LONG BEAM PULSE EXTRACTION BY THE LASER CHARGE EXCHANGE METHOD USING THE 3-MeV LINAC IN J-PARC[*]

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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 pre-diction of neutronics of ADS is required. In order to obtain the neutronics data for the ADS, the Japan Proton Accelerator Research Complex (J-PARC) is planning 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 of 250 kW. To fulfil this requirement, the Laser Charge Exchange (LCE) method has been developed. To demonstrate the long beam pulse extraction using the bright continuous laser beam with a power of 196 W, we installed the LCE device at the end of a 3-MeV linac. As a result of the experiment, a charge-exchanged proton beam with a power of 0.70 W equivalent was obtained under the J-PARC linac beam condition, and this value agreed well with the theoretical value.

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) is planning the Transmutation Physics Experimental Facility (TEF-P) [2], which is one of two facilities of the Transmutation Experimental Facility (TEF) [3]. TEF-P is a critical assembly, that is, a 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. In the subcritical core of the TEF-P, two kinds of operation modes are existed, the short pulse mode and the long pulse mode. For the short pulse mode, the subcriticality of the core was measured using the low power proton beam with a pulse time width of several ns. For the long pulse, the neutron flux distribution in the subcritical core was measured using the low power proton beam with a pulse time width of 500 µs. The power of the incident proton beam ranges from 5 W to less than 10 W for the short pulse mode, and less than 1 W for the long pulse.

On the other hand, the ADS Target Test Facility (TEF-T) [3], another experimental facility of the TEF, equips with a liquid lead-bismuth spallation target bombarded by a 400 MeV-250 kW proton beam. A proton beam provided by the J-PARC linac is shared by TEF-P and TEF-T. These two facilities are connected by one beam line from the J-PARC linac. Because the 250 kW proton beam directed to TEF-T is intense, a technique to extract a low power proton beam of 10 W with high reliability for TEF-P is indispensable.

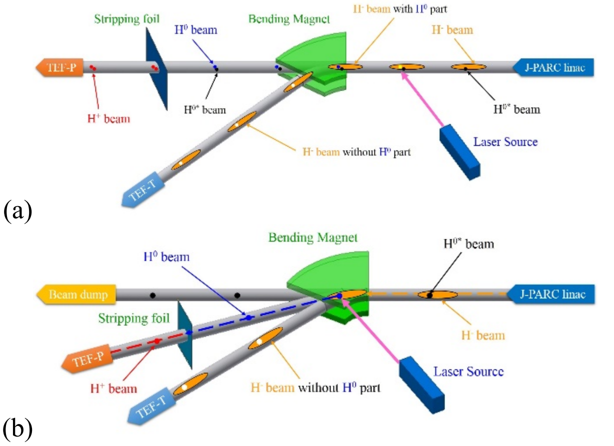

Figure 1: Conceptual diagram of the LCE device for TEF-P. For (a), the laser light is injected in the straight section of the H^- beam line. On the other hand, for (b), the laser light is injected in the bending section of the magnet. The neutralized proton due to interaction by the laser light is written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

A stripping foil has traditionally been used to extract low power proton beams from high power proton beams [4]. 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 according to the pulse time width. Hence we applied the laser charge exchange (LCE) technique, which is one of non-contact beam extraction techniques, to extract the low power proton beam. Another advantage for the LCE technique is that it is relatively easier to extract the low power proton beam with different pulse time width by exchanging the laser light source. The technique was originally developed to measure proton beam profiles [5] and has been applied to beam forming devices [6]. Recently, the LCE injection for

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the high intensity proton rings is developed [7, 8]. To apply the LCE technique to the beam extraction device for the TEF-P, a new type of LCE device was devised [9]. LCE experiments to extract the low power proton beam were conducted using a linac [10] with an energy of 3 MeV in J-PARC (hereafter, this linac is referred to as "the 3-MeV linac."). First, the high-bright short-pulse laser source was used for simulating the short pulse mode. As a result of this experiment, an extracting proton beam with a power of 7.99 ± 0.22 W equivalent was obtained under the J-PARC linac beam condition [11]. This value satisfied the power requirement (less than 10 W) of the proton beam for the TEF-P. In present work, we conducted the LCE experiment using the bright continuous laser source for simulating the long pulse mode.

LCE DEVICE

Figure 1 illustrates the concept of the LCE device for the TEF-P [9]. When a laser beam is crossed with a negative hydrogen (H^-) beam with an energy of 400 MeV from the J-PARC linac, the charge of the H^- ion becomes neutral (H^0) as shown in Fig. 1(a). Here the remaining H^- beam is introduced into a lead-bismuth spallation target in TEF-T.

The H^- ion, a bound state of one proton and two electrons, has no excited bound states. Because one of the two electrons is weakly bound to the hydrogen atom, it can easily be stripped by a laser light with a wavelength of 1670 nm or less [12]. Because these H^0 particles do not sense the magnetic field of the bending magnet, they are 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 beam duct of the beam transport line 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 beam duct of the beam transport line, the most serious problem was that unknown-strength H^{0*} particles which were not caused by the laser light were produced.

To eliminate the H^{0*} particles, we performed laser injection and beam bending in one magnet [9], 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 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."

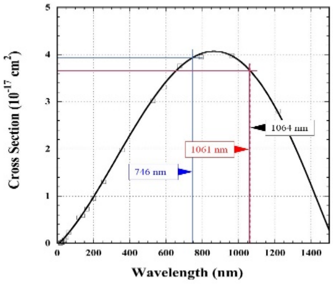

Figure 2: Photoneutralization cross-section of the H^- ions as a function of the photon wavelength in the center-of-mass frame [12]. The blue line shows the Lorentz contraction for the H^- beam with 400 MeV.

Figure 2 shows the photoneutralization cross-section of the H^- ions as a function of the photon wavelength in the center-of-mass frame [12]. We chose a fundamental wavelength of 1064 nm from a commercial Nd:YAG laser and/or diode 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 1064-nm laser light is equal to 1.07 times of that for the stationary H^- ions using 1064-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. Therefore, the photoneutralization cross-section for the H^- beam with an energy of 400 MeV is equal to 1.07 times of that with an energy of 3 MeV and it is possible to experimentally estimate the laser stripping efficiency for the J-PARC linac from the results of the LCE experiment with the 3-MeV linac.

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}	3.26×10^{-2}
Macropulse length (s)	5.0×10^{-4}	5.0×10^{-5}
Repetition rate (Hz)	25	5
Maximum beam power (W)	2.5×10^{5}	24.5
RF Frequency (MHz)	324	324

Next we will estimate the total number of the charge-exchanged H^0 particles using a product of the photoneutralization cross-section and the luminosity for the collision between the H^- beam and laser light. The total number of the charge-exchanged H^0 particles will be;

$$N_0 = N_n P = N_n\left(1-e^{-\sigma L}\right). \qquad (1)$$

Here, N_0 and N_n are the total numbers of the charge-exchanged H^0 and H^- particles per micropulse time width of the H^- beam, respectively, P is the laser stripping efficiency, L is the time-integrated luminosity and σ is the photoneutralization cross-section of the H^- ions. For the long pulse mode, the time-integrated luminosity L can be expressed as [13];

$$L = \frac{1}{\sqrt{2\pi}}\frac{1+\beta\cos\theta}{\sin\theta}\frac{N_n}{\beta c\tau}N_p\frac{1}{\sqrt{\sigma_{nx}^2+\sigma_{px}^2}}. \qquad (2)$$

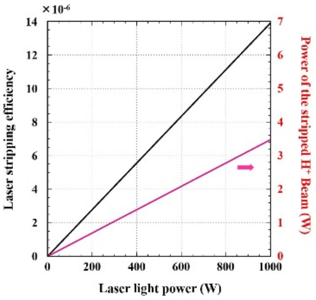

Figure 3: Laser stripping efficiency and the total number of the stripped H^+ beam as a function of the laser light power E_p in 90° collision.

Here, θ is the crossing angle between the H^- beam and the laser light (θ=0° for a head-on collision), c is the light velocity, $\beta=v/c$ (where v is the velocity of the H^- beam), τ is the interaction time of the H^- beam and the laser light, $N_p=E_p\tau\lambda/hc$ (where E_p is the laser light power, λ is the wavelength of the laser light and h is the Planck constant) is the total number of the laser photons per micropulse time width τ of the H^- beam, and σ_x and σ_y are the root-mean-square (RMS) beam size for the x (vertical) and y (horizontal) direction, respectively. Subscripts n and p indicate the H^- beam and the laser light, respectively.

Table 1 describes the specifications of the H^- beam for the J-PARC linac and the 3-MeV linac. The laser stripping efficiency and the total number of the stripped H^+ beam can be deduced by substituting the parameters for the J-PARC linac into Eqs. (1)~(2). From the result of the beam size calculation, the vertical RMS beam size for the H^- beam ($1\sigma_{nx}$) of the J-PARC linac was 2.0 mm [14]. We decided that the vertical RMS beam size for the laser light ($1\sigma_{px}$) was the same 2.0 mm as the H^- beam, and assume that the stripping efficiency from the H^0 beam to the H^+ beam passing the stripping foil is 100%. Figure 3 shows the laser stripping efficiency and the total number of the stripped H^+ beam as a function of the laser light power E_p in 90° collision. As shown in Fig. 3, the laser light power of about 300 W is required to obtain the power requirement (less than 1 W) of the stripped H^+ beam. Since the laser stripping efficiency at this laser light power is about 4×10^{-6} and the peak current of the H^- beam for the J-PARC linac is 50 mA, the peak current of the stripped H^+ beam is about 200 pA.

LCE EXPERIMENT

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. The 3-MeV linac consists of an H^- ion source, a low energy beam transport, a radio frequency quadrupole (RFQ) linac and a medium energy beam transport. For further details about these devices, see Refs. [10, 15].

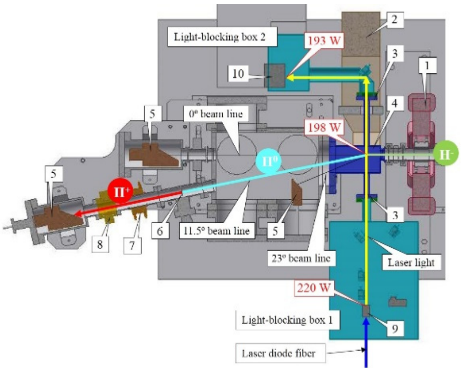

Figure 4: Schematic View of the LCE devices (1- quadrupole magnet, 2- bending magnet, 3- quartz viewing port, 4- vacuum chamber, 5- beam dump, 6- stripping foil, 7- BPM, 8- SCT, 9- beam expander, 10- laser power meter).

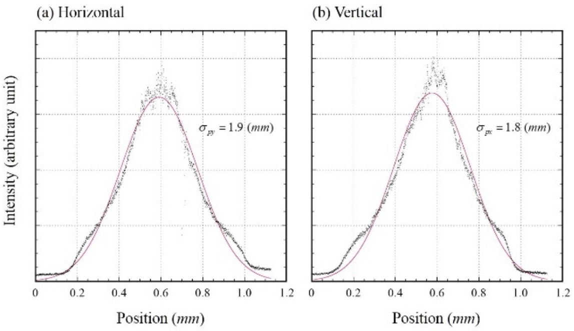

Figure 5: Intensity distributions of the laser light at the collision point with the H^- beam.

Figure 4 shows details of the LCE device installed downstream of the 3-MeV linac. The proton beam line consists of quadrupole magnets and steering magnets (1 in Fig. 4), a bending magnet (2), a vacuum chamber (4), a stripping foil (6), a beam position monitor (BPM, 7), a slow current transformer (SCT, 8), and beam dumps (5). 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.

The vacuum chamber (4) with two quartz viewing ports (3) was located between two magnetic poles of the bending magnet, in which the H^- beam collided with the diode laser light at a near right angle. As the diode laser light was injected in the center of the magnetic pole of the bending magnet, the charge-exchanged 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 11.5° beam line." The charge-exchanged H^0 beam was converted to the H^+ beam by passing the stripping foil (cobalt-base alloy foil, Haver). A BPM, a SCT, and a faraday cup (FC) also served as beam dump were positioned from the upstream to the downstream of the 11.5° beam line.

In case of the long pulse extraction, the peak current of the stripped H^+ beam was in order of 1 µA. As this current value was lower than the lower limit of the BPM and/or

SCT, these beam current monitors were not used. Therefore, the FC was used as the beam current monitor. Electrical signals from the FC were amplified by a factor of 100, and recorded by a digital oscilloscope.

As mentioned previously, the requirements for the laser system are as follows: the laser light power at the collision point was about 300 W, and the vertical RMS beam size for the laser light ($1\sigma_{px}$) was 2.0 mm. In order to satisfy these requirements, the commercial diode laser from Lumics GmbH, module number LU1064C230 [16], was selected. Figure 5 shows the intensity distribution of the laser light observed by the photon beam profiler. The vertical RMS-radius of the laser light at the collision point was estimated to be 1.8 mm by fitting the data points with the normal distribution function.

Preliminary Results

In 2018, an LCE experiment for simulating the long pulse mode was carried out according to the following procedure. First, the position of the H^- beam was measured by the BPM of the 0º beam line 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. Here, the parameters of the H^- beam from the 3-MeV linac are described in Table 1.

After exciting the bending magnet without the laser light, the H^- beam was transported to the 23°-beam dump. Colliding with the 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 to maximize the stripped H^+ beam current.

Two curves in Fig. 6 represent current waveforms of the stripped H^+ beam observed at the FC of the 11.5°-beam line. The black dashed curve was obtained under no laser light condition, while the red curve was obtained when the laser light power was 196 W. The former and latter curve was caused by the electrical noise and the stripped H^+ beam, respectively. By time-integrating the electric signal, the charge for the black dashed curve and the red curve were estimated to be 1.1×10^{-12} C and 3.9×10^{-11} C per macro-pulse, respectively. Since the latter charge amount included the background, the net charge amount subtracted the background was 3.8×10^{-11} C per macro-pulse, corresponding to 0.57 mW.

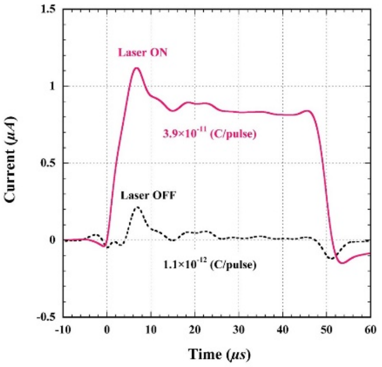

Figure 6: Current waveforms of the stripped H^+ beam with and without the laser light observed at the FC of the 11.5°-beam line.

To compare the output power of the stripped H^+ beam obtained from the laser stripping efficiency of Eq. (1) with the experimental result, the RMS widths of the H^- beam were measured by the Q scan technique. As the result, the RMS widths in the vertical and horizontal directions ($1\sigma_{nx}$, $1\sigma_{ny}$) at the collision point were estimated to be approximately about 2.0 mm and 4.3 mm, respectively. By substituting the vertical RMS width of the laser light and the H^- beam, the theoretical output power of the stripped H^+ beam was estimated to be 0.58 mW. Therefore, the experimental value agrees well with the theoretical result. If the laser light collided with the H^- beam delivered from the J-PARC linac, the stripped H^+ beam with a power of 0.70 W equivalent would be obtained according to the following equation.

$$0.57\,(\mathrm{mW})\times\frac{2.5\times10^{5}}{24.5}\times\frac{2.8\times10^{-6}}{2.3\times10^{-5}}=0.70\,(\mathrm{W}), \tag{3}$$

where the second term of the left-hand side of the equation is the ratio of the H^- beam power and the third term is the ratio of the laser stripping efficiency. This value satisfied the power requirement (less than 1 W) of the proton beam for the TEF-P. This output power of the stripped H^+ beam corresponded to the peak current of 140 pA. It is necessary to develop the beam monitor system (BPM, SCT, FC) that can be used with such weak beam current.

CONCLUSION

For the extraction of the low power H^+ beam (less than 10 W) from the high power H^- beam (400 MeV, 250 kW), the new type of LCE device was devised. The LCE experiment to extract the low power proton beam was conducted using the H^- beam from the 3-MeV linac in J-PARC. In present experiment, we used the bright continuous laser source for simulating the long pulse mode. As the result, the stripped H^+ beam with a pulse time width of 50 µs and a power of 0.57 mW was extracted. This value agrees well with the theoretical result. If the laser light from this LCE device collided with the H^- beam (400 MeV, 250 kW) delivered from the J-PARC linac, the stripped H^+ beam with a power of 0.70 W equivalent was extracted. This value almost satisfied the power requirement (less than 1 W) of the proton beam for the TEF-P.

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