Fusion Energy Firms Status Update

By John Benson

March 2025

1. Introduction

I occasionally write about fusion energy. Although this may be the holy-grail of sustainable energy production in the future, I still need to write about it in the future-tense. There are many variants of fusion energy being tested, but none of them have a clear path to an economically viable large-scale electricity generation facility.

Two of these flavors are being championed by National Labs in my home-town (Livermore, California): The National Ignition Facility (NIF) at Lawrence Livermore National Labs (LLNL) and MagLIF at Sandia National Labs (SNL) in collaboration with LLNL.

2. Inertial Confinement Fusion

The National Ignition Facility (NIF) uses laser-based inertial confinement fusion where a huge laser system, which terminated in 192 beamlines, a brief pulse of light is amplified to 500 terawatts (TWs, a terawatt is one trillion watts), and redirected to converge on a tiny target containing a mixture of deuterium (D) and tritium (T), the second and third isotopes of hydrogen.

NIF achieved the first instance of scientific breakeven controlled fusion in an experiment on December 5, 2022, with an energy gain factor of 1.5. "Scientific breakeven" only looks at the inner-most process (the implosion of the target) and measures the energy of the light delivered by the beamlines verses the energy of the fast-neutrons emitted from the fusion. On Nov. 18, 2024, a 2.2-MJ shot achieved fusion ignition at NIF for the sixth time, producing an energy yield of 4.1 MJ (an energy gain factor of 1.86).

To drill down deeper on NIF, go to the earlier post summarized and linked below.

Distant Nuclear Fusion – Update: *When we look up at night and view the stars, everything we see is shining because of distant nuclear fusion. - Carl Sagan, Cosmos.*

Note that this update was prompted by a major achievement by Lawrence Livermore Labs, National Ignition Facility. The original "Distant Nuclear Fusion" paper was posted in January 2021. I am leaving most content below that is unrelated to the recent achievement in place, and not really updating it, except for subsection 4.7. I describe the above-mentioned achievement in this subsection and reference the source.

https://energycentral.com/c/gn/distant-nuclear-fusion-%E2%80%93-update

The problem with NIF is that the lasers used are extremely inefficient (less than 1%). If calculation of the overall efficiency were to include that of the lasers (forget the efficiency of converting the emitted fast neutrons energy to heat and the heat to electricity), NIF would not come close to breakeven. Although LLNL has defined a path-forward that includes using higher efficiency lasers, they haven't even started developing the components required for this path.

Thus, the work on MagLIF (magnetized liner inertial fusion), which uses magnetic energy for initial compression of the target and has a clearer path to engineering breakeven.[1] To explore MagLIF, go to the earlier post summarized and linked below.

Pacific Fusion: The Third Path: *I do write about nuclear fusion occasionally, just not very often…*

Earlier papers covered two processes for nuclear fusion (two bullets below).

- *Steady-state magnetic confinement fusion reactors (a.k.a. Tokamak or Stellarator)*
- *Pulsed laser-driven inertial confinement fusion reactors (NIF)*

The subject of this paper is pulsed magnetic inertial confinement fusion.

https://energycentral.com/c/gn/pacific-fusion-third-path

3. Steady-state Magnetic Confinement Fusion

In addition to inertial-confinement fusion, there is a distinctly different technique. See the earlier post, summarized and linked below:

Twisted Fusion: The Stellarator, Part 2: *The short story is that there are basically two popular configurations of potential steady-state nuclear fusion reactors: The Tokamak, created by the USSR in in 1968, and an earlier design, the Stellarator, invented by American scientist Lyman Spitzer of Princeton University, which began operating in 1953 and demonstrated plasma confinement in 1951. Both of these designs had "issues." The dynamics of the Stellarator had early success, but its operation was simply too complex for the physicists at that time using then-current modeling techniques to simulate. The Tokamak also had early success, but had the same issues, and still does.*

Fast-forward to modern times. Current computer simulations allow the Stellarator designers to model the operation of their fusion reactor and optimize it. The Tokamak's problems appeared to be simpler on the surface, but the physics were much more complex, thus its issues remain to be simulated, understood and corrected.

This paper focus on the evolution of the Stellarator, recent advances and future plans.

https://energycentral.com/c/gn/twisted-fusion-stellarator-part-2

4. Updates on Other Firms

Will this be the year private companies start to transform nuclear fusion from an interminable scientific puzzle into a profitable technology for producing carbon free energy? So far, most of the dozens of efforts backed by venture capital have not gotten beyond computer predictions and small-scale prototypes. But this year, several firms will debut large new machines that, they say, will soon coax a roiling ionized gas to fusion-friendly temperatures. In theory, these bigger testbeds could even produce more heat than they use to spark fusion—a threshold known as scientific breakeven.[2]

[1] See https://en.wikipedia.org/wiki/Fusion_energy_gain_factor

[2] Daniel Clery, Science Magazine, "Private fusion firms put bold claims to the test" 1/24/2025, https://www.science.org/content/article/private-companies-aim-demonstrate-working-fusion-reactors-2025

“Fusion is a happening thing,” says physicist Michel Laberge, founder of Canada’s General Fusion, one of the startups. In the next year or two, “I think quite a few people will achieve sort of breakeven-ish numbers.”

To physicists who have labored for decades in government-funded labs to make fusion work, such timetables appear wildly optimistic, likely driven more by the needs of investors than by scientific reality. “There has been no machine in my lifetime that you’ve turned on and it immediately performed. Never,” says Steven Cowley, director of the Princeton Plasma Physics Laboratory…

Investors—and the world—will be watching keenly to see which view is right.

With fusion, many atomic nucleuses are fused to produce larger nucleuses, releasing energy in the process. But because the positively charged nuclei repel each other, sustaining the process requires intense heat and pressure, like that at the cores of stars or in a nuclear explosion. To spark controlled fusion, physicists heat isotopes of hydrogen until they form an ionized plasma, which starts to fuse at about 100 million degrees Celsius.

So far, despite billions of dollars and decades of effort, only the U.S.-based National Ignition Facility (NIF), which crushes and heats tiny capsules of fusion fuel with powerful lasers, has achieved scientific breakeven (see Sections 2 & 5). Other government-funded efforts have focused on doughnut-shaped devices called tokamaks that confine plasma with powerful magnets and heat it with microwaves and particle beams (see Section 3). ITER, a giant tokamak under construction in France that won’t start operation until next decade, is poised to become the standard bearer for that approach.

Governments are still backing fusion—the United Kingdom announced £410 million for fusion research last week. But the slow pace of those efforts and the demand for carbon-free energy as climate change warms the world has prompted many researchers to seek a faster, privately financed route. The Fusion Industry Association reported having 45 members in 2024, which had collectively raised more than $7 billion in funding.

The startups hope that speedy, iterative development typical of industry will let them steal a march on government efforts. General Fusion aims to “incrementally improve very quickly, to iterate on our plan, to learn, and to move on to get results,” says nuclear engineer Megan Wilson, the company’s chief strategy officer.

Some firms aim to make smaller, cheaper tokamaks or close cousins called stellarators, using cutting-edge technologies such as high-temperature superconductors and machine learning. Others have resurrected previously abandoned techniques, such as the field-reversed configuration (FRC), a spinning smoke ring of plasma that briefly confines itself through a magnetic field it creates.

FRCs were discovered in the 1950s, but the plasma rings only lasted microseconds. National labs and universities made them more durable in the decades after, but the work ran out of steam. Undaunted, General Fusion has used some of its $340 million in backing to develop a plasma injector that puffs an FRC ring 2 meters across into a reaction chamber. There a shock wave initiated by pistons that strike the outer wall of the reaction chamber quickly crushes the ring to one-tenth of its original size, heating it to millions of degrees.

General Fusion's new machine, dubbed LM26, will debut next month (Feb, 2025) in Vancouver, Canada, and start compressing plasma in March, with a goal to get to 100 million degrees Celsius—fusion temperature—by the end of the year, Laberge says. But LM26 will compress deuterium, not the deuterium/tritium mix required for energy generation. An actual fusion-capable reactor from the company wouldn't be ready until at least the 2030s, Laberge says—and would require much more investment.

A more secretive company, Helion, based near Seattle, is carrying out initial tests on its latest FRC-based machine, which was reportedly completed in the last few months. Known as Polaris, it simultaneously fires FRC rings from both ends of an elongated reaction chamber so they merge in the chamber's center, heating and compressing the plasma. A powerful magnet encircling the chamber compresses the FRC further until fusion starts in the fuel, a mixture of deuterium and tritium.

"The ultimate goal of Polaris is to show that we can create some electricity from fusion," says Helion spokesperson Jessie Barton. Most fusion power plant designs envision using the fast-neutrons from fusion to heat and boil water, producing steam that drives a turbine. But in Polaris, the heat will cause the plasma to swell and push back against the force of the magnets, generating electricity via induction.

Cowley[3] is not convinced of the promise of FRCs. "The problem with [FRCs] is that they are unstable, they're so unstable in most experiments that they don't confine very well either," he says. But Helion is confident: It signed an agreement with Microsoft to provide it with power by 2029. A power plant sited somewhere in Washington state would supply 50 megawatts. "The next machine that we build will be that power plant," Barton says.

A highly publicized fusion firm spun out from the Massachusetts Institute of Technology is taking a more conventional approach: a compact tokamak reactor called SPARC, which it will assemble this year. Although the machine, from Commonwealth Fusion Systems (CFS), is much smaller than ITER's tokamak, less than 5 meters in diameter compared to ITER's 16.4 meters, it is supposed to achieve similar performance for a fraction for ITER's cost, which is in excess of $25 billion. One factor: CFS is relying, for the first time in the fusion field, on high temperature superconductors to make extra strong magnets.[4]

The superconducting material is a brittle ceramic, hard to make into wire and wind into the coils needed for electromagnets, so CFS uses a steel tape spray-coated with the superconductor. Over several years, the company has developed ways to wind and weave those tapes into the two types of magnets they need. "We've now built and demonstrated both of the key technologies for SPARC," says CFS physicist Alex Creely.

This year, the company will assemble its machine's 32 magnets. "On our current schedule, we're looking to begin operations in 2026 and get net energy in 2027," Creely says. Last month, CFS announced it had signed an agreement with Dominion Energy of Virginia to build a prototype power plant in Chesterfield County in the early 2030s.

---

[3] Steven Cowley, director of the Princeton Plasma Physics Laboratory, a United States fusion lab.
[4] See "Not so Distant Nuclear Fusion," Subsection 3.1, https://energycentral.com/c/gn/not-so-distant-nuclear-fusion

Cowley is skeptical of the timetable. Superconducting tape has never been formed into such powerful magnets, and he suspects CFS will struggle to achieve the fields required. “I actually don’t think that we’ll see anything from anybody this coming year.”

Other companies, using technologies with varying levels of maturity, have also set aggressive schedules. But fusion has a habit of confounding the best laid plans. Cowley points out that NIF struggled to make any significant reactions when it opened in 2009 and spent more than a decade refining its techniques to reach fusion ignition (scientific breakeven controlled fusion on December 5, 2022).

Michl Binderbauer, CEO of TAE Technologies,[5] another FRC-focused effort that hopes to debut its new machine in 2026 or 2027, knows a lot is riding on the private, pioneering efforts. “What I hope doesn’t happen is that one of us catastrophically implodes or fails and it kind of sucks the wind out of the whole industry.”

5. Better Targets

With Inertial Confinement Fusion, targets are important. For instance, with NIF, its powerful laser banks focus their light on a “target” that about the size of a peppercorn inside of a small cylinder called a hohlraum. When they strike, the target implodes, creating the temperature and pressure necessary for fusion. The fusion emits a burst of high energy neutrons that carry the output-energy of the fusion-process.

For a more thorough description of this, go through the link to “Distant Nuclear Fusion – Update” on page 1 of this paper, then to section 4.4. Of course, with the current design the hohlraum / target assembly is complete destroyed by each “shot” (lasers firing and a fusion neutron-pulse), and these are VERY expensive to manufacture. Also, the lasers used are very inefficient, and I expect this is, in-part, because the lasers need a specific light-frequency and pulse characteristic to make everything work.

The evolution to a more efficient and economic process needed for a fusion power-plant starts with a more efficient and economic target. Lawrence Livermore National Labs (LLNL) is working on this. Since I live in Livermore, my local paper covers important happenings at LLNL pretty thoroughly, and they had an article on the next-phase target last week (February 13 edition of The Independent).

LIVERMORE – Commercial fusion technology - what the U.S. Department of Energy (DOE) says could deliver "a supply of safe, clean and relatively limitless energy" – took another step forward last week with the announcement of a new joint project between the Lawrence Livermore National Laboratory and fusion startup Focused Energy.[6]

The year-long project, funded through the DOE's Innovation Network for Fusion Energy program, will explore the use of wetted foam to hold liquid fuel within the pellets (targets) *used in fusion reactions.*

Specifically, the lab (LLNL) will run computationally intense 3D modeling of how the foam reacts to the laser shots the lab uses to initiate fusion. The results can then be applied in later, cheaper models that look at the effects of impurities within the foam, said LLNL physicist Elijah Kemp. The results will also be published in scientific journals.

---

[5] https://tae.com/

[6] David Jen, The Independent, “Lab and Startup Company Team Up on Fusion Materials,” Feb 13, 2025 Edition, https://www.independentnews.com/news/livermore_news/lab-and-startup-company-team-up-on-fusion-materials/article_5c261924-e979-11ef-bcc7-a77d14ae21ff.html

Author's comment: LLNL hosts one of the most powerful fleets of supercomputers in the world, and these just got a powerful addition:

More than 300 Lawrence Livermore National Laboratory (LLNL) employees, government officials and industry leaders gathered at LLNL on Jan. 9 to celebrate the dedication of El Capitan, the world's fastest supercomputer.[7]

Hewlett Packard Enterprise President and CEO Antonio Neri (left) and AMD Chair and CEO Lisa Su toured Lawrence Livermore National Laboratory's El Capitan and Tuolumne supercomputers, signing an El Capitan compute rack. (Photo: Garry McLeod/LLNL)

Back to Reference 6.

The German American company Focused Energy was spun off from the Technical University of Darmstadt, Germany, in 2021; it has secured an additional location in Redwood City (about mid-way down the San Francisco Peninsula). The company plans to complete a pilot fusion power plant delivering power to the grid by 2037. Focused Energy announced last October plans to build a laser development facility at another yet-to-be-determined SF Bay Area location to attract talent and build off the work at the lab's National Ignition Facility (NIF).

In 2022, LLNL's National Ignition Facility became the world's first facility to achieve what is known as ignition, where a fusion reaction produces more power than was used to start it. When running, NIF fires a laser split into 192 beams from all directions at a fuel pellet the size of a peppercorn, causing it to implode and start a fusion reaction.

---

[7] Jeremy Thomas, LLNL, "LLNL dedicates El Capitan, ushering in new era in supercomputing for national security," Jan 16, 2025, https://www.llnl.gov/article/52336/llnl-dedicates-el-capitan-ushering-new-era-supercomputing-national-security

Debbie Callahan, the target design lead at Focused Energy, said, "Think of each little part of the (pellet) sphere as being a rocket, and so it's going to jet inward, and its neighbors are going to jet inward, and you get a spherical compression, which then gets you to the temperatures and densities that you need for fusion, if you do it right."

NIF, however, was initially designed to conduct nuclear weapons experiments and not to generate power. While it is capable of firing roughly one shot per day, a power plant must fire around 10 shots per second to produce enough power to be commercially competitive on the grid, said Callahan. The industry therefore needs new methods to manufacture fuel pellets at lower cost and an unprecedented pace.

Callahan hopes that the use of foam to hold the liquid fuel within pellets, instead of freezing the fuel in place as NIF currently. does, will speed up the manufacturing process. "However, you're now adding a new thing to the system, which is this foam, and there's not a lot of experience with how this affects what we're trying to do," she continued.

The partnership involves scientists' time from both Focused Energy and LLNL, as well as use of LLNL's computers, to develop a simulation model of the foam's properties. Kemp said that NIF previously conducted wetted-foam experiments that helped establish the idea's feasibility. "Furthermore, NIF has currently the only laser capable of exploring these direct drive wetted foam concepts/ designs at full scale, so these early experimental studies are providing invaluable insights into the potential risks/benefits of additively manufactured capsules."

Callahan added that private companies within the nascent fusion industry now bring an agility unavailable to national labs.

The advantage, Callahan said, is that Focused Energy can move more quickly than a government lab. "We can take risks; we don't have all the bureaucracy. But we also want to use the expertise that you can from a national lab or large university."

Below is an image of a wetted-foam capsule / target.

6. Better Magnetic Fields

The following is a wild design. See the highlighted text below. But who knows, this could be strange enough to work.

Many fusion-energy startups talk about trying to replicate the awesome power of the sun. But only one is also trying to replicate the sun's structure, by having the reactor's powerful magnet float in a vacuum surrounded by a ball of thermonuclear plasma.[8]

In late October, Open Star Technologies, based in New Zealand, achieved "first plasma" – a cloud of ionized helium contained by a superconducting magnet suspended at the center of a prototype device called Junior.

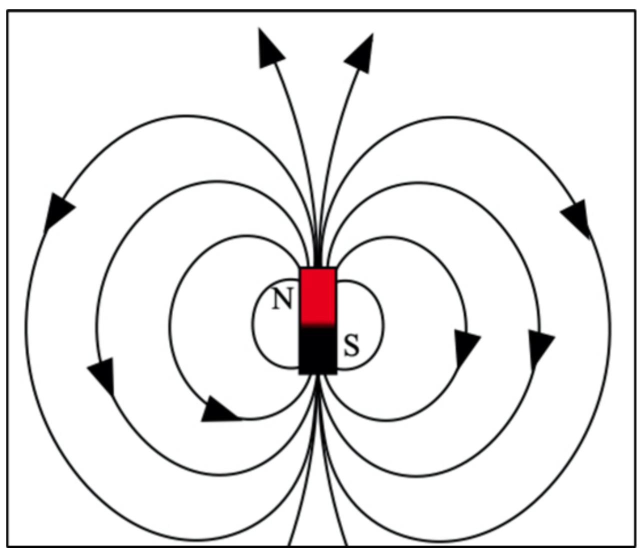
OpenStar is still years away from producing fusion, let alone net power gain, but its founder and CEO Ratu Mataira says that its design, which will eventually include that magnet hovering meters above the ground, might be humanity's best shot at achieving commercial-scale fusion energy.

"It's the only fusion configuration that nature doesn't want to destroy immediately at all times," Mataira says.

The sun undergoes fusion by virtue of its immense mass, with gravity produced by this mass forcing hydrogen nuclei to fuse into other particles and release energy. To replicate that process on Earth, some researchers and startups are using magnetic fields to squeeze hydrogen nuclei together.

OpenStar's idea is to use a dipole magnet at the center of the reactor instead of a tokamak's external magnets. Dipole magnets are common in nature:

Author's comment: A Dipole-magnet's field is inherently spherical. See the figure on the right.



Earth's own magnetic field, which protects us from stellar radiation, is an example. A dipole's big advantage is that it's naturally stable, potentially opening the door to sustained fusion reactions.

"We solve a lot of complications by moving to the dipole," says Mataira. "The one catch is that it makes the magnet look significantly harder to do."

Placing a superconducting magnet that requires chilling to a few tens of degrees above absolute zero in the center of a fusion reaction at 175 million °C might sound insane. But there is some physics working in OpenStar's favor: Mataira points out that convection in the plasma will drive heat outward toward the reactor walls, rather than inward toward the magnet.

[8] Mark Harris, IEEE Spectrum, "New Fusion Prototype Achieves First Plasma," February, 2025, https://spectrum.ieee.org/dipole-fusion-reactor

In the October experiment, the magnet was precooled to about 30 kelvins (-240 °C), which gave OpenStar an 80-minute window until it warmed up and could no longer provide the necessary magnetic field. In future iterations, the magnet will have onboard cooling from liquid helium to extend that time, although it will still need to be shut down periodically and cooled again.

There are other limits to Junior's operation. The high-temperature superconductors in the magnet still have a small amount of electrical resistance. As the reactor operates, the magnet will gradually lose energy. Superconducting magnets in tokamaks have the assistance of a wired power supply, but running cabling through the middle of a fusion reaction would be impossible.

Instead, future versions of the central unit will contain batteries to extend the life of the magnet. And then there is Junior's most sci-fi feature of all: The entire magnet unit will levitate in the center of the reactor, thanks to a permanent magnet that will be installed above the vacuum chamber.

"This is one of the least intimidating aspects of the build," says Mataira. "That's because this machine is benchmarked off the LDX levitated dipole experiment at MIT. They levitated for about six years."

LDX shut down in 2011, having proven some of the basic science and engineering behind levitated dipole reactors but never achieving fusion.

Mataira expects Junior to tread a similar path. A successor reactor will have a magnet that will be the same size as Junior's 1.2-meter-wide dipole but four limes as strong. That will help OpenStar study radio-frequency technologies to heat the plasma. However, Mataira is not expecting OpenStar to achieve fusion until at least its third generation of devices, no sooner than 2027.

Commercial OpenStar reactors, when they arrive perhaps next decade, promise to be smaller while still generating net power compared to enormous tokamaks. "We can imagine deploying 25- to 50-megawatt units for data centers in remote locations, while we develop the multigigawatt units that are going to be really important for the overall climate transition/' says Mataira.

There are a host of engineering challenges between firing up Junior and selling power, says Andrea Di Vita, a plasma physicist who worked on the Joint European Torus fusion program in the United Kingdom. "From the engineering point of view, the main issue is protection from thermal loads," he says. "But dipole can be a game-changer. The plasma pressure for a given magnetic field is 13 times higher in a dipole machine than in a tokamak. And the power from the fusion reaction if you can get there, is more than 150 times larger."

Mataira is realistic about the road ahead. OpenStar is younger than other fusion-programs, and some unforeseen problems may kill the concept. "But if you look for plasma that you can produce in a lab at a steady-state that also exist in nature, there is actually only one candidate, he says and that's a levitated dipole plasma."