# SYSTEMATIC BEAM LOSS STUDY DUE TO THE FOIL SCATTERING AT THE 3-GeV RCS OF J-PARC

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*Abstract*

The beam loss caused by the nuclear scattering together with the multiple Coulomb scattering at the main stripping foil is one of the primary concern in the RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex). A part of such beam loss becomes uncontrollable and is the dominant one from any other sources in the injection area. In order to have a realistic understanding, a systematic study with both experiment and simulation has been carried out recently. A total of seven foils within a thickness range of around 100 $\sim$ 600 $\mu$g/cm$^2$ were used including a designed one with a thickness of 200 $\mu$g/cm$^2$. The measured data were found to be consistent with simulation done almost exactly with the same experimental condition. A detail and realistic understanding through such studies become very useful in optimizing size and thickness of the stripping foil in connection with RCS power ramp-up scenario at the present injection energy of 181 MeV and also for the near future upgrade with 400 MeV.

## INTRODUCTION

The RCS of the J-PARC is already in a full operation stage and delivering a stable beam of more than 100 kW to the downstream facilities [1]. At present the injection and extraction energy are 0.181 and 3 GeV, respectively. However, the injection energy will be upgraded soon to the design energy of 0.4 GeV in order to achieve the design output goal of 1 MW beam power at the same extraction energy of 3 GeV [2].

In order to increase the number of circulating proton beam, RCS utilizes the multi-turn $H^-$ charge-exchange injection technique during the injection period of 0.5 ms [2]. The incoming $H^-$ beams from Linac are converted to proton beams by using a stripping foil placed in the middle of four closed bump magnets named as shift bump. There are also four horizontal and two vertical paint bump magnets for painting in the transverse plane. Due to the multi-turn charge-exchange injection, RCS has several sources of the uncontrolled beam losses especially, in the injection area. Among which the beam loss caused by the nuclear scattering together with the large angle multiple Coulomb scattering due to the both injected and circulating beam hitting the charge-exchange foil is the dominant one. The scattered particles with large angular distribution are promptly lost near the injection region resulting an uncontrolled beam loss, which increases as a function of the average foil hit by the circulating beam. For hands-on-maintenance, the design criteria of RCS was set to keep the uncontrolled beam loss less than 1 Watt/meter. In order to realize such a strict condition, the RCS was designed to perform a painting injection in both transverse and longitudinal planes [2, 3]. By reducing the space charge effect to some extent, the circulating beam hitting the stripping foil can also be greatly reduced through a phase space painting injection in the transverse plane. A large fraction of the uncontrolled beam loss caused by the foil scattering can thus eventually be reduced.

Aiming for understanding such a uncontrolled beam loss, recently we have started a detail investigation with both experiment and simulation. At this present stage we have tried to study first the total beam loss that connected to the foil scattering. For this purpose we made a systematic study by using seven stripping foils within a thickness range of around 100 $\sim$ 600 $\mu$g/cm$^2$. All of them were HBC (hybrid type boron-mixed carbon) foils made by Sugai group [4], where one of them was made and installed in the earlier stage of RCS beam commissioning. For the present 181 MeV injection, design foil thickness is 200 $\mu$g/cm$^2$ with a stripping efficiency of around 99.6%. A detail and realistic simulation tool has also been constructed as explained in the next section, where the simulated results were found to be consistent with experimental ones. Such a detail and realistic understanding from the present study is very important for the RCS operation strategy with the existing injection system through optimizing foil size and thickness and thus can be extended in desiging the stripping foil for the 400 MeV injection in near future.

## EXPERIMENTAL SETUP AND THE SIMULATION TECHNIQUE

The experiment was done with a injection beam energy of 181 MeV. In order to reduce any effect on the beam other than foil scattering, a peak current of the Linac beam was set as low as 5 mA, two bunches from the Linac having a pulse length as short as 100 $\mu$s (47 turns) with a chopping width of 560 ns were injected into the RCS. The RCS was in the 3 GeV acceleration mode with a repetition rate of 1 Hz, where the so-called center injection were performed (no painting bump magnets were excited and thus the injection beam was always at the center of the phase space of the circulating beam). The beam power at the 3 GeV when operating with 25 Hz with the present beam condition becomes around 20 kW and is only about 2% of the RCS design power of 1 MW. Figure 1 shows a demonstration

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of the closed orbit shift bump pattern and timing of the injected beam. In order to measure the beam loss with good accuracy, circulating beam hitting time on foil was intentionally incresed by keeping the shift bump constant at-top for further 420 ms even after the injection. Fig. 2 shows a typical stripping foil and the injection beam positioning set for the present study. All the foils were almost with a same dimension of 110 mm(H) $\times$ 40 mm(V). The injected beam center to the foil edge was kept 13 mm in the horizontal direction, whereas no offset in the vertical direction. The average foil hit was calculated to be around 250, which is more than one order of magnitude higher as compared to the normal operation mainly because of the present shift bump pattern. The average thickness of each foil was 92, 196, 260, 288, 392, 487 and 634 $\mu$g/cm$^2$ with an error of about 10 % [5]. As mentioned before, the 3rd one here with a thickness of 260 $\mu$g/cm$^2$ was made and installed in the earlier stage of the RCS beam commissioning and we have tried to investigate its thickness too in this experiment.

As for the simulation technique, it is basically the same as reported earlier [6]. The simulation tool GEANT3 for the scattering part and the SAD (Strategic Accelerator Design) for the tracking part are used together. Recently we have improved the simulation technique in order to adopt a large number of macro particles so as to make a reliable estimation of the beam loss even as a function of time and space within a reasonable CPU time. It can now give a reliable loss distribution in turn-by-turn with a very detail information of beam lost points throughout the ring. As a result, a realistic beam loss profile as a function of time and place as in the real situation can then be obtained. A realistic lattice with all updated parameters is prepared and it can automatically perform the real injection process taking into account proper edge effect of the time dependent magnetic field of the bump magnets. For each turns it identifies events hitting the stripping foil and later in the primary collimator and calculate the scattered particles distribution for those events using GEANT3, and then track all together in the ring by using SAD. Injection beam profiles in both horizontal and vertical planes were made by using Gaussian functions, where the measured Twiss parameters and the emittance (5 $\pi$ mm mrad with 4$\sigma$ cut) of the Linac beam at the RCS injection point were used. A number of $100\times10^3$ macro particles in each injection turn were used and thus those were a total of $4700\times10^3$ at the end of injection period. For simplicity at this stage, the target material in the simulation was used as carbon for all cases as there was only a 20% of boron admixture out of the rest 80% carbon in the foil and atomic weight of boron is very close to that of carbon. Furthermore, no acceleration process and no space charge effect were considered in the simulation. Those were because the experimental data for the 1st msec ($\sim$ 500 turns) out of the full 20 msec ($\sim$ 15000 turns) was used for the present study, where almost no acceleration of the beam occured. Furthermore, the experiment was done with a very low intensity and thus the space charge effect can be ignored in the first approximation.

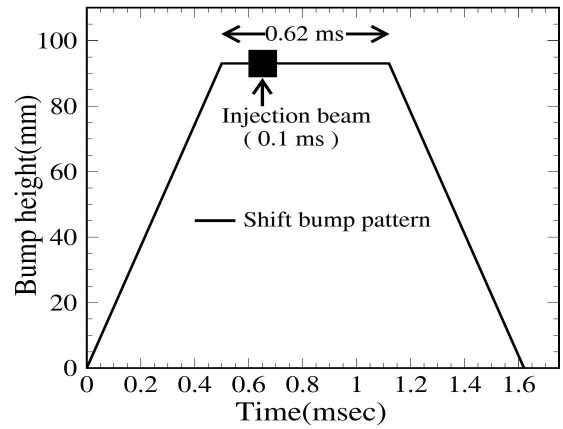


Figure 1: Shift bump pattern and the injection beam timing set for the present study. In order to measure the beam loss with good accuracy, the circulating beam hitting time on foil was intentionally increased by keeping the shift bump constant at-top for further 420 ms after the injection.

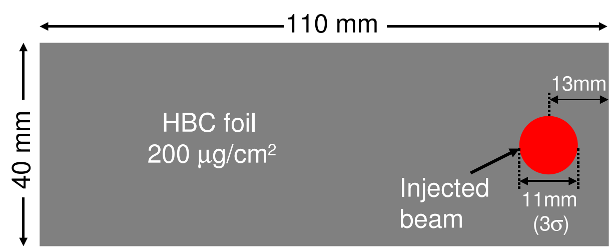


Figure 2: Typical stripping foil size and thickness in RCS. Foil edge to the injection beam center was kept 13 mm for the present study.

## RESULTS AND DISCUSSION

In the experiment, circulating beam current was measured turn-by-turn by using a WCM (Wall Current Monitor) placed in the 1st arc section of the RCS ring. The data was taken by an oscilloscope with an average of 16 shots for each foil and turn-by-turn beam survival rate after the accumulation of all charges (at the end of injection) was then obtained through off-line analysis. Figure 3 shows a comparison of the measured data to the simulated result. The comparison done here for the beam survival rate obtained at the end of 500 turns. The solid circles are the experimental data obtained with six newly installed HBC foils. Naturally beam survival rate decreases as target thickness increases and almost linear as a function of the target thickness within the present range. The solid line is a linear fit of the experimental data using which the real thickness of the early installed HBC foil is obtained to be 318 $\mu$g/cm$^2$, against the known thickness of 260 $\mu$g/cm$^2$ as shown by an empty square symbol. This foil was made earlier and replaced by the day1 foil in the early stage of RCS beam commissioning. Unfortunately, there might have any unexpected error in the thickness measurement during preparation, resulting a bit inconsistency with the direct measurement by using beam [5]. The simulated results are shown by empty circles and found to be quite good in agreement for the most cases.

The turn-by-turn beam survival rates are also compared as shown for two typical cases in Fig. 4. Due to the low intensity of the circulating beam and the large noise level, the WCM data shows rather large fluctuation but the overall trend throughout 500 turns for both cases are found to be consistent with each other.

Although a minor assumption concerning the target material, no acceleration process and no space charge effect are considered in the simulation, the overall comparison to the experimental results are quite satisfactory. Effects of such factors might be negligible for the present experimental condition. In the normal operation of RCS, circulating beam hitting time on target is more than one order lower as compared to the present setting and thus the total beam loss even with 1 MW operation is within very acceptable limit. However, a fraction of it becomes uncontrollable and lost downstream of the injection point before reaching to the secondary collimator. If unfortunately, such a loss localizes in a narrow region, even a very small fraction of it then sets a strong limitation against the high power operation [7]. As the present simulation approach gives a very detail information of the beam loss as a function of time and place, through further study it is thus possible to investigate not only the total beam loss but also a very small fraction of the uncontrolled beam loss in a realistic way so as to take measures in terms of the foil size and thickness or any other, if necessary.

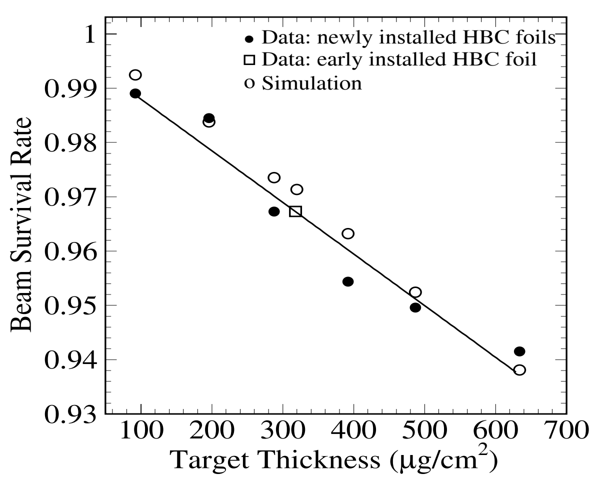


Figure 3: A comparison of the measured and simulated beam survival rate at the end of 500 turns are shown. Thickness of the earlier installed HBC foil is determined by using a linear fitting of the data measured with six newly installed HBC foils together with the data measured with that particular foil as shown by an empty square symbol.

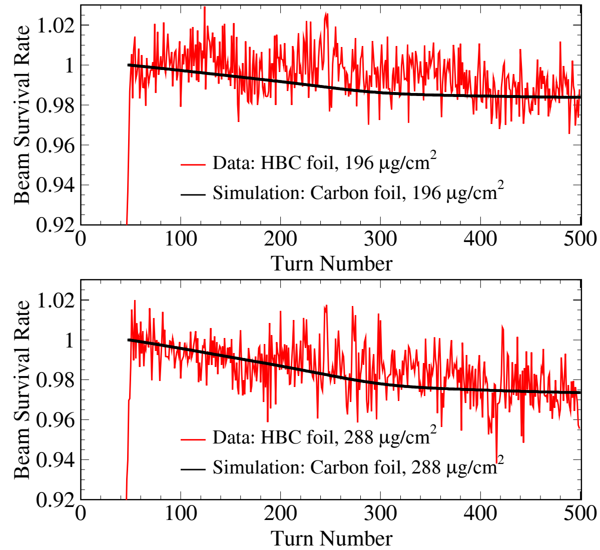


Figure 4: Comparisons of the measured and simulated turn-by-turn beam survival rates are shown for two targets with different thickness. The global shapes are found to be consistent with each other.

## SUMMARY

Through the present study we have been able to have a systematic understanding of the beam loss mechanism connected to the foil scattering. A realistic simulation tool as a combination of GEANT3 and SAD has been constructed, which can handle comparatively a large number of macro particle in a reasonable CPU time and give an accurate and detail results. The simulation results are found to be consistent with experimental data and it would be thus very useful for a realistic estimation of the beam loss caused by the foil scattering including the uncontrolled ones. As a result, necessary steps can be taken in order to control such a loss by optimizing size and thickness of the stripping foil together with other measures, if necessary in connection with RCS power ramp-up scenario with the present injection energy of 181 MeV. Similarly, it can be extended in designing the stripping foil for the near future upgrade with 400 MeV injection and in addition, such a systematic study with both experiment and simulation can be a good example for the similar existing and proposing projects.

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