Influence of the solid-to-plasma transition on the laser energy deposition in targets and subsequent hydrodynamics for direct drive inertial confinement fusion

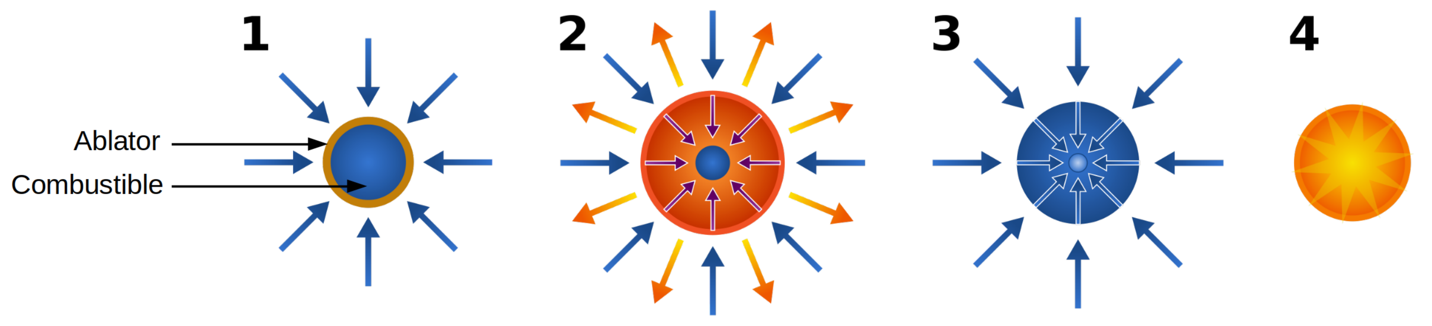
R. LIOTARD[1], A. COLAITIS[1], A. PINEAU[2], S. X. HU[2], I. V. IGUMENSHCHEV[2], G. DUCHATEAU[3]

[1] University of Bordeaux-CNRS-CEA, CELIA, 351 cours de la libération, 33405 Talence, France
[2] LLE, 250 E River Rd, Rochester, NY 14623, USA
[3] CEA-CESTA, 15 Avenue des Sablières, 33114 Le Barp, France

Introduction

Inertial Confinement Fusion (ICF) is a method of achieving nuclear fusion reactions by bringing a small mass of combustible material at high densities with the desired thermodynamic properties. To achieve this goal, high power laser beams are used to implode a spherical shell constituted of gaseous DT fuel surrounded by solid DT and a plastic ablator. The laser ionizes the ablator which is ejected and the target implodes due to the rocket effect. In radiation hydrodynamics codes modeling this process, the plastic ablator is supposed opaque to the laser radiation, which is only the case when it is already in plasma state, where the laser field is reflected at the critical density. However, the processes that lead to the transition from solid state to plasma state of the ablator are not modeled in the aforementioned codes, whereas they may have an important role in implosion symmetry, target compressibility, shock timing, and hydrodynamic instabilities.

Principle of Inertial Confinement Fusion

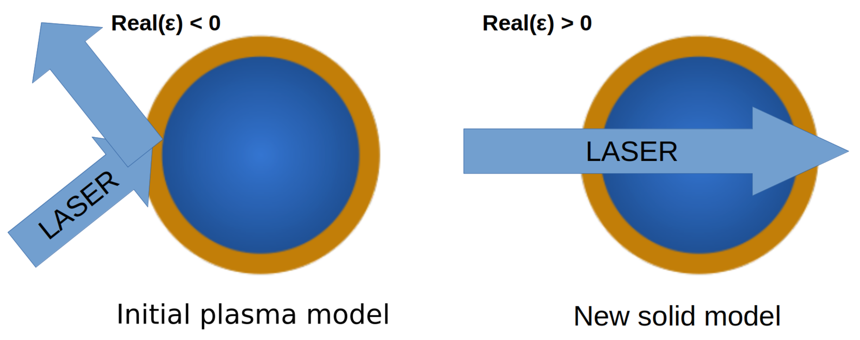


1. ICF target : combustible (DT) surrounded by a solid ablator, on which high intensity lasers are shot
2. Ablation of the outer shell material that generates a rocket effect
3. Implosion of the target
4. Ignition of the hotspot and burn of the combustible

Influence of initial solid state

Objective: model the initial state of the target

⇒ Almost zero initial free electron density => Transparent target
⇒ Modification of laser absorption
⇒ Modification of hydrodynamic parameters (thermal conduction, radiation generation/transport)



Permittivity

Approximation of geometric optics

⇒ Both trajectories ant absorption of light rays are driven by the medium permittivity ϵ

Gamaly and al. [1] came up with a formula that is suitable for solid to plasma transition

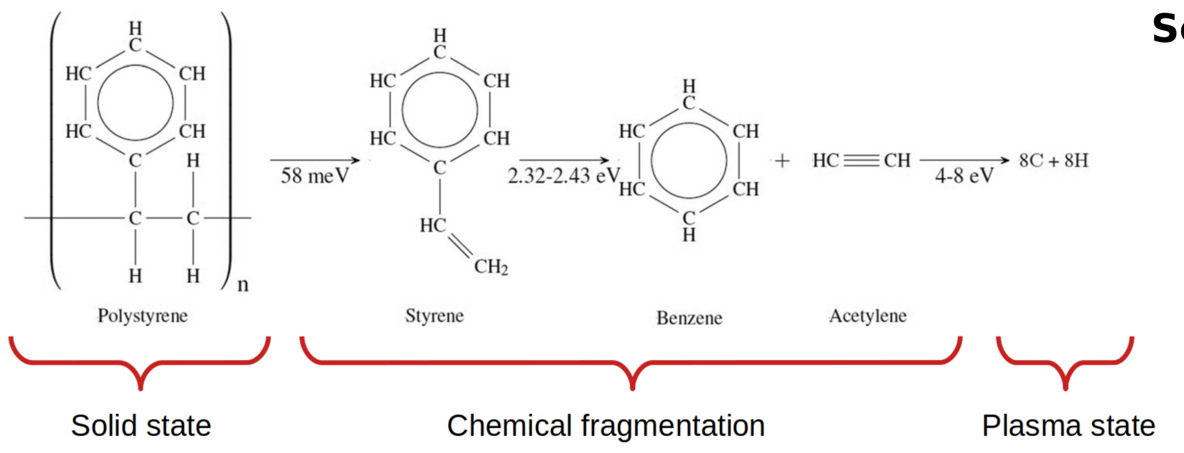
$$\epsilon = \underbrace{1+(\epsilon_f-1)\left(1-\frac{n_e}{n_v}\right)}_{\text{solid permittivity due to valence electrons}} - \underbrace{\frac{n_e}{n_c}\left(1+i\frac{\nu_c}{\omega_0}\right)^{-1}}_{\text{plasma permittivity due to free electrons}}$$

ϵ_f: permittivity of the non-ionized solid, n_e: free electron density, n_v: valence electron density, n_c critical density, ν_c: collision frequency of free electrons with the ions and neutrals of the material

Important quantities: n_e and ν_c

Modeling solid to plasma transition

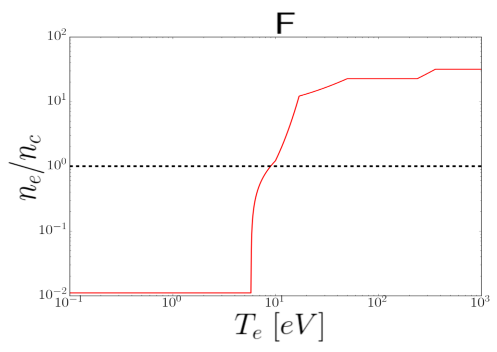
Theoretical model of the evolution of n_e and ν_c from *Pineau and al.* [2]



Solid sate:

- $\frac{dn_e}{dt} = n_v \nu_{Photoionisation}(I_{laser}, \omega_{laser}, E_{band-gap})$ [3]
- $\nu_c = \nu_{ep} + \nu_n$
- $\nu_{ep} = \nu_{ep0} * \frac{T_i}{T_{i0}}$
- $\nu_n = n_n \sigma_n \sqrt{k_B T_e / m_e}$

Chemical fragmentation:



- $n_e = F(T_e)$
- $\nu_c = \nu_{ei} + \nu_n$
- $\nu_{ei} = \frac{2\sqrt{2}\pi}{3} \frac{Z^2 e^4 n_i}{\sqrt{m_e}(k_B T_e)^{3/2}} \frac{ln\Delta}{[1+\exp(\mu_e/k_B T_e)]F_{1/2}(\mu_e/k_B T_e)}$
- $\nu_n = n_n \sigma_n \sqrt{k_B T_e / m_e}$

Codes

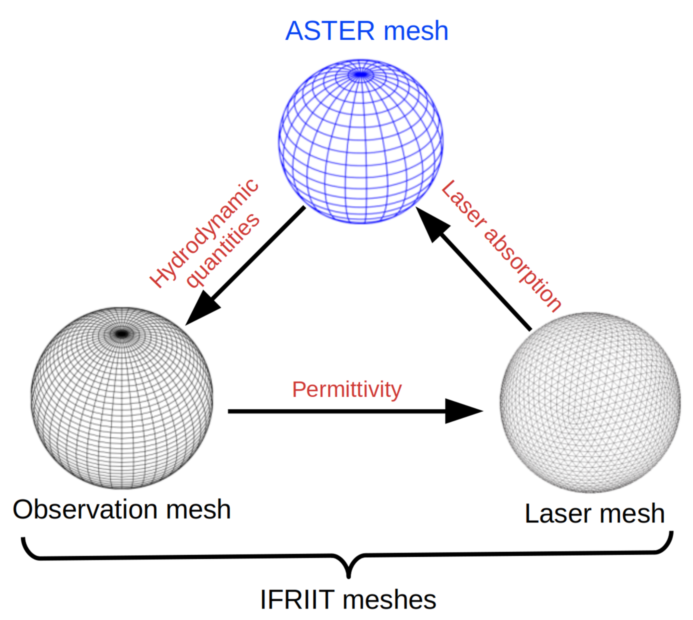
ASTER [4]:

- 3D Eulerian hydrodynamic code from LLE
- Optimized for direct drive implosion
- Native 1D laser propagation code

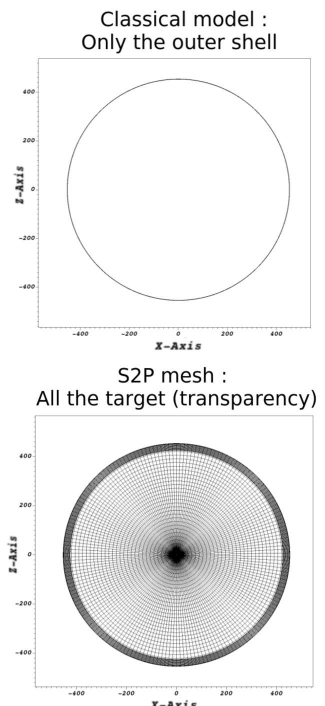
IFRIIT [5]:

- 3D laser propagation calculation code coupled to ASTER
- Optimized to calculate electric fields in spherical symmetry more precisely than usual approaches

IFRIIT-ASTER coupling diagram [5]



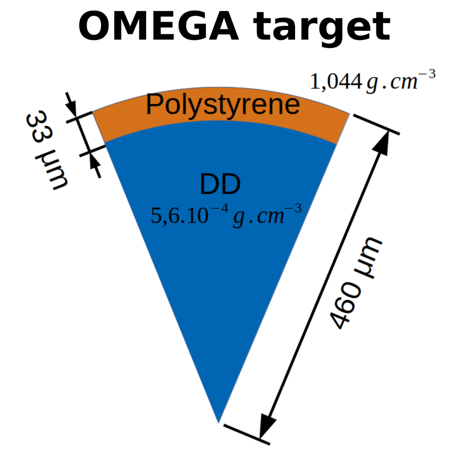
IFRIIT meshes modification



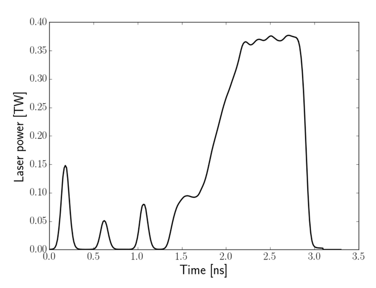
- Standard code: only coronal plasma is meshed because the target is supposed to be reflective.
- S2P mode: the target is transparent so it must be fully meshed.
- Increasing of the calculation time during the 50 first seconds of the simulation.

Parameters

OMEGA target



Laser pulse shape

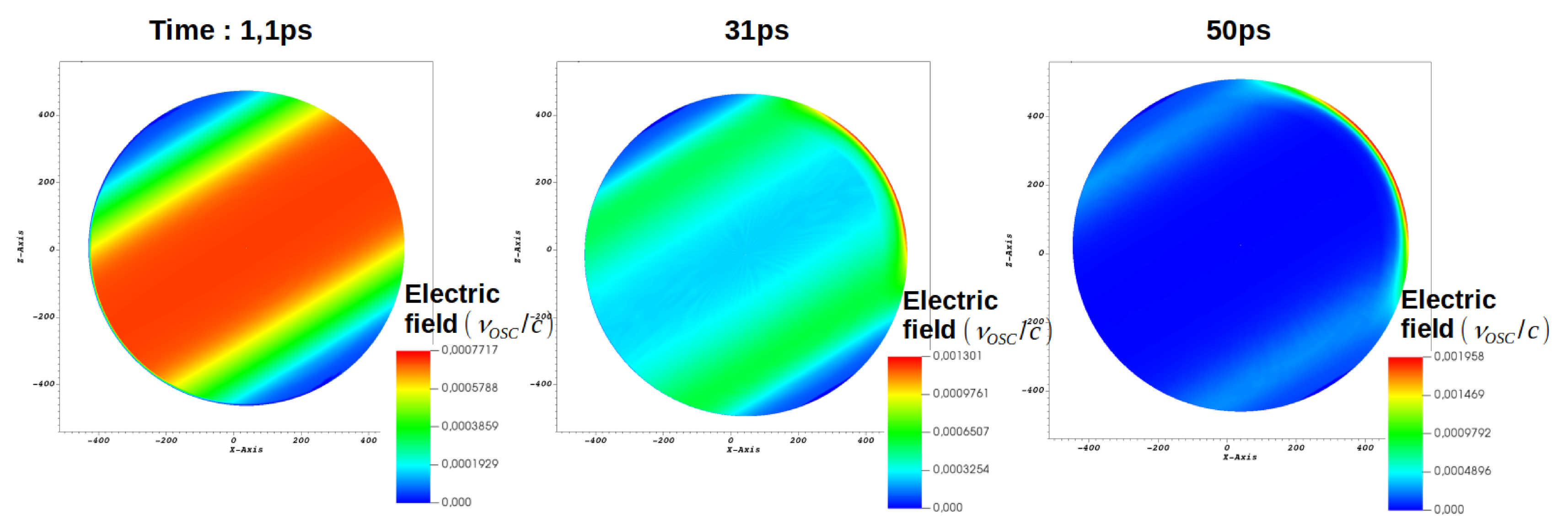


Results for one laser beam

Time = 1.1ps: Solid ablator => the laser beam goes through the target

Time = 31ps: Ablator begins to be ionized => the laser is more and more absorbed

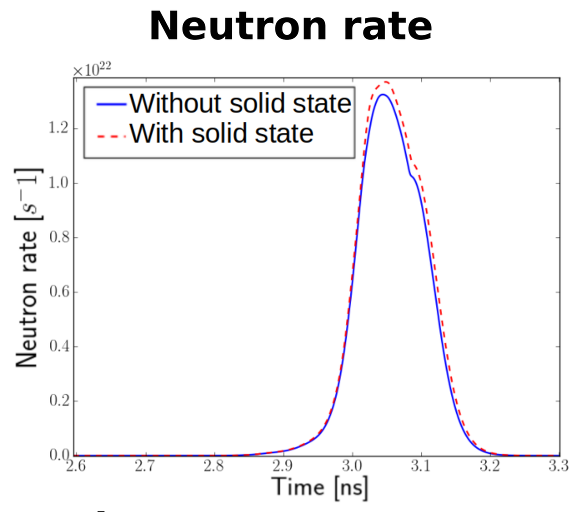
Time = 50ps: Plasma ablator => laser beam is reflected by the plasma



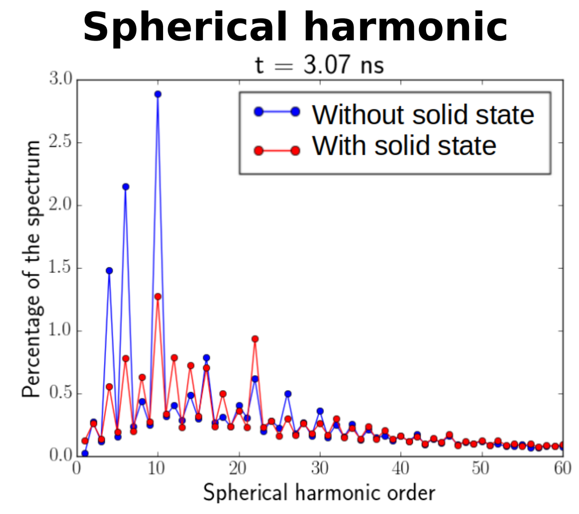
Results with OMEGA laser parameters

Results from two full time OMEGA shots (non cryogenic target) including or not the solid to plasma transition model

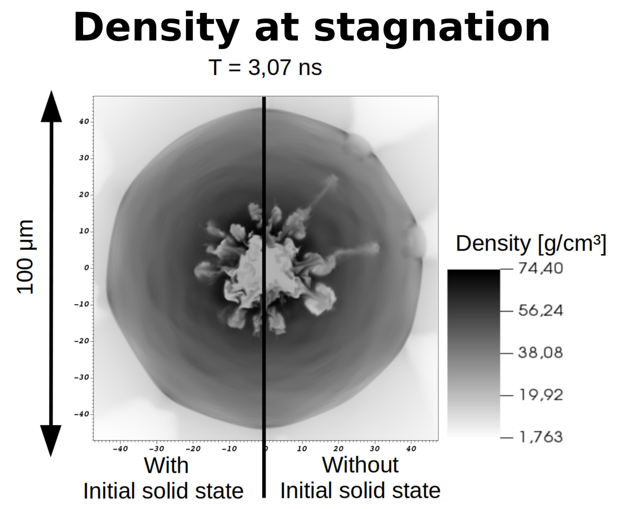
Neutron rate



Spherical harmonic



Density at stagnation



Observations:

- Solid-to-plasma transition seems to reduce some low mode instabilities during the implosion (see the spherical harmonic decomposition of ρR at stagnation).
- It is probably due to an averaging of geometric inhomogeneities of laser irradiation by the deep preheating of the polystyrene ablator.

References

1. E. G. Gamaly *u. a.*, *Opt. Soc. Am. B* **31** (2014).
2. A. Pineau *u. a.*, *Phys. Plasmas* **27**, 092703 (2020).
3. G. Duchateau, *PRE* **100**, 033201 (2019).
4. I. V. Igumenshchev *u. a.*, *Phys. Plasmas* **23**, 052702 (2016).
5. A. Colaïtis *u. a.*, *JCP* **443**, 110537 (2021).

Conclusion

The solid to plasma transition model has been implemented in an hydrodynamic code and several simulations have shown the effect of this transition on gas-filled OMEGA targets. The next objective is studying this effects on a cryogenic targets which should be more sensitive to preheat. This code could also be suitable for target with a low density outer shell, like dielectric foam.