Positioning a target in the reaction chamber of Laser Mégajoule, France's new €3 billion laser fusion laboratory.

PHYSICS

Laser fusion, with a difference

Europe's Laser Mégajoule project blazes its own trail toward nuclear ignition

By **Daniel Clery**, *in Le Barp, Aquitaine, France*

To anyone familiar with laser fusion research, a visit to Laser Mégajoule (LMJ), a €3 billion research facility completed late last year near France's Atlantic coast, triggers instant déjà vu. The site is a dead ringer for the world's leading lab, the National Ignition Facility (NIF) in California. LMJ has the same stadium-sized building, the same shiny white metal framework, the same square beam tubes and 10-meter-wide reaction chamber. The coffee is richer than NIF's, the security less obtrusive, the visitors' area larger and more informative. Overall, however, walking through LMJ's doors is like stepping into a parallel universe in which Lawrence Livermore National Laboratory, the U.S. nuclear weapons laboratory that runs NIF, has somehow come under French control.

The similarities are no coincidence. Both sites were designed for the same purpose—to train scores of powerful laser beams on a single target, subjecting it, for an instant, to outlandish extremes of temperature and pressure. The two labs have collaborated extensively, and the primary mission of each is military: replicating nuclear explosions in miniature so that weapons scientists can ensure their bombs will detonate if needed without having to test them. The French facility, like its U.S. counterpart, will also pursue a sideline in inertial fusion energy (IFE) research: crushing capsules of hydrogen isotopes with laser pulses so that the isotopes fuse into helium, releasing vast stores of energy that might one day be harnessed in a power plant.

But in a major departure from NIF's initial approach, LMJ is putting top-secret weapons research first. Once NIF was complete in 2009, Livermore researchers immediately embarked on a crash program to achieve ignition—generating a self-sustaining fusion reaction that produces as much energy as went into triggering it. They failed to reach that goal and have since changed their approach (*Science*, 21 September 2012, p. 1444).

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France's Alternative Energy and Atomic Energy Commission (CEA), which built LMJ, also wants to achieve ignition, because it's key to both weapons research and energy. "The target of ignition drives the design of the machine," says Pierre Vivini, LMJ's project leader. But generating power from laser fusion will be left to outside academic researchers, and they won't get their hands on the machine for another 2 years. When they do, some key design differences may give LMJ a better chance of triggering ignition than NIF has.

At their core, the two facilities are near-twins. Just as at NIF, LMJ researchers use a fiber laser to produce a pulse of infrared light that lasts a few billionths of a second, with just billionths of a joule of energy. This weak pulse then passes into preamplifiers, slabs of neodymium-doped glass that are pumped full of energy by xenon flash lamps just before the pulse comes through. They dump that energy into the beam, boosting it to about a joule, before the light is split into many parallel beams and sent to the main amplifiers (the same neodymium glass and flash lamps, only bigger).

LMJ has 22 main amplifier chains, arranged in four vast halls around the building, and each amplifier accommodates eight parallel beams at a time. During a laser shot, the eight beams are bounced back and forth through the amplifier four times to multiply their energy by a factor of 20,000. An elaborate array of mirrors will direct the 176 beams around all sides of the spherical reaction chamber; then a final set

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of optics will convert the beams from infrared to ultraviolet (UV) light and focus them to a needle-sharp point at the center of the chamber. Recombining all the beams delivers 1.5 megajoules of energy into the target at the center of the chamber—roughly the same as the kinetic energy of a 2-tonne truck traveling at 140 kilometers per hour. NIF's laser delivers 1.8 megajoules.

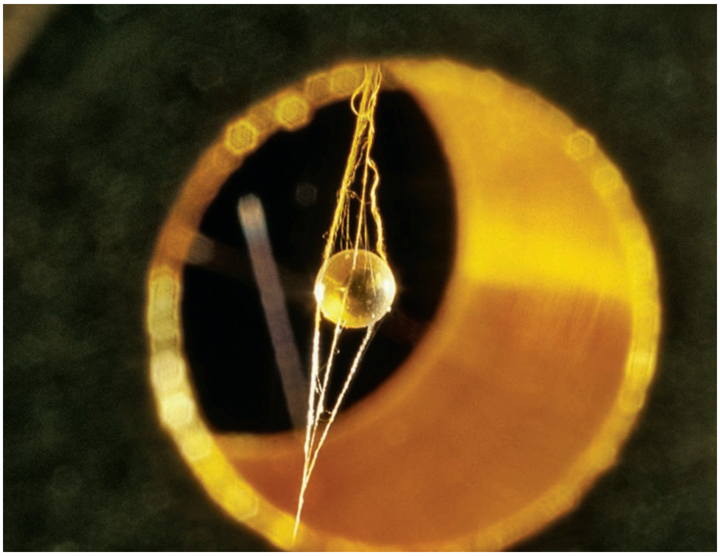
Because of funding constraints, only one main amplifier chain is now online. But that is enough to get started on nuclear weapons research, says François Geleznikoff, director of nuclear weapons at CEA: "With eight beams we can do good physics. We don't need all the beams to study weapons." The facility will add at least another two chains (16 beams) each year until it reaches full capacity sometime in the next 10 years. Well before then, academic IFE researchers from across Europe have been promised at least 20% of the machine's time. "With 50 shots per year we can really develop a serious program," says plasma physicist Dimitri Batani of the University of Bordeaux in France.

Their game plan includes some significant deviations from NIF's strategy. For example, they've won funding for a separate laser to be installed at LMJ, providing pulses much shorter and more powerful than anything NIF can match. The PETawatt Aquitaine Laser (PETAL) will generate pulses with a relatively modest 3.5 kilojoules of energy, but that energy will be crammed into a trillionth of a second, producing a power of more than a thousand trillion watts—a hundred times that of LMJ's pulses. PETAL's pulses won't be split and delivered from all directions; they'll come from a single direction timed to coincide with a pulse from the main laser. In experiments, they could provide a sudden intense kick of power or could be used like a strobe light to take snapshots of what's going on.

Experiments combining PETAL and LMJ will mimic the conditions in the interiors of stars and other astrophysical objects. Researchers will also use the powerful laser jolts to accelerate protons—an approach that could yield compact accelerators for cancer therapy. But what excites laser fusion researchers is the prospect that the short, sharp blasts from PETAL could act as a spark plug for fusion reactions.

The hope is that using PETAL in this way will allow IFE researchers to avoid some of the pitfalls that have hobbled NIF. The key element of any IFE scheme is the fuel capsule, a plastic sphere about the size of a peppercorn containing frozen deuterium and tritium—isotopes of hydrogen that are the fuel of fusion. Placed at the center of the reaction chamber, the plastic of the capsule is vaporized by the intense heating from the laser pulse, causing an implosion that crushes the fuel to 100 times the density of lead and heats it to 100 million K—which should be sufficient for fusion to ignite.

At NIF and in the weapons research experiments at LMJ, researchers trigger the implosion indirectly by enclosing the capsule in a metal can that is heated by the laser and in turn bombards the capsule with x-rays. That approach offers some advantages—it smoothes out imperfections in the laser beam, and x-rays are better than UV light at driving the implosion—but it makes the target complex and expensive, not what you want for energy generation. NIF researchers have struggled to make this approach work: Energy is lost in the process of converting light into x-rays, and the implosions do not progress smoothly.



A peppercorn-sized fusion fuel capsule suspended inside its metal can.

IFE researchers outside the weapons labs want to do things differently. By getting rid of the can and targeting beams directly on the capsule, they can avoid the complications and energy loss of converting UV light to x-rays. To get a smooth, symmetrical implosion, many advocate driving it more slowly. But then the compressed fuel won't get hot enough to start reacting on its own; it will need an extra spark to start it off.

One possible solution, known as fast ignition and pioneered at the Osaka University in Japan, is to use a short, high-powered laser pulse as the spark—the sort of pulse that PETAL can produce. Last decade, European IFE researchers proposed building a demonstration IFE reactor based on fast ignition, called HiPER. That plan lost some momentum when NIF fell far short of ignition, but its proponents hope LMJ-PETAL will give it new impetus.

Recent experiments on lower powered machines have suggested that PETAL might not pack enough punch to trigger fast ignition. But another alternative approach, pioneered at the University of Rochester in New York, might save the day. The technique, known as shock ignition, compresses the fuel capsule with a laser pulse from the main laser as in other techniques. But at the end of the pulse, the laser adds a sudden spike of power to produce a shock wave converging on the center of the fuel. When the shock hits the center, the sudden hike in pressure sparks the reaction. "Experiments at Omega [Rochester's laser] and elsewhere are encouraging, and the laser requirements [for shock ignition] look rather more benign than fast ignition at this stage," says Chris Edwards, a fusion researcher at the Central Laser Facility at the United Kingdom's Rutherford Appleton Laboratory and one of the leaders of HiPER.

In their quest for fusion energy with LMJ-PETAL, researchers face sociological and political challenges, too. The European IFE community is small and is not used to working with such a huge machine or with weapons lab levels of security. "LMJ alone is like a cathedral in the desert," Batani says. "Researchers are interested, but suspicious. Many are not convinced it is a good tool for research." CEA also needs to overcome its reluctance to share simulation codes with academic researchers for fear of helping rogue nations develop thermonuclear weapons, Batani says: "We need reliable simulations, but there is no open code." And Europe has traditionally focused on a different approach, magnetic confinement fusion, which has its own cathedral not far away: the multibillion-euro ITER, under construction in Cadarache, France.

"If shock ignition on LMJ works, politicians could become more positive," Batani says. And Europe—always an also-ran in this branch of fusion energy—might just gain some boasting rights. ■

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