STATUS OF POP DEMONSTRATION OF 400 MeV H^- LASER STRIPPING AT J-PARC RCS

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Abstract

To overcome the realistic issues and practical limitations associated with H^- charge-exchange injection (CEI) done by using a solid stripper foil, a Proof-of-principle (POP) demonstration studies of 400 MeV H^- stripping by using only lasers is under preparation at J-PARC. In this method, the H^- is first neutralized to H^0 by using an YAG laser, the H^0 is then excited (called H^{0*}) by using a UV laser and finally stripped it to proton by the YAG laser. A prototype YAG laser system has been developed including a multi-reflection laser cavity system to significantly reduce the seed laser energy. The R&D of the laser and the cavity systems are being upgraded through experimental studies for 3 MeV H^- neutralization. The R&D of the UV laser produced by higher harmonic generation from the YAG laser is also in progress. The experimental studies for the POP demonstration will be started in 2023. In this report, progress of YAG laser and the cavity systems including latest experimental results of 3 MeV H^- neutralization are mainly presented.

INTRODUCTION

The multi-turn charge-exchange injection (CEI) of H^- (negative hydrogen) conventionally done by using a thin solid stripper foil 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 with a stripper foil has been successfully utilized to achieve high-intensity beam of around 1 MW in existing accelerators [3, 4]. However, a short and unexpected lifetime of the foil as well as uncontrolled beam losses and the corresponding high residual radiation are two serious issues, especially at high-intensity operation [5–7]. The continuous efforts on durable foil production made remarkable progress on the foil lifetime [8], 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 a multi-MW beam power.

To overcome the issues and limitations associated with the stripper foil, we proposed a foil-less alternate method of H^- CEI by using only lasers [9]. Figure 1 shows a schematic view of the principle for H^- stripping to protons (p) by using only lasers. The noted laser parameters are considered for H^- of 400 MeV. In this method. 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, and finally the H^{0*} is stripped to p by removing its excited electron by the YAG laser. To establish the method, a proof-of-principle (POP) demonstration study for 400 MeV H^- stripping to proton is under preparation at the 3 GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC) [10–14].

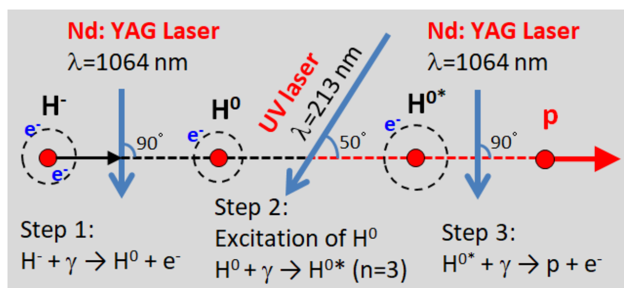

Figure 1: A schematic view of our proposed principle of H^- stripping to proton by using only lasers. Typical laser parameters for an H^- stripping at 400 MeV are also noted.

A prototype YAG laser system has been developed and further upgrades are continued for higher energy, robust uses and reliability. To significantly reduce the seed laser power, we have also developed a multi-reflection YAG laser cavity system to overlap many laser pulses at the interaction point (IP) of the laser and ion beam [15]. This year we have doubled the number of reflections from 16 to 32. The YAG laser and the cavity system are being developed through experimental studies of 3 MeV H^- neutralization J-PARC RFQ-TF (Radio Frequency Quadrupole test facility) [16]. The UV laser of 213 nm, which is a 5th harmonic of YAG laser, is also under developed by higher harmonic generation techniques from the YAG laser. In addition, to handle such a deep UV laser, R&D for the coating of UV laser optical devices have also been started. A detail strategies for a POP demonstration of 400 MeV H^- laser stripping was presented in the PASJ meeting in 2020 [13]. In this paper, progress on the YAG laser and the laser cavity system including latest experimental results of 3 MeV H^- neutralization are presented.

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THE YAG LASER AND MULTI-REFLECTION CAVITY SYSTEMS

The structure of the YAG laser system is essentially same as used in 2021 except additional upgrades were done to increase the pulse energy with a precise control for a longer duration, robust uses with a good stability. More details about the laser system can be found in [14]. In this experiment, a maximum photon energy of every single micro pulse was about 0.023 mJ with 6.17 s micro pulse interval for about 40 μs total duration.

As a requirement of huge laser energy is one big issue to realize a laser stripping with higher efficiency, a reduction of the seeder energy is highly essential. For that purpose, we have developed a multi-reflection (multi-pass) cavity system to overlap many laser pulses at the interaction point (IP) [15]. This year we have doubled reflections to 32 from that of 16 in 2021. Figure 2 shows a schematic view of the final overlaps of 32 passes at the IP, which would allow nearly a 1/32 reduction of the seeder energy. The laser beam are focused at the IP for maximizing the photon flux, while minimizing the mirror damage. The micro pulse duration of the laser was about 100 psec with a transverse spot sizes for both horizontal and vertical planes with only 0.1 mm at the IP. The output energy of each micro pulse was 0.023 mJ at maximum, which after 32 overlaps gave about 0.38 mJ. This number is nearly half than a linear consideration of 32 times increase, but photon losses due to the mirror efficiency as well as at the vacuum windows are considerably higher, which can be almost compensated with higher reflective materials and placing the cavity system in vacuum. The performance of the updated laser cavity system was tested for 3 MeV H^- neutralization in June, 2022.

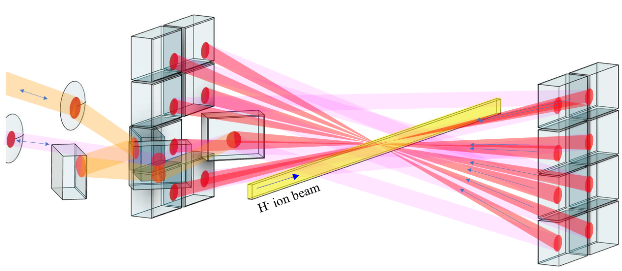

Figure 2: A schematic view of the latest multi-reflection laser cavity system with 32 reflections overlapped at the IP.

EXPERIMENTAL SETUP

The setup for 3 MeV H^- neutralization at the RFQ-TF was essentially same as done in 2021 as shown in Fig. 3. The laser output pulse is sent to the multi-reflection cavity and interact to the H^- beam. The IP is at the upstream of a bending magnet (BM). The H^- beam neutralized by the laser interaction ($H^- + \gamma = H^0 + e$) becomes neutral in charge called H^0, which is separated from the un-neutralized H^- beam by using the BM. The H^0 thus goes straight, while the H^- is bent by the BM and goes to the 11-degree beam line, which is then measured by a fast current transformer (FCT) with laser ON and OFF. Similar to the previous study, the laser pulse interval was 6.17 s instead of 3.08 s of the H^- pulse as shown in Fig. 4. As a result, the interaction occurred for every alternate H^- pulses. The neutralization yield was obtained by the FFT (Fast Fourier Transformation) of the FCT data for a signal at 162 MHz. The present geometry in this sense is very useful to uniquely detecting any signal at 162 MHz, differing from the main beam signal frequency of 324 MHz and with sufficiently less background level. The neutralization efficiency for every individual micro pulse can also be determined as the FCT can measure micro pulse structure of the H^- beam. The peak current of the H^- beam was 50 mA, same as used for J-PARC operation at present, where a macro of 50 μs was typically used.

A precise calibration of the laser to synchronize with the ion beam is very essential to ensure a perfect overlapping for a higher stripping efficiency. At first the calibration of the laser was performed by looking a neutralization peak at 162 MHz by an oscilloscope as shown in Fig. 5. The upper plot is a time domain data of the FCT for un-neutralized H^- beam of 50 μs duration with laser ON. The middle plot shows an expanded view, where a comb structure of the pulses due to neutralization for every alternate pulses can be seen, which is confirmed by an FFT analysis and finding a maximum peak height at 162 MHz as shown in the lower plot. Next, a tuning of the AWG waveform for a precise micro pulse frequency of the laser pulses is done for a perfect matching with every alternate H^- micro pulse. This gives a uniform neutralization over the entire H^- pulse as shown in Fig. 6 the amplitude of 162 MHz obtained for every 2 μs interval of the time domain data. The AWG was tuned better than 10^{-3} precision to obtain a flat neutralization over the entire macro pulse of the H^- beam.

EXPERIMENTAL RESULTS OF 3 MEV H^- NEUTRALIZATION IN 2022

Figure 7 shows an expanded view of the time domain signal at the central region from a 50 μs H^- pulse obtained by applying a maximum laser energy. A reduction of every alternate pulses can be seen caused by the neutralization occurred due to laser interaction. The neutralized H^0 beam went straight to the 0-deg beam dump. Figure 8 shows FFT spectra of the time domain signals with laser ON and OFF depicted by the red and black lines, respectively. The peak at 162 MHz appears only when the laser is ON. In order to calculate the neutralization efficiency, the time domain micro pulses are separated first with and without laser interaction. The interval of the time domain pulses then becomes 6.17s to have a frequency of 162 MHz. A ratio of the amplitude of 162 MHz peak for the pulses with and without an interaction with the laser gives a neutralization efficiency. On the other hand, we can also calculate neutralization of individual micro pulses (Fig. 7) by integrating and comparing with nearest pulse with no interaction with the laser. By using the former method, the neutralization for several μs at the middle of

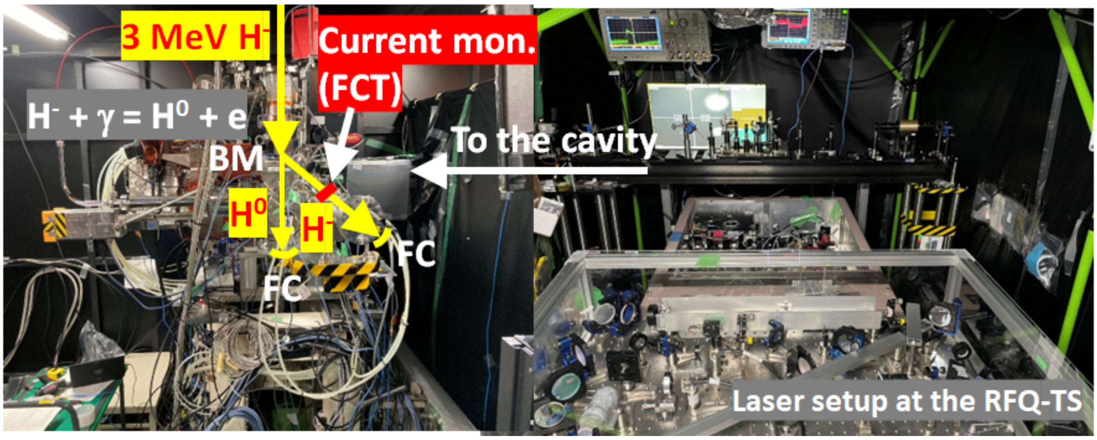

Figure 3: Setup of the laser system for 3 MeV H^- beam neutralization study at J-PARC RFQ-TF. The neutralized H^0 is separated from the un-neutralized H^- by a BM placed just downstream of the IP. The neutralization efficiency is obtained by measuring the H^- signals without and with laser taken by a current monitor (FCT) at the downstream.

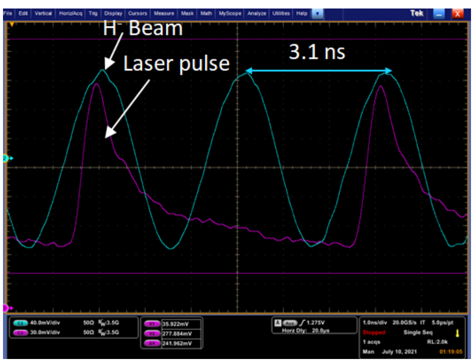

Figure 4: Synchronization of the laser pulse (purple) to every alternate H^- micro pulses (sky blue). The timing system including the logic were updated to improve a timing jitter.

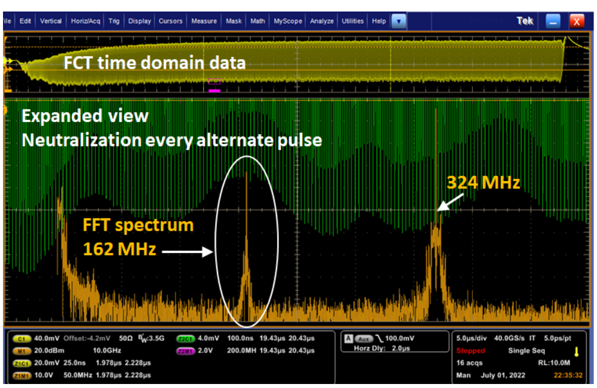

Figure 5: Online confirmation interaction by FFT analysis of the FCT time domain data for a signal at 162 MHz.

the H^- pulse was calculated to be 24.8%, which is 1.5 times higher than the previous result obtained in 2021 [15].

It is worth mentioning that the vertical laser beam size should be higher than the ion beam for a complete overlapping as the laser crosses horizontally. In our case the laser spot sizes were much smaller than the ion beam. The laser spot at the IP was moved according to permissible limit of

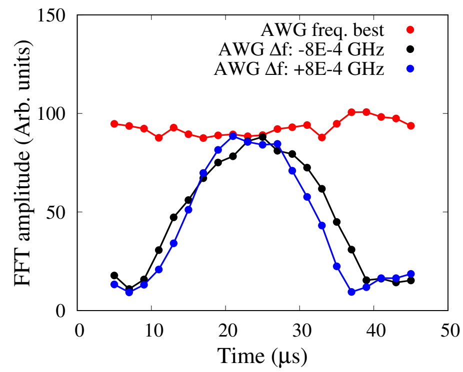

Figure 6: Tuning of the AWG waveform for a perfect matching with all alternate H^- micro pulse to obtain a flat neutralization over the entire H^- pulse.

the cavity geometry to have a higher beam size and obtained nearly a half overlapping with the ion beam. As a result, the neutralization efficiency by taking into account of the overlapping factor is estimated to be nearly 50%.

Figure 9 shows a comparison of the time dependent neutralization between obtained at the present and in 2021. The vertical axis the FFT amplitude for every 2 μs, meaning a neutralization efficiency. This time the laser pulse was tuning to be flat for a longer enough duration to obtain a uniform neutralization over the entire H^- macro pulse as compared to no such a flatness in the previous year.

Laser Energy and Pass Dependent Neutralization Efficiency

Finally we have also studied a neutralization efficiency depending on the laser energy and also the number of reflections (passes) in the cavity. The energy dependence was studied for a maximum of 32 passes, where the input energy was varied. Differing from the above setup, the laser spot size was kept original of only 0.11 mm at the IP for an interaction occurring at a tiny region with a higher photon

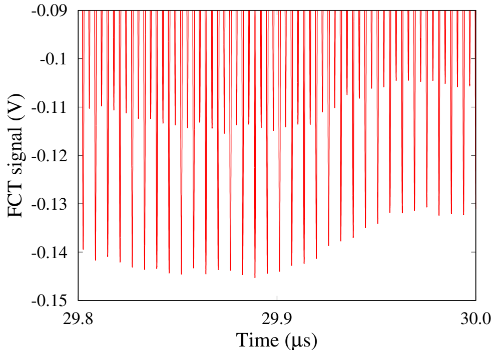

Figure 7: Expanded view of the FCT domain signal of H^- at the central region. A reduction of every alternate H^- occurred due to the neutralization with laser interaction.

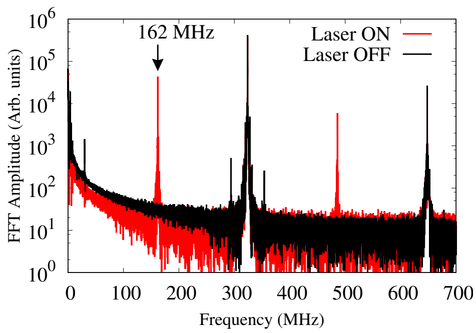

Figure 8: FFT spectra of the time domain signals with laser ON (red) and OFF (black). The peak at 162 MHz appears only with a laser ON.

flux. As as result, we estimated the spot neutralization as a function of the laser energy as shown in Fig. 10. The neutralization efficiency is almost saturated at a higher energy and was obtained to be 88%. This results indicates that a photon flux which has been obtained by applying a maximum energy for a spot size of 0.11 mm gives almost full neutralization of the spot. As a results, a bigger laser beam size well covering the ion beam beam by keeping the present photon flux can give a full neutralization of the H^- beam.

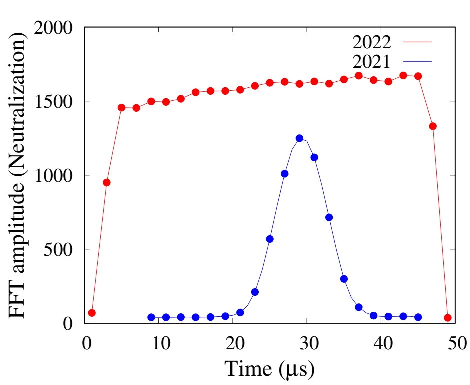

Figure 9: Comparison of the time dependent neutralization between 2022 and 2021 results. A uniform neutralization over the entire H^- macro pulse is obtained in 2022.

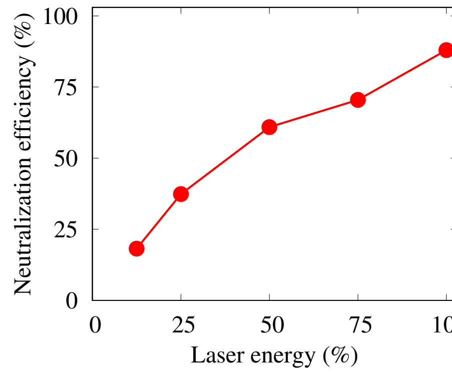

Figure 10: Neutralization efficiency of the overlap region covered by the tiny laser spot of 0.11 mm as a function of laser energy. The neutralization efficiency is almost saturated by applying a maximum laser energy.

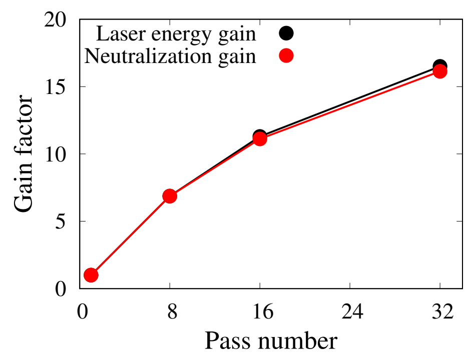

Figure 11: Comparison of the laser energy gain and the corresponding neutralization gain as a function of the number of the passes in the cavity.

Figure 11 shows a gain on the neutralization efficiency as a function of the number of reflections overlapped in the cavity. The laser energy gain, which was estimated by measuring the photon losses at the mirrors and vacuum windows during multi passes due to their reflection efficiency of each device. The laser energy gain was estimated to the about 16 for 32 passes and was quite consistent with neutralization gain shown by the black and red symbols, respectively. The present results thus demonstrate 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. At present a 1/16 reduction of the seed laser energy is obtained, which can be reached to almost 1/32 with better coating of the optical devices and placing them in vacuum.

It is worth mentioning that by reducing the laser peak power, the pulse duration was extended to more than 300 μs and measured a corresponding almost flat neutralization over 300 μs of the H^- beam by scanning the laser with 20 μs step. We have also successfully measured both longitudinal and transverse H^- beam profiles by a laser interaction. Being completely non-destructive the method would be soon applicable to J-PARC Linac for beam diagnostics, online beam monitoring and control as well.

SUMMARY

To overcome the issues and limitation associated with a stripper foil used for H^- charge-exchange injection, a proof-of-principle (POP) demonstration of 400 MeV H^- stripping to proton by using only lasers is under preparation at J-PARC RCS. A prototype YAG laser system including a multi-reflection laser cavity system to significantly reduce the seed laser power have been developed and further upgrades are continued through experimental studies for 3 MeV H^- neutralization at J-PARC RFQ-TF. The latest experimental studies were conducted in June, 2022. We have obtained nearly a doubled pulse energy from the laser, which was also precisely tuned to achieve a uniform neutralization over the entire H^- macro pulse of 50 μs. The cavity system was also upgraded to doubled the reflections to 32 from that of 16 last year. The laser energy at the IP for each pulse was obtained to be 0.38 mJ to achieve an effective neutralization of 50% for each alternative micro pulses of the H^- beam. However, due a tiny laser spot size, a spot neutralization was also estimated to be almost 100% with 32 passes. A pass dependent neutralization gain was also obtained to be 16 at 32 passes, which was consistent with the estimated laser energy gain. The laser energy gain such as the neutralization can be increased proportional to the number of passes by minimizing the photon losses in the optical devices and placing the cavity system in vacuum. For an near future application to the accelerators, we have also successfully measured both longitudinal and transverse H^- profiles by a laser interaction.

The R&D of the UV laser produced by higher harmonic generation from the YAG laser is progress. The experimental studies for the POP demonstration of 400 MeV H^- stripping to proton will be started in 2023.

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