Modeling ionization dynamics during Bessel beam propagation with a Particle-In-Cell code

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For high-speed, high-precision cutting of dielectrics, understanding laser-induced plasma formation dynamics is pivotal for controlling the energy density deposited within the solid via the laser pulse. In the past years, Bessel beams have been widely used for stealth dicing of glass or sapphire because they facilitate uniform energy deposition along an elongated rod typically measuring 400 nm in diameter, extending to centimeter-scale distances. However, conventional numerical codes for simulating pulse propagation and ionization dynamics have failed to fully capture crucial experimental characteristics, notably the exceedingly high absorption rates observed.

Our approach involves adapting the open-source, massively parallel, Particle-In-Cell (PIC) code EPOCH, incorporating background permittivity and Keldysh field- and impact-ionization modules. Focusing on simulating 100 fs Bessel pulses propagating within transparent dielectrics at intensities of 10^{14} W/cm^{2}, we compare numerical simulations to experimental results across various imaging diagnostics of the laser pulse itself.

The presentation will delve into the intricate microphysics steps of plasma formation. Our simulations enabled the identification of the pivotal process governing dense plasma formation, which hinges on the focusing angle and the nonlinear field ionization dependence. We observed a bifurcation between two regimes of the dynamics of plasma formation, yielding either a lateral plasma expansion or an increase in density. Resonance absorption, another critical phenomenon, cannot be modeled in other numerical simulations but plays a vital role in accurately modeling the intense energy density deposition within the plasma volume. Final energy densities reach megajoules per cubic centimeter, corresponding to the energy density required for generating warm dense matter.