OPERATIONAL STATUS AND LIFETIME-EXTENSION EFFORTS OF CHARGE-EXCHANGE FOILS IN THE J-PARC 3 GeV SYNCHROTRON

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Abstract

At the J-PARC 3 GeV Rapid Cycling Synchrotron (RCS), a 400 MeV negative hydrogen (H^-) beam from the linac is converted to proton (H^+) using a charge-exchange foil and then accelerated to 3 GeV. As the output beam power has increased toward the design value of 1 MW, foil deformation and breakage of the SiC support fibers caused by beam irradiation have become major issues, leading to beam dump temperature rises that obstruct stable operation. To improve the reliability of the charge-exchange foil under high power conditions, a stepwise development has been carried out. First, a pure carbon foil was developed to suppress irradiation-induced deformation. Beam operation showed reduced deformation compared with previously used hybrid boron-mixed carbon (HBC) foil and graphene thin film (GTF), and beam dump temperature rises were not observed. Next, the arc deposition parameters were optimized by increasing the anode diameter, resulting in further reduction of deformation in beam operation. Finally, carbon nanotube (CNT) wires were adopted as support material instead of SiC fibers. The CNT-supported foil was successfully operated up to 940 kW-equivalent beam power for over 1 month without support failure and beam dump temperature rises. These results demonstrate improved durability of the charge-exchange foil and support stable RCS operation toward 1 MW beam power.

INTRODUCTION

Until now, charge-exchange foils for the RCS have been fabricated in-house at Japan Atomic Energy Agency (JAEA) [1] as HBC foil [2] or have been produced using commercially available GTF [3]. For maintaining stable foil geometry, the foil is supported by a mesh of single-filament SiC fiber from both sides [4], as shown in Fig. 1(a).

In the RCS, to achieve the design beam power of 1 MW, the beam intensity has been increased incrementally [5, 6]. However, the lifetime of the charge-exchange foil has emerged as a critical issue as the beam intensity rises. When the incident particle flux from the linac exceeds 4.5×10^{18} particles per hour (equivalent to output beam power of 600 kW), beam-irradiation-induced damage has emerged prominently as breakage of the SiC fiber and deformation of the foil such as shrinkage and curling. Fig. 1(b) shows a photograph of a foil supported by SiC fiber after beam operation. Multiple SiC fibers near the foil tip where the beam was irradiated, were broken and the foil was visibly deformed. Once the supporting fibers break, the foil can no longer be restrained, and deformation becomes severe at the edges. As this deformation progresses, part of the injected beam no longer hits the foil, leading to a decrease in the charge-exchange efficiency. The injection beam that fails to charge-exchange is discarded in the beam dump. Therefore, increases in beam dump temperature occurred frequently as the beam power increased. When the temperature of the beam dump reaches its upper limit, beam operation must be stopped to protect the beam dump equipment, which constitutes a serious impediment to stable operation.

To address these issues, a stepwise development has been carried out. First, a pure carbon foil was developed to suppress irradiation-induced deformation. Next, the deposition conditions were optimized to further improve the foil durability. Finally, CNT wires were adopted to enhance the radiation resistance of the support structure. The performance of these developments has been evaluated in beam operation at the RCS.

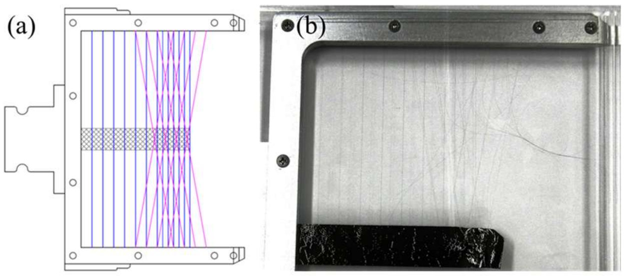

Figure 1: Schematic image of the SiC support fiber pattern (a) and Photograph of the used foil with broken SiC fiber and deformed foil (b).

RESULTS IN BEAM OPERATION

Development of Pure Carbon-based Foil

Figure 2 presents the history of beam power, beam dump temperature, and the type of charge-exchange foils used during the 2022–2023 period. During the period when HBC foil and GTF were used (November 2022 to February 2023), frequent increases in beam dump temperature occurred. Therefore, the foil position was adjusted so that the entire injection beam passed through the foil, ensuring the dump temperature did not exceed 70°C. The point at which position adjustment can no longer suppress the rise in beam dump temperature is the effective lifetime of the foil. Figure 3 shows photographs of an HBC foil taken before and after beam operation. This foil was used under beam operation conditions of 770 kW-eq, and the total number of injected H^- ions reached 2.42×10^{21}. Significant deformation can be observed near the tip where the beam is irradiated.

The deformation observed in HBC foil is considered to arise from irradiation-induced crystallization, in which

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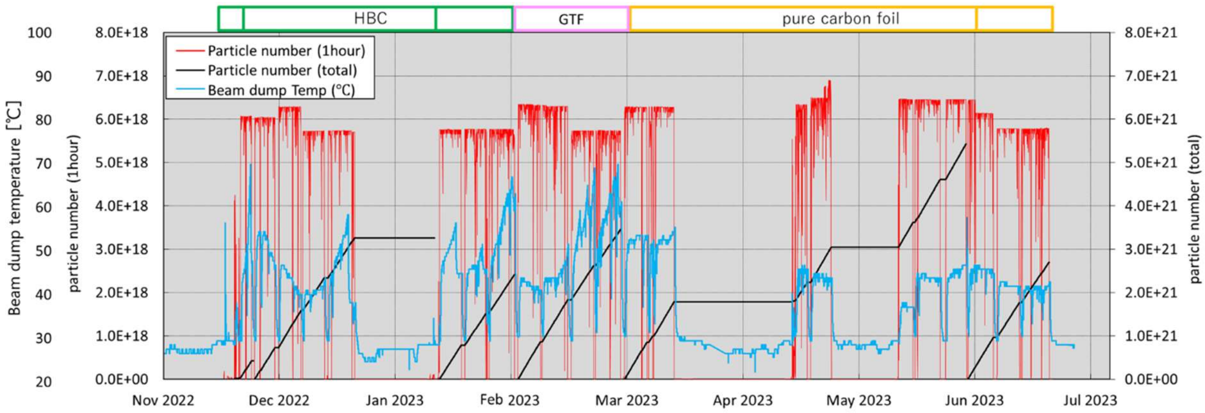

Figure 2: History of beam power and beam dump temperature during 2022-2023 and the types of foil used during that period.

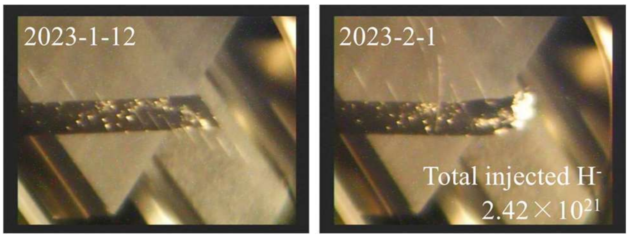

Figure 3: Photograph of the HBC foil used from 2023/1/12 to 2/1.

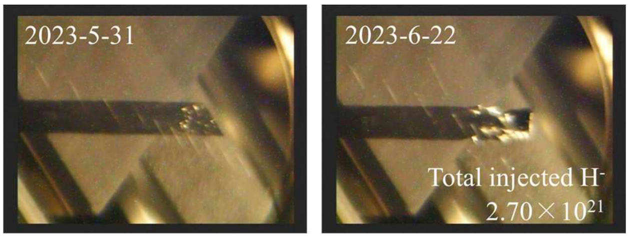

Figure 4: Photograph of the pure carbon foil used from 2023/5/31 to 6/22.

B_4C microcrystals contained in the material act as nucleation sites, leading to volumetric shrinkage [7]. In contrast, the deformation in GTF is thought to result from irradiation damage generating numerous defects in the graphene structure, thereby destroying its crystallinity. In other words, if the foil is made of pure amorphous carbon, irradiation-induced deformation may be suppressed.

Therefore, we have developed a pure carbon charge-exchange foil. When pure carbon is used as the raw material, the adhesion between the substrate and the deposited foil is weak, making it difficult to fabricate carbon foil thicker than approximately 100 μg/cm². By optimizing the arc deposition parameters and the substrate pre-treatment procedure, we succeeded in producing foil with the required thickness of 340 μg/cm².

The pure carbon foils were used for beam operation from March 2023 to June 2023. As a result, the beam dump temperature spikes that had been observed previously were eliminated during this period. Figure 4 displays photographs of the pure carbon foil taken before and after beam operation. Although the total number of injected particles is comparable to that of the foil shown in Fig. 3, the deformation at the foil tip is suppressed. The pure carbon foil exhibits less deformation under beam irradiation when compared with HBC foil and GTF. Consequently, it is less prone to causing a temperature rise in the beam dump, which indicates its suitability for long-term stable operation.

Optimization of Carbon Rod Diameter

To further improve the foil durability, we optimized the deposition conditions. Initially, foils were produced using carbon rods with a diameter of 10 mm for both the anode and cathode electrodes by arc deposition. To optimize the deposition conditions, the cathode electrode diameter was fixed at 10 mm, while the anode electrode diameter was varied in seven steps: 10, 15, 18, 20, 25, 30, and 45 mm. Multiple samples were prepared for each anode diameter.

The irradiation lifetime of each anode diameter was evaluated at the National Institutes for Quantum Science and Technology (QST) TIARA facility in Takasaki. Multiple samples for each anode diameter were irradiated by Ar^+ ions (300 keV, 1 μA) until broken. All samples had a thickness of ≈ 20 μg/cm² and were exposed through a 1 mm beam slit. The results are shown in Fig. 5. It was found that the foil lifetime depended strongly on the anode diameter. The average lifetime of samples prepared with anode diameters of 10 mm and 15 mm was approximately 50 seconds or less. In contrast, samples with an anode diameter of ≥ 18 mm exhibited a dramatic increase in lifetime, with an average exceeding 1,000 seconds. The increase in lifetime due to the difference in diameter is more than 20 times longer.

Using this method to extend the lifetime by altering the electrode diameter ratio, we fabricated the thick pure carbon foil for the RCS and evaluated its performance under beam operation. Figure 6 shows photographs taken before and after beam operation. This foil was used from 12 June to 28 June 2024; it was produced with the 20 mm anode and the 10 mm cathode. During this period, the beam power was 880 kW-eq, and the total number of H^- ions injected from the linac reached 1.65×10^{21} particles. For comparison, Fig. 7 shows photographs of the pure carbon foil fabricated using 10 mm-diameter electrodes for both the anode and cathode. The foil was used from 15 May to 12 June 2024. To compare the results under the same irradiation conditions, we show the observation image recorded on 26 May 2024, when the total number of injected H^- ions had reached 1.65×10^{21}. Neither foil exhibited any increase in beam dump temperature, but the deformation of the foil tip irradiated by the beam was clearly reduced for the foil fabricated with a 20 mm anode diameter. Thus, the foil fabricated by optimizing the electrode diameter ratio was shown to exhibit high beam resistance even under the beam conditions used in the RCS.

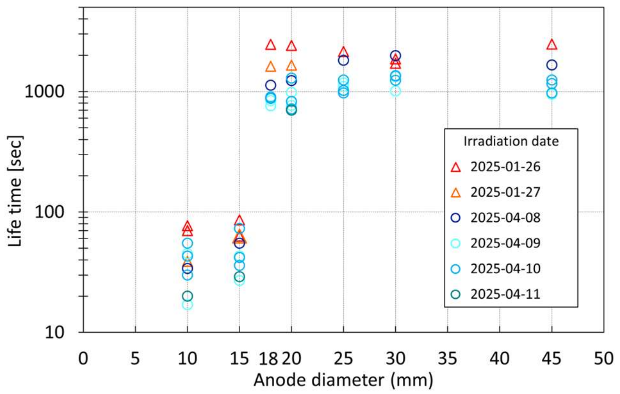

Figure 5: Pictures of irradiation lifetime of the multiple samples for each anode diameter.

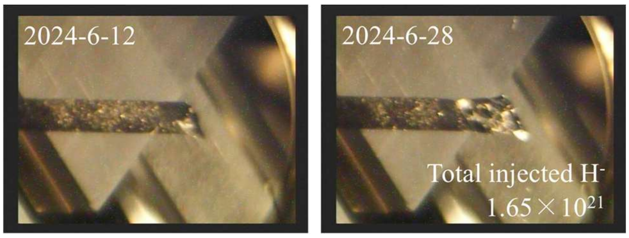

Figure 6: Photograph of the pure carbon foil used optimized carbon rod diameter.

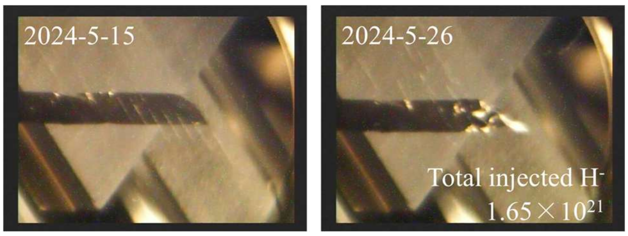

Figure 7: Photograph of the pure carbon foil used electrodes with a diameter of 10 mm anode and cathode.

Adoption of CNT Support Material

Next, to address the breakage issue of SiC support fiber, we investigated support materials that exhibit greater resistance to beam irradiation than SiC fiber. As a result, a commercially available CNT wire was selected as the support material. The CNT wire consists of filamentous CNT drawn from an aligned CNT array and twisted together [8]. This CNT wire has already been tested and has shown good results as a beam monitor probe in the J-PARC linac [9]. The CNT wires tested comprised two diameters, 20 µm and 15 µm, and the foils mounted on them were fabricated from carbon rods with an anode diameter of 20 mm and a cathode diameter of 10 mm.

Figure 8 shows observation images before and after beam operation of a foil using a CNT wire with a diameter of 20 µm as a support material. The beam operation was carried out at a beam power of 100 kW-eq for about 2 months and 940 kW-eq for over one month. The total number of injected H^- ions had reached 6.03×10^{21} particles. During this period, CNT wire breakage and foil deformation were not observed. No increase in beam dump temperature was observed that would interfere with beam operation. Figure 9 shows photographs of a foil using a 15 µm diameter CNT wire as a support material. The beam operation lasted approximately two months at the beam power of 800 kW-eq. The total number of injected H^- ions had reached 6.38×10^{21} particles. As with the foil using 20 µm diameter CNT wire, CNT wire breakage was not observed during this period. No deformation of the foil or increase in the beam dump temperature was observed.

When the beam power exceeded 700 kW-eq, SiC fiber began to break off within several hours of beam irradiation. In contrast, CNT wires of both 15 µm and 20 µm diameter demonstrate markedly superior durability under high intensity beam irradiation. We will verify the optimal wire diameter through future beam operation.

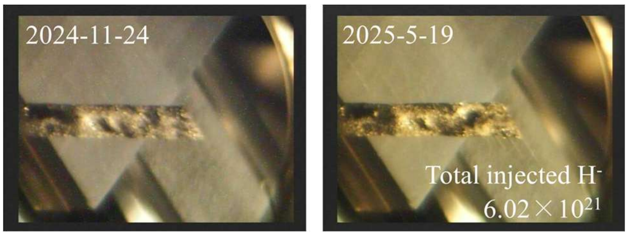

Figure 8: Photograph of the Pure carbon foil with 20 µm CNT wire as the support material.

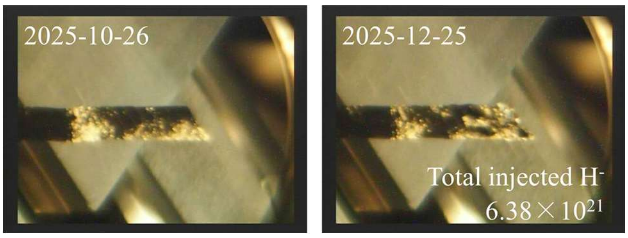

Figure 9: Photograph of the Pure carbon foil with 15 µm CNT wire as the support material.

SUMMARY

Using inexpensive and widely available pure carbon materials, thick charge-exchange foils were successfully fabricated. These pure carbon foils were confirmed to have a longer lifetime than HBC foil or GTF due to their lower deformation under beam irradiation. Moreover, when the carbon rod diameter is properly optimized, the pure carbon foil shows even smaller deformation. Furthermore, CNT wires demonstrate exceptional resistance to beam irradiation damage and are fully adequate as foil support materials. The combination of the pure carbon foil with optimized carbon rod diameter and CNT support wire is highly promising for achieving stable 1 MW operation of the RCS.

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