

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 1.3 MJ of energy on targets, for high energy density physics experiments, including fusion experiments.

In this paper, a review of the LMJ facility project is given with details on the status report and an update of the activities on the laser system, diagnostics and control system. Afterwards, some recent experimental results are presented.

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.

The LMJ is designed to perform indirect drive inertial confinement fusion (ICF) experiments on deuterium tritium targets. Aside this major objective, a broad spectrum of experiments can also be addressed from high energy density physics to basic science [2]. This keystone of the Simulation Program combines physics models improvement, 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 1.3 MJ of 0.35 μm (3ω) light and a maximum power of 400 TW.

This facility 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 diameter and 40 meters height. The target chamber and the associated equipment are located in the center of the target bay.

The first bundle of 8 beams has been commissioned at the end of 2014. The second bundle at the end of 2016 following the same commissioning process. Nineteen bundles are now operational by the end of 2025.

The laser facility offers also an ultra-high intensity capacity with the PETAL (Petawatt Aquitaine Laser) beamline thanks to the financial support of Nouvelle Aquitaine Region and European Union (FEDER). PETAL provides a single short pulse peak power laser beamline that broadens the facility experimental capabilities [3]. The LMJ and PETAL laser facilities are both hosted in a dedicated building featuring dimensions of 300 m in length, 150 m in width, and 40 m in height.

The first LMJ bundle was operated in 2014 for the first time. Over the past decade the facility has been progressively upgraded with additional bundles. It has also been used at the same time as an experimental facility. To limit the maintenance of final optics of operating bundles while mounting and commissioning novel bundles, the LMJ beamline energy and power operation has been limited by half, i.e., 3.75 kJ/1.25 TW per beamline at the wavelength of 351 nm [4]. Some laser campaigns are performed to gradually demonstrate laser performances at elevated energy and power up to the laser design limit in order to prepare full energy and power operation.

This paper summarizes the report status of the LMJ/PETAL facility. The first section gives an overview of the main laser system. The second section is dedicated on diagnostics status. The third section discusses the control system with emphasizing on the last updates. The latest experimental capabilities implemented on the LMJ/PETAL platform are then presented in the last section.

LMJ LASER SYSTEM

Laser Schema

The 176 beams (35 x 35 cm² 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. Schematically the laser system is divided into four main sub-assemblies represented on Fig. 1.

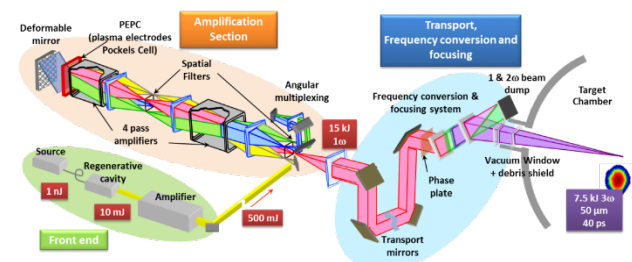


Figure 1: LMJ laser beamline.

(i) a front-end that creates and pre-amplifies the laser pulse to the joule. 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 bay), which deliver the first photons (about 1 nJ), and 88 Pre-amplifier Modules (PAM, 1 per 2 beams), including a regenerative cavity and an amplifier, which deliver a 500 mJ energy beam to the amplification section.

(ii) the main large sized amplifier that amplifies the laser beam to the multi kilo-joules level.

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.

(iii) the transport distributing the laser beams around the target chamber.

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.

(iv) the frequency conversion and focusing system that converts the amplified laser light at the wavelength of 351 nm and focuses it on the target after passing through the final optics.

Update on the LMJ Bundle Status

Since the first bundle of 8-beams commission in October 2014, the operational capabilities are increasing gradually with the frequency rate of 2 assembled bundles per year until the full completion which is expected at the end of 2025.

At mid-2025, most of bundles are operational. Two bundles are being commissioned to be operational at the end of 2025. The last bundle is finishing to be assembled and should be completed by the end of 2025.

At the end of 2026, all the bundles will be operational for physic experiments.

Bundle Commissioning

The commissioning process of a bundle is divided in two main steps:

The first step (which constitutes the larger part of the commissioning process) is conducted from a dedicated control room called integration room where all the laser operations except power shots are allowed. This prequalification begin with the validation of basic functions (VBF). The aim is to check that each equipment installed can be controlled with integration tools generally just next to the equipment. Then we perform tests to control the equipment (for example PAMs, Pockels Cells, synchronization...) from the nominal User Interface but located in the integration room (so called “IFE tests”); then the performing system functions such as laser alignment are checked (so

called “IFS tests”). At the end of the process, machine sequences are started to perform automatically system functions.

Then, using computer network configuration, the bundles are shifted from the integration room to the main control room to perform the end of the bundles commissioning ; that is to say the laser amplification with power conditioning as well as the operations which need the target bay equipment (for example: alignment of the 8 beams of the bundle on a target). Since 2023, bundles 7, 9, 20 and 25 have shifted to the main control room. The last ones are planned in the summer 2026.

The integration room is also used to perform control system enhancements tests with real equipment, unlike previous tests that are performed on simulators outside the LMJ facility.

LMJ DIAGNOSTICS

Diagnostic Presentation

Over the past decade, we have developed experimental platforms based on the use of complementary and redundant diagnostics. As of 2025, the LMJ facility operates 25 diagnostics. These diagnostics, illustrated in Fig. 2, can be grouped into several categories.

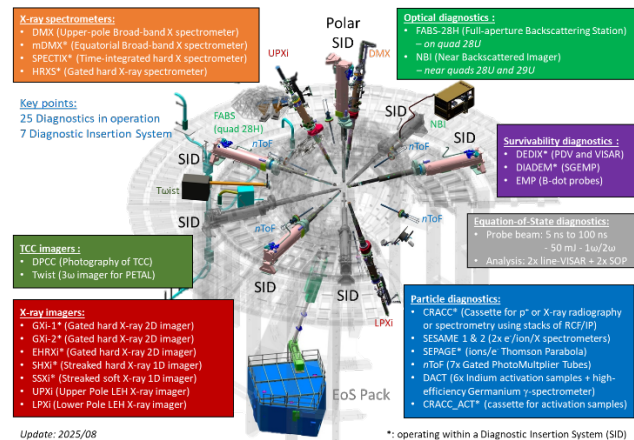


Figure 2: LMJ diagnostics status at mid-2025.

X-ray spectrometers are dedicated to the spectral characterization of plasmas. Broad-band spectrometers are used to obtain absolute X-ray spectra, which are essential for determining the radiative temperature—a key parameter in mastering hohlraum energetics. Other spectrometers, based on crystal channels, are wavelength-resolved and are dedicated to atomic physics studies, specifically NLTE (non-local thermodynamic equilibrium) spectroscopy and opacity measurements.

X-ray imagers provide images of the target’s self-emission or radiographic images using a backlighter to probe dense and hot matter. These imagers use either slit-scan cameras or gated-track cameras to produce 1D or 2D images in the soft or hard X-ray domains. They offer temporal and spatial resolutions on the order of tens of picoseconds and tens of microns, respectively. These diagnostics are used to study experiment hydrodynamics and radiative

transport, and are typically used to monitor implosion symmetry in ICF experiments. Polar imaging diagnostics are also deployed to monitor laser beam pointing on every shot.

Optical diagnostics are dedicated to measuring the power, spectrum, and angular distribution of visible light in order to determine the experiment's energy balance. These diagnostics are particularly important for characterizing laser-plasma instabilities that can impact target performance.

Equation-of-State (EoS) diagnostics are based on the VISAR/SOP technique and are mainly used in material properties and shock experiments. These diagnostics can also be used for shock timing in ICF experiments.

Survivability diagnostics are used in irradiation tests and aim to characterize the thermomechanical and electromagnetic properties of materials.

Nuclear diagnostics are used to characterize the emission of charged particles (ions, electrons, positrons) and neutral particles (gamma rays, neutrons) in fusion experiments and in experiments using the PETAL short-pulse laser to generate relativistic particles. Among these, neutron diagnostics allow for the detection of neutron generation and the characterization of nuclear properties such as neutron yield, bang time, and ion temperature.

LMJ diagnostics are either permanently installed at fixed locations in the target chamber/target bay or mounted on Diagnostic Inserter Systems (SID). SIDs are two-stage telescoping devices capable of inserting, retracting, positioning, and aligning a diagnostic within the target chamber. Since 2025, the final SID configuration has been deployed. Seven SID locations are available: one at the chamber pole and six on its equatorial plane, enabling a wide range of experimental platforms.

Update on the Diagnostics Status

During 2024/2025, three new diagnostics have been developed.

A major upgrade of the EoS-pack probe laser, which has been modernized and significantly improved in terms of capability and reliability. This laser, named LILI, was developed in partnership with the LULI laboratory at École Polytechnique (Palaiseau, France). Using a Semi-conductor Optical Amplifier (SOA) as an optical Arbitrary Waveform Generator (AWG) as a front-end seeder, along with diode-pumped amplifiers, the EoS-pack probe beam delivers square-shaped 1ω and 2ω pulses with arbitrary durations ranging from 3 to 100 ns, and tunable energy up to ~ 20 mJ. Its energy stability is around 2.8% rms, enabling outstanding performance for VISAR measurements.

A diagnostic dedicated to the study of the electromagnetic properties of materials, named DIADEM, designed to place four samples approximately 10 cm from the target and measure their self-generated electromagnetic pulse (SGEMP) response under X-ray irradiation.

A high-resolution X-ray spectrometer, named HRXS, dedicated to opacity measurements. This diagnostic includes ten measurement channels, each based on a cylin-

drical Bragg crystal in either reflection or transmission geometry. Four central channels are coupled to a framing camera with a CCD detector for time-resolved spectra (integration time of 250 ps), while the remaining lateral channels provide time-integrated spectra using CID detectors. The spectral resolution $E/\Delta E$ is ≈ 500 , and the spectral range can be set between 800 eV and 25 keV.

On average, two new diagnostics are integrated into LMJ each year. By the end of 2029, more than 33 diagnostics are expected to be in operation, offering a comprehensive experimental setup for the first phase of LMJ/PETAL, i.e. focusing on non-DT and non-cryogenic experiments.

Diagnostic Commissioning

New target diagnostics module are commissioned in a few steps:

(i) Control system commission (low level, N0): diagnostic qualification.

(ii) Update the diagnostic supervisory subsystem (N1) to communicate with the new diagnostic software plugged in. The supervisory architecture is made to keep modularity and to manage heterogeneity. Currently, 15 diagnostics are monitored by the N1. N1 is also developed in order to deal the interface with the N2 layer and the sequences. For a couple of years, the supervisory subsystem is developed to perform the diagnostic alignment. Depending on the diagnostic positioning systems, the alignment procedure differs. Currently, only diagnostics inserted on the chamber with a specific mechanism can be aligned automatically (N1 sequence). By the end of the year, diagnostics TD mounted on SID could be also automatically aligned.

(iii) Update the shot sequence (N2). Shot sequence manages shot configuration, equipment arming, triggering and post shot steps with result production. When the diagnostic control system is matured, the supervisory subsystem exchanges with the sequence to arm and trigger the selected diagnostic at the right time of the shot. From the 2 past years, 5 diagnostics (X ray imager and spectrometers) have been triggered during the shot sequence.

(iv) Update the alignment sequence (N2) in order to align the selected diagnostic on chamber centre automatically by night: a perspective for the next years.

LMJ CONTROL SYSTEM

LMJ Control System Architecture

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 on line storage. It is composed of about 700 virtual machines, 3500 physical machines, and 1300 switches.

The LMJ control system architecture [5] is built on a 4 layers architecture as shown on Fig. 3.

- Level 3 (N3): system supervisory provides facility planning and operation functions which are dedicated to the shot director

- Level 2 (N2): SVP is the supervisory system (SVP) which provides GUI to the shot director. System sequences drive subsystems through SVP interfaces with supervisory subsystems.
- Level 1 (N1): supervisory subsystems that allow operators to drive facility subsystems (power conditioning modules, preamplifier, alignment control system...)
- Level 0: equipment controls (PCs or PLCs).

The N1 and N0 layers are subdivided 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.

All the control systems developed for the supervisory layers uses a common SCADA framework. This framework includes resource management, sequence management and configuration management.

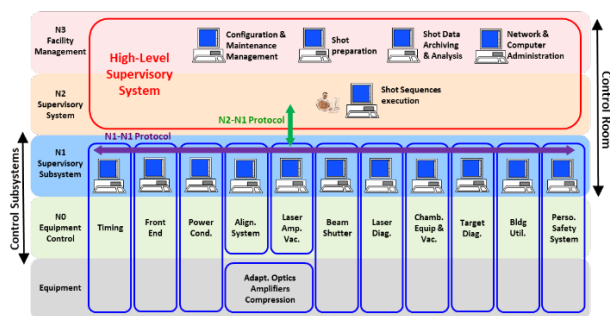


Figure 3: LMJ control system architecture.

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

In addition, operating software are 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.

Majors Software Evolutions

During the last 2 years, there have been a few challenges to tackle on the LMJ. With the addition of 2 laser beams each year and a rise in the target diagnostics necessary during the different experiments, the main issues are:

- A daily shot on the LMJ. A fully automated sequence has been developed in order to perform night activities without the presence of technical operators [8]. The fully 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 auto-

matically one after the other. With this, fully-automated sequence is performed by night in order to give technical operators more time to carry out the preparatory steps associated to the target and the TD alignment. During the last 2 years, these sequences were improved, respectively, to reduce the final optics assembly inspection duration and to improve the reliability of the laser beam alignment. The first steps were developed to perform diagnostics alignment sequence by night.

- To avoid safety shutdown of Power Conditioning Modules (PCM) [9]. A new sub-sequence has been developed in the shot sequence to test all layer 0 and Power Conditioning Modules (PCM) equipments. This sequence is a shot sequence with a 3kV set point instead of 22kV (nominal voltage to shot) and the capacitors discharge to the ground. This sequence tests high voltage (HV) power supplies, low-level communication, HV relays, dump and synchronisation triggering order. It produces report to the LMJ shot director in order to take the decision to stop the shot or not.
- The development of a modernization strategy of operational tools for the LMJ, enhancing usability and maintainability [10].
- Obsolescence issues. As the bundle commissioning has taken far more than ten years, we are facing equipment ageing. For example, the PLC of the alignment control system are now obsolete and have to be replaced. Strategy to manage the obsolescence of alignment control system by minimizing the impact on the operation of the LMJ has to be established [11].
- In addition to existing measures on the LMJ facility, an action plan has been implemented to improve the LMJ facility protection [12].

Control System Perspectives

By the end of the laser system mounting, the control system has been improved every year since the 1st bundle commissioning. The next steps for the control systems are:

- To upgrade diagnostics N1 to improve their monitoring,
- To increase the sequences reliability,
- To continue efforts to deal obsolescence issue while limiting the impact on the daily shot program.

UPDATE OF THE LMJ EXPERIMENTS CAPABILITIES

Laser Performance

Over the past decade the facility has been progressively upgraded with additional bundles. It has also been used at the same time as an experimental facility. To limit the maintenance of final optics of operating bundles while mounting and commissioning novel bundles, the LMJ beamline energy and power operation has been limited by half, i.e., 3.75 kJ/1.25 TW per beamline at the wavelength of 351 nm [4]. Some laser campaigns are performed to

gradually demonstrate laser performances at elevated energy and power up to the laser design limit in order to prepare full energy and power operation. The aim of these campaigns, designated as QPerf campaign, is to involve a gradual expansion of energy and power across a few quadruplets from the current operation performance to the maximal energy and power expected for the facility: QPerf2021 and QPerf2023 (see Fig. 4).

The quadruplets used for the highest energy level were equipped with the first argon tubing commissioned in early 2023. At the level of energy and for this pulse duration, argon tubing is mandatory to avoid longitudinal Raman scattering during beam propagation in air. Regarding QPerf2023, no abnormal damage behaviour was seen on final optics. New Qperf campaign is scheduled by the end of this year to keep on preparing the upgrade in energy and power, seeking to define the corresponding limits.

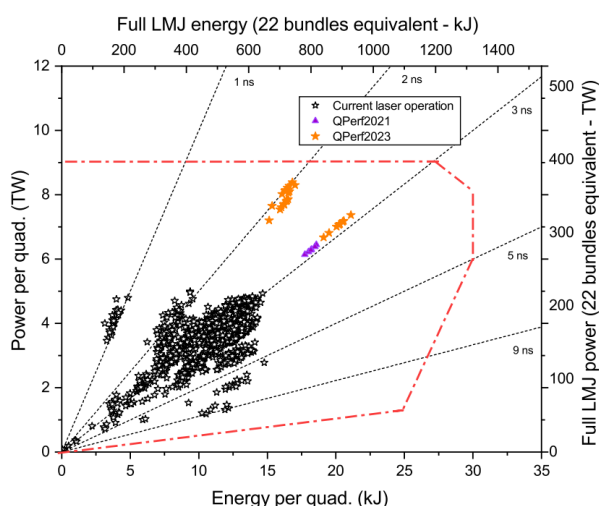


Figure 4: Diagram representing the 3ω peak power versus 3ω energy per quadruplet for the elevated energy/power laser performance campaigns QPerf2021 (purple triangles) and QPerf2023 (orange stars). Data points represented in black stars correspond to the current experimental domain for comparison. The red line represents the operational envelope. As a metric, top and right scales correspond to the full 22 quadruplet LMJ energy and power equivalent LMJ [4].

Recent Experimental Results

In direct connection with laser energy ramping up and the latest diagnostics brought into service, several new experimental platforms are being developed on the LMJ facility. The recent upgrade of the EoS-pack probe laser and the continued increase in facility energy have enabled the first equation-of-state measurements in the pressure regime exceeding 100 Mbar, marking a major step forward in high-pressure physics research on LMJ. In parallel, the commissioning of the HRXS opens the door to opacity measurements under conditions relevant to astrophysics and ICF.

The indirect-drive ICF platform has undergone significant development since the first fusion experiments were performed on LMJ in 2019 [13]. Since 2023, deuterium-

filled implosion experiments have been conducted in the ablative regime using a full suite of target diagnostics [14]. In these experiments, silicon-doped plastic capsules filled with D_2 were imploded inside empty or gas-filled, cylindrical or rugby-shaped gold hohlraums, irradiated with 10 bundles (260 kJ). This configuration ensured symmetric x-ray drive and controlled implosion symmetry. Critical diagnostic tools such as DMX have supported studies of hohlraum energetics, while FABS and NBI diagnostics have enabled investigations into laser-plasma instabilities (LPI) and their mitigation. The GXI-1 and ERHXI imagers provided spatially and temporally resolved X-ray images of the ablator and hot-spot regions, respectively, allowing for effective symmetry tuning and optimization of the implosion core.

Beyond fusion-related activities, academic access and multi-institutional collaborations continue to be a strong component of LMJ/PETAL's mission. For instance, in 2025, collaborative experiments were conducted on:

- Parametric instability generation using LMJ beams in partnership with the University of Alberta (Canada) and University of Rochester (USA), and
- Laser wakefield electron acceleration using PETAL operating at 1 PW on underdense plasma targets, in collaboration with LLNL (USA) and University of Bordeaux (France).

These campaigns demonstrate the facility's capability to support a wide range of fundamental or applied physics experiments

CONCLUSION

At the end of 2025, the LMJ facility will be operational with 19 LMJ bundles (152 beams) and the PETAL laser beam. By the end of 2027, all the bundles will be commissioned. At the same time, we are facing new challenges for the LMJ control systems, such as managing major software evolutions and obsolescence issues. Last, diagnostics and experimental platforms are being deployed in a phased and strategic manner, allowing for a progressive increase in LMJ/PETAL's experimental capabilities. This approach supports both internal research objectives and international collaborations, while preparing for future campaigns involving DT fuel and cryogenic targets.

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