SNS LASER STRIPPING FOR H- INJECTION *

V.Danilov, Y.Liu, SNS, Oak Ridge, TN USA
K.B. Beard, R.P.Johnson#, V.Dudnikov, Muons, Inc. Batavia, IL USA
M.Shinn, Jlab, Newport News, VA USA

Abstract

The ORNL spallation neutron source (SNS) user facility requires a reliable, intense beams of protons. The technique of H^- charge exchange injection into a storage ring or synchrotron has the potential to provide the needed beam currents, but it will be limited by intrinsic limitations of carbon and diamond stripping foils. A laser in combination with magnetic stripping has been used to demonstrate a new technique for high intensity proton injection, but several problems need to be solved before a practical system can be realized. Technology developed for use in Free Electron Lasers is being used to address the remaining challenges to practical implementation of laser controlled H^- charge exchange injection for the SNS. These technical challenges include (1) operation in vacuum, (2) the control of the UV laser beam to synchronize with the H^- beam and to shape the proton beam, (3) the control and stabilization of the Fabry-Perot resonator, and (4) protection of the mirrors from radiation. The first objective is to demonstrate successful power recycling in the resonator and to design the system of mirrors to be located in the accelerator vacuum chamber with the required optical and thermal stabilization.

MOTIVATION

Muons, Inc. is dedicated to developing powerful proton drivers for muon production for muon colliders, neutrino factories, and muon beam physics. This proposed Phase I SBIR laser stripping project provides us an opportunity to become the reliable research partner of many accelerator facilities to provide H^- technology.

Figure 1 shows that future operation of the ORNL SNS will be limited by the use of foils for H^- charge-exchange injection. Lifetime tests show rapid lifetime degradation for temperatures above 2500 K. In addition, each proton captured in the ring passes through the foil from 6 to 10 times, leading to uncontrolled beam loss and unwanted radioactivation, especially in the injection area.

A first laser stripping demo experiment successfully demonstrated that using a laser, rather than foil, to strip H- to H+ works. A number of technical challenges must be solved for an operational system [1].

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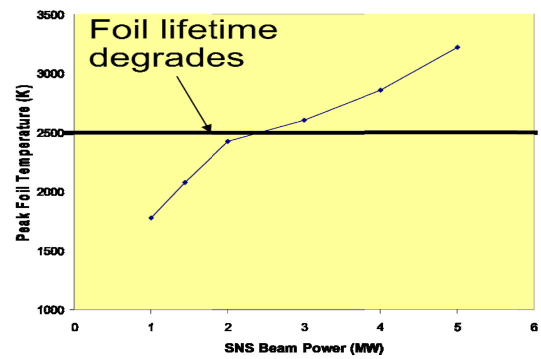

Figure 1: Peak SNS carbon stripping foil temperature as a function of beam power on target.

CONCEPT

H^- ion laser stripping was initially conceived as a 3-step stripping method: H^- conversion to H^0, H^0 excitation from ground to upper state, and finally H^0 to p conversion using photoionization. Subsequently modification of the first and third steps using Lorentz stripping and of the second using resonant Rabi oscillations for the hydrogen atom excitation were suggested.[2][3].

Stripping magnets are placed on either side of a laser-particle beam interaction point. The first magnet strips the first electron, and then the remaining neutral hydrogen beam is excited by a laser beam, and the second magnet strips the remaining electron (Figure 2).

A fundamental problem in using this method for stripping is the Doppler broadening of the hydrogen absorption line width due to the finite momentum spread of the beam. Since the neutral hydrogen beam inherits the energy spread of the H^- beam (typically ~ 0.1%), each individual atom has its own excitation frequency in its own rest frame. The relative spread of frequencies is about the same as the spread of particle energies, and therefore its absolute value is $\sim 10^{12}$ s^{-1}, while the achievable Rabi frequency is about 10^{11} s^{-1}. It has been shown that the upper state remains virtually unpopulated if the difference between the laser frequency and the transition frequency is larger than the Rabi frequency[4].

By focusing the laser beam in the plane of the H^0 beam, the angle of incidence of the laser light, and hence its frequency in the atom's rest frame, changes along the hydrogen beam path in the laser-particle beam overlap region, introducing an effective frequency ''sweep'' as the H^0 atoms traverses the laser interaction region (Figure 2). This spread is made large enough that all atoms within the spread of energies will eventually cross the resonant frequency and become excited.

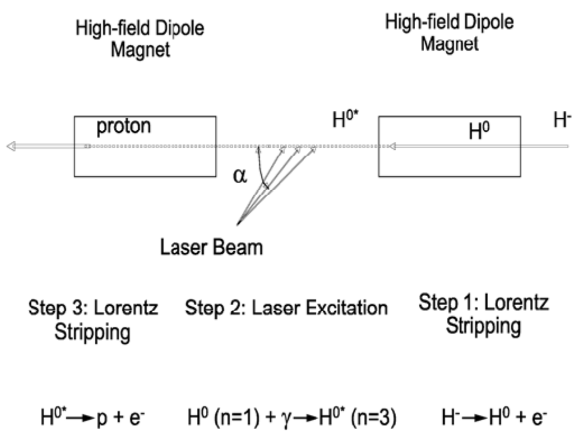

Figure 2: General scheme of frequency sweep stripping.

FIRST EXPERIMENT

The first experiment demonstrated high efficiency (about 90%) laser-assisted H^- beam conversion into protons at SNS, and agreed fairly well with the theoretical calculations, given the limited knowledge of the beam parameters[1]. The experiment used a 1 GeV H^- beam and a 13.7 MW peak power 355nm laser.

This proof of principle experiment was limited by the transmission of the laser power into the stripping chamber through a vacuum window. During the experiment, the power was restricted to 10.25 MW to avoid breaking the vacuum chamber windows (Figure 3).

Figure 3: Vacuum window which limited the laser power to the H^- beam in the experiment described above.

NEXT EXPERIMENT

In the next experiment and in the final design, the laser power will be amplified inside the vacuum chamber by a Fabry-Perot resonator (also called a cavity) and the injected laser power will be a few orders of magnitude lower. The laser power requirement will be reduced from the previous experiment by the following factors:

- Matching laser pulse time pattern to the ion beam by using mode-locked laser instead of Q-switched: ~ x25
- Using dispersion derivative transport of the H- beam to eliminate the Doppler broadening due to the energy spread: ~ x10
- Recycling the laser pulse in the vacuum chamber: ~ x10
- Vertical size and horizontal angular spread reduction: ~ x2-5

By combining all factors, the required average laser power can be reduced to between 50 and 120W, which is within reach of modern commercial lasers; however, a number of technical challenges remain.

Operation in Vacuum

Operation of optics in vacuum requires temperature stabilization and cooling to avoid distortions in the optical figure and drift. For a resonator Q of about 100, the intracavity power is on the order of 10 kW. Mirrors coated for the UV typically have losses of order 350-1000 ppm, leading to an absorbed power of about 10 W.

Jefferson Lab's Free Electron Laser (FEL) optics group has developed great expertise with handling high power laser optics in vacuum. The FEL has generated 15 kW of continuous extracted and about 150 kW of intracavity laser power to date; and the group has developed back, edge, and cryo-cooled optics. Figure 4 is an example of one of the turning mirror cassettes used to transport beam from the accelerator vault to the laboratories. This assembly is designed to transport 50 kW of average power.

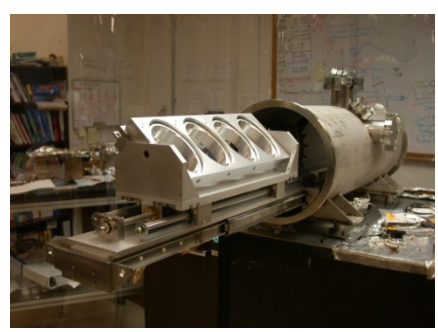

Figure 4: One of the turning mirror cassettes at the JLab FEL User Facility. Mirrors (not shown here) are back-surfaced cooled and actuated.

UV Laser Beam

The SNS group has acquired a high peak power 50ps/402.5MHz macropulse laser, are working on a ring-cavity setup with an 80.5 MHz mode-locked Ti sapphire laser. The group has recently demonstrated successful recycling of 80.5 MHz/2.5 ps laser pulses in a 402.5 MHz optical cavity and is currently addressing cavity stabilization.

Fabry-Perot resonator control and stabilization

Several cavity architectures are being considered. Possibilities are a confocal or near-concentric resonator, that looks much like the scheme shown in Figure 5 or a bow-tie resonator. JLab has the optical modeling software to model cavities: GLAD[5], Paraxia[6], and OPC (optical propagation code)[7]. For the control and stabilization of the resonator, angular adjustments are done similarly to that done by JLab [8] for their FEL. The techniques for locking of the cavity to the pump laser has been done before [9] and we would implement one of those techniques.

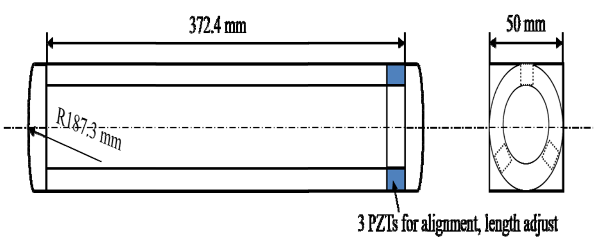

Figure 5: UV Fabry-Perot resonator from Light Machinery with Finesse: ~ 37, power amplification factor: ~ 10 and R > 92% at 355 nm.

Mirror Protection

It has been the experience of the synchrotron light, FEL and laser communities that when operating laser resonators at UV wavelengths and in a vacuum, the reflectivity invariably degrades over time. The reflectivity recovers if the optics are exposed to air, or to a low pressure oxygen plasma [10]. The source of this degradation is hydrocarbon contamination, ubiquitous in an unbaked vacuum system, cracked by the UV radiation to carbon. There is some question whether the irradiances and duty factors are sufficient to make this an operation-limiting problem, but we believe that considering this during the Phase I program is appropriate.

Stripping section lattice insertion design

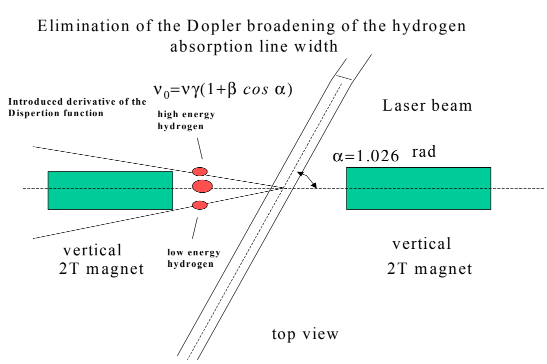

Figure 6: Schematic method of using dispersion prime to reduce the Doppler broadening caused by the H^- momentum.

Figure 6 describes a method to eliminate the need for the laser beam to have an angular divergence. By tailoring the rate of change in the lattice dispersion function, one can eliminate Doppler broadening due to the momentum spread of the H^- beam. For the 1 GeV SNS beam D'=2.58 is sufficient to compensate for the Doppler spread. Figure 7 shows the required D' as a function of H^- energy. The required D' is a very nonlinear function of energy, and a higher beam energy is preferable.

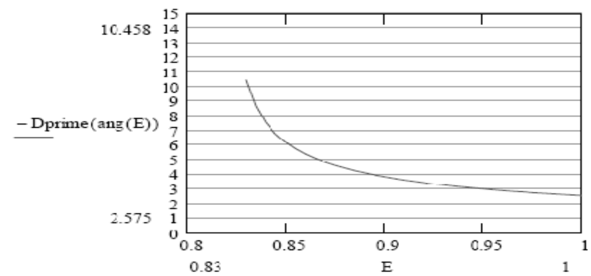

Figure 7: Required dispersion function derivative to eliminate H- Doppler broadening as a function of Energy.

SUMMARY

We fully anticipate that the combination of SNS, Jlab FEL, and Muons,Inc. expertise will produce a successful design for stripping high power H- beams.

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