ADVANCED USES OF A CURRENT TRANSFORMER AND A MULTI-WIRE PROFILE MONITOR FOR ONLINE MONITORING OF THE STRIPPER FOIL DEGRADATION IN THE 3-GeV RCS OF J-PARC

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Abstract

We have established an advanced and sophisticated uses of a current transformer and a multi-wire profile monitor for accurate measuring as well as online monitoring of the waste beam so as to know the stripper foil degradation during user operation of the J-PARC 3-GeV RCS. A more than 99.7% of the H^- beam coming from the Linac is stripped to a proton beam by using an HBC stripper foil of 200 μg/cm^2 placed in the RCS injection area. The remaining 0.3% is called the waste beam and is transported to the injected beam dump. Foil degradation such as, foil thinning and pinhole formation are believed to be the signs of a foil breaking. A sudden foil breaking is not only decreases accelerator availability but also raises maintenance issues. A proper monitoring system of the foil is thus important in order to avoid any such issues by replacing the foil with a new one in the scheduled maintenance day. The sensitivity of the present method has already been proved to be very good and is capable of monitoring a change of the foil thickness as low as 1% or even less. A single foil was used for a continuous last 7 months operation of the RCS with an extracted beam power of 300 kW (18 kW injected beam). The integrated total irradiated particles (injected H^- itself) were 8×10^{21} but there was no any degradation of the foil so far. Surprisingly an increase of the foil thickness of about 10% was observed.

INTRODUCTION

The 3-GeV Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) is a high power proton machine designed for a beam power of 1 MW [1]. The injected beam energy is 181 MeV at present but it will be upgraded to the designed 400 MeV in 2013. The extracted beam energy is 3 GeV and is simultaneously delivered to the downstream muon and neutron production targets in the Material and Life Science Facility (MLF) as well to the Main Ring (MR) at a repetition rate of 25 Hz. RCS beam power for the user operation has already been exceeded 300 KW and further more of exceeding 500 kW has also been demonstrated in recent beam studies [2, 3].

In order to increase circulating beam intensity, RCS uses conventional multi-turn H^- charge-exchange injection technique during the injection period of 0.5 ms [4]. A more than 99.7% of the incoming H^- beam from the Linac is stripped to a proton beam by using an HBC (Hybrid type Boron doped Carbon) foil of 200 μg/cm^2 placed in the injection area. It is the primary stripper foil and also called the 1st foil. The stripping efficiency is calculated by using the measured cross sections at 200 MeV on Carbon targets [5] and applying energy scaling of the cross section by $1/\beta^2$, where β is relativistic factor of the H^- ion [6]. The remaining 0.3% of the beam is called waste beam and ideally it is with partially stripped (single electron detachment at the 1st foil) becomes neutral (un-charged) and is called H^0 beam, where the un-stripped H^- are expected to be negligibly small. The H^0 and H^- (if any) are further stripped to proton beams by the secondary stripper foils named 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%).

Similar to any other high intensity machine, stripper foil lifetime is one of the big issue also in RCS. 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 [7, 8]. Due to the multi-turn injection, not only the injected beam but circulating beam also hit the primary foil nearly 20 times in average during injection period. 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. An accurate measurement of each component of the waste beams (H^0 and H^-) can thus give information on the foil degradation process.

The injection beam dump of the RCS has a capacity of only 4 kW. A complete breaking is thus not always a lifetime of the foil for high power operation as foil degradation only a little causes a significant increase waste beam so as to increase the head load on the dump. A sudden foil failure certainly reduces accelerator availability and also raises maintenance issues. A proper monitoring system of the foil is thus important in order to avoid any such issues by replacing the foil with a new one in the scheduled maintenance day. 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.

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PRESENT TECHNIQUE AND VALIDITY

In the efforts of measuring such a little fraction of the waste beam (0.3%) and moreover for monitoring a even a little change of the waste beam fraction, recently we have established two precise and independent ways which employs rather simple principle and methods by using already placed a current transformer named H0CT and a Multi-Wire Profile Monitor (MWPM) named MWPM7 placed near the injection dump. Figure 1 shows an expanded view of the RCS injection area, locations of H0CT and MWPM7 together with setup of the stripper foils for the operation/study modes of the RCS. The waste beam is measured in any of the circulating mode (a) or single-pass extraction mode (b), where all three foils are placed in right positions. However, in order to get fraction of the waste beam, injected beam itself was measured in the injection beam dump mode (c). In this case, the 1st foil is removed from the beam line and thus incoming H^- beam is stripped to proton beam at the 3rd foil and transported to the dump. As a result, a ratio of the beam signal measured in the former mode (a) or (b) to the later mode (c) gives the waste beam fraction. The measurement with H0CT and MWPM7 is done separately. Injected beam also measured by an SCT (Slow Current Transformer) placed few meter upstream of the 1st foil in order to take into account the fluctuation of the injected beam during the measurement.

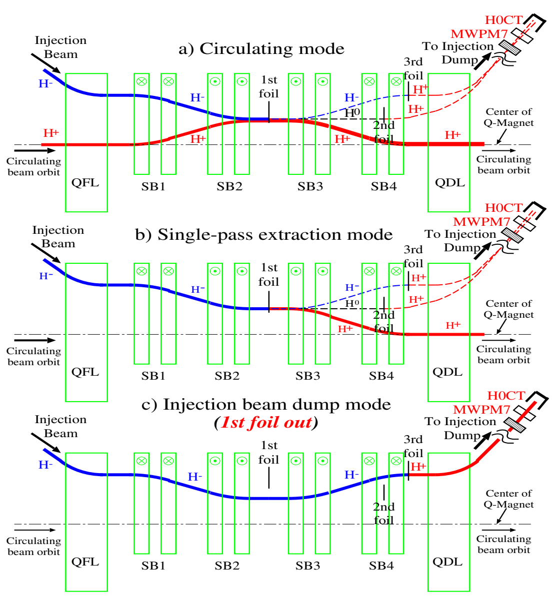

Figure 1: Close view of the RCS injection area and location of the H0CT and MWPM7. A ratio of the beam signal measured by mode (a) or (b) to that of mode (c) gives the waste beam fraction.

H0CT

The time domain signal of the H0CT is collected by an oscilloscope and a Fourier transform is done. As a result, picking up amplitude of the power spectrum corresponding to the frequency of the intermediate pulse, which depends on the RCS RF frequency gives the beam signal [9].

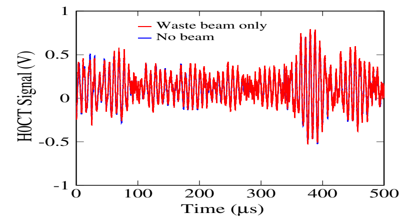

Figure 2: Time domain signals of the H0CT with beam (red) and with no beam (blue) are quite identical and is hard to extract the real information of the waste beam.

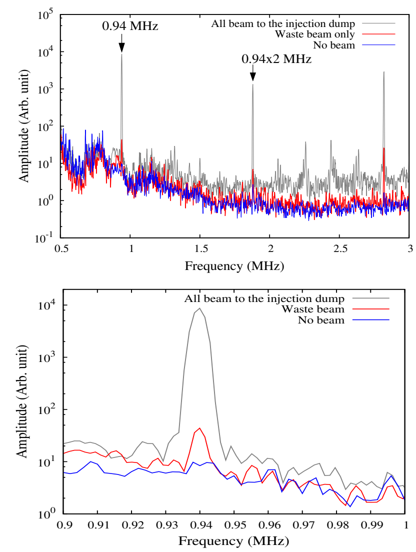

Figure 3: Fourier transform of the H0CT time domain data clearly shows the beam signal. The difference of the waste beam signal (red) from the no beam (blue) can be clearly seen in the expanded view (bottom). The spectrum shown in gray color is taken in the injection beam dump mode.

Figure 2 shows time domain signal of the H0CT with beam and with no beam for an average of 64 shots measured in the mode (b). The peak current of the H^- beam was 15 mA. The injected particles for a macro pulse length of maximum of 0.5 ms with a chopper beam-on duty factor of 56% (600 ns) was 2.5×10^{13}. Even though the time domain signal with beam and with no beam are very identical and thus hard to extract the real beam signal. However, as shown the power spectrum in Fig. 3 (middle), Fourier transform of the time domain signal on the other hand clearly identifies the beam signal (red) corresponding to the chopping frequency (h=2). In contrast to the no beam data, the signal corresponds to the expected fundamental frequency of 0.940 MHz and successive higher order harmonics at rf multiples are clearly seen with beam. The data for taken in the injection beam dump mode (gray) is also shown for confirmation. The signal that corresponds to the fundamental frequency was used for the analysis, which is shown as an expanded view in the bottom. Nearly an order higher signal of the waste beam as compared to the no beam can easily be seen. The waste beam in this case was only the H^0 component as 3rd foil was kept out from the beam line.

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A ratio of the peak height of the waste beam (red) to that of all beam (gray) for the fundamental frequency gives the H^0 fraction and is obtained to be 0.33±0.02%. The unstripped H^- component determined by the cross section for a foil thickness of around 200 μg/cm^2 should be negligibly small (10^{-7}) and is thus considered to be zero. The H^+ component can easily be known. Eventually, thickness of the present primary HBC foil is calculated to be 191±1.8 μg/cm^2. The vertical size of the primary stripper foil was 20 mm and there was thus a considerable amount of the H^-, missing 1st foil. By inserting the 3rd foil in right position, the total waste beam was measured to be 0.55±0.03%.

MWPM7

The MWPM7 is a scan type beam profile monitor. The beam profile is usually measured by 100 shots injected with 1 Hz, where MWPM7 moves by 0.2 mm/s and thus each wire moves a total of 20 mm [10]. By using MWPM7 we can simultaneously measure both H^0 and H^- (if any) components, where center of the two profiles are separated by about 70 mm. In order to get each fraction, the integrated individual profile measured by the mode (a) or (b) is normalized by the yield measured in the injection beam dump mode (c). Figure 4 shows the horizontal waste beam profile (red) measured by mode (b), together with injected beam profile (black) measured by mode (c). As also mentioned earlier, the missing H^- measured in the former mode was due to vertically 20 mm size of the 1st foil. The H^0 and H^- are obtained to be 0.32±0.01% and 0.22±0.01%, respectively. Consequently, thickness of the primary stripper foil is calculated to be 192±1.5 μg/cm^2, which is consistent with H0CT data.

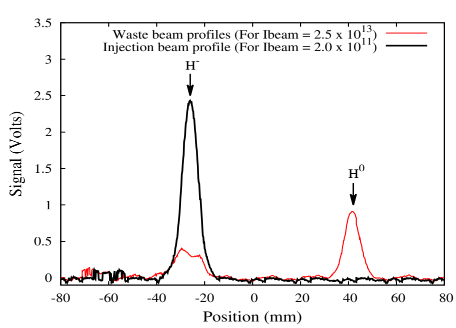

Figure 4: H^0 and H^- (if any) components of the waste beam can be measured simultaneously by the MWPM7.

TREND OF THE FOIL THICKNESS

H0CT is used as real online monitor for measuring the waste beam as a whole, while MWPM7 together with H0CT is used in the RCS beam studies in order to know detail information of the foil degradation (any change of foil thickness and/or pinhole information) by precisely measuring the H^0 and H^- fraction, respectively. MWPM7 can measure H^0 and H^- fractions simultaneous, but by removing 3rd foil in any of the two modes (a) or (b) (see Fig. 1) we can measure only H^0 component even by the H0CT.

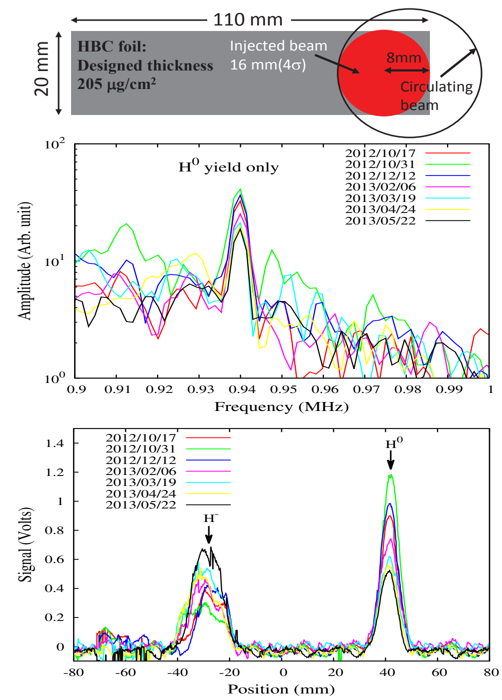

Figure 5: A continuous reduction of the H^0 yield during 7 months operation is measured by both H0CT and the MWPM7 reflecting an increase of the foil thickness. There was significant amount missing H^- due to 20 mm vertical size of the primary stripper foil as demonstrated at the top.

Figure 5 shows (middle) a clear variation of the H^0 yield measured by the H0CT almost one months interval during last 7 months operation. The corresponding MWPM7 data including H^- yield are shown at the bottom. A demonstration of the injected beam positioning on the primary foil is also shown on the top.

Figure 6 (top) shows individual H^0 and H^- fractions and and their sum measured a total of 13 times during 7 months operation. The integrated injected beam particles are also plotted as shown by the black curve. The extracted beam power of the RCS was 300 kW. That means, the injected beam power was 18 kW corresponding to 2.5×10^{13} ppp (particles per pulse). The total integrated injected particles were measured to be 8.0×10^{21}. However, due to the multi-turn injection, each circulating proton hit the foil as much as nearly 20 times in average and thus integrated particles hit the foil is estimated to be nearly 1×10^{23} in total. The measurement by two independent monitors are found to be consistent each other, where a significant decrease of the H^0 fraction as a function of the integrated injected beam has been observed. The H^- fraction was measured to be change randomly as it was the missing H^- beam at the primary stripper foil. A little change of the injected beam trajectory or injected beam profile can cause a change of the missing as H^- amount, especially in the vertical direction as the foil size in the vertical direction was 20 mm. The total amount on the other hand was with less fluctuation and was about nearly 0.5% in average. By using measured

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H^0 fraction and considering the real H^- fraction is negligibly small (as it should be $\sim 10^{-7}$ for a foil of around 200 μg/cm^2 [5, 6]), the H^+ fraction and thus the corresponding foil thickness is calculated as shown in Fig. 6 (bottom).

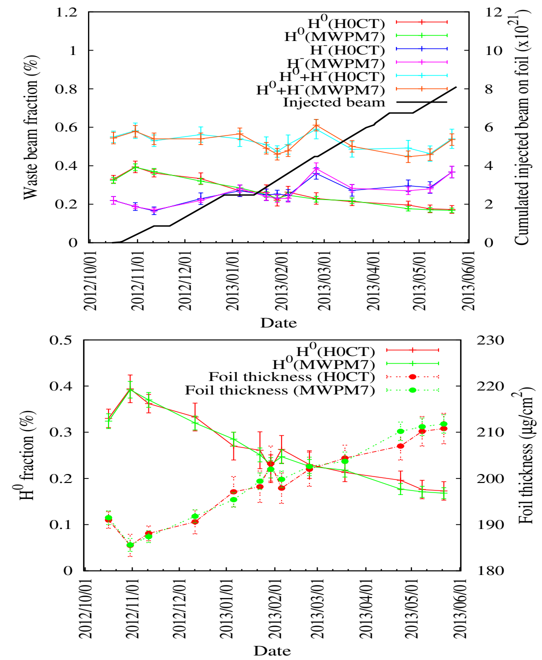

Figure 6: Individual H^0 and H^- waste beam fractions and their sum for 13 measurements during 7 months operation. The integrated injected beam is shown by the black curve. The corresponding foil thickness is shown in the bottom.

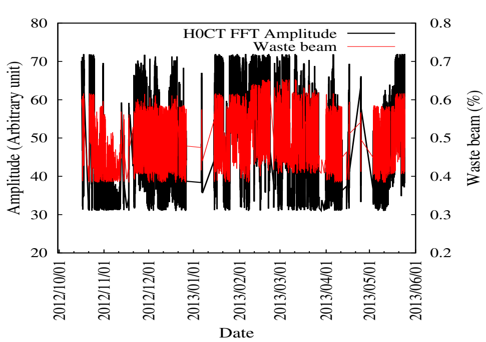

Figure 7: Online trend of the H0CT for the waste beam fraction is found to be similar to that measured several times as shown in Fig. 6 and was about 0.5% in average.

Figure 7 shows an online trend of the H0CT signal and the corresponding waste beam fraction. The waste beam fraction was 0.5% in average and the overall trend was found to be similar to that measured several times during beam studies (see Fig 6). The H0CT in such a way plays an important role for online monitoring of the waste beam and stripper foil performance during RCS operation.

Previously we observed a slight increase of the foil thickness measured for a relatively shorter period as well as for a less beam power as compared to the present data [11]. The present data shows an increase of the foil thickness as much as 10% from it initial value. Such a behavior of the foil is interesting but for clear understanding of the real phenomenon we need more data and especially, similar repeated measurements. There might have several reasons such as, so-called carbon buildup, foil shrinkage and foil deformation are involved. For the present beam power, expected foil peak temperature may not be so high ($\sim$650 K) and thus so-called carbon buildup might be the most considerable reason [7]. Foil shrinkage as well as foil deformation might also contributed in the process.

SUMMARY

Advanced uses of a current transformer and a multi-wire profile monitor made it possible for measuring even a small fraction of the waste beam with good accuracy. Online monitoring of the waste beam and recognizing any change of the foil thickness during RCS operation has also been demonstrated. Foil has a certain lifetime and usually lifetime goes shorter with higher beam power, but a foil might have degradation such as foil thinning and pinhole formation before complete breaking. As foil degradation could be a signal of a foil breaking, such a present online monitoring system would be very useful in order to know a proper replacement timing as well to avoid any sudden foil failure during operation. It may also provide useful information for deep understanding of the foil breaking mechanism.

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REFERENCES

[1] "Accelerator Technical Design Report for J-PARC" JAERI-Tech 2003-044 and KEK Report 2002-13

[2] M. Kinsho, IPAC'13, Shanghai, China, May 2013, THPWO037, p. 3848, `http://www.JACoW.org`

[3] H. Hotchi et. al., IPAC'13, Shanghai, China, May 2013, THPWO033, p. 3836, `http://www.JACoW.org`

[4] P.K. Saha et. al., Phys. Rev. ST Accel. Beams 12 (2009) 040403

[5] R.C Webber et. al., IEEE Trans. Nucl. Sci. 26 (1979) 4012

[6] W. Chou, et. al., Nucl. Ins. and Meth. A 590 (2008) 1

[7] I. Sugai et. al., Nucl. Inst. Meth. A 613 (2010), p. 457-461

[8] I. Sugai et. al., Nucl. Inst. Meth. B 269 (2011), p. 223-228

[9] P.K. Saha et. al., Phys. Rev. ST Accel. Beams 14 (2011) 072801

[10] S. Hiroki et. al., EPAC'08, Genoa, June 2008, TUPC036, p. 1151, `http://www.JACoW.org`

[11] P.K. Saha et. al., ICFA, HB2012, Beijing, China, Sept 2013, TUO1C02, p. 297, `http://www.JACoW.org`