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News & Highlights

Laser Ignition Breakthrough—and More Startups—Brighten Outlook for Nuclear Fusion

Mitch Leslie

Senior Technology Writer

In February 2024, 192 lasers at the National Ignition Facility (NIF) in Livermore, CA, USA, began pouring 2.2 MJ of energy into a gold container smaller than the tip of a person's little finger, heating it to more than three million degrees Celsius (Fig. 1) [1–4]. Inside the container was a tiny fuel capsule containing tritium and deuterium that imploded at more than 400 $km \cdot s^{-1}$, causing atoms to combine and releasing 5.2 MJ of energy [1–4].

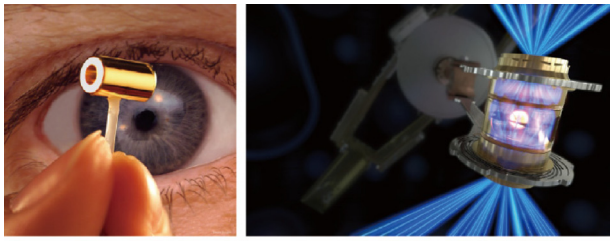
By yielding almost 2.4 times more energy than the lasers supplied [1], the experiment set a new record. The achievement was just the latest in a series of fusion firsts for the NIF, part of the US Department of Energy (DOE)'s Lawrence Livermore National Laboratory (LLNL). In December 2022, NIF touched off a fusion reaction that for the first time delivered what researchers call energy gain, producing more energy than needed to spark the reaction [3]. "Just being able to do it once was crucial," said Saskia Mordijck, an associate professor of physics at the College of William and Mary in Williamsburg, VA, USA, who studies fusion and was not connected to the research. "For so long people were trying to get there and fighting to achieve it."

NIF has now duplicated the feat multiple times, with at least three successes in 2023 alone [5]. While noteworthy, the results are also somewhat serendipitous. "NIF was built to create burning plasmas, but for nuclear weapon tests, not generating electricity," said Christopher Holland, a research scientist at the University of California, Center for Energy Research in San Diego, CA, USA.

The breakthrough comes with a few caveats. The energy accounting does not include the 350 MJ required to power up the NIF's lasers (Fig. 2) [3]. And though an energy gain of 2.4 is unprecedented, it is nowhere near large enough to make fusion practicable. To run an actual fusion facility, the ratio of total output to input (including powering the lasers or other equipment), a measure known as *Q*, will have to be more than 10—and perhaps as high as 30, said Egemen Kolemen, an associate professor of mechanical and aerospace engineering who works on fusion technology at Princeton University and the DOE's Princeton Plasma Physics Laboratory (PPPL) in Princeton, NJ, USA.

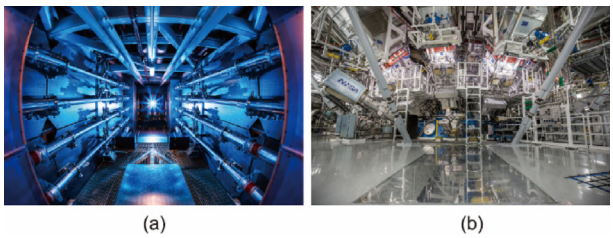
Still, NIF's success is just one of the advances that have researchers, governments, and investors excited. "We are closer" than ever before to harnessing fusion for power generation, said Dennis Whyte, professor of engineering at the Massachusetts Institute of Technology in Cambridge, MA, USA. Whyte cofounded one of the companies that is trying to generate power with fusion, Commonwealth Fusion Systems (Cambridge, MA, USA). In the public sector, national programs in the United Kingdom and China aim to launch pilot plants within the next 10–15 years [6,7]. The United States has also debuted a fusion development roadmap to deliver a pilot plant in the 2030s [8]. Perhaps more importantly, however, along with Commonwealth Fusion Systems, more than 40 companies—including some following approaches like NIL's—are pursuing fusion power, and they have drawn more than 7.1 billion USD from investors [9].

But how fast all these efforts can deliver reliable, durable plants that are cheap enough to compete with other energy sources remains the critical question. "That last bit is going to be very



(a) (b)

Fig. 1. (a) An artist's composite shows the gold-plated container that holds deuterium and tritium fuel during NIF's fusion experiments. (b) Another illustration shows how focusing NIF's 192 lasers on the container spawns X-rays that indirectly cause the capsule of fuel inside the container to implode, sparking fusion. Credit: NIF, Lawrence Livermore National Laboratory (LLNL; public domain).



(a) (b)

Fig. 2. (a) The preamplifiers at NIF shown here help boost the energy of the 192 lasers. (b) The small target for the lasers sits inside the large structure shown here. Credit: LLNL (public domain).

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difficult," said Steven Cowley, professor of astrophysical sciences at Princeton University and laboratory director of PPPL.

Fusion requires plasma, a superhot and unruly state of matter seething with ions and electrons [10]. "We have made 'fusion' happen in the laboratory for many decades," said Whyte. NIF went a step further and became the first facility to produce a burning plasma, in which the fusion reactions provide most of the energy to maintain the plasma, a pre-requisite for a fusion power plant [11].

Fusion startups and national programs are trying to generate, maintain, and control burning plasmas with a range of approaches. The UK's Spherical Tokamak for Energy Production (STEP) program, which published its designs in 2024, is following a tried-and-true route, the tokamak [7], the approach also being evaluated in the massive, multi-national sponsored, multi-billion USD International Thermonuclear Experimental Reactor (ITER) project [12]. Tokamaks feature a reaction chamber shaped like a donut or a cored apple and rely on powerful electromagnets to shape the plasma and foster fusion reactions. Although tokamaks have been around since the 1950s, the STEP design, which adopted the cored apple configuration and will be about 9 m across, includes updated technology to reduce costs and improve efficiency, such as high-temperature superconducting magnets that may cut power consumption [7].

At least four companies are pursuing laser-based designs like NIF's [9]. Xcimer Energy (Denver, CO, USA), for instance, wants to enlist even more powerful lasers that could focus up to 20 MJ of energy on a fuel capsule [13]. That innovation might circumvent one of the problems that NIF struggled with—its fuel capsules are difficult to manufacture because they must be perfectly symmetrical [14]. Xcimer's more powerful lasers could work with larger capsules that would be easier to make [13]. In addition, the NIF lasers are about 1% efficient at transforming electrical power into laser energy, and the facility can deliver a beam to a target only about ten times per week, not often enough for commercial nuclear fusion [15]. Another company, Longview Fusion Energy Systems (Orinda, CA, USA), plans to use updated lasers that are 20% efficient and can produce more than one beam every second [15]. The company has said that because it is using the same strategy as NIF, it can jump straight to a pilot plant without first building a demonstration facility to prove that the approach works [16]. In March 2024, the company signed a contract to build such a plant with Fluor, a large engineering design and construction company headquartered in Irving, TX, USA [16].

As its name implies, Zap Energy of Everett, WA, USA, is attempting to directly use electricity to spark fusion [17]. The strategy relies on a phenomenon known as a Z-pinch, in which a current creates a strong magnetic field. Inducing the field involves injecting a gas into a reaction chamber and then jolting it with up to 1 MA of current, which creates a ring-shaped plasma [18]. The plasma donut then speeds along one of the device's electrodes. When the plasma reaches the tip of the electrode, the magnetic fields compress it, raising its temperature and triggering fusion [19]. The energy produced by fusion will heat liquid metal surrounding the reaction chamber (Fig. 3), which will then boil water that drives a turbine to produce electricity [20]. Zap touts the fact that its approach does not require large, expensive magnets to wrangle the plasma, and thus its reactors could be smaller and cheaper. Mordijck, who is not connected to the company, praised its strategy and said it has delivered promising results in preliminary research. Recent tests produced temperatures of up to 3.7×10^7 °C [21]. "They got confinement temperatures that make this a viable path forward," Mordijck said.

Helion Energy, based in Everett, WA, USA, has drawn a lot of attention because of the amount of investment it has garnered—more than 600 million USD [9]—and its audacious claims [22]. Instead of a tokamak or lasers, Helion's design is a linear reaction chamber encircled by magnets [22,23]. Injectors pump gases into either end of the device, which heats them until they form ring-shaped plasmas. Using magnetic fields, the device then accelerates the plasmas toward each other at around 1.6×10^6 km·h^{-1}. The rings collide in the center of the device, where magnets also compress them, leading to fusion, the company claims [22,23]. The company says this approach is superior to other reactor designs because the device can generate power directly by inducing a current in electrical coils. In contrast, generating electricity indirectly by heating water to produce steam, like the Zap and tokamak designs will do, is less efficient [22,23].

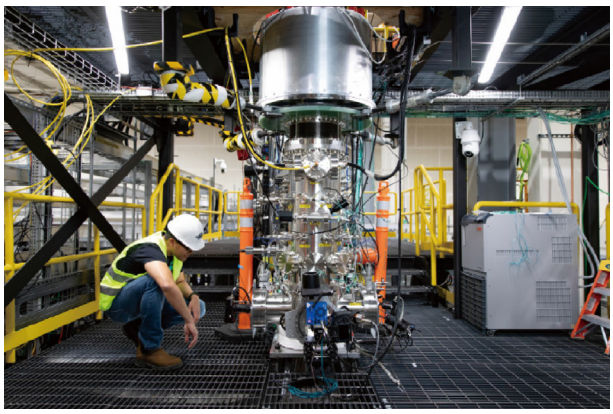

Fig. 3. The vertical reaction chamber of Zap Energy's latest reactor design, Century. Century will not produce power. But in a fusion plant generating electricity, plasmas would form here after high-voltage pulses are delivered to a mixture of tritium and deuterium. Liquid metal circulating around the reactor would absorb the heat released by fusion and then transfer that heat to water, generating steam, turning a turbine, and producing electricity. Credit: Zap Energy (public domain).

The recent progress in fusion efforts has resulted from a series of scientific and engineering advances, improvements in computer modeling, and other key developments [12]. And now, researchers are also beginning to enlist help from artificial intelligence (AI). In a pair of studies published in 2024, for example, Kolemen and his colleagues reported that AI could learn to predict and suppress two instabilities that can occur inside a tokamak. One problem, known as an edge energy burst, is a surge of energy that can cause temperatures in parts of the reaction chamber wall to increase by up to ten times, potentially damaging the container. In one study, the researchers showed that AI algorithms could learn to optimize tokamak operation, altering variables such as the shape of the plasma and the fuel injection rate, to prevent edge energy bursts [24]. When the researchers tested the capabilities of their AI algorithms in two tokamaks, they obtained a 20%–30% improvement in efficiency. AI could also curb a more serious problem called fusion plasma tearing instability, in which the plasma escapes from the magnetic fields that restrain it, halting fusion [25]. However, AI's impact on fusion technology has been relatively modest so far, Kolemen said. "It has been very useful. But has it changed the rules of the game? I do not think so."

That start-ups are pursuing a range of fusion approaches is a positive, said Holland. "I am seeing private companies take risks, and that is very exciting." If the timelines announced by some companies prove to be accurate, the answer to the question of which, if any, of these risks will pay off may come soon. For example, Commonwealth Fusion Systems has already started constructing a demonstration tokamak, known as SPARC, that will attempt to produce at least ten times as much energy as it consumes [26]. The machine could start operating as soon as 2027, Whyte said. And Commonwealth is already designing its successor, a pilot plant known as ARC. Whyte said this plant will test whether fusion can produce electricity and could be online by the early 2030s.

Helion claims it can go even faster. The company has already signed a contract to provide 50 MW of power to tech giant Microsoft (Redmond, WA, USA) and says it will start supplying that electricity in 2028 [27]. However, many experts question whether that aggressive schedule is possible [21]. Unlike many other companies in the field, Helion has not published papers confirming that its approach works, Mordijck said. "We want them to be successful because it would be good for the field," she said. "But we are worried because they are not following the traditional scientific method."

As noted above, the critical question is when will fusion power plants start delivering their long-promised abundant energy. Once a pilot plant produces electricity, a new set of hurdles becomes relevant. The plants will have to show that they can deliver energy as reliably as current facilities. And they will have to prove their durability—the steel and other materials that will go into fusion plants remain untested, and whether they can endure the hail of neutrons emitted by fusion reactions remains unclear [12]. "Utilities are not going to buy something if it has a lifetime of three months," said Cowley. Slashing costs will also be important—power companies probably will not invest until the cost of a plant falls to around six billion USD, Cowley added. Along with durability and cost, another issue is how to generate enough tritium for fusion plants [28]. Kolemen predicted that, with all these uncertainties, it will likely be at least 20 years before fusion plants begin contributing electricity to grids. Cowley agreed. "Fusion is not going to be playing a role in decarbonization for many years," he said.

Still, advances such as improved technical know-how, increased investment by governments and the private sector, and innovation by public facilities and private companies have increased the odds that efforts to develop fusion reactors will succeed. "There is no guarantee," Cowley said. But without these factors "fusion would still be 40 years away."

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