# AN EXPERIMENTAL PLAN FOR 400 MeV $H^-$ STRIPPING TO PROTON BY USING ONLY LASERS IN THE J-PARC RCS

P.K. Saha*, H. Harada, S. Kato, M. Kinsho, J-PARC Center, KEK & JAEA, Japan
Y. Irie, I. Yamane, High Energy Accelerator Research Organization, KEK, Japan

## *Abstract*

In the 3-GeV Rapid Cycling Synchrotron of Japan Proton Accelerator Research Complex, we are planning for a proof-of-principle experiment to demonstrate 400 MeV $H^-$ stripping to proton by using only laser system. In order to avoid high magnetic field required in the process of laser-assisted $H^-$ stripping, especially for lower $H^-$ energies, we are studying the possibilities of using only laser system. The method is a three step process, same as the laser-assisted $H^-$ stripping at the Spallation Neutron Source in Oak Ridge but lasers are used instead of high field magnets in the 1st step for an $H^-$ conversion to $H^0$ and in the 3rd step for an excited $H^0$ ($H^{0*}$) conversion to a proton. A Nd:YAG laser, wavelength of 1064 nm can be properly used for both 1st and 3rd steps, where commercially available the most powerful excimer laser will be used for $H^0$ excitation (n=3) in the 2nd step. Although detail R&D studies are necessary to reach to the ultimate goal and needs to proceed step by step. A tentative schedule to carry out the experiment is set to be at the end of 2017. A detail of the present method and the expected outcome are presented in this paper.

## INTRODUCTION

A stripper foil plays an important role for multi-turn $H^-$ stripping injection in order to increase the beam current in the circular accelerators. Recently, beam power of 1 MW and above have successfully been achieved by such a conventional injection method [1, 2]. 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 may be hard to maintain a 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. Other than foil lifetime, the residual activation near the stripper foil due to the foil scattering beam loss during multi-turn injection is also another uncontrollable factor and a serious issue for facility maintenance.

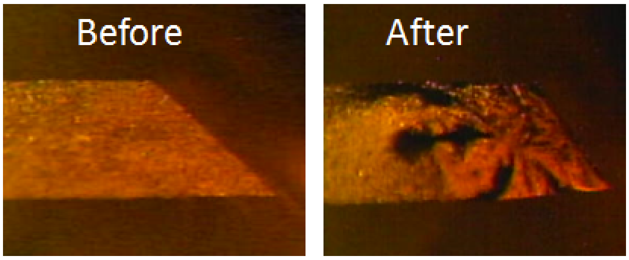

Figure 1: Stripper foil before and after operation with 0.3 MW beam power for about 5 months in the 3-GeV RCS of J-PARC. Deformation of the foil due to beam irradiation can easily be seen.

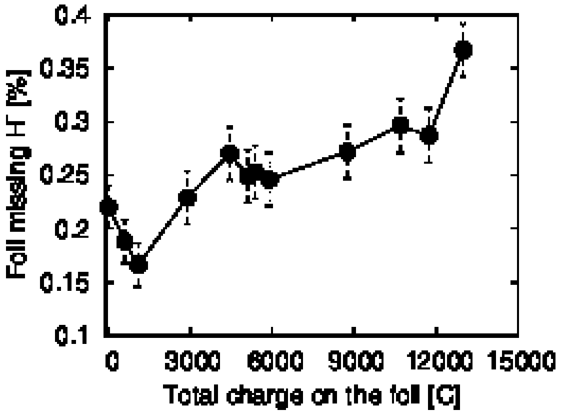

Figure 2: A trend of the stripper foil missing $H^-$ measured at the waste beam dump. The missing $H^-$ was increased nearly 3 times higher as compared to that in the beginning of the operation. At the designed operation even if a foil does not brake, the practical limitation of the foil lifetime may comes from the foil degradation.

Figure 1 shows pictures of stripper foil before and after only 0.3 MW operation at 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Organization). Although the foil was continuously used for nearly 5 months operation but the beam power was less than one third of the designed 1 MW. The total injected charge on the foil was nearly 1300 C and by taking into account the calculated average foil hits (10) of each injected proton, the total charge via foil was estimated to be 13000 C. Figure 2 shows a trend of the unstripped (missing) $H^-$ due to the stripper foil deformation as shown in Fig. 1. Those missing $H^-$ was further stripped to protons by one of the secondary foil but directed to the waste beam dump. The missing $H^-$ was measured to be increased nearly 3 times higher than those in the beginning of the operation. Ideally the waste beam should be only 0.3%, which are all the single electron stripped $H^0$ but almost no missing $H^-$. However, due the uncontrolled beam halos in the $H^-$ beam, small vertical size of foil as well as beam positioning as close as to the horizontal edge of the foil in order to minimize circulating beam hitting the foil during multi-turn injection, there was about 0.2% missing $H^-$ in the beginning. The missing $H^-$ were reduced to about 0.1% by further tuning the $H^-$ beam and adjusting the foil position as well. The operation of the machine even with such a foil deformation and missing $H^-$

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[*] E-mail address: saha.pranab@j-parc.jp

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was able continued because the beam power for the operation was less than one third of the designed 1 MW. It is thus highly concerned that at the designed operation even if a foil does not fail, the practical limitation of the foil lifetime may comes from the foil degradation due to such an increase of the $H^-$ in the waste beam dump against the limited capacity of the beam dump.

A foil-less $H^-$ charge exchange injection is thus very essential in order to ensure a stable operation of high intensity accelerators as well as to realize multi-MW beam power. As an alternate method other than using solid stripper foil, laser-assisted $H^-$ stripping are studying for 1 GeV $H^-$ beam at the SNS (Spallation Neutron Source) in Oak Ridge [4]. However, the method has a difficulty, especially at lower $H^-$ energies due to extremely high magnetic fields are needed in addition to the laser. In order to overcome that difficulty, we are studying $H^-$ stripping to protons by using only lasers. We are also planning for a proof-of-principle (POP) demonstration for the 400 MeV $H^-$ beam in the 3-GeV RCS of J-PARC. A detail of the present method, experimental strategy, tentative schedule as well as an expected outcome are presented.

## DIFFICULTIES OF LASER-ASSISTED $H^-$ STRIPPING TO PROTON AT LOWER $H^-$ ENERGIES

The laser-assisted $H^-$ stripping to protons was originally proposed nearly two decades ago [5]. The method is a three-step process of magnetic stripping, laser excitation and magnetic stripping. The $H^-$ is first converted to a neutral hydrogen atom ($H^0$) first by using Lorentz stripping in a strong magnetic field, the $H^0$ is excited ($H^{0*}$) by using laser from its ground state (n=1) to upper excited states (n≥3) and finally $H^{0*}$ is converted proton by using Lorentz stripping in a strong magnetic field again. A little modified approach to reduce Doppler broadening in the second process of laser excitation was later proposed and also successfully demonstrated by a proof-of-principle (POP) experiment at the SNS, achieved 90% stripping efficiency for a short pulse of 6 ns, 900 MeV $H^-$ [6, 7]. A more dedicated experiment was carried out recently to demonstrate 3 orders of magnitude improvement by increasing the $H^-$ pulse length 5~10 $\mu$s [4, 8, 9].

In order to apply laser-assisted $H^-$ stripping for the 400 MeV $H^-$ beam in the RCS of J-PARC, we have also briefly studied the method recently [10]. We may achieve similar excitation probability of the $H^0$ by using nearly same laser beam power but the main difficulty is to achieve an extremely high magnetic field of more than 2 T required to utilize Lorentz stripping of the $H^-$ and $H^{0*}$ in the 1st and 3rd steps because of much lower $H^-$ beam energy as compared to that of SNS. For 1 GeV SNS beam energy, the required magnetic field of 1.2 T and it was achieved for the test experimental purpose by using permanent magnets with an extremely smaller inner radius of only 1.5 cm [11]. In reality the circulating beam size is much bigger, where a typical beam size just after the injection process in the RCS as obtained in the simulation with no transverse painting injection but with full longitudinal painting to reduced the space charge effect is shown in Fig. 3. One needs a beam duct radius of nearly 6 cm at the injection point in order to avoid any uncontrolled beam losses at the injection region.

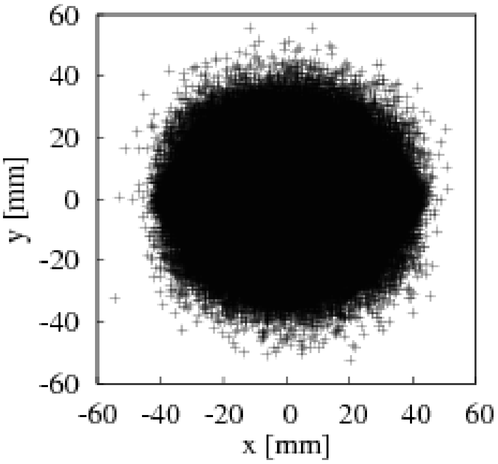

Figure 3: Circulating beam size at the end of injection period as obtained in the simulation for 1 MW beam power in the RCS of J-PARC. It may be very hard to achieve high magnetic field with an inner radius of the magnet nearly 6 cm in order to utilize needed Lorentz stripping of the $H^-$ and $H^{0*}$ for the 400 MeV $H^-$ MeV in the process of laser-assisted $H^-$ stripping.

## NEW METHOD FOR $H^-$ STRIPPING TO PROTONS BY USING ONLY LASERS

In order to overcome the difficulties of achieving high magnetic field required for the laser-assisted $H^-$ stripping to protons, especially for $H^-$ energy lower than 1 GeV, we proposed a new method where lasers can be used instead of any magnets. Figure 4 shows a schematic view of our newly proposed method for the $H^-$ stripping to proton by using only lasers. The method in principle a three step process, similar to the previous one but magnetic stripping of $H^-$ to $H^0$ and $H^{0*}$ to proton 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 former and later process, respectively. The principle in the middle or the 2nd step is exactly same as the previous method, where an $H^0$ atom from its ground state (1S) has to be excited to higher states up to n=3 (3p). The excited $H^0$ atom is denoted by $H^{0*}$. The excimer laser is one of the good choice for our case as the required laser wavelength has to be about 200 nm.

### *Optimum Laser Type and Their Wavelengths*

We have to carefully choose the laser type and their parameters in order to obtain expected efficiency at each step. Due to the Doppler effect, laser wavelength, $\lambda$ in particle laboratory frame (PLF) is shifted to $\lambda_0$ of the $H^0$ atom in

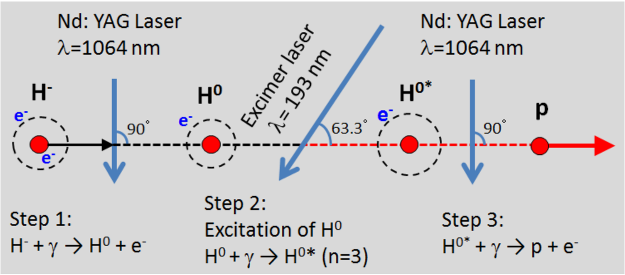

Figure 4: Schematic view of laser $H^-$ stripping to proton by using only lasers. Noted parameters are typical ones for an $H^-$ beam energy of 400 MeV.

the particle rest frame (PRF), given by

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

where $\beta$ and $\gamma$ are relativistic parameters (0.713 and 1.4263, respectively for the 400 MeV $H^-$), $\alpha$ is the collision angle between laser and the beam in the laboratory frame. 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 [12]. The $\lambda_0$ by using Eqn. 1 is calculated to be 743 nm. The photon energy ($E_{ph}$) at this wavelength is calculated to be 1.67 eV, which is much higher than the binding energy (0.75 eV) of the loosely bound electron in the $H^-$ as well as the ionization energy (1.5 eV) of and $H^{0*}$ (n=3). However, the most difficult part is a sufficient excitation of the $H^0$ atom. The $E_{ph}$ is as high as 12.1 eV for two level excitation of an $H^0$ atom, corresponds to a laser wavelength, $\lambda_0$ = 102 nm. The ArF excimer laser of 193 nm in the PLF can be a good choice for this purpose with an angle of 63.3 degree to the $H^{0*}$ atom. A summary of the laser wavelengths and the corresponding laser types are given in Table 1.

Table 1: Required Laser Wavelengths and the Corresponding Laser Types

| **Process** | $E_{ph}$ (eV) | $\lambda$ (nm) | $\alpha$ (deg.) | $\lambda_0$ (nm) | **Laser** |
|---|---|---|---|---|---|
| $H^- \rightarrow H^0$ | 1.67 | 1064 | 90 | 743 | Nd:YAG |
| $H^0 \rightarrow H^{0*}$ | 12.1 | 193 | 63 | 102 | ArF Excimer |
| $H^{0*} \rightarrow p$ | 1.67 | 1064 | 90 | 743 | Nd:YAG |

### *Required Laser Power for $H^-$ Stripping*

In this section we briefly described required laser power at each step for $H^-$ stripping to protons. The $H^-$ beam parameters for both longitudinal and transverse directions are very important in order to obtained higher stripping efficiency for a given laser beam power. The photodetachment cross sections, $\sigma$ at 743 nm is about $4\times10^{-17}$cm$^2$ [12]. The saturation density, $\Phi^s$ in PRF given by $E_{PH}/\sigma$ is calculated to be $6.7\times10^{-3}$ J/cm$^2$. We consider relatively smaller $H^-$ beam size in both longitudinal and transverse directions. For example, rms bunch length $\sigma_L$ is 30 psec, while transverse beam radius is about 1 mm. The collision time, $\tau_i$ is then calculated to be about 10 psec. The laser pulse length, $\tau_l$ should be 40 psec at minimum. The laser energy then calculated by the expression given by

$$E_{laser} = (\Phi^s/\gamma(1 + \beta cos\alpha)) \times (\pi r^2) \times (\tau_l/\tau_i) \qquad (2)$$

where, laser pulse angle $\alpha$ to the $H^-$ beam is 90 degree. The required laser energy $E_{laser}$ is estimated to 0.6 mJ, corresponding to a laser peak power of about 15 MW. As the ionization cross section of $H^{0*}$ to proton is nearly half of that photodetachment of $H^-$ to $H^0$, the laser pulse energy in the 3rd step is thus required to be about 1.2 mJ.

The required peak power of the laser for an $H^0$ excitation up to n=3 state is given to be 1 MW in Danilov's paper for 1 GeV $H^-$ beam [6, 7]. The same estimation for our 400 MeV $H^-$ beam requires nearly twice higher laser peak power due to difference of the relativistic parameters, $\beta$ and $\gamma$ have to be taken into account in the estimation. The ArF excimer lasers commercially available these days by GAM LASER INC can provide 150 mJ energy with a typical pulse length 20 ns [13]. As long as we consider very short $H^-$ pulse of 30 psec, such a laser can be a good choice for sufficient excitation of the $H^0$.

## SCHEDULE AND SETUP FOR POP $H^-$ LASER STRIPPING EXPERIMENT

Although a detail schedule for the POP experiment has not yet been fixed, the earliest chance is considered to be at the end of 2017. All equipment for the experiment are planned to installed by the end of 3 months long facility maintenance period starting from July, 2017.

We will use 400 MeV $H^-$ beam from J-PARC Linac [1], where $H^-$ beam and laser interaction point (IP) is fixed to be at the end of the straight section in the L-3BT (Linac to 3-GeV beam transport). Figure 5 shows a schematic view of the end section of J-PARC Linac and the place of the POP experiment is shown by a red rectangular box. Downstream of the IP, there are 3 branches of beam transports, where three charge fractions can be simultaneously measured as depicted in the figure. Any remaining $H^0$ we have to strip further to protons in order to measure it at the 90 degree beam dump.

Figure 6 shows a schematic view of the experimental setup. In stead of 3 lasers as shown in Fig. 4, we may use 2 lasers in this setup. The radius of $H^-$ beam pipe should be smaller in that case in order to confirm the overlap of the laser pulse guided by mirrors to the 3rd step. The allowed path length of the laser pulse is 1.4 times longer than the $H^0$ one due their velocity difference. The beam pipe radius at IP is comparatively large and may not satisfy the above setup but we can construct an appropriate beam pipe and temporarily connect for the experiment.

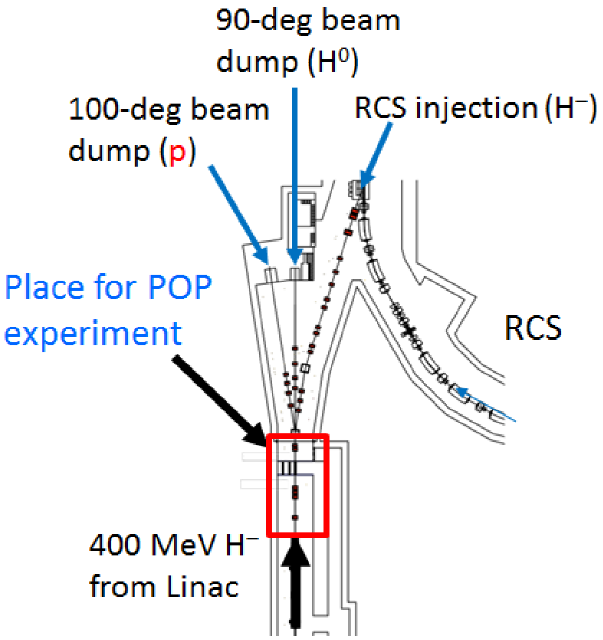

Figure 5: A schematic view of the end section of J-PARC Linac named L-3BT. The $H^-$ laser stripping POP experimental setup has to be placed in the region indicated by the red rectangular box. We can simultaneously measure all three charge fractions in the downstream. Namely, fully stripped protons, neutral $H^0$ (by further stripping) and the unstripped $H^-$ can be measured in the 100-degree, 90-degree and the RCS injection point, respectively.

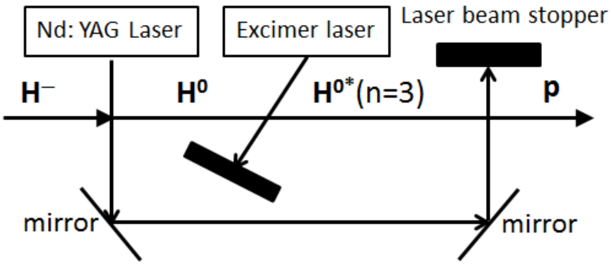

Figure 6: A schematic view of the setup for the POP experiment. One Nd:YAG laser can be efficienly used for an $H^-$ stripping to $H^0$ and $H^{0*}$ to proton through laser beam transportation by optical mirrors. The excimer laser will be used for the $H^0$ excitation.

### *Optimization of $H^-$ Beam Parameters*

Optimization of the $H^-$ beam parameters are very important in order to achieve efficient overlapping with the laser pulse. Figures 7 and 8 show simulation results of the longitudinal bunch length and the dispersion function along the Linac. The bunch length at the IP with a lower peak current can be achieved less then 30 psec as compared to that 5 times longer in the normal operation. The dispersion derivative ($D'$) plays an important role in order to minimize the laser power [6, 7], where $D'$ has to satisfy the condition given by

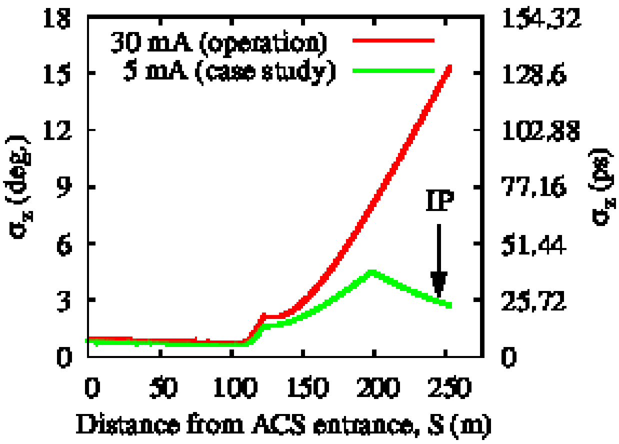

Figure 7: Simulation results of 400 MeV longitudinal $H^-$ beam size in the J-PARC Linac. The longitudinal bunch length can be reduced to less than 30 psec as desired for the POP experiment.

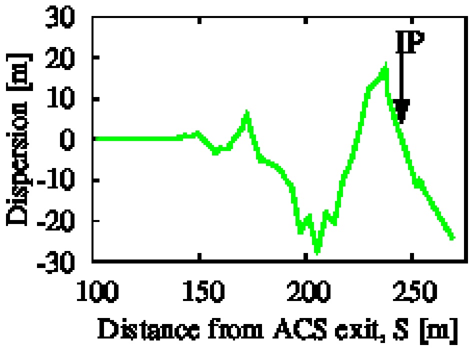

Figure 8: Calculated dispersion function as a function of the distance in the Linac starting from the end of ACS section. A dispersion derivative of required -1.3 can be achieved at the IP.

$$D' = -(\beta + cos\alpha)/sin\alpha \tag{3}$$

The $D'$ has to be -1.3 for the 400 MeV $H^-$ beam, which can be easily achieveable as shown in Fig. 8.

## AVAILABLE LASERS FOR THE POP EXPERIMENT AND EXPECTED RESULTS

The primary motivation of the POP experiment is to demonstrate the feasibility of the present method for an $H^-$ stripping to proton by using only lasers. We focus only a single micro pulse of the 400 MeV $H^-$ beam which has a frequency of 324 MHz having a typical pulse length of 30 psec. The Nd:YAG laser used for 400 MeV $H^-$ photodetachment studies in J-PARC has an energy as high as 1.6 J with a pulse length of around 20 ns [14, 15]. We can efficiently use that laser for the 1st and 3rd steps as demonstrated in Fig. 6. We will use 193 nm ArF excimer laser of the EX350A type with a specification as mentioned earlier. As for the measurement, we have several types of CTs (current transformers) and also

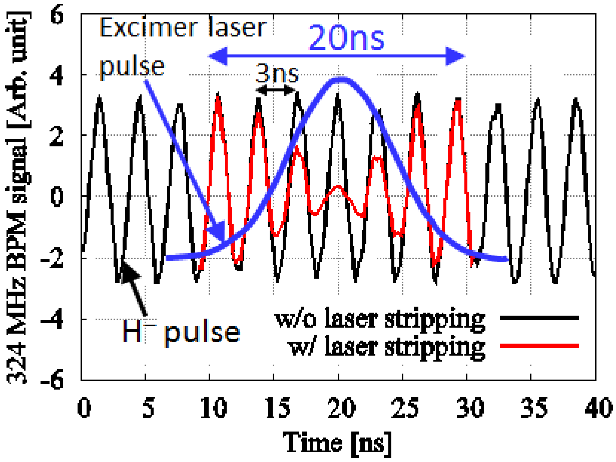

Figure 9: A typical 324 MHz H$^-$ micro pulse structure measured by BPM pickup (black). The blue curve is a given laser pulse by which the H$^-$ is expected to to protons as shown by the red curve.

BPMs (beam position monitors) capable of measuring each 324 MHz micro pulse. Figure 9 shows such a typical signal of a BPM pickup (black) measured for the H$^-$ beam. If we assume a Gaussian laser pulse like the blue curve, we expect the original H$^-$ will be stripped protons as shown by the red curve. Here we assume a 90% overlapping efficiency at the peak of the laser pulse.

The reason why we focus only on a single micro pulse in the POP experiment is that in the practical application we can utilize a laser optical resonator ring [6] which we called laser storage ring in order to cover all micro pulses during 0.5 ms injection time. The seed lasers should at least be capable of running at least 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. We have also already started detail R&D studies of the laser storage ring, which is may be the most difficult part in order to realize practical application H$^-$ laser stripping to protons.

## SUMMARY

In order to realize laser stripping of H$^-$ to proton at lower energies, we proposed a method by using only laser system in order to overcome the difficulty with high magnetic fields which utilize Lorentz stripping of H$^-$ to H$^0$ at the 1st step and H$^{0*}$ to proton at the 3rd step. Instead, we will utilize large photodetachment and photoionization cross sections for the same purposes in the 1st and 3rd steps, respectively.

We plan a proof-of-principle demonstration experiment at the end of 2017 for a 400 MeV H$^-$ beam in J-PARC. We will efficiently use one Nd:YAG laser for both 1st and 3rd steps, while an excimer laser for H$^0$ excitation up to n=3 state in the 2nd step. We expect a 90% stripping efficiency for at least a single micro pulse of the H$^-$ beam of about 30 psec, which has a frequency of 324 MHz. The practical application of H$^-$ laser stripping for the total injection period of 0.5 ms depends on the successful utilization of the laser storage ring.

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