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A TEST OF STRIPPER FOIL LIFETIME IN PSI's 72 MeV PROTON BEAM

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Abstract

A test of the lifetime of an amorphous carbon foil of ~79 μg/cm² was performed at PSI in the transfer line between Injector 2 and Ring cyclotron during the regularly beam production. The 72 MeV ~1.7 mA proton beam had a central current density of ~2.8 mA/cm². Two spots on the foil were irradiated alternatively with in total three fractions of 17, 52 and 119 mAh. Foil thickness was measured before and after irradiation at several positions via the energy loss of α-particles from a ^{241}Am source in the foil. We discuss the observed foil damage as well as the experimental setup, the estimation of the beam parameters and practical boundary conditions.

INTRODUCTION

In the proposed IsoDAR experiment a 60 MeV/amu 5 mA H_2^+ molecular beam is extracted by an electrostatic deflector from a cyclotron and transported to a Be/Li target to produce $\bar{\nu}_e$ and to investigate the existence of sterile neutrinos [1, 2]. It is convenient to strip the H_2^+ ions to produce a proton beam in order to mitigate the beam losses along the transport line and to reduce the magnetic rigidity of the beam and cost of the magnetic quadrupoles and dipoles. To achieve a dissociation efficiency of 1-10^{-9} a foil thickness of ~280 μg/cm² is required. For this test a thinner foil thickness was selected to minimize the beam losses along the transport line.

FOIL PREPARATION

The amorphous carbon foil of 69 mm x 49 mm was delivered by ACF Metals (Tucson, Arizona) with a nominal surface density of 71 μg/cm² ±10% and metallic impurities <100 ppm. At INFN-LNS the foil was floated in a water bath onto a graphite frame of 4 mm thickness. It was foreseen to mount the foil on the frame on three sides. However, it was not possible to pull the holder out of the bath without disrupting the foil. Hence, a self-adhesive Kapton tape of 20 μm thickness was attached to the holder, giving support at the fourth side. In addition, the dried foil is clamped in a sandwich between two frames. The unsupported foil area of 54 mm x 32 mm is sufficient to largely avoid activation of the frame and to accommodate for two separate beam spots.

IRRADIATION IN PROTON BEAM

Setup

We chose the location of bunch-shape measurement MXZ3/4 [3], because it is well accessible and the beam is approximately circular with Gaussian profile and has limited vertical tails in order to avoid activation of the frame. From comparison with the losses caused by the 30 μm carbon wire of the monitor, we could also predict the downstream additional beam losses and that no beam interlocks would result. (We were uncertain as to whether this would cause additional activation downstream.)

The frame was mounted onto the MXZ3 wire fork in the vault at a service day (Fig. 1). To prevent disruption of the foil during pumping and venting of the beam line, Poral filters were placed between turbo pump and pre-vacuum reservoir and at the venting valve. After pumping and beam tuning, the foil was moved to the beam axis at switched off beam to prevent damage to the Kapton strip. The beam current was increased over minutes to allow outgassing. After each fraction the foil was retracted from the beam (with beam switched off) and visually inspected through the KF-50 window at the next service day.

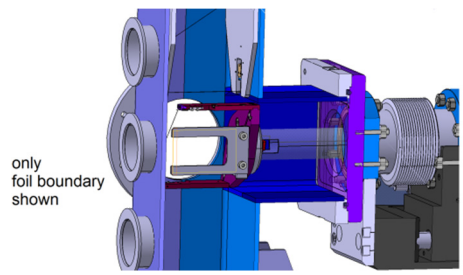

Figure 1: Frame attached to MXZ3 wire fork.

Beam Current, Charge and Density

Unfortunately, with the foil installed, the beam size could not be measured directly. Beam profiles and the dependence of beam size on beam current were, however, measured extensively in 2012/13 in the course of bunch-shape measurements [3] and have appeared to be constant over the years. Since beam optics remained unchanged for the foil measurements in 2016, we conclude from the earlier measurements to a 1σ beam width of 3.1±0.3 mm horizontally and vertically, at a beam current of 1.7 mA. Intensity profiles are close to a Gaussian but vertical tails are less developed.

Table 1: Three Irradiation Fractions at Two Spots

#	Spot	Prevalent current [mA]	Time inserted [h]	Beam charge [mAh]	Central beam charge density [mAh/cm²]
1	1	1.715	10.2	16.9	28.0
2	2	1.721 (2.037*)	31.5	51.6	85.5
3	1	1.705 (2.015*)	72.9	119	197

* Increased beam current for UCN operation: Every 5 minutes for 5 s (resulting in a central current density of 3.4 mA/cm²), followed by a decrease to 0.75 mA and a slow ramping up again within ~25 s.

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The foil temperature in the beam centre was estimated from the equilibrium of stopping power in the foil and black body radiation to be 608°C (645°C*) using an emissivity of 0.5. No loss of thickness due to the evaporation of carbon is expected. Frame temperature was estimated to stay below 60°C.

Beam Losses

Increased beam losses due to the inserted foil were measured at a few downstream loss monitors but remained far below the beam switch-off levels that protect against thermal damage. The most prominently increased signal is shown in Fig. 2 for the three irradiation fractions. Radiation surveys at service days before and after the fractions did not exhibit an increase of activation in beam lines or Ring cyclotron.

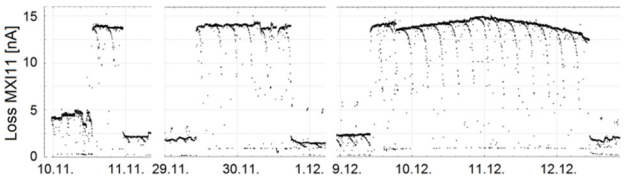

Figure 2: Signal of loss monitor MXI11, located 4.9 m downstream of the foil. (Periodic structures are due to aliasing of sampling and periodic beam current changes.)

Foil Damage

Each fraction resulted in a footprint in the foil, showing radial kinks with increasing charge (Figs. 3, 4). A sizeable rupture was observed at the location of highest charge density (Fig. 4d) after the 3rd fraction, a single retraction movement and a following 22 days waiting period. Later on, an isolated small crack in the periphery was also identified in back-light inspection (Fig. 4g). Presumably, the hole was formed from a crack, with the foil rolling in, away from the beam centre (Fig. 3). In contrary to a non-irradiated foil (Fig. 4h) the rolling in stops at the radial kinks.

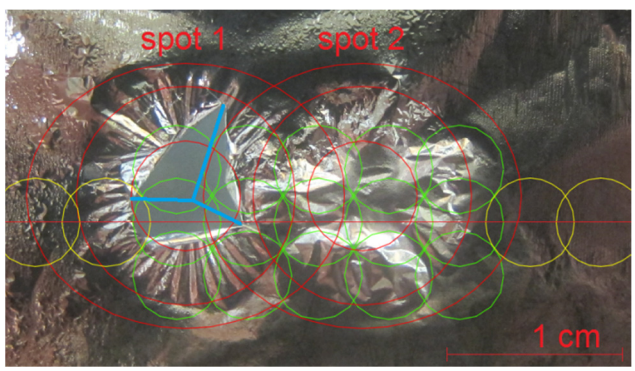

Figure 3: Foil front side after 3rd fraction (seen in beam direction). Red: Beam radius 1σ/2σ/max predicted from earlier measurements and drive movement. Only the vertical beam position was assumed to be 1.5 mm above axis for better agreement. Blue: Assumed split lines of foil. Green: Regions of thickness measurement before and after irradiation. Yellow: Ditto, only after irradiation.

The total beam loss signal MXI11 varied only by ±1.3 nA during the third fraction, which is normal. The signal increase due to the foil varied only by +10%/-15%. The variation caused by the rolling in seen in Fig. 3 would result in a larger drop. We therefore suspect, although inconclusively, that the rolling in appeared largely after irradiation. An online measurement, e.g. based on light transmission, would give better information.

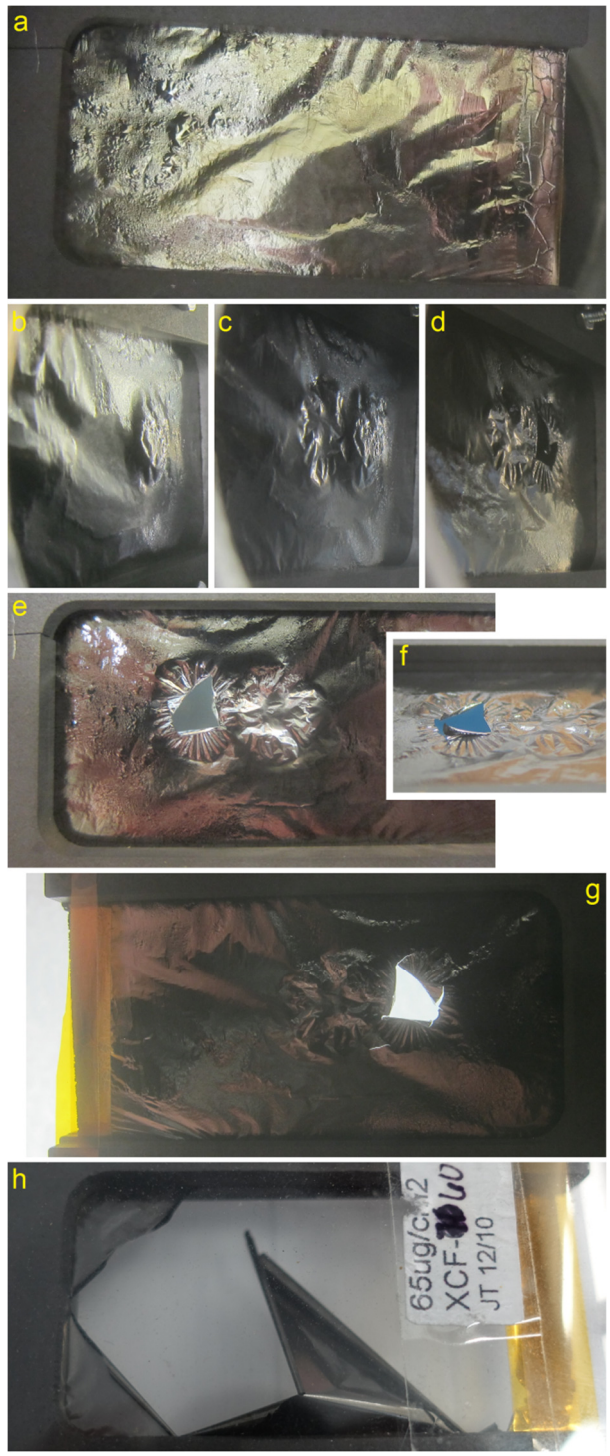

Figure 4: a) Foil before irradiation. b-d) After 1st/2nd/3rd fraction, in vacuum. e-g) Afterwards in air. h) Other foil, damaged at mounting. a,e,f,h) front, b-d, g) rear side.

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THICKNESS MEASUREMENT

Investigation of the foil thickness was performed utilizing the energy loss of α-particles traveling through matter. This is a non-destructive contact free method well suited for thin samples which are highly activated or very sensitive and frangible. But only averaged values of the energy loss over relative large areas down to a few mm^2 can be measured.

Before beam exposure an average energy attenuation of 59.8 keV of the ^{241}Am main α-peak (5485.6 keV) caused by the tested foil regions was measured. For the average α-energy of 5456 keV during the passage, the corresponding stopping power is 0.7561 keV/(μg/cm^2) [4]. It is used throughout in the following. We conclude an average foil thickness of 79.1 μg/cm^2, somewhat larger than specified.

Laboratory Setup

A ^{241}Am source of 15.2 kBq with 7 mm diameter of deposited activity was placed at one side of the foil opposite of a Canberra PD50-11-300AM ion implanted PIPS detector in a distance of 31.2 mm. Two apertures each with 6 mm diameter were placed in front of source and detector to collimate the emitted α-particles passing the foil and limit the angle of incidence with the detector surface (Fig. 5). The detector setup was placed at a flange in a vacuum chamber of same type as in the beam line. The feedthrough with frame and foil attached could be inserted unchanged. A dry prepump provided 10^{-3} mbar. The chamber was light tight to prevent detector background.

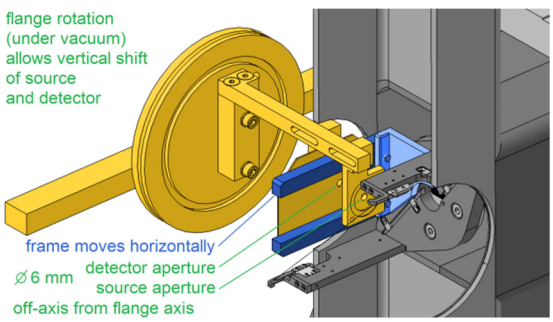

Figure 5: Setup for thickness measurement (exploded view, source, foil, detector, electronics not shown). The detector feed is transferred to the outside via an electrical feedthrough. The electronics is attached at the flange handle (in air), to keep the cable capacitance small.

A charge sensitive preamplifier (Canberra 2003BT) was connected to the PIPS detector. Standard NIM counting modules were utilized to amplify and digitize the signals. The pulse height spectra were registered using the Canberra Genie2000 spectroscopy suite. The energy resolution (FWHM) was determined from the width of the main peak to be 12.4 keV. In our set-up, changes of the peak maxima of down to 3 keV can be detected corresponding to thickness variations of 4 μg/cm^2.

Measurement and Evaluation

To check the time stability of the measurement setup, a series of 50 consecutive spectra each of 1 h counting time were conducted before beam exposure without any sample in-between the source and the detector. It was found that the position of the main ^{241}Am α-peak was changing at maximum 0.2 keV with a standard deviation of 0.06 keV. After beam exposure, the same was done placing the centre of spot 2 between the source and the detector resulting in 1.0 keV and 0.41 keV, respectively.

Individual regions of the foil (indicated by green and yellow circles in Fig. 3) were examined by recording pulse height α-spectra of 1000 s before and after the beam exposure. After five to nine consecutive measurements with the foil in-between, the foil was retracted and a "blank measurement" was performed to be sensitive to changes of the detector response. The position of the main ^{241}Am α-peak varied in all of these "blank measurements" less than 0.6 keV.

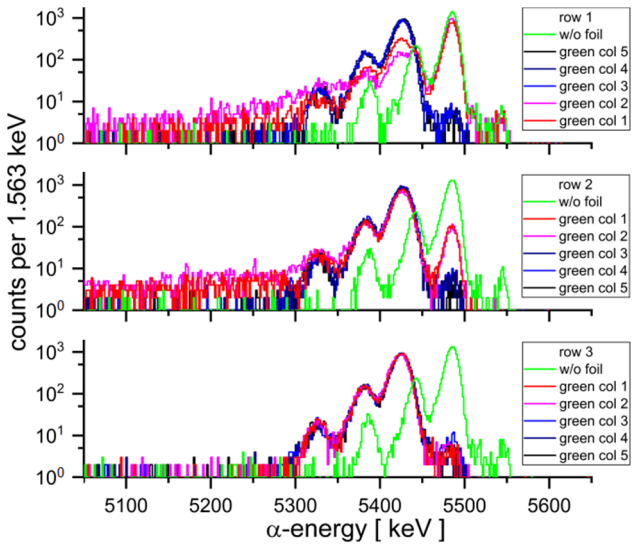

Figure 6: Post-irradiation α-spectra of green regions compared to measurements without the stripper-foil.

Table 2: Peak Shifts and Deduced Thickness Change

Row	Color	1	2	3	4	5
Column numbers are given with respect to positions of the green circles in Fig. 3 from left to right. (Ditto for yellow circles.)						
Peak shift [keV] compared to averaged blank measurements						
before beam exposure (averaged blank meas.: 5485.5 keV)						
1	green	59.8	60.2	59.7	59.6	59.5
2	green	61.2	60.7	60.2	59.7	59.7
3	green	60.4	60.4	59.6	59.4	59.6
after beam exposure (averaged blank meas.: 5485.4 keV)						
1	green	0.3	0.4	59.1	59.6	57.1
2	green	0.3	0.4	60.0	57.4	58.9
3	green	60.3	61.9	60.5	59.7	60.0
2	yellow	60.1	60.0	60.3	58.8	
Max. difference of thicknesses [μg/cm^2] before vs. after irrad.						
1	green	78.9	79.2	0.7	0.1	3.2
2	green	80.5	79.7	0.2	3.0	1.1
3	green	0.1	-2.0	-1.3	-0.4	-0.5

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At the hole location, the α-spectra consist of superposition from α-particles without and with attenuation by passing the foil. Figure 6 (red and cyan lines of rows 1, 2) illustrates this in comparison with unaffected regions and measurements without foil (green lines). This corresponds well to the findings in Fig. 3. The energy loss of the α-particles passing the foil matches almost perfectly the energy gaps between the individual α-peaks of ^{241}Am and hampers a detailed analysis. More sophisticated algorithms must be applied for a rigorous peak deconvolution, as demonstrated in [5]. However, we restrict the data evaluation of each irradiated region given in Table 2, to the determination of the maximum peak shift of the main α-peak (nominal 5485.6 keV) which corresponds to the strongest decrease in thickness in the region.

It turned out that the thicknesses of the investigated areas varied in a band of 2.4 μg/cm^2 width before beam exposure. After beam exposure, local thicknesses changed significantly only at the regions corresponding to the hole. The rolling in of the foil, however, cannot be easily deduced due to the overlaid multiplet structure of ^{241}Am.

CONCLUSION

Irradiation of spot 2 with an accumulated central beam charge density of 85 mAh/cm^2 resulted within the measurement uncertainty of the applied method of 4 μg/cm^2 not in a thickness decrease of the carbon foil. During or after the third fraction, which increased the central beam charge density of spot 1 from 28 to 225 mAh/cm^2, a hole has been formed at the spot centre. Destruction of the foil seems to be promoted by the inner tension, which is present already in the not irradiated foil. A process, somehow providing relaxation of the foil after mounting to the frame, may enhance the foil lifetime. The small thickness of the foil may be the main reason of foil rolling in. A 280 μg/cm^2 foil may result in a better performance in spite of the expected higher temperatures.

At TRIUMF, with H^- beams of comparable maximum beam current density (~1.3 mA/cm^2), thicker foils (≤2 mg/cm^2) of highly oriented pyrolytic graphite survived much higher input power surface densities, accumulated beam charges (500 mAh) [6, 7] and maximum beam charge densities (~6300 mA/cm^2) [8].

ACKNOWLEDGEMENTS

We thank Jose Alonso from LBL for proposing the foil test together with LC and for useful comments on foil handling and thickness measurement, Carmelo Marchetta for attaching the foil to the holder, Sascha Graf for designing the added mechanical parts, Roger Senn for mounting and installing the mechanical setup and conducting most of the thickness measurements and Daniela Kiselev for predicting foil activation levels.

AUTHOR CONTRIBUTIONS

LC provided foil and holder. RDr provided, set-up and maintained the α-spectroscopy electronics, supervised the thickness measurement and analysed the data. RDö conceived the beam test setup and the thickness measurement environment, coordinated the measurements, analysed the beam test data and wrote the paper with significant contributions of the other authors.

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