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H^- Stripping Simulation with a Magnet and H° Beam Extractor Design

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Abstract

The beam extraction system for the KOMAC[1] (Korea Multi-purpose Accelerator Complex) project is to be designed to partially extract H^- beam at both 100 and 260 MeV. This paper describes a simulation study of charge changing extraction with a stripper magnet and a possible design of a H° extractor by utilizing the simulation study. The method consists of converting the negative hydrogen (H^-) ion beam from the linac to a chosen intensity (0–100%) of neutral hydrogen (H°) beam having an acceptable emittance and drifting it directly onto a stripper foil followed by a downstream beamline.

I Introduction

Korea Atomic Energy Research Institute (KAERI) is planning to develop a 20 MW (1 GeV and 20 mA) cw H^+/H^- linear accelerator under the KOMAC (Korea Multi-purpose Accelerator Complex) project. The KOMAC linac is to accelerate both proton (H^+) and H^- to 1 GeV while partially extracting H^- at 100 and 260 MeV. The main feature of the extraction system is being able to regulate the current of the extracted beam. The extraction method studied for this paper is to utilize a stripper magnet for Stark effect of removal of the weakly bound electron from H^-. In the next section, a simple experimental setup for the simulation study will be described. The result from the simulation study will be given and the beam-extractor design will be followed in the subsequent section.

II H^- Stripping Simulation

A Simulation Setup

Fig. 1 shows a bending magnet through which a H^- beam is passing. H^- starts from 1 m upstream of the magnet center. As the beam is passing through the bender, the H^- beam is being bended by the magnetic field before it is converted to H° by losing an electron. Since the beam is partially extracted, some of H^- becomes a H° and the rest remains as H^-. Both beams are tracked up to 1 m downstream from the magnet center. The magnetic field[2] of the bender is given as

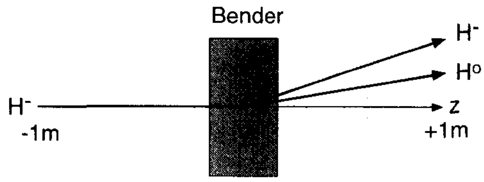

Figure 1: Simulation setup layout.

$$\begin{aligned} B(z) \;=\; & a[(1+g)\tanh\{b(z+c)\} + (1-g)\tanh\{d(z+e)\} + f] \;- \\ & a[(1+g)\tanh\{b(z-c-l)\} + (1-g)\tanh\{d(z-e-l)\} + f]. \end{aligned} \tag{1}$$

Fig. 2(a) shows an example of the bender field where the peak field is given at 2.6 T. The field shape is chosen such that the sharp peak-field strips an electron while the waist field bends the H$^-$ beam. Depending on the current given to the magnet, the field changes. Fig. 2(b) shows that the different magnetic fields possibly be given from the bender. Only the parameter 'a' in Eqn. 1 is varied to generate a different magnetic field shown in Fig. 2(b).

$$\begin{aligned} B(z) = {} & a[(1+g)\tanh\{b(z+c)\} + (1-g)\tanh\{d(z+e)\} + f] \\ & - a[(1+g)\tanh\{b(z-c-l)\} + (1-g)\tanh\{d(z-e-l)\} + f] \end{aligned}$$

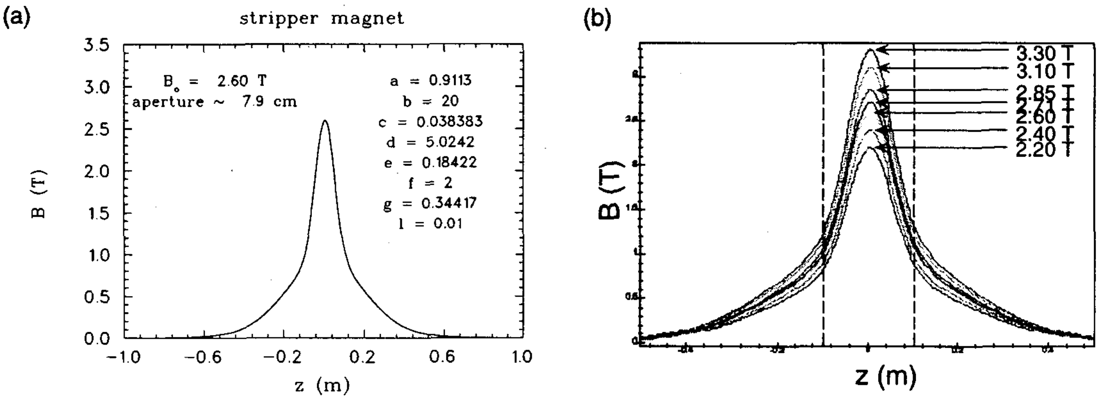

Figure 2: Magnetic field from the stripper magnet.

B Initial Distribution

The initial H$^-$ beam-center is defined to be at $x_o = y_o = 0$ mm and $x'_o = y'_o = 0$ mr. The initial beam distribution is given from the PARMILA output at the end of the coupled-cavity drift-tube linac (CCDTL) as

$$\begin{aligned} \alpha_x &= -0.002, & \beta_x &= -0.5641\,\text{mm/mr}, & \epsilon_x^{\text{rms}} &= 0.334\,\text{mm-mr}, \\ \alpha_y &= -0.002, & \beta_y &= 2.4371\,\text{mm/mr}, & \epsilon_y^{\text{rms}} &= 0.334\,\text{mm-mr}. \end{aligned} \tag{2}$$

The input parameter of the beam edge is set to be 6.6σ truncated Gaussian but since the total number of H$^-$ generated is limited to be 10,000 for the simulation, the edge is determined to be a 4.3σ beam with 6.18π mm-mr emittance.

C Electron Stripping and Tracking H$^-$

The lifetime[3] of H$^-$ is governed by the electric field it sees and it is given as

$$\tau = \frac{a_1}{E}\exp\left(\frac{a_2}{E}\right), \tag{3}$$

where $E = \gamma\beta cB$ is the H$^-$ rest-frame transverse electric field and

$$a_1 = 2.47 \times 10^{-6}\text{V}\cdot\text{s/m} \qquad \text{and} \qquad a_2 = 4.49 \times 10^{9}\text{V/m}. \tag{4}$$

The tracking[4] of H$^-$ is done by solving a first-order differential equation given as

$$\begin{aligned} \frac{dx}{dz} &= \frac{p_x}{p_z}, \\ \frac{dy}{dz} &= \frac{p_y}{p_z}, \\ \frac{dp_x}{dz} &= qB_z\frac{p_y}{p_z} - qB_y, \\ \frac{dp_y}{dz} &= qB_x - qB_z\frac{p_x}{p_z}, \\ \frac{dp_z}{dz} &= qB_y\frac{p_x}{p_z} - qB_x\frac{p_y}{p_z}, \end{aligned} \tag{5}$$

where x, y, z are the spatial coordinates of the tracked particle and p_x, p_y, p_z are the momenta along the given coordinate axes and q is the charge, and B_x, B_y, B_z are the magnetic-field components. The DIVPAG subroutine from IMSL MATH/LIBRARY is being utilized. This subroutine utilizes either the 12th order Adams-Moulton's or Gear's BDF method. This routine is tested with a case with a known analytical solution and it gives an accumulated error of 10^{-10} where 4th order Runge-Kutta gives an error of 10^{-3}.

D Simulation Result

Fig. 3 shows an output from the simulation where the peak field of the bender is at 2.6 T for the 100 MeV H^- beam. Fig. 3(a) is the initial horizontal beam divergence of H^- beam. Fig. 3(b) shows the 45% survived H^- beam after passing through the bender. The mean deflected-angle is 421.3 mr. Fig. 3(c) shows the magnetic field of the stripper with the peak field 2.6 T. The two vertical dashed-lines shows the region (~ 12.6 cm) where the stripping of an electron takes place and the horizontal line displays the minimum field (= 1.77 T) used for the electron stripping. The mean angle for the H^- beam can be estimated to be $\int_{-1m}^{1m} Bdl/B_\rho \sim 448$ mr where B_ρ is the beam rigidity (~ 1.484 T-m for 100 MeV H^- beam). The mean angle for the H^0 beam can be estimated to be $\int_{-1m}^{z_{mean}} Bdl/B_\rho \sim 216$ mr where z_{mean} is the mean axial-position of the extracted H^0-beam. The actual mean-angle for the H^0 beam is 213 mr shown in Fig. 3(d). Fig. 4 shows the result of the simulation study. From Fig. 4(a), the threshold field of stripping an electron at 100 MeV is 1 T and one for 260 MeV is 0.8 T. The minimum field

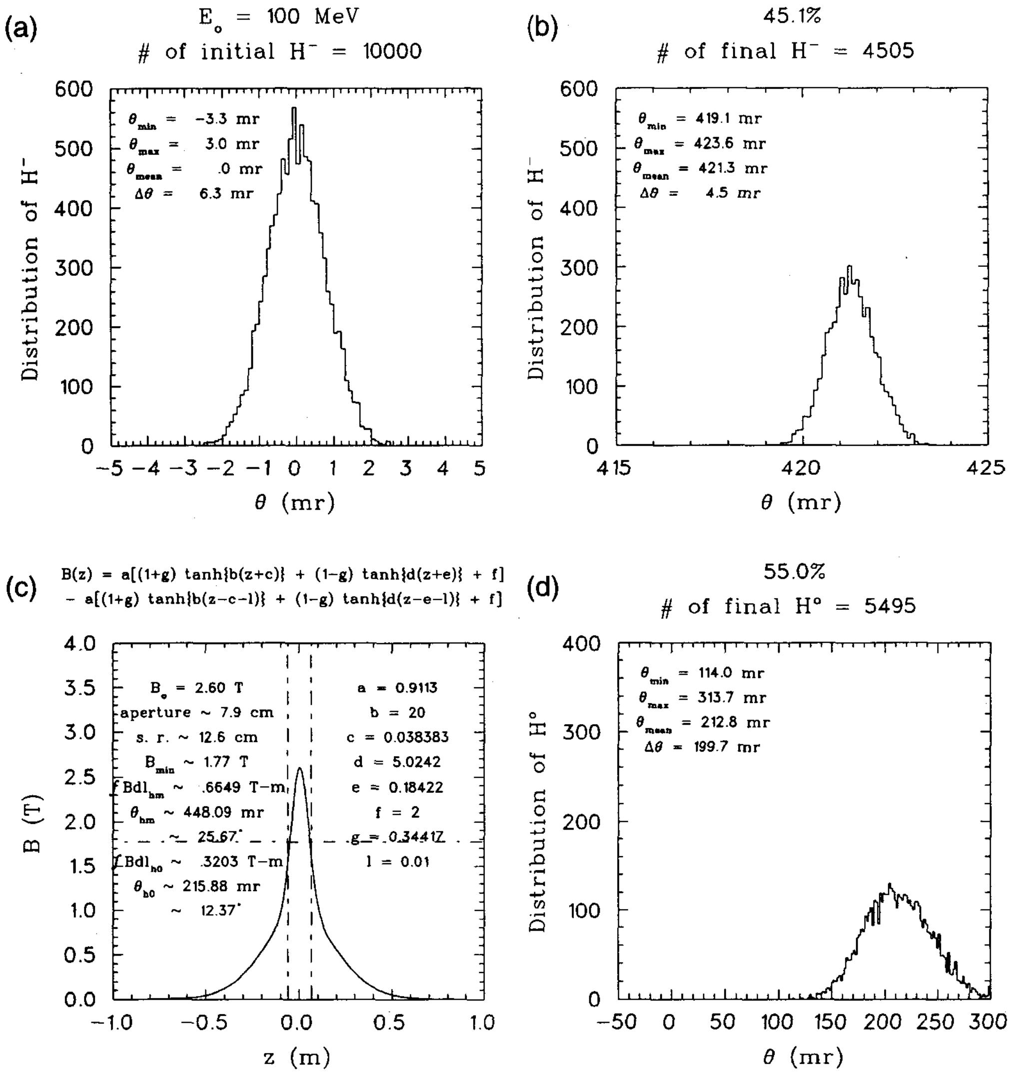

Figure 3: Output from the simulation where $B_0 = 2.6$ T.

needed for 100% conversion of the H^- beam to a H^0 beam is 3.3 T for 100 MeV and 2 T for 260 MeV. Fig. 4(b) shows an important result. For the 100 MeV beam, the H^- beam center sits between 350 mr (~ 20°) and 500 mr (~ 30°) while the H^0 beam center is between 190 mr (~ 11°) and 220 mr (~ 12.6°). For the 260 MeV beam, both beam centers are more than a factor of two smaller than those for the 100 MeV beam as shown in Fig. 4(c). Fig. 4(d) shows that the returned H^--beam to the main linac has no difficulty in dealing with since the beam width gets smaller as the H^- beam converted to H^0. The problem is the width of the H^0 beam as shown in Fig. 4(e). The H^0 beam-width grows almost a factor of 40 for 100 MeV beam. The correlation between the beam width and the stripping region is shown in Fig. 4(f). If we can design a magnet with a sharp peak-field minimizing the stripping region, we can further decrease the H^0 beam width.

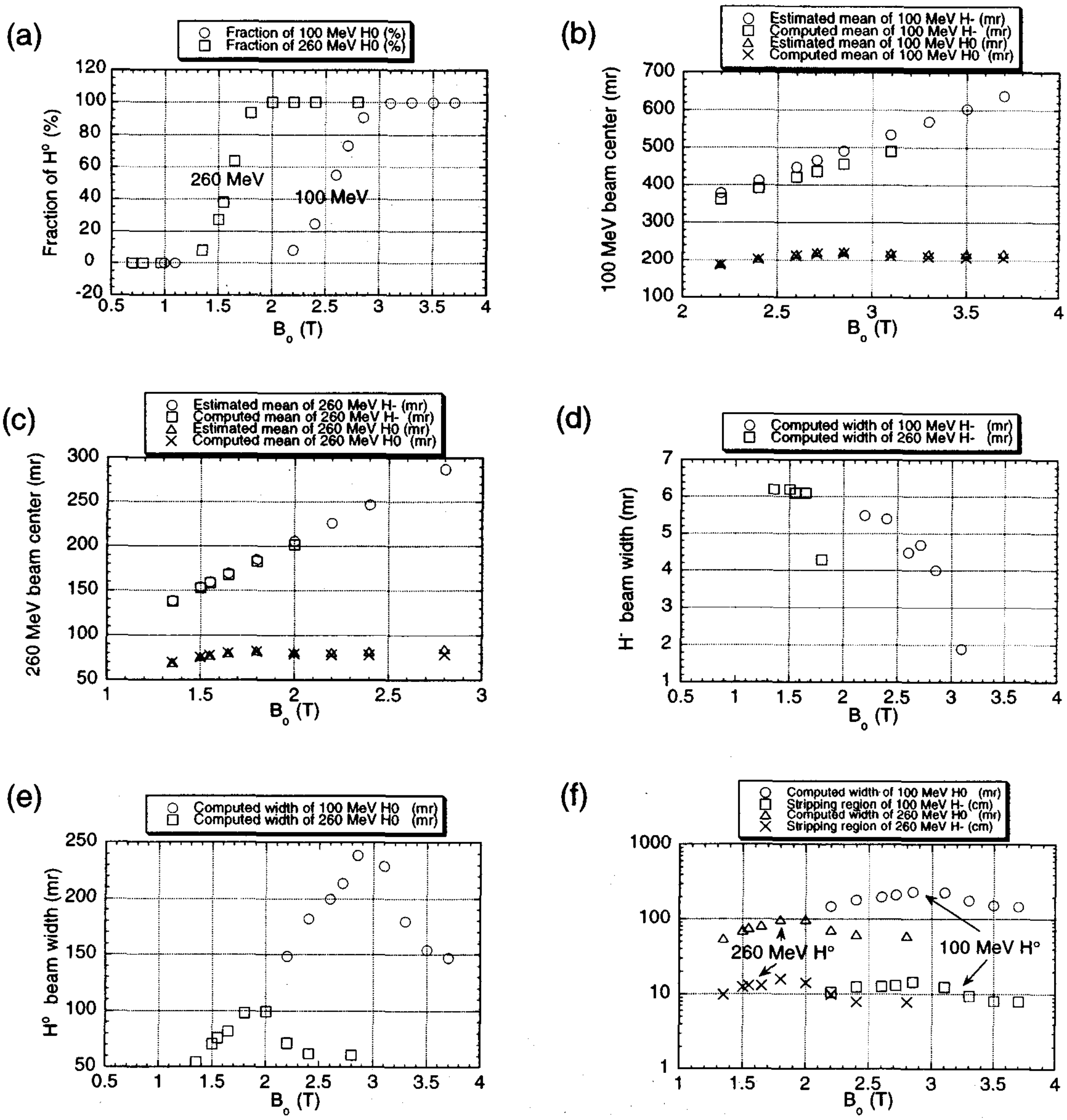

Figure 4: Simulation result.

III Beam Extractor Design

A 100 MeV H^- beam extractor is designed by utilizing the simulation result presented in the previous section. Fig. 5 shows that both H^- and H^0 beams from CCDTL (coupled-cavity drift-tube linac) are deflected by a dipole BM01. The BM01 B-field should be lower than the threshold field of 1 T to disable the production of H^0 beam.

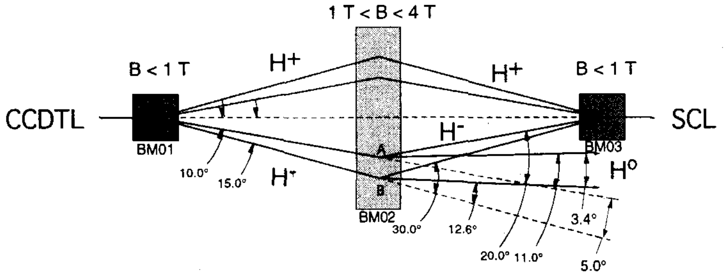

Figure 5: Beam extractor design I.

The bending angle is between 10° and 15°. For a low[*] (high[†]) current extraction, the BM01 bending-angle is close to 10° (15°). The deflected H^- beam then enter the stripper-magnet BM02 where the peak field is larger than 1 T to produce H^0 beam. For the low (high) current extraction, the stripper magnet BM02 produces H^0 beam at 11° (12.6°) from the initial H^- beam direction and bends the survived H^- by 20° (30°). Since the extracted H^0 beams for the two extreme-current cases not only have a 3.4° angular difference but two separated positions, A and B, from which H^0 beam is produced. This place a burden on the downstream H^0 beamline to handle a very large emittance H^0 beam. Fig. 6 shows a simple remedy for the problem. For the low-current extraction, the BM01 field is raised to bend the H^- beam by 20° and by inserting a dipole BM05 between the upstream bender BM01 and the stripper BM02, the H^- beam will be directed to the point O. For the high-current extraction, the BM05 field is turned off and the H^- beams is also directed to the point O. Since the H^0 production is now originated from the single position O, this will reduce the large-emittance requirement for the H^0 downstream line. However, this design still has the 3.4° angular difference between two H^0 beam directions. The remained H^- beam is directed toward the last bender BM03 by a dipole BM06 located downstream of the stripper BM02. For the H^+ beam, the beam direction is symmetrized with respect to the H^- beam by inserting two dipoles, BM07 and BM08, to provide the phase-matching condition for both beams. Finally, Fig. 7 shows the last version of the extractor design. The physical placement of the magnets is the same as the previous one shown in Fig. 6. For the high-current extraction, the BM05 and BM06 fields are turned off. For the low-current extraction, the BM01 bends the H^- beam by 16.6° so that the H^- beam directing to the stripper BM02 only has a 1.6° angular-difference compared to the high-current case. Since the stripper BM02 produces H^0 beam at 11° (12.6°) from the incoming H^- beam direction

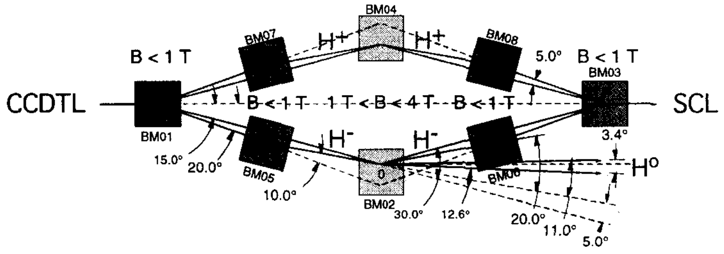

Figure 6: Beam extractor design II.

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[*] 8% extraction of the H^- beam.

[†] 100% extraction of the H^- beam.

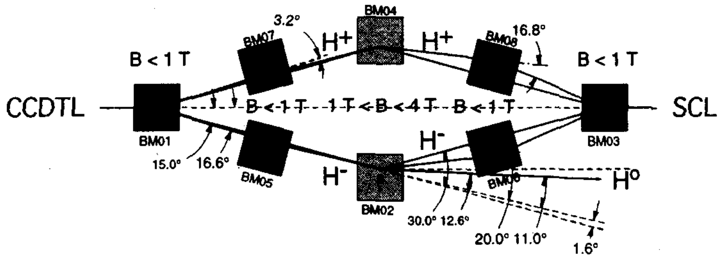

Figure 7: Beam extractor design III.

for the low (high) current extraction, the stripped H° beam will come out in the same direction regardless of the beam intensity. In an ideal situation, the stripper magnet BM02 from Fig. 5 would work the best to achieve the phase-matching condition between the H^+ and H^- beams if both beams are aligned perfectly. But in a real world, a misalignment of either the H^+ or H^- beam can not be corrected with a steering magnet since the adjusting of one beam steer away the other beam. By dividing the stripper magnet BM02 into two strippers, BM02 and BM04, an independent alignment of both beams could be achieved by separately adjusting the magnets for each beam. By varying the fields of BM04, BM07, and BM08, both the phase matching and alignment of the H^+ beam could be accomplished simultaneously.

IV Conclusions

The beam extractor will deliver a H° beam in one direction regardless of the H° current. The stripping foil should be placed as close to the stripping magnet to convert the H° to proton. It would also be advisable to put a focusing quadrupole after the foil and before a bending magnet to strip an electron from the n=3 excited H° beam. This will prevent a substantial beam loss evidently shown in the LANL Proton Storage Ring[5] (PSR). An additional study is needed to improve the field quality of the stripper magnet to reduce the angular width of the extracted H° beam.

References

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