STATUS OF THE PROOF-OF-PRINCIPLE DEMONSTRATION OF 400 MeV H⁻ LASER STRIPPING AT J-PARC

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Abstract

A proof-of-principle (POP) demonstration of 400 MeV H^- stripping to proton by using only lasers is under preparation at J-PARC. The motivation of the present research is to replace the stripper to laser to overcome realistic issues and practical limitations associated with stripper foil used for H^- charge-exchange injection (CEI) in proton accelerators. The present method comprises three steps for an H^- stripping by using lasers. The H^- is first neutralized to H^0 by using an YAG laser, the H^0 is excited to the upper states (called H^{0*}) by using a UV laser, and finally the H^{0*} is stripper to proton by the YAG laser. A prototype of the YAG laser and the laser cavity systems to reduce the seed laser pulse energy while keeping a higher stripping efficiency have been developed and will be tested for 3 MeV H^- neutralization at J-PARC test facility at the end of 2020. The UV laser needed for H^0 excitation will be developed by higher harmonic generation from the YAG laser. The effective manipulation of the H^- beam, which also plays an important role to reduce the laser energy has also being extensively carried out. The present experimental status of the POP demonstration is presented.

INTRODUCTION

The charge exchange injection (CEI) of H^- by using a solid stripper foil is an effective way to achieve high-intensity proton beam in circular accelerators [1,2]. The H^- is stripped to proton by the foil and injected into the ring for multi-turns injection. The CEI thus allows stacking of many turns by controlling linear growth in emittance due to injecting in a different charge state and it provides the opportunity of unlimited multi-turn injection until stacking particles exceed the aperture. The CEI by using stripper foil has been successfully utilized to achieve high-intensity beam of around 1 MW in modern accelerators [3,4], but a short and unexpected lifetime of the foil as well as uncontrolled beam losses and the corresponding residual radiation at the injection area are two serious issues even at a moderate beam power [5,6]. The continuous efforts on durable foil production made remarkable progress on the foil lifetime [7], but it is very difficult to deal with multi-MW beam power. It is hard to maintain reliable and longer lifetime due to overheating of the foil at high-intensity operation and might be the most serious concern and a practical limitation to realize multi-MW beam power.

In order to overcome the issues and limitations associated with the stripper foil, we are studying a new method of H^- stripping to proton by using only lasers [8]. Figure 1 shows a schematic view concept of 400 MeV H^- stripping to protons (p) by using only lasers. The H^- is first neutralized to H^0 by stripping its loosely bound electron by an 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 to p by removing its excited electron by the same YAG as in the 1st step. To establish the method, a proof-of-principle (POP) demonstration of 400 MeV H^- stripping to proton by using only lasers is under preparation at 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. The YAG laser and laser cavity systems are under development to significantly reduce the seed laser pulse energy, which will be first tested for 3 MeV H^- neutralization at the radio frequency quadrupole (RFQ) test facility (TF) [11] of the Japan Proton Accelerator Research Complex (J-PARC) at the end of 2020. The details of the laser system has been given in a separate paper [12]. In this paper the advantages of multi-pass laser cavity systems to reduce the seed laser pulse energy, simulation and experimental studies for extensive manipulations of the H^- for effective interactions with the laser pulses also for reducing the laser pulse energy as well as strategy for measuring decay photons from an excited H^0 to confirm and identify the excitation state are presented.

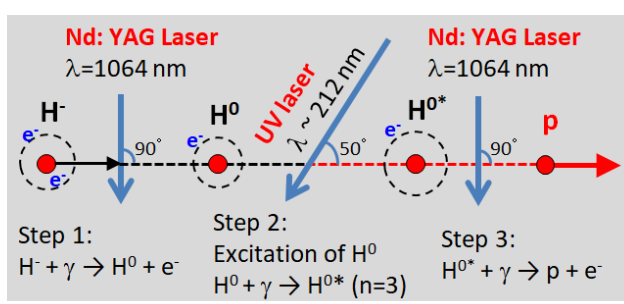

Figure 1: Schematic view of the concept of H^- stripping to proton by using only lasers. Noted parameters are for 400 MeV H^- beam energy.

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EXPERIMENTAL SETUP, REQUIRED LASER PULSE ENERGY

Figure 2 shows a schematic view of J-PARC L-3BT (Linac to 3-GeV beam transport), section, where the POP demonstration will be performed. A vacuum chamber has been installed at the end of L-3BT, where the laser and ion beam interaction point (IP) at at the center of the chamber as shown by the arrow. Downstream of IP, three charge fractions can be simultaneously measured in the separated beam lines as shown by the arrows.

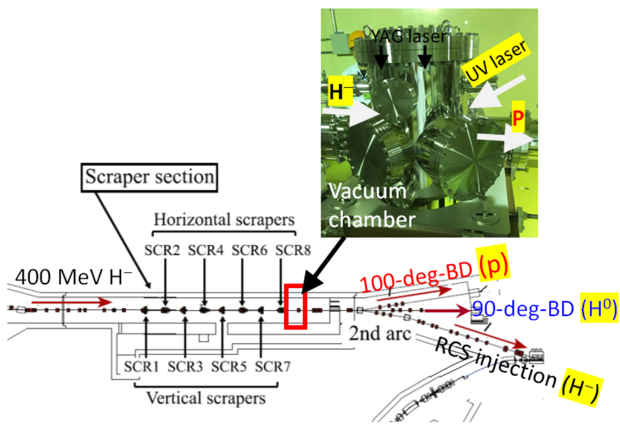

Figure 2: Setup for the POP demonstration of 400 MeV H^- stripping at the J-PARC L-3BT section. The vacuum chamber shown at the top has been installed at the end of scrapper section depicted by the red rectangular box.

Table 1 gives typical laser parameters including required laser pulse energies for 90% stripping a single H^- micro pulse with rms length of around 200 ns. Due to the Doppler effect, laser wavelength, λ in particle laboratory frame (PLF) is shifted to λ_0 of the H^- atom in the particle rest frame (PRF), given by

$$\lambda = \lambda_0(1 + \beta cos\alpha)\gamma \tag{1}$$

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 YAG laser angles for both H^- and H^{0*} stripping are set to 90 degrees to utilize maximum photodetachment and photoionization cross sections at around 750 nm of the laser wavelength in PRF [13].

The probability or the fraction of H^- neutralization passing through a laser pulse can be expressed by [14, 15],

$$F = 1 - e^{-f\sigma\tau_i}, \tag{2}$$

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

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

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.

As for the H^0 excitation, the physics process is same as that of 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 [16–18]. The required UV laser pulse energy for 90% excitation of a single H^0 pulse is then estimated to be about 3 mJ. It should be noted that we have applied dispersion derivative of the H^0 beam to cope with energy spread of the ion beam as given in detail in the next section.

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

Process	E_{ph} (eV)	λ (nm)	α (deg.)	λ_0 (nm)	E_{laser} (mJ)
$H^- \rightarrow H^0$	1.67	1064	90	743	27.93
$H^0 \rightarrow H^{0*}$	12.1	212	50	102	3.16
$H^{0*} \rightarrow p$	1.67	1064	90	743	64.52

REDUCTION OF LASER PULSE ENERGY

In order to reduce the laser pulse energy we have studied both effective manipulation of the ion beam as well multi pass laser cavity systems.

Manipulation of the H^- Beam

In order to eliminate the transition frequency spread due to the energy spread (ΔE/E) the H^- beam, a dispersion derivative (D$'$) of the H^0 beam can be successfully applied so that all particles satisfy Eq. 1 [17]. The D$'$ is expressed as

$$D' = -(\beta + cos\alpha)/sin\alpha \tag{4}$$

The D$'$ for our case has to be -1.72. Figure 3 shows a schematic view of 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.

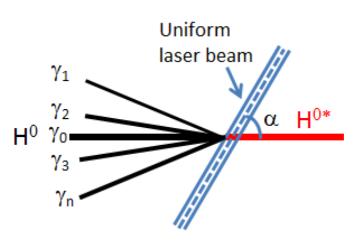

Figure 3: Schematic view of dispersion tailoring method to cope with ΔE/E of H^- beam.

Figure 4 (left) shows an estimated excitation efficiency (EE) of H^0 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 [19]. For an

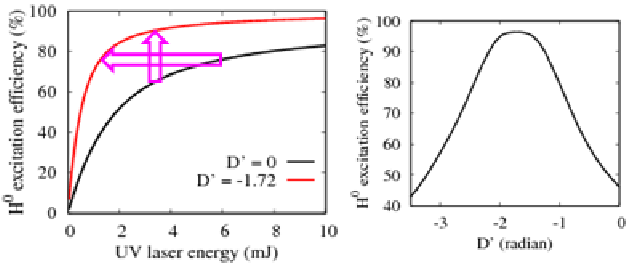

Figure 4: (Left) Estimated EE of H^0 as a function of UV laser energy with (red) and without (black) D' of the beam. The D' dependence on the EE is shown in the right plot. Even a smaller D' can significantly increase the EE as compared to its without application.

EE exceeding 80%, the UV laser pulse energy can be reduce to at least 1/5 by utilizing a D' of -1.72 (red) as compared to that of without D' (black), and a 97% EE can be achieved by using a laser pulse energy of 10 mJ. The advantage of the D' can also be more understood in the right plot of Fig. 4. The EE can be significantly increased applying even a smaller D'. The D' of even a half than the expected value of -1.72 gives nearly ~30% higher EE as compared to that without applying the D'. 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.

Figure 5 shows the simulated and a trail measurement results dispersion function (D) at the L-3BT. In this study we tried first for a D' of -1.3 at the IP. The D and D' are ideally zero at the IP (black), but the upstream quadrupole magnets (QMs) at the arc section are changed to obtain a D' of -1.3 by keeping D to zero at the IP (blue). The measured D as shown by red points were not as obtained in the simulation, especially the later part. The D' was found to be -0.73, which thus needs further studies to obtain a desired value. However, even a D' of -0.73, an EE of more than 70% can be achieved as shown in right plot in Fig. 4.

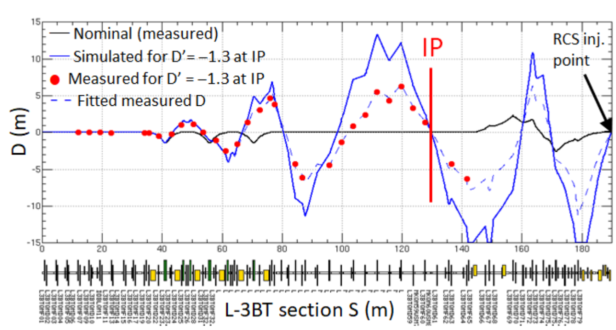

Figure 5: Simulation and a trial measurement results for D manipulation at the IP. Further studies are needed to obtain a desired D' at the IP.

Manipulation of the laser beam

The manipulation of the laser beam is mainly advanced uses of the laser pulses to reduce the seed laser energy. We are studying two methods. One of the method is a superimposition of roof-top multiple laser pulses at the IP for a single interaction with the ion beam with an intense laser pulse. At present the YAG laser cavity system with superimposition of 16 laser pulses has been developed [12]. The other method is utilizing two-mirror non-resonant multi-pass laser system for multiple interaction of the H^- beam with the reflected laser light adjusted according to the H^- and photon velocities, which has been implemented for 0.750 MeV H^- neutralization at Fermilab [15]. Although this method is easily applicable for H^- neutralization, it is comparatively difficult applying for the H^0 excitation, especially to obtain many interactions as one has to keep an exact interaction angle to populate H^{0*}.

Figure 6 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. While a laser pulse energy of 56 mJ is required for 99% neutralization by using a single interactions, 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.

The multi-pass laser cavity systems will be first tested for 3 MeV H^- neutralization at the RFQ test facility of J-PARC at the end 2020. 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.

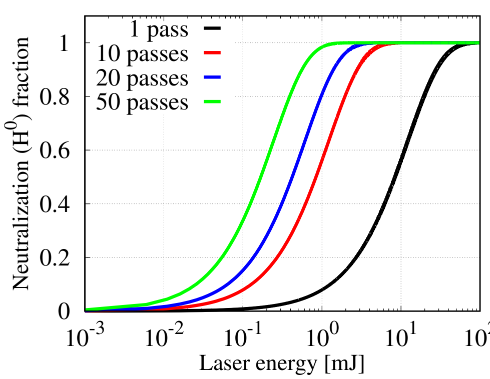

Figure 6: Estimated laser energy for neutralization of a single H^- micro pulse of 400 MeV by using multi-pass laser system.

MEASUREMENT FOR CONFIRMATION OF H^0 EXCITATION

We are also preparing a measurement system to confirm the H^0 excitation, identification of excitation state as well as the production yields by measuring the photons emitted from an excited hydrogen atom. At first we will try for

Doppler-shifted Layman spectral lines namely, L_y-α, L_y-β and L_y-γ.

Figure 7 (top) shows a schematic view of the setup for the measurement of γ from the H^0 excited to different states. The light filter (6) can be changed for measuring γs with different wavelength as we can excite to different excitation states by changing angle if the UV laser as illustrated at the bottom (left). Three view ports on the laser chamber are designed (right-bottom) all with 150° from from the sources.

Table 2 gives an estimation of the Doppler shifted wavelengths and lifetime of the Lyman lines for γ transition from the H^0 excited to 2p (n=2), 3p (n=3) and 4p (n=4) states. The values in the later two columns are estimated by considering the Doppler shift for H^0 beam at 400 MeV. The fraction yields for the longer lifetime of L_y-β and L_y-γ are estimated to be more than 80% measuring at 0.28 m from the IP. However, it remains only about 40% for the shortest lifetime of L_y-α.

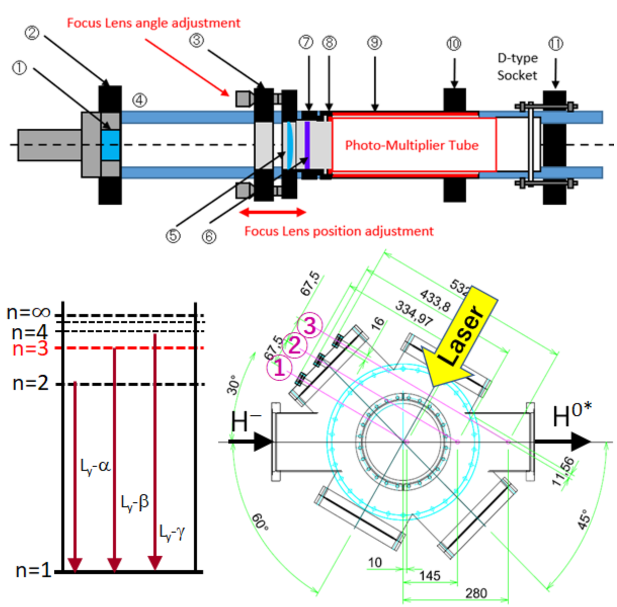

Figure 7: Setup and strategy for the measurement of γ transitions from the excited H^-. Three small view ports are designed (right-bottom) for measuring γs from 3 locations along the H^{0*} trajectory.

Table 2: Estimation of the parameters for the measurement of Lyman spectral lines due to γ transition from the H^{0*}. The Doppler shifted values of the wavelength and the lifetime are given in the later two columns.

Transition	λ_0 (nm)	τ_0 (deg.)	α (nm)	λ (ns)	τ ns
2p→1s(L_y-α)	121.57	1.61	150	280.47	2.296
3p→1s(L_y-β)	102.57	6.25	150	236.64	8.914
4p→1s(L_y-γ)	97.25	14.7	150	224.37	20.97

SUMMARY

To overcome the difficulties and realistic issues associated with the stripper foil used for H^- multi-turn charge-exchange injection for high-intensity proton beam, we are preparing for a proof-of-principle (POP) demonstration of 400 MeV H^- stripping to proton by using only lasers at J-PARC. The vacuum chamber for the POP study has been installed at the of L-3BT of J-PARC 400 MeV Linac. We will utilize both IR and UV lasers in the 3-steps process of an H^- stripping to proton. A prototype of the YAG laser and the laser cavity systems have been developed, which will be first tested for 3 MeV H^- at the J-PARC RFQ test facility at the end of 2020. For the POP demonstration, we have to develop deep UV laser system needed for the H^0 excitation.

In order to reduce the seed laser pulse energy while achieving a higher stripping efficiency, we will test two types of laser cavity systems with roof-top laser pulses at the interaction point (IP). We have continued simulation and experimental studies for extensive manipulations of the H^- beam at the IP. A dispersion derivative (D) of the H^- at the IP is very effective to cope with energy spread of in the H^-, so as to significantly reduce the laser energy. However, more experimental studies are needed to obtain a desired D' of -1.72. We are also preparing for measuring γ transition from the excited H^0 to confirm the H^0 excitation as well as the excitation state, where we can excite the H^0 to different excited states including ionization by changing the UV laser angle. The first step of the POP demonstration is planned to start at the end of 2021.

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