# STATUS OF PROOF-OF-PRINCIPLE EXPERIMENT FOR 400 MeV $H^-$ STRIPPING TO PROTONS BY USING ONLY LASERS IN THE 3-GeV RCS OF J-PARC

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*Abstract*

In the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex), experimental studies are under preparation for POP (proof-of-principle) demonstration of 400 MeV $H^-$ stripping to protons by using only lasers. The aim is to established an alternative $H^-$ stripping injection method without using any stripper foils for that purpose. This is because realistic issues involved with conventional $H^-$ stripping by using foil, such as short lifetime and extremely high residual radiation at the injection area due to the interactions of foil with the beam are already big limitations in all existing high intensity accelerators, and also serious concerns to aim for multi-MW beam power. The present method consists of 3 steps for $H^-$ stripping to protons. The $H^-$ is first neutralized to $H^0$ by using a Nd:YAG laser of 1064 nm. The ground state (n=1) $H^0$ is excited to two level higher states (n=3) producing $H^{0*}$ by using an Excimer laser of 193 nm in the 2nd step. The $H^{0*}$ is then stripped to proton in the 3rd step by using another Nd:YAG laser of 1064 nm. The characteristic feature of this method is that no magnetic field is used, which requires extremely high magnetic field at lower $H^-$ energy. The POP experimental studies will be conducted at the L-3BT (Linac to 3-GeV Beam Transport) of J-PARC. The present status and plan of POP experiment for 400 MeV $H^-$ stripping to protons are presented in this paper.

## INTRODUCTION

Similar to many other high intensity proton accelerators, multi-turn of more than 300 turns $H^-$ stripping injection by using carbon stripper foil has also been adopted in the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) [1]. There has been continuous efforts on durable foil production, which made remarkable progress on the foil lifetime [2], but it is unclear how to deal with increasing demand for multi-MW beam power. The lifetime and rapid foil failure due to overheating of the foil are serious concerns to maintain stable operation of the machine [3]. RCS beam power for operation at present is much lower than its designed 1 MW, and there has no real issues so far with foil lifetime. However, based on the measured foil degradation during present operation, the real lifetime of the foil at 1 MW operation is estimated to be quite short. The real lifetime means, how long a foil can be put in service until when foil degradation is tolerable. Foil degradation such as, change of foil thickness, pinhole formation as well as deformation of the foil rapidly deteriorate the stripping efficiency and results a significant increase of the waste beam at the injection beam dump. This is then determine the foil lifetime even if a foil failure does not occur.

On the other hand, 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 shows typical pictures of RCS stripper foil before and after beam irradiation for about 5 months, but only with 0.3 MW operation. Although the foil did not break, severe foil deformation due to beam irradiation can easily be seen. The total injected charge via 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 un-stripped (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, and directed to the waste beam dump. Ideally, the waste beam should be only 0.3%, which are all the single electron stripped $H^0$ (neutral charge) at the foil determined by the foil thickness, but there should be almost no missing $H^-$. However, due to long tail or halo in the $H^-$ beam, there exists a small fraction of missing $H^-$ in the beginning, but those increase rapidly as the foil degradation governs.

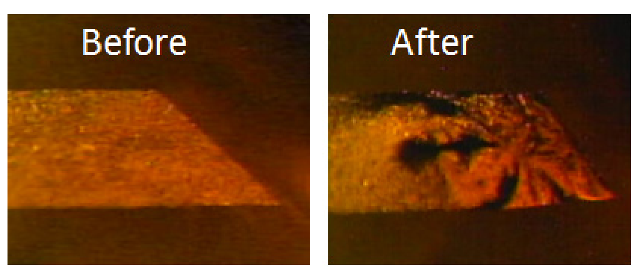


Figure 1: Typical pictures of stripper foil before and after beam irradiation for about 5 month at RCS, but only with 0.3 MW beam power. Deformation of the foil due to beam irradiation caused a rapid increase of the waste beam.

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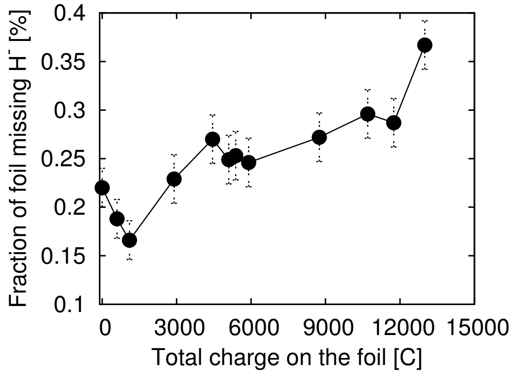


Figure 2: Measured unstripped $H^-$ as a function of charge via the foil during beam operation. The missing $H^-$ was increased nearly 3 times higher as compared to that in the beginning of the operation. Such an increase of the waste beam may limits the foil lifetime at 1 MW operation.

In order to overcome these issues, it is therefore very essential and urgent to established alternative technologies other than using solid foil for the charge-exchange injection. The idea of laser-assisted $H^-$ stripping, which is a three-step process of an $H^-$ conversion to a proton by using high magnetic fields and laser has been under development for more than a decade for 1 GeV H- beam at the SNS (Spallation Neutron Source) in Oak Ridge [4, 5]. In this method, high power laser is used only for an excitation of $H^0$, called $H^{0*}$ in the 2nd step. The $H^-$ neutralization to $H^{0*}$ and to protons are done in the 1st and 3rd step, respectively, by using high magnetic fields of more than 1 T.

However, the situation becomes further difficult at lower $H^-$ beam energies, not only in terms of laser type and its power for $H^0$ excitation, but also for achieving extremely high magnetic fields of nearly 2 T [6]. While high intensity machines usually require large physical aperture, it is very difficult to realize such high magnetic fields. As a result, we consider a completely new method for $H^-$ stripping by using only lasers [7]. In order to verify our new principle, a POP (proof-of-principle) experiment is under preparation at J-PARC for 400 MeV $H^-$ stripping by using only lasers [8].

## PRINCIPLE OF $H^-$ STRIPPING BY USING ONLY LASERS

Figure 3 shows a schematic view of present method for $H^-$ stripping to protons by using only lasers. Similar to the laser-assisted $H^-$ stripping method, it is also consists of 3 steps, except that high field magnetic stripping in the 1st ($H^-$ to $H^0$) and 3rd ($H^{0*}$ to p) processes are replaced by lasers. Widely available high power Nd:YAG lasers can be used for those purposes in order to utilized large photo-detachment and photo-ionization cross sections [9], in the former and later processes, respectively.

The 2nd step is excitation of ground state (n=1) $H^0$ atoms to two level higher (n=3) states by using an Excimer laser. The laser wavelength in the particle rest frame (PRF), (we

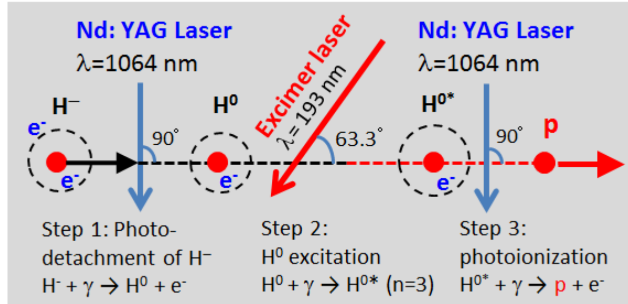


Figure 3: Schematic view of principle for $H^-$ stripping to proton by using only lasers. Noted parameters are typical ones estimated for the 400 MeV $H^-$ beam energy.

denote here as $\lambda_0$), is determined by the $H^0$ excitation energy given by,

$$\Delta E = hc/\lambda_0, \tag{1}$$

where, ΔE is 12.1 eV for exciting an $H^0$ up to n=3 states, h is the Planck constant (6.626E-34 J.s), and c is the light velocity. The $\lambda_0$ is then calculated to be 102 nm. However, we have to calculate the laser wavelength in the particle laboratory frame (PLF) (we denote here as $\lambda$), because, due to the Doppler effect, laser wavelength $\lambda$ in particle laboratory frame (PLF) is shifted to $\lambda_0$ of the $H^0$ atom in the particle rest frame (PRF), given by,

$$\lambda = \lambda_0(1 + \beta cos\alpha)\gamma, \tag{2}$$

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. For any reasonable value of $\alpha$, the Eq. 2 yields a value of $\lambda$ to be around 200 nm. As a result, we considered ArF Excimer laser of 193 nm, for which $\alpha$ is optimized to be 63.3°.

### *Estimation of Required Laser Energy*

In order to achieve maximum stripping efficiency by using given laser power, we consider an optimized $H^-$ beam parameters for both longitudinal and transverse directions. The photo-detachment cross sections, $\sigma$ at 743 nm is about $4{\times}10^{-17}$cm$^2$ [9]. The saturation density, $\Phi^s$ in PRF given by $E_{PH}/\sigma$ is calculated to be $6.7\times 10^{-3}$ 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 [7],

$$E_{laser} = (\Phi^s/\gamma(1 + \beta cos\alpha)) \times (\pi r^2) \times (\tau_l/\tau_i), \tag{3}$$

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

The principle of $H^0$ excitation is same as in the SNS, where 90% excitation efficiency has been demonstrated recently [5] by using laser peak power of 1 MW, which is consistent with the estimation given by Danilov [4, 13]. The estimation, which involves relativistic parameters, $\beta$ and $\gamma$ of $H^0$, gives nearly 1.7 times higher laser power required for 400 MeV as compared to that 1 GeV at the SNS. In order to achieve 90% excitation efficiency, the required Excimer laser energy is estimated to be about 0.07 mJ.

## STRATEGY AND PRESENT STATUS OF THE POP DEMONSTRATION

The overall success of the POP demonstration and its progress are strongly related to the careful experimental strategy, namely, place for the experimental setup, design of experimental devices, experimental methods, and also on an accurate measurement principle. We consider to carry out the experiment step-by-step, and also to measure each charge fractions in the downstream of $H^-$ and laser interaction point (IP). For that purpose, we choose to setup the experimental devices at the end of L-3BT (Linac to 3-GeV Beam Transport) of J-PARC Linac, as shown in Fig. 4. The POP experimental chamber will be installed at the place shown by the 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. As for measuring $H^0$ (if any), at the 90-deg. beam dump, we have to strip those to protons by installing a stripper foil upstream of the dump.

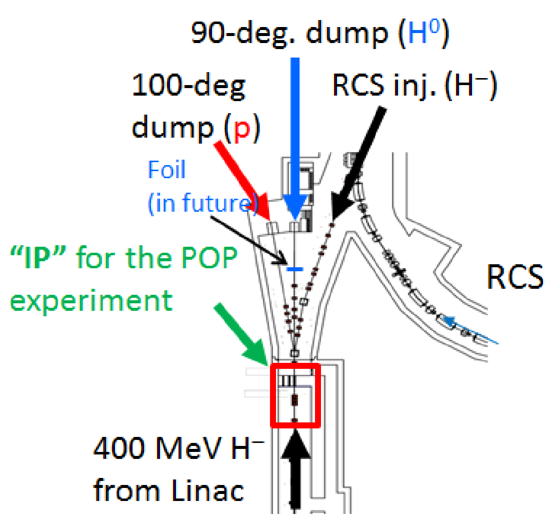


Figure 4: A schematic view of the end section J-PARC L-3BT. The $H^-$ laser stripping POP experimental devices will be installed in the place as shown by red rectangular box. We can simultaneously measure all three charge fractions in the downstream. Namely, fully stripped protons, neutral $H^0$ (by further stripping) and the unstripped $H^-$ can be measured in the 100-deg. dump, 90-deg. dump, and the RCS injection line, respectively.

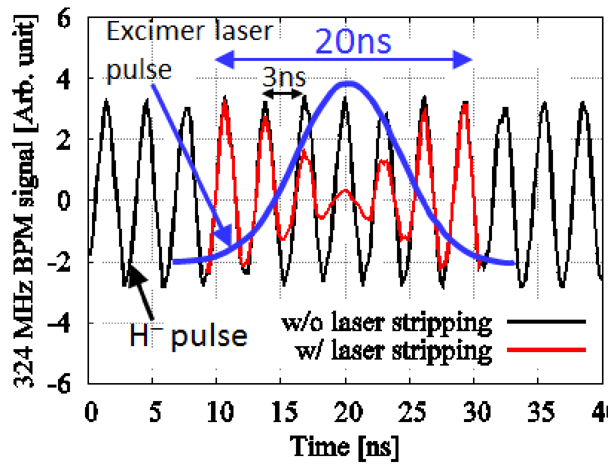


Figure 5: A typical 324 MHz $H^-$ micro pulse structure measured by BPM pickup (black). The blue curve is a given laser pulse by which the $H^-$ is expected to stripped to protons as shown by the red curve.

In the POP experiment, we focus only a single micro pulse of the 400 MeV $H^-$ beam, which has a frequency of 324 MHz, and can be optimized narrower enough to be only about 30 psec. As for the measurement, we have several types of CTs (current transformer) and also BPMs (beam position monitor). The BPMs are capable of measuring each 324 MHz micro pulse. Figure 5 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% stripping efficiency at the peak of the laser pulse, estimated based on the available laser power. The Nd:YAG lasers have enough power in order to obtain more than 90% efficiencies at both 1st and 3rd steps. The overall stripping efficiency mainly depends on the Excimer laser pulse and its effective manipulation.

The primary goal of the POP experiment is to demonstrate 90% stripping efficiency of only a single micro pulse, but we also aim for further higher stripping efficiency through systematic studies and effective manipulation of the laser and $H^-$ beams. In order to cover the whole injection period of 0.5 ms ( $10^5$ micro pulses), we can utilize a laser optical resonator ring, called laser storage ring [10]. In this case, 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. Detail studies of laser beam, optimization of the $H^-$ beam, and measurement procedures have already in progress. The Nd:YAG laser is widely used for $H^-$ neutralization as also been recently successfully demonstrated for 3 MeV $H^-$ neutralization for J-PARC TEF-P (Transmutation Physics Experimental Facility) [11]. Studies of Nd:YAG laser itself for the POP experiment as well to realize laser storage ring has already been started, which is presented in detail separately [12]. The present status of the $H^-$ beam optimization and the measurement principles are given in the next section. The vacuum chamber for the POP experiment has already been designed, which is scheduled to installed in the summer shutdown of J-PARC accelerators in 2017.

## PRELIMINARY RESULTS OF $H^-$ BEAM OPTIMIZATION

In order to achieve efficient overlapping of $H^-$ beam with the laser pulse, especially the Excimer laser, optimization of both transverse and longitudinal parameters of the $H^-$ beam is very essential. Similar to the SNS, we will also utilize the dispersion (D) tailoring method in order to eliminate transition frequency spread for $H^0$ excitation in the 2nd step [4, 13]. Figure 6 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 beam according to Eq. 2.

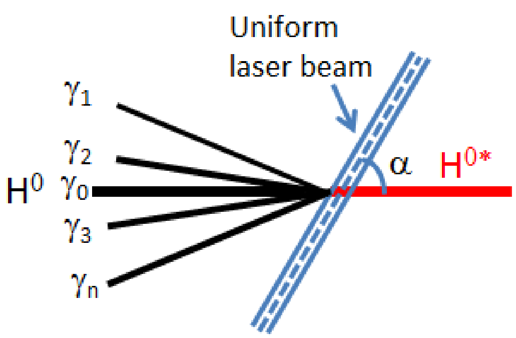


Figure 6: Schematic view of dispersion tailoring method in order to obtain same laser frequency for all hydrogen atoms in their rest frame.

The dispersion derivative ($D^{'}$) plays an important role in order to minimize the laser power [4, 13], where $D^{'}$ has to satisfy the condition given by,

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

where, $\beta$ is the relativistic parameter, and $\alpha$ is the angle between the laser and the ion beam. For $H^-$ beam energy of 400 MeV, the D' at the IP is required to be $-1.3$, where D should be kept as zero. Figure 7 shows first measurement result of dispersion function at the IP. The upstream quadrupole magnets are manipulated in order to obtain the present dispersion function. The D' at the IP is calculated to be $-0.13$, which is 1 order of magnitude smaller than expected one, but further optimization studies will be continued in order to obtain the desired value.

Figure 8 shows 1st measurement results of horizontal and vertical beta functions ($\beta_x$ and $\beta_y$, respectively), also optimized by the upstream quadrupoles at the IP. The measured values of $\beta_x$ and $\beta_y$ at the IP are obtained to be 20 m and 4 m, respectively. The measured $\beta_x$ value is exactly same as expected one, but further efforts are needed in order to obtain $\beta_y$ much smaller.

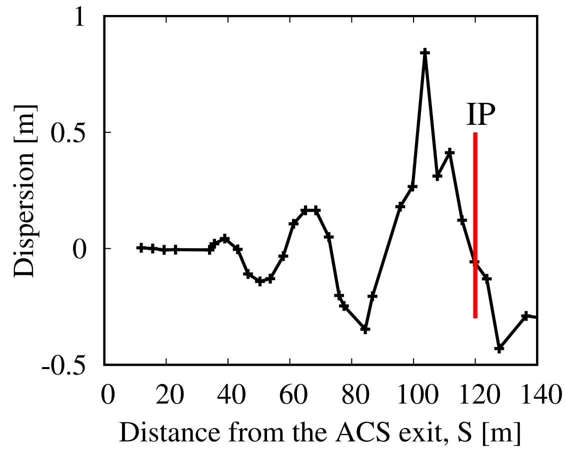


Figure 7: First measurement result of dispersion function optimization of 400 MeV $H^-$ at the IP. The D' at present is obtained to be $-0.13$, but further studies will be continued to get the desired value.

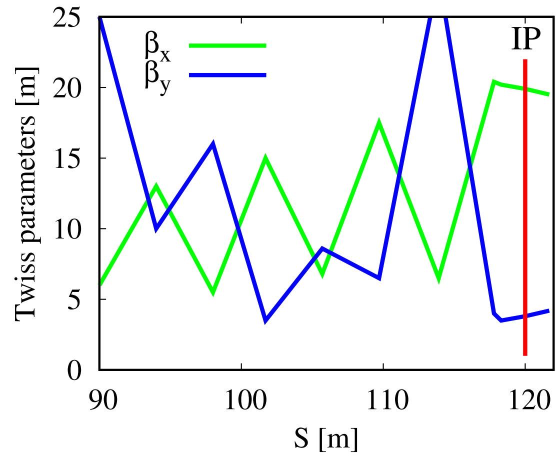


Figure 8: Measurement results of 1st trail of $\beta_x$ and $\beta_y$ optimization for the POP experiment. The measure values at the IP are already very close to expected values, but $\beta_y$ needs to be further reduced.

## MEASUREMENT PRINCIPLE OF STRIPPING EFFICIENCY OF A SINGLE MICRO PULSE

As shown in Fig. 5, our strategy is to explicitly measure stripping efficiency of single micro pulse. For that purpose, we use BPM pickup signal taken by high speed oscilloscopes. At present, instead of laser, we used one of the scrapper for stripping $H^-$ to protons, placed upstream of the IP [14]. The scrapers are charge-exchange type and used for cleanup halo or unexpected long tail in the $H^-$ beam. The scrapped $H^-$ are thus stripped to protons, and those are directed to the 100-deg. beam dump (see. Fig. 4). The thickness of the scrapper foil is thick enough (600 $\mu$g/cm$^2$) to strip more than 99.998% $H^-$ to protons if intercepted by the scrapper. In this study, we used one of the horizontal scrapper as a charge-exchange foil.

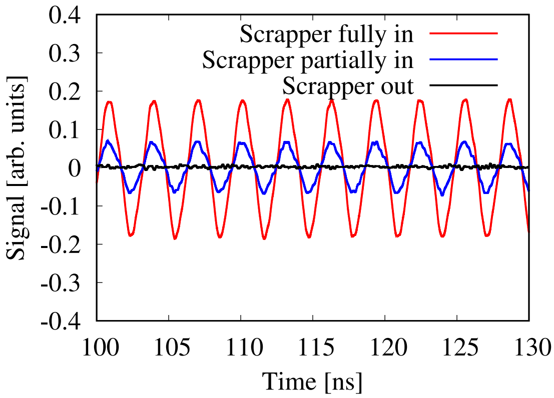


Figure 9: Measured 324 MHz proton beam signal taken by a BPM at the 100-deg. dump. The $H^-$ was stripped to protons by inserting a beam scrapper, placed upstream of the IP.

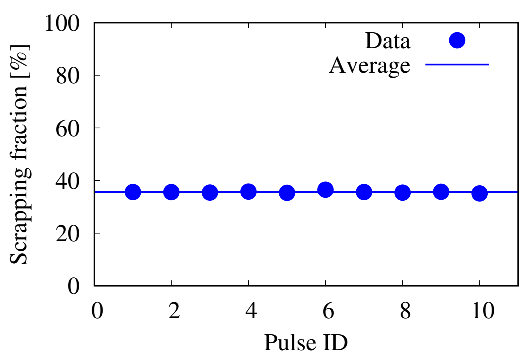


Figure 10: Calculated stripping efficiency for each individual pulse from the data shown in Fig. 9. The average value of 10 pulses is shown by the solid line.

Figure 9 shows a part of 1 medium pulse (456ns) vertical pickup signal of a BPM placed at the 100-deg. dump. Depending on the scrapper position, the charge at the 100-deg. dump changes as reflected by measured signal heights. By fully inserting the scrapper, all $H^-$ are stripped to protons to have the maximum yield (red), while is it minimum (ideally no protons) when the scrapper is moved out from the beam line (black). The un-stripped $H^-$ are also simultaneously measured at the RCS injection line.

Figure 10 shows calculated scrapping ratio for each individual 324 MHz pulse for a condition when the scrapper was partially inserted. It is calculated as a ratio of integrated signal of each pulse in blue color as compared to that in red color (Fig. 9). The average value of 10 pulses is calculated to be 35.62±0.37%. The present method can be proved to be a very unique measurement technique to obtained precise information of each micro pulse. In a similar way, it can be successfully utilized in the POP experiment in order to obtain precisely stripping efficiency of a single micro pulse to which the laser beam is overlapped. On the other hand, measurement of each micro pulse individually is also very useful for optimization and adjustment of both $H^-$ beam and laser pulses in the POP experiment.

## SUMMARY

In order to overcome short lifetime and residual radiation issues involved the conventional $H^-$ charge-exchange injection by using solid stripper foil, we proposed a POP (proof-of-principle) experiment for 400 MeV $H^-$ stripping to protons by using only lasers in the 3-GeV RCS of J-PARC. The POP experiment will be performed at the end section of L-3BT of Linac, where all 3 charge fractions can be simultaneously measured at 3 separate beam lines in the downstream of $H^-$ and laser interaction point. The vacuum chamber for the POP experiment will be installed in 2017 summer maintenance period The laser beam and $H^-$ optimization studies are in good progress, where a very unique and precise method for measuring stripping efficiency of each individual 324 MHz micro pulse has also been established. The 1st step of POP experiment, which is $H^-$ neutralization by Nd:YAG laser will be performed at the end of 2017 fiscal year. The experimental studies for $H^-$ stripping to protons will be conducted in 2018. The R&D studies of laser manipulations and experimental studies for stripping efficiency exceeding 90% will also conducted be successive years.

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## REFERENCES

[1] High-intensity Proton Accelerator Project Team,“ Accelerator Technical Design Report for J-PARC” JAERI-Tech 2003-044 and KEK Report 2002-13.

[2] I. Sugai *et al.*, *Nucl. Ins. and Meth.* A 613, 457 (2010).

[3] M. Plum *et al.*, *Phys. Rev. ST Accel. Beams* 14, 030101 (2011).

[4] V. Danilov *et al.*, *Phys. Rev. ST Accel. Beams* 10, 053501 (2007).

[5] S. Cousineau *et al.*, *Phys. Rev. Lett.* 118, 074801 (2017).

[6] P.K. Saha *et al.*, *Proc. of IPAC'15*, Richmond, VA, USA, paper THPF043, p. 3795 (2015).

[7] I. Yamane *et al.*, *Journal of PASJ*, Vol. 13, No. 2, 80 (2016).

[8] P.K. Saha *et al.*, *Proc. of HB'16*, Malmo, Sweden, paper TUPM7X01, p. 310 (2016).

[9] L. M. BRANSCOMB, “Physics of the One-And-Two-Electron Atoms”, edited by F. Bopp and H. Kleinpoppen, North-Holland, (1968).

[10] I. Yamane *et al.*, *Journal of PASJ*, Vol. 10, No. 1, 20 (2013).

[11] H. Takei *et al.*, *Proc. of IBIC'16*, Bercelona, Spain, paper WEPG45, p. 736 (2016).

[12] H. Harada *et al.*, *In this Proceedings.*

[13] V. Danilov *et al.*, *Phys. Rev. ST Accel. Beams* 6, 053501 (2003).

[14] K. Okabe *et al.*, *Nucl. Ins. and Meth.* A 811, 11 (2016).