Analysis of Hybrid Type Boron-Doped Carbon Stripper Foils in J-PARC RCS

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Abstract. J-PARC (Japan-Proton Accelerator Research Complex) requires a carbon stripper foil to strip electrons from the H beam supplied by the linac before injection into the Rapid Cycling Synchrotron (RCS) [1]. The foil thickness is about 1 μm (200 μg/cm²) corresponding to conversion efficiency of 99.7% from the primary H beams of 181 MeV energy to H⁺. We have successfully developed the Hybrid type thick Boron-doped Carbon (HBC) stripper foil, which showed a drastic improvement the lifetime without thickness reduction and shrinkage at the irradiated area. We started to study carbon stripper foils microscopically why carbon foils have considerable endurance for the beam impact by boron-doped. At first step, we made a comparison of ion irradiation effect between normal carbon and HBC by the electric microscope, ion-induced analysis. In particular, it seems that grain size of boron-rich area became much larger by irradiation for HBC. It was also observed that the boron-rich grain grew up by taking around material and generated pinholes more than 100 nm near itself consequently.

1. Introduction
A charge stripper foil is one of key technology for multi-turn injection of high power proton synchrotron. Typically carbon-based material is used to strip two electrons off the incident H beams. Recently injection of high power ring accelerators such as SNS [2] and J-PARC demands much longer lifetime for the stripping foils to reduce beam dead time. J-PARC RCS applied HBC foil which is developed with the arc-discharge method by Sugai [3]. HBC foil is much better than a normal carbon foil for uniformity and dynamic strength of large area foil and durability against irradiation of ions. The foil thickness is about 1 μm (200 μg/cm²) corresponding to conversion efficiency of 99.7%. The usual foil is composed two pieces of foil because the double foil can endure against beam irradiation.
much better than the single one [4]. The foil size is 40mm x 110mm, but the area hit by the beam is about 10mm diameter around the end. Figure 1 shows a picture of our foil’s holder which is attached by SiC wires of 10μm diameter. In order to guarantee not to disturb beam demand time by foil damage, we can exchange a new foil immediately without vacuum purge because of 15 foil’s holders in the stock chamber. The Figure 1 also shows “the magazine rack” for the foil’s holders. At the present time, HBC foil endures our usage of neutron’s generation by RCS output beam power of 200kW continuously. However, the final goal of J-PARC RCS is to provide beam output power of 1MW.

![Figure 1](image1.png)  
**Figure 1** HBC foil’s holder, the schematic diagram and “the magazine rack” which can stock 15 holders

We began to study why HBC foil has the much more durability against beam irradiation than a commercial available carbon foil, and how foils are broken by beam damage. In particular, it is important to investigate destruction mechanism by microscopic methods. In order to reveal the boron-doped effect for a carbon foil made by arc-discharge method against ion beam irradiation, ion accelerators of TIARA (Takasaki Ion Accelerators for Advanced Radiation Application) was used for ion-induced analysis. TIARA belongs in JAEA and has four accelerators, an AVF cyclotron, a 3-MV tandem accelerator, a 3-MV single-ended accelerator and a 400- kV ion implanter. This time we used ion implanter for ion irradiation and 3-MV single ended accelerator for RBS (Rutherford Backscattering Spectrometry). Furthermore, TEM (Transmission Electron Microscope) observation were tried to compare between normal carbon (NC) and HBC foil before and after ion irradiation.

### 2. Sample Preparation

Although typical foil thickness is 200μg/cm² for the practical usage, we used foil thickness of 15 μg/cm² because of ease for TEM observation. We prepared several foils each of NC and HBC foils of about 15 μg/cm². Ar⁺ of 300keV, which we use as irradiated ion from ion implanter in TIARA this time, can deliver the energy deposition by the ion beam into this thickness foil without ion implantation. The preparation method of HBC foils is the controlled DC arc discharge process. The cathode(−) was a boron-doped (25%) carbon rod of 10mm diameter while the opposite electrode(+)
was a pure graphite rod of 15mm diameter. The distance between the evaporation source of the carbon rods and the substrate on the flat glass was 250mm. NC and HBC foils were analyzed the major atomic composition with RBS. The probe beam was H\(^+\) of 3MeV from 3-MV single ended accelerator, in which the size was 1mm diameter and the current was about 15 nA on the foil surface. It is possible to obtain the boron to carbon ratio and the foil thickness information as shown in Figure 2. In HBC foil, the boron to carbon ratio is close to the rod’s component.

![Figure 2 RBS results for NC (normal carbon): left side and HBC: right side](image)

3. **Analysis Results**

3.1 Macroscopic observation for foils by irradiated ion beam

The ion beam size was about 5mm diameter and much smaller than the target sample foils. Figure 3 shows variance of the surface appearances for each of foils irradiated by Ar\(^+\) of 300keV, 300nA. It seems that surface of HBC flattened out much slower than NC by the irradiation, and HBC was not broken after smoothed out. The visual light from the foil by the energy deposition wasn’t observed. The foil surface temperature was lower than four hundred degrees C. We need to evaluate dynamic strength quantitatively before and after irradiated ion beam.

![Figure 3 Time transition of sample surface for (A) NC (normal carbon) and (B) HBC irradiated with 300keV, 300nA Ar\(^+\) ions. Aperture of the sample holder is diameter of 8mm.](image)

3.2 Microscopic observation (TEM) for foils by irradiated ion beam

We have great interest how the irradiated area of the foil changes microscopically. In TIARA we have TEM (JOEL JEM-4000F:400keV) system which can inject ion beams from the ion implanter. We tried to observe the time variation by Ar ion irradiation (300kV, 20nA, <3mm\(\phi\)) for these foils in the TEM system. Both NC and HBC had generally amorphous phase, but they involved a lot of micro
graphite grains of a few nanometer before irradiation of ions. In the NC foil case, though some graphite grains grew up, drastic change was not occurred. On the other hand, in the HBC case there were many boron-rich micro grains before and after ion irradiation. In particular, it seems that grain size of boron-rich area became much larger by irradiation in shown by the Figure 4. In the Figure 5, it was also observed that the boron-rich grain grew up by taking around material and generated pinholes more than 100 nm near itself consequently. We guess that this phenomenon is one of the destructive mechanisms of the HBC foil. We should detect atomic component and crystal structure of the boron-rich grain as shown in the black contrast.

**Figure 4** The time variation by Ar ion irradiation (300kV, 20nA) for the boron-rich area of HBC foil in the TEM system. Left side is before irradiation, and Right is after irradiation for 80min.

**Figure 5** Some large pinholes by Ar ion irradiation of HBC foil in the TEM system

4. **Summary**

At first step, some results with microscopic analysis methods, such as RBS and TEM, were demonstrated for NC and HBC foils before and after Ar⁺ ion irradiation. This time we could obtain effective microscopic techniques adapted to analyze charge stripper foils, and got some remarkable results for transition by ion beam irradiation. In the future, we will try to evaluate atomic component and structure for boron-rich area in HBC foil, and reveal relation between boron and carbon in the foil.

**References**

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