LASER DIAGNOSTIC FOR HIGH CURRENT H^- BEAMS*

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1 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 x 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 x 10^{17} photons. Because of the large photodetachment cross section, 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.

Because neither the laser photon nor the recoiling photodetached electron transfer significant momentum to the H^0 atom, the neutralized beam maintains nearly the original phase-space parameters of the H^- beam from which it was extracted.. 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 are neither disruptive to the primary beam, nor destructive to the beam diagnostic.

2 THEORY

2.1 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 Fig. 1 [1-3].

The threshold is at about 0.75 eV and the peak cross section, 4 x 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.

*Work supported by the U.S. Dept. of Energy.

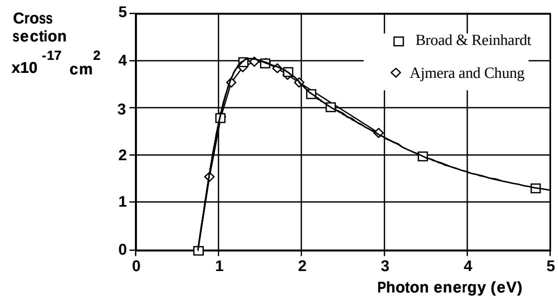

Figure 1. Photodetachment cross section of H^- vs. photon energy in the H^- rest frame.

2.2 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

$$E_{CM} = \gamma E_L (1 - \beta \cos\theta_L)$$

photon energy E_L by the equation
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.

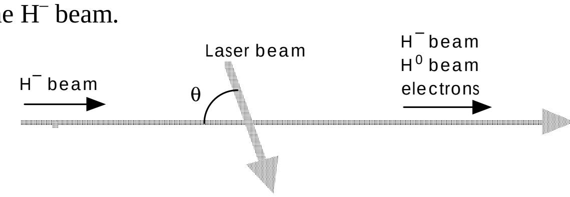

Figure 2. Geometry for laser photodetachment

2.3 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

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

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

where σ_b and σ_L are the transverse rms sizes of the H^- and laser beams normal to the plane of incidence, and $\sigma_N(E_{cm})$ 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 θ_L = 85º, E_{cm} = 2.22 eV (Lorentz-boosted photon energy in rest frame of H^-), βc = 0.875 x 3 x 10^{10} cm/s (beam velocity) N_L = 2.68 x 10^{17} (photons per laser pulse), σ_b = σ_L = 0.2 cm (rms width of laser and H^- beams), σ_N (E) = 3 x 10^{-17} cm^2 (photodetachment cross section at energy E_{cm}), is Y_1 = 1.25 x 10^8 H^0 atoms per laser pulse (single crossing). For a 10 ns laser pulse, this is an instantaneous H^0 ‘current" of 2 mA (4% of H^- current).

This technique can also be used for low-energy (< 10 MeV) H^- beams, because the detachment cross section (Fig. 1) is 3.5 x 10^{-17} cm^2 at 1.17 eV (1064 nm). Because the yield is inversely proportional to β, the H^0 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 x 10^9 atoms (51% of H^- current).

2.4 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. 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, equivalent to 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 mirror reflectivities.

2.5 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 a watt per meter at 1 GeV can lead to activation levels in the range of 10's 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 [4] and by Jason [5]. 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 [6]. 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 x 10^{-19} cm^2/atom, and scale approximately as $1/\beta^2$. For a 1 x 10^{-7} torr (273 K) vacuum, these cross sections represent stripping losses of about 0.08 and 0.6 ppm per meter respectively.

3 EXPERIMENTAL APPLICATIONS

3.1 Commercially Available Q-Switched Lasers.

Inexpensive shoe-box 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.

Solid state laser diodes, with outputs of several watts, may be useful as a device for extracting very small average currents from a H^- beam, but they are probably not suitable as a beam diagnostic. This is because the solid state laser cannot achieve the very high peak power available in a Q-switched laser, required to discriminate against the backgrounds.

3.2 Experimental Layouts and Measurements

A generic layout for a laser diagnostic is shown in Figure 3. In Fig. 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.

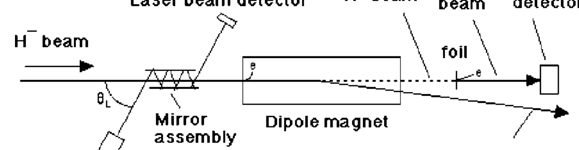

Figure 3. A generic arrangement for laser beam diagnostics.

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 [7-9]. The width of the laser wire can be of the order of 0.2 to 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 H^- beams.

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 1 x 10^{-5} of the 28 mA H^- beam (about 0.3 μA). The laser system with mirrors 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 1/1840th 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 [10]. 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 ideal.

4 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 small, inexpensive, and can be mounted on or near the beamline. Most of the proposed laser-based diagnostics techniques have already been demonstrated.

5 REFERENCES

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