# The Laser Mega-Joule : LMJ & PETAL status and Program Overview

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**Abstract**. The laser Megajoule (LMJ), developed by the French Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), will be a cornerstone of the French Simulation Program, which combines improvement of physics models, high performance numerical simulation, and experimental validation. The LMJ facility is under construction at CEA CESTA near Bordeaux and will provide the experimental capabilities to study High-Energy Density Physics (HEDP). One of its goals is to obtain ignition and burn of DT-filled capsules imploded, through indirect drive scheme, inside rugby-shape hohlraum. 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 on HEDP. This paper presents an update of LMJ & PETAL status, together with the development of the overall program including targets, plasma diagnostics and simulation tools.

## 1. Introduction

The Laser Mega-Joule (LMJ) 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's used in various domains of physics, by means of high performance numerical simulations and experimental validations.

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 …). A large panel of experiments will be done on LMJ to study physical processes at temperatures from 100 eV to 100 keV, and pressures from 1 Mbars to 100 Gbars. Among these experiments, Inertial Confinement Fusion (ICF) is the most exciting challenge, since ICF experiments fix the most stringent specifications on LMJ's performances.

The PETAL project, part of the CEA opening policy, consists in the addition of one high-energy multi-Petawatt beam to LMJ. PETAL will provide a combination 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's main characteristics and status

Designed to deliver 1.8 MJ of UV light on target with 240 beams, LMJ is under construction at CEA/CESTA at a primary stage of 176 beams. LMJ is a flashlamp-pumped neodymium-doped glass laser (1.053 µm wavelength) configured in a multi-pass power amplifier system. The 1.053 µm light is

Journal of Physics: Conference Series **688** (2016) 012067 doi:10.1088/1742-6596/688/1/012067

frequency converted to the third harmonic (0.351 µm) and focused, by means of gratings, on a target at the center of target chamber. LMJ will deliver shaped pulses from 0.3 ns to 25 ns with a maximum energy of 1.5 MJ and a maximum power of 400 TW of UV light on target.

The main building, commissioned in 2008, includes four similar laser bays, 128-meter long, situated in pairs on each side of the central target bay of 60-meter diameter and 38-meter height.

The four laser bays are completed since the end of 2013, and the laser slabs are now being installed. The 176 square 370x370 mm$^2$ beams are grouped into 22 bundles of 8 beams. In the switchyards, each individual bundle is divided into two quads, the basic independent unit for experiments, which are directed to the upper and lower hemispheres of the chamber.

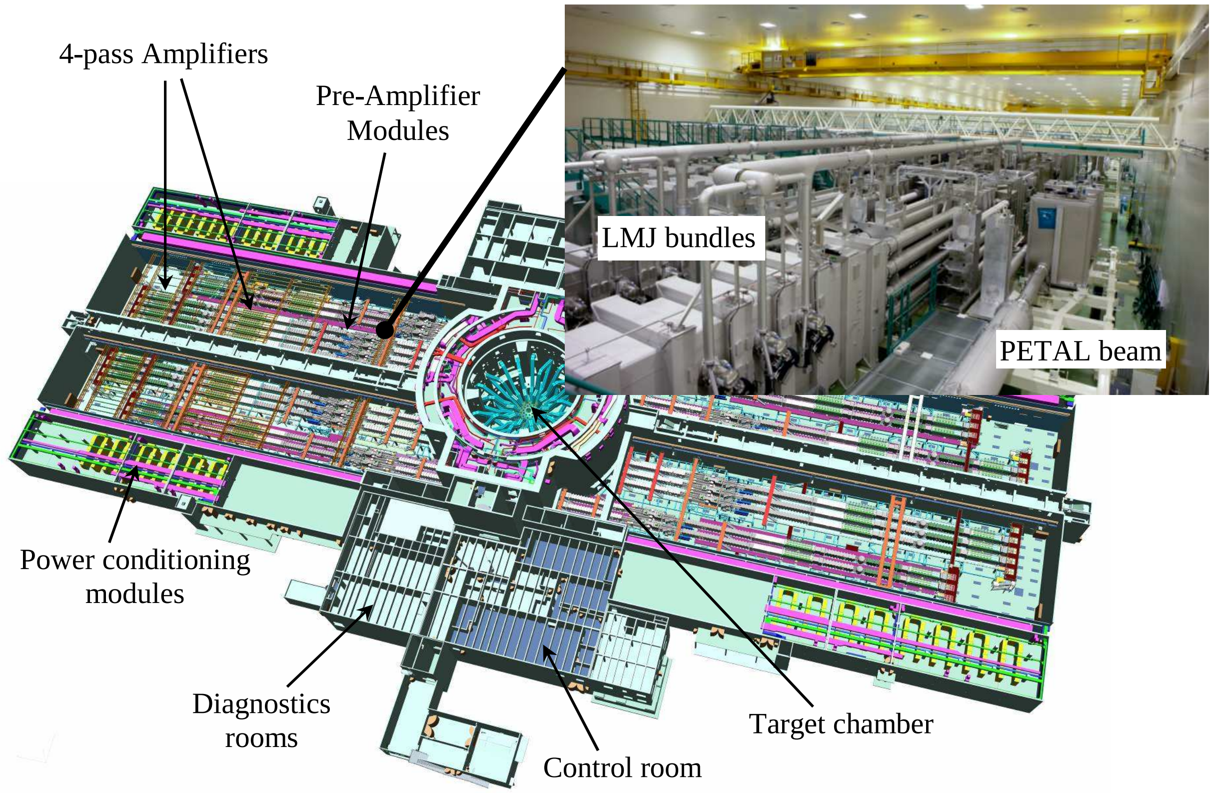


Figure 1 : Schematic view of the LMJ, and picture of one of the LMJ laser bays with 7 LMJ bundles (56 beams) and PETAL beam

At the center of the target bay, the target chamber, introduced in the building in November 2006, consists of a 10-meter diameter aluminum sphere, fitted with two hundred ports for the injection of the laser beams and the location of diagnostics. It is a 10 cm-thick aluminum sphere covered with a neutron shielding made of 40 cm thick borated concrete. LMJ is configured to operate in the “indirect drive” scheme for fusion, which directs the laser beams into cones in the upper and lower hemispheres of the target chamber. Forty quads enter the target chamber through ports that are located on two cones at 33.2° and 49° polar angles. Four other quads enter the target chamber at 59.5° polar angle, and will be dedicated to radiographic purpose.

Inside the chamber, 249 protection panels for X-ray and debris are installed (and will be removed for maintenance) by a robot. Half of the laser beam ports are today installed ; they include the final optics assembly : vacuum windows, debris shield and device to check the damages on optics.

A lot of equipments is required in the target area, among them two target positioning systems (TPS) are considered : a cryogenic TPS for fusion target and a non-cryogenic TPS for other experiments, the latter is already connected to the chamber. A set of ten diagnostic positioning systems will be installed, they will position 150 kg diagnostic with a 50 µm precision. A Reference Holder will be used for the alignment of all beams, diagnostics and target.

## 3. PETAL : a multi-Petawatt beam coupled to LMJ

The PETAL project consists in the addition of one short-pulse (500 fs to 10 ps) ultra-high-power, high-energy beam (a few kJ compressed energy) to the LMJ facility. The PETAL/LMJ facility will be an exceptional tool for HEDP, basic science as well as for the physics of ignition, in relation with the HiPER project.

The PETAL design is based on the chirped pulse amplification (CPA) technique combined with optical parametric amplification (OPA). Further, it takes the benefits of the laser developments made for the high-energy LMJ facility allowing it to reach the kilojoules level.[1]

The front end consists in a standard Ti:sapphire oscillator delivering 3nJ /100 fs / 16 nm pulse at 1053 nm wavelength. The pulse is stretched to 9 ns in an Öffner stretcher in two passes, and then amplified in the pre-amplifier module (PAM) including two OPA stages and pump laser. A 150 mJ amplified signal pulse with a shot-to-shot stability of less than 2% has been demonstrated.

The PETAL amplifier section has the same architecture as the LIL/LMJ amplifier section using a single 370 × 370 mm$^2$ beam and will deliver up to 6 kJ. The main difference is the longitudinal chromatism corrector installed in the U-turn which allows to correct 1,5 ps in two passes.

The compressor is a two-stage system. A first compressor, in air atmosphere, is used to reduce the pulse duration from 1.8 ns to 350 ps in an equivalent double pass configuration. The output mirror is segmented in order to divide the initial beam into 4 subapertures which are independently compressed and synchronized into the second compressor in a single pass configuration under vacuum. These sub-apertures are coherently added using the segmented mirror with three interferometric displacements. The pulse duration is adjustable from 0.5 to 10 ps.

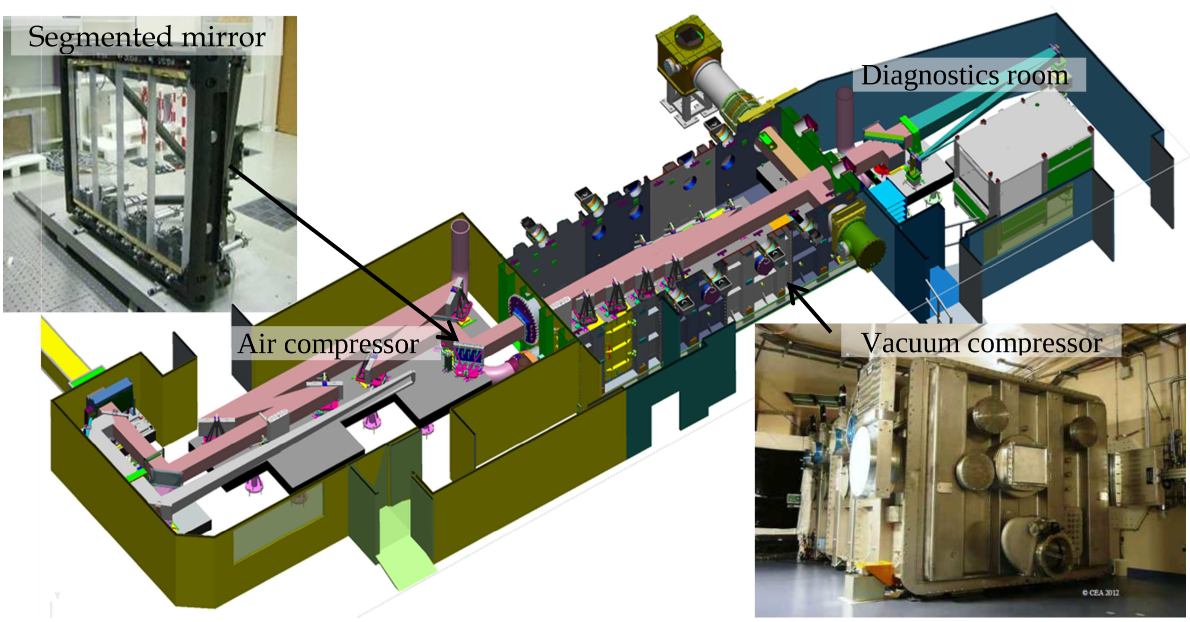


Figure 2 : Schematic view of the two stages compressor with pictures of the segmented mirror and vacuum box for the last compressor stage.

The focusing system consists in an off-axis parabola with a 90° deviation angle, followed by a pointing mirror. The focal length is 7.8 meters, and the focal spot has a 50 µm diameter, this will result in intensities above 10$^{20}$ W/cm$^2$ on target.

The PETAL performances depend on the damage threshold of optics. Great efforts have been made on gratings in order to improve their strength. The effect of electric field on damages has been demonstrated [2], and the groove profile of PETAL multilayer dielectric gratings has been optimized in order to obtain a damage threshold above 4J/cm².But the current transport mirrors cannot sustain more than 2.4 J/cm² and limit the available energy on target at a 1-2 kJ level. New technologies are required to increase this value. Several ways of improvement are identified and under investigations.

## 4. Robust path toward ignition

LMJ is designed to provide the experimental capabilities to study HEDP. A large number of experiments will be done on LMJ, covering diverse aspects of Plasma Physics (radiation transport, opacities measurements …), Materials Science (Equation of state (EOS) measurements, mechanical properties …), Hydrodynamics (Rayleigh-Taylor instabilities, turbulence …), Atomic and Nuclear Physics. Using a wide variety of pulse shapes, it will be possible to bring matter to extreme conditions, with temperatures from $10^6$ to $10^9$ K, pressures from $10^9$ to $10^{13}$ atm, and densities up to $10^3$ g/cm$^3$.

Achieving fusion with LMJ is the most constraining for the facility and requires a coordinated program associating the facility itself, as well as optimized fusion targets, plasma diagnostics, and simulation tools.

### 4.1. *Ignition "point design"*

One of the LMJ aims is to obtain ignition and burning of a DT fuel included in a capsule which is imploded, inside a high-Z rugby-shape hohlraum, through indirect drive scheme. The capsule is made of an ablator, primarily constituted of plastic (CH) that contains the fuel composed of a cryogenically cooled deuterium-tritium (DT) shell surrounding a central DT gas region.

As laser plasma interaction, coupled to energetics performances, and hydrodynamic instabilities are critical issues in ignition target design, a particular attention has been devoted to (i) the mitigation of laser plasma instabilities to reduce backscattered energy, (ii) the design of accurate shape of the hohlraum to improve energetics performance, (iii) the structure of the ablator to reduce hydrodynamic instabilities during implosion.

Taking into account these issues, an ignition indirect drive target has been designed [3], it requires 0.9 MJ and 260 TW of absorbed laser energy and power, to achieve a temperature of 300 eV in a rugby-shaped hohlraum and give a yield of about 20 MJ.

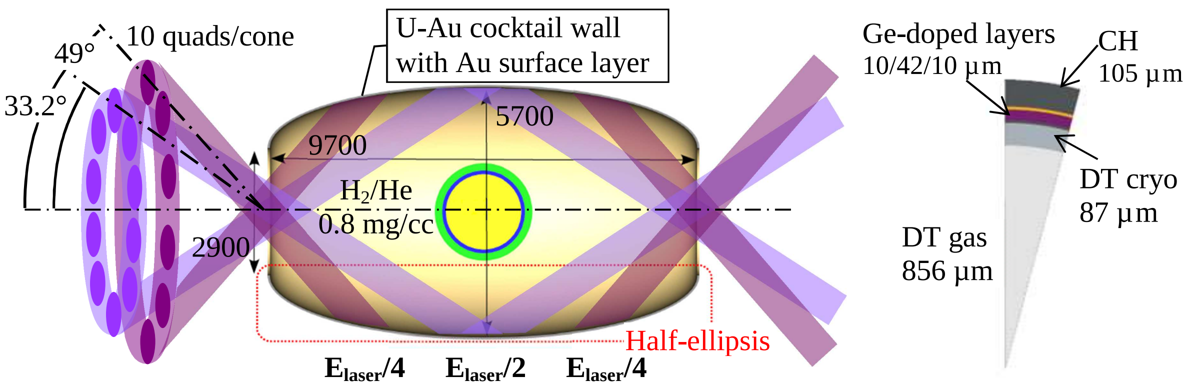


Figure 3 : Schematic view of the ignition target. The hohlraum is heated with 40 quads beams in two cones at angle 33.2° and 49° to the hohlraum axis. The ignition capsule uses several plastic layers of various thickness, some of them are doped with Germanium with varying concentration.

The hohlraum profile is made of two half ellipsis ; it has a 9.7 mm length, a 5.7 mm diameter and a 2.9 mm laser entrance hole (LEH) diameter. The hohlraum is made of U-Au cocktail wall with Au surface layer, and filled with a $H_2$/He gas mixture at a 0.8 mg/cc density to hold back the plasma from the hohlraum wall. The 40 quads enter the hohlraum through two LEH and are arranged in two cones at 33.2° and 49° providing a high ten-fold symmetry in the azimuthal plane. As the two inner cones on each side meet at the equatorial plane, the laser energy distribution is one half at the equator, and one quarter on both polar sides, which is the right energy allocation for rugby shaped hohlraum.

The capsule, with a 2.22 mm outside diameter, is made of several layers of plastic of various thickness, some of them are doped with Germanium, to absorb high-energy X-rays from the hohlraum, and with varying concentration to adapt the density gradient at the ablator-fuel interface. The inside fuel ice layer is 87µm thick and represents 0.228 mg of DT. The central part of the capsule is occupied by a 0.3 mg/cc density DT gas at a temperature of 18.3 K.

Alternative designs are under investigation with Si-doped ablators, laminated ablators [4] (stack of ~1µm thick doped and non-doped layers), or highly doped ablators (with a uniform Ge or Si distribution), and also larger target which require a bit more laser energy but less laser power and then could produce less constraints on optics.

During the LMJ power increase, starting at the end 2014, CEA will perform focused experiments dedicated to fundamental physics (EOS, opacity, transport), laser-plasma interaction, hohlraum physics, and capsule physics in order to better apprehend main aspects of fusion target behavior and improve predictive capabilities of the simulation tools. Then we will test new understanding, designs, and models in integrated implosion. This path forward will help us to secure our point design.

### *4.2. Plasma diagnostics development*

Over 30 photon and particle diagnostics are considered for LMJ, with high spatial, temporal and spectral resolution in the optical, X-ray, and nuclear domains. The early diagnostics, designed using the feedback of LIL's diagnostics, consist of :

• four hard and soft X-ray imaging systems (30 eV to 15 keV range) with a 15 to 150 µm spatial resolution and a 30 to 100 ps time resolution, providing 30 imaging channels ;

• a diagnostic set for hohlraum temperature measurements including an absolutely calibrated broadband x-ray spectrometer (30 eV to 20 keV range, 20 channels), a grating spectrometer (1 to 5 keV range), and a streaked pinhole imaging system of the emitting area ;

• an optical diagnostic set dedicated to EOS measurements including two VISAR, two SOP (Streaked Optical Pyrometer), and a reflectivity measurement ;

• a Full Aperture Backscatter System, and a Near Backscatter Imager to measure the power, spectrum, and angular distribution of backscatter light to determine the energy balance.

Other diagnostics are considered with enhanced spatial and spectral resolutions, as well as specific diagnostics for PETAL including high energy (100 keV-200 MeV) charged particles and hard X-ray (15 – 100 keV) spectrometers.

A new generation of framing and streak cameras is developed to take into account the harsh environment that will be encountered on LMJ and the electromagnetic perturbations due to PETAL.

A specific Metrology Line has been developed on the Soleil synchrotron facilities for the metrology of plasma diagnostics components using an XUV branch (30 eV to 2000 eV) and a hard X-rays branch (100 eV to 28 keV) for reference measurements. The global commissioning of diagnostics is made on the EQUINOX laser facility at CEA/Ile-de-France, and will start at the end of 2013.

### *4.3. Research program for LMJ targets*

The targets development requires numerous technologies : materials shaping, surface processing by Physical or Chemical Vapor Deposition (PVD, CVD) and electrochemistry, super critical extraction, micro-machining, laser machining, electro-machining, cryogenic studies, thermal studies, micro assembly, and characterizations. A lot of developments were made for LIL and OMEGA experiments which will be beneficial for LMJ targets. Now we are improving the assembling process using ultra-precision machining, and PVD molding technique.

We have developed a permeation filling scheme in which ignition targets are filled by permeation at room temperature under 500 bar of DT, then cooled to 20 K to withstand pressure and avoid leaks by permeation. The complete process have been tested and validated ; it guarantees the best target quality. A prototype of LMJ cryogenic equipment, the DEMOCRYTE demonstrator, has been developed for the validation of cryogenic performances, namely keep the ~18 K temperature of the DT with an inhomogeneity less than 70 µK.

However this permeation process cannot be applied for targets with impermeable layers, therefore the filling by capillaries is under study in order to expand our filling capabilities for cryogenic targets.

## 5. Conclusions

Since the building has been commissioned the LMJ is on schedule for the first experiments by end of 2014. The laser bundle assemblies of the amplifier section are already installed in the four laser bays, the mechanical frameworks of the target area is mounted around the target chamber, and most of the equipments are installed or under test. All specifications have been met on qualification sub-systems, and on the LIL facility.

The front end and compression stages of PETAL have been qualified on the LIL facility, and amplifier section, transport and focusing are now completed.

Starting in 2014 with one bundle and 4 diagnostics, LMJ will increase its capacities in the following years with the completion of other bundles and a full set of diagnostics. The improvement of physical and numerical models will accompany the experimental developments during the growth of LMJ capacities, paving a progressive way for robust ignition designs on LMJ.

LMJ/PETAL laser facility will be open to Academic research. The Institute of Laser Plasma (ILP) is working on the research program, which will be centred on 4 pillars : (i) High Energy Density Physics, (ii) Inertial Confinement Fusion, (iii) Laboratory astrophysics and nuclear physics and (iv) Acceleration and High Energy Physics.

First shots with PETAL are scheduled in 2015 and experiments combining LMJ and PETAL will be performed from 2016, giving us the possibility to address new physics.

## Acknowledgements

The PETAL project is being performed under the auspices of the Conseil Régional d’Aquitaine, of the French Ministry of Research and of the European Union and with the scientific supports of the Institut Lasers et Plasmas.

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