*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.001 (2006)*

Target studies for laser-driven fast ignition demonstration

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We have studied issues concerning target design for fast ignition [1, 2] demonstration using direct laser compression and fast heating by laser generated hot electrons. We have employed simple analytical models, 1-D simulations of target irradiation and implosion, and 2-D simulations of ignition and burn of the precompressed fuel. We consider all-DT spherical targets, compressed by laser radiation with wavelength $\lambda_c = 0.35\ \mu$m.

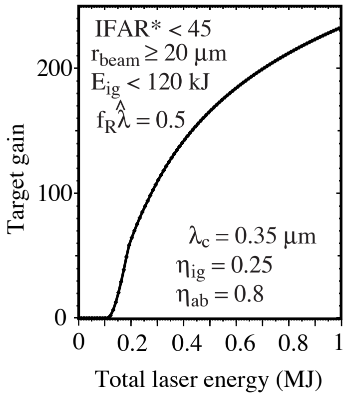


Figure 1: Gain curve from the gain model, with parameters listed in the figure.

The model (a modified version of that of Ref. [3]), accounts for ablative drive, compression at stagnation, fast ignition and burn. It assumes that hot electrons couple to the fuel with efficiency η_{ig} (for which we take the value $\eta_{ig} = 0.25$) and have average range $R(\mathrm{g/cm^2}) = 0.6 f_R T(\mathrm{MeV})$, where T is the hot electron tempererature. This is related to igniting laser intensity I_{ig} and wavelength λ_{ig} and by a ponderomotive scaling, $T(\mathrm{MeV}) = [I\hat{\lambda}^2/(1.2\times 10^{19}\mathrm{W/cm^2})]^{1/2}$. Here $\hat{\lambda} = \lambda_{ig}/(1\mu\mathrm{m})$ and f_R is a parameter, which takes into account *anomalous* effects. The model uses the ignition conditions of Ref. [4], as modified by Tabak [3] to include the effect of non-optimal focussing and range.

The model shows that achieving fast ignition with igniting laser energy E_{ig} of about 100 kJ or smaller and beam focal spot of 15–20 μm, requires $f_R\lambda_{ig} \leq 0.5$, i.e. either second harmonic Nd:glass laser radiation for ignition and/or electron range shortening. In addition, significant gain at total driver energy of 100–500 kJ also requires relatively large values of the in-flight-aspect-ratio (IFAR) of the imploding target. In the case of Fig. 1, the IFAR of a flat-adiabat target (which we call IFAR*) is limited to 45, but no gain is achieved for IFAR* < 35. These values of IFAR correspond to exponential growth factor of the ablative Rayleigh-Taylor instability (RTI) ($G_F = \int \gamma dt$, where γ is the linear growth rate) larger than 9, well above the usually accepted limit of 6 [5]. However, G_F can be substantially reduced by adiabat shaping, which we achieve by the relaxation technique [6]. It is also confirmed that significant gain at low laser energy requires fuel density of 400–500 g/cm^3 and total fuel $\rho R \geq 1.2$ g/cm^2 [7, 8].

According to Fig. 1, gain up to 100 can be achieved with total laser energy of 250 kJ. Fig. 2 shows gain contours and G_F contours in the intensity-IFAR* plane. The red circle there marks our tentative design point. Laser intensity stays well below the threshold for parametric instabilities.

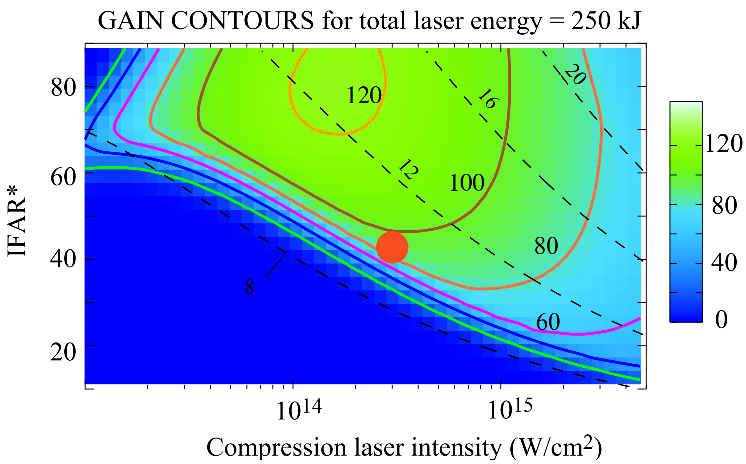
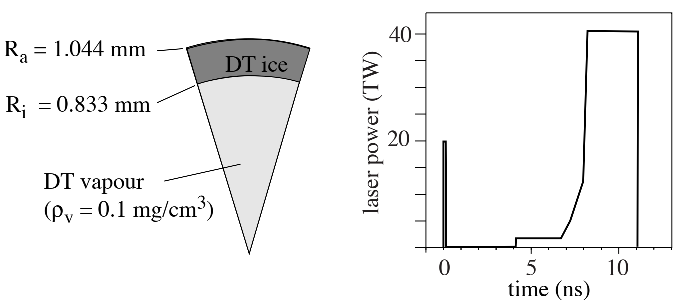


Figure 2: Iso-gain contours in the Intensity-IFAR* plane for 250 kJ total driver energy. The dashed curves indicate the values of the RTI exponential growth factor G_F for a flat adiabat target. Our reference design point is indicated by the filled red circle.

Our reference target is shown in Fig. 3. It is driven by a 132 kJ shaped laser pulse, with the prepulse required for adiabat shaping by relaxation [6], and peak power of 41 TW. The inner shell isentrope is $\alpha_{\rm in} = 1$. The target achieves a peak density of about 500 g/cm^3 and $\rho R = 1.3$–1.6 g$/$cm^2 (depending on details of the simulation model).



laser wavelength	0.35 µm
focussing optics	f/18
laser energy	132 kJ
absorbed energy	95 kJ
target mass	0.59 mg
imploding mass	0.29 mg
implosion velocity	2.4 x 10^7 cm/s
hydrodynamic efficiency	10.5%
overall coupling efficiency	7.2%
IFAR at R = 0.75 R_i	36

Figure 3: Reference target, imploded by a 132 kJ laser pulse: target sketch, laser pulse (notice the adiabat-shaping prepulse), drive parameters and implosion results.

The use of adiabat shaping reduces peak G_F by almost a factor of 2, as shown in Fig. 4. Here G_F is computed inserting the flow parameters obtained from 1-D simulations in the standard expression [9] for the ablative RTI growth rate, and integrating in time. This may slightly underestimate G_F for cases with adiabat shaping [6]; improved computations will be performed soon.

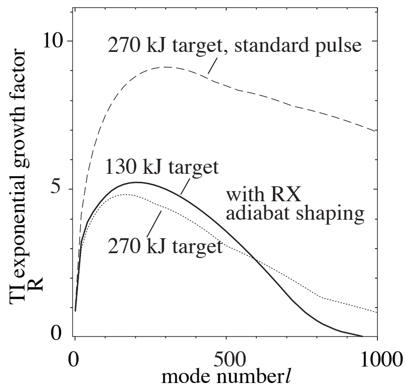


Figure 4: RTI exponential growth factors for the target of Fig. 3, and for a scaled target, driven by 270 kJ pulses, with and without adiabat shaping.

Density profiles about maximum compression are shown in Fig. 5. We also present the scaling of peak density and peak $\rho R$with laser energy (for properly scaled target and laser pulses). This result agrees with the scaling law proposed in Ref. [10]. Notice that 100 kJ compression pulses can produce assemblies with parameters close to those required for efficient burn.

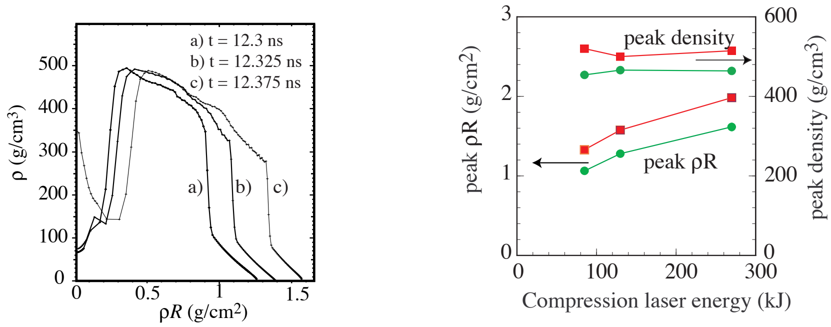


Figure 5: Left: for the same target as in Fig. 3, density profiles at times close to maximum ρR; Right: peak density and peak ρR vs energy for targets scaled from that of Fig. 3 ; the two curves for each quantity refer to simulations using different flux-limiters and different models for radiation.

Ignition and burn is presently being studied by 2-D simulations, assuming as initial conditions those computed by the 1-D run at some 25-50 ps before peak ρR. An example is shown in Fig. 6. Preliminary results indicate that the ignition beam has to couple to the dense fuel 25-30 kJ of particles with range $R \leq 1.2\ \mathrm{g/cm^2}$. A fusion yield of about 14 MJ for the reference target above and about 30 MJ for the target driven by 270 kJ is obtained. Assuming again $\eta_{ig} = 0.25$, such yields would correspond to target gain of about 50 and 75, respectively.

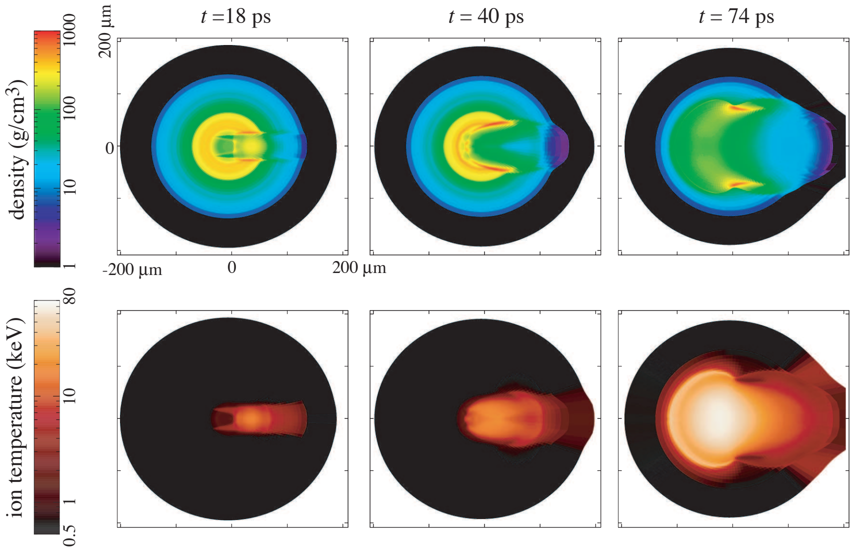


Figure 6: 2-D simulation of the ignition and subsequent burn of a target (similar to those studied in this paper) driven by a 270 kJ pulse. Burn is triggered by a 27 kJ, 20 ps pulse of particles with a range of 1.5 g/cm^2. The frames show density and temperature maps at selected times. The origin of time here corresponds to a time close to peak density in the 1-D simulation.

Acknowledgments

S. Atzeni wishes to thank R. Betti, J. Honrubia, and M. Tabak, for discussions on adiabat shaping, 1D simulations, and gain models, respectively. He also thanks M. Dunne, leader of the HiPER project, for supporting and stimulating this work.

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