INJECTION SYSTEM FOR THE J-PARC 3-GEV HIGH INTENSITY PROTON SYNCHROTRON

I. Sakai, T. Shimada*, T. Takayanagi*, K Yamamoto*, Y. Arakida, I. Sugai, Y. Takeda, S. Machida, F. Noda*, K. Shigaki*, Y. Watanabe*, Y. Ishi **, T. Kawakubo, Y. Irie,
KEK, Tsukuba, *JAERI, Tokai, ** MELCO, Kobe; JAPAN

Abstract

The J-PARC Project 3-GeV proton synchrotron is designed to accelerate 8.3×10^{13} protons per pulse at a 25Hz repetition rate for the injection energy of 400MeV. The incoming beam emittance of the 400-MeV linac is 4 π mm mrad and the acceptance in the 3-GeV synchrotron is 486π mm mrad in both the horizontal and vertical planes. Painting injection system is designed to fit in the FODO structure, which has rather short drift space. The bump orbit for painting injection is designed to have a full acceptance of the circulating orbit through the injection period. A full-acceptance bump orbit will enable both correlated and anti-correlated painting injection.

INTRODUCTION .

The J-PARC Project accelerator complex comprises a 50-GeV main synchrotron, a 3-GeV rapid-cycling synchrotron, and 400-MeV Linac. The accelerators provide high-intensity, high-energy proton beams for various scientific fields. The 3-GeV synchrotron is designed to accelerate 8.3×10^{13} protons per pulse at a 25 Hz repetition rate in the 400-MeV injection. The hardware of the 3-GeV ring is designed to accept 400-MeV injection beams.

The 3-GeV rapid cycling synchrotron (RCS) has a three-fold symmetric lattice. Each super-period consists of 9DOFO modules, which are assigned to two 3DOFO modules with a missing bend and 3DOFO modules in insertion straights. These insertion straights are designed to be dispersion free. The FODO structure requires modest quadrupole gradients, and the alternating transverse beam amplitude easily accommodates correction systems, but lacks a long uninterrupted drift space for flexible injection.

The injection system for the J-PARC 3-GeV Proton Synchrotron is designed to be constructed in the FODO structure, which has rather short drift space. The injection and collimator system will be in the same straight section. The H^- injection system uses the first whole cell and a quarter of the second cell. The collimator system is located at the latter three quarters of the second cell and the third cell. However, the system is designed to have a full acceptance for the injection bump orbit and to allow independent lattice tuning to obtain a high-intensity beam and low-loss operation.

An outline of the injection system has already been reported [1][2]. In this paper we mainly describe the challenging issues about the H^- injection line, disposal lines for un-stripped H^0 & H^- ions and the structure of the bump magnets system.

PARAMETERS FOR PAINTING INJECTION

The machine acceptance of the linac and its transport line are designed to have 30π mm mrad, and that of 3-GeV synchrotron has 486π mm mrad. The acceptable momentum dispersion ($\Delta p/p$) in the transport line and 3-GeV ring are ±0.3% and ±0.1%, respectively.

In the beam-transport line from the 180MeV Linac to the 3-GeV RCS (L3BT); the transverse emittance of the H^- beam is collimated to 4π mm mrad. In the momentum direction, $\Delta p/p$ is ±0.1%.

In the case of 400 MeV injection, the painting emittance in the ring is 216π mm mrad for the 3-GeV facilities, and 144π mm mrad for 50-GeV ring injection. The horizontal painting area is controlled by pulse steering magnets located in the injection line and bump magnets in the ring by changing the excitation level in a pulse-to-pulse mode. The vertical painting area can be

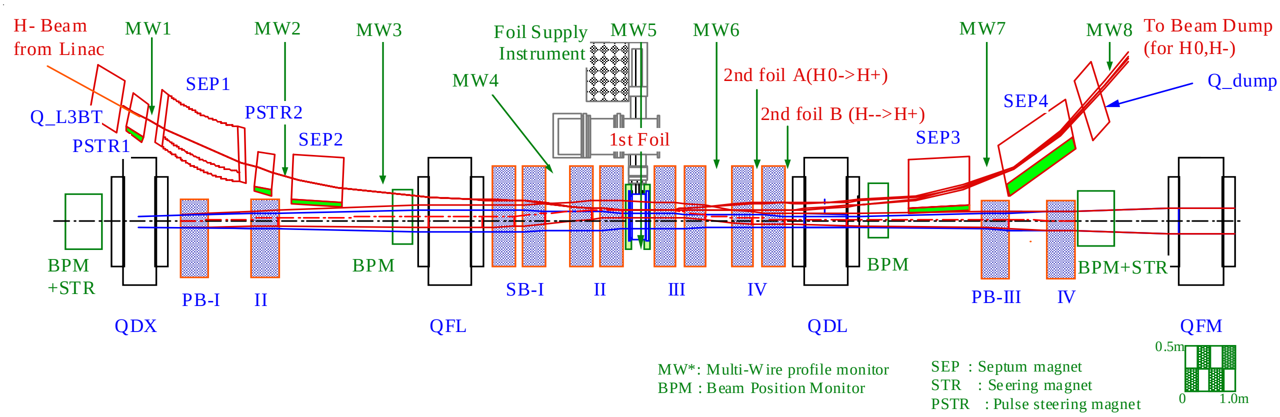

Fig.1 Outline of the H^- injection system

controlled by changing the excitation level of vertical steering magnets in the injection line.

The collimator acceptance in the 3-GeV ring is 324π mm mrad and the whole ring will have 486π mm mrad needed for the scattered beam by the first collimator to be caught subsequently by the down-stream collimator. The ring will be filled with 308 turn H^- foil-stripping charge-exchange injection. The 500μs pulses from the Linac containing 8.3 x 10^{13} protons will be injected to two-bunch RF buckets in the ring.

DESIGN OF THE MAGNETIC FIELD

The magnetic field must be carefully chosen so as to prevent the Lorentz stripping of H^- and to minimize the stripping of excited H^0.

In the upstream of the stripping foil, the H^- beam will pass through septum magnets, quadrupole magnet and closed orbit bump magnets. The maximum magnetic field is estimated to be 0.55 T for 400-MeV H^- beams. The beam loss rate is less than 10^{-6} for the above magnets. Because the injection beam power is 133 kW, and its losses by Lorentz stripping is less than 0.13 W.

After the H^- beam passes through charge-exchange foil made of 290μg/cm^2 thick carbon, a H^0 beam of 0.4 kW is produced. When a 1MW output is attained, it becomes very important to control the loss of the excited H^0 [3]. In the case that the magnetic field of the bump magnet is set to be about 0.2 T, the excited H^0 with a principal quantum number of $n \geq 6$ becomes the uncontrolled beam loss. Because of the yield of $n \geq 6$ is 0.0136 and the total H^0 beam power is 0.4 kW, the maximum uncontrolled beam loss is about 6 W. On the other hand, the excited H^0 under the condition of $n \leq 5$ reaches second foil without decay and stripped to H^+, and is led to the beam dump.

The magnetic field at the foil position is designed to be less than the value at which the bending radius of the stripped electrons is larger than 100mm, which enables a electron catcher to be settled outside of the foil. The foil position is at a distance of 350 mm from the end of the bump magnet SB-III. The trajectory of stripped electrons at the foil is traced by solving 3D differential equations with the Runge Kutta method [4]. The bending radius is estimated to be about 120 mm in the given magnetic field distribution.

CONSTRUCTION OF THE INJECTION SYSTEM IN THE FODO STRUCTURE

An outline of the injection system is shown in Fig.1. The injection system in the horizontal plane is composed of four main orbit shift bump magnets named "SB" to merge the injection beam with the circulating beam, and four other orbit paint bump magnets named "PB" for painting injection. The "SB" have a split-type structure to insert the second foil for H^0 stripping. Also the vertical painting is performed by vertical steering magnets in the injection beam line.

The incoming beams are injected at the entrance of "SB-I" to obtain a full acceptance for the injection bump orbit. The injection angle of the incoming beams with the circulating beam orbit is expanded by the magnetic field of the upper-stream F quadrupole. The angle of the disposal beam line of un-stripped H^0 and H^- are also expanded by a downstream D quadrupole magnet.

The field of the quadrupole magnets may be changed to meet varieties of operating point of the ring. The injection angles and positions at the quadrupole magnet are adjustable by steering magnets at the up-stream points of the injection line.

Horizontal painting injection is performed by an orbit shift in horizontal plane. Two additional sets of bump magnet pairs for the horizontal painting, named "PB-I, PB-II"and "PB-III, PB-IV", are located in the up-stream of the F quadrupole magnet and downstream of the D quadrupole magnet, respectively.

For vertical painting, two small vertical steering magnets, which are not shown in Fig.1 are placed in the transport line at a betatron phase of nearly π up-stream of the stripping foil to vary the injection angle and position. Painting injection in the vertical phase plane is performed by sweeping the injection angle. The phase difference will be compensated by those two vertical steering magnets.

Both correlated and anti-correlated painting injections are available by changing the excitation pattern of the vertical painting magnet

DESIGN OF THE H-INJECTION LINE AND H^-, H^0 DISPOSAL LINES

As can be seen in the Fig.1, injection area is so congested that any other focusing magnets can not be inserted in the injection area which has a length of 20 m. Furthermore, the beam needs to be injected vertically off-center for vertical painting. The corner of the F and D quadrupole magnets are thus required to have additional aperture for the injection/disposal beam lines

The beam optics of beam transport line from the Linac to RCS is designed to be insensitive to space charge effect. Space-charge effects have been analyzed by simulation on

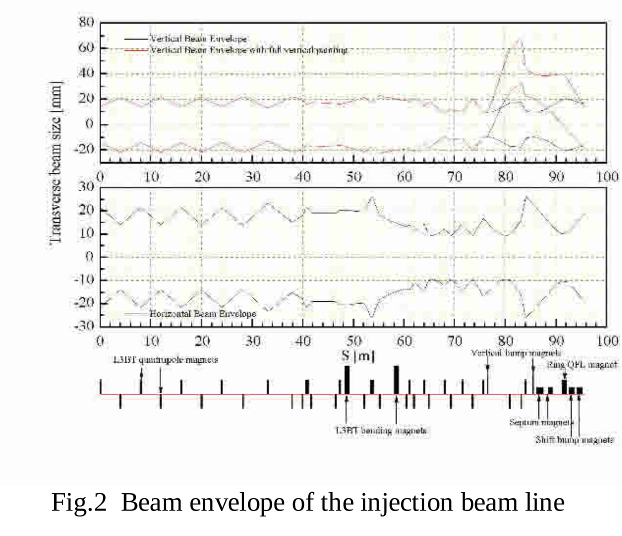

Fig.2 Beam envelope of the injection beam line

this optical design. The results estimate that the space charge effect is not much of a problem under the designed bunch lengthes of 400 MeV and 180 MeV injection.

_ Separation of THE H^0, H^- AND H^+

In the FODO structure, the beam envelope at the down-stream of F quadrupole, tilts down-stream so that the injection beam line for horizontal painting must be tilted accordingly. The separation angle of the H^0 beams and circulating H^+ beam envelope become tighter than a case of a parallel envelope of the two pairs of quadrupole doublets where $\alpha = 0$.

The separation of the H^0, H^- beams and circulating H^+ beam envelope is one of the challenging issues to design the hardware of the injection system. To solve this problem the split-type bump magnet has been investigated.

The H^0 beams, which are estimated to be 0.3% of the incoming beams, must be converted to H^+ by a second foil to divert to the beam dump. As shown in Fig.1, the second foil "A" is inserted in the middle of the fourth bump magnet, "SB-IV", by a split at the center of the core. The up-stream part of the split core is used to obtain the sufficient clearance of the H^0 and H^+ beam separation and the down-stream part kicks the H^+ ions converted from H^0.

H^- beams, which are estimated to be 3×10^{-4} % of the incoming beams, are also converted to H^+ by another second foil,"B", set at the entrance of the D quadrupole magnet,"ODL".

THE MAIN BUMP MAGNETS

Four dipole bump magnets named (SB-I~SB-IV), are identical in construction and are powered in series to give a symmetrical beam bump within the straight in an uninterrupted drift space between the focusing magnet and the defocusing one.

A cross-sectional view of the bump magnet is shown in Fig.4. The dipoles are out of the vacuum and a ceramic vacuum chamber is included in the magnet gap. The structure of the magnet is composed of two-turn coils and window frame core made by laminated silicon steel cores of which the thickness is 0.1 mm. The electrical insulation of the coil is achieved by air gap and a ceramic insulator.

The waveform of the magnetic field is trapezoid. A fall time of 100 μs is decided by the hitting probability of proton beams on the stripping foil and the temperature of the foil heated by the beam hit. The maximum temperature of the foil is estimated to be 1500ºC at the tip of the foil.[5]

The excitation current is supplied in the middle of the core through the split to form a symmetrical distribution of magnetic field along the longitudinal direction.

THE PAINTING BUMP MAGNETS

Two sets of bump magnet pairs in the upstream of the F quadrupole magnet and the downstream of the D quadrupole magnet. These four dipole bump magnets named (PB-I~PB-IV), are identical in construction and will be excited individually to form a local closed orbitinclude the F and D quadrupole magnets.

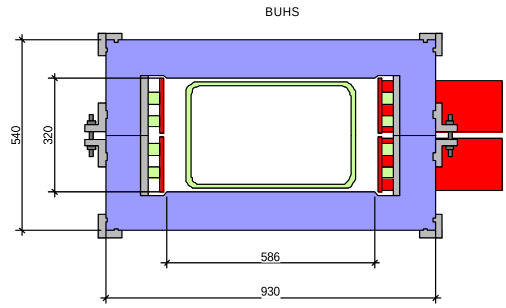

Fig.3 A cross-sectional view of the main bump magnet

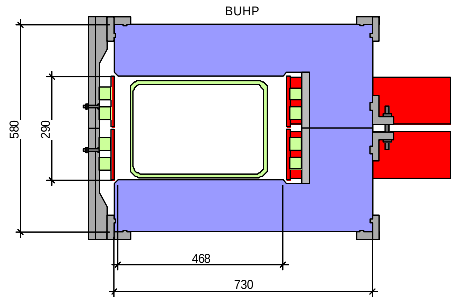

Fig.4 A cross-sectional view of the paint bump magnet

A cross-sectional view of the bump magnet is shown in Fig.4. The dipoles are out of the vacuum and a ceramic vacuum chamber is included in the magnet gap. As shown in Fig.1, at the PB-II and PB-III, the separation of the H^0, H^- beams and circulating H^+ beam envelope is insufficient to insert the type of window frame magnet. The structure of the magnet is composed of two-turn coils and C-type core. The envelopes of the circulating beam are close to the edge of the pole, where it is difficult to form a uniform magnetic field in such a wide aperture / short length magnet. The optimum structure of the core and the conductors are under investigation using 3D calculation.

SUMMARY

The injection system is designed to be constructed in the FODO structure, which has rather short drift space.

The bump orbit for painting injection has a full acceptance for the circulating beams.

The H- injection line and the H0,H- disposal lines can be designed so as to have a sufficient acceptance for low-loss injection

The painting area is optimized for both 3-GeV users and 50-GeV users in a pulse-to-pulse mode operation

REFERENCES

[1] I. Sakai et al, EPAC2002, Paris, June 2002
[2] I. Sakai et al, PAC2003, Portland, June 2003
[3] G. Rees, EPAC94, London, June 1994
[4] M. Shrakata et al, EPAC2002, Paris, June 2002
[5] K. Kuramochi et al, This proceedings