ONLINE MONITORING SYSTEM FOR THE WASTE BEAM IN THE 3-GeV RCS OF J-PARC

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Abstract

We have succeeded online monitoring of the waste beam of only about 0.4% in the 3 GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC). We use conventional monitors but established efficient measurement technique so as to measure such a waste beam even with sufficient less error. An FFT analysis of the raw signal measured by a current transformer (CT) made it possible to clearly identify the beam signal corresponding to the frequency of the intermediate pulse. The waste beam as a whole was measured to be (0.38±0.03)%. In addition, we also use a multi-wire profile monitor (MWPM) for simultaneous and separate measuring of the partially stripped (H^0) and if any un-stripped (H^-) components of the waste beam profiles. Analysis of the H^0 and H^- beam profiles give quantitative information of the foil degradation, such as foil thinning and pinhole formation, respectively. Both methods already play important roles for the RCS operation so as to directly know the stripper foil condition and would have great importance especially, for high power operation.

INTRODUCTION

The 3-GeV Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) is designed to deliver a high power proton beam of 1 MW to the neutron and muon production target in the Material and Life Science Facility (MLF) as well as to the Main Ring (MR) [1]. The injection energy of RCS is 181 MeV at present and will be upgraded to the design energy of 400 MeV next year, while the extraction energy is 3 GeV [2]. RCS operates with a repetition rate of 25 Hz and will have 8.33×10^{13} particles per pulse (ppp) at 1 MW operation. RCS beam power for the user operation at the latest was nearly 300 kW to both MLF and MR.

The incoming H^- beam from the Linac is converted to a proton beam and injected into RCS during 0.5 ms multi-turn injection period. It is done by a primary stripper foil named 1st foil placed in the middle of injection bump magnets [3]. The primary stripper foil is a double-layer type of the HBC (Hybrid type Boron doped Carbon) foil [4] with a thickness of 200 μg/cm^2 for the present injection and will be changed to 290 μg/cm^2 for 400 MeV injection. By using the cross sections measured in an earlier experiment at 200 MeV and on Carbon targets, the stripping efficiency at present is calculated to be 99.6% [5]. For 400 MeV, the extrapolated cross sections are used and the stripping efficiency is calculated to be 99.7% [6]. The remaining 0.4% or 0.3% of the beams are called waste beams and ideally they are 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. They are further stripped to proton beams by the secondary stripper foils named 2nd and 3rd foils, respectively and transported to the injection beam dump. As the main component of the waste beam is H^0, injection dump is also called the H0 dump.

A proper monitoring of the waste beam is very important and was always an issue since design stage. Because the dump has a capacity of the only 4 kW and thus a little change of the stripping efficiency would increase the waste beam so as to increase the head load on the dump. Unexpected long tail or halo of the injected beam, failure of any related accelerator components for which injected beam misses the 1st foil are also other possible sources for increasing the waste beam. Usually foil lifetime becomes shorter as beam intensity goes higher but a foil might have degradation before complete breaking. A sudden failure certainly reduces accelerator availability as well as raised maintenance issues. Degradation of a foil increases the waste beam and could be a signal of a foil breaking. One can determine a proper foil replacement timing and also can avoid a sudden failure through a reliable measurement of a foil degradation. However, not only because of the small fraction (0.3% ∼ 0.4%) but also for the large noise from the nearby complicated injection system the measurement is very difficult. As a result, a little change of the waste beam fraction is further difficult to monitor through any straightforward way even using any sophisticated monitor. In order to overcome these difficulties, we have continued our efforts and recently established a precise method which employs a rather simple principle and does not require any sophisticated monitor or device. The time domain signal of a current transformer (CT) placed near the entrance of the H0 dump is 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 gives the beam signal. Formation of intermediate pulses and the timing relation between the Linac and the RCS can be found in [7]. The waste beam in a realistic condition was measured to be (0.38±0.03)% and was consistent with expectation [8]. Being non destructive, the present method is already in operation for online monitoring of the waste beam during the RCS operation.

We have also extended our effort for measuring H^0 and H^- component separately by using a multi-wire profile

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monitor (MWPM) named MWPM7 placed near the H0CT. However, it can not be used as a real online monitor and thus we usually measure at each maintenance day during the RCS operation. Analysis of the H^0 and H^- beam profiles give quantitative information of the foil degradation, such as foil thinning and pinhole formation, respectively. It can thus not only avoid foil related issues as mentioned earlier but it may also provide useful information on the foil breaking mechanism.

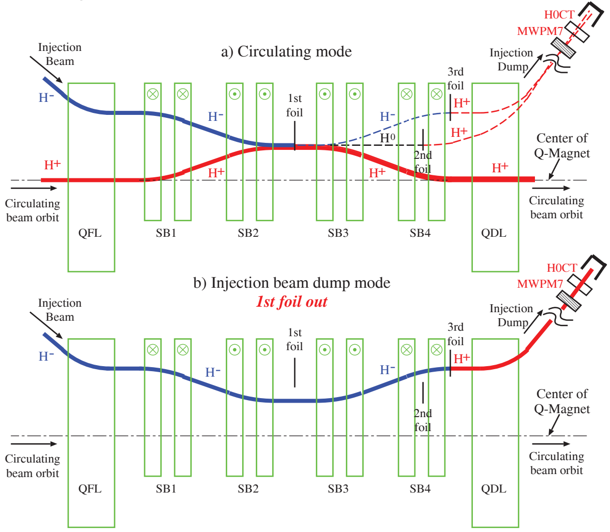

Figure 1: Close view of the RCS injection area and location of the H0CT and MWPM7. A ratio of the beam signal measured in the circulating mode (a) to the injection beam dump mode (b) gives the waste beam fraction.

MEASUREMENT PRINCIPLE AND VALIDITY

Figure 1 shows a close view of the RCS injection area, locations of H0CT and MWPM7 together with the setup of stripper foils for two operation modes of the RCS. The waste beam is measured in the circulating mode (a), where all three foils are placed in right positions. However, in order to get the waste beam fraction, injected beam itself was measured in the injection beam dump mode (b). 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) to the later mode (b) 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. A no beam data is also taken for subtracting the background.

H0CT

One of the main purposes of the H0CT is to use as a PPS (Personnel Protection System) interlock, where it checks that the (waste) beam power in the H0 dump does not exceed the design limit. The system makes an alarm if one hour integrated signal reaches close to the setting threshold. At present, beam is then usually stopped by the operator. Otherwise, beam goes automatically stopped if the integrated signal crosses the setting threshold. However, due to large noise the integrated signal contains a large error. As a result, the threshold is usually set with big margin. The noise floor also often varies and thus one needs to change thresholds from time to time. Experimental setup of the H0CT can be found in our separate article [8]. In our present approach, we first fed the amplified and buffered signal into an oscilloscope, which is controlled by an OPI (Operation Interface). The main parameters of the oscilloscope can be controlled on-line by the OPI. As a result, data can be taken as desired and averaging the signal before FFT analysis sufficiently cancels out the random noise. At present during RCS user operation, an average of 1024 injections is made first and then an FFT analysis is performed by using the Blackmann window function. As RCS runs with 25Hz, the required time for one data point is only about 40 s.

Figure 2 shows time domain signal of the H0CT with beam and with no beam for an average of 64 shots taken in the circulating mode. The peak current of the Linac beam was 15 mA. The macro pulse length was a maximum of 0.5 ms with a chopping width of 600 ns and two bunches having 2.5×10^{13} particles were injected into the RCS. Due to the waste beam fraction is small, time domain signal with beam is very identical to that with no beam and thus hard to extract the real beam signal. However, as shown the power spectrum in Fig. 3, an FFT analysis of the time domain signal on the other hand clearly identifies the beam signal (red) corresponding to the chopping frequency, which is set to the (h=2) frequency. 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. Data taken with injection dump mode (all beam to the dump) is also shown by black color for comparison. The signal that corresponds to the fundamental frequency was used for the analysis.

Figure 4 shows an expanded view of the FFT spectra highlighted near the fundamental frequency region for all three cases. The big difference between signals with beam (red) and with no beam (blue) can easily be seen. The fraction of the waste beam is then calculated from a ratio of the waste beam signal (red) to the all beam signal (black) and was obtained to be $(0.38 \pm 0.03)\%$. It was thus very consistent with the expectation of 0.4% as foil thickness was around 200 μg/cm^2 [5]. It is important to mention that in this experiment injected beam position on the foil was well optimized and we confirmed that there was no un-stripped H^- beam [8]. The linearity of the H0CT was also found to be very good.

MWPM7

The MWPM7 is scan type beam profile monitor and is also placed in the injection dump line near to the H0CT

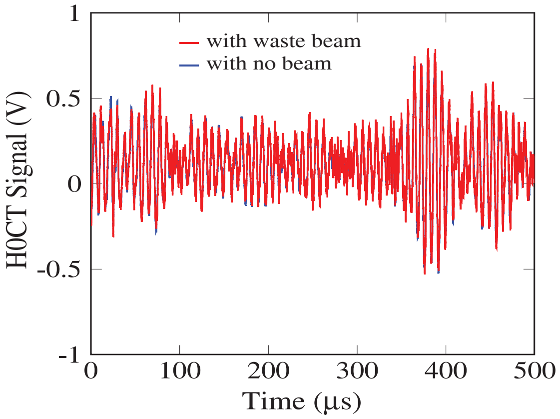

Figure 2: Time domain signals of the H0CT with beam (red) and with no beam (blue) are quite identical and is hard to extract the real information of the waste beam.

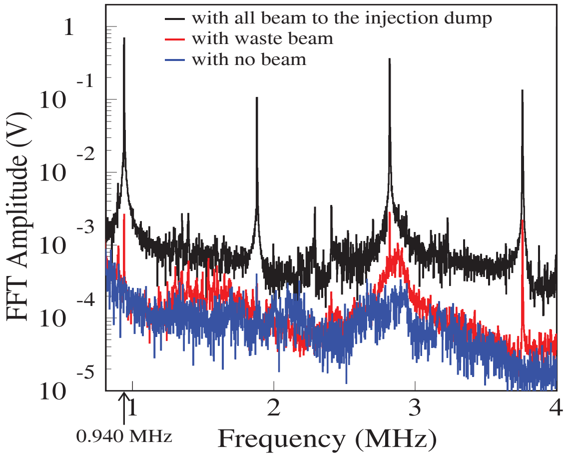

Figure 3: FFT analysis of the time domain signal clearly shows the beam signal. The spectrum with red color corresponds to the waste beam as shown in Fig. 2, whereas blue and black colors correspond to that for no beam and and all beam (injection dump mode), respectively.

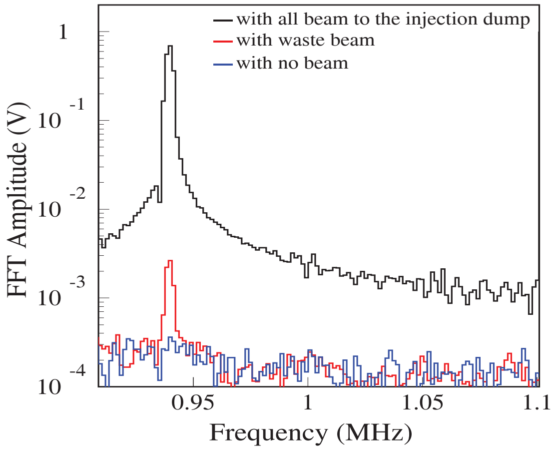

Figure 4: Expanded view of the FFT spectra near the fundamental frequency region. A clear signal of the waste beam about an order of magnitude higher as compared to the no signal with no beam data can easily be seen.

(see Fig. 1). 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 [9, 10]. The advantage of using MWPM7 is that we can simultaneously measure the partially stripped (H^0) component and un-stripped (H^-) component (if any). The H^0 and H^- beam profiles at MWPM7 are separated by about 80 mm. The same measurement principle as H0CT is also used here (see Fig. 1). Figure 5 shows the measured horizontal beam profiles. The profile shown by the black color was taken in the injection dump mode (a), and thus H^- component is only seen. The other profiles were taken in the circulating mode (b), where the thinner the foil, the larger the H^0 yield and for a foil of 52 μg/cm^2 (red), some un-stripped H^- (expected about 1.7%) fraction can also be seen. Normalizing the H^0 and H^- (if any) yields measured in the former mode (a) by the H^- yield measured in the later mode (b), gives each charge fraction. The H^+ charge fraction, which is injected into the ring can then easily be known. The profile shown by the blue color was taken by the newly installed HBC foil of 210 μg/cm^2. As expected, there exists H^0 yield only and no H^- yield at all. The H^0 fraction was found to be 0.31±0.035% and thus the foil thickness was calculated to be 208±3.4 μg/cm^2 [5].

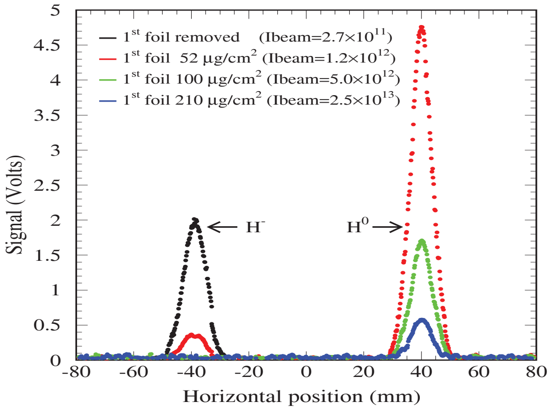

Figure 5: Simultaneous and separate measurement of each H^0 and H^- waste beam profile by the MWPM7 so as to know each fraction.

ONLINE MONITORING

We have started using H0CT as an online monitor for the waste beam since run33 in 2010. The beam power to the MLF was 120 kW. Figure 6 (bottom) shows a trend of the H0CT signal for that run. In order to reduce circulating beam hitting on foil, its position was optimized as shown in the top. The injected H^- beam measured by the SCT is also shown. The waste beam fraction was about 0.4% and there was no significant change throughout the run.

However, in order to reduce foil scattering beam loss we prepared primary stripper foils with much smaller vertical sizes. Namely, two foils with dimensions of 110×15 mm^2 and 110×20 mm^2 were installed. The circulating beam

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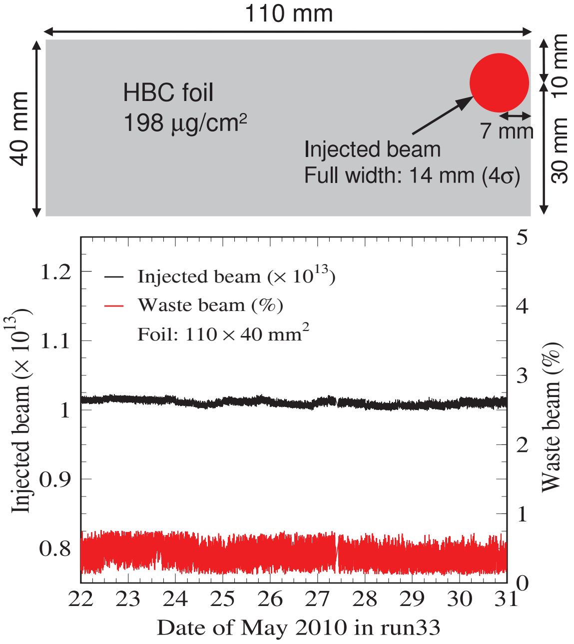

Figure 6: A trend of the H0CT signal (bottom) for about a week taken during RCS user operation for the MLF in run 33. The foil positioning with respect to the injected beam is shown in the top. The waste beam at the H0 dump was as expected of 0.4% and there was no significant change of the quantity throughout the run.

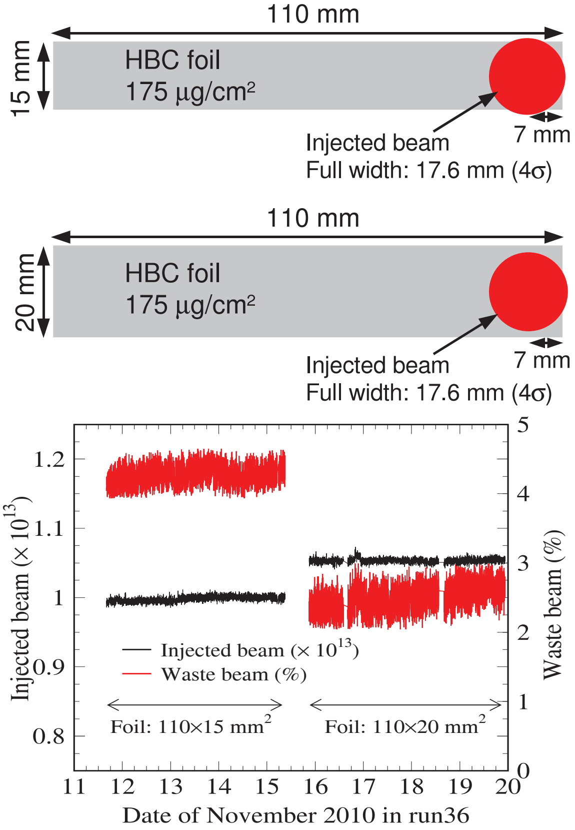

Figure 7: Trend of the H0CT signal (bottom) in run 36 with two new smaller vertical foil sizes. The injected beam profile was much wider than usual and that caused tail part of the beam miss hitting the foil (top). The waste beam was thus found to be much higher than expected.

orbit in the horizontal direction gradually goes away from the foil during transverse injection painting and thus vertical size of the foil is the main concern [3, 11]. These new foils were used in run 36. Fig. 7 shows a trend of the H0CT (bottom) for two cycles of RCS operation with the same beam power of 120 kW. A sketch of each foil with injected beam is shown at the top. Due to insufficient tuning, the transverse profile of the Linac beam was much wider than usual and thus a significant amount of tail part of the injected beam missed hitting the foil. As a result, starting with a vertical size of 15 mm, the waste beam was measured to be more than 4.0%, an order higher as compared to the expectation as well to that measured in run 33 (Fig. 6). The foil was then changed to a vertical size of 20 mm. Naturally, waste beam was greatly reduced but it was still about 2.5%. These two foils were with relatively lower thickness of 175 μg/cm^2 and thus H^0 component was calculated to be about 1% [5]. The un-stripped H$^-$ component are the remaining about 3% and 1.5 % with the vertical foil size of 15 mm and 20 mm, respectively. The trend of the waste beam however was stable during the each cycle.

The latest online data was taken during the post earthquake last 4 months operation in 2012 (run42 and 43) with a new foil of 210 μg/cm^2. The beam power to the MLF was 200 kW but it was increased to nearly 300 kW for the last 3 days before summer shutdown. Unfortunately, H0CT data could not be taken for the later part. The new foil was with a vertical size of 40 mm and started using in early March, 2012. However, due to several troubles mainly in the Linac, a stable operation was started in the middle of April. Here also the injected beam profile, especially in the vertical direction was still much wider. As a result, we did not set any vertical offset of the foil (it was 10 mm in run 33, see Fig. 6). Figure 8 shows a trend of the H0CT signal. The waste beam was as expected of about 0.3% and there was no sign of foil degradation even after 4 months operation.

Aiming for a quantitative estimation of the foil degradation, data was taken by the MWPM7 several times during 4 months operation. The purpose was to know the partially stripped H^0 and un-stripped H$^-$ fractions, separately. The waste beam profiles measured 6 times. The measured profiles and the corresponding calculated foil thickness are shown in the top and bottom of Fig. 9, respectively. Detail analysis of the present data reveals two important features: First, the H^0 yield is found to decreased slightly in the beginning but remains constant afterwords until the end. That means the foil thickness get increased slightly in the beginning but then remained the same until the end. Second, there was no observable un-stripped H$^-$ component of the waste beam and thus no indication of pinhole formation in the foil even after a total irradiation of 2.7×10^{21} injected H$^-$ beam itself. The H^0 fraction from the H^0 profile was estimated for each measurement so as to calculate the foil

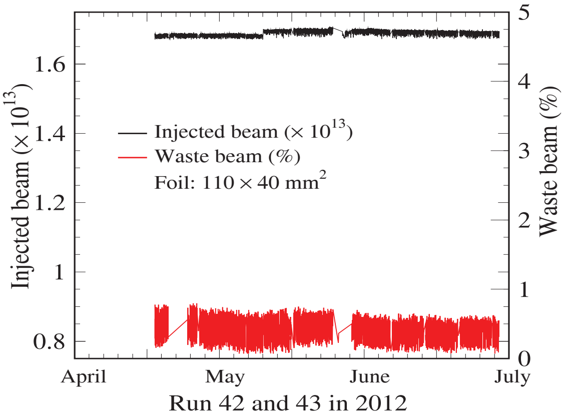

Figure 8: Trend of the H0CT signal with a new foil of 210 μg/cm^2 in the latest 4 months operation of the RCS. The waste beam was as expected of about 0.3% and there was no sign of foil degradation.

thickness. The thickness in the beginning was found to be 208±3.4 μg/cm^2 and was thus consistent with expectation.

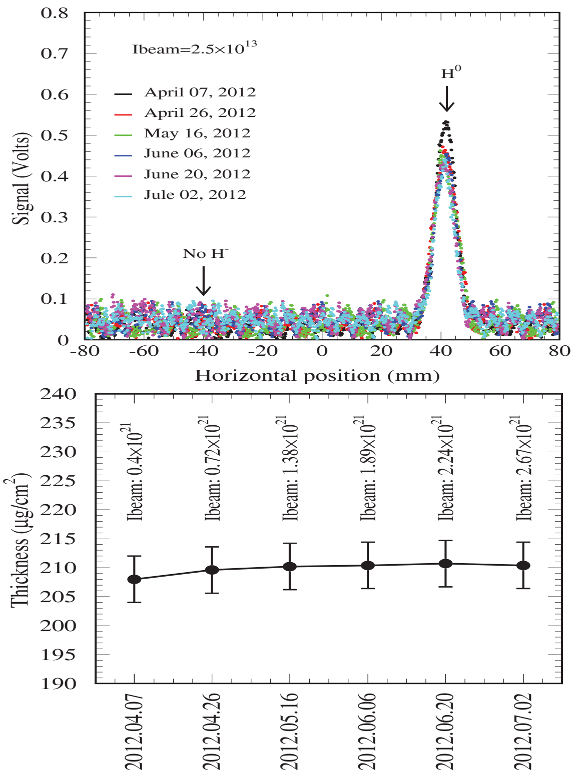

Figure 9: Waste beam profiles measured by the MWPM7 (top) and calculated foil thickness (bottom) for corresponding measurement during 4 months operation. Foil thickness was found to be increased about 1% in the beginning but remained almost unchanged in later months. However, there was no H^- yield and thus no indication of pinhole formation in the foil so far.

However, an increasing trend of the foil thickness ($\sim$1%) in the earlier period is interesting and there might have several reasons behind it. One may consider a foil shrinkage and deformation due to beam irradiation but those may not enough in order explain the whole. As a result, there might have other processes involved. We will continue using the same foil for the upcoming RCS operation with a beam power of 300 kW. Further new data might provide us more precise and valuable information.

SUMMARY

The FFT analysis of the raw signal measured by a CT made it possible to measure even only a 0.4% of the waste beam with good accuracy so as to use it successfully for online monitoring during RCS operation. It is also used for optimizing foil parameters during RCS beam studies. Explicit measurement of each component of the waste beam profiles by the MWPM7 was very useful for more detail analysis of the foil degradation. Foil has a certain lifetime and usually lifetime goes shorter with higher beam power, but a foil might have degradation such as foil thinning, 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 high power operation. It may provide useful information for further deep understanding of the foil breaking mechanism too.

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