White Papers on Research Opportunities In Inertial Fusion Energy

Expression of interest

TITLE: Inertial Fusion Science & Technology at the Laboratoire pour l'Utilisation des Lasers Intenses

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TOPICS:

- Target Physics
- Diagnostics
- Drivers
- Chamber materials

Executive Summary

The recent breakthrough experiment carried on the National Ignition Facility (NIF) has not only demonstrated a record 1.3MJ fusion yield, corresponding to 70% of the invested laser energy, but also proven that the mechanisms underlying laser-driven plasma burning and ignition physics are now well known and are efficiently mastered, thus supporting initiatives towards Inertial Fusion Energy (IFE) programs. Within their frameworks, technology R&D (e.g. on high repetition rate laser operation) and physics studies (exploring, notably, high gain fusion schemes) need to be pursued to safely transition from scientific proof-of-principle to IFE power plant demonstration.

The *Laboratoire pour l'Utilisation des Lasers Intenses* (LULI) fully supports the US efforts and express its wish to participate to the planned workshop. The lab contribution to IFE programs would be two-fold: 1/ inputs to scientific questions still preventing from reaching high gain performances and 2/ an access offer to its LULI2000 laser facility for IFE-related physics experiments at reduced scale. In addition, this contribution could be complemented by very specific technological R&D studies and by an access offer on the secondary sources deployed on the APOLLON laser facility for testbed experiments on chamber materials.

Introduction

Research activities on high-energy laser plasmas and applications, including Inertial Confinement Fusion, have started in the 60's at Ecole Polytechnique, supported by continuous technological improvements of the operated instruments, open to the user community since 1975 through open calls for access and excellence-based selection procedures. The LULI lab was created in 1988 to strengthen this last mission in establishing its facilities as national research infrastructures. LULI is now not only an academic research center of about 40 scientists (including PhDs and post-docs) seeking to deepen knowledge of High Energy Density Physics; it is also operating two key state-of-the-art laser facilities: APOLLON and LULI2000, the most relevant one for IFE studies.

The internationally-recognized expertise of the LULI researchers and of the performances of the LULI facilities are recognized through the active participation of the lab in the ESFRI-labeled 2008-2013 HiPER project, in a series of European transnational access programs since 1994 (currently within the Laserlab-Europe consortium) and of EUROfusion enabling research projects[1] since 2014. The lab is also involved in a 2020-2024 IAEA Coordinated Research Project on "Pathways to Energy from Inertial Fusion: Materials Research and Technology Development". It is finally in charge of a new International Research Network on magnetized plasma plasmas gathering the Osaka University in Japan, LLE and LLNL, in the United States, the European XFEL and HZDR in Germany, CELIA and LNCMI in France.

Activities in the context of the IFE white paper initiative

User access to the LULI laser facilities

<u>*LULI2000 capabilities*</u>

The position of the LULI2000 facility in the field of high-energy density physics is unique in academic Europe due to the coupling on target of short (ps) and long (ns) high-energy laser beams and the availability of an auxiliary beam for pump-probe experiments. The LULI2000 laser hall at Ecole Polytechnique contains 2 high-power Nd:glass laser chains (North and South), each of them delivering up to 1kJ at ω (1.053µm) in the ns regime at a repetition rate limited to 1 shot every 90 minutes. Implementation of the CPA technique on the South laser chain authorizes its operation in

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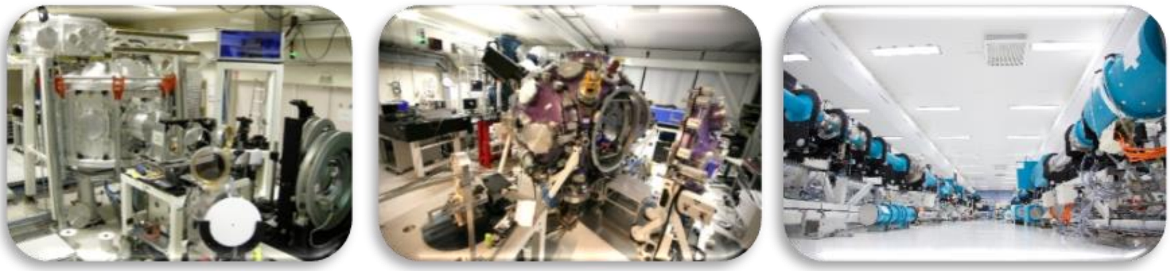
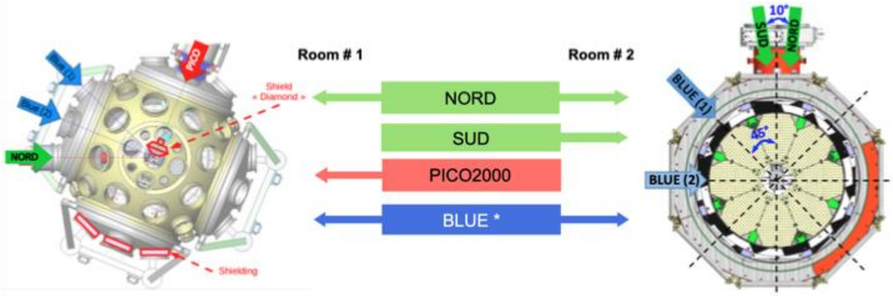
[1] "Towards Demonstration of Inertial Fusion for Energy" (2014-2018) coordinated by S. Jacquemot (LULI), "Routes to High Gain for Inertial Fusion Energy" (2019-2020) coordinated by P. Norreys (STFC-CLF) and "Advancing shock ignition for direct-drive inertial fusion" (2019-2022) coordinated by D. Batani (CELIA)

the ps regime (pico2000) and production of high-energy particle (protons, electrons) and radiation sources. To avoid any grating damage, the delivered energy is limited to ~100J in 1ps. An additional moderately energetic beam (blue: ~50J in the ns regime) is available to increase the laser-based diagnostic capabilities of the LULI2000 multi-beam facility. Valuable pump-probe experiments are thus possible. All the chains are synchronized (with ps jitters); they can be frequency-doubled and equipped with wavefront correction systems (adaptive optics) and optical smoothing techniques (i.e. phase plates, whose usefulness for generating flat shock fronts has been demonstrated in the lab in the early 90's [1]). Their laser oscillators are fully independent which allows the users having, on target, pulses with differentiated temporal shapes. In the ns regime, the pulses may be shaped upon request, over a total duration of ~1 to ~15ns.



The LULI2000 experimental areas and laser hall.

The facility includes two dedicated experimental areas (rooms #1 and #2) fully equipped with a large palette of state-of-art instrumentation. An electromagnetic pulser, allowing production of external magnetic fields of ~30T and investigation of magnetized plasmas, can be implemented close to the target chambers [2].



Layout of the LULI experimental areas.

Over the years, a suite of target diagnostics has also been developed and implemented on user experiments. In the optical range, LULI pioneered the development of the frequency-domain interferometry (FDI) technique to probe the expansion of the critical surface of a laser-produced plasma [3] and has a long expertise in using time-resolved optical pyrometry (SOP) and velocity interferometry to characterize dynamically-compressed matter, including either ablator-relevant materials (such as CH and diamond) or low-density materials (foams). The VISAR technique has moreover been pushed to some limits thanks to the development of a new fiber laser source allowing the production of up to 100ns ~10mJ ω and 2mJ 2ω pulses simultaneously. A suite of plasma diagnostics, such as multi-angle Optical Thomson Scattering at 2ω or 3ω, is also routinely running on LULI2000 to provide reliable plasma characteristics in benchmarking experiments. In the x-ray range, the ability to produce energetic secondary radiation sources thanks to pico2000, together with the lab expertise in spectroscopy, offers the capability to perform x-ray radiography and x-ray Thomson Scattering for, notably, near-LTE opacity measurements. Finally, secondary proton sources authorize EM-field probing techniques, such as proton deflectometry or radiography pioneered by the lab in the 2000's [4], to be operated.

APOLLON capabilities

The APOLLON laser facility, on the French Research Infrastructures roadmap, is based upon an OPCPA front-end and 4 Ti:Sapphire amplification stages; it is currently delivering one PW pulse

(20J / 20fs) per minute. Two fully radioprotected experimental rooms are open to users; the first one (equipped with a short focal length focusing optics) is dedicated to high-intensity and high-field experiments, while the second one (LFA), provided with a long focal length focusing optics, is dedicated to laser wake field acceleration. Qualification experiments have been completed in both experimental area [5] and the first external users will be welcomed from March 2022.

APOLLON is designed to reach a multi-PW laser peak power, following a phased approach: in conjunction with the operational 1PW beam, commissioning of a 4PW beam in 2023, upgraded later on to 8PW; subsequently, possibility of coupling the multi-PW beam to an 100J-level ns beam. APOLLON will thus ultimately become one of the most powerful multi-beam laser facilities on the international scene.

The APOLLON experimental areas and front-end.

<u>*Access offers*</u>

LULI2000 and APOLLON are open to the national and international community through a yearly call for proposals. An international and external program committee awards experimental time solely based on scientific merit criteria. The LULI lab is member of Laserlab-Europe, which allows users of both facilities to be financially supported (in terms of travel & subsistence). Proprietary access is also possible on the LULI2000 facility.

IFE-relevant current R&D activities

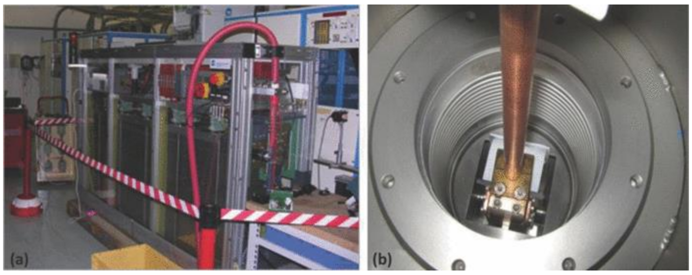
<u>*Laser-Plasma Interaction (LPI)*</u>

LULI has a long expertise in LPI studies. For ICF, the evolution and saturation of the Stimulated Raman Scattering (SRS) is a longstanding problem involving wave-wave and wave-particle non-linearities. Its understanding is of outmost importance because of potential energy losses in the laser-to-target transfer as well as because it can induce electron acceleration and cold DT preheating. One possible SRS saturation mechanism is the decay of the primary electron plasma waves, or Langmuir waves (LW), excited by the laser into a second LW set and an ion acoustic wave via the so-called Langmuir decay instability (LDI). The coalescence of the primary and secondary LW results in an electromagnetic emission at twice the plasma frequency ($2\omega_p$) and is thought to be at the origin of the EM emission observed at that frequency during solar bursts. Recently, the first experimental evidence of LDI through EM emission at $2\omega_p$ was obtained on LULI2000 [6], demonstrating that such a non-intrusive (as opposed to Thomson Scattering) $2\omega_p$ diagnostic could provide valuable inputs on fundamental non-linear processes occurring in plasmas during laser propagation toward the absorption zone in ICF schemes. Complementary studies could correlate the SRS saturation due to LDI to electron heating.

In directly-driven experiments, a significant fraction of suprathermal electrons may be produced by parametric instabilities (such as SRS and two-plasmon decay) and, by preheating the fuel, be detrimental. It is thus of importance to be able to quantify them accurately and in situ. An approach to measure their evolution inside dense laser-heated plasmas, coupling non-Maxwellian atomic kinetics and highly-resolved x-ray spectroscopy, was proposed in the late 90’s and recently demonstrated at PALS (Czech Republic) [7]; its applicability to MJ-scale implosions could be usefully considered.

Hydrodynamics

Hydrodynamics is playing a major role in ICF. The Rayleigh-Taylor instabilities, which develop both at the ablation front[2] and in the final deceleration phase[3], are for instance reducing the chance to achieve ignition by inducing mixing. Studying hydro-instabilities on hands-on medium-size laser facilities allows obtaining quantitative data in order to predict their growth, saturation, or transition to turbulence, in full-scale fusion experiments on the NIF or on LMJ-PETAL. A robust x-ray radiographic platform [8] was therefore developed at LULI to investigate hydrodynamic/MHD, magnetized or not, flows and instabilities. The platform has been deployed to explore, on LULI2000, the Atwood-number dependence of the highly nonlinear Rayleigh-Taylor instability [9] and, following implementation of the electromagnetic pulser, the influence of an external magnetic field on its growth [10]. To go deeper, the platform could be used to investigate magneto-thermal instabilities arising in ICF plasmas due to self-generated magnetic fields[4], of importance in gas-filled hohlraums. No experimental investigation has yet been undertaken and the lab has the capability to initiate such a detailed study.



The LULI pulsed power system [2].

Fundamental plasma properties: equations of state (EoS)

Knowing the EoS of materials likely to be a constituent of ICF capsule is of the primary importance for ICF. Indeed, the matter behavior along the thermodynamical path followed during compression directly impacts ignition achievement. The LULI team has a longstanding expertise on laser shock EoS measurements [13]. In the last ten years, the team has developed in situ alternative techniques to get off-Hugoniot EoS data such as quasi-isentropic laser compression, double laser shocks and laser shock in pre-compressed matter using a diamond anvil cell [14]. In terms of diagnostics, time-resolved two-wavelength VISAR coupled to optical pyrometry is today a robust tool to get reliable EoS data, providing direct temperature (of prior relevance to discriminate between theoretical models) as well as conductivity [15] values. Additional diagnostics open interesting perspectives in EoS studies: x-ray radiography, using a Lithium Fluoride (LiF) crystal detector, has recently proved its huge capability to resolve systems with less than 1µm resolution over a large field of view [16] while x-ray diffraction or XANES [17] allows obtaining a microscopic characterization of highly compressed matter. They provide both additional data to test physical hypothesis and approximations commonly used in calculations. Among the materials that could be studied using these techniques are diamond, doped and undoped, and plastic foams, wetted or not.

Magnetically-assisted implosion

As shown, a strong expertise in magnetized laser-produced plasmas has been developed, of great interest for IFE target research. Indeed, there are several critical places where magnetic fields could help increase the overall implosion and burn performances. The magnetization of the target can for instance serve to increase the ion temperature within the fuel. An open question is then: what is the stopping power of the ions in such a magnetized plasma? First experiments have already been carried out [11] and should be continued at higher magnetic field values. The growth of parametric

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[2] A. Casner et al., Phys. Plasmas 22, 056302 (2015)

[3] D.S. Clark and M. Tabak, Phys. Rev. E 72, 056308 (2005)

[4] J.J. Bisell *et al.*, Phys. Rev. Lett. 105, 175001 (2010)

instabilities, which affect laser pulses when travelling through cavities, could be contained also thanks to target magnetization. Preliminary experiments analyzing laser pulse propagation in magnetized plasmas have been performed on LULI2000 [12]; results evidenced enhanced laser pulse transmission through plasma, when magnetized, and should be extended.

Materials under irradiation

The impact of a MJ neutron yield on the first wall of the fusion chamber is a major hurdle in the development of high-repetition-rate laser fusion reactors. A number of specific reactions result from neutron interactions, such as hydrogen and helium production, atomic displacements and transmutations. Detrimental consequences include changes in thermophysical and thermomechanical properties, swelling, embrittlement, creep and sintering. Today conventional neutron sources (accelerators-based ones, spallation sources and fission reactors) are not relevant or cost-effective to study the damages caused by a burst (~100ps) of 14.4MeV DT neutron incident on a first wall chamber. In the last ten years, a significant effort has been devoted around the world to study the generation of a neutron source following laser-plasma interaction at ultra-high intensity (UHI)[5]. Nevertheless, the most efficient pitcher-catcher scheme does not produce an IFE-relevant neutron spectrum. On APOLLON, the lab intends to develop a DD neutron source based on the interaction of an UHI laser with advanced designed targets, such as low-density foam, nanostructured or 3D printed cone targets. This new source should be used to expose advanced wall materials wall to study the impact of a pulsed neutron source on their structure.

Optics & Laser technologies

There are basically three parallel laser physics routes to be explored to engineer the high-average-power laser drivers requested for Inertial Fusion Energy (IFE): 1/ significant reduction of the laser gain medium heat intake and optimization of the heat extraction to operate at high repetition rates (beyond a few Hz), 2/ Multi-Pulse Extraction (MPE) to overcome extraction fluence limits and 3/ Coherent Beam Combining (CBC).

CBC introduces a paradigm shift in laser architecture offering major opportunities for IFE laser drivers. It consists in the spatial splitting of an initial laser beam into N small-aperture sub-beams prior to amplification, followed by subsequent recombination of the amplified beams. The very large majority of ongoing laser physics research, notably at LULI, relies on fiber-based amplifiers and, therefore, operates in regimes (0.1 to ~10MHz) well above IFE needs. Average powers in the kW range are already available [18-19]. Several tools and concepts were derived over the past decade aiming at combining tens of µJ-level channels into a single mJ beam. Moving toward CBC of Joule-level channels into a single-aperture kJ beam for IFE will require extra-developments at a clearly more costly experimental level. Considering the technological and physics issues associated with LMJ/NIF ~40cm apertures, moving towards the coherent sum of a large number of sub-pupils at an energy level of 10 to 100J and with a cm-scale aperture is definitely a direction worth to explore. Moreover, CBC could also be combined with a time-domain pulse combining technique such Coherent Pulse Stacking Amplification (CPSA) or Divided Pulse amplification (DPA) techniques.

XCAN laser head (center), collimating microlens array (left) and 61 Yb-doped fiber bundle (right) [19].

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