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THE Laser MegaJoule FACILITY STATUS REPORT

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Abstract

The Laser MegaJoule (LMJ), the French 176-beam laser facility, is located at the CEA CESTA Laboratory near Bordeaux (France). It is designed to deliver about 1.4 MJ of energy on targets, for high energy density physics experiments, including fusion experiments. The first bundle of 8-beams was commissioned in October 2014 [1]. By the end of 2021, ten bundles of 8-beams are expected to be fully operational.

In this paper, we will present:

- The LMJ Bundles Status
- The main evolutions of the LMJ facility since ICALEPS2019
- The result of a major milestone for the project: 'Fusion Milestone'

INTRODUCTION

The laser Megajoule (LMJ) facility, developed by the "Commissariat à l'Energie Atomique et aux Energies Alternatives" (CEA), 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 sized to accommodate 176 beams grouped into 22 bundles of 8 beams. These will be located in the four laser bays arranged on both sides of the central target bay of 60 meter diameter and 40 meter height. The target chamber and the associated equipment are located in the center of the target bay.

The first bundle of eight 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. Seven additional bundles are now operational since the end of 2020, and the first physics experiments using the 56 operational beams took place in the second semester of 2019.

The PETAL project consists in the addition of one short-pulse (0.5 to 10 ps) ultra-high-power (1 up to 7 PW), 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 [2].

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-D fusion reaction. A subsequent phase will take into account tritium targets.

This paper describes the LMJ facility status and the new target diagnostics. A milestone physics experiments is presented to illustrate the facility capacity to realize the first thermonuclear fusion by implosion of a D_2 capsule in a cavity.

LMJ BASELINE

The 176 beams (37 × 35.6 cm² each) are grouped into 22 bundles of 8 beams. In the switch-yards, 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 switch-yard and the final optics assembly.

The front end delivers the initial laser pulse (up to 500 mJ). It provides the desired temporal pulse shape and spatial energy profile.

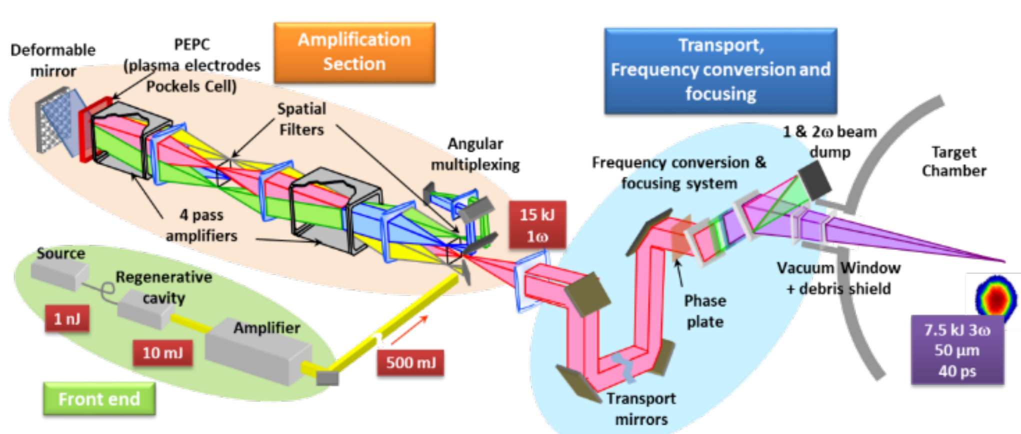

Figure 1: Laser beamline schematic diagram.

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The initial pulse leaving the front end is amplified four times through two amplifiers, in order to obtain the energy required for the experiments (up to 15 kJ at 1 ω per beam). Positioned between the two amplifiers, focusing lenses, associated to a diaphragm (spatial filter pinhole), take out the parasitic (noise) beams that may arise. Beyond the two amplifiers is a reflecting mirror (M1), making the four passes possible through angular multiplexing, as shown on Fig. 1. The surface of this mirror is deformable (being controlled by electro-mechanical actuators), allowing beam wavefront distortions to be controlled.

The 8 beams coming from the amplification section are divided into two quads. Each quad is transported over more than 40 meters into the target bay and is directed to the upper or lower hemisphere of the target chamber using six transport mirrors per beam. Each quad arrives into a frequency conversion and focusing system (SCF). Inside the SCF, the beams frequency is changed from infrared (1,053 nm) to ultraviolet (351 nm). The frequency conversion is realized by two KDP crystals, with a global efficiency of about 60%. The beams are focused on target using a 3 ω focusing grating. This specific component allows spectral separation (to ensure only 351 nm wavelength reaches the target).

LMJ BUNDLES STATUS

The completion of the LMJ facility (176 operational beams, full target bay equipment, …) requires a long period of time. During this period, we need to assemble the bundles, commission the assembled bundles, but also realize experiments addressing different physics domains with the operational bundles, in order to control the ignition process.

Today, Nine LMJ bundles (18 quads) are operational since the end of 2020. Before the end of the year, one more bundle will be operational and four more bundles should be assembled. At the end of 2021, 80 beams will be operational.

LMJ & PETAL TARGET DIAGNOSTICS

Fourteen target diagnostics are now operational around the target chamber, and two new diagnostics will be operational at the end of 2021. Table 1 summarizes the different functions and the main features of these diagnostics. Some diagnostics are insertable using a SID (System for Diagnostics Insertion). A SID is a telescoping system that provides a precise positioning of a diagnostic close to the center of the target chamber. It moves a 150 kg diagnostic with 50 µm precision. Four SID are operational: three in the equatorial plane of the target chamber, and one in a polar position on the upper hemisphere. Three more equatorial SID will be operational at the end of 2021, in 2022 and 2023.

PETAL: A PETAWATT CLASS LASER INSIDE THE LMJ FACILITY

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 (see Fig. 2).

Table 1: Target Diagnostics Description

Diagnostic	Function(s)	Insertable	Operational
GXi-1	Hard gated X-ray middle resolution imager	Yes	Yes
DMX	Multi-channel X-ray diagnostic: broadband X-Ray spectrometer + laser entry hole imager & soft-X-ray spectrometer	No	Yes
mini-DMX	Broadband X-Ray spectrometer	Yes	Yes
SSXi	Soft X-ray spectro-imager	Yes	Yes
GXi-2	Large field of view Hard X-Ray imager	Yes	Yes
SPECTIX	Hard X-Ray spectrometer	Yes	Yes
CRACC	Proton radiography (part of SEPAGE)	Yes	Yes
SESAME 1&2	Electron spectrometers	No	Yes
SEPAGE	Electron & ion/proton spectrometer & proton radiography	Yes	Yes
FABS	Full aperture scattering measurement station	No	Yes
SHXI	Streaked Hard X-Ray Imager (time resolved 1D image)	Yes	Yes
Neutron pack	Neutron yield measurement, neutron Time of Flight measurement	No	Yes
EOS pack	Velocity measurement (Visar), Shock Break Out/pyrometers	Yes, partly	Yes
DEDIX	Heterodyne velocimetry	Yes	Yes
Nbi	Near Backscattering Imaging System	No	2021
UPXi	LEH imager	No	2022
HRXi	High Resolution X-Ray imager	Yes	2022
HRXS	High resolution X-Ray spectrometer	Yes	2023
HRXi	High Resolution X-Ray imager	Yes	2022

The PETAL beam is focused in the equatorial plane of the target chamber.

PETAL Architecture

PETAL laser is based on the chirped pulse amplification (CPA) technique combined with optical parametric amplification (OPA). The front end consists in a standard Ti:Sap-

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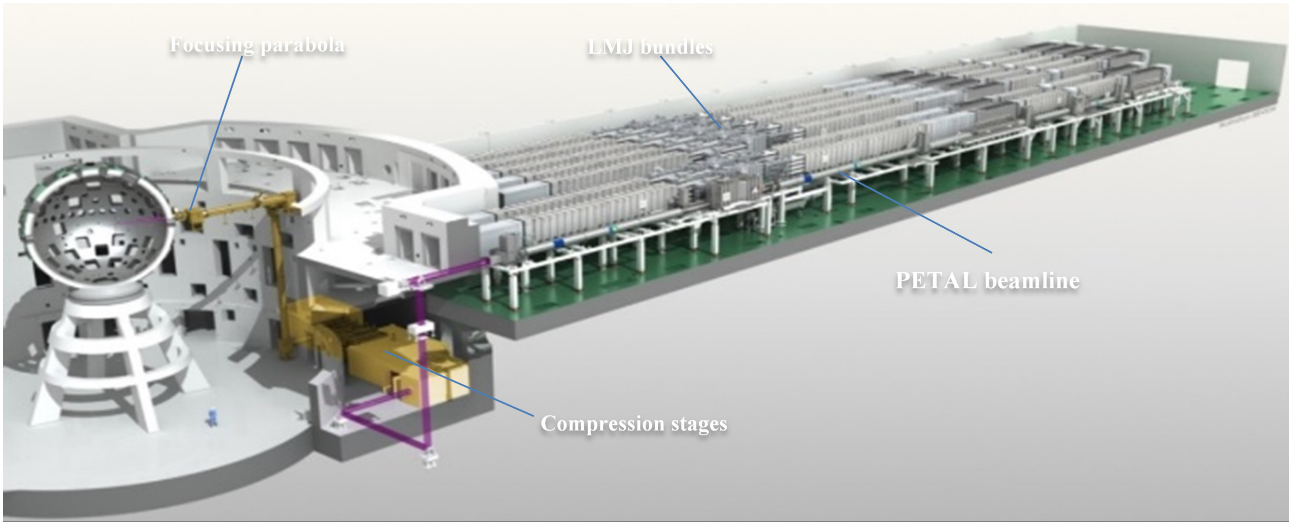

Figure 2: Implementation of PETAL. The PETAL beam is focused in the equatorial plane of the target chamber.

phire 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-stages 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.

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) [3]. 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.

The commissioning of focal spot on target and the main performance on target has been performed during the first campaigns (2nd semester 2017 to 1st semester 2019), see Fig. 3.

It concerns:

- The alignment of the sub-aperture compression stages in order to optimize the pulse compression (the mean duration was 685 fs for the 2018 shots in ps regime, the best 2018 value being 570 fs),
- the intensity on target of 9.2×10^{18} W/cm² in 2019 (intensity inferred from measurements at the end of the compressor for the 358 J @ 690 fs shot and confirmed by the TwIST measurement [4],

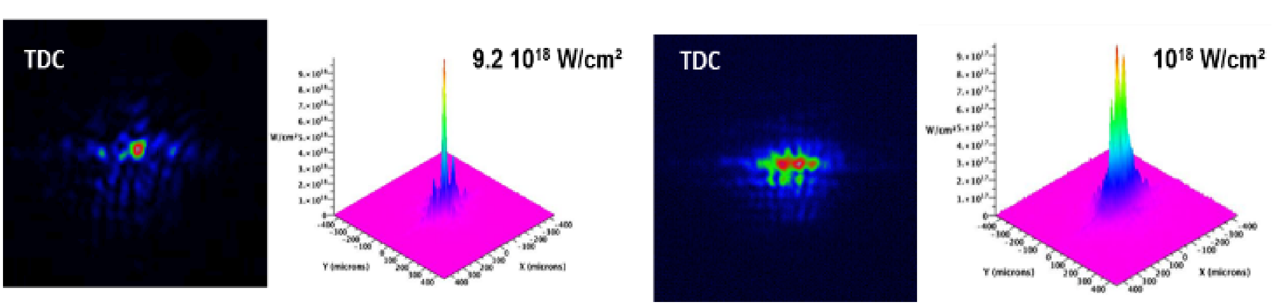

Figure 3: Focal spot (left) for the 358 J @ 690 fs shot giving 9.2×10^{18} W/cm², focal spot (right) optimized for the shot on the 25 µm wire with 396 J @ 3 ps and 10^{18} W/cm². They are measured on the compression diagnostic table TDC during shot.

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- the alignment performance (positioning, pointing) and demonstration of the first associated LMJ and PETAL laser shots on target.

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.

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.

EXPERIMENTS: "FUSION MILESTONE"

At the end of 2019 a major milestone has been reached with the fusion milestone. It was the first fusion experiments in cavity with 6 laser bundles in an indirect drive scheme. By this way, we are able to provide more than 150 kJ and 55 TW on target. Goals of this experiment were

- the realization of a thermonuclear fusion by implosion of a D_2 capsule in a Rugby cavity,
- the measurement of produced neutrons,
- the design robust to laser illumination asymmetry,
- the good capacity of prediction from our simulations.

The experiment is described on Fig. 4. The ten experiments provided a rich set of measurements for the validation of the 3D simulation code. Some of the experimental results are presented on Fig. 5.

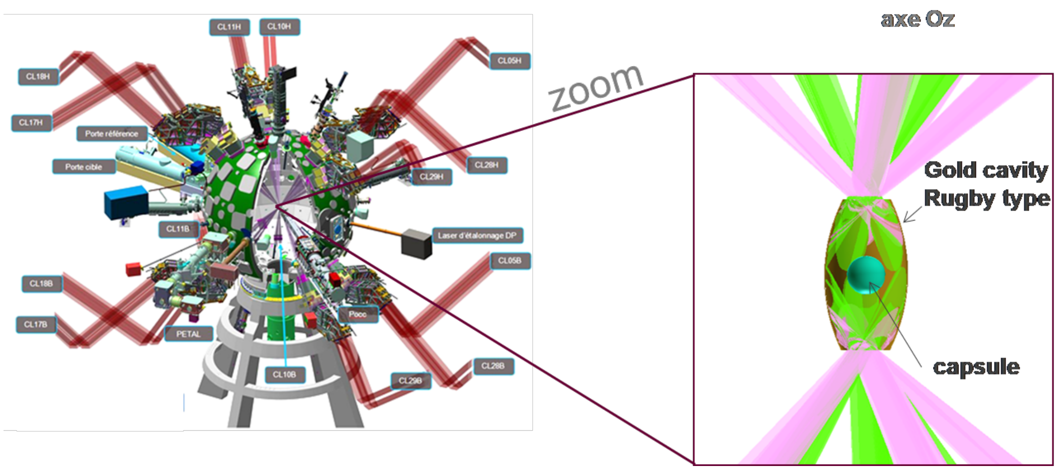

Figure 4: Experimental set-up.

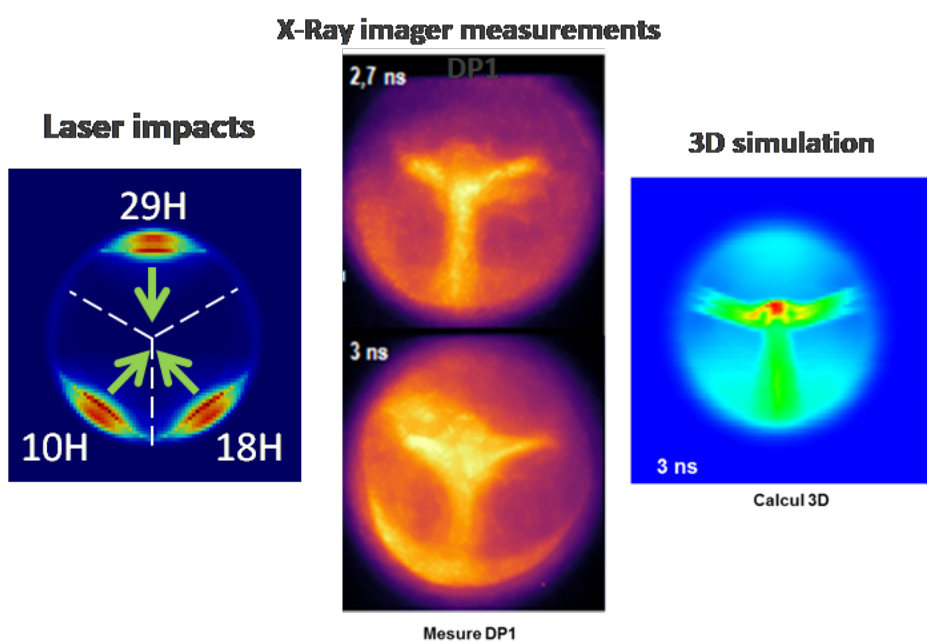

Figure 5: Hydrodynamics measurement of the cavity walls.

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CONCLUSION

At the end of 2021, The LMJ facility will be operational with ten LMJ bundles (80 beams) and with PETAL, a Petawatt class laser.

The combination of PETAL and LMJ extends the versatility of the laser facility.

From its commission in 2014, the capacity of the facility is constantly growing up. The assembly of new bundles go on following a rhythm of 2 bundles per year.

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