Improved robustness study of a shock ignited target, with DUED code including non-local electron transport and 3D laser ray-tracing

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Improved robustness study of a shock ignited target, with DUED code including non-local electron transport and 3D laser ray-tracing

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Abstract. Accurate descriptions of laser power coupling to the plasma and electron energy transport are crucial for designing shock-ignition targets and assessing their robustness (in particular with regard to laser and positioning errors). To this purpose, the 2D DUED laser fusion code has been improved with the inclusion of a 3D laser ray-tracing scheme and a model for non-local electron transport. 2D simulations with the upgraded code are presented; the dependence of the fusion yield vs target displacement is studied. Two different irradiation configurations are considered.

1. Introduction

Shock ignition [1] is a recently proposed direct-drive laser fusion scheme. The fusion target is imploded at sub-ignition velocity (250-300 km/s) by a moderate intensity laser pulse. Towards the end of the implosion, a powerful pulse (a *spike*, with intensity 5×10^{15}–10^{16} W/cm^2, for laser with wavelength $\lambda = 0.35$ μm) drives a converging shock wave, which contributes to the creation of the central hot spot required for ignition. Shock-ignition has the potential for higher gain than standard central ignition schemes, and in principle it is less sensitive to hydrodynamic instabilities than standard direct-drive schemes. In addition, a full scale demonstration may be feasible on existing facilities (such as the NIF) without major facility modification [2, 3]. Although issues remain, mainly concerning possible deleterious effects of laser-plasma instabilities (LPI's) during the interaction of the spike with the preformed plasma corona [4], shock ignition targets are currently designed using standard fluid codes for ICF, that neglect any LPI. A widely studied target is the so-called HiPER baseline target [5], originally proposed for fast ignition, but later shown to be suitable for shock ignition too [6]. Our group performed a detailed analysis of this target [7], developed models for target scaling in energy and wavelength [8, 9] and analyzed irradiation schemes [10]. All performed studies were based on simulations with the 2D DUED radiation-hydro-nuclear code [11, 12]. We have however realized that code improvements were required for a better analysis of target robustness. In Sec. 2, discuss a new 3D laser ray-tracing scheme, which allows to study realistic irradiation geometries. In addition, we have introduced in DUED a model for non-local electron transport that replaces the scheme with flux-limited thermal conduction. Results of simulations of the shock-ignited HiPER target using the upgraded code model are reported in Sec. 3.

2. Code model improvements

2.1. Non-local electron transport

We have introduced in DUED the model for non-local electron transport proposed by Schurtz *et al.* [13]. The model correctly reproduces features of electron transport in strong temperature gradients that are generally not captured by the commonly used flux-limited (local) conduction[14]. In addition, contrary to flux-limited conduction models, non-local electron transport does not require the introduction of any tunable parameter, such as the flux limiter.

Our simulations of shock-ignited targets with non-local transport show that the ablation front penetration during the implosion phase is in approximate agreement with simulations with flux-limited conductivity and flux limiter $f = 0.07$ (see Fig. 1), but also show some preheating in front of the heat wave and somewhat different profiles in the corona. The converging shock driven by the ignition spike, instead, is somewhat faster when simulated with non-local electron transport than with flux-limited transport. Target gain is unaffected by such differences.

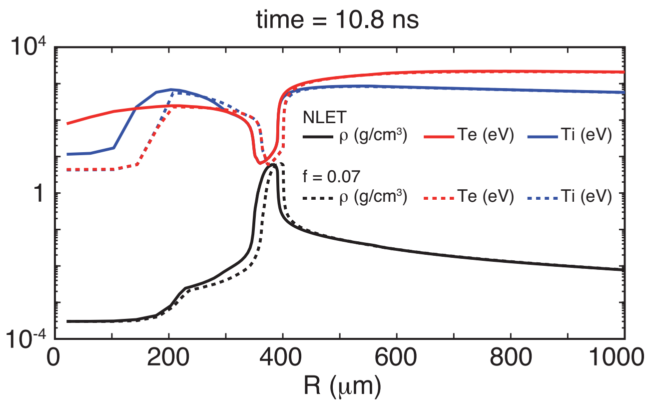

Figure 1. Density, electron and ion temperature radial profiles towards the end of the compression pulse, from 1D simulations of the HiPER baseline target with non-local electron transport (solid curves) and with flux-limited conductivity and $f = 0.07$ (dashed).

2.2. 3D laser ray-tracing

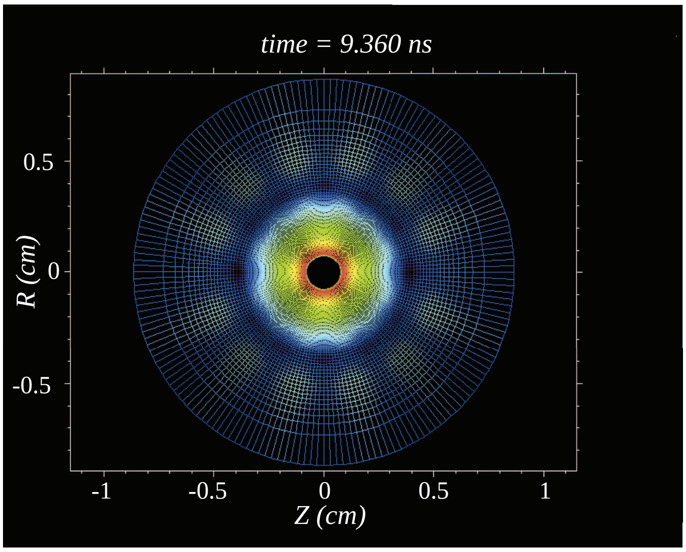

Figure 2. 2D hydrodynamic simulation with 3D laser ray-tracing. 2D Pattern of laser absorption clearly showing the separate beams entering the corona.

We have also introduced a 3D laser ray-tracing scheme in DUED, in order to simulate actual multi-beam irradiation geometry realistically. The 3D power absorption distribution is then mapped onto the 2-D axially symmetric mesh. An example is shown in Fig. 2. The finite number of rays representing each laser beam introduces numerical noise in the power absorption distribution, which in turn causes mass inhomogeneities, which seed hydrodynamic instabilities (Richtmyer-Meshov and Rayleigh-Taylor). To keep power deposition noise at very low level, without the use of smoothing techniques, we trace a very large number of rays at each step. The cross section of a laser beam was divided into 300x300 sectors in the radial and azimuthal direction. Each beamlet was represented by a ray uniformly sampled in a sector. With this choice of parameters, the irradiation non-uniformity σ_{2D}, projected onto the 2D mesh, was accurately reproduced, i.e. its value did not changed by increasing ten times the number of rays. Resort to massive parallelism turned out necessary to make simulation times acceptable. Good scalability was observed for the raytracing kernel with increasing number of computing cores. In order to have comparable times for both the raytracing step and the hydrodynamic step, about 800 - 1000 cores were used. A start-to-end implosion run with 3D raytracing could then be carried out in a few hours. Details of the implementation and analysis of noise levels will be presented elsewhere.

3. Parametric robustness studies

In this section we summarize recent studies on target robustness performed with DUED, using one or both the above improved models. All results refer to the shock-ignited HiPER baseline target. In Ref. [7] we studied gain degradation as a function of beam mispositioning (offset of the target centre with respect to the centre of the laser beams) for a target irradiated by the nominal HiPER 48-beam laser configuration. For simplicity, the simulations assumed radial irradiation, where the intensity unbalance is described via the sum of Legendre polynomials. We have now improved and extended that study, by i) making use non non-local electron transport and ii) considering different values of the power of the spike. The results are shown in Fig. 3. We see that for the nominal spike (absorbed) power of 95 TW, the allowable displacement is 10 μm (1% of the radius). Tolerance to mispositioning grows with increasing the spike power, but is in any case limited to about 2.5%.

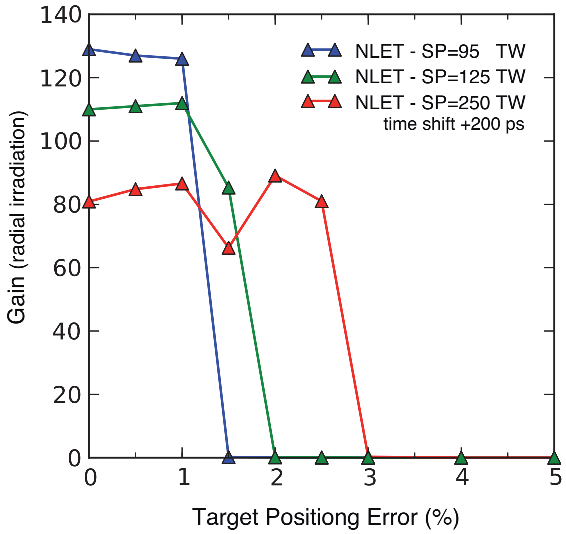

Figure 3. Target gain vs target centre offset for three different ignition spike powers. From 2D simulations of the HiPER baseline target with non-local electron transport, and radial irradiation. Note that, due to assumed radial irradiation the incident power is fully absorbed and then the gain reported here is about twice as large as the gain obtained from 1D simulations with nominal laser configuration and 2D ray-tracing.

The reference HiPER irradiation scheme for the compression stage (48 beams, each with intensity profile $\propto \exp(-r/w)^m$, with $m = 2.04$ and $w = 640$ μm) was chosen to minimize the initial irradiation nonuniformity in the absence of any laser or target positioning error. However, it has been shown that other schemes provide better uniformity during the implosion and are also less sensitive to errors (at the expense of larger laser energy to compensate for reduced absorption) [10, 15]. E.g., one may use wider superGaussian beams, with $m = 8$ and $w = 1300$ μm [10]. First simulations with 3D raytracing confirm this prediction: using the above irradiation scheme, targets can tolerate larger displacements, and achieve nearly 1D yield; the gain is reduced by about 35%. A relevant result is shown in Fig. 4, where the density maps at stagnation are compared for a target irradiated with the reference beam configuration and displaced by somewhat less than 2% and a target irradiated by the wider beams and displaced by 3%. This second target ignites and achieves a nearly 1D yield.

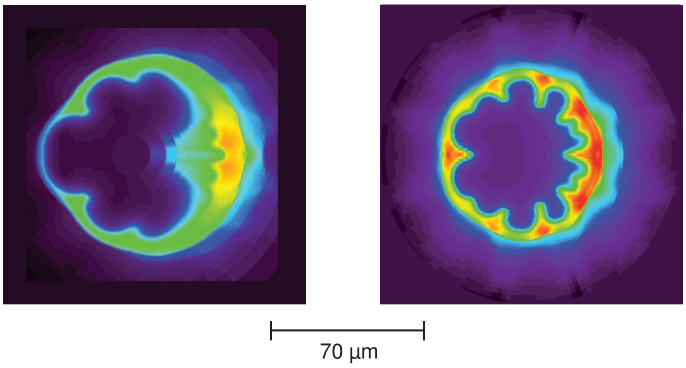

Figure 4. 2D simulations of the HiPER baseline target. Density maps at the shell stagnation for a) target displaced by 20 μm and irradiated by the reference HiPER beam configuration (left frame); b) target displaced by 30 μm and irradiated by beams with larger spots and flatter profiles and 50% larger power (right frame). Target (a) does not ignite; target (b) ignites and achieves nearly 1D yield.

In conclusion, we have improved DUED models for laser interaction and non-local electron transport. Simulation of shock ignited targets with the upgraded version of DUED essentially confirm prior results on target robustness. The code is now ready for systematic studies aiming at the optimization of irradiation schemes. It should be observed, however, that further model improvements, concerning LPI's and cross-beam-energy-transfer is required to tackle other critical issues for shock-ignition [4].

Acknowledgments
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