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SEQUENTIAL EXCITATION SCHEME FOR LASER STRIPPING OF HYDROGEN ION BEAMS*

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Abstract

A novel laser stripping scheme based on sequential excitation is proposed for foil-less charge-exchange injection of hydrogen ion (H^-) beams. Our analysis indicates that the new scheme can save the laser power by an order of magnitude for certain particle beam energies. An application to 1.3-GeV hydrogen ion beams is described.

INTRODUCTION

Three-step laser stripping has been investigated as an important "foil-less" method to realize H^- beam charge-exchange injection in high-intensity proton synchrotrons or accumulator rings [1,2]. Among the three steps, the first and third rely on Lorentz stripping while the second step uses a laser to excite hydrogen atoms. In the laser stripping experiments demonstrated at SNS [3,4], an ultra-violet (UV) laser was used to excite 1-GeV hydrogen beams from the 1s state to the 3p state. In the three-step laser stripping scheme, laser power is the primary limiting factor in achieving high stripping efficiency.

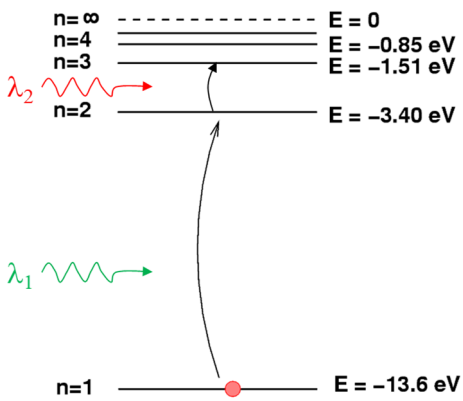

Figure 1: Diagram of sequential resonant excitation.

Here we propose a sequential resonant excitation scheme for laser stripping by using two laser beams to excite hydrogen atoms in a sequence of two steps: from the 1s state to the 2p state and from the 2p state to a higher energy state such as 3d, 4d, etc. Figure 1 shows the diagram of one example where the first laser beam (λ_1) excites the electron from the 1s state to the 2p state while the second laser beam (λ_2) excites the electron from the 2p state to the 3d state. Note that the two laser beams can have the same wavelength with different interaction angles. In the following, we investigate the efficiency of resonant excitations by using a quantity defined as "effective cross-section". The results indicate that the required laser power in sequential excitation scheme can be lowered by nearly an order of magnitude compared to the single-step excitation for a certain range of the hydrogen beam energy. An application of the proposed scheme to the laser stripping of 1.3-GeV H^- beams will be described.

CROSS-SECTION ANALYSIS

In the three-step laser stripping scheme, excitation of H^0 atoms is realized through an undamped Rabi oscillation [1,2]. To obtain the highest population in the excited state, a sufficiently high Rabi frequency ω_R must be achieved, i.e., $\omega_R \gg \Delta\omega_a$ where $\Delta\omega_a$ is the atomic linewidth of the transition. It is known from [2] that the value of ω_R^2 directly determines the efficiency of the resonant excitation. As the Rabi frequency is related with the induced transition rate A_{in} and $\Delta\omega_a$ by a simple form $\omega_R^2 \equiv A_{in} \times \Delta\omega_a$, we derive an "effective cross-section" expression for laser stripping by using the relationship between the induced transition rate and the stripping laser intensity. The cross-section value will be used to evaluate the efficiency of resonant excitations between different energy states.

Cross-sections in Laser Stripping

Interaction of atomic system and electromagnetic (EM) field has been thoroughly studied using the induced transition rate and its dependence on EM field intensity. In the presence of EM field (from the laser) whose energy density is distributed uniformly in frequency in vicinity of the transition frequency from one state to another, an atom can undergo a transition between the two states. For an assembly of fully aligned atoms, the induced transition rate A_{in} by an optimally polarized field is described by [5]

$$A_{in} = \frac{3A_{sp}\epsilon\lambda^3}{8\pi^2\hbar\Delta\omega_a}|E|^2 \qquad (1)$$

where A_{sp} is the spontaneous emission rate, ϵ is the dielectric permeability, λ is the transition wavelength, E is the electric field amplitude, and $\hbar$ is the Planck constant. For randomly aligned atoms, the constant 3 in the numerator in Eq. (1) will be replaced by 1. The term $\epsilon|E|^2$ in Eq. (1) represents the laser energy density and is related to the photon density by $\epsilon|E|^2 = \hbar\omega n_{ph,\omega}$ where $n_{ph,\omega}$ is the photon density near the transition frequency $\omega = 2\pi c/\lambda$ and c is the light speed.

In the case of laser stripping, the H^- energy spread causes a spread of resonant frequencies $\Delta\omega_D$ which is usually much larger than the transition linewidth $\Delta\omega_a$. Using the

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Doppler frequency "sweep" technique [2], one can obtain a laser spectrum with a uniform broadening and achieve a near 100% resonant excitation or laser stripping when the laser spectrum bandwidth matches $\Delta\omega_D$. In this case, the photon density of the entire laser beam, n_{ph}, is related to that near the transition frequency, $n_{ph,\omega}$, as $n_{ph}/\Delta\omega_D = n_{ph,\omega}/\Delta\omega_a$. As a result, we write Eq. (1) as

$$A_{in} = \frac{3A_{sp}\lambda^2}{4\pi\Delta\omega_D} c n_{ph}. \quad (2)$$

From the above equation we can derive an effective cross-section σ for the resonant laser excitation in the three-step laser stripping scheme as

$$\sigma = \frac{3A_{sp}\lambda^2}{4\pi\Delta\omega_D}. \quad (3)$$

As the Rabi oscillation is a highly nonlinear process, its dynamics cannot be described using rate equations based on the cross-section. However, the cross-section defined in the above equation reflects the linearly relationship between the applied photon density and the square of the Rabi frequency, which in turn determines the efficiency of the resonant excitation.

Cross-section Values for Different Transitions

Clearly, the value of the effective cross-section defined in Eq. (3) is solely dependent on the parameters of the H^0 beam: the spontaneous emission rate A_{sp} and the transition wavelength λ between the two energy levels, as well as the required laser spectrum bandwidth $\Delta\omega_D$ that is again determined only by the energy spread of the H^0 beam. We have calculated the cross-sections for different transitions in a hydrogen atom. The spontaneous emission rates used in the calculations are from the database in [6]. We assumed an energy spread of the H^- beam to be 10^{-4} in all cases. The results are summarized in Table 1.

Several conclusions can be drawn from the calculation results. 1) Compared to the cross-section of the direct photo-detachment of the first electron in H^- (2~4×10^{-17} cm^2), the cross-section values for resonant excitations that can be possibly used in the laser stripping are 2~4 orders of magnitude higher. 2) The sequential resonant excitation method, particularly the 1s-2p-3d scheme, is potentially much more efficient than the single-step 1s-3p excitation. Specifically, compared to the current 1s-3p transition, the cross-section for the 1s-2p is about six times higher and that for the 2p-3d transition is two-orders of magnitude higher. Therefore, we can assume that the excitation (stripping) efficiency of 1s-2p-3d scheme is determined by the first excitation only. 3) The cross-section value will significantly drop when the final energy state changes from 3d to higher levels.

Table 1: Calculated Cross-section Values of Different Resonant Excitations

Transition type	Transition energy gap ΔE (eV)	Transition wavelength λ (nm)	Spontaneous emission rate A_{sp} (1/s)	Laser spectrum bandwidth $\Delta\omega_D$ (Hz)	Effective cross-section σ (cm^2)
1s – 3p	12.09	102.57	1.67×10^{8}	1.83×10^{12}	2.29×10^{-15}
1s – 2p	10.20	121.57	6.26×10^{8}	1.55×10^{12}	1.43×10^{-14}
2p – 3d	1.89	656.47	6.47×10^{7}	2.87×10^{11}	2.32×10^{-13}
2p – 4d	2.55	486.27	2.06×10^{7}	3.87×10^{11}	3.01×10^{-14}
2p – 5d	2.86	434.17	9.43×10^{6}	4.34×10^{11}	9.78×10^{-15}

Impact on Stripping Laser Power

Due to the complicated temporal structure of the particle beam in most operating pulsed accelerators, the stripping laser normally has a master oscillator power amplifier (MOPA) configuration so that high peak power can be obtained with a reasonable average power. A typical MOPA system consists of a lower-power laser oscillator that generates micro-pulses, a pulse-picker to generate macropulses, burst-mode amplifier(s), and harmonic conversion optics [7]. Among those, the burst-mode amplifier is probably the most challenging technical component in providing high peak power over long time duration of the macropulse. Currently, the most powerful amplifiers are made from solid-state gain materials and typical wavelengths of the fundamental beam from such materials are within 1.0 ~ 1.1 um. Shorter wavelength laser beams are produced through high-harmonic generations.

An advantage of the sequential resonant excitation scheme is that the required laser wavelengths are longer than that in the single-step excitation scheme. This is particularly important when particle beam energy is less than 1.6 GeV. To excite the hydrogen atoms in the above energy range, the required laser wavelength in the single-step excitation scheme needs to be in the UV regime while that in the sequential excitation scheme can be moved up to the green light regime. Since the laser pulse energy is a direct product of the laser frequency and photon number, to provide a given photon density, the required laser peak power is proportional to the laser frequency, i.e., $P^{(\omega)} \propto n_{ph}\omega$. For typical MOPA lasers, the harmonic generation efficiency of the second-harmonic beam, $P^{(2\omega)}/P^{(1\omega)}$, is no more than 50% and that of the third-harmonic beam, $P^{(3\omega)}/P^{(1\omega)}$, is about 20%. Considering both the harmonic generation efficiency and the wavelength factor, the required laser power of the fundamental beam is approximately 15:4:1 to produce the

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same number of photons at the frequency of 3ω:2ω:ω, respectively. From Table 1, it can be estimated that the required laser power is reduced by a factor of 9 if one uses a 532-nm laser beam in a sequential excitation (1s-2p-3d) compared to using a 355-nm laser beam in a single step (1s-3p) excitation. In this case, the required output power of the fundamental beam (ω) from the laser amplifier is reduced by a factor of 23.

SEQUENTIAL EXCITATION LASER STRIPPING OF 1.3 GeV H⁻ BEAMS

In the Proton Power Upgrade (PPU) project [8] at SNS, the H⁻ beam energy will be increased from the current 1 GeV to 1.3 GeV as a part of the SNS accelerator complex upgrade to double the currently available proton beam power from 1.4 MW to 2.8 MW. Laser stripping of 1.3 GeV hydrogen beam provides an ideal case for the application of the sequential excitation scheme. First, it enables using the second-harmonic laser beam (wavelength in the 500 nm regime) to realize 1s-2p excitation. Second, a direct Lorentz stripping of electrons from the 2p state is impractical at this beam energy level so the second resonant excitation to a higher energy is necessary.

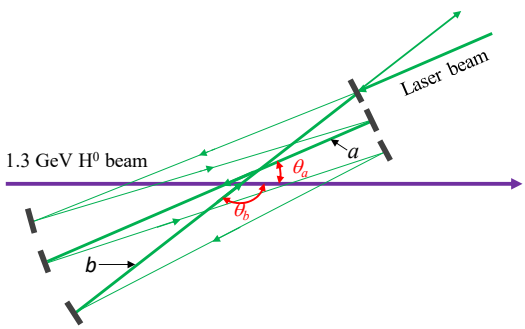

Figure 2: Schematic of sequential resonance excitation for laser stripping of 1.3 GeV hydrogen beams. Highlighted lines *a* and *b*: laser beams for the first-step citation of hydrogen from 1s to 2p and the second-step excitation from 2p to 3d, respectively. θ_a and θ_b are the corresponding interaction angles that depend on the laser wavelength. Two laser beams can be recycled with an optical cavity.

Figure 2 shows a schematic of laser stripping of 1.3 GeV hydrogen beams based on the sequential excitation (1s-2p-3d) scheme. Here two laser beams (*a* and *b*) of the same wavelength will be intercepting with the hydrogen beam at different angles. From Table 1, we know that the required laser power for the 2p-3d excitation is an order of magnitude lower than that for the 1s-2p excitation. Therefore, the same laser beam can be reused to realize both excitations. Furthermore, the two laser-particle interactions can be well configured in an optical cavity to recycle the laser power as shown in the figure. Using our double-resonance optical cavity technology [9], an enhancement factor of 50-100 can be realized for laser beams operated in a macropulse mode.

The laser power budget is discussed in the following. In our previous work [7], it was verified that a 1.5 MW peak power at 355 nm was required to achieve a 95% stripping efficiency through the 1s-3p excitation. Based on the analysis in the previous section, we can predict that the same stripping efficiency will be achieved using a 170-kW peak power laser at 532 nm through a sequential excitation (1s-2p-3d) scheme. By using a power-recycling optical cavity and assuming a power enhancement factor of 50, the required peak power of the laser can be lowered to 3.4 kW. For typical SNS beam parameters (50ps/402.5MHz micro-pulses bunched into 1ms/60Hz macropulses), the average laser power over a 1-ms macropulse is 68 W and the average laser power over 1 second is only about 4 W in this case. Such a laser beam can be possibly delivered using, for example, large-mode area optical fibers. The fiber-based transport line can drastically improve the laser beam pointing stability and mitigate the complexity of laser transport line [7].

CONCLUSION

We have described a sequential resonant excitation scheme for laser stripping of H⁻ beams. The sequential excitation scheme can reduce the stripping laser power by as much as 20 for a certain energy range of the H⁻ beam. The application of the sequential excitation scheme to the laser stripping of 1.3-GeV H⁻ beams has been discussed.

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