The world's strongest high-temperature-superconducting magnet will be used in a 2025 fusion reactor in Massachusetts.

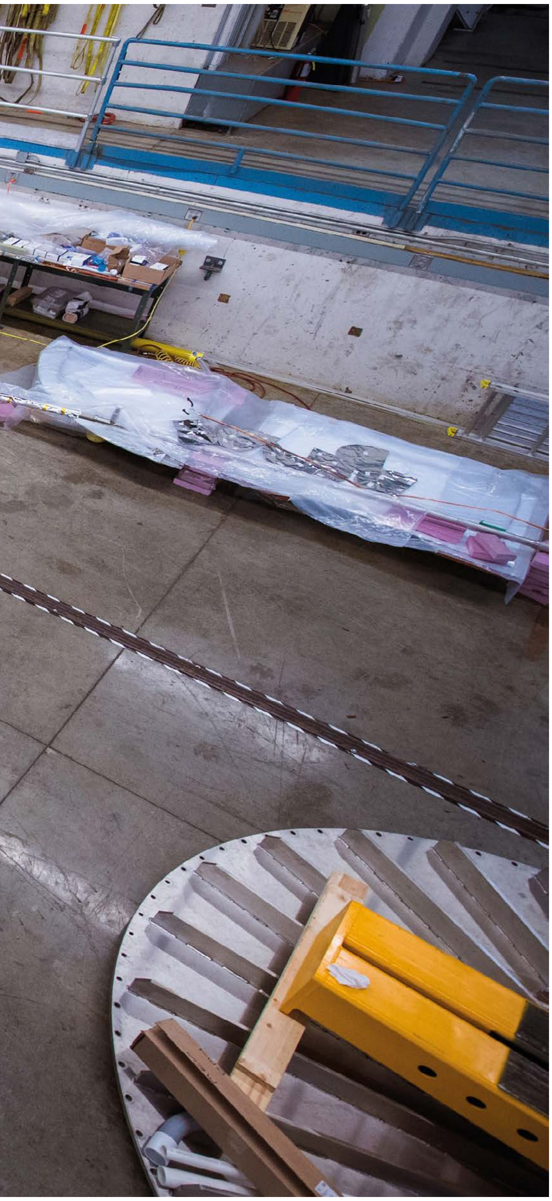
GRETCHEN ERTL, CFS/MIT-PSFC, 2021

THE RACE TO FUSION ENERGY

An emerging industry of nuclear fusion firms promises commercial reactors in the next decade. **By Philip Ball**

The ancient village of Culham, nestled in a bend of the River Thames west of London, seems an unlikely launching pad for the future. But next year, construction will start here on a gleaming building of glass and steel that could house what many people consider to be an essential technology to meet demand for clean energy in the twenty-first century and beyond.

Long derided as a prospect that is forever 30 years away, nuclear fusion seems finally to be approaching commercial viability. There are now more than 30 private fusion firms globally, according to an October survey by the Fusion Industry Association (FIA) in Washington DC, which represents companies in the sector; the 18 firms that have declared their funding say they have attracted more than US$2.4 billion in total, almost entirely from private investments. Key to these efforts are



advances in materials research and computing that are enabling technologies other than the standard designs that national and international agencies have pursued for so long.

The latest venture at Culham — the hub of UK fusion research for decades — is a demonstration plant for General Fusion (GF), a company based in Burnaby, Canada. It is scheduled to start operating in 2025, and the company aims to have reactors for sale in the early 2030s. It "will be the first power-plant-relevant large-scale demonstration", says GF's chief executive Chris Mowry — unless, that is, its competitors deliver sooner (see 'Fusion rush').

Designed by British architect Amanda Levete, GF's prototype plant illustrates the way fusion research has shifted from gargantuan state- or internationally funded enterprises to sleek, image-conscious affairs driven by private companies, often with state support. (GF will receive some UK government funding; it has not disclosed how much.)

In this respect, advocates of fusion technology say it has many parallels with the space industry. That, too, was once confined to government agencies but is now benefiting from the drive and imagination of nimble (albeit often state-assisted) private enterprise. This is "the SpaceX moment for fusion", says Mowry, referring to Elon Musk's space-flight company in Hawthorne, California.

"The mood has changed," says Thomas Klinger, a fusion specialist at the Max Planck Institute for Plasma Physics (IPP) in Greifswald, Germany. "We can smell that we're getting close." Investors sense the real prospect of returns on their money: Google and the New York City-based investment bank Goldman Sachs, for instance, are among those funding the fusion company TAE Technologies, based in Foothill Ranch, California, which has raised around $880 million so far. "Companies are starting to build things at the level of what governments can build," says Bob Mumgaard, chief executive of Commonwealth Fusion Systems (CFS), based in Cambridge, Massachusetts.

And just as private space travel is now materializing, many industry observers are forecasting that the same business model will give rise to commercial fusion — desperately needed to decarbonize the energy economy — within a decade. "There's a very good shot to get there within less than ten years," says Michl Binderbauer, chief executive of TAE Technologies. In the FIA report, a majority of respondents thought that fusion would power an electrical grid somewhere in the world in the 2030s.

Several fusion researchers who don't work for private firms told *Nature* that, although prospects are undeniably exciting, commercial fusion in a decade is overly optimistic. "Private companies say they'll have it working in ten years, but that's just to attract funders," says Tony Donné, programme manager of the Eurofusion consortium which conducts experiments at the state-run Joint European Torus, established at Culham in the late 1970s. "They all have stated constantly to be about ten years away from a working fusion reactor, and they still do."

Timelines that companies project should be regarded not so much as promises but as motivational aspirations, says Melanie Windridge, a plasma physicist who is the FIA's UK director of communications, and a communications consultant for the fusion firm Tokamak Energy, in Culham. "I think bold targets are necessary," she says. State support is also likely to be needed to build a fusion power plant that actually feeds electricity into the grid, adds Ian Chapman, chief executive of the UK Atomic Energy Authority (UKAEA).

But whether it comes from small-scale private enterprise, huge national or international fusion projects, or a bit of both, practical nuclear fusion finally seems to be on the horizon. "I'm convinced that it's going to happen", says Chapman. Chris Kelsall, chief executive of Tokamak Energy, agrees. "Sooner or later this will be cracked," he says. "And it will be transformative."

Seventy-year dream

Nuclear fusion, says Klinger, is "the only primary energy source left in the Universe" that we have yet to exploit. Ever since the process that powers the stars was harnessed in the 1950s for hydrogen bombs, technologists have dreamt of unlocking it in a more controlled manner for energy generation.

Existing nuclear power plants use fission: the release of energy when heavy atoms such as uranium decay. Fusion, by contrast, produces energy by merging very light nuclei, typically hydrogen, which can happen only at very high temperatures and pressures. Most efforts to harness it in reactors involve heating the hydrogen isotopes deuterium (D) and tritium (T) until they form a plasma — a fluid state of matter containing ionized atoms and other charged particles — and then fuse. For these isotopes, fusion starts at lower temperatures and densities than for normal hydrogen.

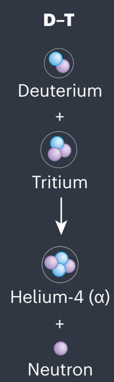
D–T fusion generates some radiation in the form of short-lived neutrons, but no long-lived radioactive waste, unlike fission. It is also safer than fission because it can be switched off easily: if the plasma is brought below critical thresholds of temperature or density, the nuclear reactions stop.

What makes it so difficult to conduct in a controlled manner, however, is the challenge of containing electrically charged plasma that is undergoing fusion at temperatures of around 100 million kelvin — much hotter than the centre of the Sun. Generally, researchers use magnetic fields to confine and levitate the plasma inside the reactor. But instabilities in this infernal fluid make containment very difficult, and have so far prevented fusion from being sustained for long enough to extract more energy than is put in to trigger it.

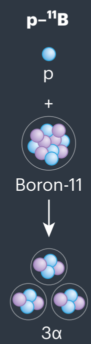
This is necessarily big science, and until this century, only state-run projects could muster the resources. The scale of the enterprise is reflected today in the world's biggest fusion effort: ITER, a fusion reactor being constructed in southern France and supported by 35 nations, including China, European Union member states, the United States, Russia, South Korea and Japan, with a price tag of at least $22 billion. Although the first test runs are scheduled for 2025, full D–T fusion is not scheduled until 2035, ultimately with the goal of continuously extracting 500 MW of power — comparable to the output of a modest coal-fired power plant — while putting 50 MW into the reactor. (These numbers refer only to the energy put directly into and drawn out of the plasma; they don't factor in other processes

FUEL MIX

Many reactors fuse deuterium (D) with tritium (T) to release energy. This mix ignites, or creates a self-sustaining fusion reaction, at around 100 million kelvin. It produces neutrons, which can make the chamber radioactive.



Other reactions, such as fusing protons (p) with boron-11 (^{11}B), don't produce neutrons, but ignition requires higher temperatures.



FUSION RUSH

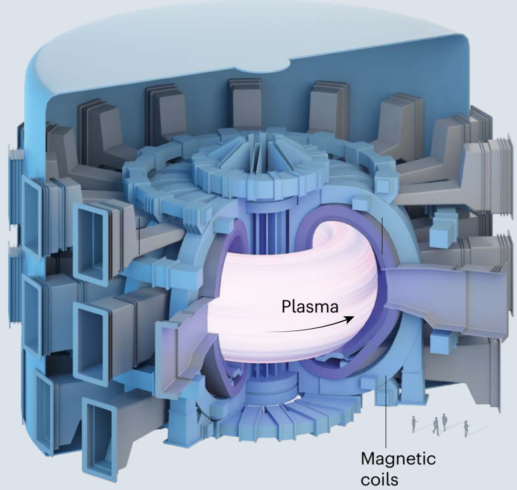
Firms and governments are developing many kinds of fusion reactor. They all heat gas to create a plasma, confined at such high temperatures that atomic nuclei fuse, releasing energy that can be harnessed for electricity. Here are five prominent designs.

Illustration by Tomáš Müller
Design by Jasiek Krzysztofiak

TOKAMAK

ITER AND OTHER FACILITIES

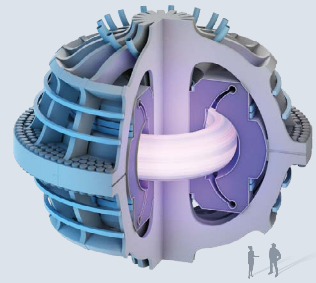
Superconducting magnetic coils — cooled by liquid helium — hold plasma in a toroidal vessel.



MINI-TOKAMAK

TOKAMAK ENERGY, COMMONWEALTH FUSION SYSTEMS AND OTHERS

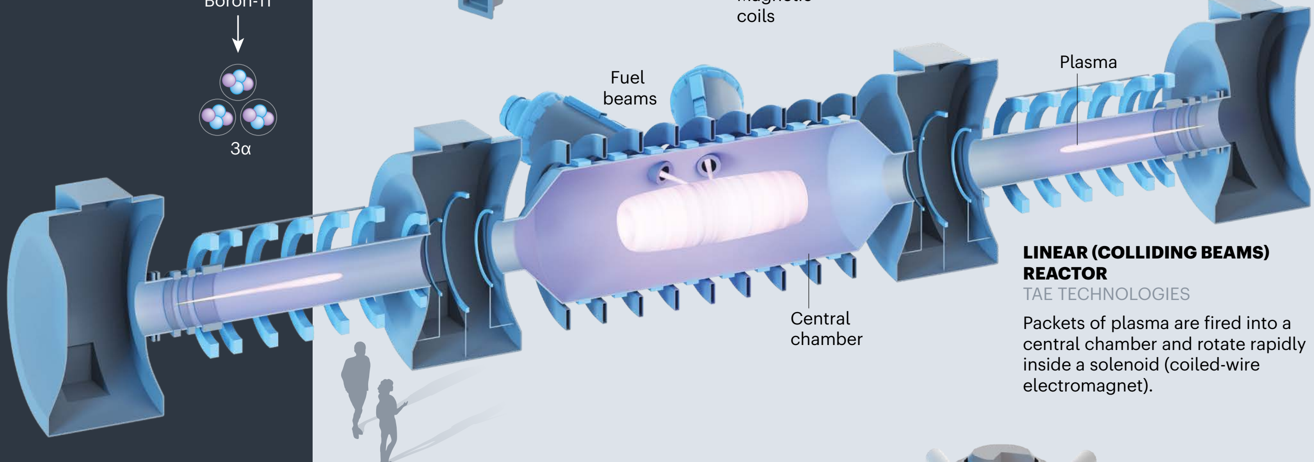
Magnets made of high-temperature superconductors produce stronger fields and can be cooled more easily, allowing more compact, spherical tokamaks to be built.



LINEAR (COLLIDING BEAMS) REACTOR

TAE TECHNOLOGIES

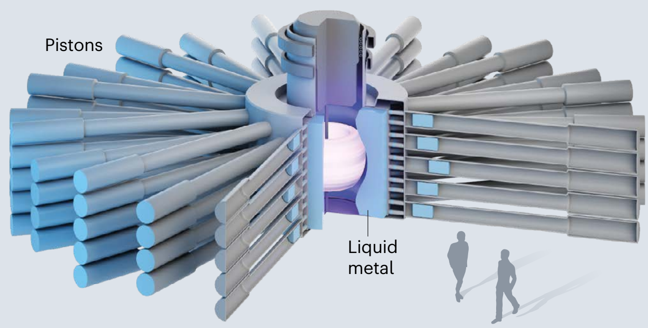
Packets of plasma are fired into a central chamber and rotate rapidly inside a solenoid (coiled-wire electromagnet).



MAGNETIZED TARGET REACTOR

GENERAL FUSION

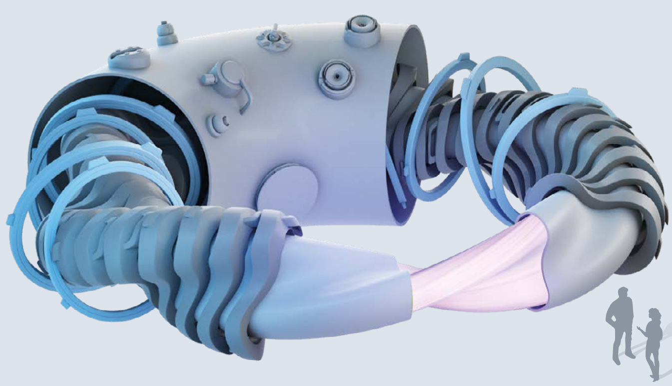
A spinning ball of liquid metal confines plasma; pistons then rapidly compress it. The plasma is allowed to expand, then compressed again.

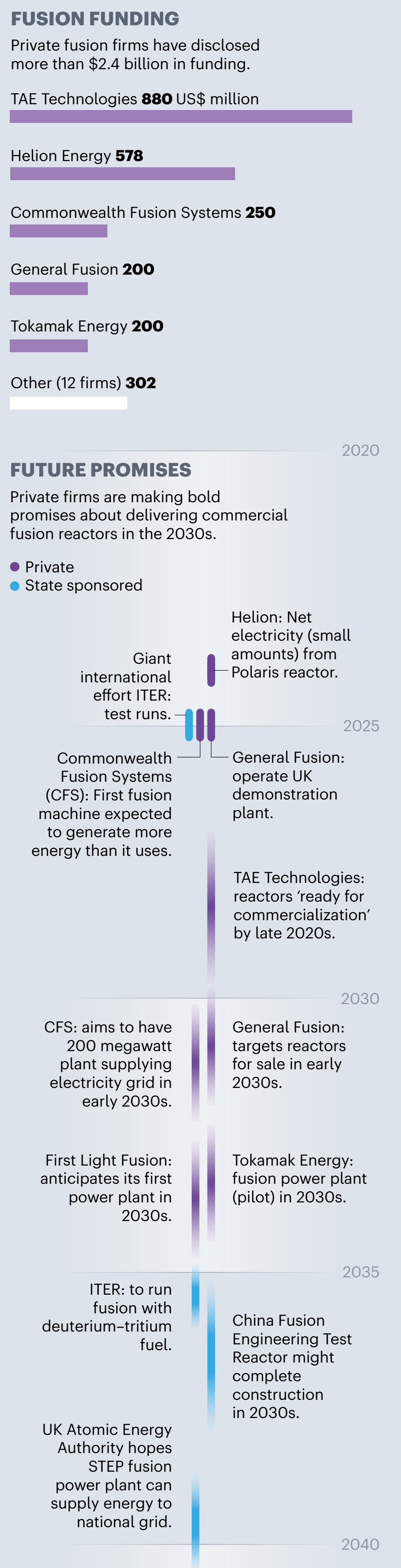


STELLARATOR

WENDELSTEIN 7-X

A complicated twisted loop of magnetic fields confines the plasma.





such as maintenance needs or the inefficiencies of converting the fusion heat output into electricity.)

A further series of big reactors might follow ITER: China, which has three fusion reactors feeding results into ITER, plans a China Fusion Engineering Testing Reactor (CFETR) in the 2030s, and both South Korea and the EU propose to build demonstration power plants that would follow on from ITER.

The big national and international efforts won't succeed soon enough to enable the decarbonization needed to address climate change, although fusion is expected to become a key part of the energy economy in the second half of the century. But private companies hope to have working and affordable devices sooner.

As with space exploration, one of the benefits of a private fusion sector is greater diversity of approaches than monolithic state enterprises can muster. ITER is using the most common approach to confining plasma, in a device called a tokamak, which uses powerful superconducting magnets to hold the plasma in a ring-shaped (toroidal) vessel. The flow of the electrically charged plasma particles themselves also generates a magnetic field that helps to confine the plasma.

But a tokamak isn't the only option. In the early days of fusion, in the 1950s, US astrophysicist Lyman Spitzer showed that magnetic fields could be configured in a twisted loop, rather like a figure of eight, to make a 'magnetic bottle' that could be filled with plasma. This design was known as a stellarator. But solving the equations describing the plasma for this complex geometry was too computationally intensive, so the concept was mostly abandoned once tokamaks had been shown to work.

As supercomputers became available in the late 1980s, however, researchers revisited the idea. This led to a stellarator project at the IPP called the Wendelstein 7-X reactor. Costing more than €1 billion (US$1.15 billion) to build, staff and operate up to its first plasma testing in 2015, with construction costs of €370 million largely borne by the German government, Wendelstein 7-X will be completed by the end of this year. Then comes a long process of working out how to operate it routinely as a demonstration project.

Stellarators have the advantage that their plasma is more easily confined, with no need (as in tokamaks) to drive strong electric currents through it to keep a lid on instabilities, says fusion physicist Josefine Proll at Eindhoven University of Technology in the Netherlands. But it's not clear whether it will be possible to implement stellarator technology in a reactor in 20–30 years. "It seems not all that likely at this moment," she says. "We have a lot of basic questions still to answer," says Klinger. "This is a first-of-a-kind machine, so one must be patient and go step by step." Private companies set shorter-term goals because they have to satisfy their stakeholders, he says – but that doesn't mean they can deliver.

Alternative designs

Some private fusion companies are sticking with the tokamak design, but scaled down. At Tokamak Energy, a team of around 165 employees is working on a spherical tokamak, shaped like an apple with its core removed. At 3.5 metres across, it will be many times smaller than the ITER tokamak, which, with surrounding cooling equipment, will be almost 30 metres wide and tall. Some state-funded schemes are considering the compact spherical design, too: the UKAEA, for example, has launched a project called STEP (Spherical Tokamak for Energy Production) that aims to create such a device in a prototype plant that would deliver at least 100 MW to the national grid by 2040. The UKAEA has shortlisted five sites to host the plant, and expects the final choice to be made next year.

Key to these designs are new kinds of magnets made from ribbons of high-temperature superconducting materials, which should produce much stronger fields than the conventional superconducting magnets used by ITER. They are "a potential game-changer", says Klinger – not just because of their higher fields, but also because conventional superconductors need liquid-helium cooling. That is an engineering nightmare: liquid helium's viscosity is almost zero, allowing it to leak through any tiny cracks. High-temperature superconductors, by contrast, can be cooled with liquid nitrogen, which is abundant, cheap and easy to store.

Both Tokamak Energy (in collaboration with CERN, Europe's particle-physics laboratory near Geneva, Switzerland) and CFS are banking on these new magnets. In August, CFS announced that it had made them in the form needed for its tokamaks – "on schedule and on budget", Mumgaard says proudly.

In 2018, CFS was spun off from the Plasma Science and Fusion Center of the Massachusetts Institute of Technology (MIT) in Cambridge, and Klinger considers the firm "the most promising, most valuable and most thought-through private fusion initiative". MIT and CFS together are preparing to build what Mumgaard calls "the first fusion machine that makes net energy" – producing more energy than goes into it. Named SPARC, it is being constructed in Devens, Massachusetts. Mumgaard says it will be running by the end of 2025, and will be "commercially relevant" because it will generate around 100 MW of power.

First Light Fusion, a company spun off from the University of Oxford, UK, in 2011, is pursuing a different strategy, called inertial confinement. Here, the fusion plasma isn't held by magnetic fields: rather, a shock wave compresses it to the immense densities needed for fusion, and the plasma retains its shape just for a split second by inertia alone, before spreading out and dissipating its energy. The idea has been around since the 1950s, and is also being studied at the US National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in California, where pea-sized plastic capsules of D–T fuel are imploded by nanosecond pulses of laser light to ignite fusion. In August, NIF reported a laser shot that produced a fleeting energy output 8 times higher than it had ever before achieved — and amounted to 70% of the energy that had gone into the reaction. That has raised hopes of net gain from inertial-confinement laser fusion, although such an energy-intensive process might be more useful for fundamental research than for large-scale power generation.

At First Light, the compression shock wave is created not by energy-hungry lasers, but by using an electromagnetic projectile gun to fire a small piece of material into a target containing the hydrogen isotopes. The company is keeping details of the process secret, but has said that to achieve fusion, it will need to fire the material at 50 kilometres per second — twice as fast as is typically achieved in current shock-wave experiments.

GF is taking yet another approach, called magnetized target fusion. It involves the plasma being compressed more slowly — for instance, using pistons — but with the aid of magnetic confinement that prevents heat from dissipating as the plasma is squeezed. This idea, suggested in the early 1970s by researchers at the US Naval Research Laboratory in Washington DC, seeks an optimal compromise between the energy-intensive high magnetic fields needed to confine a tokamak plasma, and the energy-intensive shock waves, lasers or other methods used to rapidly compress plasma in inertial-confinement designs.

GF's design for its Culham reactor uses a centrifuge to spin a chamber filled with molten lead and lithium. That motion opens a cavity in the liquid metal, where the plasma sits. A piston system pumps more liquid metal into the chamber, compressing the plasma over a few tens of milliseconds. Fusion begins; then the pressure is released and the process repeated in pulses, about once a second.

One especially neat aspect of this reactor is how it generates tritium fuel — a hugely expensive resource that can be made only in nuclear reactions, and decays rapidly. In ITER and other designs, tritium will be produced when neutrons escaping the reactor hit a lithium blanket lining the tokamak. In GF's design, tritium is made when neutrons hit lithium within the liquid-metal compression system itself.

GF has cracked key challenges only in the past few years — making a plasma target that lasts for long enough to be compressed, and smoothly and rapidly collapsing the liquid- metal cavity. The firm says, however, that after it has its UK demonstration plant operating in 2025, it will "power homes, businesses and industry with clean, reliable and affordable fusion energy by the early 2030s".

TAE Technologies has, in some ways, an even more audacious concept. It plans to abandon D–T fuel altogether, instead fusing boron-11 atoms with hydrogen-1 nuclei (protons). This idea, championed by TAE's co-founder, the Canadian plasma physicist Norman Rostoker, and dubbed p–^{11}B fusion, requires temperatures ten times greater than for D–T fusion: about one billion kelvin. The advantage is that this reaction uses only abundantly available fuel, and generates no neutrons that could contaminate the reactor. Binderbauer says that the concept offers lowers maintenance costs and a much more sustainable end goal.

In TAE reactors, the plasma is confined inside a cylindrical magnetic field made by a solenoid — a design that draws on particle-accelerator technologies. The plasma rotates around the axis; that rotation, as in a spinning top, generates inherent stability. Confinement doesn't require strong external magnetic fields; those are mostly generated by the spinning plasma itself. To keep it rotating, tangential beams of boron inject angular momentum, rather as a top is torqued by a whip.

> **"I see the booming of private fusion companies as a good sign."**

The company has made prototypes to demonstrate this set-up; since 2017, it has been working with a test system called Norman, and it is now starting work on a device called Copernicus that will run with normal hydrogen (or other non-fusing) plasmas to avoid producing neutrons. Computer simulations will show what energy would be generated if real fusion fuel were used. If TAE achieves the conditions needed for D–T fusion — which it hopes to do by around the middle of this decade — the company plans to license the technology to others who are pursuing those fuels. Binderbauer calls Copernicus a "stepping stone" to the temperatures needed for p–^{11}B fusion. "We're convinced that we can go to the billion-degree level," he says — and he hopes to see this towards the end of the decade.

Among the many other private fusion firms, Helion Energy, in Everett, Washington, has attracted the most interest from investors: this month, it announced a $500-million funding round, bringing its total to $578 million. Its aim is to generate electricity directly from fusion, rather than using the process to heat fluids and drive turbines. Helion's technique involves firing pulses of plasma together inside a linear reactor, then rapidly compressing the merged plasma with magnetic fields. When fusion occurs, the plasma expands and its magnetic field interacts with that surrounding the reactor to induce an electric current. Helion hopes to fuse a mixture of deuterium and helium-3, which would not produce neutrons as a by-product. But helium-3 itself would need to be produced by D–D fusion. The company is building a demonstration reactor called Polaris, which it aims to have in operation by 2024.

Cheaper reactors?

The reactors built by private companies, being smaller than ITER-scale projects, will be much more affordable. Tokamak Energy's co-founder, David Kingham, envisages billion-dollar devices, and Binderbauer thinks TAE's systems could be built for around $250 million.

The aim is to make small fusion reactors that are compatible with existing energy grids. Kelsall says they could also serve industries that are particularly energy-intensive, such as metal smelting — a sector that can't be supplied by renewables. Mowry adds that shipping could be another important market: devices producing around 100 MW of power are "just the right size for a large container ship".

Donné remains cautious about the prospects, however, saying that private companies "are working on aggressive time paths compared to publicly funded projects, but also have a much higher risk of potential failure". All the same, TAE, for one, insists that it is still on the track that it promised in the mid-2010s, of having a fusion device ready for commercialization by around the end of this decade.

Despite his scepticism, Donné adds: "I see the booming of private fusion companies as a good sign. There can be mutual benefits in keeping close ties between public and private fusion projects." That's certainly happening. Not only is the private fusion industry building on years of state investment in projects such as ITER, but it is benefiting from governments that see value in supporting it — which is why the UK government and the US Department of Energy are also investing in firms such as Tokamak Energy, CFS and GF. Mowry thinks that such public–private partnerships are the way forward — as they were for COVID-19 vaccines. And, as with the vaccines, fusion will be needed everywhere, especially as energy use rises in lower-income countries.

The vaccines showed "what you can do if you have the resources", says Windridge. "If we had that kind of commitment in energy, I think it would be incredible to see what can be achieved." As with the vaccines, too, society desperately needs more clean, carbon-free sources of energy. "This is an existential challenge," says Mowry. "Fusion is the vaccine for climate change."

Philip Ball is a science writer in London.