LASER STRIPPING OF H$^-$ BEAMS: THEORY AND EXPERIMENTS*

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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 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 second magnetic field. In this paper we report on the first successful proof-of-principle demonstration of this scheme to give high efficiency (around 90%) conversion of H$^-$ beam into protons at SNS in Oak Ridge. In addition, future plans on building a practical laser stripping device are discussed.

INTRODUCTION

After years of theoretical investigations of a laser stripping feasibility, the first high efficiency laser-assisted conversion of H$^-$ beam into protons was demonstrated at SNS in Oak Ridge, Tennessee [1]. It was shown how it is possible to overcome the main difficulty of the method – excite hydrogen atoms with very large (in terms of the laser spectral width) spread of transition frequencies between the ground and some upper level (level with quantum number n=3 is used in the experiment) of the hydrogen atomic beam.

The hydrogen beam was obtained from H$^-$ beam after its transfer through a 2 Tesla magnet. Since the process of one electron detachment produces a negligible energy change for the atoms, the resulting H^0 beam inherited the SNS linac relative energy spread of the order of 10^{-3}. Due to Doppler dependence of the light frequency on the ion energy, the energy spread resulted in the large absorption line width as compared to relative bandwidth of the lasers with values around 10^{-5}-10^{-6}. Even though the atomic level's excitation was investigated at the dawn of quantum mechanics, the conventional methods, such as Rabi oscillations, couldn't provide the excitation efficiency close to 100% for the typical linac beams.

We utilized Doppler dependence of the light frequency on incident angle and used a convergent laser beam. By focusing the laser beam in the plane of the two beams, 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. This spread can be made large enough that all atoms within the spread of energies will eventually cross the resonant frequency and become excited. The excited electron is stripped by the second 2 Tesla magnet of the stripping device.

The resonant excitation in two-level quantum systems has been a very developed area in application to spin physics. For linear frequency dependence on time the problem was analytically solved by Froissard and Stora [2]. However, in spectroscopy this method is quite new and we will give an analytical formula for probability of excitation in the next section. In addition, we will review other suitable excitation methods.

The section after the next presents briefly the results of a proof-of-principle laser stripping experiment that was carried out last year at SNS. The last section presents the plans to build a prototype of the real laser stripping device and the problems we confront at this moment. The conclusion will summarize the status of the laser stripping development.

THEORY OVERVIEW

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.

To check the degree of excitation we solve the quantum mechanical problem with the laser frequency linearly changing in time. The equation for this is derived in, e.g., [3], but is modified here so that the difference between the laser and transition frequencies is a linear function of time:

$$\dot{C}_1 = \frac{i\mu_{1n}E^*}{2\eta} C_n e^{i(\Delta t+\Gamma t^2/2)},$$
$$\dot{C}_n = \frac{i\mu_{n1}E}{2\eta} C_1 e^{-i(\Delta t+\Gamma t^2/2)}, \quad (2)$$

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where C_1 and C_n are the electron amplitudes for being in state 1 or n, respectively, E is the amplitude of the oscillating electric field, Δ is the laser and transition frequency difference at zero time, $\Gamma = d\omega_0/dt$ is the frequency sweep rate, $\mu_{1n} = \mu_{n1}^* = -\int d^3r\, u_1^*(\vec{r}) ezu_n(\vec{r})$ (assuming the light is polarized and the electric field is parallel with the z axis, perpendicular to the plane of interacting beams), and u_1 and u_n are the normalized wave functions of the ground and the upper excited state, respectively. In the case where the reference energy particle matches the laser and transition frequencies, the difference Δ is proportional to the relative energy offset from the reference energy and can be obtained from (1):

$$\Delta = \omega(\gamma(1+\beta\cos\alpha) + \frac{\cos\alpha}{\gamma^2\beta})\frac{\delta\gamma}{\gamma}, \quad (3)$$

where ω is the laser frequency.

The problem was analyzed in [4] and here we present only the peak laser power estimation for high efficiency stripping for the relativistic case β~1:

$$P_{peak} = \frac{\ln(1/\delta)\eta^2\varepsilon_0 c^2 \kappa\omega_0 \sin\alpha\, h}{2\mu_{1n}^2\gamma(1+\beta\cos\alpha)^2}, \quad (4)$$

where $\delta << 1$ is the ratio of unexcited to excited atoms, h is the vertical half size of the beam, ω_0 is the laser frequency in the rest frame of the atom, related to the laser frequency by (1), κ is the full relative frequency change along the beam path, which, as follows from numerical simulations, has to be 3 times larger than the FWHM relative spread of energies (or around 6 times larger than the relative rms energy spread) $\kappa \approx 6\frac{\delta\gamma(rms)}{\gamma}$ in order to reach the stripping efficiency above 90%.

Other methods were proposed to excite the levels with large absorption line width. For example, it was proposed to use the frequency sweep using dependence of magnetic field on longitudinal coordinate and associated Stark effect [5]. The other possibility to excite all atoms using narrow band laser, suggested in [5,6], is to widen the upper level by magnetic field such that the level width is made to cover the transition frequency spread due to Doppler effect, i.e., $\Delta_0/\omega_0 \approx \delta\gamma/\gamma$, where Δ_0 is the width of the upper level. Substitution of $\kappa \approx 6\Delta_0/\omega_0$ into (2) yields almost exact formula for stripping efficiency in this case (see [7]) if coefficients μ_{1n} are the same. In reality, though, these coefficients get lower for the Stark broadened levels and the needed laser power is a few times larger for that case [7]. But, in principle, formula (2) is a good estimation for all cases after substitution $\kappa \approx 6\frac{\delta\gamma(rms)}{\gamma}$. The main facts we need from it for the remainder of the paper are:

1) The laser peak power is proportional to the spread of upper level frequencies;
2) It is also proportional to the vertical size (assuming the ion and laser beams interact in horizontal plane);
3) There is strong dependence on dipole transition coefficients μ_{1n}.

For the SNS linac parameters (assuming δ≈0.1 or 90% of stripping), β≈0.875, α≈40°, $\kappa \approx 3\cdot 10^{-3}\omega_0$, $\omega_0 \approx 1.84\cdot 10^{16} Hz$, *h≈1mm*, *n=3*, and $\mu_{13} = -\int d^3r\, u_1^*(\vec{r}) ezu_3(\vec{r}) = \frac{3^3 ea_0}{2^6\sqrt{2}}$ for the transition between the 1st and 3rd states, the formula (4) yields approximately 10 MW of peak laser power. Now we explain our choice for the upper level.

Upper Level Choice

The choice of upper level is n=3. As compared to the n=2 state, it requires a more reasonable magnetic field in the second strong magnet to strip the last remaining excited electron. Roughly, we need 2 kG to strip n=3, as opposed to 1 T for n=2. In addition, when an excited particle travels in the region of large magnetic fields, a shorter stripping distance leads to fewer decay of excited states, and the lifetime of the n=3 state is 2.5 times longer than that of the n=2 state. The last fact alone may give a few more percent efficiency for n=3, because of the radiation decay of the excited state between the interaction point and the large magnetic field region (the distance, typically, is a few centimeters). Finally, upper states, for example the n=4 state, need roughly 2.25 times more laser power for excitation, even though it requires a smaller magnetic field (if abundant laser power available, it can be a good choice for stripping).

OVERVIEW OF EXPERIMENTS

The designs of the magnets, the vacuum chamber, and the laser parameters were presented in [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.

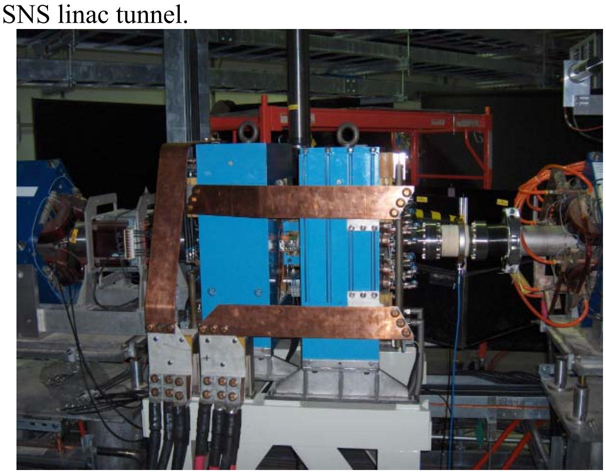

Figure 1: Side view of the experimental assembly.

Figure 1 presents the side view of the assembly. One can see three magnets – the first one (2 Tesla magnet) is for the first electron detachment, the second (small magnet) is for the interaction region shielding from the stray fields of two adjacent magnets, and the third (2 Tesla) magnet is for the stripping of the last excited electron. One can see also the ceramic break in the vacuum chamber and a current transformer on it to measure the beam current. The black pipe, hanging from the ceiling, was used in the first experiment to deliver the laser beam from the laser room roughly 100 meters from the assembly.

The third magnet was made a C-magnet to allow the laser beam to propagate from the windows with flanges (shown at the far end of the optics table in Fig. 2) to the interaction region. The laser beam piece of the vacuum chamber was made wide to provide flexibility to vary the incident angle if necessary. This proved to be very useful because the energy of the ion beam from the linac was lower than the expected 1 GeV. The experiments were done at energies around 900 MeV with the lowest incident angle of 20 degrees as compared to the initial design angle of 40 degrees for a 1 GeV beam.

Figure 2 also shows the laser beam optics to transfer the beam from the laser to the laser-ion interaction point (IP).

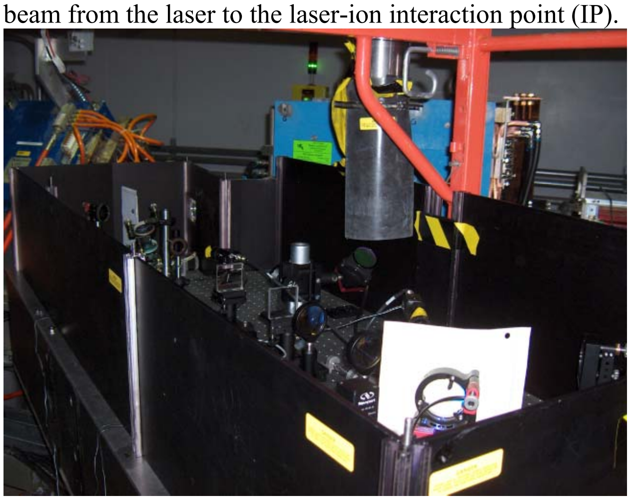

Figure 2: Laser beam optics that transfers the beam from the laser to the center of the magnet assembly through a flange window seen at the far end of the optics table.

So far we had four experimental runs:

1st experimental run (December 2005) - no stripping was seen. It failed, probably, due to loss of the laser power in the laser transfer line with the length of approximately 100 meters.

In the 2nd experimental run we had some rearrangements of the equipment. The laser (Q-switched Nd:YAG Continuum Powerlite 8030) was moved to the optics table (see Figure 2) adjacent to the magnet assembly. It tripled the laser beam power. The laser beam incident angle and beam parameters (energy of the ions) were more carefully measured. This run (March 2006) led to the first success (about 50% stripping).

The 3rd run (August 2006) was successful (around 85% stripping achieved), and the additional effects were studied.

In the 4th (and final) run in October 2006, we obtained a record 90% stripping efficiency and studied the additional effects.

Figure 3 shows one of the first observed stripping signals, recorded in the second run.

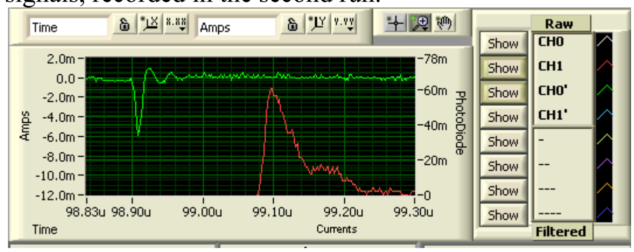

Figure 3: Laser stripping signal from current transformer (green) and reflected laser light signal from photodiode (red) used as a time reference point. The vertical scale is in milliamperes, the horizontal scale units are microseconds. The current pulse width is about 10 ns, which is slightly larger than that of the laser pulse. Photodiode signal time is shifted 200 ns from the current signal due to cable delay.

Details of the experiments and the results can be found in [1]. The next section presents our plans for a new round of laser stripping developments at SNS.

NEW DEVELOPMENTS AT SNS

A simple multiplication of 10 MW laser peak power, used in the first experiments, and the duty factor of the SNS beam (equal to 0.06) yields the average power of 0.6 MW to strip the entire ion beam. Obviously, the power is too large to make the device practical. It shows that the used Q-switch laser is not suitable for the task of stripping the entire SNS beam. That is why we stripped only a few nanosecond beam in our proof-of-principle experiment. Now, our team has a plan to demonstrate the long pulse stripping with mode-locked lasers, more suitable for the task.

To build a working laser stripping device, we need to take a few steps to reduce the required average and peak power of the laser to be able to use existing laser technology. These steps, ordered according to their importance from most to least important, are listed below:

1) Matching the laser pulse time pattern to ion beam one to reduce the laser beam idle time;

2) A dispersion derivative introduction to eliminate the Doppler broadening of the absorption line width for the laser peak power reduction;

3) Laser beam recycling to reduce the average laser power;

4) The ion bunch length reduction for the average laser power reduction;

5) The ion beam vertical size reduction for the laser peak power reduction;

6) The ion beam horizontal angular spread reduction for the peak laser power reduction.

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Now we describe these steps in detail.

Matching Laser and Ion Beam Timing Patterns

The mode locked laser pulse time pattern resembles the ion beam time pattern. For the SNS linac, the ion beam coming to the ring consists of roughly 100 ps bunches with a repetition rate of 402.5 MHz and the duty factor of 6%. For optimal light use, the laser beam has to have the same repetition pattern at the stripping region. Available mode locked lasers may have similar, typically, few times lower repetition rate with tens of picoseconds bunch durations, but with the peak power around 1 MW instead of required 10 MW. Below, we describe how to strip the entire linac beam with those lasers.

Dispersion Function Tailoring

It was shown in [4] how it is possible to reduce the necessary peak laser power to mode locked laser values. The trick is to introduce an ion beam incident angle dependence on beam energy. This can be done by introducing a dispersion derivative in the interaction region such that the resulting laser frequency (1) doesn't depend on particle's energy. Here is the formula for the needed dispersion derivative:

$$D' = -\frac{\beta + \cos\alpha}{\sin\alpha} , \qquad (5)$$

where α is the incident angle, determined by (1).

Fortunately, the SNS linac-to-ring beam transfer line has a 90 degree bend and it is possible to get the required dispersion derivative D′=2.58 for the 1 GeV ion beam and the laser wavelength of 355 nm. Figure 4 shows the dispersion function for the SNS high energy beam transfer line (HEBT), where the experimental region is located at 84 meters from the line beginning. One can see that the required large dispersion derivative can be achieved at this point.

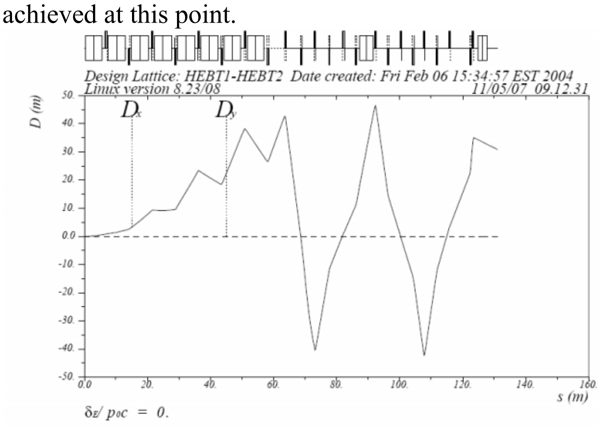

Figure 4: Dispersion function in the HEBT. The interaction point is at s=84 m.

This dispersion derivative can't be achieved for low energies where the SNS project started its operation. For example, for 900 MeV, formula (1) gives an incident angle of approximately 30 degrees. But the dispersion derivative is about 4, which is too high to be achievable in the SNS HEBT line. More reasonable values for dispersion are 3 and below. Therefore, in the present linac configuration with energies below 950 MeV the experiment is not feasible. We need energies of around 1 GeV to have this experiment done effectively.

Laser Beam Recycling

Typically, only very small portion (~10^{-7}) of photons is used for the hydrogen excitation. To further reduce the average power, we want to reuse the same laser beam 10 times, either by bouncing the light between mirrors or by using a Fabri-Perot resonator. This number comes from available technology of lens or mirror coating for ultraviolet light (see, e.g., [8]).

Ion Bunch Length Reduction

In order to make the ion beam shorter than the laser pulse, we have to reduce the ion bunch length by manipulating the superconducting linac (SCL) cavity phases. Unfortunately, in the present configuration, the beam exiting the linac has an extremely short (3 ps) bunch length and a large energy spread (more than 0.3 MeV). The bunch expands rapidly because of inherited and space charge induced energy spreads. At the point of experiment, even for low current, the FWHM bunch length becomes 120 ps. For nominal beam currents ($5*10^8$ ions per bunch), it increases above 500 ps. For the SNS power upgrade, we have plans to install cavities in the HEBT to manipulate the energy spread and bunch length, but for the intermediate stripping project these cavities won't be available. Therefore, we have to modify a linac setup to increase the bunch length (and, obviously, decrease the energy spread) in the final part of SCL. This maneuver will reduce the space charge effect on the bunch length. Preliminary estimations show that we can reduce the ion bunch length at the interaction region even to the 10 ps FWHM at expense of 54 MeV energy drop and to the 16 ps, when the energy drop is around 4 MeV. The energy decrease is related to the fact that the last linac cavities have to be used more for the ion beam defocusing than for the acceleration. More precise simulations and optimizations are underway.

Ion Beam Vertical Size Reduction

According to formula (3), the peak laser power is proportional to the vertical beam size, assuming the laser and ion beam trajectories lie in the horizontal plane. For our next experiment we can prepare the beam with 3 times smaller size. This number comes from the available range of quadrupole power supplies in the SNS HEBT line.

One more process, contributing to the vertical emittance increase, is related to the first electron stripping in the first magnet. The magnetic field has to rise fast enough to prevent large vertical emittance blow up. A possible solution for the intermediate laser striping project is described in [9].

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Horizontal Angular Spread Reduction

When the optimal dispersion function derivative is introduced, the residual transition frequency spread for ions comes from the horizontal angular spread. In order to further reduce the transition frequency spread, we should try to maximize the horizontal betatron function (while keeping the horizontal size smaller than the longitudinal one), and nullify the horizontal beta function derivative. Figure 5 shows the horizontal and vertical beta functions for the HEBT quads adjusted to laser stripping experiment needs. One can see that at 84 meters distance from the beginning (where we plan to do the next experiment) the vertical beta function is very small, and the horizontal one is large and has zero derivative with respect to the longitudinal coordinate.

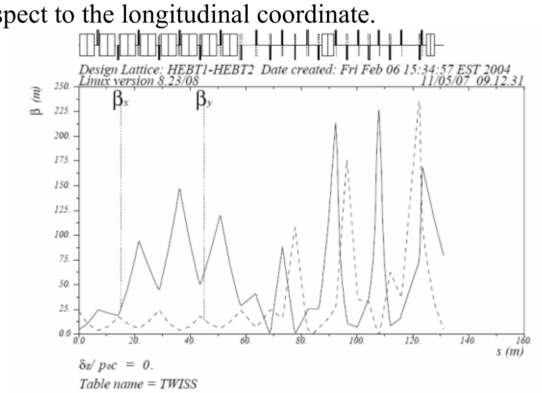

Figure 5: Horizontal and vertical betatron functions in the HEBT. The interaction point is at s=84 m.

With all the described steps, the required peak laser power for 98% stripping efficiency can be reduced to 1 MW. For the average power estimation, we take into account the fact that if we want to reuse the laser beam ten times, its repetition frequency must be 10 times smaller than that of the laser pulse, i.e. 40.25 MHz. The final number for the average laser power P_a, which affects mostly the cost of the final project, is obtained from multiplication of the above parameters (the laser peak power, the pulse duration, its repetition rate, and the duty factor):

$$P_a = 10^6 W \cdot 50 \cdot 10^{-12} s \cdot 40.25 \cdot 10^6 Hz \cdot 0.06 \approx 120 W \cdot$$

This number looks reasonable, especially when we take into account rapid progress of the laser technology. It shows that the laser stripping idea can become a reality in the near future.

CONCLUSION

After experimental demonstration of high efficiency (about 90%) laser-assisted H^- beam conversion into protons at SNS for the short laser pulse, the next step will be the long linac pulse experimental verification. This paper shows how it is possible to strip the entire linac beam by available lasers. All the required steps are described and the approaches outlined. Once long pulse stripping is demonstrated, the replacement of graphite foils with lasers will be an immediate reality.

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