H$^-$ PAINTING INJECTION SYSTEM FOR THE JKJ 3-GEV HIGH-INTENSITY PROTON SYNCHROTRON

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Abstract

The JAERI KEK Joint Project 3-GeV proton synchrotron is designed to accelerate 8.3x10^{13} protons per pulse at a 25Hz repetition rate. The incoming beam emittance of the 400-MeV linac is 4 π.mm. mrad and the acceptance in the 3 GeV synchrotron is 324 π.mm.mrad in both the horizontal and vertical planes. Painting injection is designed to realize a uniform distribution of charged particles in real 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.

1 INTRODUCTION

The 3-GeV rapid cycling synchrotron (RCS) will have 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. The insertion straight will be named I, E, and R. The injection and collimater system will be in the I straight. The H$^-$ injection system uses the first whole cell and a quarter of the second cell. The collimeter system is latter three quarters of the second cell and the third cell. The extraction system will be in the E straight. The RF system cavities will be in the R straight. These insertion straights are dispersion free.

From both experimental and simulation results, the emittance exchange due to the x-y coupling resonance induced by space-charge effects is observed in the KEK booster synchrotron[1]. Similar beam behaviors are expected, not only in the KEK booster, but also in a machine where an anti-correlated painting scheme inevitably causes an unequal transverse emittance. Careful selection of the operating tune and a sufficient acceptance for the injection bump orbit are required to design both correlated and anti-correlated painting injection.

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. To secure full acceptance for the injection bump orbit and to allow independent lattice tuning, eight bump magnets[2] for the horizontal direction and two bump magnets for the vertical direction have been devised.

Furthermore a long-stroke self-supported carbon foil has been developed for this purpose.

2 PARAMETERS FOR PAINTING INJECTION

The ring will be filled with 308 turn H$^-$ foil-stripping charge-exchange injection. The 500μs pulses from Linac containing 8.3 x 10^{13} protons will be injected to two-bunch RF buckets in the ring.

Uncontrolled beam loss is a major concerning for the maintenance of the machine. For hands-on maintenance, a full energy loss of <1W/m is required, which corresponds to an integrated uncontrolled beam loss in the ring of less than 3.5 x 10^{-4} for 1 MW.

In the beam-transport line from the 400MeV Linac to the 3-GeV RCS (L3BT); the transverse emittance of the H$^-$ beam is collimated to 4 π.mm.mrad. In the momentum direction, $\Delta p/p$ is ±0.1%. The painting emittance in the ring is 216 π mm.mrad for the 3-GeV facilities, and 144 π. mm.mrad for the 50-GeV ring injection. The ring must also accept a maximum beam momentum spread of ±1% for the beam envelope. The number of incoming beam pulses is 300 for the injection period, which is a maximum of 500μsec.

The collimater acceptance is 324 π.mm.mrad and the whole ring will have a full acceptance of 486 π.mm.mrad for second collimation trough the whole ring.

3 DESIGN OF THE BUMP MAGNETS SYSTEM WITH THE FULL ACCEPTANCE FOR THE CIRCULATING BEAMS

3.1 Outline of the injection bump orbit

A schematic layout of the H$^-$ injection system in the horizontal plane is shown in Fig.1. The eight bump magnets are put into two categories according to their roles, i.e. four closed orbit bump magnets for the charge-exchange injection and four other closed orbit bump magnet for the painting injection.

In the painting injection process, it is inevitable to form a non-uniform distribution of charged particles in the circulating beams. A nonlinear self-field may cause an unexpected blow-up of the circulating beams. To escape from uncontrolled beam loss at the injection point, the full aperture, the same as the whole ring, is required to the injection bump orbit.

A high intensity machine is required to have a wide aperture and a large gap height versus the longitudinal length. In this case, the non-linearity of the fringing field near the coil end cannot be neglected. To secure full acceptance for the structure of the bump magnets, a

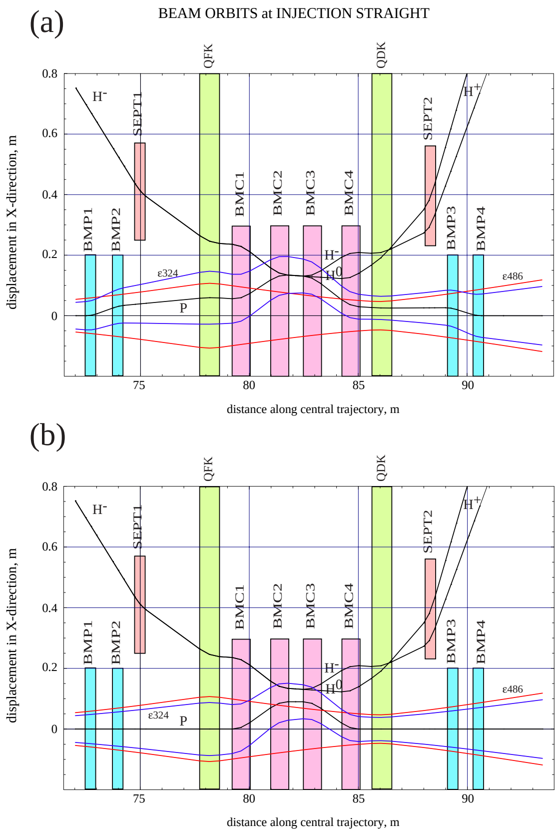

Figure 1: Outline of the injection bump orbit.
(a): Painting start, (b): Painting end.

sufficient clearance is required between the coil and the bump orbit for a good field region.

Incoming beams pass through the corner of the useful aperture of the quadrupole magnets so that the angle of incoming beams with the circulating beam orbit is expanded to get the sufficient transverse space for painting bump. In the case of lattice tuning, the injection angle at the quadrupole magnet are adjusted by the steering magnets at the up-stream points of the injection line. The injection system is designed to have the full acceptance of the bump orbit by using the bump magnets with a non-septum structure.

3.2 Fixed closed-orbit bump magnets at the injection period

Four bump magnets, named “Fixed closed orbit bump magnet” (BMC1~BMC4), which are settled in an uninterrupted drift space between the focusing magnet and defocusing one, have the role to form a closed bump orbit so that the beam impinges on a carbon stripping foil and to merge the injected beam line and the circulating beam orbit.

The stripping foil is situated between the central pairs of dipoles at the symmetry point of the “beam bump”.

The four injection dipole magnets are identical in construction and are powered in series to give a symmetrical “beam bump” within the straight section.

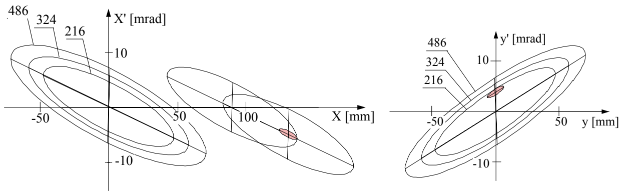

Figure 2: The painting process in the phase space.
(Left): Horizontal plane, (Right): Vertical plane.

The dipoles are out of vacuum and are single-turn window frame magnets with laminated silicon steel cores.

3.3 Horizontal painting bump magnets

Four other bump magnets, named “Painting bump magnets”(BMP1~BMP4), are distributed by the two bump magnets in the upstream of the focusing quadrupole magnet and the downstream of the defocusing quadrupole magnet. These four bump magnets have the role to sweep the closed orbit for painting injection in the horizontal plane.

The center of the closed orbit at the injection point can be swept by these four painting bump magnets. Beams are gradually injected from the center of phase space to the outside by a shift of the closed orbit, which is controlled by the decay pattern of the magnetic field of these four bump magnets. These four painting bump magnets will be excited individually to form a closed orbit laid on the quadrupole magnets. The painting process in the phase space is shown in Figure 2.

3.4 Vertical painting magnets

In the vertical plane, two direction bump magnets, which are not shown in Fig. 1, are installed on the beam-transport line at on upstream point led by π from the foil. One is the main painting magnet, and the other is an auxiliary magnet 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 of the injection angle. The painting process in the phase space is shown in Figure 2.

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

4 DESIGN OF THE MAGNETIC FIELD

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

4.1 Magnetic Stripping of H^- Ions

It is well known that an electron comes off from the H^- ion due to an external electromagnetic field. In the injection region, the H^- beam will pass through septum magnets, quadrupole magnets and fixed closed orbit bump magnets before reaching a charge-exchange foil. The maximum magnetic field of these magnets is estimated to be 0.55T for 400MeV H^- beams. The beam loss rate is less than 10^{-6} for the above magnets. Because the injection beam power is 133kW, and its losses by Lorentz stripping is less than 1W.

4.2 Fraction of excited H^0

When a H$^-$ beam passes through charge exchange foil, which is made of 290 μ g/cm^2 thick carbon, a H^0 beam of 0.4 kW is given to the excitation states. When 1MW output is attained, it becomes very important that the loss of the excitation H^0 is controlled [3].

The magnetic field of the bump magnet is set about 0.2 T. Therefore excited H^0 in the condition 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 0.4kW, the maximum uncontrolled beam loss is about 6W. On the other hand, the excited H^0 under the condition of $n<5$ reaches second foil without decayed to H$^+$ and is led to the beam dump.

4.3 Trajectory of stripped electrons

The magnetic field at the foil position is designed to be less than the value in which the bending diameter of the stripped electrons are larger than 100mm, which enables a electron catcher to be settled outside of the foil. The foil position is at a distance of 350mm from the end of the bump magnet BMC3. The trajectory of yielded electrons at the foil is traced by solving the 3D differential equations with the Runge Kutta method [4]. The bending diameter is estimated to be about 120mm in the given magnetic field distribution.

4.4 β Modulation by Bump Orbit

The horizontal bump magnets has a rectangular shape for the central beam axis. In this case, the betatron tune and vertical β function are affected by the edge focusing by the horizontal bump orbit. The maximum kick angles of the bump magnets are 57mrad and 26mrad for the fixed closed bump magnets and painting bump magnets respectively. The maximum tune shift is 0.05 in vertical plane and 0.001 in horizontal plane. The maximum inclement of the vertical β function is 10 %.

5 H$^-$ INJECTION LINE AND H$^-$, H^0 DUMP LINES

5.1 Ring lattice quadrupoles

The injection line which passes through the horizontal edge of the quadrupole is used for vertical painting. The vertical aperture at the horizontal edge of the up-stream F quadrupole must satisfy the aperture for the vertical betatron oscillation amplitude by vertical painting. The down-stream D quadrupole is in the same situation about the dump lines for un-stripped H$^-$, H^0 beams. These ring lattice quadrupoles at the injection region must have a large bore radius of 205mm. The same large bore radiusis also required from the extraction region in another super-period of the threefold symmetric lattice, where the kicked extraction beams pass through the horizontal edge of the D quadrupole.

Figure 3: Overall view of the self-supported foil

The mirror symmetrical structure of the super period requires the same large bore radius as the 12 quadrupoles in the whole ring.

5.2 Second foils

H^0 beams, which are estimated to be 0.3% of the incoming beams, are converted to H$^+$ by a second foil set at the entrance of the fourth bump magnet, “BMC4“. H$^-$ beams, which are estimated to be 3×10^{-4} % of the incoming beams, are also converted to H$^+$ by another second foil set at the entrance of the D quadrupole magnet, “QDK“. The separation of these un-stripped H^0 and H$^-$ beams is one of the key points to reduce the uncontrolled beam loss at the injection area. The widths of the second foils are adjusted by tilting, and the positions are controlled by parallel shifts.

6 SELF-SUPPORTED STRIPPING FOIL

To make sure a full acceptance of 486 π.mm.mrad at the stripping foil position, self-supported carbon foils having a horizontal length of 105mm and a vertical height of 30mm have been developed.

The self-supported carbon foil has a curved structure around the long axis and one side of the foil is fixed on the outside frame. The overall view of the foil is shown in Fig.3.

7 SUMMARY

A H$^-$ painting injection system which secures full acceptance for the injection bump orbit will be able to be inserted in the FODO lattice.

The full acceptance bump orbit will enable both correlated and anti-correlated painting injection.

Lattice tuning is available by adjusting the steering magnets in the injection line and painting bump magnets in the ring.

The injection bump magnets are free from the septum structure because of sufficient clearance between the circulating orbit and the injection (dump) orbit. It is therefore easy to have a good field region even with a wide-aperture short-length structure.

8 REFERENCES

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