Eur. Phys. J. D **44**, 207–213 (2007)
DOI: 10.1140/epjd/e2006-00165-4

THE EUROPEAN
PHYSICAL JOURNAL D

The megajoule laser program — ignition at hand

D. Besnard[a]

CEA/DAM Île-de-France, B.P. 12, 91680 Bruyères le Châtel, France

Received 21 December 2005 / Received in final form 27 March 2006
Published online 12 July 2006 –

Abstract. The French Commissariat à l'Énergie Atomique (CEA) is currently building the Laser MegaJoule (LMJ), a 240-beam laser facility, at the CEA Laboratory CESTA near Bordeaux. LMJ will be a cornerstone of CEA's "Programme Simulation", the French Stockpile Stewardship Program. LMJ is designed to deliver about 2 MJ of 0.35 μm light to targets for high energy density physics experiments, among which fusion experiments. LMJ technological choices were validated with the *Ligne d'Intégration Laser* (LIL), a scale 1 prototype of one LMJ bundle, built at CEA/CESTA. Plasma experiments started at the end of 2004 on LIL, which is already open to the scientific community through the Plasma and Lasers Institute. The construction of the LMJ building itself started in March of 2003. LMJ will be gradually commissioned from early 2011, and after an experimental program to progress toward fusion, the first fusion experiments will begin late 2012.

PACS. 52.57.-z Laser inertial confinement – 52.57.Bc Target design and fabrication – 42.60.-v Laser optical systems: design and operation

1 LMJ design and optimization

The LMJ facility is a key part of the French "Simulation Program". The LMJ is devoted to laboratory experiments on the behavior of materials under very high temperature and pressure conditions. It is a key facility for training physicists engaged in the French deterrent. It also has applications in the field of astrophysics, Inertial Fusion Energy (IFE) and fundamental physics [1]. In order to cover those different applications, the facility is designed with maximum flexibility in terms of pulse duration (from 200 ps to 25 ns) and power. Plasma diagnostics will be easily interchanged depending on the type of experiments, using special diagnostic inserters and positioners.

The LMJ most stringent specifications are dictated by fusion experiments, the first of which to be carried out late 2012. Specifications for the laser were obtained with an optimization of the laser itself together with the fusion target (Fig. 1). A fusion target is composed of a 1 cm long, usually gold, cylindrical holhraum, used to convert laser light to X-rays. X-rays smoothly irradiate a 2 mm diameter capsule, composed of a polymer ablator and DT. The laser beams are distributed in three cones that enter the holhraum through two apertures, one on each side of the holhraum. The laser beams illuminate the holhraum as quadruplets. The laser light spots locations are chosen in such a way that the converted X-rays provide a very uniform irradiation of the capsule. In order to further enhance the efficiency of the implosion, the DT contained in the capsule is solid for the most part.

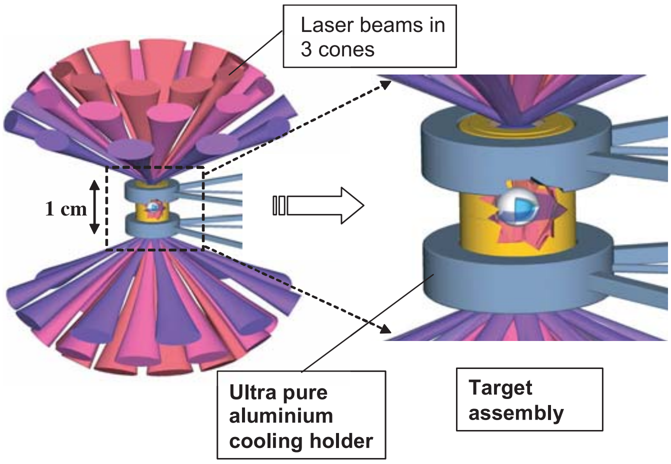

Fig. 1. (Color online) A CAD view of the LMJ cryogenic target showing the 3 cones of laser beams entering the conversion holhraum and a detail of the target assembly.

The fusion capsule is therefore composed of the ablator, a layer of solid DT, and a central gaseous DT core. The target assembly is maintained at about 18 K with an elaborate cryogenic system. Figure 1 shows the high purity aluminum target holder that refrigerates the target through thermal conduction [2].

[a] e-mail: didier.besnard@cea.fr

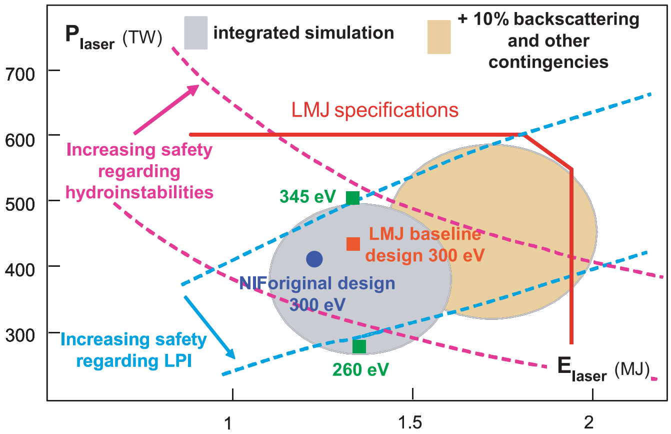

Fig. 2. (Color online) Energy/power operating domain of LMJ.

To determine LMJ and target specifications, we used numerical simulation to optimize 1D capsules imploding under shaped laser pulses. This gave the required energy and laser power. 2D integrated simulations were then performed to optimize beams position and energy balance. Such calculations accounted for laser plasma interaction within the target's holhraum, as well as symmetry requirements. Margins were added to the reference design in order to take into account the two main remaining uncertainties, that is the effect of laser parametric instabilities (LPI) and hydrodynamic instabilities (Fig. 2). With current laser specifications, 2D integrated simulations show that our point design targets delivers more than ten times as much energy as the laser energy itself. The next step is to design and optimize our fusion target, which is been done using our suite of 1D/2D/3D target implosion codes.

These codes have a rich physics package, necessary for simulating the implosion of a fusion target. They include laser-matter interaction (a raytracing package), multifluid approximations for both ions and electrons, coupling to radiation transport, as well as coupling to fast electrons, neutrons and alpha particle transport [3].

LMJ's optical scheme was first conceived with the MIRO code (Fig. 3) [4]. Each component was modeled, and the modeling later validated against experimental results coming from our prototype, the Ligne d'Integration Laser (LIL). LIL has been a testbed for our technological choices. It is operated since march 2002.

In November 2002, the infrared energy specification was demonstrated, with 20 kJ obtained on one beam. In April 2003, ultraviolet energy specification was attained, with 9.5 kJ demonstrated (one beam). These two results exceeded the specifications of respectively 15 kJ and 7.5 kJ, demonstrating the robustness of the optical scheme. The four beams focal spot was obtained in June 2004 and has validated the choice of focusing with gratings [5].

The LIL is currently used both for LMJ needs and as a physics facility in its own right. Its current status is 1 quadruplet of beams, longitudinal smoothing, a 700 microns focal spot. 12 plasma diagnostics are available (Fig. 4) [6], and a 13th will be in 2006 (VISAR + shock breakout viewing + pyrometer).

The first plasma experiments were carried out at the end of 2004. Among them let us mention the observation of a plasma jet induced by the collision of four plasmas. These plasmas are created by the LIL four laser beams, that are slightly defocused and illuminate the internal surface of a gold cone (Fig. 5). Simulations agree with experimental results, and confirm earlier experiments carried out on NOVA and GEKKO XII facilities [7].

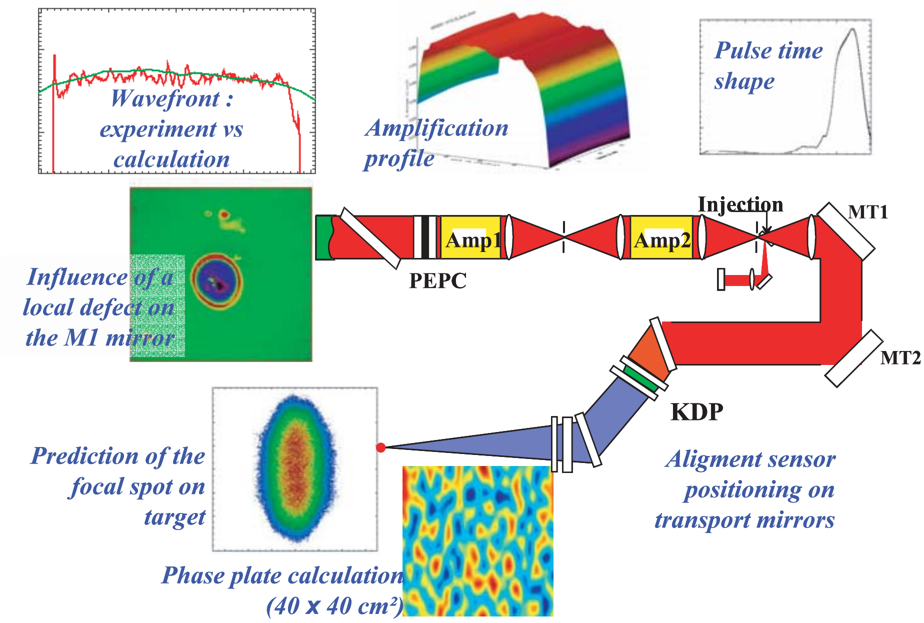

Fig. 3. (Color online) MIRO calculation of LMJ's optical scheme.

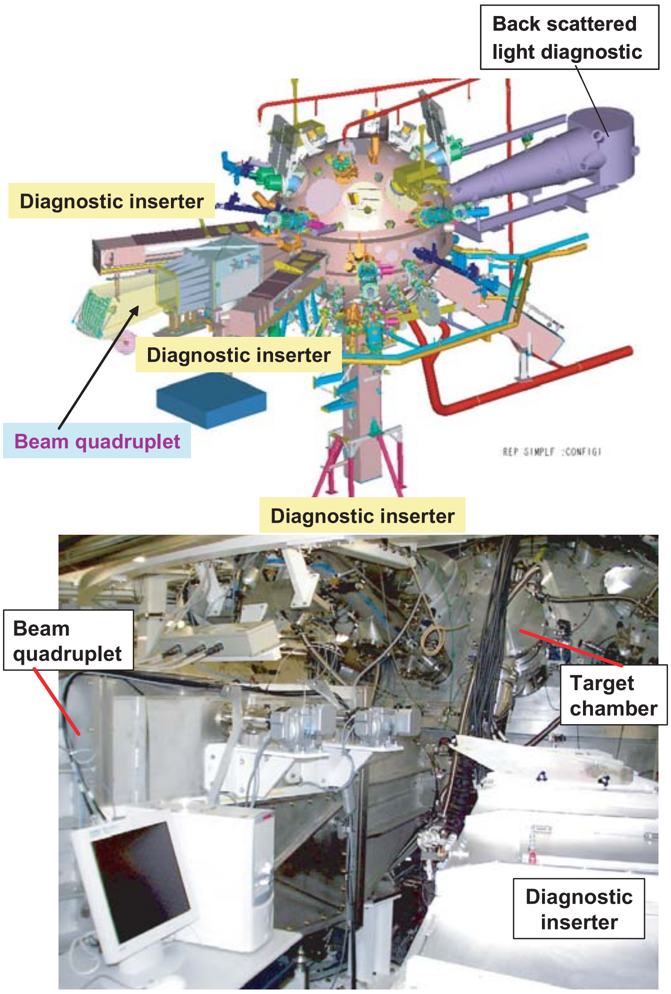

Fig. 4. (Color online) CAD view of the LIL target chamber with its diagnostics and a view of the actual target bay.

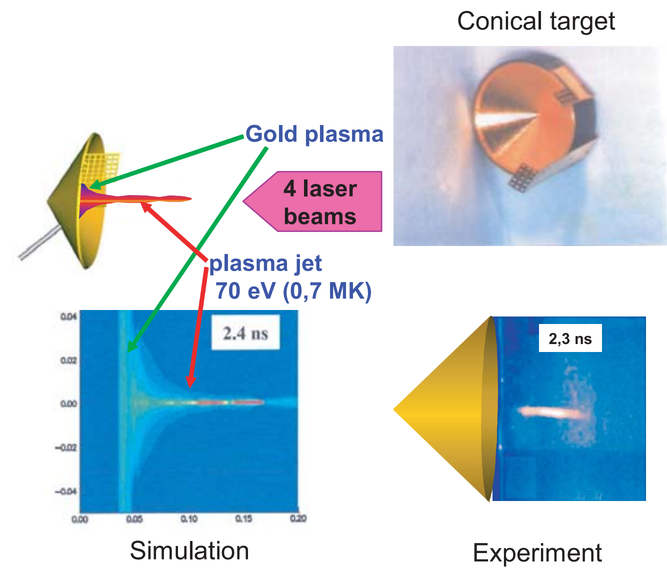

Fig. 5. (Color online) Plasma experiment on LIL, observation of a collisional plasma jet.

With 240 beams arranged in 30 bundles (8 beams per bundle), LMJ will deliver 1.8 MJ of UV light (0.35 μm). For pulse durations of about 3.5 ns, the corresponding power will be about 550 TW and significant target gains are expected with cryogenic targets (Fig. 2).

With these specifications, our baseline capsule design is proved to be robust. An extensive analysis was performed, which gave an estimate of the effect of 19 coupled parameters; these involve beam pointing accuracy, beam energy, as well as target dimensions and fabrication. To do so, a set of three models were adjusted to our reference 2D simulations: a ray-tracing model, which gives the laser flux on the holhraum's walls, a view factor model, which gives the X-ray flux on the capsule, converted from laser light, and an implosion model, giving the DT final radius (Fig. 6).

The deformation of the hot spot (where fusion reactions take place) can prevent ignition if too large. The calculations performed with our baseline design showed that the hot spot deformation's amplitude is always smaller than 10–15% of the hot spot size, demonstrating its robustness.

The overall efficiency of the baseline design is 11% (ratio of the useful energy to compress the capsule on the incoming laser energy). 3D capsule simulation started in 2004 and will gain momentum from 2006 with the availability of CEA's new computer TERA 10 (50 teraflops peak), which will be fully installed at the end of 2005.

Laser propagation through realistic plasmas has been calculated on CEA's TERA 1 (5 teraflops peak) supercomputer, with the HERA code [8]. The results show a good beam quality after propagation (Fig. 7). Experiments are planned in order to compare calculated and experimental results, and more detailed calculations will be made in 2006 using TERA 10.

LMJ's cryogenics is in itself an important program [9]. CEA – Grenoble research center, well known for its expertise in cryogenics, is at the heart of this program. Basic principles for the cryogenic target inserter were validated on a scale 1 mock-up (Fig. 8).

Capsules with solid DT shell have been characterized by interferometry and shadowgraphy, and the target assembly qualified in cryogenic environment (Figs. 9 and 10). To date, all milestones were passed and the program is right on schedule.

2 LMJ facility

The construction of the LMJ's building started in march 2003. Located 150 meters away from the existing LIL building, the four laser bays will be located on both side of the 40×40 m^2 target chamber bay (Fig. 11).

Laser and target bay concrete halls are under construction (Fig. 12). The first laser bay construction (in the Northeast LMJ laser hall) is finished. The target chamber supporting structures have started as planned on May 2005.

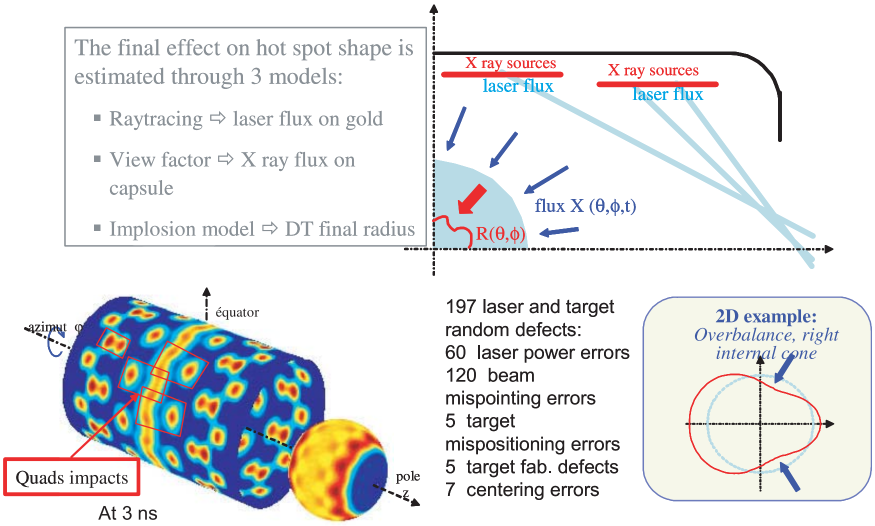

Fig. 6. (Color online) Target simulation.

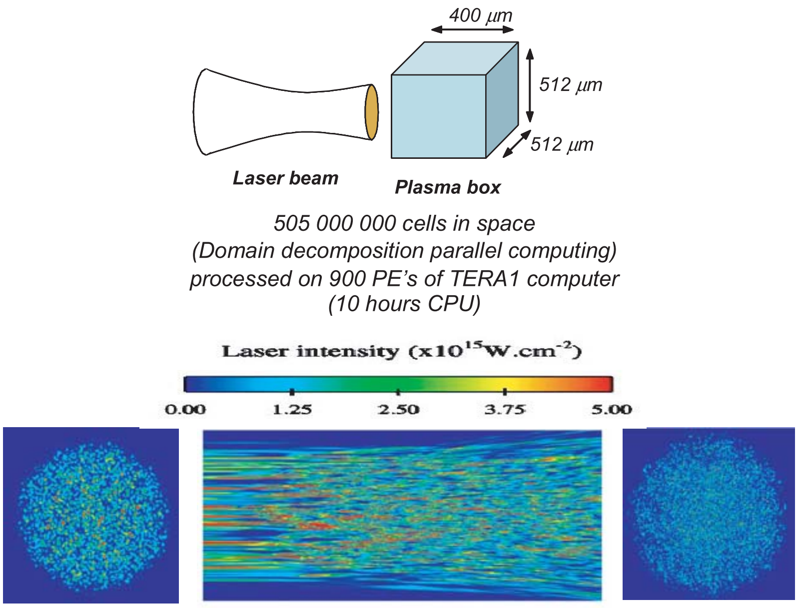

Fig. 7. (Color online) Simulation of laser propagation through a plasma.

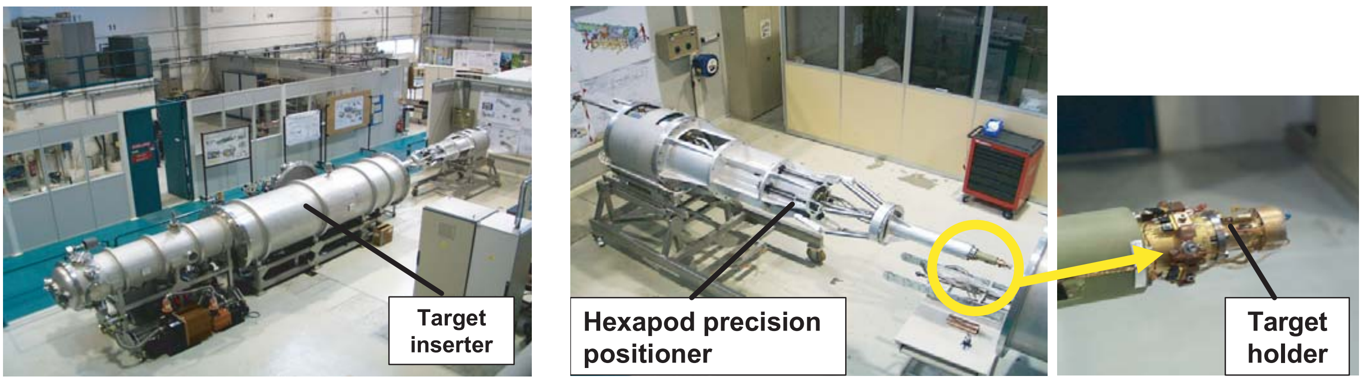

Fig. 8. (Color online) Scale 1 target inserter mock-up in CEA Grenoble – cryogenic technology for thermal control from ambient down to 18 K – left: overall view of the vacuum vessel; right: details of the target positioner and holder.

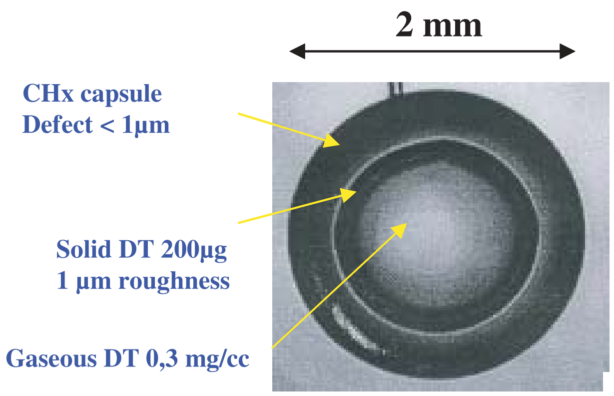

Fig. 9. (Color online) DT capsule.

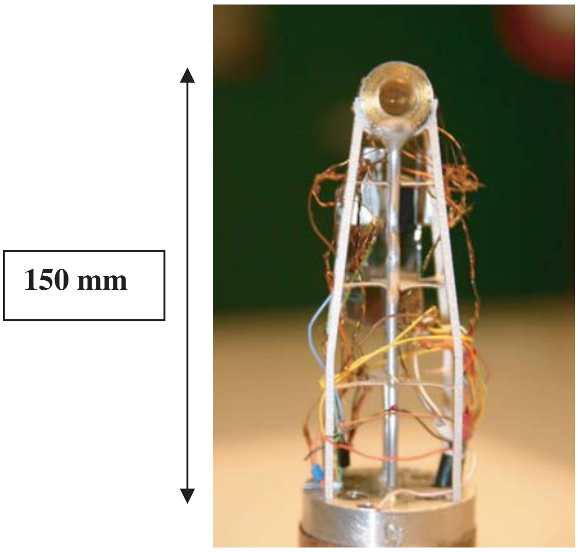

Fig. 10. (Color online) Cryogenic target assembly.

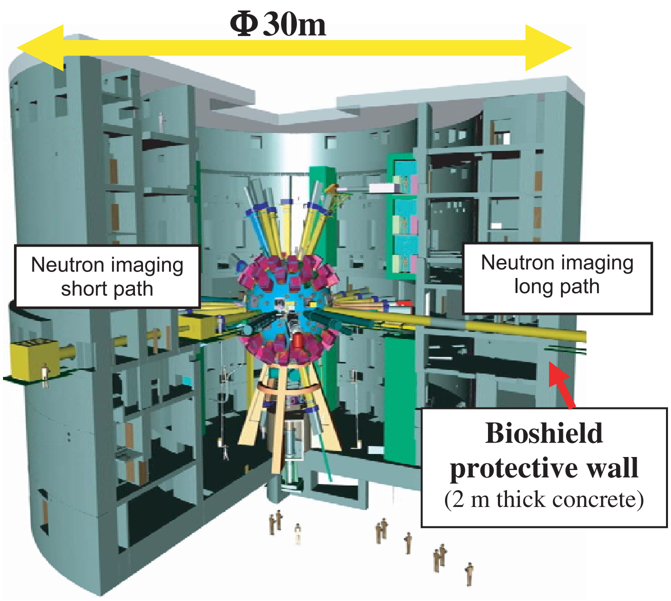

Fig. 11. (Color online) Model of the target bay.

Fig. 12. (Color online) General view of the construction site.

Fig. 13. (Color online) Target chamber under construction.

The fabrication of the target chamber is near completion (Fig. 13); the chamber will be installed in the target bay in 2006.

With a diameter of 10 m and a thickness of 10 cm of aluminum, it will have 260 holes; 80 of them can be used as laser windows, giving the maximum flexibility for experimental arrangement of the 60 quadruplets.

3 LMJ ignition and hedp programs

LIL and LMJ experimental programs are based on a detailed analysis of CEA/DAM physics modeling needs, as identified by the Simulation Program.

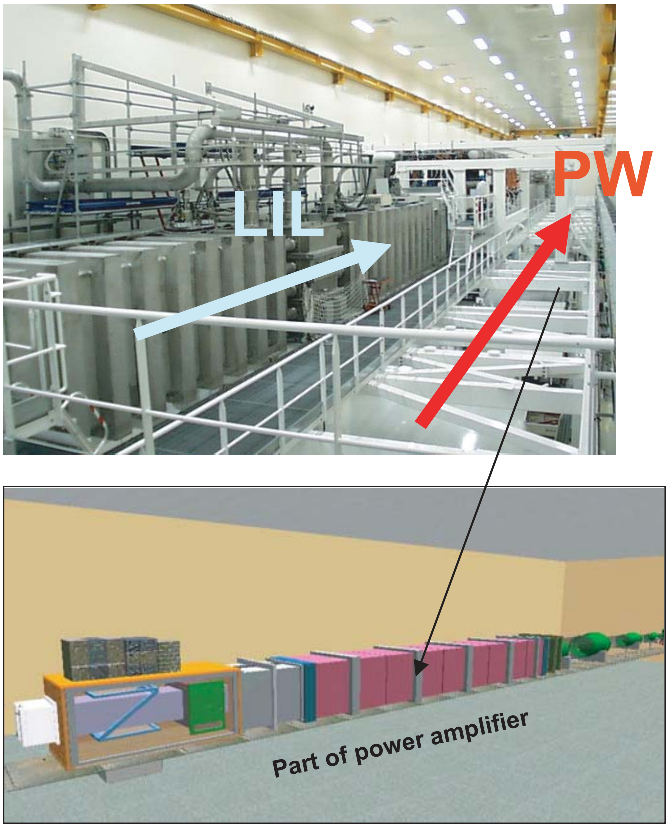

Fig. 14. (Color online) Location and CAD view of part of the multi-PW laser coupled with LIL.

LIL will first be used to test and prepare the complex experiments planned in the LMJ facility. It will also be used in its own right, as it evolves towards its 8-beam configuration. Eventually, it will be coupled to a 3.5 kJ – 7 Petawatt laser (Fig. 14), scheduled to be in operation end of 2009 [10].

To achieve ignition, a comprehensive experimental program has been planned on LMJ. After a demonstration of LMJ performances, a few shots will allow to measure the effect of the smoothing techniques that were chosen for LMJ. Then, holhraum experiments will be performed to adjust the radiation temperature with time. Symmetry will then be optimized, and eventually, after shock synchronization, capsule implosion will be checked against our simulations. With all these ingredients in place, fusion experiments can be performed.

LIL and LMJ will be open to the scientific community. Access to these facilities is organized by the Laser and Plasmas Institute (ILP). ILP was founded in March 2003 by the French research institutions CNRS, Bordeaux-1 University, École Polytechnique, and CEA. This institute gathers scientists in thirty laboratories in the fields of laser-produced hot and dense plasmas, high energy lasers and high energy density physics.

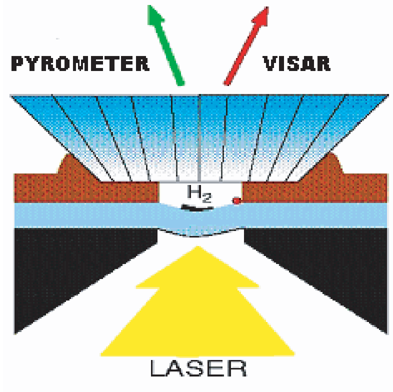

Fig. 15. (Color online) Schematics of a laser induced shock experiment.

Access to LIL is already possible. The first call for proposals was sent out in February 2005 and two projects were selected. The corresponding experiments will be carried out starting in November 2005. The request for 2006 proposals was sent out, and answers are expected for the end of 2005.

An industrial park next to LMJ will include the facilities for LMJ maintenance and for mounting LMJ components, including an ultra-clean platform. It will eventually include a research area and host interested start-ups.

Indeed, CEA emphasizes collaborative work in these fields. As an example, some experiments are currently proposed on LIL, to measure hydrogen's equation of state. This proposal is based on prior experiments performed on the VULCAN (2002) and OMEGA lasers [11]. Previous static experiments could induce an increase of a factor 7 in density at 20 GPa. Illuminating an already compressed target with LIL beams will allow to reach an additional factor of 4. Temperatures of interest (resp. pressure) are between 0.3 and 3 eV, (resp. 1 and 20 Mbar). A schematic of this experiment is shown in Figure 15.

4 Conclusion

The LIL, the prototype of LMJ, was used to validate the technological choices for LMJ. It is now a plasma physics experiments facility. In 2006, the last of the 13 plasma diagnostics will be put in operation.

The LMJ building construction begun in march 2003 and is on schedule. The target chamber, which is nearing completion, will be introduced in the building in 2006. The LMJ 240 beams will be put in operation in 2011, and first fusion experiments performed late 2012.

The author is indebted to the CEA staff for their contributions to the results presented here, and more especially, to J. Ebrardt for his help.

References

1. E.M. Campbell et al., in C. R. Acad. Sci., Série IV, Tome 1, n° 6, August 2000
2. P. Baclet et al., Fusion Sci. Techn. **45**, 276 (2004)
3. P.A. Holstein et al., Nucl. Fus. **44**, S177 (2004)
4. A. Adolf et al., in *Proceedings of the Third International Conference on Solid State Lasers for Application to Inertial Confinement Fusion*, SPIE **3492**, 44 (1998)
5. C. Cavailler et al., Plasma Phys. Contr. Fus. **46**, B135 (2004)
6. J.P. Le Breton et al., in *Proceedings of the European Conference on Laser Interaction with Matter, 2004*
7. M.C. Monteil et al., in *Proceedings of the Fourth International Conference on Inertial Fusion Science and Applications, 2005* (EDP Sciences, Les Ulis), to be published
8. S. Weber at al., Laser Part. Beams **22**, 189 (2004)
9. P. Baclet et al., Fus. Sci. Techn. **41**, 261 (2002)
10. P. Vivini, in *Proceedings of the Fourth International Conference on Inertial Fusion Science and Applications, 2005* (EDP Sciences, Les Ulis), to be published
11. P. Loubeyre, High Press. Res. **24**, 25 (2004)