Laser Diagnostic for High Current H^- Beams*

Robert E. Shafer

Los Alamos National Laboratory
Los Alamos, NM 87545

Abstract. In the last 5 years, significant technology advances have been made in the performance, size, and cost of solid-state diode-pumped lasers. These developments enable the use of compact Q-switched Nd:YAG lasers as a beam diagnostic for high current H^- beams. Because the threshold for photodetachment is only 0.75 eV, and the maximum detachment cross section is 4×10^{-17} cm^2 at 1.5 eV, A 50 mJ/pulse Q-switched Nd:YAG laser can neutralize a significant fraction of the beam in a single 10 ns wide pulse. The neutral beam maintains nearly identical parameters as the parent H^- beam, including size, divergence, energy, energy spread, and phase spread. A dipole magnet can separate the neutral beam from the H^- beam to allow diagnostics on the neutral beam without intercepting the high-current H^- beam. Such a laser system can also be used to extract a low current proton beam, or to induce fluorescence in partially stripped heavy ion beams. Possible beamline diagnostic systems will be reviewed, and the neutral beam yields will be calculated.

INTRODUCTION

Laser systems have been in use at the Los Alamos LAMPF 800 MeV proton linac and on various low-energy H^- beamlines since about 1980 to do research or diagnostics on the accelerated H^- beam. The basis for these systems is that the threshold for photodetaching an electron is about 0.75 eV, and the photodetachment cross section rises to about 4×10^{-17} cm^2 for photons of about 1.5 eV (800 nm).

A Q-switched laser, when triggered, fully discharges in a few ns. Thus a small Q-switched laser with, say 50 mJ pulse energy and 10 ns pulse length, has the instantaneous power of 5 MW. Furthermore, a 50 mJ pulse at 1064 nm wavelength contains over 2×10^{17} photons. Because the photodetachment cross section is substantial, a significant fraction of the beam can be neutralized during the laser pulse. The Q-switched laser beam can either be focused to select a thin slice of the transverse beam profile, or defocused to nearly uniformly illuminate the entire beam. Real-time

* Work supported by DOE.

measurements can be made on the extracted neutral H^0 beam to determine parameters of the H^- beam. These parameters include transverse beam profiles, beam current, and even emittances.

In the photodetachment process, the neutralized beam maintains nearly the original phase-space parameters of the H^- beam from which it was extracted. This is because neither the laser photon nor the recoiling photodetached electron transfer significant momentum to the H^0 atom. Thus the transverse spatial profile, transverse divergence, emittance, energy, energy spread, and phase spread characteristics of the H^0 and H^- beams are the nearly identical. Furthermore, because the neutralized beam will not be deflected by either electric or magnetic fields, the H^- beam parameters can be deduced from measurements on the drifting neutral beam, even after it is separated from the H^- beam by magnetic fields. Measurements on the neutral beam, even if totally destructive, will have no impact on the H^- beam from which it was extracted.

For high current H^- beams, such as the one being planned for the 1 MW Spallation Neutron Source at Oak Ridge National Laboratory, laser photodetachment of H^- ions provides a way to measure beam parameters that is neither disruptive to the primary beam, nor destructive to the beam diagnostic.

THEORY

Photodetachment Cross Section

A plot of the photodetachment (stripping) cross section vs. photon energy, in the rest frame of the H^- atom, is shown in Figure 1 (1–3).

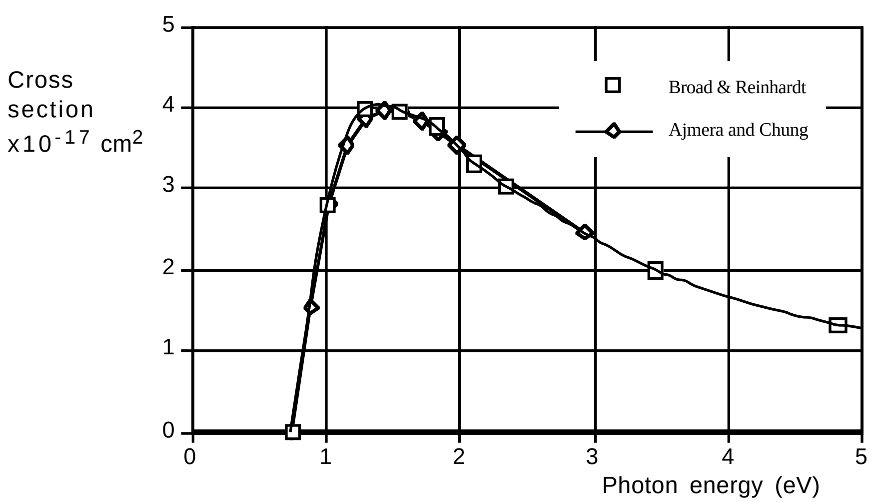

FIGURE 1. Photodetachment cross section of H^- vs. photon energy in the H^- rest frame. The threshold is at 0.75 eV (1650 nm). The maximum cross section occurs at about 1.5 eV.

The threshold is at about 0.75 eV and the peak cross section, 4×10^{-17} cm^2, is at about 1.5 eV. Because the binding energy of the remaining 1s electron in the neutral hydrogen atom is 13.6 eV, it will not be stripped by the laser.

Lorentz Transformation

Because H^- beams can be accelerated to energies of 1 GeV or more, there is a very sizable relativistic shift of the laser photon energy to higher energies in the H^- rest frame, often referred to as a "Lorentz boost". The photon energy E_{CM} in the H^- rest frame is related to the laser photon energy E_L by the equation

$$E_{CM} = \gamma E_L \left[1 - \beta \cos\left(\theta_L\right)\right] \tag{1}$$

where β and γ are the Lorentz parameters of the H^- beam, and θ_L is the laboratory angle of the laser beam relative to the H^- beam.

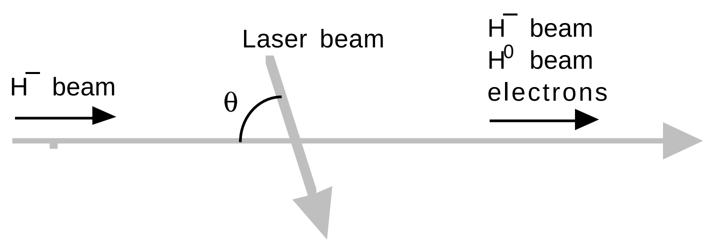

FIGURE 2. Geometry for laser photodetachment.

Photodetachment Yield

For a Gaussian-profile laser beam with N_L photons intercepting a Gaussian-profile H^- beam of current I_b at an angle θ_L, the yield Y_1 (number of neutral hydrogen atoms produced per laser-H^- beam crossing) is given approximately by (4)

$$Y_1 = \frac{I_b N_L}{e\beta c} \frac{1-\beta\cos\theta_L}{\sin\theta_L} \frac{\sigma_N\left(E_{cm}\right)}{2\pi\sigma_b\sigma_L} \int_{-\infty}^{\infty} \exp\left(\frac{-x^2}{2\sigma_b^2}\right) \exp\left(\frac{-x^2}{2\sigma_L^2}\right) dx$$

$$= \frac{I_b N_L}{\sqrt{2\pi} e\beta c} \frac{1-\beta\cos\theta_L}{\sin\theta_L} \frac{\sigma_N\left(E_{cm}\right)}{\left(\sigma_b^2+\sigma_L^2\right)^{1/2}} \tag{2}$$

where σ_b and σ_L are the transverse rms sizes of the H^- and laser beams normal to the plane of incidence, and σ_N (E_{cm}) is the photodetachment cross section at photon energy E_{cm} in the H^- rest frame.

The yield of photodetached H atoms for a 50 mJ 1064 nm Nd:YAG laser pulse on a 50 mA, 1 GeV H^- beam, using Eqs (1) and (2) and the following parameters:

- θ_L = 85° (chosen to optimize both cross section and mirror angle)

- E_{cm} = 2.22 eV (Lorentz-boosted photon energy in rest frame of H^-)
- $\beta c = 0.875 \times 3 \times 10^{10}$ cm/s (beam velocity)
- $N_L = 2.68 \times 10^{17}$ (photons per laser pulse)
- σ_b and σ_L = 0.2 cm (rms width of laser and H^- beams)
- σ_N (E) = 3×10^{-17} cm^2 (photodetachment cross section at energy E_{cm}),

is $Y_1 = 1.25 \times 10^8$ H^0 atoms per laser pulse (single crossing).

This technique can also be used for low-energy (< 10 MeV) H^- beams because the detachment cross section (Fig. 1) is 3.5×10^{-17} cm^2 at 1.17 eV (1064 nm). In fact, because the yield is inversely proportional to β, the yield is larger for low-energy beams. In the above example, if the beam energy is lowered to 2.5 MeV, the yield increases to 1.6 ˝ 10^9 atoms.

Yield Enhancement

A variety of mirror configurations for reflecting the laser beam through the H^- beam many times are possible. The simplest configuration is two parallel front-surface mirrors. Another configuration is an internally-reflecting cylindrical mirror with its axis aligned along the beam. Also, an elliptical shaped internally-reflecting mirror (integrating sphere) is possible. In theory, if the reflection coefficient is 100%, all the photons could be stored in the integrating sphere until they were either absorbed by the beam or exited through the entrance aperture. The actual reflectivity of the mirror limits the number of reflections to a few tens or hundreds of times. Another practical limit is that to take advantage of the temporal resolution of a very short Q-switched laser pulse, which is useful in maximizing signal to noise, the effective photon lifetime in the mirror should not exceed a few ns. An effective lifetime of 10 ns corresponds to a photon path length of about 300 cm, which represents about 30 reflections inside a 10 cm diameter mirror assembly. Thus the optimum mirror assembly needs to reflect the laser beam through the H^- beam only about 30 times, an easily achievable number even with modest reflectivities.

Specifically, if the laser beam passes through the H^- beam N times, the fractional yield F_N of H^0 current is related to the fractional yield F_1 of a single crossing by the relation

$$F_N = 1 - (1 - F_1)^N \cong NF_1, \tag{3}$$

where the approximation is true when the depletion of the H^- beam is not significant.

In the first example above, the average H^0 beam "current" during a 10 ns Q-switched laser pulse is about 2 mA, or 4% of the H^- beam current. Thus with N=10 mirror reflections, the total yield is about 17 mA (34% of the H^- current).

Backgrounds

There are two sources of background uniquely associated with H^- beams. They are magnetic stripping and residual gas stripping. If not controlled, these stripping mechanisms can contaminate the signal obtained by laser stripping. For high current, high energy H^- beams, these loss mechanisms can also contribute to a significant amount of activation. A beam loss of one watt per meter at 1 GeV can lead to activation levels in the range of tens of mrad/hr.

A relativistic H^- beam can be stripped by the Lorentz-transformed magnetic field of a typical beamline magnet. The theory of electric and magnetic field stripping of H^- beams is discussed by Sherk(5) and by Jason(6). As an example, the stripping loss rate of a 1 GeV H^- beam in magnetic fields of 0.3 T, 0.35 T, and 0.4 T is 0.12, 7.4, and 164 ppm per meter respectively.

A relativistic H^- beam can also be stripped by inelastic collisions with residual gas atoms. The cross sections for this process have been evaluated by Gillespie(7). As an example, the cross sections for stripping a 1 GeV H^- beam in hydrogen and nitrogen gas are about 1.2 and 8.9 ˝ 10^{-19} cm^2/atom, and scale approximately as $1/\beta^2$. For a 1×10^{-7} torr (273 K) vacuum, these cross sections represent stripping losses of about 0.08 and 0.6 ppm per meter respectively.

It is relevant here to mention the possibility of using solid state laser diodes, whose instantaneous light output power is a few watts, for beam diagnostics applications. The Q-switched Nd:YAG laser example above has an instantaneous output power of 50 mJ ÷ 10 ns = 5 MW, and yields peak photodetachment currents of a few percent of the H^- beam. Thus backgrounds of 1 ppm/meter from either magnetic or residual gas stripping will create significant interference with any laser whose peak output is only a few watts. Thus although solid-state laser diodes may be useful as a device for extracting very small average currents from a H^- beam, they are probably not suitable as a beam diagnostic.

EXPERIMENTAL APPLICATIONS

Characteristics of Commercially Available Q-Switched Lasers

Inexpensive shoebox-sized Q-switched Nd:YAG lasers can produce 10 ns long, 50 mJ, 1064 nm pulses (or harmonics) at 60 Hz. These units are totally enclosed, and can be installed directly on a beamline. The 1064 nm line is nearly ideal for general diagnostics on H^- beams, because of its proximity to the peak in the photodetachment cross section. The 10 ns pulse width is adequate for many applications where good temporal response is required, and this can be improved if necessary by using external polarizers and Pockels cells.

Possible Experimental Layouts and Measurements

A generic layout for a laser diagnostic is shown in Figure 3. In Figure 3, the Q-switched laser beam intercepts the H^- beam at an angle θ_L. A mirror assembly produces multiple passes of the laser beam. A dipole magnet separates the neutral beam from the H^- beam. If a dipole magnet, such as in a bend, is not possible, then a weak dipole field will deflect the detached electrons, which can be detected. After the neutral beam emerges from the dipole magnet, it may be foil-stripped to produce a proton beam. A variety of beam diagnostics for characterizing the resultant proton beam are possible. Because the proton beam is low power, the diagnostic may totally intercept the protons.

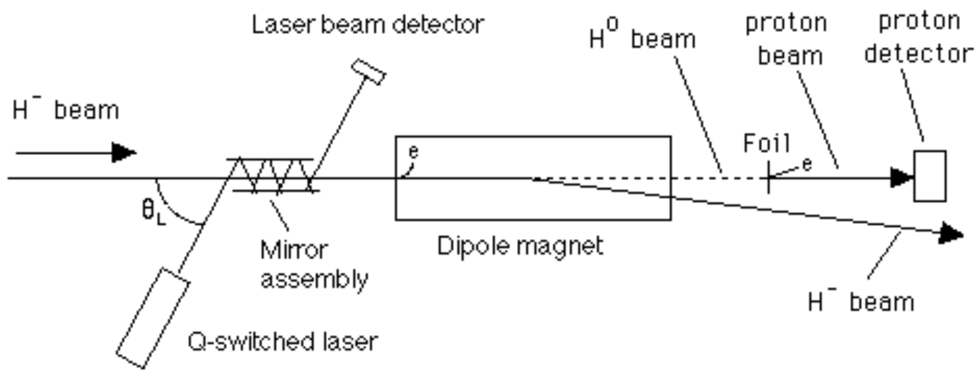

FIGURE 3. A generic arrangement for laser beam diagnostics.

A laser beam for transverse beam diagnostics can either be a thin "laser wire", neutralizing only a thin slice of the incident H^- beam, or intercept the entire beam(8–10). The width of the laser wire can be of the order of 0.2 or 0.4 mm. If used in a high dispersion region, it may be possible to measure the H^- energy spread. For measuring the proton yield, possible proton diagnostics include phototube-scintillator assemblies, Faraday cups, secondary-emission monitors, etc. Because the photodetachment yield is higher at low energies, lasers may be a good substitute for intercepting wire scanners which are particularly hard to use in low-energy, high dE/dx beams.

It may also be possible to measure the H^- phase spread by detecting the rf phase of secondary-emission electrons from the stripper foil (11). In this application, the secondary emission electrons, which maintain the temporal response of the incident charged particles, can be accelerated into a rf deflector synchronized to the rf bunch structure and through a slit to determine their rf phase to perhaps 15 or 20 ps.

Phase spread of H^- beams can also be measured using cw mode-locked lasers (12). In this method, very short laser pulses, synchronized with the beam microstructure, are used to neutralize 20 ps temporal "slices" of the H^- microbunches. These laser systems usually require special clean rooms for the laser oscillator, amplifier, and pulse compressor.

A very specific application in the proposed Spallation Neutron Source project is to measure the beam current in a 1.18 MHz, 280 ns wide, beam chopper gap, which must be less than about 0.3 μA (about 1 ˝ 10^{-5} of the 28 mA, H^- beam). The laser system can extract a neutral current of about 0.10 μA from this gap for 10 ns, equivalent to about 6200 particles. This can be measured using either charge or scintillator pulse detection techniques to determine the cleanliness of the gap. The very high dynamic range and charge sensitivity required for the beam-in-gap measurement is also useful for exploring the halo region of the primary beam. This is a difficult measurement to make with normal beam profile diagnostics.

When measurement of the photodetached H^0 atom or proton is difficult, measurement of the photodetached electron is possible. The electron has about $1/1840^{th}$ of the proton rigidity, and is easily deflected into detectors by weak magnetic fields. This technique has been used in photodetachment experiments. The photodetached electron is easily deflected by space charge forces in high current H^- beams, however, so the electron signal cannot be analyzed for obtaining accurate H^- beam emittance information.

Resonances in the photodetachment total cross section near the n=2 threshold (10.953 eV) have been used to measure H^- beam momentum and momentum spread (13). In this experiment, a 50 mJ Q-switched Nd:YAG laser operating at 266 and 355 nm was used. Both the Feshbach resonance (10.926 eV, width 30 μeV) and the shape resonance (10.975 eV, width 25 meV) can be used for this measurement, although the widths and strengths of these resonances are not optimum.

Under certain conditions, the H^- beam itself will fluoresce. Laser-induced fluorescence of a 50 MeV H^o beam has been observed (14). If a frequency-quadrupled Nd:YAG laser (266 nm wavelength) intercepts a 1 GeV H^- beam at 99.2°, the photon energy in the H^- rest frame is 10.975 eV. This is the energy for exciting the n=2 shape resonance, with the H^0 final state being either the 2s or 2p state. The cross section for the 2p final state is about 4.5 ˝ 10^{-17} cm^2 (15). The lifetime of the 2p-1s transition is about 1.6 ns (13), which Lorentz-transforms into a decay length ($\beta c\gamma\tau$) of about 87 cm in the laboratory (16). The cross section for the metastable 2s final state is about 1 ˝ 10^{-17} cm^2, and can be quenched by using a magnetic field to Stark-mix it with the 2p state (14). The wavelength and angular distribution of the 121.6 nm 2p-1s fluorescence must be Lorentz-transformed back into the laboratory reference frame. Detection of this laser-induced fluorescence may provide another alternative to detection of the photodetached electrons or protons for beam diagnostics applications.

CONCLUSION

Laser photodetachment can be used on high-current, high-energy H^- beams to carry out a wide variety of beam diagnostic measurements parasitically during normal operation, without having to operate the facility at either reduced current or duty cycle. Suitable Q-switched laser systems are inexpensive, small, and can be mounted on or near the beamline. Most of the proposed laser-based diagnostics techniques have already been demonstrated. Photodetachment can be measured by detecting either the detached H^o, the detached electron, or H^o fluorescence. This method appears to be suitable for low-energy (< 10 MeV) as well as high-energy (1 GeV) H^- beams.

REFERENCES

[1] Broad, J. T., and W. P. Reinhardt, "One and Two-electron Photoejection from H^- Atoms," *Phys. Rev. A*, **14**, pp. 2159–72 (1976). See Table IV.

[2] Ajmera, M. P., and K. T. Chung, "Photodetachment of Negative Hydrogen Ions," *Phys. Rev., A* **12**, pp. 475–79 (1975).

[3] Daskhan, M., and A. S. Ghosh, "Photodetachment Cross Section of the Negative Hydrogen Ion," *Phys. Rev. A*, **28**, pp. 2767–69 (1983).

[4] S. M. Shafroth and J. C. Austin, Eds.; *Accelerator-Based Atomic Physics Techniques and Applications*, A.I.P. Press (1997). Chapter 6 has a comprehensive discussion of photodetachment kinematics and yields, as well as a complete review of many laser experiments on H^- beams.

[5] Scherk, L., "An Improved Value for the Electron Affinity of the Negative Hydrogen Ion," *Can. J. Phys.*, **57**, p. 558 (1979).

[6] Jason, A. J., D. W. Hudgings, and O. B. VanDyck, "Neutralization of H^- Beams by Magnetic Stripping," *IEEE Trans. Nucl. Sci.*, **NS-28**, pp. 2704–6 (1981).

[7] Gillespie, G. H., "Electron-Loss Cross Sections for High Energy H^- Collisions with Low and High Z atoms," *Phys. Rev. A*, **15**, pp. 563–573 (1977), and A16, pp. 943–950 (1977).
[8] Swenson, D. R., E. P. MacKerrow, and H. C. Bryant, "Non-Invasive Diagnostics for H^- Ion Beams using Photodetachment by Focused Laser Beams," Proc. 1993 Beam Instrumentation Workshop (Santa Fe), pp. 343–52, *A.I.P. Conf. Proceedings*, **319** (1994).
[9] Connolly, R. C., et al., "A Transverse Phase Space Measurement technique for High Brightness H^- beams," *Nucl. Inst. and Meth. A*, **312**, pp. 415–419 (1992).
[10] Sandoval,D. P., "Non-Interceptive Transverse Emittance Measurement Diagnostic for an 800-MeV H^- Transport Beam," 1994 Beam instrumentation Workshop (Vancouver). *A. I. P. Conference Proceedings*, **333**.
[11] Witkover, R. L., "A Non-Destructive Bunch-Length Monitor for a Proton Linear Accelerator," *Nucl. Inst. and Meth.*, **137**, pp. 203–11 (1976).
[12] Yuan, Y. W., et. al., "Measurement of Longitudinal Phase Space in an Accelerated H^- beam using a Laser Induced Photoneutralization Method," *Nucl. Inst. and Meth., Vol. A*, **329**, pp. 381–392 (1993).
[13] MacKerrow, E. P. et al., "Laser Diagnostics For H– Beam Momentum And Momentum Spread," Reference 8, pp. 226–35 (1994).
[14] Sander, R. K. et al., "Laser-Induced Fluorescence Measurement Of A 50-Mev Hydrogen Atom Beam," *Rev. Sci. Instr.* **62**, pp. 1893–98 (1991).
[15] M. Cortes and F. Martin, "Photodetachment of H^- with Excitation to N=2," *Phys. Rev. A*, **48**, pp. 1227–38 (1993). See Figures 3–5, and associated text.
[16] Bethe, H. A. and E. E. Salpeter, "Quantum Mechanics of One and Two-Electron Atoms," Springer-Verlag (1957), see p. 266.
[17] See chapters 17 and 18 of Ref. 4 for further discussion of laser-induced fluorescence in atomic beams.