FUTURE PROSPECTS FOR LASER STRIPPING INJECTION IN HIGH INTENSITY MACHINES *

V. Danilov#, ORNL, Oak Ridge, TN U.S.A.

Abstract

With the increase of average power of present and future high intensity proton rings and rapid progress of laser technology, laser-assisted stripping become a real alternative for carbon foils that are used for charge-exchange injection. High efficiency laser stripping, achieved experimentally at Spallation Neutron Source in Oak Ridge, TN, paved the way to full scale devices of such type. This paper presents overview of machines and choices of parameters for future powerful accelerators with possible laser stripping use.

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 higher energies.

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:

$$\omega_0 = \gamma(1+\beta\cos\alpha)\omega\,, \tag{1}$$

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:

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

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 frequency difference at zero time, $\Gamma=d\omega_0/dt$ is the frequency sweep rate, $\mu_{1n}=\mu_{n1}^*=-\int d^3r\, u_1^*(\vec{r})ezu_n(\vec{r})$

---

*Research sponsored by Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy under Contract No. DE-AC05-00OR22725.

#danilovs@ornl.gov

(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 $\beta \sim 1$:

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

where $\delta \ll 1$ 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 $\delta \approx 0.1$ or 90% of stripping), $\beta \approx 0.875$, $\alpha \approx 40°$, $\kappa \approx 3\cdot 10^{-3}\omega_0$, $\omega_0 \approx 1.84\cdot 10^{16}\,Hz$, $h \approx 1mm$, $n=3$, and $\mu_{13} = -\int d^3r\, u_1^*(\vec{r})ezu_3(\vec{r}) = \frac{3^3 ea_0}{2^6\sqrt{2}} \approx 0.298ea_0$ 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:

$$\mu_{12} = -\int d^3r\, u_1^*(\vec{r})ezu_2(\vec{r}) = \frac{2^7 ea_0}{3^5\sqrt{2}} \approx 0.372ea_0,$$

$$\mu_{14} = -\int d^3r\, u_1^*(\vec{r})ezu_4(\vec{r}) = \frac{2^{11} ea_0}{5^6\sqrt{5}} \approx 0.176ea_0.$$

Now we briefly describe what determines the 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. At the same time, the probability of the upper state excitation decreases with the increase of the upper level main quantum number (see the dipole transition coefficients above). The optimum for medium energy beams range from n=2 to n=4. We describe the particular optimal choice for the SNS and future accelerators in the last section.

STATUS OF LASER STRIPPING PROJECT AT SNS

We briefly describe the first developments of laser stripping at SNS. Some of the ideas can be useful in application to the future projects laser stripping.

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 [8]. 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 1 shows the Fabri-Perot cavity ordered for tests.

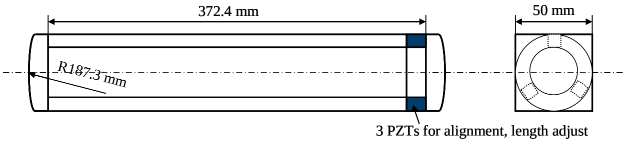

Figure 1: Drawing of Fabri-Perot cavity for the SNS laser stripping intermediate experiment.

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 2 shows the outline of the cavity with the third harmonic crystal inside.

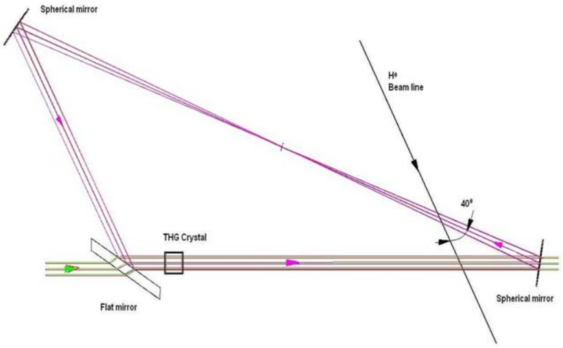

Figure 2: Cavity with the third harmonic crystal.

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 [9].

LASER STRIPPING FOR FUTURE 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 beam.

Upper Level Choice for Future Projects

Fortunately, the two mentioned above future projects have energy above 3.23 GeV – this is the minimal energy when the most convenient 1064 nm light can reach the n=2 level of hydrogen in head-on collision. For 4 GeV beam the incident angle has to be 47.5 degrees for this upper level; for n=3 state the angle is about 9 degrees. This small angle can pose difficulties in building Fabri-Perot cavity, but we still may consider this option. The other states are not accessible by 1064 nm light at 4 GeV energy. At Project X 8 GeV energy n=2 and n=3 states don't have much difference. The accident angles are 95 and 85 degrees, respectively. Even though the n=3 level requires 50% more laser power for the same stripping efficiency, it can be the choice if one wants to use weaker magnets for second electron stripping.

Project X team may want to consider using lasers with the 2 μm wavelength. There is a 4-fold laser power decrease for the same stripping efficiency due to geometrical factors – the incident angle for n=2 becomes 43 degrees. But the lasers at this wavelength may not be as powerful and developed as for the 1064 nm. This topic requires a further analysis and is omitted below – we cover only 1064 nm wavelength light.

Laser Peak Power for High Efficiency Stripping

Looking at formulas (4), one can see that the laser power needed for stripping goes down with energy, with dipole coefficients increase and the decrease of the vertical size. For the SNS POP experiment parameters high efficiency stripping was achievable at 10 MW level. That is why we are going to introduce the dispersion derivative at IP (see previous section) to reduce the needed peak power to 1 MW level. Dispersion derivative introduction is more difficult choice for both Project X and the new LHC linac because their transfer lines don't plan to have the strong bending magnets. But taking into account higher energies, larger dipole transition coefficients, and possible vertical size reduction to, e.g., 0.3 mm size and below, the peak power for high efficiency (above 95%) stripping drops below 1 MW.

Figure 3 shows the excitation probability for n=2 level as a function of time for the 1064 nm light and 4 GeV H^- beam. Three lines correspond to a reference particle (red line), a particle with 1 rms energy offset (the rms energy spread is taken to be $0.6*10^{-3}$ that corresponds to a typical SNS beam spread) (blue line), and a particle with three rms energy offset (green line). The rest of parameters of the Gaussian laser beam are: its peak power is 0.5 MW, the Rayleigh range is 4.6 mm, the waist at IP is 0.6 mm, and the distance of IP from the laser beam waist is 7 cm. The beam is very diverging for two reasons: the first is to have spread of frequencies to cover the Doppler width of the 2nd level; the second is to have large size of the beam at the laser window to avoid its damage by the laser.

One can see that even for 3 rms energy deviation, the excitation probability is above 95%. The overall efficiency is close to 100%, but we have to point out that the vertical rms size as to be smaller than 0.3 mm, and the linac beam halo is negligible in the estimate. The stripping inefficiency in this case will be determined by how close is the magnetic field to the IP (we cover this topic below where we discuss the general IP configuration).

Reducing the Average Laser Power

Even though the needed laser peak power is moderate, it is very hard to extend it to 1 ms pulse width to strip the entire linac beam. Here we propose to use Fabri-Perot cavity to amplify the laser pulse to a MW peak power levels. The infrared diapason is the best for this option. The mirrors with 99.99% reflection are common for this range. If one gets coefficient Q_c=1000 of peak power amplification in the Fabri-Perot cavity, and uses mode-locked laser with linac beam repetition rate of LHC linac that is 352 MHz, the average power P_{av} of the laser for the new LHC linac becomes

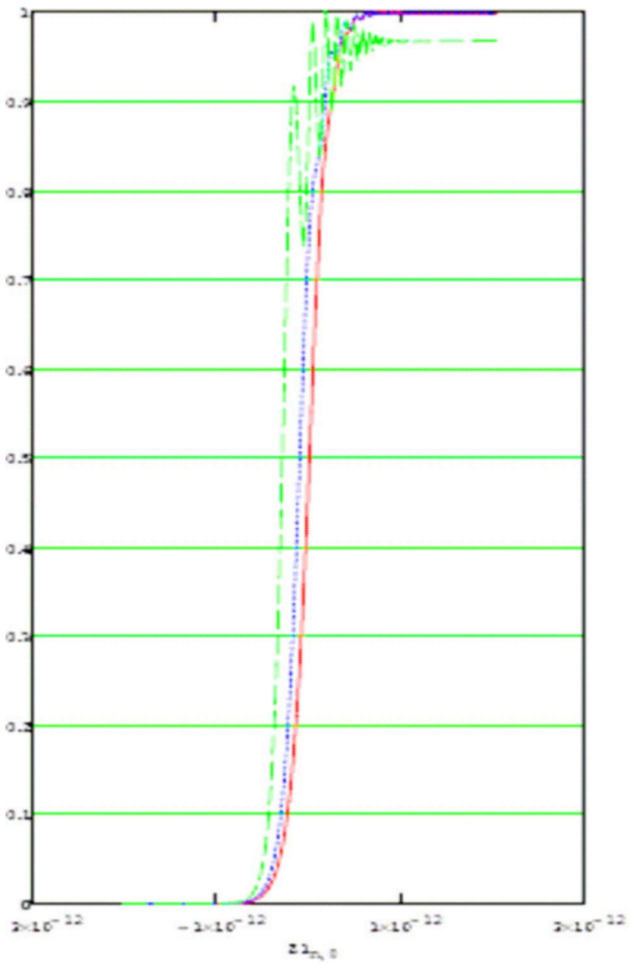

Figure 3: Excitation of n=2 level as a function of time for 4 GeV beam for 3 various particle energy.

$$P_{av}=2Hz*50ps*352MHz*0.6ms*0.5MW/Q_c\approx 0.01W,$$

where we assumed 2 Hz repetition rate for the new LHC booster, 50 ps linac bunch duration, and one pulse duration of 0.6 ms.

Choice of the Laser

In light of this low numbers for the average laser power, one can consider not using mode-locked lasers, but CW laser that work only when the linac bunch train is coming to the ring (in other words, having its duty factor equal to that of the accelerator facility). In this case the average power will grow by factor 60, and there is a serious problem related to whether the Fabri-Perot cavity can withstand this power during 1 ms pulse. The cavity has to have amplification of 1000 in order to use available kilowatt CW infrared lasers (the list of the powerful solid-state fiber laser can be found in [10]). In any case, the parameters of the laser light should be achieved in a long pulse (600 μs for the LHC linac, and 1 ms for the Project X) – this is an area of future R&D laser stripping projects.

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 the LHC power upgrade linac and for the Project X (even though n=3 level is also an attractive option).

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 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., [11]):

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

if the laser is perpendicular to the magnetic field that is the same as being parallel to the rest frame electric field.

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

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

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

Figure 4 shows how the lifetime of the *n*=2 states depends on the magnetic field for LHC Power Upgrade case (the data for the upper states lifetime is taken from [12]). 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.

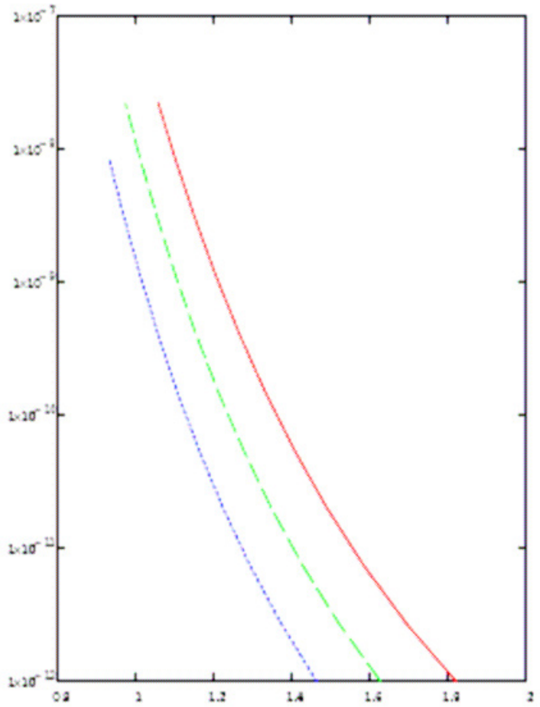

Figure 4 Lifetime of the three n=2 eigenstates as a function of magnetic field (in Tesla) for 4 GeV neutral hydrogen atom. The blue dotted line corresponds to *n1*=0, *n2*=1, *m*=0, the green dashed line – to *n1*=0, *n2*=0, *m*=1, and the solid red line – to *n1*=1, *n2*=0, *m*=0.

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]. There exists possibility to use I. Yamane method [6] that utilizes the Stark broadening as opposed to the laser light frequency sweeping, but it is not demonstrated yet – for the n=2 level there should be not much difference in required laser power [7], but the choice of the other laser parameters might be different from the one in our case.

For n=3 level the situation is more involved. The laser power for the excitation is higher due to reduction of the dipole transition coefficients. It can be partially compensated by the decrease of the incident angle. But special precautions have to be taken to avoid a large broadening of the levels by magnetic field. In addition to broadening, the levels split and shifted. Therefore the resonant frequency may miss the levels and the excitations may disappear. This topic is a matter of optimization and development at SNS and will be covered in the next papers on the laser stripping method.

Injection Region Requirements for Laser Stripping

There are a few special requirements, imposed by this method of laser stripping on the configuration of magnets and values of beta functions at the laser stripping point.

First, the laser stripping point has to be as close as possible to the second magnet for the second electron stripping. This requirement comes from the need to avoid undesired decay of the excited state into the lower states that leads to a stripping efficiency decrease. For example, each centimetre of the distance between strong stripping field (for 4 GeV it is around 1.5 T) and the Interaction Point leads to 0.4 % loss of efficiency for the n=2 state at 4 GeV.

The second important requirement comes from emittance increase due to the second electron stripping (here we assume the first electron stripping emittance increase is much smaller). For the state (6) the angular rms spread is 0.07 mrad. If one wants to keep the resulting emittance increase much lower than the final ring emittance (for LHC booster the normalized emittance has to be 3 microns [13]), then the beta function in direction of the second magnet bend should be much lower than a certain limit. For estimations we assume the beta derivative is small and the emittance increase is given by $0.07*10^{-3}*\beta$. This has to be much lower than the booster emittance $0.07\cdot 10^{-3}\beta << 3\cdot 10^{-6}/\gamma$ that results in $\beta << 120\,m$.

There exist one interesting opportunity with the laser stripping injection – one can arrange the first, the second stripping magnets, and the beta functions such that the resulting emittance is the same as the required ring emittance. It would mean that the injection painting is unnecessary in this case – the painting will be done automatically by stripping magnets. This topic requires more studies and is a subject of future work.

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 future projects are discussed.

ACKNOWLEDGMENTS

This work is done by many people from various labs. The author thanks the SNS laser stripping team and numerous colleagues from the other labs for participation in laser stripping development.

REFERENCES

[1] V. Danilov, A. Aleksandrov, S. Assadi, J. Barhen, W. Blokland, Y. Braiman, D. Brown, C. Deibele, W. Grice, S. Henderson, J. Holmes, Y. Liu, A. Shishlo, A. Webster, and I. N. Nesterenko, “Proof-of-principle demonstration of high efficiency laser-assisted H$^-$ beam conversion to protons”, PRSTAB **10**, 5 (2007) 053501.
[2] M. Froissart and R. Stora, Nucl. Instrum. Methods Phys. Res., **7**, 297-305 (1960).
[3] R. Boyd, “Nonlinear Optics”, Academic Press Inc. (1992) p. 214.
[4] V. Danilov *et al*, SNS TechNote 3, April, 2002, V. Danilov *et al*, Phys. Rev. ST Accel. Beams 6, 053501 (2003).
[5] U. Gastaldi, ICFA-HB2002, AIP Conference Proc. 642, Batavia, Il (2002) p.337.
[6] I. Yamane *et. al.*, KEK Preprint 2002-76 (2002).
[7] V. Danilov, A. Aleksandrov, S. Assadi, J. Barhen, Y. Braiman, W. Grice, A. Shishlo, S. Henderson, B. Lang, Y. Liu, G. Murdoch, K. Potter, D. Berkaev, V. Kobets, I. Koop, V. Kuz’minykh, Yu. Shatunov, D. Shwartz, 33 ICFA Workshop on High Intensity Hadron Beams, Bensheim, Germany, October 2004.
[8] V. Danilov *et al*, “Laser Stripping of H- beams: Theory and Experiments”, PAC 2007, Albuquerque, NM (2007) A. Aleksandrov *et al*, SNS TechNote 176, May, 2007.
[9] I. Jovanovich *et al*, “High-energy Picosecond Laser Pulse Recirculation for Compton Scattering”, PAC 2007, Albuquerque, NM (2007).
[10] http://www.ipgphotonics.com/products_1micron.htm
[11] H. Bethe and E. Salpeter, “Quantum Mechanics of One- and Two-electron Atoms”, Springer-Verlag (1957) p. 29.
[12] R. J. Damburg and V. V. Kolosov, “Theoretical Studies of Hydrogen Atoms in Electric Fields”, in “Rydberg States of Atoms and Molecules”, R. F. Stebbings, F. B. Dunning, Cambridge University Press, 1983, pp. 31-71.
[13] R. Garoby, M. Benedikt, A. Fabich, F. Gerigk, “Comparison of Options for the Injector of PS2”, CARE-Note-2007-008-HHH, CERN, CH.