PROGRESS STATUS OF PROOF-OF-PRINCIPLE DEMONSTRATION OF 400 MeV H⁻ LASER STRIPPING AT J-PARC 3-GeV RCS

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Abstract

In order to overcome the practical limitations and issues associated with stripper foil used for H^- charge-exchange injection in proton accelerators, we are studying an alternative H^- stripping injection method by using lasers. The short and unexpected foil lifetime due to high intensity beam irradiation and an extremely high residual radiation at the injection area due to foil scattering beam losses are already big limitations in all existing accelerators. It is thus a serious concern aiming for next generation multi-MW proton accelerators. In a three steps process, the H^- is first neutralized to H^0 by using a Nd:YAG laser of 1064 nm, the H^0 is excited to 2nd excited state, producing H^{0*} by using an excimer laser of 193 nm in the 2nd step and finally the H^{0*} is then stripped to proton by using the Nd:YAG laser again. To establish the new principle, a POP (proof-of-principle) demonstration for 400 MeV H^- stripping to protons by using only lasers will be performed at the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex). The latest progress status of POP experiment is 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]. The two electrons from the H^- are stripped of by the foil to inject protons into the ring. The fundamental advantage of the CEI is that, it allows stacking many turns without linear growth in emittance because of injecting in a different charge state. The technique 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 [1, 2], 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 [3], 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 [4]. In addition, extremely high residual activation at the injection area due to foil scattering beam losses is also another serious issue for facility maintenance [5].

In order to overcome the limitations and issues associated with the stripper foil, a foil-less H^- CEI is thus very essential. The laser-assisted H^- stripping was proposed two decades ago [6], and it is being extensively studied for 1 GeV H^- at the SNS (Spallation Neutron Source) in Oak Ridge [7–9]. However, the method has a difficulty, especially at lower H^- energies due to extremely high magnetic fields are required in addition to the laser [10]. To overcome the difficulties of using high magnetic fields, we proposed a new method of H^- stripping to protons by using only lasers [11]. To establish our method, a proof-of-principle (POP) demonstration of 400 MeV H^- stripping by using only lasers is under preparation at J-PARC. The progress status of the POP experiment, especially the measurement and simulation results of H^- beam manipulations to reduce the laser power are presented.

PRINCIPLE OF H⁻ STRIPPING BY USING ONLY LASERS

Figure 1 shows a schematic view of our method for H^- stripping to protons (p) by using only lasers. Similar to the laser-assisted H^- stripping method [7], it also has 3 steps, but high field magnetic strippings in the 1st (H^- to H^0) and 3rd (H^{0*} to p) steps are replaced by lasers. The widely available Nd:YAG lasers can be used for those purposes to utilize large photo-detachment and photo-ionization cross sections [12], in the 1st and 3rd steps, respectively. In the 2nd step, the ground state (1s) H^0 is excited to two level higher (3p) states, producing H^{0*} by using an ArF excimer laser of 193 nm.

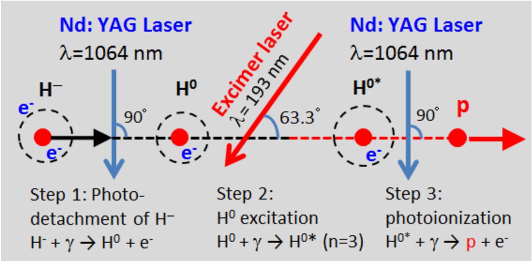

Figure 1: Schematic view of the principle of H^- stripping to proton by using only lasers. Noted parameters are estimated for the 400 MeV H^- beam energy.

Table 1 gives the 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^0 atom in the particle rest frame (PRF) as

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

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 Nd:YAG laser angles for both H^- and H^{0*} are set to be 90 degrees in order to utilize the maximum photodetachment and photoionization cross sections given for λ_0 at around 750 nm [12].

Table 1: Lasers Parameters for 400 MeV H^- Stripping to p

Process	E_{ph} (eV)	λ (nm)	α (deg.)	λ_0 (nm)	**Laser**
$H^- \rightarrow H^0$	1.67	1064	90	743	Nd:YAG
$H^0 \rightarrow H^{0*}$	12.1	193	63.3	102	ArF excimer
$H^{0*} \rightarrow p$	1.67	1064	90	743	Nd:YAG

EXPERIMENTAL SETUP AND STRATEGY

Figure 2 shows a schematic view of the end section of J-PARC L-3BT (Linac to 3-GeV beam transport), where experimental studies for 400 MeV H^- stripping by using lasers 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. Namely, fully stripped p, neutral H^0, and any unstripped H^- can be measured in the 100-degree beam dump, 90-degree beam dump and the RCS injection line, respectively. The H^0 being neutral charge, we will install a carbon foil at the 90-degree beam dump, to strip them to protons to measure.

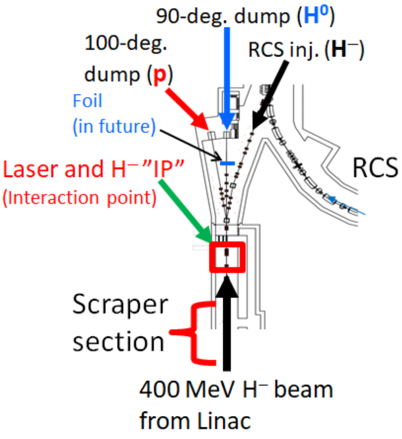

Figure 2: Schematic view of end section of J-PARC L-3BT. Experimental devices for the laser and H^- IP will be placed at the red rectangular box. All three charge fractions can be simultaneously measured in the downstream beam lines.

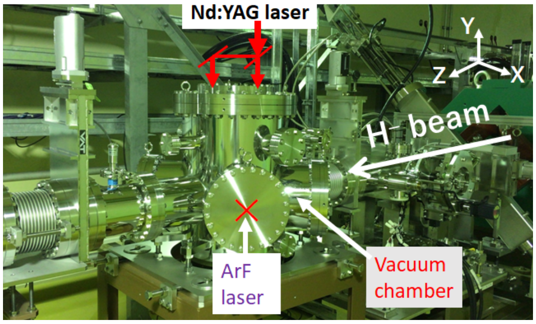

Figure 3: Picture of vacuum chamber installed in the beam line. The laser windows are relatively bigger for multiple purposes including variation of the laser angle for eventually varying the laser wavelength by utilizing the Doppler effect.

Figure 3 shows the picture of the vacuum chamber, which is installed for the POP demonstration and development studies of 400 MeV H^- laser stripping. The split Nd:YAG laser lights are sent vertically, where the ArF excimer laser is horizontally for interacting with H^0 at the center of the chamber defined as IP. The laser window sizes are designed with relatively bigger sizes bigger sizes for multiple purposes. For example, by changing the interaction angle we can eventually change λ_0 due to Doppler effect (Eq. 1) to measure the dependence of the production yield on laser wavelength or in other words the cross section. The designed angle of the ArF laser is 63.3°, but it can be varied down to 47° to try for direction ionization of the ground state H^0 (−13.6 eV). However, to minimize the laser power, especially for the excimer laser, extensive manipulation and optimization of both H^- beam and the lasers are required.

MANIPULATION OF THE H^- BEAM

In order to achieve sufficient H^- overlapping with the laser pulses, especially for H^0 excitation, extensive manipulations of the H^- (H^0) beam are very essential. One of the most important parameter is the dispersion derivative (D') of the H^- to eliminate the transition frequency spread due to the energy spread in the H^- beam, so that all particles satisfy Eq. 1 [7, 8]. The D' is expressed as

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

where, β is the relativistic parameter of the H^- and α is the interaction angle. The D' is −1.3 for the H^0 excitation.

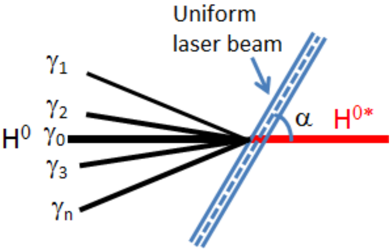

Figure 4: Schematic view of the dispersion tailoring method to cope with energy spread in the H^- beam.

Figure 4 shows a schematic view of dispersion tailoring method, where hydrogen atom 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 5 shows the estimated excitation efficiency (EE) of the H^0 to H^{0*} (3p) as a function of excimer laser peak power (P_{peak}). The simulation tool developed at the SNS was adopted for the present purpose [13]. We considered our typical Twiss parameters of H^- beam at the IP including a lowest momentum spread ($\Delta p/p$) of 0.06% as obtained so far. It can be easily seen that the laser power can be reduced to around 1/5 by utilizing the dispersion tailoring method with $D^{'} = -1.3$ from that of with $D^{'} = 0$ as shown by the red and black lines, respectively. An excimer laser pulse energy of 10 mJ with 10 ns duration gives a P_{peak} of 1 MW to obtain H^0 excitation efficiency of about 90% by utilizing a complete cancellation of the energy spread with $D^{'}$ of -1.3.

Figure 6, shows 1st measurement result of dispersion function (D) manipulation at the L-3BT. The start position ($S = 0$) is at the exit of Linac ACS (Annular Coupled Structure) acceleration section, where the H^- beam energy is reached to 400 MeV. The S at 190 m corresponds to the RCS stripper foil location, but the D were measured up to near the IP ($S = 150$ m). The D and its derivative $D^{'}$ are ideally kept zero throughout the straight section, but in a trial study the $D^{'}$ is obtained to be -0.13 by keeping D to be zero at the IP as shown by the black and red lines, respectively. Further studies are planned to obtain a desired $D^{'}$ at the IP.

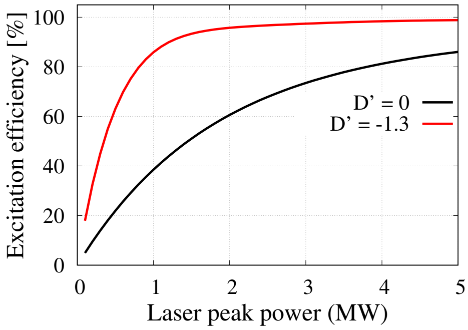

Figure 5: Estimated EE of the H^0 to H^{0*} as a function of P_{peak} of the excimer laser with (red) and without (black) D$^{'}$ of the beam. A P_{peak} of 1 MW gives 90% EE for $D^{'}$ of -1.3

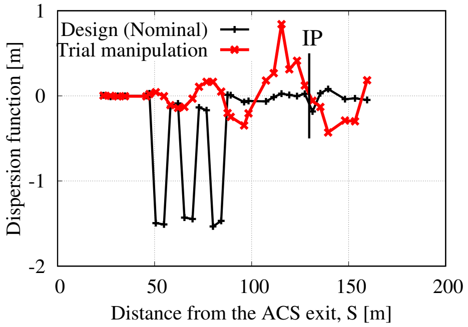

Figure 6: A trial measurement results of D manipulation at the IP. The D$^{'}$ is obtained to be -0.13 in a first trial. The measurements were done up to the end of L-3BT straight section. Further studies are planned to obtain a desired value.

Simulation Results of H^- Beam Manipulations

Recently we have done more simulation studies for extensive manipulations of the H^- beam. Figure 7 shows simulation result of manipulated horizontal D along the L-3BT up to the RCS injection point. The quadrupole magnets (QMs) in the arc section are changed to obtain a $D^{'}$ of -1.3 by keeping D to zero at the IP (red line), while QMs at the downstream of the IP are also optimized for a reasonable optical function up to the RCS injection point.

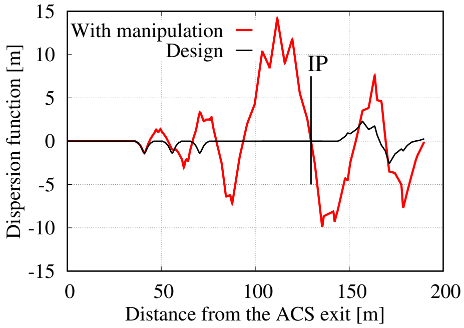

Figure 7: Recent simulation results of horizontal D manipulation of the H^- beam. A desired $D^{'}$ of -1.3 can be achieved by keeping D to zero at the IP.

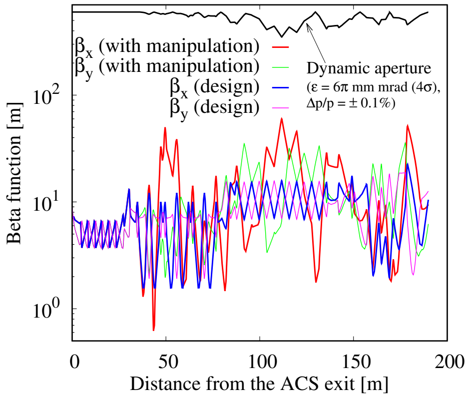

Figure 8: Estimated beta functions (red and green) while manipulating $D^{'}$ for -1.3 as shown in Fig. 7.

Figure 8 shows the estimated optical beta functions while a $D^{'}$ of -1.3 was achieved as shown in Fig. 7. The designed beta functions are also plotted together for comparison. The beta functions, especially the horizontal one (β_x) becomes modulated, but it was kept well below 100 m to make sure that the beam can be well transported to the desired destination without any significant beam losses. The black line at the top shows the horizontal dynamic aperture by considering 4σ transverse emittance of the beam. The horizontal angular divergence (α_x) of H^- at the IP is about 0.48 radian, which is also essential to minimize to zero in order to reduce the angular spread of the laser spot. Further simulation studies are in progress to minimize α_x to zero. The present simulation was done without including the space charge (SC) effect as the H^- peak current can be lowered to ignore the SC effect, but the SC effect will be taken into account in the next simulation.

Figure 9 shows the longitudinal simulation results for highest H^- peak current of 50 mA. The 324 MHz rms bunch length, σ_z (red) and rms momentum spread, $\Delta p/p$ (black) are plotted as a function of the 2nd debuncher (DB2) amplitude. The DB2 is located several 10 meters upstream of the IP and it is used to control and optimize $\Delta p/p$ of the H$^-$ beam for the RCS injection. Typically, DB2 is operated near 2 MW/m for the operation. The measured $\Delta p/p$ is this case is around 0.15%, where the expected bunch length is about 200 ps. However, for the POP experiment, we can extremely manipulate both σ_z and $\Delta p/p$ for more than one order of magnitude smaller than their nominal values. If the $\Delta p/p$ is covered by the $D^{'}$ (Fig. 7), we can utilize very short pulse H$^-$ beam to reduce the laser energy.

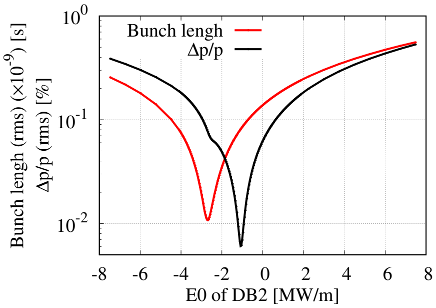

Figure 9: Simulation results of σ_z and $\Delta p/p$ of 324 MHz H$^-$ micro pulse at the peak current of 50 mA. These parameters can also be well manipulated according to the strategy of the laser stripping POP demonstration.

EXPECTED STRIPPING EFFICIENCY

The primary motivation of the POP demonstration is to establish the feasibility of the present method of H$^-$ stripping to proton by using only lasers. We consider only a single micro pulse of the 400 MeV H$^-$ beam with a pulse duration of 100 ps (variable), which has a frequency of 324 MHz. As the laser pulses are long enough (10 ns FWHM), we consider a longer H$^-$ pulse with smaller momentum spread manipulated by the DB2 as shown in Fig. 9. The Nd:YAG laser energy is sufficiently enough for stripping at the 1st and 3rd steps, while the excitation efficiency of the ArF laser determines the overall result. Figure 10 shows a typical H$^-$ signal (black) measured by a BPM pickup. A typical excimer laser pulse is shown by the blue curve. The red curve an expected change of the H$^-$ signal due to its stripping to p by the lasers, where 90% EE is can be achieved for at least a single pulse which overlaps with at the center of the laser pulse. We have already established the measurement technique by using BPM pickup signal as given in detail in an earlier report [14].

The reason why we consider only a single micro pulse for the POP demonstration is that in the practical application we can utilize a laser optical resonator ring, which we called laser storage ring [15] or any new applications to cover all micro pulses during 0.5 ms long injection time. The seed lasers would be needed capable of running only at 25 Hz. The laser pulse will be injected into the laser storage ring of 324 MHz, where laser pumping has to be done in order to recover the laser energy loss during multiple transmissions through optical devices in the ring. Detail R&D studies of the lasers for the POP demonstration and also for further development are in progress [15].

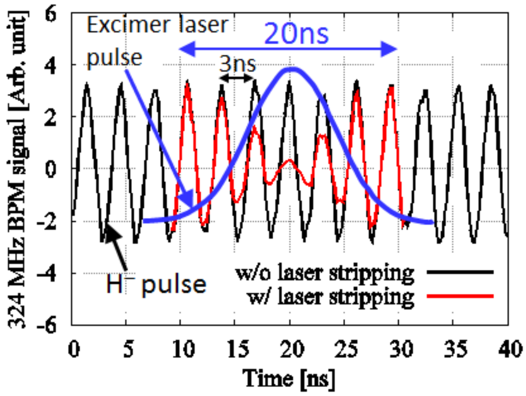

Figure 10: A typical 324 MHz H$^-$ micro pulse structure measured by BPM pickup (black). The blue curve demonstrates an excimer laser pulse. The H$^-$ pulses are expected change like the red curve due to its stripping to p by the lasers. Here we assume 90% EE at the peak of the laser pulse.

APPLICATION OF TWO MIRROR CAVITY TO REDUCE LASER ENERGY

In addition to the R&D of the laser resonator ring or any other applications for the laser stripping CEI system, it is also important to study for reducing individual pulse energy of the laser. One efficient way is to consider an application of two mirror laser cavity systems at the IP as a next step after the POP demonstration. Such a cavity system called “Linac laser notcher” with Nd:YAG laser for 0.750 MeV H$^-$ beam neutralization to make a gap in the CW beam was developed at Fermi National Accelerator Laboratory (FNAL), and it has already been implemented for the accelerator routine operation [16]. The laser light takes multiple reflections in the cavity so that the H$^-$ pulse has multiple interactions while passing through the cavity. The reduction of the laser energy is almost proportional to the number of interactions take place. In principle, the maximum number of interaction can be reached up to the number of laser reflections.

Figure 11 shows a schematic view of two mirror cavity considered for vertical multiple reflections of the Nd:YAG laser, which can be applied for the 1st and 3rd steps of our laser stripping scheme at J-PARC. The ArF excimer laser is shown for only a single pass, but a similar cavity can be considered in the horizontal direction too.

Figure 12 shows estimated neutralization fraction (NF) of the H$^-$ as a function of laser for multiple interactions by using two mirror laser cavity as shown in Fig. 11 [17]. The energy of the seed laser can be reduced by about one order of magnitude for 10 interactions as compared to that of a single interaction. Similarly, such a reduction of the UV laser energy would be very efficient for the H^0 excitation.

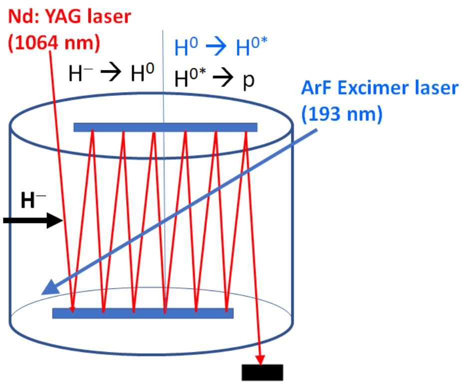

Figure 11: Schematic view of application two mirror laser cavity system for multiple interactions of the H^- and H^{0*} at the 1st and 3rd steps. Similarly, another cavity system can also be applied for the H^0 excitation by excimer laser.

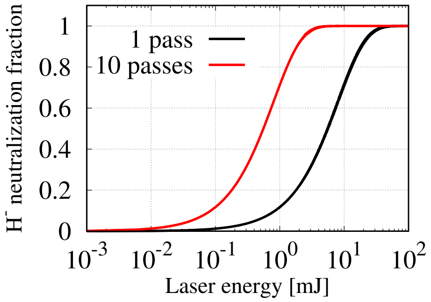

Figure 12: Estimated NF of H^- as a function of laser energy for multiple interactions in a laser cavity. The energy of the seed laser can be reduced by one order of magnitude for 10 interactions as compared to that of a single interaction.

SUMMARY

In order to overcome short lifetime and residual radiation issues involved in the conventional H^- charge-exchange injection by using stripper foil, we are studying an alternative H^- stripping injection method by using lasers at J-PARC. To establish our new method a POP demonstration of 400 MeV H^- stripping to protons by using only lasers will be will be carried out first. The advantage of the present method over the proceeding research at the SNS is to avoid the difficulties of using extremely high magnetic fields for stripping of H^- to H^0 and H^{0*} to p in the 1st and 3rd steps, respectively.

The POP demonstration will be carried out at the L-3BT of J-PARC Linac for the H^- beam energy of 400 MeV. The vacuum chamber for the POP experiment has already been installed in the beam line. At first, we will study the H^- neutralization (1st step) by using a Nd:YAG laser of 1064 nm. The POP demonstration will be carried out in 2019. We expect about 90% stripping efficiency for at least a single micro pulse of the H^- beam of about 100 ps. The practical application of H^- laser stripping for the total injection period of 0.5 ms depends on the successful utilization of the laser resonator ring or any other useful applications.

Recently, we have performed numerical simulations for extensive manipulations of the H^- beam for both transverse and longitudinal directions. Such manipulations are very essential and must be realize to reduce the laser power. Detail experimental studies for the H^- beam manipulations will be carried out soon.

In order to sufficiently reduce the energy of individual laser pulse, we also consider an application of the two mirror cavity system at the IP for multiple interactions of H^- (and H^0) pulse with the reflected laser pulses, while passing through the laser cavity.

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