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TOWARDS OPERATIONAL SCALABILITY FOR H⁻ LASER ASSISTED CHARGE EXCHANGE*

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Abstract

The experimental development of H- laser assisted charge exchange, a.k.a. laser stripping, has been ongoing at the SNS accelerator since 2006 in a three-phase approach. The first two phases associated with proof-of-principle and proof-of-practically experiments have been successfully completed and demonstrated >90% H^- stripping efficiency for up to 10 µs. The final phase is a proof-of-scalability stage to demonstrate that the method can be deployed for realistic beam duty factors. The experimental component of this effort is centered on achieving high efficiency stripping through the use of a laser power amplification scheme to recycle the macropulse laser light at the interaction point of the H^- stripping. Such a recycling cavity will be necessary for any future operational laser stripping system with at least millisecond duration H^- pulses. The status of the next experimental phase and the challenges associated with deploying the recycling cavity into the laser stripping experiment are discussed.

INTRODUCTION

Laser stripping is a non-interceptive method of charge exchange that utilizes two magnets and laser to strip both electrons from a high energy H^- beam. The method overcomes technological limitations associated with the use of a stripper foil in the conventional implementation of charge exchange, and is scalable to arbitrarily high beam power densities.

The experimental evolution of the laser stripping method has proceeded along a three-phase approach: 1) A proof-of-principle experiment to validate the concept (2006), 2) A proof-of-practicality experiment to demonstrate stripping for realistic pulse configurations (2016), and 3) A proof-of-scalability experiment to demonstrate scalability of the technique to operational parameter regimes. The first two phases of the evolution have been completed and successfully yielded stripping efficiencies of >90%, comparable to the foil-based approach. The final proof-of-scalability phase is in preparation now and is the subject of this paper.

The primary challenge in maturing the laser stripping method is related to the required laser power. For a 1 GeV H^- beam, high efficiency stripping requires a peak laser power of 1 MW in the UV range. Maintaining this beam power for the millisecond timescales associated with realistic H^- beams requires average laser powers beyond state-of-the-art capability. The previous phase of this program took aim at this challenge by demonstrating laser power savings techniques based on ion and laser beam manipulations. This resulted in a three order of magnitude advancement in the stripped beam pulse duration compared with the proof of principle experiment, using the same average laser power [1] [2].

From this point, scaling to millisecond pulse durations requires an additional factor of one-hundred in laser power savings. The method of approach for achieving this is through a power enhancement optical cavity (also called a power recycling cavity) that will realize a high peak power laser beam inside the cavity through a coherent addition of the incoming lower power laser pulses.

The goal of the proof-of-scalability phase is to demonstrate laser stripping for the same duration of pulse (tens of microseconds) using the power recycling cavity to show that high efficiency stripping (>90%) can be achieved with only 1-2% of the laser power. This scenario is consistent with what would be required for the amplification of the laser power in a full duty factor operational system.

This paper presents a brief overview of the experimental configuration and results of the previous laser stripping experiment. It reports on progress on the power recycling cavity, and the plan for a set of upcoming experiments including integrating the recycling cavity into the experimental vessel, and addressing carry-over challenges from the previous experiment.

REVIEW OF 10 µs STRIPPING EXPERIMENT

The 10 µs experiment was a proof-of-practicality experiment that utilized several laser and ion beam manipulation techniques to reduce the required laser power. Here, we briefly review aspects of the experiment relevant to the next phase of development.

Experimental Configuration

The laser stripping experiment was located at the Spallation Neutron Source (SNS) accelerator, in the transport line downstream of the 1 GeV superconducting linac. This location was chosen because it satisfies the optics requirements for the ion beam power savings techniques. The interaction point (IP) for the experiment is

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housed inside an experimental vessel which contains the two stripper magnets mounted on a vertical actuator to allow insertion for the experiment and retraction during normal SNS beam production. The vessel has window entrance and exit ports for the laser light. A wirescanner is located at the IP for measuring and tuning the beam size, and a beam current monitor (BCM) is located just downstream of the second stripping magnet to provide confirmation of the charge conversion. In order to protect the laser from radiation damage and to provide experimental flexibility, the laser is located in a remote building and transported to the interaction point in a normal pressure pipe. The transport line for the laser light is 70 m long and has 8 mirrors [3]. A small local optics table is located adjacent to the IP for fine tuning the laser.

The laser was operated with the same temporal structure as the ion beam. Specifically, the laser operated with 10 µs macropulses composed of 50 ps micropulses, repeating at the SNS linac frequency of 402.5 MHz. The peak UV laser power at the interaction point was ~2 MW, though most of the experiment was conducted with 1 MW to prevent damage to the vessel window.

Result and Challenges

The 10 µs experiment demonstrated >90% stripping efficiency for a 10 µs beam [1]. A significant challenge encountered during the experiment was pulse to pulse variation in the stripping efficiency due to positional jitter of the laser spot at the IP on the order of ±0.1 mm. While this jitter slowed tuning process for the experiment, for the final result the jitter could be factored out by gathering a statistically large sample of beam shots.

PROOF-OF-SCALABILITY EXPERIMENT

The proof-of-scalability experiment will demonstrate that the laser stripping technique is scalable to operational beam parameters using today's available laser technology. The challenge comes from the available average laser power. A successful proof-of-scalability demonstrates high efficiency stripping with input laser powers that would be typical for operationally-realistic millisecond pulse durations. This relies on a laser power recycling cavity to amplify the input power to ~1 MW peak power required for the stripping. Specially, this translates to a goal to establishing a recycling cavity with ~100 enhancement to demonstrate high efficiency (>90%) laser stripping for 10 – 100 µs H^- beam pulses using only 1-2% of the peak laser power used in the previous 10 µs stripping experiment.

The two main efforts involved in this stage are developing the cavity in the lab, and solving the laser jitter issue, required for stable operation of the cavity. These efforts are described below. Finally, the configuration of the experiment with the recycling cavity and minimized jitter is described.

Laser Power Recycling Cavity

External optical cavities have been used to recycle laser power in a number of previous laser-particle interaction experiments. In all previous work, optical cavities were applied in conjunction with single-frequency lasers or continuous-mode pulses.

For this project a double-resonance enhancement cavity (DREC) scheme was developed as a robust locking scheme to realize cavity enhancement of burst mode laser pulses [4], shown schematically in Fig. 1. The double resonance of a cavity to two incoming beams can be realized by tuning the frequency difference between two beams.

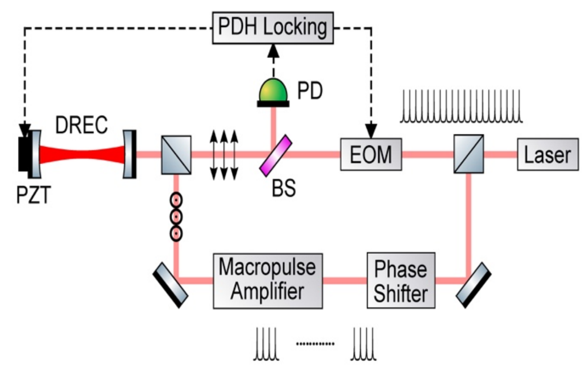

Figure 1. Schematic of double-resonant power enhancement cavity.

A critical issue in the power recycling of high power UV pulses is the laser induced damage of the mirror coating. For this purpose, a Fabry-Perot cavity which enables large mode size has been designed. The cavity is operating at a near-concentric configuration and the cavity length is set at ~745 mm which corresponds to a repetition rate of 201.25 MHz, i.e., half of the RF frequency of the SNS H^- beam. The resulting beam size on the mirror surface is about 2 mm in diameter. The cavity platform is located in a customized vacuum chamber with excellent vibration isolation from all directions. At the double resonance condition, the peak power of the burst-mode UV pulses is measured to be 1.05 MW [4]. At this power level, no laser-induced mirror coating damage has been identified. This experiment demonstrated that the DREC can be used to recycle burst-mode UV pulses with 1 MW peak power. An enhancement factor of 100 is expected through future optimization of the cavity mirror coating and beam alignment. Next steps will focus on developed technology into a reliable instrument for the experimental demonstration of cavity-enhanced laser stripping.

The major challenge in the present stripping laser parameters is related to the UV wavelength which is required due to the low beam energy (~ 1 GeV) of the current linac. For higher beam energy such as 1.3 GeV envisioned in the SNS proton power upgrade (PPU) project, a 532nm laser beam can be used to excite the hydrogen atom to the n=2 state, which will significantly mitigate challenges in both the power availability of the stripping laser and laser-induced damage threshold in recycling cavity.

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Addressing Jitter

An important component of this phase of the experiment is to improve the position stability of the laser. Fig. 2 below shows a typical distribution of shot-to-shot stripping efficiencies. As seen, high efficiency stripping is achieved only for a few points when the laser and ion beam are perfectly aligned.

While the positional jitter was a minor handicap in the previous phase, a recycling cavity requires a stable input beam and thus for the next step it is a performance-limiting issue. In addition, the presence of the jitter severely limits the ability to study the physics parameters sensitivities of the laser stripping process. Resolving or even improving the jitter would allow for an in-depth parameter sensitivity study of the laser stripping process even for the current 10 μs configuration already built and available.

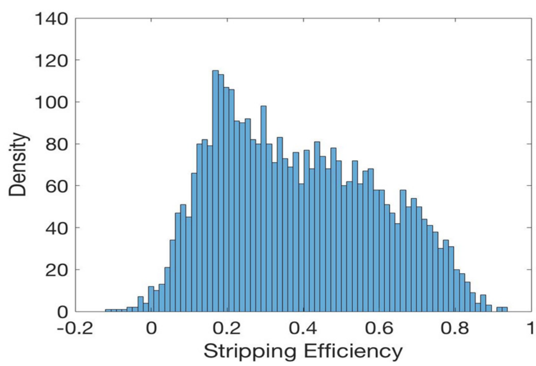

Figure 2. Plot of the distribution of ~3700 shot-to-shot laser stripping efficiencies during the previous 10 μs experiment.

A detailed simulation of the laser stripping experiment has been developed in the pyORBIT code [5]. The model will be used to benchmark the stripping efficiency distribution for the measured level of jitter. This will help determine of the laser positional jitter was only the factor contributing to the observed shot-to-shot differences in stripping efficiency.

Another effort will be centered on modifying the laser system hardware to rectify the jitter. This jitter, on the order of ±0.1 mm at the IP, has two components: laser macropulse pulse-to-pulse stability and laser drift over the transport line distance. The macropulse laser jitter will be addressed using the new diode pumped scheme. For the transport line drift component of the jitter, a feedback stabilization system will be implemented using the continuous-mode UV beam that is already a component of the laser system in the developed recycling cavity configuration. Because the laser transport line for the stripping experiment is already installed, this development effort can begin immediately.

Future Experiments

In the case that the feedback stabilization and the adjustments made to the laser system architecture do not reduce the jitter to a level sufficient for the recycling cavity, then the fall-back plan will be to move the primary laser into the tunnel, adjacent to the experimental vessel. Although the region of the stripping experiment has only very low levels of residual radiation (<5 mrem/hr), shielding would be placed around the laser to prevent radiation damage to the electronics. This is a last-choice option that considerably constrains the experimental schedule.

The majority of infrastructure developed in the previous experiment can be directly reused without modification in the next phase. The single exception is the experimental vessel, which will be adapted to incorporate the recycling cavity. This is a straightforward modification that was anticipated during the design of the vessel.

A number of "lessons learned" from the previous experiment will be used to optimize the set-up procedure to increase accuracy and reproducibility. The improved position stability in the laser will greatly expedite the tuning process. The set-up procedure will also benefit from the increase in SNS beam energy to the baseline 1 GeV energy due to recent plasma processing efforts [6]. This will eliminate a time-consuming step associated with raising the beam energy from the production value to 1 GeV for the stripping experiment.

Future stripping experiments will preserve the same ion beam and laser parameters at the IP as the previous experiment. The key differences in the experiments will be a more stable laser beam that will allow for physics studies of the stripping process, and a program to establish the same laser peak power at the IP through the power recycling optical cavity. It is possible that in the future the pulse duration will be extended up to a factor of 10 for experiments with the recycling cavity.

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