THE LASER MEGAJOULE FACILITY STATUS REPORT

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Abstract

The Laser MegaJoule (LMJ), a 176-beam laser facility developed by CEA, is located at the CESTA site near Bordeaux. The LMJ facility is part of the French Simulation Program, which combines improvement of theoretical models and data used in various domains of physics, high performance numerical simulations and experimental validation. It is designed to deliver about 1.4 MJ of energy on targets, for high energy density physics experiments, including fusion experiments.

In this paper, a review of the LMJ facility and the PETAL project is given with details on the status report and an update of the activities. Afterwards, a presentation of the Target Diagnostic is given. In addition, a brief description of the LMJ Control System is given with the major software developments during the last 2 years. Finally, the major recent experiments on LMJ are presented.

Key words: Laser facility, LMJ, PETAL, Control Systems.

INTRODUCTION

Since it definitively abandoned nuclear testing, France relies on the Simulation Program to guarantee the operational performance and safety of its nuclear deterrent weapons throughout their lifetime.

Successful simulation requires both:

Qualified computer codes that integrate laboratory-validated physics models to simulate weapon functioning;

Teams of qualified physicists to use these codes.

In this respect, the Megajoule Laser (LMJ) [1] plays a vital role, as it is used to validate the numerical codes and certify the skills of French physicists.

In fact, the LMJ is designed to provide the experimental capabilities to study High Energy Density Physics (HEDP). The LMJ is a keystone of the Simulation Program, which combines improvement of physics models, high performance numerical simulation, and experimental validation, in order to guarantee the safety and the reliability of French deterrent weapons. When completed, the LMJ will deliver a total energy of 1.4 MJ of 0.35 µm (3ω) light and a maximum power of 400 TW.

The LMJ is dimensioned to accommodate 176 beams grouped into 22 bundles of 8 beams. These beams are located in the four laser bays arranged on both sides of the central target bay of 60 meters length and 40 meters height. The target chamber and the associated equipment are located in the center of the target bay.

The LMJ technological choices were validated on the LIL, a scale-1 prototype composed of 1 bundle of 4 beams. The first bundle of 8 beams has been commissioned at the end of 2014. The second bundle has been commissioned at the end of 2016 following the same commissioning process. Fifteen bundles are now operational by the end of 2023, and the physics experiments using the 80 operational beams took place during the first semester of 2023.

Furthermore, there is the PETAL laser beam which consists in the addition of one short-pulse (0.5 to 10 ps) ultra-high-power (1 up to 7 PW) with a high-energy beam (1 up to 3.5 kJ) to the LMJ facility. PETAL offers a combination of a very high intensity petawatt beam, synchronized with the nanosecond beams of the LMJ.

The first phase of nuclear commissioning of LMJ has been achieved to take into account high-energy particles created by PETAL, and neutron production from D_2 fusion reaction. A subsequent phase will take into account DT targets by 2030.

THE LMJ PROJECT

Presentation of the LMJ Facility

The LMJ facility is a flash-lamp-pumped neodymium-doped glass laser (1.053 µm wavelength) configured in a multi-pass power amplifier system. The 1.053 µm wavelength is converted to the third harmonic (0.351 µm) and focused, by means of gratings, on a target at the center of the target chamber. Once fully commissioned, with 176 beams (44 quads) operational, LMJ will deliver shaped pulses from 0.7 ns to 25 ns with a maximum energy of 1.4 MJ and a maximum power of 400 TW of UV light on the target (Figure 1).

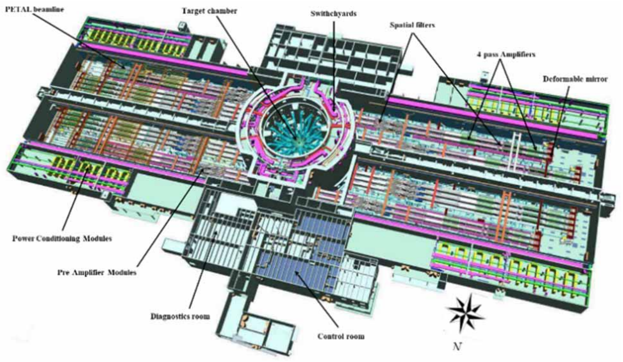

Figure 1: Schematic view of the Laser Megajoule showing the main elements of the laser system.

At the center of the target bay, the target chamber consists of a 10 meter diameter aluminium sphere, equipped with two hundred ports for the injection of the laser beams, the location of diagnostics and target holders. It is a 10 cm thick aluminium sphere covered with a neutron shielding made of 40 cm thick borated concrete. The inside is covered by protection panels for X-ray and debris.

LMJ is configured to operate in the “indirect drive” scheme, which drives 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

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other quads enter the target chamber at 59.5° polar angle, and are dedicated to radiographic purpose.

The main building includes four similar laser bays, 128 meters long, situated in pairs on each side of the central target bay.

The 44 laser beam ports include the final optics assembly: vacuum windows, debris shields and device to check the damages on optics.

Many pieces of equipment are required in the target area:

- a Reference Holder (PRC) for the alignment of all laser beams, target diagnostics and target,
- a Target Positioning System (PCNC),
- a set of visualization stations for target positioning (SOPAC stations, as System for Optical Positioning and Alignment inside Chamber),
- a Target Chamber Diagnostic Module (MDCC) for final optics inspection, beam blockers and vacuum window integrity [2],
- a set of target diagnostics manipulator, called Systems for Insertion of Diagnostic (SID).

Description of the LMJ Baseline

The 176 beams (37 x 35.6 cm^2 each) are grouped into 22 bundles of 8 beams. In the switchyards, each individual bundle is divided into two quads of 4 beams, the basic independent unit for experiments, which are directed to the upper and lower hemispheres of the target chamber.

Basically, an LMJ laser beam line is composed of three parts: the front-end, the amplifying section, the switchyard and the final optics assembly (Figure 2).

The front end delivers the initial laser pulse (up to 500mJ). It provides the desired temporal pulse shape and spatial energy profile as well as its spectrum and enables synchronization of all the beams.

The front end is made of four sources (one per laser hall), which deliver the first photons (about 1 nJ), and 88 Preamplifier Modules (PAM, 1 per 2 beams), including a regenerative cavity and an amplifier, which deliver a 500 mJ energy beam to the amplification section.

In the amplification section, the beams are grouped in bundle of 8 beams and they are amplified 30 000 times to reach energy of 15-18 kJ per beam. The amplification section includes two 4-pass amplifiers, two spatial filters, a Plasma Electrode Pockels Cell (PEPC), a polarizer and a deformable mirror for wavefront correction.

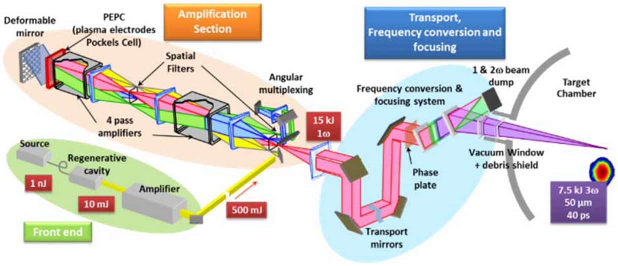

Figure 2: LMJ laser beamline.

In the switchyards, each bundle (composed of 8 beams) coming from the amplification section are divided into two quads of 4 beams. Each quad is transported over more than 40 meters into the target bay and is directed to the upper or the lower hemisphere of the target chamber using six transport mirrors per beam. The quad is the basic independent unit for experiments.

Update on the LMJ Bundle Status

The completion of the LMJ facility (176 operational beams, full target bay equipment …), as decided by CEA, requires a long period of time. During this period, there are different activities such as the assembly of new bundles, the commission of the assembled bundles, the realization of experiments addressing different physics domains with the operational bundles, in order to reach later the ignition process and finally the maintenance of the equipment with the operational bundles.

The first bundle of 8-beams was commissioned in October 2014 with the realization of the first experiment on the LMJ facility. The operational capabilities are increasing gradually every year with the frequency rate of 2 assembled bundles per year until the full completion which is expected by 2025. By the end of 2023, two more bundles will be operational and two more bundles will be assembled on the LMJ such that 18 bundles of 8 beams will be assembled on the LMJ and 15 bundles are expected to be fully operational for physic experiments.

PETAL PROJECT

The PETAL project consists in the addition of one short-pulse (0.5 to 10 ps) ultra-high-power (1 to 7 PW), high-energy beam (1 to 3.5 kJ) to the LMJ facility. The PETAL beam is focused in the equatorial plane of the target chamber.

PETAL Configuration and Characteristics

PETAL laser is based on the Chirped Pulse Amplification (CPA) technique combined with optical parametric amplification (OPA). It benefits from the laser developments made for the high-energy LMJ facility allowing it to reach the kilojoule level.

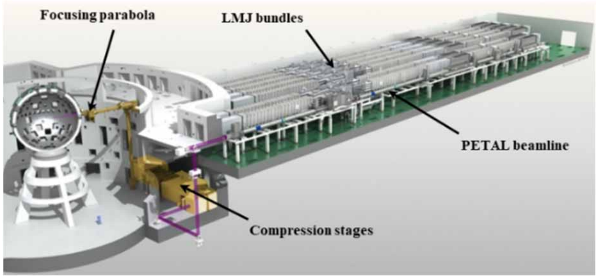

Figure 3: Implementation of PETAL laser on the LMJ facility.

The front end 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. The initial pulse (3 nJ /100 fs / 16 nm) is stretched to 9 ns in an Offner stretcher in eight passes. Then the pulse is sent to the Pre-Amplifier Module (PAM) including OPA stages and pump laser to reach 150 mJ.

The PETAL amplifying section has the same architecture as the LMJ using a single beam instead of the 8 beams of an LMJ line. It uses 16 amplifier laser slabs arranged in two sets and delivering up to 6 kJ (1.7 ns / 3 nm). The main differences with the LMJ amplifying section baseline are the wavefront and chromatism corrections.

The compression scheme is a two-stage system. The first compressor, in air atmosphere, reduces the pulse duration from 1.7 ns to 350 ps. The output mirror is segmented in order to divide the initial beam into 4 sub-apertures which are independently compressed and synchronized into the second compressor under vacuum. These sub-apertures are coherently added using the segmented mirror with three interferometric displacements for each sub-aperture. The pulse duration is adjustable from 0.5 to 10 ps.

After a transport under vacuum, the beam is focused in the equatorial plane of the LMJ chamber via an off-axis parabolic mirror with a 90° deviation angle, followed by a pointing mirror (Figure.3).

PETAL Performances

The first high energy test shots in the compressor stage of PETAL were performed in May 2015. They demonstrated the Petawatt capabilities of PETAL with a 1.15 PW power shot (850 J energy and 700 fs duration). This Petawatt 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 [3].

The commissioning of focal spot on target and the main performance during the first campaigns (2nd semester of 2017 to 1st semester of 2019) on target has been realized with the alignment performance (positioning, pointing) and demonstration of the first associated LMJ and PETAL laser shots on target (Figure 4).

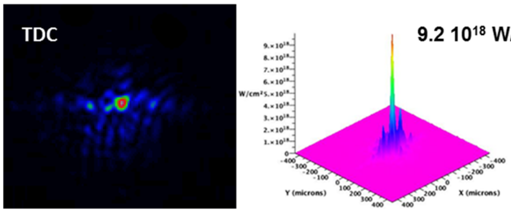

Figure 4: Focal spot for the 358 J @ 690 fs shot giving 9.2 1018W/cm².

Specific optimizations have been made to deliver 10 ps pulses on target and to shot for the 1st time on PETAL on a 25 µm wire (Figure 5).

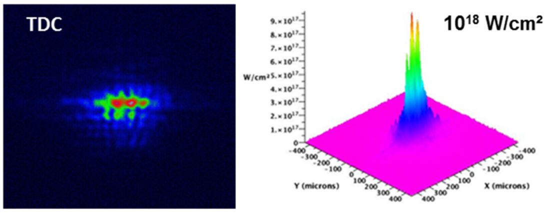

Figure 5: (Optimized) focal spot for the shot on the 25 µm wire with 396 J @ 3 ps and 1018 W/cm².

PETAL Status & Perspectives

The next improvement of PETAL performances will concern:

- The upgrade of optics under vacuum in order to increase the transported energy (ongoing action),
- The improvement on damage threshold,
- The temporal contrast measurement,
- And the focal spot optimization and characterization.

LMJ TARGET DIAGNOSTIC

Target Diagnostic Status on LMJ

Target Diagnostics (TD) are a key tool for numerous physical data acquisition during LMJ and PETAL physic experiments. CEA aims to develop more than 30 of this equipment with high spatial, temporal and spectral resolution in the optical, UV and X-ray bands, and nuclear domains.

There are actually 20 Target Diagnostics (TD) that are fully operational around the target chamber for the different LMJ experiments. As explained in [4], some diagnostics are positioned permanently around the target chamber while the remaining TD are placed in the backend area of the LMJ and are positioned around the target chamber using a SID (System for Diagnostics Insertion) when needed. A SID is a telescoping system that provides a precise positioning of a diagnostic close to the center of the target chamber. It positions a 150 kg diagnostic with 50 µm resolution. There are actually 6 SID on the LMJ: five SID on the equatorial plane of the target chamber and one SID in a polar position on the upper hemisphere.

Classification of TD

Each Target Diagnostic will be dedicated to one or several kinds of measurements like X-ray, visible, UV or particles like neutron…

The Target Diagnostics are classified into 4 main categories, namely:

- X-ray imagers
- X-ray spectrometers
- Visible/UV diagnostics
- Particles diagnostics

The following table, Table 1, summarizes the list of target diagnostics present on the LMJ with their functions and features.

Table1: Target diagnostics present on the LMJ

Target diagnostic	Main feature	Classification
GXI-1	Hard gated x-ray middle resolution imager	X-ray Imagers
GXI-2	Large field of view Hard X-Ray imager	
SHXI	Streaked Hard x-Ray Imager (Time resolved 1D images)	
UPXi	Upper Polar x-ray imager (LEM measurement)	
LPXi	Lower Polar x-ray imager (LEM measurement)	
SSXI	Streaked Soft x-ray imager (High resolution)	
ERHXI	Enhanced Resolution Hard x-ray Imager	
DMX	Multi-channel x-ray diagnostic for Hohlraum energetics measurements (Broadband X-Ray spectrometer, laser entry hole imager and soft-X-ray spectrometer)	X-ray Spectrometer
mini-DMX	Broadband X-Ray spectrometer	
HRXS	High resolution X-ray spectrometer	
SPECTIX	Hard X-ray spectrometer	
EOS pack	Velocity measurement (Visar)	Visible/UV diagnostics
FABS	Full Aperture Backscatter station	
NBI	Near Backscatter Imaging System	
Neutron pack	Neutron yield, ion temperature and neutron bang time measurement	Particles diagnostics
SEPAGE	Electron and Ion spectrometer	
SESAME 1 & 2	Electron and Proton spectrometers	
CRACC	Proton radiography	
DEDIX	Sample holder with heterodyne velocimetry	

TD and SID Perspectives

At least two new Target Diagnostics are integrated each year on the LMJ and around 10 TD are under construction and will be available on LMJ by 2030.

The future target diagnostics on the LMJ include:

- A gated soft X-ray imager;
- A broad band spectrometer (2nd mini-DMX);
- High resolution hard X-ray imagers;
- Spatially resolved spectrometers (soft and hard X-ray).

LMJ CONTROL SYSTEM

LMJ Control System Architecture

The LMJ facility has a Control System which is divided into 4 layers (Figure 6).

The N1 and N0 layers are divided into 12 major subsystems, corresponding to the main functions of the beam's control system. The shot sequences execution controls the states of each subsystem to lead to the shot.

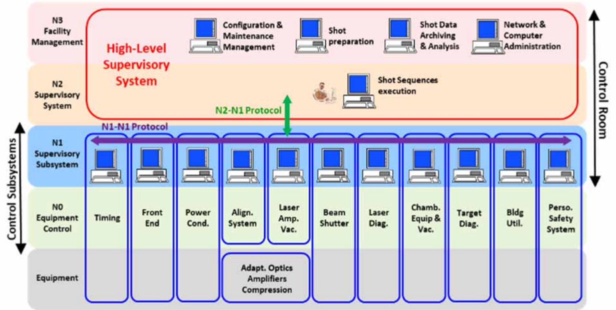

Figure 6: LMJ Control System architecture.

The main functions of the LMJ control system are shots execution and machine operations: power conditioning controls, laser settings, laser diagnostics, laser alignment, vacuum control, target alignment, target diagnostics [5].

All these components are triggered with a high precision Timing and Triggering system [6]. The control system has also a lot of other major functions: personnel safety, shot data processing, maintenance management.

The LMJ control system has to manage over 50 000 control points, 150 000 alarms, and several gigabytes of data per shot, with a 2 years online storage. It is composed of a dozen of central servers supporting about two hundred of virtual machines at the central controls level and about 450 PLC's or rack mount PC's at low levels.

In addition, scientific software is used to automate, secure and optimize the operations on the LMJ facility. They contribute to the smooth running of the experiment process (from the setup to the results). They are integrated in the maintenance process (from the supply chain to the asset management) [7]. They are linked together in order to exchange data and they interact with the control system.

Major Software Evolutions Since ICALEPCS 2021

During the last 2 years, there have been a few challenging issues on the LMJ. With the addition of 2 laser beams each year and a rise in the target diagnostics number during the different experiment, the main issue is the maintain of daily shot on the LMJ. As a result, a full automated sequence has been developed in order to perform night activities without the presence of technical operators [8]. The full automated sequence contains 2 sub-sequences: one for final optics assembly inspection after each shot and one for laser beam alignment for the next shot. They take into account all the prerequisites for their good performances and are scheduled automatically one after the other. With this full automated sequence, the technical operators have more time to carry out during the day all the preparatory steps associated to the target and the TD alignment.

With the full completion of the LMJ by 2025, there is consequently a rise in the number of laser beams involved in the LMJ experiments each year. Moreover, there is an increase in the number of Target Diagnostics on the LMJ and therefore, there is a challenging issue on the TD alignment for daily shot. A future software evolution on the full automated sequence is to perform TD alignment during the night activities. This implies that LMJ control system need to be modify for the beam alignment and the TD N0 and N1 layers.

Another challenging issue is the realization of experiments using the LMJ laser beams with the PETAL laser. Actually, the LMJ laser beams are driven by the LMJ sequence management (on the N2 Supervisory System) while the PETAL laser beam has its own sequence management [9]. Consequently, for a combined LMJ-PETAL experiment, it is necessary to perform a synchronization work in order to achieve a successful shot. On the LMJ, the meeting point between LMJ and PETAL beams is defined through the timers associated to the electrical charge of the different Power Conditioning Module (PCM). There have been software developments on the LMJ PCM in order to avoid security shutdown on the PCM and therefore guarantee the success of the LMJ-PETAL experiments [10]. In addition, there are more updates that have been identified in order to secure the reliability of the PCM material.

LMJ EXPERIMENTS & RESULTS

Final Optics Preservation Experiments

Large fusion scale laser facilities aim at delivering megajoule laser energy in the UV spectrum and nanosecond regime. Due to the extreme laser energies, the laser damage of final optics of such beamlines is an important issue that must be addressed. Therefore, for a better knowledge of damage phenomenon on the LMJ facility, an experimental campaign took place in 2021 with a dedicated full-size optical component to study damage growth at increased energy, on the beamline, i.e. in the real environment of the optics on a large laser facility. We study damage growth at LMJ enhanced energy from 3.75 kJ to 4.7 kJ.

Damage sites were detected thanks to an optimized local signal-to-noise ratio algorithm, called LASNR [11]. This algorithm permits to get rid of the background elements illuminated by the LEDs and to detect small bright elements in a noisy background. For each damage site, the difference in dimension was calculated between the acquisition performed after each laser shot and the acquisition performed before the first laser shot (Figure 7).

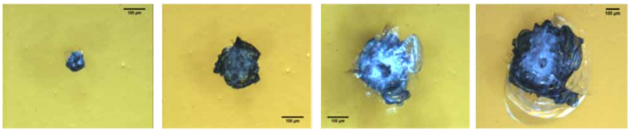

Figure 7: Damage sites seen under the microscope at the beginning at left and at the end of the LMJ onsite experiments.

Fusion Experiments

In 2022 and 2023, fusion experiments have been continued and upgraded on LMJ with additional laser beams and diagnostics. The 2019 experiments constituted the first fusion measurements on LMJ using 6 laser bundles (48 beams) in few ns square laser pulses interacting with a rugby cavity containing a D_2-filled capsule. The 2022-2023 experiments used 10 bundles (80 beams) and longer than 10 ns shaped laser pulses, which enabled a symmetric laser irradiation. Moreover, the experimental setup has been extended with a completion of the diagnostic set: the polar hard X-ray imagers, the absolutely calibrated Near Backscatter Imager (NBI) [12] for measuring the backscattered light outside the focusing cone of quadruplets 28U and 29U as well as the Enhanced Resolution Hard X-Ray Imager [13] for equatorial hot-spot imaging have been commissioned.

Different measurement series have been carried out, with both rugby or cylinder cavities, and either empty or with a CH4 gas filling. High-resolution hot-spot imaging enabled to perform first tests of implosion symmetry and symmetry tuning, and precise Brillouin backscattering measurements were conducted. Both hydrodynamic codes and backscattering prediction modules could be benchmarked. Laser Plasma Instability mitigation strategies could also be tested, paving the way for future implosion experiments with higher laser power and energy.

CONCLUSION

The LMJ facility is now operational with 15 LMJ bundles (120 beams) at the end of 2023 and a PETAL laser. The combination of PETAL and LMJ extends the versatility of the laser facility. In fact, the LMJ-PETAL facility, offering the combination of a very high intensity multi-petawatt beam, synchronized with high-energy nanosecond beams, strongly expands the LMJ experimental field on HEDP.

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