Overview of the Laser Mega Joule (LMJ) Facility and PETAL Project in France

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The Laser Megajoule (LMJ) developed by the *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. LMJ is under construction at CEA CESTA at a primary stage of 1.5 MJ, 370 TW and 176 beams. LMJ will perform High Energy Density Physics (HEDP) experiments starting from the end of 2014. One of LMJ's main goals is to obtain ignition and burn of DT-filled capsule imploded, through indirect drive scheme, inside rugby-shape hohlraum. The PETAL project consists in the addition of one short-pulse (500 fs to 10 ps) ultra-high-power, high-energy beam (few kJ) to LMJ. PETAL will offer a combination of a very high intensity multi-petawatt beam, synchronized with the nanosecond beams of LMJ. PETAL will expand the LMJ experimental field on HEDP.

Key Words: Megajoule class laser, Inertial confinement fusion, Petawatt laser

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. The heart of this program is the Simulation Standard which combined reference data's, 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's.

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 ...). Nowadays CEA is validating its theoretical models and simulation codes at the tens kJ levels through design and interpretation of experiments on facilities such as LIL (Ligne d'Intégration Laser, LMJ prototype) and Omega (University of Rochester). The LMJ facility will give the opportunity to add a MJ energy step to reinforce the predictive capabilities of the advanced theoretical models and simulation codes of the Simulation Program.

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

The LMJ Facility is shown schematically in Fig. 1.

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 LMJ 3,100 glass laser slabs will be capable of delivering more than 3 MJ of 1.053 μm light that is subsequently frequency converted to the third harmonic (0.351 μm) and focused 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 370 TW of UV light on target.

The main building, commissioned in 2008 after 5 years of construction work, covers a total area of 40,000 m^2 (300 m long $\times$ 150 m wide). It includes four similar laser bays, 128-meter long, situated in pairs on each side of the central target bay. The target bay is a cylinder of 60-meter diameter and 38-meter height, with a 2-meter thick concrete wall for biological protection. At the center of the target bay the target chamber consists of a 10-meter diameter aluminum sphere,

Fig. 1 Schematic view of the Laser Mega Joule showing the main elements of the laser system.

fitted with two hundred ports for the injection of the laser beams and the location of diagnostics.

The four laser bays are completed since the end of 2013, and the laser slabs are now being installed.

The 176 beams are grouped into 22 bundles of 8 beams. In the switchyards, each individual bundle is divided into two quads, which are directed to the upper and lower hemispheres of the chamber. The quad is the basic independent unit for experiments.

The LMJ target chamber is arranged with a vertical axis. 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.

This configuration is optimized for illuminating the fusion capsule mounted inside rugby-shape hohlraums using x-rays generated from the hot walls of the hohlraum to implode the capsule (see section 3.1).

The target chamber was introduced in the building in November 2006. It is a 10 cm-thick aluminum sphere with a 10 m diameter. The chamber is covered with a neutron shielding made of 40 cm thick borated concrete.

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 $50\text{ }\mu\text{m}$ precision. A Reference Holder will be used for the alignment of all beams, diagnostics and target.

3. LMJ program

LMJ is designed to provide the experimental capabilities to study High Energy Density Physics (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 temperature 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.

3.1 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 cavity or “hohlraum”, through indirect drive scheme in which the laser energy is converted into x-rays in the hohlraum. Those x-rays fill the hohlraum and drive the spherical fuel capsule placed at the center of the hohlraum. The hohlraum is filled with a low density gas, to hold back the plasma from the hohlraum wall. The capsule is made of a shell, or “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. Ablated by the x-rays, the ablator implodes resulting in compression and heating of the DT fuel.

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,¹⁾ 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.

The hohlraum profile is made of two half ellipsis (see Fig. 2); 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 H₂/He gas mixture at a 0.8 mg/cc density. 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 87 μm 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 ablators²⁾ (stack of ~1 μm 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. Then we will test new understanding, designs, and models in integrated implosion. This path for-

ward will help us to secure our point design.

3.2 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), a streaked pinhole imaging system of the emitting area,
- an optical diagnostic set dedicated to EOS measurements including two VISAR (Velocity Interferometer System for Any Reflector), 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.

Diagnostics development for LMJ requires taking into account the harsh environment that will be encountered on LMJ and the electromagnetic perturbations due to PETAL. Therefore development of a new generation of framing and streak cameras is necessary. These developments also demand some supporting facilities for metrology, tests and commissioning.

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 of detectors spectral sensitivity, or mirror reflectivity for instance.

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.

3.3 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.

Concerning cryogenic target for ignition, 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. We have developed a permeation filling scheme in which 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.

However this process cannot be applied for some kinds of

Fig. 2 Schematic of the ignition hohlraum and capsule. The hohlraum is heated with 160 laser beams in two cones at angle 33.2° and 49° to the hohlraum axis. The fusion capsule uses several plastic layers of various thickness, some of them are doped with Germanium with varying concentration.

targets with impermeable layers, therefore the filling by capillaries is under study in order to expand our filling capabilities for ignition target.

4. PETAL: a multi-Petawatt beam coupled to LMJ

The PETAL project, part of the CEA opening policy, 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. PETAL will offer a unique combination of a very high intensity multi-petawatt beam, synchronized with the nanosecond beams of the LMJ. PETAL will extend the LMJ experimentations field.

The PETAL/LMJ facility will be an exceptional tool for basic science as well as for the physics of ignition, in both cases in relation with the HiPER project.³⁾

The PETAL design is based on the chirped pulse amplification (CPA) technique combined with optical parametric amplification (OPA).⁴⁾ Further, it takes the benefits of the laser developments made for the high-energy LMJ facility allowing it to reach the kilojoules level.

Fig. 3 shows the implementation of PETAL in the LMJ facility; the PETAL beamline occupies the place of a LMJ bundle in one of the four laser bays; the compressor stages are situated at the bottom level of the target bay, and after a transport under vacuum, the beam is focused in the equatorial plane of the LMJ chamber via an off-axis parabola.

4.1 The front end

The front end, designed to amplify femtosecond pulses to energy of 100 mJ without non-linear effects, consists in a standard Ti:sapphire mode locked oscillator delivering 3 nJ / 100 fs / 16 nm pulse at 77.76 MHz and 1053 nm wavelength. One pulse is selected with a Pockels cell and stretched to 9 ns in an Öffner stretcher in two passes. Then, after coupling into a single-mode fiber, the pulse is sent to the pre-amplifier module (PAM) including OPA stages and pump laser. The pump module includes a temporal pulse shaping for compensation of the saturation effects in the power amplification stages in order to create a constant parametric gain in the OPA stages over duration of 5 ns. The OPA scheme consists of two cascaded 25 mm long LBO crystals and a 15 mm long BBO crystal. A 150 mJ amplified signal pulse with a shot-to-shot stability of less than 2% has been demonstrated.

4.2 The amplifier section

The PETAL amplifier section has the same architecture as

the LIL/LMJ amplifier section using a single $370 \times 370 \text{ mm}^2$ beam. It is a four passes system with angular multiplexing and U-Turn. It uses 16 amplifier laser slabs arranged in two sets and will deliver up to 6 kJ. At this stage, due to gain narrowing, the bandwidth is reduced to 3.2 nm and duration to 1.8 ns.

The main differences with the LIL/LMJ power chain are the wavefront and chromatism corrections.⁵⁾

4.3 The compression stages

The subaperture compression scheme has been retained (Fig. 4). The compressor is a two-stage system coupled to a segmented mirror allowing the final beam adjustments. 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 with classical precision into the second compressor in a single pass configuration under vacuum.⁶⁾ These sub-apertures are coherently added using only the segmented mirror with three interferometric displacements. In this scheme, accurate alignment is required on one mirror instead of being needed on each grating of the four mosaics in the classical scheme. The pulse duration is adjustable from 0.5 to 10 ps.

4.4 Focusing 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 $50 \mu\text{m}$ diameter, this will result in intensities above 10^{20} W/cm^2 on target.

Due to the 4 sub-apertures of the beam, a multi-beam option is available: a segmented pointing mirror could redirect the beams towards two separate focuses.

4.5 Performances

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,⁷⁾ and the groove profile of PETAL multilayer dielectric gratings has been optimized in order to obtain a damage threshold above 4 J/cm^2 . But transport mirrors cannot sustain more than 2.4 J/cm^2 compared to the 4 J/cm^2 specified value. Therefore, the current mirrors limit the available energy on target at a 1-2 kJ level. New technologies are required to increase this value and the intensity on target. Several ways of improvement are identified and under investi-

Fig. 3 Implementation of PETAL in the LMJ Facility. The Petal beam is focused in the equatorial plane of the target chamber.

Fig. 4 Compressor stages with a subaperture compression scheme: first stage in air and second stage in vacuum with 4 independent compressors.

gations.

5. PETAL scientific program

LMJ/PETAL laser facility will be open to Academic research from groups in France and in Europe and (through collaboration) also to overseas research groups. A percentage of at least 20% of laser shots will be provided for use to academic research.

As LMJ/PETAL is approaching operation, there is a need to develop a scientific program defining the research challenges and the priorities for the new facility.

The ILP (Institute of Laser Plasma), which federates the French research groups working on the physics of laser produced plasmas, has therefore taken the initiative of organizing several working groups in order to define the research programs for the 10-15 years to come. Such program will be centered on 4 “pillars”:

- High Energy Density Physics
- Inertial Confinement Fusion
- Laboratory astrophysics and nuclear physics
- Acceleration and High Energy Physics

A strategy needs to be defined in order to achieve some of the big challenges within the European forces and competences. A final priority list would help to establish future plans, taking into account:

Fig. 5 View of one of the four LMJ laser bay with 7 LMJ bundles and the PETAL amplifier section.

i) the “established” competency of the European scientific community,

ii) the diagnostics tools, which will be available in conjunction with the initial LMJ/PETAL configuration.

Such diagnostics tools will include those developed within the PETAL+ project as well as the initial diagnostics developed for LMJ (including X-ray spectroscopy and X-ray imaging). PETAL+ is a complementary academic project, coordinated by the University of Bordeaux, dedicated to construction of the first specific PETAL diagnostics. It is supported by the National funding agency ANR in the framework of the National program EquipEx devoted to scientific equipment of high quality. The diagnostics are currently under development and will be delivered by 2015. These include a dedicated spectrometer able to register x-rays from 7 to 100 keV, a charged-particle spectrometer in particular for the detection of protons and ions, and a spectrometer for detection of electrons.

The study of the direct drive approach to Inertial Confinement Fusion plays a central role in the scientific program for LMJ/PETAL. Indeed LMJ has been primarily designed to achieve ignition of fusion target, and PETAL has also been built mainly in relation with ICF experiments (for instance to allow backlighting of imploded targets, to perform advanced experiments in the field of fast ignition, etc.).

The direct drive approach naturally seems to be more adapted to the future production of energy (simpler scheme, higher efficiency ...). However it is known to be more prone to non-uniformities of laser irradiation and development of hydrodynamics instabilities. Fast ignition and Shock ignition approaches to direct drive ICF have indeed been devised in order to relax such extreme uniformity constraints.

Shock ignition seems nowadays to be a preferential pathway to direct-drive ICF because it does not rely on such an exotic, and still uncontrollable, physics as Fast ignition (the generation of relativistic electron beam, their propagation in the plasma, energy deposition in the compressed core). Moreover shock ignition is largely compatible with present-day (“NIF and LMJ-like”) laser technology. There is, in principle, the possibility to realize a full-scale demonstration of shock ignition on LMJ within the next decade. This requires however several scientific issues to be solved.

These concern on one side the basic physics of shock ignition and of laser-plasma interaction in an intensity regime up to 10^{16} W/cm², and on the other side it requires the ability of performing PPD (Polar Direct Drive) compression.

Many fundamental experiments can be performed using the LMJ/PETAL facility in its initial configuration, including:

- the ability to demonstrate efficient coupling of the intense laser beam (shock spike) through an extended plasma corona and to produced shock pressures as high as 300 Mbar at the ablation front;
- the study of the impact of parametric instabilities in a shock ignition relevant intensity regime;
- the study of the generation of hot electrons, their impact on shock formation and or target compression.

Other experiments will be dedicated to the simulation of astrophysical phenomena (experiments can be envisioned to address some astrophysical situations where conditions such as length and temporal scales, density, temperature, and pressure are rigorously scaled via dimensionless parameters) and to particle acceleration and high energy physics, such as acceleration of electrons to very high energies (from 100 GeV to 1 TeV) that can be expected via channel-guided acceleration by laser wakefield in large scale and low density plasma; achievement of extreme laser power and electron energy using the Cascaded Compression Conversion (C3) scheme, which couples CPA, OPCPA & Backward Raman (or Brillouin) Amplification; or study of accelerated ion beams which offer new opportunities for development of compact ion accelerators that could lead to medical applications (hadron therapy).

6. Conclusions

Since the building has been commissioned in December 2008, 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 subsystems, and on the LIL facility.

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.

The front end and compression stages of PETAL have been qualified on the LIL facility, and amplifier section is now completed. First shots are scheduled in 2015 and experiments combining LMJ and PETAL will be performed from 2016, giving us the possibility to address new physics.

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