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STATUS OF PROOF-OF-PRINCIPLE DEMONSTRATION OF 400 MeV H- STRIPPING TO PROTON BY USING ONLY LASERS AT J-PARC

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Abstract

In order to demonstrate the Proof-of-Principle (POP) of H^- stripping to protons by using only lasers, experimental preparations at the RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) are in progress. The ultimate goal is to make a breakthrough in the conventional H^- charge-exchange injection by overcoming the practical limitations and issues associated with stripper foil used for that purpose so far. Extremely high residual radiation due foil scattering beam losses as well as unreliable and short lifetime of the foil are already serious issues in all existing high intensity proton machines. To established our new principle, a POP demonstration will be carried out for the 400 MeV H- beam energy. A vacuum chamber for the POP demonstration has been installed at the end section of J-PARC Linac. During previous year we have many progresses on studies of H- beam manipulations, establishment of measurement principle and also R&D of the lasers. The present status and detail strategy of the POP demonstration of 400 MeV H- stripping to protons by using only lasers 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 a synchrotron or storage ring [1,2]. Two electrons from the H^- are stripped of by the foil, leaving only protons to inject into the circular accelerators. 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. By using CEI with foil, high power beam of 1 MW has already been achieved [1,2], but the next generation innovative physics research as well as industrial applications require multi-MW beam power. Although continuous efforts on durable foil production made remarkable progress on the foil lifetime [3], 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 a multi-MW beam power [4]. In addition, extremely high residual activation near the stripper foil due to foil scattering beam losses during injection is also another serious issue for facility maintenance [5].

The lifetime of the foil does not always mean a complete breaking or failure of the foil. Due to high power beam irradiation, foil degradation such as, foil thinning, pinhole formation and deformations cause a rapid increase of the waste beam, and it results a foil replacement with a new one. A frequent replacement of the foil magazine involves unhealthy exposure to radiation for the workers. To reduce the number of hits on the foil by the circulating beam, large amplitude transverse painting injection scheme by using controlled time dependent offset of the circulating beam during the injection time has been adopted in the RCS [6–8]. On the other hand, a relatively thicker foil of 333 μg/cm^2 is used to achieve higher stripping efficiency of 99.7% due to limited capacity of the waste beam dump at RCS [9]. The stripping efficiency drops even for a little of foil thinning and results an increase of the waste beam power. Significant foil degradation has already been measured even only at 0.3 MW beam power operation of J-PARC RCS [10,11]. At the design 1 MW beam power and beyond, the practical limitation of the foil lifetime may comes from foil degradation, which results an increase of the waste beam power at the dump.

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 originally proposed two decades ago [12], and it is being extensively studied for 1 GeV H^- beam at the SNS (Spallation Neutron Source) in Oak Ridge [13–15]. However, the method has a difficulty, especially at lower H^- energies due to extremely high magnetic fields are needed in addition to the laser [16]. To overcome the difficulties with extremely high magnetic fields, we proposed a new method of H^- stripping to protons by using only lasers [17]. To establish our method, a proof-of-principle (POP) demonstration of 400 MeV H^- stripping to protons by using only lasers will be performed at J-PARC.

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

In order to avoid the difficulties of using extremely high magnetic field required in the laser-assisted H^- stripping method, especially at lower H^- beam energy, we consider a new method by using only lasers [17]. Figure 1 shows a schematic view of our newly proposed method. It is similar to the laser-assisted H^- stripping method but magnetic stripping of H^- to H^0 and H^{0*} to proton (p) in the 1st and 3rd steps, respectively are replaced by lasers. The widely available high power Nd:YAG lasers can be used for those purposes in order to utilized large photo-detachment and photoionization cross sections, in the 1st and 3rd steps, re-

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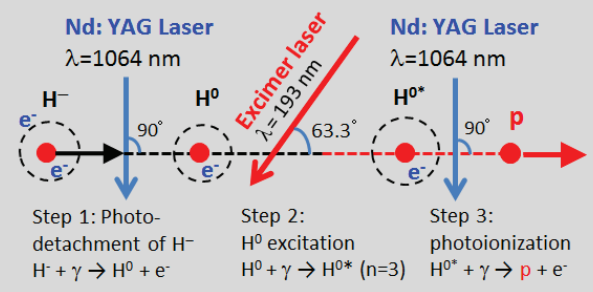

Figure 1: Schematic view of H^- stripping to proton by using only lasers. Noted parameters are typical ones for the 400 MeV H^- beam energy.

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

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

spectively. The 2nd step is the excitation of ground state n=1 (1s) H^0 atom to higher states up to n=3 (3p) denoted as H^{0*}. An ArF excimer laser of 193 nm is suitable for that purpose.

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), 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 advantage of using Nd:YAG lasers for the 1st and 3rd steps is that the direct 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 [18].

EXPERIMENTAL SETUP AND PRESENT STATUS OF POP DEMONSTRATION

Figure 2 shows a schematic view of the end section of J-PARC L-3BT (Linac to 3-GeV beam transport), where the POP demonstration of 400 MeV H^- stripping by lasers has to be carried out. The red rectangular box at the downstream of the beam halo scraper section shows the place to set experimental devices for the laser and H^- interaction point (IP). Downstream of the IP, three charge fractions can be simultaneously measured in the separated beam lines. Namely, fully stripped p, neutral H^0 (by further stripping) and the 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.

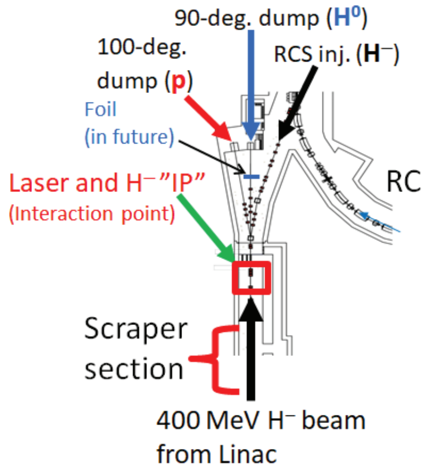

Figure 2: Schematic view of end section of J-PARC L-3BT. The red rectangular box at the downstream of the scraper section shows the place to set experimental devices for the IP of laser and H^- beam. All three charge fractions can be simultaneously measured in the downstream beam lines.

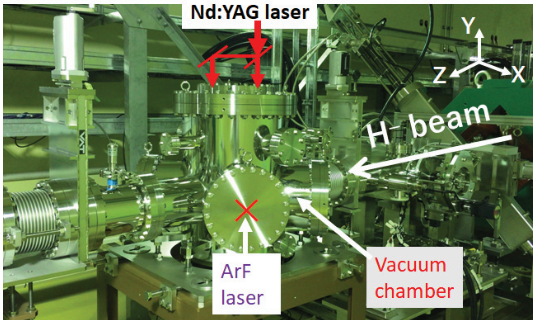

Figure 3: Picture of vacuum chamber installed in the beam line. The laser windows are relatively bigger for multiple purposes including variation of the laser angle for eventually varying the laser wavelength by utilizing the Doppler effect.

Figure 3 shows the picture of the vacuum chamber which has already been installed in the beam line the POP demonstration of 400 MeV H^- stripping by lasers. The Nd:YAG lasers light splitting by the beam splitter will be directed vertically from the top, where the ArF excimer laser will be in the horizontal direction interaction with H^0 at the center of the chamber defined as IP. The window sizes in the chamber for laser lights are comparatively bigger for multiple purposes. 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. For example. 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).

Optimization of the H^- Beam

In order to achieve sufficient H^- overlapping with the laser pulse, especially for higher excitation of the H^0, optimizations of the H^- (H^0) beam are very important. For example, to eliminate the transition frequency spread due to the energy spread in the H^- beam, so that all particles satisfy Eq. 1, the dispersion derivative (D') of the H^- is very essential [13,14]. 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, shows the 1st measurement result of the dispersion (D) function along the L-3BT including the laser stripping IP region. The D and its derivative D' are ideally kept zero, but in a trial we obtained D' of about -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 the D' as required and also for the transverse beam manipulations at the IP.

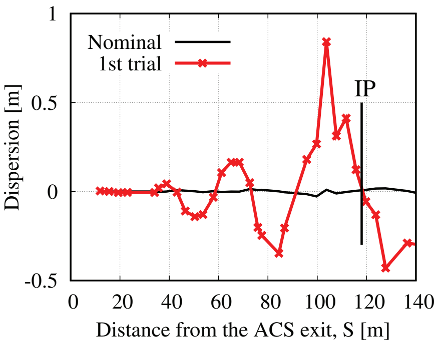

Figure 4: First measurement results of D function manipulation at the IP. The D' is obtained to be -0.13 in a first trial. Further studies will be done to obtain a required value.

Progress of R&D Studies of Lasers

In addition to the H^- manipulation, detail R&D studies of the lasers are also very essential to meet the experimental requirements. The R&D studies of the lasers for the POP demonstration and also for realistic implementation of the H^- CEI system by using lasers have been started recently. At present, detail studies are being done mainly for the 1064 nm Nd:YAG laser. Figure 5 shows the transverse profile at maximum energy of 200 mJ measured at the exit of the laser without any optimization. Further studies are in progress. Realistic setup for the laser beam transportation has been constructed in the laser room to optimize before installing at the accelerator tunnel. The control of the laser beam angle without changing its position at the desired location by using automatic stage controller has also been done successfully. As for the excimer laser, the detail R&D studies are expected to start soon. However, at the first stage, we planned to study the H^- neutralization (step 1) by using Nd:YAG laser in this fiscal year.

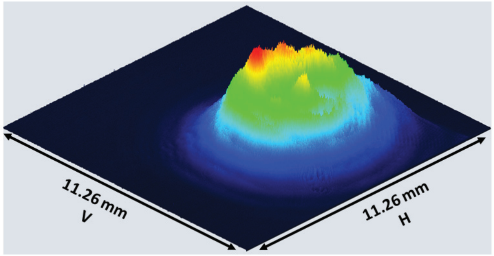

Figure 5: Typical transverse profile of 1064 nm Nd:YAG laser with 200 mJ. The profile can be optimized as required depending on the H^- beam at the IP.

Measurement Technique of Stripping Efficiency

Figure 6 shows the typical pulse structures of the Linac beam at different stages including the injected ones in the RCS. For the POP demonstration, we consider only a single micro pulse of the 400 MeV H^- beam with around 100 ps duration (variable), which has a frequency of 324 MHz as shown at the bottom of the figure. It is very essential to established a precise technique to measure even a single and tiny micro pulse. For that purpose, we consider using stripline BPM (beam position monitor) pickup signal taken by a fast oscilloscope.

To demonstrate the measurement technique we used one of the horizontal charge-exchange type beam halo scraper (carbon foil) placed upstream of the IP [19]. The scraper are used to remove halo in the H^- beam. The part of the H^- intercepted by scraper are stripped to p and dumped to the 100-degree beam dump (see. Fig. 2). The scraper foil is thick enough (600 μg/cm^2) to strip more than 99.998% of H^- to protons, if intercepted by the scraper [9]. The un-stripped H^- at the RCS injection line and the stripped p at the 100-degree beam beam dump line separated by bending magnets at the downstream of IP are simultaneously measured by two BPMs.

Figure 7 shows expanded view of few micro pulses for p (left) and H^- (right) measured by BPM pickups for different positioning of the scraper. The p at the 100-degree beam dump is maximum when the H^- beam is fully intercepted by scraper, while it is minimum (nothing) when the scraper is removed from the beam line. The opposite situation is true for the H^- beam measured at the RCS injection line. The p charge fraction for each pulse is obtained from the ratio of integrated yields with scraper partially in (red) to that with scraper fully in (pink). The H^- fraction is also individually obtained in the same way (ratio of data with black and blue). Figure 8 shows p and H^- charge fractions for some typical pulses, when the scraper was partially inserted. The solid lines are averaged values for these 10 pulses and were obtained to be 35.67±0.26%, and 64.15±0.25%, for p and H^-, respectively. The charge fractions of each individual 324 MHz micro pulse is precisely obtained from the measured H^- and p pulses. The present method can be thus utilized for measuring the stripping efficiency of a single micro pulse in the POP demonstration.

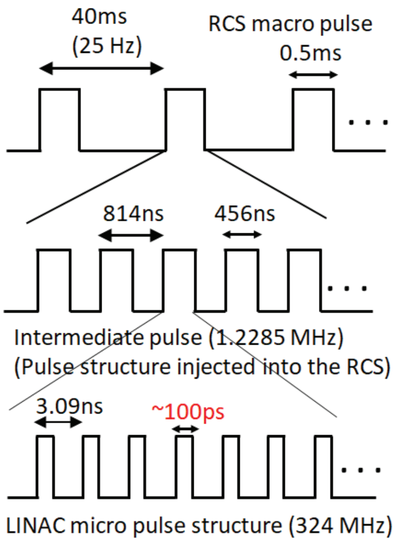

Figure 6: Pulse structures of the Linac beam. A single micro pulse at 324 MHz of around 100 ps is considered for the POP demonstration of 400 MeV H⁻ stripping by using lasers.

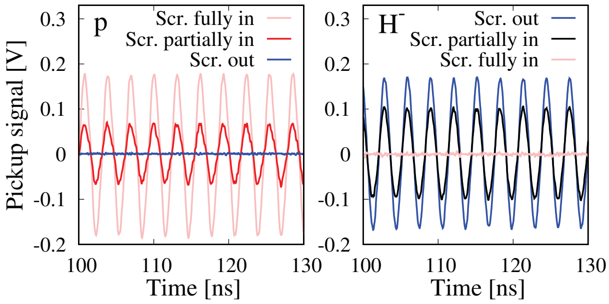

Figure 7: Expanded view of few micro pulses for p (left) and H⁻ (right) simultaneously measured by BPM pickups at the 100-degree beam dump and the RCS injection lines, respectively for different positioning of the scraper.

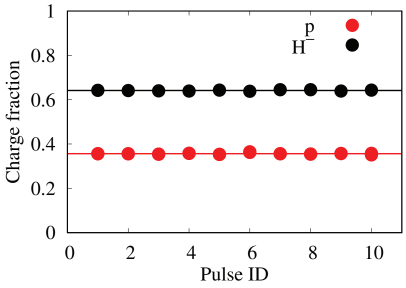

Figure 8: The p and H⁻ charge fractions for individual micro pulse were obtained from the ratio of integrated yields as shown in Fig. 7.

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. 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 9 shows the estimated excitation efficiency (EE) of the H^0 to H^{0*} (n=3) as a function of peak power (Ppeak) of the ArF 193 nm excimer laser. An excimer laser pulse energy of 10 mJ with 10 ns duration gives a Ppeak of 1 MW to obtain EE of about 90%.

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.

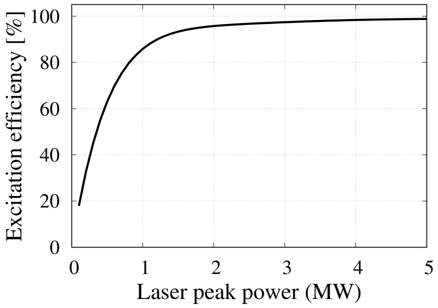

Figure 9: Estimated EE of the H^0 to H^{0*} (n=3) as a function of Ppeak of the excimer laser. The EE can be achieved nearly 90% with Ppeak of 1 MW (10 mJ).

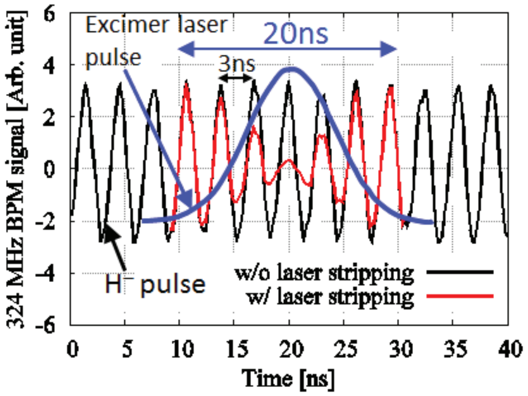

Figure 10: A typical 324 MHz H⁻ micro pulse structure measured by BPM pickup (black). The blue curve demonstrates an excimer laser pulse. The H⁻ pulses are expected change like the red curve due to its stripping to p by the lasers. Here we assume 90% EE at the peak of the laser pulse.

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 [13], which we called laser storage ring 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 laser for that purpose have also been started.

APPLICATION OF TWO MIRROR CAVITY FOR REDUCING 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 [20]. 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 [21]. 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.

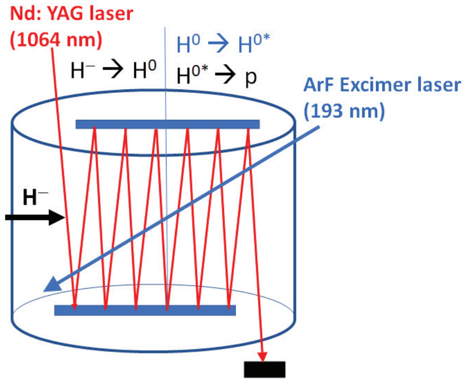

Figure 11: Schematic view of application two mirror laser cavity system for multiple interactions of the H^- and H^0* at the 1st and 3rd steps. Similarly, another cavity system can also be applied for the H^0 excitation by excimer laser.

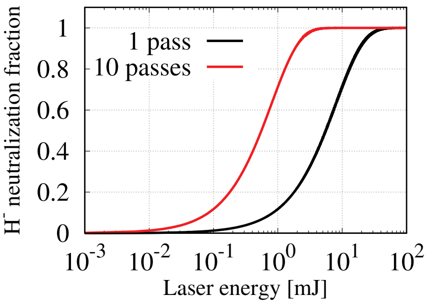

Figure 12: Estimated NF of H^- as a function of laser energy for multiple interactions in a laser cavity. The energy of the seed laser can be reduced by one order of magnitude for 10 interactions as compared to that of a single interaction.

SUMMARY

In order to realize laser stripping H^- charge exchange injection system, a POP demonstration of H^- stripping to protons by using only lasers will be performed at J-PARC. 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 at the 1st and 3rd steps, respectively. The lower the H^- beam energy, the higher the magnetic fields are required. Instead, we will utilize large photodetachment and photoionization cross sections for the same purposes.

The POP demonstration will be carried out at the L-3BT of J-PARC Linac for the H^- beam energy of 400 MeV. At first, we plan to study the 1st step in this fiscal year, which is the neutralization of 400 MeV H^- by the Nd:YAG laser of 1064 nm. For the POP demonstration, the Nd:YAG laser pulse splitted by beam splitter will be used for both 1st and 3rd steps, while an excimer laser will be used for H^0 excitation up to n=3 state. 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.

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

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