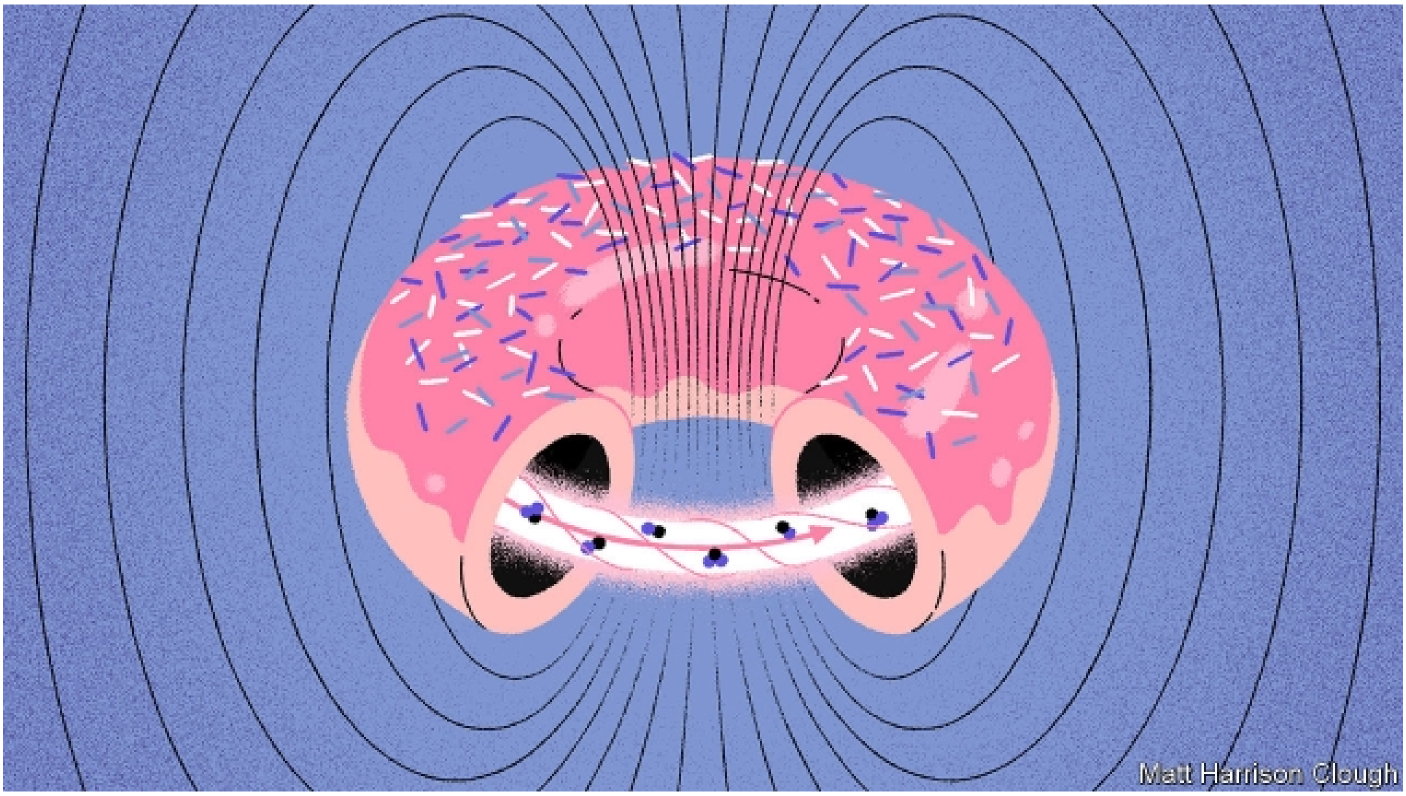
Alternative energy

Fusion power is attracting private-sector interest

Reactor designs are inspired by everything from smoke rings to shrimps



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IN 1920 Arthur Eddington, an English astrophysicist, gave a lecture to the British will one day learn how to release it and use it for his service. The store is well nigh inexhaustible, if only it could be tapped."

Eddington speculated that the energy in question was released by the nuclei of hydrogen atoms fusing to form the nuclei of helium atoms. He knew that a helium nucleus weighs slightly less than four hydrogen nuclei and he suspected that the difference, converted into energy according to the then-recently discovered formula, $E=mc^2$, would be enough to power the sun. He was right about this. He was also right about people's dreams of exploiting it. They began looking shortly after Eddington's speculations were confirmed, and they still dream of it today—for the fuel needed is abundant, and the process of generation carbon-free.

In one important aspect, though, the dream of human-controlled nuclear fusion has changed in recent years. From Zeta, the first, fumbling attempt to build a fusion reactor, at Harwell in southern England, in the 1950s, to Iter, the latest over-budget, over-deadline behemoth in the south of France (see article), fusion has been the province of governments. Not any more. Now there is commercial interest. Firms in North America and Europe are designing and planning to build what they hope will be profitable fusion reactors. Their projects have different approaches and different amounts of money behind them. But they all have one thing in common, a desire to bury the old joke that commercial fusion power is 30 years away—and always will be.

In light of the work of Eddington and his successors fusion power on Earth is often described as mimicking the process which powers the sun. That is not quite true. Solar fusion builds up helium nuclei, which are composed of two protons and two neutrons, one particle at a time out of individual protons, the nuclei of hydrogen atoms—with the surplus positive electric charges being spirited away by particles of antimatter called positrons. The average period required to complete this reaction is about a billion years.

Fortunately, there is a short cut. This is to employ hydrogen atoms pre-loaded with neutrons—either one (deuterium) or two (tritium). One in every 6,000 hydrogen atoms on Earth is actually deuterium, meaning the substance e extracted from water. Tritium, which is

optimal mix in a given set of circumstances is known as the Lawson criterion, after John Lawson, who was associated with Zeta.

These days most attempts to achieve the Lawson criterion are made using machines called tokamaks, which were devised in the 1950s by Andrei Sakharov, a Soviet physicist who later became famous as a human-rights campaigner. And it is the tokamak route that several of the commercial fusion-power wannabes are travelling along. One such is Commonwealth Fusion Systems (CFS), a spin-out from the plasma physics laboratory of the Massachusetts Institute of Technology, in Cambridge, Massachusetts. Another is Tokamak Energy, a spin-out from the UK Atomic Energy Authority's research laboratory at Culham—Harwell's successor.

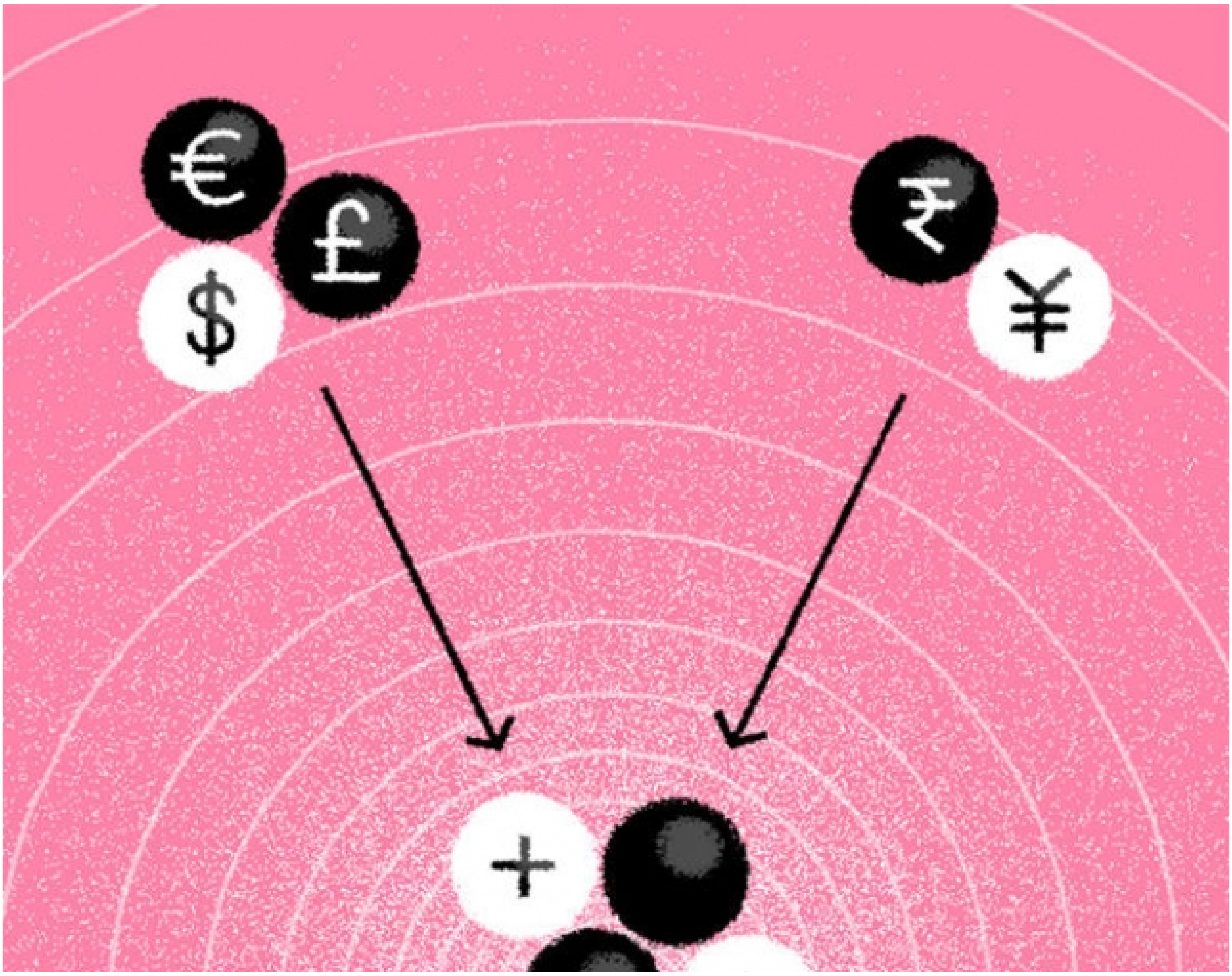
The Lawson and the profits

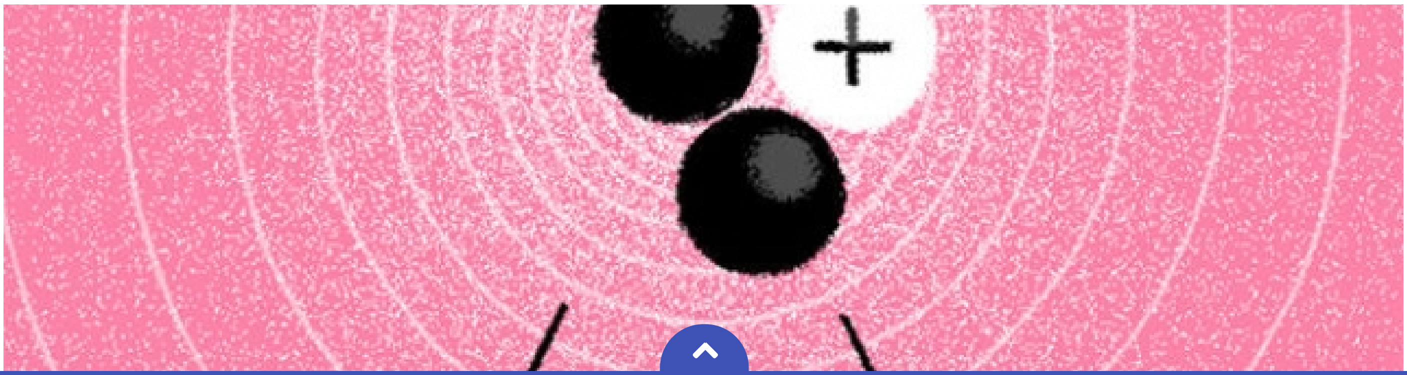
A conventional tokamak is a hollow torus, reminiscent of a doughnut or a bagel, with superconducting electromagnets wound around it. This torus contains the fuel, which is a plasma (a gas in which the electrons and atomic nuclei have been separated) that is composed of deuterium and tritium. The magnets serve both to heat the plasma and to confine it—thus maintaining its density and keeping it away from the torus wall, for if it touches the wall it instantly cools down.

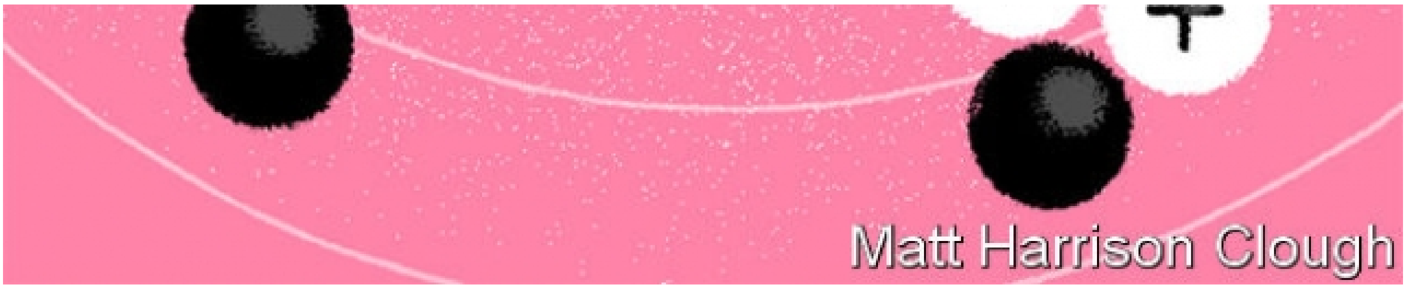
Tokamaks are normally large machines. Iter's torus, for example, will have a volume of 830 cubic metres. The CFS reactor's torus, though, will have about a sixty-fifth of the volume of Iter's. It can get away with such a small volume because it has more powerful magnets that squeeze the plasma more tightly. As a bonus, these magnets become superconducting at relatively high temperatures, so can be cooled using liquid nitrogen, which is cheap, rather than liquid helium, which is expensive.

Tokamak Energy's researchers have also been using nitrogen-cooled superconductors for their magnets. The firm has, however, eschewed the conventional shape of a tokamak in favour of something that, while still having a [illegible]e in the middle, more resembles a cored

magnetism is generated by the movement of the electrically charged particles in the plasma itself, as that plasma spins in a vortex similar to a smoke ring.







Matt Harrison Clough

In General Fusion's machine the spinning plasma is, after it has been fired into a spherical reaction chamber, compressed rapidly by the simultaneous release of hundreds of pistons attached to the chamber's exterior. These induce a shock wave that compresses the deuterium-tritium fuel, increasing its density a thousandfold and pushing its temperature up from 5m°C to 150m°C. Improving these two parameters of the Lawson calculation means that the brevity of the third, time, no longer matters. That, at least, is the theory. Christofer Mowry, General Fusion's boss, hopes to demonstrate the truth of it by building an experimental plant within five years.

TAE Technologies, of Foothill Ranch, California, also uses a self-confining plasma, in its case a phenomenon called field-reversed configuration (FRC). TAE's latest device, unveiled in July 2017, is a 25-metre-long machine named Norman, after Norman Rostoker, a plasma physicist at the University of California, Irvine, who was the company's founder and who died in 2014.

Norman is a cylindrical reactor. Plasma injectors at each end of the cylinder fire FRCs simultaneously towards each other at around 1m kilometres a second. When the vortices meet, they merge into a cigar-shaped cloud three metres long and around half a metre wide that is kept spinning, and thus hot and stable, by beams of deuterium atoms fired into it from outside.

So far, Norman has produced vortices with temperatures of 3.5m°C that last around ten milliseconds, rather than the microseconds of a conventional FRC. TAE hopes, by the end of this year, to have increased that temperature round 30m°C, and tripled the plasma's

material, thus releasing the energy of motion as heat. That heat would be used to raise steam and drive a turbine. If the absorbing material chosen were lithium, this arrangement would have the bonus of generating new tritium to feed back into the reaction.

The downside of such an approach is that the rest of the reactor will absorb neutrons as well, making the whole thing radioactive (though nothing like as radioactive as a conventional fission reactor) and ultimately damaging its structure. Also, each step in the process loses energy. The proton-boron method offers a more elegant way to generate electricity because alpha particles are positively charged, and can thus induce a current directly in an external conductor. No heating is involved and the alpha particles never escape to cause damage elsewhere.

There is, of course, a catch. Proton-boron fusion requires temperatures of billions of degrees. That is an order of magnitude hotter than anything achieved so far in a fusion experiment. And although such plasma temperatures have been produced in laboratories in other circumstances, how TAE will do it with the equipment they are using is unclear.

The mighty shrimp

TAE is radical in its choice of fuel. But other forms of fusion radicalism are possible, too. And, in the actual design of its reactor, the most radical of the lot is probably the path being pursued by First Light Fusion—spun out of Oxford University. Though First Light's process aims to extract energy from a conventional mixture of deuterium and tritium, the technology it plans to use to do so was inspired by a shrimp.

Pistol shrimps are marine crustaceans that are among the loudest animals on the planet. Their noise is generated by a specialised claw half as long as the creature's body, and is used to stun prey. When the claw snaps shut, the rapid change in pressure this creates produces vapour-filled voids called cavitation bubbles in the surrounding water. When these bubbles collapse the shock waves produce a sound as powerful as the noise made by a Saturn V rocket taking off. This is enough to kill small fish—which the shrimps then eat.

them will, calculations suggest, be forced into a small enough space for long enough to fuse. Whether those calculations are correct will be tested later this year.

Put your money where your mouth is

There is, then, no shortage of ideas about how a practical fusion reactor might be built. But any investor also faces the question of how long it will take to get a new idea to work. In the field of fusion, the most crucial milestone on that road is probably the achievement of gain. This is the point when more energy comes out of a fusing plasma than went into creating it.

Everyone talks a good story about this. CFS wants to achieve gain by 2025. So does Tokamak Energy. TAE's next device, Copernicus, will, the firm says, not only achieve gain, but will also be a power-station demonstrator. Indeed, TAE aspires to supply fusion-based electricity to the grid by 2030. Which is also the year that Tokamak Energy says it will start generating grid-scale electricity—from power plants with a capacity of the order of 100MW. First Light Fusion predicts that reactors using its technology will be in place some time in the 2030s.

All this optimism should be viewed cautiously, especially from companies that need to raise capital for future experiments. Capital is, however, being raised. TAE has rustled up $600m in private funding so far. General Fusion has raised over $100m, Tokamak Energy £50m ($65m) and First Light, which is still at the earliest stages of progress, £25m.

Challenges no doubt lie ahead. As Stephen Dean, of Fusion Power Associates, a foundation that follows the field, observes, "the history of fusion doesn't give you a lot of confidence that there won't be a problem. You know we've been at it for 50 years and there's always been a problem." Nevertheless, he also says that he knows of no showstoppers for any of the private companies. "They're all based on good physics. They're all good people that are doing these programmes." And the prize is enormous. If even one of the fusion startups succeeds, the world's electricity supply will be guaranteed—and carbon free—for ever.

CORRECTION (May 7th 2019): *An earlier ver of this article said that General Fusion used a*