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Measurement of continuous degradation of a stripper foil during six months operation with 300 kW beam power in the 3-GeV RCS of J-PARC

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Abstract

In the 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC), we have clearly measured a continuous degradation of a stripper foil during more than six months operation with a beam power of 300 kW. A hybrid-type boron doped carbon (HBC) stripper foil of 200 μg/cm^2 was used for 181 MeV H^- stripping injection. In order to know an absolute change of the foil thickness as well as information on the pinhole formation, we precisely measured an absolute change of the partially-stripped H^0 and the un-stripped H^- waste beams. Two absolutely independent monitor systems were used and the results were found to be very consistent with each other. The foil thickness at the injected beam spot was measured to be gradually thickening and it was more than 10% thicker at the end compared to the initial thickness, where the measurement accuracy was obtained to be better than 2%. The missing un-stripped H^- were also measured to be gradually increasing due to foil deformation and curling but there was however no clear indication of foil thinning or pinhole formation.

Keywords: stripper foil, H^- stripping injection, foil degradation, J-PARC, Rapid Cycling Synchrotron

Introduction

In order to achieve a high power proton beam of 1 MW, a multi-turn H^- stripping injection is adopted in the 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC) [1]. More than 99.7% of the H^- beam is stripped to proton beam and injected into the ring for several hundred turns in order to have 8.3×10^{13} protons per pulse (ppp). The remaining 0.3% of the H^- beam is mostly partially-stripped and is called H^0 beam, while the un-stripped H^- is ideally negligibly small. These are called the waste beams and are further stripped to proton beams by secondary foils but they are deflected to the injection beam dump. The kinetic energy of the H$^-$ beam was 181 MeV at the 1st stage but it has been upgraded already to the designed value of 400 MeV at the end of 2013 [2]. The beam is accelerated up to 3 GeV and simultaneously delivered to the two downstream facilities at a repetition rate of 25 Hz. The beam power for user operation was 300 kW at the latest.

In the RCS, a hybrid-type boron doped carbon (HBC) stripper foil is used for stripping a negative hydrogen (H$^-$) beam to a proton beam (H$^+$) [3]. The lifetime of the stripper foil is one of the most concerning issue, especially for a 1 MW operation. A sudden foil failure not only reduces accelerator availability but also raises maintenance issues. Foil degradation such as a change of its thickness either thinning or thickening, pinhole formation as well as any foil deformation due to high intensity beam irradiation might be a foil breaking signal and is also addressed as foil deterioration. One can thus avoid a foil failure during operation by a proper monitoring of the foil degradation so as changing the foil to a new one in an appropriate time during accelerator maintenance day. However, a complete breaking does not always define the real lifetime of the foil in accelerator operation. For example, the RCS injection beam dump has a capacity of only 4 kW, where the ideal waste beam power at 1 MW operation is 0.4 kW. However, there has already been a significant un-stripped H$^-$ is measured at the injection beam dump even at the present 300 kW operation because of long tail or halo in the H$^-$ beam, which misses the primary stripper foil. The heat load on the dump is then increased beyond the design value because of an excess un-stripped H$^-$. In addition, a foil thinning and pinhole formation in the foil further cause an increase of the waste beam power and this limits the foil lifetime. In order to cover until long tail of the injected H$^-$ beam, one needs a larger stripper foil but then the uncontrolled beam losses are significantly increased due to foil scattering when the circulating beam is hitting the foil during multi-turn injection. A foil thickening might occur due to crinkling caused by the wrinkling and foil shrinkage. The beam losses due to foil scattering are increased with strong foil thickening, while foil missing H$^-$ are also increased not only by pinholes in the foil but also due to any foil deformation. A little of foil degradation is thus very crucial at 1 MW operation in the RCS. Due to the multi-turn injection for more than 200 turns at 181 MeV, one injected proton hits the foil as much as nearly 20 times in average. The heat load on the foil thus highly depends on the circulating beam hitting the foil. A smaller size foil stronger against foil degradation is therefore highly required.

In our earlier measurements as reported in the previous conference, there was no any clear indication of foil degradation concerning any change of the foil thickness [4]. There was certainly no pinhole formation. However, at that time the injected beam power was comparatively lower and also the measurement could not last for a longer period. Unfortunately, we had to exchange that foil to a new one in order to install many other foils for the 300 kW operation. The present study starting in October 2012 was continued for more than six months operation of the RCS while H^- injection energy was 181 MeV. The accelerated proton beam power at 3 GeV was 300 kW and thus a total of 2.5×10^{13} ppp were delivered to the users. The injected beam power was 18 kW, while the waste beam power in ideal consideration (only H^0 of 0.3% and no un-stripped H^-) was estimated to be 54 W. We measured an absolute change of the partially-stripped H^0 and the un-stripped H^- in order to estimate an absolute change of the foil thickness and to get information on pinhole formation or any sort of foil deterioration, respectively. The measurement was done during operation every alternate week at the maintenance day. The present measurement differs from the earlier one not only by 1.5 times higher injected beam intensity but due to the experimental condition, the average foil hit of each circulating proton was also estimated to be about twice higher. A multi-wire profile monitor (MWPM) named MWM7 was only used in the earlier measurement but in addition to that we used another further high precision current transformer (CT) named H0CT placed closed to the MWPM7 at the end of waste beam transport line. The purpose of the H0CT and its well performance for online monitoring of the waste beam has already been presented in a separate article [5]. The cumulated injected H^- beam itself at the end of measurement cycle was measured to be as high as 8.1×10^{21} particles. The injected charge via foil was calculated to be 1300 C. The average foil hit of each circulating proton was estimated to about 20. The cumulated beam hitting and the corresponding total charge on the foil were thus estimated to be 1.62×10^{23} particles and 26000 C, respectively. The foil at the injected beam spot was measured to be continuously thickening and it was more than 10% thicker at the end as compared to its initial thickness. The measurement accuracy was obtained to be better than 2%. The measured un-stripped H^- waste beam had gradually increased, which might be due to foil deformation, but there was no clear indication of pinhole formation during the measurement.

Experimental setup and measurement principle

The experimental setup as well as the measurement principles were almost the same as reported earlier [4]. However, in addition to the multi-wire profile monitor, named MWPM7, we used another further high precision current transformer, named H0CT, placed close to the MWPM7 at the end of waste beam transport line as shown in Fig. 1. By using these monitor systems we have also measured stripping cross sections of 181 MeV H^- through a carbon foil with good accuracy [6]. In this study we used our experimental cross sections in order to estimate the foil thickness. Details of the RCS stripper foils were given in our earlier report [4]. A hybrid-type of 20 % boron doped carbon foil called HBC foil was used for H^- stripping injection. The design thickness of the primary stripper foil at 181 MeV injection is 200 μg/cm^2 in order to have a stripping efficiency of 99.7%. The partially-stripped H^0 and un-stripped H^- (if any) are further stripped by the secondary foils named 2nd and 3rd foils, respectively and are deflected to the injection beam dump. The secondary foils are relatively thicker and their stripping efficiencies are estimated to be almost 100% (99.9999%).

Figure 2 shows a typical dimension of the 1st stripper foil along with the injected beam and it's positioning as was set in the present operation. In order to reduce circulating beam hitting the foil, the vertical foil size was reduced to 20 mm, half of the size used in the previous measurement period. As a result, there were considerable un-stripped (missing) H^- ions at the 1st foil due to the long tail or beam halo in the injected beam.

The two beam study modes of the RCS as shown in Fig. 1 were utilized in the present measurements. In the upper mode (Fig. 1a) named single pass extraction mode (also called one third-dump mode), all three foils were set in place and the fully stripped H^+ ions were injected into the RCS but they did not circulate back to the foil as they were directed to the extraction beam dump transporting one-third of the RCS circumference. The H^0 and H^- yields were measured at the injection beam dump by using MWPM7 and H0CT separately. However, in the lower mode (Fig. 1b) named injection beam dump mode (also called H0 dump mode), the 1st foil was removed from the beam line and thus the incoming H^- beam was stripped to H^+ by the 3rd foil and deflected to the H0 dump. It was then measured by the MWPM7 and H0CT in a similar way. A ratio of the signals measured in the previous mode to the later mode thus gave the H^- and H^0 charge fractions in the injected beam. The integrated yield of the corresponding beam profiles measured by the MWPM7 were used for the analysis, while for the H0CT a Fast Fourier Transformation (FFT) analysis of the time domain signal and picking up amplitude of the power spectrum corresponding to the frequency of the intermediate pulses (chopping frequency) of the injected beam, which depends on the RCS rf system was used [5]. The chopping frequency at 181 MeV injection for RCS rf with dual harmonic (h=2) is typically 0.94 MHz .

The H^0 and H^- yields can simultaneously be measured by the MWPM7 as two beam profiles are well separated to get each integrated yield but with H0CT we separately measured H^0 and H^- yields by removing the 3rd and 2nd foil, respectively in the single pass extraction mode [5]. In order to take into account any fluctuation of the injected H^- during the measurement, it was always measured by a slow current transformer (SCT), placed several meter upstream of the 1st foil. Data without beam were also taken in order to subtract the background from the measurement. Once H^- and H^0 charge fractions were measured, the H^+ charge fraction or the stripping efficiency can easily be calculated as 1- (H^- fraction + H^0 fraction). The thickness of the 1st foil was thus estimated by using the measured cross sections.

Figure 3 shows typical horizontal beam profiles measured by the MWPM7. In the one-third dump mode, both secondary foils were set in place and both un-stripped H^- and partially-stripped H^0 profiles were simultaneously measured as shown in green color. The only H^0 profile separately measured by removing the 3rd foil is shown by the red color. The beam profile shown in blue color was measured in the H0 dump mode (1st foil out) and thus all injected H^- were stripped to H^+ by the 3rd foil and deflected to the injection beam dump. The injected beam intensity in the later case was controlled by the number of pulses in order to make sure that the beam profile did not saturate. In order to obtain H^- and H^0 fractions, the integrated yields of the H^- and H^0 beam profiles (green) measured in the former mode was normalized by the H^- profile yield (blue) measured in the later mode. The H^- and H^0 fractions were obtained to be (0.22 ± 0.02) % and (0.32 ± 0.03) %, respectively. However, due to a smaller vertical foil size and horizontal beam positioning on the foil with no margin (see Fig. 2), the measured un-stripped

H^- fraction in this case were those missed the 1st foil due to the long tail or beam halo in the injected H^- beam. It was confirmed by using a rather large foil and well positioning the injected beam on the foil. There was no any measureable un-stripped H^- yield. It is because that the cross section for the H^- production is extremely small. The H^- fraction for a 200 μg/cm^2 foil is estimated to be as low as 1×10^{-5} % and hence it can be neglected. The foil thickness based on the H^0 fraction and by using our measured cross section at 181 MeV [6] is estimated to be 192.4 ± 2.8 μg/cm^2, which is found to be consistent with expected design thickness of 200 μg/cm^2.

Figure 4 shows the FFT spectra of the H0CT time domain signal and its peak near the fundamental frequency (0.94 MHz) region measured in similar experimental conditions as MWPM7 except that a maximum of injected beam intensity was used for all cases. The spectrum shown in green color was for the H^- and H^0 yields measured together, while only the H^0 yield measured by removing the 3rd foil is shown in red color. The signals peaking at 0.94 MHz and clearly coincided with that measured in the H0 dump mode (blue) can easily be identified. There was no any such a signal for the background data. The signal heights difference between green and red gives the un-stripped H^- yield. The H^- and H^0 charge fractions, based on the H0CT data, are obtained to be (0.22 ± 0.02)% and (0.33 ± 0.02)%, respectively. The foil thickness was calculated to be 192.0 ± 2.0 μg/cm^2 and this was well consistent with MWPM7 result.

Experimental results

Figure 5 shows the un-stripped H^- and partially-stripped H^0 beam profiles for several cases out of total twelve measurements during six months. The injection H^- beam orbit was always monitored and adjusted if necessary in order to keep injection beam positioning unchanged so as to know any change of foil thickness and pinhole formation at the injection beam hitting area. A continuous change of the measured H^0 beam profile height is very interesting as it is directly related to a change of the foil thickness. A gradually decreasing H^0 yield reflects a foil thickening gradually. On the other hand, the un-stripped H^- beam profile height so as its yield was measured to be gradually increasing. The reason might be due to a continuous deformation of the foil because the tail part of the H^- beam which misses the 1st foil was increased. Further discussions are given in more detail in the next section.

Figure 6 shows a trend of the partially stripped H^0 signal only, obtained by the H0CT measured in the one-third dump mode by removing the 3rd foil. Similar to the MWPM7, H^0 signal measured by the H0CT was also found to have gradually decreased.

Figure 7 shows a trend of the absolute H^- and partially-stripped H^0 fractions as obtained by both MWPM7 and H0CT measurements. The H^- fractions are measured to have increased gradually while the H^0 fractions continuously decreased. The cumulated injected beam is shown by the black curve as plotted with respect to the right vertical axis.

Figure 8 shows three photographs of the foil taken before beam irradiation (top), after 2 months beam exposure (middle) and at the end of operation (bottom). The deformation of the foil occurred due to the beam irradiation and a continuous deterioration of the foil can easily be seen. The vertical foil size was almost of the same size as the injected beam and in the horizontal direction beam positioning on the foil was set without any margin. As a result, tail parts of the injected H^- missing the 1st foil might increase gradually because of developing foil deformation.

Figure 9 shows a trend of the H^0 fractions only and the estimated corresponding thickness of the foil as plotted with respect to the left and right vertical axis, respectively. As H^- production cross section is negligibly small, foil thickness for each measurement was calculated basing on the corresponding H^0 fraction. The accumulated injected charge on the foil was calculated basing on the measured injected particles and they summed to 1300 C in total at the end of the operation. However, by considering average foil hits of 20 for each circulating beam, the total charge on the foil can thus calculated to be 26000 C. The H^0 fraction was found to be decreasing almost linearly resulting in a linear foil thickening. The foil thickness in the beginning was measured to be 192 μg/cm^2, but it was found to have thickened by more than 10% and was 212 μg/cm^2 at the end. The results obtained by both MWPM7 and H0CT were found to be very consistent with each other.

Discussion

An absolute foil thickening measured in the present experiment suggests a strong wrinkling or curling caused by the beam irradiation. There was no such clear indication in our earlier measurement which might be due to a lower injected beam intensity [4]. There was also no measurable un-stripped H^- at the earlier study. However, due to the higher injected beam power as well as experimental condition, the instantaneous heat load on the foil is estimated to be now a factor three higher compared to that in the previous study. The measurement period was also relatively longer. The foil was seen to have been continuously deformed and as a result, the un-stripped H^- had increased. It is worth mentioning that the effect of a foil wrinkling or curling was also measured at the Los Alamos Proton Storage Ring (PSR) as was reported earlier [7]. The foil scattering beam loss normalized by the injected charge via foil was shown to have been increased during operation indicating a foil thickening. The relative change of the foil thickness measured for various foils had a strong dependence on foil materials. The beam loss was measured to be reduced significantly when replacing a foil by a new one and thus the foil lifetime was not necessarily the time until complete breaking. In the present experiment, however, we have directly measured an absolute change of the foil thickness. The measured foil thickening of 10% was considered to be due to foil deformation and crinkling of the foil caused by the strong wrinkling and foil shrinkage. The effective path of the injected H^- beam was no longer perpendicular to the surface of the foil and was thus gradually getting longer. However, it was hard to extract any clear information on the pinhole formation. The un-stripped H^- beam profile measured by the MWPM7 was rather flat and had three components, because the tail part or beam halo in the H^- missed the 1st foil in three sides (upper and lower sides in the vertical and right side in the horizontal directions) as can be seen in Fig. 2. By inserting the foil more in the horizontal direction, the H^- missing from the horizontal direction was found to be reduced. In addition, no un-stripped H^- was also measured by using a bigger foil size. The profile height changed gradually but the shape remained almost the same until the end. The H^- missing the 1st stripper foil might gradually increase due to continuous foil deterioration and hence the un-stripped H^- should accordingly have increased.

During the present operation, the injected beam power at 181 MeV was only 15% (18 kW) of the designed one (133 kW) at 400 MeV injection. It is thus a big concern for 1 MW operation as foil temperature might increase by more than a factor three compared to the present setup with about 600 K. In this case the foil degradation could be much faster. The injection beam dump has a capacity of only 4 kW. Foil deterioration causes not only an increase of the heat load on the dump due to an increased current of un-stripped H^-, but scattering in the foil and the corresponding uncontrolled beam losses at the injection area is also increased, which is due to a foil thickening. The acceptable lifetime of the foil for acceleration operation would be then shorter. It is very important to test different foil types in order to find foils best suited for high intensity operation. Recently the injection energy has been upgraded to 400 MeV and we have just started the same type measurement with a new foil. The beam power for the operation will be increased gradually. It is now interesting to obtain such a foil degradation rate as a function of increasing beam power and beam current on the foil.

Summary

We have measured continuous degradation of a stripper foil used for more than six months operation in the J-PARC 3-GeV RCS. The injected beam power at injection energy of 181 MeV was 18 kW, while the extracted beam power was 300 kW at 3 GeV. The foil degradation caused by wrinkling or curling due to the beam irradiation generates a foil thickening of more than 10% of its initial thickness. The cumulated injected H^- particles at the end of operation were 8.1×10^{21}, which corresponds to a charge of 1300 C via the foil. However, taking into account the average foil hits of 20 for one circulating proton, the cumulated particles hit the foil and the corresponding total charge via the foil was estimated to be as high as 8.1×10^{23} particles and 26000 C, respectively. Due to a developing foil deformation, the tail part and beam halo in the injected H^- missing the foil was measured to have been gradually increased. Such a foil deterioration rate could be more severe for gradually increasing high intensity operation towards 1 MW. The acceptable lifetime of the foil is thus a big concern. It is necessary to study other foil types in order to find the best foil so as to minimize the number of foil changes. Replacement of the foil magazine against a new one requires not only time but also involves unhealthy exposure to radiation for the workers. However, in order to avoid foil failure during operation as well as to ensure best uses of the mounted foils, the present measurement technique can play an important role for determining a proper foil replacement time by quantitatively monitoring any foil degradation.

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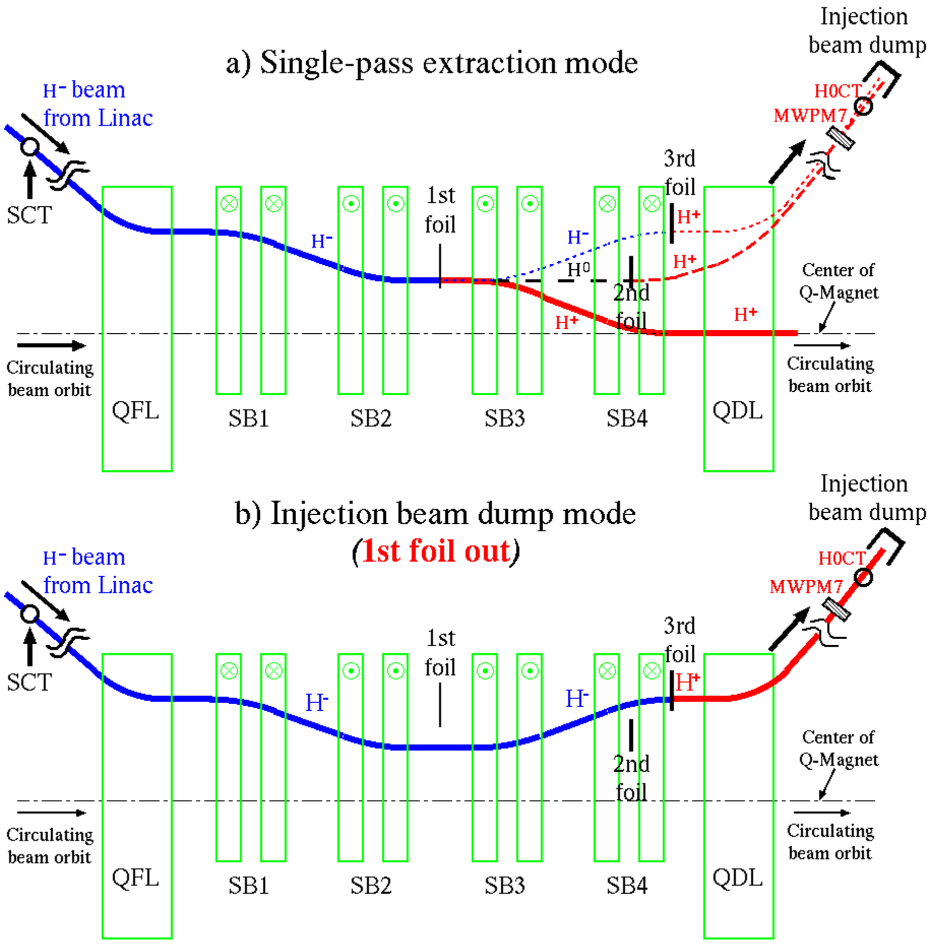

Fig.1: Experimental setup and measurement principles. Lines (full, broken and dotted) stand for different beam orbits. One multi-wire profile monitor (MWPM) named MWPM7 and a current transformer (CT) named H0CT placed at the end injection beam dump transport line were used for the present measurements. In the single-pass extraction mode (also called one-third mode), see Fig. 1a, all foils were set in place and the un-stripped H^- and partially stripped H^0 were thus measured. In the injection beam dump mode (also called H^0 dump mode), see Fig. 1b, the first foil was removed from the beam line and thus the complete injected beam was stripped by the 3rd foil only and it was then deflected to the H^0 dump and measured by the MWPM7 and H0CT. The H^- and H^0 charge fractions were obtained by taking a ratio of the H^- and H^0 yields measured in the former mode to the H^- yield measured in the later mode. The measurements were separately done by using MWPM7 and the H0CT.

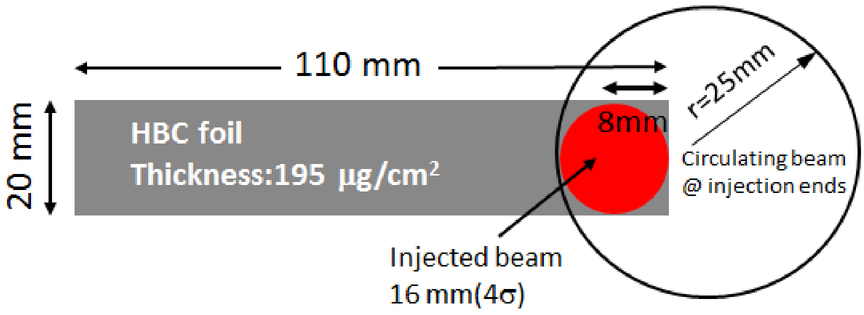

Fig. 2: The vertical size of the stripper foil during present operation of the RCS was reduced from the usual 40 mm so far to now 20 mm and the injected beam was also well positioned in order to minimize beam losses due to scattering of the circulating beam by hitting the foil. However, there was a considerable amount of un-stripped foil missing H^- due to long tail or halo in the injected beam.

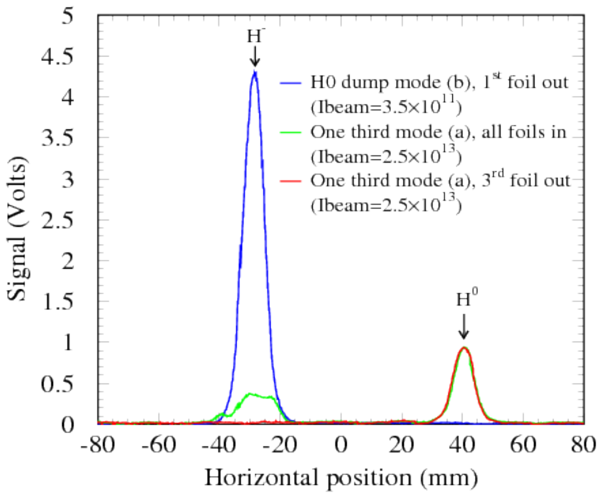

Fig. 3: The horizontal beam profiles as measured by the MWPM7. In the one-third mode (see Fig. 1 (a)), the un-stripped H^- and partially stripped H^0 measured together (green), while the H^0 only (red) was also separately measured by removing the 3rd foil. The injected H^- itself measured in the H0 dump mode (see Fig. 1b) is shown by the profile in blue color. The H^- and H^0 fractions in the injected beam were obtained by taking a ratio of the integrated H^- and H^0 profile yields measured in the former mode to the H^- yield measured in the later mode. The un-stripped H^- profile (green) measured in the former mode (green) was the corresponding missing H^- at the 1st foil due to long tail or beam halo in the injected beam.

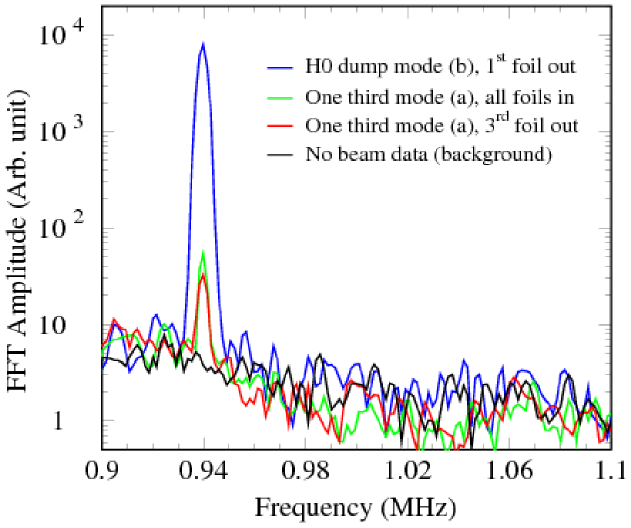

Fig. 4: FFT of the H0CT time domain data for the un-stripped H^- and partially-stripped H^0 measured together (green) and only the H^0 one (red) clearly show the beam signal coinciding with the signal measured for all injected beam (blue) at the expected chopping frequency of 0.94 MHz. The FFT peak height for the fundamental frequency was used for the analysis. In this case a ratio of the H^- and H^0 peak heights obtained in the former mode to the H^- peak height obtained in the later mode were used to get the H^- and H^0 fractions.

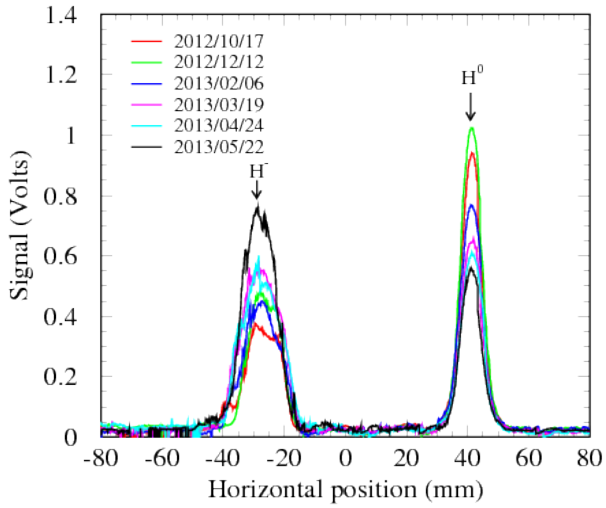

Figure 5: The measured un-stripped H^- (injected beam missing the 1st foil) and partially stripped H^0 beam profiles during more than six months operation. The H^- had gradually increased due to foil deformation while a decreasing H^0 yield clearly reflects a foil thickening due to strong foil shrinkage, wrinkling or curling.

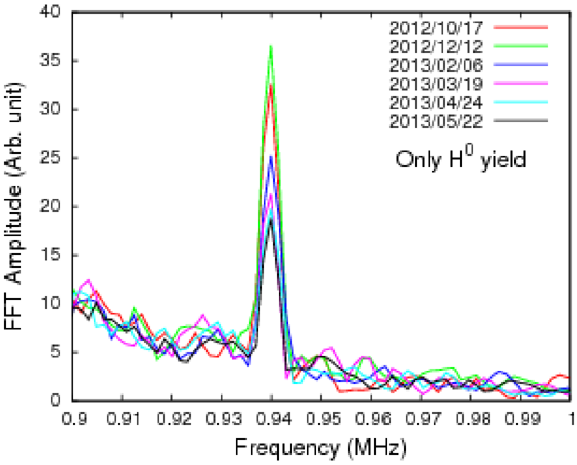

Fig. 6: The FFT spectra for only the H^0 yield as measured by the H0CT during operation. A similar decreasing trend of the H^0 yield as MWPM7 data is also obtained by the H0CT.

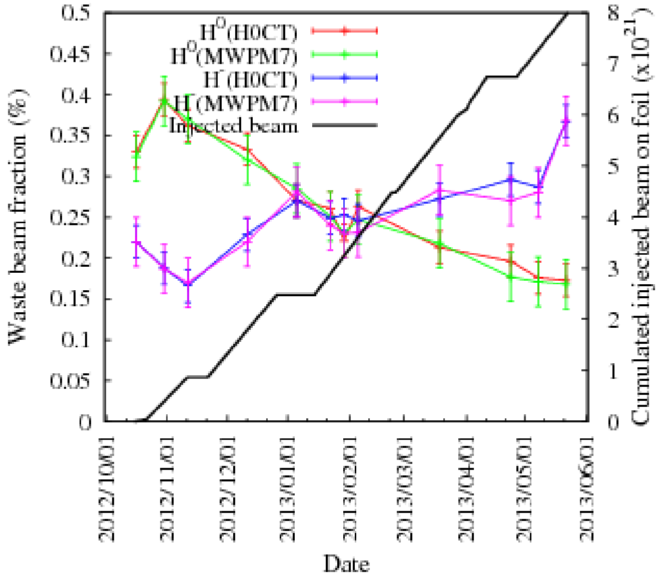

Fig. 7: Trends of the absolute un-stripped H^- and partially stripped H^0 yields for all measurements during the present experiment are plotted with respect to the left vertical axis. The cumulated injected H^- is also shown with respect to the right vertical axis.

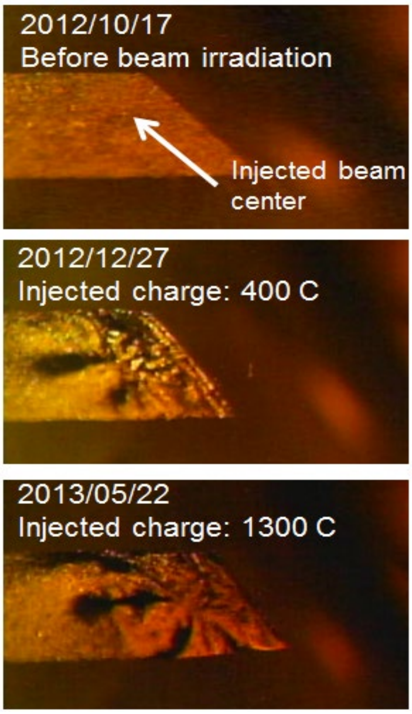

Fig. 8: Photographs of the newly mounted foil (top), after 2 months beam exposure (middle) and at the end (bottom) show strong deformation occurred due to beam irradiation.

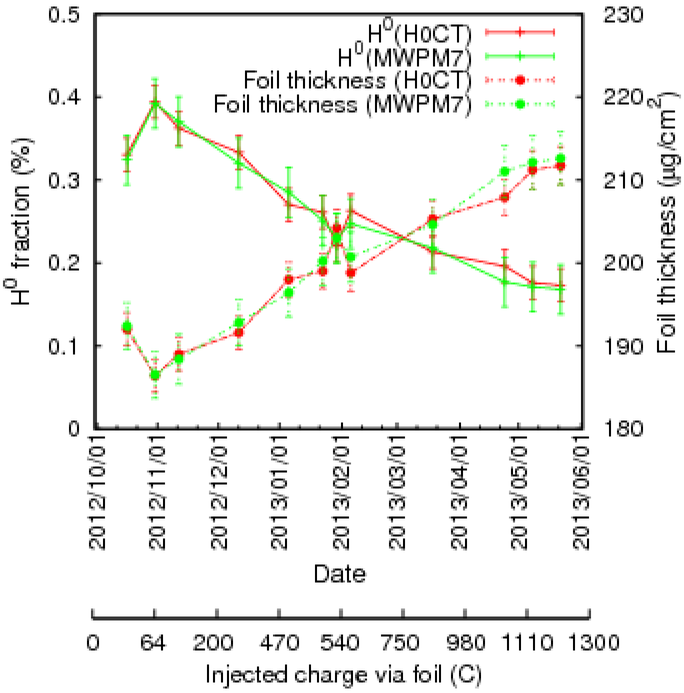

Fig. 9: The absolute value of the measured H^0 fraction and the corresponding estimated foil thickness are shown with respect to the left and right vertical axes. The cumulated (only injected) charge via the foil is also shown by an additional horizontal axis at the bottom. At the injected beam hitting area the foil had thickened by more than 10%

compared to its initial thickness. The results obtained by the two monitor systems are found to be consistent with each other.