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BEAM EXTRACTION BY THE LASER CHARGE EXCHANGE METHOD USING THE 3-MEV LINAC IN J-PARC*

H. Takei†, K. Hirano, and Shin-ichiro Meigo, J-PARC Center, Japan Atomic Energy Agency, Tokai, Ibaraki, JAPAN
K. Tsutsumi, Nippon Advanced Technology Co., Ltd., Tokai, Ibaraki, Japan

Abstract

The Accelerator-driven System (ADS) is one of the candidates for transmuting long-lived nuclides, such as minor actinide (MA), produced by nuclear reactors. For efficient transmutation of the MA, a precise prediction of neutronics of ADS is required. In order to obtain the neutronics data for the ADS, the Japan Proton Accelerator Research Complex (J-PARC) has a plan to build the Transmutation Physics Experimental Facility (TEF-P), in which a 400-MeV negative proton (H^-) beam will be delivered from the J-PARC linac. Since the TEF-P requires a stable proton beam with a power of less than 10 W, a stable and meticulous beam extraction method is required to extract a small amount of the proton beam from the high power beam using 250 kW. To fulfil this requirement, the Laser Charge Exchange (LCE) method has been developed. The LCE strips the electron of the H^- beam and neutral protons will separate at the bending magnet in the proton beam transport. To demonstrate the charge exchange of the H^-, a LCE experiment was conducted using a linac with energy of 3 MeV in J-PARC. As a result of the experiment, a charge-exchanged H^+ beam with a power of 7.99±0.22 W equivalent was obtained under the J-PARC linac beam condition, and this value almost satisfied the power requirement of the proton beam for the TEF-P.

INTRODUCTION

The Accelerator-driven System (ADS) is one of candidates for transmuting long-lived nuclides such as minor actinide (MA) produced by nuclear reactors [1]. For the efficient transmutation of MA, precise prediction of the neutronic performance of ADS is required. In order to obtain the neutronics data for the ADS, the Japan Proton Accelerator Research Complex (J-PARC) has a plan to build the Transmutation Physics Experimental Facility (TEF-P) [2], one of the two buildings of the Transmutation Experimental Facility (TEF) [3]. The critical assembly installed in the TEF-P, which is a small and low power reactor, operates below 500 W to prevent excessive radio-activation. To perform the experiments at the TEF-P with such reactor power, with an effective neutron multiplication factor (k_{eff}) of around 0.97, the incident proton beam power must be less than 10 W. Because the J-PARC accelerators focus on much higher beam power, a low power proton beam extraction device of high reliability is indispensable.

The development of a laser charge exchange (LCE) technique for extraction of the low power proton beam from the high power proton beam is now underway. The LCE technique was originally developed to measure the proton beam profile [4] and applied to the beam forming device [5]. To apply the LCE technique to the beam extraction device for the TEF-P, it is important to evaluate the efficiency of conversion to the low power proton beam and the long-term power stability of the low power proton beam in order to keep the thermal power of the assembly constant. Thus, a LCE experiment to measure the power of the low power proton beam was conducted using a linac with energy of 3 MeV in J-PARC. As already mentioned the preliminary results of the LCE experiment [6], the latest results are presented in this paper.

LCE DEVICE IN THE MAGNETIC FIELD

Figure 1 illustrates the concept of the LCE device for the TEF-P [7]. When a laser beam is injected into a negative proton (H^-) beam with energy of 400 MeV from the J-PARC linac, the charge of the H^- beam crossed with the laser beam becomes neutral (H^0). Here, the remaining H^- beam is introduced to the lead-bismuth spallation target in the ADS Target Test Facility (TEF-T) [3], other building of the TEF.

Since the outer electron of the H^- is very weakly bound to the atom, it can easily be stripped by a laser light in the wavelength range of 800~1100 nm as shown in Fig.2 [8].

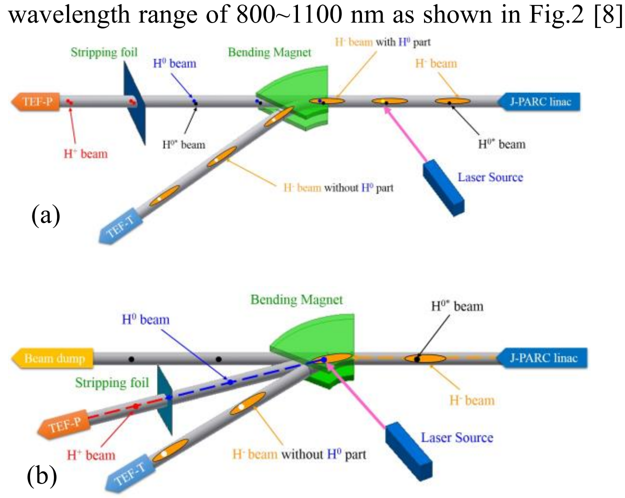

Figure 1: Conceptual diagram of the LCE device for TEF-P. For (a), the laser light is injected in the straight section of the H^- beam line. On the other hand, for (b), the laser light is injected in the bending section of the magnet. The neutralized proton due to interaction by the laser light is written as "H^0", and the pre-neutralized proton due to interaction by the remaining gas in accelerator tubes is written as "H^{0*}".

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† takei.hayanori@jaea.go.jp

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These H^0 protons do not sense the magnetic field of a bending magnet, and are completely separated from the remaining H^- beam at the exit of the bending magnet. However, it is well-known that pre-neutralized H^0 particles are produced by collision with the remaining gas in accelerator tubes and are transported with the main proton beam. When we apply the LCE technique to the H^- beam with the pre-neutralized protons, it becomes impossible to predict the total power of the extracted beam.

To eliminate the pre-neutralized protons, we were trying to perform laser injection and beam bending simultaneously in one magnet [7]. When the laser is injected in the magnetic field of the bending magnet, the pre-neutralized proton goes straight along the beam inlet direction and can be separated from the clean low power proton beam at the exit of the bending magnet. The charge-exchanged H^0 beam reaches the stripping foil. After passing the stripping foil, the H^0 beam is converted to a positive proton (H^+) beam and then delivered to the TEF-P target. A material with a low melting temperature will be used as the stripping foil to avoid high power beam injection to the TEF-P target. Hereafter, the low power H^+ beam extracted from the high power H^- beam by using this LCE strategy is referred to as "the stripped H^+ beam."

Figure 2 shows the photoneutralization cross-section of H^- ions as a function of photon wavelength in the centre-of-mass frame. We chose a fundamental wavelength of 1064 nm from the commercial Nd:YAG laser because this wavelength is near the peak of the photoneutralization cross-section of H^- ions. Even taking the Lorentz contraction effect into consideration, the photoneutralization cross-section for the H^- beam with energy of 400 MeV using the fundamental wavelength of Nd:YAG laser is almost the same as that for the stationary H^- ions using the 1064-

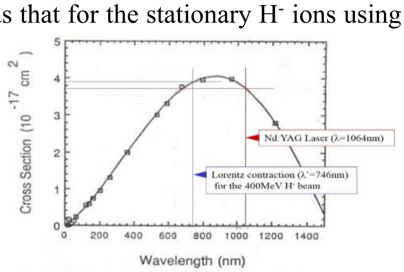

Figure 2: Cross section for H^- photoneutralization as a function of photon wavelength in the centre-of-mass frame [8]. The blue line shows the Lorentz contraction for the H^- beam with 400 MeV.

Table 1: Specifications of the H^- Beam for the J-PARC Linac and the 3-MeV Linac

	J-PARC linac	3-MeV linac
Energy (MeV)	400	3
Maximum beam current (A)	5.0×10^{-2}	3.0×10^{-2}
Macropulse length (s)	5.0×10^{-4}	2.0×10^{-4}
Repetition rate (Hz)	25	25
Maximum beam power (W)	2.5×10^{5}	4.5×10^{2}
RF Frequency (MHz)	324	324
Beam power for a micro-bunch (W)	1.57	6.95×10^{-3}

nm laser light. On the other hand, the Lorentz contraction effect of the collision with the 3-MeV H^- beam and the 1064-nm laser light is insignificant. It is possible to experimentally estimate the conversion efficiency of the LCE for the TEF-P from the results of the LCE experiment with the 3-MeV linac.

Table 1 describes the specifications of the H^- beam for the J-PARC linac and the 3-MeV linac. Here, the 3-MeV linac has two operational modes. Specifications for one of these two modes, *i.e.* the LCE experiment mode, are represented in this table. Based on theoretical considerations [9], the outer electrons of the H^- ions can be stripped with an efficiency of almost 100% by using a commercial Nd:YAG laser having a pulse power of a few joules. Therefore, it is expected that a stripped H^+ beam with a power of 1.57 W can be obtained from a micro-bunch of the H^- beam delivered from the J-PARC linac.

LCE EXPERIMENT

Experimental Devices

At J-PARC, a linac with energy of 3 MeV has been constructed for the development of accelerator components such as beam scrapers, bunch shape monitors, laser profile monitors, and so on. This linac consists of an H^- ion source, a low energy beam transport, a radio frequency quadrupole (RFQ) linac, a medium energy beam transport, and beam dumps. For further details about these devices, see ref. [10]. Hereafter, the linac with energy of 3 MeV is referred to as "the 3-MeV linac."

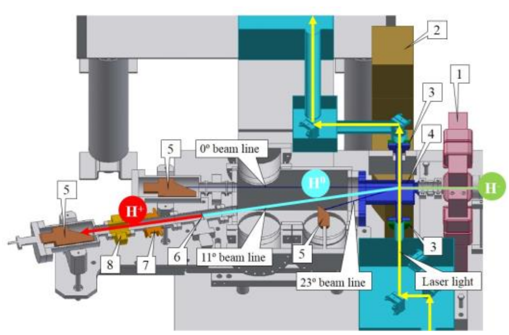

Figure 3: Schematic View of the LCE devices (1-quadrupole magnet, 2-bending magnet, 3-quartz viewing port, 4-vacuum chamber, 5-beam dump, 6-stripping foil, 7-BPM, 8-SCT).

Table 2: Specifications of the Nd:YAG Laser and the He-Ne Laser

	Nd:YAG laser	He-Ne laser
Operation mode	Pulsed	Continuous Wave
Wavelength (m)	1.064×10^{-6}	6.328×10^{-7}
Pulse width (s)	$(5\sim9)\times10^{-9}$	--
Pulse energy (J)	1.6	--
Pulse repetition rate (Hz)	25	--
Power (W)	40	2.0×10^{-2}

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As shown in Fig. 3, the proton beam line consists of three quadrupole magnets which have a steering function, a bending magnet, a beam position monitor (BPM), beam current monitors, and beam dumps. The LCE devices were installed at the end of the proton beam line. That is, the titanium vacuum chamber was located between two magnetic poles of the bending magnet, in which the H^- beam collided with the Nd:YAG laser light at a near right angle. Two quartz viewing ports were fitted to the vacuum chamber. The commercial high power Q-switched Nd:YAG laser was located on an anti-vibration table. Table 2 describes the specifications of the Nd:YAG laser. The laser light was reflected by ten plane mirrors and transmitted through one quartz viewing port from the laser main body to the collision point. This optical path length was 4.25 m. After the collision with the H^- beam, the laser light was propagated to the termination point in the light-blocking box used for the laser light diagnostics. During the propagation, which was 3.16 m in length, there were five reflections by the plane mirror and one transmission through the quartz viewing port.

In this light-blocking box, three types of diagnostics for the Nd:YAG laser light were located. The first was a laser power meter to measure and absorb the laser light, the second was a photon beam profiler to measure the profile and the position of the laser light, and the third was a biplanar phototube to measure the time structure of the laser light.

To keep the H^+ beam power constant over longer periods, it was important to keep the position of the Nd:YAG laser light at the collision point constant. However, it was difficult to adjust the position of the invisible laser pulse of the Nd:YAG laser. Therefore, the visible laser light from the commercial He-Ne laser was used as a guide beam. The specifications of the He-Ne laser are also described in Table 2.

The trajectory of the H^- beam from the RFQ was bent by the bending magnet with a deflection angle of 23°, and transported to the beam dump provided in the most downstream part of the 23° beam line. As the Nd:YAG laser light was injected in the centre of the magnetic pole of the bending magnet, the H^0 beam was transported to the beam line with the deflection angle of 11.5° and introduced to the stripping foil. Hereafter, this beam line is referred to as "the 11° beam line." The H^0 beam was converted to the H^+ beam by passing the stripping foil. From the upstream to the downstream of the 11° beam line, a BPM, a slow current transformer (SCT), and a Faraday cup (FC) serving as a beam dump were positioned. These instructions are a typical implementation of the requirements.

Experimental Method

In FY2016, a LCE experiment to measure the power and its stability of the stripped H^+ beam was conducted using the H^- beam derived from the 3-MeV linac.

First, the position of the H^- beam was measured by the BPM without exciting the bending magnet, and the trajectory of the H^- beam was adjusted by using steering magnets so that the H^- beam was passed through the centre position of the BPM. Beam width and emittance of the H^- beam were obtained with the beam emittance monitor placed 0.3 m downstream of the quadrupole magnet by using Q scan technique. As a result of the measurement, the root-mean-square (RMS) width in the vertical and horizontal direction (σ_v, σ_h) at the collision point was estimated as about 1.7 and 3.7 mm, respectively.

After exciting the bending magnet, the H^- beam was transported to the 23° beam dump and collided with the Nd:YAG laser light. Then, the deflection angle of the H^- beam was decided by fine-tuning the magnetic field strength of the bending magnet so that the stripped H^+ beam was passed through the centre position of the BPM located in the 11° beam line. By using beam current monitors such as SCT and FC, the current amount of the stripped H^+ beam was measured.

Figures 4 and 5 show the photon profile located near the collision point. The origin *O* in the Fig. 4 represents the centroid of the photon profile. From this figure, it can be seen that the vertical RMS-radius of the Nd:YAG laser light could be estimated as 2.1 mm at the collision point with the H^- beam. Therefore, from the viewpoint of the vertical direction for the H^- beam, the narrow H^- beam collided with the wide Nd:YAG laser light.

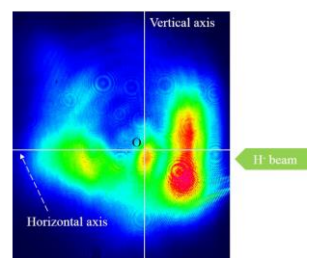

Figure 4: Two-dimensional photon profile for the Nd:YAG laser near the collision point with the H^- beam.

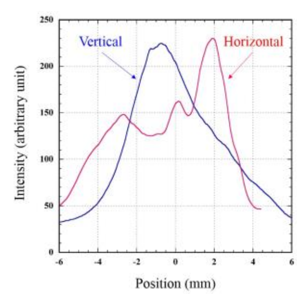

Figure 5: Intensity distributions of the Nd:YAG laser light near the collision point with the H^- beam.

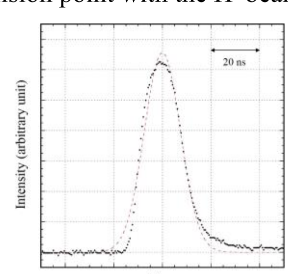

Figure 6: Time structure of the Nd:YAG laser light at the termination point.

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In addition, the Nd:YAG laser power was set to 64% of the rated output power (25.6 W, 1.0 J/pulse) to protect the quartz viewing port. The power of the Nd:YAG laser light gradually decreased until it reached the collision point due to the reflection by 10 plane mirrors and the transmission through a quartz viewing ports, and the laser power at the collision point was 23.5 W. Consequently, the total transmittance was estimated as 92%. The energy density per unit area for the Nd:YAG laser light injected to the quartz viewing port was estimated as 3.7 J/cm^2, which was lower than the damage threshold for the Nd:YAG laser (10 J/cm^2).

Figure 6 shows the time structure of the Nd:YAG laser light. From this figure, the time spread with a power of 23.5 W was estimated as 7.43 ns (1σ). It was obvious that a pulse of the Nd:YAG laser light collided with the 6.0 micro-bunches of the H$^-$ beam. Therefore, a stripped H$^+$ beam with a power of 9.5 W equivalent could be obtained under the assumption that the conversion efficiency for each micro-bunch of the H$^-$ beam was 100%.

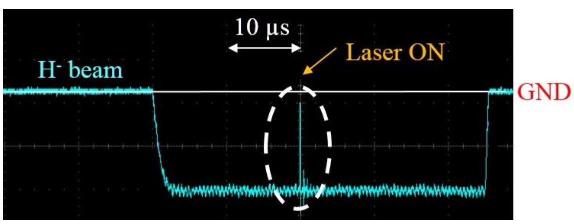

Figure 7: Current waveform of the H$^-$ beam observed at the 23° beam dump.

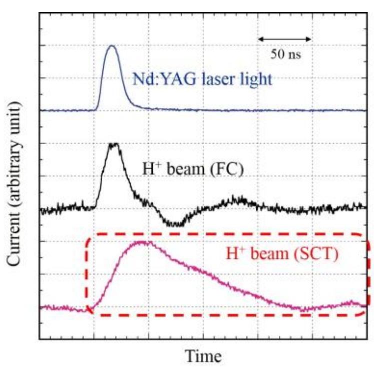

Figure 8: Current waveform of the H$^+$ beam observed at the 23° beam dump.

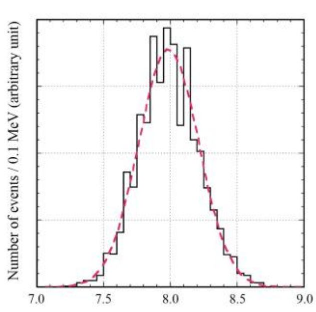

Figure 9: Current waveform of the H$^+$ beam observed at the 23° beam dump.

Preliminary Results

The light-blue broken line in Fig. 7 represents the current waveform of the H$^-$ beam observed at the 23° beam dump. This light-blue current waveform represents a single macropulse, and the rapid rise and fall part surrounded by the white dotted circle is due to the lack of the H$^-$ beam caused by the LCE. This lack was observed from the first shot of the Nd:YAG laser light after beginning the LCE experiment, and then we confirmed the collision between the H$^-$ beam and the Nd:YAG laser light. Figure 8 shows the pulse waveform of the Nd:YAG laser light observed at the biplanar phototube and the H$^+$ beam observed at the FC and SCT of the 11° beam line. From the figure, it can be seen that the pulse waveform of the H$^+$ beam was obtained after the laser light, and the power of the H$^+$ beam was 0.0359 W from the time integral of the H$^+$ beam current inside the dotted-red rectangle. If the laser light from this Nd:YAG laser system collided with the H$^-$ beam delivered from the J-PARC linac, a stripped H$^+$ beam with a power of 7.99 W would be obtained from the following equation.

$$0.0359\ (W) \times \frac{400\ (MeV)}{3\ (MeV)} \times \frac{50\ (mA)}{30\ (mA)} = 7.99\ (W) \qquad (1)$$

This value almost satisfied the power requirement (less than 10 W) of the proton beam for the TEF-P.

Figure 9 shows the power distribution of the stripped H$^+$ beam observed at the SCT. Here, the value of the horizontal axis represents the converted power under the J-PARC linac beam condition. By the approximation of the standard normal distribution, the power spread of the stripped H$^+$ beam was estimated as 0.22 W (1σ).

CONCLUSION

For the extraction of the low power H$^+$ beam (less than 10 W) from the high power H$^-$ beam (400 MeV, 250 kW) by the LCE technique, the LCE experiment to measure the power and its stability of the stripped H$^+$ beam was conducted using the H$^-$ beam from the 3-MeV linac in J-PARC. As a result of this experiment, the stripped H$^+$ beam with a power of 7.99±0.22 W equivalent was obtained under the J-PARC linac beam condition, and this value almost satisfied the power requirement (less than 10 W) of the proton beam for the TEF-P.

REFERENCES

[1] K. Tsujimoto *et al.*, "Feasibility of Lead-Bismuth-Cooled Accelerator-Driven System for Minor-Actinide Transmutation", *Nucl. Tech.*, vol. 161, pp. 315-328, 2008.

[2] H. Oigawa *et al.*, "Conceptual Design of Transmutation Experimental Facility", in *Proc. Int. Conf. on back-end of the fuel cycle: from research to solutions (Global 2001)*, Paris, France, 2001.

[3] F. Maekawa and Transmutation Experimental Facility Design Team, "J-PARC Transmutation Experimental Facility Program", submitted for publication.

[4] Y. Liu *et al.*, "Laser wire beam profile monitor in the spallation neutron source (SNS) superconducting linac", *Nucl. Instr. Meth.*, vol. A612, pp. 241-253, 2010.

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-WEPCF08

[5] D.E. Johnson *et al.*, in *Proc. 6th Int. Particle Accelerator Conf. (IPAC2015)*, VA, USA, May 3-8, 2015, paper WEPTY028.

[6] H. Takei *et al.*, "Present Status of the Laser Charge Exchange Test Using the 3-MeV Linac in J-PARC", in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16)*, Barcelona, Spain, Sep. 2016, paper WEPG45, pp. 737-740.

[7] S. Meigo, "Conceptual design of proton beam transport system for ADS facilities at J-PARC", *J. Nucl. Mater.*, vol. 450, pp. 8-15, 2014.

[8] John T. Broad and William P. Reinhardt, "One- and two-electron photoejection from H^- : A multichannel J-matrix calculation", *Phys. Rev.*, vol. A14, pp. 2159-2173, 1976.

[9] S. Meigo *et al.*, "A Feasibility Study of H^- Beam Extraction Technique Using YAG Laser", JAERI, Tokai, Ibaraki, JAPAN, Rep. JAERI-Tech 2002-095, Dec. 2002, (in Japanese).

[10] K. Hirano *et al.*, "Development of beam scrapers using a 3-MeV linac at J-PARC", in *Proc. 13th Annual Meeting of Particle Accelerator Society of Japan*, Chiba, Aug. 2016, paper MOP005, (in Japanese).