5-YAER PROGRESS OF H$^-$ LASER STRIPPING AT J-PARC RCS

P.K. Saha[A*], H. Harada[A], H. Yoneda[B], Y. Michine[B], G. Onoda[B], A. Sato[C], I. Yamada[A], M. Yoshimoto[A], M. Kinsho[A], T. Shibata[D], I. Yamane[D], Y. Irie[D]
[A] J-PARC Center, KEK and JAEA, Tokai-mura, Ibaraki, Japan
[B] Univ. of Electro-Communications, Tokyo 182-1112, Japan
[C] NAT, Tokai-mura, Ibaraki 319-1112, Japan
[D] KEK, Tsukuba, Ibaraki 305-0801, Japan

Abstract

To overcome the realistic issues and practical limitations associated with a stripper foil used for H$^-$ charge-exchange injection (CEI) at proton accelerators for high-intensity beam, we proposed a foil-less H$^-$ CEI by using only lasers. For that purpose, a POP (proof-of-principle) demonstration of 400 MeV H$^-$ stripping to proton by using lasers is under preparation at the Rapid Cycling Synchrotron of Japan Proton Accelerator Research Complex. The YAG laser will be used for stripping two electrons in the H$^-$, where a deep UV laser will be used for exciting deeply bound electron in the H^0 (after stripping 1st electron) for finally stripping to proton. A prototype YAG laser and also a multi-reflection cavity systems have been developed through experimental studies of 3 MeV H$^-$ neutralization. We achieved 25% neutralization efficiency, while minimizing 1/16 reduction of the seed laser energy by utilizing the multi-pass cavity. We have also applied a laser stripping to noble non-destructive H$^-$ beam diagnostics. The R&D of the UV laser is in progress. Installation of the remote laser system has been almost completed to start the POP test and implementation of non-destructive beam diagnostics at 400 MeV H$^-$ beam in the beginning of 2025. The progress of H$^-$ laser stripping during past 5 years is presented.

INTRODUCTION

The multi-turn charge-exchange injection of H$^-$ (negative hydrogen) by using a thin solid stripper foil is an effective way to achieve high-intensity proton beam [1–4]. However, a short and unexpected lifetime of the foil as well as the uncontrolled beam losses caused by foil scattering of the circulating beam during injection period and the corresponding high residual radiation are serious issues at high-intensity machines [5–7]. Although, remarkable progress has been made for producing stronger foils [8], but it is still hard to maintain reliable and longer lifetime due to overheating of the foil at high-intensity [9], and it is one of the big concern to realize next generation multi-MW proton accelerators.

Laser manipulations of the H$^-$ beam by single or double neutralization is a very promising technique and highly essential to utilize in accelerator process, such as beam diagnostics, collimation, extraction, pulse chopping as well as stripping for the present and future high-intensity proton accelerators. To overcome the realistic issues and practical limitations associated with a stripper foil, a foil-less H$^-$ charge-exchange injection by using only lasers is under studied at J-PARC [10]. To establish the method, a POP (proof-of-principle) demonstration of 400 MeV H$^-$ stripping to proton by using only lasers is under preparation [11–13]. Figure 1 shows a schematic view of the present concept. The H$^-$ is first neutralized to H^0 by removing its outer most electron by an YAG laser of 1064 nm. The ground state (1s) electron in the H^0 is excited to 3rd excited state (3p) named H^{0*} by using a deep UV laser of 213 nm to finally stripped to proton (p) by using the YAG laser again. A prototype YAG laser system and also a completely new type of multi-reflection cavity have been developed step by step for higher and long pulse energy, robust uses, reliability and long term stability through experimental studies of 3 MeV H$^-$ neutralization at J-PARC RFQ test facility (RFQ-TF) [14].

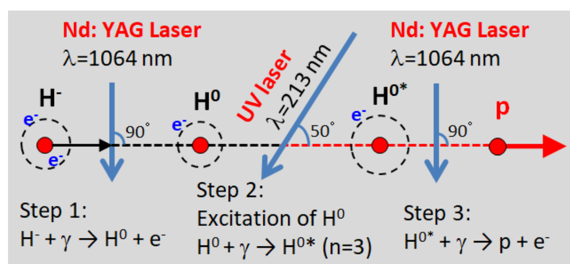

Figure 1: A schematic view of the principle of H$^-$ stripping to proton by using only lasers at J-PARC. Noted parameters are optimized for 400 H$^-$ beam energy.

THE YAG LASER AND MULTI-REFLECTION CAVITY SYSTEMS

Figure 2 shows a layout of the YAG laser system [13]. A combination of Arbitrary Wave Generator (AWG) and Electro Optic Modulator is used to generate programmable short pulse at high quality and high repetition, which is then fed into multi stage fiber amplifier systems. The design repetition rate is same as the H$^-$ micro pulse frequency of 324 MHz, but at present it is set 162 MHz for experimental studies to mainly uniquely identifying the interaction signal at a different frequency than that of the main beam and with a quite less background level. The laser pulses are further amplified by Laser diode for several hundred mJ/micro pulse and then transfer to the multi-reflection cavity system. The laser energy at the latest experiment was 150 mJ for a

* E-mail address: saha.pranab@j-parc.jp

duration of about 40μs. The micro pulse length was typically 100 psec (σ) with 0.023 mJ/pulse at 6.2 ns interval, corresponding to a frequency of 162 MHz.

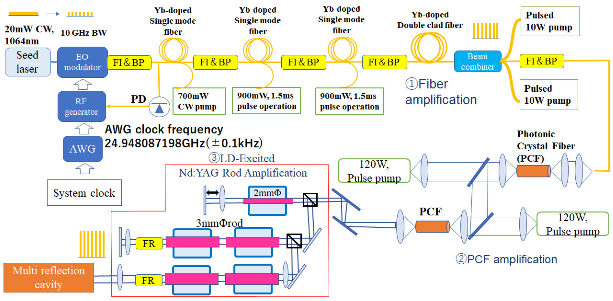

Figure 2: A schematic view of the YAG laser system developed for the POP demonstration through experimental studies of 3 MeV H$^-$ neutralization.

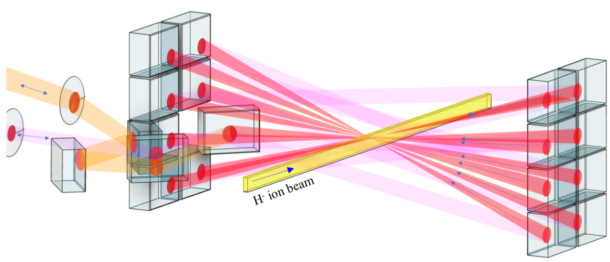

Figure 3: A schematic view of multi-reflection YAG cavity laser cavity system for 32 passes, which was also successfully tested for 3 MeV H$^-$ neutralization.

To achieve a higher stripping efficiency a higher laser energy/pulse is required, while a laser pulse with high energy is hard to handle. To minimize the seed laser energy, we have developed a multi-reflection YAG laser cavity system to overlap many laser pulses at the interaction point (IP). Figure 3 shows a schematic view of the final part of the cavity developed for 32 passes. This can essentially reduce the seeder power to ~1/32 by considering negligible photon losses for high efficiency optical devices and vacuum windows. A roof-top transverse tiny light image produced at the upstream of the cavity is transferred to the IP for maximizing the photon flux, while maximizing spots size at the mirrors to minimize their damage. A micro pulse energy of 0.023 mJ after 32 overlaps at the IP was obtained to be 0.38 mJ, nearly half than the number of passes, which was due to photon losses mainly at the vacuum windows (~1%/pass) because of less efficient windows are used at this stage. The laser system and the cavity were tested for 3 MeV H$^-$ neutralization at the latest in 2022. We have also developed high efficient vacuum windows with loss rate much less than 0.1%/pass, which will be used for the 400 MeV test.

EXPERIMENTAL RESULTS OF THE 3 MeV H$^-$ NEUTRALIZATION

Figure 4 shows the experimental setup for 3 MeV H$^-$ neutralization at the RFQ-TF. The IP is set at the upstream of a bending magnet (BM). The H$^-$ beam neutralized by the laser (H$^-$ + γ = H^0 + e) becomes neutral (H^0), which is separated from the primary H$^-$ by the BM. The H$^-$ is deflected by the BM and goes to the 11-degree beam line and measured by a fast current transformer (FCT) from which a neutralization efficiency is determined. The peak current of the H$^-$ beam was 50 mA, same as for J-PARC Linac, where a macro pulse of 50 μs was used.

Figure 5 shows an expanded view of the time domain signal of the FCT at the center of a 50 μs H$^-$ macro pulse. A pulse height reduction for every alternate H$^-$ pulses due to a neutralization can be seen. Figure 6 shows FFT spectra of the time domain signals of the FCT with laser ON and OFF depicted by the red and black lines, respectively. The FFT peak at 162 MHz appears only when the laser is ON, which gives the neutralization fraction.

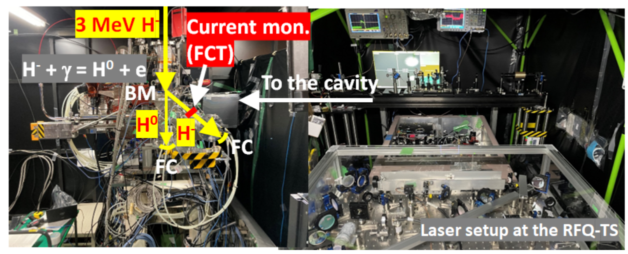

Figure 4: Setup of the laser system for 3 MeV H$^-$ beam neutralization study at J-PARC RFQ-TF. The neutralization fraction is obtained by measuring the H$^-$ signals with laser ON and OFF by the FCT.

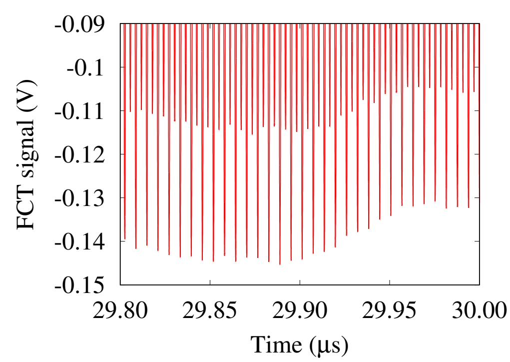

Figure 5: Expanded view of the H$^-$ time domain signal taken by the FCT. Neutralization occurs for every alternate H$^-$ micro pulse.

The neutralization fraction for every 2 μs was calculated as shown in Fig. 7. The AWG waveform was carefully tuned with a precision better than 10^{-3} GHz for a precise micro pulse frequency of the light pulse to obtain a flat neutralization of nearly 20% over the entire H$^-$ macro pulse (red), while a maximum neutralization of 25% (blue) at the center of the H$^-$ macro pulse has also been obtained by using a peaky laser pulse. We also calculated the neutralization of individual micro pulses (Fig. 5) by integrating and comparing with neighboring un-neutralized pulse, which was also consistent with the FFT analysis results. Figure 8

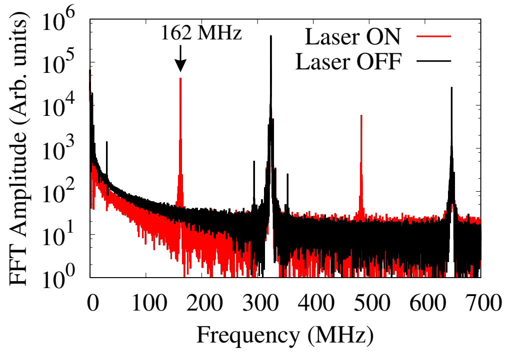

Figure 6: FFT spectra of the FCT for laser ON (red) and OFF (black). The peak at 162 MHz with laser ON corresponds to a neutralization signal.

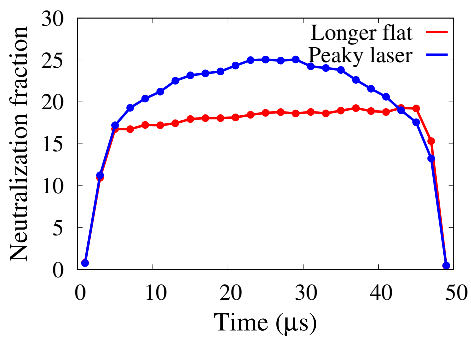

Figure 7: Time dependent neutralization throughout the H^- macro pulse. A uniform neutralization of nearly 20% for the entire H^- pulse is obtained. A further higher efficiency of 25% at the center has also been obtain by using a peaky laser pulse.

shows the pass number dependence laser energy gain and the corresponding neutralization. We obtained 16 times energy gain for 32 passes, nearly 1/2 than expected mainly due to significant photon losses at vacuum windows, which can be overcome by using newly developed high efficiency windows in the next experiment.

It is also worth mentioning that we have demonstrated non-destructive measurement of both longitudinal and transverse beam profiles of the H^- beam at 3 MeV by laser manipulation, which will be implemented for beam diagnostics as well as online beam monitoring at 400 MeV.

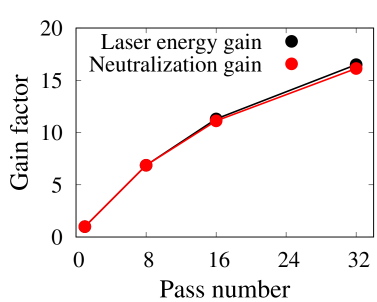

Figure 8: Pass dependent laser energy gain and the corresponding neutralization gain.

DEVELOPMENT OF HIGH-REFLECTIVE VACUUM WINDOW

As the cavity system is placed outside the vacuum chamber, a minimization of the photon loss at the vacuum windows is required. We have developed vacuum windows with high efficient coating for the YAG laser by which the photon loss can be reduced to more than 2 orders of magnitude lower from that of present windows. Figure 9 shows an estimated pass dependent laser energy loss with present 1.1% and the newly developed one with 0.1% and 0.01% photon losses depicted by the black, blue and red lines, respectively. The photon loss can be reduced to even less than 2% to achieve nearly 0.73 mJ at the IP by using only 0.023 mJ/pulse from the seeder. As a result, a seed laser energy of only 0.2 mJ gives more than 6 mJ energy at the IP to obtain more than 95% neutralization as shown by the red curve in Fig. 10 [15, 16]. The black line is estimated based on the present experimental result of 18% neutralization obtained by 0.023 mJ/pulse from the seeder (0.38 mJ at the IP). It is worth mentioning that we also plan to further double the number of reflections to 64. As a result, the seeder pulse energy can be further reduced and further higher neutralization can be achieved as well. Such a reduction of the seeder pulse energy is thus very effective to reduce average power of the seed laser to cover the whole injection period as well as minimize damage of the optical devices.

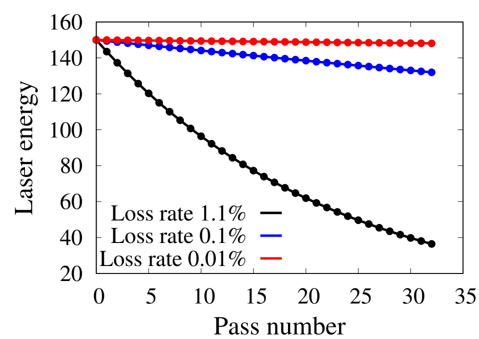

Figure 9: Pass dependent laser energy due to photon losses at vacuum windows for the present (red) and with newly developed higher efficiency ones with different loss rates.

PREPARATION STATUS OF THE POP TEST AT 400 MeV

Figure 11 shows a schematic view of J-PARC L-3BT (Linac to 3-GeV beam transport), where the POP demonstration will be performed. The IP is set at the end of L-3BT as shown by the red rectangular box where a vacuum chamber has been installed. All three charge fractions can be simultaneously measured at the downstream separated according to their charge after interaction with lasers at the IP.

Figure 12 shows a schematic view of laser transport line. A remotely controlled laser transportation systems is located outside the accelerator tunnel. The main later system is mainly remaining to install at the 2nd floor (2F) of L-3BT

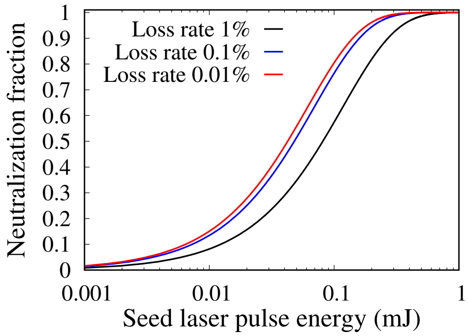

Figure 10: Estimated neutralization as a function of the seed laser pulse energy by considering the energy gain in the cavity and the photon loss rates at vacuum windows. A seeder pulse energy of only 0.2 mJ gives more than 6 mJ at the IP for 32 passes in the cavity with a loss rate of 0.01% by using newly developed vacuum windows to obtain a more than 95% neutralization.

power supply (PS) building. The laser will be transported from there to the POP chamber for about 70 m through separate vacuum pipes for the YAG and UV lasers, which has already been completed and tested for the laser alignment and stability by using a green laser. The 1st stage of the POP test for 400 MeV neutralization and beam diagnostic studies are expected to start in the beginning of 2025. The R&D of a short pulse UV laser as well as optical devices to handle such a deep UV laser have also been started through close collaboration with the manufacturer. Once the UV laser is ready, the POP demonstration study of 400 MeV H^- stripping to proton by using only lasers is expected to start at the end of 2025.

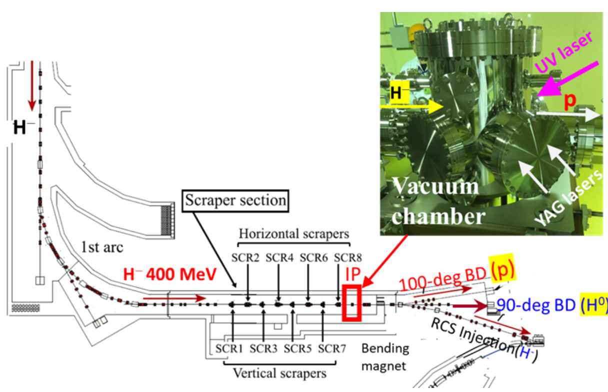

Figure 11: A schematic view of the L-3BT, where a vacuum chamber has been installed for the POP test.

SUMMARY

To overcome stripper foil issues and limitations, a foil-less H^- charge-exchange injection by using only lasers is under development at J-PARC. To establish the method a POP demonstration of 400 MeV H^- stripping to proton by using only lasers is under preparation. A prototype YAG laser system including a multi-reflection laser cavity system

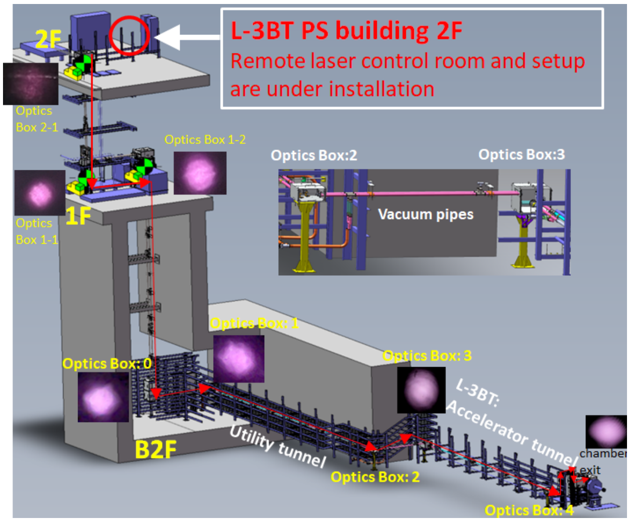

Figure 12: A schematic view of the remotely control laser transportation system installed outside the accelerator tunnel of L-3BT. The main laser system is under installation in the 2F of L-3BT PS building.

to significantly reduce the seed laser power have been developed and tested for 3 MeV H^- neutralization at J-PARC RFQ-TF. A maximum of 25% neutralization has been obtained by 0.38 mJ energy at the IP with 32 passes in the cavity by using only 0.023 mJ micro pulse energy of the seed laser. We obtained a laser energy gain of 16 times which was thus 1/16 reduction due to photon losses at the vacuum windows. We have already developed new windows for 2 orders of magnitude lower photon loss to gain nearly 32 times achieving ~1/32 reduction which will be used for the 400 MeV test. As a result, a seeder pulse energy of only 0.2 mJ gives more than 6 mJ at the IP to obtain more than 95% neutralization. We also plan to double the reflections to 64. Such a reduction of the seeder pulse energy is thus very effective to reduce average power of the seed laser. A remotely controlled laser transportation system has been installed where is main laser system in under installation in the 2F of L-3BT PS to start neutralization of MeV H^- and non-destructive beam diagnostic studies first in the beginning of 2025. The R&D of a short UV laser produced by higher harmonic generation from the YAG laser is also in progress, where detail studies will be started after setting the YAG laser system at the L-3BT. The POP demonstration of the laser stripping at 400 MeV H^- is expected to start at the end of 2025.

ACKNOWLEDGMENTS

The authors would like to acknowledge our J-PARC colleagues for continuous support and cooperation in the present research. This work was supported by the JSPS KAKENHI Grant Number JP20H04456, JAEA HOUGA research funds as well as US-Japan collaboration funds for high-power neutrino beams.

REFERENCES

[1] High-intensity Proton Accelerator Project Team, "Accelerator Technical Design Report for J-PARC", JAERI-Tech 2003-044 and KEK Report 2002-13.

[2] J. Wei *et al.*, "Low-loss design for the high-intensity accumulator ring of the Spallation Neutron Source", *Phys. Rev. Accel. Beams*, vol. 3, p. 080101, 2000.

[3] H. Hotchi *et al.*, "RECENT PROGRESS OF 1-MW BEAM TUNING IN THE J-PARC 3-GeV RCS", *Proc. of IPAC'16*, Busan, Korea, 2016, paper MOPOR004, p. 592.

[4] S.M. Cousineau *et al.*, "A FIFTEEN YEAR PERSPECTIVE ON THE DESIGN AND PERFORMANCE OF THE SNS ACCELERATOR", *Proc. of HB'16*, Malmo, Sweden, 2016, paper MOAM4P40, p. 9.

[5] M.A. Plum *et al.*, "Stripper foil failure modes and cures at the Oak Ridge Spallation Neutron Source", *Phys. Rev. Accel. Beams*, vol. 14, p. 030102, 2011.

[6] M. Yoshimoto *et al.*, "Radio-Activation Caused by Secondary Particles Due to Nuclear Reactions at the Stripper Foil in the J-PARC RCS", *Proc. of IPAC'17*, Copenhagen, Denmark, 2017, paper TUPVA093, p. 2300.

[7] P.K. Saha *et al.*, "RECENT RESULTS OF BEAM LOSS MITIGATION AND EXTREMELY LOW BEAM LOSS OPERATION OF J-PARC RCS", *Proc. of IPAC'22*, Bangkok, Thailand, 2022, paper WEOYGD1, p. 1616.

[8] I. Sugai *et al.*, "Development of thick hybrid-type carbon stripper foils with high durability at 1800 K for RCS of J-PARC", *Nucl. Ins. and Meth. A*, vol. 590, p. 16, 2006.

[9] P.K. Saha *et al.*, " First measurement and online monitoring of the stripper foil thinning and pinhole formation to achieve a longer foil lifetime in high-intensity accelerators", *Phys. Rev. Accel. Beams*, vol. 23, p. 082801, 2020.

[10] Isao Yamane, Hiroyuki Harada, Saha Pranab and Shinichi Kato, *J. of Part. Acc. Soc. Japan* vol. 13, p. 1 2016 (In Japanese).

[11] P.K. Saha *et al.*, " Status of Proof-of-Principle Demonstration of 400 MeV H^- Stripping to Proton by Using Only Lasers at J-PARC", *Proc. of HB'18*, Daejeon, Korea, 2018, paper THP1WC02, p. 422.

[12] P.K. Saha *et al.*, " Studies of Laser Power Reduction for the Laser Stripping of 400 MeV H^- beam at J-PARC RCS", *JPS Conf. Proc.*, vol. 33, p. 011025, 2021.

[13] H. Harada *et al.*, "Development of Laser System for Laser Stripping Injection", *JPS Conf. Proc.*, vol. 33, p. 011026, 2021.

[14] Y. Kondo *et al.*, "Upgrade of the 3-MeV LINAC for Testing of Accelerator Components at J-PARC", *Proc. of IPAC'19*, Melbourne, Australia, 2019, paper MOPTS046, p. 960.

[15] R.C. Connolly *et al.*, *Nucl. Inst. and Meth. A* 312, p. 415, 1992.

[16] David E. Johnson *et al.*, *Proc. of LINAC'16*, East Lansing, MI, USA, 2016, paper TH2A01, p. 710.