ICANS-XI International Collaboration on Advanced Neutron Sources
KEK, Tsukuba, October 22-26, 1990

Treatment of H^0 and H^- beams spilled at the stripper foil at full energy charge-exchange injection scheme

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ABSTRACT

The charge-exchange injection into a synchrotron to generate high-intensity pulsed proton beams for a spallation neutron source is reviewed while focusing on the treatment of H^0 and H^- beams spilled at the stripper foil. After charge-exchange injection is briefly outlined, scattering by foil atoms and causes to spill H^0 and H^- beams are described. These spilled beams can amount to several μA and should be carefully treated. It is then shown that a direct H^- injection system needs to be considerably long and requires a very long straight section. Because of its simplicity, two-step H^0 injection has very wide applicability to various types of rings. However, it has a problem of emittance growth due to angular divergence in the stripper magnet and an ion-optical mismatch at the stripper foil. These problems are discussed, including a new proposal for a measure to remedy this problem. The laser photoionization injection is also briefly mentioned.

I. INTRODUCTION

We now have two accelerators for generating high-intensity pulsed proton beams for a spallation neutron source, PSR (LANL) [1] and ISIS (RAL) [2]. We can learn many things about such accelerators from operational experience of these machines over several years .

One noticeable feature of these machine is that even a very small beam loss, especially when the energy of lost particles is high, can produce such high residual activity that maintenance becomes dangerous; as a result, the operational beam current is limited. In fact, even through experience at the KEK 500-MeV booster synchrotron, we know that the loss of a 500 MeV beam should be suppressed to below about 0.3 μA. A 0.3 μA beam current is a very small fraction of the beam current that an accelerator for the spallation neutron source is required to have.

How to treat H^0 and H^- beams spilled at the stripper foil during injection is one of important subjects to reduce beam loss. These H^0 and H^- beams are produced at the stripping foil when the injected H^- (or H^0) beam is charge-exchanged and spilled without being captured by the synchrotron. Because the currents of these beams can be several μA, serious activation might take place if we handle these beams improperly, especially during full-energy injection. Although this subject is serious [3], it has not yet been discussed in detail. This paper is intended to deal with this subject in some detail.

II. OUTLOOK ON THE CHARGE-EXCHANGE INJECTION INTO A HIGH INTENSITY PROTON SYNCHROTRON

As an example of a pulsed proton beam for a spallation neutron source, JHP has proposed a 1-GeV proton beam with a 200 μA average intensity in the form of a 200 nsec beam pulse repeated at 50 Hz. Although the beam energy of both PSR and ISIS is 800 MeV, the design aims regarding the beam intensity are of the same order as JHP: 100 μA for PSR and 200 μA for ISIS. In order to obtain such a high-energy, high-intensity pulsed beam, two different methods are currently being used. Of course, charge-exchange injection into a synchrotron is essential for both methods.

One is a method using low-enery injection and acceleration; it has been adopted in ISIS. The injection energy of ISIS is 70 MeV, accelerating the injected beam to 800 MeV. Because the space charge limit of a synchrotron is very low for low energy, such as 70 MeV, an especially large acceptance ($A_x = 540\ \pi\mu mr$, $A_y = 430\ \pi\mu mr$) is necessary for beam pipes of ISIS in order to accomodate the required intensity of the proton beam. A very powerful rf power supply is also necessary to accelerate high-intesity beams under heavy beam loading. With respect to injection, there are some advantages due to the low injection energy. One advantage is that the H^0 beam (which is spilled at the stripper foil and amounts to about 2 % of the total beam) and a small amount of H^- beam (which is also spilled at the stripper foil) can be stopped in the injection straight section. Another advantage is that halo collection during injection and in the early stage of acceleration is very effective, since the beam energy is low and the amplitude of the betatron oscillation damps with acceleration.

The other is a method using full-energy injection and compression; this method has been adopted at PSR. At first, the H^- beam is accelerated by a linac to full energy, at which the beam is used to generate neutrons in the target. Then, the H^- beam is injected into a synchrotron and compressed to a short beam pulse by means of an rf-bucket. Since the space charge limit is sufficiently high, the synchrotron does not require any especially large acceptance. For example, either A_x or A_y is 120 $\pi\mu mr$ for PSR. Without acceleration, d.c. magnets are adequate for use as synchrotron magnets. In this method, however, beam loss during injection should be reduced to as little as possible, since the injection energy is so very high. How to treat the H^0 and H^- beams spilled at the stripper foil during injection is described in detail in later sections (sections IV and V).

Two charge-exchange injection schemes are applicable for full-energy injection. One is the two-step H^0 injection scheme. The other is the direct H^- injection scheme. In the two-step H^0 injection scheme, the H^- beam transported from the injector linac is first converted to an H^0 beam in a stripper magnet placed just upstream of the synchrotron bend magnet. Then, passing through the magnetic field of the bend magnet, the H^0 beam is injected into a straight section of the synchrotron and charge-exchanged to a proton beam by a stripper foil. The proton beam is finally captured in the synchrotron. In this scheme, the H^0 beam is obtained by converting an H^- beam through magnetic field dissociation (so-called Lorentz stripping) in a stripper magnet. When the beam energy is sufficiently high, the charge-exchange efficiency can be nearly 100 % for an ordinary iron-core stripper magnet. When the beam energy is lower than 800 MeV, however, this scheme is not applicable, since the charge-exchange efficiency rapidly decreases with the beam energy. One of the most atractive features of this scheme is that the injection system is very simple, since the H^0 beam penetrates the synchrotron magnets without any interaction. There are, however, two problems regarding this scheme [4]. One is the problem of the angular divergence accompanying magnetic stripping from the H^- to the H^0 beam; the other is the difficulty to match the H^0 beam to the ring optics. These problems are discussed in section V.

In the direct H^- injection scheme, the H^- beam is guided to an injection magnet placed in a straight section and overlapped an orbit of the proton beam circulating in the synchrotron by the injection magnet. The H^- beam is then injected to the stripper foil and a proton beam formed by stripping is captured in the synchrotron. When the energy of the H^- beam is high, however, the magnetic field of the injection-line magnets should be sufficiently low in order to avoide any magnetic stripping. Thus, the inflection magnet which guides the H^- beam to the injection magnet and the injection magnet, itself, become large; as a result, the total injection system becomes large. Moreovere, because a part of the injected H^- beam is spilled downstream of the stripper foil, not only the H^0 beam but also this spilled H^- beam must be properly treated not to produce severe activation around the injection straight. This problem is described in the following section.

The current charge-exchange injection is, more or less, based on the stripper foil. Though this stripper foil is very convenient for stripping the electrons of high-energy H^- ions or H^0 atoms, it also has many bad effects on the beam: energy loss, emittance growth due to multiple electron scattering and particle loss due to both nuclear and Coulomb scattering. The last effects are especially harmful because the scattered particles can not be controlled, resulting in activation of the ring. In order to reduce this uncontrolled beam loss, the foil-hitting probability of accumulated particles is reduced to as low as possible by varying the injection bump orbit in such a way that the orbit of the captured beam goes away from the stripper foil. It is for the same purpose that such a special-shape stripper foil as a postage-stamp foil [5] or the corner foil [3][6] be developed. Recently, a high-power laser beam has been proposed to replace the stripper foil in the two-step H^0 injection scheme in order to avoid these harmful effects of the stripper foil [7]. This new injection scheme with a laser beam is briefly discussed in section VI.

Another important item regarding injection is phase space painting, which is a method used to control the particle distribution in the ring beam phase space, so that space-charge effects of the accumulated beam are as small as possible. Beam-painting methods both in transverse and longitudinal phase space have been investigated and sophisticated methods are proposed [8]. In any case, phase-space painting should be consistent with any reduction of the foil-hitting probability.

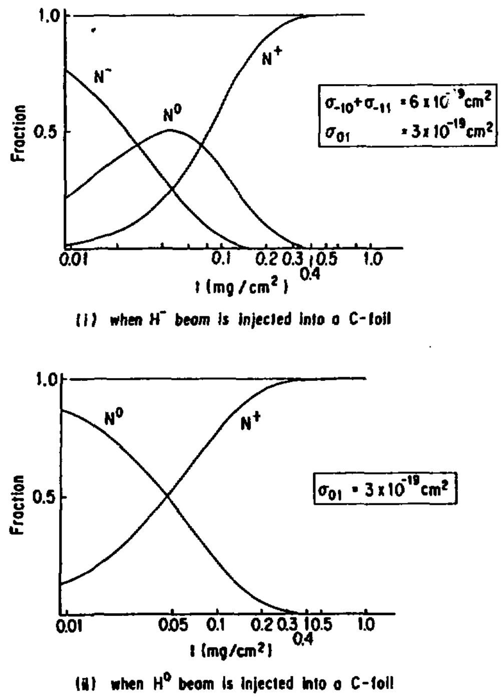

Fig. 1 Dependence of the charge state distribution upon thickness of the carbon foil. Beam energy is 1 GeV.

III. SCATTERING BY THE FOIL ATOMS AND CAUSES OF SPILLING H^0 AND H^- BEAMS

When a 1-GeV H^- or H^0 beam traverses a thin carbon foil, the charge state distribution of the beam changes, depending upon the foil thickness (Fig. 1). These curves were calculated with the cross sections shown in the figure. In order to convert an injected beam to a proton beam with an efficiency of 98%, a stripper carbon foil with a thickness of 300 or 250 μg/cm^2 is necessary for th H$^-$ or H^0 injected beam, respectively. The effects of this foil to the beam is as follows in the case o direct H$^-$ injection (the estimation method is described in ref. [3]):

- Energy loss per passage (ΔE) is ~600eV.
- Emittance growth per passage ($\Delta\varepsilon$) is ~0.005 πμmr when the emittance of an injected beam is 1. πμmr and the beta-function at the foil is 15 m.

Though these are not so large, and even negligible when the average foil passage number is severa tens, beam losses due to scattering by foil atoms and nuclei are far more severe:

- The beam loss rate per passage due to nuclear scattering (L_n) is ~5.6×10^{-6}.
- The beam loss rate per passage due to large-angle Coulomb scattering (L_c) is ~4.0×10^{-6}, provide that particles scattered by an angle larger than 2.8 mr are lost.
- The beam loss rate per passage due to large energy transfer (L_s) is ~1.3×10^{-5}, provided tha particles which lose an energy larger than 1 MeV become lost from the rf bucket.

Thus, the total beam loss rate (L) is

$$L = L_n + L_c + L_s = 2.2 \times 10^{-5}. \qquad (1)$$

This means that when the accumulated particles pass the foil an average of 50 times, the fraction o the lost beam particles reaches 1.1×10^{-3} and the lost current exceeds 0.2 μA. In the JHP case, i order to accumulate 2.5×10^{13} protons the H$^-$ beam should be injected during 600 turns of the rin cycle; accumulated particles pass the foil location 300 times on the average. Therefore, the foil-hitting probability should be suppressed to 10 % or lower. As far as the foil-hitting probability is concerned, the lower the better.

In order to reduce the foil-hitting probability, the foil is placed outside of the ring acceptance and the proton beam captured in the ring is moved away from the foil as soon as possible by varying the injection bump orbit. Moreover, the shape of stripper foil is designed as the postage stamp or the corner foil shown in Fig. 2, and the injected beam is positioned just inside of the foil edge. Fig. 3 schematically shows the situation regarding the foil and beams both upsream and downstream of the foil in the case of direct H$^-$ injection. There are three beams downstream of the foil: a proton, H$^-$ and H^0. Because the H$^-$ beam is injected just inside of the foil edge, it is very possible for a part of beam periphery to wander out of and miss the foil. This part thus remains as a H$^-$ beam. The amount of this part is expected to widely vary from negligible to several % of the injected beam, depending upon the partcle distribution of the beam and the beam positioning in the foil. Although several % of the beam is far more than the amount of the part lost by scattering, this part can be controlled and transported to a beam dump with a suitable beam guiding system. The H^0 beam downstream of the foil is produced from the main part of the injected beam, and amounts about 2 % of the beam or ~4 μA. This part is also controllable and is produced as a result of selecting a

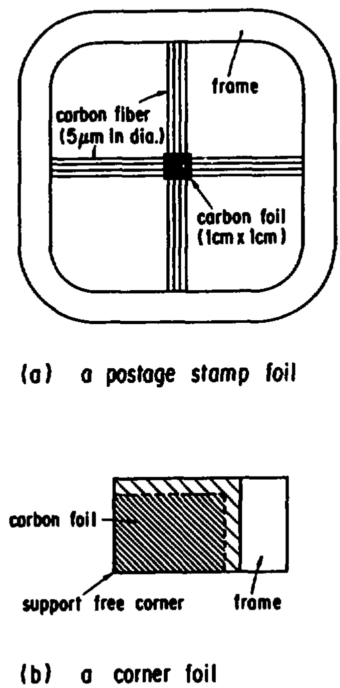

Fig. 2 A postage-stamp foil and a corner foil.

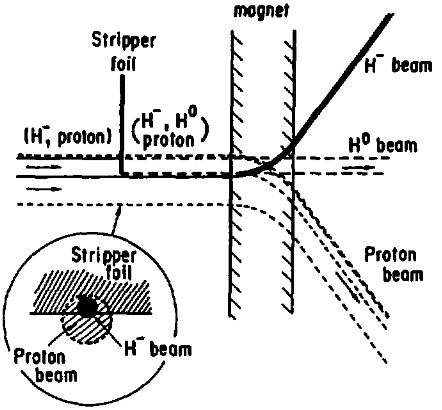

Fig. 3 Beams upstream and downstream of the stripper foil during H- injection.

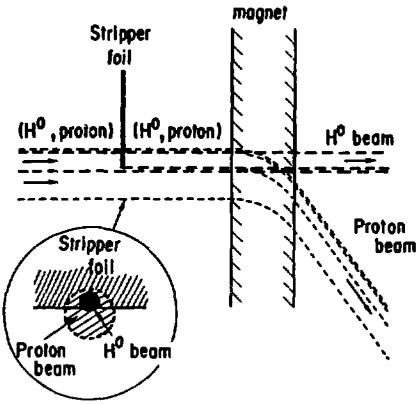

Fig. 4 Beams upstream and downstream of the stripper foil during H^0 injection.

thinner foil with a 98 % charge-exchange efficiency in order to reduce any uncontrollable beam loss due to scattering. This H^0 beam is considered to be as stable as an injected H^- beam and is desirable to be transported to an experimental room for experimental usage.

The case of H^0 injection is illustrated in Fig. 4. For the same reason as in H^- injection, the H^0 beam is injected just inside of the foil edge; a part of the beam periphery misses the foil. About 2 % of the beam which passes the foil also remains as an H^0 beam without being charge-exchanged to a proton beam. In this case, however, both of these parts are of the same kind and comprise an H^0 beam. This H^0 beam has a current of several μA and is considered to be useful in physics experiments.

In both of the cases mentioned above, one or two beams with probably several μA intensity are spilled downstream of the foil. This beam current is higher than the empirical limit (0.3 μA) of the beam loss by more than one order of magnitude. Thus, if several % of these spilled beams is lost, significant activation occurs around the injection straight section. We can not be too careful in the treatment of these spilled beams.

IV. DIRECT H- INJECTION SYSTEM FOR A SUFFICIENTLY LONG STRAIGHT SECTION

Though examples of sufficiently long straight sections used to insert a direct H^- injection system are found in papers of G. H. Rees [6] and E. P. Colton [9], neither of these papers describe in detail the treatment of spilled H^0 and H^- beams. Although we can consider a complicated and sophisticated system for the direct H^- injection system, we restrict ourselves to a rather simple system and do not deal with any unnecessarily complicated systems.

Roughly grouping, there are four components necessary for a direct H^- injection system:
- a set of dipole magnets to form an injection bump orbit,
- a stripper foil,
- an inflection magnet system to guide the injected H^- beam near to the injection magnet, and
- an extraction magnet system for spilled H^0 and H^- beams.

In order to suppress any emittance growth and particle loss at the stripper foil as little as possible, the beta-function of the ring optics should be small at the foil in both horizontal and vertical planes. Requiring, furthermore, easiness to match the injected beam to the ring optics, we consider a special insertion that has a waist with a sufficiently small beta-function (= 3 m) in both planes at the center. At each end of this insertion, a set of quadrupole magnets is placed to match the insertion optics to the adjacent ring optics. Therefore, the four components mentioned above should be accommodated between these adjacent quadrupole magnets. Hereafter, this insertion is called "injection insertion".

When the waist with a β_0 beta-function is formed at the stripper foil, the β beta-function at a point with a distance of L from the foil is given by

$$\beta = \beta_0 + L^2 / \beta_0. \tag{2}$$

When we take a moderate value of 15 m for the beta-function at the end of the injection insertion, then

$$L = 6\,\mathrm{m} \qquad (\text{where } \beta = 15\,\mathrm{m}). \tag{3}$$

This means that a typical length of such an insertion may be about 12 m.

Figs. 5 and 6 show examples of a conceptual design which arranges four components in the above mentioned insertion. Fig 5 shows an example which conducts both the H^0 and H^- beams together to a beam dump. On the other hand, Fig. 6 shows an example which separately conducts the H^- beam to a beam dump and the H^0 beam to an experimental room.

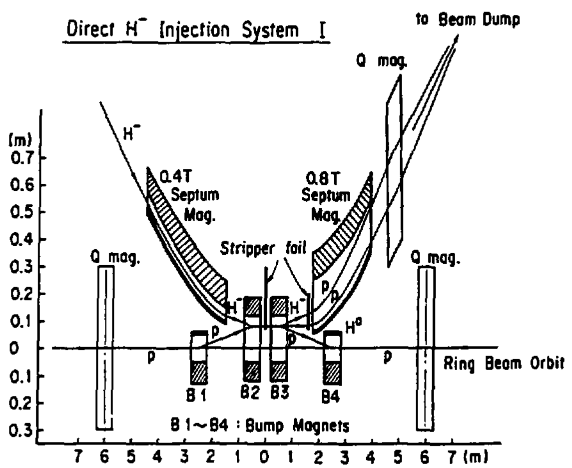

Fig. 5 Direct H^- injection system I.

The second bump magnet is called "injection magnet" in this paper. The maximun displacement of the bump orbit is usually taken so that the stripper foil at which the orbit passes comes out of the ring acceptance. Here, it is taken as 80 mm so as to meet further requirements as well; the spilled H^0 beam should sufficiently clear the fourth bump magnet and should not require a long distance for the proton beam to separate from the H^0 beam by enough space to insert the septum coil of the bump magnet between them. In such a situation, two outer bump magnets, the inflection magnet and the extraction maget should be of the septum type. The magnetic field of the inflection magnet should be taken to be lower than 0.4 T in order to avoid considerable amount of magnetic field dissociation of the injected H^- beam. It takes more than 3 m to inflect a 1-GeV H^- beam by 30 cm. Spilled H^0 and H^- beams are extracted with a septum magnet after being converted to proton beams by a stripper foil. In order to extract these beams 30 cm from the bump orbit, a septum magnet of about 2 m is necessary when a 0.8 T magnetic field is available for the septum magnet. When both spilled H^0 and H^- beams are extracted together, as shown in Fig. 5, the first quadrupole magnet downstream of the septum requires a very large horizontal aperture, since these two beams are considerably separated from each other.

When a spilled H^0 beam is used for experiments, it may be desirable that the control of one beam does not affect the other beam, as shown in Fig. 6. In both cases illustrated in Figs.5 and 6 it may be considerably useful to monitor the current and profile of each beam at a location where these beams clearly separate from each other.

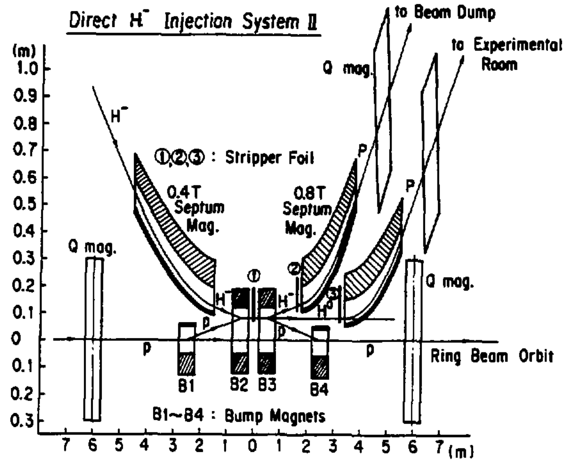

Fig. 6 Direct H⁻ injection system II.

V. H^0 INJECTION SYSTEM FOR A SHORT STRAIGHT SECTION

The typical length of a straight section may be 5 or 6 m for an 800-MeV or 1-GeV synchrotron with a usual higher symmetric FODO lattice. It is impossible to insert the injection insertion described in the last section in such a short straight section. Even if the ring lattice is used as it is without any insertion and, moreovere, the bump orbit is formed with an aid of the lattice focusing force, the straight section is not sufficiently long to accommodate all of the stripper foil, the injection magnet, the inflection septum magnet for the injected H⁻ beam and the extraction septum magnet for the spilled H^0 and H⁻ beams. It is therefore very difficult to accommodate a direct H⁻ injection system in a straight section of this type ring. When one is accepted as the superperiodicity, a special H⁻ injection system may be considered [10]. In such a system, treatment of the spilled H^0 and H⁻ beams is also one of the major subjects.

On the other hand, a two-step H^0 injection system is capable of being accommodated in a short straight section, since it does not have any inflection magnet for the injected H⁻ beam or any extraction magnet for the spilled H⁻ beam. Fig. 7 shows an example of a two-step H^0 injection system. The H^0 beam, which is formed in the stripper magnet, passes the gap of a synchrotron bend magnet without interaction and injects to the stripper foil. The stripper foil is placed outside of the ring acceptance. The proton beam formed at the foil is captured on an orbit oscillating around the bump orbit. As the bump orbit is varied, the captured proton beam wanders away from the foil and a continuously formed proton beam is painted over the phase space of the ring beam. One spilled beam is an H^0 beam which consists of two parts (as described in section III). Because the current of this H^0 beam amounts to several μA, it should be transported and used in an experimental room

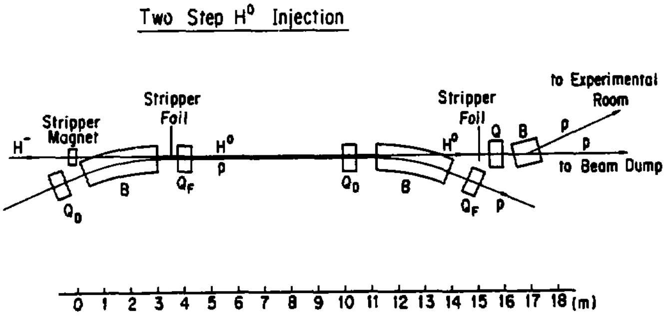

Fig. 7 Example of a two-step H^0 injection system.

after passing any current and profile monitors to obtain useful imformation concerning the injection tuning. It should be noticed that this type injection system is also applicable to the arc part of a racetrack-type ring where there is no straight section, except for very short spaces between the bend and quadrupole magnets.

A two-step H^0 injection system has been constructed and operated for several years at PSR. In the system at PSR, the stripper foil is placed at a location different from that shown in Fig. 7 and shortly downstream of the Q_F guadrupole magnet. This difference is very important to the matching of the H^0 beam to the ring optics [11]. The PSR injection system also has no magnet to switch the spilled H^0 beam to the experimental room. Experience at PSR have indicated that two-step H^0 injection has two problems [4]. One is an angular divergence accompanying the charge-exchange process in the stripper magnet, and the other is a mismatch of H^0 beam to the ring optics at the stripper foil.

Because the magnetic field dissociation is a stochastic phenomenon, the place where each H^- ion is changed to an H^0 atom is distributed along the beam path in the stripper magnet. Thus the distribution of the path length, over which each particle flies as an H^- ion, results in an angular divergence or an emittance growth of the formed H^0 beam. When the beta-function of the H^- beam at the stripper magnet is β^- and the r.m.s. angular divergence is $\Delta\phi$, r.m.s. emittances ε^- and ε_0 of the H^- and H^0 beam have the relation:

$$\varepsilon_0 = K\,\varepsilon^-, \text{ and} \quad (4)$$
$$K = \mathrm{SQRT}\{\,1 + \beta^-(\Delta\phi)^2/\varepsilon^-\,\}, \quad (5)$$

where both the phase-space particle distribution of the H^0 and H^- beams and the distribution of the angular divergence are assumed to be Gaussian. This angular divergence becomes smaller when the field gradient at the place where the stripping mainly occurs becomes steeper. The stripper magnet of PSR is an iron-core magnet which has a special pole shape in order to generate a very high field gradient [12]. Since the main gap is required to generate a field higher than 1.8 T, it is as narrow as 11 mm. Furthermore, a vacuum envelope is also inserted in the gap. As a result, the aperture for the beam is only 10 mm. In the bending plane, however, the aperture is as wide as 53 mm. The JHP compressor/stretcher ring proposal also assumes a similar stripper magnet. In such a stripper magnet, $\Delta\phi$ is ~0.37 mr for an 800-MeV beam; it is estimated to be ~0.26 mr for a 1-GeV beam. K thus has a value of about 3 for usual operation of PSR; a similar value is expected for the JHP proposal.

The other problem is that the H^0 beam formed by the above-mentioned stripper magnet can not be sufficiently matched to the ring optics at the foil. Since this problem is discussed in detail in another paper [11], only some important points are described here. In the H^0 injection system of PSR, the stripper foil is located shortly downstream of a Q_F quadrupole magnet and the bending plane of the stripper magnet is horizontal. With this arrangement, the H^0 beam may be matched in the vertical plane, but hardly in the horizontal plane. Because the gap of the stripper magnet is narrow, it is also difficult to perfectly match in the vertical plane. On the other hand, the stripper foil is placed between a bending magnet and the following Q_F quadrupole magnet and the bending plane of the stripper magnet is set to be vertical in the case of JHP proposal as shown in Fig. 7. In this case, the H^0 beam can be matched both in horizontal and vertical planes. A small mismatch, however, can not be actually avoided, since matching at the foil contradicts any suppression of emittance growth in the stripper magnet. The degree of this mismatch is defined by a mismatch factor [4],

$$C = (\beta_0\gamma - 2\alpha_0\alpha + \beta\gamma_0)/2, \quad (6)$$

where (β_0, α_0, γ_0) and (β, α, γ) are Twiss parameters of the H^0 beam and the ring optics at the foil. When matching is perfect, C reduces to 1. We then have

$$\varepsilon = C\,\varepsilon_0, \tag{7}$$

where ε is the emittance of the just-formed proton beam, and the tail of the proton distribution becomes longer than the Gaussian distribution [13]. The mismatch factor for the PSR is about 3.5 in the horizontal plane; for the JHP proposal, the mismatch factors are 1.2 and 1.6 in the horizontal and vertical plane, respectively.

VI. DISCUSSION

For full energy injection, a direct H^- injection scheme or a two-step H^0 injection scheme may be applicable. Direct H^- injection does not introduce any emittance growth like that which occurs in the stripper magnet, and is able to match the H^- beam to the ring optics at the stripper foil. However it requires a ring with a especially long straight section since a direct H^- injection system is considerably long (as is described in section IV). On the other hand, although two-step H^0 injection has noticeably atractive features (simplicity of the injection system and wide applicability to various types of rings), it introduces a beam angular divergence in the stripper magnet and an optical mismatch at the stripper foil. These eventually result in an emittance growth with a factor (K x C), where K and C are defined in equations (5) and (6), respectively. So it is desirable to minimize (KxC) factors in both horizontal and vertical planes. Minimization of these factors is described in another paper [11]. This emittance growth is basically caused by the angular divergence. Although the mismatch of the H^0 beam to the ring optics can be completely removed when the angular divergence becomes small, a small emittance growth in the stripper magnet cannot be removed. Therefore, when we can tolerate a small emittance growth, the two-step H^0 injection is very useful. Otherwise, we should adopt the direct H^- injection scheme and a ring with a sufficiently long straight section.

It may be worthwhile to examine the feasibility of a split-type superconducting solenoid as a new type of stripper magnet. An 8 T split coil magnet with a sufficiently wide gap is now commercially available. It may be possible to design a superconducting stripper magnet having a field gradient in the coil region that is a few times higher than that produced by an ordinary iron core stripper magnet. In the proposal for JHP, H^- to H^0 conversion mainly takes place around a point with 1.3 T, and the r.m.s. angular divergence is estimated to be 0.26 mr when the field gradient is 1.29 T/cm. Due to the proposed optics the emittance growth K in the stripper magnet is estimated to be 2.8 and the mismatch factor C in the vertical plane 1.6. If the field gradient is made higher and the angular divergence smaller by a factor 3, K will be reduce to 1.4 and C to 1, giving a perfect match. The mismatch in the horizontal plane may be easily removed by moving the waist slightly upstream of the stripper magnet, since the small mismatch in the proposal for JHP is to be produced by placing the waist at the gap of the stripper magnet. Furthermore, if a stripper magnet has a very high maximum field, a very steep field gradient and a beam aperture slightly larger than the currently available stripper magnet, the applicability of the two-step H^0 injection scheme is extended to such a low injection energy as the scheme is not applicable at the moment.

As described in section III, the stripper foil has many bad effects on the beam. Uncontrollable beam loss due to scattering is not negligible, especially in the full-energy injection scheme. To avoid this difficulty, it has been proposed to use a high-power laser beam instead of a foil [7]. This is a new type of two-step H^0 injection scheme. The first step involves magnetic field dissociation using a stripper magnet; the second step nvolves photoionization using a high-power laser beam. The reason why the first step does not use a laser beam is that the cross section of the photodetachment reaction (

$H^- + h\nu \rightarrow H^0 + e$) is very small. This photodetachment reaction has been fully investigated both theoretically and experimentally [14], and it is known that the cross section has the maximum value 4 x 10^{-17} cm^2 when the photon wavelength is 0.8 μm. Photoionization during the second step uses a two-step ionization ($H^0(1s) + h\nu \rightarrow H^0(2p)$ and $H^0(2p) + h\nu \rightarrow p + e$) instead of direct ionization ($H^0(1s) + h\nu \rightarrow p + e$), since the cross section of the last reaction is also as small as ~10^{-17} cm^2. The cross sections, $\sigma_{1s\rightarrow 2p}$ and $\sigma_{2p\rightarrow ion}$, of the former reactions are both ~10^{-15} cm^2 and these reactions become applicable for charge-exchange injection into a synchrotron when a laser beam with ~100 kw/cm^2 as the power density is available. Actually, in order to cover the usual beam size (several mm in diameter) and momentum spread ($\Delta p/p \sim 10^{-3}$) of a conventional injected beam, a charge-exchange system requires several commercially available standard lasers. A system using FEL (Free Electron Laser) is also applicable and may be advantageous in covering the momentum spread of the injected beam, since its intrinsic wavelength spread is fairly large. In any case, these systems seem to be quite complex. Because the area around the injection straight section is apt to contain a considerably high radiation field, any system installed in the area should be sufficiently tolerant to radiation and free from too much maintenance and tuning work which involves directly touching the machine.

VII. SUMMARY

Two methods are applicable to generate a high-intensity pulsed proton beam for a spallation neutron source. One is a low-energy injection and acceleration method and the other is a full-energy injection and compression method. The latter method has two options regarding its injection scheme: the direct H^- injection scheme and the two-step H^0 injection scheme.

Although full-energy injection is advantageous with respect to the space-charge limit, beam loss due to scattering by stripper foil atoms is very harmful. In order to suppress the amount of uncontrollable beam loss to a tolerable level, we should, instead, accept some fraction of the injected beam being spilled downstream of the stripper foil. This spilled beam is controllable and should be carefully treated, since it amounts to several μA and has two components.

A standard direct H^- injection system consists of four components: a stripper foil, a set of bump magnets, an inflection magnet system for the injected H^- beam and an extraction magnet system for the spilled H^- and H^0 beams. Because the entire injection system becomes considerably long, it requires an especially long straight section, as in a racetrack-type ring.

On the other hand, the two-step H^0 injection system does not require such a long straight section, since both injected and spilled H^0 beams pass through ring magnets without interaction. It thus has a very wide applicability to various types of rings.

Two-step H^0 injection, however, has two problems: an angular divergence due to the stripping process in the stripper magnet and a mismatch of the H^0 beam to the ring optics. In the case of the FODO lattice, the mismatch can be removed by placing the foil between the bend and the following quadrupole magnet and setting the bending plane of the stripper magnet to be the same as the divergent plane of the quadrupole magnet.

The emittance growth is based on the angular divergence introduced in the stripping process. If the angular divergence is sufficiently reduced, the mismatch at the foil can be eliminated; the emittance growth at the stripper magnet can also be reduced to a tolerable level.

Though the idea to use a high-power laser beam instead of a stripper foil is atractive, it will require much development for a complicated system comprising a high power laser or FEL to replace a foil, since the foil-hitting probability can be reduced to a tolerable level and the foil does not require so much maintenance service.

ACKNOWLEDGEMENT

The author wishes to express his heartfelt thanks to Prof. M. Kihara for many stimulating discussions and much encouragement.

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