attributed to increased deformation, which introduces variations in ion path length through the foil. Spatial variations in  $\sigma$  (Fig. 6) further confirm the impact of non-uniform deformation, with CERN foils exhibiting variations exceeding 35% after extended irradiation.

## CONCLUSIONS

Carbon stripper foils were successfully fabricated by DC magnetron sputtering onto copper supporting frames, followed by selective chemical etching. The foils were tested at LINAC 3 and benchmarked against reference foils from GSI.

The initial  $Pb^{54+}$  yields are acceptable and reproducible, although slightly lower than those of reference foils, likely due to higher porosity. The initial momentum spread from these foils is also comparable, however, it increases significantly with irradiation due to severe foil deformation induced by thermal effects.

While the performance of these CERN foils remains below that of state-of-the-art GSI foils, they meet the requirements for use as spare components in LINAC 3. Future improvements should focus on reducing initial porosity through improved handling conditions and enhancing structural stability via optimization of deposition parameters or post-deposition annealing. The influence of thermal expansion mismatch between the carbon film and copper frame should also be further investigated.

## REFERENCES

- [1] Bettina Lommel *et al.*, “Preparation of different carbon stripper foils and application in beam diagnostics”, EPJ Web of Conferences 285, 05002 (2023).  
[doi:10.1051/epjconf/202328505002](https://doi.org/10.1051/epjconf/202328505002)
- [2] G. Bellodi, S. Bertolo, D. Kuchler, E. Mahner, R. Scrivens and F. Wenander, “Stripper foil investigations at Linac3”, CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2020-0016, Mar. 2020.
- [3] J. Roberston, “Diamond-Like amorphous carbon”, *Mater. Sci. Eng.: R. Rep.*, vol. 37, pp. 129-281, 2002.  
[doi:10.1016/S0927-796X\(02\)00005-0](https://doi.org/10.1016/S0927-796X(02)00005-0)