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EXECUTIVE SUMMARY OF THE THESIS

Theoretical study of high-power laser interaction with novel nano-structured foam materials for inertial confinement fusion research

LAUREA MAGISTRALE IN NUCLEAR ENGINEERING - INGEGNERIA NUCLEARE

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1. Introduction

The nuclear fusion is the most promising way to produce green energy in the next future. Nowadays, there are a number of technical issues which must be resolved in order to build fusion power plants. There are no nuclear fusion reactors able to be used for commercial distribution. On the other hand there are many experimental devices which are able to sustain, for a short time, the conditions required for nuclear fusions taking place in a controlled environment. The environment into which controlled fusions can take place is the most severe we can think of due to the benchmarks related to the order of magnitude of the physical quantities involved. To do so there are two main approaches to nuclear fusion which are called Magnetic Confinement Fusion (MCF) and Inertial Confinement Fusion (ICF). In the former a very hot and rarefied plasma column is confined for a long time into a closed chamber through a proper magnetic field. In the latter the conditions for fusion are achieved by irradiating with multiple high-intensity laser beams the fuel pellet, which is a layered sphere: once irradiated by high-intensity lasers the most extenal layer is ablated (so the name ablator) leading to a compression of the inner layers through the so called rocket-effect. In my thesis work the focus has been on the analysis of innovative materials for ICF applications. The aforementioned devices for ICF can be subdivided into two main schemes, namely, direct drive and indirect drive. In both these configurations the we have the ablator, whose role is twofold. It has to convert as much laser energy as possible into mechanical energy available in the form of shock waves and these shock waves have to lead the implosion isotropically and isoentropically.The ablator must be a low-Z material in order to maximize the coversion efficiency of laser energy into mechanical energy. An high-Z material would emit X-rays which would lead to a lower laser to mechanical energy conversion efficiency.

Nowadays there are many materials under investigation for realizing the ablator. One of the most promising is High Density Carbon (HDC) in the form of diamond [2]. On the other hand we have foams materials, which are a class of fractal-like low density materials that are acquiring great interest due to their peculiar behaviour under irradiation. One of the aim of my thesis work is to investigate the advantages of using a carbon foam ablator instead of a HDC one.

In the indirect scheme the fuel pellet is not directly ablated by the high intensity lasers. It is placed in a chamber called *"hohlraum"*. The lasers are directed onto the internal surface of the hohlraum, which must be a high-Z materials since it has to convert as much as possible the laser energy into X-rays. This intermediate step, which unavoidably leads to a lower efficiency of the laser to mechanical energy conversion, has the aim of ensuring a more symmetric implosion. The radiation temperature profile is not different from that of black body, which is isotropic by definition. Nearly all the hohlraum's design proposed worldwide involve the use of gold. Gold (High Density Gold, HDG) is a high-Z material, exhibiting a very high efficiency in converting the laser energy into X-rays and it is very simple to be processed.

In [5] a Low Density Gold (LDG) hohlraum has been proposed. The simulations they performed have shown that the LDG target exhibits better properties respect to the HDG target. The code they adopted is the very same which has been used for carrying out my simulative work, MULTI-FM 1D. In [5] the authors refer to the low density homogeneous gold target as foam gold target despite the fact that the internal fractal structure has not been considered. This is the reason why I refer to that target as LDG, since it is not a foam. To make and attempt to properly reproduce the effect of the internal structure of the foam, I performed simulations with the MULTI-FM code and compared them with the results of [5].

For what concerns the techniques adopted for producing foams they can be subdived into Chemical Deposition (CD) and Pulsed Laser Deposition (PLD). PLD allows for producing high purity foam such as a pure carbon or gold foam. The main difference with respect to the former ones is the internal structure; foams produced by CD exhibit a micrometric internal structure while those produced by PLD exhibit a nanometric internal structure and are more often referred as *Cluster Assembled*. This is a very important point. The role of the internal structure is quite understood but the differences in the behaviour due to a change from microstructure to nanostructure is a new problem. Having that said, this will be the subject for a dedicated experimental campaign since the role of the nanostructure in ICF applications is not completely clear. At Politecnico di Milano the NanoLab group is carrying out a huge theoretical and experimental work concerning the production of foam target through Pulsed Laser Deposition for their applications in particles acceleration and generation. A part of my work has been to investigate the possible applications of these materials for producing devices for ICF, namely, for ablators and hohlraums.

2. The physics behind MULTI-FM

The MULTI-FM code has the aim of simulating the laser matter interaction in the typical regimes involved in ICF (laser intensities in the order of $10^{13-14}\mathrm{W/cm^2}$), with the integration of a model for reproducing the laser absorption and the plasma evolution of a foam. It is a two-fluid code (electron and ion populations), which is based on mass, momentum, energy conservation and radiation transport equations.

$$\frac{\partial \rho}{\partial t} = -\rho^2 \frac{\partial v}{\partial m} \tag{1a}$$

$$\frac{\partial v}{\partial t} = -\frac{\partial (P_i + P_e + P_\nu)}{\partial m} \tag{1b}$$

$$\frac{\partial e_e}{\partial t} = -P_e \frac{\partial v}{\partial t} - \frac{\partial q}{\partial m} + \frac{E_{ei}}{\rho} + \frac{S_e}{\rho} + \frac{Q}{\rho} \tag{1c}$$

$$\frac{\partial e_i}{\partial t} = -(P_i + P_\nu)\frac{\partial v}{\partial t} - \frac{E_{ei}}{\rho} \tag{1d}$$

$$\mu \partial_m I(m,\mu,\nu,t) = \frac{\chi}{\rho}(T,\rho,\nu)(I_S(t,\rho,\nu) - I(m,\mu,\nu,t)) \tag{1e}$$

This system of equations represents what is known as radiation hydrodynamics. A tabular Equation Of State (EOS), which is a relation among temperature density and pressure, is what is adopted to close this system. The quantity m is the positional lagrangian coordinate, ρ is the density, v is the total fluid velocity, P_e, P_i are the electron and ion pressures respectively, P_ν is the viscous pressure, artificially introduced in order to numerically smooth shock fronts, q is the thermal flux, $E_{ei} = \frac{3\nu_e m_e n_e k}{m_i}(T_i - T_e)$ is the power per unit volume transferred from electrons to ions (k is the Boltzmann's constant), S_e is the deposition of the laser and Q is the total emission rate per unit volume. I is the specific intensity of radiation of frequency ν at a position m traveling in the direction $arcos(\mu)$ at time t,χ/ρ is the opacity expressed in units of surface per mass,I_S is the source intensity function which accounts for the light emission of the matter. The total emission rate Q is what realises the bridge between the matter and the photon field. This system alone is not adequate to describe what happens in a foam. Some modifications are needed as reported in [3]. The equations need to be properly adjusted to take into account the homogeneization process acting in a foam once is irradiated by a high-intesity lasers. Pores starts to be filled by the generated plasma, and this evolution is related to a non homogeneous density distribution which is responsible for:

- The higher absorption capability of foams;
- The slower shock formation;
- the slower heat conduction;
- The higher pressure enstablished;

In [3] the method adopted consists in multiplying the right hand side of the momentum balance and the heat flux tems by the complement of the quantity called IsFoam, which is a function of space and time. At the beginning of the irradiation $IsFoam$ is equal to 1. As the irradiation goes on it continuosly decreases until the homogeneization process is completed, where it is equal to 0. The quantity $1 - IsFoam$ is 0 and the beginning of the irradiation where the ions and the electrons are not freed and so cannot constitute two fluid populations.So, at the beginning of the irradiation the heat flux, which is described by the Spitzer's model which assumes the phenomena as fully related to electrons, and the momentum transport are suppressed. A the end of the homogeneization, where the two fluid populations are completely developed, the thermal conduction and the momentum transport are fully active. This explains why the limitator $1 - IsFoam$ is applied only to the right hand side of the momentum balance and to the heat conduction term. The radiation hydrodynamics equations properly manipulated to simulate the foam environment represent the physics on which the MULTI-FM code is based.

3. Carbon foams and ablators

The available literature about foams [3, 4] already shown that foams are expected to be more efficient in converting the laser energy into mechanical energy available for a strong shock formation respect to a homogeneous material. Due to the fractal internal structure the material usually exhibits pores. Those who do not can be approached by means of the same mathematical treatment thinking at the pore in an equivalet way [6]. Once ablated by a HIL a homogenization process takes place and a plasma is generated as a consequence. The physics of this mechanism is still not completely clear. Nevertheless we can take advantage of it for designing an ablator. An important requirement for a material to be used as an ablator is that it must be constituted by low-Z elements, as explained above. Moreover, X-rays would preheat the ablator prior the hydrodynamic development of the mechanical waves, leading to a less efficient shock formation. The typical foams under investigation at the ABC facility in Centro Ricerche ENEA are made of plastics; low-Z, simple manufacturing, micro-metric internal structure. The foams of my interest are those produced by PLD. An internal porous structure leads to an improvement in terms of pressure levels. This fact can be explained by considering that the shock propagates slower in a foam (respect to an ideal homogeneous material having the same density) due to the presence of the pores. Moreover the shock formation itself is delayed due to the internal structure: the energy absorption develops in a larger volume. This effect depends on the pores dimension: The bigger the pores the slower the shock formation so the higher the pressure. In order to understand the influence of the density on the shock wave formation velocity I performed some simulations with the MULTI-FM 1D code. The results obtained for the bulk homogeneous carbon show that this material has useful features for being employed as ablator in fusion capsules[2].

My simulations show that higher pressure levels can be achieved though the use of carbon foams, as expected due to the previous studies coundcted on plastic foam ablators [3]. Another potential advantage for using foams is due to the fact that blast waves (which are usually formed in homogeneous target irradiated by a HIL) do

EOS	Thickness cm	Pore μm	Density g/cm^3	Intensity W/cm^2
Carbon as ideal gas	0.01	10	0.06	6×10^{13}

Table 1: Optimized carbon target parameters

not develop. These blast waves are thought to be one of the causes for Rayleigh-Taylor instability. As written in [1] the risk for Rayleigh-Taylor is a real one. During the implosion's acceleration phase, the ablation front of the imploding shell is unstable to the RT instability. Despite the ablation improve the stabilization process, it is calculated and observed that defects on the capsule surface grow several hundreds of times. These defects are another source for this instability. The preheat, which could lead to a mixing of the ablator and the cold fuel into the hotspot, is another cause for RT. So the use of foams could be really useful since one of the main causes is removed.

In view of a future experimental campaign, I perfomed simulations having the aim to find out which are the best target parameters in order to maximize the pressure level. The parameters are grouped in Table 1:

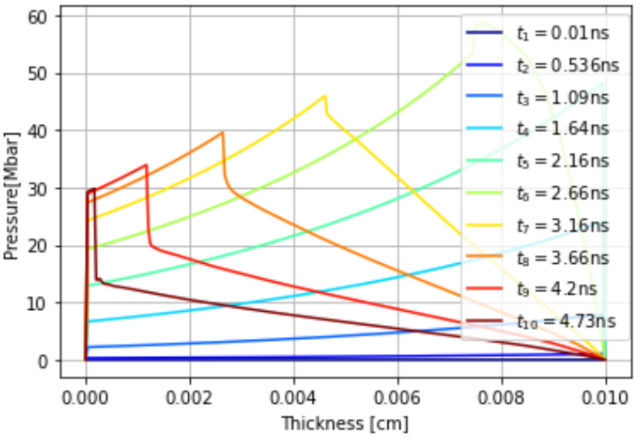

Figure 1: Pressure evolution in the optimized carbon foam target.

In Figure 1 is shown the pressure evolution into the carbon foam ablator. As can be seen the ablator is able to sustain the laser pulse, maximizing the the absorbtion of the laser energy and the final pressure. Talking about the PLD deposition regime, as explained in section 5.1.1 of my thesis, the ns-PLD seems to be the most appropriate one. To conclude the analysis of the carbon foam target I have studied how to measure the pressure levels in a real experiment. This is not an easy task, as I explained in chapter 5 of my thesis. Nevertheless,it is possible to obtain an estimation of the pressure level reached, which can be used to make the comparison among the carbon foam cases (different pores dimension) and the HDC case. For this purpose, a method based on the analysis of the craters formed on a solid layer placed on the rear side of the foam target can be adopted [4].

4. Gold foams and hohlraums

An high-Z material behaves quite differently with respect to a low-Z one once irradiated by a high intensity laser. Due to the self-generated photon field which couples with the matter, the shock generation is less effective since a non negligible amount of energy is transferred to the photon population.Taking advantage on this effect, the recent numerical work of Ref. [5] has shown the feasibility of using low-density gold foam as radiator for making an efficient hohlraum. By a proper choice of the laser parameters an higher conversion efficiency into X-rays can be achieved. However the simulations as done in [5] do not consider any effect related to the internal structure of the gold foam. This is where I want to give a contribution by performing simulations taking the internal structure into account through an upgraded version of MULTI-FM 1D. So I reproduced their results using the proper laser and target parameters. In section 4.4 of my thesis these comparisons show a very good agreement between their simulations and mine. Then I performed simulations which properly account for the internal porous structure.

In the low density homogeneous gold case a mechanical wave is generated, but it is not comparable to the one generated in the bulk case. In Figure 2 is shown the result of the optimized gold foam target. As can be seen the density profile is completely flat. The physics of the simulation is telling us that in these conditions, having a strong radiation field, there are no me-

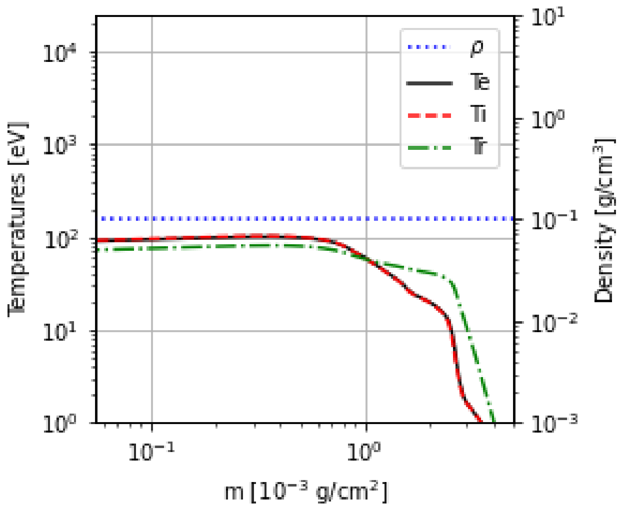

Figure 2: This is the result of my simulation about a gold foam target taking into account for internal structure, assuming 1 μm as pores dimension.

chanical waves developed into the target. The radiation field (X-rays) which is developed due to the laser matter interaction sees the target as subcritical, which means that it is able to deeply penetrate the target. The radiative heat wave is supersonic; it is converting in plasma all the matter leaving the plasma as immobile. All the energy deposited by the laser is transferred to this mechanism. The three temperatures plotted after the radiative heat wave formation are almost completely superimposed, meaning that ions and electrons are thermalized and in equilibrium with the radiation field. This can be also interpreted by saying that the reemission zone (which is the one associated to the X-ray emission) is way much more extended respect to the bulk gold case. This fact, if validated by experiments, would means that gold foams could be employed as new hohlraum materials, more efficient in converting the laser energy in X-rays.
Also for the gold case I performed simulations having the aim to properly design a target to be used at the ABC facility. In the gold case the thickness is not a crucial parameter. It is enough to guarantee that the target will last all the laser time since that will maximize the X ray production. The pore dimension is an extimation since the PLD technique produces nanostructured materials. The value assumed for the density is the lower limit for a gold foam produced by PLD. The table with the optimized foam target parameters is shown below in table 2. As explained in section 5.2.1 of my thesis the PLD regime through which this target may realized is the fs-PLD.
As final effort I have studied how to realize an experiment at the ABC facility having the aim of verifying if the results of my simulations and those performed in [5] are actually in agreement with the experimental data. To do so we have to verify which is the regime at which the radiative heat wave travels, if it is subsonic (so the radiative heat wave develops slower or at the same velocity of the shock wave) or supersonic (so the radiative heat wave develops faster than the shock wave). An X-ray streak camera is adopted in order to look for the shock breakout.

5. Conclusions

The final outcome of my work is twofold. I have studied carbon foams and I have shown that these materials can be better ablators taking into account the role of the pores. The simulations I performed for the HDC and LDC cases are original too since to the best of my knowledge there are no available articles in literature approaching this problems by using MULTI-FM. I designed an optimized carbon foam target using parameters belonging to a realistic range for a real ablator having the aim to maximize the final pressure (table 1). For what concerns gold, in order to validate the reliability of my results I performed a comparison between the simulations shown in [5] and the ones obtained with the MULTI-FM code. Moving to the foam case I have shown that the role of the internal structure is a crucial one since my simulations predict that mechanical waves are almost completely suppressed respect to both the HDG and LDG, which means that a gold foam hohlraum may exhibit even higher efficiency of converting the laser light into X-rays. Also in this last case I designed a target having the aim of understanding which would be the parameters in play in a real situation.

6. Acknowledgements

First I want to thank professor Matteo Passoni who gave me the opportunity to start this new collaboration with the Centro Ricerche ENEA through my thesis. From this point of view a

EOS	Thickness cm	Pore $[\mu m]$	Density $[\frac{g}{cm^3}]$	Intensity $[\frac{W}{cm^2}]$
Gold as ideal gas	0.05	1	0.1	10^{14}

Table 2: Optimized gold target

general thanks goes to the Politecnico di Milano and the ENEA that, as istitutions, have represented a solid base during my formation. Last but not least I want to thank my family. There are no proper words to explain how big their contribution has been.

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