Jet effusion from a metal droplet irradiated by a polarized ultrashort laser pulse

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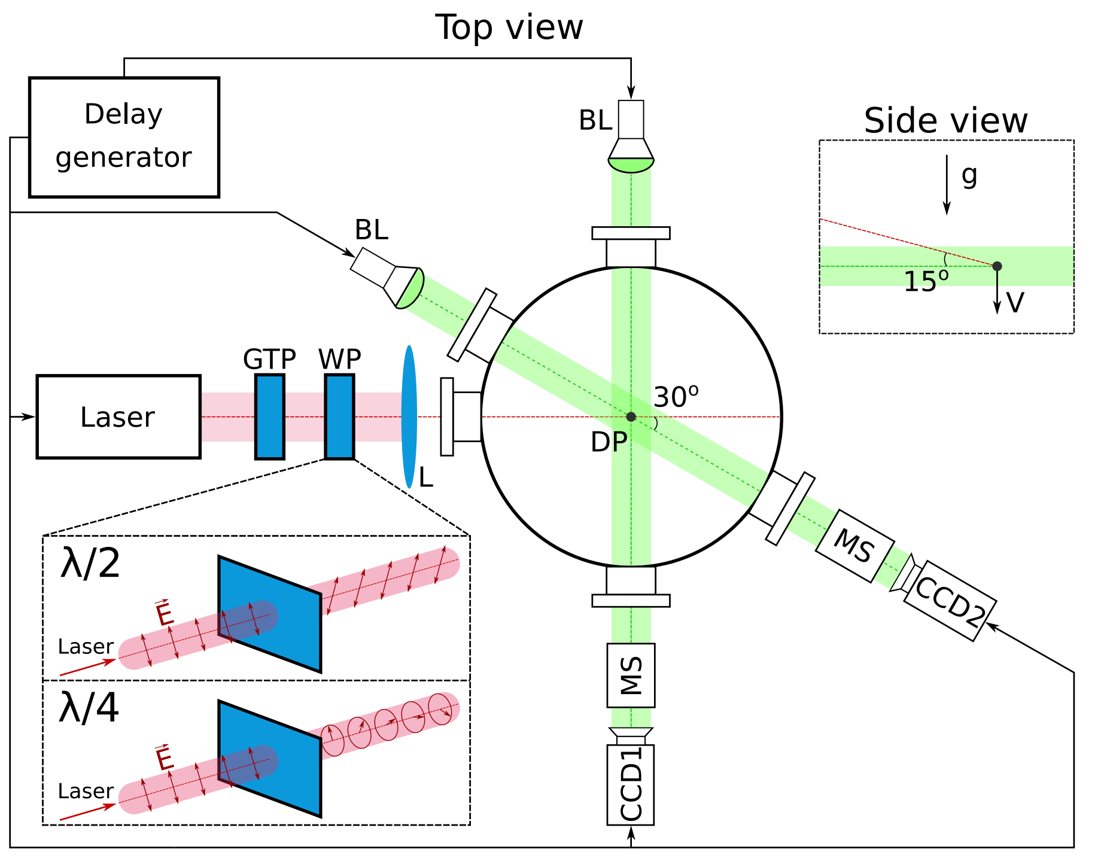
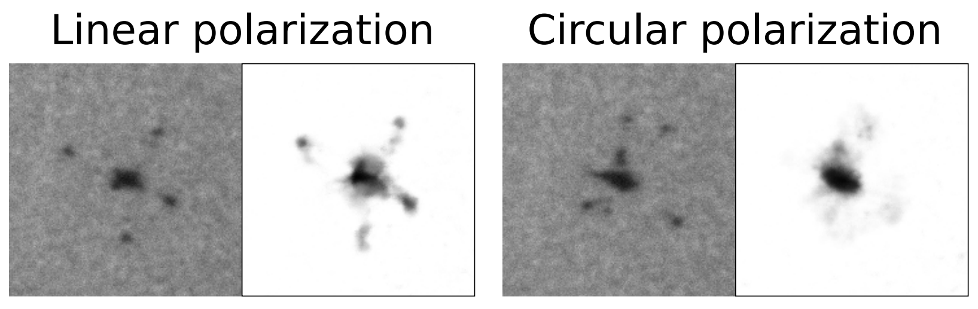
Introduction

Fragmentation of liquid metal droplets irradiated by linearly and circularly polarized femtosecond laser pulses was observed in experiment. The obtained shadowgraph snapshots demonstrate that the circularly polarized pulse may produce several randomly-oriented jets effused from the expanding droplets, while the linearly polarized laser pulse generates strictly the cruciform jets. The latter orientation is tied with polarization plane, rotation of which causes rotation of the cruciform jets on the same angle. To shed light on the experimental data we performed molecular dynamics simulation of droplet expansion induced by angle-dependent heating. Our simulations show that the jet directions are determined by an oriented angle-dependent energy distribution on the frontal hemisphere layer of droplet after absorption of linearly polarized light. As a result, such flow velocity distribution within the frontal shell assisted by surface tension forms two high-speed opposite jets oriented across the electric field vector as in our experiment.A shock-wave pulse generated in the frontal layer has angle-dependent amplitude inherited from the oriented energy absorption. The release part of shock pulse produces a cavitation zone nearby the droplet center, and thus an expanding spherical shell is formed from the droplet. The flow velocities within the rearside hemisphere of the shell, produced after reflection of the shock wave from the rear side of droplet, generate two low-speed opposite jets oriented along the electric field vector. Thus we found that the cruciform jets are originated independently from the frontal and rear sides of droplet, and a pair of frontal jets is faster than a pair of rearside jets.

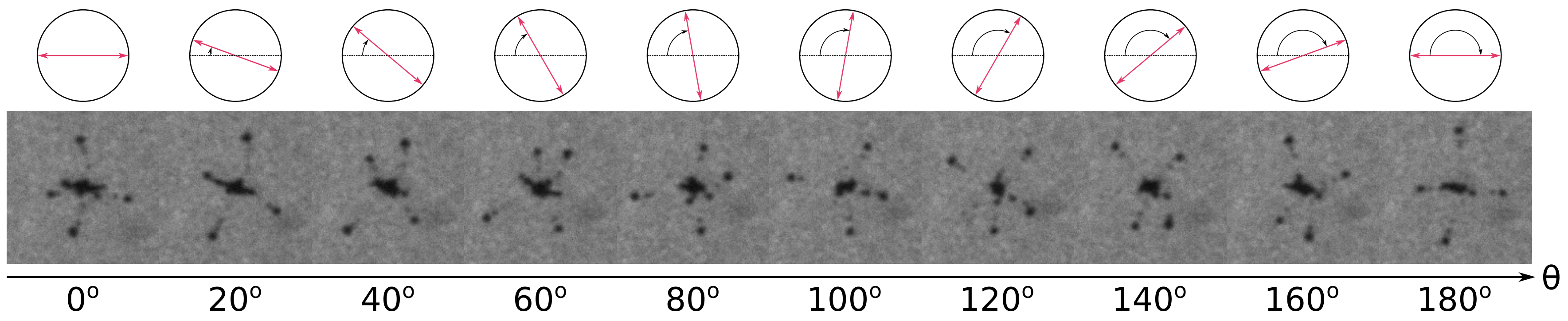
The experimental setup and results

The experiment is performed in a vacuum chamber, where the residual gas pressure is less than 10^{-2} Pa. Sn-In liquid alloy targets (in a mass proportion of 52% to 48%) are used with the diameter of approximately 30 μm. We use a Ti:sapphire laser (λ= 800 nm) with a fixed pulse duration τ = 120 fs and a Gaussian intensity profile in the focal plane to irradiate liquid tin droplet. The size of the focal spot, defined as the full width at half height is 200 μm. The laser-pulse energy in the experiments is approximately 1.15 mJ. The corresponding intensity of the laser pulses is 3.0×10^{13} W/cm^2 .





Shadowgraphs that were made during the experiments demonstrate formation of cross-like structures as a result of droplet break up. We observe formation of jets along the line of laser pulse and also in the perpendicular plane. Cross-shape jets are observed in our experiments only for linearly polarized laser pulse. For non-polarized laser pulse direction and number of jets can be different for different experiments.

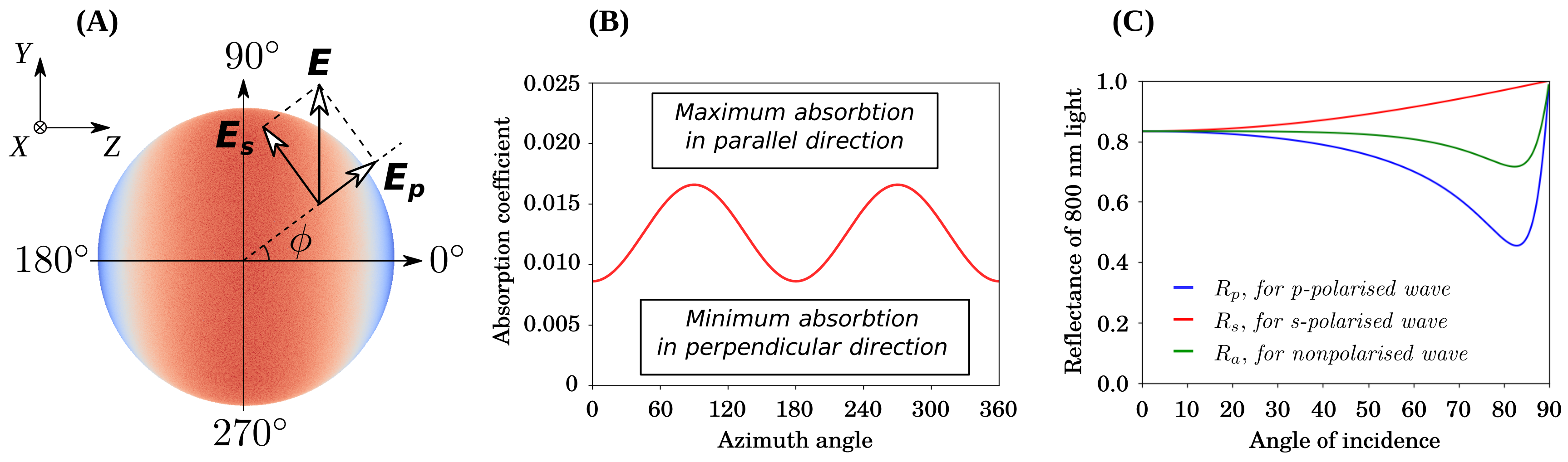


By rotating the half-waveplate we can rotate the polarization plane of the laser radiation. The snapshots of the fragmented droplet taken at the same moment of time for different polarization plane orientation demonstrate that jets are guided by the rotation of the laser polarization plane. Moreover, the jets directions in the experiments are correlated with the direction of the laser radiation electric field vector **E**.

MD model of liquid tin

To unveil the mechanisms leading to jets formation after the droplet break up we perform simulations using the molecular dynamics simulations. For liquid tin we use EAM-potential fitted with stress-matching method. It gives the correct equation of state and surface tension that is responsible for cavitation and spallation processes. Here it should be noted that size of the simulated droplet is smaller than in experiments by two orders of magnitude (the diameter is 240 nm). But in our previous work we demonstrated similarity in fragmentation of droplets with different diameters that allows us to simulate smaller droplets.

Surface heating after laser pulse irradia



Temperature distribution after irradiation depends on angle of incidence and also on azimuth angle.

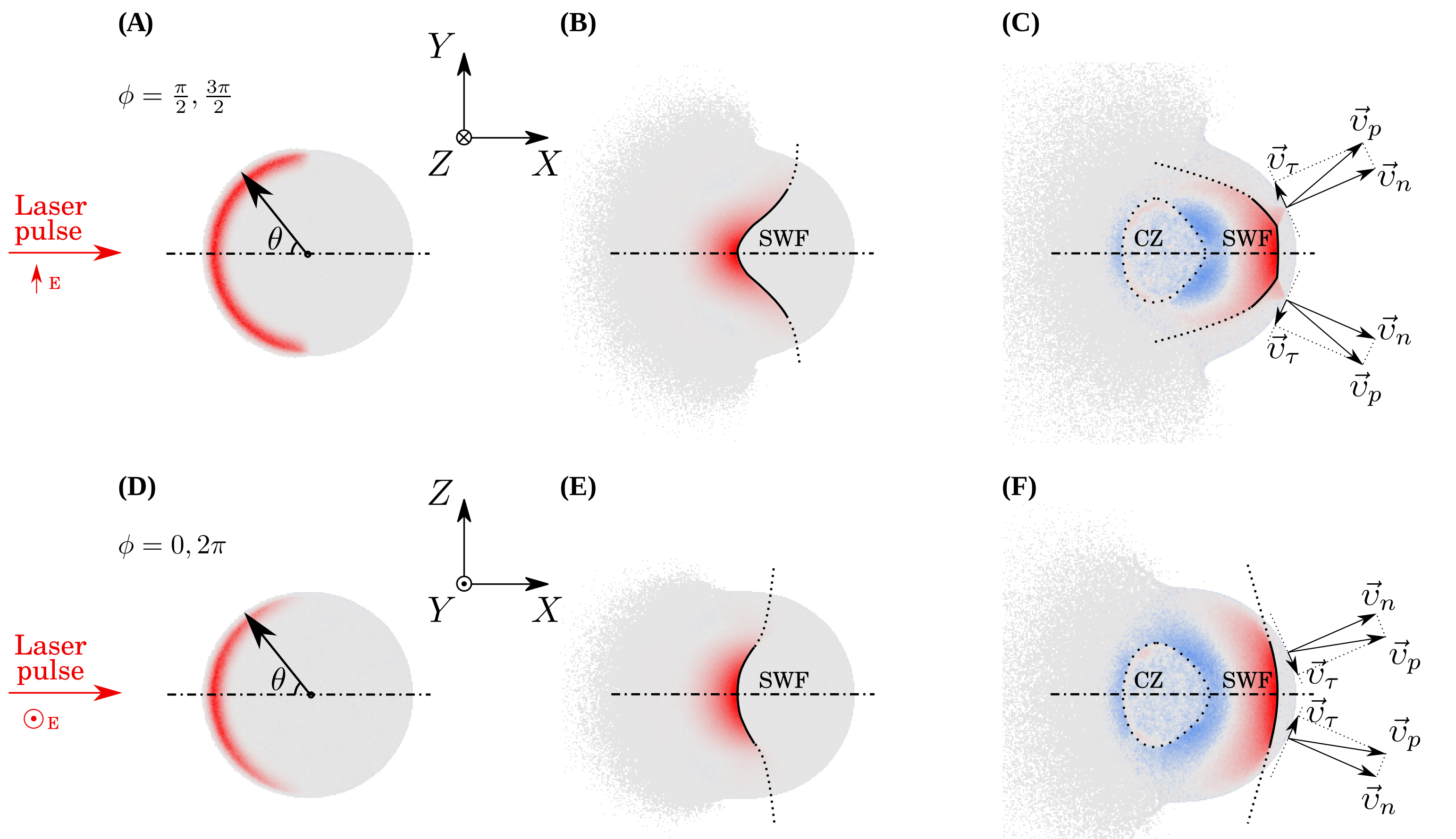
$$T(r,\theta,\phi) = \alpha(\theta,\phi) T_m e^{-(r-R)^2/\delta_h^2}$$

$$\alpha(\theta,\phi) = [(1-R_s)\cos^2\phi + (1-R_p)\sin^2\phi]\cos\theta$$

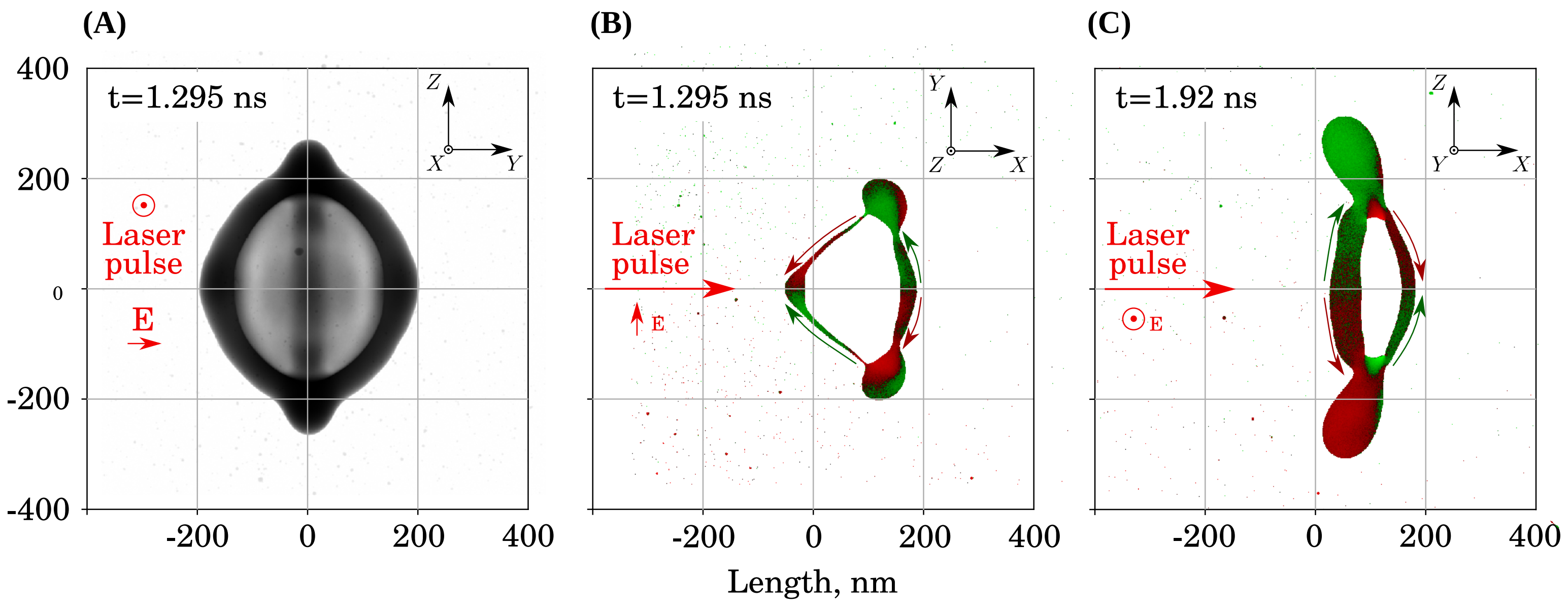
The reflection coefficients of s- and p-polarized radiation - Rs and Rp, correspondingly, are determined from the generalized Fresnel formulas with the real part of the material refractive index n=2.96 and imaginary part k=7.44 which were experimentally measured for radiation with the wavelength 800 nm.

Simulation results

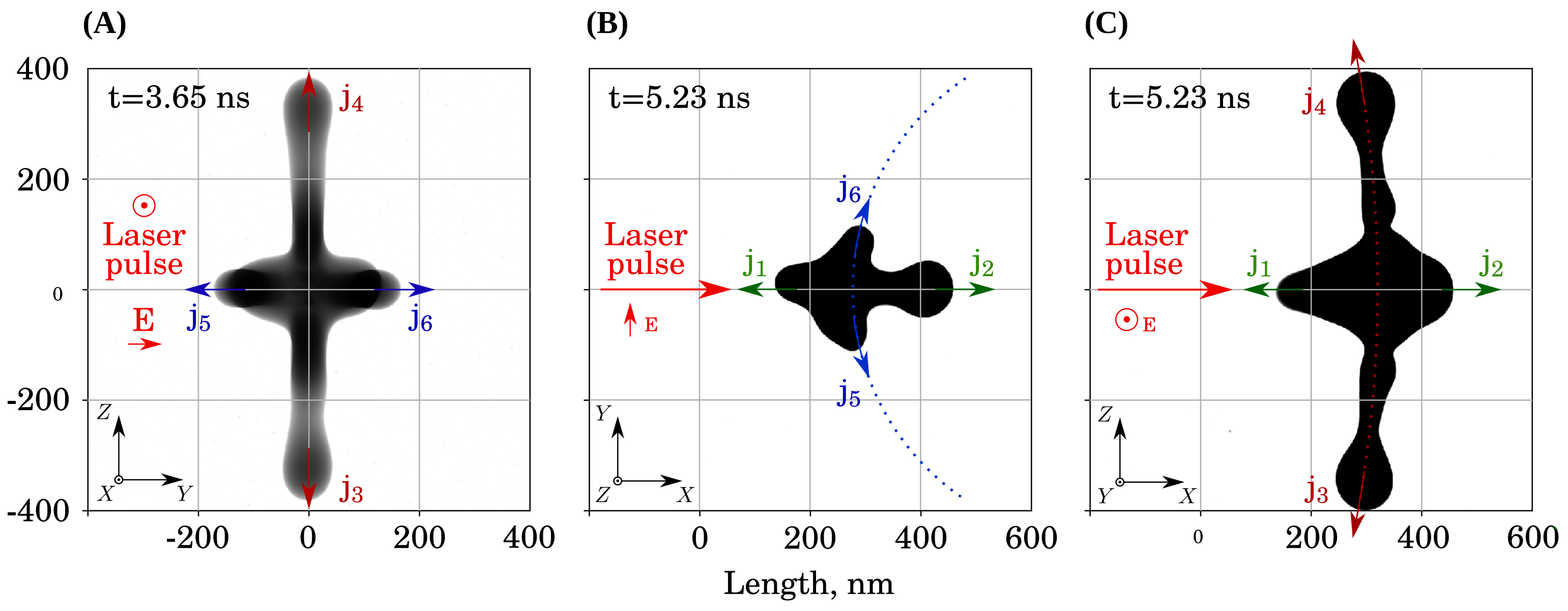
Fast laser energy deposition leads to formation of short pressure pulse which is different in the planes that are parallel (A) and perpendicular (D) to the vector of electromagnetic field strength. So, as a result of asymmetric heating, a pressure field formed on the frontal surface of the droplet will be maximum along the Y direction and minimum along the Z direction. Such a pressure field induces flow on the frontal surface, which leads to the accumulation of liquid and its elongation along the direction perpendicular to the vector of electromagnetic field strength. That is why axis Z will be preferred direction of flow at the frontal part of the droplet. At the rear surface, on the contrary, axis Y will be preferred. As a result of asymmetric heating, the shock wave front will be strongly curved. From the pressure maps one can see that the curvature radius of the shock wave front is smaller than the droplet radius in the plane parallel to the vector **E** (B), in the plane thaht is perpendicular to the vector **E** it is almost flat (E). Reflection of such a shock wave from the rear surface will induce a converging flow along Z direction (F) and diverging flow along Y direction (C). As a result, the asymmetric character of heating leads to the elongation on the frontal part of the droplet in the direction perpendicular to the vector **E**, on the rear surface - in the parallel direction.



The evolution of the droplet shape after the formation of a central cavity is determined by the flow induced by the shock wave propagating through the droplet. Simulation demonstrates that the frontal part stretches in the Z direction, while rear part of the shell, on the contrary, is elongated along the Y direction, parallel to the vector **E**. Also it should be noted that an inverse flow pattern is formed in perpendicular planes.



At a late time after the rupture of the cavity shell simulation demonstarte formation of cross-like structures: two high-velocity jets across the vector **E** from the frontal part of the shell and two low-velocity jets along the vector **E** from the rearside surface. In our simulation we also observe two tiny jets along the laser beam.



Conclusion

Heating and propagation of shock waves leading to fragmentation of liquid tin droplets irradiated by linearly polarized ultrashort laser pulses were studied and modelled in this work.

Recently we demonstrated experimentally that irradiation with circularly polarized or unpolarized light results in formation of jets during the droplet expansion, while their number and direction were accidental. In this work with the use of linearly polarized light, we discovered the formation of cruciform jets, which fly away in roughly perpendicular directions. Moreover, it was demonstrated by rotating the polarization vector that the jet directions are strictly determined by the electric field vector of laser light. There are two high-speed jets oriented across the electric field vector E and two low-speed jets oriented along E. We also observed two tiny jets directed along the laser axis, which are formed later on.

To shed light on the experimental data we performed molecular dynamics simulation of droplet expansion induced by angle-dependent heating. Almost isochoric heating of the thin surface layer depends on the angle between a polarization vector and a normal to the droplet surface, which result in a cross flow pattern on the frontal (irradiated) and rear side surfaces. We demonstrated that the flow velocity field within the frontal layer of droplet, which is formed as a result of heating, leads to the formation of two opposite jets oriented across the electric field vector E. Conversely, reflection of the shock wave from the rear surface accelerates material in such a way that the formed flow velocity field in the rearside shell generates two opposite jets oriented along the vector E. We also found in MD simulation, that a pair of frontal jets is faster than a pair of rearside jets, as it was observed in our experiments. Surface tension leads to the formation of two tiny jets along the laser beam late on the droplet fragmentation.

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