Particle-In-Cell simulations of ultrafast laser interaction with transparent solids

Kazem Ardaneh*, Remo Giust, Benoît Morel, Remi Meyer, and François Courvoisier†
FEMTO-ST Institute, 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 the ERC-funded project PULSAR which aims at developing new ultrafast laser materials processing technologies. The context is mass fabrication where new technologies are needed to process materials that are always new, on extremely large surfaces, with sub-micron resolution. Ultrafast laser processing is an ideal candidate, however, even with high pulse energy, laser processing remains limited to point by point removal of ultra-thin nanoscale layers from the material surface. Our objective is to create within solids large, controlled microexplosions yielding to ablation of large volumes. But usually, plasma shields out the incoming laser light and prevents reaching extreme internal temperatures at the nanoscale.

We develop a drastically different regime of laser ablation based on spatio-temporally shaped laser pulses where the laser-plasma interaction is controlled to increase the energy density absorbed by the plasma within a transparent solid up to typically one to two orders of magnitude. Our group has experimentally demonstrated that femtosecond pulse shaped as a Bessel beam create a long nanoplasma channel. In brief, a Bessel beam corresponds to a cylindrical focusing on a line, with a conical energy flow. In specific conditions, the plasma is sufficiently energetic to open a void nanochannel in the material with a single laser pulse. The question is to model and understand this regime accurately enough to enable the development of other geometries of interaction in a variety of materials.

However, current ultrashort pulse propagation models are inadequate to capture the physics at play. We identified that a key physical element is the interaction of the pulse with the laser-generated nanoplasma. In PULSAR-PIC, we use the Particle-In-Cell (PIC) technique to model the interaction between femtosecond Bessel pulses and nanoscale plasmas generated in the bulk of transparent materials. We explore plasma physics in an unprecedented regime where the plasma has a radius on the order of the laser wavelength and extends over distances much longer than the Rayleigh range. Our PIC simulations are computationally very demanding because we both need a very high spatial resolution within the nanoplasma and the shaped beam is much larger and involves high focusing angles.We use EPOCH, an MPI parallelized electromagnetic PIC code, to perform our numerical simulations. For the simplest cases, we already use up to 4096 cores to complete a typical simulation.

We will present our first results dealing with the development of a new type of antenna that generates Bessel beams in PIC codes, and the analysis of the interaction of the Bessel beam with a pre-formed plasma. Phenomena of field enhancement and plasma reshaping will be discussed. In particular, for the first time a very high absorption factor of the plasma was determined, compatible with values measured in experimental observations.

PULSAR-PIC aims to extend this work to several important geometries, including the ionization phenomena, which are expected to allow quantitative comparisons with experiments. We anticipate this work will impact on plasma physics, on the development of new technology for ultrafast laser materials processing. We also expect to impact on the field of laser-plasma interaction with shaped beams that are increasingly attractive.

This work has been supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No 682032-PULSAR), Région Bourgogne Franche-Comté and the EIPHI Graduate School (ANR-17-EURE-0002). Numerical simulations have been performed using the PRACE Research Infrastructure resource MARCONI-KNL within the Project "PULSARPIC" (PRA19_4980).