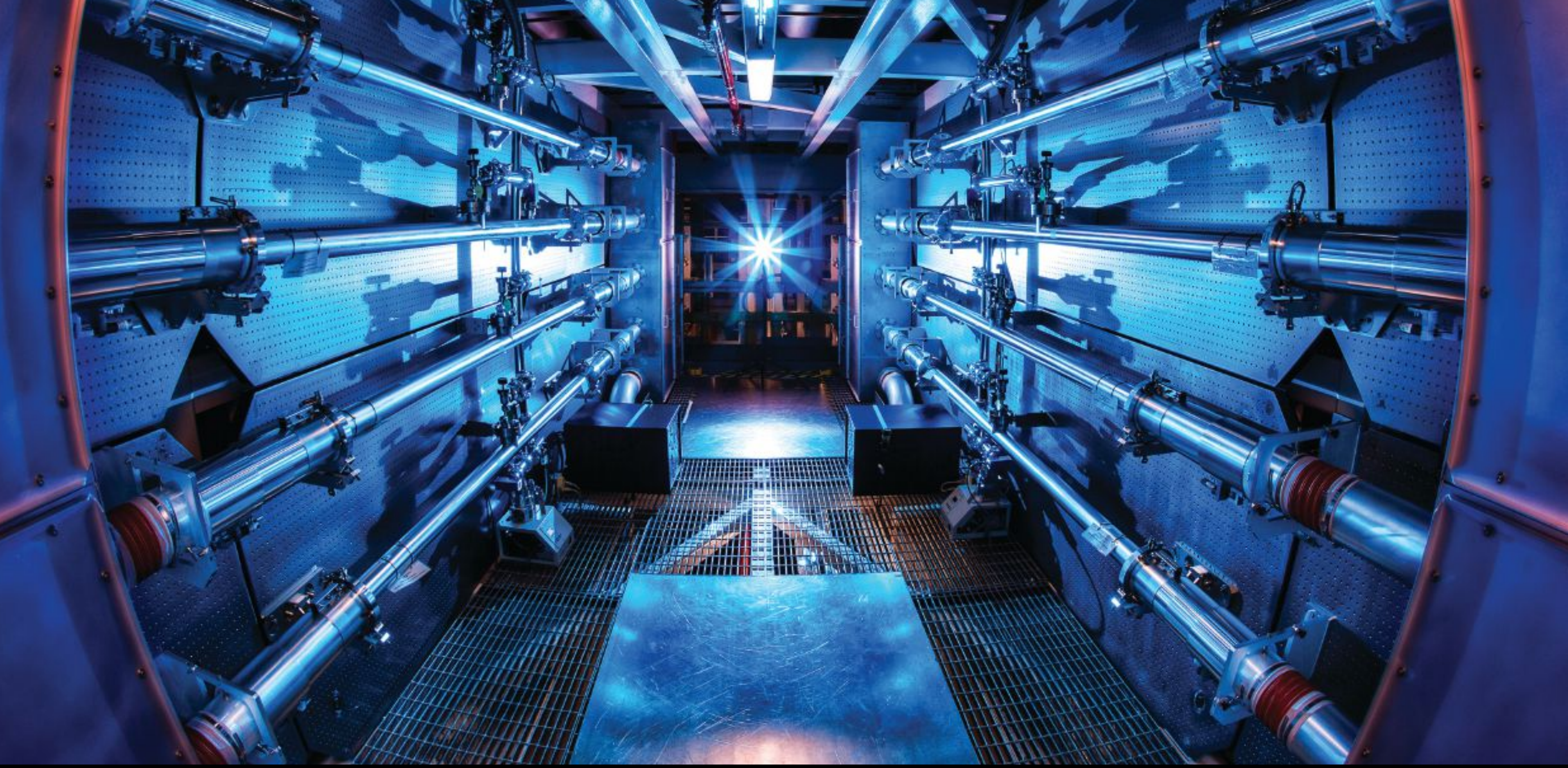


Is Fusion Ready for Prime Time?

BY ALAN S. BROWN

Physicists promised clean, green fusion power for decades and never delivered. Now, new technologies and massive investments promise changes.

Researchers have believed that fusion energy is just around the corner since the 1950s. Yet, the process by which stars transform hydrogen plasma into helium with a slight loss of mass that becomes energy remains tantalizingly out of reach. Today's mega-projects are still struggling with translating the Sun's environment to Earth-bound reactors.

Now, however, innovative technologies backed by billions of venture capital dollars are changing the game. Many startups believe they could reach "Q," the point where fusion produces more energy than it takes to initiate, within this decade.

Governments are also giving fusion a second look, said Scott Hsu, who heads the U.S. Department of Energy's fusion program. They are finding it harder to achieve net-zero carbon emissions than they thought, and fusion has the potential to provide vast quantities of clean baseline energy without the risks associated with nuclear fission.

Hsu believes they have cause for optimism. "Technology push and market pull are both happening at the same time and at unprecedented levels," he said. After spending 70 years mastering fusion plasmas, both government-funded mega-projects and dozens of startups are leveraging that knowledge to refine or develop innovative fusion technologies.

On the mega-project side, the National Ignition Facility in Livermore, CA, achieved a record-breaking 0.7 Q self-sustaining burning plasma, if only for a few moments. Experiments at U.K.'s Joint European Torus (JET) reaffirmed predictions that the $25 billion International Thermonuclear Experimental Reactor (ITER) under construction in France could surpass Q by 2035. Reactors in South Korea and China set records for prolonged plasma confinement.

Startups are promising faster results. Small companies, building on breakthroughs in high-temperature superconductors, advanced computing, and three-quarters of a century of research, are developing dozens of impressive new designs into the future. Commonwealth Fusion Systems, for example, demonstrated a powerful 20 Tesla superconducting magnet, the key to smaller, more affordable reactors. Helion Energy and Tokamak Energy both pushed plasma temperatures above the 100 million Kelvin needed for fusion, and General Fusion proved its ability to compress plasma precisely.

Excited private investors have injected $5 billion into 33 fusion startups over the past two years, according to a study by the Fusion Industry Association. Over the past year, Commonwealth alone raised $1.8 billion and Helion Energy, $500 million. For the first time, Hsu said, private capital is exceeding government spending, enabling researchers to quickly turn designs into pilot plants.

Not everyone is so sanguine. Daniel Jassby, a former research physicist at Princeton Plasma Laboratory, likens today's optimism to a pandemic of marketing and financial hype that breaks out periodically. He does not expect commercial fusion until the next century.

Jassby argues that no one has produced fusion on anything approaching commercial scale. Mega-projects have sustained fusion for only a handful of seconds at best. Many startups have failed to meet self-proclaimed goals and most others have not yet demonstrated any actual fusion.

Jassby sees many gaps in fundamental knowledge. Most reactor designs are based on empirical models, which have a poor record of scaling up. Reactors consume colossal amounts of electricity creating and controlling plasma, and he sees no scientific breakthroughs that will push Q to the very high levels needed to make electricity profitably. We may not even have enough hydrogen isotopes to fuel a large fleet of fusion power plants.

Both sides make valid points. The only way to resolve them is to see if one of those startups can build a commercial power plant.

GETTING TO Q

While fusion on Earth is similar to natural fusion on the Sun, it is their differences that make commercial fusion so difficult to achieve. Stars have huge gravitational fields that squeeze hydrogen ions together at 15 million K, causing them to fuse and form helium and energy.

To replicate a star on Earth, researchers must find a way to confine plasma. Since they cannot achieve the densities found in stars, they must combine the hydrogen isotopes most likely to fuse, deuterium and tritium. Even then, they must heat the D-T mixture to 100 million K to provide enough energy for fusion.

Since the 1960s, physicists have attempted to use powerful magnets to confine a hot D-T plasma as it spins around a donut-shaped reactor called a tokamak. The technology is very well characterized and forms the basis for the JET and ITER reactors.

Tokamaks use a variety of magnetic fields to do this. Toroidal fields that run along their circumference of the torus' chamber are created by powerful ring-shaped magnets that encircle the donut. A powerful alternating current coil in the donut's center creates a poloidal magnetic field within the plasma that runs perpendicular to the toroidal field, complemented by poloidal magnets above and below the reactor. By balancing these magnetic fields, researchers shape and densify the plasma to achieve fusion.

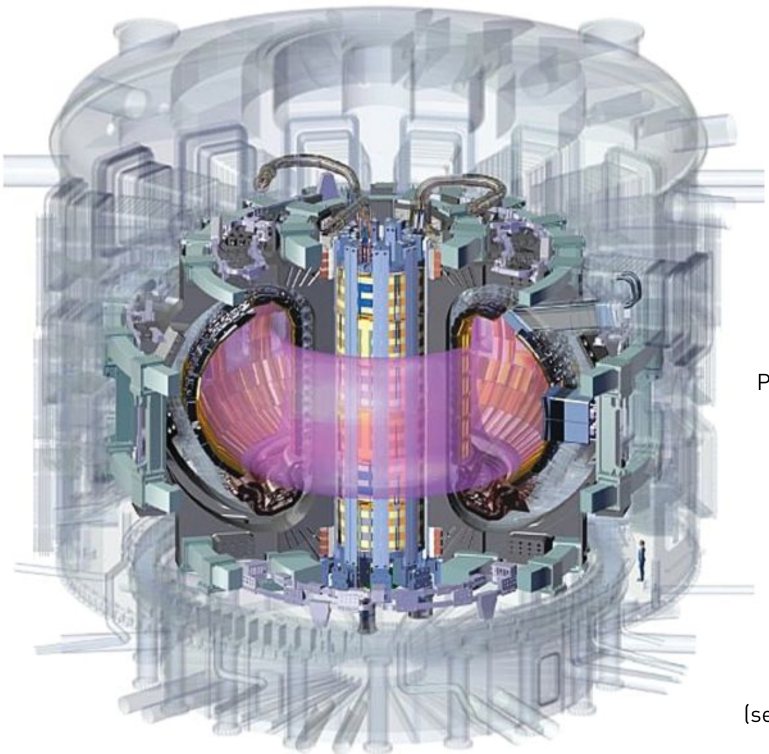
High-energy plasmas are difficult to control, said Chris Hegna, a professor of engineering physics at University of Wisconsin-Madison and co-founder of Type One Energy, a fusion startup.

"Tokamak plasmas require currents that can be the source of instabilities. These instabilities can cause the plasma column to deform towards the reactor walls. This can produce a thermal collapse of the plasma and a transient electric field that accelerates electrons to high enough energies that they could damage the walls of the reactor."

Another successful route to fusion is inertial confinement, a technique proposed in the 1970s. It uses powerful lasers to implode a D-T target with enough density and heat to trigger fusion. It took decades to develop powerful enough lasers to make this work.

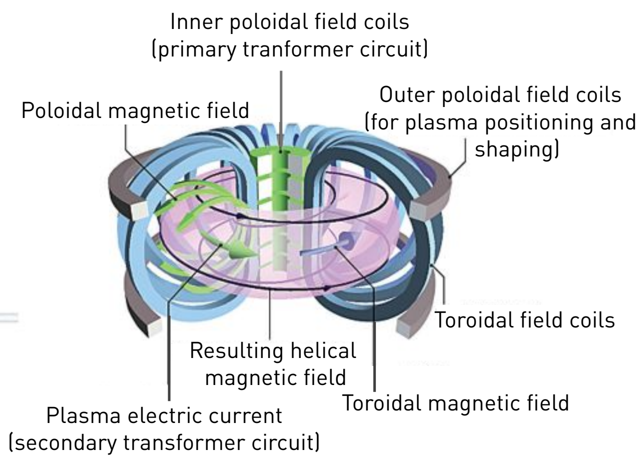
In 2009, the $3.5 billion National Ignition Facility opened. To achieve fusion, it encases a pea-sized D-T target inside a tiny container called a hohlraum. NIF's 192 UV lasers then blast the hohlraum with 500 trillion watts of peak power. This implodes the target while X-rays generated by laser beams converging on the hohlraum's interior surface heat the plasma.

At first, NIF underperformed. Then, in August 2021, it achieved a plasma that yielded 70 percent of the energy used to initiate it, a record for any fusion system. The reaction began in the core and was about to propagate into the surrounding D-T shell before expansion cooling killed it.



Left: The $20+ billion ITER tokamak reactor hopes to achieve break-even fusion performance in the 2030s. Credit: DOE.

Below: Tokamak reactors use poloidal and toroidal magnetic fields generated by a variety of magnets and the plasma itself to shape hot, energetic plasmas to achieve fusion. Credit: US ITER.



Subsequent experiments yielded no more than half that value. One theory is that NIF's aging lasers and minute variations in the hohlraum shaped the implosion in unexpected ways. Untangling those interactions will take time.

NIF has other issues. Targeting and timing the output of 192 lasers with pinpoint precision will always be difficult. Lasers are also inefficient X-ray generators, Jassby said. High-energy ion beams might do a better job, but Jassby believes they will take decades of development.

Still, magnetic and inertial confinement face the same problem: both take an enormous amount of energy to generate a fusion reaction. To overcome that barrier, researchers must push Q way above 1.

Jassby points to ITER as an example: "Computer projections show it will have a Q of 10, but if it actually gets there, its net energy balance will be about zero." That's because ITER uses enormous amounts of energy to run its vacuum pumping system, cool its superconductors to 4-5 K, recover tritium, move coolant, and run its computer, diagnostics, and HVAC systems.

"ITER consumes 75 to 110 MW of electrical power even when it's not operating. To inject 50 MW of heating power at 50 percent efficiency will require another 100 MW. So, ITER will consume 200 MW each pulse. If it produces 500 MW of power [Q=10] and converts that to electricity at 40 percent efficiency, it will generate 200 MW of power, barely matching its energy consumption."

Many startups say they can surmount this hurdle, but how?

SMALLER TOKAMAKS

If any company is the poster child for commercial fusion, it is MIT spinoff Commonwealth Fusion. It raised $1.8 billion in 2022 alone — a lot of money for a company born from a chance conversation and a class project.

This happened a few years after Dennis Whyte, now professor of engineering and director of MIT's Plasma Science & Fusion Center, came to MIT in 2006. He decided to resurrect MIT's principles of fusion engineering course at a time when most of the action in fusion was on the physics side.

For Whyte, the best part of the class came when he asked his students to form teams and try to solve one of fusion's top-20 challenges. Yet, even though he enjoyed his class, Whyte was growing increasingly frustrated at fusion energy's slow pace.

"My scientific community had underestimated the challenges of putting together ITER, the largest and most complex engineering project envisioned by humanity," he said. "I didn't think it was ever going to lead to a power plant."

Then fate intervened. Whyte stepped out of his office and saw a colleague carrying a strand of ribbon in his hand. "What's that?" he asked. It was a new type of high-temperature superconductor (HTS) wire under development in a lab 50 feet away from his doorway. The researchers were trying to develop HTS wire to make powerful magnets for MRI and nuclear magnetic resonance (NMR) equipment. No one had thought about applying them to fusion.

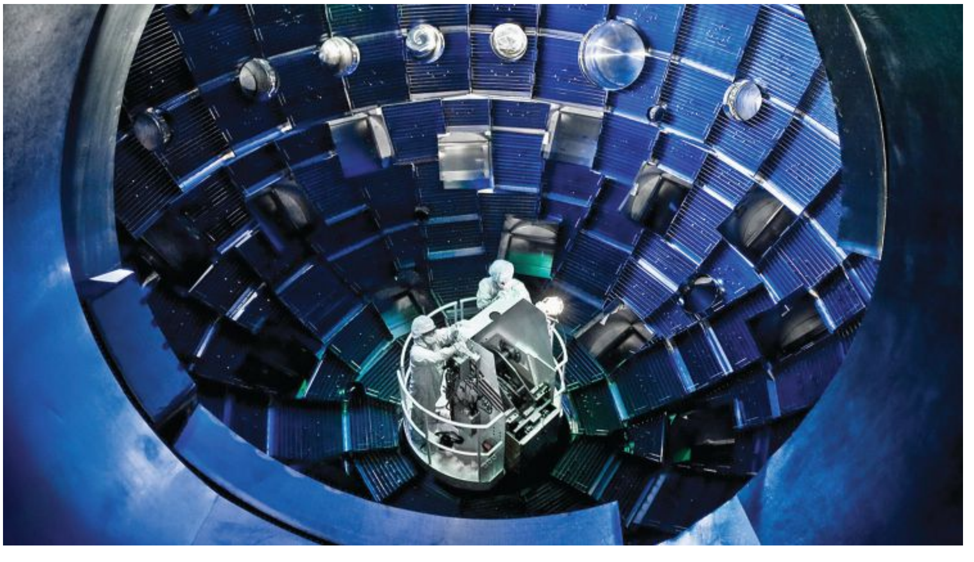
Superconductors were not new. ITER planned to make its magnets from 500 metric tons of niobium-tin low-temperature (LTS) superconductors. Yet, LTS had limitations: their magnetic fields are limited to 10-11 Tesla and they had to be chilled to a scant 4 K above absolute zero.

HTS could burst past these limitations. It could carry enormous amounts of current, produce larger magnetic fields, and operate higher temperatures that require less energy to sustain. Magnets made from these materials could achieve orders of magnitude better performance in fusion.

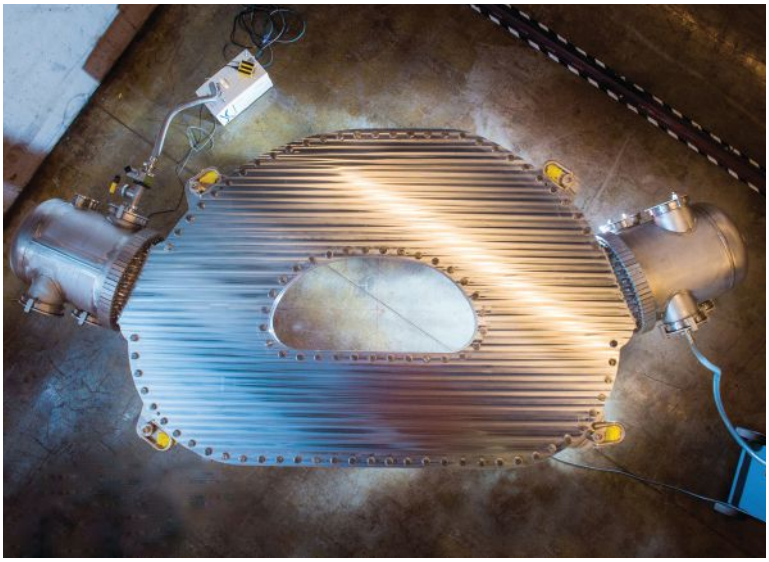
Whyte introduced his class to HTS wires, but after the semester, he realized that he had not taken full advantage of HTS' disruptive potential. So, he posed a more ambitious challenge for his next class: design a 500 MW fusion device and make it as small as possible.

What emerged was the conceptual idea for Commonwealth Fusion's ARC reactor, named after a reactor built by Marvel Comic's Tony Stark (Iron Man), who attended MIT. The reactor would be powerful, small (about the size of JET), and affordable.

To turn ARC into a reality, Whyte and several of his students formed Commonwealth Fusion. Its first order of business was to collaborate with MIT to develop a new class of fusion-ready HTS wire.



The inside of the National Ignition Facility's 10-meter-diameter target chamber, where 192 powerful lasers implode a deuterium-trititum pellet to initiate fusion. Credit: Lawrence Livermore National Laboratory.



Fabricated by Commonwealth Fusion Systems and MIT's Plasma Science and Fusion Center, this large-bore, full-scale magnet used high-temperature superconductors to produce a 20 tesla magnetic field, the strongest ever for a fusion magnet. Credit: Gretchen Ertl, MIT.

An illustration of SPARC, a compact, high-field tokamak now under construction by a joint Commonwealth Fusion Systems-MIT. Roughly the size of today's experimental tokamaks, it is designed to generate up to 100 MW of plasma energy for 10 seconds. Credit: T. Henderson, MIT.

The result was VIPER, for vacuum pressure impregnated, insulated, partially transposed, extruded, and roll-formed. It consists of a flat steel ribbon a fraction of a millimeter thick coated with a buffer layer and topped with a microns-thin layer of rare earth-barium-copper-oxide (REBCO) HTS that carries 1,000 Amperes with ease.

The structure solves one of the key issues facing HTS wires: stress. REBCO naturally resists magnetic fields that would scramble its complex crystals and kill its superconductivity. Yet, large magnetic fields also generate enormous physical forces that would do the same thing to its structure.

VIPER's structural steel substrate and its magnet construction methods enable Commonwealth's magnet to tolerate 900 megapascals (MPa) of force without a significant drop in performance. This enabled the company to demonstrate a 20 Tesla magnet, twice as powerful as the low-temperature superconductor magnets being built for ITER.

High fields boost small reactor performance in big ways. The smaller the reactor, the denser the plasma. "If we increase the plasma density by a factor of two, we increase the fusion power output by a factor of four," Whyte said. "That increases the amount of power you make per unit volume of fuel, which is a key economic driver of the cost of fusion."

ARC also relies on a central HTS A/C coil core to rapidly ramp up current and magnetic fields while withstanding thousands of cycles. This will enable ARC to produce fusion through repetitive pulses that may last tens of minutes. By forgoing continuous fusion, ARC simplifies reactor design and slashes costs.

Commonwealth is currently putting the finishing touches on its SPARC reactor, a 1.85-meter diameter ARC prototype that will generate a 100 MW of plasma for 10 seconds.

Whyte believes it will be the first fusion plant to achieve Q>1. He calls it the team's Kitty Hawk moment, where fusion proves it can fly.

"The most difficult conditions necessary for fusion have already been obtained," he said. "We've exceeded 100 million degrees and the density and containment times required for fusion. We've just never done them all together."

If all goes well, ARC will leap over that hurdle and open the door to commercial fusion.

ROLLER COASTERS

Tokamaks are not the only magnetic confinement game in town. Stellarators are the second best-characterized reactor and have several potential benefits over tokamak designs, said Type One's Hegna.

"With stellarators, there is no need to rely on plasma currents to provide the confining poloidal magnetic field," he said. "Instead, stellarators use only external magnetic fields. You don't have to worry about plasma current drive systems and you avoid instability-inducing disruptions."

Unfortunately, that simplicity comes at a cost: stellarator magnets bend and twist around the reactor like a roller coaster, no two magnets shaped or angled the same. For engineers used to dealing with symmetrical designs, stellarators are nightmares.

"In the early days, people came up with designs, but they had poor plasma confinement properties," Hegna said. "Still, they made something, saw how it worked, and moved forward. The real breakthroughs came in the late 1980s and 1990s, when researchers began using high-fidelity computation to optimize their coils. We could start with prescribing the plasma physics properties we wanted, then ask if coils could be constructed to produce the desired magnetic field."

The resulting roller coaster designs made stellarators practical. So did HTS wiring. Type One, like several other startups, is leveraging Commonwealth Fusion's VIPER HTS wires. Type One, however, must still show that it can bend and twist HTS magnets into the shapes it needs to make the stellarator work.

Type One has also embraced additive manufacturing, creating its own build platform to make parts that are both large and intricate. This has greatly accelerated efforts to build its Starblazer reactor.

Starblazer is based on lessons learned from University of Wisconsin's 2.4-meter-diameter HSX stellarator built in 2007 and Germany's 5.5-meter W7-X stellarator demonstrated in 2018. German researchers hope improvements they are now developing will boost W7-X performance to tokamak levels and achieve run times measured in minutes rather than seconds.

To get there, stellarators must overcome some inherent weaknesses. Confinement times, for example, are two or three times shorter than an equivalent tokamak. Yet this is at least partially balanced by their higher plasma densities.

"There's some trade-off between the two," Hegna said. "It becomes a much more complicated problem when you start considering reactor styles or reactor processes."

Type One is betting that new software will yield a deeper understanding of turbulence so it can improve its reactors and control systems to prolong confinement. Hegna remains optimistic that Type One's stellarators will exceed Q>1 by the early 2030s.

ZAP

Z-pinch fusion relies only on the attraction of electrical currents. Is requires no magnetic coils and could produce fusion for a fraction of the cost of magnetic confinement or inertial fusion systems.

The process is simplicity itself, said Matthew Thompson, vice president of engineering for Zap Energy, which is developing the process. "You simply run a large current through a gas," he said. "This creates the plasma and a powerful magnetic field that heats and pinches [compresses] the gas so you get fusion reactions."

Z-pinch is also well characterized, but not in a good way. The concept dates to the 1950s, when it was one of the first fusion technologies. The reason researchers abandoned Z-pinch is that its plasmas are wildly unstable.

"The plasma starts to look like sausages on a line, with some parts over-pinched and others under-pinched," Thompson said. "Or it starts to corkscrew. Russian researchers developed tokamaks to confine those instabilities."

Led by Uri Shumlak, University of Washington, researchers spent 20 years perfecting the use of shear to stabilize Z-pinch plasmas. Thompson likens the concept to changing lanes on a highway: "If everyone is going down the highway at the same speed, it's easy to change lanes. But if each lane were 100 mph faster than the other, nobody could ever change lanes. So that's what we're trying to do with our plasma — have it moving faster than the gas layers around it to suppress the formation of instabilities."

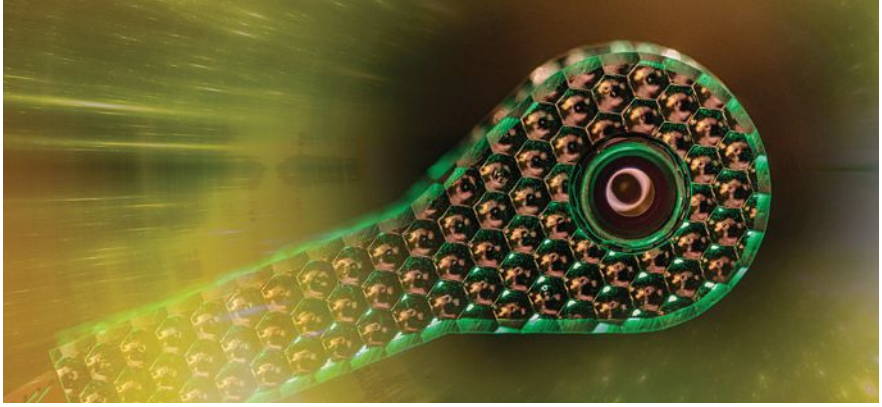
Shumlak co-founded Zap in 2017. The next year, his team announced that his lab-scale FuZE reactor had boosted plasma stability times by a factor of 5,000 and had achieved deuterium fusion for several microseconds. Lawrence Livermore National Laboratory confirmed this in 2021.

Since then, Zap has raised almost $190 million and has begun construction of its new FuZE-Q reactor. It will require massive power supplies, large capacitor banks, and finely tuned switching to produce an optimal Z-pinch at 650 kA, Thompson said. He expects it to hold the Z-pinch stable for 100 msec, five to ten times longer than the FuZE reactor, and achieve significant amounts of fusion, he added.

"Z-pinch poses significant challenges, but a lot of the technology is at a high readiness level," he said. "We don't need lasers that don't exist yet or high-temperature superconductors to make it work."

Below: A 3D model of plasma moving through a roller coaster-like series of superconducting stellarator solenoid coils in the experimental Wendelstein 7-X fusion device. Credit: Max Planck Institute for Plasma Physics.

Left: Zap Energy's Z-pinch reactor does not rely on magnets to stabilize its plasma. Instead, it uses shear created by different layers of plasma moving at different speeds to maintain control. Credit: Zap Energy.



This stylized image shows a cryogenic target used in inertial fusion experiments to achieve a record fusion output of 1.3 megajoules at the National Ignition Facility in 2021. Credit: James Wickboldt, LLNL.

"WE DON'T NEED LASERS THAT DON'T EXIST YET OR HIGH-TEMPRATRURE SUPERCONDUCTORS TO MAKE IT WORK."

FUEL FOR THE FUTURE

Even optimists have daunting hurdles to overcome. One involves the models used to design and predict reactor performance. Since they are based on empirical data rather than first principles, they may not scale well or properly apply the results of one reactor to another.

"Look at the National Ignition Facility," Jassby said. "Their initial yield was 1,000 times lower than they expected. It took 10 years to approach where they are now." The two tokamaks Jassby helped build at Princeton Plasma Laboratory also initially underperformed, though by a factor of 10.

"It's like the models used to predict stock market performance," he said. "They have all the parameters needed to predict the past, but not the ones needed to predict the future."

David Hatch, a research professor at the Institute for Fusion Studies at University of Texas at Austin, is more optimistic. He specializes in applying modeling and machine learning to fusion.

"I work with tokamaks and I think the models are really good, depending on what part of the problem we're asking about," he said. "The challenge is to model everything at one go because the variation in time and length scales is extreme."

Many tokamak and stellarator models are quite mature and HTS does not change that much, he said. While they model the plasma core reliably, modeling the edge, near the wall, is more challenging and uncertain. Such models would require additional validation before using them to simulate non-tokamak/stellarator designs, Hatch added.

Hatch also works with machine learning firm Sapientai. "One of the things we focus on is starting with small amounts of data and building models that can point experiments to regions of parameter space that we can use to create better models and learn more about the process," he said. The company is currently working with CT Fusion, General Fusion, General Atomics, and Princeton Plasma Physics Lab.

Another critique of fusion involves fuel. The ideal mix is half deuterium and half tritium, but tritium is extraordinarily scarce. The total global stockpile is about 25 kilograms and tritium has a short, 12.3-year half-life. The only commercial supply of tritium comes from 19 Canada Deuterium Uranium (CANDU) reactors, which are slated to close. No wonder tritium costs up to $100,000 per gram.

Most fusion reactors expect to create their own fuel supply through nuclear alchemy. Fusion generates energetic neutrons. These will give up their energy by interacting with coolants. While the heated coolants drive the power turbines, the less energetic neutrons will interact with lithium-6 isotopes and transmute them into tritium and helium. Reactors will also recycle the unused 99 percent of the tritium fuel.

Not everyone believes this will produce enough tritium to fuel a fleet of fusion reactors. Mohamed Abdou, director of the Fusion Science and Technology Center at University of California, Los Angeles, expects even the best systems will produce only a scant bit more tritium than they need for fuel. They will lose some of that through leaks and maintenance shutdowns.

Yet, Whyte is confident that ARC's lithium-salt cooling system could produce 15 to 20 percent excess tritium. "We're building an experiment now to prove it works," he said.

Some startups, like TAE Technologies (hydrogen-boron) and Helion Energy (deuterium-helium-3) are pursuing routes to fusion that use no tritium, though they will have to operate far above 100 K. Others are testing new reactor designs, from spherical tokamaks and magnetic mirrors to shock-driven inertial confinement and hypervelocity gradient fields. Each of the 33 startups surveyed by Fusion Energy Association has its own spin on the technology.

In the end, empirical results will determine whether the optimists or pessimists are right. DOE's Hsu sides with the optimists. "We still have challenges ahead, but over the past 20 or 30 years, most of the big science problems have been solved. We're finally in a position to see a light at the end of the tunnel," he said.

"The influx of venture capital over the past two years has changed the game," he added. "If we combine public and private funding, I think we have a chance to get to breakeven in the 2020s and pilot scale electricity on the grid in the 2030s."

ALAN S. BROWN has written broadly about engineering, technology, and science for more than 30 years. He is a board member of Science Writers in New York, a writer for The Kavli Foundation, a former senior editor of ASME's *Mechanical Engineering* magazine, and contributes to a wide range of publications. He graduated *magna cum laude* in 1974 from Hofstra University and can be reached at: **insight01@verizon.net.**