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STATUS OF THE LASER MANIPULATIONS OF H⁻ BEAM AT J-PARC

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Abstract

To establish H^- charge-exchange injection by replacing the carbon foil, a POP (proof-of-principle) demonstration of 400 MeV H^- stripping to proton by using only lasers is under preparation at J-PARC. At Fermilab H^- neutralization at 0.75 MeV is utilized by establishing a laser Notcher system to produce a gap in the CW H^- pulse train needed for a clean extraction from the ring. Our common goal is to establish an effective recycling/reusing of the seeder pulse to reduce its power. At J-PARC, a prototype YAG laser system and also a new type of multi-reflection cavity system have been developed and upgrades are continued through experimental studies of 3 MeV H^- neutralization. We succeeded to overlap 32 reflections at the interaction point and achieved 25% neutralization by using only around 20 µJ micro pulse energy. We have also demonstrated non-destructive measurements of longitudinal and transverse beam profiles of the H^- beam at 3 MeVa and will be implemented to 400 MeV H^- beam. The laser cavity as well as the beam diagnostic techniques and can also be easily applicable to present Fermilab linac as well as to the PIP-II linac. The laser system installation at J-PARC linac as well as preparation of the UV laser are under progress to start the POP experimental studies in 2023.

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 uncontrolled beam losses and the corresponding high residual radiation are two serious issues, especially at high-intensity operation [5–7]. Although, remarkable progress has been made for producing stronger foils [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 and might be a serious concern and a practical limitation to realize a multi-MW beam power.

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, stripping, collimation, extraction and pulse chopping for the present and future proton accelerators. At J-PARC, the H^- stripping to proton by using only lasers is under preparation to establish H^- charge-exchange injection by replacing the carbon foil [9]. Figure 1 shows a schematic view of the concept for H^- stripping at 400 MeV. 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, and finally the H^{0*} is stripped to proton (p) by removing the excited electron from the H^{0*} by using the YAG laser. To establish the method, we are preparing for a POP demonstration at the Japan Proton Accelerator Research Complex (J-PARC) [10, 11]. A prototype YAG laser system and also a completely new type of multi-reflection cavity have been developed and step by step further developments are continued for higher energy, robust uses, reliability and long term stability through experimental studies of 3 MeV H^- neutralization at J-PARC RFQ test facility (RFQ-TF) [12].

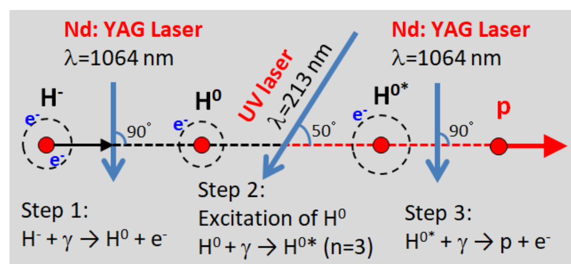

Figure 1: A schematic view of the principle of H^- stripping to proton by using only lasers. Typical laser parameters for an H^- stripping at 400 MeV are also noted.

OVERVIEW OF THE YAG LASER AND MULTI-REFLECTION CAVITY SYSTEMS

Figure 2 shows a layout the prototype YAG laser system [11]. In the beginning, a combination of Arbitrary Wave Generator (AWG) and Electro Optic Modulator is used to generate programmable short pulse with high quality and high repetition laser pulses and 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 to 162 MHz mainly for clearly and uniquely identifying the interaction signal at a different frequency than that of the main beam and also at a less background. The laser pulses are finally amplified by Laser diode for about several mJ/micro pulse (design). The laser output pulses are then transfer to the multi-reflection cavity system. At the latest, the laser energy was 150 mJ for a duration of about 40 µs. The micro pulse length was typically 100 psec (σ) with 0.023 mJ/pulse at 6.172 ns interval.

As laser power is one of the main concern to achieve a higher efficiency as well as difficulties to handle a high power laser, we have developed a multi-reflection YAG laser

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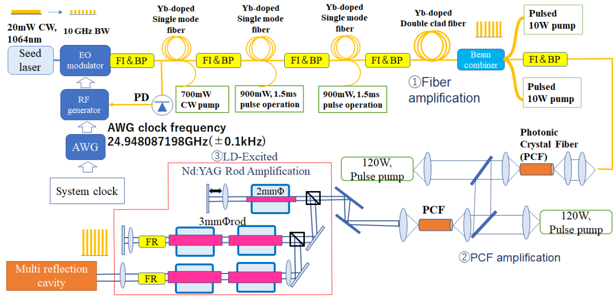

Figure 2: Schematic view of the YAG laser system for the POP demonstration of 400 MeV H$^-$ stripping at J-PARC.

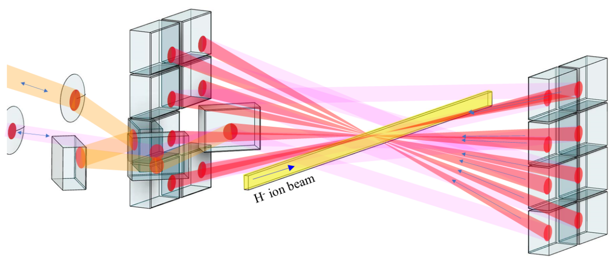

Figure 3: A schematic view of the latest multi-reflection laser cavity system for overlapping 32 passes at the IP.

cavity system to overlap many laser pulses at the interaction point (IP) of the laser and ion beam. Figure 3 shows a schematic view of the final part of the latest cavity developed for 32 reflections. This can essentially reduce the seeder power to ~1/32, if the light losses at the optical devices, mainly at vacuum windows can be minimized by using high efficiency materials or placing the cavity in vacuum. 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 bigger spots 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) as the cavity was set outside the beam chamber. Vacuum chambers with higher efficiency are under development to reduce the loss less than 0.1%. The latest laser system and the cavity were tested for 3 MeV H$^-$ neutralization in June, 2022.

EXPERIMENTAL RESULTS

Figure 4 shows the experimental setup for 3 MeV H$^-$ neutralization at the RFQ-TF. The IP is 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). 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 reduction of the pulse height at every alternate H$^-$ pulses occurred due to neutralization by a laser interaction. 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 peak at 162 MHz appears only when the laser is ON, which was used for calculating the neutralization fraction.

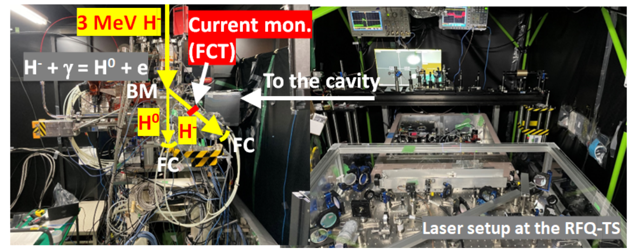

Figure 4: Setup of the laser system for 3 MeV H$^-$ beam neutralization study at RFQ-TF. The neutralization efficiency is obtained from the FCT data.

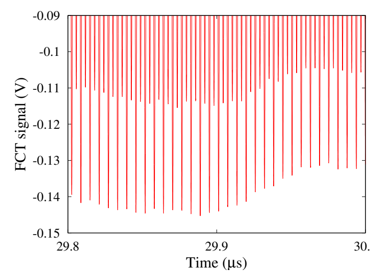

Figure 5: Expanded view of the H$^-$ signal taken by the FCT. The neutralization occurs for every alternate H$^-$ micro pulse.

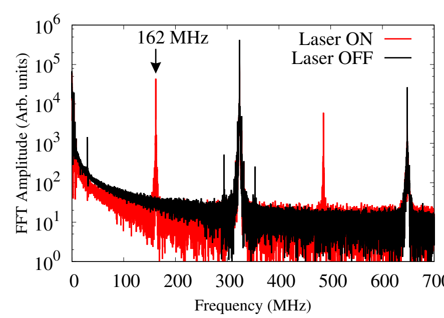

Figure 6: FFT spectra of the FCT time domain signals with laser ON (red) and OFF (black). The peak at 162 MHz corresponds to a neutralization signal.

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 18% over the entire H$^-$ macro pulse (red), while by using a further peaky laser pulse, a higher neutralization fraction of 25% around the middle of the H$^-$ macro pulse was obtained as depicted by the blue color. 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 shows the pass number dependence laser energy gain

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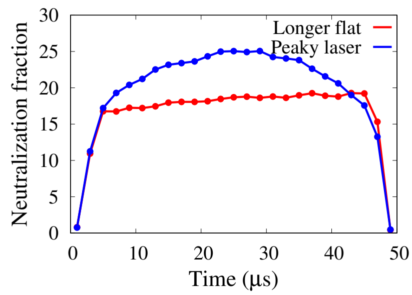

Figure 7: Time dependent neutralization over the entire H⁻ macro pulse. A uniform neutralization throughout the H⁻ pulse has been obtained. A further higher efficiency at the central part has also been obtain by using a peaky laser pulse.

and the corresponding neutralization. The present results demonstrate the merit of the cavity to increase the laser pulse energy at the IP by reducing the seeder energy, although it is 1/16 at present due to significant photon losses at vacuum windows, but it can be reached to ~1/32 in the next trial by replacing the windows with high efficiency coating.

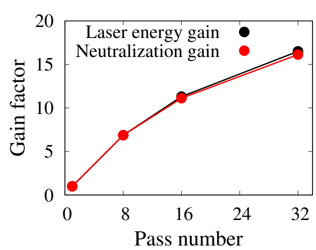

Figure 8: Comparison of the pass dependent laser energy gain and the corresponding neutralization gain.

Near Future Goal

Figure 9 shows the estimated pass dependent laser energy drop with 1% and 0.1% photon losses at vacuum windows at present (red) and under development (blue) higher efficient windows, respectively. A 75% reduction of the laser energy can be improved to 10% by using a newly developed windows. As a result, the laser energy for each interaction can be increase to 0.38 mJ to 0.672 mJ.

Figure 10 shows the estimated neutralization as a function of the seeded pulse energy [13, 14]. At present with 1% photon loss/pass at the vacuum windows gives 18% neutralization (red) for 0.023 mJ/pulse from the seeder (0.38 mJ at the IP), but it can be increased to 30% (blue) by minimizing the window losses to 0.1%. As a result, a seeder pulse energy of only 0.15 mJ will give more than 4 mJ energy at the IP to obtain a more than 90% neutralization. In addition, we also plan to further increase the number of reflections.

SUMMARY

To established H⁻ charge-exchange injection by using lasers instead of carbon foil, a POP demonstration of 400 MeV H⁻ stripping to proton by using only lasers is

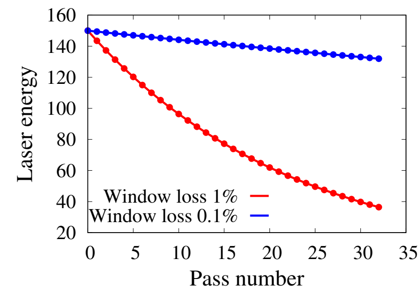

Figure 9: Estimated pass dependent laser energy drop due to photon loss at vacuum windows at present (red) and with under development higher efficiency ones.

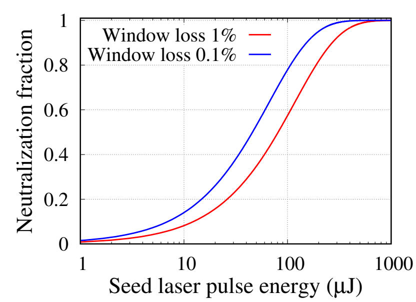

Figure 10: Estimated seeder pulse energy versus neutralization for two cases of photon losses at vacuum windows.

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 tested for 3 MeV H⁻ neutralization at J-PARC RFQ-TF. A maximum neutralization of 25% has been obtained by 0.38 mJ energy at the IP with 32 passes of 0.023 mJ micro pulse energy from the seeder. A reduction of the seeder was 1/16 at present due to photon losses at the vacuum windows, but it will be reached to ~1/32 by replacing with much less reflective windows. Then a same pulse energy from the seeder will give more than 4 mJ at the IP to obtain a more than 90% neutralization. In this study we have also demonstrated completely non-destructive longitudinal and transverse H⁻ profiles by a laser interaction, and will be applied for the 400 MeV. We believe that the J-PARC cavity as well as non-destructive beam diagnostics techniques can easily be applicable to present Fermilab Linac as well as to the PIP-II linac in future. The R&D of the UV laser produced by higher harmonic generation from the YAG laser is also in progress. The POP experimental studies for 400 MeV H⁻ stripping to proton at J-PARC will be started in 2023.

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