Overview of the Laser Megajoule First Experiments

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Abstract. Since the operational commissioning of the Laser Megajoule (LMJ) in October 2014, several experimental campaigns have been achieved, with the first eight beams, and demonstrated LMJ's aptitudes for the Simulation Program. The Simulation Program of the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) combines improvement of physics models, high performance numerical simulation, and experimental validation. The LMJ, designed to provide the experimental capabilities to study High Energy Density Physics (HEDP), is a keystone of this Program.

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. Using a variety of pulse shapes, it will be possible to bring material to extreme conditions with temperature of 100's MK and pressures of 100's Gbar. One of the LMJ's goals is to obtain ignition and burn of DT with the indirect drive approach. The experiments performed since the commissioning were dedicated to radiative transport, implosion hydrodynamics and hydrodynamic instabilities in order to validate radiative hydrodynamics simulations and prepare ignition. LMJ will increase its capacities in the following years with the completion of other beams and a set of 26 diagnostics.

A PW beam, the PETAL project, has been added to the LMJ. It is a short-pulse (ps) ultra-high-power, high-energy beam (kJ). The first high energy test shots of PETAL have demonstrated the PW capabilities of PETAL with a record of 1.2 PW. Experiments combining LMJ and PETAL will then start in 2017, giving the possibility to address a new physics.

1. Introduction

FIG.1. LMJ aerial view – Inside the LMJ target chamber.

The Laser Megajoule (LMJ), under construction at CEA CESTA (near Bordeaux), is part of the French Simulation Program developed by the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA). The Simulation Program aims to improve the theoretical models and data used in various domains of physics, by means of high performance baseline calculators, i.e. numerical simulations and experimental validations. The heart of this program is the Simulation Standard which combines reference data, physical models, and numerical methods. This Standard is regularly upgraded by comparison of numerical predictions and results of experiments, which can lead to an improvement of physical models or numerical methods used in the prediction, or to a new set of more precise data.

LMJ offers unique capabilities for the Simulation Program, providing an extraordinary instrument to study High Energy Density Physics (HEDP) and Basic Science (equation of state, atomic physics, nuclear physics…).

The PETAL project, part of the CEA opening policy, consists in the addition of one high-energy multi-Petawatt beam to LMJ. PETAL will give the opportunity to combine of a very high intensity beam, synchronized with the very high energy beams of LMJ. LMJ/PETAL will be an exceptional tool for academic research, offering the opportunity to study matter in extreme conditions.

2. LMJ commissioning

2.1. LMJ main characteristics

A description of the LMJ facility can be found in [1, 2], and a schematic view in FIG. 2. 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 and 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 target 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).

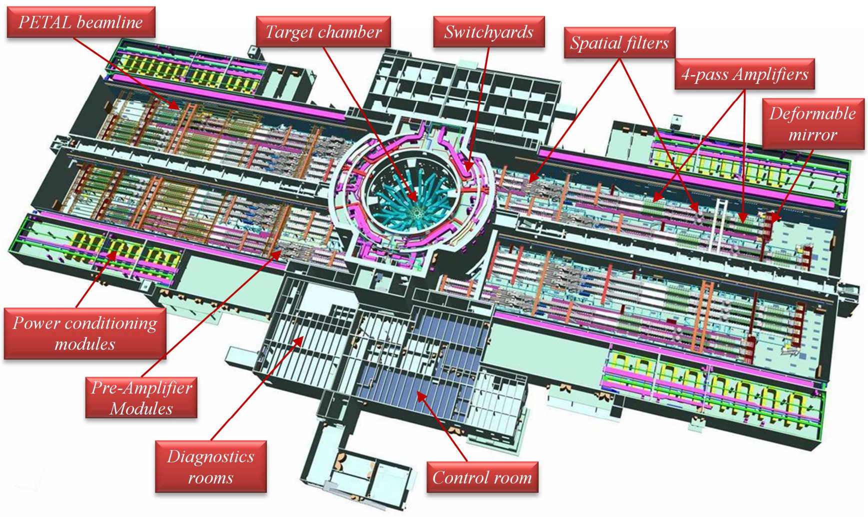

FIG.2. Schematic view of the LMJ showing the main elements of the laser system.

Using a variety of pulse shapes, it will be possible to bring materials to extreme conditions with temperature of 100’s MK and pressures of 100’s Gbar. One of the LMJ’s goals is to obtain ignition and burn of DT fuel contained in a capsule imploded by X-ray produced by the interaction of laser beams with a hohlraum (indirect drive approach); this Inertial Confinement Fusion (ICF) objective set the most stringent specifications on LMJ’s attributes. Most of the components have been qualified on the LIL (Ligne d’Intégration Laser) prototype, from 2002 to 2014.

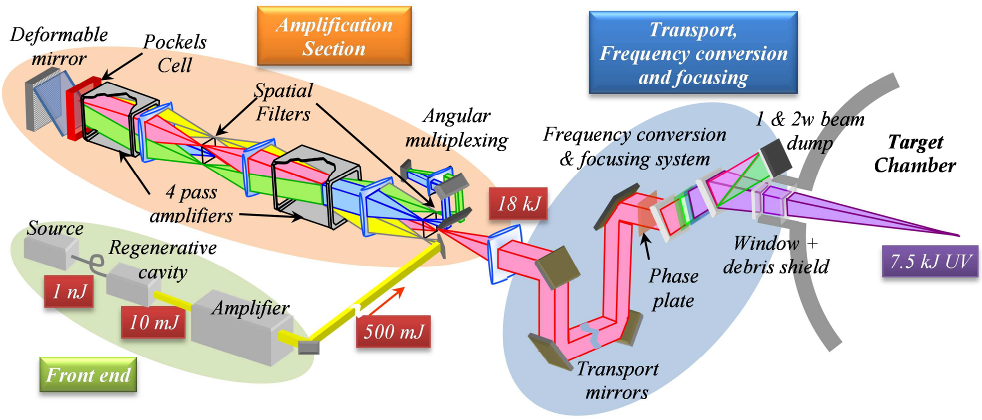

FIG.3. Architecture of one LMJ beamline.
The basic unit for experiment is a quad made of 4 identical beamlines.

2.2. LMJ first bundle commissioning

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 were 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, 4 systems are activated: two X-ray Imaging systems and two drive diagnostic systems (broadband spectrometers DMX and mini-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 performances, 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.

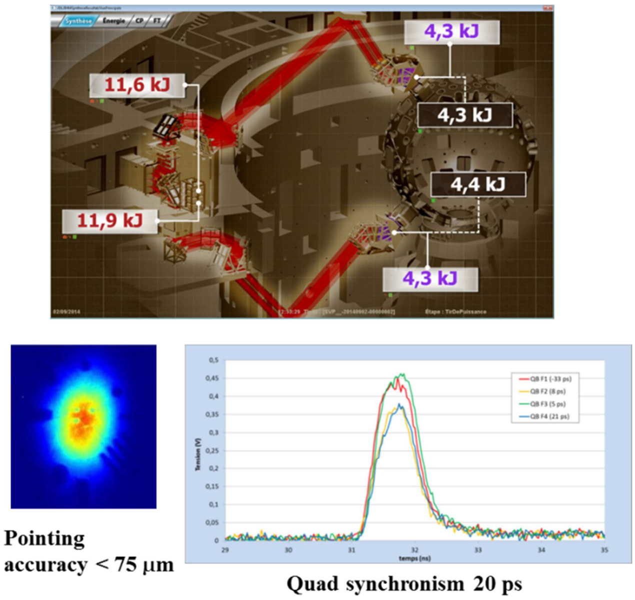

FIG.4. October 2014: LMJ has demonstrated that it fulfills all specifications required for the beginning of experiments, with the first operational bundle (2 quads).

2.3. LMJ schedule

Three main activities are performed on LMJ during the year: mounting of new bundle, activation and qualification of the previous mounted bundles and plasma experiments.

LMJ is working in two shifts; the first one is dedicated to the mounting of new bundles all the year longs, and the second one is dedicated to either activation and qualification or plasma experiments (see FIG. 5.).

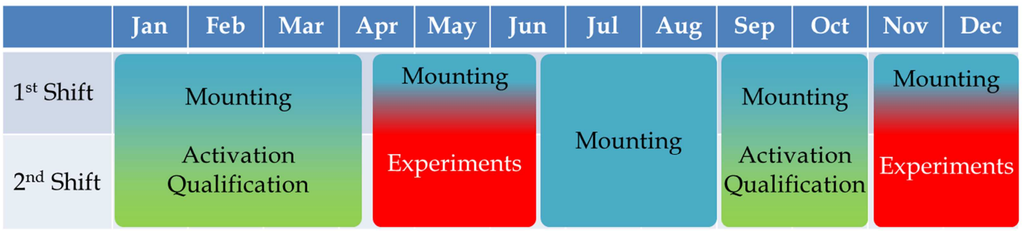

FIG. 5. LMJ schedule.

As only one shift is usually dedicated to experiments, it allows one shot per day during 4 months. With both shifts, 2 shots per day have been obtained several times. In the next years, 50 physics shots and 30 preparation shots (diagnostic qualification, pointing, synchronization…) are planned per year.

3. LMJ experimental program

3.1. Experimental topics

The CEA is developing a thematic approach for the experimental program on LMJ; this program is associated to a progressive power and energy increase of the facility. LMJ will enhance its capabilities in the next years with the completion of other bundles and a full set of diagnostics. The program is based on a progressive pathway with dedicated experiments. Eight experimental topics have been identified for the Simulation Program. They are summarized in TABLE 1.

Topic	Mechanisms to be addressed	Physics to be controlled
Hohlraum energetics	Laser plasma interaction, X-ray conversion	Radiation flux
Fundamental data	Equation of state, opacities	Matter's behavior under high P and T°
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

TABLE 1. Experimental topics of the Simulation Program.

3.2. Experimental campaigns of Radiation transport

The first LMJ campaign took place in October 2014, immediately after commissioning. The objective was to demonstrate LMJ capabilities to perform experiments for the Simulation Program, and to address radiative hydrodynamics of hohlraum. 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 of different thicknesses 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 FIG. 6.).

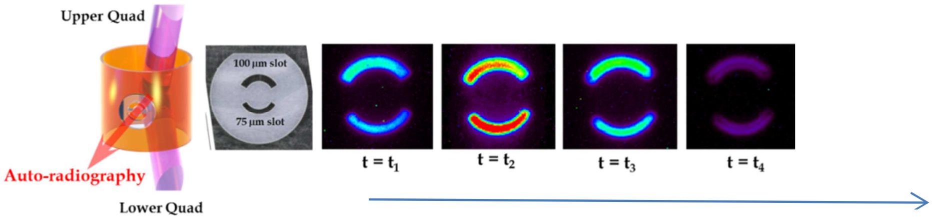

FIG.6. Schematic of the slot closure experiment (left), and example of data obtained on a Ta_2O_5 aerogel (right)

Studies of slot closure dynamics continue, with the Radiatives losses campaign in April 2016. X-ray conversion takes place in a gold hohlraum, with the shield in front of the LEH (Laser Entrance Hole) to keep 2D symmetry (FIG.7). The samples, made of aluminium, present empty slots or slots filled with CH, in order to delay slot closure. Two broadband spectrometers (DMX and mini-DMX) were used to measure radiation temperature in the gold hohlraum and radiative losses through the slots.

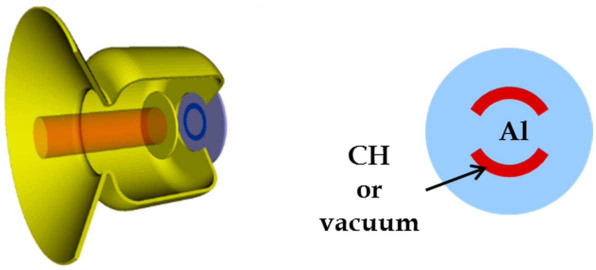

FIG.7. Gold hohlraum with LEH shield and samples with empty or filled with CH.

The campaign was realized with a very good shot cadence (one shot per day during 9 days). An example of results is shown on FIG. 8, for one of the soft X-ray channel of mini-DMX, compared to the simulation. Simulations show a very high sensitivity to the sample characteristics (thickness, slot width…).

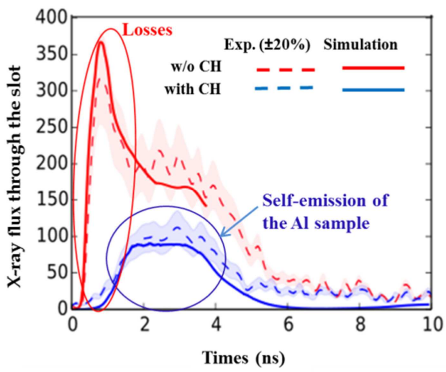

FIG.8. First results for Radiatives losses campaign.

3.3. Experimental campaign of Implosion Hydrodynamics

The campaign performed in May 2015 was dedicated to implosion driven by an asymmetric X-ray flux, 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 Titanium or Scandium 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.

FIG. 9. 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.

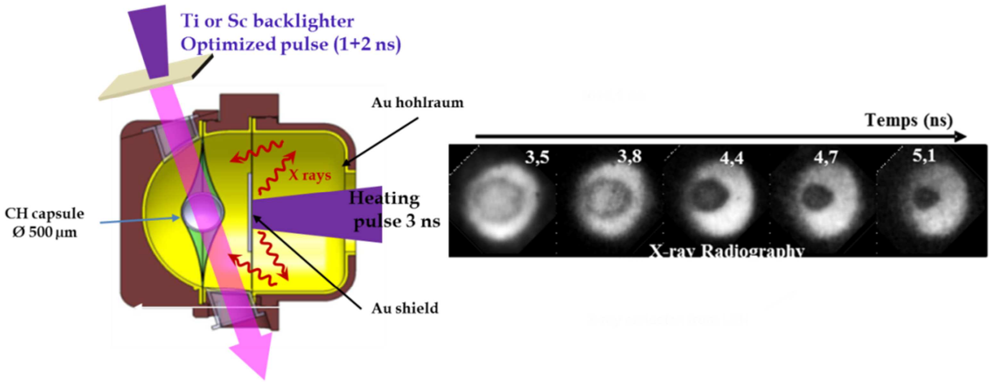

FIG. 9. Schematic of the asymmetrically driven implosion experiment, and example of data obtained with a Titanium backlighter.

Different shots were then realized with a capsule positioning at different distances from the shield, and with different shield sizes. The FIG. 9. shows that implosion is less convergent with a big shield.

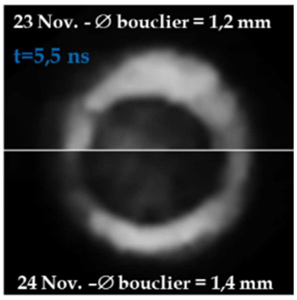

FIG. 10. X-ray radiography of two capsules, with two different shield sizes.

Other results show that implosion geometry is depending on capsule-shield distance too. The next campaign (2017) will use shimmed capsule with modulated shell thickness in order to balance the asymmetric drive.

3.4. Experimental campaign of Hydrodynamic instabilities

Another campaign in 2015 was dedicated to the study of hydrodynamic instabilities which could come from a local feature on a capsule (for example the capillary to fill the capsule and/or the drop of glue to stick the capillary to the capsule**)**.

The experiment was done in a planar geometry with the characterization of the plasma jet produced by a local bump on a plane target made of Ta_2O_5 aerogel. The jet comes from the coalescence of the shocks produced by the laser beams heating the target. The dynamics of the plasma jet, propagating in plastic foam positioned behind the target, was characterized by radiography on a long timescale (30 ns) with a Scandium backlighter.

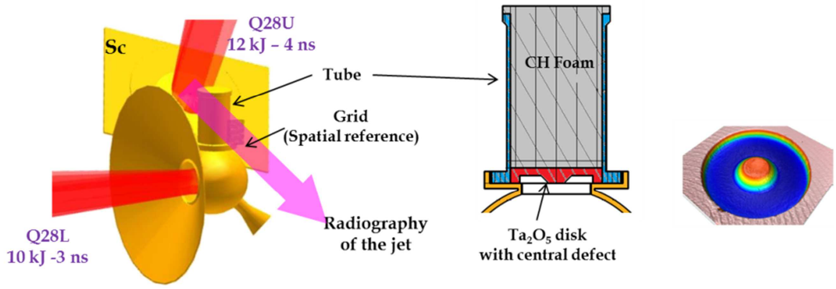

FIG. 11. Target singularity campaign.

The radiographies were of very good quality for each of the shoots, and simulations in good agreement with the experimental results on a long time scale. FIG. 12. shows that the length of the jet is in good agreement with simulation.

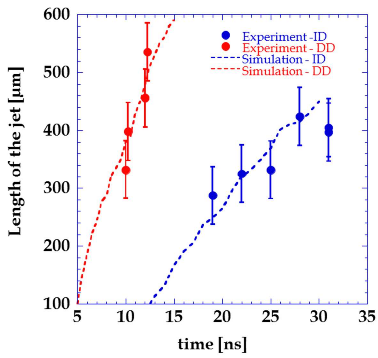

FIG. 12. Length of the jet versus time for Target singularity campaign.

4. LMJ Program overview

All these experiments, done with the first 8 beams and the first 4 plasma diagnostics, were performed in order to validate radiative hydrodynamics simulations and prepare ignition. LMJ capacities will increase in the following years with the completion of other beams and a set of 26 diagnostics in order to address new topics such as laser-plasma interaction, equation of state and opacity measuring, and so on. TABLE 2 describes the six LMJ configurations, function of operated quads and total energy, SID and diagnostics.

	Experimental configurations of LMJ					
	1st	2nd	3rd	4th	5th	6th
Quads	2	4 (+ PETAL)	10 (+ PETAL)	14 to 18 (+ PETAL)	22 to 41 (+ PETAL)	44 (+ PETAL)
Total Energy	25 kJ*	60 kJ	150 kJ	250 to 320 kJ	0.53 to 1 MJ	1.5 MJ
SID	2	3	4	5	6	Up to 10
Diag.**	4 *2 X-ray Imagers* *2 X-ray Spectro.*	8 *3 X-ray Imagers* *3 X-ray Spectro.* *2 Particles Diag.*	11 *4 X-ray Imagers* *3 X-ray Spectro.* *2 Particles Diag.* *2 Optical Diag.*	19 *8 X-ray Imagers* *4 X-ray Spectro.* *3 Particles Diag.* *4 Optical Diag.*	26 *10 X-ray Imagers* *7 X-ray Spectro.* *4 Particles Diag.* *5 Optical Diag.*	26+ *10 X-ray Imagers* *7 X-ray Spectro…* *4 Particles Diag…* *5 Optical Diag…*

TABLE 2. LMJ experimental configurations.

** Limited to reduce final optics maintenance during production phase.*
*** Including PETAL diagnostics (PETAL+ project).*

The phase from the first to the sixth experimental configuration will permit to explore some of the experimental topics of the Simulation program:

- Radiation transport in complex configuration, and energy balance in hohlraums in order to control the radiative drive as a function of time;

- Fundamental data for equations of states 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 tuning in order to obtain a more than 350 km/s implosion velocity with the full LMJ.

This period will be also useful for the handling of the facility, including training of the operational crew and control of performances (precisions, reproducibility).

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.

This program, summarized in FIG. 13., allows to draw a robust roadmap for ignition.

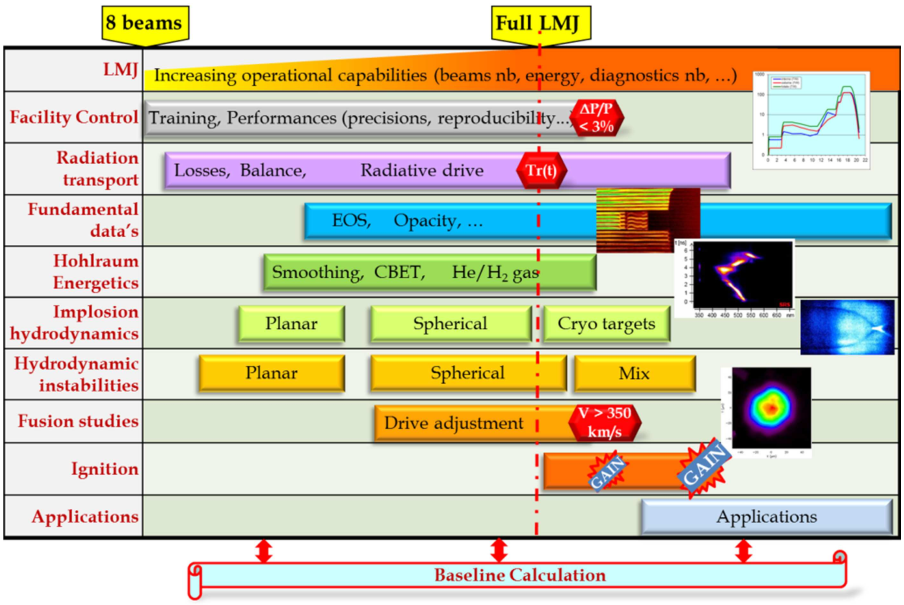

FIG. 13. Roadmap for ignition.

5. The PETAL status

To complete the experimental capabilities of LMJ, a PW beam, the PETAL project, has been added to the LMJ’s beams.

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 extand the LMJ experimental field for HEDP. A description PETAL can be found in [1].

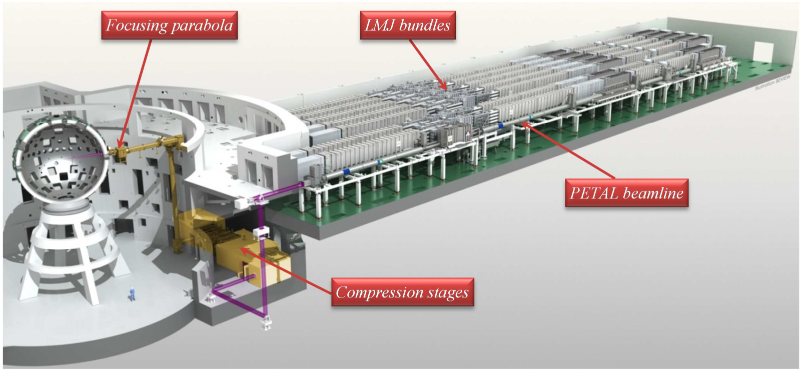

FIG. 14. Implementation of PETAL in the LMJ facility.
The PETAL beam is focused in the equatorial plane of the target chamber.

FIG. 15. PETAL inside the LMJ facility.

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.

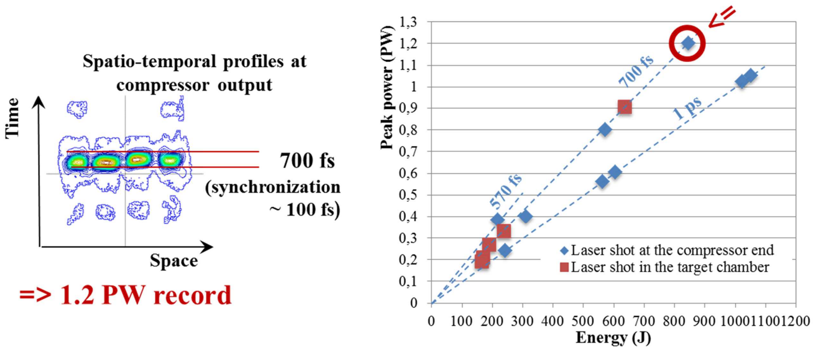

FIG.16. First high energy shots in May 2015: 1,2 PW - 846 J/700 fs.

PETAL energy is today limited by damage threshold of optics after compression. PETAL gratings have been optimized and a damage threshold above 4 J/cm² (cross section) has been obtained [4].

The PETAL performances until 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 issue is the electromagnetic pulse (EMP) generation; before performing experiments, EMP mitigation are required in order to protect LMJ equipment. Several concepts have been identified and are under test.

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.

For the first call for experiments (2017-2018), four experiments have been selected among 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 has been announced in 2016 for experiments to be performed in 2019 and 2020.

Acknowledgements

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References

[1] Miquel J L, Batani D and Blanchot N 2014, *Review of Laser Engineering* **42** 131-6

A. Casner *et al.* 2015, *High Energy Density Physics* **17** 2-11

[2] Vivini P *et al.* 2015, *High Power Lasers Fusion Research III* : *Proceedings SPIE* **9345** 934503

[3] Blanchot N *et al., these proceedings*

[4] Neauport J *et al.* 2007, *Opt. Express* **15** 12508-22