Laser driver developments at CEA from the pioneers to the LMJ

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ABSTRACT

The year 2024 will mark the 10th anniversary of the commissioning of the Laser Megajoule (LMJ) Inertial Confinement Fusion Laser first bundle of 8 laser beams. About 400 experiments on target were carried out in this period of time. Currently 11 bundles are in operation at half energy and power for experiments delivering up to 330kJ UV on target. The full system will be completed within few years. In this paper, we take the opportunity of the anniversary to look back from the beginning. We detail an historical review of the laser system development carried out at CEA DAM since 1962. We illustrate the different laser systems built and how they evolved as laser technology evolved with some pioneering results from frequency conversion to pulse compression. We then detail the LMJ design and architecture and focus on laser damage management in the different sub-assemblies of the system. We review the performance reached at half/energy and power with half bundles completed. We finally show the laser campaign performed since 2021 to test the energy/power increase on a few numbers of bundles, preparing the LMJ operation at full performance.

Keywords: high-power laser, high-energy laser, laser damage, fusion

1. 1962 TO THE MEGAJOULE LASER

Shortly after the discovery of the laser by T Maiman in 1960 [1], scientists had the idea of using these energetic and intense optical sources to heat plasmas [2, 3]. This was the beginning of the development and operation of multiple generations of high energy and/or power laser facilities worldwide. At CEA in France, eleven generations of main high-energy laser systems were used to study hot plasmas (see Fig 1). These facilities were located at CEA Limeil (from 1962 to 1999) and since then at CEA Cesta.

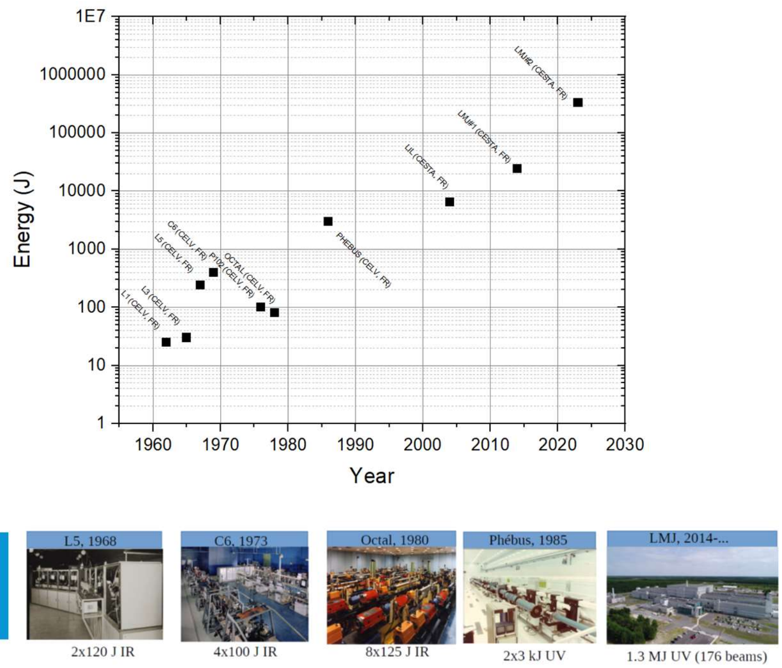

Figure 1: Main generation of high energy, high power laser in operation at CEA from 1962 to 2024. LMJ laser is represented at first light (one bundle = 8 beamlines in 2014) and in tis 2024 configuration (11 bundles = 88 beamlines)

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Some of the main performance, as well as important laser results, are detailed below:

- L1: From CGE company, commissioned in 1962, Ruby laser, 25 J, ms pulse duration (laser spiking).
- L2: From CGE company, commissioned in 1962, Ruby laser, 7 J, 50 ns pulse duration (Q-switching - Kerr cell).
- L3: From CGE company, commissioned in 1964, 2 lasers (one ruby, one Nd:silicate glass) 1 J 30 ns pulse duration.
- L4: From CGE company, commissioned in 1965, first beamline constituted of an oscillator and Nd :silicate glass rod amplifiers (2 ø16mm + 2 ø32mm). Efforts to develop aspheric lenses to improve focusing and increase intensity in collaboration with Institut d'Optique (J. P. Marioge, Paris).
- L5: From CGE company, commissioned in 1967, 2 beamlines, 2 x 120 J, 30 ns pulse duration, Φ16 mm oscillator (Q-switched) + Pockels cell and 5 rod amplifiers (up to Φ 45 mm) Nd doped silicate glass (Sovirel). 1st demonstration of D_2 neutrons on the L5 laser obtained in 1969 [5].
- C6: From CGE company, commissioned in 1967, 4 laser lines with 3 rod amplifiers (up to 64mm diameter, Nd:silicate glass) delivering 4 x 100 J at 1,5 ns. Faraday rotator to protect optics from backscattering. Used for the first second harmonic generation experiments (30% yield of green) with a KDP crystal grown by Quartz & Silice (France) [6] and first D2 neutrons triggered in green [7].
- P101: 1 beamline (mode locked Nd:YAG oscillator from QUANTEL + Rod + Slab Nd:silicate amplifiers (up to Φ 80 mm). First slab amplifiers used in this system (CGE-CILAS)
- P102: 1 beamline, commissioned in 1976, 100 J – 100 ps at commissioning. Rod amplifiers + slab amplifiers (128 mm diameter). Oscillator (QUANTEL) with complex temporal pulse shaping ability, pupil imaging, spatial filters, laser beam smoothing with optical fibers… Multiple upgrades for laser development purposes. The most iconic: 1st CPA demonstration on a High-energy laser system in collaboration with G. Mourou [8].
- PHEBUS : Developped by Laurence Livermore National lab and sub-contractors. Identical to 2 Nova beamlines [9]. 2 beamlines 10 kJ, ns, 1053 nm 4,5 kJ – ns – 527 nm / 3 kJ – ns – 351 nm + 1 radiographic beamline (1 kJ – ns – 1053 n to 05 kJ – ns – 351 nm). Nd: phosphate slab amplifiers up to 460 mm diameter. Mosaic of KDP for THG, automatic alignement, temporal shaping, etc…[10, 11]

2. THE MEGAJOULE LASER ERA.

The Laser Megajoule (LMJ) is one of the most powerful inertial confinement fusion laser facilities in the world, alongside the National Ignition Facility (NIF) in the United States. The project started with a first laser test bundle called the LIL (Laser Integration Line), which operated from 2004 to 2014. The LIL was used for qualification purposes and as an experimental facility for laser plasma experiments [12]. The construction of the LMJ facility started in 2003 and the first photons were emitted by laser bundle #28 in 2014. Currently, 11 laser bundles, each consisting of 88 large-aperture laser beams of 0.35×0.35 m², are in operation. These beams deliver up to 330 kJ of energy per day at a wavelength of 351 nm to a target positioned at the center of a 10 meters diameter vacuum chamber. The LIL/LMJ beamline incorporates many innovations compared to the previous generation of lasers: large 0.35x0.35 square apertures, 4-pass main amplifiers, deformable mirror for wavefront correction, optically addressable light valve for spatial contrast reduction, high damage resitance manufacturing processes for optics, beam steering and focusing gratings... A short-pulse high-intensity CPA laser beam, called PETAL, adds a PW capacity to the experimental facility [13]. Today, the LMJ laser is operated at half energy and half power to allow user experiments to be carried out on the same type of additional bundles to be assembled and commissioned. Laser campaigns are also performed since 2021 (QPerf2021 and QPerf 2023) to prepare for full energy and power operation of the facility [14]. These tests include various improvements in terms of laser beam performance (spatial and temporal modulation reduction) and UV optics high damage manufacturing processes. For these experiments, performed with a limited number of laser beams and shots, we have designed a specific optic to investigate damage growth [15]. This optic was used to calibrate our instrument for measuring damage size from measured integrated intensity. This technic is much more accurate than the dimension estimated from the number of pixels [16].

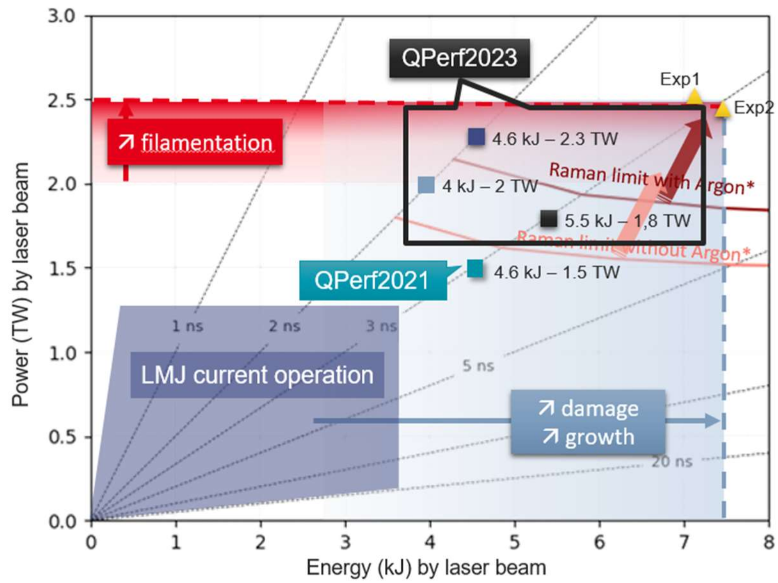

Figure 2: Energy/Power LMJ beamline diagram representing current operation and laser performance (dark blue) and QPerf campaigns carried out in 2021 and 2023 to prepare operation at higher energy and power.

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REFERENCES

[1] Maiman, T. *"Stimulated Optical Radiation in Ruby"*. Nature 187, 493–494 (1960).

[2] Basov N. G., Krokhin O. L., "*On the Condition of Plasma Heating by Optical Generator Radiation*", 3rd International Conference on Quantum Elec., Paris (1963)

[3] Dawson J. M., "*On the production of Plasma by Giant Pulses Lasers* " Physics of Fluids, **7**, 7 (1964)

[4] de Metz J., "*Optical Design of a Laser System for Nuclear Fusion Research*," Appl. Opt. 10, 1609-1614 (1971)

[5] Floux F, Cognard D, Bobin JL, Delobeau F and Fauquignon C, "*Reactions nucléiares de fusion engnedrées par un faisceau laser*" C. R. Acad Sc. Paris 269 (1969)

[6] Carion, A., Lancelot, J., De Metz, J., & Saleres, A. (1973). « *Fusion reactions in a plasma created by the second harmonic of a Nd glass laser"*. Physics Letters A, 45(6), 439-440.

[7] Sauteret, C., Husson, D., Thiell, G., Seznec, S., Gary, S., Migus, A., & Mourou, G. "*Generation of 20-TW pulses of picosecond duration using chirped-pulse amplification in a Nd: glass power chain"*. Optics letters, 16(4), 238-240 (1991).

[8] Strickland, Donna, and Gerard Mourou. "*Compression of amplified chirped optical pulses."* Optics communications 55.6 (1985): 447-449.

[9] Simmons, William W., and Robert O. Godwin. "Nova laser fusion facility—design, engineering, and assembly overview." *Nuclear Technology-Fusion* 4.1 (1983): 8-24.

[10] Andre, M., A. Coudeville, and R. Dautray. *PHEBUS: a new powerful laser facility for ICF research*. No. CEA-CONF--8557. CEA Centre d'Etudes de Limeil, 1986.

[11] Fleurot, Noel Andre, et al. "*Output pulse and energy capabilities of the PHEBUS laser facility*." Industrial and Scientific Uses of High-Power Lasers. Vol. 1502. SPIE, 1991.

[12] Julien, X., Adolf, A., Bar, E., Beau, V., Bordenave, E., Chiès, T., ... & Thiell, G. “*LIL laser performance statu”s*. In High Power Lasers for Fusion Research (Vol. 7916, pp. 223-235). SPIE (2011).
[13] Blanchot, N., Béhar, G., Chapuis, J. C., Chappuis, C., Chardavoine, S., Charrier, J. F., ... & Laniesse, F.. “*1.15 PW–850 J compressed beam demonstration using the PETAL facility*”. Optics Express, 25(15), 16957-16970. (2017)
[14] Neauport, J., et al. "Laser Megajoule performance status." Applied Optics 63.16 (2024): 4447-4464.
[15] Lacombe C, Lamaignère L, Hallo G, Sozet M, Donval T, Razé G, Ameil C, Benoit M, Gaudfrin F, Bordenave E, Bonod N, Néauport J. *Full-scale optic designed for onsite study of damage growth at the Laser MegaJoule facility*. Opt Express. 30;31(3):4291-4305 (2023).
[16] G. Hallo, C. Lacombe, M. Fouchier, M. Zerrad, J. Néauport, and F. Hild, "*Optical model-based calibration of gray levels for laser damage size assessment*," Opt. Lett. 48, 481-484 (2023)