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MeV negative ion source from ultra-intense laser-matter interaction[a)]

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Experimental demonstration of negative ion acceleration to MeV energies from sub-micron size
droplets of water spray irradiated by ultra-intense laser pulses is presented. Thanks to the specific
target configuration and laser parameters, more than 10^9 negative ions per steradian solid angle in
5% energy bandwidth are accelerated in a stable and reliable manner. To our knowledge, by virtue
of the ultra-short duration of the emission, this is by far the brightest negative ion source reported.
The data also indicate the existence of beams of neutrals with at least similar numbers and energies.
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I. INTRODUCTION

Laser acceleration of ions is an intrinsic feature of laser-produced plasmas. Laser-driven positive ions are extensively studied for their possible applications, e.g., in cancer therapy, conventional accelerator injectors, and ignition of controlled thermonuclear fusion.[1] They have been already applied in high resolution radiography.

This work highlights another important property of laser plasma interaction, namely the capability of acting as a source of high energy and high brightness negative ion beams. Negative ions are employed for many processing applications, and in the accelerator technology, including injectors dedicated to heating of tokamak plasmas (e.g., the negative ion-based Neutral Beam Injection (NBI) system in the International Thermonuclear Experimental Reactor (ITER) and the next generation of particle accelerators such as spallation sources ESS and SNS).

In general, while several types of positive ion sources are readily available for different applications, the negative ion source development has lagged behind, because handling loosely bound negative ions is a technological challenge. In the present paper, we propose a method of negative ion generation based on two electron capture mechanism during the collision of laser accelerated high energy positive ions with atoms or molecules in a tenuous medium (in the specific case of the experiment reported, a water spray target[2]) while preserving most of their original kinetic energy acquired in the acceleration process. This relatively simple and reliable method overcomes many technological challenges.

II. EXPERIMENTAL SETUP

A mist of water droplets (spray) is formed by adiabatic expansion of superheated water vapour through a hypersonic nozzle into a vacuum.[3,4] The schematic of the generator is shown in Fig. 1. It comprises of a solenoid driven pulsed valve (from Parker Hannifin company), a heated channel, and the hypersonic conical nozzle. For target optimization and system synchronization, the spray is pulsed by an electromagnetic valve every 6 s with a pulse duration of 2 ms, which keeps the background pressure before each spray pulse on a 10^{-5} mbar level.

Water (99.9% *v/v*—water volume concentration) with 35 bar backing pressure is injected upon opening of the valve into the heated channel (1 mm in diameter and 15 mm in length) at a temperature of up to 150 °C. Though the heater is in direct thermal contact with the channel, a 9 mm Polypenco PEEK 450 G insulator is used to separate it from the valve in order to keep the temperature of the liquid inside the valve below the boiling temperature. The injected water is vaporized in the heating channel and a superheated vapour under high pressure is formed. The latter expands through a hypersonic
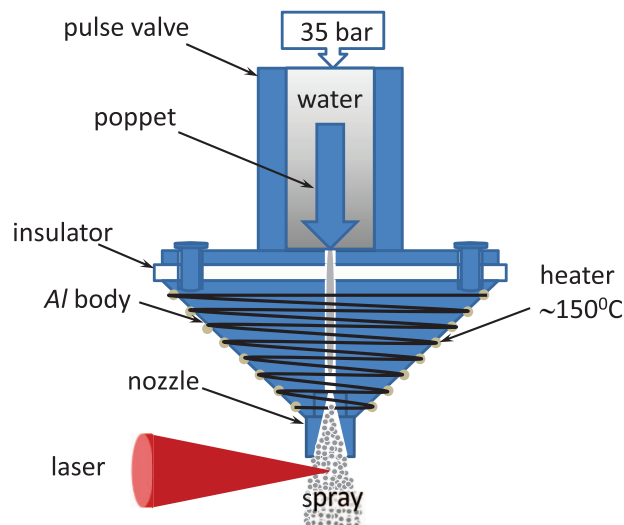

FIG. 1. (Color online) Spray generator.
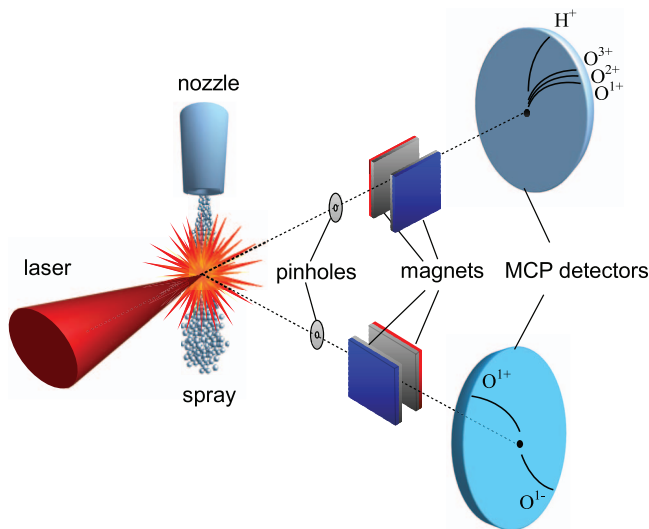
FIG. 2. (Color online) Experimental setup.

FIG. 3. Ion spectra in forward and transverse directions.

nozzle, with 8 mm long conical section and $2\varphi = 7°$ opening angle, into a vacuum and forms a spray of sub-micron liquid droplets. The scattering of electromagnetic radiation by spherical particles, called Mie scattering,[5] and transmission measurement of the spray was employed to characterize the size of individual droplets and density of the spray. Droplet diameter was determined to be $d = (0.15 \pm 0.01)$ μm, the droplet number density at about 1 mm below the nozzle was $(7.5 \pm 0.7) \times 10^{10}$ droplets cm^{-3}, and the mean atomic density was $>10^{18}$ atoms cm^{-3} (Ref. [3]).

In our experiments, the spray target was irradiated by 40 fs, 1 J Ti: Sapphire laser pulses at Max-Born-Institute, Berlin. With an $f/2.5$ off-axis parabolic mirror, a maximum vacuum intensity of 5×10^{19} W/cm^2 was reached. The temporal contrast of the laser pulse, characterized by a scanning third order cross correlator, several picoseconds before the pulse peak had a relative value of about 10^{-8}.

The experimental setup is presented in Fig. 2. The charged particles are detected by the two identical Thomson spectrometers, where particles deflected in parallel electric and magnetic fields will create spectra as parabolic traces on the detector. Particles with different mass-to-charge ratios lie on separate parabolas. The position of a particle on the trace depends on its energy: the higher the ion energy, the less the ion is deviated from the point where undeflected particles and x-rays would hit the detector (zero point).

III. RESULTS AND DISCUSSION

Ion spectra in forward and transverse directions detected by micro-channel plate detectors are shown in Fig. 3. While in the forward direction only positive ions are measured, in the transverse direction one can observe ion traces on either side of the zero point, corresponding to singly-charged, positive, and negative oxygen ions. Interestingly, only O^{1+} and O^{1-} ions have been detected in the transverse direction while in the forward direction one sees also different oxygen ion species and protons. The emission properties of O^{1+} and O^{1-} ions in the transverse direction appear
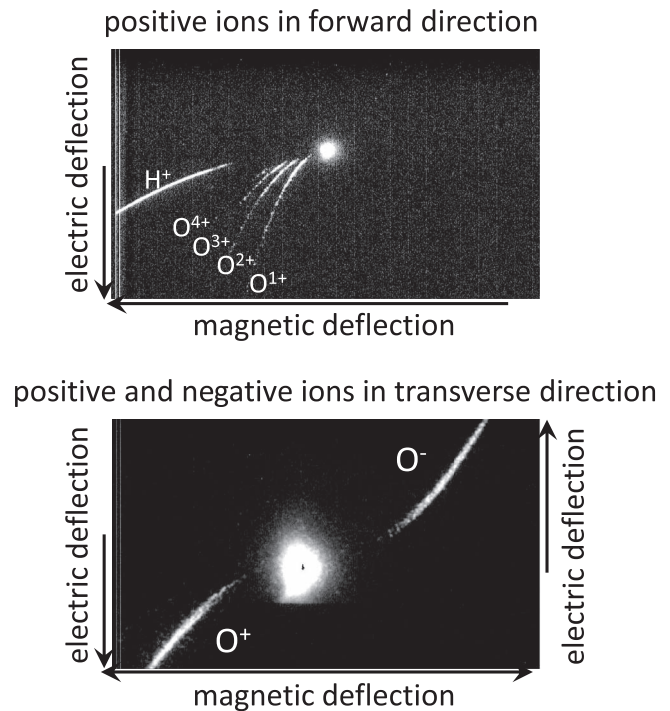
to be highly correlated. Figure 4 shows the dependence of the maximum energies for O^{1+} and O^{1-} ions emitted in the transverse direction on the position of the laser focus inside the spray. The production of negative ions was remarkably stable and reproducible if the laser pulse was focused well inside the spray during its steady flow stage. The observed asymmetric distribution of accelerated ions can be understood if one considers the interaction geometry. The laser pulse ionizes droplets and heats electrons along its propagation path. The subsequent plasma expansion creates a narrow channel of hot, low density plasma. Consequently ions propagating in the forward direction are not affected significantly by the interaction with the low density plasma, and maintain the features (spectrum and charge state) defined by the acceleration process. The ions propagating in the transverse direction cross a significant length of denser, cold medium and can undergo recombination processes.

The propagation of highly charged oxygen ions in the lateral direction is highly collisional ($n_0\sigma l \gg 1$), therefore in the cascade of recombination chain of elastic collisions: $O^{n+} \rightarrow O^{(n+1)}$, the neutral products may maintain the high energy, which makes the inverse processes of in-flight ionization possible. As a result of these competing recombination-ionization processes, oxygen ions with single charge will emerge from the spray.

During the collisions of high energy oxygen ion with the atoms in the spray, processes of electron capture and loss have high probability. These are resonant processes, which achieve the maximum probability if the fast ion velocity is of the same order of the velocity of bound electrons in the atom. The velocity of a 1 MeV oxygen ion, 3.4×10^6 m/s, is indeed of the order of the electron velocity in the atom.[6] The
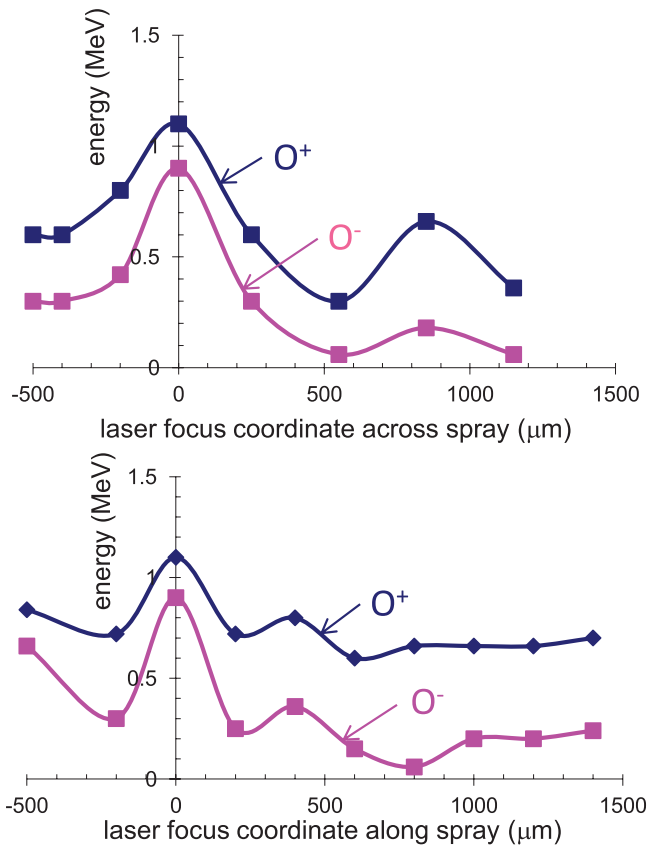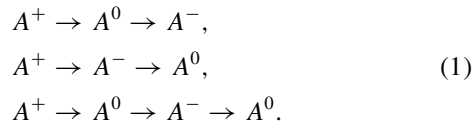
FIG. 4. (Color online) Ion energy dependence on laser focus position in spray. 0 is the centre of the spray defined with the accuracy of $\pm 100 \, \mu$m. The positive sign in the lower figure shows the direction of laser propagation.

competitive electron capture and loss processes are

$$A^+ \rightarrow A^0 \rightarrow A^-,$$
$$A^+ \rightarrow A^- \rightarrow A^0, \qquad (1)$$
$$A^+ \rightarrow A^0 \rightarrow A^- \rightarrow A^0.$$

According to Ref. 7, the cross-section of the electron capture process of a positive oxygen ion in a collision with an oxygen atom is $\sigma_{10} \approx 18 \times 10^{-16}$ cm^2 ($O^+ \rightarrow O$) for an impacting particle energy of 400 keV. For high energy neutral oxygen atom collision with another oxygen atom at rest, the electron loss cross section is: $\sigma_{01} \approx 6 \times 10^{-16}$ cm^2 ($O \rightarrow O^+$) and $\sigma_{0-1} \approx 1 \times 10^{-16}$ cm^2 for the electron capture ($O \rightarrow O^-$).[7–9] These cross-sections remain nearly constant for impacting particle energies in the range of a few hundred keV.

In the electron capture and loss processes (1) one would expect that the largest contribution to the generation of O^- comes from the ions, which have originally single positive charge, as these two species are close in the charge-exchange reactions chain. Therefore, because the interactions proceed almost elastically, one observes that the O^- maximum energy varies similarly as the maximum energy of the O^+ ions (Fig. 4).

An estimate of the brightness of the negative ion source leads to extremely high values, exceeding 10^8 A cm^{-2} sr^{-1}, if one considers the emission of 10^9 negative ions with energy around 1 MeV in 5% energy bandwidth formed at the edge of the spray (within the range 50 μm) during 10 ps in colli-

sions of ∼1 MeV O^+ ions with neutrals. The source volume is approximated to the transverse projection of the laser-focal volume: $6 \times 70 \, \mu$m^2 (focal spot diameter times confocal parameter). This is by far the highest brightness reported for a negative ion source, which arises mainly due to the ultrashort duration of the emission.[10]

Our interpretation implies the existence of a large number of fast neutral oxygen atoms with about MeV energies according to the possible charge-exchange processes (1). This could be verified in future experiments, although there are already indirect indications of their presence in the experimental spectra. The "zero" points in the spectrometers (Fig. 3) are formed by neutrals and x-ray photons emitted from the interaction region.[11] The x-ray emission is expected to be almost isotropic. Because of lower absorption in the ionized medium encountered in the forward direction, x-rays are preferentially observed in the forward direction.[12] On the contrary, the neutral oxygen atoms, arising from a chain of charge-exchange processes (1) would be emitted mostly in the transverse direction. The signal given by the spectrometer's "zero" point in the transverse direction is ten times stronger than in the forward direction, which is then consistent with a signal due to fast neutrals (∼10^{10} neutrals collected through the spectrometer pinhole).

In general, laser-based negative ion acceleration can be an attractive option in the near future to overcome limitations imposed on ion pulse duration and emittance in currently available negative ion sources. This approach could offer a significant increase (3–4 orders of magnitude) in the achieved source brightness avoiding high costs and many technological challenges typical for conventional accelerator technology. However, there will be also many new technical challenges for the laser-based negative ion source.

ACKNOWLEDGMENTS

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