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Perfect matching for two-step H^0 injection into a ring with a DBFO lattice and minimization of the overall emittance growth

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ABSTRACT

A procedure is given for achieving perfect matching in two-step H^0 injection into a DBFO lattice. It is at first shown that the foil should be located between B and F and the stripper magnet should be set so that the bending plane is vertical in order to make the H^0 beam match the ring optics. Then, the Twiss parameters of the H^- beam are determined so as to be converted to those of the H^0 beam which matches the ring optics through the charge-exchange process in the stripper magnet. It is shown that, though perfect matching at the foil can be achieved, the emittance growth in the stripper magnet can not be made to completely disappear. A factor K is defined as a measure of the emittance growth in the stripper magnet. When C is the mismatch factor at the foil, (KxC) is a measure of the total emittance growth during the entire charge-exchange process. The (KxC) factor should be minimized in an actual application, resulting that a small K as well as a small C will remain.

I. INTRODUCTION

When we inject an H^- beam into a synchrotron through charge-exchange injection, a two-step H^0 injection scheme may be applicable, as well as a direct H^- injection scheme, if the energy of the H^- beam is as high as about 1 GeV. Of the two steps, the first is formation of an H^0 beam from the H^- beam by the magnetic field detachment of H^- ions in a stripper magnet. The second step is the stripping of the H^0 beam by a stripper foil. The H^0 beam is injected into the foil by passing it through the magnetic field of the synchrotron magnets without any interaction. The formed proton beam is finally captured in the synchrotron.

This method has been adopted in LANL PSR. The following two problems have been found from several years of operational experience[1]. One is beam angular divergence due to the stripping process in the stripper magnet; the other is an ion-optical mismatch of the H^0 beam with the ring optics at the stripper foil. Both of these bad effects result in emittance growth; a considerably large increase of emittance can be introduced during the entire charge-exchange process from an H^- to a proton beam. The two-step H^0 injection scheme, however, is very widely applicable to various types of rings, since a system of the scheme is very simple. This scheme may be very attractive when a highly symmetric ring is desirable for some reason, or when many straight sections must be devoted to the slow extraction system and/or the rf system to form extremely short beam bunches like the JHP compressor/stretcher ring. It is very important to understand the full potential of the two-step H^0 injection scheme. We, therefore, discuss how to perfectly match the beam with the ring optics in this scheme and how much the beam emittance grows as a result. It is also discussed how small the emittance growth can be made.

II. THE MISMATCH FACTOR, C, AND AN H^0 BEAM MATCHED WITH THE RING OPTICS

Suppose that a beam with Twiss parameters β_0, α_0 and γ_0 is injected into a ring point where the Twiss parameters of the ring optics are α, β and γ. In this case, mismatching makes the emittance of the beam formed in the ring, ε, larger than the emittance of the injected beam, ε^0, by a so-called mismatch factor C:

$$C = (\beta_0\gamma + \gamma_0\beta - 2\alpha_0\alpha) / 2, \text{ and} \quad (1)$$

$$\varepsilon = C\varepsilon^0. \quad (2)$$

If the particle distribution of the injected beam is Gaussian, the distribution tail of the formed beam becomes slightly longer than the Gaussian [2]. When matching is perfect, β_0, α_0 and consequently γ_0 are equal to β, α and γ, respectively, and C reduces to 1.

We now suppose injection of an H^0 beam into a ring with a DBFO lattice using charg-exchange by a stripper foil. The beta-functions of the ring may be like β_x (horizontal) and β_y (vertical) indicated by the thin solid lines in Fig. 1. This is an example from the case of the JHP compressor/stretcher ring [3]. The stripper foil is usually placed at the point FOIL1 or FOIL2 between the magnets. FOIL1 is the location proposed in the JHP compressor/stretcher ring [4] and FOIL2 is the location adopted at PSR. Beta-functions of the H^0 beam matching at respective foil location are $\beta_x(H^01)$ and $\beta_y(H^01)$ or $\beta_x(H^02)$ and $\beta_y(H^02)$ shown by thick solid or broken lines. As an H^0 beam drifts, even in the field of the bend or quadrupole magnet, its beta-function depicts a parabola that connects with the ring beta-function in such a manner that $\beta(H^0) = \beta(\text{ring})$ and $\beta'(H^0) = \beta'(\text{ring})$ at the foil location. Here, the emittance growth due to multiple scattering in the foil is supposed to be negligibly small, since the beam energy is sufficiently high and the average foil hitting number can be sufficiently small [4]. As

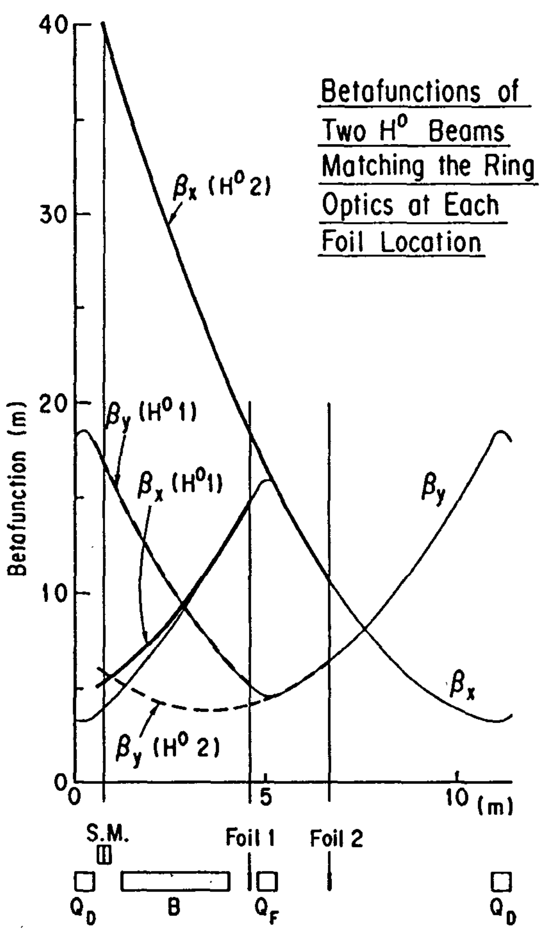

Fig. 1 Two H^0 beams matching the ring optics at the locations of FOIL1 or FOIL2. β_x and β_y are the ring beta-functions in the horizontal and vertical planes, respectively. $\beta_x(H^01)$ and $\beta_y(H^01)$ [$\beta_x(H^02)$ and $\beta_y(H^02)$] are also horizontal and vertical beta-functions of the H^0 beam matching with the ring optics at the locations of FOIL1 [FOIL2].

can be seen from this figure, beta-functions of the matched H^0 beam depend strongly upon which location the foil is placed (between B and Q_F or between Q_F and Q_D), but not so strongly upon the difference of the foil location between the two magnets for each case.The stripper magnet is placed imediately upstream of the bend magnet (shown as S.M. in the figure).

In order to generate a very high maximum field as well as a very high field gradient, the gap of the stripper magnet is considerably narrow; consequently, half of the beam aperture is as narrow as 5 mm for a currently available stripper magnet. The beam aperture in the bending plane may be taken to be sufficiently wide. Thus, when the foil is placed at the FOIL2 location, the stripper magnet should be set with the gap vertical and the bending plane horizontal. In this case, the horizontal beam size and, correspondingly, the horizontal emittance growth becomes very large in the stripper magnet. On the other hand, when the foil is placed at the FOIL1 location, it is necessary to set the stripper magnet with the gap horizontal and the bending plane vertical. This is because the vertical beam aperture is not sufficiently wide to accomodate the entire beam, including a 5σ emittance with a considerably large beta-function. For example of the JHP proposal, the 3σ emittance of the injected H^- beam is assumed to be 1.44 $\pi\mu$mr. Then, provided that the vertical beta-function is 16.69 m, a half of the 5σ beam size is 8.2 mm and can not go through the 5 mm wide half aperture.

Comparing FOIL1 and FOIL2 as the foil location, FOIL2 has a disadvatage in that the beta-function $\beta_x(H^02)$ becomes very large at the stripper magnet. It is therefore better to place the stripper foil at the location of FOIL1. In the JHP case, ring Twiss parameters at FOIL1 are as follows:

$$\beta_x = 14.84 \text{ m}, \alpha_x = -1.78 \quad \text{and} \quad \beta_y = 5.136 \text{ m}, \alpha_y = 0.867. \tag{3}$$

We have then following Twiss parameters for the H^0 beam at the stripper magnet:

$$\beta_x(H^01) = 5.348 \text{ m}, \alpha_x(H^01) = -0.709 \text{ and } \beta_y(H^01) = 16.69 \text{ m}, \alpha_y(H^01) = 2.17. \tag{4}$$

III. MATCHED H^- BEAM AND THE EMITTANCE GROWTH FACTOR, K

The stripper magnet converts an H^- beam to an H^0 beam by magnetic field detachment of H^- ions with high velocity [5] [6]. Because this detachment is a stochastic process, a distribution is introduced to path lengths that particles fly as H^- ions before being changed to H^0 atoms. The angular divergence of the beam takes place corresponding to the distribution of angles by which particles are bent by the magnetic field while they are H^- ions. The angular distribution is well fitted to a Gaussian distribution, and the r.m.s. angular divergence can be estimated from the field distribution in the stripper magnet. With the stripper magnet of PSR, the r.m.s. angular divergence is 0.37 mr for an 800 MeV H^- beam. With the same stripper magnet, the r.m.s. angular divergence is estimated to be 0.26 mr for a 1 GeV H^- beam.

When the r.m.s. emittance and Twiss parameters of the injected H^- beam are ε^-, β^- and α^- in the stripper magnet, those of the formed H^0 beam at the same location are described as

$$\varepsilon^0 = K\varepsilon^-, \tag{5}$$

$$\beta(H^0) = \beta^- / K, \text{ and} \tag{6}$$

$$\alpha(H^0) = \alpha^- / K, \tag{7}$$

where

$$K = \text{SQRT}\{ 1 + \beta^-(\Delta\phi)^2 / \varepsilon^- \}. \tag{8}$$

$\Delta\phi$ is the r.m.s. angular divergence in the stripper magnet. K is the rate of emittance growth in the stripping process, hereafter called the emittance growth factor. The beta-function of the H^- beam that is to be converted to an H^0 beam with a given beta-function $\beta(H^0)$ is derived from equations (6) and (8) as follows,

$$\beta^- = \{ (\beta(H^0)\, \Delta\phi)^2 / \varepsilon^- + SQRT\{ [(\beta(H^0)\, \Delta\phi)^2 / \varepsilon^-]^2 + 4\, [\beta(H^0)]^2 \} \} / 2. \quad (9)$$

Using these equations, vertical Twiss parameters and the emittance growth factor of the H^- beam (which is converted to the H^0 beam matched with the ring optics at the FOIL1 location) are obtained as follows:

$$\beta_y^- = 120 \text{ m}, \qquad \alpha_y^- = 15.6, \text{ and} \quad (10)$$
$$K_y = 7.2. \quad (11)$$

Since there is no angular divergence in the horizontal plane, Twiss parameters don't change, and we have

$$\beta_x^- = 5.348 \text{ m}, \qquad \alpha_x^- = -0.709, \text{ and} \quad (12)$$
$$K_x = 1. \quad (13)$$

Although β_y^- is considerably large, the vertical beam size is not so large, since the emittance of the H^- beam is sufficiently small. There is therefore no problem in forming such an H^- beam in the injection beam line. The emittance growth in the stripper magnet, however, is as large as 7.2.

It is thus possible to form an H^- beam which is converted to an H^0 beam matching the ring optics at the stripper foil. However, the beam emittance becomes considerably large. As the equation (8) implies, K becomes smaller as the beam size becomes smaller. However, if β_y^- is made smaller in order to reduce the emittance growth in the stripper magnet, of course, the formed H^0 beam becomes unmatched with the ring optics and some emittance growth occurs at the stripper foil corresponding to the mismatch factor.

IV. MINIMIZATION OF THE TOTAL EMITTANCE GROWTH DURING THE TWO-STEP CHARGE-EXCHANGE PROCESS

As can be seen from equations (2) and (5),

$$\varepsilon = (KxC)\, \varepsilon^-. \quad (14)$$

This means that the overall emittance growth during the two-step charge-exchange process can be expressed by the factor (KxC). It is therefore the minimum (KxC) that indicates the best condition to be realized. We should thus select the direction of stripper magnet and form an H^- beam in such a manner so as to minimize the (KxC) factor. The minimum (KxC) is easily found by calculating a map of (KxC) over the two-dimensional plane of β^- and α^- variables.

(i) When the stripper foil is placed at the location of FOIL1 and the stripper magnet at S.M. with the bending plane vertical, the minimum (KxC) in the vertical plane is obtained as

$$K_y x C_y = 4.53, \qquad (K_y = 2.84, \text{ and } C_y = 1.59). \quad (15)$$

The Twiss parameters of the H^- beam at the stripper magnet are

$$\beta_y^- = 16.74 \text{ m} \qquad \text{and} \qquad \alpha_y^- = 2.17. \tag{16}$$

In the horizontal plane, a matched H^0 beam can be formed from the H^- beam with the Twiss parameter set (12) without any emittance growth in the stripper magnet. We thus have

$$K_x x C_x = 1, \qquad (K_x = 1, \text{and } C_x = 1). \tag{17}$$

(ii) If the increase in the (KxC) factor is shared by both planes, both of the (KxC) factors can be kept at fairly small values. In the last example, the gap direction of stripper magnet is chosen to be horizontal, since a matched H^- beam can pass the gap without any scraping. Conversely, if the gap direction is set to be vertical and the vertical beam size is diminished so that 5σ emittance can pass the gap without scraping, a remarkably small (KxC) can be obtained in the horizontal (or the stripper magnet bending) plane, although a small mismatch factor is introduced in the vertical plane. The result of searching for the minimum (KxC) factor under such a condition is

$$K_x x C_x = 2.13 \qquad (K_x = 1.80, C_x = 1.18), \text{and} \tag{18}$$

$$K_y x C_y = 1.52, \qquad (K_y = 1.00, C_y = 1.52). \tag{19}$$

Here,

$$\beta_x^- = 5.34 \text{ m}, \qquad \alpha_x^- = -0.714, \text{and} \tag{20}$$

$$\beta_y^- = 6.25 \text{ m}, \qquad \alpha_y^- = 0.800. \tag{21}$$

This set of (KxC) factors is considered to be the minimum atainable by the currently available stripper magnet.

V. DISCUSSION

As is shown in section III, when the H^- beam is adjusted on the condition that the stripper foil is placed at FOIL1 of Fig. 1 and the stripper magnet at S.M., with the bending plane vertical, we can make the H^0 beam formed at the stripper magnet or the proton beam formed by the stripper foil perfectly match the ring optics. However, under these conditions a considerably large emittance growth ($K_y = 7.2$) occurs in the bending plane of the stripper magnet. If the increase of KxC is shared by both the horizontal and vertical planes, emittance growth in each plane can be supressed to about 2 ($K_x x C_x = 2.13$, $K_y x C_y = 1.52$) using a currently available stripper magnet. Conversely, this indicates one of the capability limits of the present two-step H^0 injection process. Whether such an amount of emittance growth is permissible or not seems to depend upon the beam condition required for each accelerator. In the case of the JHP compressor / stretcher ring, in order to stack 2.5 x 10^{13} ppp (protons per pulse) a beam with an emittance as large as 30 $\pi\mu$mr is formed from a 1.44 $\pi\mu$mr H^- beam by beam painting. In such a situation, no serious problem can be introduced by a few times emittance growth during the charge-exchange process from an H^- to a proton beam. Beam painting will be slightly influenced by the emittance growth, because the beam size used for painting becomes about one and a half times larger. When such a small emittance growth does not matter, the two-step H^0 injection scheme is very useful since its injection system is very simple and doesn't require such a long straight section as the direct H^- injection system.

The cause of the emittance growth is the angular divergence, $\Delta\phi$, in the stripper magnet. When an H^0 beam with a beta-function of $\beta(H^0)$ is formed from an H^- beam with an emittance ε^-, the emittance growth factor, K, is expressed as

$$K = \{ \beta(H^0)(\Delta\phi)^2/\varepsilon^- + SQRT\{ [\beta(H^0)(\Delta\phi)^2/\varepsilon^-]^2 + 4 \} \}/2. \quad (22)$$

For an r.m.s. emittance of $\varepsilon^- = 0.16\ \pi\mu mr$ and $\beta(H^0) = 16.69$ m, the $\Delta\phi$ dependence of K is shown in Fig.2. This figure shows that $\Delta\phi$ should be reduced in order to suppress the emittance growth. In order to reduce $\Delta\phi$, it is necessary to increase the field gradient of the stripper magnet. A split-type superconducting solenoid may be useful for this purpose.

In paragraph (ii) of section IV, an H^0 beam mismatching with the ring optics is formed to pass through the narrow aperture of the stripper magnet in the gap direction. If the aperture is expanded to twice the size of the currently available stripper magnet, a matched H^0 beam will be formed in the gap direction from an H^- beam with the same Twiss parameters as those of the H^0 beam.

Thus, the angular divergence in the stripper magnet represents the basic shortage of the two-step H^0 injection scheme. However, if a small emittance growth due to the angular divergence is permissible, the scheme will be very useful. The usefulness of the scheme should be raised by improving the stripper magnet to generate a higher field gradient and to have a wider gap.

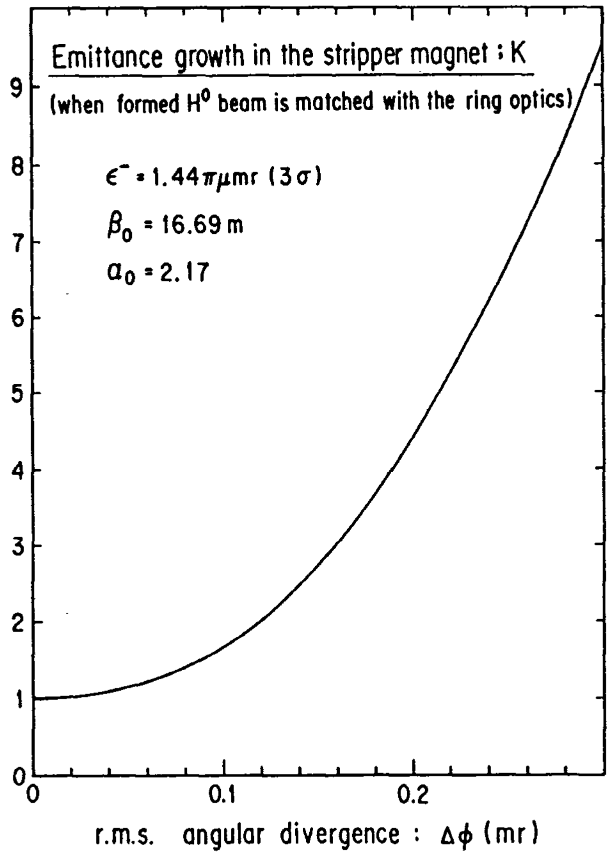

Fig. 2 Dependence of the emittance growth factor, K, upon the angular divergence in the stripper magnet. $\beta(H^0) = 16.69$ m, and ε^- (r.m.s.) = $0.16\ \pi\mu mr$.

VI. CONCLUSION

Using the two-step H^0 injection scheme, an injected beam can be formed so as to perfectly match the beam optics of a synchrotron having a DBFO lattice. Then, however, a large emittance growth occurs in the same plane as that of the bending of the stripper magnet. In the case of the JHP compressor/stretcher ring, the overall emittance growth (KxC) during the charge-exchange process can be supressed to about 2 in both the horizontal and vertical planes by adjusting the emittance growth factor, K, in the stripper magnet and the mismatch factor, C, at the foil. This is one of the capability limits of the present two-step H^0 injection system. If the stripper magnet is improved to have a higher field gradient and a wider gap using such a new technique as the superconducting solenoid, the emittance growth will be made smaller and the two-step H^0 injection scheme will be more useful.

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Q(G.H.Rees): For 2 stage injection (H^-,H^0), have you considered introducing mismatch at the stripping foil to reduce subsequent foil transits?

A(I.Yamane): I have not yet considered. But if we can form a similar beam as the H^- beam by the two step injection, the situation does not differ so much. I think we can form a similar beam except for the emittance growth by the two step H^0 injection. Because of the emittance growth, the beam size becomes a little larger and the foil-bitting probability becomes a little larger.

Q(I.S.K.Gardner): How flexible is the H^0 injection compared with the H^- injection for the correction of small mis-alignments in the linac beam. In the H^0 case will small movements of the beam in the high gradient stripper magnet not cause match charges.

A(I.Yamane): The flexibility in the H^0 injection may be less than in the H^- injection. But the difference is not so large. The beta-function in the stripper magnet usually is considerably small. So movement of the beam in the stripper magnet is considered to be correspondingly small.