Intense Few-Cycle Pulse, Conical Pit Interaction Simulations Predicting Extreme Material States

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Abstract: We use fully three-dimensional particle-in-cell simulations to model intense few-cycle pulses interacting with nano-structured conical pits in fused silica and report on laser damage creation of high energy density conditions and excited electron dynamics.

1. Introduction

The 2018 National Academies of Science report: "Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light" [1], emphasizes the important science and potential applications of intense lasers with future exawatt-scale systems in mind. One limiting factor for future systems will be the laser-induced damage threshold (LIDT) of optical components such as mirrors, and repair strategies. At the National Ignition Facility, certain laser damage sites on optics are repaired using CO_2 lasers, creating conical pits [2]. We explore how nano-structured conical pits may alter the damage threshold of optics for few cycle pulses, and identify a novel technique to create High Energy Density (HED) ($\gtrsim$ 100 kJ cm^{-3}) target conditions during the laser-matter interaction.

2. Approach, Results, and Discussion

We use particle-in-cell (PIC) simulations, where the fields are modeled electromagnetically on a grid and particles are modeled kinetically with a smaller number of 'macroparticles' than physical particles. PIC simulations are often used to study relativistic laser-plasma interactions (potentially with tunneling ionization), although there is limited work starting from a neutral target [3] and considering LIDT relevant intensities with molecular ionization [4]. We use the 3D PIC code EPOCH [5], where we have added a Keldysh photoionization model [6], to simulate an 800 nm, 7 fs full-width-at-half-maximum, 1.7×10^{14} W cm^{-2} intensity laser normally incident on a 4 μm thick slab of fused silica (SiO_2) as illustrated in Fig. 1(a). This setup is similar to experiments in Ref. [7] near the LIDT of fused silica, where the pulse has a beam waist of 4.65 μm. The laser is introduced at the xz boundary and propagates in the positive y direction and is linearly polarized in the z direction. The grid has a resolution of 10 nm in y and 20 nm in x and z. As shown in Fig. 1(a), we consider conical pits on the laser axis, where the cone radius is 400 nm, and we consider heights of 0 (flat), 0.1 μm, 0.2 μm, 0.3 μm, 0.4 μm, 0.7 μm, and 1.0 μm.

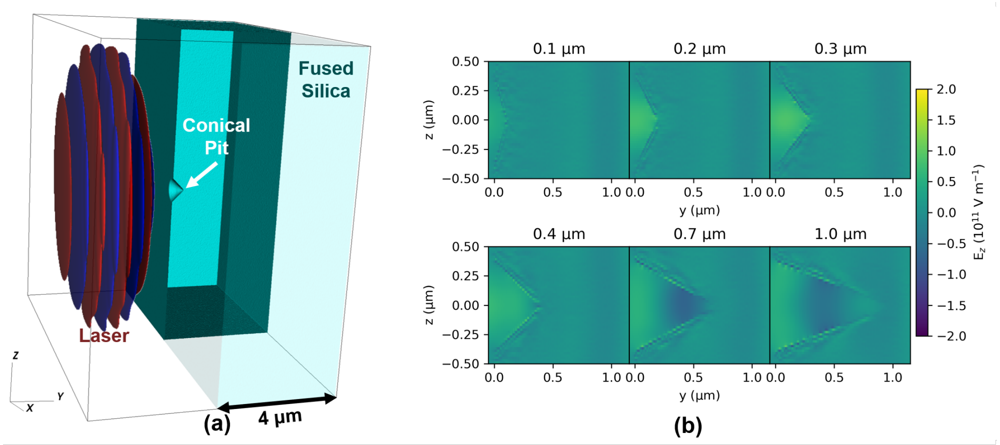

Fig. 1. A sketch of simulation setup for the height h=0.4 μm inset cone is shown in (a). In (b), a slice of the z component of the electric field is plotted at 22 fs for different cone heights.

Cones and similar shapes are often proposed to enhance/confine laser fields and effectively increase the intensity (e.g. [8]), although the pre-pulse of a laser often significantly modifies the cone shape before the main pulse arrives. If the main pulse is near, or even below, the LIDT for the material, pre-pulse effects can be ameliorated. In Fig. 1(b), we see a strong enhancement to the electric field inside of the conical pits. The conical pits also increase the interaction time of the pulse with the sides of the cones and alter the reflection dynamics of the pulse.

PIC simulations have a kinetic description of the particles, which allows us to readily determine the energy density and particle energies compared to 2D finite-difference time-domain (FDTD) approaches [9]. Figure 2(a) shows the electron energy density along a 2D slice of each simulation, where, for reference, the damage threshold is $\sim$54 kJ cm^{-3} for fused silica [7]. The simulations with steeper cones predict peak energy densities exceeding 100 kJ cm^{-3} near the cones due to the local enhancement of the laser-pulse electric field, indicating a lower LIDT. The peak electron energies are drastically increased by an order of magnitude, as shown in Fig. 2(b). An effective electron mass is used to model the electrons, which may over predict the free-electron energy, although still highlights to potential for keV-scale energies, which may have potential applications such as a photocathode.

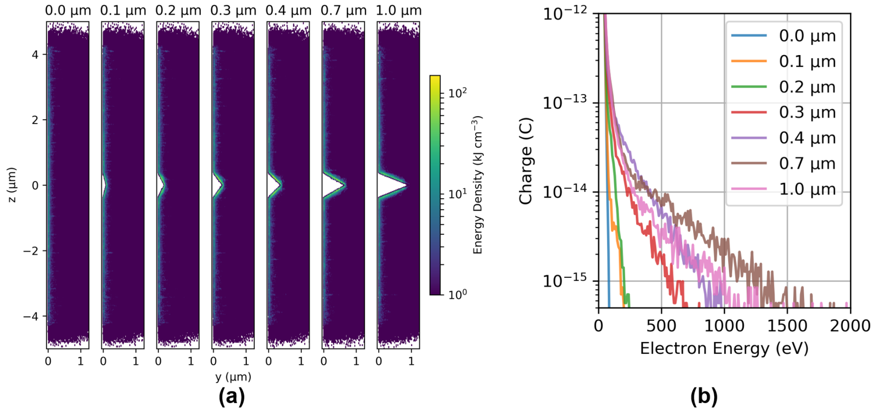

Fig. 2. In (a) the electron energy density at 24 fs is plotted along a slice of the z axis for the various cone heights. In this figure, the peak energy densities from h=0 to h=1 µm are 29, 50, 79, 144, 135, 128, and 73 kJ cm^{-3} respectively. In (b), the excited electron energy spectra at 30 fs is shown.

These conical pits in dielectric solids are of fundamental interest due to their ability to produce local field enhancement. This field enhancement may be critical for laser induced damage (LID) initiation, but may be also utilized to repair LID of optics at sub-LIDT fluence. They also may provide a novel way to create HED conditions and produce energetic electrons with relatively little laser energy. Future work will also consider nonlinear optical effects [4] and improved models of laser-solid interactions suitable for few-cycle laser pulses.

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