

# Not so Distant Nuclear Fusion

By John Benson

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## 1. Introduction

It is an interesting time for nuclear power, and this paper will explain why. The last post on nuclear power is 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 (1980, p. 238)*

*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/qn/distant-nuclear-fusion-%E2%80%93-update>

This post mostly deals with nuclear fusion, but unlike the last post it will cover fusion power plants that may be on-line within the next decade. Also, it will cover some recent news about fission power plants, including in section 2 below.

## 2. The last of the U.S. Giants Come to Life

*March 2023: The first new nuclear reactor built in the U.S. in the last 30 years reached a milestone last week that brings it tantalizingly close to syncing up with the electrical grid and generating power for customers. But this is not the dawn of the long-threatened nuclear renaissance — it’s more like the swan song of the conventional nuclear industry in the U.S.<sup>1</sup>*

*Vogtle 3, one of a pair of 1,100-megawatt nuclear reactors being constructed by Georgia Power (and several other regional utilities), has reached “initial criticality,” the utility announced last week. That ominous-sounding phrase means that plant operators have safely started a self-sustaining nuclear fission reaction inside the reactor. Atoms are being split, and the heat from that reaction will soon be harnessed to produce steam, power a turbine and generate electricity.*

*Construction started for the two reactors in 2009, with plans to get them online by 2017, but the project is six years overdue and has cost utility customers well over \$30 billion, more than double the original price tag. The Department of Energy’s Loan Programs Office provided about \$12 billion in loan guarantees to help complete the project against a backdrop of spending freezes and lawsuits.*

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<sup>1</sup> Eric Wesoff, Canary Media, “Georgia’s big new nuclear reactors could be the last built in the US,” 13 March, 2023, <https://www.canarymedia.com/articles/nuclear/georgias-big-new-nuclear-reactors-could-be-the-last-built-in-the-us#:~:text=The%20NRC%20has%20issued%20permits%20for%20eight%20more.none%20of%20these%20are%20expected%20to%20be%20completed.>

*The two new reactors are joining two existing ones at Plant Vogtle. When all four reactors are online, it will be the largest nuclear-generating complex in the U.S., surpassing the output of the three-reactor site at Palo Verde, Arizona. The Vogtle expansion entails installing two AP1000 pressurized-water reactors from Westinghouse — the first deployment of that model in the U.S. China already has four AP1000 units in operation and four more under construction.*

*As Georgia Power tells it, with the Unit 3 reactor reaching criticality, plant operators will increase power to enable the generator to synchronize with the electric grid and ultimately come up to full power. According to the utility, Unit 3 is projected to come into service in May or June of this year. Unit 4 is expected to be placed in service in late 2023 or early 2024.*

*If and when Georgia's two new Vogtle reactors become fully operational, they will be the first nuclear reactors to have completed the full licensing process under the U.S. Nuclear Regulatory Commission. All other reactors in operation began licensing before the NRC opened its doors in 1975.*

## **2.1. Future Fission Power**

*I asked three experts on nuclear power what would be the next commercial reactors to come online in the U.S.*

*"Vogtle 3 and then Vogtle 4. And then most likely nothing," said Gregory Jaczko, a former chair of the Nuclear Regulatory Commission.*

*"Unfortunately, no Gen 3+ reactors are scheduled to come online. The next development will most likely come from 'advanced reactors,' aka Gen 4," said the second expert. Advanced reactors, including small modular reactors, are significantly different in design than the "Gen 3" light-water design being deployed at Vogtle, employing new sizes, fuels and coolants...*

*The NRC has issued permits for eight more nuclear reactors to be built at or near existing plant sites in the U.S., but none of these are expected to be completed. Instead, the industry is betting on advanced nuclear reactors to save the day...*

## **2.2. Update on Vogtle 3 & 4**

*Aug 2023: Georgia Power Co. has said that workers have begun loading radioactive fuel into a second new nuclear reactor in Georgia, allowing the reactor to potentially begin generating electricity in the coming months.<sup>2</sup>*

*Workers will transfer 157 fuel assemblies into the reactor core at Plant Vogtle, southeast of Augusta, in the next few days, where there are already three reactors operating at the plant, the company said.*

*Two reactors have been operating for decades, while the third reactor entered commercial operation on 31st July, becoming the first newly built nuclear unit in the US in decades...*

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<sup>2</sup> Big News Network via Energy Central, "First new US nuclear reactor in decades gets OK to receive fuel," Aug 21, 2023, [https://energycentral.com/news/first-new-us-nuclear-reactor-decades-gets-ok-receive-fuel?utm\\_medium=eNL&utm\\_campaign=DAILY\\_NEWS&utm\\_content=416684&utm\\_source=2023\\_08\\_23](https://energycentral.com/news/first-new-us-nuclear-reactor-decades-gets-ok-receive-fuel?utm_medium=eNL&utm_campaign=DAILY_NEWS&utm_content=416684&utm_source=2023_08_23)

Unit 4 is supposed to begin operating in March 2024, the company said.

The US Nuclear Regulatory Commission ruled that Unit 4 was ready to be supplied with nuclear fuel in July.

### **2.3. Update for NuScale and Other Small Reactors**

*The advanced reactor closest to market in the U.S. is being developed by NuScale, which has a nonbinding agreement to build a first-of-its-kind SMR project in Idaho. The company has already raised its projected power cost from \$58 per megawatt-hour to \$89, even though it's still years away from even beginning construction. The first module at the plant is set to begin commercial operation in December 2029, NuScale says, but nuclear project timelines are inevitably Pollyannaish and wildly off-base.<sup>1</sup>*

*NuScale's regulatory journey with the NRC has been long and arduous, and it's far from over. Advanced reactors such as TerraPower's Natrium, which are significantly different in design from existing light-water reactors, face an even steeper regulatory climb. And they'll have to contend with broken or nonexistent supply chains because the more highly concentrated uranium fuels used by most advanced reactors are currently unavailable in large quantities outside of Russia.*

## **3. Future Fusion**

There are several Fusion Startups on the East Coast and West Coast. All think that smaller is better.

### **3.1. Commonwealth Fusion Systems**

*In the site of a former U.S. Army Reserve base near Boston, an unusual structure is rising from the rolling hills. Brandon Sorbom, the scientific director of Commonwealth Fusion Systems (CFS), leads me toward the center of the building's cross-shaped footprint, weaving among scaffolding, forklifts, and teams of welders and painters. Descending a stairway to a deep basement walled with 2.5-meter-thick concrete, he gestures toward a large, circular hole at the center of the room's high ceiling, its edges supported by four stout columns.<sup>3</sup>*

*"Within a few months, if we stick to schedule, that's where the Sparc tokamak will rest," Sorbom says. Surrounding a doughnut-shaped vacuum chamber, a 3-meter-tall stack of high-temperature superconducting magnets will create a powerful magnetic field to squeeze and corral a swirling, superheated mass of hydrogen plasma. Mimicking the process that fuels the sun, the hydrogen ions— isotopes called deuterium and tritium— will accelerate and collide with such force that they fuse into helium and release highly energetic neutrons.*

*CFS, a startup spun out of decades of research at the Massachusetts Institute of Technology (MIT), is among the leaders of a new wave of fusion-energy projects that have emerged in the past decade, taking advantage of technological advances as well as a surge in private-sector investment. Fusion-energy companies have now raised more than US \$5 billion, the majority of it since 2021, according to Andrew Holland, the director of the Fusion Industry Association. These companies all intend to demonstrate positive energy gain—to get more energy out of their reactions than is used to trigger them—by the end of the decade.*

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<sup>3</sup> Tom Clynes, IEEE Spectrum, "This Fusion Reactor is Held Together with Tape," July 15, 2023, <https://spectrum.ieee.org/fusion-2662267312>

*“At that point, we’ll be one step closer to a new era of carbon-free baseload electricity,” says Sorbom. “We just hope we can do it in time to be a major part of the solution to the climate crisis.”*

*What sets CFS’s technology apart is its use of high-temperature superconducting tape, which is layered and stacked to create extremely strong electromagnets that will shape and confine the unruly plasma and keep the bulk of the charged particles away from the tokamak’s walls. The company believes that this novel approach will allow it to build a high-performance tokamak that is much smaller and less expensive than would be possible with previous approaches.*

*Currently, there are two main research avenues to fusion energy. Magnetic confinement uses electromagnets to confine plasma, typically inside a tokamak. Inertial confinement compresses and heats a target filled with fuel—often using lasers—to kick-start a reaction.*

*Progress on both approaches is accelerating, due to advances both in materials science and in high-speed computing, modeling, and simulation. Among the magnetic-confinement crowd, CFS leads the pack in fundraising, having secured more than \$2 billion to build its Sparc pilot plant.*

*In general, superconducting materials can conduct direct-current electricity without resistance and energy loss when cooled below a critical temperature. High-temperature superconducting (HTS) magnets, as the name suggests, can superconduct at much higher temperatures than the superconducting magnets traditionally used in tokamaks, which typically need more complex and expensive cooling systems involving liquid helium. Although “high temperature” might suggest something that could burn you, HTS materials operate in a range of 20 to 77 kelvins (around –200 to –250 °C). That’s still cold, but it’s much warmer than what’s needed for typical superconductors, which can only function at temperatures close to absolute zero.*

*“These new materials are allowing a new path to fusion energy, because in addition to their superconducting abilities at higher cryogenic temperatures, they are also able to go to very high magnetic fields,” says Scott Hsu, a senior advisor at the U.S. Department of Energy (DOE) and the agency’s lead fusion coordinator. “These properties provide the possibility to design smaller, less complex, and lower-cost fusion systems that are quicker to build and easier to take apart for maintenance.”*

*Compact tokamaks like CFS’s could reverse the developmental trends that have dominated the last 40 years of fusion energy, which have fixated on building bigger and bigger machines. The largest by far is Iter, a collaborative international effort to build a massive tokamak in Cadarache, France. Under construction since 2013, the Iter fusion experiment (formerly called the International Thermonuclear Experimental Reactor) has devoured the majority of the world’s public funds dedicated to fusion-energy research. The Iter Organization overseeing the project now estimates a \$22 billion price tag for the experiment, dwarfing the original 2006 estimate of \$5.6 billion.*

*“Iter is a tremendously exciting and useful experiment, but it has a size problem,” says CFS’s Sorbom. “If you could somehow shrink that tokamak, you could build it much faster and cheaper.”*

*But that's not going to happen. With Iter's long-term planning horizon and international collaborative structure, it's too far along to benefit from the cutting-edge HTS magnets that are allowing CFS to build its Sparc tokamak one-fortieth the size of Iter, in a fraction of the time and cost.*

*It's tempting to conjure a "David and Goliath" narrative out of the storyline of small companies like CFS going up against Iter, one of the most expensive science experiments of all time. But in many ways, CFS's Sparc stands on the shoulders of Iter. The Iter project has greatly increased researchers' knowledge about magnetic-confinement fusion and spurred the development of the industry's highly specialized global supply chain and workforce. Indeed, each of CFS's six founders have worked on different aspects of Iter and contributed to its foundational physics.*

*Among them is plasma physicist Bob Mumgaard, who pioneered ways to measure the distribution of electrical current within tokamak plasmas. In 2015, Mumgaard huddled with a group of his fellow MIT researchers to rethink the approach to fusion power. High-temperature superconductors had been gradually improving since 1986, when they were discovered by IBM researchers Johannes Georg Bednorz and Karl Alexander Müller—an achievement that won the pair the 1987 Nobel Prize in Physics. Since then, experiments with ceramic and rare-earth materials and new configurations have boosted HTS performance and raised the temperatures at which they can operate. This has radically improved what can be done with high-voltage transmission lines, MRIs, and energy storage.*

*"With these materials finally becoming commercially available, we realized that we didn't need to make additional physics breakthroughs," says Mumgaard, who cofounded CFS in 2018 and is now the company's CEO. "In fact, from a physicist's standpoint, our machines look kind of boring; we're relying on plasma physics that's well established by Iter and other experiments. Instead, we decided to put all our risk in the magnet technology. We theorized that we could get extremely high performance through the brute force of the magnetic field."*

*The team's superconductor of choice was yttrium barium copper oxide, or YBCO. To make YBCO tape, some manufacturers first use a laser to vaporize bulk YBCO into a plume. That plume then deposits as a thin film of YBCO onto a steel substrate, which is followed by an oxygenation process to change the YBCO's structure into a state that enables superconductivity.*

*After Sorbom's experiments—which became the basis for his doctoral thesis—confirmed that the YBCO tape could withstand the pummeling of fast neutrons squeezed from fusing atoms, a joint MIT/CFS team began the tricky process of acquiring the expensive, brittle HTS tape and winding it into coils. Over two years, the team managed to buy up most of the world's supply of 4-millimeter-wide HTS tape—the largest amount of HTS tape ever procured—sourcing it as far afield as Japan and Russia.*

*Technicians painstakingly wound the tape into 16 coils, which were then assembled into a "pancake stack" to create a toroidal field magnet that could surround a section of tokamak. In September 2021, at MIT's Plasma Science and Fusion Center, the team energized the magnet and watched as the field it produced strengthened to an intense 20 tesla—about 400,000 times as strong as the typical value for Earth's magnetic field, and more than strong enough to lift an aircraft carrier out of the water. The team kept the magnet energized in a steady state for about 5 hours.*

*“We showed that we could basically hand-build 16 winding coils and assemble them into one high-performing magnet,” says Sorbom. “But can we do that over and over again, and do it very quickly?”*

*To magnetize Sparc, the CFS team will need to duplicate that feat 18 times. Near the Sparc site, a magnet-assembly facility is ramping up production. “We’ve cut the assembly time in half, but we’ll need to cut that time again by a factor of four to crank them out on schedule,” Sorbom says. Each of the winding packs will be built and tested, then integrated into toroidal field coils and moved to a final-assembly hall, where the 18 identical coils and surrounding structures will be consolidated and then installed around the tokamak.*

*With no antecedent, CFS’s magnet-building process represents the most critical path for the whole project—and one that is complicated by supply-chain challenges. CFS has been working to establish additional suppliers in the United States, Europe, and Asia, and to develop manufacturing capabilities in-house, which will lay the groundwork for building fusion power plants in the future.*

*Ahmed Diallo, program director for fusion programs at the DOE’s Advanced Research Projects Agency–Energy (ARPA-E), frames the HTS shortage in terms of national competitiveness. “China is pushing to make 3,000 kilometers of HTS tape a year, and we’d like to be able to turn out more than 10,000 km a year to keep fusion on a fast track. Right now we are looking at novel ways to generate high-throughput manufacturing processes and also bring down the cost,” which can add \$100 million or more to the price of an HTS-magnetized tokamak.*

*“We’re going from making a few centimeters a year to hundreds of kilometers,” says Guinevere Shaw, program manager at the DOE’s Office of Fusion Energy Sciences. “For the United States to lead in building tokamaks, we need to figure out how to leapfrog ahead with HTS production, which is a complex enterprise that very few institutions can do.”*

*Of the 10,000 km of tape that will be needed for Sparc, CFS says it currently has about a third of it on site, and firm orders for the rest. After assembly, the company’s timeline calls for the device to generate first plasma in late 2025, then demonstrate a fusion-energy gain factor ( $Q$ ) greater than 1—in other words, a net gain, meaning the fusion reaction produces more energy than is required to sustain it—by early 2026 at the latest. That’s an aggressive timeline, and nearly every fusion project to date has fallen short of its optimistic promises.*

*And yet, the plasma physics for Sparc was validated in a series of seven peer-reviewed papers published in the *Journal of Plasma Physics*. CFS’s simulations predict that the Sparc design will produce 50 to 100 megawatts of fusion power, achieving a  $Q$  greater than 10, which is commensurate with gain factor projections for *Iter*.*

### **3.1.1. Fusion Power Plant**

*As difficult as it will be, successfully producing an energy gain of 10 or more in a fusion experiment may still prove to be easier than the subsequent challenge of using nuclear fusion to put electricity on the grid. For the latter challenge, CFS is already working on what the company says will be the world’s first fusion power plant. Arc, as the company has dubbed Sparc’s successor, will be designed to demonstrate the technology required for economically competitive mass production of fusion power.*

*“We’re doing much of the work on Arc in parallel with Sparc, so that we will have the subsystems ready, and the partners,” says Sorbom, who notes that CFS is currently engaged in dozens of collaborations with U.S. national labs and universities as well as international research institutes.*

*But, unlike the fusion reactions themselves—where the physics theory is well-established, if only partially executed—many fundamental questions remain unanswered when it comes to producing electricity from nuclear fusion. The engineering challenge of building complex systems that can harvest the energy and convert it to electricity without being destroyed by radiation poses a series of tall engineering and materials hurdles.*

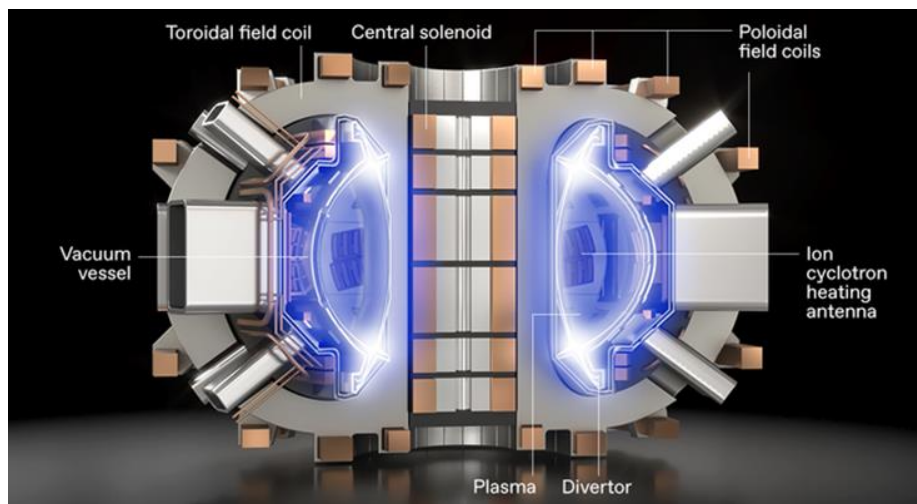
*Among them is a means to extract heat from the device for generating electrical power. At this point, CFS’s preferred approach is to use a blanket of molten salt, which could also breed tritium (also known as hydrogen-3), a rare isotope used to fuel magnetic confinement reactors.*

*The working design calls for a continuously flowing loop of salt to be pumped into a tank surrounding the plasma chamber, where it absorbs radiated neutrons. The molten salt is then pumped outside the tokamak, where its heat energy is transferred into a fluid that drives a turbine to generate electricity. Because nearly all of the power that Arc produces is absorbed in the molten-salt blanket, load on the magnet-cooling system is minimal.*

*The molten salt will likely be a mixture of lithium fluoride and beryllium fluoride, known as FLiBe. This combo allows the salt to do double duty as a breeding medium in which some of the fusion neutrons interact with lithium atoms and change them into tritium. The tritium is then filtered out of the blanket and recycled into fusion fuel.*

*FLiBe is the focus of an ongoing research partnership with MIT’s Plasma Science and Fusion Center, funded by ARPA-E. It’s one of several DOE programs that are pushing fusion research forward with grants and pairings between private industry and DOE’s national laboratories. But whether FLiBe will work better than other approaches—if at all—is still an educated guess.*

*The DOE-funded research collaboration illustrates the difference in approaches between countries. In most nations, fusion is funded by government-specified development.*



*Commonwealth Fusion Systems hopes its Sparc fusion reactor will be able to produce between 50 and 100 megawatts of power and demonstrate a net gain greater than 10. Sparc’s success is a crucial step toward fusion becoming an economically competitive source of power, an outcome that CFS expects the reactor’s successor, Arc, to fulfill.*

*T. HENDERSON/CFS/MIT PLASMA SCIENCE AND FUSION CENTER*

*Toroidal field coils: These 18 primary, D-shaped magnets circle the tokamak and force the plasma into a doughnut shape.*

*Central solenoid: This magnet drives an electric current through the plasma to cause it to twist, which prevents the plasma from expanding outward.*

*Poloidal field coils: These magnets, located at both the top and bottom of the reactor, hold the plasma in place so that it doesn't drift too far in any direction.*

*Ion cyclotron heating antennas: Also called radiofrequency heating antennas, these antennas bombard the plasma with 120-megahertz radio waves to heat it.*

*Plasma: Made up of two isotopes of hydrogen (deuterium and tritium), the plasma is the fuel that drives the fusion process.*

*Divertor: Essentially the heat exhaust of the reactor, the divertor absorbs excess heat from the plasma into pieces of tungsten.*

*Vacuum vessel: The chamber holding the plasma must be held in vacuum to prevent contamination from other air molecules, which would impede the fusion reaction.*

*"In the United States our new strategy to accelerate fusion energy R&D is to partner with the private sector, targeting public funding in ways that leverage and encourage private capital flow to a diversified portfolio of fusion technological and commercialization approaches," says Scott Hsu of the DOE, which in May announced \$46 million in milestone-based funding to advance commercial fusion development via public-private partnerships.*

*These investments, coupled with a steady stream of technical milestones, are boosting confidence in the possibility of an accelerating time scale for fusion power. In May, Zap Energy*

### **3.2. Zap Energy & Helion Energy**

*...A sleepy strip mall beside Boeing's sprawling campus in Everett, WA isn't necessarily where you'd expect to find technology promising to harness the power of the sun, release humanity from the grip of fossil fuels, and unlock an estimated US \$40 trillion market.<sup>4</sup>*

*But here, and in an even more anonymous office park nearby, startup Zap Energy is trialing a prototype reactor that is already producing high-energy neutrons from nuclear fusion—if not yet enough to send power back into the grid.*

*The unglamorous location is no accident, says Derek Sutherland, Zap's senior research scientist. "If you squint hard enough, building a fusion system is not that different from building an airplane," he tells Spectrum on a visit in June. "It requires a little bit of retooling and retraining but you can transfer a lot of those skills."*

*Zap isn't the only fusion company fishing in aviation's talent pool. Less than two miles away, Helion Energy has its own facility, purchased from a Boeing contractor and housing its own operational fusion prototype built in part by aerospace veterans. The two startups represent a unique concentration of fusion expertise and funding, and epitomize a new confidence that fusion power is now a solvable engineering challenge rather than an eternally elusive scientific puzzle.*

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<sup>4</sup> Mark Harris IEEE Spectrum, "Welcome to Fusion City, USA," June 29, 2023, <https://spectrum.ieee.org/fusion>

*Zap's Fuze-Q prototype sits in an odor-free air-conditioned room and makes only a barely-audible tick when it operates. Since going active last summer, the office-desk-size device has housed thousands of fusion reactions, each generating reams of data as Zap gradually ramps it up towards the temperatures, plasma densities, and reaction times necessary to generate more power than it consumes. The entire fusion process is about as dramatic as flipping a light switch, and Sutherland walks us right up to the small reactor shortly after one such operation...*

*"The two main drivers of cost are complexity and size," says Sutherland. "Zap excels at reducing both of those as much as possible because the system has no cryogenics, no superconducting coils, no auxiliary heating, and no magnets."*

*Zap and Helion are leading the charge for what is often called "alternative fusion"—the belief that gargantuan systems are neither necessary nor desirable in the search for practical fusion power.*

*Fusing together ions of some light elements in a gaseous plasma can release a bunch of energy if—and it's a big if—you can overcome their mutual electrostatic repulsion. That means increasing the ions' kinetic energy until they're moving fast enough (i.e. they're hot enough) to collide and fuse. ITER's reactor is a traditional tokamak design that aims to ignite a burning plasma ten times hotter than the Sun, in a giant hollow donut 20 meters wide. The larger the donut, the more power is produced; thus ITER's gargantuan size...*

*Zap and Helion's bet is that instead of trying to coax a continuous fusion reaction to life, it will be easier to string together short pulses of fusion activity. Zap's pulses start with a puff of deuterium (an isotope of hydrogen) plasma at one end of a meter-long vacuum tube, at the center of which is an electrode. The plasma is accelerated down the tube until it reaches the tapered end of the electrode, at which point magnetic forces pinch it into a tight column, with different layers flowing at different speeds. This sheared flow keeps the plasma stable and generating high energy neutrons until it collapses. At the moment, that happens after about ten microseconds. In a commercial device, it will need to last closer to a hundred, and the fuel will include a short-lived, expensive, and hard-to-find isotope of hydrogen called tritium.*

*"There will be a few more devices between Fuze-Q and a pilot plant," says Sutherland. "We think five to 10 years is realistic. But we also think that maybe it doesn't do the public any favors to hear us promise you a plant in five years."*

*Just up the road in Everett, Helion has gone one step further than promising a pilot reactor. It has already sold 50 megawatts of power to Microsoft, for delivery in 2028. This confidence is reflected in Helion's modern, securely-gated campus, home to three cavernous warehouses and an auxiliary site crawling with earth movers. Many of Helion's 160 staff work in its largest 150,000 square feet warehouse, where components for its seventh and final prototype Polaris are now being assembled.*

*My visit starts in Helion's capacitor "kitchen," so-called for the various processes involving in coating, testing, and baking the thousands of oil-filled capacitors Polaris will need. Huge banks of capacitors are the only way to quickly deliver the massive pulses of energy necessary to kick-start both Zap's and Helion's fusion reactions. Zap's capacitor bank will store 1.5 megajoules of energy—about a third of the energy released from a kilo of TNT. Helion's will store a staggering 50 MJ, requiring 150 shipping containers full of capacitors, synchronized with semiconductor switches to discharge in less a millisecond.*

*When complete, Helion's reactor will be bigger than Zap's, about two meters tall and 12 meters long. Its initial jolt powers a series of electromagnets at either end of Polaris that form and accelerate clouds of plasma towards their common center. It is at the reactor's narrowest point—subject to the strongest magnetic field—that fusion briefly occurs. Like Zap's design, Helion's commercial reactor is intended to pulse about once per second and generate 50 MW. But there are some big differences.*

*For a start, Helion will fuse deuterium with helium-3, an ultra-rare and extremely expensive isotope of helium, in a reaction that produces relatively few neutrons. That isn't a problem for Helion because it doesn't need neutrons to boil water but instead produces electricity directly from the fusion reaction. In Polaris, each fusion pulse should cause the plasma to expand, increasing its magnetic flux and inducing electric current in the magnetic coils that ultimately flows back to the capacitors.*

*"The National Ignition Facility experiment last year proved key science in igniting a plasma for the first time," says David Kirtley, Helion's founder and CEO. "But in the process they threw away 99.9 percent of the input energy. We have proven our system can recover 95 percent, so we only lose about 5 percent of the energy that we put into the fuel. That means we have to do that much less fusion to reach net gain."*

*Relatively few fusion start-ups are planning to use helium-3 as a fuel, which is so scarce that some experts have even suggested mining it on the moon. Polaris, however, should be able to produce its own helium-3 from deuterium, and Helion claims that it has already generated (although not separated) a small amount.*

*With just 100 capacitors and one of the formation magnet coils built so far, Kirtley's plan is to assemble Polaris by January 2024. Helion will then gradually increase power and compression through the year. "If all the scaling holds and everything works the way we expect, we should be able to recover enough electromagnetic energy from the fusion system to recharge those banks plus a little bit extra," he says. "And that little bit extra is net electricity."*

*But even Polaris is unlikely to produce any leftover power once the energy demands of cooling and switching systems are factored in. That will fall to Polaris's successor, a pilot fusion reactor aiming to fulfill Microsoft's power contract sometime in 2028. While the location of that has yet to be determined, it's likely to remain in the state.*

*"We're in a period of transition from science towards engineering, but we still have plasma physicists on staff and we will for quite some time," says Zap's Sutherland. "We're trying to decarbonize the energy base load for the entire planet. If Zap (and/or Helion's Polaris and/or CFS's Arc) works, it will change the world."*