Production of negative ions and generation of intense neutral beams by laser irradiation*

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(Received 20 August 1974)

10 A of H⁻ ion current is produced by a CO₂ laser on NaH targets. A scheme of resonant
detachment of electrons from negative ions by the laser is also discussed.

Intense neutral beams of deuterium or tritium with
energies above 100 keV are ideal for heating plasmas
to fusion temperatures and can also provide the energeti-
cal particle sources required for a wet wood burner. The
conventional method of neutralizing a positive ion beam
by charge exchange becomes inefficient at energies
above 60 keV. On the other hand, neutralization of a
negative ion beam by detaching the extra electron ap-
tears feasible up to quite high energies.

We wish to describe a novel method of producing D⁻
in a dense cold plasma produced by laser irradiation
of an alkali hydride target. Preliminary data on the
production of H⁻ ions with currents up to 10 A in 10
μsec demonstrate the promising features of this method
and their qualitative agreements with the predictions
from the Saha equation. The pulse duration of negative
ions is proportional to that of the laser and therefore
could be lengthened by extending the duration of the
laser pulse. An irradiation scheme of detaching the
electron from the accelerated negative ion is also
described.

The central idea of our method is to produce a plasma
of low electron temperature with a high density of hydro-
gen atoms such that the production of H⁻ is enhanced
according to the Saha equation:

$$N_{H}^{-} \approx N_0 N_2 \exp\left(\frac{E}{kT_e}\right),$$

where $N_0^{-}$, $N_2$ are the densities of the negative hydro-
gen ion and the neutral atom, respectively; $E$, is the
binding energy of the additional electron in the negative
hydrogen ion $= 0.754$ eV; $T_e$ is the electron temperature, and

$$\lambda^3 = 2(2m\hbar^2/\pi kT_e)^{3/2}.$$

The laser-produced plasma satisfies these require-
ments if the radiation power density is not excessive
and the target is composed of atoms of sufficiently low
ionization potential. We have therefore chosen an alkali
hydride as a target and a CO₂ laser in the energy range
1–6 J and pulse duration of 200 ns.

The experimental arrangement consists of a simply
suspended target of NaH powder held inside a crucible
in a vacuum of $10^{-6}$ mm. After the vaporization and sub-
sequent ionization by the laser beam which enters the
chamber through a focusing lens and a low-loss optical
window, the expanding plasma is observed with a
shielded probe. A localized B field of maximum 920 G
produced with an array of permanent magnets is used to
discriminate the electrons which have much smaller
Larmor radii compared with the H⁻ ions of typical
radius of $0.1–0.5$ cm.

This discrimination scheme has been tested with a
separate steady-state negative-ion (SF₆⁻) plasma in a
background argon and electron plasma. A nearly sym-
metric Langmuir curve showing approximately equal
positive and negative ion currents is observed (Fig. 1)
after the plasma is “strained” through the magnetic
field. A further advantage of this magnetic scheme is
that it restricts the electrons to the vicinity of the tar-
gent, this not only increases the electron population near
the target but also leaves the outside region (consisting
of H⁺ and Na⁺) free of electrons. The probability of
collisional detachment of electrons from H⁻ ions in the
outside region is also reduced.

The detection probes (see Fig. 2) were placed so that
the magnetic field was perpendicular to the narrow
ceramic aperture 0.47 cm in length and 0.04 cm in
diameter. Only particles with a significant Larmor

![FIG. 1. Nearly symmetric Langmuir curve of a plasma of
positive argon ions and negative SF₆⁻ ions produced by a mag-
netic grid which discriminates against electrons.](image)

![FIG. 2. Experimental configuration used to detect H⁺ ions. The
recessed probe collects H⁺ ions deflected by the magnetic field
in the clockwise direction. Reversing the B field changes the
optimum probe location to the lower position to collect the
counterclockwise rotating H⁺ ions. The probe current vs its
horizontal position is also shown.](image)
radius and the correct sense of rotation could reach the recessed collector which had an exposed area of $7 \times 10^{-3}$ cm$^2$. The probe shaft was solid copper and shielded the collector wire.

The detection of $H^-$ was further distinguished from that of electrons by their longer time delay taken to reach the probe. The expanding velocity of $H^-$ is measured by the time-of-flight method to be $10^5 - 10^6$ cm/ sec depending on the laser power as shown in Fig. 3. In this configuration an axial probe was used in conjunction with a magnetic field. To avoid too high an electron temperature near the target, which is unfavorable to the formation of $H^-$ we have placed the target 1 cm away from the focal point. The illuminated area of the target is approximately 5 mm in diameter. Our measurements at various laser power levels summarized in Figs. 3 and 4. At lower laser energy the observed $H^-$ density is higher while the expanding velocity $V_d$ is lower. This agrees with Eq. (1) in that a lower $T_e$ produces more negative ions.

Once the negative ions are produced, they can be accelerated to the desired energy. The electron bound to this accelerated negative ion could be resonantly detached in the illumination of a laser beam of the appropriate wavelength ($\leq 1.5 \mu$). Using a detachment cross section of $10^{-17}$ cm$^2$ we compute that for an illumination length of 1 m a laser of 35 kW/cm$^2$ is required. The required intensity might be achieved by reflecting the laser beam back and forth through the interaction region many times; in this way the required power should be in the range of 1 kW/cm$^2$.

We wish to thank Professor F. F. Chen for the use of his laser facility.

*Research supported by the Atomic Energy Commission.

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**Fig. 3.** Density and expansion velocity of negative ions as a function of laser energy at a distance of 5 cm from the target.

**Fig. 4.** Total negative ion current vs laser energy in joules at a distance of 5 cm from the target. Optimization of the target position and laser power could produce up to 10 A of $H^-$ ions as shown by the solid vertical bar at the highest power.

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**Short CO$_2$ laser pulse generation by optical free induction decay**

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(Received 30 May 1974)

Short CO$_2$ laser pulses, adjustable in the range between 0.1 and 0.5 nsec, have been produced by a new pulse-shaping technique. A laser breakdown spark is the active switching element, but the pulse is actually generated by optical free induction decay in a passive linear medium. This approach features simplicity, fast rise time, high contrast ratio, unity switching efficiency, and is suitable as the input to high-power amplifier stages.

Although laser-induced breakdown has been an easily observed$^1$ and dramatic effect, it is only now beginning to find its way into applications. Recent experiments have shown that laser-induced breakdown in gases can be accompanied by substantial spectral broadening$^2$ and self-phase modulation.$^3$ These observations indicate that the plasma cuts off transmission of the incident beam in a time as short as 30 psec.$^3$

The basic concept$^2$ of short-pulse generation from a laser spark is to employ a spectral filter which rejects the incident laser wavelength, but transmits the sidebands produced by the sudden plasma growth. Among the types of spectral filters which have been suggested are the Michelson interferometer,$^4$ the Fabry-Perot etalon,$^5$ and the grating monochromator.$^6$ Of these, only the grating device, especially in the form of a