A Preliminary Study of the Proton Storage Ring for the Neutron Science Project at JAERI

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Abstract

The goal of the proposed Neutron Science Project (NSP) at JAERI is to provide a short pulsed proton beam of less than 1μs with an average beam power of 5MW. To achieve such purpose, a proton storage ring operated at 50Hz with $4.17\text{x}10^{14}$ protons per pulse at 1.5GeV is required. The preliminary study of the ring which satisfies specification of the neutron science project is described in this paper.

1. Introduction

Japan Atomic Energy Research Institute, JAERI, has been proposing the Neutron Science Project (NSP) which is composed of research facilities based on a proton linac and a proton storage ring with an energy of 1.5GeV[1]. The proposed NSP is aiming at exploring new basic researches and nuclear technologies such as condensed matter physics and nuclear waste transmutation based on a proton accelerator. In the proton storage ring, the pulsed beam from the linac is accumulated, and high intensity pulsed beam is produced for the neutron scattering experiment. The goal of the proton storage ring is to provide a short pulsed proton beam of less than 1μs with an average beam power of 5MW with two rings. This paper describes the preliminary study of the 2.5MW proton storage ring. Figure 1 shows a layout of the 2.5MW proton storage ring including the High Energy Beam Transport (HEBT) line which connects the 1.5GeV linac to a proton storage ring. The beam coming out of the linac is a 1.5GeV H^- beam and 1.86ms long with a peak current of 30mA. The beam is chopped to the pulse length of 400ns with 270ns gap. The beam is compressed by means of a multi-turn charge exchange injection. When a harmonic number of the ring is 1, a circumference and a revolution frequency are 185m and 1.49MHz, respectively. The single bunch in the ring is contained by rf resonant cavity. To achieve a beam power of 2.5MW with this beam structure, it is necessary to accumulate 2777 bunches. This corresponds to $2.08\text{x}10^{14}$ protons. When the beam injection is completed, accumulated protons are extracted from the ring during 1 turn. The average current circulating in the ring with 1.49MHz revolution frequency becomes 49.75A. At such a high average current, a beam loss of a very small fraction makes a very high radioactivity around the ring. It is necessary to examine reduction and localization of the beam loss with sufficient consideration of the divergence of the beam by the space charge force, the resonance phenomena by the tune shift, longitudinal instability, e-p instability and so on.

2. High Energy Beam Transport Line

The High Energy Beam Transport line (HEBT) connects the 1.5GeV linac to a proton storage ring. A major requirement of this line is to have low uncontrolled beam loss in the ring in order to allow hands on maintenance. To achieve such low beam losses in the ring, the beam must be prepared very carefully before injection. The HEBT not only matches the beam into the ring, but also determines the beam quality at injection. The HEBT has following functions : (a) matching of the beam from the linac into the transport line, (b) horizontal and vertical betatron and momentum collimation, (c) focusing the H^- beam to the correct spot size for injection, and (d) halo cleanup. To reduce the probability of uncontrolled beam losses, HEBT is equipped with many beam halo scrapers. The ratio of aperture to rms beam size is kept greater than 10 throughout the line. The maximum magnetic field in dipole and quadrupole is kept less than 1.8kG to keep H^- stripping losses to acceptable levels. More detail study of HEBT system, for example the magnet lattice, components, etc., has been performed.

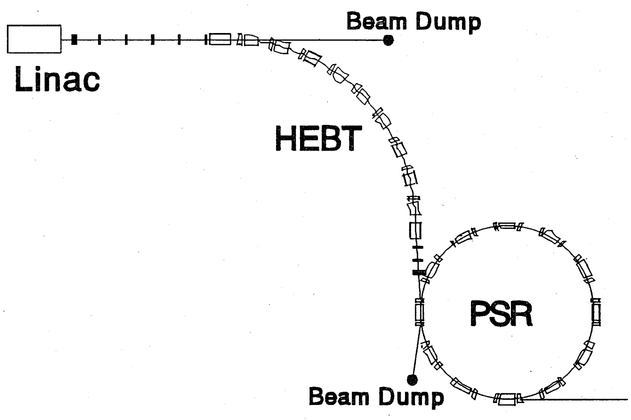

Fig. 1 Layout of a 2.5MW Proton Storage Ring

3. Storage Ring

Magnet Lattice

The magnet lattice is temporarily selected to be normal 12 cell FBDO lattice. FBDO lattice is chosen for its smoothness betatron function variation around the ring. This lattice ensures the distance between defocusing quadruple magnet and focusing quadruple magnet at 7.5m. The operation tune is in the range where a phase advance per 1 cell becomes 80~110 degrees and provisionally selected to be $(\nu_x,\nu_y) = (3.85,3.75)$. The betatron function and energy dispersion function have been evaluated by using the lattice analysis program "MAD" developed at CERN. The calculated data are shown in Fig. 2

A large transverse beam emittance is required in the ring to restrict the transverse space charge tune shift. The chosen values for an un-normalized 100% transverse emittance of an injected H^- beam, a ring acceptance and a collimator acceptance are 2πmm-mrad, 530πmm-mrad and 200πmm-mrad, respectively. This transverse emittance restricts the space charge tune shift to less than 0.1. Preliminary lattice function and design parameter of the storage ring are summarized in Table 1.

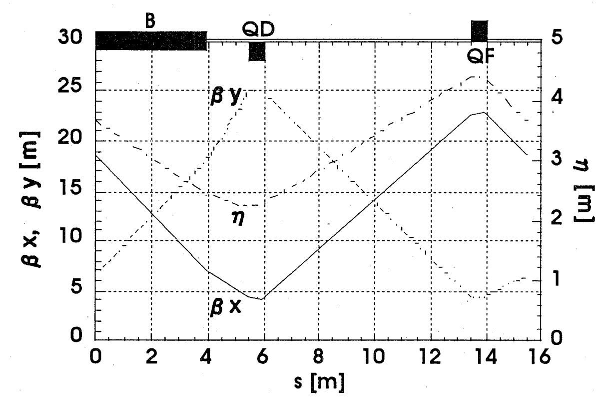

Fig. 2 Betatron and Dispersion Function of 12Cell FBDO Lattice

Beam Injection

There is a main source of beam loss in an injection area and hence the most critical item for the ring because the main loss is due to H^- or H^+ beam intersection with a stripping foil during and after injection. There are two types of injection method for charge exchange. One is the direct H^- injection method in which H^- beam is converted to H^+ beam with the stripping foil located in the injection magnet. The other method is the H^0 injection method in which H^- beam is firstly converted to H^0 beam in a stripping magnet outside of the ring and then H^0 beam is injected to the stripping foil inside the ring. In both method, it is very important to minimize delayed stripping of H^0 atoms in the ring. The lifetime of H^0 atoms depends on the Stark state in the magnet [2]. The lifetime of

Table 1 Preliminary lattice function and design parameters

Beam Average Power	2.5 MW / ring
Kinetic Energy	1.5 GeV
Average Current	1.67 mA / ring
Repetition Frequency	50 Hz
Linac Peak Current	30 mA
Linac Pulse Length	3.72 ms
Number of Turns Injected	2777 turns/ ring
Injected Beam Gap	270 ns
Injected Pulse Length	400 ns
Harmonic Number	1
Revolution Frequency	1.49 MHz
Circumference	185.4 m
Magnetic Rigidity	7.51 Tm
Circulating Current	49.75 A / ring
No. of Circulating Protons	2.08×10^{14} protons / ring
Lattice	12 Cell FBDO
Ring Acceptance	530π mm-mrad
Collimator Acceptance	200π mm-mrad
Tunes	$(\nu_x,\nu_y) = (3.85,3.75)$
Transition Energy	$\gamma_t = 3.54$
Space-Charge Tune Shift	< -0.1
Rf Cavity	
Frequency	1.49 MHz
Harmonic Number	1
Voltage	21 kV
Kicker Magnet	
Reflection Angle	10 mrad
Magnetic Field Strength	0.02 T
Length	3.8 m

1.5GeV H^0 atoms is shown in Fig. 3. In case of H^0 injection method, because there is no injection magnetic, the H^0 atoms excited by the foil become H^+ ions in a bending magnet. When the magnetic field strength of bending magnet is 1T, the life time of the atoms whose principal quantum number n is high (>3) becomes less than 10ps. An injection magnet is normally used for injecting H^- ions to the ring in H^- injection method. When the magnetic field strength of the injection magnet is 0.15T, atoms with $n\leqq4$ remain as H^0 and may be removed from the ring, and atoms with n>5 rapidly become H^+ and are accepted in the ring. At present it is under consideration which method should be adopted to reduce the beam loss in the ring.

A large transverse beam emittance is required not only to restrict the transverse space charge tune shift but also to reduce the circulating proton beam intersection with a stripping foil. To obtain the large transverse emittance the phase-space painting is also considered [3].

Radio Frequency Cavity

Though the acceleration of the beam is not carried out in

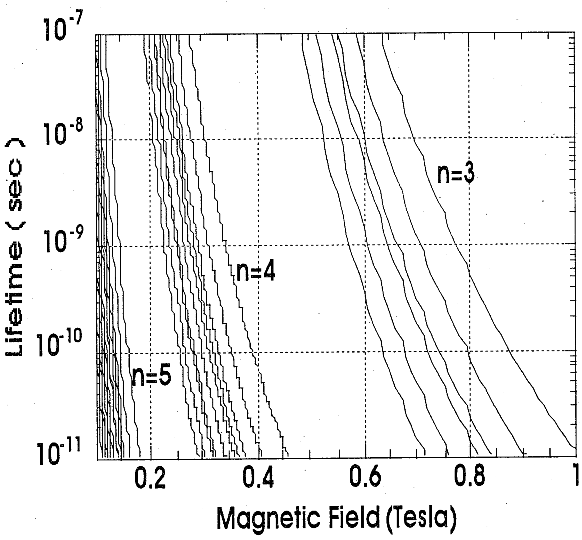

Fig. 3 Stark State Lifetimes in Lab. Frame

the rf cavity, the rf cavity is required for maintaining the bunch structure in the storage ring. The injection beam is chopped at the bunch revolution frequency of 1.49MHz. The necessary cavity voltage is the sum of voltage V_p which is proportional to the momentum spread of the injection beam and voltage V_{sc} which supplements the decreasing voltage by the space charge effect. The V_p voltage is about 13.5kV by assuming that the momentum spread is to be $\pm 0.41\%$. The necessary V_{sc} voltage changes according to the accumulated number of beam bunches. When all beam bunches are accumulated, the V_{sc} voltage becomes about 7.5kV under the condition that the longitudinal distribution is parabolic. The rf voltage is raised from 13.5kV to 21kV to maintain the beam bunches during injection.

The rf cavity consists of capacities, resistors, and ferrite. Because the circulating current is about 49.75A, it is likely that the cavity characteristics should be changed due to the high frequency magnetic field induced by circulating current. Therefore, the rf cavity is important issue to be developed.

Beam Extraction

The fast extraction method is used from the request of the neutron scattering experiment. In this extraction method, when injection of all bunches is completed, accumulated beam is extracted from the ring during 1 turn. An interval between bunches is 270ns from the injection beam pulse structure which is chopped 670ns bunch width with 60% duty cycle. It is necessary that the magnetic field of a kicker magnet is enough to extract the beam from the ring to less than 270ns and is kept the strength to more than 400ns. In fact, the required field rise time of kicker magnet is less than 150ns considering the increase of the beam bunch due to synchrotron oscillation and divergence by the space charge effect during multi-turn ring injection. When the un-normalized 100% extraction emittance, beta function, dispersion function, and momentum spread are 200πmm-mrad, 15m, 3m, and 0.41%, respectively, the reflection angle becomes about 10 mrad. A kicker magnet of 0.02T and 3.8m is required in order to realize this extraction process.

4. Upgrade Path

The phase I construction of the NSP project is a 1.5MW spallation neutron source. A systematical upgrade path has been proposed. The upgrade from 1.5MW to 2.5MW will be achieved by increasing a peak current or a pulse length of the linac beam. The upgrade from 2.5MW to 5MW will be accomplished by providing a second ring to aim the beams from both rings at the same target. In this case, the beam transport system has to combine the beam bunches from the two rings into a single pulse of less than 1μs duration.

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