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LMJ & PETAL Status and first experiments

J-L Miquel

CEA/DAM Île de France, Bruyères le Châtel, 91297 Arpajon Cedex, France

jean-luc.miquel@cea.fr

Abstract. The laser Megajoule (LMJ) facility is designed to provide the experimental capabilities to study High Energy Density Physics (HEDP). The LMJ is part of the Simulation Program, which combines improvement of physics models, high performance numerical simulation, and experimental validation. Since the operational commissioning of the LMJ, in October 2014, several experimental campaigns have been achieved. They have demonstrated the good performances of LMJ and demonstrated its aptitudes to perform experiments for the Simulation Program. The PETAL project consists in the addition of one short-pulse (ps) ultra-high-power, high-energy beam (kJ) to the LMJ facility. The first high energy test shots in the compressor stage of PETAL, performed in May 2015, have reached a power of 1.2 PW. PETAL will offer a combination of a very high intensity multi-petawatt beam, synchronized with the nanosecond beams of the LMJ. This combination will expand the LMJ experimental field in HEDP. LMJ-PETAL is open to the academic communities; the first experiments are planned in 2017.

1. Introduction

The laser Megajoule (LMJ) facility, developed by The Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), is designed to provide the experimental capabilities to study High Energy Density Physics (HEDP). LMJ is part of the Simulation Program which is a keystone of guarantee of French nuclear deterrence. It combines improvement of physics models, high performance numerical simulation, and experimental validation. The heart of this Program is the Simulation Standard which couples Reference data, Physical models and Numerical methods. It will be regularly upgraded according to experimental results obtained on LMJ.

LMJ offers unique capabilities for the Simulation Program. When completed, the 176 beams of the facility will deliver a total energy of 1.4 MJ of 0.35 μm (3ω) light and a maximum power of 400 TW. A large panel of experiments will be done to study physical processes at temperatures from 100 eV to 100 keV and pressures from 1 Mbar to 100 Gbar. These experiments will validate the advanced theoretical models of the Simulation Program, and provide accurate data (equation of state, atomic and nuclear data). Among these experiments, Ignition is the most exciting challenge since ICF experiments define the most stringent specifications.

The operational commissioning of the LMJ, with the first bundle (eight beams), was declared in October 2014. Since this date, several experimental campaigns have been achieved, in order to qualify the LMJ experimental capabilities, and to validate radiative hydrodynamics simulations. They have demonstrated the LMJ aptitudes to perform experiments for the Simulation Program.

2. Program overview

The CEA is developing a thematic approach for the experimental program on LMJ; this program is coupled to a progressive power and energy increase of the facility. LMJ will enhance its capacities in

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the next years with the completion of other bundles and a full set of diagnostics. The program is based on a gradual pathway with dedicated experiments. Eight experimental topics have been identified for the Simulation program and summarized in table 1.

Table 1. Experimental topics of the Simulation program.

Topic	Mechanisms to be addressed	Physics to be controlled
Hohlraum energetics	Laser plasma interaction, X-ray conversion	Radiation flux
Fundamental data's	Equation of state, Opacities	Matter's behavior under high pressure and temperature
Radiation transport	X-ray absorption, losses, reemission	Energy transport
Implosion hydrodynamics	Implosion velocity, Shock tuning	Compression
Hydrodynamic instabilities	Instabilities growth, turbulence	Mixing
Fusion studies	Thermodynamic conditions, initiation of fusion reactions	Ignition conditions
Ignition	Study of different kind of ignition targets	DT burning
Applications	Coupling of ignition target with another target	Complex powerful system

The carrying out of these experimental themes depends on the experimental capabilities of the facility and particularly the laser configuration (number of beams) and the availability of diagnostics. Therefore a diagnostics development plan has been developed, it is summarized in the table 2.

This program allows to draw a robust roadmap for ignition: during the next years LMJ will increase its operational capabilities with the completion of new beams, providing more energy, and the implementation of new diagnostics. This period of time will be useful for the handling of the facility, including training of the operational crew and control of performances (precisions, reproducibility). This phase will also be exploited to tackle some of the experimental topics of the Simulation program:

- Radiation transport taking into account losses, and energy balance in hohlraums in order to control the radiative drive as a function of time,
- Fundamental data with the obtaining of equation of state and opacities of materials relevant for the Simulation program
- Hohlraum energetics with the qualification of smoothing, and control of crossed beam energy transfer, in He/H_2 gas-filled hohlraums,
- Implosion hydrodynamics in planar and then convergent geometry,
- Hydrodynamic instabilities from linear growth to turbulence, in planar and convergent geometry,
- And, at last, Fusion studies with drive adjustment in order to manage a more than 350 km/s implosion velocity with the full LMJ.

After LMJ completion, some topics as Radiation transport and Fundamental data will be continued at higher energy, and some other as Implosion hydrodynamics and Hydrodynamic instabilities will be focused on ignition target, using cryogenic equipment, in order to control mix in the hot spot. Then experiments will be dedicated to the Ignition topic to obtain a significant gain, and the target design will be improved to increase the gain. The last topic, Applications, dedicated to the control of powerful system will couple an ignition target to another type of target to obtain, for instance, Fundamental data's in a very high temperature and pressure domain.

All the experiments performed during the phase of power increase and after completion of LMJ will contribute to improve the simulation standards.

Table 2. Diagnostics development plan. Some diagnostics (number 6,7 and 10) are developed in the framework of PETAL+ project (see section 5.3).

	Type	Performances : spectral range, resolution, field of view	Date of delivery
1	Gated hard X-ray Imager 1	12 images, 0.5 – 15 keV, 30 µm resol./ 3 mm fov	2014
2	Drive diagnostic DMX : Broad-band X-ray Spectrometer Grating spectrometer Laser Entrance Hole (LEH) imager	 0.03 – 20 keV 1 – 5 keV 0.5 - 2 keV, 100 µm res./2 mm fov)	2015
3	Gated hard X-ray Imager 2	12 images, 0.5 – 15 keV, 150 µm res./ 15 mm fov	2015
4	Streaked soft X-ray Imager	2 images, 0.05 – 1.5 keV, 30 µm / 5 mm fov	2016
5	Broad-band X-ray Spectr. (miniDMX)	0.03 – 4 keV	2016
6	*Hard X-ray Spectrometer (PETAL+)*	*15 – 100 keV*	*2016*
7	*Electron Spectrometer (PETAL+)*	*5 – 150 MeV*	*2016*
8	EOS pack	2 VISARs, 1D & 2D SBO, reflectivity	2017
9	Streaked hard X-ray Imager	4 images, 0.5 – 10 keV, 50 µm/5 mm fov	2017
10	*Ion Spectrom. and Imager (PETAL+)*	*0,1 – 200 MeV*	*2017*
11	Polar X-ray Imager 1 (LEH)		2017
12	Full Aperture Backscatter System	Raman & Brillouin range	2018
13	Near Backscatter Imager	Raman & Brillouin range	2018
14	Polar X-ray Imager 2 (LEH)		2018
15	Enhanced resol. hard X-ray Imager	5 µm resolution	2019
16	High resolution X-ray Spectrometer		2019
17	Neutron pack		2019
18	Gated soft X-ray Imager		2020
19	High resol. X-ray Spectro-Imager		2020

3. LMJ present status

A description of the LMJ facility can be found in [1, 2], and a schematic view in figure 1. In the laser bays, the framework and equipment of the four laser bays are completed, the optical and electronic components are now being installed. The first bundle is completed, activated and used since 2014, four other bundles are being mounted and will be activated in 2016 & 2017. In the switchyard each bundle is divided into two quads of four beams which are directed to the upper and lower hemispheres of the chamber using six transport mirrors per beam. In the target bay the beams are converted to 3ω and focused using gratings in the SCF (System for frequency Conversion and Focusing).

The first high energy test shots at 1ω and then at 3ω on calibrated calorimeter were performed in August and September 2014 and gave a good spatial uniformity [2]. Alignment and synchronization of the 8 beams at the chamber center was achieved with a dedicated diagnostic: the “Nanojoule active target” at the center of the target chamber, which uses a CCD for alignment and measurement of focal spot at low energy, and silicon photodiode for synchronization of the beams.

In the Target bay, the first diagnostics manipulator (SID) and associated equipment have been qualified mid-2014. LMJ diagnostics are complex systems coupling several measurements; at present, 3 systems are activated (see table 2): two X-ray Imaging systems and one drive diagnostic system (DMX). The first X-ray imager has been used to qualify the pointing accuracy, which is between 19 and 75 µm (6 shots) for a specification of less than 100 µm.

According to these good results, the LMJ has demonstrated that it meets all specifications required to begin experiments. The official commissioning was declared by Prime Minister Manuel Valls on October 23rd 2014.

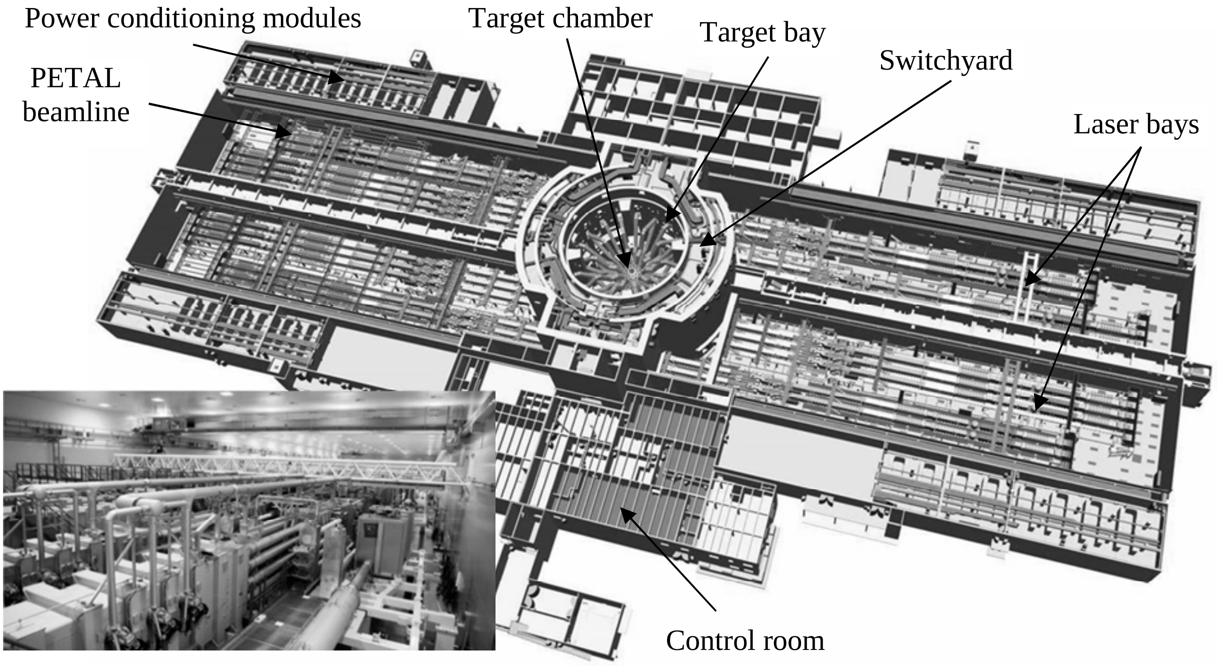

Figure 1. Schematic view of the Laser MegaJoule facility and picture of one of the four laser bays with 7 LMJ bundles and PETAL beamline on the right which occupies the place of one LMJ bundle.

4. LMJ experiments

The first LMJ Campaign took place in October 2014. The objective was to demonstrate LMJ capabilities to perform experiments for the Simulation program. The experiment was dedicated to radiation transport, and particularly to the dynamics of slot closure, in well-controlled material, due to the radiative flux produced by a gold hohlraum. Closure dynamics was diagnosed by auto-radiography, explicitly the hard x-ray produced by the impact of beams on the hohlraum wall was used as a back-lighter. Several materials have been studied: Ta_2O_5 aerogel and Gold samples. Nice results were obtained from the first shot with Ta_2O_5 aerogel sample with a 200 µm thickness and 100 and 75 µm slot widths. Details of the phenomena were well predicted by the simulations as the late phenomena of the closure dynamics showing a denser plasma zone in the middle of the slot due to plasma collision (image on the right in figure 2).

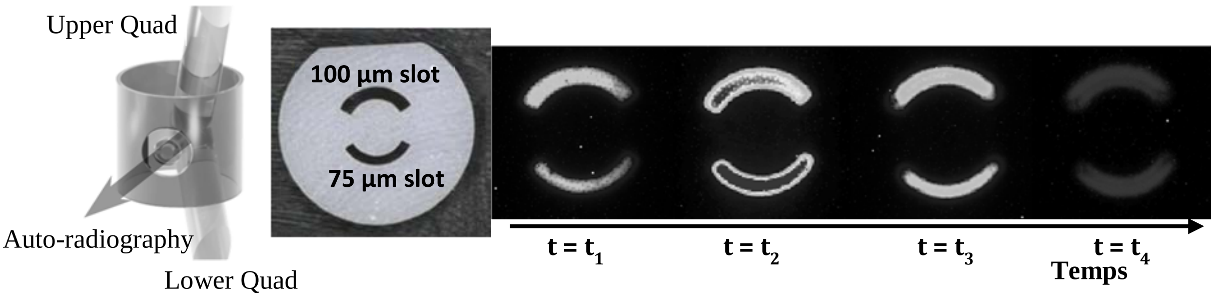

Figure 2. Schematic of the slot closure experiment, and example of data obtained on a Ta_2O_5 aerogel.

A second campaign was performed in May 2015 and dedicated to asymmetrically driven implosion with the objective of qualification of the radiographic capabilities of LMJ. The implosion of capsule in hohlraum with LEH shield heated by the first quad was diagnosed by Ti or Sc back-lighter produced by the other quad used with an optimized pulse (1 ns pre-pulse followed by a 2 ns pulse). The target presented several complexities, as the two diagnostic holes in a 3D geometry for radiographic axis, and 3D plastic plugs (50 µm wall thickness, 500 µm diameter) to avoid diagnostic holes closing.

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Figure 3 shows an example of the nice results obtained during this campaign. The egg shape of the capsule, predicted by simulation, is due to the anisotropic distribution of the drive around the capsule.

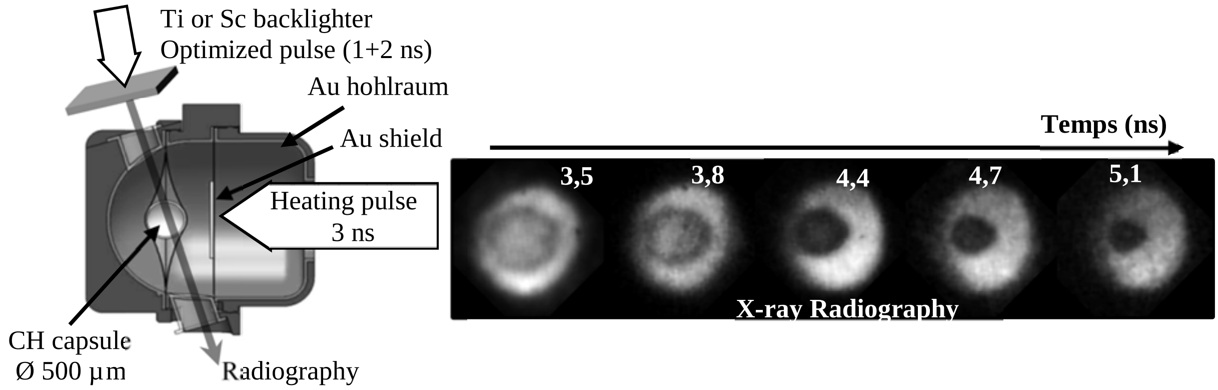

Figure 3. Schematic of the asymmetrically driven implosion experiment, and example of data obtained with a Ti back-lighter.

The program will continue with :

- the pursuit of Asymmetrical implosion with a capsule positioning at different distances from the shield, and a modification of capsule thickness to control the implosion symmetry ;
- Hydrodynamic instabilities with the characterization of the plasma jet produced by a local defect in a planar geometry ;
- Radiation transport with the pursuit of slot closure with quantitative measurement of losses, Radiative balance in hohlraums and Rosseland opacities;
- Hohlraum energetics with X-ray conversion and Characterization of magnetic fields;
- EoS of reference materials (Quartz, Al, Diamond) at the beginning …

These experiments require new diagnostics that will be delivered in the next years : see table 2.

5. PETAL status

The PETAL project consists in the addition of one short-pulse (ps) ultra-high-power, high-energy beam (kJ) to the LMJ facility. PETAL will offer a combination of a very high intensity multi-petawatt beam, synchronized with the nanosecond beams of the LMJ. This combination will expand the LMJ experimental field in HEDP. A description PETAL can be found in [1]

The first high energy test shots in the compressor stage of PETAL were performed in May 2015; they demonstrated the PW capabilities of PETAL with a 1.2 PW power shot (840 J energy and 700 fs duration) [3]. This PW power has then been brought to the LMJ target chamber center in December 2015, and a test shot coupling LMJ and PETAL has been performed at the same date.

PETAL energy is today limited by damage threshold of optics after compression. PETAL gratings have been optimized and a damage threshold above 4J/cm² (cross section) has been obtained [4]. Nevertheless test on transport mirror revealed a 2.4 J/cm² damage threshold at 500 fs; this corresponds to a maximal energy in the beam of ~1 kJ, taking into account beam modulations.

The PETAL performance before entering the compressor will be improved in the next year with an upgraded spatial uniformity and a better filling of sub-aperture of the beam. With these improvements a 2 PW beam is easily reachable. Moreover a better characterization will be obtained with the activation of all diagnostics (pulse contrast, focal spot, …). Concerning mirror damage threshold, new technologies are needed. Several ways of improvement have been identified with new coating materials, improvement of coating processes, new design of layers, and adjustment of layers thickness. Another matter is the electromagnetic pulse (EMP) generation; before performing experiments, EMP mitigation is required in order to protect LMJ equipment. Several concepts have been identified and are under test [5].

The PETAL+ Project is dedicated to the first PETAL plasma diagnostics [6]. It is funded by the

French National Agency for Research (ANR), managed by the University of Bordeaux and developed by CEA. It includes manipulators derived from LMJ SID (for diagnostics compatibility); two modules of electron spectrometer using a magnetic field for 5 - 150 MeV electrons; a hard X-ray spectrometer using a transmission crystals (Quartz and LiF) for 15 – 100 keV X-ray; and a charged particles diagnostic made of proton spectrometer and imaging system (for proton-radiography) for 100 keV-200 MeV proton, coupled to an electron spectrometer for 100 keV – 150 MeV electrons using two Thomson parabolas.

Experiments combining LMJ and PETAL will start in 2016, giving the possibility to address a new physics.

6. Access of the Academic Community to LMJ-PETAL

The CEA-DAM has promoted for several decades national and international collaborations. Between 2005 and 2014, access to the LIL facility has been given to the scientific communities. With the LMJ and PETAL facilities, the CEA-DAM is once again in a position to welcome national and international teams. The academic access to LMJ-PETAL and the selection of the proposals for experiments is done through the Institute Laser & Plasmas (ILP) with the help of the PETAL international Scientific Advisory Committee. The LMJ-PETAL User guide provides the necessary technical references to researchers for the writing of Letter of Intent of experimental proposals to be performed on LMJ-PETAL. Regularly updated version of this LMJ-PETAL User guide is available on LMJ website at http://www-lmj.cea.fr/en/ForUsers.htm.

The first experimental configuration (end 2016) will include 4 LMJ quads and the PETAL beam in the equatorial plane of the target chamber. For the first call for experiments (2017-2018), 4 experiments have been selected from 16 proposals:

- Study of the interplay between B field and heat transport in ICF conditions (Magnetic reconnection), proposed by Dr R. Smets (LPP, Ecole Polytechnique, France).
- Amplification of magnetic fields in radiative plasmas - Magnetogenesis and turbulence in galaxy, proposed by Prof. G. Gregori (Department of Physics, University of Oxford, UK).
- Strong Shock generation by laser plasma interaction in presence or not of laser smoothing (SSD) in the context of shock ignition studies, proposed by Dr. S. Baton (LULI, Ecole Polytechnique, France), and Dr. X. Ribeyre (CELIA, France).
- Interacting radiative shock: an opportunity to study astrophysical objects in the Laboratory, proposed by Dr. M. Koenig (LULI , Ecole Polytechnique, France).

The next call for proposals will be announced in 2016 for experiments to be performed in 2019.

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