Progress in indirect drive hohlraum design for laser ICF. Self-generated magnetic field and non-local heat flux : simulation with 2D radiation-hydrodynamic code and experimental validation.

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Abstract. In indirect drive scheme, the laser light is converted in X-rays in a hohlraum made of a high-Z material. Part of this radiation flux is absorbed by a microballoon, filled with DT, and placed in the center of the hohlraum, leading to its implosion, ignition and burn. The right control of radiation fluxes, spectrum and energy, is then an issue for the LMJ target design. The presentation will give the status of our knowledge and last improvements in our codes to reproduce at best hohlraum energetics. Validation of our simulations is ensured by a large experimental program. Hohlraum energetics cover two themes : radiation energy and flux characterization inside the hohlraum, and symmetry.

Introduction

In an indirect drive scheme, the precise control of radiation around the DT-filled micro balloon is an essential condition to achieve an efficient implosion.
Inside indirect drive hohlraums, the absorbed laser energy is carried by electrons from the hot, underdense corona, to the collisional part of the target. The transfer of energy by electron conduction is then an important process that must be reproduced as accurately as possible by our models and codes. According to the plasma conditions, the ablation wave, the X-ray emission, either still the release of some parametric instabilities depend on heat conduction.
In radiation-hydrodynamic codes the Spitzer-Härm (S-H) formula is the standard formulation to calculate the heat conduction. A Fokker-Planck or Particule In Cell (PIC) code, that consumes a lot of computer time and memory, cannot be coupled to other detailed physics, in most of cases, to simulate an experiment all along the few nanoseconds of pulse duration. However, in order to reproduce or at least to be in better agreement with the experimental results, one must limit the S-H flux to a fraction of the free streaming flux. This flux-limiter depends on the nature of the target, on the laser pulse, its wavelength, its temporal shape, on the experimental configuration, etc…This apparent inhibition of electrons transport may be related to various mechanisms among which non-local transport effects and intense self-generated magnetic fields are the most probable (corroborated by theory and experiments).
A recent improvement of our 2D radiation hydrodynamic code FCI2 takes both effects into account. This paper introduces a broad outline of the hypothesis and equations, refering to published papers. Our main purpose here is to present experimental validations in various configurations : X-ray conversion on open geometry, X-flux measurements and symmetry characterization in hohlraums.

Non-local heat flux and self-generated magnetic fields simulation

The S-H formalism assumes the hypothesis of a quasi-LTE plasma (the main part of the electrons velocity distribution function can be written as isotropic and Maxwellian : the anisotropic part is a perturbation). On the contrary we know since the beginning of the eighties (Bell, Luciani, Mora, and al. work [1]) that the main part of distribution function cannot be considered as Maxwellian in most of laser configurations. The departure from the Maxwellian function is however weak enough to respect the main constraints of hydrodynamic code, but invalidates the calculation of the heat conduction. The use of Fokker-Planck codes (F-P) demonstrated that the electrons responsible for the heat flux (3-4 times the thermal velocity) could transport their energy further than calculated with a classical radiation-hydrodynamic code (the mean free path varies as v^4). The discrepancy between hydrodynamic and kinetic simulation gets larger as the temperature gradient is sharper. At a local point in the plasma the calculation of the heat flux requires not only local values of fluid quantities (e.g. Te, Ne, Z …) but also values of these quantities on all points enclosed in a domain of a few electron mean free path. The heat flux is, in this sense, non-local.
Various authors proposed macroscopic formulae, that do not use explicitly the velocity distribution function but reproduce the main characteristics of a kinetic flow, and that can be easily introduced in a hydrodynamic code. Most of these formulae contain adjustable parameters fitted on F-P calculations and are restricted to 1D slab geometry [1].

Considering that the use of a 2D code is necessary to reproduce most of our laser experiments, a new non-local model, designed for implementation in a 2D hydro-code, was developed at CEA-DIF [2]. This model can be obtained by two different ways. First is a multi-dimension extension of the previous 1D formulae, it can be written as a convolution between the S-H classic formula and a non-local kernel. This kernel, which becomes a tensor in 2D, takes into account the real distance crossed by the electrons that transport the heat flux. The integration is made on the whole space and the calculation uses the P1 approximation, that is verified by a F-P code. The second approach is more deductive. Its starts from the F-P equation : after a first order development on the base of Legendre polynomials, one can build, using an iterative method, a simplified equation describing the electrons energy transport. The convolution product of the first approach is a solution of this multi-groups equation. Under this latter form, the model presents several advantages : it can treat spherical or cylindrical geometries, take into account correctly the symmetry and boundary conditions, and use diffusion solvers in the codes.
The model has been implemented in the radiation-hydrodynamic code FCI2, and compared to results of 1D and 2D Fokker-Planck codes in idealized situations. The results are in very good agreement [2].

The non local character of the heat flux is not the only process which can explain the limitation of the Spitzer-Härm streaming. Since the 70's [3], magnetic fields have been known to exist in laser produced plasmas. Strong magnetic fields (above 1 MG in high power laser plasmas) are generated and can affect considerably all transport coefficients. The source of these fields is multiple : supra-thermal electrons fluxes, electrons pressure gradient effects, etc. ; the scale is the focal laser spots.
Although known for a long time, the implementation of corresponding MHD equations in a radiation-hydro code is complex. Physically, the effect of the fields is very simple : an electron which moves in the neighborhood of a magnetic line is diverted or even captured if the field is

intense enough (Lorentz force). Magnetic fields in the neighbourhood of a temperature gradient will provoke two effects : the electron flux along the gradient is reduced, and a transverse flux is created (Righi-Leduc effect). In high power laser plasmas, the reduction of the flux may be very important (superior to a factor 10) and can explain the use of the limiter (in the zones where the fields are present). The reduction of the electron mean free path by the magnetic field has a direct effect on the non-local character of the heat flux: in the case of intense magnetic fields, the deformation of the spherical part of the distribution function due to the non-local effects may be reduced or cancelled. So the deviation from the local model, *i.e.* using a Maxwellian function, decreases as the magnetic field increases.

Even in the simplest cases, as a planar target illuminated by a single smoothed laser beam, both mechanism can simultaneously exist in overlapping regions. To obtain a consistent treatment in the FCI2 code, we use the following coupling strategy [4]. In the case of the convolution product as well as in the transport equation of electrons flux, we replace the Spitzer-Härm formula by the Braginskii one [5] (Braginskii formula degenerates towards Spitzer-Härm without magnetic field); the electron mean free path is reduced according to the magnetic field intensity (in order to avoid the delocalization of local fluxes).

An open geometry experiment on Phebus

This experiment was performed on the 3ω, 6 kJ on 2 beams, laser facility Phebus (at CELV-France) in 1996. A thin planar (about 1 μm) gold target was illuminated by a single smoothed beam (3 kJ) with a 1.5 ns square pulse. The objective of the experiment was to characterize the X-ray emission on the focal spot, in different ranges of frequency, spatial and time resolved imaging. The experimental set up is shown just below in Fig. 1.

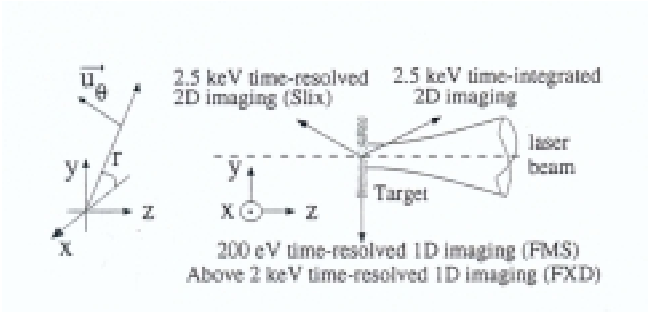

Fig. 1 : Experimental set-up

We will not present in this paper detailed results of measurements and interpretation which were published in [4]. No simulations with Spitzer-Härm model, whatever the flux limiter coefficient may be, of FMS diagnostic (1D time resolved X-imaging in the range 200 eV) or SLIX (2D X-imaging every 100 ps in the range 2 keV) were able to accurately reproduce the data, suggesting that some physics was missing.

Only our multi-dimensional model taking into account non-local electron heat transport and self-generated magnetic field effects (both effects were needed), inserted in FCI2, gave calculations in good agreement with the experimental data.

In the simulations, magnetic fields of 1.7 MG were calculated on the periphery of focal spot, as shown in Fig. 2 below.

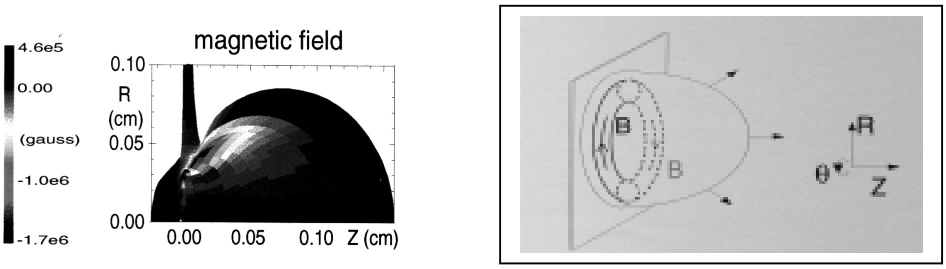

Fig. 2 : Iso-level map (left) in the laser laser illuminated foil of gold of the magnetic fields (MG) The magnetic fields are perpendicular to the R and Z axes as drawn on the right.

Simulations in hohlraums

A large experimental program was performed on Nova up to 1999 (30 kJ LLNL laser facility) within the framework of a CEA-DOE collaboration, and is going on at Omega facility (~ 20 kJ, Univ. of Rochester). Cylindrical gold target, gas-filled or empty, illuminated with laser for indirect drive were experimented in order to characterize hohlraum energetics: inside radiation flux, time resolved spectrum and energy, and symmetry from foam balls ablation front observation [6] and [7]. Standard experimental set-up is presented in Fig. 3.

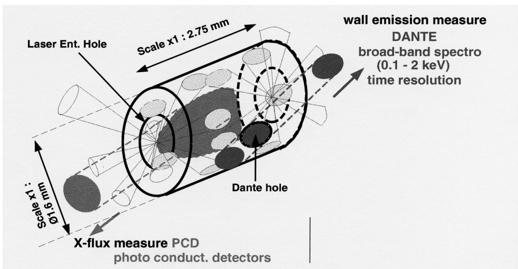

Fig. 3 : Dante and PCD were standard diagnostics on Nova to measure radiaton fluxes through holes. Dimensions are for standard scale 1 hohlraums.

Simulations demonstrate that our new model does not significantly modify the radiation parameters in the hohlraum : radiation temperature and spectrum are kept unchanged. Previous interpretation of radiation diagnostics as Dante and PCD with Spitzer-Härm (and adapted flux limiter) is therefore valid. X-flux symmetry, that can be characterized with a D2-filled target implosion (self X-ray emission measurement during burn) or a foam-ball (the ablation front progression is visualized) is not modified either.

On the contrary, electron thermal conduction is significantly modified at the edge of the laser spots and near laser entrance holes (LEH). As a consequence, electron temperatures are larger (~+ 20% Te) and gradients steeper, especially on the axis of the hohlraum and near LEH. A comparison of electron temperature calculations with the two models is shown in Fig. 4. In the hohlraum, magnetic fields of 1 MG are calculated on the periphery of the focal spots.

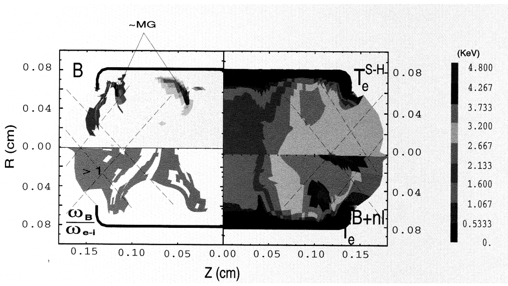

Fig. 4 : Electron temperature maps calculated with Spitzer-Härm (S-H) or new model (B+nl), at maximum laser power time. Localization of B-fields is shown, with level. When Hall parameter (ω_B/ω_{e-i}) is above 1, B-fields play a role.

Electron temperature gradients and levels calculated with non-local + magnetic fields model are corraborated by measurements from Thomson scattering probe [8].

Conclusion

A non local heat flux model was recently implemented in our 2D radiation hydrodynamic code FCI2. So a better treatment of the heat conduction allows us to get rid of the adjustable flux limiter, that was previously necessary when the S-H formula was used. High intensity magnetic fields, generated in our laser plasmas and playing an active part in the electron transport, are now taken in account as well. Hopefully these new treatments do not affect the radiation drive inside the hohlraum ; only hydrodynamics is sgnificantly modified. This last point could change our mind about hohlraum plasmas behaviour in relation with parametric instabilities.

References

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