FIRST RESULTS OF SNS LASER STRIPPING EXPERIMENT

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Abstract

Thin carbon foils are used as strippers for charge exchange injection into high intensity proton rings. However, the stripping foils become radioactive and produce uncontrolled beam loss, which is one of the main factors limiting beam power in high intensity proton rings.

Recently, we presented a scheme for laser stripping of an H^- beam for the Spallation Neutron Source ring. First, H^- atoms are converted to H^0 by a magnetic field, then H^0 atoms are excited from the ground state to the upper levels by a laser, and the excited states are converted to protons by a magnetic field.

This paper presents first results of the SNS laser stripping proof-of-principle experiment. The experimental setup is described, and possible explanations of the data are discussed.

INTRODUCTION

H^- ion laser stripping was initially proposed by Zelensky, *et al* [1]. This paper described the 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 photo ionization. Since the initial proposal of the method, modification of the first and third steps using Lorentz stripping was suggested [2]. For the second step it was proposed to utilize resonant Rabi oscillations for the hydrogen atom excitation. The main complication was outlined in [2]: the energy spread of the ions is too large to excite the entire beam. A variety of methods have been proposed to overcome this difficulty (see, for instance, [3]). Two of these proposals have become foundations for the proof-of-principle (POP) experiments described below:

1) The frequency sweep excitation [4].

2) The broadening of the upper levels by a magnetic field, which is Lorentz-transformed to an electric field in the beam rest frame [5].

The next section describes the physics of the first approach and the Spallation Neutron Source setup to conduct the experiment. Section III describes the first results of the experiments. Finally, the conclusion presents the status of laser stripping development at the Spallation Neutron Source (SNS) project in Oak Ridge, Tennessee.

BASIC PHYSICS AND EXPERIMENTAL SETUP

A narrow-band laser with frequency equal to the transition frequency between the ground state and any of the upper states of the Hydrogen atom forces an electron to perform oscillations between the two states (so-called Rabi oscillations). A fundamental problem in using this method for stripping is Doppler broadening of the hydrogen absorption line width due to the finite momentum spread of the beam. The laser frequency, ω_0, in the H^0 atom rest frame is related to the light frequency, ω, in the laboratory frame as follows:

$$\omega_0 = \gamma(1+\beta\cos\alpha)\omega, \quad (1)$$

where α is the angle between the laser and H^0 beam in the laboratory frame. For the *n=3* upper state the required wavelength is λ_0 =102.6 nm, and the frequency is $\omega_0=2\pi c/\lambda_0=1.84*10^{16}$ Hz. Since the neutral hydrogen beam inherits the energy spread of the H^- beam (which typically has a fractional value of a few times 10^{-4}), 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 ~10^{12} sec^{-1}. The achievable Rabi frequency is about 10^{11} sec^{-1}. It is shown in ref. [6] that the upper state remains virtually unpopulated if the difference between the laser frequency and the transition frequency is larger than the Rabi frequency.

Consider the arrangement shown in Figure 1. Stripping magnets of the type mentioned in the abstract 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. By preparing a diverging laser beam, the angle of incidence of the laser light changes along the hydrogen beam path in the laser-particle beam overlap region. The laser frequency remains fixed, but because of the Doppler dependence of the rest-frame laser frequency on the incident angle, the frequency of the light in the atom's rest frame decreases as the angle increases. This introduces an effective frequency "sweep" as the hydrogen beam traverses the laser interaction region, which can be made large enough so that all atoms within the spread of energies will eventually cross the resonant frequency and be excited.

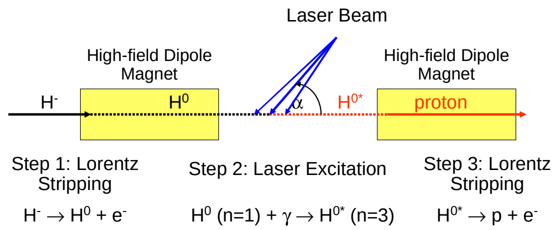

Figure 1 General scheme of frequency sweep stripping.

Previous papers [4] presented a detailed calculation of the process along with a practical approach to a proof-of-principle experiment at the SNS project. The designs of the magnets, the vacuum chamber, and the laser parameters were presented in Ref. [7]. The assembly was manufactured by Novosibirsk Institute of Nuclear Physics in 2005 and installed at the end of the same year in the SNS linac tunnel. Figure 2 presents the right-side view of the assembly. One can see three magnets – the first one is for the first electron detachment, the second is for the interaction region shielding from the stray fields of two adjacent magnets, and the third magnet is for the stripping of the last excited electron. The proton beam current is measured by the current transformer that can be seen placed on ceramic piece of the vacuum chamber.

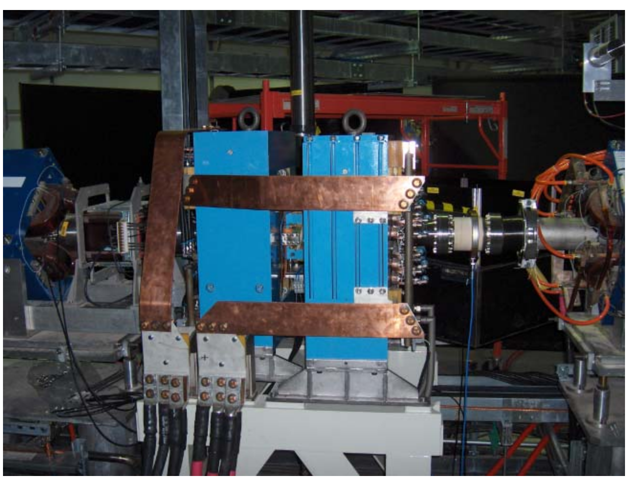

Figure 2 Principal scheme of laser stripping via the Broad Stark State.

Figure 3 shows the laser beam optics that forms an elliptical beam and sends it through the flange window to the interaction point in the middle of the small magnet. The metal pipe, hanging from the ceiling, is the laser light transfer line from the laser room that is located at about 50 meters from the table. This line was used to transport the laser light for the first, unsuccessful experiment, carried out in December of 2005. In March of 2006 this line was abandoned for the following reasons: the transmission of the 3rd harmonic (355 nm) of Nd:YaG laser was poor, not more than 30%. So we lacked laser power for the experiment. An attempt to use a more powerful laser was stalled because some lenses and mirrors were damaged by the 355 nm laser light. So, in the second run (March, 2006),

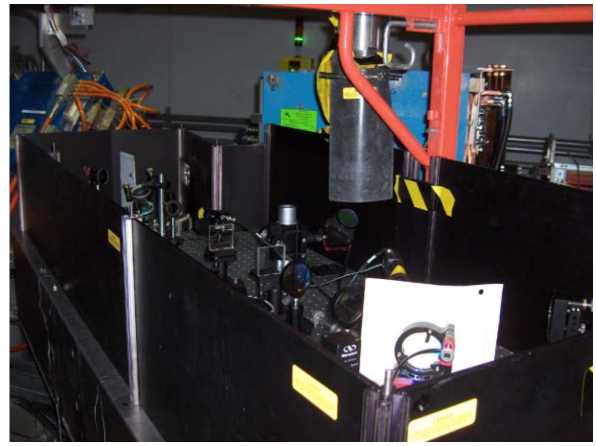

Figure 3 Preliminary engineering design of laser stripping insertion for SNS experiment (top view).

we put the laser directly on the table, in spite of high radiation levels. This solved the laser beam transport problems: it allowed us to get high laser power at the interaction point that led to a first success, namely substantial (around 50%) conversion of the ion beam into protons.

EXPERIMENTAL RESULTS AND COMPARISON WITH SIMULATIONS

As we mentioned in the previous section, so far there have been two runs in the experiments at SNS. In the first run, in December 2005, because of the low peak laser power at the table and, probably, for other reasons as well, no proton current was observed in the current transformer. In the second, March 2006 run our group made more thorough preparations for the experiment. The main difference was that the same laser was moved into the tunnel on top of the table, shown in Fig. 3 The laser power in the third harmonic was around 17±5% MW, with full width at half max of 7.1 ns. The laser divergence was around 3.6±1.8mrad and the vertical laser beam size was around 1mm rms. For these laser beam parameters we predict above 90% stripping efficiency for optimized ion beam parameters. The angle of the laser beam with the chamber axis was 30.8°.

To verify overlap of the ion and laser beams at the interaction point, the experiment started with the observation of one electron stripping by 1064 nm light with four times the above power. A drop in the current was observed, and so the laser light was switched to 355 nm (the 3rd harmonic beam from the same laser), and the energy of the ion beam was set to 770 MeV corresponding to a high cross section for one electron detachment due to the existence of a long lived H^- ion state, known as the shape resonance (see, e.g. [8]). The reduction of current with duration of about 10 ns was observed immediately and the observed one electron stripping efficiency of about 20% was in line with expectations. This was done with the strong magnets of the experimental setup turned off – otherwise the electron would be stripped by the magnetic field. The central, small magnet was turned on to get enough deflection of stripped electrons to separate them from the ion beam. Figure 4 shows the current signal (white line) with the dip at about 200 ns from the end of the beam pulse. The red line presents a signal from photodiode that was installed near the optical table and detected stray light from the laser. The broader spike is due to bandwidth limitation of the photodiode and the 200 ns time shift between the photodiode signal and the current dip is due to different lengths of cables to the oscilloscope.

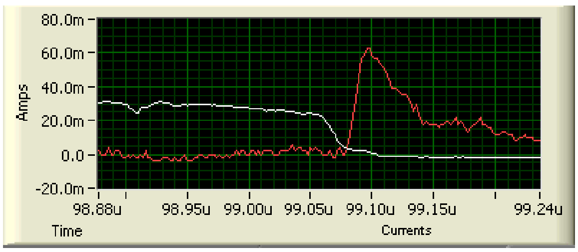

Figure 4 Ion beam current (white line) and the signal from photodiode (red line). One can see the dip in the beam current 200 ns from the end of the pulse.

After the one electron detachment was observed, the vertical position of the ion beam was adjusted to maximize the beams overlap. Then, two strong magnets were turned on, the energy was shifted to 923 MeV that corresponded to maximum of calculated stripping efficiency and the proton beam signal with duration of about that of the laser pulse, was observed!

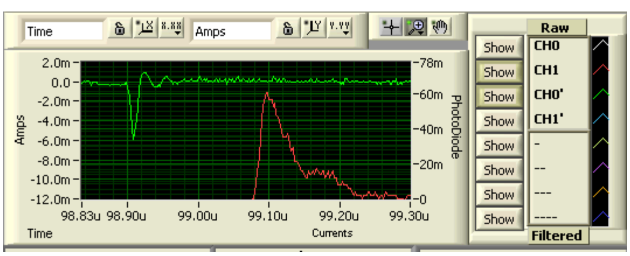

Figure 5 Proton beam signal (green line), shifted forward 200 ns relative to the photodiode signal (red line).

Figure 5 shows one of the first observed proton signals. Its polarity is inverted compared to the H$^-$ beam signal in Fig.4. Its width was about 10 ns and the laser pulse duration was 7.1 ns. It indicates that there is some broadening of the short pulses by the current transformer, along with some ringing in the circuit after the proton beam is gone (see green line in Fig. 5). This was taken into account when we used data to estimate the stripping efficiency. After the adjustment of the vertical ion beam coordinate to maximize the signal, the first (and only) energy scan was performed. Its results are shown in Fig.6 Dots with error bars represent the experimental points. The horizontal axis shows the ion beam energy, and blue and red lines represent the calculated efficiency vs energy for ion beam sizes 0.8 and 1.2 mm respectively. The ion beam energy spread was taken 0.5 MeV in the calculations. The actual ion beam size was not known in this experiment – some measurements before and after the experiment showed different values for the beam size, depending on the linac lattice – from 0.7 to 2.4 mm.

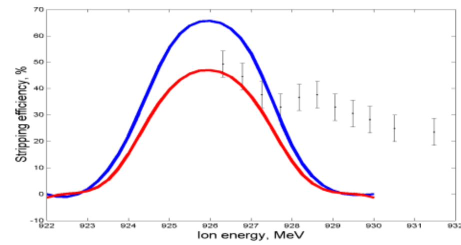

Figure 6 Experimental data (dots with error bars) and two calculated efficiency vs energy curves for 0.8 mm (blue line) and 1.2 mm (red line) vertical sizes of the ion beam.

The experiment stopped suddenly due to a leak in the vacuum chamber near the laser beam absorber. It appeared, probably, due to a large heat load from the laser beam. The beam characteristics were not exactly known at the moment and were measured afterwards. One can see that the measured resonance width is a factor of 2-3 larger, probably, due to increased energy spread from the linac in these particular sets of experiments.

CONCLUSIONS

The first substantial (about 50%) stripping was observed at SNS. The results are roughly about what we expected from calculation. We believe disagreements are related to our limited knowledge of the beam parameters. More accurate beam data could not be obtained due to the sudden leak in the vacuum chamber, which stopped the linac operation. We would like to continue experiments this summer to reach 90% efficiency and start the next round of the laser stripping development.

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