# Sequential excitation scheme for laser stripping for a $H^-$ beam

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A new scheme with sequential resonant excitation for laser assisted charge exchange injection of $H^-$ beams is proposed. In contrast with the one step excitation scheme, the proposed scheme requires significantly less laser power for high efficiency stripping. It also provides greater flexibility in the choice of laser wavelength for a given beam energy and extends the range of energies where laser stripping can be effectively applied. Calculations and experimental plans for 1.0 GeV and 1.3 GeV $H^-$ beams at the Spallation Neutron Source are presented. Results indicate that the sequential excitation scheme allows the use of more convenient green laser with much smaller power in place of the UV laser previously used.

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## I. INTRODUCTION

The laser assisted charge exchange method is being developed as an alternative option to the foil-based scheme, which suffers from limiting complications associated with foil lifetime and induced residual radiation from particle scattering in the foil [1]. The theoretical basis for laser assisted charge exchange, a.k.a. laser stripping, was introduced in [2], and further refined in subsequent works to overcome limitations caused by the inherent energy spread in the beam. The experimental evolution of the concept began in 2006 at the Spallation Neutron Source accelerator with a proof of principle demonstration [3] followed by a proof of practicality demonstration [4,5], both resulting in stripping efficiencies > 90%. Other similar approaches to laser stripping are also under development [6], but have not yet reached the experimental phase. To date, the largest challenge with the laser stripping method is the high average laser power required for full duty cycle applications. While the most recent set of experiments has partially addressed this challenge for the existing scheme, a significant gap remains between the required laser power and the commercially available laser technology.

The laser assisted charge exchange scheme developed for stripping 1 GeV $H^-$ beams at the Spallation Neutron Source accelerator (SNS) consists of a three step process whereby the first electron is Lorentz stripped in a magnet field ($H^-$ to $H^0$), the second electron is then excited by a laser from the $n = 1$ to $n = 3$ quantum state [$H^0(1s) + \gamma(UV) \rightarrow H^{0*}(3p)$], and finally the excited electron is Lorentz stripped by the second identical magnet ($H^{0*}$ to protons). The second step excitation is accomplished by a UV laser with 355 nm wavelength [2]. The Lorentz stripping of $H^-$ and $H^{0*}(3p)$ in the magnetic field is simple compared to the 2nd excitation step. The laser wavelength $\lambda_l$ (in the laboratory rest frame) needed for $H^0$ excitation is related to the excitation wavelength (or the wavelength in the $H^0$ rest frame) $\lambda_{1\rightarrow3}$ between $n = 1$ and $n = 3$ states:

$$\lambda_l = \lambda_{1\rightarrow3}\gamma[1 + \beta\cos(\alpha)] \tag{1}$$

where $\beta$,$\gamma$ are relativistic parameters depending on the beam energy and $\alpha$ is the laser-particle interaction angle. A minimum level of excited state 3p with $n = 3$ is needed for Lorentz stripping of a 1 GeV beam because the electron is strongly bound to the atom in the lower excited state and cannot be Lorentz stripped by a conventional $\leq 2$ T magnet. Thus, for the proof of principle and the proof of practicality experiments at the SNS [3–5], 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 532 nm laser or a fundamental 1064 nm laser and 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).

The 1st and the 3rd laser stripping steps of Lorentz stripping in a magnetic field stay the same. The proposed

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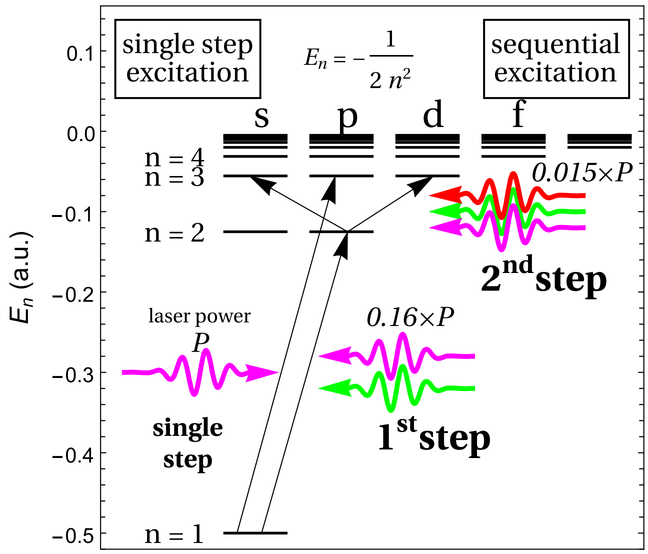


FIG. 1. Sequential excitation vs single step excitation of hydrogen atom for $H^-$ beam energies below 2 GeV. The sequential scheme represents wide choice of different laser wavelength and smaller relative laser power needed for excitation compared to the single step excitation.

scheme has the following advantages: (1) Each step of the sequential excitation 1s → 2p and 2p → 3d requires smaller laser power due to stronger quantum electric transition dipole of the H atom compared with the single step 1s → 3p. (2) Alternative laser wavelengths, such as the 2nd harmonic 515 nm or 532 nm 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. In total, (1) and (2) result in approximately an order of magnitude in laser power savings by using the double excitation scheme. This savings can be used to simplify 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. In this paper the sequential excitation scheme for the SNS beam with 1.0 GeV 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.

## II. CHALLENGES OF LASER STRIPPING BELOW 2 GEV

There are a number of technical issues to be considered when choosing parameters for practical implementation of the three step laser assisted charge exchange injection: (1) *First stripping magnet*. Lorentz stripping of the first electron requires sufficiently strong magnetic field. The required magnetic field strength depends exponentially on the energy of the ions [2]. As the magnets need to be very compact to be incorporated into an injection region, the most feasible approach is to use normal conducting EM or PM magnet technology. In this case the maximum magnetic field is limited to 2T, limiting the minimum possible ion beam energy to 400 MeV. (2) *Laser parameters and excited ion energy level*. The laser beam required for efficient stripping needs to have temporal structure close to the ion beam in the rf linac: a stream of picosecond pulses at hundreds of MHz frequency with tens of $\mu$J per pulse. The best laser technology with the required parameters readily available today is the Nd:YAG mode-locked laser, with fundamental operating wavelength of 1064 nm. Shorter wavelengths can be obtained through harmonic generation at wavelengths of 532, 355, and 266 nm. However, the available laser power drops dramatically as the wavelength gets shorter. As laser power is the primary challenge for $H^-$ laser assisted charge exchange [2], it is therefore, advantageous to use as long a wavelength as possible. The exact wavelength corresponding to the excitation energy in the moving hydrogen atom frame of reference can be adjusted by proper selection of the laser beam incidence angle $\alpha$, according to Eq. (1). However, there is a maximum cutoff wavelength corresponding to head on collision, which depends on the moving hydrogen atom energy. The required wavelength also depends on the energy difference between the ground level $n = 1$ and the desired excited level $n = 2$, 3, 4 or higher. In general, the excitation efficiency is higher for smaller energy difference between the levels. (3) *Second stripping magnet*. Lorentz stripping of the second electron can require even higher magnetic field than the first depending on the binding energy. The binding energy depends on the energy level of the excited electron. It is largest for $n = 2$ and reduces as $1/n^2$ for higher levels. In addition, the second magnet needs to be compact and have an open structure, such as a c-magnet to accommodate passage of the circulating beam.

Figures 2–4 illustrate the boundaries of the range of parameters defined by the factors discussed above for each of the $n = 2$, 3, and 4 excited energy levels. The lower bound on the ion beam energy for the first electron Lorentz stripping is shown by the vertical dashed line at 400 MeV. This limit does not depend on the selected excitation level. The vertical solid line shows the lower bound on the ion beam energy due to the requirements for Lorentz stripping of the second electron, which does depend on the selection of the excitation level (a 1.5T magnetic field and 5 mm stripping length were assumed for this calculation). The colored curves show the required interaction angle of the laser with the ion beam versus the ion energy for various wavelengths of a Nd:YAG laser harmonics: red −1063 nm, green −532 nm, blue −355 nm, and magenta −266 nm.

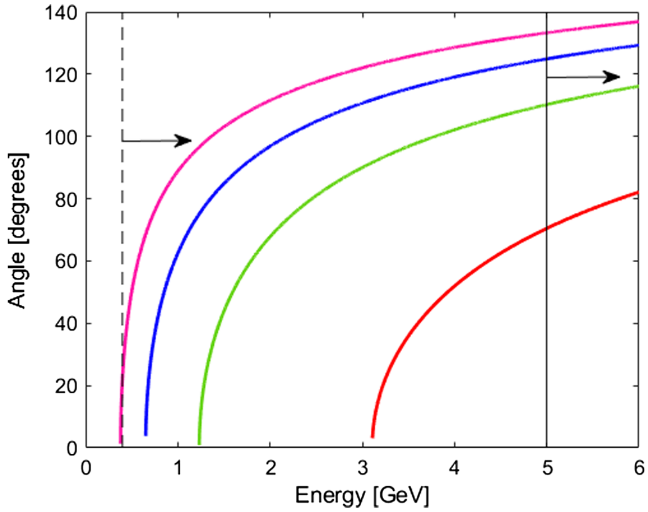


FIG. 2. The range of the beam energy and interaction angle required for 1-step excitation to the $n = 2$ level. The dashed vertical line indicates the energy threshold for the first electron Lorentz stripping. The solid vertical line indicates the energy threshold for the second electron Lorentz stripping. The colored curves show the required laser-to-ion angle vs the ion energy for the first four harmonics of a Nd:YAG laser: red −1063 nm, green −532 nm, blue −355 nm, magenta −266 nm.

As Fig. 2 demonstrates, the $n = 2$ level is very attractive choice because it allows the lowest injection energy for a given laser wavelength. For example, 533 nm harmonic (green) can be used at the SNS Proton Power Upgrade (PPU) [7] injection energy of 1.3 GeV. Unfortunately, the threshold for the Lorentz stripping in the second magnet of the $n = 2$ electron of ∼5 GeV is much higher than the linac energy, as indicated by the solid line. Excitation to the $n = 3$ level reduces the required energy threshold for the Lorentz stripping in the second magnet from (5 GeV to

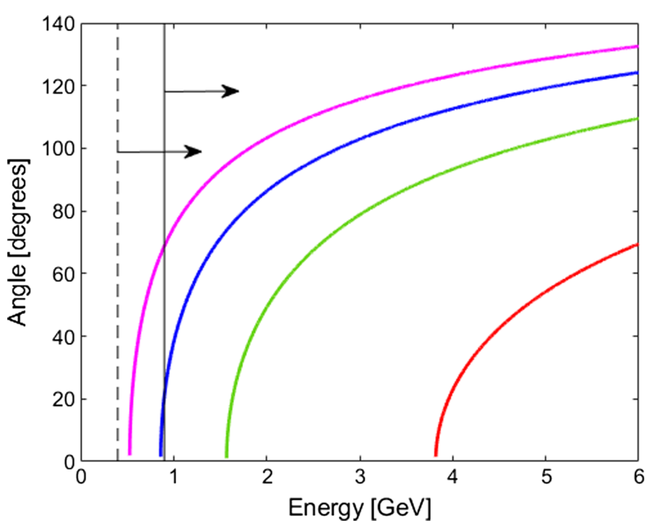


FIG. 3. The beam energy and laser wavelength required for 1-step excitation to the $n = 3$ level. Lines and color scheme is the same as in Fig. 2.

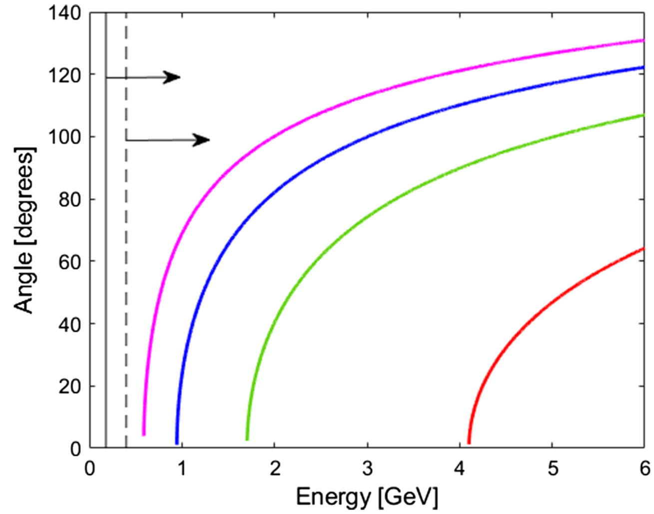


FIG. 4. The beam energy and laser wavelength required for 1-step excitation to the $n = 4$ level. Lines and color scheme are the same as in Fig. 2.

∼1 GeV), as can be seen by comparing Fig. 2 with Fig. 3. This brings all the required parameters to just within reach for the SNS linac operating at 1 GeV with 355 nm laser wavelength. Therefore, the $n = 3$ level was chosen for the SNS laser stripping experiments. Figure 4 shows that excitation to $n = 4$ brings the Lorentz stripping in the second magnet threshold to below the 1st electron stripping threshold. Design of the 2nd striping magnet becomes an easy task, but UV light at 266 nm or 355 nm must be used at energies below 2 GeV.

## III. 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 $n = 1$ corresponds to the ground state. Every excited state with $n > 1$ has $n^2$ degenerate levels with different orbital quantum numbers l and magnetic quantum numbers m. During excitation the atom can be excited from the 1st ground state with $\{n, l, m\} = \{1, 0, 0\}$ to some upper state with $n > 1$ and $\Delta l = \pm 1$. The first step in the sequential excitation is from the ground state to the 2p state with $\{n, l, m\} = \{2, 1, 0\}$. Here $m = 0$ corresponds to the state excited by a laser with the electric field polarization along z-axis. A more detailed discussion of the physics of excitation by a laser can be found in [2].

The excitation efficiency depends on the vector product parameter $\mathbf{E}\boldsymbol{\mu}$ like $\mathrm{Eff} = \mathrm{f}(\mathbf{E}\boldsymbol{\mu})$, where $\mathbf{E}$ is vector of amplitude electric field of the laser and $\boldsymbol{\mu}$ is the electric transition dipole vector. The general form of the transition dipole moment between any two levels in spherical coordinates for $|l_2 - l_1| = 1$ is defined by the following equation:

$$\mu_z\{n_1,l_1,0\to n_2,l_2,0\} = \frac{(1+l_1+l_2)}{(l_1+l_2)(2+l_1+l_2)}\sqrt{(n_1-1-l_1)!(n_2-1-l_2)!(l_1+n_1)!(l_2+n_2)!(1+2l_1)(1+2l_2)} \times \sum_{i=l_2}^{n_2-1}\sum_{j=l_1}^{n_1-1}\frac{(-2)^{i+j+1}(3+i+j)!n_1^{i+2}n_2^{j+2}}{(n_1+n_2)^{i+j+4}(i-l_2)!(j-l_1)!(1+j+l_1)!(1+i+l_2)!(n_1-1-j)!(n_2-1-i)!} \quad (2)$$

Also, the condition $m_1 = m_2 = 0$ shows that excitation between levels is performed by a polarized laser along the z-axis. From this, the transition vector between the 1s-2p levels is $\boldsymbol{\mu}_{1s\to2p} = \{0,0,128\sqrt{2}/243\}$ (a.u.). For a z-axis polarized laser this parameter will be $\mathbf{E}\boldsymbol{\mu} = E_z 128\sqrt{2}/243$. Considering that the electric field component corresponds to laser power like $E_z \sim \sqrt{P}$, the efficiency excitation in the particle's rest frame can be written as $\mathrm{Eff} = \mathrm{f}(\sqrt{P_{12}}128\sqrt{2}/243)$, where $P_{12}$ is the power required for the excitation 1s → 2p. On the other hand, the electric transition dipole excitation 1s → 3p state $\{n,l,m\} = \{3,1,0\}$ equals $\boldsymbol{\mu}_{1s\to3p} = \{0,0,27/(64\sqrt{2})\}$ (a.u.) [2]. By comparing the two cases one can conclude that the laser power required for the same excitation efficiency relate as $\sqrt{P_{12}}128\sqrt{2}/243 = \sqrt{P_{13}}27/(64\sqrt{2})$. Thus in total, the laser power required for excitation of the 2p level is $P_{12} \approx 0.16P_{13}$, or about 6 times smaller than laser power required for the 3p level excitation as its shown in Fig. 1. The electric transition dipole for the second step excitation is $\boldsymbol{\mu}_{2p\to3d} = \{0,0,110592\sqrt{3}/78125\}$ (a.u.) and requires even smaller laser power for excitation, $P_{23} \approx 0.015P_{13}$ (see Fig. 1). In this way, the power required for the efficient sequential excitation is defined by the first step 1s → 2p. It should be noted that the second step will excite both the 2p → 3d and the 2p → 3s levels (see Fig. 1). The dipole moment 2p → 3s is very small $\{0,0,3456\sqrt{6}/15625\}$ and corresponds to about 5% of the total excitation efficiency distribution for both the 3s and 3d levels. For this reason, excitation of the 3s state will be omitted in our calculations.

## IV. 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 energy of 1 GeV to 1.3 GeV as a part of the SNS accelerator complex upgrade to double the proton beam power from the current 1.4 MW to 2.8 MW. Laser stripping of a 1.3 GeV 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 it can be moved up to the green wavelength regime. This section provides an analysis of parameters for such a scheme for the SNS 1.3 GeV scenario.

### A. Analysis and simulation

From Eq. (1), we can calculate that the 1st and the 2nd step excitation by green laser with $\lambda = 532$ nm have $\alpha_1 = 22.90$ and $\alpha_2 = 136.60$ angles of interaction. After the first step excitation, the 2p state atom decays back into 1st state due to spontaneous radiation. The exponential lifetime of the 2p state is 1.6 ns. The $H^{0*}$ beam with 1.3 GeV energy can travel 10.4 mm with 1% decay loss. Consequentially, the sequential point of excitation 2p → 3d must be within this distance in order to avoid loss of laser stripping efficiency. Figure 5 shows an example schematic of the concept.

Table I gives the 1% decay loss of the excited $H^{0*}$ beam in terms of distance for different beam energies and different excited states. Results in the table indicate that the second stripping magnet must be not further than 10–15 mm from the second excitation point to maintain high total laser stripping. For the existing experimental vessel the distance between the second excitation point and the second stripping magnet is about 10 cm corresponding to 3%–4% losses that is acceptable for a proof of principle experiment. The magnetic fields from the first and the second stripping magnet have opposite polarity and therefore the net field is zero in the center between the magnets and remains small in the vicinity of the interaction point. The more detailed study of magnetic field [8] shows that magnetic field below 1 mT is acceptable at the excitation point. Figure 6 shows simulations of laser stripping for the SNS beam and compares the single step excitation and the sequential excitation methods for various ion beam

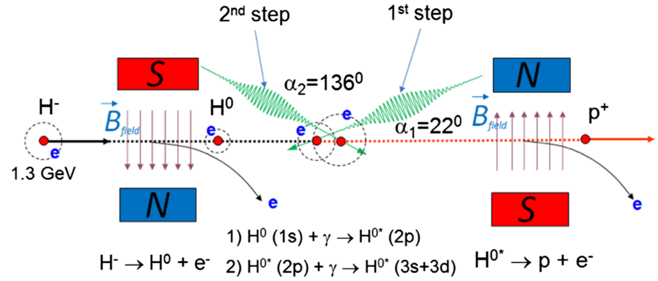


FIG. 5. Schematic of sequential lase stripping concept for 1.3 GeV beam and two interceptions with green lasers.

TABLE I. Decay time/rate for 1% of loss in terms of travel distance for different energies and excited states of $H^{0*}$ beam.

| Beam Energy | 2p → 1s | 3p → 1s | 3p → 2s | 3s → 2p | 3d → 2p |
|---|---|---|---|---|---|
| 0.7 GeV | 6.8 mm | 25.7 mm | 192.0 mm | 204.0 mm | 10.0 mm |
| 1.0 GeV | 8.6 mm | 32.5 mm | 242.0 mm | 258.0 mm | 12.6 mm |
| 1.3 GeV | 10.4 mm | 39.0 mm | 290.0 mm | 309.0 mm | 15.1 mm |

energies. The laser stripping efficiency in the sequential excitation scheme is primarily defined by the excitation efficiency of the larger first step 1s → 2p, thus for simplicity simulations are shown only for this step. In general, the results of the Fig. 6 have been simulated with the help of PYORBIT code [8,9] that involves quantum mechanical interaction of laser beam and bunch of $H^0$ particles. The code calculates interaction of individual particle excitation/stripping efficiency and averages over the whole bunch. More details can be found in earlier works [2,8].

The simulation utilizes the laser stripping model incorporated into the PYORBIT simulation code [10], and is based on the $H^0$ beam parameters from the last SNS experiment [4,5]. Figure 6 indicates that for the same excitation efficiency sequential scheme needs about 0.16 of the laser peak power required for the 1s → 3p excitation which agrees with the above estimations. The calculation efficiency curve 1s → 3p has very good agreement with the experimental stripping efficiency (95%–98%) achieved at the SNS for a UV laser with 2–3 MW peak power [4].

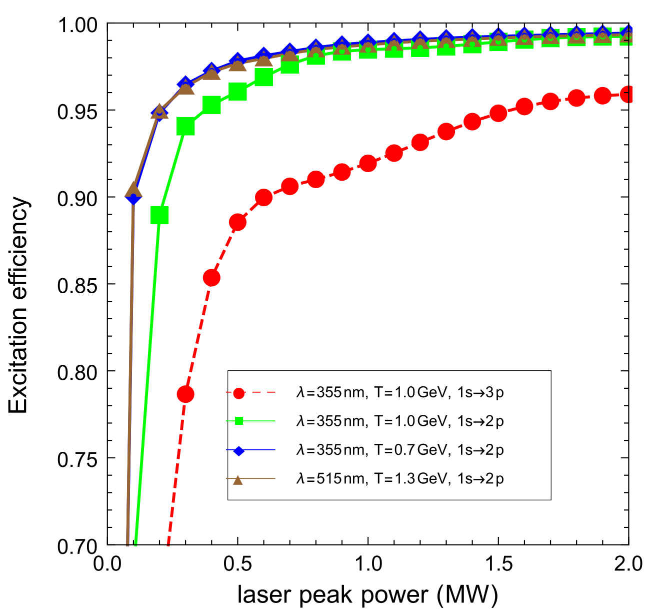


FIG. 6. Simulation of excitation efficiency of single step laser stripping vs sequential scheme laser stripping for different wavelength and $H^0$ beam energies.

### B. Laser system

Currently, most high power lasers (amplifiers) are normally made from solid-state gain materials with the lasing wavelengths within 1.0–1.1 $\mu$m. The green light (wavelength 500 nm) is generated from the second harmonic of the above laser while the UV light (wavelength 350 nm) is a result of the third-harmonic generation. Typical efficiencies for the second and third-harmonic generations are 50% and 20%, respectively. Combined with the excitation efficiency discussed in the previous section, the sequential excitation laser stripping of 1.3 GeV $H^-$ beam can mitigate the stripping laser power requirement by more than an order of magnitude compared with the single-excitation scheme. Replacement of the UV laser with a green laser source also offers advantages in laser operation by reducing power loss in the laser transport line and risks of optics surface damage due to intense UV laser pulses.

Figure 5 shows a schematic of laser stripping of 1.3 GeV hydrogen beams based on the sequential excitation (1s → 2p, 2p → 3d) scheme. Here two laser beams of the same wavelength will be intercepting the hydrogen beam at different angles. The stripping laser wavelength can be either 532 nm or 515 nm, which are discussed in more details in Table II. It is noted that the two laser beams can be well configured in an optical cavity scheme to recycle the laser power as shown in Fig. 7. Using our double-resonance optical cavity technology [11], 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.

## V. 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 magnet 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

TABLE II. Available lasers at the green wavelength regime. Interaction angles are calculated for a 1.3 GeV beam.

| Laser Type | I | II |
|---|---|---|
| Wavelength | 532 nm | 515 nm |
| Interaction angle $\alpha_1$ | 23.20° | 31.29° |
| Interaction angle $\alpha_2$ | 136.66° | 137.67° |
| Fundamental wavelength | 1064 nm | 1030 nm |
| Laser Materials | Fiber seeder+Nd: YAG amp | Fiber seeder+Nd:YAG thin disk amp |
| Peak Power | 1 MW | 100 kW |
| Average power | 2 kW | 200 W |
| Stripping efficiency | 0.99 | 0.90 |
| Availability | Commercially available | Demonstrated in laboratory [12] |

planned to prove feasibility of the proposed scheme. (1) As a first step, diagnostics will be developed to validate 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 980 MeV ion beam using a 355 nm laser wavelength as shown in Fig. 8. Note that according to Eq. (1) the one step excitation ($\lambda = 355$ nm, $\mathrm{T} \sim 1.0$ GeV, $1\mathrm{s} \rightarrow 3\mathrm{p}$) and the sequential scheme ($\lambda = 355$ nm, $\mathrm{T} \sim 0.7$ GeV, $1\mathrm{s} \rightarrow 2\mathrm{p}$) have the same angle of interaction. Thus ion beam energy can be easily changed to 720 MeV 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 720 MeV. 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 121 nm 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, as listed in Table I. 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. The photons wavelength and angular distributions in the laboratory frame of reference are shown in Fig. 9(a) and 9(b). 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 of fluorescence photons at this angle is 200 nm, as seen in Fig. 6(a). Light with this wavelength passes easily through a fused silica glass window and, at the same time, is well separated from the 355 nm laser wavelength [shown by the dashed line in Fig. 9(a)] to avoid the background signal from the laser light reflections. A Hamamatsu R6834 photomultiplier tube (PMT) is a good detector option because it has good sensitivity at 200 nm wavelength and is insensitive to 355 nm light. The PMT current can be estimated as

$$I_{\mathrm{PMT}} = I_b k g_1 l g_2 \frac{d^2}{8 l^2} g_3 G \qquad (3)$$

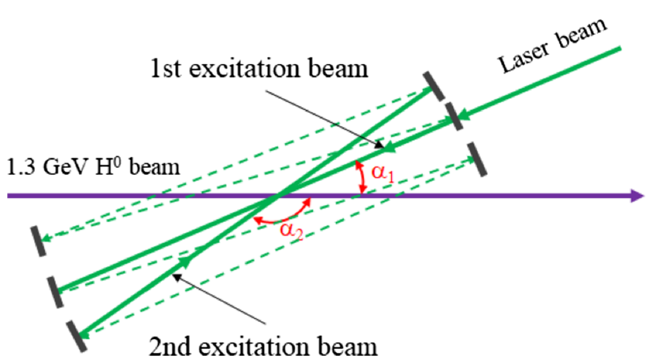


FIG. 7. Schematic of sequential resonance excitation for 1.3 GeV $H^-$ beam laser stripping. 1 and 2 depend on the laser wavelength. Note that the two laser beams can be recycled with a single optical cavity indicated by addition mirrors and dashed lines.

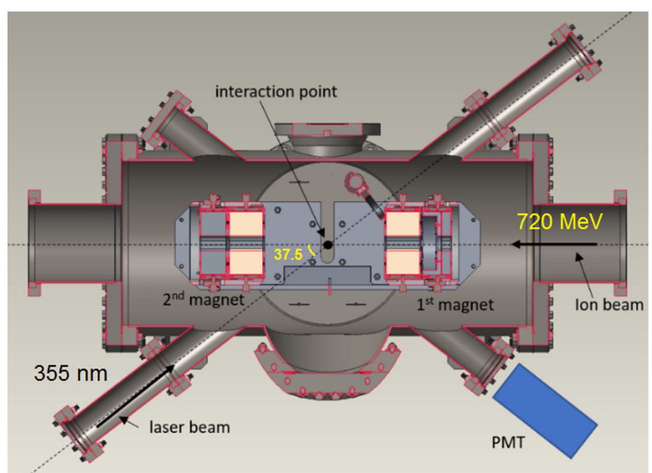


FIG. 8. Layout of the experimental vacuum chamber for the ground level to $n = 2$ level excitation efficiency measurement. The PMT for detecting the fluorescence photons is at the bottom right corner.

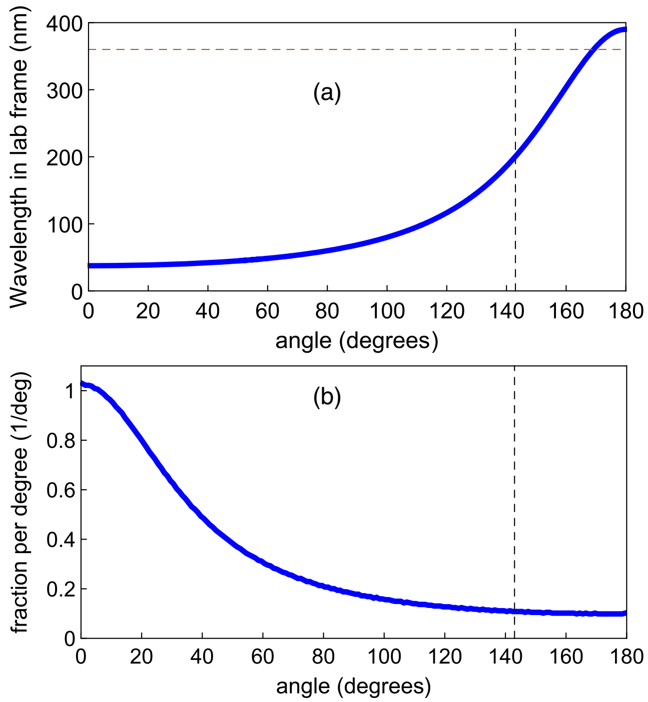


FIG. 9. (a) Dependence of the florescence wavelength on the detection angle in the laboratory reference frame; the yellow horizontal dashed line indicates the laser wavelength. (b) Dependence of the photons flux density on the angle in the laboratory frame. Detection angle of 142 degrees is shown by vertical dashed line on both graphs.

where $I_b$ is the ion beam current; $k$ is the efficiency of excitation from the ground level to the $n = 2$ level; $g_1$ is number of fluorescence photons emitted per unit of length, from the Table I; $l$ is the distance from the interaction point to the magnet entrance (the area visible by the PMT); $g_2$ is the fraction of photons per radian at the detection angle as show in Fig. 9(b); $d$ is the PMT photocathode diameter; $R$ is the distance from the photons emission points to the PMT (middle of the range); $g_3$ is the PMT photocathode efficiency; $G$ is the PMT gain. With the proposed experimental parameters of $I_b = 10$ mA, $g_1 = 1.5 \times 10^{-3}$ mm$^{-1}$, $l = 140$ mm, $g_2 = 0.15$, $R = 430$ mm, $g_3 = 0.8$, $G = 10^5$, the range of the PTM output current is 0.01–10 mA when the excitation current is changing from 0.1% to 100%. This is the optimal operating point for the R6834 PMT. (2) As a second step, three mirrors will be added in the vacuum vessel as shown in Fig. 10 to provide two laser beams with 355 nm wavelength to intercept the ion beam at the angles optimized for exciting electrons in the 1 GeV 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.

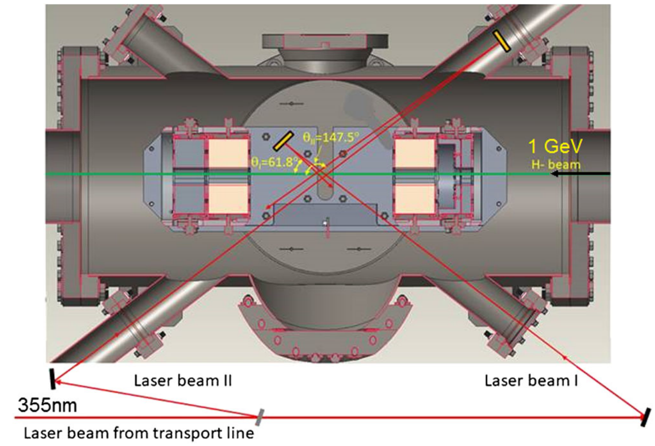


FIG. 10. Layout of the experimental vacuum chamber for the prove of principle laser stripping with sequential excitation.

## VI. SUMMARY AND DISCUSSION

The proposed sequential resonant excitation scheme provides a path to an operational laser assisted charge exchange system that is far more attractive than previous concepts, resulting in substantial power savings and flexibility in the choice of laser wavelength. In particular for the SNS PPU 1.3 GeV, 2.8 MW upgrade scenario, the concept is feasible with existing commercially available green laser technology. The PPU project is baselined for foil-based charge exchange, with foils expected to survive at 2.8 MW. However the injection region is currently the highest point of residual radiation in the accelerator due to foil scattering, and is expected to increase at higher powers. Laser stripping has the advantage of completely mitigating this source of beam loss, as well opening the door to beam power densities beyond the foil sublimation failure limitation. Currently, the precise foil failure limit is estimated to be less than 10 MW for the SNS design parameters, and likely in the 6–8 MW range [13]. The laser-assisted charge exchange method should be fully developed prior to future beam power densities reaching the this level. Operational robustness requires that the first production level laser assisted charge exchange system to be deployed in parallel with a foil based system. Such a system needs years of development to achieve required reliability, and therefore it is critical to pursue this development now.

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