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Micrometer-sized negative-ion accelerator based on ultrashort laser pulse interaction with transparent solids

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We report here energetic (>100 keV) negative hydrogen ions (H^-) generated in the interaction of moderately intense (10^{18} W cm^{-2}) ultrashort laser pulses (45 fs) with transparent hydrogen containing solid targets. An unambiguous and consistent detection of negative hydrogen ions, with a flux of 8×10^{11} H^- ions/sr, has been observed in every single laser shot, using a Thomson parabola ion spectrograph. Simple estimates based on charge transfer cross sections match well with experimental observations. Our method offers the implementation of an intense, ultrashort laser based negative-ion source at a higher repetition rate, which can be important for various applications.

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Particle accelerators [1] have contributed immensely in the exploration of newer frontiers of nuclear and particle physics [2], managing nuclear waste [3], curing cancer [4], and many more. Their vast potential usage has led to numerous such devices of different capabilities [5], with far reaching consequences towards scientific and technological advancements. In recent times, they have been envisaged as an essential tool for the exploration of fundamental particles, nuclear transmutations, subcritical reactors for future power sources, heavy ion based inertial fusion schemes [6], etc. Although protons are used for these applications, for applications such as spallation neutron sources, where one has to use a storage ring to make the pulse duration short for time of flight experiments, one has to start with H^- ions, accelerate them, and then convert them to H^+ for storage and subsequent use. The conventional ways of producing negative ions involve charge exchange processes between positive ions with alkali metal vapors [7] or alkali hydrides [8], and volume and surface devices [9–11], demanding a plasma temperature of only a few eV [12].

Apart from the accelerators, the use of negative ions has generated considerable interest in neutral beam injection in magnetic confinement based fusion devices [13,14], surface science [15], nerve cell engineering [16], inertial confinement fusion (ICF) [6] schemes, etc. In particular, for ICF related research, the negative ions offer a commendable advantage over the use of positive ions as they can be easily photodetached [17,18] to form neutrals in the path, completely bypassing the space charge issues.

With regard to the scenario presented so far, a new approach towards producing energetic charge particles on a tabletop using ultraintense lasers (UILs) has emerged [19]. The potential of an intense, ultrashort laser-matter interaction towards understanding the highly nonlinear, nonperturbative physics, as well as its technological ramifications such as in compact tabletop particle accelerators [20], hadron therapy [21], fast ignition scheme of ICF [22], etc., has made it very appealing, based on which ion sources have also been proposed [23]. The charge particle beam generated through this approach offers an inherently ultrashort duration, high brightness, high repetition rate operation [24] which can open an altogether different dimension in producing bunched accelerated ion beams when used in tandem with accelerators.

Contrary to the conventional sources of negative ions demanding low temperatures and low density plasmas [7,8], the UILs offer relatively high temperature, solid density plasmas. Although it appears counterintuitive at first, we show that even in this adverse situation, an efficient generation of negative ions can be achieved with full control over their characteristics. Preliminary investigations towards producing negative ions using ultrashort lasers interacting with clusters [25] or liquid drop [26] and spray [27] targets have been reported, where the origin of the negative ions has been attributed to recombination and electron attachment to high velocity positive ions while expanding through the surrounding plasma. The inherent disadvantage of these schemes is a low repetition rate (limited to a few Hz), which can be overcome with our present technique.

In this Rapid Communication, we demonstrate the generation of energetic H^- ions from the interaction of an ultraintense laser pulse with easily available solid transparent targets containing hydrogen. It is shown that by using low debris, nontoxic, transparent solid targets such as polymethyl methacrylate [PMMA, $(C_5H_8O_2)_n$], consistent energetic H^- ion production, with control over the flux and energy of the ions, is possible. The negative ions produced from the low debris solid target may offer a higher repetition rate source for the negative ions.

The experiments were performed with a 45 fs, 10 TW Ti:sapphire laser system, as shown in Fig. 1. The laser pulse was focused on a 5 mm thick PMMA sheet by an $f/7$ off-axis parabolic mirror, at an angle of 45° with respect to the target front surface normal direction. The focal spot diameter was measured to be 10 μm [full width at half maximum (FWHM)], giving a maximum intensity of 3×10^{18} W cm^{-2}. The base pressure in the plasma chamber was 5×10^{-5} mbar. For an unambiguous detection of the incoming charge particles, a Thomson parabola ion spectrograph (TPIS) [28] was placed normal to the target front surface, with a multichannel plate (MCP) as the detector, followed by a 16 bit electron multiplying CCD (EMCCD) camera. The TPIS has an entrance aperture of 300 μm in diameter, subtending a solid angle of 5.8×10^{-7} sr onto the plasma. The best focal position

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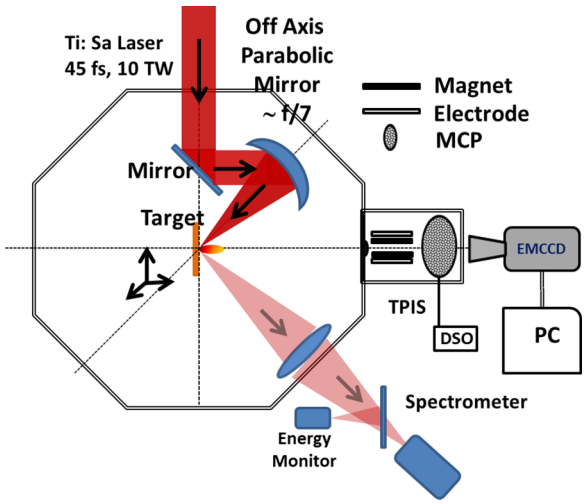

FIG. 1. (Color online) A schematic diagram of the experimental setup for producing energetic negative hydrogen ions using ultrashort laser pulse irradiation of solids.

($Z = 0$, reference position) was determined by maximizing the proton energy. For $Z > 0$, the target is moved towards the laser (i.e., the focal plane being moved inside the target).

Figure 2 shows typical parabolic traces of H^-, H^+, and other positive ions (C, O) recorded by the TPIS. A consistent generation of H^- in every single laser shot was observed, although with lower flux compared to the H^+. Based on the calibration of the TPIS with CR-39 track detector counts, the cumulative flux of H^- ions was estimated to be 8×10^{11} H^- ions/sr. In this case, one observes smearing of the positive-ion traces due to the larger focal spot of the beam at the target front surface.

The variation of the H^- spectrum with the geometrical focal position [Fig. 3(a)] was studied. It was observed that when the target front surface (facing the laser) is at $Z = 0$, the positive-ion energies were maximum with distinct sharp parabolic traces, but no H^- ions were detected. However, as the

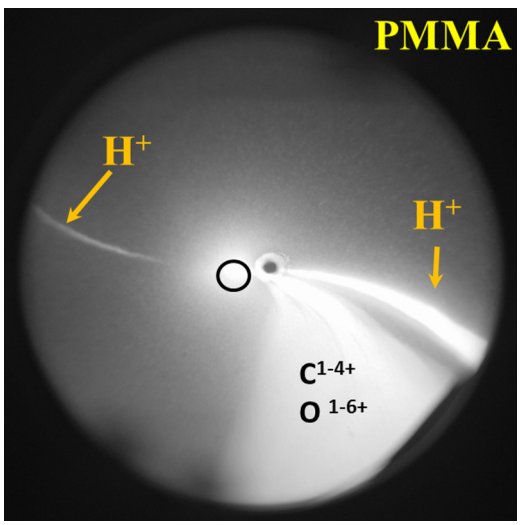

FIG. 2. (Color online) Typical parabolic traces obtained using the TPIS, showing the protons and H^- ions.

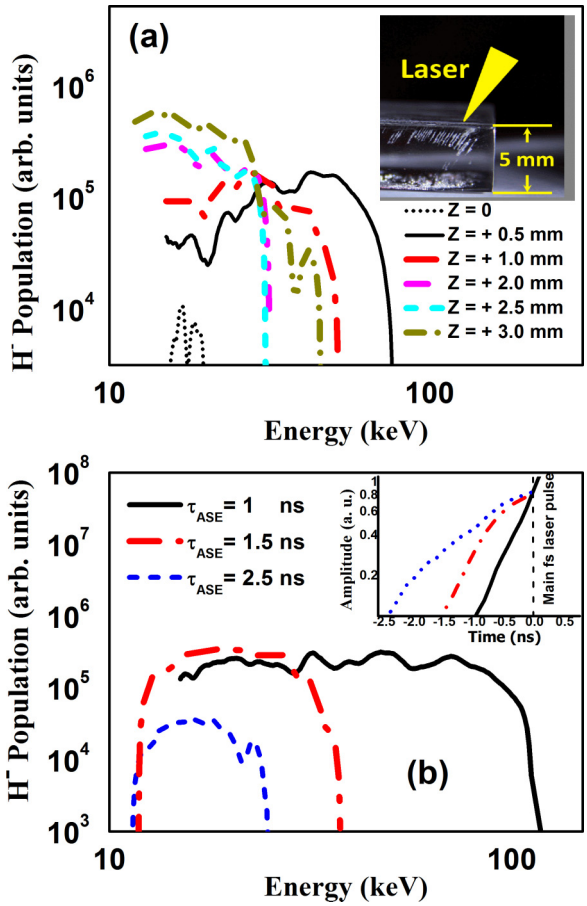

FIG. 3. (Color online) (a) Energy distribution of the H^- ions at different focal positions of the laser beam. The positive direction implies the sample has been moved towards the laser incident direction. The inset shows the self-focusing channels formed inside PMMA, perhaps by the ASE prepulse. (b) The effect of the laser prepulse on H^- production. The laser prepulse levels at different settings are shown in the inset.

target was shifted towards the laser, strong traces (emission) of the H^- ion started to appear, along with the expected reduction in the proton energy. As the target is moved considerably off from the $Z = 0$ position, the H^- ion flux and energy decrease. A similar trend was observed when the target is moved in the opposite direction.

It is well known that only 0.754 eV energy is required to break off the H^- ions and release the extra electron. The plasma formed by UIL has a relatively higher temperature than the prescribed range of plasma temperatures for conventional negative-ion sources [8]. Therefore, the generation and sustenance of H^- ions in the plasma [25] formed on the surface is ruled out. In the case of a normal glass target (containing no H) and for an opaque CH target, under no conditions were H^- ions observed. However, with a transparent CR-39 target containing H, we could observe H^- ions as in the case of the PMMA target.

The PMMA, being a transparent material, acts somewhat as a plasma mirror [29] to the incident laser pulse. At the best prepulse condition [$\tau_{ASE} = 1$ ns, inset of Fig. 3(b)], the Amplified Spontaneous Emission (ASE) prepulse associated

with the main femtosecond pulse goes through the sample either without forming a plasma or forming an underdense plasma on the target surface. It is the main femtosecond laser pulse which forms a strong overdense plasma on the sample surface. The generated energetic electrons leave the interaction zone, producing a charge separation field which drags protons along with it. Since there is a velocity distribution of electrons and protons, any overlap of the velocity profiles in space at any given instant of time forms the possibility of charge exchange during the expansion phase, after leaving the target. With PMMA being a hydrogen enriched target, this effect is pronounced as compared to other nonhydrogen containing targets, such as glass or metals. Notably, protons can capture extra electrons not just directly from electrons but also from the surrounding carbon and oxygen ions [25].

It is observed from Fig. 3(b) that even a slight increase in the laser prepulse drastically reduces the total H^- ion production. When the prepulse level is raised, it forms an overdense preplasma cloud which hinders the clean interaction of the main femtosecond laser pulse with the target and considerably reduces the sustenance of H^- ions by collisions.

The charge composition of the H^- ion produced by a H^+ beam passing through the expanding PMMA plasma can be expressed as

$$dN_q/dZ = n_0(N_{q+1}\sigma_{q+1,q} - N_q\sigma_{q,q+1} + N_{q-1}\sigma_{q-1,q} - N_q\sigma_{q,q-1}), \quad (1)$$

with N_q representing the number of negative ions ($q = -1$), neutral atoms ($q = 0$), and positive ions ($q = +1$), n_0 is the average density of the material in the region of interaction, and $\sigma_{q+1,q}$ and $\sigma_{q,q+1}$ represent the electron capture and electron loss cross sections. Since in this case the phenomena are going to be highly collisional in nature ($n_0\sigma L > 1$, L being the effective interaction length), the left hand side of Eq. (1) can be made zero. Simplifying this, the fraction of H^- (N_{H^-}) converted from a beam of H^+ (N_{H^+}) can be expressed as a ratio of charge exchange cross sections $N_{H^-}/N_{H^+} = \sigma_{10}\sigma_{0\bar{1}}/\sigma_{01}\sigma_{\bar{1}0}$. So, if the cross sections are known explicitly [5,30] in the case of C, H, and O atom collisions with projectile H^+, following the rule of additivity [31] of collision cross sections, the fraction of H^- can be estimated for a given beam of H^+. The direct interaction cross sections of electrons and protons are taken into account. These cross sections primarily refer to cold materials and are taken as the weighted average of the constituent elements (C, H, O) present in PMMA ($C_5H_8O_2$) with their respective proportions. Notably, in the given energy range, the available cross sections are very limited or scattered in the literature [5,30]. Figure 4 shows the ion energy spectra of H^+ (dashed curve, black) and H^- (thick solid curve, red) ions for the parabolic traces shown in Fig. 2. The H^- ions with energies up to 140 keV are clearly observed.

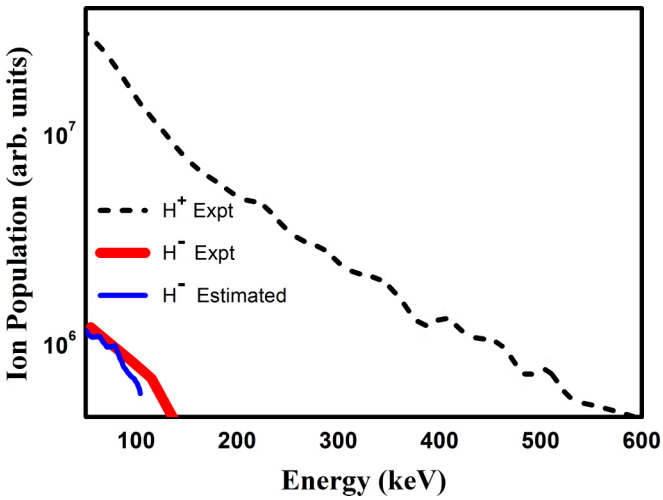

FIG. 4. (Color online) The ion energy spectra corresponding to parabolic traces shown in Fig. 2: H^+ (dashed curve, black) and H^- (thick solid curve, red). The thin solid curve (blue) shows the estimated spectrum of the H^- ions, derived from the observed H^+ spectrum.

Considering the observed H^+ distribution as a starting point, and using the above mentioned formalism, we have estimated the H^- fractions expected in the beam, shown as the thin solid (blue) curve in Fig. 4. It is seen that a simple estimate based on charge transfer cross sections matches well with the observed H^- distribution. Although the cross sections used for the estimation are primarily for the cold atoms, the presence of excited atoms [25,26] cannot be ruled out. They will also contribute to the charge exchange. Therefore, a slight mismatch of the estimated and observed H^- spectrum, especially at a higher energy range, is expected.

In conclusion, we have observed energetic (>100 keV) H^- ion emission from a moderately intense, femtosecond laser pulse interaction with transparent hydrogen containing solid targets, in every laser shot. The present approach offers control over the negative-ion characteristics by simple changes in the laser irradiation conditions. We believe this study will be important for the realization of a low debris, high repetition rate, and energetic H^- ion source for various scientific and technological applications.

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