BEAM LOSS ISSUES CONNECTED TO THE FOIL SCATTERING: ESTIMATION VS. MEASUREMENT AT THE RCS OF J-PARC

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Abstract

We have started a detail investigation of the beam loss issues connected to the nuclear scattering together with the multiple Coulomb scattering at the charge-exchange foil during the multi-turn injection in the Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC). The present work is an extension of our earlier studies on these issues, where almost all realistic parameters including injection beam profiles obtained through the beam commissioning of the RCS have been introduced in the simulation and some experimental data on the beam loss were also taken for comparison. Although the final goal of this study is to make a systematic analysis even with using many simulation models, preliminary result obtained in the first stage is reported in this paper.

INTRODUCTION

The Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) acts as an injector to the main ring (MR) as well as delivers a high power beam to the the spallation neutron target in the Material and Life Science Facility (MLF) [1]. The RCS has a three-fold symmetric lattice with a circumference of 348.333 meter. Each super-period comprised two 3-DOFO arc modules with missing bends and a 3-DOFO insertion. The three insertions are named I, E and R and are dispersion free. The injection and the transverse collimation systems are located in the I insertion, the extraction system in the E insertion and the RF cavities are in the R insertion. The H^- injection system occupies about one-third of the I insertion, while the collimation system occupies the rest.

Figure 1 shows the general layout of the RCS charge-exchange injection system. RCS utilizes the multi-turn H^- charge-exchange injection technique in order to increase the number of circulating proton beam, and thus finally to achieve a high power output beam of 1 MW at the extraction energy of 3 GeV. The incoming H^- beams from Linac are converted to proton beams with a charge-exchange stripping foil placed in the middle of four closed bump magnets named as shift bump (SB1∼4). The other four bump magnets (PBH1∼4) are known as horizontal paint bump magnets, with the first two being located upstream of the QFL and the other two downstream of the QDL. Painting in the vertical direction are performed with two vertical paint bump magnets (PBV1 and PBV2) placed in the L3BT (Linac-to-3GeV-Beam-Transport) line.

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Like any other H^- charge-exchange injection system, RCS also has a big issue of well controlling the beam loss at the injection region. There are several sources of the uncontrolled beam loss in the RCS injection region. Among which the beam loss caused by the nuclear scattering together with the multiple Coulomb scattering due to the circulating beam hitting the charge-exchange foil is the dominant one [2, 3]. 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 have the uncontrolled beam loss of 1 Watt/meter. In order to realize such a strict condition, the RCS was designed to perform a painting injection in both horizontal and vertical planes [1, 4]. In addition of reducing the space charge effect, the circulating beam hitting the charge-exchange foil can also be greatly reduced through a phase space painting injection in the transverse direction. A large fraction of the uncontrolled beam loss caused by the foil scattering can thus eventually be reduced.

The present work is basically an extension of our earlier studies on the beam loss estimation connected to the foil scattering. In our earlier series of reports, we presented some results of such beam losses estimated with different simulation models and approaches [2, 3, 5]. However, in those simulations there were some limitations in terms of a realistic injection process taking into account the edge focusing effect of the time dependent magnetic field of the bump magnets, a realistic injection beam profiles, etc. Recently we have been able to overcome these limitations and thus started a detail and more realistic investigation of the beam loss connected to the foil scattering. Some experimental data on the beam loss related to these issue were taken so as to compare that with the simulation results. The final goal of this study is to make a systematic study even with using several simulation tools but only a preliminary result is reported in this paper. A detail understanding from this study would be very useful to guide RCS operation strategy with the existing injection system and finally for a fair upgrade of the RCS injection system for the 400 MeV injection in near future.

SIMULATION APPROACH AND THE EXPERIMENTAL CONDITION

At the present stage of our updated simulation approach, the simulation tool GEANT3 [6] for the scattering part and the SAD (Strategic Accelerator Design) [7] for the track-

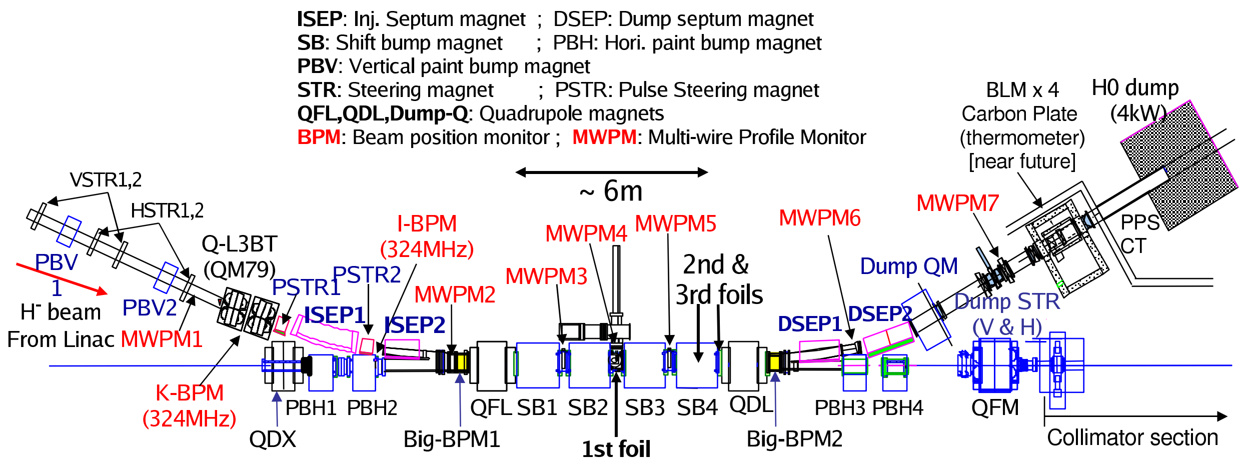

Figure 1: A schematic view of RCS injection and successive H0 dump line. A brief definition of each elements are provided at the top of the figure.

ing part are used together. The reliability of GEANT3 for the present purpose was found to be quite satisfactory as demonstrated in our earlier report [3], while SAD has also been proved to be powerful and useful in designs, simulations, commissioning and improvement of many accelerator complex. Concerning the present simulation tools and approach, they are basically the same as we used earlier [3]. However, we have made numerous improvements as mentioned in the later part of the previous section. In addition, one more significant improvement is that we have succeeded to make a very efficient simulation in term of CPU time by an automated shell script routine. The present routine can automatically take into account the real injection process with proper edge effect of the time dependent magnetic field of the bump magnets. It can identify events hitting in the foil and later in the primary collimator and calculate the scattered particles distribution for those events using GEANT3 and then track in the ring using SAD. A realistic lattice with all update parameters is prepared for the tracking, where the tracking proceeds from one element to the next throughout the ring. If once in the beginning, the number of injection turns, field pattern of the bump magnets and the maximum number of turns are defined, the program proceeds automatically. For each turn it gives loss point of each lost particle including the phase space information at that point. As a result, a detail of the beam loss profile as a function of time and place as in the real situation can then be obtained using the present simulation technique. At the present stage, we consider no acceleration process as well as the space charge effect in the simulation for simplicity. The experimental data also during the injection period is used, where basically no acceleration of the beam occurs. In fact, the beam loss connected to the foil scattering occurs mainly during the injection period and continue little more depending on the injection process, decay pattern of the magnetic field of the bump magnets and the foil position.

As for the experimental condition, the injection beam energy was 181 MeV with a peak current of 15 mA. Two bunches from the Linac having a pulse length of 500 μs (235 turns) with a chopping width of 420 ns were injected into the RCS. The RCS was in the 3 GeV acceleration mode with a repetition rate of 25Hz, 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). A total number of 1.77×10^{13} particles per pulse in average after the extraction were detected using a CT near the extraction dump and that corresponded to a output beam power of 210 kW. The circulating beam current signal was picked up by a Wall Current Monitor (WCM) placed in the first arc section and from which the turn-by-turn beam survival rate was extracted.

In the simulation, injection beam profiles in both horizontal and vertical planes were made using Gaussian functions, where the measured Twiss parameters and the emittance (5 π mm mrad with 4σ cut) of the Linac beam at the RCS charge-exchange foil were used. A number of 1×10^4 macro particles in each injection turn were used and thus those were a total of 235×10^4 at the end of injection period. In order to increase the event rate in the simulation, the thickness of the charge-exchange carbon foil was considered to be 2.6 mg/cm^2, which was 10 times thicker than used in reality. Although may not fair but at this preliminary stage the simulated result was divided by 10 so as to compare with the experimental data.

RESULTS AND DISCUSSIONS

The comparison of the simulation result with the experimental data done here at the end of the injection period (235 turns). Figure 2 shows the simulated average foil hit of the circulating beam at the charge-exchange foil as a function of turn numbers. The average foil hit means the number of times a particle hit the foil during circulation including the injection beam. Although a center injection was performed, a large fraction of the circulating beam did not hit the foil because of the mismatch injection. As a result, the average foil hit was found to comparatively reduced from the linear increasing in the beginning and almost saturated near the end of the injection period. At the end of injection, it was found to be about 80, which was even 4 times higher as compared to that of using a design painting injection.

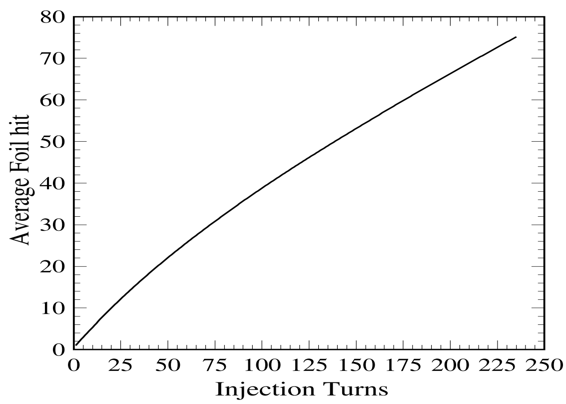

Figure 2: Average foil hit during the injection period as found in the present simulation.

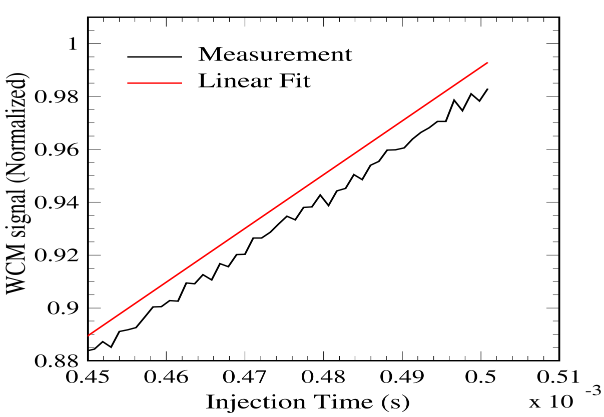

Figure 3: Normalized circulating beam current (black line) during accumulation in the injection period made from the data taken with a WCM and shown near the end of the injection. The red line is an extrapolated one drawn by using the fitting result (with a first order polynomial) of the measured data in the beginning of the accumulation for about 50μs (24 turns). The difference of the black and red lines give the beam loss rate at any point in the time scale.

The experimental data taken by WCM and highlighted near the end of the injection period is shown in Figure 3. The horizontal axis is the time in second and vertical axis is the normalized beam current during accumulation. In order to extract the beam loss rate during the injection period, experimental data (black line) in the beginning for about 50 μs (24 turns) was fitted with a first order polynomial function and using the fitting result, a linear line (red line) was extrapolated until the end. As in such an experimental condition, the beam loss increases as a function of time and the survival rate decreases from the linear increasing, experimental data just after the injection was thus fitted for this purpose. The difference of the red and black lines at any point in the time scale gave the beam loss rate at that point and was found to be 1% at the end of the injection. In the simulation, a total of 22×10^4 particles were found to be lost during the injection period of 235 turns, from which the total beam loss was calculated to be $\frac{22\times10^4}{235\times10^4}$ = 9.4% and normmalizing by the target thickness ($\frac{1}{10}$), the final result became 0.94%. The simulation result thus found to be very consistent with the experimental result, although more detail simulation with much larger number of macro particles using the realistic target thickness should be performed. The error of the experimental data should also be estimated. Further simulation is in progress with comparatively large number of macro particles, from which precise profiles of the loss as a function of time and place can then be obtained. A comparison of such detail information to the experimental result finally would be very useful in handling the beam loss, especially the uncontrolled one caused by the nuclear scattering together with the large angle multiple Coulomb scattering at the charge-exchange foil.

SUMMARY

We have been able to make an efficient combination of two simulation tools (GEANT3 and SAD), using which detail and systematic studies of the beam loss caused by the nuclear scattering together with the multiple Coulomb scattering at the charge-exchange foil can be performed. Taking into account all realistic parameters the simulation can automatically proceed with realistic injection process for a precise estimation of the beam loss profile as a function of time and place. The simulation speed also becomes about one order magnitude faster from our earlier technique. As a first step of our new developed approach, a preliminary result comparing with the experimental data are present here and found to agreed well, where the detail study is underway. In the next step of our present approach, combination of other simulation routines for the tracking part (in stead of SAD at present) precisely taking into account the space charge effect as well as the acceleration process are also in consideration.

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