OVERVIEW OF INJECTION/EXTRACTION BEAM LOSS MECHANISM

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Abstract

Low beam loss operation is a crucial part for high intensity hadron machines. The beam loss gives a serious damage to surrounding equipment and increases human exposure during the maintenance. The beam loss at the injection and extraction process can be one of the major source in the whole beam loss in the ring. We review the beam loss mechanism related with linac to ring injection, ring to ring injection, one turn extraction (fast extraction) and slow extraction by showing the J-PARC ring as an example.

INTRODUCTION

High intensity proton accelerator complex comprises a linac and an accumulator or a rapid cycle synchrotron (RCS). A larger facility has a slow cycle synchrotron following the RCS as a booster.

Negative hydrogen (H^-) is generated by an ion source and accelerated by the linac, and injected into the accumulator or the RCS by a charge exchange injection using a stripping foil. The beam accelerated by the ring is extracted by one turn extraction (fast extraction) and delivered to the facility like a spallation neutron source. The beam from the ring is injected into the slow cycle synchrotron by a bunch to bucket injection. The beam accelerated by the slow cycle synchrotron is delivered to experimental area by the fast extraction or the slow extraction. In Figure 1, we show the J-PARC accelerator complex as an example of the high intensity proton accelerator facility [1].

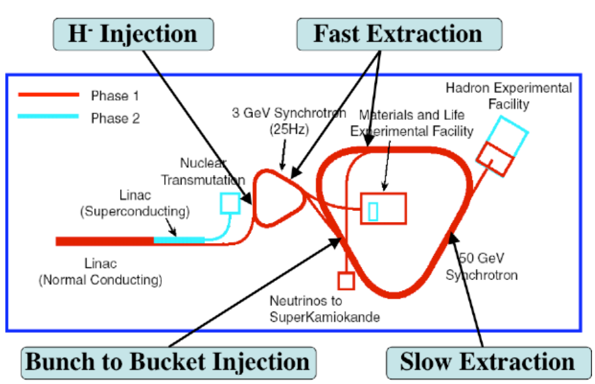

Figure 1: Layout of the J-PARC accelerator complex and locations of injections and extractions.

LINAC TO RING INJECTION

H^- charge exchange injection method is adopted to inject the beam from a linac to the following ring. Figure

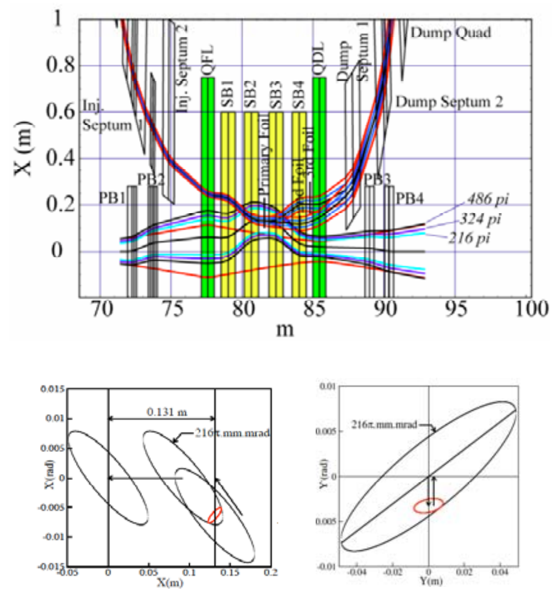

Figure 2: Injection layout of the J-PARC RCS [2] and phase space relation between linac beam and painted beam [3].

2 shows a layout of the charge exchange injection area in the J-PARC RCS. The horizontal painting is done by 4 shift bump magnets and 4 paint bump magnets. The field of the shift bump magnets is constant during injection. Vertical painting is performed by a bump magnet located π upstream from the stripping foil. The RCS uses three stripping foils. Purpose of each foil is explained in the later sub-section.

Lorentz stripping

Moving H^- ions feel an electric field from the magnetic field in the magnet. The electron of H^- ions is stripped by the electric field and resultant neutral H^0 is lost in the beam line.

Magnetic field at the transfer line from the linac to the RCS of the J-PARC was designed to be B < 0.4 T (ρ > 8 m) at 400 MeV energy operation. Fractional beam loss by the Lorentz stripping is 1.7×10^{-11}/m which corresponds to 2.2×10^{-6} W/m for designed 133 kW beam (see Figure 3). The beam loss is negligibly small.

Fractional charge states by carbon foil

The charge exchange efficiency to H^+ by the carbon foil depends on the thickness of the carbon foil. Thinner foil gives a better efficiency, but brings a worse scattering

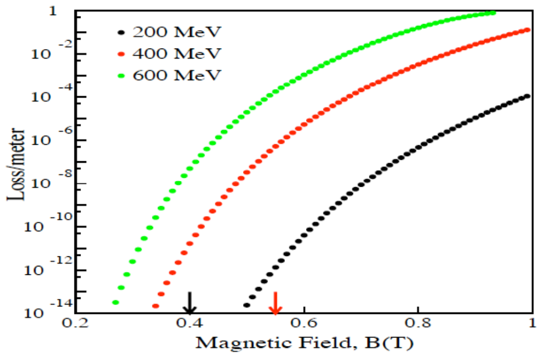

Figure 3: Fractional beam loss per meter by Lorentz stripping as a function of the magnetic field.

effect. The foil thickness is chosen from these two things. Figure 4 shows the charge state fraction as a function of thickness of the carbon foil at 200 and 400 MeV energy. The charge state fraction and corresponding beam powers for the J-PARC RCS are summarized in Table 1. The charge exchange fraction to H^+ achieves to 99.6-99.7%. Almost all of H^0 and H^- beam are charge exchanged by the second and the third foil respectively, and delivered to the dump.

Figure 4 shows the life time of H^0 excited state as a function of the field. The H^0 with the principal number higher than 6-7 decays in the bump field before reaching the second foil and is lost downstream of the bump magnet. This loss mechanism is called as "fast turn loss". The fraction for total H^0 states (beam loss power) is 1.6% (8 W) and 3% (3 W) at 400 MeV and 180 MeV, respectively.

Scattering by carbon foil

The beam injected and circulated in the ring can hit again on the charge exchange foil. This foil hitting probability is estimated to be roughly 20 times for the J-PARC RCS injection when the linac beam emittance is ideal.

The energy loss, energy struggling and scattering effects have been examined by a combination of GEANT and SAD tracking. Momentum loss Δp/p is 3 and 7×10^{-3}% at 400 and 180 MeV injection. Momentum spread due to the struggling is 0.2-0.3%. The beam loss can be caused by the nuclear reaction. Dominant nuclear reactions are (p,p)

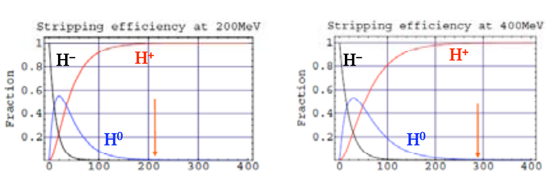

Figure 4: Charge state fraction as a function of the thickness of the carbon foil for 200 and 400 MeV energy.

Table 1: Charge state fraction and corresponding beam power at the two injection energies for the J-PARC RCS.

- 400 MeV Injection (280 μg/cm^2)
  - H^- -> H^+ : 99.6% (132.5 kW)
  - H^- -> H^0 : 0.37% (0.49 kW)
  - H^- -> H^- : 6×10^{-5}% (0.08 W)
- 180 MeV Injection (210 μg/cm^2)
  - H^- -> H^+ : 99.7% (35.9 kW)
  - H^- -> H^0 : 0.29% (0.10 kW)
  - H^- -> H^- : 7×10^{-6}% (0.003 W)

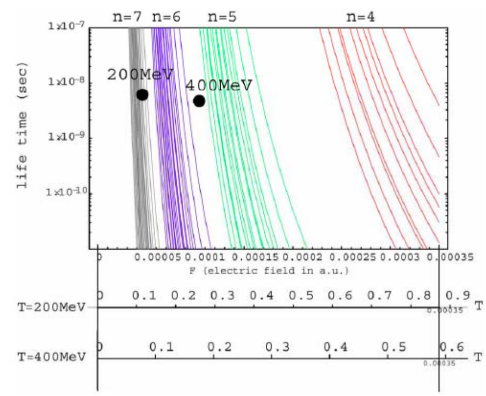

Figure 5: Life time of H^0 excited state in the field.

and (p,n). This loss in the injection region is estimated to be 16 and 4 W at 400 and 180 MeV injection, respectively. Particles with a large amplitude by the multiple scattering can be lost in the injection region before reaching the downstream collimators. This loss is estimated to be 10 W and 6 W at 400 and 180 MeV injection, respectively.

Shift/paint bump magnets

The edge focus of the shift and paint bump magnets makes vertical β modulation during injection. Figure 6 shows the vertical β modulation as a function of the injection time for the J-PARC RCS [1]. The β modulation is mainly caused by the shift bump excitation. The maximum β modulation is 11%. There is no beam loss by this modulation, since the ring has acceptance of 2 times larger than the painted phase space area. The edge focus force also breaks the ring super-periodicity. The resonance excitation by this effect would be carefully examined. The magnetic field in the bump magnets slightly changes by a coupling with the adjacent quadrupole magnet. As s result, the orbit in the ring is distorted during injection. This study is reported in reference [4].

Linac Beam

Larger transverse emittance of the beam from the linac increases a miss-hit probability for the foil. The miss-hit

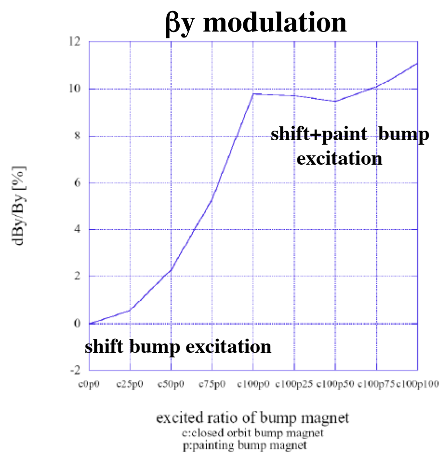

Figure 6: β_y modulation produced by the shift/paint bump magnets during injection time.

H^- can be delivered to the dump though the third foil. It also increases the foil hitting probability and increases beam losses related with the foil scattering as mentioned in the previous sub-section. Transverse halo of the linac beam can be scraped by collimators at the upstream transfer line. The transverse emittance also increases by a field error or a stability of the injection magnets. Longitudinal profile of the linac beam is also important. The beam with a large momentum spread worsens a longitudinal paint uniformity and decreases a bunching factor.

Rf chopper

An rf chopper is used to eliminate beam distributed outside the ring rf bucket beforehand. Schematic relation between the chopped injected beam and the rf bucket is shown in Figure 7.

In the J-PARC, the rf chopper is located at the beam line between the RFQ and the DTL. The beam is deflected out transversally by the transverse rf field of the rf chopper cavity. Required chopping efficiency (ratio of residual beam intensity for a chopped period and that for an un-chopped period) is order of 10^{-4}. Beam test performed at KEK cite showed that the chopping efficiency is within 10^{-4} level for the low peak beam intensity. For the high intensity operation, the beam halo from the RFQ may reduce the efficiency. If serious, we may need to increase a deflection angle of the rf chopper or to put a collimator upstream of the chopper cavity.

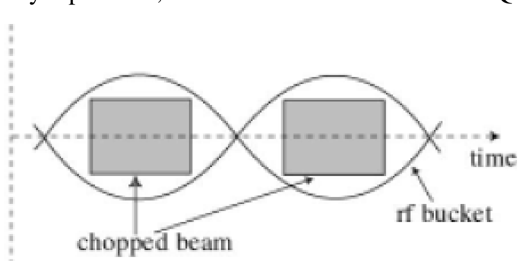

Figure 7: Chopped beam and rf bucket.

FAST EXTRACTION

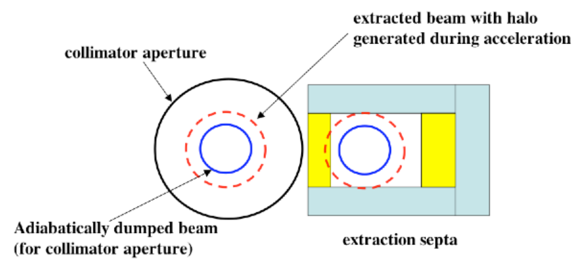

Figure 8: Relation between the beam size, the collimator and the extraction aperture.

Fast extraction (one turn extraction) uses kickers and magnetic septa. Kicker field rises within a beam gap. A very small beam loss (~0.1%) can be obtained for this extraction. But, very high intensity machine, such a beam loss is not neglected and may cause a serious radiation problem.

Extracted beam size and aperture

Extraction acceptance is determined by the magnetic septa and quadrupole magnets near the septa. An accumulator ring like SNS can have the acceptance larger enough than the ring collimator aperture. This case, no loss due to the aperture limitation is expected. In case of the synchrotron, adiabatic dumping works during acceleration. On the other hands, the emittance growth continues during acceleration, especially at the beginning of the acceleration. The extracted beam emittance including the halo is rather larger than that of the adiabatic dumping emittance. For the J-PARC RCS, extraction acceptance has been designed so as to have the same aperture as the collimator aperture. Such a design gives a margin enough for the beam loss. On the other hands, it makes a design of extraction hardware difficult, since it needs a large kick angle for the kickers and a large gap aperture for the magnetic septa.

Higher energy synchrotron case, extracted acceptance can not be generally chosen to have same one as that of the collimator. For example, the fast extraction acceptance of the J-PARC main ring has 19.5π mm·mrad. When the collimator aperture is chosen to be 54π mm·mrad, the emittance shrinks up to 5π mm·mrad by adiabatic dumping only from 3 to 40 GeV. Therefore the aperture margin is 4 times. The schematic relation between the collimator, extraction apertures and beam size is shown in Figure 8. For the slow cycle synchrotron, halo estimation by the space charge for extracted beam is quite difficult, since it needs a huge simulation time. Long

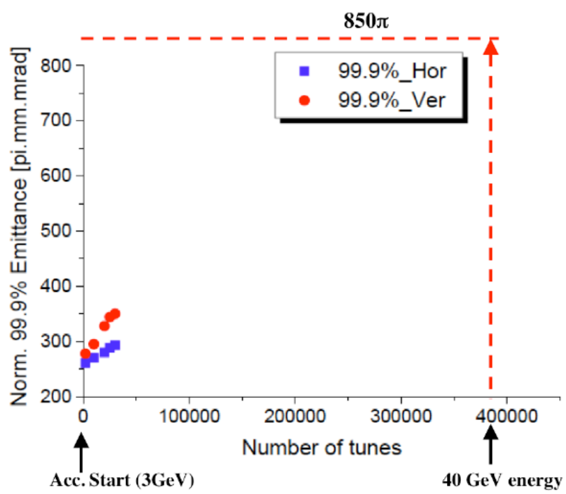

Figure 9: Long term space charge simulation during acceleration for the J-PARC main ring.

term space charge simulation using ORBIT code is now in progress for the J-PARC main ring. Figure 9 shows a preliminary result for 99.9% normalized emittance with acceleration time. Macro particle number is 91000 for 1.25×10^{13} ppb. The normalized acceptance of the fast extraction is 850π mm·mrad at 40 GeV energy. The 99.9% normalized emittance is increasing in the beginning of acceleration. Slight saturation can be seen at the end of the simulation. Further simulation time is necessary to estimate the beam loss at the fast extraction.

Other possible losses

Other possible beam loss sources of the fast extraction are as followed:

- In case the kicker rise time (1-99%) is longer than the beam gap.
- In case residual beam is in the beam gap. It can be a problem for the accumulator ring. The SNS ring introduces a gap clean device. In the case of the synchrotron it has no problem, if an rf manipulation is not adopted at the top energy.
- If magnetic septa for the extraction are operated at the DC, a leakage field to the circulating side makes β modulation and excites the resonance during injection energy.

RING TO RING INJECTION

Injection from the primary ring to the secondary ring is bunch to bucket transfer. In this method, beam bunches of the primary ring is extracted at one turn (fast extraction) and injected into the secondary ring at one turn by the magnetic septa and kickers. Bunches from the primary ring is transferred into the rf bucket of the secondary ring by a synchronization technique.

Halo of beam from the primary ring

Halo of the beam extracted from the primary ring causes the beam loss in the secondary ring. The beam halo can be scraped by collimators placed in a transfer line from the primary to secondary ring. The J-PARC has the collimators at a transfer line between the RCS and the MR. The collimators are placed in three FODO cells with 120 degree phase advance each. Each straight section has a pair of L-shape movable jaws surrounded by the iron shield. Figure 10 shows a beam simulation by STRUCT code. The 3 GeV beam from the RCS has the halo generated by the space charge in the RCS ring. The main ring has an acceptance of 81 π mm·mrad. Beam outside of the 81 π mm·mrad is 0.112 kW for 32 kW total beam, when the jaw position is set not to scrape any beam. The outside particles are lost in the main ring. When the jaws position is set to 65π mm·mrad, outside particles drastically reduces to 10 W. In this case, beam power deposit in the collimators is 550 W. Thus the transfer line collimators are useful to reduce the beam loss at the secondary ring.

Other possible losses

Other possible beam loss sources of the ring to ring injection are as followed:

- Longitudinal mismatch for the rf bucket, and synchronization error.
- Field error of the extraction and injection kickers should be typically within 1%. Required field errors for the magnetic septa are typically order of 10^{-3}. If the transfer line has a pulse switching magnet, field error due to an eddy current should be reduced.
- The injection kicker rise time (1-99%) longer than

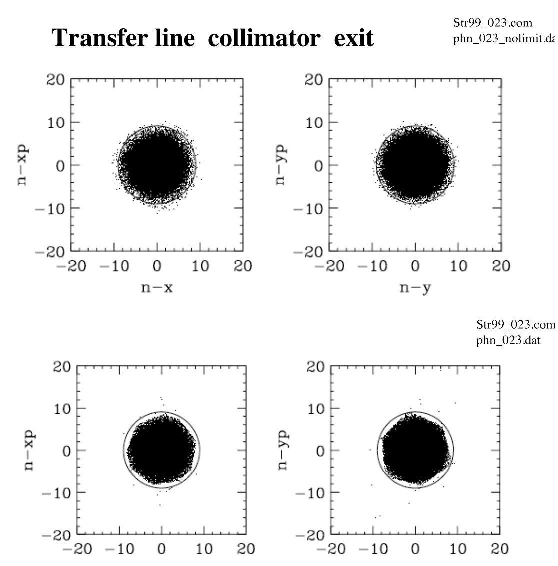

Figure 10: Simulation of the beam halo scraped by the collimators located the transfer line from the J-PARC RCS to MR.

a bunch gap. The jitter of the kicker timing is also important.

- A leakage field of the injection septa to the circulating side makes β modulation and excites the resonance.
- Errors of steering, betatron amplitude and dispersion at the injection point produce a dilution in the ring and increase the emittance of the injected beam.

SLOW EXTRACTION

Beam loss for the slow extraction can not be avoided. Slow extraction from a high beam intensity proton machine is crutial part from the viewpoint of radiation problem. Figure 11 shows a schematic drawing of the beam hit on the ESS wires. Most of the coming beam with betatron amplitude grown by the resonance path through the gap between the electrode and the earth wires, and are deflected by the electrostatic field. A portion of the coming beam hits in front of the wires (head-on hits) and from both sides (side hit). The hit rate on the wires depends on thickness of the wires, turn separation and angular spread of the coming beam. In order to reduce the hit rate, slow extraction scheme is designed so that the coming beam has a large turn separation and a small angular spread. Thinner wires are preferable but their alignment error and distortion by the electric field should be taken into account.

The actual beam loss on the wires to produce the radiation is not equivalent with the hit rate, which is typically 10% level of the hit rate. The remaining particles are multiple scattered without nuclear reaction and goes out to extracted side or circulating side as shown in Figure 11. The particles scattered to the extraction side go to the downstream magnetic septa and are extracted from the ring or lost by hits on the magnetic septa coils etc. A part of scattered particles path through a nonlinear field of the quadrupole magnet, which distorts the phase space distribution. Particles scattered to the circulating side can go round in the ring and are extracted from the ring or lost. The beam loss simulation has been performed for the J-PARC main ring slow extraction. Many 80 μm tungsten wires aligned longitudinally are replaced by a bulk plate with an equivalent mass density in the MARS model. The ESS length is 1.5m. The hit rate is 1% of the full beam (750 kW). Two collimators are placed between the ESS and the magnetic septa. Total beam loss in the whole ring

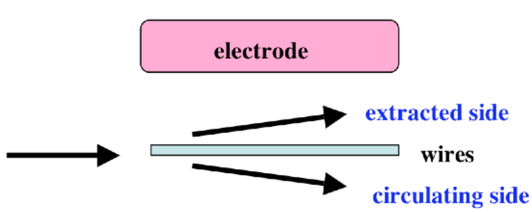

Figure 11: Beam scattered by the electrostatic wires for the slow extraction.

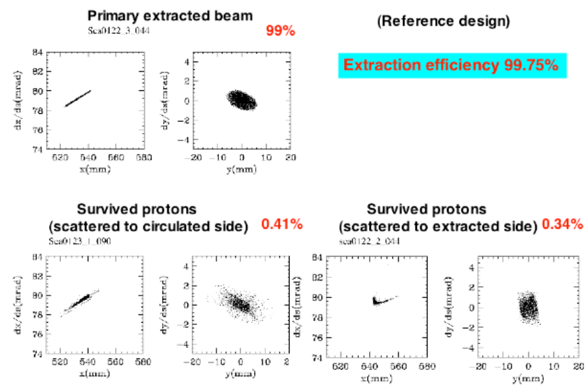

Figure 12: Phase space distributions of primary and halo beam extracted from the J-PARC. The beam halo is generated by the scattering on the ESS wires.

is 1.9 kW, which includes the loss at these collimators. The remaining scattered particles extract from the ring without any loss in the ring. Figure 12 shows the phase space distributions of "primary" extracted beam and "scattered "extracted beam at the ring exit. The scattered particles comprise a halo of beam extracted from the ring. The halo can be accepted by the transport line to the experimental facility. Development of the ESS with a thinner septum is now underway.

DISCUSSION

Actual beam loss of the injection/extraction can be caused by other reasons besides mechanisms described above. Fine beam tuning for the injection or extraction is very important to reduce the beam loss, since the high intensity proton machine is often operated under a critical condition. Few beam tuning knobs make a proper beam tuning difficult. Lack or error of diagnostics brings the same situation.

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