**The Future for Fusion**

*Is fusion power the solution to the energy crisis? Kit Chapman finds out*

On 21 December 2021, a sleepy corner of Oxfordshire, UK, became ten times hotter than the core of the Sun. Inside the silvery, doughnut-shaped Joint European Torus (Jet), an energy pulse of plasma was sustained for five seconds. It only produced 59 megajoules of energy – around 11 megawatts, barely enough to power a small home for a day – but everyone watching knew what the burst meant. It was a new world record for energy produced by nuclear fusion.

Jet is based at the Culham Centre for Fusion Energy, the UK’s national laboratory for fusion research, an part of the wider Eurofusion collaboration of 28 European countries. Fernanda Rimini, Eurofusion’s senior exploitation manager at Jet, was one of the few to witness the event live. “I thought ‘I’m an adult, I’ve been there, I’ve done that, it’s not going to be exciting’. I was wrong. We were in this weird pandemic situation, there were only half a dozen people in the control room, we couldn’t have the whole team there… but we had the real-time measurement of neutrons. We’d scaled it, so the top was 10 megawatts. And when it went off the scale, we knew. We went home and had a bottle of bubbly.”

For the uninitiated, producing such a low amount of energy in a facility that costs millions may seem like a waste of time. The idea of fusion power and its promise of near-limitless, clean energy has been around for a century, but a viable reactor still seems decades away. So why is fusion power worth getting excited about, and is it the future of energy, or merely a pipedream?

**Fusion for beginners**

Nuclear fusion is the combining of two atomic nuclei together to form a new, heavier nucleus. It’s how all of the elements heavier than hydrogen are formed, usually in the intense cosmic furnace of stars. Any nuclear fusion reaction that produces an atom lighter than iron-56 or nickel-62 is usually exothermic, resulting in the release of energy in the form of neutrons. We see, and benefit, from the process every day: the Sun generates its energy through nuclear fusion, fusing around 500 million tonnes of hydrogen into helium every second. (Although this sounds impressive, the Sun is relatively inefficient as a nuclear reactor; it only achieves fusion in its core and relies on gravity, a comparatively weak force, to drive its reaction rates.)

Existing nuclear power relies on nuclear fission, the process of atoms apart to produce lighter ones. To make plants viable, they have to use heavy, radioactive elements such as uranium and plutonium. However, fission is less energy efficient than fusion, and produces higher quantities of radioactive waste. In contrast, fusion reactors could use any light element, but hydrogen, as the lightest and third most abundant element on Earth, makes the most sense, particularly in the form of its two heavier isotopes, deuterium and tritium. These contain one and two neutrons respectively, and are used to add to the energy output. “What you produce is a helium particle, which remains in the plasma,” Rimini says, “heat in the plasma itself, and a neutron. The energy you produce is more than what you put in. It takes very little to produce this energy, and you delete the spare products [so there’s little waste]. It's very, very efficient.”

“If we can make it work, it will be the ultimate energy source,” explains Tammy Ma, a plasma physicist at Lawrence Livermore National Laboratory, US. “There are no carbon by-products, and we can obtain our fuel from, essentially, seawater. It’s plentiful, so there’s lots of benefits if we can make it work.” The catch, she adds, is that nuclei are small and difficult to collide together for fusion to occur. And, as nuclei are positively charged because of their protons, they repel each other in a process known as Coulomb repulsion. “You need high density and high temperatures,” Ma says, “to get the atoms bouncing around close enough together with enough energy to have enough probability to actually collide and overcome repulsion. And that’s why it’s so darn hard.”

It's this challenge – essentially how to replicate the interior of a star – that has led to very different angles to try and make fusion energy achievable. It’s a race that will decide how the world will be powered in the future.

**Power vacuums**

JET is the spearhead of the European search for a viable fusion reactor. It centres on heating its deuterium and tritium to around 150 million°C, using magnetic fields to confine the plasma created. “It uses a tokamak,” says Rimini, “which is a toroidal shape, a doughnut which is slightly elongated, and you inject some gas, which you ionise. This mix of ions and electrons mean you can tie them to magnetic field lines, so if you produce the right magnetic field, the particle remains confined. Next, you need to heat them. We do that by inject high-energy neutron particles – they have to be neutrons [neutrally charged] or they don’t go through the fields – and then we heat the plasma by radio waves at different frequencies. There are a lot of subtleties, but basically the wave will transfer, by resonance, some of its energy to the ions or electrons, and this will increase the temperature.”

A tokamak, then, is basically a circular cauldron, in a vacuum, for creating the conditions for fusion. Although it’s hard to reach the required temperatures, once done it’s highly efficient: during the December 2021 test, the team burned only around 0.1mg of tritium to produce the 59 megajoule record.

As mentioned, this is a relatively small amount of energy, and still only around 70 per cent of that required to initiate the reaction, meaning it wouldn’t work as a power plant. Yet far from being the result of decades of research, Jet is only a steppingstone to the next European project, the International Thermonuclear Experimental Reactor (Iter), under construction near Nice, France. When it comes online in 2025, it will be the largest tokamak in the world, and hopes to produce an energy output 10 times greater than its start-up requirement. A follow-up class of tokamak, Demo, is already in the planning stages. Currently, Jet’s focus is to run experiments to help Iter’s design process, with the tokamak scheduled for decommissioning in 2023.

At Lawrence Livermore National Laboratory, Ma’s team takes a very different approach. “We use very energetic lasers,” explains Ma. “We basically compress a fuel pellet that contains deuterium and tritium up to the very high densities and temperatures that make fusion possible – meeting a state where they can overcome Coulomb repulsion.”

Ma’s team does this at the lab’s National Ignition Facility. “It’s the world’s largest, most energetic laser,” she explains. “It’s 192 separate lasers, each one of which is close to the most energetic in the world. It’s housed in a building that’s three American football fields, or two [Association] football fields, wide and 10 storeys tall, which is needed for all the amplifying objects. In fact, it’s the world’s largest optical instrument too!” When it fires, the facility’s beams are directed via 3070 sheets of phosphate glass doped with neodymium, each weighing 42kg and set at Brewster’s angle, which reduces reflective loss. “The idea is we take all of that energy, which comes to about 1.9 megajoules, and focus it down on a target the size of a small BB, about 2–3mm in diameter.”

The target fuel pellet consists of a *hohlraum*, or empty space. The laser comes in via an entrance, hits the inside wall, and generates x-rays, which compress the pellet. “The x-ray energy ablates the outside surface of the capsule,” Ma continues. “It flies off at a few 100 kilometres a second and, by conservation of momentum, the rest of the capsule has to drive inwards. That process keeps and compresses the deuterium and tritium in the middle into fusion conditions.” This shrinks the fuel in the pellet to around 100 times the density of lead, and heats it to 100 million °C. A single shot takes a few hundred picoseconds – roughly a million times faster than the blink of an eye – and uses around 1000 times the power of the entire US electrical grid. Fortunately, the short time period means the team keeps its electrical bills down to around $14 (£11) per shot.

The team at Lawrence Livermore have also achieved huge milestones in the past year, obtaining a stage called ‘burning plasma’, where more energy is produced than fuel spent. “The idea behind fusion energy is that you produce more energy than you put in,” says Ma. “Right now, we have demonstrated 70% ignition threshold – that was our big shot, last August. But for a power plant to work, the economics have to work out, too. You’d need to be gaining something in the order of 50–100 times more energy than you put in. So finding a target design, and an overall approach that can give you those high gains, is one of the big challenges for us right now.”

**Material concerns**

The greatest problem faced in fusion isn’t achieving the incredible temperatures required – it’s the materials science required to maintain that environment long-term. It’s why Jet couldn’t go past a few seconds, explains Rimini. “Jet is based on fairly old copper coils for the magnetic fields. They’re not water cooled, so they’re only designed to run for 10–15 seconds at most.”

Culham has built a new Materials Research Facility to tackle such problems. One of the staff searching for solutions is Greg Bailey, a computational nuclear physicist. “The copper magnets get too hot,” he says. “So, in the future, we’re using superconducting magnets. And hopefully we’ll learn more.” These material changes have already happened in the past. “Jet actually changed the material of its walls,” Bailey says. “Initially we’d made the walls out of carbon, because that made life easier for the experiments. It should have been perfect, but, actually, it was terrible! We were getting a lot of tritium retention – we were losing our fuel into the wall, the hydrogen was drifting inside. So we had to change it.”

The design challenges discovered and solved by Jet are already being fed into Iter, says Bailey. “What does a material for a reactor need to be? Resistant to damage [from radiation], it needs to be able to take the temperatures and extreme environments, and maintain its mechanical properties during its lifetime. So, in terms of a fusion reactor, the vast majority is probably going to be steel. The really interesting bits come inside the vacuum vessels, your housing, because they’re going to be facing extremes. They need armour, obviously.”

This has resulted in plans for Iter to be covered by 440 ‘blanket’ modules, weighing up to 4.6 tonnes, which cover the steel of the tokamak’s structure. Neutrons discharged during the reaction the enter the blanket can be slowed, and their kinetic energy transferred to a coolant system for another form of power. It’s hoped the blanket can also be used to solve another issue for reactors: their feedstock.

“There’s plenty of deuterium on Earth,” Bailey says, “but deuterium produces much lower energy neutrons, it’s not really a viable source to make a power plant. And tritium is not naturally occurring.” To obtain their tritium, the team uses lithium-6, which can break apart through fission. Although this is naturally occurring, the problem is that lithium is already in high demand for its use in Li–ion batteries. “Frankly, when lithium comes into our reactor, we’re going to destroy it,” Bailey says. “The fuel is not the problem, it’s how you produce it.”

This is where the blanket could come in, explains Bailey. “A lot of designs right now are mixing lithium with lead, or lithium with ceramic and some beryllium in there… the idea is that you get deuterium and tritium, the fusion reactor turns on, and neutrons smash into the blanket and tritium breeding reactions can occur. We can then extract that tritium to refuel the reactor. And, obviously, the neutron radiation into the blanket will cause a huge amount of heating.” It’s still not perfected yet, but Bailey is confident the experiments done at Culham will show the way, potentially in collaboration with in the private sector; already, fusion is attracting major investors, including Amazon’s Jeff Bezos. “If we want to do fusion on an industrial scale,” says Rimini, “we need to start building that supply chain now. We need to start evolving the industry.”

At Lawrence Livermore, Ma’s team face different materials obstacles. “We need to develop supporting technologies,” she says. “That includes lasers that are highly efficient and can run at a high repetition rate. We’re a scientific demonstration facility. For a power plant to work, we’d have to repeat the reaction about 10 times a second to get the maths to work out. And we need new materials that can withstand the high radiation fluxes and debris that we’re generating.”

This is the main stumbling block, Ma concedes. “There are a lot of commonalities between the different fusion approaches,” she says. “The materials issues, the tritium fuel cycle issues, the thermal conversion issues are all the same. We can make good progress in the next five to 10 years, if we have sufficient funding. But technologically, there’s no showstopper that we know of.”

No one in the fusion community, regardless of the technique used, is expecting these problems to be solved overnight. And, despite the promise of fusion now being a century old, the current challenges mean that the technology won’t be ready for decades. It won’t be a short-term solution to rising costs of energy or reducing carbon emissions. “However,” Ma adds, “we do believe that long term it has to be a component for net zero emissions for the world. And, once we figure it out, we could build a powerplant anywhere. It’s an energy source that will contribute to energy equity and benefit society on a large scale. That’s the benefit of fusion if we can make it.”

For now, then, fusion energy on a commercial scale remains a distant dream. And yet, given its potential, it’s a dream worth having.

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