In-depth Energy & environment

# Fusion future

By System Administrator 12th February 2007 10:00 am

As the debate over global warming rages, a £7bn international project, ITER, is trying to prove that nuclear fusion may ultimately provide us with cheap, safe energy.

It begins with a synthesised voice counting down from 10. After it hits one, there is silence. Then a faint but unearthly noise; somewhere between the roar of motorway traffic and the shriek of a jet engine at full throttle. Two flat computer screens light up with an extraordinary image; a fat, inverted teardrop of pinkish light — flaring to white around the edge and dark in the centre — illuminates the interior of a tightly curved tube. The centre of the teardrop is inky black.

'That bit's too hot to emit light,' says my guide. 'It emits X-rays.'

'So how hot is that?' I ask. 'It's a hundred million degrees Celsius,' he says. 'Ten times hotter than the sun. It's the hottest place in the solar system, for just a few seconds.'

'And that's where fusion would happen?' 'Oh, yes.'

This is a fairly normal day at Joint European Torus (JET), the world's largest nuclear fusion experiment, in the Oxfordshire countryside. Now more than 20 years old, JET holds the record for producing power from nuclear fusion — 16MW of energy. But its record-holding days are numbered.

Last November representatives from the EU and six other countries (Japan, China, Russia, Korea, India and the US) signed an agreement to build ITER, JET's successor, at Cadarache in the south of France. Closely based on the design of JET but twice the size, ITER is intended to be the first fusion reactor to reach the long-sought goal of net energy — getting more power

It is a huge undertaking and one in which JET will continue to play a vital role. Both machines are a type of reactor known as a tokamak — a Russian acronym meaning 'toroidal chamber in magnetic coils'. First invented in the 1950s, tokamaks are doughnut-shaped (toroidal) vacuum chambers that use magnetic fields to confine and manipulate the hot soup of atomic nuclei, free electrons and elementary particles known as plasma. This is the raw material for nuclear fusion.

Fusion occurs when the nuclei of different types of hydrogen atom, deuterium (D) and tritium (T), join together to form a helium nucleus. This reaction releases energy and a single neutron, which is ejected from the helium nucleus with great force. Fusion reactors aim to capture both the released energy and the kinetic energy of the speeding neutron.

The energy released is enormous. The problem is that the hydrogen nuclei are both positively charged and repel each other. Forcing the particles close enough together to fuse, maintaining the high temperature and keeping the plasma away from the walls of the reactor takes a huge energy input.

So far no reactor, not even JET, has managed to generate more power through fusion than was needed to produce the phenomenon in the first place. In fact, of the 16 tokamaks now in operation around the world, only JET has the radiation shielding and handling facilities to use tritium, which is radioactive. This means it is the only one that can now produce fusion; one of the factors that makes it an ideal test-bed for ITER.

Once fusion begins inside ITER, the helium nuclei (also known as alpha particles) produced by the reaction will collide with the other particles in the plasma, heating up the material. As this alpha heating builds up, the external heating sources for the plasma — injection of fast deuterium atoms and radio-frequency heating — can be reduced, so the plasma sustains itself. This state is known as burning and has never been achieved on a fusion reactor because it can only occur in a relatively large volume of plasma.

'We have produced a fusion reaction from D-T operation at JET,' said research director Francesco Romanelli. 'But for self-sustaining reaction we need the power lost by the plasma to be lower than the power generated by the fusion reaction, and to reduce the losses you have to increase the size.'

The confinement of the plasma is produced by three sets of magnets, one in the centre of the torus (the central solenoid, CS), one encasing the torus itself (the toroidal field magnet, TF) and another set of magnets positioned outside the torus (the poloidal field magnet, PF). Because the particles in the plasma are charged, magnetic fields make them move. The fields produced by the CS and the TF magnets combine to make the particles move around the torus. 'If you think of a charged particle moving around, this field makes it follow a spiral path, The strength of the plasma current is a measure of the tokamak's confinement capabilities; a strong current means the particles in the plasma are forced closer together. 'Most of the world's tokamaks work at around 1MA plasma current,' said Romanelli. 'JET is the only one capable of 5MA. ITER will have 15MA.' The current also acts as a heating element, in the same way as the glowing filament in an electric light bulb heats the air around it.

The PF magnets 'provide the magnetic bottle,' said Mitchell. 'The electrons are flowing around the plasma but to keep them away from the wall you need a set of magnetic fields that push in.'

On JET, these magnets are made from conventional conductors and the electricity needed to maintain the fields is an important factor in why it cannot produce net power. But on ITER, they will be superconductors — by far the largest superconducting magnets ever built. This will reduce the power needed to keep the reactor running. 'I think you can forget a tokamak if it hasn't got superconductors,' said Mitchell.

'ITER is a unique case, in many ways. The fields are much larger than any other tokamak and it's also unusual in that it's a nuclear machine, actually producing fusion. That means that it has lots of neutrons in it, so there's the problem of shielding the magnets. And it's by far the largest in terms of energy stored [in the magnets]. They hold about 50GJ, and the next one down is 700MJ.'

ITER will use two types of superconductor in its magnets. The PF coils will be made from an alloy of niobium (Nb) and titanium, which is a relatively easy material to work, Mitchell says: 'It's nice and ductile, we can wind those here on site.'

The CS and TF coils will be made from a compound of niobium and tin (Nb3Sn), which is quite a different proposition, however. 'It makes very powerful magnets, which is why we need it — we need a field strength of 12 tesla. But it's a pain because it's brittle. You form the coils when it's in a ductile form, then you put it through a heat treatment at 600°C for 200 hours.

'The previous biggest Nb3Sn coils made were the models we made in Japan; we used 30 tonnes of material in those. For ITER, we'll use 300 tonnes. It's a huge engineering challenge, although the problems are mostly actually in mechanical engineering, dealing with the stresses in the large steel support structures.'

The magnet materials are low-temperature superconductors and the entire vacuum chamber and magnets are contained within a cryostatic chamber cooled by supercritical helium at 4.5K.

and cryonics mean that it will produce 10 times more power than it consumes.

ITER's unique operating conditions are also leading to more changes in its construction materials. The deuterium-tritium plasma has consequences for the materials used in the vacuum vessel, particularly the wall that directly faces the plasma. Existing tokamaks, including JET, are lined with tiles made from a carbon-fibre composite, which has very low thermal conductivity, is mechanically tough, and is resistant to the magnetic forces. But it cannot be used in ITER.

'If you look at yourself in a mirror, you'll see why you can't use carbon in ITER,' said Guy Matthews, head of the 'ITER-like wall' project at JET. 'What you're looking at is hydrocarbon chemistry, which is very complex and rich. If you have a hydrogen plasma and put it next to graphite, it will form all sorts of hydrocarbons. In ITER, that would build up reservoirs of tritium, and we absolutely don't want that.'

Instead, ITER will be lined with metal. It has to be a metal that can withstand the high vacuum and exceedingly high temperatures inside the torus, so hard engineering metals such as tungsten were considered.

But ITER settled on using a more exotic metal for most of the inside surface: beryllium. 'It's a relatively high-melting metal, lighter than aluminium, stiffer than steel,' explained Matthews. It's also a very low atomic number, which means the atoms contain few electrons — this means that the plasma is very tolerant of the material, as it can't shed many electrons into the plasma flux.

Almost inevitably, JET is the only tokamak with experience of, and facilities for, handling beryllium. The metal is toxic and carcinogenic and must be handled under strict precautions. 'We had a stock of previously-used beryllium components which we had recycled back into fresh ones,' explained Matthews, 'and that gave us four tonnes of it, which we're making into tiles for a new wall for JET.'

The lining of the torus has a profound influence on the way the plasma behaves, Matthews said, as the impurities the plasma picks up from the walls of the torus change its composition. Once the new wall is installed, JET will be used as a dress-rehearsal to determine an operating regime for the beryllium-lined ITER.

Beryllium is brittle. The heat inside the torus will make it expand and contract and these thermal stresses could crack the beryllium tiles. For this reason they are scored with a deep grid of cuts, known as castellations, which prevent these stresses developing across a wide area, and shaped into a series of carefully angled ridges so the heat from the plasma cannot impinge at right-angles to a surface. 'We have to develop machine protection schemes,' said Matthews. 'Carbon fibre sublimes if it overheats but beryllium has a definite melting point, Replacing the tiles in JET will be a major job; there are 5,000 and the removal of the carbon composite tiles and fitting of the new beryllium skin has to be done using JET's remote handling system. 'We have an objective to replace the entire inside of the machine in slightly less than a year's shutdown period — the new wall should be in place in 2009,' said Matthews.

The only part of the reactor not lined with beryllium is the trench at the base of the torus, called the diverter, where the plasma particles are slowed down to exhaust their energy. Because the plasma is relatively non-energetic in this region, it can be lined with a heavier metal with more electrons in its structure. ITER will use tungsten tiles in this region and JET will also test this configuration.

ITER's beryllium tiles will be significantly different from JET's. On JET, plasma pulses last less than 10s, so the tiles are solid beryllium, thick enough to absorb the heat from a pulse. ITER's 10-minute pulses will generate much more heat, so its plasma-facing wall will consist of a layer of beryllium bonded to a copper-chromium-zirconium alloy, which is in turn bonded onto the structural stainless steel that forms the vacuum vessel. An active cooling system will extend from the steel layer into the copper alloy.

Making this metal sandwich illustrates how the seven-partner structure of ITER can complicate matters. Six of the partners will contribute to the vacuum vessel wall, explained Kimihiro Ioki, head of the vacuum vessel, ports and thermal shield section at ITER. The beryllium can be attached to the copper alloy by two methods— fast brazing or hot, isostatic pressing (HIPing). 'Five of the parties have agreed to HIPing but the Russian party prefers to keep brazing; they have very good brazing technology but no HIPing capability in the country,' said Ioki.

Brazing can make beryllium even more brittle, as it can form intermetallic compounds with the copper layer. This, Ioki said, is especially a problem in curved components, where there tend to be a lot of defects. 'So we've simplified the geometry of the torus,' he said. Rather than a smooth, doubly-curved surface, the torus will be made from a large number of flat facets with relatively few curved components. 'HIPing can cope with curved surfaces, but even for HIPing there are advantages to the faceted structure — it's cheaper and we can prepare spare parts much more easily.'

Ioki is also in charge of a part of the project that has not been attempted anywhere else. Known as the blanket, this consists of a series of modules containing lithium. Once the fusion reaction is under way, the fast neutrons will strike the lithium and convert it into tritium, which will diffuse into the plasma to fuel the fusion reaction.

In a commercial fusion reactor, the entire inside surface would be covered with a tritium-breeding blanket but even in ITER's later stages, more than a decade into its operation, only

So even when ITER reaches its hoped-for performance, it will still not be entirely self-sustaining. Some tritium will be supplied from outside the reactor and the heating systems will still be used, as part of the system to control the plasma.

All of these components and systems are in the test phase and everyone involved with ITER stresses that it is a scientific experiment, not a power station. 'Even though it will have a 500MW output, it won't be connected to electricity generation machinery,' said Kaname Ikeda, ITER's director-general. 'There will be a next step, a demonstration plant known as DEMO, to stand between ITER and a possible commercial fusion power station.'

According to the project's schedule, ITER will produce its first plasma in 2016, with first D-T fusion in around 2020. 'We're committed to 2016,' said Ikeda. 'We're on schedule but we're building a team here and implementing a design review. ITER is a very complex machine and it's a real challenge.'

Part of Ikeda's challenge is to manage the budget for ITER: €5bn (£3.3bn) for construction, and €5bn for 20 years' operation and decommissioning. This figure has led to criticism from some energy analysts and environmentalists, who would prefer the money to be spent on development and deployment of renewable energy generation technologies; these, they argue, are available now.

But Ikeda is adamant that fusion is not only a good investment but a vital one. 'We need the widest variety of energy sources and with the problems of global warming, fusion is a good candidate,' he said.

It produces no greenhouse gases and more importantly is incredibly efficient — for a given mass of fuel, fusion should produce hundreds of times more energy than nuclear fission and millions of times more than fossil fuels.

According to the Royal Society, the mass of lithium in a laptop computer battery and the deuterium in half a bath of water could provide enough fusion power to last an average person 30 years.

Moreover, unlike fission, fusion technology has no military applications, and a catastrophic nuclear accident such as Chernobyl or Three Mile Island is impossible, because the reactor only ever contains enough fuel for a few minutes' operation. The plasma inside ITER would weigh less than a gramme and in an accident would release 'less energy than you'd get in a hot bath,' according to JET's Guy Matthews.

The only nuclear waste it produces is the tokamak itself, which would be rendered radioactive by the neutron bombardment. However, the activity would diminish to safe levels

As for the cost, Ikeda insists it is good value. There is a simple comparison, he said. At current oil prices and rates of consumption, the entire ITER budget — construction, operation and decommissioning — is less than the amount the world spends on oil in three days.