REALISTIC BEAM LOSS ESTIMATION FROM THE NUCLEAR SCATTERING AT THE RCS CHARGE-EXCHANGE FOIL

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Abstract

The RCS(rapid cycling synchrotron) is the heart of J-PARC(Japan Proton Accelerator Research Complex) project, which acts as an injector to the MR(main ring) as well as a high power beam for the spallation neutron source. The expected goal of the project is thus strongly depends on the well performance of RCS, where beam losses might be one of the strong barrier in order to realize the goal for such a high intensity accelerator. A very precise estimation of the beam losses and their cures is thus a very important issue at this stage, when the project is under construction. In this paper, we focus on the realistic estimation of the beam loss caused by the nuclear scattering together with multiple coulomb scattering at the charge-exchange foil. The simulation program SAD for tracking the particles in the ring and the GEANT to simulate the particles distribution taking into account the nuclear and multiple scattering at the charge-exchange foil were used together for the present purpose.

INTRODUCTION

Fig. 1 shows the general layout of the RCS. The RCS has a three-fold symmetric lattice with circumference of 348.333 meter, where each super-period comprising two 3-DOFO arc modules with missing bends and a 3-DOFO insertion. The three insertions are named as I, E and R and are dispersion free. The injection and the collimation systems are in the I insertion, while the extraction and the RF cavities are in the E and R insertions, respectively. The H^- injection system occupies the 1st and a quarter of the 2nd cell, where the collimation system occupies the three quarter of the 2nd cell and the 3rd cell. The main issue of designing the RCS is to control and localize the beam loss as well as to minimize the uncontrolled beam losses as much as possible. The expected goal of the RCS is to achieve a output power of 1MW with 8.3×10^{13} protons per pulse at a repetition rate of 25Hz, where the injection and extraction energies are 0.4 and 3.0 GeV, respectively. However, at the first stage of the operation, the injection energy is chosen to be 181 MeV with an expected output power of 0.6 MW.

The present work concerns about the beam loss caused by the nuclear scattering together with the multiple coulomb scattering at the charge-exchange foil. The charge-exchange(stripping) foil is used to strip the incoming H^- Linac beam to H^+ so as to accelerator in the ring, which is located in the middle of four horizontal shift bump magnets (see fig. 1) . In order to mitigate the space-charge effect, beam density can be controlled by multi turn painting injection (500 μsec, about 235 turns) in the transverse direction and an RF operation mode in the longitudinal direction. Due to the multi turn injection, circulating beam hitting the stripping foil during the injection process cannot be avoided and was estimated to be about 20 times in average, by the ASSICM simulation code[1]. The circulating beam will then be scattered with some probability due to the nuclear scattering together with the multiple coulomb scattering. The scattered particles with large angular distribution will hit the beam pipe promptly resulting an uncontrolled beam loss. For the particles with small scattering angles will move forward and can be collected in the collimator section. The scattered particles distribution is a function the particle energy and the foil thickness. The foil thickness is thus an important issue in order to keep its stripping efficiency as high as possible with less scattering effect. At present the stripping carbon foil thickness is considered to be 200 μgm/cm^2 for 181 MeV injection (290 μgm/cm^2 for 400 MeV injection).

In RCS, the expected beam loss is 1 Watt/meter except the collimator area for hands-on-maintenance, where injection area is the most complicated one due to the above factors. A very precise estimation of the beam loss as well as the loss points in the ring, especially from the above factors is the main concern of the present work as it has not been estimated in detail yet. The scattered particles which will be lost before reaching to the collimator is defined as uncontrolled beam loss. There are also several other sources of the uncontrolled beam losses in the injection area like, Lorentz stripping of the H^- before reaching the foil and the H^0(partially stripped H^-, $H^-\rightarrow H^0$, 0.4% with 181 MeV) excited states loss which are comparatively lower as compared to the loss from the nuclear scattering effect and those already estimated and reported elsewhere[2].

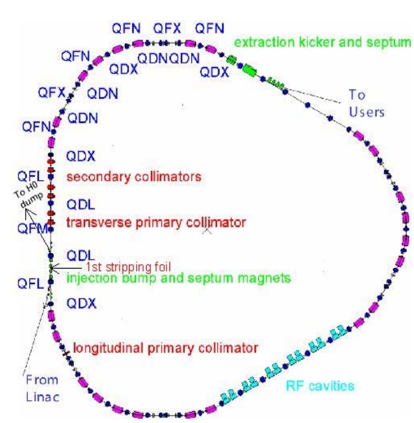

Figure 1: General layout of RCS.

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SIMULATION TOOLS AND APPROACH

As mentioned earlier, we used GEANT[3] simulation code together with SAD(Strategic Accelerator Design)[4] simulation program for the present purpose. The GEANT was used to simulate the particles distribution at the stripping foil, taking into account the nuclear elastic and inelastic scattering as well as the multiple scattering effect and then track them in the ring using SAD in order to know the loss point. At first, the reliability of GEANT was checked by simulating the nuclear elastic(p,p) and inelastic(p,n) reactions in the carbon foil. The total cross section(σ_T) from the simulation result was found to be 0.380 barn for the 181 MeV proton beam with the foil thickness of 200 μgm/cm^2, which was a very good agreement to the experimental data[5]. We also checked the total cross section for the 400 MeV injection using the foil thickness of 290 μgm/cm^2 and found a very similar result. The angular distribution of the differential cross section simulated by GEANT was also compared to the experimental data[6] and was found to reproduce fairly well.

As for the multiple coulomb scattering, the rms(root mean square) scattering angle defined in the text books[7, 8] is compared to the scattering angle simulated by the GEANT, which again was very consistent and promising as explained below. The mean square scattering angle taking into account the multiple coulomb scattering effect is described by the following equation according to ref.[7]

$$\langle \Theta^2 \rangle \simeq 4\pi N \left(\frac{2zZe^2}{pv} \right)^2 ln(204Z^{-1/3})t \qquad (1)$$

where, N is the number of atoms per unit volume of the target, z and Z are the charge of the projectile and the target, respectively, e the electronic charge, p and v the momentum and velocity, respectively, of the projectile and t the target thickness. Solving the equation 1 for a proton beam of 181 MeV traversing a 0.001766 cm thick ^{12}C target, gives the rms scattering angle ($\sqrt{\langle \Theta^2 \rangle}$) of 0.03275°, where the GEANT also gave a very similar value(0.03281°). It was also found to be very consistent with the incident energy of 400 MeV. The another issue may be the energy-loss and the energy-struggling of the incident particles(protons) to the target(foil), although may be negligible as the foil is already very thin. We have calculated numerically and compared to GEANT output and found they were consistent. The energy-loss($\Delta p/p$) for the 181 MeV beam passing through the foil 20 times of 200 μgm/cm^2 thick was found to be 7 $\times 10^{-3}$%, whereas the energy-struggling was about 0.06%(rms width) and the corresponding loss was very negligible.

The GEANT was then used to simulate the realistic distribution of the particles taking into account the nuclear and multiple scattering effect at the charge-exchange foil. The scattered particles simulated by GEANT than track by SAD, where the latest RCS lattice parameter was used. The real apertures of all bending and quadrupole magnets as well as the aperture of the transverse primary collimator were set as designed. The RF system was used as a stationary mode(no acceleration) and there was no space-charge force was called. The RCS has a physical aperture of 486π.mm.mrad, where the collimator aperture is designed to be 324π.mm.mrad As for the initial beam profile, a uniform distribution having an emittance of 216π.mm.mrad in both horizontal and vertical plane was used in the simulation. The nominal painting area for the RCS injection is 216π.mm.mrad. At present the simulation was done for only one operating point of the betatron tune(Q$_x$=6.68,Q$_y$=6.27). The tracking was done step by step from each element to the next and after coming back to the start point(stripping foil), again GEANT was used. After 20 turns, no more foil/GEANT was used but tracking was continued for another several ten turns when there was no loss found anywhere in the ring.

RESULTS AND DISCUSSIONS

Figure 2 shows the normalized horizontal phase space distribution of the particles at the stripping foil after 150 turns, where the nuclear and multiple scattering were considered only for the initial 20 turns. The initial beam energy was 181 MeV, where the foil thickness was 200 μgm/cm^2. The boundary of the initial distribution(216π.mm.mrad) and the collimator apperture(324π.mm.mrad) are shown by the red and blue circle, respectively. The distance from the stripping foil to the transverse primary collimator is about 14 meter and the betatron phase advance is about 90°. The particles scattered at the foil can be seen in the figure, although the lost particles are not drawn. Table 1 summarizes the number of loss particles including the loss point in the ring, where the total number of the initial particles used in the simulation was 5.031$\times$10^5. Most of the particles were found to lost in the collimator and there was not so significant number in the injection area. The names "QDL" and "QFM" in the table are both quadrapole magnets but the former one is in the injection area, whereas the later one is located just before the transverse primary collimator.

The total injection beam power is 36kW(kilo Watt) when the injection beam energy is 181 MeV, where the corresponding loss due to the nuclear and multiple scattering was found to be about 72W in total. The particles lost at the collimator is defined as the "controllable" loss but the rest are defined as the "uncontrollable" loss and was about 10W in total for the 181 MeV injection. We have also done the similar simulation for the 400 MeV injection, where the foil thickness was 290 μgm/cm^2. The total loss was found to be then about 155W, where the "uncontrollable" loss was about 24W. The contribution of the loss only due to the nuclear reaction [(p,p) and (p,n)] was also checked by turning off the multiple scattering flag in GEANT and was found to be 4.2W and 15.6W for 181 MeV and 400 MeV, respectively, where almost all of them lost at the injection area and are "uncontrollable".

From the present simulation results, it is found that the

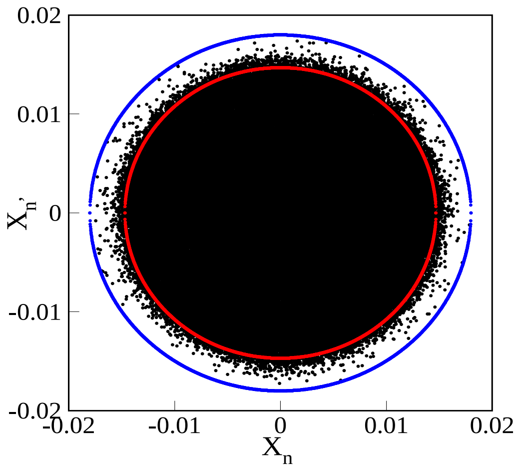

Figure 2: Normalized horizontal phase space distribution at the charge-exchange foil after 150 turns. The red circle represents the boundary of an emittance of 216π.mm.mrad(initial distribution), where the blue one is that for 324π.mm.mrad (collimator aperture). The particles scattered at the charge-exchange foil resulting an increase of the emittance can be seen in the figure. The lost particles distribution is not drawn here, which were outside of the 324π.mm.mrad boundary line.

Table 1: Summary of the loss table after 150 turns for the 181 MeV injection using the foil thickness of 200 μgm/cm^2. The average foil hitting rate was assumed to be 20, where the total number of the initial particles were 5.031×10^5

Lost Point	**Lost particles in total**	**Loss in Watt**
QDL entrance	42	3.0
QFM entrance	94	6.73
QFM exit	4	0.286
Primary Collimator	871	62.32
Total	**1011**	**72.336**

total "uncontrollable" loss, especially for the 400 MeV injection is already a significant number and crosses the realistic design of RCS(1W/m). It can be controlled by well designing the foil thickness but in the same time, the charge-exchange efficiency should also be kept in mind. The present figure of loss may be somehow acceptable as an extreme limit but several other factors(if any) may increase the loss significantly. For example, the increase of the injection beam emittance due to the non-linear field and the field errors of the magnets as well as the coupling/interference field of the adjacent magnets will increase the foil traversal/hitting rates so as to increase the beam loss. The falling time of the horizontal shift bump magnets after the painting process is finished can also be a source of increasing the foil hitting rate, if it cannot be done within the expected time. We extended the simulation assuming the foil hitting rate more than 20 times and found the loss increases significantly. As an example, if the foil hitting rate is increased by 25%, the corresponding beam loss then increases by about 39%. A more realistic simulation taking into account those factors is in progress. We also would like to adopt the real painting process (about 235 turns multi turn injection) by using the SIMPSONS and/or ORBIT simulation code so as to realize the more realistic beam losses in the ring not only from the nuclear and multiple scattering effect but with all possible sources including the space-charge force.

SUMMARY

We have estimated a realistic beam loss in the RCS caused by the nuclear scattering including the multiple coulomb scattering effect at the charge-exchange foil. The simulation tool GEANT used for the scattering part was found to reproduced very well the experimental data as well as simulated the expected distribution of the scattering angle taking into account the multiple coulomb scattering effect. For the first time the present simulation approach found to be a very good technique for the detail and precise estimation of the beam loss caused by the nuclear scattering at the charge-exchange foil. The foil thickness can be then well designed for any accelerator ring that uses the charge-exchange injection process considering the beam loss as well as its charge-exchange efficiency. In RCS, we found the beam loss caused by the nuclear scattering together with the multiple scattering was about 72W and 155W for the 181 MeV and 400 MeV injection, respectively, whereas beam loss by the nuclear scattering only was about 4.2W and 15.6W for the 181 MeV and 400 MeV injection, respectively. The present design of the RCS foil thickness may be acceptable by considering the charge-exchange efficiency. Making thiner the foil is limited by the acceptance of the H^0 dump line as the stripping efficiency goes down resulting an increase of the partially stripped H^0 beam. A more realistic estimation of the beam loss by adopting the real painting process with SIMPSONS and/or ORBIT simulation code together with the GEANT for the nuclear and multiple scattering effect is in progress.

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