

Laser prepulse-induced deformation dynamics in tin microdroplets for extreme ultraviolet light source applications

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This paper presents a detailed numerical investigation of the deformation dynamics of spherical tin (Sn) microdroplets under the action of laser prepulses, which is an essential process for optimizing extreme ultraviolet (EUV) lithography targets. A hybrid simulation method is developed, combining a single-fluid radiation hydrodynamics model for laser-produced plasmas with a two-phase flow model that incorporates surface tension effects. Two distinct scenarios are analyzed using this hybrid approach: nanosecond and picosecond prepulses, each characterized by markedly different energy deposition and deformation mechanisms. The simulations capture the full deformation process from initial laser impact to the capillary timescale, reproducing target morphologies that show good agreement with experimental observations. Detailed quantitative analyses of droplet expansion rates and geometries are also provided. Finally, the impact of the predeformed targets on EUV emission performance is evaluated by simulating the interaction of a CO₂ main pulse with the deformed structures. This study offers significant insights into laser-droplet interactions and contributes to the development of precise control strategies for optimizing EUV target shaping.

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I. INTRODUCTION

The interaction of laser pulses with liquid droplets gives rise to complex hydrodynamic phenomena, including shock wave propagation, rapid and explosive phase transitions, droplet deformation, and fragmentation. These phenomena have attracted significant attention, largely driven by the development of laser-produced plasma (LPP) sources for extreme ultraviolet (EUV) lithography [1–4]. Currently, EUV light sources use a double-pulse scheme to generate in-band EUV radiation within a 2% bandwidth centered at 13.5 nm [1–3]. In this configuration, an initial low-energy laser pulse, known as the prepulse, impinges on a spherical tin (Sn) microdroplet (diameter $\sim 30\text{--}50\text{ }\mu\text{m}$) to induce deformation. The prepulse can be either a nanosecond pulse with a relatively long duration ($\sim 10\text{ ns}$) or a picosecond pulse with a short duration (less than 100 ps) [1–3]. After a time delay on the order of microseconds, a high-energy main pulse, typically a CO₂ laser with a wavelength of 10.6 μm in industrial applications, irradiates the deformed target and generates a hot ($\sim 20\text{--}40\text{ eV}$) and dense ($\sim 10^{17}\text{--}10^{20}\text{ e}^-/\text{cm}^3$) plasma. This

plasma contains a large population of highly charged Sn ions (Sn⁸⁺–Sn¹⁴⁺) and emits EUV radiation with a spectral peak centered at 13.5 nm [2,3,5–7].

The size and material distribution of the deformed target produced by the prepulse are critical for determining the energy conversion efficiency (CE), which is defined as ratio of in-band energy radiated toward the plasma-facing collector mirror to laser energy, as well as for scaling EUV output power. Industrially relevant EUV sources typically operate with deformed Sn targets a few hundred micrometers in diameter, formed within several microseconds following the prepulse impact [1–3]. In addition, the droplet deformation driven by the prepulse also leads to the generation of micron-sized fragment debris, referred to as neutral cluster debris, which can significantly reduce the lifetime of the collection optics in commercial EUV systems [8,9]. Maximizing the CE of EUV light sources to values exceeding 6%, while minimizing the production of neutral cluster debris, requires precise control of the droplet deformation and target shaping. Achieving this control, in turn, demands a detailed understanding of the coupling between the laser and the droplet, as well as the hydrodynamic response of the droplet to prepulse impact on microsecond timescales.

To date, numerous experimental and simulation studies have investigated the deformation of Sn microdroplets following impact by laser prepulses of varying durations [10–26]. In particular, time-resolved shadowgraph imaging experiments [10–20] have revealed that short and long prepulses give rise to distinct deformation mechanisms, resulting in markedly different final morphologies of the target. For short pulses, deformation is dominated by strong shock-wave-induced

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cavity expansion, often accompanied by spallation, leading to the formation of an acornlike structure [11–14]. In contrast, long pulses induce deformation into a thin, elongated liquid sheet [10,16–18].

The hydrodynamic response of Sn droplets to laser prepulse impact has been extensively investigated in previous analytical and numerical studies [10,12,14,17,21–23,26,27]. Specifically, radiation hydrodynamics codes such as RALEF2D [10,14,17], HEIGHTS [28], and RHDLP [27] have been widely employed to simulate the deformation processes of Sn droplets. However, as most radiation hydrodynamics codes do not incorporate the effects of surface tension, these simulations are typically limited to the early stages of deformation. Alternatively, the smooth particle hydrodynamics (SPH) method has been applied to simulate deformation induced by short laser pulses. As demonstrated by Grigoryev *et al.* [12] and Koukouvinis *et al.* [26], SPH simulations can accurately resolve the formation and propagation of strong shock waves within the droplet shortly after laser impact, along with the development of cavitation and spallation regions. However, due to limitations in particle number and computational efficiency, SPH methods are also constrained to early-time simulations. In addition, Gelderblom *et al.* [21] proposed a boundary integral (BI) method for modeling laser-induced droplet deformation. While the BI method can precisely capture lateral deformation and sheet thinning, it does not account for the subsequent fragmentation of the elongated liquid sheet.

Furthermore, Gelderblom *et al.* [21] and Reijers *et al.* [22] presented analytical solutions describing the early-time flow fields within the droplet following nanosecond laser pulse impact. These studies offer valuable insights into recoil pressure generation and the resulting dynamics that initiate droplet deformation. However, the validity of these analytical models is limited to early times before significant morphological changes occur. Klein *et al.* [23] further extended analytical modeling to the fragmentation regime, investigating how the early laser-matter interaction influences late-time fragmentation of liquid droplets subjected to nanosecond laser pulses.

Existing analytical and numerical studies have significantly advanced our understanding of the early deformation dynamics of Sn droplets. However, in EUV sources, the main pulse must interact with low-density, spatially extended targets to achieve high CE. These target conditions typically arise only several microseconds after prepulse impact. Moreover, neutral debris generation on similar timescales poses major challenges to the longevity of optical components. Consequently, it is essential to conduct comprehensive simulations that capture the full evolution from the initial laser-droplet interaction to the late-time fragmentation stage, over microsecond timescales [29,30]. This requirement goes beyond the temporal and physical scope of most previously developed models.

To address this gap, we propose a hybrid simulation method that enables detailed investigation of Sn droplet deformation induced by both nanosecond and picosecond laser prepulses. This approach couples single-fluid radiation hydrodynamics with two-phase flow modeling to simulate the deformation process across multiple physical regimes and timescales. For nanosecond prepulse-induced deformation, the simulations provide comprehensive results, including the

spatial distribution of plasma state parameters during laser irradiation, pressure wave propagation within the droplet, the surface-tension-driven morphological evolution of the target, fragmentation behavior, and the time-resolved development of propulsion velocity and sheet radius. In this work, fragmentation refers to the onset of partial breakup or rim detachment of the expanded tin sheet, rather than complete disintegration of the target. For picosecond prepulse-induced deformation, the simulations capture key features such as the propagation of strong shock waves within the droplet, the formation of cavitation and spallation regions, the evolution of front and rear shell positions, and the temporal dynamics of the cavitation shell radius. Simulation results are systematically compared with experimental observations and analytical predictions, showing good agreement in all cases.

II. NUMERICAL MODELLING

Prepulse-induced deformation of Sn droplets typically involves several key stages: laser-droplet interaction, plasma generation, inertial-scale deformation, and surface-tension-driven evolution on capillary timescale. The capillary timescale refers to the characteristic period over which surface tension becomes dominant over inertial forces, governing the subsequent deformation and retraction of the droplet [2]. To simulate the full deformation process from the onset of laser irradiation through to the capillary regime, we propose a hybrid simulation method. This approach combines a single-fluid radiation hydrodynamics simulation with a two-phase flow simulation that accounts for surface tension effects. The radiation hydrodynamics simulations are performed using the RHDLP code [27], while the two-phase flow simulations are conducted using the ECOGEN code [31].

A. Brief description of the simulation codes

RHDLP is a single-fluid, two-temperature radiation hydrodynamics code in the Eulerian frame specifically developed for LPP [27]. In this code, we assume that the temperatures of electrons and ions are equal, yet distinct from the radiation temperature. RHDLP integrates a suite of modules encompassing hydrodynamics, heat conduction, radiation transport, laser energy deposition, equations of state, charge state distribution, and spectral simulation. The code adopts the Flux-Limited Multigroup Diffusion approximation [32] for modeling radiation transport, thereby approximating the free-streaming limit.

Laser propagation and energy deposition in RHDLP are simulated through a hybrid methodology [27,33] that merges geometrical-optics ray tracing in subcritical plasma regions with a one-dimensional (1D) solution of the Helmholtz wave equation in supercritical regions. Thermodynamic properties of Sn are ascertained using a quotidian equation of state [34]. The charge state distribution and average ionization degree are calculated by a steady-state collisional-radiation model based on screened-hydrogenic approximation [35,36]. The absorption coefficients for Sn, used in solving the radiative transport equation, are primarily sourced from the THERMOS database [37]. A detailed description of the RHDLP code is provided in our previous publication [27].

Two-phase flow simulations are performed using ECOGEN, an open-source, thermodynamically well-posed computational fluid dynamics code designed for multiphase, compressible, and multiphysics flow problems [31]. ECOGEN is based on a diffuse interface method and supports the simulation of additional physical processes, including surface tension, viscosity, and heat conduction. In addition, the code incorporates a low-Mach preconditioning technique [38], which enables accurate modeling of low-speed flows and extends its applicability across a wide range of flow regimes. The governing equations are modified Euler equations incorporating relaxation processes, following the formulations by Kapila *et al.* [39] and Saurel *et al.* [40]. A comprehensive description of the ECOGEN code, including the numerical methods used for solving the governing equations, is provided in Refs. [31,40,41] and is not repeated here.

B. Implementation of the hybrid simulation

The hybrid simulation approach is divided into three consecutive steps. In the first step, a radiation hydrodynamics simulation is performed using the RHDLP code. For a nanosecond prepulse, the simulation captures the initial interaction between the laser and the Sn droplet, plasma generation, the propagation of pressure waves within the droplet, and the early stages of droplet deformation. The RHDLP simulation typically terminates between 50 and 100 ns, depending on the state of the surrounding plasma. The simulation is halted once the plasma reaches a low-density ($\sim 10^{-5} \text{ g/cm}^3$) and low-temperature (below 0.5 eV) state, in which radiative transfer, heat conduction, and plasma flow have a negligible influence on the subsequent deformation of the droplet. In contrast, for short-pulse-width picosecond or femtosecond prepulses, the simulation primarily includes laser-droplet interaction, plasma formation, and the generation of a strong shock wave at the droplet surface. The RHDLP simulation in this case is typically terminated between 0.1 and 1 ns. At this stage, the shock wave has already formed at the droplet surface, and the subsequent deformation is driven by the propagation of this shock wave within the droplet. The contribution of the plasma to the ongoing deformation process is considered negligible beyond this stage.

In the second step, the output from the final time step of the RHDLP simulation is postprocessed to perform liquid-gas phase separation. For nanosecond prepulse, a critical density threshold is defined to distinguish between the liquid and gas phases. Through a series of convergence and sensitivity tests, the threshold was determined to be 0.2 g/cm^3 , as values below this level had negligible influence on droplet dynamics, whereas higher thresholds led to unphysical truncation of the dense liquid core. This choice ensures both physical consistency and numerical convergence in representing the liquid-gas interface. It should be noted that 0.2 g/cm^3 corresponds specifically to the nanosecond prepulse parameters used in this study and may vary for different laser conditions or target materials. Regions with densities greater than this threshold are classified as liquid, while those with lower densities are identified as gas. For the picosecond prepulse case, the RHDLP simulation is terminated at a stage when the shock wave has formed only on the laser-irradiated side

of the droplet surface, leaving most of the droplet interior undisturbed. As a result, the liquid-gas distinction is defined based on the droplet's surface: the region inside the droplet is considered liquid, while the region outside is treated as gas.

In the third step, the data obtained after liquid-gas partitioning are used as initial conditions for the two-phase flow simulations in ECOGEN. This code, which incorporates surface tension effects, is then employed to simulate the droplet deformation dynamics up to the capillary timescale. Both the RHDLP and ECOGEN simulations are performed on a two-dimensional axisymmetric mesh in cylindrical coordinates (r, z). To ensure seamless data transfer and consistency between the two simulation stages, the grid resolution is kept identical across both codes.

C. Simulation parameters

In this study, two different types of prepulse-induced deformation of Sn droplets are simulated using the hybrid simulation method. In all cases, the initial Sn droplet has a density of 6.9 g/cm^3 and a radius $R_0 = 25 \text{ }\mu\text{m}$. The background gas is hydrogen with a density of 10^{-8} g/cm^3 , and the initial temperatures of both the Sn droplet and the background gas are set to 300 K. For the nanosecond prepulse, an Nd: YAG laser pulse is used, with a wavelength of 1064 nm and a pulse energy of 2.0 mJ. The laser has a Gaussian temporal profile with a full width at half maximum (FWHM) pulse duration τ_p of 10 ns, peaking at 15 ns, and a Gaussian spatial profile with a focal spot diameter of $60 \text{ }\mu\text{m}$ [10]. For the picosecond prepulse, a short laser pulse with a wavelength of 1064 nm, an FWHM duration of 1.5 ps, a pulse energy of 3.0 mJ, and a Gaussian focal spot with a diameter of $50 \text{ }\mu\text{m}$ is used [14]. The Nd: YAG laser was selected for the prepulse in this study due to its advantages in ablation efficiency, high spatial beam quality for stable interaction with droplets, and its flexibility in both spatial and temporal pulse shaping [1].

To investigate the effect of predeformed target geometry on radiative performance and CE in a double-pulse EUV light source configuration, we further simulate the interaction of a main laser pulse with both nanosecond and picosecond predeformed targets, as described in Sec. IV. The main pulse is modeled as a CO_2 laser pulse with a wavelength of $10.6 \text{ }\mu\text{m}$, a pulse energy of 100 mJ, and a focal spot diameter of $400 \text{ }\mu\text{m}$. This main pulse configuration has also been employed in the experimental investigation of the double-pulse EUV source scheme by Tomita *et al.* [42].

The temporal profiles of the prepulse and main pulse, along with the key time definitions used in the simulations, are illustrated in Fig. 1. The moment of peak power of the prepulse is defined as the zero point of the simulation time axis. The parameter t_p denotes a time point referenced to this zero point. When the main pulse is applied, t_p also represents the delay between the main pulse and the prepulse, effectively indicating the moment at which the main pulse interacts with the predeformed target. The parameter t_m specifies the time at which the plasma state parameters, such as temperature and electron density, are extracted following main pulse irradiation. Finally, Δt refers to the time window used for integrating the EUV radiation and calculating the CE of the

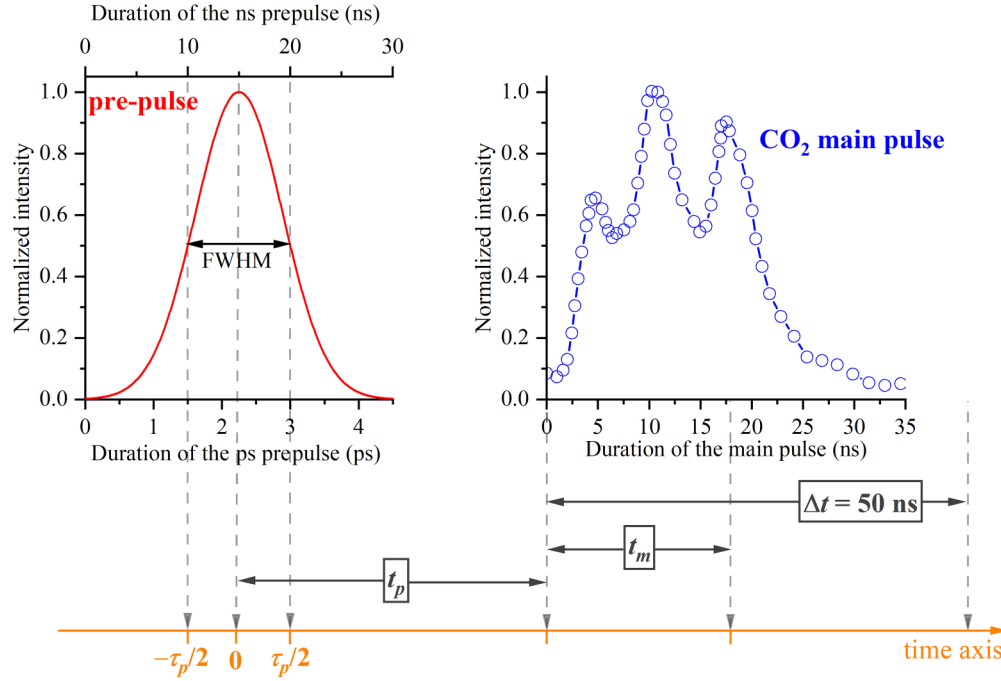


FIG. 1. Temporal profiles of the prepulse and main pulse [42], along with the key time definitions used in the simulations. t_p denotes a time point relative to the reference zero point, defined as the moment of peak power of the prepulse. When the main pulse is applied, t_p also corresponds to the delay between the main and prepulses. t_m indicates the time at which plasma state parameters are extracted following main pulse irradiation. Δt refers to the time window used for integrating the EUV radiation and calculating the CE of the plasma generated by the main pulse acting on the predeformed target. τ_p denotes the duration of the prepulse.

plasma generated by the main pulse acting on the predeformed target.

III. DEFORMATION DYNAMICS OF Sn DROPLETS

In this section, we conduct a detailed simulation and analysis of the deformation dynamics of Sn droplets induced by nanosecond and picosecond prepulses.

A. Deformation of a Sn droplet induced by a nanosecond prepulse

Nanosecond prepulse-induced deformation of Sn droplets can be broadly categorized into four sequential stages: (1) laser-droplet interaction resulting in plasma formation; (2) plasma expansion that generates recoil pressure on the droplet surface; (3) droplet propulsion and radial expansion driven by this recoil pressure over inertial timescales; and (4) surface-tension-dominated evolution and eventual fragmentation of the resulting thin, disk-shaped target over capillary timescales. These four processes are analyzed in detail in the following section.

Figure 2 shows the temperature and density distributions during the nanosecond prepulse impact obtained from the RHDLP simulation. The nanosecond laser pulse impacting the Sn microdroplet rapidly raised the temperature of the irradiated droplet surface beyond the boiling point, leading to the generation of some Sn vapor near the surface. This vapor reached a peak temperature of no more than 1 eV and a maximum density of approximately 0.01 g/cm³, as depicted in Figs. 2(a) and 2(e). The vapor produced by the

laser pulse front acted as a transparent thin medium, allowing most of the laser beam to reach the droplet's surface. However, a small fraction of the incoming laser radiation was absorbed via electron-neutral inverse Bremsstrahlung by the gradually heated vapor, leading to vapor breakdown and initial plasma formation, as shown in Figs. 2(b) and 2(f). The initial plasma then continued to absorb laser energy primarily through inverse bremsstrahlung (mainly electron-ion inverse bremsstrahlung), significantly increasing the plasma temperature and density. Since the plasma critical density interface ($n_e = 10^{21}$ cm⁻³) was proximate to the droplet surface and the laser energy was predominantly deposited there, the high-temperature plasma regions shown in Figs. 2(b)–2(d) were also near the surface. In the later phase of the Gaussian temporal profile (post 5 ns), the plasma temperature swiftly declined due to factors such as the reduction in laser energy, rapid plasma expansion, conversion of internal energy to kinetic energy, and energy loss from thermal radiation. As observed in Figs. 2(c) and 2(d), the peak plasma temperature of 11 eV at 1 ns decreased to 8 eV by 7 ns.

The plasma generated by laser-droplet interaction exhibits a flow length scale (i.e., the distance between the droplet surface and plasma critical surface) of approximately 5 μ m and a flow velocity of about 5×10^4 m/s. Flow scale and velocity establish a hydrodynamic timescale of ~ 0.1 ns for the plasma. Given that the Gaussian laser pulse duration (30 ns) in our simulation significantly exceeds this hydrodynamic timescale, a quasi-steady-state plasma ablation front with a duration of approximately 10 ns emerges at the droplet surface (as shown in Fig. 2, persisting from -5 to 5 ns during the laser pulse irradiation). Concurrently, the plasma pressure near the

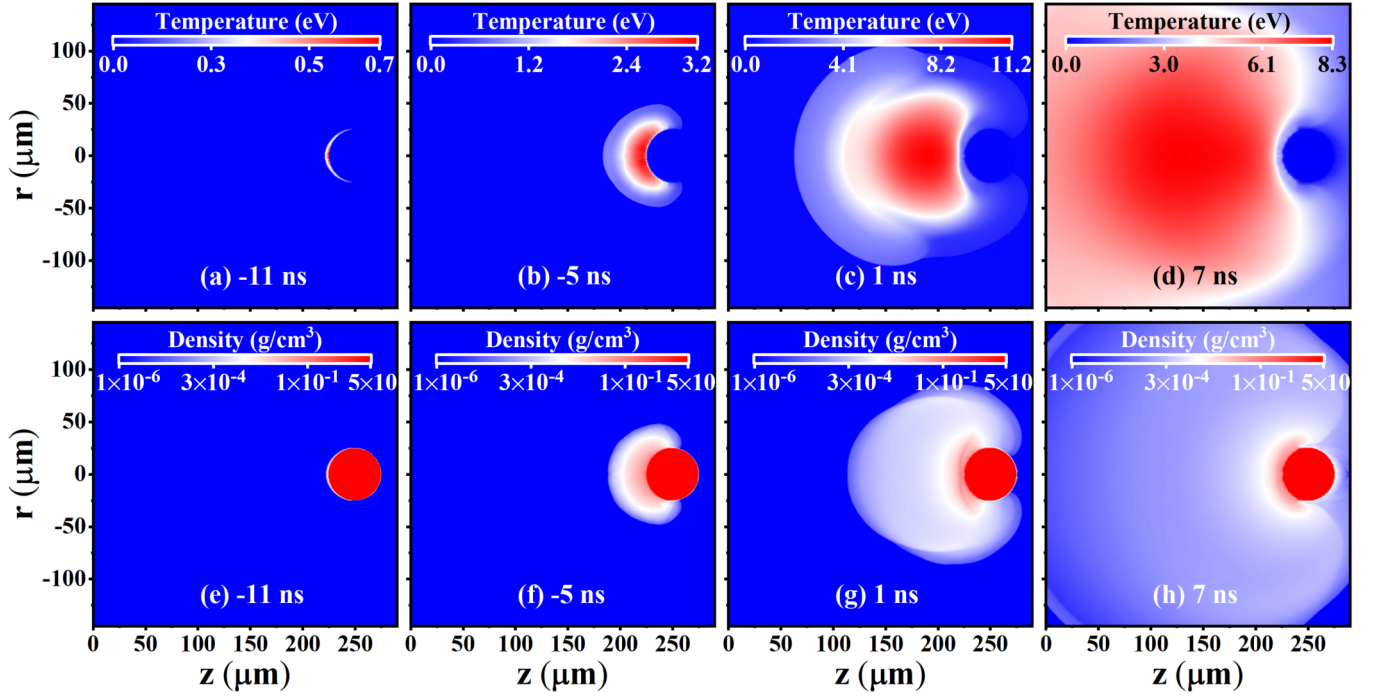


FIG. 2. Temperature distributions (top row) and density distributions (bottom row) from RHDLP simulations at selected delay times during nanosecond prepulse interaction with a Sn microdroplet. The laser pulse propagates from left to right. The center of the droplet is located at $r = 0, z = 250$ μm.

droplet surface manifests dual effects: it propagates inward as pressure waves while simultaneously imparting pressure impulses that induce axial propulsion and radial expansion of the droplet.

Figures 3(a)–3(c) present the pressure distribution and velocity field within the region $210 < z < 290$ μm and $-40 < r < 40$ μm at 15, 35, and 65 ns, respectively. The white solid lines delineate the initial spherical droplet, while the black arrows represent velocity vectors. The laser propagates from left to right in the figure shown. Within the droplet interior, upon termination of the laser pulse irradiation ($t_p = 15$ ns), the pressure wave had propagated past the droplet center and established a compression zone within the region $210 < z < 250$ μm. As the pressure wave continued to propagate with sound speed, the maximum pressure inside the droplet rapidly decreased. By 35 ns, the compression zone had advanced to the $245 < z < 260$ μm region, followed immediately by a low-pressure rarefaction zone. At 65 ns, the pressure wave approached the droplet's rear side while exhibiting a concurrent further reduction in pressure. The liquid acoustic timescale corresponding to pressure wave propagation through the entire droplet at the speed of sound measures approximately 70 ns. This wave propagation causes changes in the density distribution within the droplet. Due to the relatively low energy of the nanosecond prepulse employed in this study, the amplitude of the resulting pressure wave remains moderate. As it propagates through the droplet, it induces only weak density inhomogeneities. In contrast, when either a higher-energy nanosecond pulse or a high-intensity picosecond pulse is used, a significantly stronger shock wave can be generated at the droplet surface. This shock propagates inward and may

produce a large central cavity through shock focusing, as discussed in the following sections.

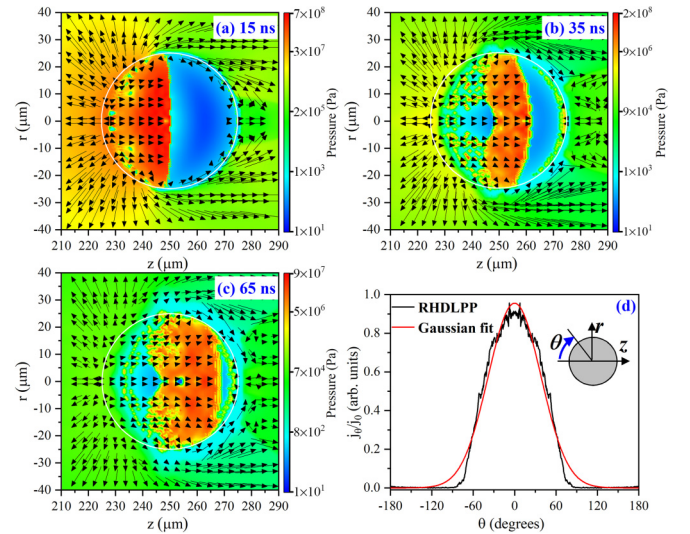


FIG. 3. Pressure distribution and velocity field from RHDLP simulations at (a) 15 ns, (b) 35 ns, and (c) 65 ns. The white solid lines indicate the initial spherical droplet located at $r = 0, z = 250$ μm. Black arrows represent the velocity vectors. The laser pulse propagates from left to right. (d) Normalized local impulse at the droplet-plasma interface, calculated using the RHDLP code (black solid curve), along with its Gaussian fit (red solid curve). The inset shows schematic diagrams of the r - z plane and polar coordinate system.

As mentioned previously, the pressure exerted by the expanding plasma imparts forward momentum, P , to the droplet, thereby governing its propulsion and expansion dynamics. The relationship between the plasma pressure and the acquired forward momentum in polar coordinates is expressed as

$$P = 2\pi R_0^2 \int_0^\pi j_\theta \sin\theta \cos\theta d\theta, \quad j_\theta = \int_0^{t_f} p_a(t, \theta) dt. \quad (1)$$

where j_θ is the local impulse as the time integral of the local pressure and $p_a(t, \theta)$ represents the plasma pressure at the droplet surface as a function of time t and polar angle θ [17,21]. The RHDLP results demonstrate that over 90% of the total pressure impulse is contributed by the plasma near the droplet surface during the laser pulse duration; therefore, we set the upper integration limit t_f to the laser pulse duration of 30 ns. The momentum imparted to the droplet can be characterized by the spatial profile of j_θ [10,17,21,22]. Figure 3(d) displays the profile of the normalized local impulse j_θ/j_0 at the droplet-plasma interface, where j_0 denotes the pressure impulse at the droplet pole $\theta = 0^\circ$. The black solid line in the figure represents the RHDLP simulation results, which we have transformed from the axisymmetric r - z coordinate to the polar coordinate. It can be observed that the profile of this localized impulse is well fitted by a Gaussian function $j_\theta = j_0 \exp[-\theta^2/(2\sigma^2)]$, as indicated by the red curve in the figure. This Gaussian fitting is fully consistent with the Gaussian-type pressure boundary condition proposed by Gelderblom *et al.* [21], which arises from a spatially Gaussian-distributed laser pulse. The fitting result reveals an angular size σ (i.e., standard deviation) of the pressure distribution equal to 38° , a value that closely matches the fitting results reported in Ref. [10].

The angular size σ is directly correlated with the laser focusing conditions [21]. A tighter-focused laser beam produces a narrower local impulse j_θ on the droplet surface, corresponding to a smaller angular size. This angular size further governs the energy partition between deformation kinetic energy and propulsion kinetic energy within the total kinetic energy, as well as the morphological evolution of the deformed target [21]. For instance, a smaller σ leads to enhanced lateral expansion rates, thinner sheets, more inhomogeneous thickness distribution of the deformed target, and more pronounced curvature of the deformed target. Based on the angular size σ obtained under the simulation conditions in this work, we predict that the evolved deformed target will develop into a thin sheet with slight curvature. A more detailed discussion on the morphological characteristics of the deformed target will be presented in the following sections. Moreover, it is noteworthy that the local impulse generated by the spatially Gaussian-distributed laser beam deviates slightly from an ideal Gaussian profile, as evidenced by the discrepancy observed in the simulation results shown in Fig. 3(d).

Following the liquid acoustic timescale, the subsequent droplet deformation occurs over an extended inertial timescale $\tau_i \sim R_0/U \sim 1 \mu\text{s}$, where U denotes the droplet propulsion velocity. The characteristic outcome of this deformation is the formation of a disklike target geometry, which undergoes contraction and fragmentation over an even longer capillary timescale $\tau_c = \sqrt{\rho R_0^3/\gamma} \sim 10 \mu\text{s}$, defined by the liquid

density ρ and surface tension γ [2]. Notably, to further simulate the deformation of the droplet beyond a few hundred nanoseconds, single-fluid radiation-hydrodynamics codes that do not incorporate surface tension effects are no longer applicable. As demonstrated by our previous simulations [27], the RHDLP code predicts that the deformed target will expand indefinitely over time, particularly in the radial direction. Simultaneously, the density will diffuse into space without forming a sharp liquid-gas interface. However, such deformation behavior is not physically realistic. The cooled liquid target should maintain a well-defined boundary. Additionally, due to the effects of surface tension, radial expansion will be suppressed, and after a certain period, the deformed target will undergo fragmentation [23]. To capture these critical effects, we employed the hybrid simulation method introduced in Sec. II, which combines RHDLP and ECOGEN codes. Using this approach, we performed droplet deformation simulations up to the capillary timescale. The RHDLP simulation result at 85 ns was processed and used as the initial condition for the ECOGEN simulation. In the ECOGEN code, the surface tension of the Sn droplet was set to $\gamma = 0.544 \text{ N/m}$ [23].

Figure 4 presents the morphology of the deformed Sn droplet at different times as simulated by ECOGEN. Figures 4(a) and 4(b) depict the early stages of deformation, occurring within hundreds of nanoseconds after laser impact. At this stage, inertial forces dominate: The plasma-induced pressure impulse rapidly pushes the liquid outward before surface tension can respond. As a result, the droplet flattens and expands radially, forming a broad, thicker sheet from its initially compact shape. A nascent rim structure begins to form at the periphery as liquid accumulates along the edge. The rim forms due to mass accumulation at the leading edge as the liquid rushes outward. By Fig. 4(c), the Sn droplet has evolved into an expansive, thin sheet with a relatively smooth surface, significantly larger in diameter than the original droplet. Surface tension has not yet had time to retract the liquid, so the sheet continues to stretch.

In Figs. 4(d) and 4(e), the sheet continues to expand radially along the r direction, with the rim structure remaining clearly discernible. The outward expansion begins to decelerate as the initial inertial impulse dissipates. Concurrently, surface tension acts on the free edges of the sheet, initiating rim retraction. The interplay of forces becomes evident: while inertia has stretched the droplet into a sheet, surface tension seeks to minimize the surface area, potentially causing slight contraction at the edges. The region just inside the rim, commonly referred to as the “neck” [23], begins to thin as the rim’s momentum carries it outward ahead of the rest of the fluid.

Figures 4(f) and 4(g) illustrate the emergence of a pronounced neck and the onset of sheet breakup. In Fig. 4(f), the neck has become highly slender, indicating that surface tension is pulling the sheet inward while the heavier rim maintains outward momentum, potentially leading to a pinching effect. The rim remains thick but may start exhibiting slight nonuniformities due to instabilities. By Fig. 4(g), the neck has thinned to the point of rupture, leading to the fragmentation of the once-continuous sheet. The outer rim detaches, effectively pinching off into a separate droplet. This breakup mechanism aligns with experimental observations [23,24], where the

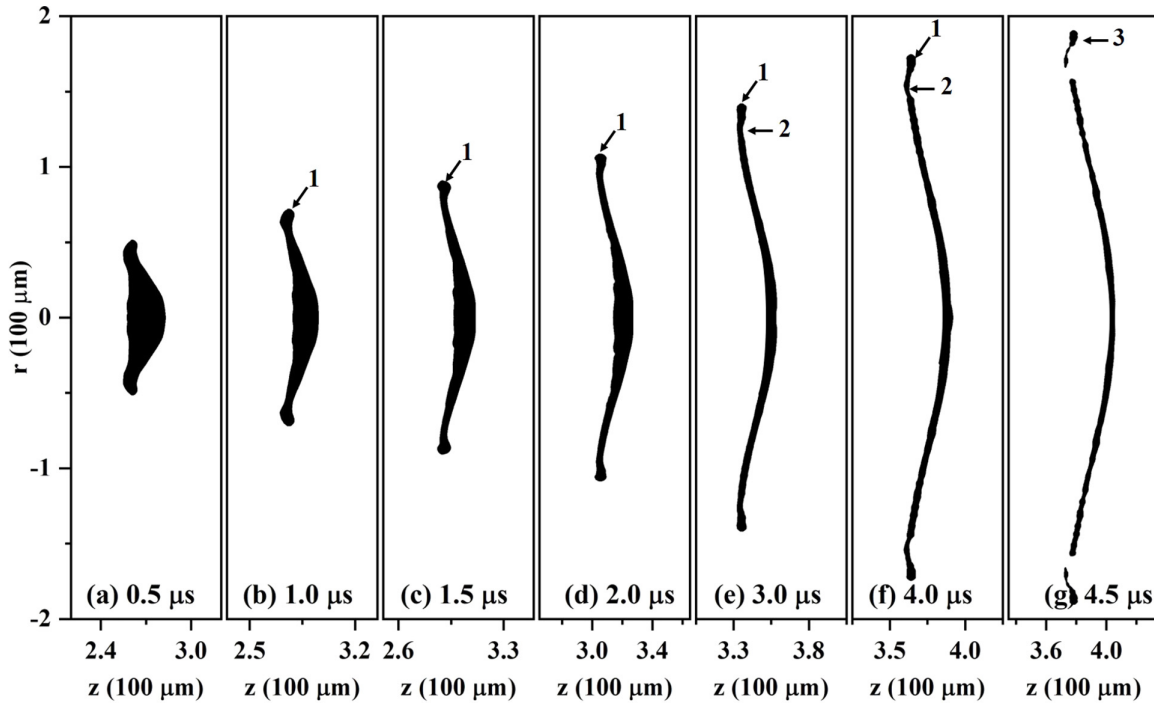


FIG. 4. Morphology of the deformed tin target obtained from ECOGEN simulation. Several features are explicitly indicated in selected images by the following numbers: (1) rim, (2) neck, and (3) fragment.

sheet tears near the rim due to the growth of small holes or thinning in the neck region. The onset of fragmentation is governed by hydrodynamic instabilities [23,24]: Rayleigh-Taylor instabilities, driven by the acceleration of the denser liquid sheet into the surrounding air or vacuum, can nucleate holes, while Rayleigh-Plateau instabilities along the rim can induce undulations and ligament formation. These instabilities likely contribute to the tiny undulations and breakup patterns observed in Fig. 4(g).

Throughout this deformation sequence, inertial and surface tension forces compete to shape the droplet's evolution. In the early stages, inertia dominates: the laser pulse deposits energy almost instantaneously, launching the droplet outward at high velocity. This results in a high Weber number, defined as $We = \rho R_0 U^2 / \gamma$, where ρ is the liquid density, R_0 is the initial droplet radius, U is the propulsive velocity, and γ is the surface tension. In this simulation, the propulsive velocity is $U = 34.5$ m/s (as shown in Fig. 5), yielding $We = 377$. This high Weber number indicates that inertial forces initially overwhelm surface tension, allowing the droplet to undergo significant deformation without immediate recoil. During this phase, the droplet expands into a thin sheet. However, surface tension is present from the outset, resisting the creation of new surface area, albeit on a longer timescale. As the initial kinetic burst dissipates, surface tension becomes the dominant force, evident on the microsecond timescale when expansion stalls and features such as the rim and neck appear. Surface tension acts to retract the liquid and minimize surface area, thinning the neck and slowing the rim's growth. In essence, inertial forces drive the droplet outward, while surface tension pulls it back together. The rim exemplifies this interplay: inertia flings liquid outward into the rim, while surface tension resists further expansion, potentially causing curling or beading

at the edges. Ultimately, fragmentation is governed by the interaction of these forces. In regions where inertia has stretched the fluid extremely thin, such as the sheet center and neck, surface tension can induce rupture, either by pulling the film apart at weak points or by amplifying instability growth. These mechanisms drive the transition from a continuous sheet to a fragmented state, as observed in Figs. 4(f) and 4(g).

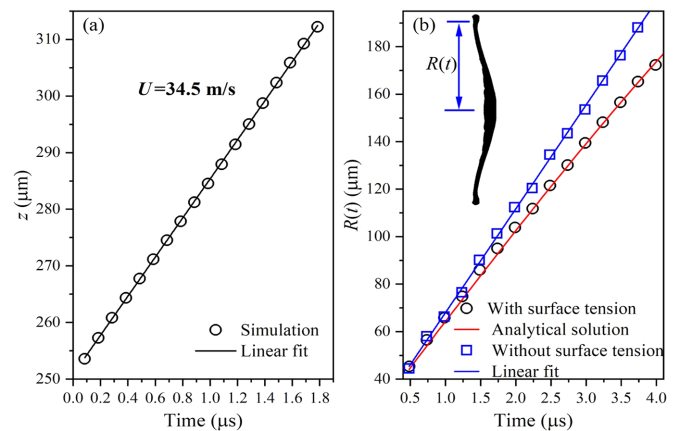


FIG. 5. (a) Time-dependent position of the center of mass of the deformed Sn target along the laser propagation axis z . (b) Temporal evolution of the sheet radius of the deformed Sn target, obtained from ECOGEN simulations with surface tension included (black open circles) and excluded (blue open squares). The red solid line represents the theoretical prediction based on the thin-sheet model [21], while the blue solid line represents a linear fit to the simulation results without surface tension.

Based on the target morphology in Fig. 4, we extracted the z coordinate of the center of mass of the deformed target at different delay times, as shown by the black circles in Fig. 5(a). It is evident that the z coordinate of the center of mass increases linearly with delay time. A linear fit to the data reveals a propulsion velocity $U = 34.5$ m/s along the z axis. Kurilovich *et al.* proposed a power-law relationship for the propulsion velocity U , $U = K_U E_{od}^\alpha$, with constant values of the proportionality factor K_U (m/s mJ $^\alpha$) and the exponent α [16,17]. Different studies have reported similar values for the parameter α , which is generally around 0.6. However, the values of K_U vary slightly, ranging from 35 to 41 [10,16,17]. E_{od} is defined as the incident laser energy illuminating the droplet surface, which accounts for the geometric overlap between the Gaussian laser beam profile and the spherical droplet surface, expressed as $E_{od} = E(1 - 2^{-D_0^2/d^2})$, where D_0 and d represent the droplet diameter and the laser focal spot diameter, respectively [16,17]. Under the simulation conditions in this study, E_{od} is equal to 0.76 mJ. By fixing the value of α at 0.6 and K_U at 41, the power-law relationship yields $U = 34.9$ m/s. This result is in perfect agreement with the propulsion velocity obtained from our simulation.

In addition, we performed a comparative analysis of the time evolution of the sheet radius $R(t)$ of the expanding thin sheet prior to fragmentation. This was done using ECOGEN simulations that either included or excluded the effects of surface tension, as shown in Fig. 5(b). The definition of $R(t)$ is illustrated in the inset of the figure. In Fig. 5(b), the black open circles represent the simulation results obtained with surface tension included, while the red solid line corresponds to the analytical prediction based on the thin-sheet model [21]. The blue open squares show the simulation results without surface tension. For times earlier than 1.5 μ s, the sheet radius increases approximately linearly as the droplet expands radially. A linear fit yields an expansion velocity of approximately 43.8 m/s. In this stage, the results with and without surface tension show minimal differences, indicating that the expansion is dominated by inertial forces and that surface tension has a negligible influence. As the expansion continues, the radial kinetic energy is gradually dissipated, and surface tension begins to play a more significant role in resisting further expansion. This is reflected in the slower growth of $R(t)$ after 1.5 μ s in the simulation that includes surface tension. The deceleration of the radial expansion persists until approximately 4 μ s, at which point the deformed target undergoes fragmentation.

Regarding the evolution of the radius of the Sn sheet, Gelderblom *et al.* proposed a thin-sheet model for quantitative analysis [21]. In this model, the time-dependent radius $R(t)$ is given by

$$R(t) = R_0 \cos(\sqrt{3}t/\tau_c) + R_0 \left(\frac{2}{3}\right)^{1/2} \left(\frac{E_{k,d}}{E_{k,cm}}\right)^{1/2} W_e^{1/2} \sin(\sqrt{3}t/\tau_c). \quad (2)$$

Here, the ratio $E_{k,d}/E_{k,cm}$ represents the partitioning of the total kinetic energy imparted by the laser impact into deformation kinetic energy $E_{k,d}$ and the kinetic energy associated with the center-of-mass motion $E_{k,cm}$. This partitioning is determined by the laser beam profile and has been identified

as a key parameter governing the evolution of droplet morphology.

Under the conditions of our simulation, we obtain $E_{k,d}/E_{k,cm} = 0.65$ using the RHDLP code. According to experimental studies in Ref. [10] and the analytical model in Ref. [21], this kinetic energy ratio is directly determined by the angular size σ . As presented in the previous section, we calculated σ to be 38° , which is in very good agreement with both experimental and analytical results. By substituting $E_{k,d}/E_{k,cm}$ into Eq. (2), we obtain an analytical solution for $R(t)$, represented by the red solid line in Fig. 5(b). The thin-sheet model prediction closely matches our simulation data, considering that it is derived from first principles without any fitting parameters. In our comparison, we truncate the simulation data at the onset of fragmentation, as the assumption of a thin sheet with constant mass is no longer valid beyond this point [21].

B. Deformation of a Sn droplet induced by a picosecond prepulse

Picosecond prepulse-induced deformation of Sn droplets can be broadly divided into several sequential processes: rapid heating of a thin surface layer by the laser pulse, shock wave formation at the irradiated surface, propagation of the shock wave into the droplet interior, and subsequent cavitation and spallation leading to violent droplet deformation. These processes are analyzed in detail in the following sections.

Figure 6 presents the pressure and density distributions inside the Sn microdroplet. The white circular solid line in the figure represents the initial Sn droplet, with its spherical center located at $r = 0$, $z = 200$ μ m. Upon impact of the picosecond laser pulse, approximately 18% of the incident laser energy is absorbed by a thin near-surface layer, approximately 0.1 μ m thick. This rapid energy deposition induces almost instantaneous heating, generating a hemispherical shock wave. The laser-induced shock imposes extreme pressure at the front surface, which then propagates inward.

At the moment of shock formation (0.3 ns after laser impact), the pressure at the laser-irradiated front hemisphere reaches approximately 50 GPa, corresponding to the peak pressure at shock launch. As the shock wave propagates into the droplet, the pressure profile exhibits a sharp peak at the shock front, followed by a compressed region. During the first few nanoseconds, the peak pressure at the shock front decreases from the initial ~ 50 GPa to the tens-of-gigapascals range due to geometric spreading and energy dissipation within the material. Specifically, simulation data indicate that the peak pressure drops to 32.8 GPa after 2 ns of propagation [see Figs. 6(a) and 6(b)].

Due to the spherical structure of the droplet, the shock wave converges toward its center. This spherical convergence results in partial pressure amplification at the center. As shown in Fig. 6(c), the peak pressure briefly rises to 43.4 GPa as the shock wave front approaches and passes through the center at around 5 ns. This phenomenon is attributed to hydrodynamic focusing [12], wherein the shock's energy is concentrated into a smaller volume near the focal point at the center. Consequently, the pressure in the central region increases slightly compared to the expected monotonic decay observed in a

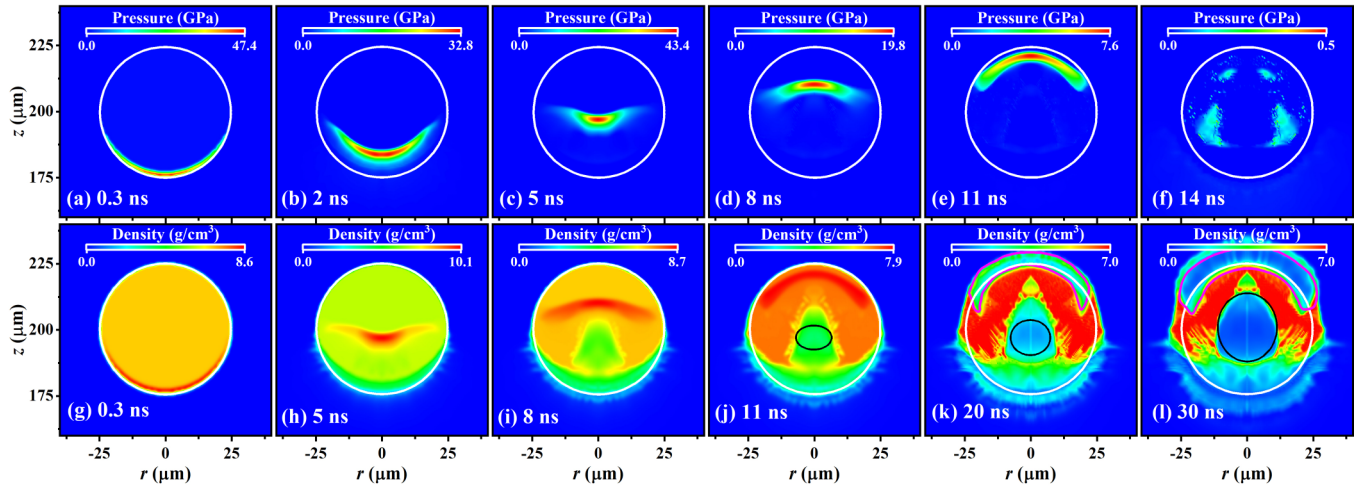


FIG. 6. Spatial distributions of pressure (top row) and density (bottom row) at various delay times following picosecond laser irradiation. The laser propagates upward along the z axis. The initial spherical Sn droplet is centered at $(r = 0, z = 200 \mu\text{m})$, as indicated by the white solid line. In panels (j)–(l), the central cavitation region is enclosed by the black solid line, while the spallation region on the rear side of the droplet is highlighted by the magenta solid line in panels (k) and (l).

1D planar shock [43], where pressure would continuously decrease with distance. After passing through the center, the shock begins to diverge toward the rear side of the droplet, causing its intensity to gradually diminish.

By $t = 8$ ns, the shock wave has propagated beyond the center of the droplet but has not yet reached the rear surface. At this stage, the shock front is located in the rear half of the droplet, positioned between the center and the back surface. The pressure perturbations remain confined within the droplet's volume, and the back surface remains unperturbed. At this time, the peak pressure at the shock front decreases to 19.8 GPa [see Fig. 6(d)].

At approximately 11 ns, the shock front reaches the interior of the droplet's rear surface, generating a momentary high-pressure region at that boundary [see Fig. 6(e)]. However, since the rear surface is a free boundary interfacing with the low-pressure background gas, the shock cannot propagate further into a dense medium. Instead, it reflects as a rarefaction (expansion) wave, propagating back into the droplet. Consequently, the pressure at the rear surface drops almost immediately after shock breakout as the surface material is released into the background gas. By 14 ns, the pressure distribution inside the droplet undergoes a rapid transition: the departure of the shock wave leaves behind a low-pressure region near the rear surface due to the reflected rarefaction wave [see Fig. 6(f)].

Regarding the density distribution, the Sn droplet initially exists as a homogeneous liquid sphere with a density of 6.9 g/cm^3 . Prior to laser impact, the density is homogeneous throughout the droplet at this value. When the laser-driven shock wave forms and propagates into the droplet, it compresses the material immediately ahead of the shock front. This compression increases the local density at the shock front as compared to the initial state, as shown in Figs. 6(g) and 6(h).

As the shock wave propagates through the droplet, it leaves behind a trail of disturbed material. Behind the shock front, the pressure decreases, and the material undergoes expansion

(rarefaction). By the time the shock has passed the droplet's center (after ~ 5 ns), the core begins to experience a reduction in density. The material at the center has absorbed significant energy, and as the shock front moves onward, the central region expands and partially vaporizes, resulting in a density lower than the initial 6.9 g/cm^3 . In other words, the first low-density region (cavity) starts to form at the center of the droplet shortly after the shock wave converges and subsequently diverges from that area. This phenomenon is a direct consequence of the shock's passage: the shock imparts energy, followed by rarefaction, which causes the central liquid to expand and transition into a mixture of liquid and vapor. By $t = 8$ ns, the shock wave has propagated into the rear half of the droplet, and the central density has noticeably dropped below 6.9 g/cm^3 , indicating the onset of cavitation in the core, as shown in Fig. 6(i). At $t = 11$ ns and $t = 20$ ns, this cavitation becomes particularly pronounced, as seen in the black curves in Figs. 6(j) and 6(k). Meanwhile, the droplet's periphery, where the shock wave has either not yet reached or has only weakly perturbed, remains close to the initial density. As a result, at $t = 8$ ns, the droplet exhibits a dense outer shell surrounding a lower-density core.

When the shock reaches and breaks out of the backside at $t \approx 20$ ns, a second significant rarefaction event is triggered. The sudden release of pressure at the back surface causes the layer of liquid near that surface to undergo tensile unloading. If the tension exceeds the liquid's cohesion, the liquid at the back can rupture, leading to cavitation there (often termed spallation at the free surface). In this case, the reflection of the shock as a rarefaction wave creates a second low-density region adjacent to the backside, as seen in the magenta curves in Fig. 6(k). By 30 ns, the droplet contains two distinct low-density chambers: one roughly near the droplet center (from the shock's focusing and subsequent expansion) and a second near the rear surface (from the shock breakout and spallation), as shown in Fig. 6(l). The remaining liquid is redistributed mostly into two dense layers or shells: a front shell (the material originally at the periphery and front,

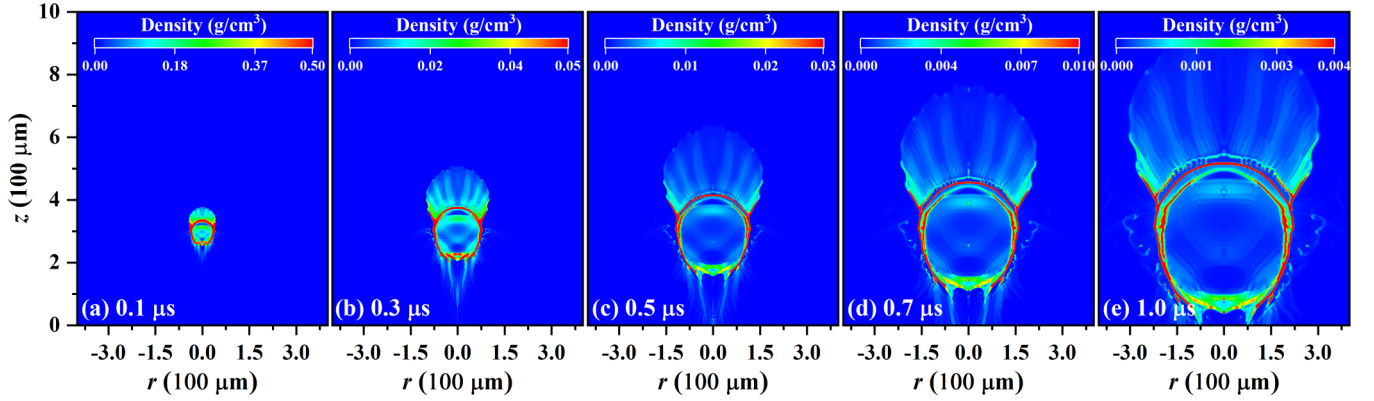


FIG. 7. Density distributions of the deformed Sn target obtained from ECOGEN simulation. Each panel shows the target morphology at a different delay time following picosecond laser irradiation.

which was compressed by the shock but not vaporized) and a rear shell (the material just ahead of the back surface that did not entirely escape). Throughout this process, the global mass conservation is maintained (aside from minor mass loss due to vapor escaping the back): the average density of the droplet's material (liquid-vapor mixture) remains close to the initial 6.9 g/cm^3 , but the spatial distribution becomes highly nonuniform.

The effects of cavitation and spallation triggered explosive deformation of the droplet. Figure 7 shows the density distributions of the deformed target at 0.1, 0.3, 0.5, 0.7, and $1.0 \mu\text{s}$, as obtained from ECOGEN simulations. It can be observed that the initially spherical Sn microdroplets gradually evolve into an acornlike structure characterized by two distinct low-density regions, which can be approximated as two conjoined coaxial spheroids [11]. The central low-density cavity originates from a cavitation mechanism, while the dispersed low-density region on the rear side, opposite to the laser incidence, results from a spallation process. This shape conforms well to the results of stroboscopic shadow photography in Refs. [11,12] and numerical simulations in Ref. [14].

To quantitatively analyze the deformation target expansion, we extracted the positions of the rear and front shells, Z_r and Z_f , along the laser beam axis (z axis), as well as the radius R_t of the cavitation shell, as functions of time, as shown in Fig. 8. In the figure, the black hollow squares represent the simulation results obtained from ECOGEN, while the red solid line denotes the corresponding linear fit. The insets in each subfigure, respectively, illustrate the definitions of Z_r , Z_f , and R_t . As shown in Figs. 8(a) and 8(b), the positional changes of the front and rear shells prior to $1 \mu\text{s}$ exhibit a linear relationship. The expansion velocities, U_r for the rear shell and U_f for the front shell, are obtained through linear fitting as 631.4 and 104.1 m/s , respectively. These values are in good agreement with the experimental measurements reported in Ref. [11].

For the radius R_t of the cavitation shell shown in Fig. 8(c), the simulation results indicate a similarly linear time evolution up to $3 \mu\text{s}$, with an expansion velocity V_R of 163.1 m/s . This result is in good agreement with the corresponding experimental measurements [13,25]. In addition, analogous to the thin-sheet model [Eq. (1)] used for nanosecond

laser-induced deformation of Sn droplets, Kurilovich *et al.* derived an analytical expression for the time evolution of the radius R_t in short prepulse-induced deformation, based on the Rayleigh-Plesset equation, in the following form [13]:

$$R_t = R_0 \cos(\pi t/\tau_c) + R_0 \sqrt{W_e/12} \sin(\pi t/\tau_c), \quad (3)$$

where τ_c is the capillary timescale, defined as $\tau_c = \pi \sqrt{\rho R_0^3/(12\gamma)}$, and W_e is the Weber number, given by $W_e = \rho R_0 \dot{R}(t=0)^2/\gamma$. $\dot{R}(t=0)$ denotes the initial expansion velocity of the cavitation shell. Since the shell exhibits a finite thickness at the initial stage, specifically within approximately 100 ns following the termination of the picosecond laser pulse, accurately determining $\dot{R}(t=0)$ proves to be challenging. Therefore, we adopt the expansion velocity V_R extracted between 0.1 and $1 \mu\text{s}$ from Fig. 8(c) as an approximation for $\dot{R}(t=0)$. That is, we assume a constant expansion velocity of 163.1 m/s during the microsecond timescale following the laser pulse. The analytical solution for the radius R_t of the cavitation shell, given by Eq. (3), is shown as the blue solid line in Fig. 8(c). The simulation results are found to be in good overall agreement with the analytical solution up to $3 \mu\text{s}$.

IV. MAIN PULSE IRRADIATION OF PREDEFORMED TARGETS

Based on the understanding of the dynamics of Sn droplet deformation induced by the prepulse, precise control of the size and material distribution of the deformed target, together with careful optimization of the delay time between the prepulse and the main pulse, is essential for maximizing the CE and achieving stable, high-intensity EUV output in laser-produced plasma EUV sources. In this section, we simulate the spatial distribution of plasma parameters and the corresponding EUV emission profile by irradiating predeformed targets with the main pulse at different delay times. The predeformed target configurations are taken from the preceding simulations involving nanosecond and picosecond prepulses.

We first consider the scenario in which the main pulse irradiates the predeformed target generated by the nanosecond prepulse. Figure 9 presents the spatial distributions of plasma temperature and electron density resulting from main pulse irradiation of nanosecond predeformed targets at delay times

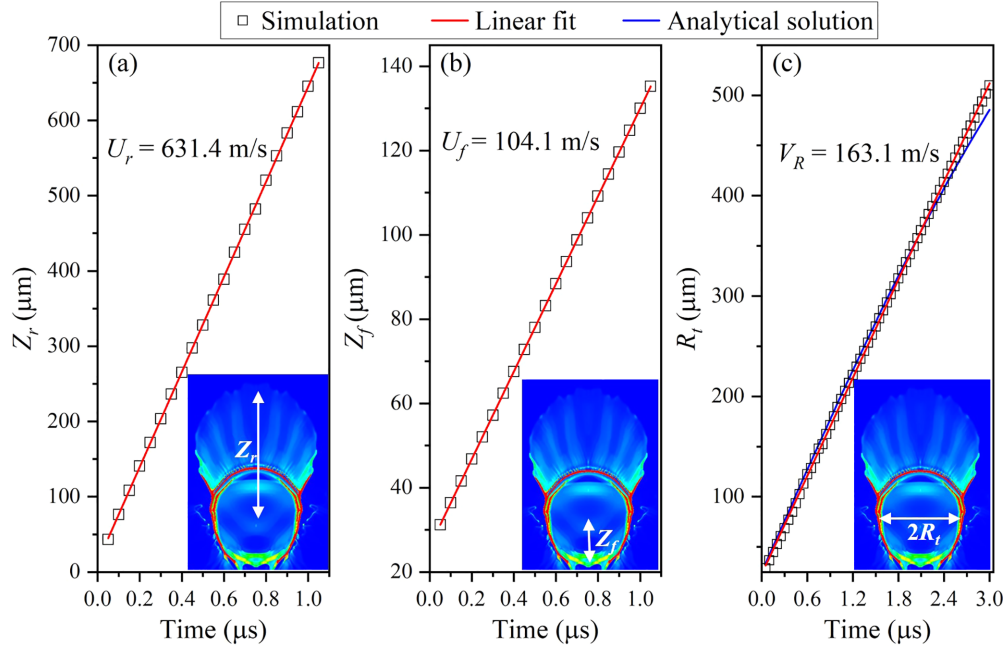


FIG. 8. Temporal evolution of the positions of the rear and front shells, Z_r and Z_f , along the laser beam axis (z axis), as well as the radius R_l of the cavitation shell. The black hollow squares represent simulation results obtained using the ECOGEN code, while the red solid line indicates the corresponding linear fit. The solid blue line represents the analytical solution.

$t_p = 0, 0.5, 1, 2, 3$, and $4 \mu\text{s}$. The plasma parameters are extracted at a delay time of $t_m = 18 \text{ ns}$ after the main pulse. The temperature and electron density distributions are shown in the r - z plane for $r > 0$ and $r < 0$, respectively. The black solid line denotes the critical electron density of the CO_2 laser, $n_e = 10^{19} \text{ cm}^{-3}$, while the orange solid line indicates

$n_e = 10^{18} \text{ cm}^{-3}$. In the region between these two lines, where the electron density satisfies $10^{18} \text{ cm}^{-3} < n_e < 10^{19} \text{ cm}^{-3}$, the plasma temperature ranges between 18 and 28 eV. Under these conditions, the average charge state is greater than 8 and less than 14, corresponding to the optimal regime for EUV emission near a wavelength of 13.5 nm. Therefore, the region

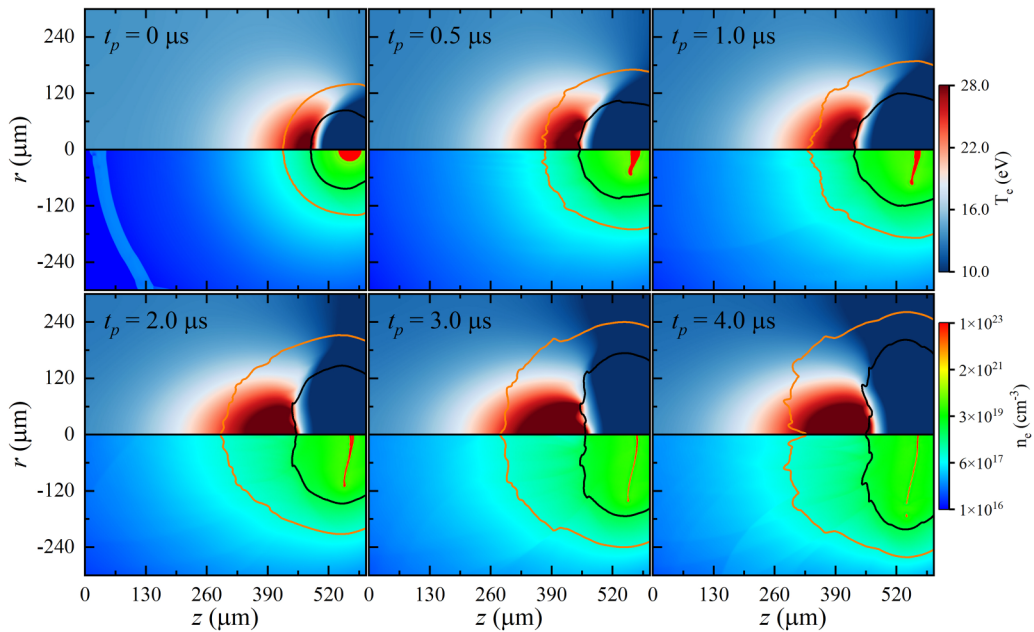


FIG. 9. Spatial distributions of plasma temperature (shown in the r - z plane for $r > 0$) and electron density (shown in the r - z plane for $r < 0$) resulting from main pulse irradiation of nanosecond predeformed targets at delay times $t_p = 0, 0.5, 1, 2, 3$, and $4 \mu\text{s}$. The black solid line represents the critical electron density of CO_2 laser light, $n_e = 10^{19} \text{ cm}^{-3}$, while the orange solid line corresponds to $n_e = 10^{18} \text{ cm}^{-3}$. The main pulse propagates from left to right.

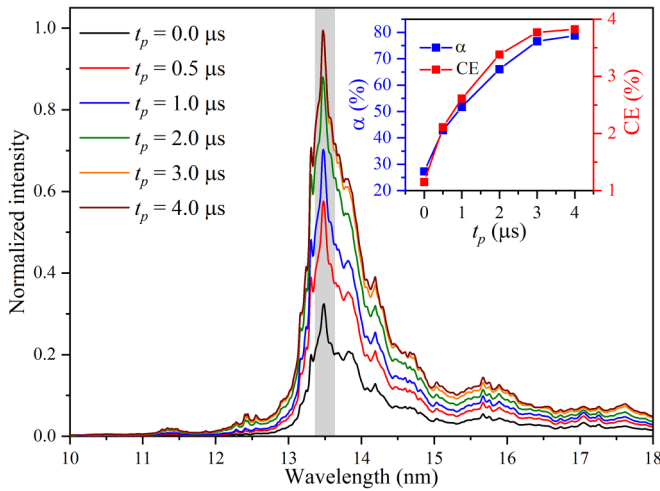


FIG. 10. Simulated EUV spectra in the 10–18 nm range resulting from main pulse irradiation of nanosecond predefined Sn targets at different delay times t_p . The shaded region indicates the in-band EUV emission around 13.5 nm. The insets display the laser absorptivity α and CE as functions of t_p .

bounded by the black and orange lines in Fig. 9 can be interpreted as the effective EUV-emitting region. For early-stage deformed targets with $t_p \leq 1 \mu$ s, the EUV-emitting region produced by the main pulse is relatively small. This is because the radius of the deformed target is still smaller than the focal spot size of the main pulse, resulting in partial laser energy missing the target. In particular, the case of $t_p = 0 \mu$ s corresponds to irradiation of an undeformed spherical Sn droplet, and the length of the EUV-emitting region is only about 60 μ m. Here, the length is defined as the axial distance between the two electron density contours at $r = 0$ in Fig. 9. As t_p increases, the radius of the deformed target gradually exceeds that of the main pulse, while the target density decreases. This improves the energy coupling between the laser and the target, leading to an increase in the length of the EUV-emitting region. At $t_p = 2 \mu$ s, the length reaches approximately 160 μ m. For $t_p = 3$ and 4 μ s, the EUV-emitting region reaches a length of about 180 μ m, with little difference between the two cases, as the target size and density remain nearly unchanged.

The results in Fig. 9 indicate that the EUV-emitting region reaches a significantly larger size at $t_p \geq 2 \mu$ s, suggesting that stronger in-band EUV radiation and higher CE should be expected. To confirm this, we performed additional simulations of the EUV emission in the 10–18 nm spectral range for plasmas generated by the main pulse interacting with nanosecond predefined targets at different delay times. The results are shown in Fig. 10. The overall workflow of the RHDLP code for EUV radiation simulation can be summarized as follows: First, exploiting the axisymmetry of the plasma, the two-dimensional distribution of plasma state parameters is rotated about the symmetry axis to construct a three-dimensional plasma configuration. Next, multiple EUV ray paths are defined based on the geometry of the spectrometer slit and the orientation of the three-dimensional plasma, allowing for ray-tracing analysis. Finally, the steady-state radiative transfer equation is solved along each ray path to determine

the radiation intensity as a function of photon frequency at the ray end point. The radiation parameters required to solve the radiative transfer equation, such as the absorption coefficient, are computed using a detailed-level-accounting (DLA) model. This model includes contributions from radiative transitions involving both singly and multiply excited states of ions ranging from Sn^{6+} to Sn^{16+} . In addition, Busquet's ionization temperature method is employed within the DLA model to match the charge state distribution of a nonlocal thermodynamic equilibrium (non-LTE) plasma with an LTE-based computation [6]. The resulting EUV spectra were computed at an observation angle of 60° relative to the laser incidence axis and integrated over a 50 ns time window. Further details of the spectral simulation methodology can be found in our previous work [27,44] and are not repeated here.

As shown in Fig. 10, the spectral intensity within the in-band region (shaded in gray) increases with t_p , and the intensity and spectral shape become nearly identical at $t_p = 3$ and 4 μ s. This evolution is consistent with the growth of the EUV-emitting region observed in Fig. 9. Furthermore, assuming isotropic EUV emission, the CE values extracted from the simulations at different t_p are shown as red squares in the inset of Fig. 10. The CE increases rapidly with delay time and reaches a plateau at $t_p = 3\text{--}4 \mu$ s. This trend closely matches that of the laser energy absorption rate by the predefined target and plasma, denoted by α and shown as blue squares in the inset. Both α and CE increase with t_p and stabilize at high values in the 3–4 μ s range. It should be emphasized that the CE values reported in Fig. 10 are derived under idealized laser conditions for both the prepulse and main pulse, including perfect Gaussian spatial beam profiles, noiseless temporal profiles, and ideal beam alignment. Additionally, the predicted CE values are highly sensitive to the underlying radiation data employed in the radiation hydrodynamics simulations, such as opacities and emissivities. As a result, the primary value of Fig. 10 lies not in the absolute CE values, but in the overall trend of CE evolution with respect to the delay time between the prepulse and the main pulse.

By combining the spatial plasma distributions shown in Fig. 9 with the spectral and CE results presented in Fig. 10, we conclude that the optimal delay time between the main pulse and the prepulse, under the nanosecond prepulse conditions used in this study, lies in the range of 3–4 μ s. For delay times shorter than 3 μ s, the CE remains relatively low due to insufficient target expansion. In contrast, delay times exceeding 4 μ s may result in excessive fragmentation of the predefined target and a heightened risk of neutral debris generation, which could accelerate the degradation of collection optics. It should be noted that, in addition to neutral debris, energetic Sn ions produced by the interaction of the main pulse with the predefined target can also contribute to optical contamination [2]. However, a detailed analysis of the expansion dynamics of both neutral and ionic debris is beyond the scope of this paper and will be addressed in future work.

Finally, we examine the case in which the main pulse irradiates the predefined target generated by the picosecond prepulse. EUV radiation in the 10–18 nm spectral range and the corresponding CE values are simulated for various delay

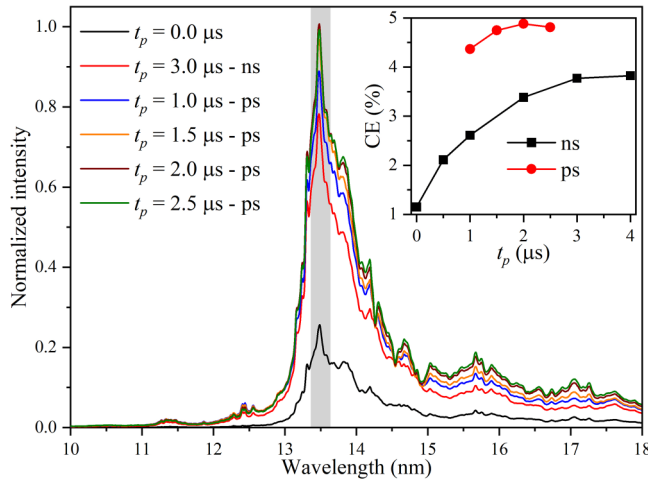


FIG. 11. Simulated EUV spectra in the 10–18 nm range resulting from main pulse irradiation of picosecond predeformed Sn targets at different delay times t_p . The shaded region indicates the in-band EUV emission around 13.5 nm. The inset shows the CE as a function of t_p for both nanosecond and picosecond prepulse cases.

times. The resulting EUV spectra are presented in Fig. 11, and the corresponding CE values are shown in the inset. It is evident that both the EUV spectral intensity and CE reach their maximum values for delay times greater than 1.5 μs . Based on these results, the optimal delay time between the main pulse and the picosecond prepulse is determined to be approximately 2 μs under the conditions considered in this study. Moreover, the spectral intensity and CE obtained with the picosecond prepulse are significantly higher than those observed for the nanosecond prepulse case. This enhancement can be attributed to the differences in the spatial and density distributions of the predeformed targets. In the nanosecond prepulse case, a disk-shaped target is formed with a sufficiently large diameter. However, the target remains relatively dense, exceeding 1.0 g/cm³ even at $t_p = 3 \mu\text{s}$. This high density limits the CE to about 3%–4%. In contrast, the picosecond prepulse produces a more isotropic, acorn-shaped target with significantly lower density. For example, at $t_p = 2 \mu\text{s}$, the density of the predeformed target is only 0.002 g/cm³, corresponding to a particle number density of approximately 10^{19} cm^{-3} . It is well established that the optimal ion density for efficient EUV emission near 13.5 nm lies in the range of 10^{17} – 10^{19} cm^{-3} [1]. The low-density target produced by the picosecond prepulse can therefore be almost fully ionized by the main pulse, resulting in the generation of intense EUV radiation.

V. CONCLUSIONS

In summary, this work establishes a hybrid numerical method that successfully captures the entire deformation evolution of Sn microdroplets induced by laser prepulses, from the initial laser-plasma interaction through inertial expansion and into the surface-tension-dominated regime. By coupling radiation hydrodynamics (RHDLP) with two-phase flow modeling (ECOGEN), we have demonstrated the ability to resolve complex multiphase phenomena that occur under

both nanosecond and picosecond prepulse excitation. The simulation results comprehensively reproduce the distinct deformation mechanisms associated with long and short laser pulses, and they compare favorably with experimental observations and analytical benchmarks across these regimes.

For nanosecond prepulse, the hybrid approach effectively captures the intricate interplay between laser-induced plasma pressure and fluid dynamic forces, especially the critical role of surface tension at later stages of deformation. Initially, a plasma is generated at the droplet surface, rapidly driving pressure waves inward and subsequently causing a strong outward inertial expansion. Our simulations detailed the development of a thin disklike morphology and clearly illustrated the formation of characteristic rim structures. The radial expansion is initially driven by inertial forces imparted by plasma-induced momentum, but gradually, surface tension forces become dominant, resisting further expansion and initiating breakup at the droplet periphery. Our findings, including the observed radial expansion velocities, fragmentation patterns, and the temporal evolution of the droplet morphology, closely match experimental data and predictions from analytical thin-sheet models, demonstrating the robustness and accuracy of our numerical methods.

For picosecond prepulses, the hybrid simulations detail a markedly different deformation path dominated by shock physics. Simulations revealed rapid energy deposition leading to intense shock wave formation that quickly propagates toward the droplet center. This shock convergence amplifies local pressure, creating a central cavitation region, followed by spallation at the droplet's rear surface due to reflected rarefaction waves. These physical processes collectively result in an acorn-shaped droplet morphology, a hallmark of short-pulse interactions. Detailed analyses of density distributions, shock propagation dynamics, and the velocities of the rear and front shells further validate our model against established experimental and analytical benchmarks.

Finally, by incorporating main pulse interactions into the simulation framework, thereby modeling the complete double-pulse sequence, we establish a direct connection between prepulse-induced target morphology and EUV plasma generation. This extension enables a predictive assessment of how specific prepulse configurations influence EUV yield and plasma characteristics, effectively bridging target shaping and source performance.

Through this work, we underscore the importance of accurately modeling the interactions between radiation hydrodynamics and multiphase fluid dynamics, especially incorporating detailed treatments of surface tension for longer timescale phenomena. Building on the present study, future investigations should address several open questions. First, extending the simulations to fully three-dimensional (3D) geometry is an important next step. While the axisymmetric assumption is justified for normal incidence on an ideal spherical droplet, real prepulse lasers or droplet streams may introduce asymmetries (e.g., slight misalignment or elliptical beam profiles) that lead to nonaxisymmetric deformations [20]. A 3D simulation would capture such effect as off-axis tilt in the deformed sheet, which is relevant to ensuring the shaped target is optimally oriented for the main pulse. Additionally,

future work could investigate the effect of different droplet sizes and laser parameters using the same hybrid approach, to generalize the findings for various EUV target compositions.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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