Recent Advances in Ignition Target Physics at CEA

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Abstract. The objective of the Ignition Physics Program at CEA is to burn DT capsules on the Laser MegaJoule (LMJ) at the beginning of the next decade. Recent progress on Laser Plasma Interaction, hohlraum energetics, symmetry, ablator physics and hydrodynamic instabilities allow to remove most of these latter, to precise laser and target specifications and to elaborate a strategy toward ignition. These studies include theoretical work, numerical simulations, diagnostics developments and experiments partly done in collaboration with the US DOE. Construction of facilities is ongoing : LMJ beam prototype is planed to fire 7 kJ at the center of the target chamber at 0.35 mm at the end of 2002 and the LMJ (a 240 beams 1.8 MJ laser) is planned to be ready for experiments at the end of 2009.

1. Introduction

Ignition and gain achievement through the Inertial Fusion Confinement approach is a challenge for science and technology. The specifications to be reached in the plasma has been well known for some time [1] : $\rho R > 0.3$ g/cm^2 and $T > 6$ keV in the « hot spot » and $\rho R >$ 2g/cm^2 in the « cold » compressed fuel. This implies a huge compression from the initial slim capsule of solid DT. This latter could be compressed from different power sources : heavy ions, pulsed power and lasers. CEA, having experienced power lasers from the sixties, have a thorough knowledge of this technology and focused on it his efforts to reach ignition.

The laser energy can hit the capsule either directly or indirectly after thermalization in a « hohlraum ». This second solution have several advantages (radiation field uniformity around the capsule, x-rays ablation efficiency, …) even though several theoretical and technological issues remain.

The following picture shows the main physical processes leading to ignition through the laser indirect drive scenario.

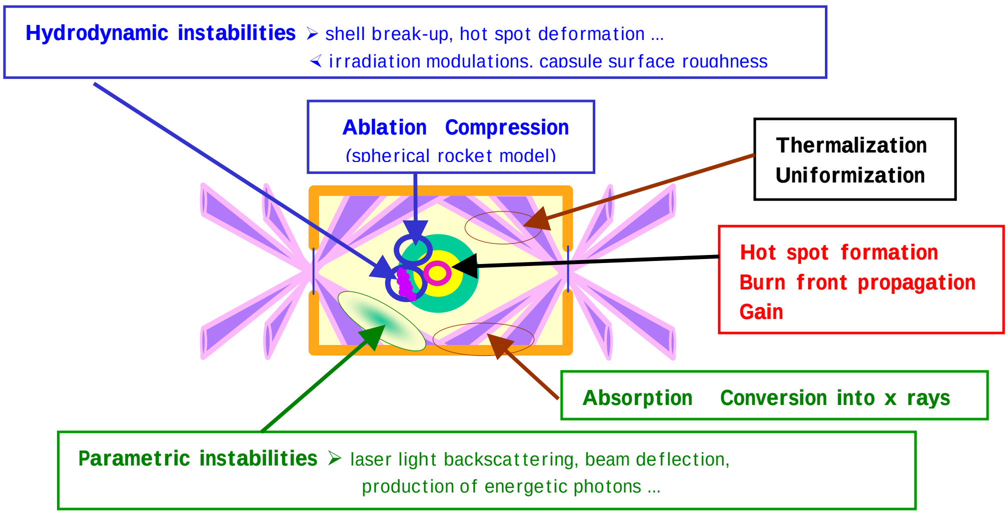

FIG. 1. The physical processes leading to Ignition Through the Laser Indirect Drive scenario

We will show that hohlraum energetics, symmetry and ablative implosion are reasonably well mastered. Nevertheless some issues are remaining in the process of laser plasma interaction leading to hohlraum energy feeding and, in the other hand, in the implosion stability control. Let us emphasize the close US DOE/CEA collaboration in these fields.

While theoretical and experimental work is ongoing in the target physics area, facility construction follows his own planning. The first step is commissioning the « Ligne d'Integration Laser » (LIL) a prototype of the laser beams of the large laser facility designed to reach ignition (LMJ).

Meeting the target specifications is also very challenging : an important research and development program is ongoing in several directions : cryogenic target assemblies, microballoon synthesis, DT filling and ice layer conformation, operational devices for LMJ filling and transport.

2. Laser Plasma Interaction

The use of filling gas, and then polyimide membranes to block the laser entrance holes (LEHs), enhances the development of filamentation and parametric instabilities (Raman and Brillouin) which leads to (*i*) energy losses by backscattering, (*ii*) laser beam deflection and (*iii*) energy exchange between crossing beams (at LEHs), and which affects both the radiation temperature level and the x-ray irradiation symmetry.

Understanding LPI dynamics is intricate due to largely different temporal and spatial scales, from macroscopic (corresponding to hydrodynamics dimension and duration) to microscopic (of the order of magnitude of laser wavelength and pulsation) ones. Integrated experiments are then required to quantify LPI hazards.

In 2003, a milestone campaign is scheduled on the LIL to test the efficiency of the baseline LMJ optical smoothing solution, in term of keeping (*i*) LPI reflectivities and (*ii*) focal spot enlargement and deflection - when passing through LEH - below tolerable thresholds. Dedicated targets, compatible with the one-sided irradiation provided by one LIL quadruplet, and pulse shape are considered (figure 2). PIRANAH computations (FCI2 post-processor, developed by M. Casanova, which localizes the instabilities and qualitatively assesses the risk they induce) show that gas-filled "cans", when shot along their axis, seem suitable to produce a 10% critical, 3 keV plasma to study SRS along the LMJ inner cone, while "halfraums" will be used for SBS along the outer one.

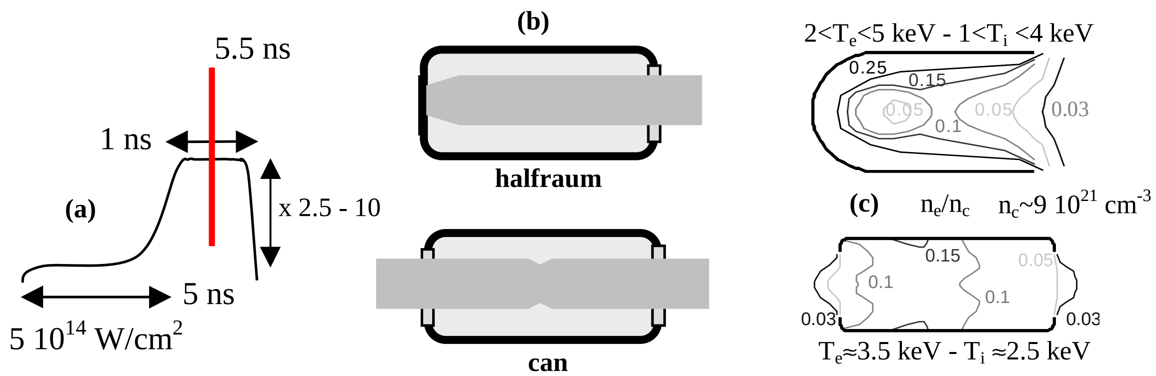

FIG. 2: Design of the first LPI experiments on LIL: (a) laser pulse shape, (b) targets and (c) preliminary FCI2 density isocontours and temperatures average values.

But significant progress have been recently made by intermediate-scale LPI computations, following the development of fast multi-dimensional codes benefiting from increasing computing resources: 1 Teraflop in 2002 from a SMP cluster, the TERA computer. The PARAX code [2] couple paraxial laser wave propagation to 3D linear hydrodynamic response when HERA [3] handle the plasma flow with an AMR method (now 2D, 3D being ongoing). For example, figure 3 shows the use of PARAX to quantify the laser beam deviation in LMJ plasmas and to check various smoothing techniques. Reduced gain models and saturation mechanisms will be soon included, once validated through kinetic PIC simulations (using E. Lefebvre’s CALDER code).

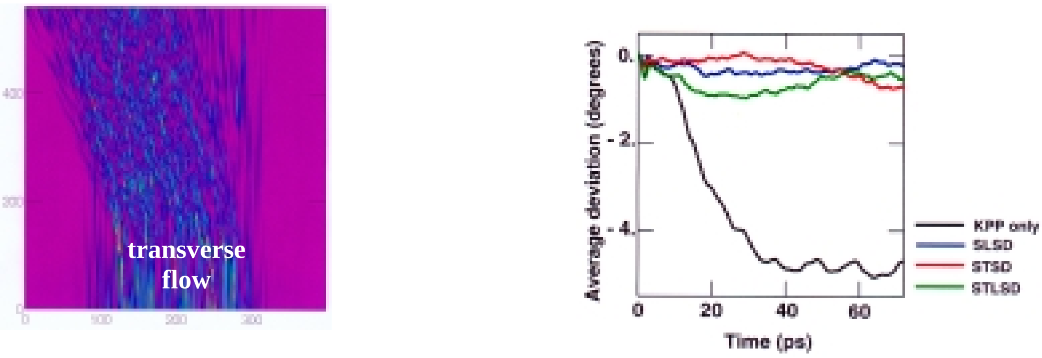

FIG.3: When a 84 GHz bandwidth is applied, all the Smoothing by Spectral Dispersion techniques strongly reduce beam bending (<I>= 2 10^{15} W/cm^2)

3. Hohlraum physics (energetics and symmetry)

All the history of hohlraum radiation is now clearly understood for 1 to 5 ns long square or shaped laser pulses [4], with the help of series of experiments (performed since the 80’s on various laser facilities) and accurate diagnostics. Among them, the absolutely calibrated, time resolved (Δt=100 ps), broad-band (50 eV – 20 keV) DMX spectrometer [5] provides equivalent black-body temperatures with a ±4% accuracy. In addition, LIL first quad experiments will check FCI2 ability to predict hohlraum radiation fluxes when driven by a longer (20 ns) nominal LMJ pulse.

New models, to take into account self-generated magnetic fields and non local features of electron heat transport in laser-created plasmas, have also been recently developed (and implemented in FCI2) [6] and [7] and contribute to this overall comprehension. They have been partly validated during experiments performed at LLE/UR. Owing to its 60 beams, the OMEGA direct drive actually provides a well-suited 1D spherical irradiation configuration for studying atomic physics and transport (free from magnetic fields and lateral conduction).

Correct restitution of previous NOVA experiments, measuring (through x-ray radiography) capsule distortions during indirectly-driven argon-doped D_2 implosions [8], gives confidence on the simulation of hohlraum hydrodynamics and x-ray irradiation history. But energy balance procedure (required in the LMJ baseline design to control implosion symmetry: figure 4) has still to be validated for a “3 illumination rings” configuration. A new series of experiments have then been designed and planned on the LLE/UR OMEGA laser facility.

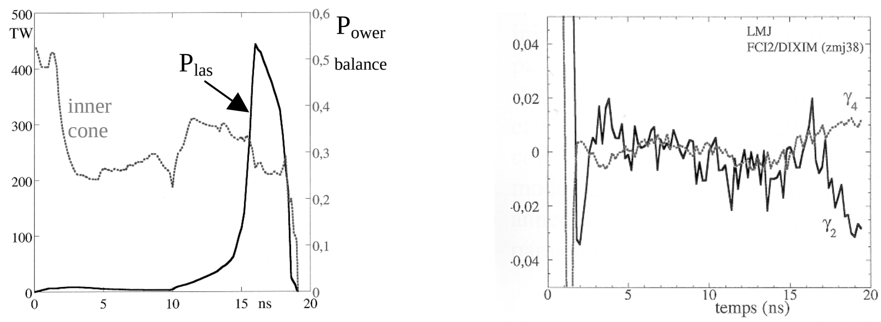

FIG. 4 : LMJ power balance (only the inner cone pulse is affected) and (right) induced FCI2 2nd and 4th Legendre components at the ablation front for the nominal LMJ target.

4. Hydrodynamic instabilities

In this field, the experimental approach has been conducted in the framework of the DOE/CEA collaboration. A large amount of work has been done on Nova and was reported previously. The sensibility of the RT growth to x-ray preheating and convergence effects (described with the help of a Bell-Plesset formalism) has been demonstrated [9] and[10]. To go further, a new "rugby-ball" hohlraum, avoiding any chance of glint and imprinting, has been designed by M. Vandenboomgaerde and is experimented on the OMEGA laser facility (figure 5). A new diagnostic, HRXI, derived from the BIMITOX Wolter microscope previously used on the Phébus laser facility [11], has also been installed to observe the sample motion with very high accuracy.

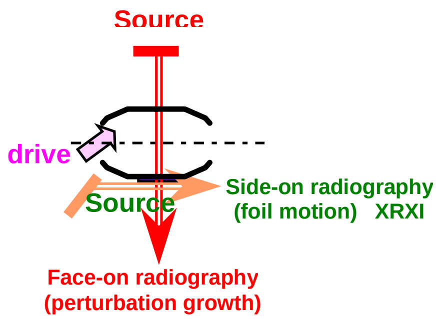

FIG. 5 : Planar instability experiment implemented on the Omega Laser (LLE, Rochester) in the framework of the DOE/CEA collaboration.

Due to the problem complexity, direct numerical simulations are still the best tool to study in a comprehensive way the hydrodynamic stability of an ignition capsule. However, modeling by part the different sources of instability during the implosion helps getting more confidence in our calculations and, especially in the case of 2D simulations, is necessary to get some 3D insight versus 2D evolution. Different theoretical approaches have been studied at CEA-DIF, mostly focused on ablation front stability.

Rigorous derivations by asymptotic analysis have been done on simplified flows, in order to study analytically the effect of density gradient [12] and convection velocity [13]. Analysis of more representative flows leads to mixed analytical and numerical models; two of them have been developed in the frame of a PhD thesis. In the first place, linear perturbations of a planar self-similar solution of hydrodynamics with non linear heat conduction have been obtained by spectral methods. Contrary to most modelings of the ablation front, the flow here studied is non stationary and compressible. The second model has been developed by analogy with propagation of flame fronts [14]. A spectral model studying the linear perturbation and developed by the combustion community has been adapted to direct drive ablation fronts in the isobaric hypothesis. Growth rates can be determined by this model in the whole range of wave numbers and compare well with the dispersion curve calculated by Betti and Goncharov for ICF applications.

A complementary approach for carrying out more detailed studies of the linear regime consists in solving numerically the linearly perturbed equations of hydrodynamics with heat conduction. Toward this aim, a numerical code named SILEX has been developed for treating unsteady compressible flows in planar or spherical geometries. In return for very precise numerical schemes [15], the linear growth of a complete spectrum of initial defects can be calculated in an accurate way and more easily than by complete 2D simulations.

As can been seen, most of this work have been focused on linear stability. A weakly non linear eulerian theory developed for the Richtmyer-Meshkov instability [16] has been recently applied to the classical Rayleigh-Taylor instability. Analysis of the weakly non linear stability of an ablation front is under achievement.

5. Target design for ignition

In the Laser MégaJoule indirect drive ignition design, the time-averaged radiation asymmetry on a Deuterium-Tritium (DT) capsule must be minimized to achieve high-yield implosions. A two-dimensional model estimates the of power imbalance, laser beam pointing and target fabrication errors time-averaged effect on the final DT deformation, which is then compared to an ignition threshold. As these errors will take random values from one LMJ shot to another, the robustness study aims at quantifying the probability of failing to reach ignition [17].

The work was recently focused on laser power imbalance. Two types of error sources in laser performances were distinguished, according to whether they take long-time (more than the laser pulse duration) or short-time (less than the laser pulse duration) correlated values. Indeed, as the final DT deformation results from the whole laser pulse history, the failure probability depends on the error time-correlation. A 1D time model of the laser beam power, from the front-end to the target, was developed to quantify the variations of the output power imbalance due to the source contributions.

6. Facility construction

The first step of LMJ project is the LIL (the "Ligne d'Integration Laser", a 60 kJ 8 beams prototype of the LMJ beams). All laser structures and optical components (for 2 beams) were installed end of February in the building (a picture of LIL building is seen on figure 6). Laser beam is based on a four passes structure through 18 laser slabs, four passes obtained by the so-called "U-Turn" concept. Beam focusing is achieved by 3 ω gratings" which avoid any remaining 1 ω and 2 ω light inside the target chamber.

7 kJ at the center of the target chamber (at 3 ω) are planned at the end of 2002.

The LMJ building (300 meters long, 150 meters wide … see figure 7),will start mid 2003 and the laser itself will be completed end 2009 (240 beams, 1.8 MJ, 600 TW).

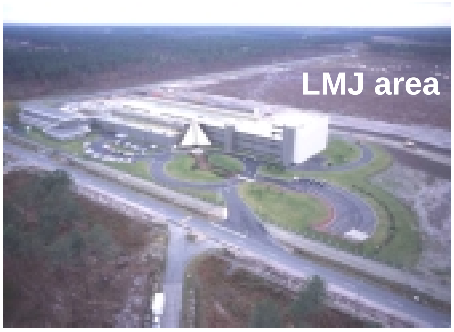

FIG. 6 : The LIL building seen in 2000

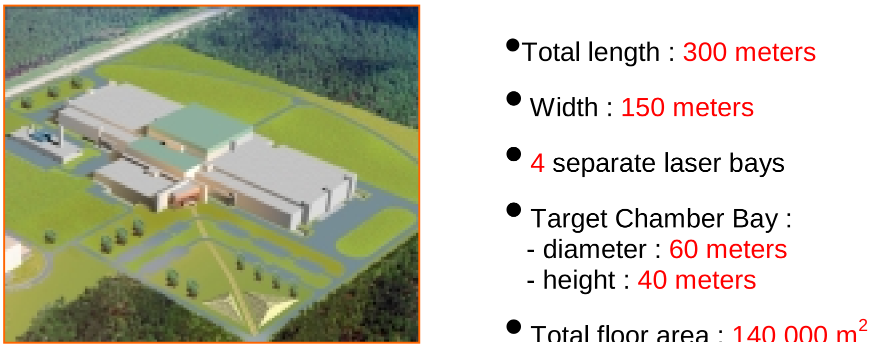

FIG 7 : An artist view of the LMJ building

7. Target fabrication

The project has been divided in several tasks :

- The Cryogenic Target Assemblies (CTAs) development,
- The CHx µ-shell synthesis [20], [21],
- The study of the DT filling, and the ice layer conformation [18],
- The technological developments for the operational devices for LMJ CTAs filling and transport [18].

The CTA (figures 1 and 2) has to meet a lot of severe specifications towards implosion physics or its own thermal environment, and to respect a lot of interfaces with the permeation cell of the filling station, the several cryogenic grippers, the LMJ interaction chamber,… :

- tightness in the permeation cell under 1300 bars of DT gas,
- thermal symmetry around the plastic µ-shell
- vibrations of the target assembly connected to the cryogenic target holder,
- activation and redeposition of material after a LMJ shot,…

Therefore, the CTA definition is very complex, and induces a lot of challenging tasks for its fabrication. During the last year, many improvements have been achieved allowing the realization of the first CTA prototype at scale one.

FIG. 8 : A picture of the CTA

The LMJ cryogenic system fills (figure 9), transports and inserts on the Cryogenic Target Positioner (CTP) [19] individual Cryogenic Target Assemblies (CTAs), which are manipulated at about 20K by several cryogenic grippers. 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 are under test: permeation cell, cryogenic DT pressure intensifier, 3D machine to manipulate the target assemblies at 20K …

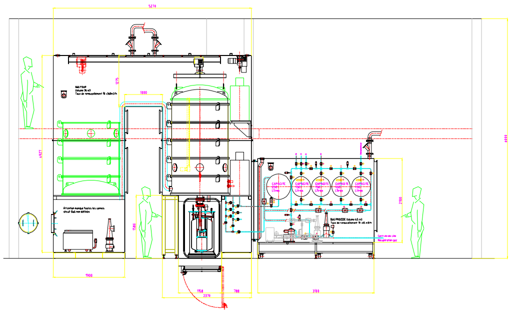

FIG. 9 : LMJ filling station

The CHx ablator of the µ-shell (figure 10) is obtained by glow discharge polymerization on a sacrificial thin polymer mandrel. This mandrel is eliminated after CHx 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. However, the middle range roughness (modes from 20 to 100) has to be lowered to reach LMJ specifications.

Besides, doped coatings for opacity optimization (Br, Ge), for diagnostics (Ti) or for infrared redistribution compatibility (CDx) have now to be studied.

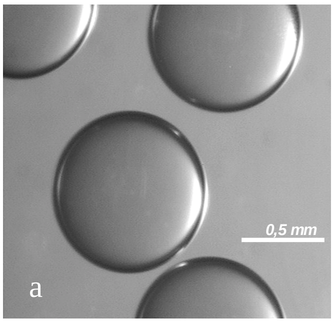

FIG.10. : LMJ CH_x μ-shells

Infrared heating has been chosen as the nominal way of conformation. As the DT layers have to be redistributed at 18.2K, β-layering is not effective, and studies about this technique have been stopped.

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