MEASUREMENT OF THE STRIPPING EFFICIENCY FOR HBC STRIPPER FOIL IN THE 3-GeV RCS OF J-PARC

P.K. Saha*, M. Yoshimoto, S. Hatakeyama, H. Hotchi, H. Harada, Y. Yamazaki, M. Kinsho, J-PARC Center, KEK&JAEA, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
Y. Irie, I. Sugai, KEK, 1-1 Oho, Tsukuba-shi, Ibaraki 305-0801, Japan

Abstract

We have carried out an experimental measurement of the stripping efficiency for the newly developed hybrid type boron doped carbon stripper foil known as HBC foil. The HBC foil is used for an H^- charge-exchange injection in the Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex and plays an important role in the stable operation of the RCS. We have developed a rather simple but very precise method which determines the stripping efficiency very accurately. Importance of knowing an accurate stripping efficiency or in other words the foil thickness so as to determine realistic operational parameters for the RCS operation is discussed.

INTRODUCTION

In order to increase the number circulating protons, the 3-GeV Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) utilizes the multi-turn H^- charge-exchange injection technique during the injection period of 0.5 ms [1]. Incoming H^- beam from the Linac is converted to a proton beam by using the primary stripper foil named the 1^{st} foil placed in the middle of injection bump magnets. The primary stripper foil is a double-layer type of the HBC (Hybrid type Boron doped Carbon) foil [2] used with a thickness of 200 μg/cm^2 at the present 181 MeV injection and will be changed to a thickness of 290 μg/cm^2 at the upgraded injection energy of 400 MeV in near future. The stripping efficiencies are expected to be 99.6% and 99.7% for the present and later case, respectively [3, 4]. The remaining 0.4% or 0.3% of the beam are called the waste beams and ideally they are mostly with partially stripped (single electron detachment at the 1^{st} foil) becomes neutral (un-charged) and is called H^0 beam. They are further stripped to a proton beam by the secondary stripper foil named 2^{nd} foil and transported to the injection beam dump called H0 dump. The un-stripped (H^-) component of the beam usually should be very small and is negligible but if there is such a beam they are also stripped to a proton beam by another secondary foil named 3^{rd} foil and is also transported to the injection beam dump. The secondary stripper foils are much thicker (500 μg/cm^2) than the primary one and the stripping efficiencies are thus expected to be almost 100% (99.9999% [3]).

In the RCS, it is very important to design as well as to use a realistic foils especially, the primary one in terms of the thickness as well as the size. Due to the multi-turn injection system circulating beam hits the foil more than 20 times in average and thus uncontrolled beam loss near the injection area due to the foil scattering is not negligible [5]. Such a beam loss would be much more significant over the stripping efficiency gain by using a thicker foil [6]. As a result, a primary foil with a stripping efficiency of 100% is quite impossible to use in reality. A thinner foil on the other hand makes an increase of the waste beam in the injection dump and thus a higher capacity dump would then be needed, which is both space and money consuming. The injection dump of the RCS has a capacity of only 4 kW, where the design waste beam power with all design parameters at the near future 400 MeV injection is expected to be 0.4 kW (0.3% of 133 kW injected beam). A 10% thinner foil for example, simply cause an increase of the waste beam of nearly twice than the above number. Any pinholes in the foil, long tail of the injected beam as well as tight optimization of the injected beam positioning on the foil in order to reduced circulating beam hitting on the foil, additionally cause a significant increase of the un-stripped H^- component of the waste beam. There is no experimental measurement of the cross section of the HBC foil. Although the present HBC foils are with a 20% of boron admixture out of 80% carbon [2], it is very important to experimentally determine the stripping efficiency of the HBC foil.

EXPERIMENTAL TECHNIQUE

Our present approach is to explicitly measure the partially stripped H^0 and un-stripped H^- components of the waste beam and from which the stripping efficiency can be determined. However, H^- contribution determined by the cross section with a foil thickness of around 200 μg/cm^2 is negligibly small [3], the stripping efficiency thus can be obtained by measuring the H^0 component. Because of the single pass traversal, waste beam measurement is straightforward. However, as the fraction of the waste beam is ideally very small, one needs a very sophisticated idea and/or a sophisticated device or monitor. The present idea employs a simple principle and does not need any sophisticated device or monitor. The signal measured by an already placed Current Transformer (CT) named H0CT ([7]) is first collected by an oscilloscope and then a fast Fourier transformation (FFT) analysis is done. As a result, picking up the amplitude of the power spectrum corresponding to the frequency of the intermediate pulse, which depends on the frequency of the RCS RF system [8] gives the beam signal. The ratio

* Electronic address: saha.pranab@j-parc.jp

of such a signal measured with a foil to that measured by transporting all of the injected beam to the H0 dump (by removing 1^{st} foil) gives the fraction of the waste beam.

We used the following two operation modes of the RCS, namely (a) injection beam dump mode and (b) the single-pass extraction mode as demonstrated in Fig. 1. In the former mode, primary foil is kept out and thus injected beam directly goes to the H0 dump by stripping at the 3^{rd} foil. However, the primary foil is placed at the right position in the later mode and thus only the waste beams are transported to the H0 dump. If there is no pinholes and the foil is big enough then a proper positioning of the injected beam on foil makes sure that the waste beam is almost with the partially stripped H^0 component. As a result, the rest of the beam which is injected injected into the ring thus gives the stripping efficiency. It is important to mention that, by removing the 3^{rd} foil in the later mode, we can explicitly measure the H^0 component as in this case the un-stripped H^- beam does not stripped to proton beam because of no 3^{rd} foil and thus can not be transported to the H0 dump. Similarly, the H^- component itself can also be measured by removing the 2^{nd} foil. It may be important to mention that the fundamental checks of the apparatus including the linearity of the H0CT were proved to be very good[7].

EXPERIMENTAL RESULTS

Figure 2 shows the time domain signal of the H0CT taken in the single pass extraction mode with beam (red) and with no beam (blue). Due to only a small fraction of the waste beam, the time domain signals with and without beam are almost identical and it is thus very hard to extract the real beam signal from this data. However, present idea of doing an FFT analysis on the other hand clearly identifies the signal corresponding to the chopping frequency (h=2) as shown the power spectra in Fig. 3. In contrast to the no beam data, the signal corresponds to the fundamental frequency of 0.940 MHz which was set for the present operation and successive higher order harmonics at RF multiples are clearly seen. The spectrum taken in the injection beam dump mode (all beam to the H0 dump) is also shown together with black color. The signal that corresponds to the fundamental frequency is used for the analysis.

In the next step, we measured individual component (H^0 and H^-) of the waste beams. As also mentioned earlier, by using separately the 2^{nd} and 3^{rd} foil in the single pass extraction mode, it was possible to explicitly measure the H^0 and H^- component, respectively. The waste beam with using the present primary stripper foil was found mainly to be the partially stripped H^0 one, while the un-stripped H^- component was negligible.

The fraction of the waste beam is calculated by taking a ratio of the FFT peak heights with the single pass extraction mode (red) to the injection beam dump mode (black) and was found to be (0.38±0.03)%. The stripping efficiency is then calculated to be 100-0.38 = (99.62±0.03)%. As the un-stripped H^- is negligibly small, measured waste beam

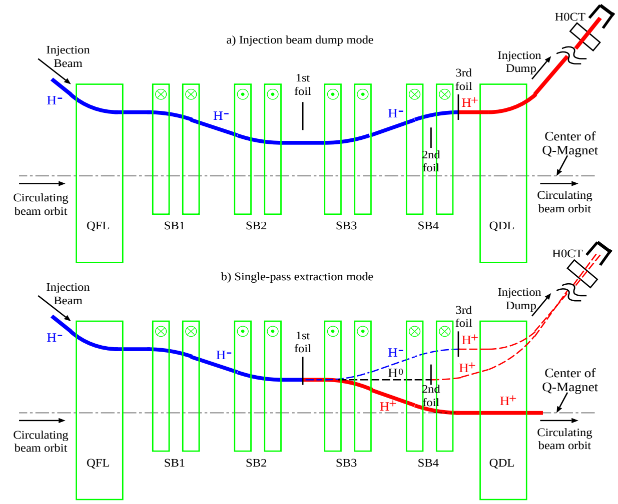

Figure 1: RCS operation modes used for the present measurement. A ratio of the H0CT signals measured in the single-pass extraction mode (b) to that with injection beam dump mode (a) gives the total fraction of the waste beam.

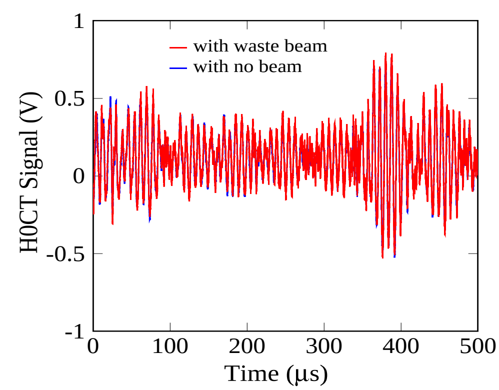

Figure 2: Time domain signals of the H0CT measured for the waste beam (red) and with no beam (blue) are found to very identical ideally due to only a very small fraction of the waste beam and the large noise. It was thus hard to extract the real beam signal at this stage.

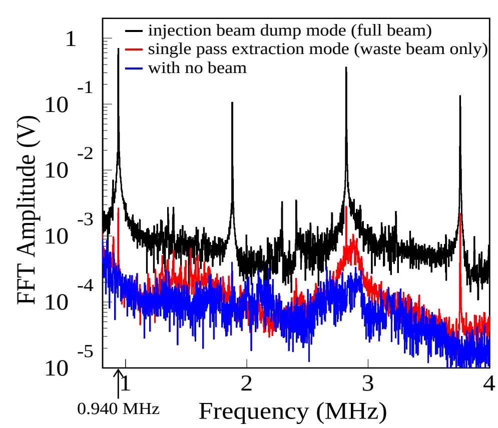

Figure 3: Frequency domain signals of the H0CT obtained by an FFT analysis of the time domain signals. A clear signal with beam at the expected frequency as compared to no signal with no beam can easily be seen.

is considered to be the partially stripped H^0 component and by using the old experimental data (although measured for carbon targets [3]), the thickness of the present primary HBC foil is calculated to be 201±2.6 μg/cm^2, which is consistent to the expected known thickness of 196 μg/cm^2.

However, in order to reduce the uncontrolled beam loss due to the foil scattering, we had to prepare our 2nd generation primary stripper foils with much smaller sizes especially, the vertical size. The vertical size of the foil is the main issue concerning the average foil hit in the present painting injection scheme [5]. In the summer shutdown of 2010, we installed two foils with dimensions of 110×15 mm^2 and 110×20 mm^2. Same as the above procedure, we tried to investigate the stripping efficiencies of these new foils. However, the macro pulse length of the injected beam was was 0.2 in stead of 0.5 ms in the first measurement and was thus the resolution of the FFT spectra were a bit worse.

Figure 4 shows the FFT spectra of the H0CT measured for the waste beams with vertical sizes of 15 mm (pink) and 20 mm (green). In the same measurement, spectra with the old foil with vertical size of 40 mm (see Fig. 3) and with no foil are also shown by the red and black colors, respectively. Due to the unexpectedly wider injected beam profile, waste beams especially, the un-stripped H^- was increased because of the injected beam missed hitting the primary foil was increased with smaller foils. Unfortunately, the H^- and H^0 component could not separately measured with H0CT but it was done by using a multi-wire profile monitor named MWPM7 located near the H0CT.

The fractions of the total waste beam with vertical foil sizes of 15 mm, 20 mm and 40 mm are found to be 4.16%, 1.84% and 0.61%, respectively. The corresponding unstripped H^- component by using MWPM7 data is estimated to be 3.24%, 1.13% and 0.23%, respectively. As a result, the partially stripped H^0 components are calculated to be (0.92±0.08)%, (0.71±0.08)% and (0.38±0.08)%, respectively. However, missing H^- component should also contribute to the H^0 component if hitting the primary foil and thus the H^0 components are recalculated to be (0.95±0.08)%, (0.72±0.08)% and (0.38±0.08)%, respectively. The stripping efficiencies are thus obtained to be (99.05±0.08)%, (99.28±0.08)% and (99.62±0.08)% and eventually the thickness of these three foils are experimentally determined to be 171±3 μg/cm^2, 180±4 μg/cm^2 and 201±4 μg/cm^2, respectively.

It is important to mention that the measured thickness 201±4 μg/cm^2 with vertical foil size of 40 mm here again is close to the design (known) thickness of 196 μg/cm^2 as well as consistent with our earlier measurement as presented above. However, the two smaller foils are although known to be the same thickness of 195 μg/cm^2 (different only with their vertical sizes), measurements disagree and both foils are found to be thinner as compared to the designed value. Although beam loss due to foil scattering was reduced, the residual radiation near the H0 dump was found to be increased by an order of magnitude higher because of the waste beams (H^- and H^0) increased by using

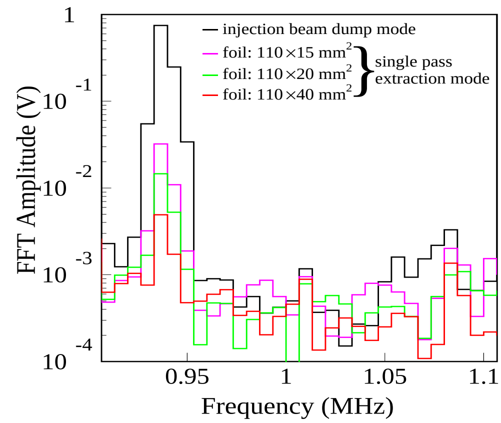

Figure 4: FFT spectra measured for the waste beams with different vertical foil sizes shown by highlighting near the fundamental frequency region. Due to unexpectedly wider injected beam profile, the injected beam missed hitting the primary foil was increased and eventually increased the waste beam with smaller vertical sizes of the foil.

the smallest foil (15mm) for the RCS user operation. As the partially stripped H^0 component is determined by the foil thickness, the foil was then changed to the medium size of 20 mm in order to reduced missing H^- as much as possible at the primary foil. Finally by a proper positioning of the injected beam on foil, a suitable parameter was obtained for the RCS user operation by keeping a balance between the foil scattering beam loss in the ring and the amount of the waste beam at the injection dump.

SUMMARY

Our present approach of doing an FFT analysis on the raw signal made it possible to measure the waste beam intensity with a good accuracy. This then allows to determine the stripping efficiency of the newly developed HBC stripper foils used for the H^- charge exchange injection in the RCS of J-PARC. The thickness of the original stripper foil used for the RCS operation so far is measured to be 201±2.6 μg/cm^2 and is quite consistent to that with designed value. However, by using the latest foils the partially stripped H^0 component of the waste beam was found to be about 2.5 times higher than expected and thus they were estimated to be less thinner as compared to the expectation.

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