A NOVEL SOLUTION FOR H^- LASER STRIPPING

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Abstract

This paper presents a scheme for 3-step stripping of H^- beam. First, H^- atoms are converted to H^0 by a magnetic field, then H^0 atoms are excited from the ground state to the upper levels by a laser, and the excited states can be converted to protons by a magnetic field. The laser excitation encounters difficulties, related to the energy spread of the beam. The Doppler broadening of the absorption line width due to momentum spread is so large that a narrow bandwidth laser can excite only a small fraction of atoms to the upper levels. For the broad laser spectrum it is not evident how to excite all the atoms simultaneously. A special solution is found to overcome this problem. The experimental setup to satisfy the solution and to reduce the average laser power is presented.

I. Introduction

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.

The U.S. Spallation Neutron Source Project (1 Gev, 1.4 MW) [1] relies on carbon stripping foils for H^- charge exchange injection into the ring. Though the foil assembly is well optimized, it requires an involved maintenance. The foil mechanism itself may represent a large impedance for the beam, and the lifetime of stripping foils impacts the reliability of the facility. Besides, foil manufacture for high intensity operation is expensive. The other projects (e.g. Japan Atomic Energy Research Insitute ring for the neutron source (1.5 GeV, 5 MW), European Spallation Source (1.334 GeV, 5 MW)) encounter even more serious problems from the standpoint of residual radioactivity.

The laser stripping has many potential advantages over the stripping foil:

1) the light beam is easy to operate with;

2) it doesn't produce radioactive elements;

3) the laser stripping could be turned off and on in nanoseconds, leading to a possibility to clean the residual beam in gap (10^{-3} – 10^{-4} of the regular linear density) and to clean the tails left by slower LEBT chopper (if they were not lost in the linac), therefore one can

eliminate H^- beam chopper, which will be built to clean the beam gap after the Radio Frequency Quadruple (RFQ);

4) uncontrolled losses due to multiple traversals of the stripping foil by stored protons are eliminated;

5) foil lifetime issues are eliminated;

6) the laser stripping employs the resonant method of the hydrogen excitation, which depends on particles energy. This automatically provides the possibility to measure the beam energy with good accuracy after the acceleration in the SNS linac.

A charge-exchange injection method without stripping foil was proposed by Zelensky *et al.* [2]. A more feasible scheme, which consists first of a magnetic stripping of H^-, followed by laser excitation from n=1 to n=3 state of hydrogen, second, and, finally, magnetic stripping of n=3 excited hydrogen atoms, was proposed by I. Yamane [3]. In the next sections we present a scheme, which differs from the latter one by a different laser setup for the hydrogen excitation.

II. Lorentz Stripping of H^- ions and H^0 excited states by a Magnetic Field

A transverse magnetic field in laboratory frame produces an electric field in the rest frame of H-ions according to the Lorentz transformation of the fields:

$$| E_\perp | = \beta\gamma c \, | B_\perp |, \tag{1}$$

where $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$; v and c are the velocities of ion and light, respectively. B is the magnetic field in Tesla. The electric field in the rest frame essentially modifies the potential well for the electrons, leading to their possible escape from the region of potential minimum. For 1GeV H^- ions only several kilogauss field is enough to sufficiently strip one electron, because the binding energy of this electron is rather small (0.755 eV). As for the H^0 ground state, the magnetic field of the order of 40 T is needed to sufficiently strip the remaining electron. Therefore, some additional measures should be taken to facilitate the hydrogen atom stripping. It was suggested in [3] that one possible way to strip the last electron is to excite it to n=3 state by a laser through optical-nutation process (we discuss the process in the next section). The excited states of the hydrogen are much easy to strip by a magnetic field – for 1 GeV atom energy the required field for the stripping is of the order of 1 Tesla (for n=3 state) and even less for upper states.

If we don't use complicated nonlinear magnetic fields for the injection, we have an increase of the transverse angular spread due to probabilistic nature of the Lorentz stripping process. To choose the needed magnetic field configuration, we use simplified criteria – the magnetic scheme is satisfactory, if the spread of H^0 angles after the stripping is about the same or less than the initial spread from the linac. Now we estimate the needed magnetic field using the above criteria.

The average angle deflection φ in any arbitrary magnetic field *B(s)* (assuming small change in transverse coordinate and exponential conversion of H^- to H^0) is given by:

$$\varphi = \int_0^\infty \frac{ds}{\beta c\gamma\tau(s)} \exp\left(-\int_0^s \frac{ds'}{\beta c\gamma\tau(s')}\right) \cdot \int_0^s \frac{ds'}{\rho(s')}, \tag{2}$$

where $\tau(s) = \frac{A_1}{\beta\gamma c\,|\,B(s)\,|}\exp(\frac{A_2}{\beta\gamma c\,|\,B(s)\,|})$ is the lifetime of H^- in the rest frame of the ion (see e.g. [4]), with A_1=2.47±0.09 10^{-14} MVs/cm, A_2=44.94±0.10 MV/cm, and $\rho(s) = \frac{\gamma mv}{eB(s)}$ is the curvature radius for the H^- ion trajectory in the given magnetic field *B(s)*. The rms spread σ_φ of the angles is:

$$\sigma_\varphi = \sqrt{\int_0^\infty \frac{ds}{\beta c\gamma\tau(s)}\exp(-\int_0^s \frac{ds'}{\beta c\gamma\tau(s')})\cdot(\int_0^s \frac{ds'}{\rho(s')} - \varphi)^2} \ . \tag{3}$$

If we take 2 Tesla magnet with the gap 10 cm (which is equal to the gap of the SNS ring septum), we can approximate the field linearly within the edge as $B(s)=B_h*s/0.05$ (with B_h =1 Tesla). After substituting into equation (3) we get $\sigma_\varphi=10^{-3}$, and the linac angular spread for the β=1m is about 10^{-3} also. Therefore, without any optimization, room temperature magnet of 2 Tesla will do the job. All the stripping should occur in the fringe field of the magnet, but in order not to decrease this field the length of the magnet should be about 20 cm.

It was noticed in [3] that n=3 state of H^0 atom has about the same dependence of the lifetime on the magnetic field (even more steep dependence), therefore the excited hydrogen atoms can be stripped with similar 2 Tesla magnet. One can chose n=4 or higher excited states for the hydrogen (it requires shorter wavelength laser). In this case the required field drops to 0.5 Tesla. This possibility will be discussed later. In the next section we consider the laser excitation process.

III. Laser Excitation of Hydrogen from Ground to Upper States

When a Hydrogen atom is placed in the laser beam with frequency equal to the transition frequency between the ground and any other state, the electron wave function starts to oscillate between the two states with frequency (called Rabi frequency) proportional to the amplitude of the laser electric field. Appendix 1 presents the mathematical description of the process. We duplicate the result from Appendix 1 for the Rabi frequency for states n=1 and n=3:

$$\Omega = \frac{3^3 e a_0}{2^6\sqrt{2}}\sqrt{\frac{2Q_0}{c\varepsilon_0}}\,/\,\hbar\ , \tag{4}$$

where ε_0 is the permittivity of free space, Q_0 is the laser power density in W/m^2, a_0 is the Bohr radius. The excited state has quantum numbers n=3, l=1, m=0, if the light is polarized in the vertical direction.

The advantage of this method of excitation is that in the resonant case all the laser spectral density effectively interacts with the atom, compared to the case of electron photodetachment, where the process has broad spectrum of interaction but requires orders of magnitude higher power density. But a laser excitation process has its own drawbacks.

The first drawback is that the process requires transition frequencies larger than the inverse time of the upper state decay. The lifetime of the n=3 state, for example, is about 5 nanoseconds. This means that the device for excitation should be much shorter than the decay length, equal to 5 ns *c = 1.5 m. For our laser parameters the interaction region will be about 1 cm, therefore this is not a significant limitation.

A more serious problem is the Doppler broadening of the Hydrogen absorption line width. The laser wavelength λ_0 in the H^0 atom rest frame is related to the wavelength λ in the laboratory frame by the following formula:

$$\lambda_0 = \frac{\lambda}{\gamma(1+\beta\cos\alpha)}, \tag{5}$$

where α is the angle between the laser and H^0 beam in laboratory frame. For the n=3 upper state the required wavelength is λ_0 =102.6 nm. Since the hydrogen beam inherits the energy spread of the H^- beam (of the order of 10^{-3}), each individual atom has its own laser frequency in its own rest frame. The relative spread of frequencies is about the same as the spread of particle energies – about 10^{12} sec^{-1}. The achievable Rabi frequency is about 10^{11} sec^{-1}. The formula (8a) in Appendix 1 shows that the upper state is not excited if the difference between the laser and the transition frequency is larger than the Rabi frequency. But in our case the spread is much larger than the Rabi frequency and the narrow band laser can excite only small fraction of the atoms into upper state. Paper [3] suggests that we should have a broadband width laser to cover the whole range of the hydrogen transition frequencies. If this is done by a laser with many lines in its spectrum, it can excite more atoms, but we need about 100% of the atoms to have simultaneously π phase advance of Rabi oscillation, which is problematic. The solution for this problem was not presented. Now we want to show how to excite all of the atoms with various energies to achieve the excitation efficiency about 100%.

We present a novel solution to this problem that consists of two major elements. The first part is a **special method (based on quantum Froissart-Stora problem) to excite all the atoms almost simultaneously**. The second new element is **the method of significant reduction of the absorption line width due to the particle energy spread by the dispersion function derivative introduction**.

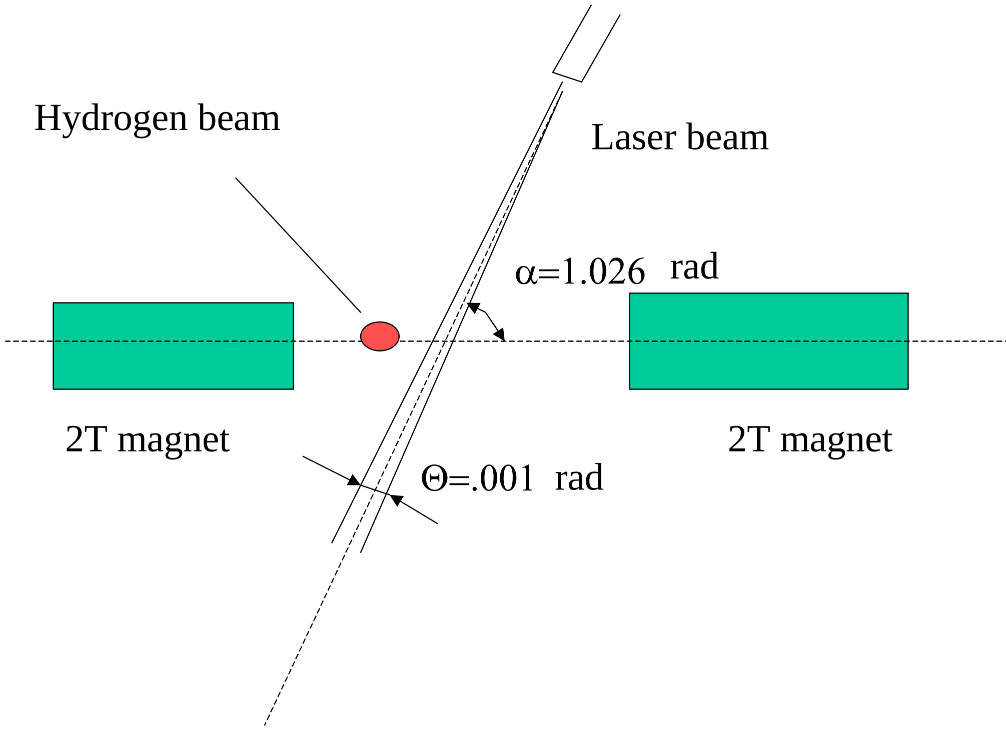

Figure 1 Experimental setup for the laser excitation of the hydrogen beam (top view).

Now we consider the slowly varying frequency system. This can be achieved by introducing the divergence of the laser beam so that the angle of the H^0 beam and the laser beam along the beam path is decreasing. Because of the Dopler dependence of the laser frequency in the atom's rest frame on the angle (see equation (5)), the frequency of the light as seen by the atoms will decrease as the angle increases. Figure 1 shows the experimental setup to get needed frequency sweep in the rest frame of the H^0 beam. Since the atoms are distributed in energy, the laser frequency will differ for different atoms, but if the "frequency sweep" range is large enough, all the atoms will eventually cross the resonant frequency and will be excited. To check the degree of excitation we need to solve quantum mechanical problem with the laser frequency linearly changing in time. The equation for this is derived in Appendix 1 (see eq (4a)) except for the fact that now the difference of the laser and transition frequencies is a linear function of time:

$$\begin{aligned} \dot{C}_1 &= \frac{i\mu_{1n}E^*}{2\hbar} C_n e^{i\Gamma t^2/2}, \\ \dot{C}_n &= \frac{i\mu_{n1}E}{2\hbar} C_1 e^{-i\Gamma t^2/2}, \end{aligned} \tag{6}$$

where C_1, C_n are probability amplitudes to be in the state 1 or n, respectively, $\Gamma=d\omega_0/dt$ is the light frequency derivative with respect to time, $\mu_{1n}=\mu_{n1}^{*}=-\int d^3r\, u_1^{*}(\vec{r})ezu_n(\vec{r})$ (assuming the light is polarized and the electric field is parallel with the *z* axis), and u_1 and u_n are the normalized wave functions of the ground and the upper excited state, respectively. Marcell Froissart and Raymond Stora obtained the full solution to this problem [6] in connection with the electron spin motion. The initial conditions for the problem are $C_1=1$, $C_n=0$. The equations are integrated from $t=-\infty$ to at $t=\infty$. The probability C_n^2 for the system to finish in the upper state is:

$$C_n^2=(1-\exp(-\frac{\pi\Omega^2}{2\Gamma}))^2, \tag{7}$$

where $\Omega=\mu_{1n}\sqrt{\frac{2Q_0}{c\varepsilon_0}}/\hbar$ is the Rabi frequency, Q_0 is the laser power density in W/m^2. One can see that if the frequency derivative Γ is small, the atoms are excited to the upper n state, and vice versa. The exponential dependence of the excitation probability on the parameters makes it easy to approach 100% effectiveness of the excitation. Now we present the calculation for realistic laser and hydrogen beams.

The parameters of the beam are taken from the baseline design values for the SNS Super Conducting Linac (SCL) output. The parameters may be different by a factor of 2 in real life; therefore we need to provide some flexibility or contingency in our experimental setup. We take the kinetic energy of the beam equal to E=1 GeV, the emittance of the beam equal to ε=0.6*10^{-6} m*rad, the β-function is about β=5 meters, the beam size is Δ=1.7 mm rms radius, the relative rms energy spread is δ=0.2*10^{-3}, the interaction time is chosen 100 times less than the n=3 state decay time, namely T=0.05 nsec. To complete the laser power estimation we need to choose the laser wavelength. We consider a powerful Excimer (XeCl) laser with the wavelength λ=308 nm.

With this wavelength the angle between the hydrogen and the laser beam equal to α=58.8° in order the light to have 102.6 nm wavelength in the hydrogen atom rest frame. The first step is to determine the Rabi frequency. It comes from equation (7). If we require 99 percent efficiency, the exponent in (7) should be equal to –5:

$$\frac{\pi\Omega^2}{2\Gamma}=\frac{\pi\Omega^2T}{2\kappa\omega_0}=5\ , \tag{8}$$

where κ=10^{-3} is the relative frequency change along the beam path, which is taken to be five times as big as the relative energy spread of the beam to cover all the particles. This is achieved by making intersection angle θ (see Figure 1) change of the laser beam along the hydrogen beam path from –0.0005 to +0.0005 radian. For our parameters this gives a value for the Rabi frequency: Ω=1.08 10^{12} sec^{-1}, the power density of the laser beam Q_0=2.703 10^8 W/cm^2 in the rest frame of the beam is needed. In the laboratory frame the laser density is smaller by about factor of 10 and is given by:

$$Q_0=Q\gamma^2(1+\beta\cos\alpha)^2. \tag{9}$$

The total area of the laser beam is $S = T\gamma c 2\Delta \sin(\alpha)\pi / 4 \approx 0.84 cm^2$. Now the peak power of laser is **P=Q*S=25.4 MW**. Therefore without any optimization we get peak power, which is available at this moment in Excimer lasers. Figure 2 shows a simulation of the excitation of the n=3 state excitation for the above parameters. The horizontal axis is time in the rest frame of the hydrogen atom (t=0 corresponds to exact resonance between the laser and the transition frequencies). The vertical axis shows the probability of the excitation. The red line represents the solution of equation (6) for the finite time from – 3 10^{-11} to +3 10^{-11} seconds. The blue line shows the Froissart-Stora asymptotic solution.

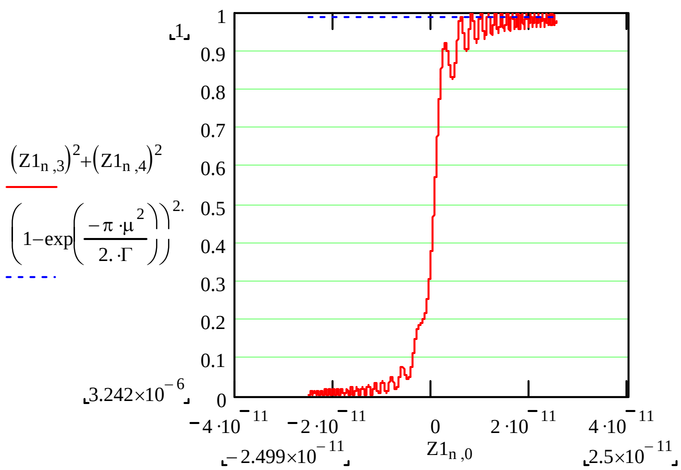

Figure 2 Simulation for the n=3 state excitation in the field of the laser with slowly increasing frequency.

Laser beam recycling can reduce the average power. For example, one can use optical resonator with the quality factor 10^4-10^5 to store the laser beam for 1 ms of the ring injection time. It will reduce the average power by factor 10^4-10^5. Also, the duty factor of the SNS facility is 0.06, so that one may require only about 200 W average power if the system is well developed. There exist even more optimized scheme that will be discussed at the end of Section V. It will require power less than 100 W.

Other ways to optimize the power usage may include **vertical size reduction** (a factor of 5 is available), and **introducing the dispersion derivative to eliminate the Dopler broadening** of the absorption line width. The idea is the following. The rest frame frequency of the laser light is:

$$\nu_0 = \nu\gamma(1+\beta\cos\alpha)\,, \qquad (10)$$

where α is the angle between the laser and H^0 beam in laboratory frame, ν is the laser frequency in the laboratory frame. Let's assume now that the particle angle depends on the energy. We use the following well-known dependence of the angle on the relativistic gamma $\frac{\partial\alpha}{\partial\gamma} = -D'/\gamma$.

When we equate the derivative of expression (10) with respect to the γ to zero, we find the appropriate

$$D' = -\frac{1+\cos\alpha(2-\beta)}{\beta\sin\alpha}. \qquad (11)$$

If the dispersion derivative satisfies (11), all the hydrogen ions have the same laser light frequency in their rest frames. Figure 3 shows the experimental setup in this case.

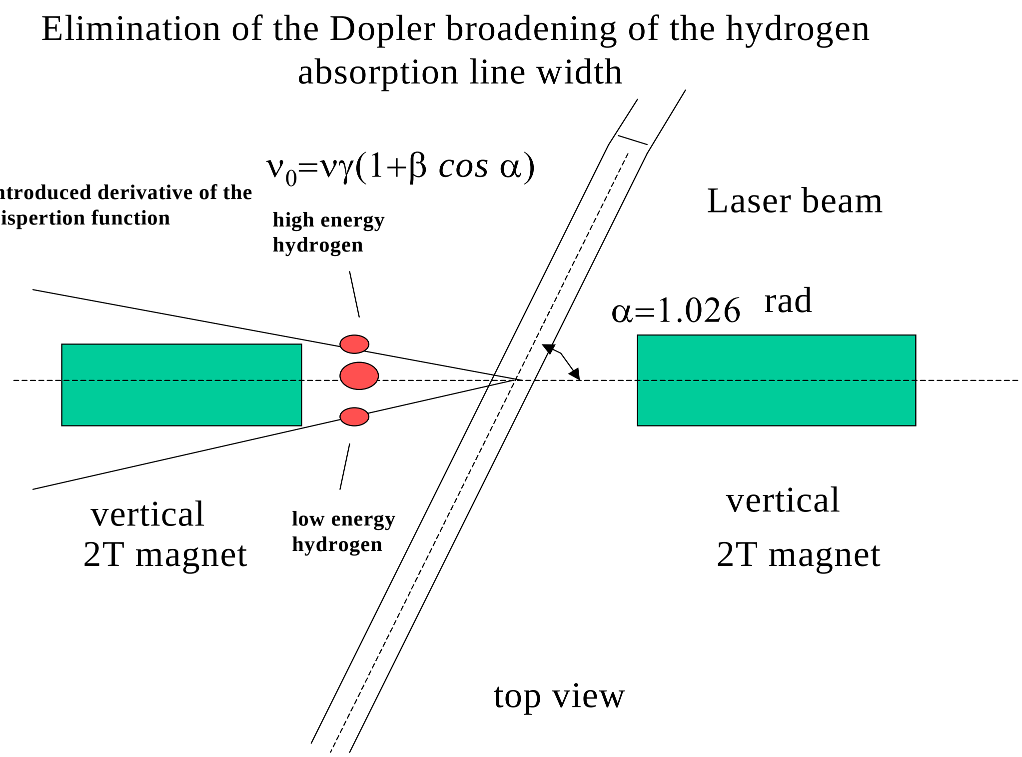

Figure 3 Interaction region setup for the Dopler broadening elimination.

The **final problem to overcome is the betatron angular spread.** One can increase the horizontal beta function to decrease the angle spread, e.g. to increase the beta function to 3000 meters. However, in this case the horizontal beam size becomes 3 cm rms, which is comparable to the circulating beam in the ring. It may be possible to introduce a special insertion with the x-y coupling to produce low vertical size and low horizontal angular spread beam with acceptable horizontal size. These possibilities will be explored at a later stage of the experiment.

For the first stage, a 20 MW peak power laser (average power can be in the 100 Watt range) is sufficient to make proof of principle experiment.

IV. Laser requirements for the first stage of experiment

It turns out that if we decrease the horizontal beam size while keeping constant the total power of the laser beam, the probability of the excitation stays constant also (see equations (7-8)). It is shown in Appendix 2 that the Gaussian beam doesn't have diffraction limitation; therefore the horizontal size could be set equal to the vertical for convenience. The angle between the laser and the hydrogen beams should be again varying from –0.0005 to +0.0005 radian along the hydrogen beam path. This solution gives the first option for the experiment.

Option 1 For this option we need to have about 20 MW peak power Excimer (XeCl) laser. It should produce the round Gaussian beam with sigma 1.36 mm and the intersection angle should cover ± 0.0005-radian range. The parameters for the Gaussian beam for about 90% stripping are calculated in Appendix 2: round beam with the waist $W_0=7.2*10^{-5}$ m, the distance from the waist z=2.0 m, the Gaussian beam parameter z0=0.053 m, the laser beam rms size 1.36 mm, and total needed power is integrated over the laser beam cross section and equal to 12 MW.

As we further squeeze the laser beam horizontally, the Rabi frequency overcomes the Doppler spread of the transition frequencies. In this case we don't need the angular convergence for the laser beam, but it should be made very small in horizontal size. It turns out that this option also requires approximately the same peak power from the laser to excite more than 90% of the hydrogen atoms.

Option 2 For this option we need to keep same power, but squeeze the laser beam horizontally to 100 μm or less and eliminate any laser beam convergence at the interaction point. As it mentioned in Appendix 2, this should give also high probability of the excitation.

In order to have these options, we must have variable beam size.

Besides, the laser beam angle should be controlled with accuracy much better than 10^{-3} rad – it looks like 10^{-5} radian accuracy in the laser beam direction is needed to achieve the reliable stripping.

The laser beam angle should be controlled with accuracy much better than 10^{-3} rad – it looks like 10^{-5} radian accuracy in the laser beam direction is needed to achieve the reliable stripping. The main requirements from laser system: (a) short wavelength, (a) high power, (c) narrow bandwidth, and (d) controllable beam divergence. We designed an optical system that is capable to deliver the required beam. In the first stage, we are planning to use a single laser (to demonstrate the feasibility of the ionization process). Later on, frequency and phase locked (synchronized) array of lasers will be used to cover the required beam area and to increase the power (if necessary).

Our proposed optical design is demonstrated in Figure 4. It include the following main optical components:

(1) XeCl excimer laser (possible product LPX210) wavelength 308 nm, pulse width ~20ns, repetition rate <100Hz, energy ~400 mJ, peak power 20 MW.

(2) Injection laser: wavelength tunable dye laser (possible product SCANmate 2E C-400 dye laser) Nd:YAG pump, wavelength 370-860 nm, bandwidth 0.3 pm, pulse width ~5ns, energy <90 mJ.

(3) Second harmonic generation (SHG) system to convert the injection laser output wavelength to 308 nm nonlinear crystal (e.g.Lithium-borate (LBO)), optics.

(4) Beam-forming optical system to achieve a certain beam divergence angle

(5) A ring resonator for trapping of optical pulse.

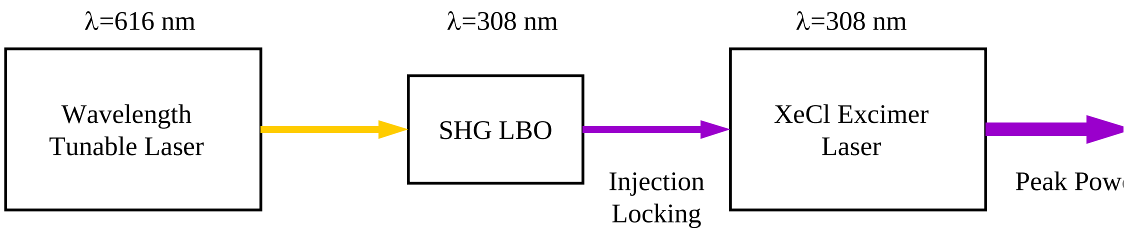

Figure 4 Laser setup for the first stage of the experiment.

Fig. 4 shows the schematic of the light source proposed for the first stage of experiment. We use a pulsed XeCl excimer laser with optical injection. The XeCl excimer laser has the center wavelength 308 nm, the pulse width 20ns, the pulse repetition rate <100Hz, and the peak output power about 20 MW. To achieve spectrum narrowing and single mode behavior, we propose to use injection locking. Injection locking has been successfully applied to narrow spectrum of the excimer lasers. For example, spectrum narrowing to 1pm in a high power ArF excimer laser injection locked by an all solid state fourth harmonic (193.4 nm) seed source of 773.6 nm Ti:sapphire laser radiation was reported [8-9]. The proposed injection laser is tunable dye laser pumped by Nd:YAG laser. The wavelength of the dye laser is tunable over the range of 370-860 nm and will be operated at the wavelength of 616 nm with the bandwith of 0.3 pm. A second harmonic generation system (SHG) will be used to convert the injection laser output wavelength to 308 nm to fit the wavelength of the excimer laser. We will use a nonlinear crystal (e.g. Lithium-borate (LBO)) as a second harmonic generator. With the successful injection, we expect to achieve a single mode Excimer laser at 308 nm with the spectral bandwidth 0.3 pm (1 GHz) and the peak output power up to 20 MW.

We assume the laser beam has an elliptical profile and a Gaussian beam distribution in both horizontal and vertical direction. We need to have a variable beam size – two examples are: the round beam with the waist $W_0=7.2*10^{-5}$ m, the distance from the waist z=2.0 m, the laser beam rms size 1.36 mm, total power is 12 MW. If we squeeze the horizontal size to rms 50 μm, we get the second example for the high efficiency stripping. With having about 10 MW power, we get the beam with the same vertical parameters, but horizontal parameters become: the waist W_0=100 μm (which is equal in this case to the double rms beam size), the distance from the waist z=0.0 meters. In calculations it gives approximately same efficiency of the stripping – about 90 %. We need to vary the beam size from one option to another in order to investigate the most optimal way of stripping.

V. Laser setup for the second stage of the experiment

The second stage aims on developing the laser scheme for full 60 Hz SNS facility cycle. The main goal of this stage is to show that the required laser beam can be obtained with the moderate average power of the laser.

Since it is relatively simple to match the laser pulse repetition rate with the SNS facility cycle, the essential point in the second state of the experiment is to expand the pulse width to 1 ms that is equal to the ring injection time. A high-Q optical ring resonator is proposed as a possible solution. Figure 5 schematically shows how such resonator works. The pulsed light output from the injection-locked XeCl laser is linearly polarized (p-polarization) and will be transmitted into the resonator through the polarization beam splitter (PBS). The resonator length is designed according to the laser pulse width T_w as $L = \frac{cT_w}{2n}$ where n is the refractive index of the resonator and c is the light speed. A Pockels cell is mounted in the resonator to control the polarization state of the light inside the resonator. When the control signal of the Pockels cell is appropriately set to cause a half wave retardation, i.e., $V=V_{\pi/2}$, the injected p-polarized light will be changed to the s-polarized light. The control signal is reset to 0 after a time interval that is exactly the same as the pulse width. As a result, the injected light is totally changed to the s-polarization and will stay in the ring resonator since the PBS completely reflects the s-polarized beam. Figures 5(b)-(d) illustrate the timing of the input optical pulse, the control signal of the Pockels cell, and the resulted optical signal inside the resonator. Here, T_0 is the period corresponding to the SNS operation cycle and T'_w is the time duration where the light intensity decreases from P_0 to P_1, a limit level for achieving the expected stripping efficiency. T'_w is related with the Q-value of the resonator as well as resonator parameters in the form

$$T'_w = \frac{Q}{2\pi} T_w = \frac{T_w}{\left|\ln\left(\xi(1-\eta)\right)\right|},$$

where ξ is the total mirror reflectivity of the resonator and η is the loss.

To increase the pulse width from 20 ns to 1 ms, one needs a resonator with the Q value as high as 10^5!

Two techniques are proposed to soften the requirement of high Q. One way is to reduce the Q value by expanding the laser pulse width. But this results in the decrease of the peak power. A possible way is to shrink the vertical size of the H^- beam and hence the laser beam so that the peak power requirement can be reduced. If one can squeeze the vertical size of the laser beam to 50 μm, the pulse width can be expanded to the order of 100 ns while keeping the enough peak power. As a result, the requirement on the Q value of the resonator can be reduced at least one order.

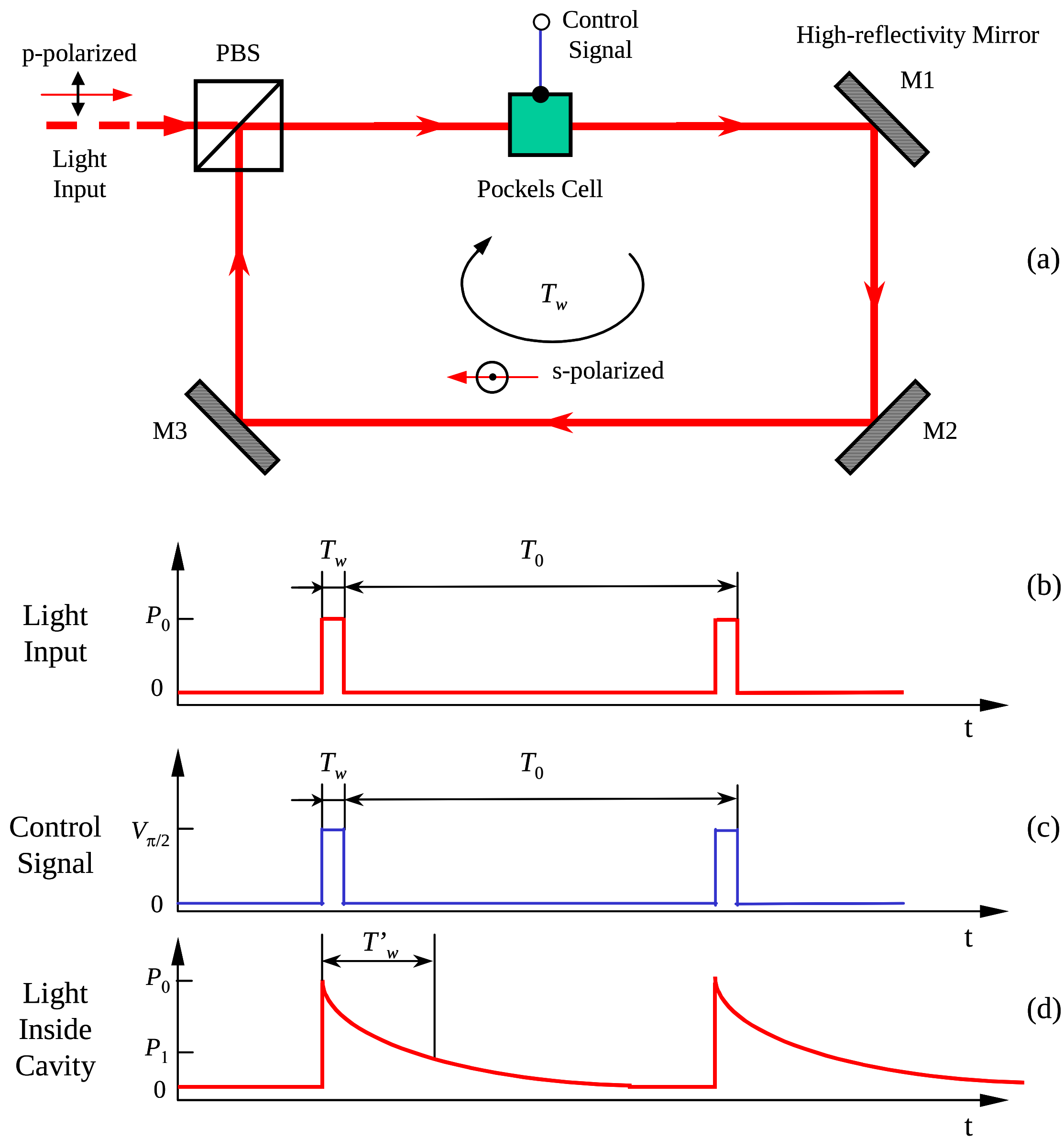

Figure 5 Schematic of ring resonator for trapping of optical pulse.

Another technique is to use a synchronized laser array. The principle is based on *friendly operated moderate power lasers*. Non-coherent addition of laser beams is of marginal advancement in power concentration and the challenge is to synchronize lasers and to combine them into a coherent unit. The lasers included in the array are, in principle, identical in frequency and amplitude. By definition, the total output power, P_{tot}, increases proportionally to the number of lasers forming the array, (N), i.e. $P_{tot} \propto NP_0$, where P_0 denotes the output power of each array element including dissipative losses. The total output intensity, I_{tot}, (***power per unit area***) depends though on the degree of coherence among the lasers. If emissions from all the lasers are not coherent, the beam intensity produced by the array scales as $I_{tot} \propto NI_0$, where I_0 is the beam intensity of a single laser. However, if emissions from all the lasers are in-phase, $I_{tot} \propto N^2 I_0$. Clearly, such a high intensity will be observed only over a very narrow area, since the total power is preserved. For a non-coherent beam, the "bright" area will be much broader. The proposed effort discusses a novel *scalable* laser-array concept that utilizes the nonlinear dynamics of the array with the focus on Excimer lasers. This concept translates to significant improvement in energy that can be deposited on a target, and consequent savings in laser dimensions and power requirement. The concept will be validated through prototype development.

Injection locking has been successfully used to obtain single mode emission in high power diode lasers or laser arrays. Figure 6 illustrates the general methodology used to illuminate the facet of a slave laser array by an external, single frequency, master laser beam. The incident angle can be adjusted to stimulate a specific mode, which could generate high coherent output power. An alternative approach is to feedback part of the output beam through grating, etalon, or phase conjugate mirror.

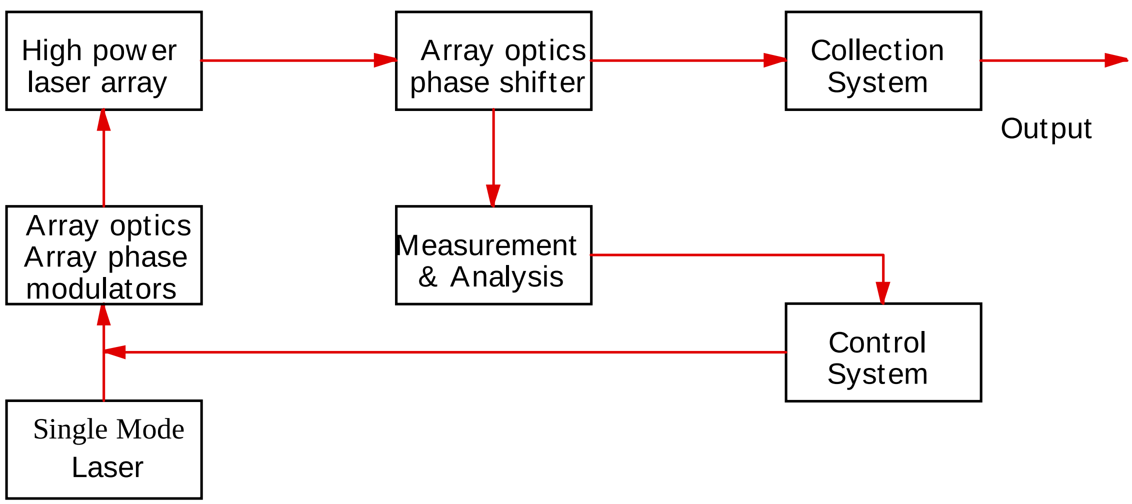

Figure 6. A general methodology used to injection lock laser array.

After all the possible schemes and scenarios for the laser stripping device, we come up with the **most optimal scheme** (at this moment) that has least average laser power and looks feasible. Figure 7 shows the general setup for the stripping device. The linac beam is coming to the ring with 400 MHz frequency. Each bunch has about 30 ps duration. The laser beam should have bunches about 100 ps to cover the linac bunches. The repetition frequency should be equal to the ring revolution frequency, which is about 1 MHz. Each laser bunch is injected to the laser beam recycler (see Figure 5) and it should circulate there with 400 MHz frequency to strip all incoming linac bunches. The Laser Recycler should have quality factor Q about 1000 in order to have small light damping during the ring revolution time. When the proton bunch gap arrives at the point of the stripper, the circulating in the Recycler laser bunch is extracted, and the entire linac beam goes to the linac dump, providing clean beam gap in the ring. When the head of the ring proton beam arrives at the stripping point, the laser bunch is injected to the recycling system and the stripping resumes. The laser system should work for 1 ms, then be at rest for 15 ms, and so on, to match the linac beam time structure. If we take into account this 6% duty factor, and assume the peak power of the laser beam to be 10 MW (approximately same as in the above cases), we come up with the average power: **P=60000 (number of pulses per second)× 10 MW (peak power) ×100 10^{-12} (pulse duration)= 60 W!** This number is below all expectations! It looks like if the laser recycler and the laser with 1 MHZ frequency are developed, the problem of laser stripping will become solvable in straightforward manner.

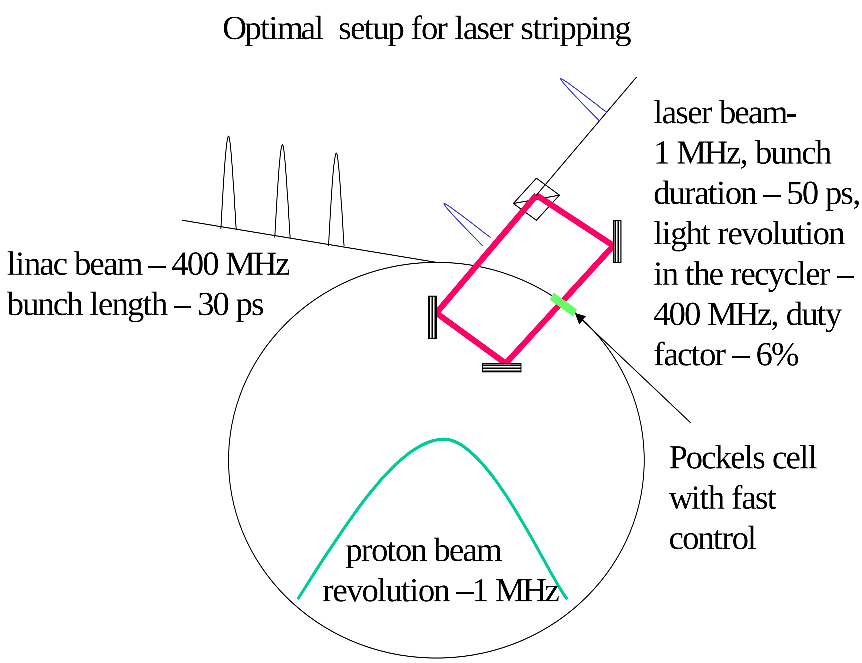

Figure 7 Optimal setup for the laser stripping.

Analytical and Computer Modeling

To support our experiments, analytical and computer modeling will be performed. The motivation for these studies is to optimize injection and laser performances and to achieve robust and stable behavior of the laser (laser array). The injection control model for pulsed Excimer lasers is reported in [10]. We will modify this model for our experiment and determine parameter values based on the collected data.

The ORNL Center for Computational Sciences (CCS) houses three massively parallel supercomputers with a total capacity of 5.5 teraflops. "Falcon" is a Compaq AlphaServer SC system of 64 nodes, 4.5 TB disk space, 128 GB memory with peak performance of .5 teraflops. "Eagle" is an IBM RS/6000 SP system of 184 nodes, 9.2 TB disk space, and 369 GB memory with peak performance of 1.08 teraflops. "Cheetah" is an IBM Power4 system of 24 nodes with 32 processors each, 40 TB disk space, 1020 GB memory with peak performance of 4 teraflops.

ORNL is a co-developer of and customer for the computer industry's leading data storage system. The High Performance Storage System (HPSS) leads the computer industry in data capacity and transfer speeds: more than 70 terabytes are stored in the production installation and 12,000 new files a day can be placed into storage. From distributed locations, calculations generating terabytes of information can be stored and retrieved in chunks of 250 megabytes using a high-speed llink, ESnet, DOE's semiprivate portion of the Internet.

VI. Required beam and interaction region parameters. Diagnostics.

The interaction region must have small vertical beam size in order to save laser power. The H^- stripping should be made in vertical direction in order to have a small horizontal angular spread. The first stripping magnet should be of undulator type with the steepest achievable horizontal magnetic field. The second magnet (after the hydrogen excitation) should have the same parameters. It is also desirable to maintain the average bend angle equal to zero. This makes the commissioning much more simple compared to the case when the hydrogen medium trajectory varies with the magnet strength.

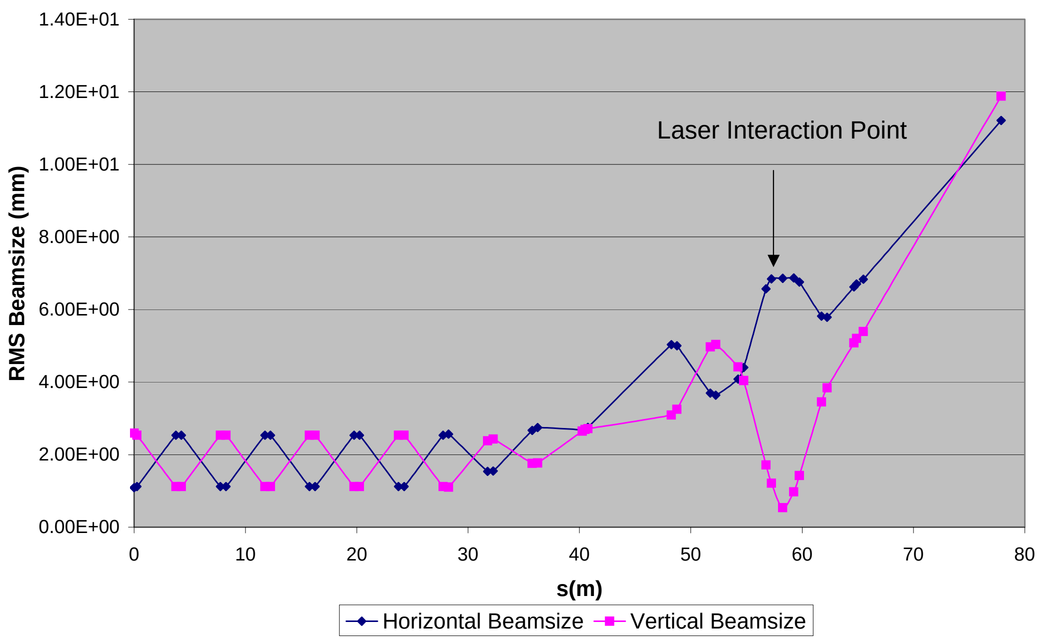

Figure 7. Horizontal and vertical RMS beamsizes in the linac dump line. The proposed interaction point is indicated.

By modifying the optical functions in the linac dump line, appropriate interaction region beam sizes can be achieved. Figure 7 shows the beam sizes in the line in which the optical functions have been adjusted to produce a beam waist in the vertical plane at a location equidistant from nearby quadrupoles. This solution achieves a waist with 1 meter of free space on either side of the interaction point. In addition, the angular divergences have been minimized as well. The interaction region RMS beam sizes are 0.54 mm and 6.9 mm for vertical and horizontal, respectively.

Another important detail is related to the residual magnetic field at the interaction point. The magnetic field transforms into an electric field in the rest frame of the hydrogen atoms. This, in turn, produces Stark energy level shifts. The maximal energy level spread due to the electric field is:

$$\Delta E = \frac{3E\ n(n-1)}{510^{11} V/m} Ry = \frac{3\gamma\beta c\ B(T)\ n(n-1)}{510^{11} V/m} Ry \approx 2\,10^{-2} B(T) Ry\,,$$

for the n=3 state. In order to limit the Stark effect to about 10^{-5} of the level energy level difference, one must maintain the residual magnetic field to less than 5 Gs in the region. This requires building one additional magnet, which is used to cancel the residual field, as measured by a field probe at the interaction point.

The diagnostics must measure the proton current to H^- current ratio with percent accuracy within 20 ns – the duration of the laser pulse at the first stage of the experiment.

VII. The choice of the upper state main quantum number discussion

One possibility is to make experiments with n=4 or even higher states. The Rabi frequency for this transition is equal to:

$$\Omega = \frac{2^{11} 3 e a_0}{5^6 \sqrt{5}} \sqrt{\frac{2Q_0}{c\varepsilon_0}} / \hbar \approx 0.176 e a_0 \sqrt{\frac{2Q_0}{c\varepsilon_0}} / \hbar\,.$$

It means that in order to maintain the same frequency as for the n=3 state, the power should be 3 times larger. But the angle of the laser α should be reduced to produce the resonant frequency with the same Excimer laser. It give some increase in the efficiency. For a 1 GeV beam and 308nm laser, two times more power is needed to excite the n=4 state than the n=3 state. Nevertheless, this option should be considered if we use more sophisticated excitation of the hydrogen with possible use of the Stark effect to produce energy shifts with the particles angles in order to eliminate the angular dependence of the hydrogen excitation probability.

VIII. Conclusion

The paper presents feasible method for laser stripping injection. It is found how to eliminate the major problem, reported in [3], namely, the Dopler broadening of the absorption line width due to the particle beam energy spread. Two left problems to overcome are the angular horizontal spread of H^- beam and efficient recycling of the laser beam. Both problems look solvable – the possible solutions are discussed in the paper.

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Appendix 1 Rabi oscillation calculations

For hydrogen atoms in the rest frame, dominant interaction with the laser light comes from the electric field. We neglect spin and electron Lorentz force interaction with the magnetic field of the light (which is about $\alpha \approx 1/137$ times weaker than the interaction with the electric field). Follow [5], we start with the Shrodinger equation for electron in the field of the proton and an alternating electric field:

$$i\hbar\frac{\partial\psi}{\partial t} = (-\frac{\hbar^2}{2m_e}\nabla^2 - \frac{e^2}{r} - e\vec{r}\cdot\vec{E}(t))\psi\ , \qquad (1a)$$

where $\vec{E}(t) = (\vec{E}e^{-i\omega t} + c.c.)/2$ is the electric field from the laser beam. We consider only two states 1 and n and the transition between them in the first approximation assuming the electric field term is small. The atomic function can be represented as:

$$\psi(\vec{r},t) = C_1(t)u_1(\vec{r})e^{-i\omega_1 t} + C_n(t)u_n(\vec{r})e^{-i\omega_n t}\ , \qquad (2a)$$

where $u_{1,n}$ correspond to the ground and upper state (n=2,3…) wave functions (orthonormal and normalized to unity in our case), respectively. We substitute (2a) into (1a) and multiply by u_1*, then integrate over the whole space to obtain the first equation for the coefficients. The same manipulations with u_2* yield the second equation. The equations for C_1 and C_n are the following:

$$\dot{C}_1 = \frac{1}{i\hbar} C_n V_{1n} e^{-i\omega_{1n}t}, \quad \dot{C}_n = \frac{1}{i\hbar} C_1 V_{n1} e^{i\omega_{1n}t}, \tag{3a}$$

where $V_{1n} = V_{n1}^* = -\int d^3r\, u_1^*(\vec{r}) e\vec{r} \cdot \vec{E}(t) u_n(\vec{r})$, $\omega_{1N} = -\omega_{N1} = \omega_1 - \omega_N$. Taking into account electric field dependence on time $\vec{E}(t) = (\vec{E}e^{-i\omega t} + \vec{E}^* e^{i\omega t})/2$ and keeping only slowly oscillating terms, we get from (3a):

$$\dot{C}_1 = \frac{i\mu_{1n}E^*}{2\hbar} C_n e^{i\Delta t}, \quad \dot{C}_n = \frac{i\mu_{n1}E}{2\hbar} C_1 e^{-i\Delta t}, \tag{4a}$$

where $\Delta = \omega - \omega_{N1}$, $\mu_{1n} = \mu_{n1}^* = -\int d^3r\, u_1^*(\vec{r}) ez u_n(\vec{r})$ (assuming the light is polarized and the electric field is parallel with the axis *z*). If the coefficients were constant, complex exponents $C_i \approx \exp(-i\lambda t)$ would give the solution to this equation with

$$\lambda_\pm = -\frac{\Delta}{2} \pm \frac{\Omega'}{2}, \tag{5a}$$

where $\Omega' = (|\Omega|^2 + \Delta^2)^{1/2}$, and $\Omega = E\mu_{1n}/\hbar$ stands for the Rabi frequency. The Rabi frequency is proportional to the amplitude of the electric field oscillation *E*. The Rabi frequency can also be expressed in terms of the energy density of the laser:

$$\Omega = \mu_{1n} \sqrt{\frac{2Q_0}{c\varepsilon_0}} / \hbar, \tag{6a}$$

where ε_0 is the permittivity of free space, Q_0 is the laser power density in W/m^2. For the particular case of the n=1 and n=3 state

$$\mu_{1n} = -\int d^3r\, u_1^*(\vec{r}) ez u_n(\vec{r}) = \frac{3^3 e a_0}{2^6\sqrt{2}}, \tag{7a}$$

where a_0 is the Bohr radius, $z=r\cos\theta$, $u_1 = \frac{2e^{-\frac{r}{a_0}}}{\sqrt{4\pi}}$, and $u_3 = \frac{8e^{-\frac{r}{3a_0}}\frac{r}{a_0}(1-\frac{r}{6a_0})}{27\sqrt{6}\sqrt{4\pi}}$. The latter wave function corresponds to n=3, l=1, m=0 state. The other states with n=3 are not excited in the first approximation.

The solution for the population C_n^2 of the excited state, for atoms initially in the ground state (C_1=1, C_n=0), is:

$$C_n = \frac{|\Omega|^2}{\Omega'^2}\sin^2(\frac{1}{2}\Omega' t), \quad (8a)$$

where again $\Omega'=(|\Omega|^2+\Delta^2)^{1/2}$, and $\Omega = E\mu_{1n}/\hbar$.

Appendix 2 Upper level excitation for realistic Gaussian beam

The realistic laser beam has the Gaussian shape and is described with the help of function U(r) [7]:

$$U(\vec{r}) = \frac{W_0}{W(z)}\exp(-\frac{r^2}{W^2(z)})\exp(-jkz - jk\frac{r^2}{2R(z)} + j\zeta(z)), \quad (1a2)$$

where r is the transverse coordinate, z is the longitudinal coordinate, $k=\omega/c$, $W(z) = W_0(1+\frac{z^2}{z_0^2})^{1/2}$, $R(z) = z(1+\frac{z_0^2}{z^2})$, $\zeta(z) = \tan^{-1}\frac{z}{z_0} + \varphi$, z_0,φ are the arbitrary constants, and $W_0 = (\frac{\lambda z_0}{\pi})^{1/2}$. This function satisfies the Helmholtz equation and it can be used to express electromagnetic field. If we choose the electric field direction in vertical y direction, omitting the time dependence exp(jωt), the expressions for the electric and the magnetic fields are:

$$
\begin{aligned}
E_x &= 0, \\
E_y &= -E_0 U(\vec{r}), \\
E_z &= E_0 \frac{x}{z + jz_0} U(\vec{r}), \\
H_x &= E_0 \sqrt{\frac{\varepsilon_0}{\mu_0}} U(\vec{r}), \\
H_y &= 0, \\
H_z &= 0.
\end{aligned} \tag{2a2}
$$

To describe the fields in the rest frame of the hydrogen atom, we must transform the fields and coordinates into the new system. Figure 1a2 shows the coordinates notations. The expressions (2a2) for the fields are given in the laboratory frame *xyz*, the new system *x'y'z'* is shifted in the z coordinate and rotated around the *y*-axis by π/2-α angle. The third system *x"y"z"* (the hydrogen rest frame system) is moving along the *x'* axis with velocity V. The resulting transformation from the third to the first system is:

$$
\begin{aligned}
x &= \gamma(x'' + Vt'')\sin\alpha + z''\cos\alpha, \\
z &= S + z''\sin\alpha - \gamma(x'' + Vt'')\cos\alpha, \\
y &= y'', \\
t &= \gamma(t'' + \frac{V}{c^2}x''),
\end{aligned} \tag{3a2}
$$

where S is the shift of the interaction point from the laser beam waist, α is the angle determined by the Dopler effect and the 3-1 transition frequency; α=58.8° for the λ=308 nm.

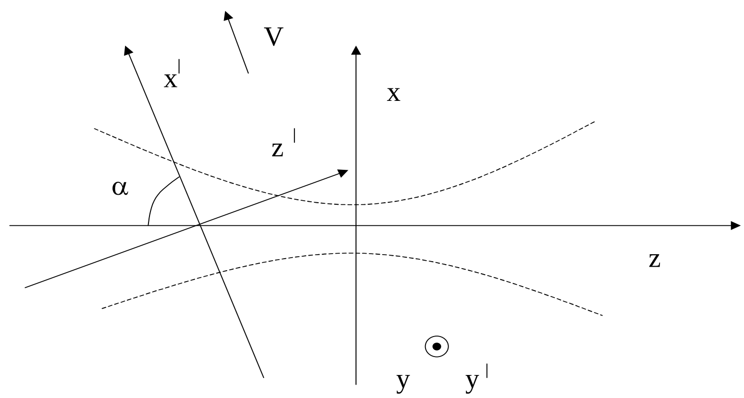

Figure 1a2 Coordinates notation for the hydrogen atom in the field of the Gaussian beam.

Taking into account rotation and Lorentz transformation of the fields, neglecting the longitudinal electric field in (2a2) under assumption that $z>>x$, neglecting the longitudinal coordinate z change during the interaction, and choosing the coordinates x'' and z'' equal to zero for the hydrogen atom in its rest frame, we obtain the electric field in the rest frame of the hydrogen atom:

$$E(t'') = E_0\gamma(1+\beta\cos\alpha)\exp(-\frac{y''^2+(\gamma Vt'')^2}{W_0^2(1+\frac{S^2}{z_0^2})} + j\omega t''\gamma(1+\beta\cos\alpha) - jk\frac{y''^2+(\gamma Vt'')^2}{2S(1+\frac{z_0^2}{S^2})} + j\varphi)$$

,

where φ is the almost constant phase of the oscillation, ω is the laser frequency, and E_0 is the electric field amplitude at the interaction point in the laboratory frame. The vertical coordinate Gaussian dependence hints that the laser beam vertically should cover the hydrogen beam. For our next calculations we, having this in mind, put $y''=0$ for simplicity. Now we take equation (4a) and substitute the electric field. We obtain:

$$\dot{C}_1 = \frac{i\mu_{1n}E_0\gamma(1+\beta\cos\alpha)}{2\hbar}C_n e^{-\frac{t^2}{2\sigma_t^2}-i\Delta t},$$
$$\dot{C}_n = \frac{i\mu_{n1}E_0\gamma(1+\beta\cos\alpha)}{2\hbar}C_1 e^{-\frac{t^2}{2\sigma_t^2}-i\Delta t}, \qquad (4a2)$$

where $\mu_{1n} = -\int d^3r\, u_1^*(\vec{r}) ezu_n(\vec{r}) = \frac{3^3 ea_0}{2^6\sqrt{2}}$ for n=3 state, $\sigma_t = \frac{W_0(1+\frac{S^2}{z_0^2})^{1/2}}{\sqrt{2}\gamma V}$,

$\Delta = \omega\frac{d\gamma}{\gamma}(1+(1+\frac{1}{\gamma^2})\cos\alpha) + \frac{\Gamma t}{2}$, $\Gamma = \frac{k(\gamma V)^2}{S(1+\frac{z_0^2}{S^2})}$, and the transition frequency ω_0 is

expressed via laser frequency ω by the Dopler expression $\omega_0 = \omega(1+(1-\frac{1}{\gamma^2})\cos\alpha)$.

For the simulation we take $\sigma_t = \frac{2\pi}{\omega_0}12000$ equal to 12000 oscillations in the rest frame of the atom. $\Gamma = 0.0005\frac{\omega_0}{\sigma_t}$, which corresponds to 0.0005 frequency sweep over the laser beam rms size. For this set of parameters S>>z_0, $\Gamma\sigma_t^2 \approx \frac{S}{z_0} = 12\pi$, z0=0.053 m, S=2.0 m, the laser beam rms size 1.36 mm, W0=7.2 10^{-5}m.

Figure 2a2 shows the result for the given parameters and for the Rabi frequency $\mu_{31}E_0\gamma(1+\beta\cos\alpha)/\hbar = 2.5\,10^{12}\,s^{-1}$. The red line shows the particle with $5*10^{-4}$ frequency deviation from the transition frequency, which is about 2.5 rms design linac energy spread. The final number for the probability is about 80% that means that even particles at the distribution tails will be efficiently stripped. To obtain the precise number for the average stripping efficiency one needs involved simulation for the energy and angle distributions. We anticipate this efficiency to be better than 95%.

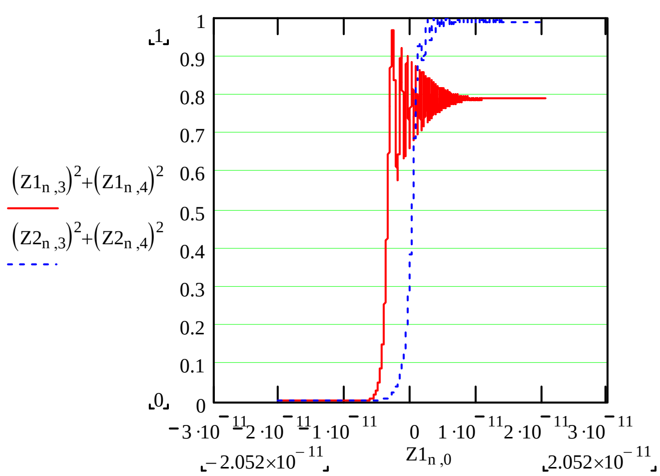

Figure 2a2 Probability of the n=3 excitation versus time for reference energy particle (blue line) and the particle with the relative energy deviation 0.0005 (red line).

As for the laser power, for the round beam with 0.136 cm rms (for the electric field distribution rms is 1.41 times larger), the peak power is 12 MW, similar to what was estimated in section 3.

It turns out that if we squeeze the beam horizontally to 50 μm while keeping the laser power the same, the excitation probability also exceeds 90% - in this case without any angular spread. The reason is that the power density becomes so big that the Rabi frequency for all the particles becomes larger than the Dopler spread of the absorption line width. In this case all the particles excited in the same manner. But the required power density needed is still around 10 MW.