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Numerical simulations and stability study of double ablation front structures, using radiation transport effects in direct-drive ICF

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In an ICF experiment, a target filled with fuel is irradiated by hundreds lasers beams. A lower density plasma corona is then formed, and accelerates a massive fuel plasma inward. The ablation surface between the two regions, called ablation front, subject to the acceleration, is unstable in regard to the Rayleigh-Taylor (RT) instability. This instability is known to amplify density perturbations at the ablation front during the acceleration phase. The growth rate of this instability must be well determined to achieve the fusion conditions.

In the direct-drive ICF approach, a scheme to reduce the RT instability has been proposed by [1]. A significant reduction of the RT growth has been observed in experiments using a self-radiation target. Two ablation fronts are then existing, one driven by electron conduction, and a second ahead driven by radiations. This structure could lead to reduce the RT growth, since the basic flow is modified, due to radiation effects (larger characteristic length and ablation velocity).

In this work, we are studying firstly the double ablation front structure obtained by numerical simulations, using an ICF code including a multigroup radiation treatment [5]. The behaviour of such structures, for different laser intensities and the intensity threshold for the structure to exist are then characterised.

Secondly, an analytical form for the Planck and Rosseland means opacity are used to introduce the radiative transfert into a code dedicated to linear perturbations calculations of unsteady flows [6]. This numerical approach allows to compute directly the linear perturbations occuring at the double ablation structure during the different phases of irradiation.

Thirdly, a scheme to determine the RT growth rate is proposed by [2]. Two coupled equations for perturbations are obtained using the Kull isobaric approximation [3], and can be solved to give the linear growth. Some indications about the way to formulate the problem and a discussion about the hypothesis used are given.

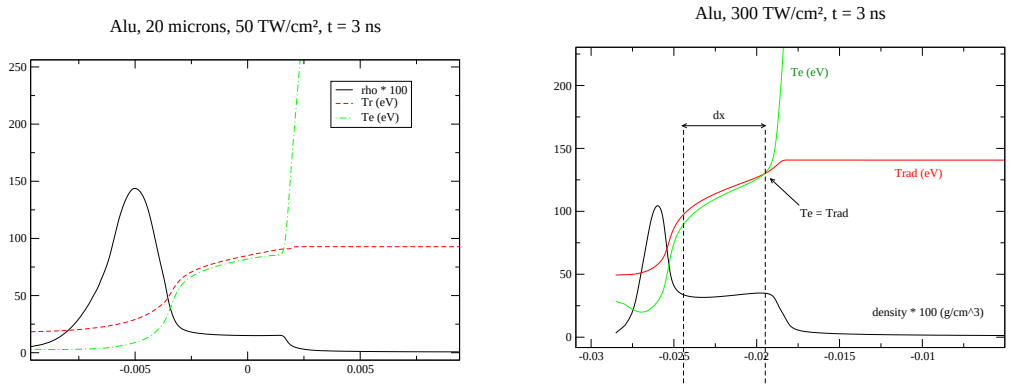

Figure 1: Profiles of density ρ, and temperatures T_e et T_r for Al target at $I_L = 50$ and 300 $TW/cm^2, t = 3\ ns$

Double ablation front structure obtained by numerical simulations

1D simulations are used intensively in ICF target design. In this work, the ICF 2-D Lagrangian code CHIC is used. It includes laser absorption, classical flux limited thermal transport, different ionisation models (Thomas-Fermi, "fully ionised") and different equation-of-state packages (SESAME, CELIA's tables, or ideal gaz). A multigroup radiation diffusive transport is included. Double ablation front structures have been obtained, using high Z targets (Aluminium), and doped plastic targets. These structures are very clearly defined in the case of Aluminium targets, so this material was used preferentially in this study with a 20 μm thick target. To investigate the behaviour of such structures for different laser intensities, and the intensity threshold for the structure to exist, many simulations using CHIC, for laser intensity from $I_L = 1$ to 500 TW/cm^2 were carried out. For lowest intensities (1 to 30 TW/cm^2), the structure appears only after some nanoseconds (typicaly after 2 ns).

For highest values of laser intensity, the structure appears before the acceleration phase, and lasts during some nanoseconds ($\sim 4\ ns$). The structures are then well defined; two ablation fronts separated by a region of quasi constant density are obtained (see fig[1]). The front near the cold material is driven by radiative conduction, while the front near the corona is driven by electron conduction. Estimations of the flux ratio at the two fronts give

$$\frac{S_r}{S_r + Q_e} = \begin{cases} 0,99 & at\ the\ first\ front\ (at\ maximum\ density) \\ 0,10 & at\ the\ second\ front \end{cases}$$

The quasi constant density region seems to be in local thermal equilibrium (the temperatures T_e and T_r are almost the same). This region (called "plateau") is then studied. The two fronts, since they are driven by different energy transport mecanisms, have different velocities so that the region is expanding in time. Two points are fixed on density profiles, and the length dx between

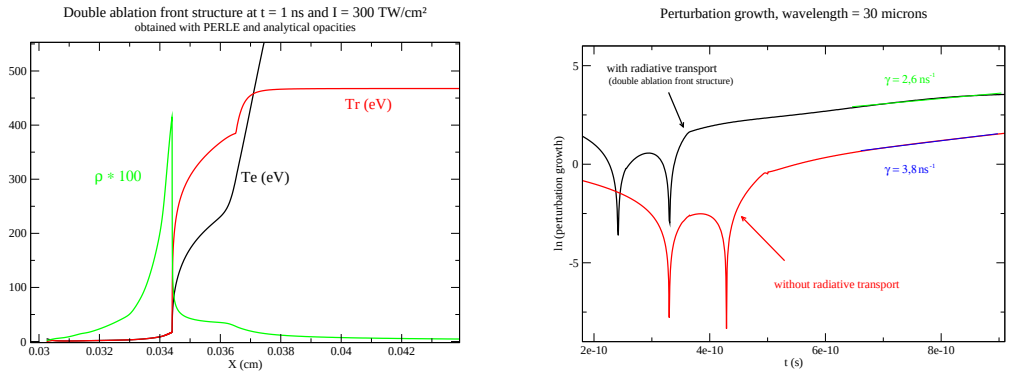

Figure 2: Similar density and temperature profiles for simulation with analytical opacities (PERLE) during acceleration phase, and perturbation growth for the wavelength 30 μm

these points at different times during a simulation is estimated; the expression obtained for the expansion of the region with time is approximately given by (expression obtained only once the structure is well defined): $dx_{\mu m} \sim 15,8 t_{ns} - 6$. In the same way, a relation between the value of the maximum density and the value of the density in the middle of the plateau is then found to be :

$\frac{\rho_{mini}}{I_L} \sim 0,1 \frac{\rho_{max}}{I_L} + 8,4.10^{-4}$ (depends directly on the laser intensity I_L given in TW/cm^2).

An analytical form for the Planck and Rosseland means opacity

An analytical form for the Planck and Rosseland means opacity is needed to introduce the radiative transfert into the code dedicated to linear perturbations calculations of unsteady flows (PERLE). The linear perturbations occuring at the double ablation structure during the different phases of irradiation are then directly computed.

This code doesn't use a multigroup radiation diffusive transfert, but we can approach the Planck and Rosseland means opacity (κ_P and κ_R respectively) with expression given by [4] and [2]:

$$\kappa_R = \alpha T_e^{q_{a1}} \rho^{q_b} \; if \; T_e < T_t, \; \alpha T_e^{q_{a2}} \rho^{q_b} \; if \; T_e > T_t,$$

and $\kappa_P = r \kappa_R$, with r a constant > 1; T_t is a transition temperature in the behavior of the opacities, and the powers q_{a1} and q_{a2} are evaluated using calculations of opacities (for Al target, typically $q_{a1} \sim -7/3$, $q_{a2} \sim -20/3$, $q_b \sim 1$ and $T_t \sim 280\, eV$). Similar profiles are obtained between the simulations effectued with the multigroup radiation treatment in CHIC and the analytical opacities in PERLE (and similar temporal evolution too) (see fig[2]).

A first study was done to calculate the growth rate for density perturbations using PERLE. The existence of a double ablation front structure seems to reduce the value of the growth rate, as for the wavelength 30 μm (see fig[2]).

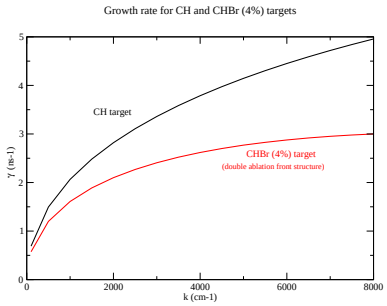

Figure 3: Growth rate obtained for CH and CHBr targets

A model for perturbations growth using the Kull isobaric approximation

A model to know RT growth rate is proposed by [2]. Two coupled equations for perturbations are obtained using the Kull isobaric approximation [3], and can be solved to give the RT linear growth rate. The hydrodynamical equations are then coupled with the radiative transfert; once the flow variables have been normalized with the typical parameters of the model (temperature, velocity, density and pressure taken at the maximum density, and typical length of the radiative front), the equations for hydrodynamical and radiation transfert are linearized. The perturbed equations can be solved using appropriate boundary conditions and continuity conditions at the interface formed by the transition in the behaviour of the opacities (see [2] for details).

The isobaric approximation near the ablation front region is a strong hypothesis of this model; in numerical simulations, a pressure gradient in the ablation front region exists (30% of difference), so that this isobaric approximation could be discussed as a little gradient of pressure could be taken into account in the equations.

However, this model has already been used in cases where both Fr number and thermal conductivity coefficient ν were < 1 and has given good results. This model is then used for $CHBr_{4\%}$ target; a reduction of the growth rate has been obtained (see fig[3]).

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