Ionization Clamping in Ultrafast Optical Breakdown of Transparent Solids

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When a femtosecond, near-infrared laser pulse with the energy exceeding about 100 nJ is tightly focused below the surface of a transparent solid, rapid deposition of the electromagnetic energy into the material drives a microexplosion, resulting in the production of a microscopic void. Microexplosion voids are surrounded by shells of densified matter that can contain exotic, super-dense material phases. It has been suggested that the transient pressure attainable inside the microexplosion exceeds 10 TPa, which is of the same order as pressure inside the cores of large planets and is comparable to what can be realized in the laser-driven shocks at the national-scale laser facilities.

Computing the distribution of energy deposited by the laser field into the material, under the conditions of the representative microexplosion experiments, is important for the optimization of the interaction, yet it is a challenging problem. For the adequate description of the physics involved, the fully vectorial, 3D Maxwell propagator for the optical field has to be used, which is computationally very expensive. The propagator needs to be coupled to the adequate material response model accounting for significant ionization and plasma kinetics. Attempts to address this challenge in the past relied on various simplifying assumptions that made quantitative comparison with experiments, under relevant conditions, unfeasible.

The results of numerical simulations, that we present, reveal a robust self-regulating mechanism – ionization clamping, that rigidly clamps the peak attainable values of the major physical quantities, such as optical fluence, the degree of ionization, and plasma temperature. Importantly, the clamping is shown to be essentially independent of the vast variations of the material parameters, making our results quantitatively valid even given large uncertainties of the numerical values of those parameters. Our results show that the previous reports have grossly, by up to two orders of magnitude, overestimated the peak temperatures and pressures attainable through the in-volume excitation of transparent dielectrics by tightly focused ultrashort laser pulses. We suggest potential routes towards overcoming the clamping limits. As an example of a potential approach, we discuss experiments on the generation of large internal voids in sapphire by ultrafast, tightly focused, simultaneously spatially and temporally focused (SSTF) laser beams.

References

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