The characterization of a laser-produced negative-hydrogen-ion plasma

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The parameters of a plasma produced by irradiation of alkali hydride targets with a ruby-laser pulse are experimentally measured. Positive- and negative-ion abundances are determined with a quadrupole mass analyzer. Electron temperature was measured with rapidly swept Langmuir probes. Negative (H\textsuperscript{+}) ion temperature was obtained using the mass analyzer and focusing grids. The electron density near the target was determined by optical holography. The quantity of negative ions produced per laser pulse make the source attractive for the future development of high-energy neutral-beam systems.

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I. INTRODUCTION

Heating of plasmas to thermonuclear temperatures by a neutral-beam injection in magnetic confinement devices is a well-established method. Past experiments on Tokamaks and mirrors utilized energetic neutral beams prepared from positive-ion beams\(^1\) by the charge-exchange process with a background neutral gas. Beam energies of up to 40 keV were used in these experiments. The next generation of fusion devices, both Tokamak and mirror class, will utilize beam energies of 80–120 keV (Doublet III, Mirror Test Fusion Facility, Tokamak Fusion Test Reactor) which still will be generated from the positive-ion beams. However, as the size of the dense target plasma increases, the neutral-beam energy has to increase in order to penetrate into the center of the confined plasma. Therefore, it is envisioned that the future fusion experiments and the fusion reactors based on the magnetic confinement will utilize beam energies well in excess of 200 keV. At these energies, the charge-exchange cross section\(^2\) for the process H\textsuperscript{+} + H\textsuperscript{2} \rightarrow H\textsuperscript{0} + H\textsuperscript{+} (where \(*\) indicates the energetic particle) drops three orders of magnitude when compared to the value at 10 keV. The efficiency of the neutral-beam injection system based on positive-ion acceleration drops accordingly, and the system would be uneconomical in a fusion reactor.

An alternative procedure is the production of neutral beams from the negative-hydrogen- or deuterium-ion beams. The second electron binding energy is 0.754 eV, and it is relatively easy to detach it by a charge transfer in the background gas. The cross section is relatively independent of energy,\(^2\) decreasing by a factor of 10 only between 10 keV and 1 MeV.

Current research on negative-ion beams for fusion application is being performed at several laboratories in the United States\(^3\) and abroad.\(^4\) Negative ions in these experiments are generated by a charge-exchange process in cesium or in sodium vapor\(^5\) or plasma chemistry effects near the surface.\(^6\)

An alternate scheme was proposed by Dawson.\(^6\) The plasma produced by a laser light incident on an alkali hydride target may sustain a copious negative-hydro-

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\[ N_{\text{He}} = \lambda^3 N_e N_0 \exp(E^*/kT_e), \]

where \(\lambda^3 = 2(2\pi \hbar^2 / m k T_e)^{3/2}\) and \(E^* = 0.754\) eV is the binding energy of the electron to the \(H^+\) ion. Note that the presence of other ions and neutrals (Na\textsuperscript{+}, Na\textsuperscript{0}, and H\textsuperscript{+}) is neglected here so this represents only partial equilibrium. Since the observed ratio of \(N_{\text{He}} / N_e > 0.1\) and the electron and neutral densities are of the order of \(10^{15} \text{ cm}^{-3}\) close to the target, Eq. (1) requires \(T_e < 0.5\) eV. The electron temperature must be low in any case to prevent the destruction of the \(H^+\) ions.

Temperature measurements were made sufficiently far from the target so that the plasma was collisionless, and tenuous enough to use probes. The ions and electrons, once collisionless, are thought to preserve the temperature they attained during the initial phase of the expansion. The plasma density was measured downstream from the target by Langmuir probes and near the target by optical holography.

II. EXPERIMENTAL ARRANGEMENT

The experiments were performed in an evacuated chamber with the arrangement schematically shown in Fig. 1. A ruby-laser pulse (\(\sim 40\) nsec) is produced by an oscillator-amplifier system and Q-switched using a Kerr cell. The ruby-light pulse (\(\lambda = 6943\) Å) is reflected by two prisms towards a focusing lens \(f = 25\) cm. Once in the chamber, it encounters steering optics (two additional prisms) which allow greater flexibility in the
beam positioning. The focal spot is ~1 mm laser energy is 2 J.

After approximately 15 shots are fired, the NaH or NaD material develops a small crater ~1 mm in diameter, and the target spot is relocated by the guiding prisms or by shifting of the target material. It was found that the data are repeatable when the focusing lens is translated 1 cm about the optimum focal position on the target surface. The material erosion by the focused light is minimized when the target (which is shipped as a sandy powder) is packed under pressure. The material was always handled in an argon atmosphere to ensure its purity; this was found important for the H⁺ production. When NaH is exposed to air for more than 10 min, there is a pronounced visible change of the material surface since NaH is highly hygroscopic, and a marked decrease or entire disappearance of H⁻ ion production.

Data were obtained in the configurations where a quadrupole mass analyzer, hereafter referred to as QA, was located at the far end of the system, facing the target, or in a position where its axis was perpendicular to the longitudinal axis of the expansion chamber (Fig. 1). In the second case, a magnetic field produced by two coils, 32 cm in diameter, was applied to deflect the diffusing plasma to the QA. Data obtained on H⁺/H²⁺ ratios with the magnetic field and quadrupole located as in Fig. 1, vertically mounted and facing down, are similar to those obtained with no magnetic field and the quadrupole facing the target.

A Faraday cup capable of measuring the positive-ion energy distribution was located 80 cm from the target. It could not, however, distinguish between Na⁺ and H⁺ ions. Radial Langmuir probes were located at several distances, as shown on Fig. 1. In addition, an axially movable Langmuir probe (not shown) could be moved to within 50 cm of the target.

The main effort was to identify the H⁺ ions and measure their abundance in the plasma with respect to the H⁺ ions. The mass separation of the plasma species (H⁺, H²⁺, H⁻, and Na⁺) was done by the QA. The charge identification (polarity) is performed by the proper biasing of the quadrupole mass analyzer. This is done with the use of focusing grids which select the particle charge and energy with the proper potential difference between the QA entrance and first dynode of the electron multiplier in the detection stage. Mass calibration was done by bleeding various gases into the chamber. To detect neutrals, an ionizing filament at the QA entrance was employed.

Figure 2(a) shows the experimental results of a mass sweep near the hydrogen-ion line taken over many successive laser shots using a NaH target. Both positive and negative ions are clearly identified for different bias potentials as described above, and the H⁺, H²⁺, and H⁻ lines are obtained. Points on the graph represent the peak amplitudes of the signals received from the electron channel multiplier of the quadrupole mass analyzer (1-MΩ termination) for a different setting of the rf-field amplitude applied to the quadrupole rods.

This data was taken with the quadrupole mounted in the vertical position (see Fig. 1) and a guiding magnetic field used to deliver particles to it. This arrangement
will be discussed in more detail in Sec. III. Note that \( H^0 \) and \( H^+ \) are clearly resolved in this case. One also sees that the number of \( H^+ \) and \( H^0 \) ions collected are comparable.

Fast neutrals having the same expansion velocity as the plasma are produced by the stripping of \( H^+ \) ions or by the charge exchange of \( H^+ \) near the target. The fast neutrals propagate with the plasma cloud and cannot be reflected by any focus or bias voltage since they are uncharged. If the internal energy of these atoms (\( H^0 \) and \( Na^0 \)) is sufficient to produce secondary-electron emission from the first dynode, the resulting current signal of the analyzer is mass independent. Fast neutrals reach the entrance aperture of the quadrupole mass analyzer if the aperture is within the direct line of sight of the target region.

The problem of the mass-independent signal was eliminated in two ways. The first way consists in mounting the analyzer at right angles to the line of sight as mentioned above and deflecting the plasma to it by the magnetic field. There is evidence that the plasma trajectories are not those of single particles, and although the configuration is interesting, misleading information about the ratios of various species in the bulk plasma may be obtained. To overcome the fast-neutral problem without using a magnetic field, an aluminum plate with a small hole (diameter 1 mm) was placed ~30 cm from the target and the quadrupole mass analyzer was placed in a position facing directly towards the target (Fig. 1). The plasma density in this configuration was decreased by the pinhole, but the neutrals were essentially eliminated by the aluminum plate. Negative-to-positive ion density ratios were measured in this arrangement and in the case when magnetic field deflection to a vertical mass analyzer was used.

The experimental results of a mass sweep taken over many successive laser shots with NaD target are shown in Fig. 2(b). The quadrupole faced the target and the pinhole was used as it is described above. Again, both positive and negative deuterium ions are clearly identified and \( D^+ \), \( D^0 \), and \( D^0 \) lines are obtained. The linewidth is broader as compared to the NaH target line sweep [Fig. 2(a)]. This is caused by not having NaD isotopically pure. There is some residual NaH present, causing the line broadening.

### III. MASS COMPOSITION OF THE DRIFTING PLASMA

The data discussed in this section were taken 60–120 cm from the target. In this region, the plasma was spatially uniform at a given time and densities were low enough to use Langmuir probes and the mass spectrometer.

Figure 3(a) shows the dependence of the peak quadrupole signal amplitudes on the laser input energy using the sodium hydride target. These data were taken with the mass analyzer in line with the target and using the plate and pinhole to eliminate the fast neutrals as described earlier. There was no applied magnetic field. The analyzer was located ~114 cm from the target. The solid line is a fifth-order polynomial fit to the experimental data by computer. Note that both \( H^+ \) and \( H^0 \) signals increase with increasing laser energy with \( H^+ \) reaching a saturation of around 1.0 J, while \( H^0 \) increases slightly. The \( H^0/H^+ \) ratio is generated from a computer-fitted polynomial. Using this statistically averaged data, \( H^0/H^+ = 0.2 \) and is relatively independent of the laser energy in the range shown.
Figure 3(b) shows the data obtained with a sodium deuteride (NaD) target for identical conditions as described above. In this case, the D⁺, D⁻, and D²⁺ dependence on the incident laser light energy is shown. Again, the D²⁻/D⁻ ratio can be generated and is similar to that obtained for a sodium hydride target (~0.2).

When the quadrupole was located perpendicular to the plasma streaming direction, the problem of fast neutrals was bypassed. With small or zero magnetic field applied to the Helmholtz coils shown in Fig. 1, there is no positive- or negative-ion signal. The magnetic field is then increased and negative ions are detected. The field was reversed; the QA was set for positive-hydrogen detection and collected current as a function of magnetic field monitored. These results are displayed in Fig. 4. One sees that a peak is observed in collected current for both species around 25 G. In a 25-G field, the hydrogen-ion Larmor radius is 4/[T_e(eV)]¹⁄² cm. Since the radius of curvature necessary for collection is 10 cm, this implies an ion temperature on the order of 5 eV or an equivalent drift velocity. One notes that, if the field is arranged to deflect H⁺ into the quadrupole, some H⁺ is detected as well. This can occur for either one of two reasons. First, if the ions are collisional, the particle path cannot be analyzed in terms of single trajectories. The Spitzer° ion-ion collision time is, however, 25–100 μsec and the ions are nearly collisionless at a temperature of 0.1–1 eV and a density of 3×10¹⁰ cm⁻³. A second possibility is the generation of space charge causing a polarization drift or some enhanced collisional process. If a pinhole is positioned in the drift tube, then no H⁺ is seen when the magnetic field is biased to collect negative ions. A collective effect is, therefore, suggested. With no pinhole and the QA situated at 90° to the incoming beam, the ratio of H⁺/H⁻ is enhanced with respect to that obtained from the straight path collection when B = 0.

Examples of this enhancement are shown in Fig. 5. Two different experimental situations are presented. The sign of the magnetic field shown relates to the deflection of positive (+ sign) or negative (− sign) ions to the quadrupole analyzer. In the case of B = −32 G, the local plasma at the quadrupole entrance aperture vicinity has a greater abundance of H⁺ ions than H⁻ ions. When the field direction is changed (+32 G), the H⁺ ions are now more abundant. This suggests a partial H⁺ ex-

![FIG. 3. Dependence of the quadrupole peak current as a function of laser energy for (a) NaH and (b) NaD targets. The ratio of H⁺/H⁻ are shown. The data was taken with no external magnetic field; the mass analyzer was in line of sight of the target.

![FIG. 4. Dependence of quadrupole peak current (NaH target) on the solenoidal guide field. The quadrupole was mounted at 90° with respect to the drift tube axis. The signal peaks at a magnetic field for which R₁, of the incoming beam is approximately the radius of curvature necessary for collection.](image-url)
traction scheme. Combination of the crossed magnetic fields and accelerating potentials may enable the direct extraction of H⁺ from the plasma source. Since the H⁺ density is high, the creating of a charge-neutral plasma consisting of H⁺ and H⁻ ions with a small fraction of electrons appears to be possible using a magnetic barrier.

The QA was also set to detect sodium ions and neutrals. The Na⁺ signal was quite weak and just above noise when the detector was placed in line of sight with the target. No neutral Na signal was observed above noise. We must add, however, that the ionizing filament used in conjunction with the QA has 1% efficiency, so that neutral densities must be far in excess of ionic ones for neutral-particle detection here.

IV. PLASMA PROPERTIES—TEMPORAL SEQUENCE

To better understand the plasma composition, a time-of-flight analysis was undertaken. Figure 6 shows the sequence of events indicating the arrival time of the plasma pulse after irradiation with a 40-nsec 0.7-J laser pulse. The distances indicated on the right-hand side are from the target to the instrument indicated. The Faraday cup (upper trace) collects all positive particles; it cannot distinguish between H⁺ and Na⁺. The arrival time of the signal peak indicates a speed of 4.5 cm/µsec, while that of H⁺ is 5.2 cm/µsec. The H⁺ velocity agrees well with the flight time of electrons (5.1 cm/µsec) to a Langmuir probe.

We may add that the electron temperature measured 80 cm from the target is indeed quite cold. A discussion of temperature measurements will follow.

The time-of-flight data indicates that the large ion drift velocities originate via an ambipolar field produced by the mobile electrons. This will be discussed in Sec. VIII. The negative hydrogen ions, which may be somewhat cooler than H⁺ or have maximum production at a somewhat later time, trails behind, and can be space-charge neutralized by the tail of the H⁺ pulse.

V. ELECTRON TEMPERATURE

The electron temperature was measured initially on a shot-by-shot basis and later using a rapidly swept Langmuir probe.

In the first case, the laser energy was held between 0.2 and 0.35 J, and the bias voltage to a Langmuir probe 90 cm from the target was varied. The planar disk-shaped probe had 0.5-cm² area and was coated with ceramic on one side so as to be directional.

Figure 7 shows the collected current as a function of bias voltage on a linear and semilog scale. This curve was generated at the arrival time of the density maxima. From the upper curve one sees a sharp break at 2 V. If this is taken to be the plasma potential, an electron temperature of 0.4 eV is obtained. The continuing increase of the electron saturation current has been observed in streaming plasmas and has been attributed to a modification of the plasma potential in the vicinity of the probe.
If a "temperature" is obtained by fitting the data above 2 V on semilog paper, it turns out to be 4 eV, which seems too high. The problem is rectified, however, with the use of a rapidly swept probe.

A fast operational amplifier was used to provide a ramp voltage to the Langmuir probe. A timer was utilized to sweep the probe at any time during the plasma's presence. These results are shown in Fig. 8. Two Langmuir probes were placed side by side. One probe was swept, while the second probe was used in the saturation region to determine the temporal duration of the plasma pulse. In the lower curve [Fig. 8(b)], the electron saturation current is shown as a function of time. Several swept Langmuir probe curves (the probe was swept at 0.75 V/500 nsec) are inserted at the times they were taken. The relevant part of the curve, which is the electron thermal current region, is swept in 1.5 μsec which is short when compared to plasma duration.

One notes at early and late times that the Langmuir curves have a well-defined plasma potential. The central curve, however, shows a complicated-looking saturation region. In this curve there appears to be two knees. The second region cannot be attributed to a "second" higher-temperature component since it does not rise exponentially. In all cases, however, the portion to the right of the floating potential fits well to an exponential and leads to reasonable electron temperatures. $T_e$ is quite low [about 0.25 eV, Fig. 6(a)] when the electron density is highest and collisional thermalization between ions and electrons is effective and then rises to 0.7 eV when the density has dropped to several percent of its peak value. The important point to note is that $T_e$ is always less than the binding energy of the extra electron to hydrogen, and appreciably less than this when the plasma density is highest.
VI. H-ION TEMPERATURE

To get an estimate of the H\textsuperscript+ temperature, the quadrupole tuned to the H\textsuperscript+ line and situated at 90° to the particle stream was used as an energy analyzer by varying the focus voltage. The results of this measurement are displayed in Fig. 9. Current-voltage traces derived from the temporal evolution of the QA signal are displayed in Fig. 9(a). These were taken at time $T=t_2$ or 50 μsec after a 40-nsec 0.7-J pulse irradiated the target. On a log scale [Fig. 9(b)] the trace is highly linear, suggesting a temperature of 2.2 eV. One must be careful, however, since the plasma arriving at the quadrupole is drifting with an energy $E_D$ equivalent to 13 eV.

If the arriving plasma ions have a distribution function which is taken to be a drifting-Maxwellian, it may be expressed as

$$f(v) = n_0 \left( \frac{M}{2\pi kT_i} \right)^{1/2} \exp \left( -\frac{1}{2} \frac{M (v - v_D)^2}{kT_i} \right)$$

Here the drift velocity is mixed with the particle velocity as a quadratic in the exponential. The logarithmic slope of current collected,

$$I_{\text{measured}} = e \int_0^\infty f(v) v \, dv,$$

is therefore not simply related to the ion temperature $kT_i$. The experimentally measured distribution function is well approximated by a function of the form $C \times \exp\left[ (M/V_D - v_D^2)/2\overline{E} \right]$. This distribution is not Maxwellian and the quantity $\overline{E}$ is not to be interpreted as a temperature. For $E_D \gg \overline{E}$, the distribution above may be fitted to a Maxwellian by denoting the e-folding velocity of the measured distribution as $v_D$, and defining the ion temperature as $kT_i = \frac{1}{2} M(V_D - v_D)^2$. The approximate distribution e-folds at

$$\overline{E} = \frac{1}{2} M |v_D - v_D^2|,$$

and using the definition above for the ion temperature, we may relate

$$kT_i = \overline{E}^2/4E_D, \text{ if } E_D = \frac{1}{2} MV_D^2 > \overline{E}.$$

In this experiment, $E_D \sim 13$ eV and $\overline{E} = 2.2$ eV, which implies $T_i \sim 0.1$ eV. Similar experimental analysis done at different times of the plasma arrival yields the data shown in Fig. 9(c).

VII. HOLOGRAPHY OF THE TARGET PLASMA

Two important quantities are the total number of par-

![Image](image-url)
particles produced in a single laser shot and the spatial density dependence near the target. The former quantity may be estimated from Langmuir probe taken downstream. A far better probe, however, consists of holography taken of the dense plasma in the vicinity of the target. Since the plasma drift recorded downstream is in the order of 4 cm/µsec, one would expect a significant blurring of the fringe pattern if a laser pulse of duration \( \tau > \Delta Z \) (mm)/\( V_{\text{drift}} \) were used. Here \( \Delta Z \) is the spatial extent of a fringe in the limit of an infinitely short duration laser camera pulse. Therefore, to review 1-mm detail, a camera pulse of several nanoseconds is required. This may be accomplished by pulse chopping the camera laser which ordinarily delivers a 50-nsec pulse.

The holographic setup is in other respects standard. The pulsed chopped 5-nsec camera pulse was split, and the reference beam transversed the system through large side ports shown in Fig. 1. The camera laser was timed to photograph the plasma at any time after the target was struck.

Figure 10 shows two reconstructed holograms. The upper one was taken 600 nsec after the target was irradiated with a 1.3-J laser pulse. The plasma is hemispherical with an extent of 2.3 mm to the furthest observable fringe. The average line-of-sight density \( N_e \) is related to the fringe number \( q \) and path length \( d \) by

\[
N_e = 8.04 \times 10^{19} q/d \text{ cm}^{-3},
\]

where ruby light (6943 Å) is considered. On this photograph, 4.5 fringes are easily visible which places the density at \( 6 \times 10^{17} \text{ cm}^{-3} \) at a distance 0.3 mm from the target and for a light path through the plasma of 6 mm. When the plasma arrives at a Langmuir probe 1 m away, it has a temporal width of 20 µsec (FWHM) which indicates a spatial extent of approximately 70 cm. The plasma now fills a volume approximately 10^6 times larger; the density must be \( 10^{10} - 10^{11} \text{ cm}^{-3} \) which is what is observed by Langmuir probes at this location.

One must also estimate the contribution to the fringe shift due to neutral particles. The change in index of

![Figure 10](image-url)
refraction may be approximated closely by

$$\Delta \mu (\text{neutral}) = 2\pi \alpha N_e,$$

where $\alpha$ is the polarizability and $N_e$ is the neutral density. For neutral hydrogen atoms ($H^0$) the polarizability was measured to be $4.66 a_0^{-1}$, where $a_0$ is the Bohr radius. For a neutral density equal to that of the ion density near the target, the contribution due to neutrals is less than 1%. (The same is true for $H^0$, $\alpha H/\alpha H^0 \approx 0.8$.)

The neutral density is certainly not two orders of magnitude larger than that of the electrons since this would have easily been observed by the QA operating in the neutral-particle detection mode. The QA ionizing filament operates at 1% efficiency; however, the neutral signals were never above the detector noise levels.

The second hologram in Fig. 10(b) shows the effect of crater formation on the plasma production. Here the target was struck 15 times in the same location, a crater was formed in the NaH, and subsequently this hologram was taken 1.2 $\mu$s after the 16th laser pulse. One sees fewer fringes which tend to flare out in space. A clean target area exhibits hemispherical fringes at this delay time. Since the crater may extend 2 mm into the target, one expects a significant interaction with the crater walls which affects the high-density-region shape.

VIII. INTERPRETATION OF THE PLASMA DRIFT VELOCITY

The plasma species are observed to have a significant drift velocity. The electrons, for example, drift with a directed energy in excess of the binding energy of $H^+$. Although the present observations are not detailed enough to track the temporal evolution of this drift near the target, a reasonable hypothesis may be drawn from the available data.

The large electric fields generated in the focused laser light pulse ionize the target and produce a dense plasma, and therefore a density gradient, very close to the surface.

Since the electrons are far more mobile than the ions, a sheath is produced in which electric fields accelerate ions outward. Calculation of this is complicated since the electron temperature must vary in time as the sheath moves outward. It is conceivable that in this region $T_e$ is larger than the temperature measured at the lower-density region. After some initial expansion of plasma has occurred, a substantial density gradient (Fig. 10) still exists.

For infinitely massive ions and electrons in Boltzmann equilibrium with the potential, one may write

$$\frac{1}{n_e} \frac{dn_e}{dx} = \frac{-eE}{(kT_e)},$$

where $(kT_e)$ is an average electron temperature. The measured value of $dn_e/dx = 2.2 \times 10^{11}$ cm$^{-2}$ implies potentials of the order of $20kT_e$ exist. Adiabatic expansion of the hemisphere can further cool $T_e$ by a factor of 10 over this distance. The initial electron temperature is not known, but Eq. 6 implies that an average temperature of several volts 1–2 mm from the target is necessary to account for the observed drift velocity.

IX. SUMMARY AND CONCLUSIONS

The laser-produced plasma from the sodium hydride and sodium deuteride targets was characterized in the low- ($\sim 10^{11}$ cm$^{-2}$) and high-density ($\sim 10^{17}$ cm$^{-2}$) regions. The plasma composition, electron and ion temperatures, and the electron density was determined in the low-density region; the electron density near the target was measured by double-pulse holography. The large density ratio of $H^+/H^0$ observed (0.1–0.2) cannot be explained by the Saha equation [Eq. (1)] if sodium neutrals and ions are included in the formulation.

A favorable property of the laser-produced plasma as far as the negative-ion extraction is concerned is relatively low electron and ion temperature ($T_e \approx 0.4$ and $T_i \approx 0.1$ eV). Other important favorable features are the efficiency of the negative-ion production and a small neutral background pressures. In order to estimate the energy spent to produce a negative ion, we used the hologram in Fig. 10 to determine the initial plasma volume, its average density, and the total number of ions produced. The plasma pours off of the target for more than 1 $\mu$s, which is evidenced by the holographic fringe pattern as a function of time. The matter contained in the hemispherical volume in Fig. 10(a) is, therefore, replaced five times within 1 $\mu$s. A conservative estimate, based on this, places the total number of produced ions at $3 \times 10^{16}$. 20% of these are the negative ions, $H^-$. For the incident laser pulse energy, 1.3 J, the energy spent is 1.4 keV per H$. If a 20% efficient CO$_2$ laser is used, the total energy spent would be $\sim 7$ keV per H$^-$ ion, which is better than that of other existing negative-ion production schemes by at least a factor of 10.

Advanced fusion devices require the neutral-beam injection for a large fraction of the experimental time, which in Tokamaks or mirrors is approaching 1 sec and will ultimately reach a steady-state operation. Therefore, in order to develop a usable neutral beam based on the negative-ion extraction from the plasma produced by the laser irradiation of alkali hydride target, a steady-state source has to be developed. A possible scheme involves a repetively pulsed CO$_2$ laser producing the plasma, which is then confined in a magnetic trap to smooth the density variation in time. The accelerator itself would be coupled to the confining region. The requirement on the repetitive CO$_2$ laser (1 kHz) delivering 0.1–1 J of the light energy per pulse ($\Delta t \sim 100$ nsec) is within the current state of technology.

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