DEVELOPMENT OF TWO-MIRROR MULTI-PASS LASER SYSTEM TO REDUCE LASER POWER FOR LASER STRIPPING INJECTION AT J-PARC 3-GeV RCS

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Abstract

In order to overcome realistic issues and practical limitations associated with stripper foil used for H^- charge-exchange injection (CEI) in proton accelerators, an alternative method of H^- stripping to proton by using only lasers is under studied at the 3-GeV RCS of J-PARC. To established our new method, first a POP (proof-of-principle) demonstration of 400 MeV H^- stripping to proton by using only lasers will be performed. To reduce the laser energy, which is one of the main difficulties in the laser stripping CEI, we have considered several methods in this research. One way is to utilize a two-mirror non-resonant multi-pass laser system for multiple interactions of the H^- beam with reflected laser light. The seed laser energy can be significantly reduced, which is inversely proportional to the number of interactions. Another method is a superimposition of a lower energy laser pulse in a resonant cavity system with multiple mirrors to obtain at least an order of magnitude higher laser energy at the H^- interaction point. Development of multi-pass laser systems are in progress by using Nd:YAG laser of 1064 nm, which will be first tested for 3 MeV H^- beam neutralization at J-PARC test facility. The concept of multi-pass laser system and its merits including experimental strategies are presented.

INTRODUCTION

The charge exchange injection (CEI) of H^- by using a stripper foil is an effective way to increase the proton beam power in circular accelerators [1, 2]. Two electrons from the H^- are stripped by using a solid foil to inject protons into the circular accelerator. The fundamental advantage of the CEI is that, it allows stacking of many turns because of no linear growth in emittance due to injecting in a different charge state and thus provides the opportunity of unlimited multi-turn injection until stacking particles exceed aperture of the circular accelerators. Although high power beam up to about 1 MW has been achieved by using CEI with foil [3, 4], the next generation innovative physics research as well as industrial applications require multi-MW beam power. The continuous efforts on durable foil production made remarkable progress on the foil lifetime [5], but it is still unclear how to deal with multi-MW beam power. It is hard to maintain reliable and longer lifetime due to overheating of the foil, and may be it is the most serious concern and a practical limitation to realize multi-MW beam power [6]. In addition, extremely high residual activation at the injection area due to foil scattering beam losses is also another serious issue for regular facility maintenance [7].

In order to overcome the limitations and issues associated with the stripper foil, we have proposed a new method of foil-less H^- stripping to proton (p) by using only lasers [8]. To establish our method, we are preparing for a proof-of-principle (POP) demonstration of 400 MeV H^- stripping to protons by using only lasers in the 3-GeV rapid cycling synchrotron (RCS) at the Japan Proton Accelerator Research Complex (J-PARC) [9, 10]. However, requirement of a high power laser is one of the main difficulties in the laser stripping of H^-, especially to obtain a higher efficiency as can be easily obtained by using a stripper foil. The aim of this work is to develop laser systems as well as experimental verifications to achieve higher stripping efficiency by significant reduction of the seed laser power. A Nd:YAG laser system for H^- neutralization is under development now, which will be tested first for 3 MeV H^- neutralization at the J-PARC RFQ test facility (TF).

PRINCIPLE OF H^- STRIPPING TO PROTON BY USING ONLY LASERS

Figure 1 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 (photodetachment) to H^0 by stripping its loosely bound electron by using a Nd:YAG laser of 1064 nm. The ground state (1s) electron in the H^0 is excited to 3rd excited state (3p) denoted as H^{0*} by using a deep UV laser of around 200 nm, while the H^{0*} is stripped (photoionization) to p by removing its excited electron by using the same Nd:YAG as in the 1st step. Our new method is superior to the preceding research of laser-assisted H^- stripping which was proposed nearly 20 years ago [11] and also being extensively studied for 1-GeV H^- at the SNS (Spallation Neutron Source) in Oak Ridge [12–14]. This is because the laser-assisted H^- stripping requires extremely high magnetic fields for H^- neutralization as well as the excited electron stripping after H^0 excitation by using a laser. The lower the H^- energy the higher the magnetic field is thus required [15].

Table 1 gives details of laser parameters for the present purpose. Due to the Doppler effect, laser wavelength, λ in particle laboratory frame (PLF) is shifted to λ_0 of the H^-

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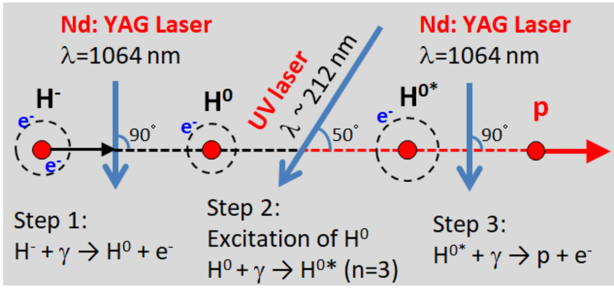

Figure 1: Schematic view of the principle of H^- stripping to proton by using only lasers. Noted parameters are estimated for the 400 MeV H^- beam energy.

atom in the particle rest frame (PRF), given by

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

where β (0.713) and γ (1.4263) are relativistic parameters of H^- at 400 MeV, α is the collision angle between laser and the beam in PLF. The advantage of using Nd:YAG lasers for the 1st and 3rd steps is that a high power IR (Infra red) laser beams can be used for those purposes. The laser beam angle to both H^- and H^{0*} are set to be 90 degrees in order to utilize the maximum photodetachment and photoionization cross sections given to around 750 nm of the laser wavelength in PRF [16].

Table 1: Laser Types and Their Typical Parameters for 400 MeV H^- Stripping to Proton

Process	E_{ph} (eV)	λ (nm)	α (deg.)	λ_0 (nm)	**Laser** type
$H^- \rightarrow H^0$	1.67	1064	90	743	Nd:YAG
$H^0 \rightarrow H^{0*}$	12.1	212	50	102	UV
$H^{0*} \rightarrow p$	1.67	1064	90	743	Nd:YAG

ESTIMATION OF LASER ENERGY FOR 400 MeV H⁻ STRIPPING

Figure 2 shows an estimated neutralization efficiency as a function of the laser pulse energy for a single H^- micro pulse at 400 MeV, which has a typical temporal rms length of 200 ns. The laser pulse energy which also depends on the transverse H^- beam sizes are typically 1.5 mm (σ) for both horizontal and vertical planes. For the total beam size we take up to $\pm 3\sigma$ value, which is calculated to be 9.0 mm. The H^- neutralization for 0.750 MeV H^- has been extensively studied at FNAL (Fermi National Accelerator Laboratory) [17].

The probability or the fraction of H^- neutralization passing through a laser pulse can be expressed by [18],

$$F = 1 - e^{-f\sigma\tau_i}, \quad (2)$$

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

$$f = \gamma\left(\frac{E_l\lambda}{hctA}\right)(1 - \beta cos\theta), \quad (3)$$

where E_l is the laser pulse energy, λ is the laser wavelength in particle lab frame (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 90 deg.

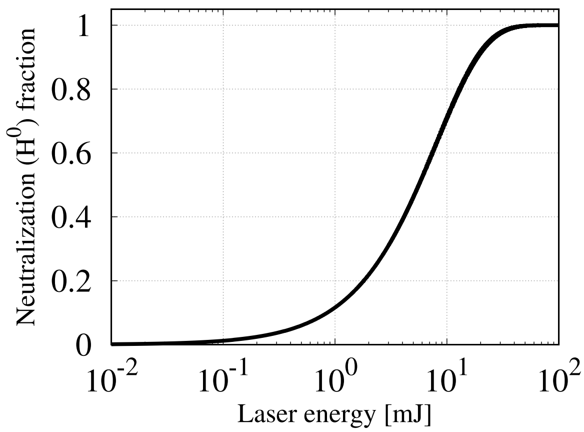

Figure 2: Estimated laser energy for neutralization of a single micro pulse of 400 MeV H^- with realistic parameters. A laser energy of nearly 56 mJ at the IP is required to achieve 99% neutralization efficiency.

Table 2: Estimated Laser Energy per Pulse for a Single H^- Stripping to Proton at 400 MeV

Efficiency (%)	$H^- \rightarrow H^0$ E_{PLB}(mJ)	$H^0 \rightarrow H^{0*}$ E_{PLB}(mJ)	$H^{0*} \rightarrow p$ E_{PLB}(mJ)
90	27.93	3.16	64.52
95	36.34	4.12	83.94
99	55.86	6.32	129.0

Table 2 gives numerical values of the laser pulse energy for a single H^- micro pulse stripping above 90% in the 1st and 3rd steps. The laser energy for H^{0*} ionization in the 3rd step can be estimated by the same way in Eq. (2) except that the photoionization cross section nearly half from that of photodetachment one. The laser energy for the photoionization is also required to be nearly twice than that of photodetachment. However, by proper manipulations of both transverse and longitudinal H^- beam sizes, the required laser pulse energy can be well reduced. Nevertheless, new ideas have to be established to reduce the seed laser energy for stripping each 324 MHz micro pulse as the total laser power would be extremely high for stripping all of 91000 micro pulses during 0.5 ms (duty factor 0.56) injection period, which is the one of the main aims in this study.

As for the H^0 excitation the physics process in same as that being studied at the SNS, except that we need a deep UV laser of around 200 nm and the corresponding relativistic parameters needed to estimate the required laser energy [12–14]. Based on the estimation given in Ref. [12], a UV laser energy of around 6 mJ would be required for 99% excitation of a single H^0 pulse. But, if the excitation efficiency is relaxed to 90%, the required laser energy can be reduced to around 3 mJ. Similar to the electrons stripping in the 1st and 3rd steps, the UV laser energy can be also be reduced by a proper manipulations of the H^- beam.

REDUCTION OF LASER ENERGY BY USING MULTI-PASS LASER SYSTEM

As presented in the previous section that a huge laser energy is required to obtain a higher stripping efficiency as usually achieved by using a stripper foil. For a single micro pulse stripping the above laser pulse energy could be available, but for the covering the whole injection period of 0.5, an efficient reduction of the seed laser energy is therefore very essential to realize a laser stripping injection system. For that purpose, we have considered several methods to sufficiently reduce the seed laser energy. One of the methods is to utilize a two-mirror non-resonant multi-pass laser system for multiple interaction of the H^- beam with reflected laser light adjusted according to the H^- and and photon velocities. The seed laser energy can be significantly reduced, which is inversely proportional to the number of interactions. Another method is a superimposition of a lower energy laser pulse inside a resonant cavity system with multiple mirrors to obtain at least an order of magnitude higher laser energy at the H^- interaction point. In this paper we present our present study results of the laser energy reduction by using the former method of two-mirror non-resonant multi-pass laser system. Such a laser system is being used for neutralization of only a few micro pulses of 0.750 MeV H^- at FNAL [17]. However, we have to develop it for extremely higher energy than FNAL and also to obtain a higher stripping efficiency. A careful development of the laser system is thus highly required.

Figure 3 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

$$F_N = 1 - (1 - F)^N \tag{4}$$

where, F is neutralization fraction for 1 pass as expressed by Eq. (2). Figure 4 shows the estimated laser pulse energy required for neutralization of a single H^- micro pulse of 400 MeV by multiple interactions with multi-pass laser as demonstrated in Fig. 3. While a laser pulse energy of 56 mJ is required for 99% neutralization by using a single interaction, it can be reduced to one order of magnitude lower of only 5.6 mJ by utilizing 10 passes and only around 1 mJ for 50 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, as the H^- velocity at 400 MeV is only 30% slower than the photon velocity, the mirror spacing should be close enough to utilize many passes. As the transverse H^- beam sizes are relatively small at the IP, a successful utilization of such a multi-pass laser system would not be a serious issue.

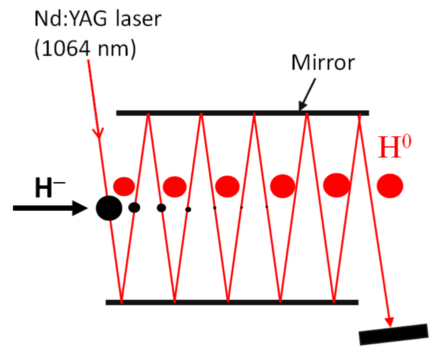

Figure 3: Schematic view of application two mirror laser multi-pass laser system for H^- neutralization with multiple interactions with the reflected laser beam. The seed laser energy per pulse can be reduced by the inverse power of the number of interactions.

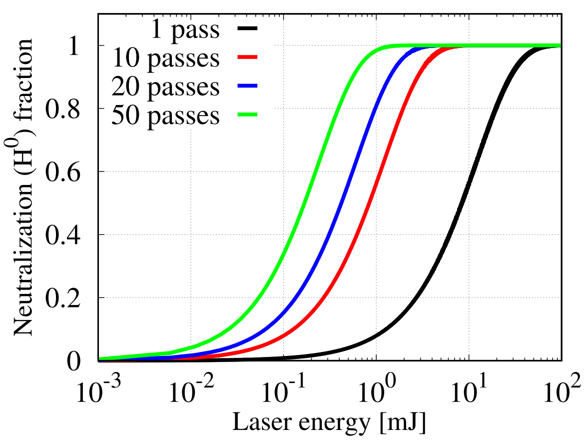

Figure 4: Estimated laser energy for neutralization of a single micro pulse of 400 MeV H^- with realistic parameters by multiple interactions with multi-pass laser. A laser pulse energy can be reduced to one of magnitude by only 10 passes as shown by the red line.

NEUTRALIZATION OF 3-MeV H^- BY USING MULTI-PASS LASER SYSTEM

We have already started developing a multi-pass laser system for 3 MeV H^- neutralization studies first at J-PARC RFQ-TF (radio frequency quadrupole-test facility) [19]. Figure 5 shows a photograph of the downstream of the RFQ-TF. A new vacuum chamber is under designed to installed in the gap between the last quadrupole magnet (QM) and the bending magnet (BM). A schematic view of the multi-pass laser system is shown by the red zigzag lines. The neutral H^0 and the un-stripped H^- can be separated by the bending magnetic field as shown by the arrows.

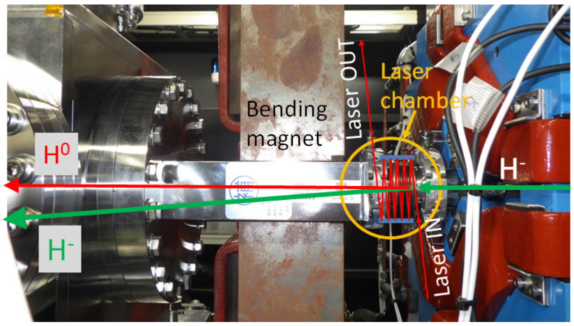

Figure 5: Photograph of the downstream part of the RFQ-TF at J-PARC. A new vacuum chamber will be installed in between the last QM and the BM for 3 MeV H^- neutralization studies by using multi-pass laser system.

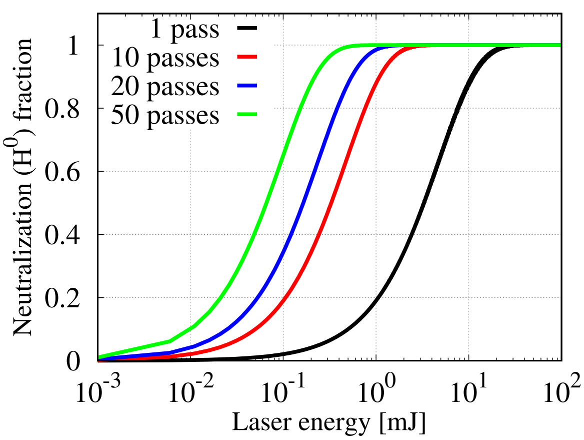

Figure 6: Estimated laser energy for neutralization of a single micro pulse of 3 MeV H^- with realistic parameters by multiple interactions with multi-pass laser.

A required laser energy for 3 MeV H^- neutralization essentially can be estimated by using the Eq. (2) by taking into account the ion beam parameters as well as photodetachment cross section for the 3 MeV case. The ion beam parameters, especially the relativistic ones are quite different due to extremely lower energy than 400 MeV. Figure 6 shows the 3 MeV H^- neutralization fractions as a function of the laser energy by considering multi-pass laser system, including one with a single interaction (1 pass). Except the relativistic parameters and the photodetachment cross section, all other parameters are kept same as used for the 400 MeV case. The photodetachment cross section for the 3 MeV H^- neutralization (λ_0 = 1064 nm) is nearly 20% smaller than that for the 400 MeV (λ_0 = 1064 nm) [16]. However, because of extremely smaller H^- velocity, the interaction time is longer as compared to that for the 400 MeV case. The required laser energy thus can be reduced, which is only less than 20 mJ for achieving 99% neutralization efficiency even for a single interaction.

At present a multi-pass laser system is under development collaborating with the University of Electro-Communication, Tokyo. In addition to the multi-pass laser system as shown in Fig. 3, another method to reduce the seed laser energy has also been considered. In this case a superimposition of a lower energy laser pulse inside a resonant cavity system with multiple mirrors is considered to obtain at least an order of magnitude higher laser energy from that of a seed pulse at the H^- interaction point. The first experimental study for 3 MeV H^- neutralization will be carried out in November, 2019. Once an efficient multi-pass laser system is developed for the 3 MeV H^- neutralization, it can be easily applied for the POP experiment of 400 MeV laser stripping as well as for laser stripping injection system.

SUMMARY

In order to realize a laser stripping H^- charge-exchange injection (CEI) system, the H^- stripping to proton by using only lasers is under studied at the 3-GeV RCS of J-PARC. The purpose is to overcome the realistic issues and practical limitations associated with stripper foil used for H^- CEI in almost all proton accelerators worldwide. To established our new method, first a POP (proof-of-principle) demonstration of 400 MeV H^- stripping to proton by using only lasers will be performed.

However, one of the main difficulties with laser stripping is that one needs relatively high power lasers to realize a higher stripping efficiency as can be easily obtained by using a stripper foil. To overcome this issue, we have considered several methods to reduce the seed laser power. One way is to utilize a two-mirror multi-pass laser system for multiple interaction of the H^- beam with reflected laser light adjusted according to the H^- and and photon velocities. The seed laser energy which is inversely proportional to the number of interactions can be thus significantly reduced. We have estimated the required laser energy for a single and multi-pass by using realistic ion beam parameters. We have also considered another method which is a superimposition of a lower energy laser pulse inside a resonant cavity system with multiple mirrors to obtain an order of magnitude higher laser energy as compared to the seed pulse at the H^- IP.

At present we are developing a multi-pass laser system for the Nd:YAG laser of 1064 nm, which will be first tested and optimized for 3 MeV H^- beam neutralization at J-PARC RFQ test facility. Once a multi-pass laser system is developed for the 3 MeV H^- neutralization, it can be easily applied for the POP demonstration of 400 MeV laser stripping as well as for the first implementation of a laser stripping injection system.

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