

# DEVELOPMENT OF HYBRID TYPE CARBON STRIPPER FOILS WITH HIGH DURABILITY AGAINST 1800K FOR RCS OF J-PARC

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## Abstract

The Japan-Proton Accelerator Research Complexes (J-PARC) requires thick carbon stripper foils (250-500  $\mu\text{g}/\text{cm}^2$ ) to strip electrons from the  $\text{H}^-$  beam supplied by the linac before injection into the RCS (Rapid Cycling Synchrotron). The 200 MeV  $\text{H}^-$  beam from the linac has a pulse length of 0.5 ms with a repetition rate of 25 Hz and an average beam current of 335  $\mu\text{A}$ . For this high-energy and high-intensity beam, conventional carbon stripper foils will break in a very short time and even a diamond foil will be ruptured at around 1800 K by the MW class accelerator. Thus, thick carbon stripper foils with high durability at 1800 K produced by energy deposition in the foil are indispensable for this accelerator. Recently, we have successfully developed hybrid type thick boron doped carbon stripper foils, which showed a drastic improvement not only the lifetime, but also thickness reduction and shrinkage at high temperature during long beam irradiation. In this report the preparation procedure and lifetime measurements with a 3.2 MeV,  $\text{Ne}^+$  beam are presented.

## INTRODUCTION

Fig. 1 shows the layout of the RCS with the injection and extraction beam transport line. A 200 MeV (first stage)  $\text{H}^-$  beam from the J-PARC linac is stripped directly to  $\text{H}^+$  by a  $300 \pm 50 \mu\text{g}/\text{cm}^2$  thick carbon foil before injection into the RCS, in which the  $\text{H}^-$  beam is post-stripped by carbon foils placed at three different positions. At the 1st position, the primary  $\text{H}^-$  beams are converted to  $\text{H}^+$  with an efficiency of about 99.6 - 99.7%, and the unconverted fraction of the beam can be converted  $\text{H}^+$  at the 2nd and the 3rd position and transported to the beam dump. Finally unconverted  $\text{H}^-$  beams are also transported to the beam dump by a magnet. The lifetime of the carbon stripper foils strongly depends upon the beam current intensity and density. Due to the energy loss of the  $\text{H}^-$  beam in the carbon foil at the injection stage and due to collisions with the circulating bunched beam, which is much more intense than the  $\text{H}^-$  injection beam, the temperature of the stripper foils becomes very high.

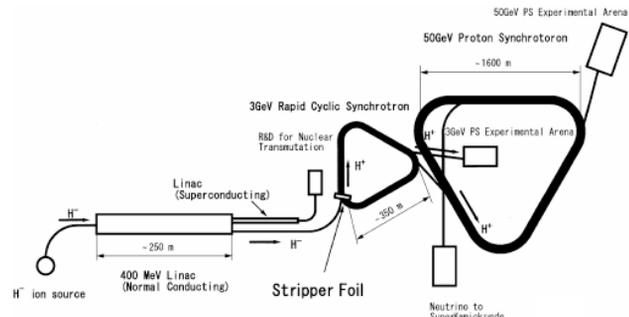


Fig.1 Schematic layout of the accelerator complex of J-PARC

The properties of the injection beam for the 3 GeV ring of the J-PARC are listed in Table 1. These data are relevant for the development of desired carbon stripper foils.

Table 1

Injection beam and stripper foil properties of the 3 GeV ring at J-PARC

Kinetic energy	200 MeV (first stage) 400 MeV(second stage)
Beam Pulse length	0.5ms
Repetition rate	25 Hz
Average beam current	0.333mA
Beam size	10 mm x 10 mm
Foil thickness	250- 500 $\mu\text{g}/\text{cm}^2$
Foil peak temperature	> 2000K

The energy deposition of the  $\text{H}^-$  injected beam is only about  $0.5 \text{ W}/\text{cm}^2$ . Hence, most of energy deposition is originating from the circulating beams. The thermal power of the 3.2 MeV  $\text{Ne}^+$  DC beam is nearly same as those by 200 and 400MeV proton beams. Thus it seems justified to use a 3.2 MeV  $\text{Ne}^+$  DC beam in the lifetime measurements of the stripper foils.

During irradiation of carbon stripper foils with pulsed 200 and 400 MeV  $\text{H}^-$  ions of high current density, the peak temperature of the foils with  $250\text{-}500\mu\text{g}/\text{cm}^2$

thickness may rise above 1800 K and the limiting effect on the lifetime might be thinning due to evaporation until burning of a hole. In order to solve these issues, there are mainly two ways. The one is to use a diamond foil [1], and the other is to apply the new laser stripping technique [2]. The diamond foil might be a very attractive candidate for ion stripping due to its drastically high thermal conductivity (five times higher, compared to copper). In our investigations, however, the foil ruptured, may be, by changing into graphite structure above  $1800 \pm 100$  K [3]. The laser stripping technique is also an attractive method. It is, however, presently in an early stage of development. Hence, the development of long-lived type of carbon stripper foil with high durability at 1800 K is one of the key technologies for the 3 GeV proton beam at the RCS of J-PARC.

## EXPERIMENTAL RESULTS

For this purpose, we have prepared cluster carbon stripper foils of  $130 \mu\text{g}/\text{cm}^2$  thickness by means of the controlled AC/DC arc-discharge (CADAD) method, as a test preparation [4]. Although the foils had a very long lifetime, we found that the foil thickness reduced to about 25% of the original thickness and pinholes were observed at the irradiated area. In addition, the maximum accessible foil thickness turned out to be  $170 \pm 30 \mu\text{g}/\text{cm}^2$  due to lack of adhesion to the substrate. To overcome these problems, We succeeded in developing a Boron mixed type of carbon stripper foil of  $250\text{-}400 \mu\text{g}/\text{cm}^2$  accessible thickness. Comparative measurements of the lifetime and other properties of this hybrid type stripper foils as well as of the diamond foils and of the best available commercial foils were performed with a 3.2 MeV  $\text{Ne}^+$  DC ion beam.

This carbon discharge-arc evaporation source was installed in a new vacuum chamber (EBX-2000C) of dimensions  $750 \times 750 \times 900 \text{ mm}^3$ . It is equipped with a cryo-pump of 5000 l/s pumping speed for  $\text{N}_2$ , which produces a basic vacuum of  $4 \cdot 10^{-6}$  Pa in the empty chamber. The distance between the evaporation source and the substrate was 180 mm. The principal axis of both electrodes was tilted by  $45^\circ$  against the plane of the substrate holder. As mentioned in ref. [4-6], the lifetime of the foil was found to be correlated to the expression  $R = W_c / (W_c + W_a)^{-1}$  calculated in %, where  $W_c$  and  $W_a$  are the carbon source weight losses due to ablation from the cathode and the anode electrodes, respectively. In the

present preparation, the ratio R was kept between 60 and 70 %. The layer thickness was controlled with a quartz thickness monitor and measured after deposition. For carbon layer deposition, the pressure in the vacuum chamber was  $8 \times 10^{-5}$  to  $2 \times 10^{-4}$  Pa with DC arc power on, when the arc was off, the pressure was  $3 \times 10^{-5}$  Pa. Stripper foils prepared by this method are referred to as HBC-foils (Hybrid Boron mixed Carbon stripper foils). Fig.2 shows the inside view of the arc-evaporation sources.



Fig.2 Arc-discharge evaporation-source in EBX-2000C cryo-vacuum pump apparatus

The lifetime measurements were performed with a 3.2 MeV  $\text{Ne}^+$  DC beam of  $2.5 \pm 0.5 \mu\text{A}$  and 3.5 mm beam spot diameter, supplied from the Van de Graff accelerator at the Tokyo Institute of Technology. In this case, the lifetime was determined as a total integrated irradiation dose ( $\text{mC}/\text{cm}^2$ ) until foil rupture occurred assuming a constant current during irradiation. We investigated four foils of the HBC type of  $200\text{-}380 \mu\text{g}/\text{cm}^2$ , three diamond foils (DM-foils) of  $350 \mu\text{g}/\text{cm}^2$ , two diamond foils of 680 and  $780 \mu\text{g}/\text{cm}^2$ , and, for comparison, four commercially available thick foils (CM-foils) of  $200\text{-}400 \mu\text{g}/\text{cm}^2$ . The diamond film was deposited by Kobe-Steel company and Sumitomo Electric Industries, Ltd. in Japan on a 0.5 mm thick Si substrate. It had to be prepared self supporting by chemically etching the Si substrate except for an approximately 18 mm outer circle frame, which survived etching due to coating with a Kapton film.

In this lifetime measurement, we used the ribbon type foils of 20 mm x 30 mm and the foils were mounted on an Al holder (38 mm x 58 mm). We observed the state of shrinkage, brittle and rupture from a viewing port. Table 2 shows the results of the lifetime measurements.

Table 2

Maximum and average lifetime of HBC-foil, DM-foil and CM-foil measured with a 3.3 MeV, Ne<sup>+</sup> ion beam of 3μA on a 3.5 mm diameter beam spot

Type of foils	HBC-foil	DM-foil	CM-foil
Max. lifetime (mC/cm <sup>2</sup> )	9800	104	24
Average (mC/cm <sup>2</sup> )	5600	88	20

Fig.3 shows a relationship the lifetime as a function of the thickness of commercially available best carbon foil. From this picture, we can clearly see the short lifetime and the decreasing of lifetime with increase the thickness of foil, The rupture of these foils in thicker than around 300 μg/cm<sup>2</sup> is caused by high temperature (>1400K) due to energy deposition in the foil.

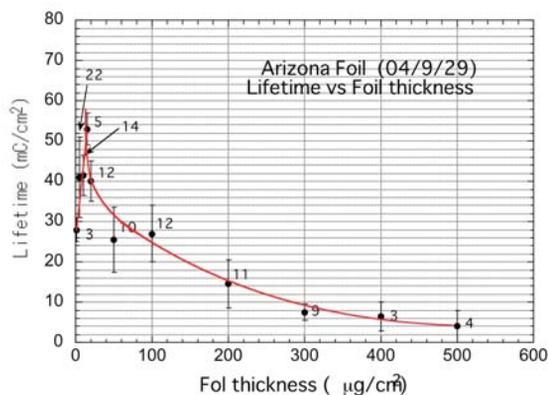


Fig.3 Lifetime vs foil thickness. Error bars represent root mean square errors and the numbers attached to the points are the number of samples measured.

The HBC-foil did not show any shrinkage even after a long time irradiation of approximately 9800 mC/cm<sup>2</sup> at temperature of 1600±200 K. The thickness of the foil was reduced, but not by more than 20 % of the original thickness, as measured with an α particle thickness gauge [7]. The tested DM-foil in Fig.4(b) showed a little pale dark color after a few minutes of irradiation, and it became a deeply dark color with more than irradiation time, and then it was broken at approximately 104 mC/cm<sup>2</sup> at the irradiated area. The temperature of the foil during irradiation was approximately 1700±100 K. In this case, the foil did not show any shrinkage until the foil was broken. The CM-foil showed a strong shrinkage after approximately 20 mC/cm<sup>2</sup>, it continued to shrink, and

then the foil broke by making a hole. The maximum temperature was 1600±200 K.

## SUMMARY

We have successfully developed HBC-foils using the CDAD method, and the HBC-foils showed the following great improvements:

- (1) Strong adhesion to the substrate and thus the foils could be prepared with thickness up to a maximum of 480 μg/cm<sup>2</sup>.
- (2) Noticeably less shrinkage than for foils made by the CADAD method, and thickness reduction less than 20 %, even after long-time irradiation at the high temperature of 1600±200K.
- (3) A maximum lifetime of a HBC-foil of 9800 mC/cm<sup>2</sup> corresponding to approximately 408 times longer or 94 times longer than those of the best CM foils or high quality diamond (DM) foils, respectively.

In conclusion, this method is a simple and promising one for production of long-lived carbon stripper foils thicker than 200 μg/cm<sup>2</sup> for use in J-PARC.

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