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Title: Quantitative monitoring of the stripper foil degradation in the 3-GeV Rapid Cycling Synchrotron of the Japan Proton Accelerator Research Complex

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Abstract

An HBC (Hybrid-type Boron doped Carbon) stripper foil of 200 μg/cm^2 is used for the present H$^-$ injection beam energy of 181 MeV in the 3-GeV Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC). A stripper foil has a certain lifetime and usually lifetime goes shorter for high power operation. Foil degradation such as foil thinning and pinhole formation caused by the radiation might be a signal of the foil breaking. As a result, one can avoid sudden foil breaking by an efficient monitoring of the foil degradation. We have succeeded measuring even a little change of the stripper foil thickness during user operation of the RCS. It is the main motivation of the present work. A single foil was irradiated with a total of 2.7×10^{21} particles (injected H$^-$ itself) during 4 months continuous operation of the RCS but we did not observe any indication of the foil degradation.

Keywords:

J-PARC, 3-GeV RCS, HBC stripper foil, foil degradation, foil breaking, waste beam

Introduction

The 3-GeV Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) is designed to have a beam power of 1 MW for the Material and Life Science Experimental Facility (MLF) and for the Main Ring (MR) injection [1]. The injection and extraction energies are 400 MeV and 3 GeV, respectively. However, the injection energy at present is 181 MeV and will be upgraded to 400 MeV in the next year. The RCS operates at 25 Hz and will have 8.33×10^{13} particles per pulse for 1 MW operation. RCS beam power during last operation cycle was 200 kW but at the latest for 3 days before 2012 summer shutdown, nearly 300 kW having about 2.5×10^{13} particles per pulse were delivered to the MLF.

In order to increase circulating beam intensity, RCS uses conventional multiturn H^- charge-exchange injection technique during the injection period of 0.5 ms [2]. For this purpose, a newly developed HBC (Hybrid-type Boron doped Carbon) stripper foil with a thickness of 200 $\mu g/cm^2$ is used [3]. However, similar to any other high intensity proton accelerator, lifetime of the primary stripper foil is one big issue also in the 3-GeV RCS in order to maintain a stable operation. A foil breaking might be a resultant factors of many reasons involved during beam irradiation. Such as, a very high temperature rise of both instant and average, thermal buckling, shrinkage due to mechanical stress, carbon buildup and foil degradation [3, 4]. Although there has been significant progress for foil manufacturing in recent days the real lifetime may depends on uses. For example, type of the foil and thickness, beam energy and beam intensity, injection scheme as well as the type of accelerator might determine the real lifetime. The best way of knowing the foil lifetime then might be the beam based measurement. Due to the multiturn injection, not only the injected beam but circulating beam also hit the primary foil during injection period as shown in Figure 1. The average foil hit for each circulating proton is calculated to be about 20 for the design injection pattern at 1 MW operation. However, the injected beam size is relatively smaller as compared to the circulating beam and always hit in the same position of the foil. The injected beam then might have a bigger influence on the foil breaking. For a relatively thicker foil like the present one used in the RCS, it has already been demonstrated that before a complete breaking, thickness of a foil degrades as well as pinholes are formed due to the beam irradiation [3]. However, it is very important to know such a foil degradation through beam based measurement in a high intensity accelerator like RCS. The motivation of the present work is to determine the foil lifetime through performing an explicit and simultaneous measurement of the foil thinning and pinhole formation during RCS operation. Because, a complete breaking is not always a lifetime of the foil with high power operation as only a little of foil thinning and/or pinhole formation would increase waste beam. A sudden failure of the foil certainly reduces the accelerator availability. A proper maintenance of the broken foil is also an issue. The injection beam dump of the RCS has a capacity of only 4 kW. The design waste beam power is about 0.4 kW (if only H^0) but due to several factors for an optimized operation parameters such as, optimized injected beam positioning on the foil (to reduced circulating beam hitting on foil as much as possible), injected beam halo or the unexpected long tail of the injected beam, the waste beam is found to be increased twice as compared to the design value, when a smaller vertical size (20 mm) of the foil is used. As a result, only due a few percent of the foil thinning would exceed the limit of the injection dump for 1 MW operation. Foil lifetime would be then determined by the dump limit.

The beam power of the RCS will be increased gradually, and the behavior of foil lifetime and foil degradation curve could be very useful data in order to learn more about the foil breaking mechanism. As for the RCS operation, based on the measured foil degradation data a foil can be replaced to a new one in proper scheduled time of the accelerator operation. That could avoid any unscheduled downtime related to foil issue. Such a measured data would also be useful to manage the uses of the 15 stripper foils mounted at a time in the present foil magazine. Each foil should last for at least 15 days in order to change the whole magazine in a scheduled shutdown period. If the foil lifetime is much shorter than 15 days the schedule has to be revised in order to change the foil magazine but in that case also present study can determine a proper replacement timing as well as a proper uses of each foil.

RCS Stripper Foil

Figure 2 shows a layout of the RCS injection and waste beam dump line. The primary stripper foil named 1st foil is placed in the middle of 4 injection chicane magnets (SB 1~4). In addition, two more secondary foils named 2nd and 3rd foil, respectively are also placed a little further downstream of the primary foil. All foils are so-called HBC foils [3]. By using the cross sections determined from the past experimental data with 200 MeV on Carbon target, the stripping efficiency of the primary stripper foil is calculated to be about 99.6% [5]. The remaining 0.4% of the beams are called waste beam. They are mostly with the partially stripped H^0 beam (single electron detachment from the H^- beam), where the un-stripped H^- beam ideally should be negligibly small if there is no pinholes in the foil and injected beam is well optimized on the foil. The H^0 and H^- (if any) beams are further stripped to proton beams by the 2nd and 3rd foils, respectively and transported to the injection beam dump. The secondary foils are relatively thicker (500 μg/cm^2) and thus stripping efficiencies are calculated to be almost 100% (99.9999%). For the upgraded 400 MeV injection, a stripper foil of 290 μg/cm^2 will be used. The stripping efficiency is expected to be 99.7%. A thicker primary stripper foil easily increases the stripping efficiency but in the same time that increases the un-controlled beam loss in the injection area caused by the foil scattering, where a circulating proton hits the foil by an average of 20 times. A thinner foil on the other hand, greatly increases the H^0 beam. A higher capacity beam dump then would be needed and is both money and space consuming. In addition, one should also be keep in mind that an increase of the uncontrolled beam loss caused by the H^0 exited states during traversal through the bending field of the chicane bump (SB, see Fig. 2), before reaching to the 2nd foil. As a result, thickness of the primary stripper foil is designed to be 200 μg/cm^2 and 290 μg/cm^2 for the present 181 MeV and upgraded 400 MeV injection, respectively.

The RCS output beam power for the user operation is now nearly 300 kW. The corresponding injected beam power is 18 kW and thus the waste beam power is only about 0.054 kW (0.4% of 18 kW). In principle, a foil thinning of about 67% can be tolerated as the waste beam dump has a capacity of 4 kW. Namely, a design foil of thickness 200 $\mu g/cm^2$ with a stripping efficiency of 99.6% can be used until the thickness goes down to about 66 $\mu g/cm^2$ having a stripping efficiency of 78%.

Experimental Setup and Principle

As the initial thickness of the foil is 200 $\mu g/cm^2$, the waste beam in principle should only be the partially stripped H^0 component (0.4%) of the injected beam because of the un-stripped H^- one is expected to be negligibly small. As a result, an increase of the H^0 yield would be a signal of the foil thinning, where any un-stripped H^- yield should indicate the pinhole formation in the foil. In order to measure the foil degradation, we measured the waste beam at the injection dump time to time. We used a Multi-wire profile monitor (MWPM) named MWPM7 in order to measured the beam profiles of H^0 and H^- (if any) [6-7]. Figure 3 shows the experimental setup and principle used for the present measurement. The MWPM7 is placed almost at the end of the injection dump line and is a scan type beam profile monitor. The beam profile is usually measured by 100 shots injected with 1Hz, where MWPM7 moves by 0.2 mm/s and thus each wire moves a total of 20 mm.

We always measure the waste beam during the RCS operation period, so-called circulating mode (Figure 3.a). However, in order to get the H^0 and H^- beam fraction we should measure the injected beam profile and it is done in the injection beam dump mode (Figure 3.b). In this case, 1st foil is keep out from the beam line and thus all of the incoming H^- beam is stripped to H^+ by the 3rd foil and then transported to the dump. It is then measured by the MWPM7. This gives the yield of the injected beam itself. As also mentioned earlier that the secondary foils (2nd and 3rd) are relatively thicker (500 $\mu g/cm^2$) and thus stripping efficiencies are calculated to be almost 100%. Normalizing H^0 and H^- waste beam yields measured in the former mode to the injected beam yield measured in the later mode gives the H^0 and H^- beam fractions. Once H^0 and H^- fractions are known, the H+ fraction which is injected into the ring in the circulating mode or in other words, the stripping efficiency can easily be known. One should also need to measure fluctuation of the injected beam itself, which may vary shot by shot and time to time. It is always monitored by an SCT (slow current transformer) placed about 20m upstream of the RCS injection point (primary foil). A no beam data is also always taken in order to subtract the background.

Figure 4 shows an example of the horizontal beam profiles measured by MWPM7. It is important to mention that the H^- and H^0 beam profiles are separated by about 80 mm at the MWPM7 and thus we can measure both profiles simultaneous and independently. The beam profile shown by the black color corresponds to all injected H^- beam goes to the dump (stripping to H^+ by the 3rd foil) in the injection beam dump mode. Three other profiles correspond to the partially stripped H^0 and un-stripped H^- beam go to the dump in the circulating mode. The thinner the foil, the larger the visible H^0 yield and for a foil of 52 μg/cm^2 (red), some un-stripped H^- (expected ~1.7%) yield can also be seen. As expected, the blue color profile with a primary stripper foil 200 μg/cm^2 does not show any un-stripped H^- yield but only the partially stripped H^0 component. Then by normalizing the H^0 and H^- (if any) yields by the injected beam yield (black) taken in the injection dump mode, we obtained partially stripped H^0 and un-stripped (H^-) beam fractions and we could extract the foil thickness.

Experimental Results and Discussion

Figure 5 shows a linearity of the MWMP7 measured in the injection beam dump mode. As in the nominal case, only 0.4% of the beam is suppose to pass through MWPM7 and we aim to measure a quantitative time dependent change of this fraction due to the thickness change and/or pinhole formation, a good linearity for the monitor is essential. The linearity of the MWPM7 was checked for beam intensities of around 0.4% of the full injected beam. The H^- beam intensity from the Linac was changed by the number of intermediate pulses (also known as mini pulses, 467 in total for the full beam) and the beam profile is measured by the MWPM7 in the injection beam dump mode. The integrated yield of the measured beam profile was normalized by the corresponding beam intensity. The linearity was found to be good in the measured intensity range. The partially stripped H^0 beam hits different positions of the MWPM7 (separated by 80 mm from the H^- position as shown in Figure 4), and we assume it is linear; thus we can normalize the H^0 yield measured in the circulating mode by the H^- one measured in the injection beam dump mode, in order to extract the H^0 beam fraction. From Figure 4, the H^0 yield (blue color) measured for a primary stripper foil of 200 μg/cm^2 is normalized by the H^- yield (black color) measured in the circulating mode. As a result, the H^0 fraction was obtained to be 0.31 ± 0.035%. Because we do not observer any un-stripped H^-, the H+ fraction is then calculated to be 99.69%. By using the given experimental cross section measured for 200 MeV [5], the thickness of the present HBC foil was estimated to be 208 ± 4 μg/cm^2 and is found to be consistent with the design thickness of 200 μg/cm^2. No experimental data were measured for 181 MeV, so we used the given cross section measured for

200 MeV. On the other hand, as our present purpose is to monitor time dependent foil degradation, i.e., a relative change of the foil thickness, we can use above data. We have also performed separate numerous methods in order to estimated the design foil thickness with good accuracy as reported separately in this proceedings [8].

We have started using this foil for the RCS operation since March 5th, 2012. The user operation was continued for about 4 months (until July 2nd, 2012) for a beam power of 200 kW to the MLF and 300 kW equivalent beam power to MR (except MR slow operation for about 3 weeks at the end). The beam power to the MLF was also increased close to 300 kW for the last 3 days operation. However, during the 4 months operation, beam was off for several days in two periods due to the troubles in the Linac accelerator, beam studies and there was also several scheduled single maintenance day (almost twice a month for half day always). The total injected (H^-) beam irradiated on the primary stripper foil was then about 2.7×10^{21} particles. It is worth mentioning that for the present 200 kW operation, each circulating proton beam hits the foil by an average of about 10 times (20 for the design power of 1 MW). As a result, a total of 2.7×10^{22} particles were hit the foil during the operation. In order to check the foil degradation, we measured the waste beam (H^0 and H^-) yields by the MWPM7 almost every maintenance day. Foil degradation (foil thinning) would reflect an increase of the H^0 yield. Any event in the H^- peak position would indicate pinhole formation in the foil.

Figure 6 shows measured beam profiles taken for 6 times during 4 months operation. Unfortunately, such a data could not be taken in the beginning of operation and it was taken first about one month later in April 7th. However, the irradiated beam in the first one month was not so significant amount because of accelerator troubles and studies as mentioned earlier. Detail analysis of the present data reveals that the H^0 yield in the 2nd measurement seems to be decreased slightly but remains stabilized until the end of the irradiation time. Decreasing of the H^0 yield might surprisingly indicate that the foil thickness got increased a little bit in the beginning by any reason but there was no indication of degradation of the thickness. On the other hand, there was also no any observable un-stripped H^- component throughout operation and thus no indication of forming pinhole in the foil. For each measurement, H^0 fraction so as the corresponding foil thickness was calculated as shown in Figure 7. Except for an indication of the increasing trend of the thickness in the beginning, the average thickness was found to remain constant for about 210 $\mu g/cm^2$.

An increasing trend of the foil thickness in the beginning is interesting but the change is even smaller (1%) as compared to the present measurement error of about 2%. We need more data in order to realize more precisely. As a result, we do not have clear understanding yet in order to explain such a phenomenon, which usually believed to observe in thinner foils [4]. However, for the present beam power foil peak temperature may not so high (~ 650 K) and thus so-called carbon buildup might occur so as increase the thickness. Two other common reasons might be foil shrinkage and foil deformation. The deformation might tilt the foil along the injected beam axis in the longitudinal direction. The foil beam interaction was increased so as to increase the stripping efficiency equivalent to an increase of the thickness. However, the present foil has only about 1.0 μm length in the longitudinal direction. One needs about 8 degrees tilted in order to explain 1% change of the thickness. As a result, there might have any other processes involved.

The user operation of the J-PARC after 2012 summer shutdown was resumed in November. Due to maintenance of the foil system, we had to replace all stripper foils with new ones for RCS continuous operation nearly one year until July, 2013. We will carry on same study until we observe any degradation for which waste beam power reaches close to the injection dump limit or even any sudden foil break happens. Recently, we are also trying to focus on reducing error level further by taking several calibration data as well as introducing more efficient measurement technique. For example, we will try to measure the linearity of MWPM7 wires in different positions such as the wires hit by the H^0 beam. Instead of the RCS circulating mode, we will use another mode called single turn extraction mode, where injected beam in the RCS ring is extracted after travelling 1/3 of the circumference and do not come back to the stripper foil. A further unexpected background event can then be reduced. The data presented here was taken in each maintenance day, where study time was very limited and all sorts of calibration data could be taken. However, if the foil has significant and time dependent degradation before complete breaking in the present beam power, the present resolution of the monitor system is even useful in order to measure such a trend.

Conclusion

We have established a self consistent method in order to estimate thickness of the stripper foil with relatively good accuracy. The present measurement error for the thickness is about 2 % and might be enough for a quantitative monitoring of the stripper foil degradation during user operation of the RCS even with the present beam power of

300 kW.

It is expected that a foil should have degradation, such as foil thinning, pinhole formation before complete breaking and lifetime of a foil generally goes shorter for higher beam power. A sudden failure of the foil certainly creates several issues for a stable operation of the accelerator but then a proper monitoring system of the foil degradation can certainly avoid sudden failure related to any such reasons by replacing it with a new one in proper time.

The present primary stripper foil was used for continuous 4 months operation of the RCS in the last cycle, where a total of about 2.7×10^{21} particles (only injected H^-) were irradiated. We did not observe any kind of foil degradation so far. As a result, there was no issue to replacing the foil during the operation.

Only 15 foils can be installed at a time in the present foil magazine and thus a proper uses of the foil is also important in order to meet the scheduled accelerator operation. The present quantitative monitoring system in such a way would be able to play an important role for this most sensitive issue with stripper foil for high power operation of the 3-GeV RCS.

Acknowledgment

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Figure Captions:

Figure 1: Dimension of the primary stripper foil used for the present RCS operation. The injected and circulating beams (at the end of injection) are also shown. Due to the multiturn injection, each circulating beam hits the foil by an average of 20 times. Foil peak temperature for 1 MW operation is estimated to be more than 1000 K.

Figure 2: Layout of the RCS injection and the waste beam dump line. The primary stripper foil named 1st foil with a thickness of 200 μg/cm^2 is placed in the middle of 4 chicane magnets and has a stripping efficiency of 99.6% at the present injection energy of 181 MeV. The rest of 0.4% are called waste beams and are mainly with the partially stripped H^0, while un-stripped H^- is negligibly small. They are further stripped to H^+ by the 2nd and 3rd foil, respectively and transported to the injection beam dump.

Figure 3: Experimental setup and principle of the present measurement. A Multi-wire Profile Monitor (MWPM) named MWPM7 is used to measure the waste beam during the RCS operation. The waste beam yield measured in the circulating mode (a) is normalized by the injected beam yield measured in the injection beam dump mode (b) in order to get the waste beam fraction so as to calculate the foil thickness.

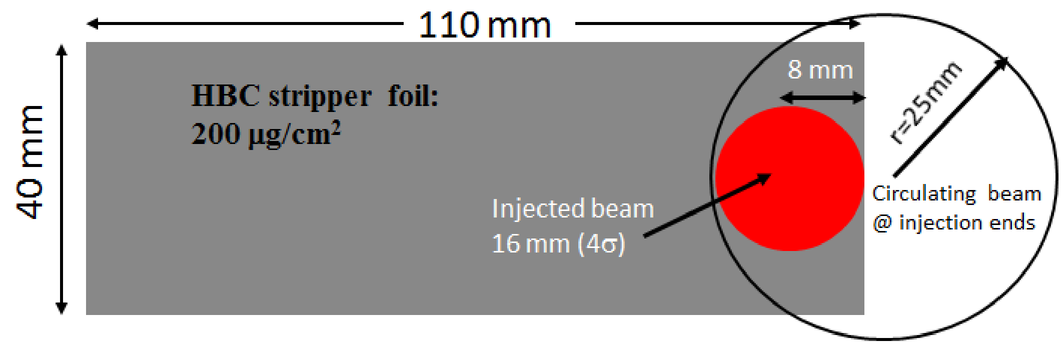
Figure 4: Horizontal beam profiles measured by the MWPM7 are shown. The horizontal and vertical axes are position and signal of beam at MWPM7, respectively. The H^0 and H^- beam positions differs by 80 mm and thus a simultaneous measurement of the H^0 and H^- waste beam components can be done.

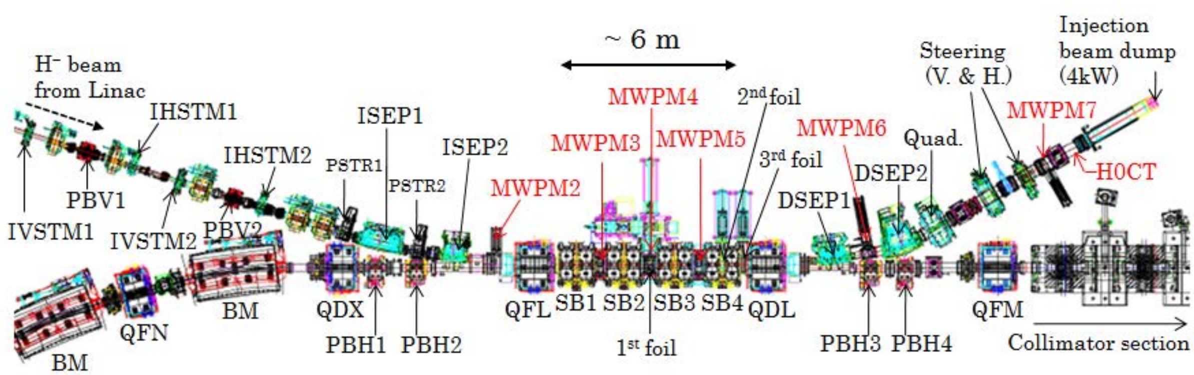
Figure 5: Linearity of the MWPM7 measured in the injection beam dump mode. The horizontal scale is the injected H^- particles, where vertical scale is the integrated H^+ yield obtained from the MWPM7 profile normalized by the corresponding injected particles.

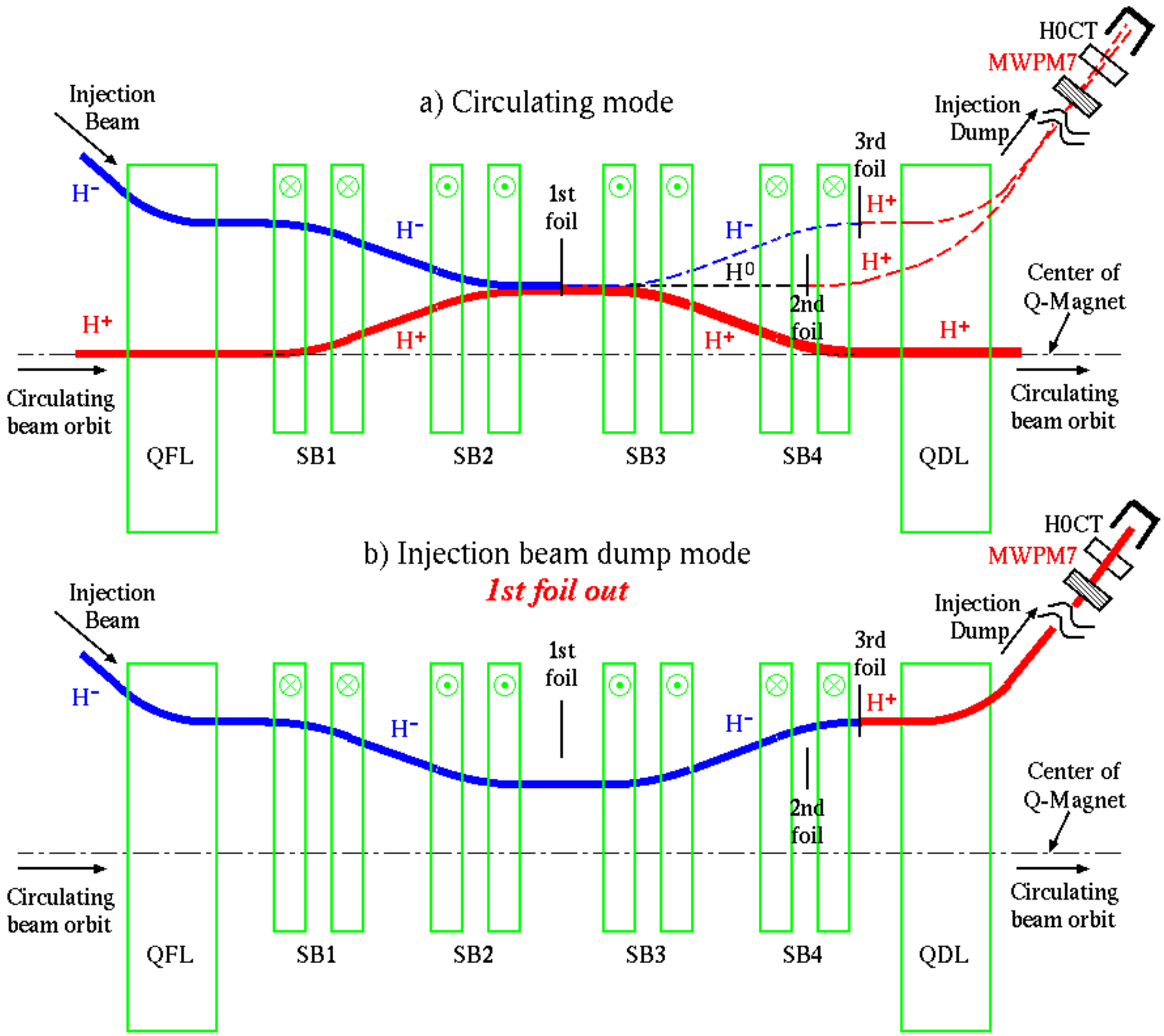
Figure 6: Waste beam profiles measured 6 times during 4 months operation of the RCS. The H^0 yield was found to decrease a little from the 2nd measurement but there was almost no change after words until the end. A decrease of the H^0 yield from the 2nd measurement interestingly indicates an increase of the foil thickness. In addition, there was no yield in the H^- region also indicating no pinhole formation in the foil.

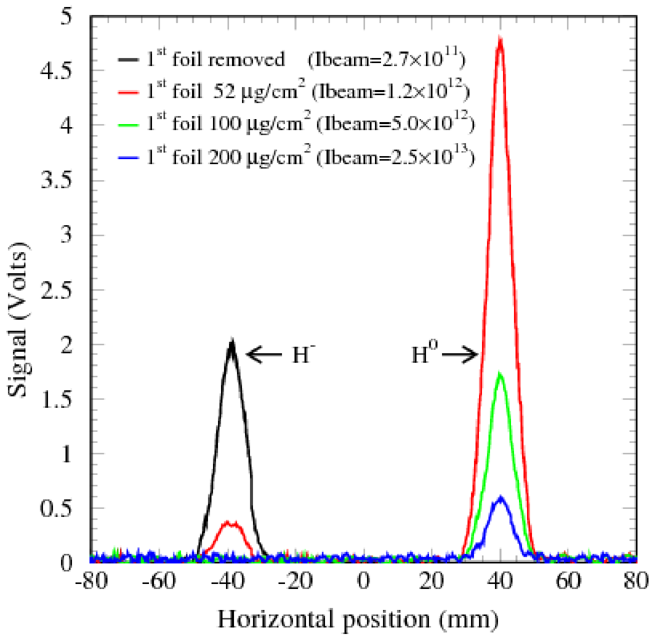
Figure 7: The H^0 fraction for each measurement so as the corresponding calculated foil thickness is shown in the left and right vertical scales, respectively. Horizontal axis is the cumulated injected beam at each measurement date.

Except for a little increase of the thickness in the beginning, the thickness was found to remain same throughout the operation and there was also no pinhole formation in the foil as we did not observe any H^- yield (Fig. 6). As a result, there was no indication of the foil degradation so far.

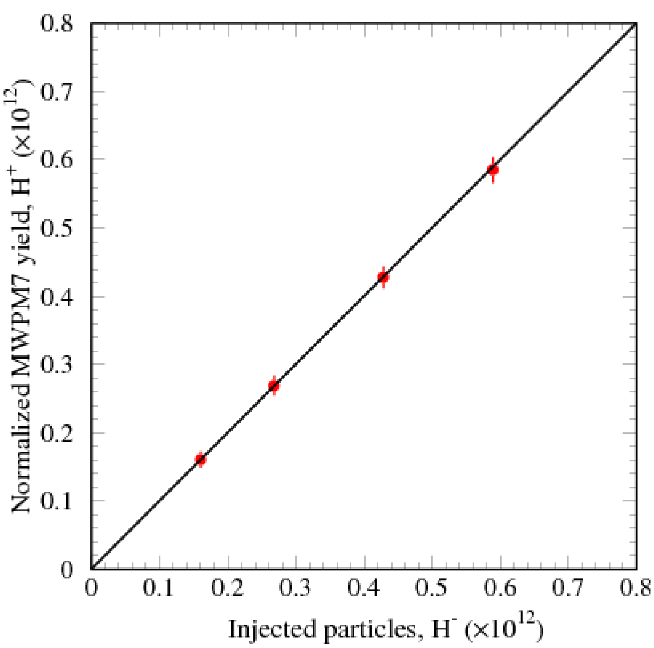




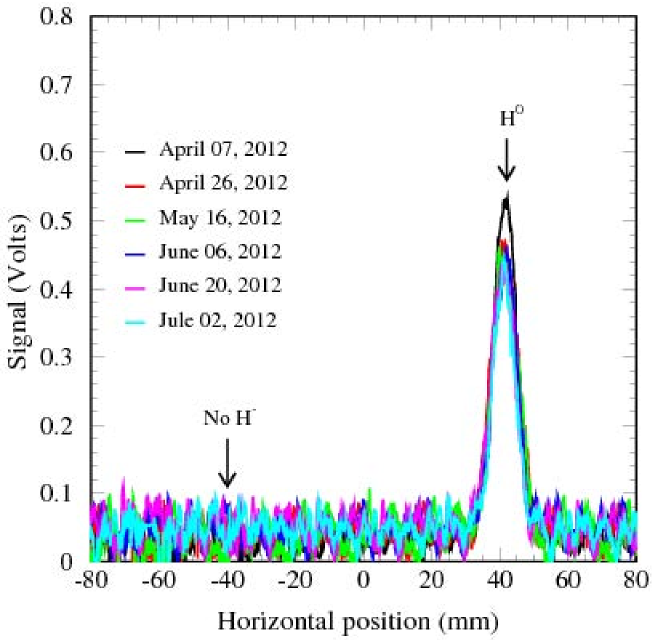

a) Circulating mode
Injection Beam
H-
H+
Circulating beam orbit
QFL
SB1
SB2
SB3
SB4
QDL
1st foil
2nd foil
3rd foil
H0
Center of Q-Magnet
Injection Dump
H0CT
MWPM7
b) Injection beam dump mode
1st foil out

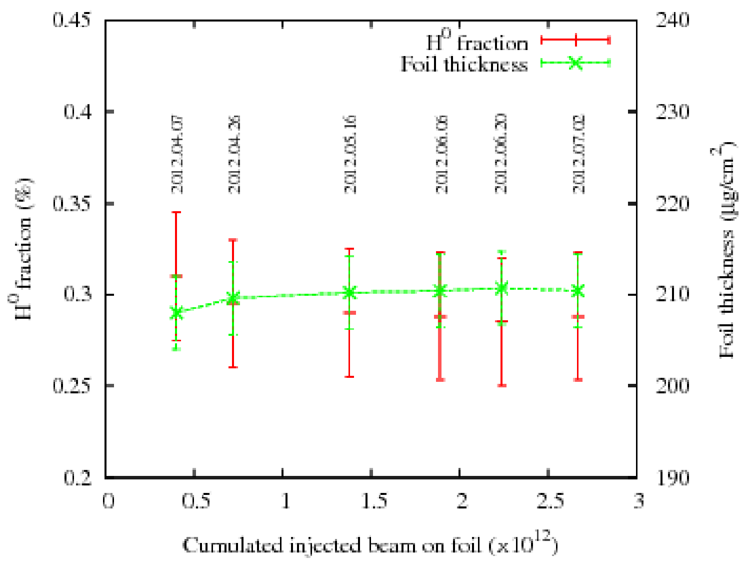


1st foil removed (Ibeam=2.7×10^11)
1st foil 52 μg/cm2 (Ibeam=1.2×10^12)
1st foil 100 μg/cm2 (Ibeam=5.0×10^12)
1st foil 200 μg/cm2 (Ibeam=2.5×10^13)
H-
H0
Signal (Volts)
Horizontal position (mm)



Normalized MWPM7 yield, H+ (×10^12)
Injected particles, H- (×10^12)


Signal (Volts)
Horizontal position (mm)
April 07, 2012
April 26, 2012
May 16, 2012
June 06, 2012
June 20, 2012
Jule 02, 2012
H0
No H-
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-80
-60
-40
-20
0
20
40
60
80


H0 fraction
Foil thickness
2012.04.07
2012.04.26
2012.05.16
2012.06.06
2012.06.20
2012.07.02
H0 fraction (%)
Foil thickness (µg/cm2)
Cumulated injected beam on foil (x1012)
0.45
0.4
0.35
0.3
0.25
0.2
240
230
220
210
200
190
0
0.5
1
1.5
2
2.5
3

275