STATUS OF PREPARATIONS FOR A 10 MICROSECOND LASER-ASSISTED H$^-$ BEAM STRIPPING EXPERIMENT

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Abstract

At the Spallation Neutron Source accelerator preparations are underway for a 10 us laser-assisted H- stripping experiment. This is a three orders of magnitude increase in pulse duration compared the to initial 2006 proof of principle experiment. The focus of the experiment is the validation of methods that reduce the average laser power requirement, including laser-ion beam temporal matching, ion beam dispersion tailoring, and specialized longitudinal and transverse optics. In this presentation we report on the status of preparations and the anticipated schedule for the experiment.

INTRODUCTION

Many high intensity hadron synchrotrons accumulate beam through the process of charge exchange injection, whereby an H$^-$ ion is converted to a proton via passage through a thin carbon foil that strips the two electrons. This method has been demonstrated to work for beam powers up to 1.4 MW. However, the survivability of the carbon stripper foils beyond the 1.4 MW level is unknown. Evidence of foil damage including tears, curls, and bracket melts, is routinely observed at high power hadron facilities such as the Spallation Neutron Source (SNS) [1]. The damage is exponentially worse with increasing beam powers. Although there are a number of research programs dedicated to improving foil durability [2], currently there is no viable alternative technology to replace the foils once the power limit is reached.

Beyond the issue of foil survivability, there is also the problem of beam scattering in the foil. This leads to emittance dilution and more importantly, beam loss and radiation. At the SNS and similar accelerators, the injection region is the hottest area of the accelerator.

The idea of using a laser and two magnets to replace the carbon foil in the charge-exchange process was proposed almost three decades ago. In this scenario the first, loosely bound electron is Lorentz stripped from the ion using a magnetic field. Because the second, more tightly bound electron cannot be stripped with a conventional magnet, a laser is used to resonantly excite the electron to a more loosely bound state (typically n=3 or n=4), whereby it can be Lorentz stripped with a second magnet, resulting in a proton. Figure 1 illustrates the concept.

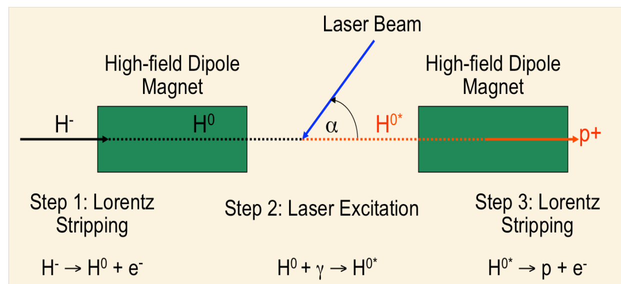

Figure 1: The laser stripping concept.

This method was successfully demonstrated in a 2006 proof of principle experiment at the SNS, where 90% stripping of a 6 ns, 900 MeV H$^-$ beam was accomplished using a 355 nm laser and two magnets. Unfortunately, a straightforward scaling of this experiment to the full SNS duty cycle would require ~600 kW of average laser power, which is not feasible. Rather, it is necessary to reduce the average laser power requirement through laser and ion beam manipulations [3,4].

At SNS, preparations are underway for the next laser stripping experiment. The goal of the experiment is to achieve 90% stripping efficiency of a 5-10 us, 1 GeV H$^-$ beam. The central theme of the experiment is the validation of methods used to reduce the required average laser power. For a future operational system that would strip millisecond-level pulses, these methods would be employed along with a power recycling optical cavity. The recycling cavity is under development in the laser lab at SNS, but is not part of the current stripping experiment.

This paper describes the configuration for the 10 us experiment, the work underway to prepare the ion and laser beam parameters, and the schedule.

EXPERIMENTAL CONFIGURATION AND HARDWARE

Four primary goals drove the design of the experimental configuration:

1) Achieve high efficiency stripping.
2) Protect the laser.
3) Prevent disruptions to production beam operations.
4) Provide schedule flexibility for the experiment.

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The final design, based on these goals, is described below.

Interaction Point Location

The experiment will take place in the SNS High Energy Beam Transport (HEBT) line, which transports the beam from the end of the superconducting linac (SCL) to the ring, and contains a 90° bend. The desired ion beam optics, described in a forthcoming section, necessitates that the interaction point be located downstream of the bend. Beyond this consideration, it is convenient to have several independently powered upstream quadrupoles for tuning flexibility, and it is also preferable to be located in a low radiation region. The final location of the interaction point (IP) that satisfies these objectives is near the end of the HEBT between a pair of quadrupoles (QH28 and QV29). One disadvantage of this location is that most of the diagnostics that will be used to measure and configure the beam parameters are ~30-40 meters upstream, requiring the use of models to predict the optics at the IP. To partially address this issue, a pair of additional wirescanner will be added – one at the interaction point, and another one a few meters downstream of the IP.

Laser Remote Placement

Two options were considered for the location of the laser station: 1) In the tunnel adjacent to the IP, and 2) in the ring service building, approximately 70 meters from the IP. Obviously, from the standpoint of the laser optics, the first option is far simpler. However, placing the laser in the tunnel introduces a host of other problems, all stemming from the need to protect the laser from radiation damage. Loss of the high power UV laser due to radiation exposure would represent a single-point failure for the entire experiment, and as such, the laser cannot be left in the tunnel during production beam operations. The in-tunnel scenario would require installing the laser, performing the experiment, and then removing the laser all during a dedicated accelerator physics study period. The longest accelerator physics blocks of time are associated with the start up periods following the twice-annual maintenance outages. Experience has shown that this time often evaporates the wake of equipment turn-on issues.

Due to the restrictive schedule logistics associated with the in tunnel option, the decision was made to place the main laser outside of the tunnel, in the ring service building. The UV laser will be transported ~70 m from the ring service building to a small final focusing table adjacent to the IP. This configuration provides flexibility for the experimental schedule while also protecting the laser. Underlying concerns regarding the laser power loss in transport and the laser pointing stability have been investigated this past year and will be discussed later in this document.

Experimental Station

The experimental station contains the IP, windows to accommodate entrance and exit of the laser, diagnostics at the IP and downstream of the IP, and two dipole magnets to strip the electrons. A drawing of the experimental station is given in Figure 2 below.

The two stripping magnets that convert H- to H^0 upstream of the IP, and then $H^{0}*$ to p+ downstream of the IP have unique design requirements. First, the field gradient must be large in order to minimize the induced angular spread in the beam from the probabilistic nature of the stripping. In addition, the magnetic field must not be present during nominal beam operations. The final design of the magnet that meets these requirements is a Halbach cylindrical array with 1.2 T peak field and 40 T/m field gradient, arranged with opposite polarity on either side of the IP in order that there should be approximately zero field at the IP. Due this arrangement and the charge state change between the magnets, a cumulative kick of ~17 mrad will be imparted to the beam. To compensate, corrector magnets have been placed on the outside of each stripper magnet. The stripper-corrector magnet pairs will be mounted on actuators for remote insertion and retraction from the beam pipe. The design of the magnet is described in more detail in [5].

The experimental station contains one pair of optical ports for entrance and exit of the laser, and second pair for viewing and for flexibility in the laser placement. In order to reduce the laser power density on the exit window to prevent breakage, a defocusing lens is located between the IP and the exit window.

While most of the diagnostics used to prepare the beam will be 30-40 m upstream of the IP, the experimental station will contain a dual-plane wirescanner at the location of the IP to verify the beam size, and a BCM just downstream of the IP to measure the stripped beam fraction. In addition, the second wirescanner will be placed downstream of the next quadrupole to assist in the ion beam optics tune up.

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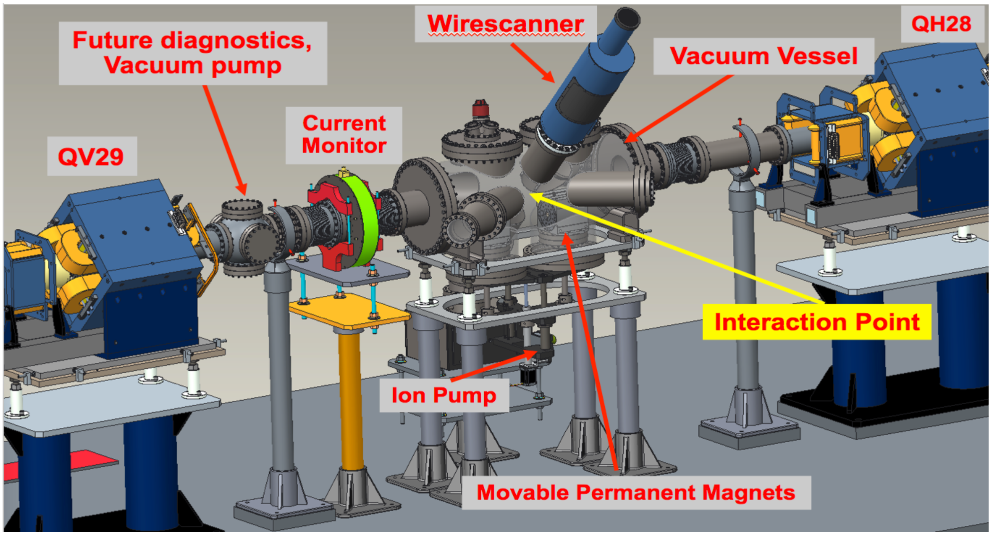

Figure 2: The final design of the experimental station.

PARAMETER REALIZATION EFFORTS

The central theme of this experiment is the validation of methods for reducing the required average laser power. These methods, described below, involve placing the ion beam in an off-nominal Twiss configuration, and temporally matching the laser and ion beam. Altogether, these methods reduce the required average laser power from 600 kW to 50 W.

Laser Configuration

Obviously, a significant savings in laser power can be realized by having the laser on only when beam is present. The SNS beam has a 402.5 MHz microstructure and a nominal 6% duty factor; the duty factor for this experiment is even lower. The laser system for the experiment is a frequency tripled, master oscillator power amplification (MOPA) scheme. The 355 nm final laser wavelength preserves the choice of the n=3 H^- excited state that was used in the initial proof of principle experiment. The laser has been demonstrated to operate in burst mode with 10 us, 10 Hz macrostructure, and 402.5 MHz, 30 – 55 ps microstructure, identical to the ion beam parameters for the experiment. The laser scheme and measured microstructure are shown together in Figure 3.

A major concern with the remote placement of the laser was the amount of power loss in transport, and whether enough laser power would be available at the IP to provide 90% stripping. Answering this question involved separate efforts to measure the total available UV laser power, and to measure the power loss on the windows, the mirrors, and in air.

Because it is not possible to directly measure picosecond level UV laser pulses, an optical correlator was developed to perform the measurement [6]. Using this device, the final power measurements gave laser powers in the range of 1.35 – 2 MW for micropulses lengths of 30 – 55 ps (FWHM), with power varying inversely to pulse length.

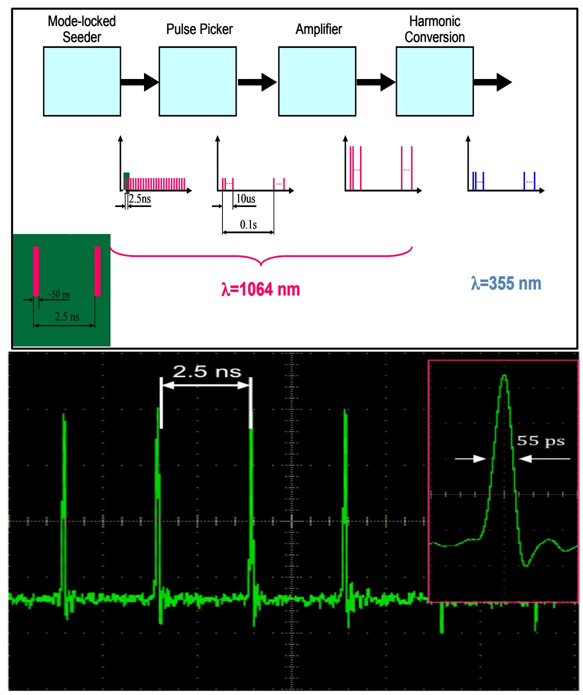

Figure 3: (Top) Laser amplification scheme. (Bottom) Laser microstructure measurement.

To estimate the laser power loss in transport, an eight meter, four-mirror mock up of the transport line was set up in the laser lab. The mirror loss was measured independently to be < 1 % per reflection. The laser was cycled through six iterations of the loop for a total of 48 meters of transport. The power loss was measured on every cycle and the results were extrapolated to 70 m, the estimated transport line length. The final estimates predict 1/3 of the laser power will be lost in transport, due primarily to Fresnel diffraction at the aperture and higher order mode losses, which diminishes with distance. Given the initial laser power measured with the optical correlator, the remaining available laser power at

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the IP should be sufficient to support 90% efficient H^- stripping.

Finally, the last major concern with the laser transport line is the pointing stability due to mechanical vibrations and temperature drift. One mirror on the laser table will be driven with a pair of Piezoelectric actuators to provide compensation for slow drifts on the order of 1 Hz or slower. Experience with the laser-based beam diagnostics systems in the SNS SCL/HEBT tunnel indicates that this feedback control should provide sufficient laser beam pointing stability for the laser-ion beam interaction.

Ion Beam Optics

The ion beam Twiss parameters in both the transverse and longitudinal planes can be configured to provide savings in the laser power budget. First, it is necessary to squeeze the bunch longitudinally to maximize the laser-ion beam cross section. The nominal micropulse length in the SNS HEBT is ~150 ps. For full overlap with the laser beam, this experiment requires that the micropulse length be ≤ 25 ps. The last few cavities in the SCL can be used to manipulate the bunch length, and a bunch shape monitor (BSM) in the HEBT, capable of measuring picosecond-level micropulses, is used to measure the length.

A complicating factor is the space charge of the bunch, which causes expansion of the micropulses between the end of the SCL and the IP, to the level of about 1 degree of length per milliamp of current. In an operational system, dedicated cavities would be located just upstream of the IP such that this was not an issue. However, for the current experiment the beam current will be limited to 1 – 5 mA for this reason. At these currents the microbunch lengths of σ_l < 25 picoseconds have been routinely configured, as shown in Figure 4.

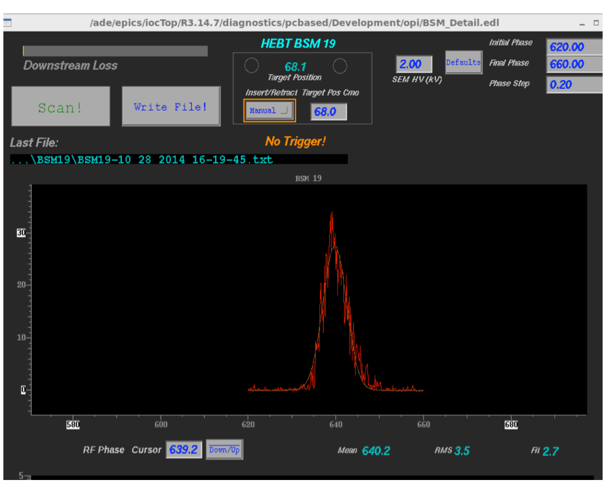

Figure 4: BSM measurement of a 22 ps microbunch.

In the transverse plane, the goal is to minimize the excitation frequency spread and maximize the cross section for interaction with the laser. First, dispersion tailoring can be used to eliminate the transition frequency spread due to beam energy spread [2]. This method capitalizes on the fact that the required laser frequency for excitation in the rest frame is a combination of the particle energy and the angle between the ion beam and the laser, as shown below:

$$f_{\text{rest frame}}(1 \to 3) = \gamma_n (1 + \beta_n \cos(\alpha_n)) f_{\text{beam frame}}$$

Conceptually, the idea is to set the dispersion derivative such that each combination of particle energy γ_n and angle α_n yields the same value of the laser frequency in the ion beam rest frame. For the SNS 1 GeV beam, this scenario corresponds to a dispersion function with values D=0 and D'=-2.6 at the IP. Given the upstream arc and the large number of independently powered quadrupoles, this is readily accomplished and has been demonstrated on multiple occasions.

After dispersion tailoring, the residual transition frequency spread is due to transverse divergence of the beam. Since the experiment will be conducted in the x-z plane, it will be advantageous to eliminate this spread by having α_x = 0 at the IP. Finally, to maximize the cross section of the laser with the ion beam, the vertical size should be as small as possible.

Experiments conducted over the last year have demonstrated all of the required Twiss parameters separately, with best measured shown below in Table 1 below. The details of these measurements are available in [7], in these proceedings. For the moment, the Twiss parameters are fit at location 30 m upstream of the IP, which introduces the possibility of propagate error. The measurements will be repeated when the experimental station wirescanners are installed. In the near future, efforts will focus on simultaneous demonstration of all ion beam parameters.

Table 1: Measured Ion Beam Optics Parameters

Parameter	Measured Value
σ_l	22.3 (picoseconds)
D, D'	0 (meters), -2.4 (radians)
α_x	0 (radians)
σ_y	0.1 (mm)

FINAL SIMULATIONS

In recent simulations done with the pyORBIT code [8] which include all the measured parameters, the stripping efficiency was calculated versus the laser radius and divergence [6]. The results are shown in Figure 5. While there is a region of very high stripping efficiency, it is yet unknown if the laser density for these parameters exceeds the damage threshold of the defocusing lens. This is currently under investigation.

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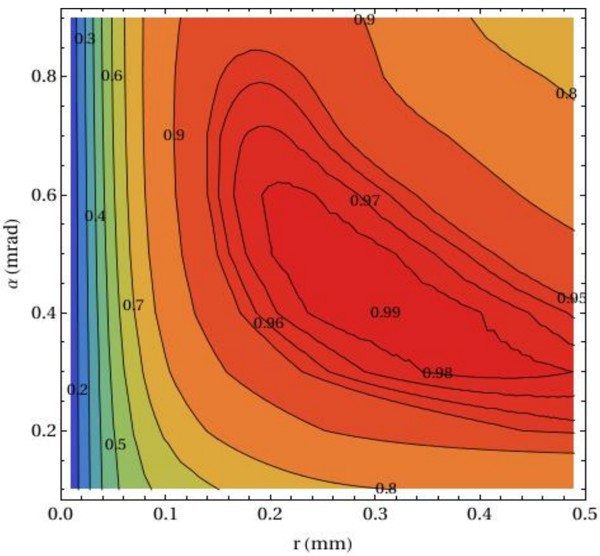

Figure 5: Simulated laser stripping efficiency versus laser radius and divergence.

SCHEDULE

This project has been planned over a 3 year time period, with an end date of May 2016. The primary focus of the first year was to choose the interaction point location, decide on the laser placement, and verify the ion and laser beam parameters. This work is complete. During the second year, the design of the stripping magnets and the experimental vessel was completed; they are now being manufactured with expected delivery dates in mid-winter. The diagnostics hardware are complete and ready for installation. The laser transport line design has just begun.

Installation of the diagnostics will commence in winter of 2015; the experimental vessel and stripping magnets will be installed in summer 2015; the transport line will be installed, along with the final optics table, in either summer of 2015 or winter of 2106. The first stripping experiments will commence in spring of 2016.

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