The use of the 2D code POLLUX in modelling extreme ultra-violet laser interactions

Contact: andrew.rossall@york.ac.uk

A. K. Rossall and G. J. Tallents
York Plasma Institute, Department of Physics,
University of York,
YO10 5DD, United Kingdom

Abstract

A simulation study is presented examining the interaction of moderate irradiance ($> 10^9$ W cm^{-2}) extreme ultra-violet (EUV) lasers with solid material. By modifying the radiative-hydrodynamic code, POLLUX, to include absorption via direct photoionisation and other relevant atomic physics, the unique ablation properties of EUV lasers has been investigated. The increased target penetration due a typically higher than solid critical density, results in direct heating at solid density, producing warm dense matter. To demonstrate this, the example of an Ar based capillary discharge laser ($\lambda = 46.9$nm) interacting with a planar plastic target has been simulated. The produced plasma is shown to be close to solid density with a temperature of ~ 2 eV.

1 Introduction

Extreme ultra-violet (EUV) lasers have the brilliance required to directly generate plasma from solid material. Novel experiments are being carried out at facilities such as FLASH in Hamburg [1, 2, 3] or using table-top systems such as the capillary discharge laser [4, 5, 6, 7]. By irradiating a solid target with an EUV laser, the sample is heated via direct photoionisation with a high target penetration, which results in temperatures of a few eV at densities close to solid. Visible and infra-red laser pulses cannot penetrate directly into solid material as the critical density is below that of the solid target, resulting in the majority of the heating occurring in the expanding plasma. Reducing the wavelength to the EUV region allows for a tighter focus, due to the reduction in the diffraction limit, and provides higher target penetration. These are potentially desirable properties for a number of applications, such as, micro-machining, mass spectrometry and the coating of refractory material on to substrates. The plasmas produced by the EUV interaction are in the warm dense matter (WDM) regime and could aid our understanding of the interiors of Jovian planets [8] and inertial confinement fusion [9], as the compression pathway of the D-T pellet across the temperature/density plane passes through the WDM regime. The presented work examines the use of the radiative hydrodynamic code POLLUX, modified to include atomic physics relevant to the EUV interaction, to model ablation and the properties of a plasma produced by irradiating a solid plastic target with an Ar based capillary discharge laser, operating at $\lambda = 46.9$nm ($E_p = 26.4$eV), with a pulse length of 800ps and a fluence of 8 J cm^{-2}.

2 POLLUX

POLLUX is a 2D Eulerian radiative-hydrodynamic code, written at the University of York, and was originally developed to simulate the interaction of optical and infrared high power laser irradiation of a solid target and the subsequently produced strongly ionised plasma [10, 11]. The code solves the three first-order quasi-linear partial differential equations of hydrodynamic flow using the flux corrected transport model of Boris and Book [12] with an upwind algorithm [13] for the first term. Energy is absorbed by the plasma and distributed through electron-ion collisions, the equilibration of which is determined by the Spitzer plasma collision rate [14]. For calculation of the equation-of-state (EOS) variables, POLLUX utilizes inline hydrodynamic EOS subroutines from the Chart-D equation-of-state package developed at Sandia National Laboratories [15].

3 Atomic Physics

The modifications to the code include the addition of a superconfiguration approach to model ionisation dependant atomic structure, reducing the total number of levels and thus the run time, enabling more efficient use with a fluid code. The Flexible Atomic Code (FAC) [16], is used to solve the radial wavefunction to provide a detailed list of levels for a specific element. Energetically similar levels are grouped into a set of 'supershells', where the energy of the supershell is the average energy of the included levels weighted by degeneracy. This structure, combined with data for the photoionisation cross-sections are included in an input file for POLLUX. The amount of energy deposited by the EUV laser in each of the target cells is then determined simply by using the Beer-Lambert law, accounting for both inverse bremsstrahlung and photoionisation. The energy absorbed via inverse bremsstrahlung is transferred to the plasma electrons as is the excess photon energy above the ionisation threshold ($E_p - E_i$). To ensure conservation of energy, the ionisation energy, E_i is transferred to the chemical potential of the ions in the EOS routine. Ionisation and excited level populations are calculated assuming local thermodynamic equilibrium (LTE) and using the Saha-Boltzmann relation. Although the plasma created on a short timescale is expected to be a highly non-equilibrium plasma, it has been shown that due to the high densities, the plasma equilibrates on a timescale of 10s of femtoseconds [17, 18]. The assumption of LTE on the hydrodynamic timescale (>1ps) is therefore valid in this case.

4 Simulations

The simulations shown here (figure 1) are for the interaction of a capillary discharge laser, operating with a photon energy of 26eV, a pulse length of 800ps, and a fluence of 8 J cm^{-2}, with a planar Parylene-N target.

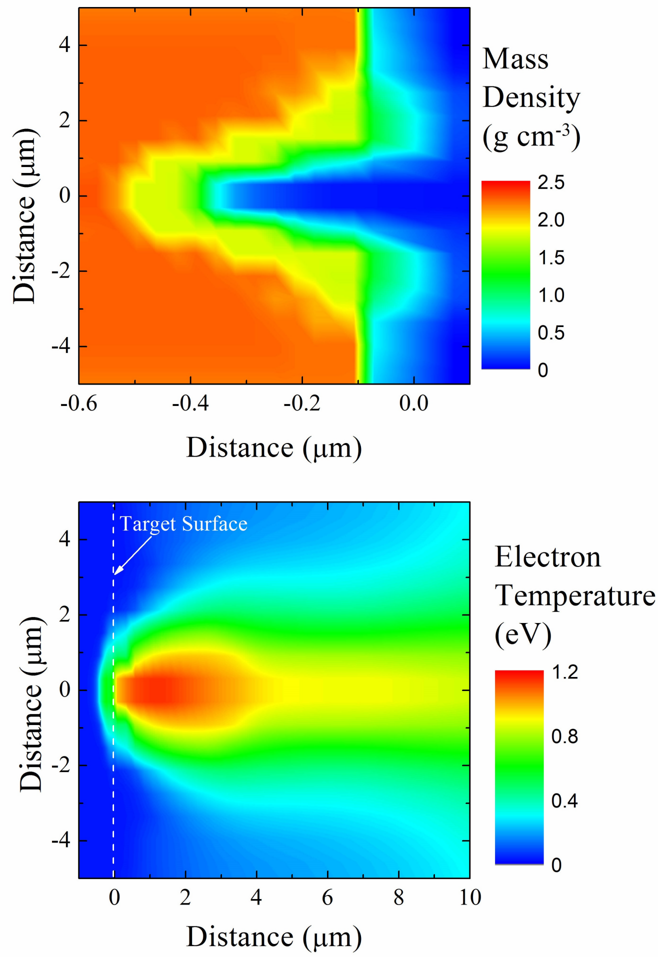

Figure 1: Mass density (top) and electron temperature plots (bottom) showing the ablation and heating of Parylene-N by an EUV capillary discharge laser ($E_p = 26$eV), with a peak irradiance of 1×10^{10} W cm^{-2} and focal diameter of 650nm. . The simulation time is at the end of the pulse, $t = 800$ps. EUV laser propagates from right to left, along the $y = 0$ axis.

5 Conclusion

A radiative-hydrodynamic code, developed to study high power optical laser interactions with solids, has been modified to include absorption via photoionisation, relevant to the interaction of EUV lasers with matter. A simulation study has been carried out examining the ablation properties of a capillary discharge laser where it has been shown that such lasers can be used to directly generate warm dense matter. EUV lasers have favourable ablation properties, such as increased target penetration and a reduction in focal spot size, making them useful in applications such as micro-machining.

References

[1] Costello J T 2007 *Journal of Physics: Conference Series* **88** 012057

[2] Berrah N, Bozek J, Costello J, Düsterer S, Fang L, Feldhaus J, Fukuzawa H, Hoener M, Jiang Y, Johnsson P, Kennedy E, Meyer M, Moshammer R, Radcliffe P, Richter M, Rouzée A, Rudenko A, Sorokin A, Tiedtke K, Ueda K, Ullrich J and Vrakking M 2010 *Journal of Modern Optics* **57** 1015–1040

[3] Richter M, Amusia M, Bobashev S, Feigl T, Juranić P, Martins M, Sorokin A and Tiedtke K 2009 *Physical Review Letters* **102** 163002

[4] Bravo H, Szapiro B, Wachulak P, Marconi M, Chao W, Anderson E, Menoni C and Rocca J 2012 *Selected Topics in Quantum Electronics, IEEE Journal of* **18** 443–448

[5] Benware B, Macchietto C, Moreno C and Rocca J 1998 *Physical Review Letters* **81** 5804–5807

[6] Heinbuch S, Dong F, Rocca J J and Bernstein E R 2008 *Journal of the Optical Society of America B* **25** B85

[7] Vaschenko G, Etxarri A G, Menoni C S, Rocca J J, Hemberg O, Bloom S, Chao W, Anderson E H, Attwood D T, Lu Y and Parkinson B 2006 *Optics Letters* **31** 3615

[8] Guillot T 1999 *Science* **286** 72–77

[9] Dittrich T R, Haan S W, Marinak M M, Pollaine S M, Hinkel D E, Munro D H, Verdon C P, Strobel G L, McEachern R, Cook R C, Roberts C C, Wilson D C, Bradley P A, Foreman L R and Varnum W S 1999 *Physics of Plasmas* **6** 2164

[10] Pert G 1983 *Journal of Computational Physics* **49** 1–43

[11] Pert G J *Journal of Plasma Physics* **41** 263–280

[12] Boris J and Book D 1976 *Journal of Computational Physics* **20** 397–431

[13] Courant R, Isaacson E and Rees M 1952 *Communications on Pure and Applied Mathematics* **5** 243–255

[14] Spitzer L and Härm R 1953 *Physical Review* **89** 977–981

[15] Thompson S L 1970 *Sandia National Laboratories Report* **SC-RR-70-2**

[16] Gu M F 2008 *Canadian Journal of Physics* **86** 675–689

[17] Rossall A K, Aslanyan V and Tallents G J 2013 High energy density plasmas produced by x-ray and extreme ultraviolet lasers *SPIE Optical Engineering + Applications* ed Klisnick A and Menoni C S (International Society for Optics and Photonics) pp 884912–884912–9 URL http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1746165

[18] Aslanyan V and Tallents G J 2014 *Physics of Plasmas* **21** 062702