ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLH10

EFFICIENCY ESTIMATION FOR SEQUENTIAL EXCITATION LASER STRIPPING OF H^- BEAM*

T.V. Gorlov, A.V. Aleksandrov, S.M. Cousineau, Y. Liu, A. Rakhman
Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

A new laser stripping scheme for charge exchange injection of H^- beams is considered. The sequential scheme for the planned demonstration experiment includes a two-step excitation that requires much smaller laser power compared to the traditional one-step excitation. The new scheme can be applied to a wider range of H^- beam energies and provides more flexibility on the choice of laser frequency. In this paper we discuss the two-step excitation method and estimate laser stripping parameters and stripping efficiency for the SNS accelerator and for its future H^- energy upgrade to 1.3 GeV.

INTRODUCTION

In this paper we develop laser stripping technology and propose a new laser stripping scheme that would allow the reduction of laser power needed for high efficiency stripping. The standard laser stripping scheme proposed in [1] consists of a three step process where the first electron is Lorentz stripped in a magnetic field (H^- to H^0), the second electron is then excited by a laser from the n=1 to n=3 quantum state, and finally the excited electron is Lorentz stripped by a second identical magnet into protons. The second step excitation is accomplished by a UV laser with 355nm wavelength [1]. A minimum excitation level of n=3 (3p state) is needed for Lorentz stripping of a 1 GeV beam because the electron is strongly bound to the atom in the lower states and cannot be Lorentz stripped by a conventional ≤2T magnet. Thus, for the proof of principle and the proof of practicality experiments at the SNS [2, 3, 4], a 3rd harmonic UV laser with 355 nm wavelength was used for single step excitation (1s→3p) of the 1 GeV H^0 beam. From the standpoint of laser technology, due to nonlinear frequency conversion process, the 3rd harmonic UV laser is often less powerful as compared to 2nd harmonic 532nm laser or to a fundamental 1064 nm laser, and it needs to be enhanced by an optical cavity. In this paper we propose to use sequential excitation to excite the H^0 atom from the ground 1st state to the 2nd state (1s→2p), followed by excitation from the 2nd to the 3rd state (2p →3d) using the same recycled laser (see Fig. 1).

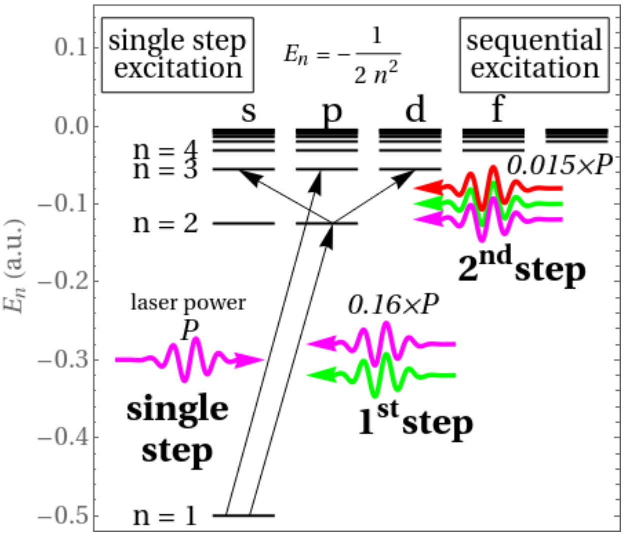

Figure 1: Sequential excitation vs. single step excitation of a hydrogen atom for H^- beam energies below 2 GeV.

As shown in Fig. 1, The sequential scheme allows a wide choice of laser wavelength and requires smaller laser power for excitation compared to the single step excitation. The 1st and the 3rd laser stripping steps of Lorentz stripping in a magnetic field stay the same. The proposed scheme has the following advantages:

- Each step of the sequential excitation 1s→2p and 2p→3d requires smaller laser power due to stronger quantum electric dipole transition of the H atom compared with the single step 1s→3p.
- Alternative laser wavelengths, such as the 2nd harmonic 515nm or 532nm green lasers, are possible. Compared to UV laser, these wavelengths are easier to generate and recycle in a power enhancement optical cavity. The available power is ~5 times higher.

For this reason, for the same excitation efficiency, the sequential excitation scheme with two smaller excitation steps requires roughly 6 times less laser power than the single excitation scheme. This savings can be used to improve the laser system using a low power laser to achieve the same stripping efficiency, or to use the laser power with an optical cavity for stripping H^- beams with larger emittance or energy spread. Also, the sequential scheme gives more flexibility for beam energy by choosing different sequential levels that can be useful for similar projects [5]. In this paper the sequential excitation scheme for SNS beam with 1.0GeV and 1.3 GeV will be estimated. The preliminary design of an experimental implementation of the scheme, utilizing the UV laser configuration already in place at the SNS is also discussed.

---

*This work has been supported by Oak Ridge National Laboratory, managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLH10

CONCEPT OF SEQUENTIAL RESONANT EXCITATION

According to quantum mechanical theory, the different energy levels of an atomic unperturbed hydrogen atom in vacuum are defined by the relation: $E_n=-1/(2n^2)$ (a.u.), where n is the principal quantum number, and n=1 is the ground state. During excitation the atom can be excited from the ground state with $\{n, l, m\}=\{1,0,0\}$ to some upper state with $\Delta l=\pm1$. The first step in the sequential excitation is from the ground state to the 2p state with $\{n, l, m\}=\{2,1,0\}$. Because the excitation efficiency depends on the product of the electric field component of the laser E and the atomic dipole transition μ as Efficiency=f(Eμ) we can calculate the relative laser power $P\sim E^2$ needed for excitation of different atomic levels. Dipole moments of the first 1s→2p and the second 2p→3d sequential transitions equal $\mu_{12}=(128\sqrt{2})/243$ (a.u.), and $\mu_{23}=(110592\sqrt{2})/78125$ (a.u.) respectively. The dipole moment of the single excitation step 1s→3p equals $\mu_{13}=27/(64\sqrt{2})$ (a.u.). Using these, we can estimate that the power required for the sequential step $P_{1s\rightarrow2p}$ is about 6 times smaller than that required for the single step excitation $P_{1s\rightarrow3p}$:

$$\frac{p_{1s\rightarrow3p}}{p_{1s\rightarrow2p}}=\frac{\mu_{12}^2}{\mu_{13}^2}\approx6.236 \tag{1}$$

The sequential scheme of excitation requires much less power according to the fundamental atomic properties of hydrogen.

SEQUENTIAL EXCITATION SCHEME FOR 1.3 GEV H$^-$ BEAM USING GREEN LASER

In the Proton Power Upgrade (PPU) project at SNS, the H$^-$ beam energy will be increased from the current 1GeV to 1.3GeV as a part of the SNS accelerator complex upgrade to double the proton beam power from the current 1.4MW to 2.8MW. Laser stripping of a 1.3GeV hydrogen beam provides an ideal case for application of the sequential excitation scheme. To excite the hydrogen atoms at this energy, the required laser wavelength in the single-step excitation scheme needs to be in the UV regime, while that in the sequential excitation scheme is in the green wavelength regime. This section provides an analysis of parameters for such a scheme for the SNS 1.3 GeV scenario.

We can calculate that for 1.3GeV energy the 1st and the 2nd step excitation by a green laser with λ=532nm have α_1=22.9 degree and α_2=136.6 degree angles of interaction. Figure 2 shows a schematic of the concept. Here two laser beams of the same wavelength intercept the hydrogen beam at different angles. The laser wavelength can be either 532 nm or 515 nm. It is noted that the two laser beams can be well configured in an optical cavity scheme to recycle the laser power. Using our double-resonance optical cavity technology [6], an enhancement factor of 50-100 can be realized, which can further reduce the stripping laser power requirement and make it possible to conceive a fiber-based laser transport line to replace the current free-space transport line.

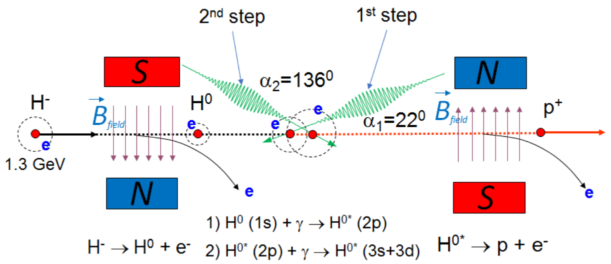

Figure 2: Schematic of sequential laser stripping concept for 1.3 GeV beam and two interceptions with green lasers.

Figure 3 shows simulations of laser stripping for the SNS beam and compares the single step excitation and the sequential excitation methods for various ion beam energies. The laser stripping efficiency in the sequential excitation scheme is primarily defined by the excitation efficiency of the larger 1st step 1s→2p, thus for simplicity simulations are shown only for this step. The simulation utilizes the laser stripping model incorporated into the pyORBIT simulation code [7] and is based on the H^0 beam parameters from the last SNS experiment [3, 4]. Figure 3 indicates that for the same excitation efficiency the sequential scheme needs only about 0.16 laser peak power from that is required for the 1s→3p excitation which agrees with the above estimations.

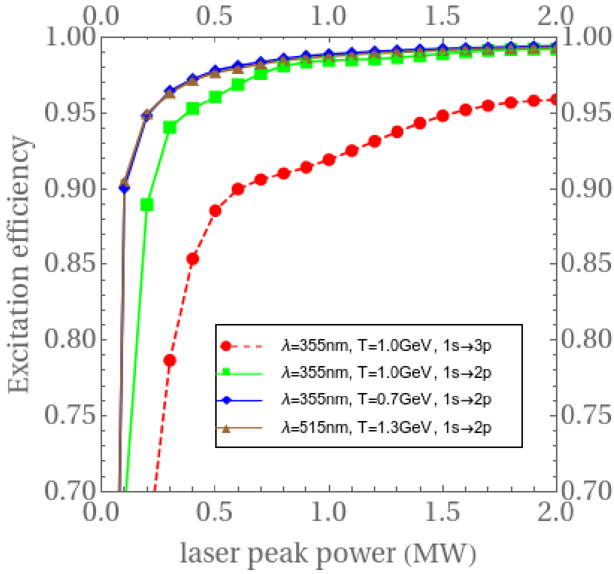

Figure 3: Schematic of sequential laser stripping concept for 1.3GeV beam and two interceptions with green lasers.

PLAN FOR EXPERIMENTAL VALIDATION OF CONCEPT AT SNS

The sequential excitation scheme promises significant advantages in practical implementation of laser assisted charge exchange: greatly reduced average laser power, and simpler stripping mag-net design. However, it requires a more complex optical arrangement with independent alignment of two laser beams. A tool for measuring the efficiency of the excitation from the ground state to the n=2 level needs to be developed to optimize the intermediate step, which takes place for zero hydrogen atom charge and, therefore, is blind to all charge sensitive diagnostics. A series of experiments using the existing UV-based laser stripping equipment in the SNS linac is planned to prove feasibility of the proposed scheme.

Experiment 1

As a first step, diagnostics will be developed to validate the high efficiency of the n=2 excitation. The existing SNS laser stripping experimental apparatus has a fixed laser-to-ion beam angle of 37.5 degrees, optimized for n=3 excitation of a 980MeV ion beam using a 355nm laser wavelength as shown in Fig. 4.

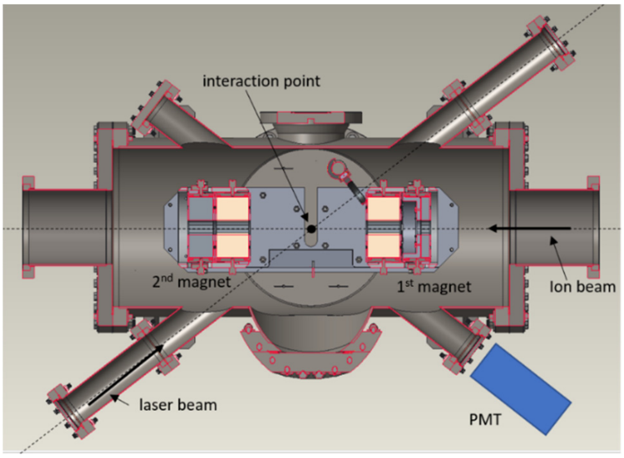

Figure 4: Layout of the experimental vacuum chamber for the ground level to n=2 level excitation efficiency measurement. The PMT for detecting the fluorescence photons is at the bottom right corner.

Note that one step excitation λ = 355nm; T~1.0 GeV, 1s→3p) and the sequential scheme λ = 355nm; T~0.7 GeV, 1s→2p) have the same H^0 beam parameters and angle of interaction. Thus, ion beam energy can be easily changed to 720MeV and the existing experimental vessel can be used. The first stripping magnet, which is a fixed field permanent magnet, has enough magnetic field strength to strip the first electron with 100% efficiency at 720MeV. The second magnet is too weak to strip the electron from the n=2 level, and therefore a luminescence detection diagnostic will be added to measure efficiency of the excitation process. The excited electron has a finite lifetime in the n=2 state and will fall back to the ground state emitting a photon with 121nm wavelength in the ion rest frame of reference. In the laboratory frame of reference, the excited level lifetime corresponds to a few millimeters of distance traveled by the ion after interacting with the laser beam. The number of the emitted photons is equal to the number of the excited ions; therefore, it is a direct measure of the excitation efficiency. It is convenient to collect the photons at 142.5 degrees angle: first, there is an unused port in the vacuum chamber; second, the wavelength is 200nm, which passes easily through a fused silica glass and, at the same time is well separated from the 355nm to avoid picking up signal from the laser pulse. A Hamamatsu R6834 Photo-Multiplier Tube (PMT) is a good detector option because it has good sensitivity at 200nm wavelength and is insensitive to 355nm light. The PMT current can be estimated as

$$I_pMT = I_bkfgd^2/(16\pi D^2), \qquad (2)$$

where I_b is the ion beam current; k is the efficiency of excitation from the ground level to the n=2 level; f is the fraction of photons per radian at the detection angle; d is the PMT photocathode diameter and D is the distance from the interaction point to the PMT photocatode. With the proposed experimental parameters Ib=10mA, f=0.15, g=105, d=25mm, D=430mm, the range for the PMT current is 0.01-1A when the excitation efficiency varies from 0.1% to 100%. This is the optimal operating point for the R6834 PMT.

Experiment 2

Three mirrors will be added in the vacuum vessel to provide two laser beams with 355nm wavelength to intercept the ion beam at the angles optimized for exciting electrons in the 1GeV ions from the ground level to the level n=2 first, and then, immediately, from the level n=2 to the level n=3. The electrons at the energy level n=3 will be stripped in the magnetic field of the second magnet. The two laser beams will have independent controls for the angle and position for precise alignment with the ion beam. The fluorescent light detection system described above will be used to tune the first laser for the highest excitation efficiency. The second laser beam will be tuned to achieve the maximum proton current after the second magnet.

ACKNOWLEDGEMENTS

This work has been supported by Oak Ridge National Laboratory, managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy.

REFERENCES

[1] V. Danilov *et al.*, "Three-step H- charge exchange injection with a narrow-band laser," *Phys. Rev. ST Accel. Beams.*, vol. 6, p. 053501, May 2003. doi:10.1103/PhysRevSTAB.6.053501

[2] V. Danilov *et al.*, "Proof-of-principle demonstration of high efficiency laser-assisted H- beam conversion to protons," *Phys. Rev. Accel. Beams*, vol. 10, p. 053501, May 2007. doi:10.1103/PhysRevSTAB.10.053501

[3] S. Cousineau *et al.*, "First demonstration of laser-assisted charge exchange for microsecond duration H- beams," *Phys. Rev. Lett.*, vol. 118, p. 074801, Feb. 2017. doi:10.1103/PhysRevLett.118.074801

[4] S. Cousineau *et al.*, "High efficiency laser-assisted H- charge exchange for microsecond duration beams," *Phys Rev. Accel. Beams*, vol. 20, p. 120402, Dec. 2017. doi:10.1103/PhysRevAccelBeams.20.120402

[5] P. K. Saha, H. Harada, S. Kato, M. Kinsho, Y. Irie, and I. Yamane, "An Experimental Plan for 400 MeV H- Stripping to Proton by Using Only Lasers in the J-PARC RCS", in *Proc. HB'16*, Malmö, Sweden, Jul. 2016, pp. 310-314. doi:10.18429/JACoW-HB2016-TUPM7X01

[6] A. Rakhman, M. Notcutt, and Y. Liu, “Power enhancement of burst-mode ultraviolet pulses using a doubly resonant optical cavity”, *Opt. Lett.*, vol. 40, no. 23, pp. 5562-5565, 2015. `doi:10.1364/OL.40.005562`

[7] T. V. Gorlov and A. P. Shishlo, “Modeling Laser Stripping with the Python ORBIT Code”, in *Proc. 10th Int. Computational Accelerator Physics Conf. (ICAP'09)*, San Francisco, CA, USA, Aug.-Sep. 2009, paper TH3IOPK03, pp. 184-189.