First Demonstration of Laser-Assisted Charge Exchange for Microsecond Duration H^- Beams

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This Letter reports on the first demonstration of laser-assisted H^- charge exchange for microsecond duration H^- beam pulses. Laser-assisted charge exchange injection is a breakthrough technology that overcomes long-standing limitations associated with the traditional method of producing high intensity, time structured beams of protons in accelerators via the use of carbon foils for charge exchange injection. The central theme of this experiment is the demonstration of novel techniques that reduce the laser power requirement to allow high efficiency stripping of microsecond duration beams with commercial laser technology.

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Many accelerator applications require short, intense pulses of protons. The standard method for producing these beams is through multiturn, H^- charge exchange injection into a synchrotron or storage ring. In this process, an incoming H^- beam pulse from a linear accelerator is merged with a circulating proton beam in a ring using a magnetic field. The merged beam is then stripped of its electrons to yield a single species proton beam [1]. The process is repeated until the desired proton beam intensity in the ring is achieved. Compared with other beam accumulation scenarios such as direct injection of protons, this technique reduces the phase space area of the final beam and also minimizes beam loss [2].

In the conventional implementation of the charge exchange method, the electrons are removed from the H^- ions by passing the merged beam through a thin (micrometer) carbon foil. Unfortunately, the presence of the foil introduces serious performance issues. First, there is a limitation on mean foil lifetimes in a high power beam environment. The primary failure mechanism for carbon foils is sublimation at high temperatures, which translates into restrictions on the allowable beam power density. Accelerators are already operating close to this limit [3]. Beyond the problem of survivability, the foils also produce beam loss from particle scattering, resulting in restrictively high radiation levels in the injection region [4]. Both of these issues scale with beam power density and place hard limits on the achievable beam parameters in proton accelerators.

Laser-assisted charge exchange injection, also called laser stripping, offers an attractive alternative that replaces the foil-based configuration with a laser and magnet ensemble. In this material-free version of the charge exchange method, the first, loosely bound outer electron is Lorentz stripped by a high field dipole magnet, converting H^- to H^0. While in theory it is possible to remove the second electron using direct laser photodetachment, it would require excessively high peak laser powers. Instead, a laser is used to produce resonant excitation of the remaining electron to a higher quantum state (H^{0*}) with lower binding energy [5], and then it is Lorentz stripped by a second dipole magnet to produce a proton (H^{0*} to p). The process is shown schematically in Fig. 1 below. This method is scalable to arbitrarily high beam power densities, and it completely relieves the issue of beam loss and radiation from particle scattering.

For decades, the concept of laser stripping saw no experimental realization. This was due to a fundamental

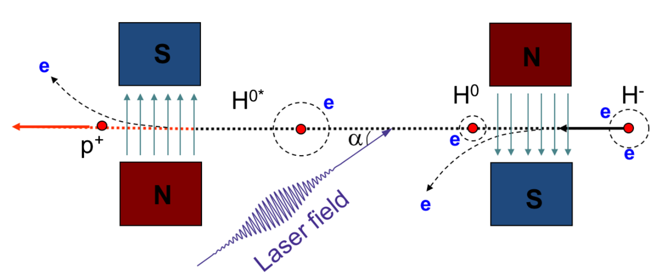

FIG. 1. Schematic of the laser stripping concept in this experiment, showing Lorentz stripping of the first electron by a dipole magnet in the first step (the far right), resonant excitation of the second electron by the laser in the second step (the middle), and, finally, stripping of the excited electron by the second dipole magnet (the left).

complication arising from the inherent energy spread in the ion beam, translating into a spread in the resonant excitation frequency of the ion beam particles, beyond the obtainable laser bandwidths. In 2006, this problem was overcome in a proof-of-principle (POP) experiment that utilized a diverging laser to induce a frequency sweep in the rest frame of the ion beam [6]. Consider the Doppler equation that relates the frequency of the laser in the lab frame to the frequency in the ion beam frame [7]:

$$f_{\text{beam frame}} = \gamma[1 + \beta\cos(\alpha)] f_{\text{lab frame}}, \tag{1}$$

where γ and β are the relativistic factors of the ion beam, and α is the angle of intersection between the laser and the ion beam. Clearly, a diverging laser yields a spread in α, and hence a sweep in frequency.

The POP experiment was located at the Spallation Neutron Source (SNS) accelerator, a 1.4 MW, 1 GeV pulsed H^- superconducting linear accelerator [8]. A Q-switched UV laser with a 0.4° divergence angle was used to produce the frequency sweep. This configuration required 10 MW of peak laser power to provide the requisite laser power density for high efficiency excitation of the intermediate H^0 beam. The laser duty factor was 7 ns at 30 Hz, for an average laser power of about 2 W. The experiment successfully demonstrated 90% conversion of H^- to protons for a 6 ns duration, 1 GeV H^- beam. This marked the start of the experimental evolution of the laser stripping method. Other methods of direct ionization with lasers are under study [9] but have not yet reached the experimental phase.

While the POP demonstration was a landmark accomplishment that validated the concept, the stripped beam pulse was still orders of magnitude shorter than a typical ion beam macropulse. Unfortunately, a direct scaling of the POP experiment to the full SNS ion beam pulse duty factor of 1 ms and 60 Hz yields a required average UV laser power of approximately 600 kW. This is greatly in excess of state-of-the-art laser technology, which is on the order of tens of watts. Thus, in order to extend the laser stripping method into the realm of practical ion pulse lengths, it is necessary to reduce the required average laser power to feasible levels. The goal of this experiment is to achieve a 3 orders of magnitude reduction in the laser power requirement in order to strip microsecond duration H^- beam pulses. The techniques employed to achieve the laser power savings are based on innovative manipulations of both the laser and ion beam configurations. They are described in detail in Ref. [10], and are briefly reviewed here: (1) Temporal matching of the laser pulse to the H^- pulse structure. An H^- macropulse at the SNS accelerator has a complex multilevel time structure resulting in a 6% duty factor. A straightforward way to reduce the average laser power is to temporally match the laser to the ion beam. The three-level time structure of the SNS H^- beam is shown in Fig. 2, along

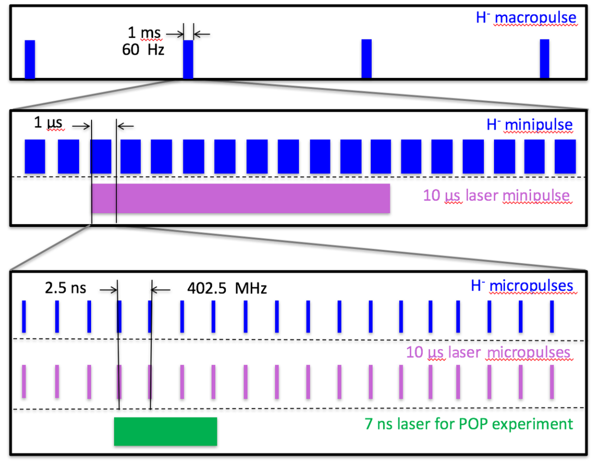

FIG. 2. The macropulse (top), minipulse (middle), and micropulse (bottom) structure of the H^- beam (blue), the laser in this 10 μs experiment (light purple), and the laser in the POP experiment (green).

with the time structure for the temporally matched laser in this experiment, and the time structure of the laser in the previous POP experiment. The temporal matching of the laser beam results in a factor of 70 reduction in the average laser power requirement. (2) Tailoring of the H^- beam trajectories. Recall that in the POP experiment, a diverging laser beam was used to address the issue of excitation frequency spread. While this was effective, it was not economical from the laser power standpoint because a diverging laser beam requires a higher peak power to maintain the required photon density for high efficiency stripping. Following the POP experiment, it was realized that the excitation frequency spread could be addressed in a more fundamental fashion by introducing a correlation in the ion beam trajectories such that, for every ion beam particle, the combination of energy and angle [γ and α in Eq. (1)] produces roughly the same excitation frequency. This greatly reduces the necessary divergence of the laser and provides an additional factor of 10 savings in laser peak power. (3) Optimization of H^- beam size and divergence. The final laser power savings come from zeroing out the horizontal divergence of the ion beam at the interaction point, and minimizing the longitudinal and transverse ion beam sizes in the plane of interaction. The ideal longitudinal beam length and transverse beam sizes are about $\sim$35 ps and ≤ 0.1 mm rms, respectively, which is about an order of magnitude smaller than the nominal ion beam size in each plane. The revised beam size parameters result in a factor of 2–5 reduction in required peak laser power.

Taken together, these ion and laser beam manipulations reduce the required average laser power by 3 orders of magnitude. With this, it is possible to strip microsecond-long H^- pulses with available UV laser technology. The specific goal of this experiment was to implement these techniques in a real accelerator environment to demonstrate high efficiency stripping for a 10 μs, 1 GeV H^- beam using commercial laser technology. This represents a 3 orders of magnitude increase in the pulse duration compared to the POP experiment, and it serves as a proof-of-practicality demonstration of the laser stripping method.

For this experiment, the $n = 3$ excited state was chosen for the H^{0*} excitation, which requires 102.6 nm of laser light in the rest frame of the ion beam. Considering the Doppler frequency shift in Eq. (1) for a 1 GeV H^0 beam intercepting the laser at an angle $\alpha = 37.5°$, this yields a 355 nm laser wavelength in the lab frame. For the given ion and laser beam parameters, a peak laser power of 1 MW is required for high efficiency resonant excitation of H^0 [11].

A macropulsed laser has been developed to deliver the 355 nm UV laser pulses with the necessary power and temporal structure, as described above [12]. The laser has a master oscillator power amplifier configuration. The master oscillator is an actively mode-locked fiber laser generating 402.5 MHz pulses at 1064.5 nm, and the pulse width is tunable over 55–85 ps. Prior to power amplification, a macropulse is formed by using an acousto-optic modulator and the macropulse duration is adjustable from submicroseconds to a few tens of microseconds at a repetition of 10 Hz. The three-stage Nd:YAG amplifiers provide 6 orders of magnitude power amplification to the input macropulse and the amplified IR light is converted to its third harmonic by two lithium triborate crystals. The pulse width of the UV light has been characterized using a multifunctional optical correlator [13]. At 10 μs macropulse, the maximum peak power of the UV pulses measured 3.5 MW at the (micro) pulse width of 33 ± 1 ps.

The experiment had to be accommodated within the existing SNS accelerator infrastructure—which was sufficient, if not always ideal. In order to achieve the laser power savings techniques (2) and (3) above, the interaction point (IP) of the laser and ion beam had to be placed at a beam line position which is significantly downstream of the superconducting linac. Since the superconducting linac provides the longitudinal focusing for the ion beam, this had the effect of limiting the beam current to 1 mA or below in order to maintain the proper longitudinal beam size at the IP in the presence of Coulomb force debunching over the drift length.

A schematic of the experimental layout in the tunnel is shown in Fig. 3. The experimental vessel consisted of two retractable 1 T dipole magnets on either side of IP to strip the electrons, a transverse profile monitor at the IP to measure the transverse beam size in each plane, and a dual

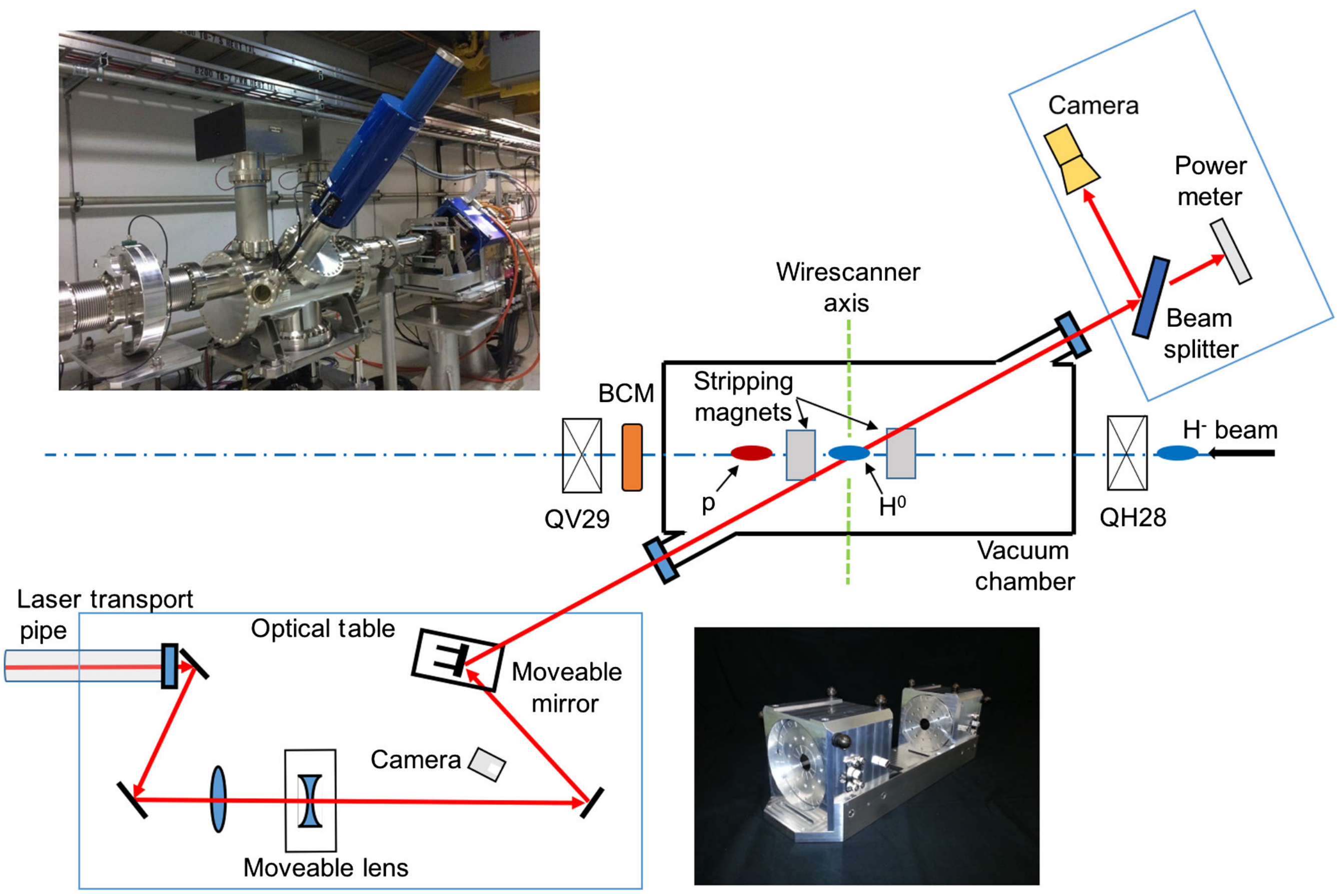

FIG. 3. Schematic of the experimental layout, and photo of the as-installed experimental vessel (top left) and the stripper magnet ensemble (bottom right).

polarity beam current monitor (BCM) to confirm the conversion of H^- to H^0 and to p. In order to protect the laser from radiation damage and to provide flexibility for the experiment, the laser was remotely placed in a service building and transported in an atmospheric-pressure pipe to a local optics table adjacent to the experimental vessel. The laser transport line was 70 m long and contained eight reflection points. This transport resulted in about a one-third loss in the laser peak power, and a positional jitter of the laser spot at the IP of about ± 0.1 mm (rms), which is significant compared to the vertical ion beam size. Neither of these issues compromised the success of the experiment, nor would they be a limitation in a full scale production laser stripping system, where the laser would be placed more locally.

The execution of the experiment consisted of setting up the ion beam optics, aligning the relative position and phase of the ion and laser beam, and tuning the resonant excitation frequency of the laser by manipulating the angle α between the laser and the ion beam. During the experiment, the micropulses are synchronized to the 402.5 MHz rf timing of the SNS accelerator, while the macropulse is timed to an independent beam diagnostics device. Both phases are remotely adjusted at appropriate accuracy to ensure overlap between laser and ion beam pulses. While the position and phase adjustments were accomplished prior to the actual stripping using either H^- or H^0 beam signals, the only signature of the correct resonant frequency is the stripping event itself.

After tuning all parameters, a strong proton beam signal was obtained, indicating successful stripping of both electrons. The results of the BCM measurements for the H^- beam before stripping and the proton beam after stripping are shown in Fig. 4. The blue line in the figure indicates the average beam current signal for an unstripped 11 μs H^- beam containing 11 minipulses, and the red lines show eight measurements of the corresponding stripped proton beam. The laser pulse length was 10 μs, such that the last minipulse in the H^- beam was not intercepted by the laser and therefore remains as H^0, as indicated by the null signal on the BCM.

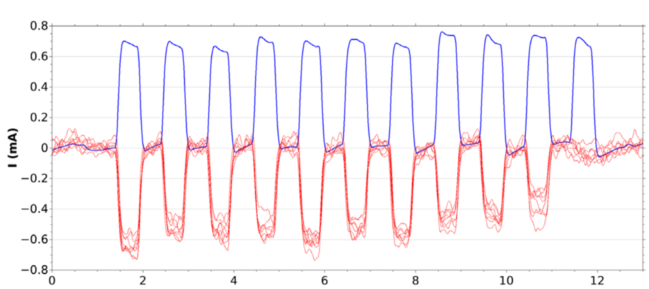

FIG. 4. The experimental results. The average beam current for a 11 μs H^- beam measured by the beam current monitor at the interaction point before stripping (blue), and eight separately measured stripped proton beam pulses on the same beam current monitor during stripping (red).

A discussion of the stripped beam measurement error is useful here. There are three mechanisms contributing to variations in the stripped beam measurement: the H^- pulse-to-pulse current variation, the noise on the BCM, and the laser position and intensity jitter. The H^- ion beam current was measured to be stable within 2% by an independent diagnostics device upstream of the experiment. The noise level of the BCM was measured to be approximately 10%. For the stripping efficiency calculations, a reference H^- was found by averaging the BCM signal over hundreds of pulses to eliminate this noise. However, because the laser positional jitter was large enough that the laser could completely miss the ion beam sometimes, an averaging for the stripped beam is not valid. The jitter is an artifact of the remote laser placement and is not related in any way to the physical process of the stripping. Therefore, to find the maximum stripping efficiency, it is necessary to gather statistics for hundreds of minipulses and identify the largest stripped beam current signals, which represent adequate ion and laser beam overlap. These correspond to pulses such as those shown in red in Fig. 4. With this method, the maximum stripping efficiency, calculated as the ratio of the highest current proton minipulse to the averaged H^- current, was $\geq 99\%$. The error on the measurement is up to 10% (the BCM error), translating to a minimum stripping efficiency of $\geq 89\%$.

This experiment successfully demonstrated that laser stripping can be accomplished for microsecond-long pulse lengths by manipulating the ion and laser beams to reduce the required average laser power. The achieved stripping efficiencies are comparable to the foil-based stripping efficiencies of about 95%–98%. Yet, the duration of the laser stripping event is still 2 orders of magnitude below typical millisecond operational pulse lengths. Since the cross section for the photon-particle interaction in the laser stripping process is extremely small, the stripping event results in negligible laser power loss. Thus, the laser power can be recycled if the interaction point is located inside an optical cavity, providing a path forward for full pulse length stripping. Such external optical cavities have been routinely applied to recycle the power from single-frequency lasers or mode-locked lasers which have pico- or femtosecond pulses repeating at tens of megahertz to gigahertz. However, this experiment requires a burst-mode laser with a small duty factor. In such cases, it is difficult to generate an effective error signal within the short duration of the laser burst, and the conventional cavity locking technique is not suitable. As part of the development of the next step of this experiment, a different locking method using a double-resonance optical cavity scheme is being developed to realize cavity enhancement of burst-mode laser pulses [14]. The goal of the cavity is to produce millisecond-long pulse lengths with 1 MW peak power, and to apply this technique in the laser stripping experiment to demonstrate high efficiency laser stripping of full millisecond duration H^- macropulses.

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