RECENT PROGRESS OF LASER STRIPPING POP DEMONSTRATION STUDY AT J-PARC RCS

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Abstract

To realize the laser charge-exchange injection (LCEI) of H^- beam, a Proof-of-principle (POP) demonstration of 400 MeV H^- stripping to proton by using only lasers is under preparation at J-PARC RCS. The conventional H^- CEI done by using a stripper foil has serious issues associated with its short and unexpected lifetime as well as extremely high residual radiation caused by uncontrolled foil scattering beam losses. It is thus extremely difficult to realize a next generation proton accelerator with multi-MW beam power. The present method comprises three steps for an H^- stripping by using lasers. The H^- is first neutralized to H^0 by an YAG laser, the H^0 is then excited to an upper state (called H^{0*}) by using a UV laser, which is finally stripped to proton by the YAG laser. The R&D of YAG laser system is in advanced stage and we have also developed a multi-reflection laser cavity system to significantly reduce the seed laser power, which was also tested for 3 MeV H^- beam neutralization. The R&D of the UV laser produced by higher harmonic generation from the YAG laser has also been started. The experimental studies for the POP demonstration will be started in 2022.

INTRODUCTION

A thin solid stripper foil used for H^- (negative hydrogen) beam stripping to proton (p) beam for multi-turn charge-exchange injection (CEI) is an effective way to achieve high-intensity proton beam [1, 2]. The CEI allows stacking of many turns because of ideally no beam emittance growth due to injecting in a different charge state and it provides the opportunity of unlimited multi-turn injection until stacking particles exceed the aperture. The CEI by using a stripper foil has been successfully utilized to achieve high-intensity beam of around 1 MW in modern accelerators [3, 4]. However, a short and unexpected lifetime of the foil as well as uncontrolled beam losses and the corresponding high residual radiation at the injection area are two serious issues, especially at high-intensity operation [5, 6]. The continuous efforts on durable foil production made remarkable progress on the foil lifetime [7], but it is still unclear how to deal with multi-MW beam power. It is hard to maintain reliable and longer lifetime due to overheating of the foil at high-intensity operation and might be the most serious concern and a practical limitation to realize multi-MW beam power.

To overcome the issues and limitations associated with the stripper foil, we proposed an alternative method of H^- stripping to proton by using only lasers [8]. Figure 1 shows a schematic view of our concept for 400 MeV H^- stripping to protons (p) by using only lasers. The H^- is first neutralized to H^0 by stripping its loosely bound electron by an YAG laser of 1064 nm. The ground state (1s) electron in the H^0 is excited to 3rd excited state (3p) denoted as H^{0*} by using a deep UV laser of around 200 nm, while the H^{0*} is stripped to p by removing its excited electron by the same YAG as in the 1st step. To establish the method, we are preparing for a proof-of-principle (POP) demonstration study for 400 MeV H^- stripping to proton by using only lasers at the 3 GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC) [9–13].

The R&D of the YAG laser system is an advanced stage at present. To significantly reduce the seed laser power, we have also developed a multi-reflection laser cavity system, and already achieved a superimposition of 32 laser pulses at the interaction point (IP) of the laser and ion beam. The development of the YAG laser and the cavity system is continuing through experimental studies of 3 MeV H^- neutralization at the radio frequency quadrupole (RFQ) test facility (TF) [14] of J-PARC. In this paper, the experimental results of 3 MeV H^- neutralization are mainly presented. The H^- beam manipulations, which is also essential to achieve higher stripping efficiency by minimizing the laser pulse energy as well as R&D status of a monitor system for measuring and decay γs to confirm and identify the level of an excited H^0 were presented in 2020 PASJ meeting [12].

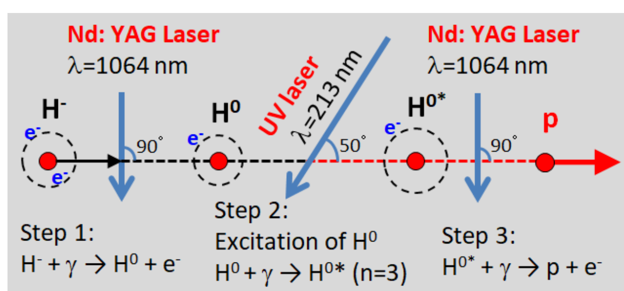

Figure 1: Schematic view of the concept of H^- stripping to proton by using only lasers. Noted laser parameters are for 400 MeV H^- beam stripping.

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YAG LASER AND MULTI-REFLECTION CAVITY SYSTEMS IN BRIEF

Figure 2 shows a layout the prototype YAG laser system, which is under development for the POP demonstration. In the beginning, a combination of AWG (Arbitrary Wave Generator) and EOM (Electro OPTIC Modulator) is used to generate programmable short pulse with high quality and high repetition laser pulses and fed into successive multi stage fiber amplifier systems. The design repetition rate would be same as the frequency of H^- micro pulse, which is 324 MHz. The laser pulses are finally amplified by Laser diode (LD) for about 10 mJ, which is also variable by changing the input power of the LD. The laser output pulses are then transfer to the multi-reflection cavity system. More details about the laser system can be found in [13].

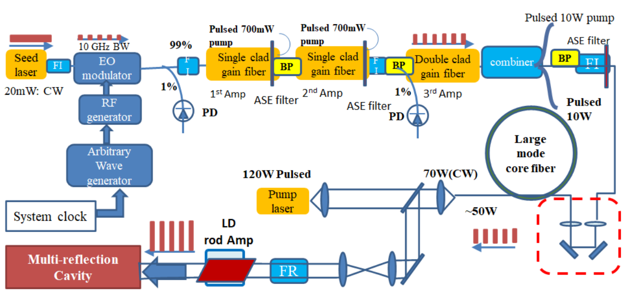

Figure 2: Schematic view of under development prototype YAG laser system for the POP demonstration.

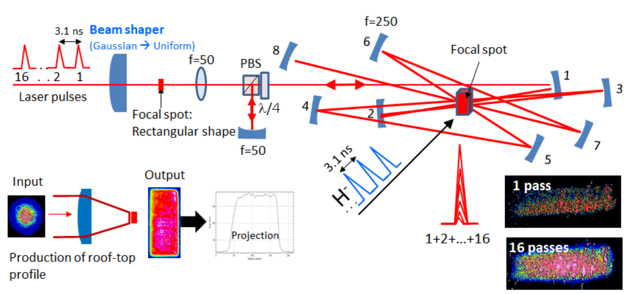

Figure 3: Schematic view of the newly developed multi-reflection laser cavity system to reduce the seed laser power. A beam shaper is used to transform a Gaussian to uniform laser pulse before transferring to the cavity.

Figure 3 shows a schematic view of the multi-pass laser cavity system developed to significantly reduce the seed laser power by superimposition of many laser pulses at the interaction point (IP). One another feature of this system is that we produced a Gaussian to roof-top transverse laser profile by using a beam shaper installed at the upstream of the cavity, which is transferred to the cavity by carefully designing the cavity system with 1:5 image relay optics. A projection of the profile is shown at the left bottom of the figure, which is quite flat at-top. The laser spot after 16 reflections is shown at the right bottom of the figure, which is also quite uniform. At the latest, a maximum overlap of 32 laser pulses has also been achieved. A uniform laser pulse is very essential to reduce the peak density as well as for an efficient overlap with the ion beam at the crossing, especially at the vertical plane.

EXPERIMENTAL SETUP FOR 3 MeV H^- NEUTRALIZATION

The R&D of the YAG laser system is in good progress through step by step experimental studies of 3 MeV H^- beam neutralization at J-PARC RFQ-TF. Figure 4 (right) shows a partial picture of the laser system setup for study at the RFQ-TF in June-July, 2021. The picture in the right shows 3 MeV beam line after the RFQ exit [14] . The laser output pulse is sent to the multi-reflection cavity system from right to the left, where the IP is set at upstream of a bending magnet (BM). The neutralized H^0 and the un-neutralized H^- beam are separated by using the BM. The H^- beam neutralized by the laser interaction ($H^- + \gamma = H^0 + e$) becomes neutral in charge and goes straight, while the H^- is bent by the BM and goes to the 11-degree bent beam line and is measured by a current monitor (FCT) with laser ON and OFF. An FFT analysis of the FCT time domain signal is done and a ratio of the FFT amplitudes at 324 MHz with laser OFF and ON thus gives the neutralization efficiency.

EXPERIMENTAL RESULTS

The first 3 MeV H^- beam neutralization experimental study was carried out at the end of 2020. However, we used a long pulse CW laser, which had a quite low peak energy only of around 1 μJ, but we could clearly measured the neutralization, which was about 0.5%. The main purpose of this experiment was to check the laser system and the cavity for future improvements, and it was thus quite successful.

The next experiment was carried out in June-July, 2021. We developed a short pulse laser of about 100 psec with the same frequency of 324 MHz as the ion beam. However, due to the cavity space limitation, the laser pulse was synchronized to every alternate H^- micro pulses, which has duration of 50 μs. The laser pulse interval was thus 6.17 ns. It is also to be noted that the beam shaper for producing roof-top laser profile was not used. The individual laser pulse energy was about 7 μJ, where we used a superimposition of maximum of 16 reflections in the cavity and obtained nearly 100 μJ.

Figure 5 shows a snapshot of the laser timing to the H^- beam taken by an oscilloscope. The laser pulse (purple) frequency was 6.17 ns, instead of 3.09 ns of the H^- beam of 50 μs pulse length. The neutralization occurred for every alternate H^- micro pulses, which was confirmed by math (FFT) analysis and finding a signal at 162 MHz as shown in Fig. 6. In the offline analysis we also confirmed that a signal at 162 MHz appears only with laser ON. From FFT analysis with 4 μs step we obtained a realistic shape and duration of the laser pulse as shown in Fig. 7. The maximum neutralization occurred at around 30 μs of the H^- pulse.

Figure 8 shows an expanded view of the FCT time domain data with laser ON. The height of every alternate pulses reduced due to the neutralization occurred. The neutralization

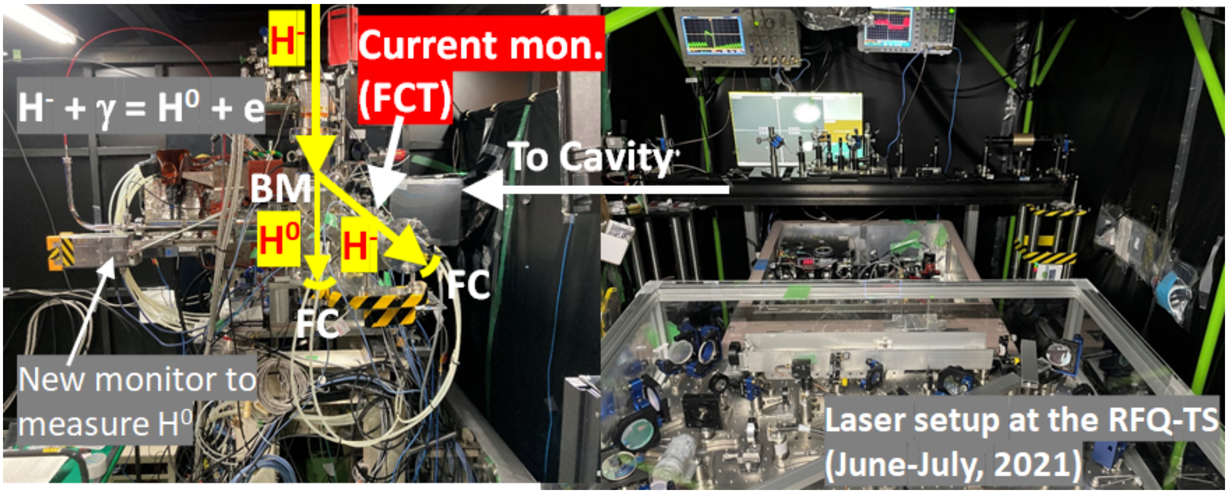

Figure 4: Setup of the laser system and the 3 MeV H^- beam line at J-PARC RFQ-TF. The neutralized H^0 is separated from the un-neutralized H^- by a BM placed just downstream of the IP. The H^- signals without and with laser taken by a current monitor (FCT) located at the downstream of the bent beam line are used to obtain the neutralization efficiency.

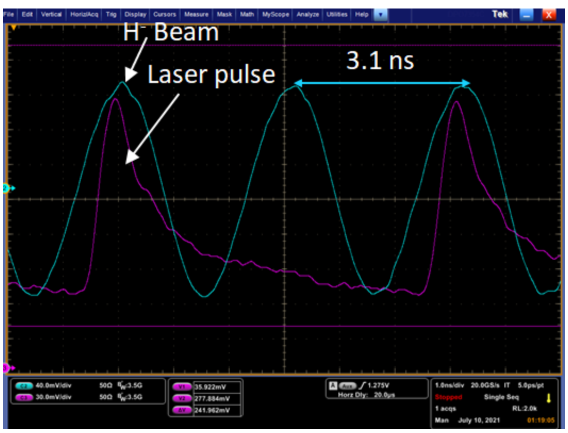

Figure 5: Laser pulse (purple) synchronized to every alternate H^- micro pulses (sky blue).

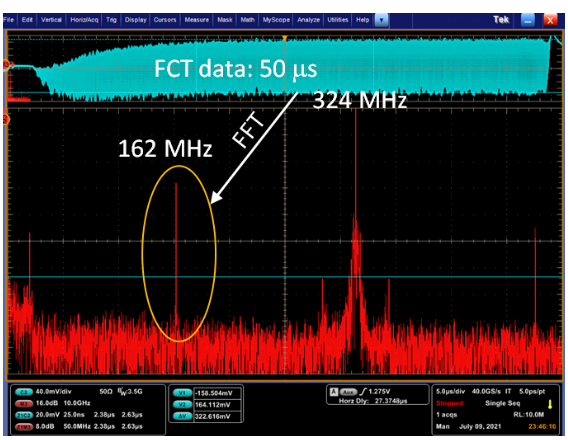

Figure 6: Online confirmation of laser and H^- beam interaction by FFT analysis of the FCT time domain data for a signal at 162 MHz as the neutralization occurred for every alternate H^- beam pulses.

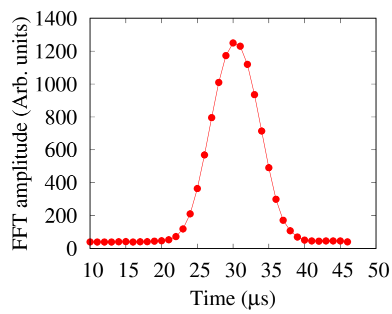

Figure 7: The shape and duration of the laser pulse obtained by FFT analysis of the FCT data for 4 μs steps. The maximum neutralization was at around 30 μs of the H^- pulse.

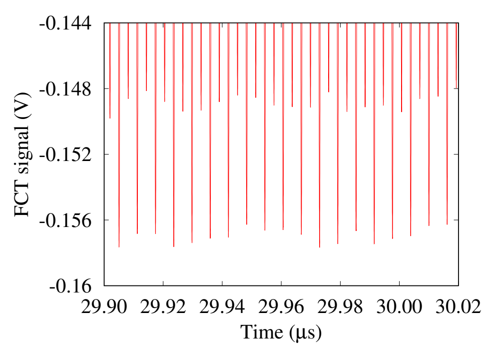

Figure 8: Expanded view of the FCT time domain signal of H^- at the central region. The height of every alternate pulses reduced due to the neutralization with laser interaction.

efficiency was calculated by comparing the nearest pulse, which had no interaction with the laser. Figure 9 shows the neutralization efficiency for several H^- micro pulses at around 30 μs. We obtained a maximum efficiency of 8.5%, and in average (7.4 ± 0.8)%, which is more than one order of magnitude higher neutralization efficiency as compared to our previous trial.

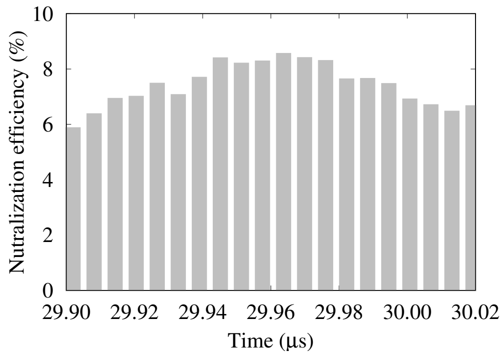

Figure 9: Neutralization efficiency of several pulses at around at around 30 μs of the H$^-$ pulse, the maximum efficiency was 8.5% and in average it was (7.4$\pm$0.8)%.

We also studied the neutralization efficiency dependence on the number of passes in the cavity. Figure 10 shows the FFT scan results taken for 1, 4, 8 and 16 passes in the cavity. The amplitude of 162 MHz increased almost linearly with respect to the number of passes as summarized in the Table 1. This result thus demonstrates the merit of the present multi-reflection cavity system to increase the laser pulse energy at the IP, by reducing the seed lase pulse energy.

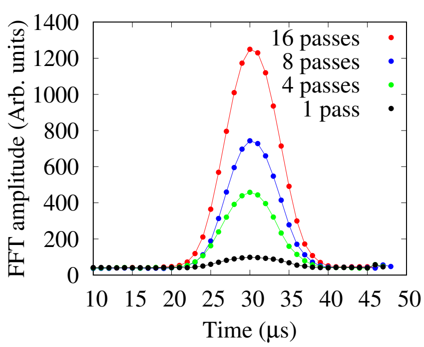

Figure 10: FFT amplitudes of 162 MHz of the FCT data with respect to the number of laser passes in the cavity. The efficiency increases by increasing the laser pulse energy at the IP with number of passes.

Table 1: Measured Neutralization Efficiency Dependence on the Number of Reflections (Passes) in the Cavity

Passes	**Pulse energy** (μJ)	**Neut. eff.** (%)	**Factor** (data)
1	6.9	0.60 $\pm$ 0.08	1
4	25.6	2.53 $\pm$ 0.24	4.2
8	48.3	4.50 $\pm$ 0.40	7.5
16	93.3	7.40 $\pm$ 0.80	12.3

At the end, we increased laser pulse energy by about 20% and obtained a neutralization efficiency of 8.5%. Finally, we also studied the efficiency dependence on the vertical H$^-$ beam size. This is because, the interaction occurs horizontally, where an overlap in the vertical plane to the laser spot size is important as the laser spot size was relatively smaller (~ 0.5 mm). Figure 11 shows measured neutralization efficiency as a function of the vertical H$^-$ beam size. The vertical H$^-$ beam size is ideally 2.2 mm, which was reduced to 0.72 mm to almost doubled the efficiency to 16.5%. As a result, we obtained 33% higher neutralization efficiency as compared to our previous result in 2020.

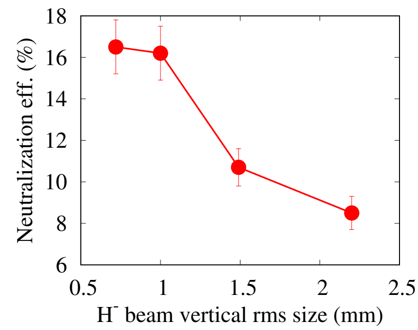

Figure 11: Neutralization dependence on the vertical size of the H$^-$ beam. A maximum efficiency of 16.5% was obtained by minimizing the beam size to 0.72 mm.

SUMMARY

A proof-of-principle (POP) demonstration study for 400 MeV H$^-$ stripping to proton by using only lasers is under preparation at J-PARC RCS. The aim of this research is to establish a foil-less H$^-$ charge-exchange injection to overcome the difficulties and realistic issues associated with the stripper foil used for that purpose. The R&D of a prototype YAG laser system is in good progress, and we have also developed a multi-reflection laser cavity system to significantly reduce the seed laser power, which was also tested for 3 MeV H$^-$ beam neutralization at J-PARC RFQ-TF. In the recent experiment, we obtained a maximum neutralization efficiency of 16.5%, which is 33% higher than our previous trail in 2020. We have also successfully demonstrated the merit of the present cavity system by changing the number passes in the cavity. We could increase the laser pulse energy 14 times by using 16 passes and the neutralization efficiency also accordingly increased. The R&D of the UV laser produced by higher harmonic generation from the YAG laser has also been started. The experimental studies for the POP demonstration of 400 MeV H$^-$ stripping to proton will be started in 2022.

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