PRESENT DESIGN AND CALCULATION FOR THE INJECTION-DUMP LINE OF THE RCS AT J-PARC

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Abstract

The construction of J-PARC(Japan proton accelerator research complex) is in a rapid progress, where the first beam commissioning of 3-GeV RCS(rapid cycling synchrotron) is expected to be start on May, 2007. The present work concerns the very final design as well as the calculation of the injection line until the beam dump. This includes an accurate and safe aperture list of all elements in the injection-dump line as well as an accurate estimation of the uncontrolled beam losses so as to optimize them concerning mainly the radiation issues and moreover for the hands-on maintenance.

INTRODUCTION

The RCS of J-PARC will act as an injector to the main ring as well as a high-power beam for the spallation neutron source. The expected goal of RCS is to achieve a output beam power of 1 MW with the injection and extraction energy of 0.4 and 3.0 GeV, respectively with 8.3×10^{13} protons per pulse at a repetition rate of 25 Hz [1]. However, at the first stage, the injection energy and the is chosen to be 0.181 GeV with the beam power of 0.6 MW at the extraction. The RCS has a three-fold symmetric lattice over its 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 I, E and R and are dispersion free. The injection and the collimation systems are in the I insertion, where the extraction and RF cavities are located in the E and R intersections, respectively. The H^- injection system occupies the first and a quarter of the 2nd cell, where the collimation system occupies the three quarters 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. In order to defuse the space-charge force, beam density will be controlled by utilizing the painting injection in the transverse direction and an RF operation mode in the longitudinal direction. The total length of the injection-dump line of RCS from the last quadrupole of the LINAC(L3BT) to the entrance of the beam dump is about 26 meter.

The present work concerns the very first part of the RCS, which is the injection system. As a very high beam power (1 MW at goal) with kinetic energy of 3 GeV has to be achieved at the extraction, an accurate design of the injection system is thus utmost necessary. Especially, a safe and economic design of all magnets in the injection-dump line concerning their apertures and stable operation as well. In addition, all the uncontrolled beam losses have to be minimize and localize as much as possible and moreover all loss points have to be figure out so as to optimize them for a stable operation of the ring. For the hands on maintenance a full energy loss of less than 1 W/m is required(except for the collimation area).

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RCS INJECTION SYSTEM AND THE BEAM SIZE CALCULATION

The H^- injection system of RCS comprising eight closed orbit bump magnets in the horizontal direction(HBM) and two bump magnets in the vertical direction. In addition, there are four septum magnets(ISEP1-2, DSEP1-2), four steering magnets(ISTR1-2, DSTR1-2), two big quadrupole magnets (QFL and QDL, circulating beam also passes through them) and one more focusing quadrupole(Q-DUMP) in the dump line after DSEP2 [1]

Among eight HBMs, four are the horizontal bump magnets for the charge-exchange injection. They are called as the shift bump magnets(BMC1-4), which are placed in an uninterrupted drift space between two quadrupole magnets (QFL and QDL) and have the role to form a closed bump orbit. The other four are called and the painting bump magnets(BMP1-4). First two of them are located upstream of the focusing quadrupole(QFL) and the other two are at the downstream of the defocusing quadrupole(QDL). These four bump magnets have the role to sweep the closed orbit for painting injection in the horizontal plane. In the vertical plane, two bump magnets are installed; One is the main painting magnet led by π from the foil, the other is auxiliary one to adjust the phase difference from the main painting magnet to the foil position. Painting injection in the vertical phase plane is performed by sweeping the injection angle, where both correlated and anti-correlated can be done by changing the excitation pattern of the vertical painting magnets.

The location of the self-supported long-stroke main carbon stripping foil is almost at the center of four BMC. The length and the vertical height of this foil are 105 mm and 35 mm, respectively to ensure a full acceptance of the ring(486π.mm.mrad). Two other foils are also placed at the gap and at the end of 4th BMC for the un-stripped H^0 and H^-, respectively.

The calculation for the beam envelope in the injection-dump line has been done by using the SAD(strategic Accelerator design) simulation program. A very wide range of the betatron tune for both horizontal and

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vertical(ν_x,ν_y=6.1∼6.9) was considered, where the present operating point is chosen to be at (6.68,6.27). In addition to the main injection mode(Paint inj.), another mode (center inj., for the beam commissioning) is also considered in the calculation. Useful parameters in the calculation are as follows; The incoming H^- beam from the LINAC is expected have the transverse emittance of 6π.mm.mrad with a momentum spread(Δp/p) of ±0.1%. The painting emittance in the ring is 216π.mm.mrad, which will be filled with about 250 turns H^- foil-stripping charge-exchange injection. The collimator acceptance is 324π.mm.mrad and the whole ring has a full acceptance of 486π.mm.mrad.

Figure 1 shows a schematic diagram of the painting process in RCS for both horizontal and vertical planes. The twiss parameter β at the foil for both LINAC beam and the circulating beam are the same(∼11 m), whereas the sign of α of the injection beam is opposite as compared to that of circulating beam(focusing QFL acts as a defocusing one for the H^- beam). Then the injection is so-called a mismatch type as can be seen in the figure. The incoming beam from the LINAC should be narrow as much as possible in order to reduce the foil heating probability. The center of the injection beam at the first time locates at 131 mm and -6.3 mrad in the XX' plane and 0.0 mm and -2.8 mrad in the YY' plane. These parameters are found to be a bit change when the betatron tune of the ring is changed and was taken into account in the present calculation. In the RCS injection, both correlated and anti-correlated painting process can be performed as shown by two arrows in the vertical plane. In the calculation of the beam size, the emittance of the injection beam is assumed to be 30π.mm.mrad with Δp/p=0.3% considering beam blow-up by several factors. In addition, within the present limitation of the painting magnets, about 275π.mm.mrad and 324π.mm.mrad phase-space injection in the horizontal and vertical plane, respectively, are also considered mainly for the study as well as for the beam commissioning.

Figure 2 shows the typical horizontal beam envelope with only the reference tune(6.68,6.27). The primary foil location is located at S=0. Here, only the injection beam(upto the foil) and the un-stripped H^0 and H^- beam sizes are shown by different symbols. For the un-stripped H^0 and H^- beams, 2nd and 3rd foil, respectively, will used to strip them to H^+ so as to forward to the beam dump as also treated the same was in the calculation. They have very different trajectories as can be seen in the figure and thus require a very wider apertures of all beam elements. The dump quadrupole magnet(Q-DUMP) will be use to focus the beam at the window of the beam dump. In the present calculation of the beam size, the orbit distortion, β modulation and modulation of the dispersion are taken 9 mm in total. From the present calculation of the beam size, the aperture list of all magnets and other elements in the injection-dump line are at the very final stage. The main parameters including beam sizes of the four septum magnets in the injection-dump line are presented in table 1.

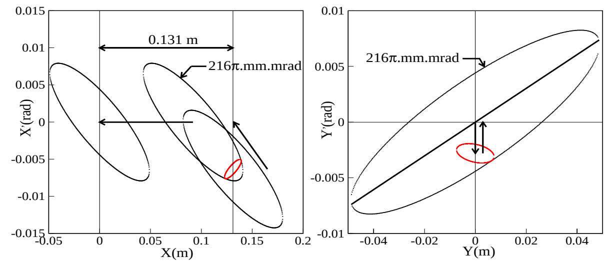

Figure 1: A demonstration of the paining process in the phase space (left: horizontal, right:vertical). The circulating beam emittance is 216π.mm.mrad, whereas the injection beam emittance is 6π.mm.mrad.

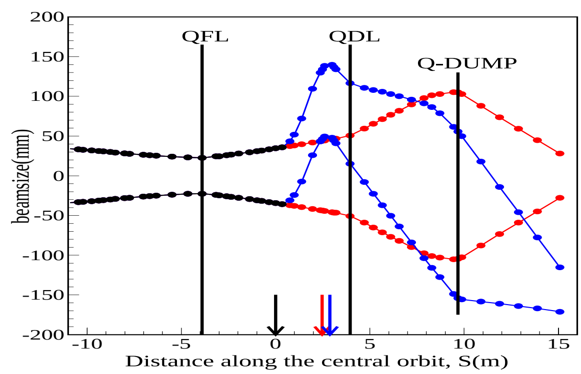

Figure 2: Typical beam envelope(horizontal) in the inj-dump line along the central orbit of the ring with the reference tune(6.68,6.27). The primary foil location is at S=0. The black circles are the incoming H^- beam, whereas the red and blue circles are the un-stripped H^0 and H^- beam, respectively, where the corresponding foil locations are shown by arrows.

ESTIMATION OF THE UNCONTROLLED BEAM LOSSES

In this section we present the estimation of the uncontrolled beam losses at the RCS injection system. As the beam loss issues are the main concerns like any accelerator ring, the injection system of RCS is designed to keep the uncontrolled beam loss to a minimum level. For example, the injection bump orbit is designed to have the full aper-

Table 1: Main parameters including the beam sizes at the four septum magnets in the injection-dump line with 181 MeV injection.

Magnet name	Length (m)	Mag. Field(B) Tesla(T)	Beam size (mm)[X×Y]
ISEP1	1.300	0.270	130×64
ISEP2	0.650	0.324	160×69
DSEP1	0.900	0.303	236×62
DSEP2	0.900	0.734	288×61

ture as the whole ring and the magnetic field is carefully chosen to prevent the premature stripping of both H^- and H^0. However, a very precise estimation of the uncontrolled beam loss is quite necessary concerning the hands-on maintenance and for a safe operation as well. Following are the several sources of the uncontrolled beam losses in their estimation in the RCS injection system:

H^- stripping loss in the Magnetic Field

When a H^- ion passing through a transverse magnetic field, the electron from it tends to detached due to an external electromagnetic field. The breakup is a probabilistic process and quantum mechanical in nature. Figure 3 shows the H^- stripping loss rate per unit meter as a function of the magnetic field. Various symbols corresponds to various energies of H^- ion as indicated in the figure. In the RCS injection system, H^- beam will pass about 5 meters through several magnets before reaching to the primary foil. The maximum magnetic field of those magnets are estimated to be 0.4 and 0.55T for 181 and 400 MeV, respectively. The beam loss because of the Lorentz stripping is then estimated to be less 1W in both cases.

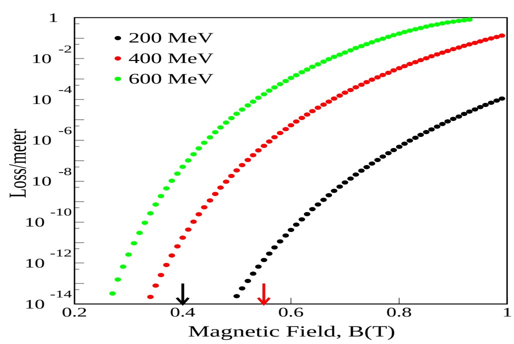

Figure 3: The Lorentz stripping loss of H^-. The maximum field setting of the the injection magnets are shown by black and red arrows for 181 MeV and 400 MeV, respectively.

H^0 excited states losses

One of the major concern of the uncontrolled beam loss in the RCS injection system comes from the excited H^0 states losses. We found that about 0.4% of the incoming H^- beam(200 MeV) leaves as neutral(H^0) passing through a 200 μg/cm^2 thick carbon foil [2] (0.3% for 400 MeV with 290 μg/cm^2). This 0.4% (145KW with 181 MeV) H^0 beam distributes according to the empirical n^{-3} law among excited states, where n represents the principal quantum number. Figure 4 shows the life time of each excited state with all sub-states in the magnetic field. The two circles in the figure represent the operation points of the bump magnets with the beam energy of 181 MeV(left,0.16T) and 400 MeV(right,0.23T), respectively. Here we simply treated the excited states greater than each individual mark ($n \geq 7$ for 181 MeV and $n \geq 5$ for 400 MeV) as the uncontrolled beam losses. We then calculated the fraction of each state yield and the uncontrolled beam losses from the H^0 excited states are found to be about 3W and 8W at maximum for the 181 and 400 MeV injection, respectively. However, for a more precise estimation, a detail study concerning the tracking of higher excited states are underway.

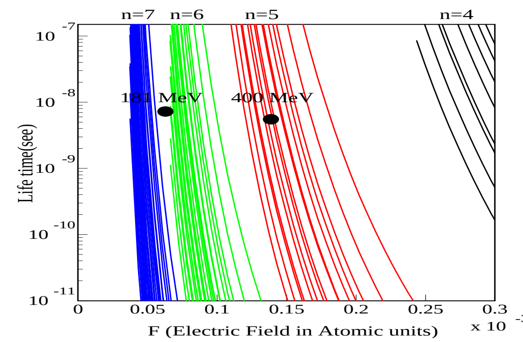

Figure 4: Life time of the excited states of H^0 as a function of electric potential. See text for details.

Beam loss from the Nuclear Scattering at the Foil

This is also a major concern of the uncontrolled beam loss issue in the RCS injection. Unfortunately, it has not been investigated elaborately yet. The estimation is in progress, where we are trying to get the angular distribution of the particles at the foil by using the GEANT simulation as well as to track them using SAD in order to get the real distribution of the loss including loss points. Experimental data on the nuclear scattering at the very low energy region is thus necessary for a precise estimation. Numerical estimation shows a loss of about 12W if the total cross section of 0.331 barn and the average foil hitting rate is assumed to be about 20 [3].

SUMMARY AND FUTURE PROSPECTS

We have carried out an elaborate calculation in order to determine the apertures of all magnets together with all elements in the injection-dump line of 3-GeV RCS. The uncontrolled beam losses in the present system are estimated at the injection energy of both 181 and 400 MeV. We found that the total uncontrolled beam loss stays a very minimum and/or acceptable level around the injection system although a final and very realistic estimation concerning mainly the nuclear scattering at the foil is underway and hope to be completed in a few months.

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