Physics of femtosecond laser-induced nanoplasmas

Kazem Ardaneh*, Remi Meyer, Mostafa Hassan, Remo Giust, Benoit Morel, and Francois Courvoisier†
FEMTO-ST Institute, CNRS and Univ Bourgogne Franche-Comte,
15B avenue des Montboucons, 25030 Besançon, France
*kazem.ardaneh@femto-st.fr
†francois.courvoisier@femto-st.fr

PRACE-funded PULSAR-PIC project is part of an ERC-funded project PULSAR which aims at developing new ultrafast laser materials processing technologies. The context is mass fabrication where ultrashort laser pulses are used to process materials on submicron precision. A key aspect is to control the energy deposition in nano-plasmas created within the bulk of solid transparent dielectrics such as sapphire or glass. Indeed, this condition can create microexplosions that yield to the formation of voids within solids. These voids are crucial to develop faster processing technologies, such as high-speed cutting or fast fabrication of through-channels for microelectronics that are for now difficult to process using conventional lithography. A key aspect of our work is therefore to understand and control the formation of energetic plasmas inside the bulk of materials.

Using conventional Gaussian beams, it is however difficult to reach high plasma densities because the plasma decreases the index of refraction, which defocuses the input laser pulse. Thanks to the project, we demonstrated a different regime where high plasma densities can be reached: it is based on using femtosecond pulse spatially shaped as a Bessel beam. This beam has a conical structure, which creates a cylinder of plasma with typically 100-200 nm in diameter, over a length that can scale from some tens of micrometers to centimeters by appropriately scaling the input pulse energy. However, a strong experimental difficulty is the lack of direct diagnostic of the plasma density. In this work, we circumvented this difficult problem by comparing numerical simulations to a set of indirect experimental diagnostics.

Conventionally, the propagation of laser pulses inside materials is simulated using models where the free-electron plasma generated by the pulse is considered either static or as a fluid. The originality of our approach is that we used a much more refined approach, the Particle-In-Cell model, which solves full 3D Maxwell's equations and particles trajectories. We used EPOCH code, an MPI-parallelized code, to simulate the interaction between a femtosecond laser pulse and a nanoplasma. A typical simulation requires at least 4096 cores during 24 hours. We had to repeat the simulation to find nanoplasma shape and distribution that could match together 4 optical diagnostics.

This allowed us to demonstrate that not only the plasma densities reached experimentally in the regime of micro-explosion is over-critical, but also to show that the most important mechanism for the laser pulse absorption into the plasma is collisionless absorption, which is conventionally not modelled by other approaches. We could then study the process of field enhancement, electron energization, absorption as well as the emission of second-harmonic. More in-depth studies have followed, including the effect of the plasma profile and the formation of plasmons or Langmuir waves.

This work is at the frontier of the quantum/classical weekly/strongly coupled plasma. It opens very new perspectives in the fields of high energy density physics, nonlinear optics, THz field emission, synthesis of new material phases, and laser material processing.

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