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LASER STRIPPING OF H⁻ BEAM*

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Abstract

Basic principles of laser assisted charge exchange injection for H^- ion and H^0 beams are presented. Theoretical aspects of electromagnetic interaction of laser with hydrogen atom and H^- ions are discussed. Laser excitation, photoionization and interaction of atoms and ions with a strong electro-magnetic fields are discussed and compared. Different techniques of LACE for stripping of high current stochastic beams are presented. The optimum parameters of LACE are estimated and compared for various ion beam energies. Experimental developments of laser stripping at the SNS are reviewed. Future plans of LACE at the SNS and J-PARC are discussed.

INTRODUCTION

In this paper we review basic principles and the current status of Laser Assisted Charge Exchange injection LACE at the Spallation Neutron Source SNS. Some other options of LACE with parameters different from SNS are also discussed. For example J-PARC project is developing LACE for H^- beam injection [1–3] and we will discuss challenges and options for it.

Development of LACE is motivated by issues with foil-based charge exchange injection at high-power. Foil heating imposes limitations on the power density before excessive heating leads to foil sublimation. Interaction of the beam with foil material represents a major source of loss, with the injection region of the SNS being the most activated area of the accelerator outside of the neutron production target. Additionally, interaction of beam with the foil causes mechanical deformation of foils that can lead to operational uncertainty, as curled, twisted, or otherwise compromised foils can change the effective thickness of foils modifying the stripping, or loss characteristics [4].

The concept of photo-detachment of neutral atoms or ions by lasers has been known for a long time but the cross-section of that process is too small that makes it practically inapplicable for high efficiency ionization or stripping of 99% of the beam. I. Yamane and V. Danilov proposed the concept of the effective three step laser assisted charge exchange injection LACE [5, 6] that involves realistic powerful lasers and strong magnetic fields for stripping of H^- beam without any foil: $H^- \rightarrow p^+ + 2e^-$. Later on, the idea has been demonstrated experimentally in proof-of-principles experiments at the SNS [7]. The experiment demonstrated high efficiency ~90% stripping of very short ~6 ns longitudinal H^- beam. The real accelerated beam of SNS has 402.5 MHz structure from RF system with multi-microseconds duration. Another experiment [8] demonstrated high efficiency ~90% stripping of few microsecond beam. In this way experiment demonstrated scalability of stripping from shorter to longer pulses. Another experiment at the SNS [9, 10] demonstrated four step LACE scheme that is supposed to be more effective than three step scheme [6] at some particular H^- beam energies.

All LACE experiments carried out at SNS have been performed for beam in the LINAC without real accumulation of the protons into the Ring. The experimental stand was located in the LINAC part of SNS and demonstrated pure stripping of single pass beam $H^- \rightarrow p^+ + 2e^-$ followed by the full beam loss of protons and unstripped H^0 downstream of the experiment. The real operational LACE must provide injection and accumulation of the proton beam into the Ring and this is much more challenging problem than simple demonstration of high efficiency electron detachment. Reference [11] demonstrated the scope of problems and constrains for development of the real LACE system for SNS. The problem becomes even more challenging assuming that SNS has been designed for foil based operation and LACE must be embedded into this existing design as an experimental addition without interference into the foil based operation of SNS.

LACE design and optimization strongly depends on beam parameters and must be considered and developed individually for different accelerator facilities. The beam energy is one of the most key parameters around which we can start designing LACE project. From general considerations of LACE theory we can say that more H^- beam energy will simplify the design in general. Anyway, every particular energy requires individual consideration and 100 MeV difference for the beam energy can dramatically change the whole design of LACE.

The future Proton Power Upgrade PPU project of SNS will update the beam energy from 1.0 GeV to 1.3 GeV [12]. The new energy makes a big difference for choice of LACE optimal scheme compared to 1.0 GeV scheme used in our previous experiments. We discussed different LACE options for 1.3 GeV energy in Ref. [13].

We begin this paper with basic theory of interaction of electromagnetic field and lasers with a single H^0 atom and

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H^- ion that is relatively simple. Then we will discuss experimental LACE techniques that is much more complicated because real hadron beams with stochastic distribution interacts with a totally different result than single particle. It normally normally leads up to lower stripping efficiency. We will discuss different experimental techniques of H^- and laser beam tuning that allow to suppress the stochastic effect of realistic beams and increase LACE stripping efficiency to a desired level.

PHOTODETACHMENT OF H^- AND H^0

Photodetachment of one electron from H^- ion by laser: $H^- + \gamma \rightarrow H^0 + e^-$ causes transition of external electron from bound state to continuum. This is a linear process powerwise that can be characterised by cross-section with maximum $\sigma = 4.0 \times 10^{-21}$ m^2 for $\lambda = 800$ nm laser wavelength in the particle rest frame [14]. Photodetachment of neutral hydrogen atom $H^0 + \gamma \rightarrow p^+ + e^-$ can also be characterized by photoionization cross-section calculated by simple quantum-mechanical theory [15]. The maximum cross-section $\sigma = 6.3 \times 10^{-22}$ m^2 corresponds to laser wavelength $\lambda = 91$ nm for threshold energy of ionization of hydrogen atom $E = 1/2$ a.u. Figure 1 represents wavefunctions of hydrogen ion and neutral atom in different excited and non-excited states.

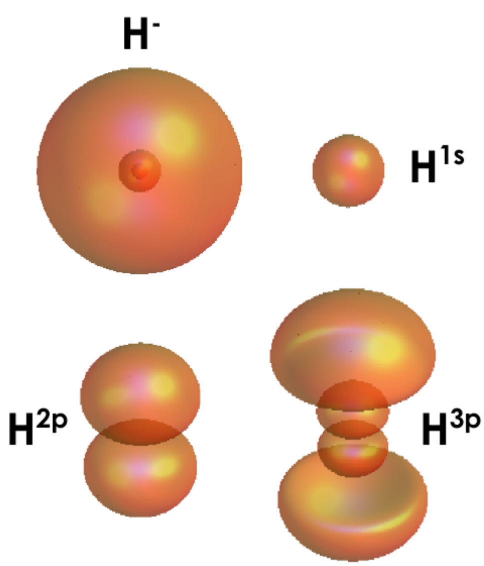

Figure 1: Wavefunctions of different species of hydrogen atom and ion.

From Table 1 it is seen that cross-sections of photodetachment are very small. Efficiency of photodetachment can be estimated by integration of two Gaussian laser and hydrogen bunches interacting in laboratory frame with relativistic energies. Calculation [13] show that high-efficiency photodetachment at 99% level requires enormous average laser power for full-duty length of H^- beam of microseconds duration.

Table 1: Cross-sections of photodetachment and optimal laser wavelength for different species of hydrogen atom and ion.

H Species	Cross-section σ	Wavelength λ
H^-	4.0×10^{-21} m^2	800 nm
$H^0(1s)$	6.3×10^{-22} m^2	91 nm
$H^0(2p)$	1.7×10^{-21} m^2	364 nm
$H^0(3p)$	3.3×10^{-22} m^2	820 nm

H STRIPPING IN MAGNETIC FIELDS

For relatively high energies > 600 MeV of H^0 and H^- beams it is more effective to use Lorentz ionization in magnetic fields. Strong transverse magnetic field B in laboratory frame transforms into electric field E in the particle rest frame of relativistic beam:

$$E = \gamma v B \qquad (1)$$

Hydrogen ion H^- becomes unstable in this electric field and decays quickly $H^- \rightarrow H^0 + e^-$. Lifetime of H^- can be calculated by empirical formula [16]. Lifetime of neutral hydrogen atom in electric field can be calculated numerically and analytically using perturbation theory of hydrogen atom in external electric field [17]. Realistic permanent magnet with field of the order of 1 - 2 T can do stripping of 1 GeV H^- beam. Figure 2 shows stripping of H^- ion with 1 GeV energy in a linearly growing magnetic field.

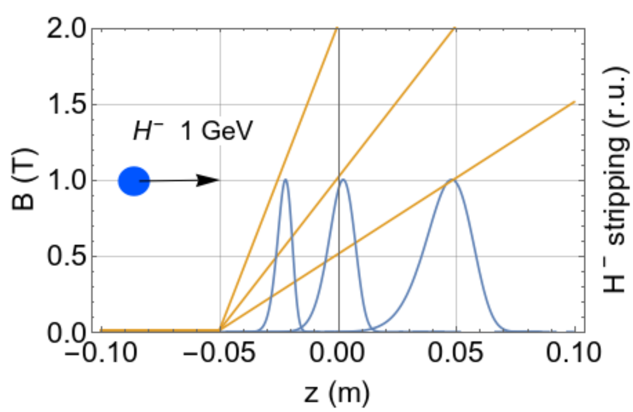

Figure 2: Stripping of H^- beam with 1 GeV energy in a different transverse magnetic fields that linearly grow from left to right. Lower curves show stripping rate/probability distribution along z-direction of the H^- ion.

The lower curves of Fig. 2 show stripping rate or probability distribution along H^- beam direction. It is seen that H^- beam gets maximum stripping rate at about 1 T magnetic field.

The neutral atom H^0_{1s} has much stronger quantum mechanical connection of its electron to the proton. Simulations show that it requires very strong non-realistic magnetic field for Lorentz stripping. Figure 3 demonstrates Lorentz stripping of 1 GeV H^0 beam in 30 T magnet. Stripping field for

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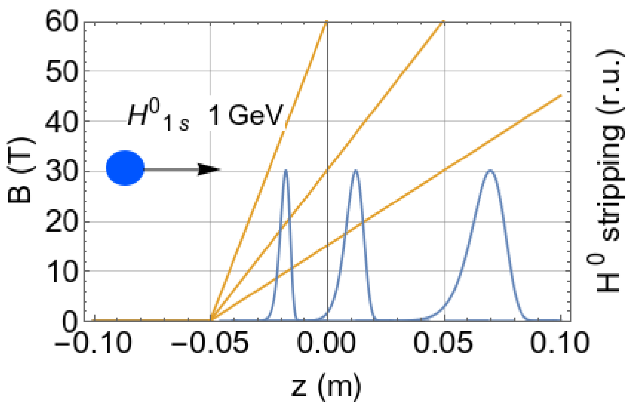

Figure 3: Stripping of H^0_{1s} neutral hydrogen beam with 1 GeV energy in a different transverse magnetic fields. Lower curves show stripping rate/probability distribution along z-direction of the H^0 atom.

neutral hydrogen atom can be reduced to realistic 1 T magnet but it would require high energy H^0 beam up to 100 GeV.

The neutral hydrogen beam in 3p-excited state can be stripped as easily as H^- beam (see Fig. 4). Reference [13]

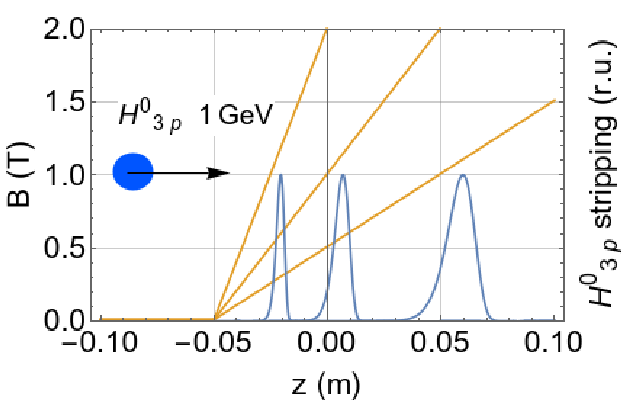

Figure 4: Stripping of H^0_{3p} neutral hydrogen beam with 1 GeV energy in a different transverse magnetic fields. Lower curves show stripping rate/probability distribution along z-direction of the H^0 atom.

shows that it is required about 5 T magnetic field for Lorentz stripping of 2p excited state hydrogen with 1.3 GeV beam energy. From all figures on Lorentz stripping it is seen that longitudinal stripping spread of hydrogen beam depends on gradient of stripping magnetic field. More gradient gives the lower longitudinal stripping spread that finally leads to a smaller emittance growth and better quality of the stripped beam.

THREE STEP LACE SCHEME

In 2003 V. Danilov proposed practically possible scheme of LACE [6]: $H^- \rightarrow p^+ + 2\,e^-$ based on Lorentz stripping parameters in the previous section. Figure 5 represents schematics of the three step LACE scheme.

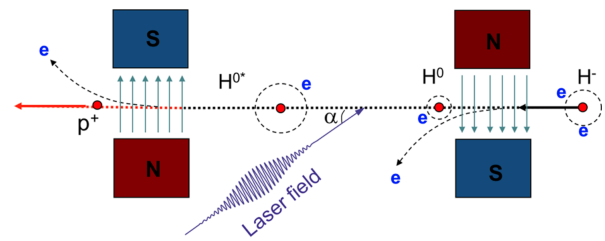

Figure 5: Three step LACE scheme.

The first and the third steps are straightforward schemes of Lorentz stripping of H^- and H^0_{3p} by permanent magnets (see Figs. 2 and 4). The second step is a resonant excitation of hydrogen atom by laser from 1s state to 3p excited state. The resonant excitation energy levels of hydrogen atom can be calculated from $E_n = -1/2n^2$. The resonant excitation energy of photon between 1s and 3p levels are calculated as $E_3 - E_1 = 4/9$ a.u. Resonant laser wavelength λ_0=102 nm in particle rest frame can be adjusted by external laser with given wavelength λ and angle of interaction α using relativistic Doppler effect [6]:

$$\lambda_0 = \frac{\lambda}{\gamma_p(1 + \beta_p \cos\alpha)} \qquad (2)$$

It is seen from Eq. (2) that resonant excitation is much more sensitive on beam energy/momentum p than Lorentz stripping. For this reason, LACE scheme must be developed and optimized individually for project with particular beam energy. It has been shown that high efficiency resonant excitation requires hundreds of times smaller laser power than power needed for direct photodetachment considered in the first section.

EXPERIMENTAL METHODS OF LACE FOR REALISTIC BEAMS

Equation (2) represents ideal resonant condition for single particle excitation moving with particular momentum p and single laser directed at angle α in laboratory frame. The real H^- beam has angular-energy distribution that keeps most of the bunch particle out of resonance. In this way, by tuning experimentally laser angle for design particle using condition (2) will result to low efficiency statistical excitation of the whole bunch because most of the bunch particle will be out of resonance. The real LACE requires different experimental methods for improvement excitation efficiency of the whole bunch in order to increase total stripping efficiency.

Laser Divergence Tuning

The first method of high-efficiency excitation is using of the chirped-pulse laser beam in particle rest frame by tuning up laser beam divergence in laboratory frame [6]. In other words, it means that laser with angular divergence $\delta\alpha$ around design angle α will provide good resonant conditions for most of bunch particles with longitudinal momentum spread δp around design particle p.

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H⁻ Beam Tailoring

It is seen from Eq. (2) that particles with different angles $\alpha(p)$ can have perfect resonance with different p with other parameters fixed. Normally, the angular and momentum distribution $\delta\alpha$ and δp is not correlated for real stochastic H^- beams. Anyway we can tune up correlation in a phase-space $\{\alpha, p\}$ distribution by tuning dispersion function of H^- at the interaction point. Faster particles $p + \delta p$ can have bigger angle $\alpha + \delta\alpha$ and slower particles $p - \delta p$ can have smaller angle $\alpha - \delta\alpha$ within the hydrogen bunch. In this way we can provide good resonant condition (2) for most particles and get high efficiency excitation. Dispersion derivative D' parameter of H^- beam in a plane of interaction with laser is responsible for optimal correlation between $\{\alpha, p\}$ parameters distribution. SNS accelerator has strong bending magnets to control dispersion function as needed at the interaction point of LACE experiments (see Fig. 6).

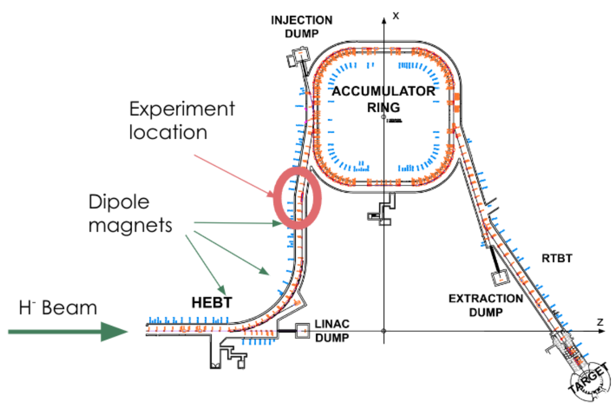

Figure 6: Schematics of SNS injection system, location of the LACE experiment and beam transportation.

Sequential Scheme of Excitation

There is a way to reduce laser power for 1s→3p excitation developed in [9] and experimentally demonstrated in [10]. Sequential two step excitation 1s→2p→{3s,3d} requires exactly the same total photon energy as 1s→3p excitation but the quantum mechanical dipole moment transition of every sequential step is much stronger than for the single 1s→3p step. In this way, sequential scheme requires smaller laser power for excitation than the single step scheme.

Crab-crossing LACE Scheme

Crab-crossing scheme to increase LACE efficiency is another way of H^- beam tuning [18]. The scheme improves space overlap between laser and hydrogen beam. It is required for high efficiency interaction that laser pulse would have comparable or bigger longitudinal size than hydrogen bunch. In a real experiment the laser pulse is smaller and the interaction is not that effective. It is possible to tune up hydrogen beam orientation by tuning dispersion function to provide "head-on" interaction between two beams in the particles rest frame. The crab-crossing scheme also needs strong dipole magnets for dispersion tuning at the interaction point of the LACE experiments (see Fig. 6).

Broad Shape Resonance of Hydrogen Atom

Another idea of high efficiency resonant excitation of stochastic hydrogen beam with momentum angular spread has been proposed in [19] and calculated in details in [20]. Static electric field creates perturbation of hydrogen atom and its quantum states and energy levels in the particle rest frame. this effect is called as Stark effect. A very strong electric field turns discrete energy levels E_n into continuum spectrum with some spectrum width: $E_n \rightarrow E_n \pm \delta E$. In this way precise resonant wavelength in (2) becomes more tolerable: $\lambda_0 \rightarrow \lambda_0 + \delta\lambda$ that also provides good resonant conditions for most particles of the hydrogen bunch with angular-momentum distribution. Electric field in particle rest frame can be created by external magnetic field in laboratory frame similarly to Lorentz stripping. Excitation of hydrogen beam must be carried out directly in a magnetic field.

The method of broad shape resonant excitation is hard to apply practically because it will work properly only within a small range of hydrogen beam energy about 4 GeV. First of all, it is reasonable to apply this effect only for 1s→2p excitation using σ polarization of laser beam i.e. E-polarization of laser must be perpendicular to static electric field in the particle rest frame. Hydrogen states in parabolic system of coordinates have parabolic quantum numbers $\{n_1, n_2, m\}$. 1s→2p, σ-polarized excitation has the following form in parabolic system of coordinates: $\{0,0,0\} \rightarrow \{0,0,\pm 1\}$. Those two parabolic states of hydrogen atom are the only two quantum states not affected by Stark effect. In this way we can get positive effect of resonance broadening of $\{0,0,\pm 1\}$ level without negative effect of Stark splitting of the excited state. Calculations show that reasonable broadening of the $\{0,0,\pm 1\}$ state requires minimum 4 GeV beam energy and about 2 Tesla magnet. The resonant broadening will have about optimum effect at these parameters. After excitation the Lorentz stripping requires minimum 4 GeV beam energy for striping of $\{0,0,\pm 1\}$ state by using 1 to 2 T magnet. The broadening of $\{0,0,\pm 1\}$ also has limitation for strong electric fields. The upper level becomes broader for stronger fields but the dipole moment transition $\{0,0,0\} \rightarrow \{0,0,\pm 1\}$ becomes smaller. Calculations [20] show that optimal broadening is located at about 4 GeV beam energy in 2 T magnetic field.

LACE SCHEME FOR 4 GeV H⁻ BEAM

The ideal scheme of LACE would involve excitation of H^0 atom using the most effective transition 1s→2p by the most powerful and narrow-band laser of λ=1064 nm wavelength and using realistic permanent 1 to 2 T magnet for stripping H^- and H^0_{2p} beams. Calculations show that 4 GeV is the most optimal energy of the beam that satisfy all listed conditions. The angle of interaction between the laser and the hadron beam is α=47^0. In the normal three step LACE scheme (see the Fig. 5) we use two different magnets for H^- and H^0 stripping in order to avoid Stark effect for 3p level. For this reason, we use magnets of opposite polarities and laser

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interaction point between them with transverse magnetic field B=0. As we already mentioned, 1s→2p excitation state by σ-polarized laser is not affected by Stark effect so the scheme can be simplified by using only one magnet and excitation point inside of it (see Fig. 7).

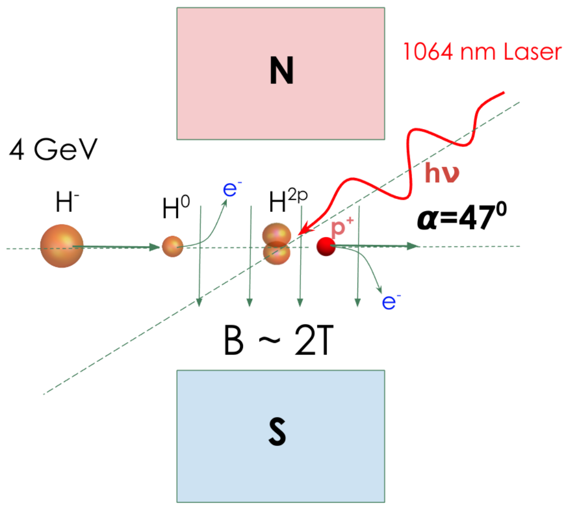

Figure 7: The most optimal LACE scheme for 4GeV beam.

Using only one magnet has a few advantages instead of using two magnet scheme.

- It makes scheme the most compact, simpler and can be designed and placed in a real charge-exchange area.
- 2p excited state has no spontaneous decay: $H^0_{2p} \rightarrow H^0_{1s} + \gamma$ after excitation point and Lorentz stripping point compared to the scheme of the three step scheme because it is being excited and stripped immediately in a strong magnetic field. In this way it has no efficiency loss due to the mechanism of decay and stripping efficiency can be as much as 100%.
- As it was shown in [20], strong magnetic field about 2 T makes the most optimal broadening of 2p excited state that simplify resonant excitation and compensates momentum-angular beam spread without using laser divergence.

FUTURE PLANS FOR LACE AT THE SNS

In Ref. [11] we considered design for real LACE injection of the proton beam into the ring at the SNS. It has been shown that real LACE project has a number of problems and challenges at the injection area (see Fig. 8) compared to demonstration experiments carried out at the SNS.

Before we design the LACE at the injection area we are planning to do stripping experiments for 1.3 GeV in the LINAC area the at the same location (see Fig. 6) replacing old experimental vessel with the new one. The new experimental vessel is designed for 1.3 GeV beam stripping and has more possibilities of using different LACE schemes, different angles and different laser wavelengths (see the Figure 9). Figure 10 represents possible mechanism of excitation of hydrogen beam by different lasers.

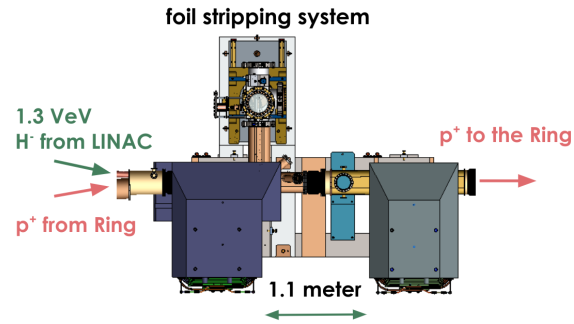

Figure 8: Foil operated design of the injection area for 1.3 GeV proton power upgrade PPU project [12].

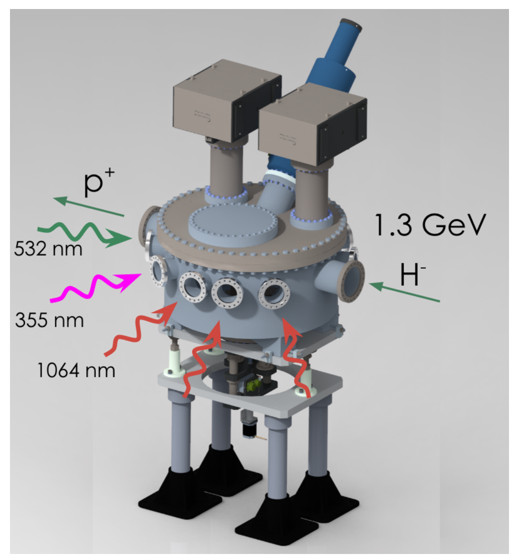

Figure 9: Design of experimental vessel for the next series of LACE experiments in LINAC area for 1.3 GeV H⁻ beam.

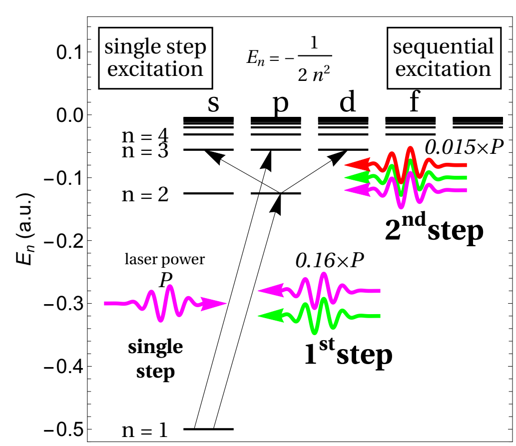

Figure 10: Schematics of hydrogen atom and different mechanisms of resonant excitation by different lasers.

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REFERENCES

[1] I. Yamane, "Foil-free charge-exchange injection for J-PARC RCS", KEK, Japan, KEK Report 2021-3, July 2021.

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

[3] P. Saha, "Status of Laser Stripping Activities and Experimental Results", *US-Japan High-Power Neutrino Beams Meeting*, March 27, 2023.

[4] M. Plum, "H^- Charge Exchange Injection Issues at High Power", in *Proc. HB'16*, Malmö, Sweden, Jul. 2016, pp. 304–309. doi:10.18429/JACoW-HB2016-TUPM6X01

[5] I. Yamane, "H^- charge-exchange injection without hazardous stripping foils", *Phys. Rev. Accel. Beams*, vol. 1, p. 053501, 1998. doi:10.1103/PhysRevSTAB.1.053501

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

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

[8] S. Cousineau *et al.*, "First Demonstration of Laser-Assisted Charge Exchange for Microsecond Duration H^- Beams", *Phys. Rev. Lett.*, vol.118, p. 074801, 2017. doi:10.1103/PhysRevLett.118.074801

[9] T. Gorlov, A. Aleksandrov, S. Cousineau, Y. Liu, A. Rakhman, and A. Shishlo, "Sequential excitation scheme for laser stripping for a H^- beam", *Phys. Rev. Accel. Beams*, vol. 22, p. 121601, 2019. doi:10.1103/PhysRevAccelBeams.22.121601

[10] A. Aleksandrov *et al.*, "Experimental demonstration of sequential excitation scheme for H^- laser assisted charge exchange", *Phys. Rev. Accel. Beams*, vol. 26, p. 043501, 2023. doi:10.1103/PhysRevAccelBeams.26.043501

[11] T. Gorlov, A. Oguz, A. Aleksandrov, N. Evans, S. Cousineau, and Y. Liu, "Laser assisted charge exchange injection into the ring at the SNS", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 1311-1313. doi:10.18429/JACoW-IPAC2023-TUOGA1

[12] J. Galambos *et al.*, "Final design report proton power upgrade project", https://neutrons.ornl.gov/sites/default/files/Final_Design_Report.pdf

[13] T. Gorlov *et al.* , "Laser stripping for 1.3 GeV H^- beam at the SNS" in *Proc. NAPAC'22*, Albuquerque, NM, USA, Aug. 2022, pp. 702–704. doi:10.18429/JACoW-NAPAC2022-WEPA33

[14] J. T. Broad, W. P. Reinhardt, "One- and two-electron photoejection from H^-: A multichannel J-matrix calculation", *Phys. Rev. A*, vol. 14, p. 2159, 1976. doi:10.1103/PhysRevA.14.2159

[15] H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One and Two Electron Atoms*, Berlin, Germany, Springer, 1957.

[16] A. Chao, K. Mess, M. Tigner, and F. Zimmermann, *Handbook of Accelerator Physics and Engineering*, Singapore, World Scientific Publishing, 2013.

[17] R. J. Damburg and V. V. Kolosov, "A hydrogen atom in a uniform electric field. III," *J. Phys. B: At. Mol. Phys.*, vol. 12, p. 2637, 1979. doi:10.1088/0022-3700/12/16/011

[18] A. Aleksandrov *et al.*, "A Crab-Crossing Scheme for Laser-Ion Beam Applications", in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 639–641. doi:10.18429/JACoW-NAPAC2019-WEYBB5

[19] I. Yamane, T. Suzuki, and K. Takayama, KEK, Japan, KEK Report No. 2002-76, 2002.

[20] T. Gorlov and V. Danilov, "Effective calculation of laser stripping via a broad shape resonance", *Phys. Rev. Accel. Beams*, vol. 13, p. 074002, 2010. doi:10.1103/PhysRevSTAB.13.074002