Beam Extraction by the Laser Charge Exchange Method Using the 3-MeV LINAC in J-PARC*)

Hayanori TAKEI, Koichiro HIRANO, Kazuyoshi TSUTSUMI[1)] and Shin-ichiro MEIGO

J-PARC Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan

[1)]*Nippon Advanced Technology Co., Ltd., Tokai, Ibaraki 319-1112, Japan*

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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 the efficient transmutation of MA, a precise prediction of the neutronics of the ADS is required. To obtain 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 positive proton (H^+) beam will be delivered from the J-PARC linac. Because the TEF-P requires a stable and low background proton beam with a power of less than 10 W, a stable and meticulous beam extraction method is required to extract the low power proton beam from the high power negative hydrogen (H^-) beam of 250 kW. To fulfill this requirement, a new type of Laser Charge Exchange (LCE) device was developed. A feature of this LCE device is the elimination of the background protons that are not extracted by the LCE technique. To demonstrate the charge exchange of H^-, an LCE experiment was conducted using a linac with an 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 nearly satisfied the power requirement of the proton beam for the TEF-P.

Keywords: laser charge exchange method, Accelerator-Driven System (ADS), Japan Proton Accelerator Research Complex (J-PARC), Transmutation Experimental Facility (TEF), beam extraction, 3-MeV linac

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1. Introduction

The Accelerator-driven System (ADS) is one of the candidates for transmuting long-lived nuclides such as minor actinide (MA) produced by nuclear reactors [1]. For the efficient transmutation of MA, precise predictions of the neutronic performance of ADS are required. To obtain 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]. TEF-P is a critical assembly, a small and low power nuclear reactor, and is operated at most 500 W to prevent excessive activation of the core. To perform the experiments at the TEF-P with such a reactor power, with an effective neutron multiplication factor (k_{eff}) of approximately 0.97, the incident proton beam power must be less than 10 W. Because the J-PARC accelerators focus on much higher beam powers, a low power proton beam extraction device of high reliability is indispensable.

A stripping foil has traditionally been used to extract low power proton beams from high power proton beams [4]. Because there is a problem of an unexpectedly high power beam extraction due to the deformation of the stripping foil, and it is difficult to extract a very weak proton beam, a non-contact beam extraction device is required. The laser charge exchange (LCE) technique, which is one non-contact beam extraction technique, was originally developed to measure proton beam profiles [5] and has been applied to beam forming devices [6]. To apply the LCE technique to the beam extraction device for the TEF-P, a new type of LCE device to eliminate the background protons that are not removed by the LCE technique was devised [7]. It is also important to evaluate the conversion efficiency and the long-term power stability of the low power proton beam in order to keep the thermal power of the critical assembly constant. Therefore, an LCE experiment to measure the power of the low power proton beam was conducted using a linac with an energy of 3 MeV in J-PARC (hereafter, this linac is referred to as "the 3-MeV linac."). In this paper, the results of the LCE experiment are presented.

2. LCE Device in the Bending Magnet

Figure 1 illustrates the concept of the LCE device for the TEF-P [7]. When a laser beam is injected into a negative hydrogen (H^-) beam with an energy of 400 MeV from the J-PARC linac, the charge of the H^- ion crossed with the

author's e-mail: takei.hayanori@jaea.go.jp

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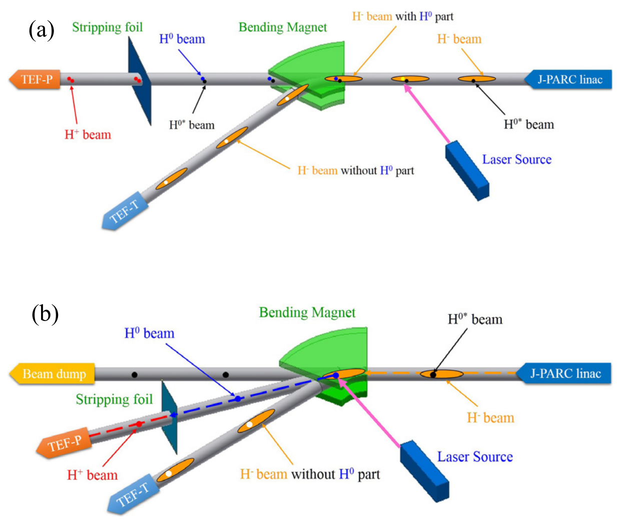

Fig. 1 Conceptual diagram of the LCE device for the TEF-P. In panel (a), the laser light is injected into the straight section of the H⁻ beam line. Conversely, in panel (b), the laser light is injected into the bending section of the magnet. The neutralized protons due to interaction with the laser light are indicated as "H^0", and the pre-neutralized protons due to interaction with the remaining gas in the accelerator tubes are indicated as "H^{0*}".

laser beam becomes neutral (H^0), as shown in Fig. 1 (a). Here the remaining H^- beam is introduced into a lead–bismuth spallation target in the ADS Target Test Facility (TEF-T) [3], another experimental facility of the TEF.

Because the outer electron of the H^- ion is weakly bound to the hydrogen atom, it can easily be stripped by a laser light with a wavelength of 1670 nm or less [8]. Because these H^0 protons do not sense the magnetic field of a bending magnet, they are completely separated from the remaining H^- beam at the exit of the bending magnet. However, it is wellknown that pre-neutralized H^0 (H^{0*}) particles are produced by collisions of H^- with the remaining gas in the accelerator tubes and are transported with the main H^- beam. When we apply the LCE technique to the H^- beam with the H^{0*} particles, the charge-exchanged H^0 beam is contaminated with the H^{0*} particles which behave like a background component. Because the amount of H^{0*} particles depends on the vacuum in the accelerator tubes, it is impossible to predict the total power of the extracted beam.

To eliminate the H^{0*} particles, we performed laser injection and beam bending in one magnet [7], as shown in Fig. 1 (b). When the laser is injected into the magnetic field of the bending magnet, the H^{0*} particles move straight along the beam inlet direction and can be separated from the charge-exchanged 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 into a positive proton (H^+) beam and then delivered to the TEF-P target. Because the

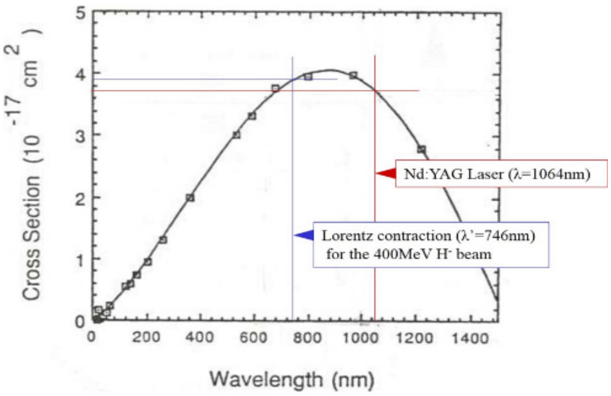

Fig. 2 Cross-section for the H^- photoneutralization as a function of the photon wavelength in the center-of-mass frame [8]. The blue line shows the Lorentz contraction for the H^- beam with 400 MeV.

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}

power of the charge-exchanged H^0 beam is quite low, the deformation of the stripping foil can be ignored. Hereafter, the low power H^+ beam extracted from the high power H^- beam using this LCE strategy is referred to as "the stripped H^+ beam".

Figure 2 shows the photoneutralization cross-section of the H^- ions as a function of the photon wavelength in the center-of-mass frame. We chose a fundamental wavelength of 1064 nm from a commercial Nd:YAG laser because this wavelength is near the peak of the photoneutralization cross-section of the H^- ions. Even taking the Lorentz contraction effect into consideration, the photoneutralization cross-section for the H^- beam with an energy of 400 MeV using the fundamental wavelength of the Nd:YAG laser is nearly the same as that for the stationary H^- ions using 1064-nm laser light. Conversely, the Lorentz contraction effect of the collision with the 3-MeV H^- beam and the 1064-nm laser light is insignificant. Therefore, the photoneutralization cross-section for the H^- beam with an energy of 400 MeV is nearly equal to that with an energy of 3 MeV, and it is possible to experimentally estimate the conversion efficiency of the LCE for the J-PARC linac 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. Based on theoretical considerations [9], the outer electrons of the H$^-$ ions can be stripped with an efficiency of nearly 100% using a commercial Nd:YAG laser with 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.

3. LCE Experiment

3.1 Experimental devices

At J-PARC, the 3-MeV linac was constructed for the development of accelerator components such as beam scrapers, bunch shape monitors, and laser profile monitors. 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].

As shown in Figs. 3 and 4, the proton beam line consists of the quadrupole magnet (1 in Fig. 4), which has a steering function, a bending magnet (2), a beam position monitor (BPM, 7), beam current monitors (8), and beam dumps (5). Figure 5 shows the setup of the LCE experiment. The LCE devices were installed at the end of the proton beam line. That is, the vacuum chamber (4 in Fig. 4) 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 (3 in Fig. 4) were fitted to the vacuum chamber. The commercial high power Q-switched Nd:YAG laser was located in the light-blocking box used for the lasers (Fig. 3). 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. A photon beam profiler was located near the collision point to measure the profile and the position of the laser light. After the collision with the H$^-$ beam, the laser light was transmitted to the termination point in the light-blocking box used for the laser light diagnostics (Fig. 3). During the transmission, 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 installed. The first was a laser power meter to measure and absorb the laser light, the second was a biplanar phototube to measure the time structure of the laser light, and the third was the photon profiler.

To keep the H$^+$ beam power constant over the required periods, it is important to keep the position of the Nd:YAG laser light at the collision point constant. However, it is 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 given in Table 2.

The trajectory of the H$^-$ beam from the 3-MeV linac

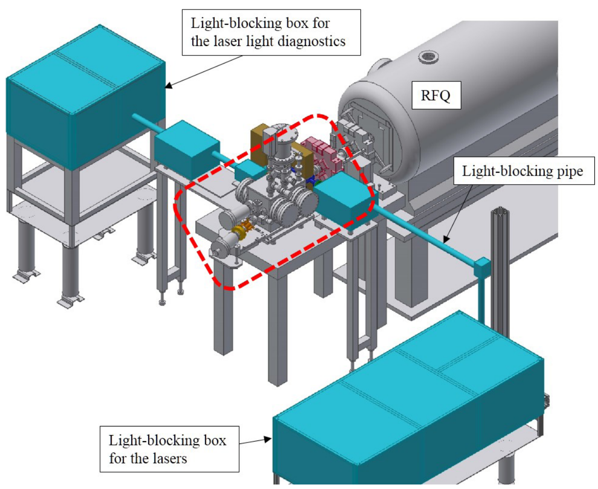

Fig. 3 Layout of the 3-MeV linac with the laser system. The laser system is shown in light blue. An enlargement of the portion surrounded by the red dashed rectangle is shown in Fig. 4.

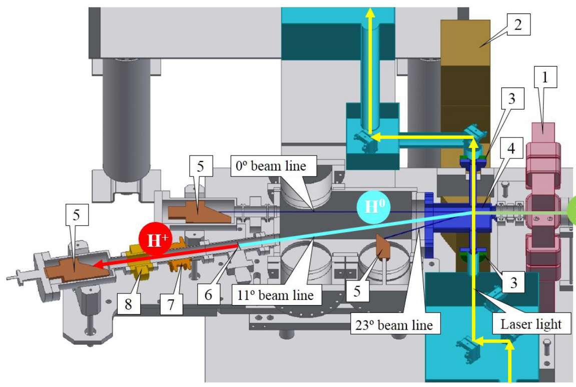

Fig. 4 Schematic view of the LCE devices (1-quadrupole magnet, 2-bending magnet, 3-quartz viewing port, 4-vacuum chamber, 5-beam dump, 6-stripping foil, 7-BPM, and 8-SCT).

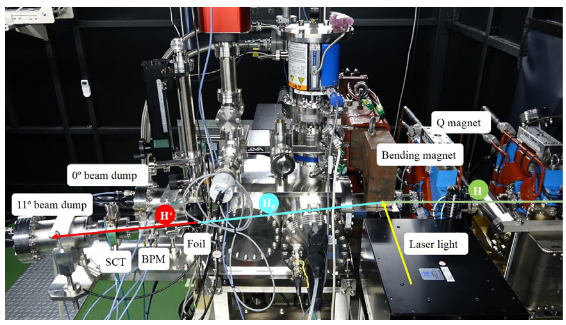

Fig. 5 Setup of the LCE experiment.

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}

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. Because the Nd:YAG laser light was injected in between a pair of magnetic poles 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. A BPM, a slow current transformer (SCT), and a beam dump serving as a Faraday cup (FC) were positioned from the upstream to the downstream of the 11°-beam line.

3.2 Experiment

In FY2016, an LCE experiment to measure the power and stability of the stripped H^+ beam was conducted using the H^- beam derived from the 3-MeV linac (see Figs. 1 (b) and 4).

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 using steering magnets so that the H^- beam passed through the center position of the BPM. The beam width and emittance of the H^- beam were obtained by the beam emittance monitor placed 0.3 m downstream of the quadrupole magnet using the Q scan technique. As a result of the measurement, the root-mean-square (RMS) widths in the vertical and horizontal directions (σ_v, σ_h) at the collision point were estimated to be approximately about 1.7 mm and 3.7 mm, respectively.

After exciting the bending magnet without the Nd:YAG laser light, the H^- beam was transported to the 23°-beam dump. Colliding with the Nd:YAG laser light and the H^- beam, 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 passed through the center position of the BPM located along the 11°-beam line. The stripped H^+ beam current was measured using beam current monitors such as SCT and FC.

Figures 6 and 7 show the photon profile for the Nd:YAG laser observed by the photon beam profiler located near the collision point. The origin O in Fig. 6 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 can be estimated to be 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.

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 the ten plane mirrors and the transmission through the quartz viewing port, and the laser power at the collision point was 23.5 W. Consequently, the total transmittance was estimated to be 92%. The energy density per unit area for the Nd:YAG laser light injected into the quartz viewing port was estimated to be 3.7 J/cm^2, which is lower than the damage threshold for the Nd:YAG laser (10 J/cm^2 for a 10 ns pulse).

Figure 8 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 to be 7.43 ns (1σ). Time-integrating the time distribution of the Nd:YAG laser light and the H^- beam, reveals 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

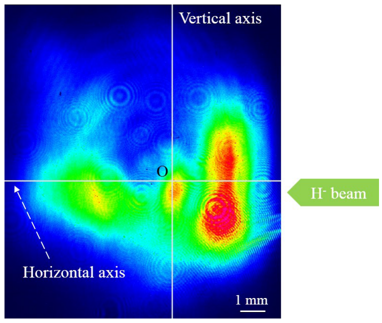

Fig. 6 Two-dimensional photon profile for the Nd:YAG laser near the collision point with the H^- beam.

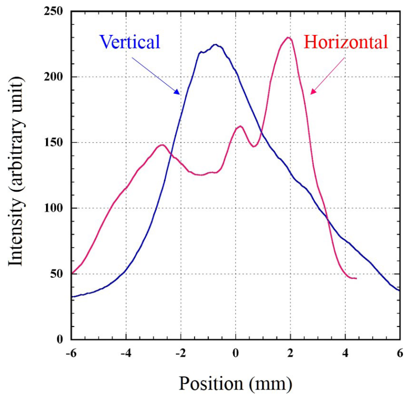

Fig. 7 Intensity distributions of the Nd:YAG laser light near the collision point with the H^- beam.

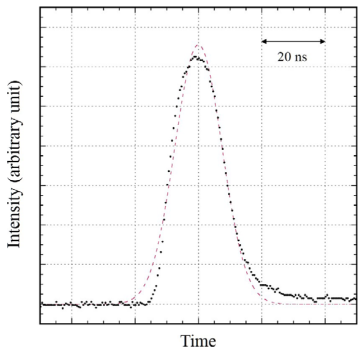

Fig. 8 Time structure of the Nd:YAG laser light at the termination point.

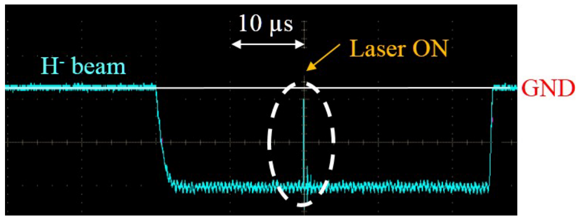

Fig. 9 Current waveform of the H^- beam observed at the 23°-beam dump.

efficiency for each micro-bunch of the H^- beam is 100%.

3.3 Results

The light-blue line in Fig. 9 represents the current waveform of the H^- beam observed at the 23°-beam dump. This current waveform represents a single macro-pulse, and the sharp drop in the white dashed circle results from the lack of the H^- beam on the 23°-beam line due to the photoneutralization by the LCE. This lack was observed from the first shot of the Nd:YAG laser light after beginning the LCE experiment; then, we confirmed the collision between the H^- beam and the Nd:YAG laser light. Figure 10 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. The total power of the H^+ beam was estimated to be 0.0359 W by time-integrating the H^+ beam current measured by the SCT inside the red dashed rectangle. As mentioned previously, the photoneutralization cross-section for the H^- beam with an energy of 400 MeV is nearly equal to that with an energy of 3 MeV. 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 according to the following equation.

$$0.0359\,[\mathrm{W}] \times \frac{400\,[\mathrm{MeV}]}{3\,[\mathrm{MeV}]} \times \frac{50\,[\mathrm{mA}]}{30\,[\mathrm{mA}]} = 7.99\,[\mathrm{W}]. \tag{1}$$

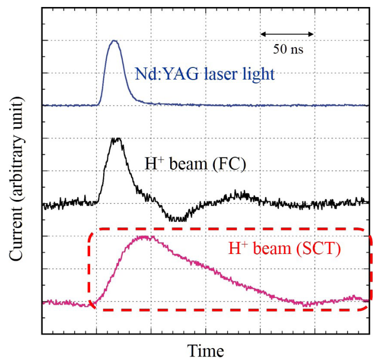

Fig. 10 Waveform of the Nd:YAG laser pulse and the H^+ beam observed at the FC and SCT of the 11°-beam line.

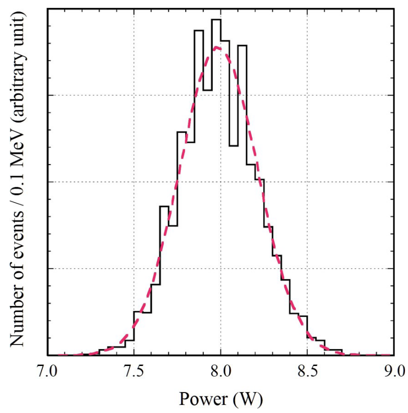

Fig. 11 Power distribution of the stripped H^+ beam observed at the SCT.

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

Figure 11 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. According to the approximation of the standard normal distribution, the power spread of the stripped H^+ beam was estimated to be 0.22 W (1σ).

4. Conclusions

For the extraction of a low power H^+ beam (less than 10 W) from a high power H^- beam (400 MeV, 250 kW), a new type of LCE device to eliminate the background for the low power proton beam was devised. To measure the power and stability of the stripped H^+ beam, an LCE experiment was conducted using the H^- beam from the 3-MeV linac in J-PARC. As a result of this experiment, a stripped H^+ beam with a power of 7.99 ± 0.22 W equivalent was obtained under the J-PARC linac beam condition. This value nearly satisfied the power requirement (less than 10 W) of the proton beam for the TEF-P.

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