Nuclear Fusion: Breakthrough in Inertial Confinement*

Indulekha Kavila

On 13th December, the U.S. Department of Energy (DOE) and DOE's National Nuclear Security Administration (NNSA) announced the achievement of fusion ignition at Lawrence Livermore National Laboratory (LLNL) as the culmination of the hard work of many dedicated scientists, engineers, technicians, and administrative team members. At 1:03 a.m. on 5th December, 192 giant lasers at the laboratory's National Ignition Facility (NIF) achieved ignition, where the energy generated by fusion equals the energy of the incoming lasers that start the reaction (scientific energy breakeven). In a brief moment lasting less than 100 trillionths of a second, the 192 lasers together delivered 2.05 megajoules of energy (generating and delivering which required 3 megajoules of energy!) blasting a small cylinder (the hohlraum made of high atomic number material like uranium or gold) about the size of a pencil eraser that contained a frozen nubbin of hydrogen encased in diamond (low atomic number material). A flood of neutrons flowed out carrying around 3 megajoules of energy, a factor of 1.5 in energy gain. The laser beams entered from the top and bottom of the cylinder producing X-rays on impingement which then caused vaporization and outward escape of the outer surface. The reaction force produced on the remainder of the target accelerated it inwards, compressing the fuel. The shock waves created also travel inward through the target. Sufficiently powerful shock waves can compress and heat the fuel at the center such that fusion occurs ($^2\text{H} + {}^3\text{H} \rightarrow {}^4_2\text{He} + n + 17.6$ MeV). The fusion reactions release high-energy particles, which collide with the high-density fuel around them and slow down. This heats the fuel further and can potentially cause that fuel to undergo fusion as well. Given high enough density and temperature, this heating process can result in a chain reaction, burning outward from the center where the shock wave started the reaction. This can lead to a significant portion of the fuel in the target undergoing fusion and releasing significant amounts of energy. The condition is known as ignition. In the experiment reported, the BB-size (4.57 mm diameter) deuterium + tritium fuel pellet imploded, and the fuel was compressed and heated to fusion conditions. And a most fundamental science basis for inertial fusion energy (IFE) was demonstrated.

In a fusion reaction, the nuclei of two lightweight atoms collide and join forming a more tightly bound heavier atom and releasing the binding energy. The energy released is a million times than what is released in chemical reactions like the burning of fossil fuels. Fusion taking place in stellar cores (density ~150 g/cc and temperature ~16 million kelvin in the Sun's core, for example) powers the stars. In ICF (Inertial Confinement Fusion; for fusion via magnetic confinement see [1] for example; see also [2]), the inertia of the fuel, which will make it retain

---

*Vol.28, No.1, DOI: https://doi.org/10.1007/s12045-023-1533-4

the high state of compression long enough to ignite fusion, is used. The nuclei traveling towards each other should overcome mutual electrostatic repulsion/tunnel through the electrostatic barrier as allowed quantum mechanically. The rates needed require temperatures around 100 million kelvin. Also, enough fuel (in experimental fuel pellets, this is typically ∼10 milligrams) must be held together for long enough. The pioneers recognized that laser heating alone of the fusion fuel would not be enough, and to achieve energy gain, the laser would also have to compress the fuel to about 1000 times its liquid density (to ∼200 g/cm^3) and a small laser fusion project was started. The energy must be delivered quickly to compress the core and create a suitable shock wave. The laser beams must also be so focussed and the surfaces in interaction with the laser and the forces in action sufficiently even so that implosion rather than the squirting off of the fuel to a side takes place (for details, please see [3]).

The story began in the nineteen sixties, soon after the discovery of the laser, when a group of physicists led by John H. Nuckolls hypothesized that lasers could be used to induce fusion in a laboratory setting via the interaction of intense radiation with matter. This revolutionary idea blossomed into ICF, spinning off more than 60 years of research and development in lasers, optics, diagnostics, target fabrication, computer modeling and simulation, and experimental design. This led to the development of a series of increasingly powerful and sophisticated laser systems leading to the creation of the NIF with ignition as its goal. NIF, located at the LLNL, is the size of a sports stadium. Ignition was achieved at the NIF through dedicated efforts from LLNL employees and countless collaborators from other major laboratories (Los Alamos National Laboratory, Sandia National Laboratories, and Nevada National Security Site; General Atomics) and academic institutions (University of Rochester's Laboratory for Laser Energetics, the Massachusetts Institute of Technology, the University of California, Berkeley, Princeton University) and international partners (like United Kingdom's Atomic Weapons Establishment and the French Alternative Energies and Atomic Energy Commission) and the government (USA's DOE, NNSA, and the Congress). Sophisticated lasers may be put to many other uses, too, like, for example, in precision metrology, isotope separation, and communications.

Making an inertial fusion power plant in the future, creating the amount of electricity produced by typical power plants today, will require new drivers capable of igniting targets in rapid succession (five to ten targets per second) and new target chambers with large coolant flows to remove the fusion heat. The leading candidate driver for such high pulse rates would use beams of heavy ions (such as lead ions), which are produced in a high-current pulsed accelerator and are focused onto the target with magnetic lenses. LLNL is doing experiments on a ring-shaped heavy-ion accelerator called a recirculating induction accelerator. LLNL is also developing new types of solid-state lasers, called diode-pumped solid-state lasers, as a potential alternative driver for power plants. Instead of using flashlamps as in the NIF, powerful arrays of small solid-state laser diodes are used to optically pump experimental lasers of the type developed at LLNL to ten pulses per second.

"Probably decades," Kimberly S. Budil, the Director of LLNL, had said during the news conference. "Not six decades, I don't think. I think not five decades, which is what we used to say. I think it's moving into the foreground, and probably, with concerted effort and investment, a few decades of research on the underlying technologies could put us in a position to build a power plant."

Box 1.

The saga: 1972: the Lawrence Livermore National Laboratory's (LLNL) Laser program started; 1975: the Lab's first ICF laser Janus was built with two beams and 50 to 100 pounds of laser glass; the same year, the one-beam Cyclops laser was developed; 1976: the two-beam Argus was built; 1977: the 20-beam Shiva became operational delivering 10 kilojoules of energy in a billionth of a second; 1983: the Novette laser came on line creating the first soft-X-ray laser; 1984: the Nova laser, 10 times more powerful than Shiva, was produced; 1997: construction of the National Ignition Facility (NIF) with 192 laser beams (which together produces 1.8 million joules–approximately 500 trillion watts of power for 3 billionths of a second–of laser energy in the near-ultraviolet spectral region) and 200 tons of optics begins.

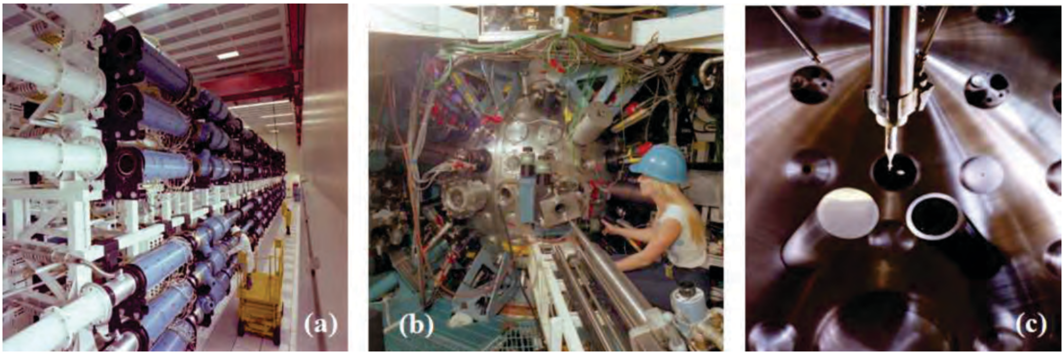
The light from the NIF's beams is tightly focused onto a tiny target filled with cryogenic fusion fuel located inside a 10-meter-diameter spherical chamber equipped with the most advanced diagnostic equipment. Novette achieved enhanced laser to target plasma energy coupling utilizing frequency tripled light. The community computer code called LASNEX, developed for laser fusion is the "work horse" of fusion predictions for scientists working in the USA.

The dramatis personae: "...a unique blend of physicists, engineers, chemists, computer scientists, technicians, and administrative staff who worked as integrated teams, and leadership who recognized that the tasks would be multidecades long and never lost sight of the goals."

Fusion Energy: The aim: "...fusion energy for providing clean power to combat climate change and maintaining a safe and reliable nuclear stockpile that can act as a nuclear deterrent without nuclear testing."

Shiva: The Shiva laser was a powerful 20-beam infrared neodymium glass (silica glass) laser built at LLNL in 1977 for the study of ICF and long-scale-length laser-plasma interactions. Presumably, the device was named after the multi-armed form of the Hindu god Shiva, due to the laser's multi-beamed structure, or maybe after the power of the beam from Shiva's third eye, due to the power of the laser. Shiva was instrumental in demonstrating a particular problem in compressing targets with lasers, leading to a major new device being constructed to address these problems, the Nova laser.

On the run towards clean energy: Most climate scientists and policymakers say that to achieve the goal of limiting global warming to 2 degrees Celsius, or the even more ambitious target of 1.5 degrees Celsius of warming, the world must reach net-zero emissions by 2050.



(a) Shiva amplifier chains showing spatial filter tubes (white) and Nd:glass amplifier structures (short blue tubes closest to camera). Portions of the 1982 Disney film *Tron* were filmed at the site. Picture credit: Wikipedia – LLNL employee - Maxine Trost of the LLNL Public Affairs Office (`http://www.llnl.gov/pao/`) upload. **(b)** Shiva target chamber during maintenance. Picture credit: from LLNL document *Laser Programs, The First 25 Years*. **(c)** View inside the Shiva target chamber, 1978. The needle-like object in the center of the image is the target holder, various instruments are pointed to image the explosions at its tip. Picture credit: Wikipedia – LLNL employee - Maxine Trost of the LLNL Public Affairs Office (`http://www.llnl.gov/pao/`) upload.

Suggested Reading

[1] L. Coblentz, Megaprojects: ITER: Moving Towards Industrial-scale Fusion Energy: Indian Contribution, *Resonance*, Vol.24 No.10, pp.1111–1123, 2019. `https://www.ias.ac.in/article/fulltext/reso/024/10/1111-1123`

[2] I. Kavila, Major Breakthrough in Nuclear Fusion Reactor Technology, *Resonance*, Vol.27 No.3, pp.473–4, 2022. `https://www.ias.ac.in/article/fulltext/reso/027/03/0473-0474`

[3] *Laser Programs, The First 25 years, 1972–1997*. `https://www.osti.gov/servlets/purl/16710`.

Indulekha Kavila
Thiruvananthapuram
Email: `kindulekha@gmail.com`