Recent Advances in Indirect Drive ICF Physics at CEA

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Abstract. The objective of Target Physics Program at CEA is the achievement of ignition on the LMJ, a glass laser facility of 1.8 MJ which will be completed by 2008. It is composed of theoretical work, experimental work and numerical simulations. An important part of experimental studies is made in collaboration with U.S. DOE Laboratories : Lawrence Livermore National Laboratory, Los Alamos National Laboratory and the Laboratory for Laser Energetics at the University of Rochester. Experiments were performed on Phebus, NOVA (LLNL) and OMEGA (LLE) ; they included diagnostics developments. Recent efforts have been focused on Laser Plasma Interaction, hohlraum energetics, symmetry, ablator physics and hydrodynamic instabilities. Ongoing work prepare the first experiments on the LIL which is a prototype facility of the LMJ (8 of its 240 beams). They will be performed by 2002. Recent progress in ICF target physics allows us to precise laser specifications to achieve ignition with reasonable margin.

Introduction

The main goal of the LMJ is high energy density physics for different applications : the French “simulation” program, basic science (as laboratory astrophysics) and also energy applications. But the first milestone at the end of this decade is the achievement of ignition. CEA has a comprehensive program of ignition preparedness which has been presented several times [1]. We just recall that the LMJ will have 240 beams grouped by 4 (60 quadruplets) and give routinely 600 TW, 1.8 MJ at 0.35µm. The other specifications are : a pointing accuracy on target of 50µm, a power stability of 7%, a shot-rate ability of 600/year. The first step of the LMJ project is building the LIL (a 60 kJ, 8 beams facility as a prototype of the LMJ). The building has been completed mid 98 and space frame is now completed. The mounting of first amplifiers is ongoing and the certification of the first quadruplet will be done at the end of 2001. Building the LMJ itself will follow and the first shot on target is planned at the end of 2008. Ignition preparedness is forecast to need 2 years, so ignition is foreseen at the end of 2010.

The current work is focused on the indirect drive scheme with the following baseline design (fig. 1).

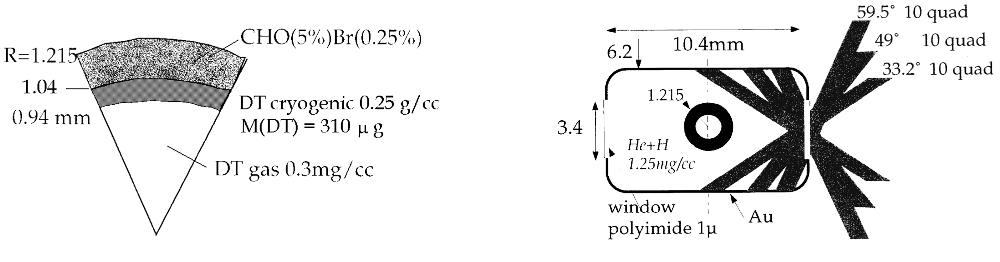


FIG. 1. Capsule and Hohlraum geometry for LMJ baseline target

We chose to have 3 cones of laser beams in each hemisphere with angles ranging from 33° to 60°. The 3 cones can illuminate 3 rings on the hohlraum wall, or can be gathered in 2 rings like NIF . We will therefore have some flexibility in choosing different "illumination configurations" without moving the beams. The laser pulse is calculated to generate driving temperature in the hohlraum which optimize the implosion hydrodynamics [3].

Phebus having been shot-down at mid 99, CEA no longer has any large laser facility until LIL, so we are currently performing experimental work at LULI facilities (Ecole

Polytechnique) and on OMEGA, at Rochester (LLE), in the framework of the ongoing DOE-CEA collaboration.

The purpose of this paper is to summarize the recent advances and ongoing work, for the different plasma physics areas, as well as the main milestones of LIL and LMJ project, for CEA ignition preparedness.

2. Laser Plasma Interaction

Years of laser plasma interaction experiments on the NOVA laser at Livermore have shown that to some extent, optical smoothing (using phase plates and 1D smoothing by spectral dispersion) can be efficient to keep the Raman and Brillouin backscattering low, and to control beam steering in the cavity. These experiments, as well as those done on PHEBUS, provide us with a large database of results which are still being interpreted.

In 2002, a milestone campaign is scheduled on LIL to complement this database and to check the efficiency of the baseline LMJ optical smoothing solution (1D SSD combined with the grating focusing of the LMJ final optics assembly) [2]. At that time, LIL will feature 4 beams delivering 30 kJ of laser energy at 3ω with a flexible pulse shaping capability. The 4 beams will be focused together as a so-called « quadruplet » on a elliptical 1200x600 μm^2 or circular 600x600 μm^2 focal spot.

Meanwhile, we are developing and improving a suite of LPI codes, following three complementary paths : the inclusion of parametric instability saturation mechanisms in our 2D hydrocode post-processor (PIRANAH) [4], the development of paraxial codes (PARAX [5], an existing one, and HERA/ILP, a new one, with AMR hydrodynamics) and the study of reduced models with a kinetic multidimensional code (CALDER) [6]. These studies will leverage our increasing computing resources (a 5 teraflop SMP cluster in 2002). Together with the LIL experiments, they will give us the improved understanding and predictive capability of laser plasma interaction that are needed for a successful achievement of ignition on the LMJ.

Aside of this work which is mainly devoted to the Indirect drive approach, some studies are dealing with the Fast Ignition scenario and others Ultra High Intensity lasers applications. For example we are exploring particle and photon production with Ultra-Intense lasers [7].

3. Hohlraum physics

A lot of experiments has been performed on NOVA, PHEBUS and GEKKO XII to measure the hohlraum radiation temperature. This database give a good confidence in the control of the cavity temperature level [8]. The experiments performed on NOVA used DANTE, a broad band spectrometer, measuring through a hole made for the purpose in the wall of the hohlraum. From the beginning, we saw, at the late time of the laser pulse, a discrepancy between measurements and calculations. Since 1997 new measurements have been made through the laser entrance hole. They allowed to exhibit mainly a line of sight obscuration in the previous experiments and also some calculation artifacts in the analysis calculations. So, hereafter, we can claim that we understand the hohlraum temperatures all along their history.

Self-generated magnetic fields could play a significant role in hohlraum physics (probably more on size and location of focal spot than on radiation temperature. We have recently added a new package in FCI2 [9] to calculate non local electronic heat conduction [10] and electrons deflection by self generated magnetic fields. This package allows a rather good interpretation of a focal spot imaging experiment performed on Phebus few years ago (in 1996) [11].

Some issues remain about X-ray conversion as : NLTE atomic physics and time-resolved X-ray conversion connected with thermal transport. Radiation temperature history is measured by broad band X-ray spectrometers. We developed such a device during the last years with up to 18 channels. This spectrometer called DMX was installed on the OMEGA target chamber to be compared with the DANTE of LLNL. We have planed with DOE to provide the NIF with one device of this type.

4. Irradiation symmetry

As shown in the introduction, the LMJ baseline design includes an irradiation scheme with 3 beam cones on each side of the hohlraum illuminating its walls by 2x3 rings. We have been able to show, by numerical calculations, that it is possible to mock up the LMJ X-ray symmetry on OMEGA with 40 beams and a scaled hohlraum. Based on this design, we have studied at OMEGA the symmetry of the implosion by the techniques already used on NOVA [12] : imaging the X-ray emission at maximum compression of capsule implosion through a thin wall hohlraum, or following progression of the ablation front of foam-balls with radiography. Analysis of results is ongoing.

5. Hydrodynamic instabilities

Experiments were performed on the Nova laser in the framework of DOE/CEA collaboration in order to measure the Rayleigh-Taylor growth at the ablation front in cylindrical and, more recently, spherically convergent geometries [13]. Perturbations, initially located at the surface of doped plastic capsules, were diagnosed by an x-ray backlighting source. Late experiment have addressed modes 24 and 32 Legendre perturbations [14]. The data growth factor of the modulation optical depth reaches 150. From numerical simulations, it appears that the perturbation growth is very sensitive to the incident x-rays spectrum. High convergence implosions are drastically affected by the energy level around the gold M-band range. For moderate convergence ratios at the ablation front, close to 2, the dominant effect of convergence is simply the shrinking of the wavelength (“passive convergence”) [13]. For higher convergence ratios, spherically convergence geometry effects, as expected from “Bell-Plesset” analysis, are evidenced.

On the other hand we have designed for several years, ablator characterization experiments on NOVA. Recently theses experiments slightly changed to become ablator Rayleigh-Taylor experiments. So we experimented with LLNL, BeCu ablators with initial modulations of 50 or 70 μm wavelengths. The experimental results are correctly reproduced by 2D FCI2 simulations.

From a theoretical point of view, linear stability of flows resulting from constant heating of planar targets with laser have been studied. Similar kind of flows can be observed in combustion systems. A spectral model, directly taken from flame front theory, has been developed [15].

6. Target fabrication

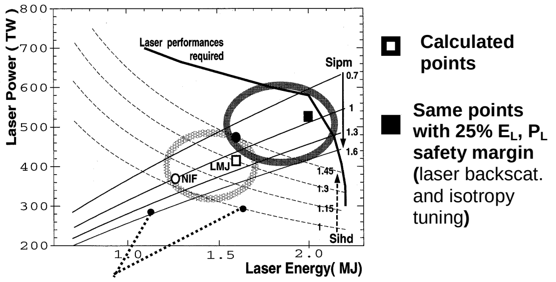
For the LMJ target synthesis and filling, some important results have been achieved recently .The CH_x ablator of the μ-shell is obtained by glow discharge polymerization on a sacrificial thin polymer mandrel[16]. This mandrel is eliminated after CH_x deposition by a thermal treatment and permeation through the coating. Very thick deposits (175μm) on spherical mandrels with very low high frequencies roughness (about 10nm) have been performed very recently. The cryogenic target assembly has been defined. It takes into account a lot of specifications (tightness in the permeation cell under 1300 bars of DT gas, thermal symmetry around the plastic µ-shell, vibrations of the target assembly, activation and redeposition of material after a LMJ shot, …). The CH_x µ-shell is filled with DT in a specific filling station [17]. To reduce the pressure inside the µ-shell, the permeation cell is cooled at 20K. The residual pressure is then the DT vapor pressure, about 200mbars at the triple point. The conception of this device has been completed this year. The most critical parts will be tested until 2003 (permeation cell, cryogenic DT pressure intensifier, 3D machine to manipulate the targets assemblies at 20K, …).

7. Target design for ignition

A dimensional analysis shows that a design (laser+hohlraum+shell) can be characterized by only four independent parameters, for instance: E_{laser}, $R_{capsule}$, M_{DT}, $R_{hohlraum}$ (the radius of the sphere of same surface as the cylindrical hohlraum). We impose two conditions on the design in order to ensure ignition : the first condition is on the kinetic energy of DT which must be 20% above the threshold (ignition without gain for the same mass of the DT). The second condition is that the ratio $R_{hohlraum}/R_{capsule}$ must be larger than 4 to smooth the irradiation non-uniformity on the shell. In the E_{laser}/P_{laser} plane, each point now represents an ignition design for which both conditions are satisfied (fig. 2). The technical possibilities of the laser can also be expressed as a curve in this plane.

There are two other major issues in the LMJ target design : parametric instabilities giving rise to laser light backscattering the by the plasma in the hohlraum and, in the other hand, hydrodynamic instabilities in the shell which may quench the ignition. To determine an operating region for the LMJ we used two safety factors S to insure against these instabilities : S_{ipm} for parametric instabilities and S_{ihd} for hydrodynamic instabilities.

Combining these safety constraints (S>1) with the implosion model determines the operating region of the laser (fig. 7). Moreover we take a 25% margin on the laser features used in the simulations in order to take into account the uncertainties and the losses (backscattering and uniformity tuning by beam phasing).



S_{ipm} is a safety factor for sensitivity to parametric instabilities
S_{ihd} is a safety factor for sensitivity to hydrodynamic instabilities

FIG. 2. Laser operating region and isocontours of safety factors S. The thick curve gives the technical possibilities of the laser. The operating region is in the ellipse. The hydro instability isocontours S_{ihd} and the parametric instability isocontours S_{ipm} are the thin curves. The 2 points correspond to optimized shells: NIF and Limeil 1215 at 3.5 MK.

The following table shows the characteristics and the performances of NIF and LMJ baseline capsules as calculated in the same conditions by the 1D code FCI1 with optimized drive. Integrated 2D calculations are also performed.

	LMJ	**NIF**
Radiation Temperature (max.)	**300 eV**	**300 eV**
External Radius	**1215µm**	**1110µm**
Ablator Thickness	**175µm**	**160µm**
DT thickness / DT masse	**100µm / 310µg**	**80µm / 209µg**
In Flight Aspect Ratio (max.)	**37**	**37**
Convergence Ratio (hot spot)	**46**	**45**
E fusion (MJ) / E laser (MJ)	**33 / 1.6**	**19 / 1.3**
Gain	**20**	**15**

We have studied the sensitivity of LMJ capsule yield to experimental uncertainties [18]. As a first step, a computing line, based on a radiation view-factor code, allows to estimate the hot spot deformation as a function of small variations of the 2D-parameters (laser powers and pointing of each 6 cones, target dimensions, …) around the nominal point. Then, a reliability code calculates the non-ignition probability versus standard deviations of these parameters for our baseline target design.

9 References

[1] JOLAS et al. : *Progress in Target Physics at CEA to achieve DT ignition on LMJ*, in LABAUNE, Hogan and Tanaka, IFSA99, Elsevier, Paris (2000), pp 68-73.

[2] VIDEAU, Rouyer, Garnier, and Migus : J. Opt. Soc. Am. A, **16**, 1672-1681 (1999).

[3] SAILLARD : *Hydrodynamique de l'implosion d'une cible FCI*,
Comptes Rendus de l'Académie des Sciences **1/IV**, 705, (2000).

[4] MOURENAS, Divol, Casanova and Rousseaux : submitted to Phys. of Plasmas

[5] RIAZUELO and Bonnaud : in LABAUNE, Hogan and Tanaka, IFSA99, Elsevier, Paris (2000), pp 337-342.

[6] CURTET, Bonnaud, Lefebvre, and Charpentier : in LABAUNE, Hogan and Tanaka, IFSA99, Elsevier, Paris (2000), pp 359-362.

[7] LEFEBVRE, Toupin, and Bonnaud, *Energetic particle and photon production with ultra-intense lasers*, in LABAUNE, Hogan and Tanaka, IFSA99, Elsevier, Paris (2000), pp 1020-1025.

[8] LINDL : *Inertial Confinement Fusion.*, Springer-Verlag, New York (1998).

[9] SCHURTZ : in *La Fusion Thermonucléaire par Laser* edited by Dautray and Watteau, Eyrolles, Paris (1994).

[10] SCHURTZ, Nicolaï and Busquet : Phys. of Plasmas **7,** 4238 (2000).

[11] NICOLAÏ, Vandenboomgaerde, Canaud and Chaigneau :
Phys. of Plasmas **7,** 4250 (2000).

[12] HAUER et al. : Rev. Sci. Instrum. **66**, 672 (1995).

[13] CHERFILS et al. : Phys. Rev. Lett. **83**, 5507 (1999).
GLENDINNING et al. : Phys. of Plasmas **7**, 2033 (2000).

[14] GALMICHE et al. : *Numerical analysis of spherically convergent Rayleigh-Taylor experiments*, ECLIM2000, Praha.

[15] MASSE, Hallo and Tallot : *Direct drive ablation front stability ….*
in LABAUNE, Hogan and Tanaka, IFSA99, Elsevier, Paris (2000), pp 220-223.

[16] THEOBALD, Baclet, Legaie, Durand : *Properties of a CH coatings prepared by PECVD for laser fusion targets*, ANS Fusion Technology, **38**, n°1, July 2000, p 62.

[17] BACLET, Fleury, Perrin, Chatain : *The Filling Facility for the Megajoule Laser Cryogenic Targets*, Target Fab. Meeting 99, 08-11 Nov. 1999, Catalina, California.

[18] POGGI and Giorla : *2D simul. of the rad. asym. on a LMJ targ. with a view-factor code*, in LABAUNE, Hogan and Tanaka, IFSA99, Elsevier, Paris (2000), pp82-87.
GIORLA, Poggi , Paillard and Leromain *: Azimuthal radiation symmetry around the LMJ capsule*, ECLIM2000, Praha.