Charge separation effects in laser-induced plasma plumes: Hybrid ℓDSMC-CRM-PIC simulations

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Pulsed laser ablation of metal targets has a wide variety of applications in microfabrication. This photoinduced material removal is accompanied by the expansion of the ablation plume from an irradiated target. High temperatures and intense laser radiation result in the partial ionization of the metal vapor. This plasma plume may contain a large amount of high-velocity runaway electrons which can induce various charge separation effects. For example, under certain conditions, such as low background gas pressures, experimentally observed plumes are characterized by a bimodal distribution of mass and plasma emission intensity [1]. This plume splitting phenomenon is usually explained by a charge imbalance across the plasma plume induced by runaway electrons and subsequent acceleration of the plume's ion component by the self-consistent internal electromagnetic field. Definitive theoretical proof of this hypothesis, however, has not yet been obtained.

In the present work, a hybrid ℓDSMC-CRM-PIC computational model, which accounts for the charge separation effects and the effects of the self-consistent electrostatic field in laser-induced plasma plumes is developed. The model includes a thermal model that predicts material removal in addition to the ℓDSMC-CRM-PIC model. The hybrid ℓDSMC-CRM-PIC method has three major components to predict plasma expansion. First, the lumped particle direct simulation Monte Carlo (ℓDSMC) method treats electrons as explicit simulated particles and accounts for collisional processes between major fractions of neutral and charged particles. Second, the collisional-radiative model (CRM) accounts for important electron- and radiation-induced processes involving minor fractions of excited ions and neutral atoms. Lastly, the particle-in-cell (PIC) method determines the internal electrostatic field and the acceleration of charged particles by Coulomb forces.

The hybrid ℓDSMC-CRM-PIC approach is applied to study the one-dimensional plume expansion process induced by irradiation of a copper target in argon background gas by 10 ns Gaussian laser pulse at a wavelength of 1064 nm. The laser fluence and argon background pressure range from 5-15 Jcm^{-2} and 0 to 0.1 bar respectively. To reveal the effect of charge separation on the plume expansion rate and flow structure, the results are systematically compared with the results that are obtained with the previously developed hybrid ℓDSMC-CRM model, where local plasma quasi-neutrality is enforced. The results show strong effects of plasma non-equilibrium under all conditions considered. The charge separation effects are found to be important at lower background pressures. The simulation results are compared with published experimental results for plume expansion rate, speed of the fast and slow components, electron temperature, and net ablation depth.

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References:

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