FIRST STEPS TOWARD LASER STRIPPING IMPLEMENTATION*

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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, the first laser-assisted high efficiency conversion of H^- beam into protons was successfully demonstrated for a short laser pulse at Spallation Neutron Source project in Oak Ridge, Tennessee. The next step will be to build a stripping device to make 1-10 microsecond pulses stripping. The associated problems and possible solutions for projects with large ranges of H^- beam energies are described.

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 that it is possible to overcome the main difficulty of the method – to excite hydrogen atoms with very large spread of transition frequencies between the ground and some upper level of the hydrogen atomic beam. A level with quantum number n=3 is used in the experiment; the upper level choice for the SNS, as well as the other projects with possible laser stripping applications, is covered in detail in the next section.

The hydrogen beam was obtained from an 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 the Doppler dependence of the light frequency on the ion energy, the energy spread resulted in a large absorption line width as compared to relative bandwidth of 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 an excitation efficiency close to 100% for the typical linac beams.

We utilized the Doppler dependence of light frequency on incident angle and 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 a 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 the probability of excitation in the next section. In addition, we review other suitable excitation methods.

After this, we will present briefly the results of a proof-of-principle laser stripping experiment that was carried out last year at SNS, as well as the plans to build a prototype of the real laser stripping device and the challenges, associated with this.

The last sections cover different choices of upper levels and magnetic fields for projects with larger energies, as well as new phenomena that may appear when the density of the resonant atom medium becomes large.

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:

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

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:

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

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

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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):

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

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 of β~1:

$$P_{peak}=\frac{\ln(1/\delta)\hbar^2\varepsilon_0c^2\kappa\omega_0\sin\alpha\, h}{2\mu_{1n}^2\gamma(1+\beta\cos\alpha)^2}, \qquad (4)$$

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 a large absorption line width. For example, it was proposed to use the frequency sweep using the dependence of magnetic field on longitudinal coordinate and the associated Stark effect [5]. The other possibility to excite all atoms using narrow band laser, suggested in [6], is to widen the upper level with a magnetic field such that the level width is made to cover the transition frequency spread due to the 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 (4) yields almost the exact formula for the 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 required laser power is a few times larger for that case [7]. But, in principle, formula (2) is a good estimation for all cases after substituting $\kappa\approx 6\frac{\delta\gamma(rms)}{\gamma}$. 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 the dipole transition coefficients μ_{1n}.

For the SNS linac parameters (assuming $\delta\approx0.1$ or 90% of stripping), $\beta\approx0.875$, $\alpha\approx40°$, $\kappa\approx3\cdot10^{-3}\omega_0$, $\omega_0\approx1.84\cdot10^{16}Hz$, *h≈1mm,* *n=3*, and

$$\mu_{13}=-\int d^3r\, u_1^{*}(\vec{r})ezu_3(\vec{r})=\frac{3^3ea_0}{2^6\sqrt{2}}\approx0.298ea_0$$

for the transition between the 1st and 3rd states, the formula (4) yields approximately 10 MW of peak laser power. For comparison and for the next material, we present here the dipole transition coefficients for the *n*=2 and *n*=4 levels:

$$\mu_{12}=-\int d^3r\, u_1^{*}(\vec{r})ezu_2(\vec{r})=\frac{2^7ea_0}{3^5\sqrt{2}}\approx0.372ea_0,$$

$$\mu_{14}=-\int d^3r\, u_1^{*}(\vec{r})ezu_4(\vec{r})=\frac{2^{11}ea_0}{5^6\sqrt{5}}\approx0.176ea_0.$$

Now we explain our choice for the upper level.

Upper Level Choice

The upper level choice depends on beam energy. The laser excitation and the consequent magnetic stripping strongly depend on relativistic β and γ via the Doppler Effect and the electromagnetic field transformation from the laboratory to the beam rest frame. First, we start with the SNS case.

The SNS choice of upper level was *n*=3. First of all, we use the third harmonic (355 nm) of the most convenient 1064nm light. For 1 GeV energy, only this (and higher) harmonics can reach the upper levels. 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 reality, we have to have not just stripping, but stripping with the low emittance growth. For this, the fields have to be around 1 T for n=3, and 5 T for n=2 for SNS $\gamma\approx2$ (we cover the effect of emittance growth below). 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).

The optimal choice of parameters is different for higher energy beams. If the energy of SNS becomes 1.3 GeV (as planned for its power upgrade) even the second harmonic with 532 nm wavelength can excite upper level n=2 with 23 degrees incident angle. The magnetic field for stripping still has to be higher than 4 T, but this becomes an attractive option since 532 nm light is in a very convenient wavelength region for laser beam recycling (we'll explain the term in the next section containing new developments of the laser stripping device for the SNS project). We cover other projects in the next to last section.

Magnetic Stripping of Excited Level

The upper levels in our case, except for the principle quantum number *n*, have two others quantum numbers fixed with *l*=1 and *m*=0 with respect to the axis of electric field polarization (in the above material, it is called the *z* axis) . We consider here the case with *n*=2 as being the most simplest and promising for most of projects higher energy.

The quantum numbers for this level are related to the polar coordinates. The eigenvalues of the levels in the rest frame electric field, resulting from the laboratory system magnetic field, are calculated in the parabolic coordinates and are different from ones of the polar system. Therefore, in the adiabatic process of excited atoms entering the field, the initial excited state splits, in general, into some number of the Stark eigenstates depending on the angle between the laser polarization and the electric field in the atom rest frame that is perpendicular to the laboratory frame magnetic field.

We consider for simplicity two opposite cases: the laser electric field is parallel, and perpendicular to the r electric field (the other cases can be obtained in the same manner). For the laser and the electric field parallel, the projection of angular momentum on this axis (*z* axis) is equal to zero (*m*=0). The excited state in the field-free region has quantum numbers *n*=2, *l*=1, *m*=0. We denote it as *S(2,1,0)*. The parabolic quantum numbers, other than m, are *n, n1, n2* (*n=n1+n2+m+1*). We denote the eigenfunctions as *P(n,n1,n2,m)*. These eigenfunctions are related to each other in the following way (see, e.g., [8]):

$$S(2,1,0) = \frac{1}{\sqrt{2}} P(2,1,0,0) - \frac{1}{\sqrt{2}} P(2,0,1,0)\,. \quad (5)$$

For *m*=1 case (the laser polarization is perpendicular to *z* axis of rest frame electric field from magnets), the relation is:

$$S(2,1,1) = P(2,0,0,1)\,. \quad (6)$$

It tells us that if the laser polarization and the stripping magnetic field are parallel, the excited state will be split into two parabolic states; if they are perpendicular, there will be no split.

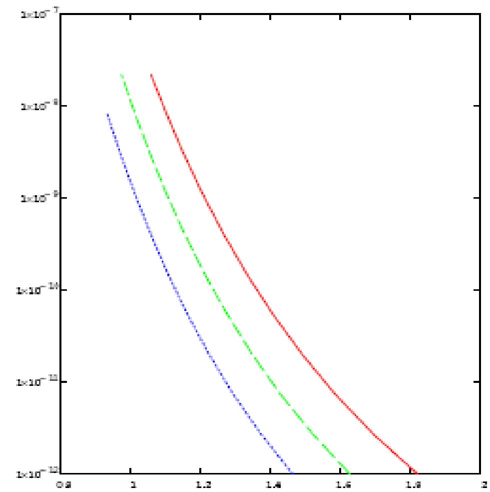

Figure 1: Lifetime of the three n=2 eigenstates as a function of magnetic field (in Tesla) for 4 GeV neutral hydrogen atom. The blue dotted line corresponds to *n1*=0, *n2*=1, *m*=0, the green dashed line – to *n1*=0, *n2*=0, *m*=1, and the solid red line – to *n1*=1, *n2*=0, *m*=0.

Figure 1 shows how the lifetime of the *n*=2 states depend on the magnetic field for LHC Power Upgrade case (these data are taken from [9]). If we use this data for the angular spread calculations (the method of calculations can be found in [4]) in the field of a 2 Tesla magnet with a 5 cm gap, we get an rms angular spread of 0.07 mrad for the state (6) and a rms angular spread of 0.12 mrad for (5). The big difference is related to the split of the upper level into two states when the polarization is perpendicular to the magnetic field.

These estimations are valid only if the excitation happens in the field-free region - the level shifts from the Stark effect have to be smaller than the resonant Rabi frequency. If they are of the same order, the excitation gets more complicated and it is necessary to consider transitions between parabolic states in the magnetic field – they are, in general, a superposition of polar eigen states. The only one-to-one correspondence happens for case (6). In this case the laser polarization is parallel with the magnetic field and the excitation occurs in the same manner as described before until the inverse lifetime become similar to the Rabi frequency – after this, the excitation drops rapidly as the upper level widens [7].

STATUS OF LASER STRIPPING PROJECT AT SNS

The laser stripping program was started at SNS 5 years ago, culminating in successful proof-of-principle laser stripping experiments. We had a total four experimental runs:

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

In the 2nd experimental run we had some rearrangement of the equipment. The laser (Q-switched

Nd:YAG Continuum Powerlite 8030) was moved to the optics table adjacent to the magnet assembly. This 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 with about 50% stripping efficiency.

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

In the 4th (and final) run in October 2006, we obtained a record 90% stripping efficiency (with roughly 10 MW peak laser power available) and studied the additional effects. Details of the experiments and the results can be found in [1].

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 needed 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 of 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.

These steps were described in detail in [10]. The new developments in beam recycling schemes were made since then. We describe these developments below.

Laser Beam Recycling Development

Typically, only a very small portion ($\sim 10^{-7}$) 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. Figure 2 shows the Fabri-Perot cavity ordered for tests.

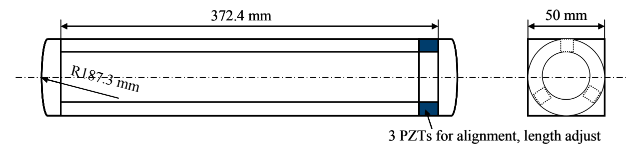

Figure 2: Drawing of Fabri-Perot cavity for the SNS laser stripping intermediate experiment.

The reflectivity of the mirrors for 355 nm light is chosen to be 92%. We would like to test the amplification of the light in the cavity this summer. The 50 ps light pulses will be sent to the cavity with a 402.5 MHz repetition rate. These tests are aimed at checking if the laser is stable enough to produce the interference between pulses. The mechanical stability and lens position feedback will be tested as well. If the tests are not successful, we move on to testing another light recycling scheme. Figure 3 shows the outline of the cavity with the third harmonic crystal inside.

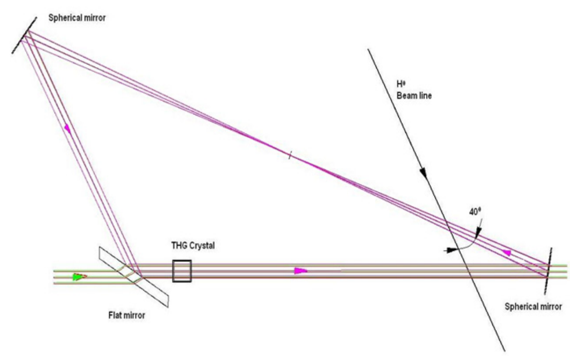

Figure 3: Cavity with the third harmonic crystal.

In this scheme we plan to inject the first and the second harmonic of 1064 nm light through the flat mirror, shown in the left bottom corner, which has to have very low reflectivity for these two harmonics. The crystal converts the light into the third harmonic. All the mirrors should have very high reflectivity for the 355 nm light, so that the laser pulse gets trapped in the cavity. A similar optics but with the second harmonic crystal inside has been tested successfully before [11].

LASER STRIPPING FOR OTHER PROJECTS

Future projects with H^- beams tend to have higher energy than that of the SNS. This is driven by the need to reduce space charge effects at the ring injection energy. We focus on two future projects: the 4 GeV linac for the LHC new booster, and the Fermilab Project X with 8 GeV beams.

Both projects can build the laser stripping device with the existing technology. The reason for this is the following: for the LHC new linac with 4 GeV beam energy, and for Fermilab Project X with 8 GeV, the level n=2 can be excited by most common 1064 nm laser with incident angle equal to 47.5 and 95 degrees, respectively. The magnetic stripping of the n=2 level is described in detail in the first section. The reqiured peak laser power for these projects is also much lower than that needed for the SNS laser stripping. This comes from two facts: higher dipole transition coefficients for n=2 as compared with the n=3 level, and relativistic amplification of the laser power in the rest frame of the hydrogen beam. A 1 MW peak power beam could do the excitation even without the dispersion derivative introduction. The levels can be achieved in, e.g., Fabri-Perot cavity with high degree of confidence and the overall average laser power could be reduced to the few-watt level.

ATOM EXCITATION AND WAVE TRAPPING IN DENSE MEDIUM

Usually, the beam density is so small that its influence on the wave is completely neglected. If we consider the case of dense beams (the beam dimensions are large as compared to light reflection length) then the waves can be trapped in the medium. Moreover, the atoms with induced dipole moments start to interact strongly with each other, leading to a possibility of creating some atomic patterns when the medium is relatively cold, therefore the whole phenomenon gets striking similarity with the ball lightning effect. The wave trapping and the induced dipole interactions are described in [12].

CONCLUSION

After experimental demonstration of high efficiency laser stripping the study has been done to build prototypes of real stripping device. The developments of the prototype, as well as possible solutions for projects other than the SNS are described.

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