High aspect ratio nanoplasma generation in dielectrics by femtosecond Bessel beams

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Controlling the energy deposition mechanism in matter is very important for applications in the high-speed/high-precision cutting of dielectrics. In the laser-matter interaction, the key component in energy deposition is the generated plasma. Bessel beams have a great advantage in the generation of high-density plasmas inside matter due to their conical structure, which allows the uniform distribution of energy in a rod with ~400nm in diameter that extends over a large distance (10's µm to centimeter scale). One of the first phenomena responsible for the destructuration of the matter is the ionization by the field, closely followed by collisional ionization. These two ionization processes create a plasma with a rapidly increasing density. Here, we investigate with Particle-In-Cell simulations the microphysics of ionization and laser-plasma interaction. Previous simulations codes simulating pulse propagation could not retrieve the main characteristics of the experimental data, specifically the very high absorption[1].

In our experiments, a single 100 fs Bessel pulse at central wavelength 800 nm was focused inside transparent dielectrics at intensities of 10^{14} W.cm^{-2}. To reproduce the experiments, we have performed simulations using the massively parallel EPOCH particle-in-cell (PIC) code[2]. This approach allowed us retrieving sucessfully several experimental diagnostic: near and far field of the pump pulse after interaction, second harmonic generation pattern. Figure 1 (a) and (b) show the Ex component of the electric field and the free electron density after the generation of an over-critical hot plasma using a Bessel beam. There is strong field enhancement at the surface of the plasma and defusing of the laser beam. The pulse energy linearly decreases along the plasma length with a total absorption of 60%. The main absorption process is renonance absorption. Importantly, we have demonstrated the energy storage mechanism into the plasma is collisionless (Landau damping), which could not be captured in previous simulations. The deposited energy density in the plasma volume is about 10^6 J.cm^{-3} which corresponds to the energy density allowing the generation of warm dense matter[3].

Using Bessel beams, it is possible to reach cm-scale over-critical hot plasmas inside solids which is a promising use for laser ablation and for studying warm dense matter. Moreover, simulations will help us to get a better understanding of the mechnisms involved in the formation of those plasmas such as resonance absorption that we can see on Fig. 1 a).

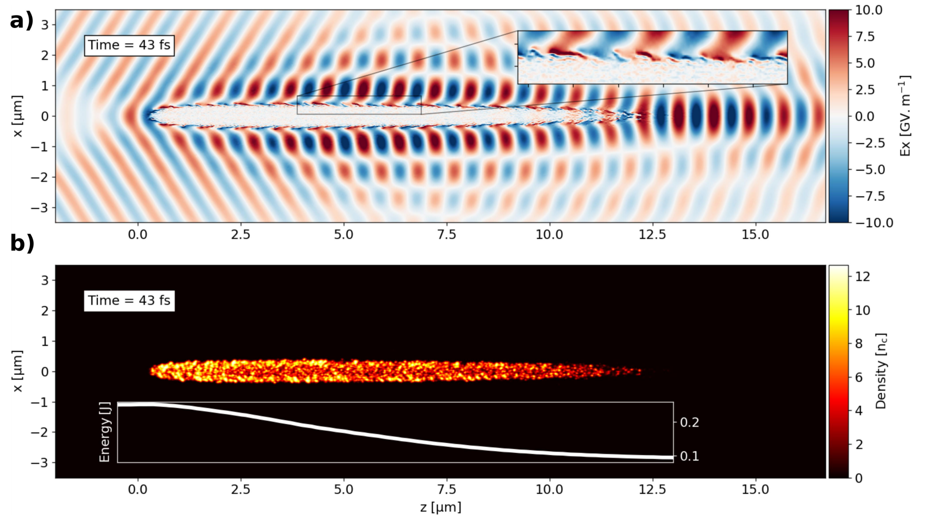

Figure 1. Simulation of a) the electric field and b) the free electron density generated by a femtosecond Bessel beam inside matter.

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[2] D. Arber, K. Bennett, C. S. Brady, et al, Plasma Phys. Control Fusion. 57, 113001 (2015)

[3] K. Ardaneh, R. Meyer, M. Hassan, R. Giust, B. Morel, A. Couairon,G. Bonnaud & F. Courvoisier " Femtosecond laser-induced sub-wavelength plasma inside dielectrics: I. Field enhancement", https://doi.org/10.48550/arXiv.2205.01709 (2022)