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Studies of Laser Power Reduction for the Laser Stripping of 400 MeV H^- beam at J-PARC RCS

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The H^- (negative hydrogen) stripping to proton by using a solid stripper foil for charge-exchange injection is only an established way to achieve high-intensity proton beam in circular accelerators. However, a short and unexpected lifetime of the stripper foil, as well as uncontrolled beam losses and the corresponding residual radiation at the injection area, are two serious issues even with a moderate beam power. To avoid the realistic issues associated with foil, we proposed an alternative method of H^- stripping by using only lasers. To establish our method, we are preparing for a Proof-of-Principle demonstration of 400 MeV H^- stripping to proton by using lasers at Japan Proton Accelerator Research Complex (J-PARC). However, to achieve a higher stripping efficiency, the laser power is the most concerning issues in this case. To overcome this difficulty, we have studied both an extensive manipulation of the H^- beam and advanced uses of the laser. These include utilizing a dispersion derivative of the H^- beam to cope with its large momentum spread, while multi-pass laser system for multiple interactions of the H^- beam with lasers. We have found that the laser power can be reduced to more than an order of magnitude by applying a combination of the two methods.

KEYWORDS: High-intensity proton beam, charge-exchange injection, laser stripping, laser power reduction

1. Introduction

The multi-turn charge-exchange injection (CEI) of H^- (negative hydrogen) is an effective way to increase the proton (p) beam intensity in synchrotrons or storage rings [1-2]. Solid stripper foils are usually used to strip two electrons from the H^- leaving only p to inject into a circular accelerator. However, a short and unexpected lifetime of the stripper foil as well as uncontrolled foil scattering beam losses and the corresponding residual radiation are two serious issues even with a moderate beam power [3, 4].

Figure 1 shows a typical RCS stripper foil before (left) and after (right) only 244 C injection charge via the foil at 150 kW beam power operation. Although the foil did not break, severe foil deformation due to beam irradiation can easily be seen. To obtain the foil degradation, such as a foil thinning and governing pinholes, we precisely measured the waste beams of partially stripped H^0 and un-stripped H^-, respectively [5, 6]. The H^0 was measured to be increased more than twice from the initial value, corresponding to a severe foil thinning of 11% as shown in Fig. 2. The present value of 244 C corresponds to only 7 days if RCS operates at 1 MW beam power. A realistic foil lifetime is thus limited by such a severe degradation to replace it with a new one due to higher beam load in the waste beam dump as well to avoid any foil failure during operation. It is therefore very hard to put a foil in service at further higher beam intensity to achieve multi-MW beam power. On the other hand, the residual activation at the injection area due to un-controlled large-angle foil scattering beam losses of the circulating beam during the injection period is also one another serious issue even at a lower beam power.

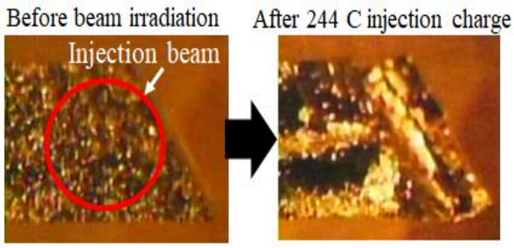

Fig. 1. Photographs of a typical RCS foil before and after only 244 C injection charge irradiation at 150 kW beam power operation.

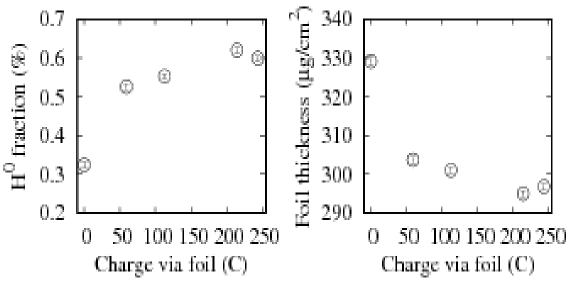

Fig. 2. Quantitative measurement of the foil degradation. The foil thickness based on the measured H^0 fraction was estimated to be reduced 11% after only 244 C injection charge irradiation.

In order to eliminate the limitations and issues associated with the stripper foil, we have proposed a new method of foil-less H^- stripping to p by using only lasers [7]. At first, we will perform a proof-of-principle (POP) demonstration of 400 MeV H^- stripping to p by using only lasers at the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC [8]. However, the laser power, especially to achieve a higher stripping efficiency, is the most concerning issue in this case. To overcome this issue, we have studied both manipulations of the H^- beam and advanced uses of the lasers. These include utilizing a dispersion derivative of the H^- beam to cope with its large momentum spread, while multi-pass laser system to utilize multiple interactions of the H^- beam with lasers. In this study we have found that the laser pulse energy can be reduced to more than an order of magnitude by applying a combination of the two methods.

2. Principle of H^- Stripping to Proton by Using Only Lasers

Figure 3 shows a schematic view of our method for H^- stripping to protons (p) by using only lasers. The method consists of three steps. The H^- is first neutralized to H^- by using an IR (Infrared) laser, the ground state (1s) electron of H^0 is then excited to 3rd excited state (3p) denoted as H^{0*} by using a deep UV (Ultraviolet) laser, and finally the H^{0*} is stripped to p by using the same IR laser. The present method is superior to the preceding research of laser-assisted H^- stripping, which was proposed nearly 20 years ago [9], and also being extensively studied for 1 GeV H^- at the SNS (Spallation Neutron Source) [10, 11]. This is because we excluded the difficulties of using extremely high magnetic fields by lasers for stripping electrons at the 1st and 3rd steps. We studied earlier that a more than 2 T magnetic field is necessary for stripping an H^- at 400 MeV [12].

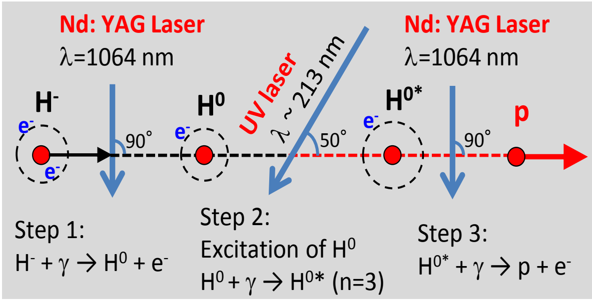

Fig. 3. Schematic view of the principle of H^- stripping of using only lasers. The noted parameters are estimated for the H^- beam energy at 400 MeV.

The YAG laser angle to both H^- and H^{0*} are set to 90 degrees to utilize the maximum photo detachment and photoionization cross sections at around 750 nm of the laser wavelength in particle rest frame (PRF). Due to the Doppler effect, the laser wavelength,

Table I. Laser types and their typical parameters for 400 MeV H^- stripping to proton.

Process	λ(nm)	α(deg.)	λ_0(nm)	Laser type
H^- to H^0	1064	90	743	YAG laser
H^0(n=1) to H^{0*}(n=3)	213	50	102	5th harmonic of YAG laser
H^{0*}(n=3) to proton	1064	90	743	YAG laser

λ in particle laboratory frame (PLF) is shifted to λ_0 of the H^- atom in the PRF, given by,

$$\lambda = \lambda_0(1+\beta cos\alpha)\gamma \qquad (1)$$

Where, β (0.712) and γ (1.4263) are relativistic parameters, α is the collision angle between laser and the H^- beam in PLF. Table 1 gives details of laser parameters optimized for the 400 MeV H^- beam energy.

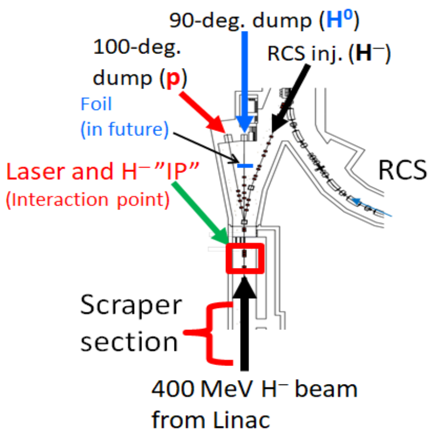

Fig. 4. Schematic view of J-PARC L-3BT. The "IP" is the laser and H^- interaction point. All charge fractions at the downstream beam lines can be simultaneously measured.

Figure 4 shows a schematic view of the end section of J-PARC L-3BT (Linac to 3-GeV beam transport), where the POP demonstration will be performed. Downstream of the laser and H^- beam interaction point (IP), three charge fractions can be simultaneously measured in the separated beam lines as depicted by the arrows.
However, the requirement of huge laser pulse energy, especially the UV laser for H^0 excitation is one of the key issues to achieve a higher stripping efficiency and eventually to realize a laser stripping CEI. To sufficiently reduce the laser pulse energy, we have studied manipulations of the H^- beam parameters as well as a multi-pass laser system, as presented in the next section.

3. Reduction of Laser Pulse Energy

In this section, methods for the significant reduction of the laser pulse energy by manipulations of both H^- beam and the laser are presented.

3.1 Manipulations of the H^- beam

Due to finite energy spread (ΔE/E) in the H^- beam, which is quite big (~0.1%), elimination of the transition frequency spread is highly important to achieve a sufficient overlapping with the laser, especially for the H^0 excitation. This can be done by utilizing a dispersion derivative (D') of the H^0 beam, so that all particles satisfy Eq. 1 [10]. The D' is expressed as,

$$D' = -(\beta + cos\alpha)/sin\alpha \qquad (2)$$

The D' for our case needed to be −1.72.

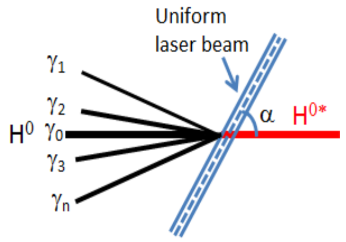

Fig. 5. Schematic view of the dispersion tailoring method to cope with ΔE/E in the ion beam.

Figure 5 shows a schematic view of the dispersion tailoring method, where H^0 with different energies will have the same laser frequency in their rest frame, because of a relative change of the angle to the laser according to Eq. 1. Figure 6 shows an estimated excitation efficiency (EE) of a ground state H^0 pulse to H^{0*} (3p) as a function of UV laser pulse energy. The pyORBIT simulation tool initially developed at the SNS was adopted for the present purpose [13]. The UV laser energy for an EE exceeding 80% can be reduce to at least 1/5 by utilizing a D' of −1.72 (red) as compared to that of without D' (black). A 97% EE can be achieved by using a laser pulse energy of 10 mJ. A further reduction of the laser energy is also possible by minimizing longitudinal and transverse beam sizes as well as betatron angular spread of the H^- beam at the IP.

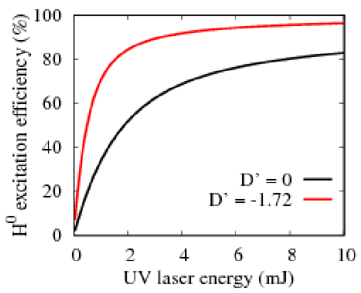

Fig. 6. Estimated UV laser pulse energy versus EE of a single H^0 pulse with and without utilizing

Figure 7 shows the simulated and a trail measured dispersion function (D) in the last section of L-3BT. The IP is at a longitudinal position of 376 m. Both D and D' are ideally zero at the IP, but the upstream quadrupole magnets (QMs) at the arc section are changed to obtain a D' −1.72 by keeping D to zero at the IP (black). The D in ideal condition was measured to be as expected (green) with almost zero at the straight section. However, the manipulated D measured for the present purpose (red), especially at the downstream part, was not as expected. The D at the IP was almost zero, but the D' was found to be ~ −1.0, much lower than the required value. This could happen due to nonlinearities of the magnetic fields of few QMs, which were increased nearly 30% for such a huge dispersion leakage. Due to limited study time no detail studies could be done, but it will be done in the next beam study. However, a D' of −1.0 even gives an EE of nearly 80% as shown in Fig. 8.

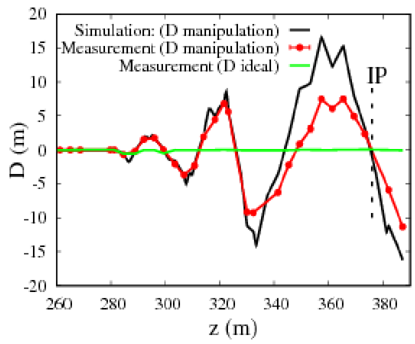

Fig. 7. Simulated (black) and a measurement (red) for a D' of −1.72. The D' in a trail measurement was obtained to be −1.0. Further studies are necessary to achieve a desired D' of

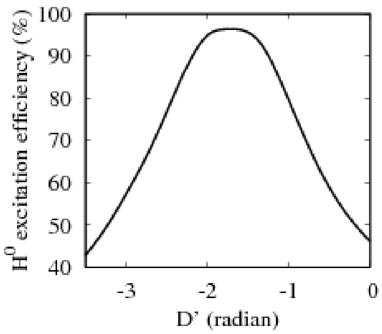

Fig. 8. Numerical estimation of EE as a function of D'. A D' of even −1.0 gives an EE of nearly 80% as compared to only 40% with D' = 0.

3.2 Manipulations of the Laser Beam

The manipulation of the laser beam is an advanced use of the laser pulse to reduce the seed laser energy. We are developing a two-mirror non-resonant multi-passes laser system

for multiple interactions of the H^- beam with the reflected laser light adjusted according to the $H^-$and photon velocities. The method for a lower duty has been successfully implemented for 0.750 MeV H^- neutralization at Fermilab [14]. Figure 9 shows a schematic view of a multi-pass laser system by using two plain mirrors for H^- neutralization with multiple interactions with the reflected laser beam. The mirror spacing and the incident angle of the laser should be adjusted according to the ion beam and the photon velocities to have interaction for every passes of the reflected photons. As a result, the reduction of the laser energy is inversely proportional to the number of interactions take place. The fraction of neutralization for N passes can be expressed by,

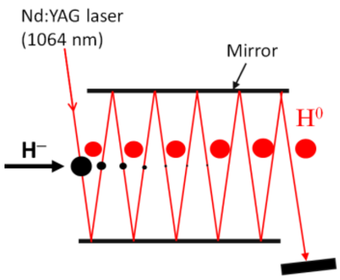

Fig. 9. Schematic view of two mirror multi-pass laser system for H^- neutralization.

$$F_N = 1 - (1 - F)^N \quad (3)$$

where, F is the neutralization fraction for a single pass interaction and is expressed as [15],

$$F = 1 - e^{-f\sigma\tau_i} \quad (4)$$

where, f is the flux of photons/cm^2/see at the IP for H^- in the PRF, σ is the neutralization cross section and τ_i is the interaction time. The f can be expressed as,

$$f = \gamma(E_l\lambda/hctA)(1 - \beta\cos\theta) \quad (5)$$

where, E_l is the laser pulse energy, λ is the laser wavelength in PLF, A is the laser cross sectional area, h is the Planck's constant, c is the speed of light, t is the laser pulse length, γ, β are relativistic parameters and θ is the interaction angle, which is almost 90 degree.

Figure 10 shows the estimated laser pulse energy required for the neutralization of a single H^- micro pulse by utilizing multiple interactions. The seed laser pulse energy can be reduced to one order of magnitude by utilizing 10 passes. Similarly, the laser energy for the photoionization process in the 3rd step as well as H^0 excitation in the 2nd step can also be reduced. However, according to our vacuum chamber configuration, the UV laser can be configured for 4 interactions with an H^0 pulse by ensuring the interaction angle, which should be exactly 50 degree for H^{0*} population. This will enable us for 1/4 reduction of the UV laser pulse energy. As a result, the H^- manipulation for a D' to cope with ΔE/E of the H^- beam and laser manipulation by multi-passes for multiple interactions together gives more than an order of magnitude reduction of the laser pulse energy. In addition to the above application, we are also developing a superimposition of 8 lower energy laser pulses at the IP for a single interaction with an intense laser pulse. We will try and optimized both methods first for 3 MeV H^- neutralization at the end of 2020 before applying for the 400 MeV H^- stripping.

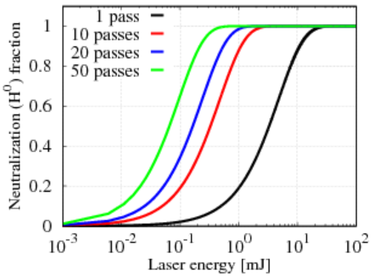

Fig. 10. Estimated laser pulse energy for H^- neutralization by using multi-pass laser system.

4. Summary

To overcome the limitations and issues associated with the stripper foil used for H^-charge-exchange injection for high-intensity proton beam, we have proposed an alternative method of H^- stripping by using only lasers. We are preparing for a POP demonstration of 400 MeV H^- stripping to proton at J-PARC. However, the requirement of high power laser is the one most difficult issue, especially to achieve a higher stripping efficiency. To overcome this issue, we have studied manipulations of H^- beam as well as developing laser systems for advanced uses. A dispersion derivative of the H^- beam is used to ensure that no extra laser energy is required to cope with energy spread in the H^- beam. In addition, a multi-pass laser system is utilized for multiple interactions of the H^- beam with lasers. We have found that well manipulations of the H^- beam and the laser together enable us more than an order of magnitude reduction of the seed laser pulse energy. Such a reduction of the laser pulse energy is highly essential for a realistic implementation of the laser stripping H^- charge-exchange injection system to the present and future high-intensity proton accelerators.

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