Numerical study of femtosecond laser pulse interaction with water spray target

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1. INTRODUCTION

Interaction of ultrashort laser pulses of very high intensities with matter is of great interest in last two decades due to various phenomena observed during the interaction. For the studies of femtosecond laser pulse interaction with matter and related particle acceleration, two types of targets are typically used - gas-jets and thin solid foils. However, alternative targets were also proposed. Experiments on proton acceleration and negative ion generation were made with the so-called water spray target which consists of many submicron water microdroplets [1]. In this contribution, which is complementary to the previous paper [2] studying laser interaction with single droplets, we investigate the interaction of femtosecond laser pulse with the cloud of such droplets by two-dimensional particle-in-cell simulations. In this paper with limited number of pages, we choose to illustrate the influence of the distance between submicron droplets on the laser pulse propagation, absorption, and proton acceleration inside the clouds.

2. SIMULATION METHOD AND PARAMETERS

In this set of simulations, we calculated the interaction of femtosecond laser pulse with the cloud of droplets with a given distance of one from each other (the droplets were distributed uniformly). The droplet of diameter of 150 nm initially consists of protons and O^{1+} ions in ratio 2:1 (we assumed water droplets) and the initial density of electrons is equal to 19 n_{ec} (where n_{ec} is the electron critical density) as in Ref. [2]. Field and collisional ionization is implemented in the simulations, which means that the charge of oxygen ions is increased mostly to O^{6+} or to O^{8+} [2] and electron density

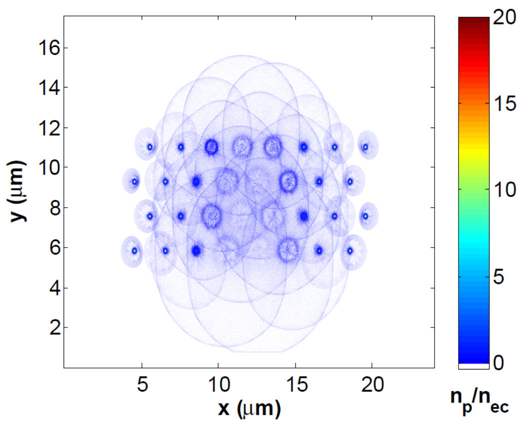

Figure 1: Proton densities after the irradiation of the cloud of 4x8 droplets by 40 fs laser pulse of maximum amplitude a_0=3.

in droplets can exceed 50 n_{ec} after ionization events. The laser pulse of amplitude a_0=3.0 ($I = 1.9 \times 10^{19}$ W/cm^2) has $\sin^2$ temporal shape of the length 16τ, where τ=2.67 fs is the laser wave period (for the wavelength λ=800 nm). The laser beam width at FWHM is set to 3.8 μm.

To investigate the influence of the distance between the droplets, we employed several target configurations in our simulations. The droplets were uniformly distributed with the distance of neighboring droplets from 2 μm downto 0.5 μm. Two configurations have been chosen for this paper - cloud of 4x8 droplets (4 rows of 8 droplets perpendicularly to the direction of laser pulse propagation) for the distance of neighboring droplets equal to 2 μm and 13x28 droplets for 0.5 μm.

3. RESULTS AND DISCUSSION

The initial configuration of droplets is apparent from Fig. 1 showing densities of protons at the end of simulation (about 150 fs after laser-target interaction) with the cloud of 4x8 droplets. The laser pulse propagated from the bottom to the top. It can be observed that the droplets in the laser propagation area expanded rapidly. Protons are removed almost completely from the center of the target in those droplets. Since the proton charge to mass ratio is higher compared with oxygen ions, the protons are attracted by accelerating electric fields prior to oxygen ions. Thus, oxygen ions as heavier positively charged particles substituted protons in the center of droplets irradiated by a strong laser field. Although the droplets on sides of the cloud are not irradiated directly by the laser field, they are influenced by escaping hot electrons together with scattered laser light. In Fig. 1, one can also observe slower expansion of the droplets on the sides. The droplets on the sides expand asymmetrically depending on their position in the cloud - their expansion is faster in the direction outside from the cloud where they are not influenced by other expanding droplets from inner layers of the cloud.

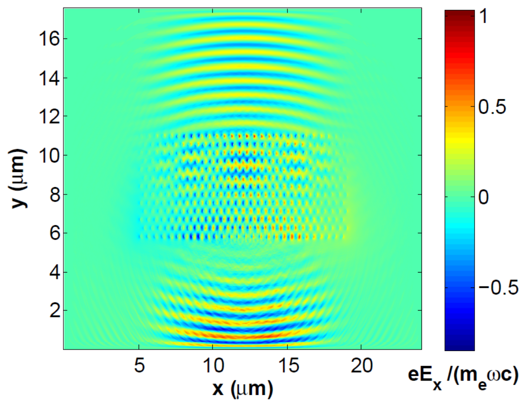

Figure 2: Perpendicular electric field (along x-axis) in the simulation box after the interaction of 40 fs laser pulse of amplitude $a_0 = 3$ with the cloud of 13x28 droplets. The distance of neighboring droplets is 0.5 μm. One can observe that reflected laser wave has higher amplitude that the wave which penetrates through the cloud. However, most of the laser pulse energy is absorbed (75%).

The energy spectra of protons accelerated in various directions may differ substantially, especially when the distance of neighboring droplets is smaller and the laser propagation length in the cloud is relatively short. For denser clouds of subwavelength droplets, the laser light is strongly absorbed and reflected on the front side of the cloud (the side irradiated by the laser). Fig. 2 shows electric field of the laser wave at the end of laser-target interaction for the cloud of 13x28 droplets (the distance of neighboring droplets is equal to 0.5 μm in this case). It can be observed that a larger part of the laser wave is reflected than propagating through the cloud. However, we found that most of the laser pulse energy (about 75%) is absorbed in the cloud of droplets.

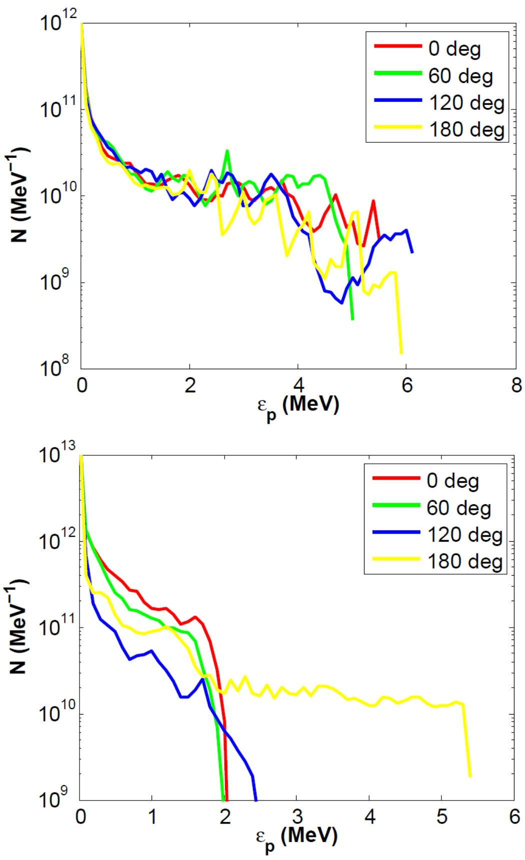

Figure 3: Energy spectra of protons accelerated in various directions after the interaction of 40 fs laser pulse of maximum amplitude a_0=3 with the cloud of 4x8 droples (upper figure) and 13x28 droplets (lower figure). 0 deg = direction of laser pulse propagation through the cloud (forward). 60 deg, 120 deg, and 180 deg are directions deflected from the forward direction about 60°, 120°, and 180° (opposite - backward - direction), respectively. All protons accelerated in a given angle ±10° are taken into account.

The propagation of the laser pulse is strongly related to the acceleration of ions. The acceleration is driven mainly by hot electrons. For single droplet, the maximum energies only slightly differ in various directions and the highest number of accelerated protons is at maximum proton energy [2]. For cloud of droplets, the number of protons is decreasing (in average) with increasing energy (see Fig. 3). In fact, the proton energy spectra from the cloud of droplets are the sum of spectra of many expanding single droplets - one can observe small modulations in the spectra formed due to single expanding droplets - but it also shows some group effect. Protons with the highest maximum energies are accelerated in the backward direction (in the opposite direction - 180° - to the laser propagation direction), although the number of accelerated protons is higher in the forward direction.

The relative difference in maximum energies is significant for the cloud of 13x28 droplets in contrast to the cloud of 4x8 droplets. The difference can be explained by the laser pulse propagation inside the cloud together with electron dynamics in the cloud. For 4x8 droplets, the laser pulse is only slightly absorbed, reflected, or scattered in the front part of the cloud. For the cloud of 13x28 droplets, the distance between droplets is too low and the laser pulse is mostly absorbed or reflected on the front side of the cloud (see Fig. 2). A slightly higher number of protons accelerated in the forward direction compared with the backward direction (even if the maximum energies are higher in the opposite direction) can be explained by a part of hot electrons transported in the forward direction through the cloud (in the direction of the propagating laser wave). Since the number of accelerated protons depends mainly on the density of hot electrons [3], they are accelerated in a higher number in the forward direction. On the other hand, the highest intensity of the laser irradiated droplets on the front side of the cloud. A higher intensity of laser radiation leads to a higher electron temperature, which is translated rather to the higher maximum proton energy than the number of protons. Since the acceleration length in the forward direction is limited on the front side of the cloud of droplets, only protons in the backward direction can be accelerated to the highest energies.

Acknowledgments

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