FASTER FUSION

tokamak energy
a faster way to fusion

What is fusion?

Fusion is the energy of the stars. It is the joining together of small atomic nuclei to make larger ones, and it is the mechanism by which all the heavier elements in the universe are made.

Fusion can only happen at very high temperatures because it is the forcing together of particles that would usually be very far apart. Nuclei are all positively charged particles, so they keep away from each other. Naturally particles with the same electric charge, just like magnets of the same polarity, will repel. Nuclei don't want to come together, so the only way for fusion to occur is to heat things up a lot - like in the centre of stars.

Why do we care?

The whole world needs a base-load power source that is abundant, safe and CO2-free. Fusion is one of the few options we have.

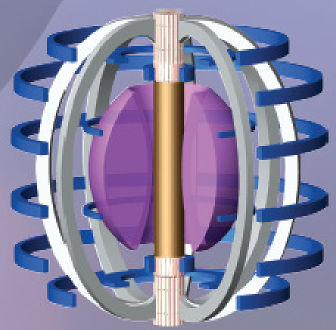
But how could we make the energy of the stars?

Admittedly it's tricky. It involves heating our fuel to hotter than the centre of the Sun – over a hundred million degrees. At these temperatures, the electrons of atoms break away from their nuclei and we have a soup of very fast-moving, charged particles called *plasma*. Somehow we have to confine this, or trap it, so that we can keep the fuel hot enough for long enough for fusion to occur. Different methods have been proposed to do this. The main contenders are: inertial fusion (or laser fusion), which uses lasers to heat and confine the fuel; or magnetic fusion which uses magnetic fields to trap the hot plasma.

Within the field of magnetic fusion, the *tokamak* machine is the most developed and understood.

What is a tokamak?

The word "tokamak" is a Russian acronym that stands for "toroidal chamber magnetic coils". That is, the tokamak is a toroidal – or ring-doughnut-shaped – vessel with magnetic coils that make a trap for the plasma. The plasma is heated using microwaves or powerful particle injectors (think of it a bit like the steam heating the milk for a cappuccino) and it has to be stabilised by carefully controlling the shape of the magnetic fields.



Magnetic coil structure of our next tokamak ST40 with plasma (purple) inside. The magnetic coils make a trap for the hot plasma, keeping it away from the walls.

When will we be using fusion power?

That is the billion-dollar question! Research started in the 1950s and the big joke is that fusion is 30 years away… and always will be. We don't think that's true – we think faster fusion is possible – but it is a lot harder than was originally thought. Globally, tens of thousands of people are working on it, and we are making progress, but it takes time, money and intelligent new minds coming into the field to solve the puzzle of how to create fusion power on Earth.

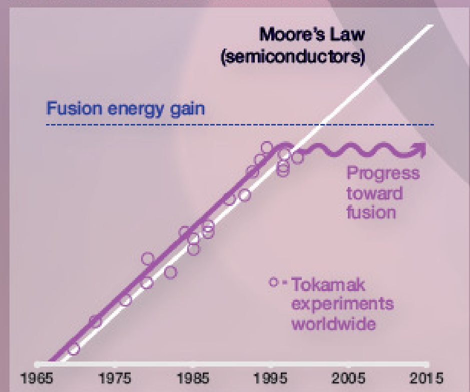
Tokamak Energy aims to demonstrate fusion energy gain in a compact tokamak in 5 years, and first electricity from fusion in 10 years.

Remember, this is a new science – we don't know yet what is going to happen! But if we don't try we certainly will not succeed.

Why has it taken so long?

Did you know that scientists have *actually achieved fusion?* We have made fusion reactions happen, but so far we have put more energy in to do it than we have got out. The JET tokamak in the UK holds the world record for fusion power. In 1997 JET made 16MW – about 65% of what was put in.

Problem: Progress in fusion has slowed



Steve adjusts the magnets on the ST25

Progress towards fusion power was rapid for 30 years – slightly faster than Moore's law for computers. But progress has not been so rapid since the JET runs in 1997. Why?

The answer lies in the physics. The fusion power we get out depends on the efficiency of the machine, the strength of the magnetic field and the size (volume) of the toroidal vessel.

$$P \propto \beta^2 \times B_T^4 \times V$$

Back in 1985, when engineers were designing the next step tokamak after JET, the efficiency of the machines and the magnetic fields achievable were limited by the technology of the time. Increasing size seemed the only way forward. The world agreed to construct the giant ITER tokamak in France. Feats of engineering such as this take time. Construction is now, in 2015, well underway but ITER won't be operating for several years yet.

It also turns out that plasma physics is very complicated. Keeping hot plasma trapped requires a good understanding of how it behaves. We are now in a better position to improve the performance of our fusion plasmas.

Can we achieve fusion faster?

We certainly hope so. In the last few decades, new technologies have emerged. Building on all the work that has gone into JET and ITER, it now seems feasible that by using slightly different *spherical* tokamaks combined with High Temperature Superconductors for magnets we could make smaller, cheaper machines and thereby make progress faster.

What is a spherical tokamak?

A spherical tokamak is one that is squashed up so it looks more like a cored apple than a ring doughnut.

What is High Temperature Superconductor?

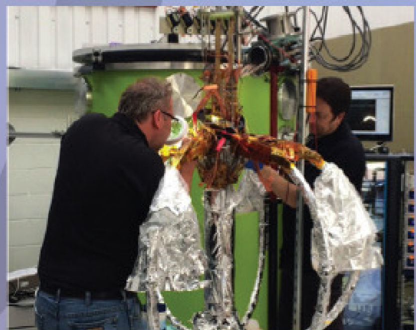
A superconductor is a material that has zero electrical resistance so, when current flows through it, the material doesn't heat up. This property usually only comes into effect when the material is extremely cold. Conventional superconductors are cooled by liquid helium to -269C (or 4K). A High Temperature Superconductor, called HTS, is one that becomes superconducting at a much higher temperature, around the boiling point of liquid nitrogen at -196C (77K). That's still pretty cold, but it represents a big saving in energy to cool the superconductors.

How can these help fusion?

Spherical tokamaks can generate higher plasma pressure for a given magnetic field. In other words, they have a higher *efficiency* than conventional tokamaks. High Temperature Superconductors can give higher *magnetic field* than conventional superconductors. Combined, this means we can achieve higher fusion power without increasing the machine size.

High Temperature Superconductors materials can also be made into narrow tapes that can be wound into magnets that take up considerably less space than conventional superconductor magnets, so they will work with the squashed-up shape of the spherical tokamak.

Recently, a re-evaluation of experimental databases has suggested that smaller, cheaper tokamak fusion pilot plants and reactors may be possible (Costley et al, Nuclear Fusion, 2015). In principle we could attain similar fusion performance to an ITER-scale device at only about 1/20th the size. Also, it's not always best to generate the highest absolute fusion power. What is important is the fusion gain – the ratio of the power out to the power in – that is, how much extra energy we can get out. It could be that using several low-power machines with high gain is better than using one big, high-power machine. This scenario also gives operational flexibility to the power station operator.



Gideon and Steve working on the High Temperature Superconducting magnets for the ST25 (HTS)

What is Tokamak Energy doing?

Tokamak Energy Ltd is a private company based at Culham and with tokamaks operating at Milton Park in Oxfordshire. Funded largely by investors, we aim to reach fusion by a step-wise, iterative approach starting small.

1. **ST25** – Our first experimental tokamak at Milton Park has conventional copper magnets and is developing capabilities crucial for reactor operation. It can be operated remotely.

2. **ST25 (HTS)** – The *world's first tokamak* with High Temperature Superconducting (HTS) magnets is pioneering this new technology. We plan to run plasmas for 24 hours.

3. **ST40** – When construction is complete, this will be the world's highest-field spherical tokamak (>2 Tesla). It will have copper magnets and will verify theoretical predictions of improved confinement in high-field spherical tokamaks.

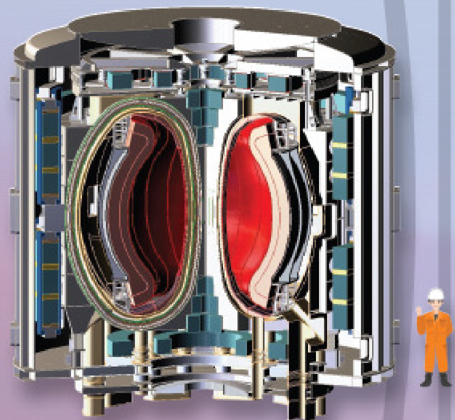
4. **ST60** – An HTS tokamak combining the knowledge gained on the previous machines to demonstrate *fusion energy gain* – up to 50MW of fusion power. Another *world first* for us!

5. **ST140** – Our concept for the first fusion power plant module, designed in collaboration with Oxford Instruments and Princeton, USA. It will produce over 150MW and could be used alone or as part of a "farm" of modular reactors.

For the future we see a modular series of such 100-200 MW power plants. These could be manufactured to a constant design and shipped around the world.

Are we nearly there yet?

We hope so, but we don't know for sure. Science is an exploration so we don't yet know what we will encounter. It is important to try different approaches and be flexible if we are to make progress. We are heartened to see different companies, such as Lockheed Martin and General Fusion, trying different methods alongside the mainstream government-funded fusion programmes. Even if things don't always work out as planned, this teaches us something, and all this different research will contribute to achieving fusion power on Earth.



ST140 - Our concept for the first fusion power module

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