Ultrafast Bessel beam-induced nanoplasmas in solid dielectrics

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Abstract

Laser nano-machining and studies of warm dense matter require the generation of hot plasmas. We investigate the generation of elongated hot, nano-plasma rods within transparent dielectrics. We demonstrate the key role of collisionless resonance absorption.

Ultrafast, infrared laser pulses are ideal tools to process transparent materials with submicron precision. This is because the nonlinear ionization allows depositing energy within the bulk of materials. It opens the way for 3D micro-processing. In this context, a key aspect is to control the energy deposition process. In contrast with *surface* processing, the energy deposition via electron-hole plasma formation *in the bulk* is highly coupled to the nonlinear pulse propagation. We investigate the generation of high-aspect ratio nano-plasmas inside dielectrics. They find several applications in the field of fast laser separation, drilling of through vias for microelectronics or to generate relatively large volumes of warm dense matter. It is a thermodynamical state that is still very challenging to study and model since it lies between condensed matter physics and hot plasmas. Its physics is relevant to the interior of several astrophysical objects such as brown dwarfs and planets [1].

A key challenge for these three applications is therefore to reach high plasma densities and high energy density. Using conventional Gaussian beams, this is however very difficult since the plasma generated by the onset of the pulse defocuses the trailing part: this enlarges the width of the plasma, preventing the deposition of high energy density. Here, we demonstrate that Bessel beams can overcome this problem. The Bessel beam has a conical structure, illuminating the laser-generated plasma from the side. This “propagation-invariant” structure is very beneficial since it enables the generation of nano-plasmas up to cm-scale in length with only mJ pulse energy [2]. This presentation will review several recent results unveiling the physics at play during plasma formation within the bulk of dielectrics.

First, using a hydro-code including ionization [3], we identify different regimes of plasma build-up: depending on the focusing strength, laser pulse and materials parameters, the plasma can either grow transversely while remaining with low density. In another regime, we identify a peculiar effect where – if appropriate conditions are met- a plasma rod with very small diameter (typ <200 nm) can be generated.

Second, when the plasma rod is small, over-critical densities can be reached. We demonstrate that in this case, the phenomenon of resonance absorption efficiently transfers energy from the laser wave to the plasma. Importantly, we demonstrate that the damping is mostly collisionless – which was not taken into account in most propagation models at state of the art.

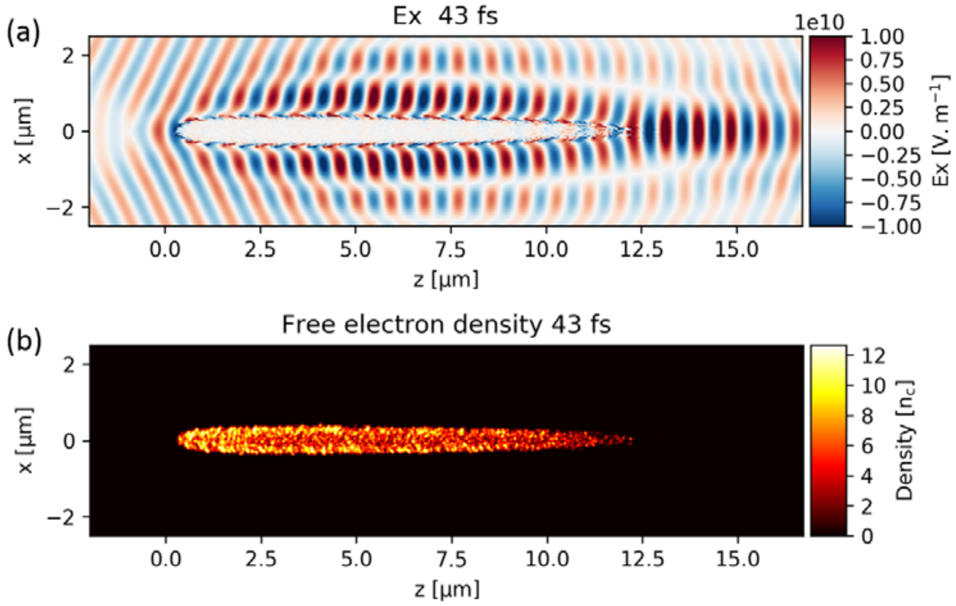

Fig. 1 Results of Particle-In-Cell simulation including ionization. (a) Spatial distribution of the component of the electric field along the laser polarization, 43 fs after the pulse peak; (b) Spatial distribution of the free electrons.

We compare our experimental data to the results of Particle-In-Cell simulations based on EPOCH code. We circumvent the absence of direct measurement of the plasma density distribution by running a series of simulations of laser-pre-plasma interaction, in absence of ionization, to match four different experimental diagnostics, including observation of second harmonic generation. This allows us to retrieve plasma density and shape. We find that the nano-plasma temperature is estimated in the range of 10 eV, well in the range of warm dense matter [4].

The study of the microphysics of the laser-plasma interaction shows interesting side effects as particle acceleration up to several keV within the field by transit acceleration, as well as the formation of a double layer, which produces a static electric field. Second harmonic and THz are also emitted.

We have recently adapted an ionization module for EPOCH to simulate field ionization and collisional ionization in solids, based on the Keldysh model. The full model is well in line with our previous results, as shown in Figure 1. Overall, this work 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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