HBC Foil Beam Study and Long-term Observation at the 3-GeV RCS in J-PARC

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Abstract. The HBC foils are installed in the J-PARC RCS for the charge-exchange H⁻ beam injection. In order to examine the characteristics of the HBC foils, beam studies for the HBC foil were carried out from the viewpoint of foil’s life time and the beam survival rate due to foils. According to the compromise between charge-exchange efficiency and foil scattering beam loss, we selected the foil thickness of about 200μg/cm² for user operation. The measurement of the charge-exchange efficiencies of the HBC foils is found to be consistent with expectation. The long-term observation during the user operation as well as the HBC foil endurance test for its life time evaluation was carried out. In the beginning of the beam irradiation the voluminous outgassing from the foil occurred and the foil was found to deform drastically but after that the outgassing decrease gradually and foil deformation didn’t become worse. There was no noticeable deterioration of the stripping foils even after one year user operation, which corresponds to about 1.41x10²¹ particles irradiation.

1. Introduction

Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose research facility for materials and life sciences, nuclear and particle physics, and nuclear engineering with MW class proton beam at 3GeV and at several 10GeV. It is a joint project between Japan Atomic Energy Agency (JAEA) and High energy Accelerator Research Organization (KEK), and is located in Tokai-Mura in Japan. The accelerator complex consists of a 400-MeV linear accelerator (LINAC), a 3-GeV Rapid Cycling Synchrotron (RCS), and a 50-GeV Main Ring Synchrotron (MR) [1]. The RCS is designed to accelerate the H⁺ beam from 400MeV to 3GeV and with 8.3x10¹⁷ protons per pulse at a repetition rate of 25Hz, which corresponds to a beam power of 1MW. At the first stage, the beam energy injected from the LINAC to the RCS is 181MeV but the extraction energy is same as 3GeV. Therefore the RCS aims to achieve the beam power of 0.6MW [2]. In the RCS, the charge-exchange H⁺ beam injection scheme with stripping foils is adopted to realize the MW class high-power proton beam [3]. In accelerator, multi bunched beams are injected from an injector repeatedly and are stacked in a circulating accelerator to increase the beam intensity. But Liouville’s theorem precludes that identical particles are injected over the phase space volume occupied already by other particles. The charge-exchange injection scheme is one of the beating Liouville’s theorem techniques. Figure 1 shows the schematic diagram of the charge-exchange H⁺ beam injection scheme at the RCS. The H⁺ particles enriched with electrons are produced in the ion source and are accelerated to 181MeV in the LINAC. In RCS, horizontal bump magnets are excited at the injection period and thus the injected H⁺
particles are bent onto the circulating beam orbit. The H⁻ particles are then encountered a thin foil, which stripped two electrons from the H⁻. Thus H⁺ particles exit from the foil and were placed in the same phase space volume as an existing bunch of protons already circulating in the ring. On the other hand, there are partially stripped H⁰ particles and un-stripped H⁻ particles slightly. In order to control the H⁰ and H⁻ beams, there are two more stripping foils named 2nd and 3rd foil and are installed downstream of the 1st foil. The partially stripped H⁰ and the un-stripped H⁻ beams are further stripped to H⁺ by the 2nd and 3rd foils respectively and are transported to the injection beam dump called H₀-beam dump (H₀-BD).

The important key issues for the charge-exchange H⁻ injection with stripping foil are foil's life time and beam survival rate due to foils. Thus various beam studies for stripping foil were carried out. In this paper, we report the beam studies results concerned with foil’s life time and beam survival rate due to foils.

2. Experimental Procedures and Results

The charge-exchange H⁻ injection technique is already utilized in various accelerator laboratories around the world, and several kinds of the foils are used in respective laboratories. We adopt the Hybrid type thick Boron-doped Carbon (HBC) stripping foils in the J-PARC RCS. The HBC foils are developed by Sugai group in KEK, which improved the lifetime drastically [4]. So far the HBC foil doesn’t have certain achievements in the high power user operation, although it has the lifetime’s advantage in the beam irradiation test. Aiming the higher power beam operation, the HBC foil has been installed in the RCS ring on September 2008, and various beam studies in the RCS are carried out to examine the characteristics of the HBC foils [5].

2.1. Beam survival rate due to stripping foil

The thickness of the thin foil is one of the key parameters. Charge-exchange efficiency depends on the stripping foil thickness. The higher the thickness of the stripping foil, the more charge-exchange efficiency increases but the beam loss due to the foil scattering due to foil beam interaction increases too. Thus the optimum foil thickness is a compromise between charge-exchange efficiency and beam loss due to foil scattering.

To optimize the foil thickness, the beam survival and the stripping efficiency were measured using various thicknesses HBC foils from 100µg/cm² to 600 µg/cm² (nominal values; 92, 196, 288, 392, 487, 634 µg/cm²). In the user operation, the bunched beams of 250turns are injected into the RCS ring. But in this beam study, the number of the injecting beam bunches are limited to 50turns and a long flattop pattern of the bump magnets was adopted and the beam injection timing is set at the start of the flattop, so foil hitting probability increases, to clear the foil scattering beam loss. Circulating beam intensity was measured by a Wall Current Monitor (WCM) and is shown in figure 2. Injection beam is stacked in the ring and then the beam intensity increases. After the injection, the beam intensity seems to remain constant. Then beam intensities at the various timing are compared as shown figure 3. In figure 3, red circles are obtained just after the injection (50 turns) has finished. The higher the thickness of the stripping foil, the more circulating beam intensity increased, but the beam intensity was saturated with the foil thickness more than 300µg/cm². Thus the red circles are similar to the charge-exchange efficiency. The other marks are obtained after the bump magnets are turned off in other words the circulating beam doesn’t hit the scattering foil thus there were no observable reduction. The difference between red circles and other marks means the foil scattering beam loss and it increases depending on the foil thickness. Figure 4
shows the analysis results of the beam survival rate due to foil scattering beam loss as a function of the foil thickness. The foil scattering beam loss is directly proportional to the foil thickness. According to the compromise between charge-exchange efficiency and foil scattering beam loss, we selected the foil thickness of about 200\(\mu\)g/cm\(^2\) for user operation.

**Figure 2.** Typical result of the measured circulating beam intensity with WCM, wave patterns of bump magnet and injection beam. (In this case, foil thickness of 196\(\mu\)g/cm\(^2\) were used.)

**Figure 4.** Analysis results of the beam survival rate due to foil scattering beam loss as a function of the foil thickness.

**Figure 3.** Beam intensities measured by WCM as a function of the foil thickness. Red circles are obtained just after the injection has finished. The higher the thickness of the stripping foil, the more circulating beam intensity increased, but the beam intensity was saturated with the foil thickness more than 300\(\mu\)g/cm\(^2\). Thus the red circles are similar to the charge-exchange efficiency. The other marks are obtained after the bump magnets are turned off in other words the circulating beam doesn’t hit the scattering foil thus there were no observable reduction. The difference between red circles and other marks means the foil scattering beam loss and it increases depending on the foil thickness.

In order to obtain the HBC foil’s charge-exchange efficiency directly, partially stripped (H\(^+\)) beam component and un-stripped (H\(^-\)) beam component were measured respectively at the two beam monitors installed at the front of the H0-BD. One is the multi wire profile monitor 7 (MWPM7), and the other is a H0-current transformer (H0-CT). In this experiment, several thinner foils whose thickness was less than 200 \(\mu\)g/cm\(^2\) (nominal values; 52, 78, 158 \(\mu\)g/cm\(^2\)) were used, because these two component signals were increased clearly [6]. Figure 5 shows the measurement result with MWPM7. At the front of the H0-BD, H\(^+\) and H\(^-\) components were separated and then two beam profiles can be measured. When the 1\(^{st}\) stripping foil was removed from beam orbit, the entire injected H\(^-\) beam was converted to H\(^+\) at the 3\(^{rd}\) stripping foil and the H\(^+\) beam was transported to H0-BD because the 3\(^{rd}\) foil thickness is 500 \(\mu\)g/cm\(^2\) and has charge-exchange efficiency of almost 100\%. Thus the each charge-exchange efficiency from H\(^-\) to H\(^+\) or H\(^0\) can be obtained by comparing between the peak signals of MWPM7 with or without the 1\(^{st}\) stripping foil, in principle. However as seen in figure
5, the MWPM7 signal doesn’t have a good resolution and thus small peak signal is hard to separate from the background noise. In the case of H0-CT measurement, it has very high resolution with Fast Fourier Transform (FFT) data analysis techniques and even very small signal can be picked up and separated from the background noise [6]. However measurement signal with H0-CT with nominal setting of all stripping foils means a total beam current transported to the H0-BD and thus H₀ and H⁻ components can’t be separated. But as seen in figure 1, not only the 1st stripping foil but also the 2nd or 3rd stripping foil can be removed from the beam orbit independently in the J-PARC RCS. When the 1st foil is installed on the beam orbit, we can separately measure the partially stripped H₀ beam component and un-stripping H⁻ beam component with the H0-CT, by removing the 2nd and 3rd stripping foil, respectively. And total injected H⁻ beam can be measured with the H0-CT by removing the only 1st stripping foil. In Figure 6, the measured charge-exchange efficiencies from H⁻ to H⁺ and H₀ are summarized. Open circles are measurement results and solid lines are calculation results with cross sections given in the previous experiment with normal Carbon [7]. The measured charge-exchange efficiencies of the HBC foils are consistent with expectation at the present. As there is only 20% of Boron rest of 80 Carbon in the HBC foil, the charge-exchange efficiency is believed to be almost same as Carbon foil.

![Figure 5](image5.png)

**Figure 5.** Measurement results of H₀ and H⁻ beam profile with MWPM7 with thinner stripping foils.

![Figure 6](image6.png)

**Figure 6.** Measurement result of the charge-exchange efficiencies from H⁻ to H⁺ and H₀ with H0-CT. Lines are calculated from the previous experimental cross section shown by solid dots.

2.2. Life time of the stripping foil

A life time of the stripping foil is one of the most important key issues, because it respects tightly an available beam operation time in the J-PARC. Progress in the foil’s life time can be expected by adopting the HBC stripping foil. We tried the HBC foil endurance test. The outgassing from the HBC foil and the foil deformations during the beam irradiation were observed. The beam irradiation on the new stripping foil with thickness of 196 µg/cm² was started since RUN26 in October 2009. The outgassing from the HBC foil and the foil deformations during the beam irradiation are summarized in figure 7. The upper graph in figure 7 shows the trend of the vacuum pressure measured by a Cold-Cathode ionization Gauge (CCG) installed in the neighborhood of the HBC foil and total irradiation particle in every run cycle. At the start of the beam irradiation, the voluminous outgassing from the foil occurred. After that, the outgassing from the HBC foil was decreased and it seems to be stable after the RUN29. Since Run33 started, the beam power at user operation increased from 120kW to 200kW, but the outgassing did not to increase. The lower photos in figure 7 show the deformations of the HBC foils.
during the beam irradiation. A surface condition of the HBC foil including a form and a texture was varied quickly until RUN28, for which about $2.5 \times 10^{20}$ particles were irradiated on foil. But afterward, it seems the process of the foil deformation has stopped. During the one year of the user operation (a total of about $1.4 \times 10^{21}$ particles irradiation), there was no noticeable deterioration of the stripping foil.

![Figure 7. Trends of outgassing from the foil and the deformations on the foils during the beam irradiation.](image)

**Figure 7.** Trends of outgassing from the foil and the deformations on the foils during the beam irradiation. The upper graph plots the vacuum pressure measured by the CCG around the stripping foil and the total irradiated particle every run cycle. The lower photos show the deformations of the HBC foils during the beam irradiation.

### 3. Summary

In the J-PARC RCS, the HBC stripping foil was adopted for the charge-exchange $H^+$ beam injection. The important key issues for the charge-exchange injection with the stripping foil are foil’s lifetime and beam survival rate due to foils. Thus the foil beam study and long-term observation are carried out from the viewpoint of two key issues.

In order to evaluate the beam survival rate due to HBC stripping foil, circulating beam intensity was measured with various thickness stripping foils. According to the compromise between charge-exchange efficiency and foil scattering beam loss, we selected the foil thickness of about 200 $\mu g/cm^2$ for user operation. Moreover the charge-exchange efficiencies in the HBC foil were measured with MWPM7 and H0-CT directly. The measured charge-exchange efficiencies of the HBC foil are consistent with the expectation at the present. In our future plan, not only HBC foils but also normal Carbon foils of various thicknesses will be produced and a difference between their charge-exchange efficiencies will be examined in the J-PARC RCS.

The long-term observation during the user operation as well as the HBC foil endurance test for its lifetime evaluation was carried out. The outgassing from the HBC foil and the foil deformations during the beam irradiation were observed. At the start of the beam irradiation, the voluminous outgassing from the foil occurred and the foil was deformed drastically. Even after about $2.5 \times 10^{20}$ particles irradiation, the outgassing rate from the foil was stable and the foil deformation did not become worse, and also no
noticeable deterioration of the stripping foils could be seen. During the one year of the user operation (a total of about \(1.41 \times 10^{21}\) particles irradiation), there was no noticeable deterioration of the stripping foils. Until now, the causal relation between the outgassing from the foil and foil’s deformation during the beam irradiation is still unclear. Thus we will install a quadruple mass spectrometry near the stripping foil, and detailed analysis of the outgassing from the stripping foil will be done.

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