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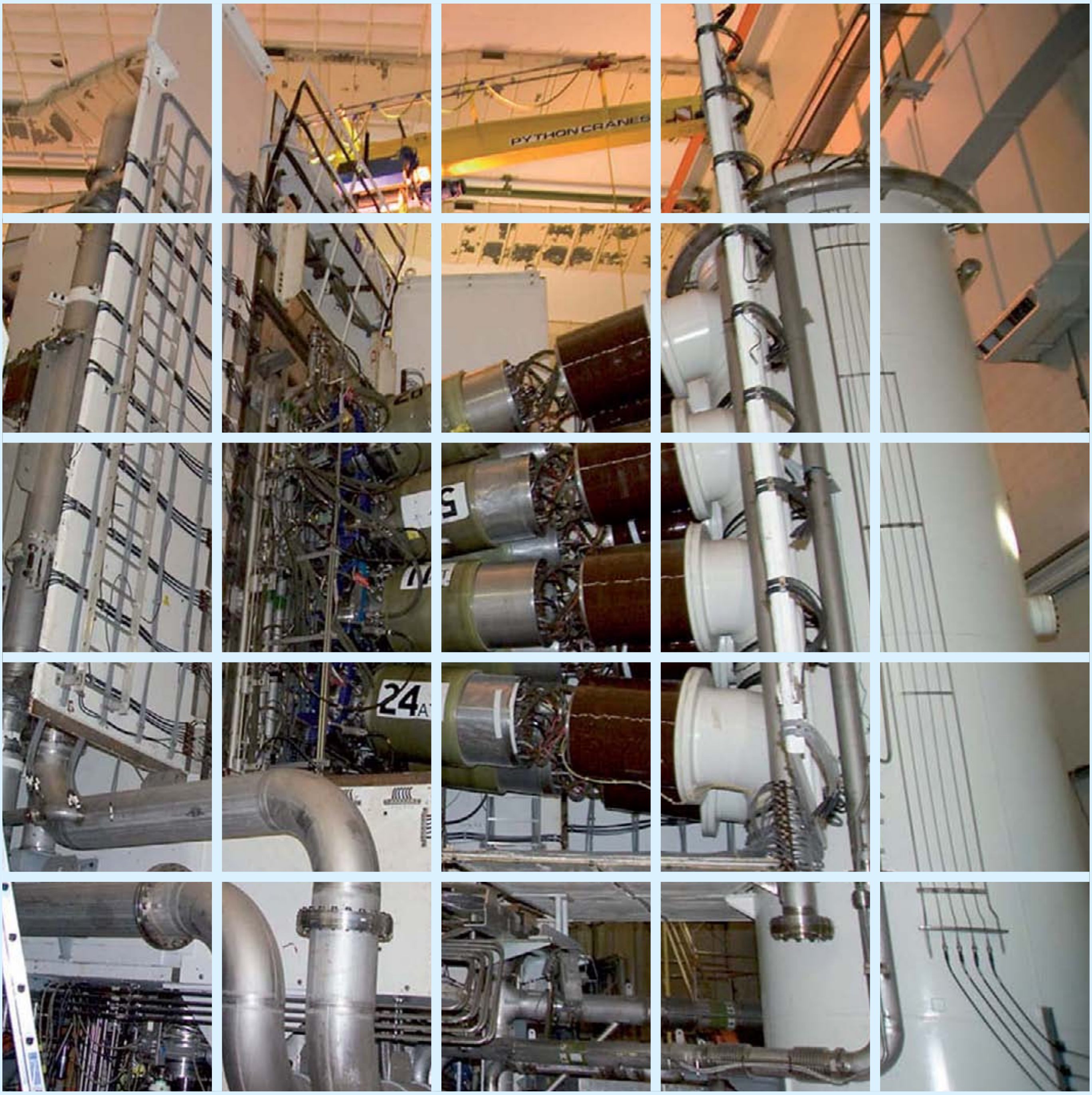
FUSION CHALLENGES AND SOLUTIONS



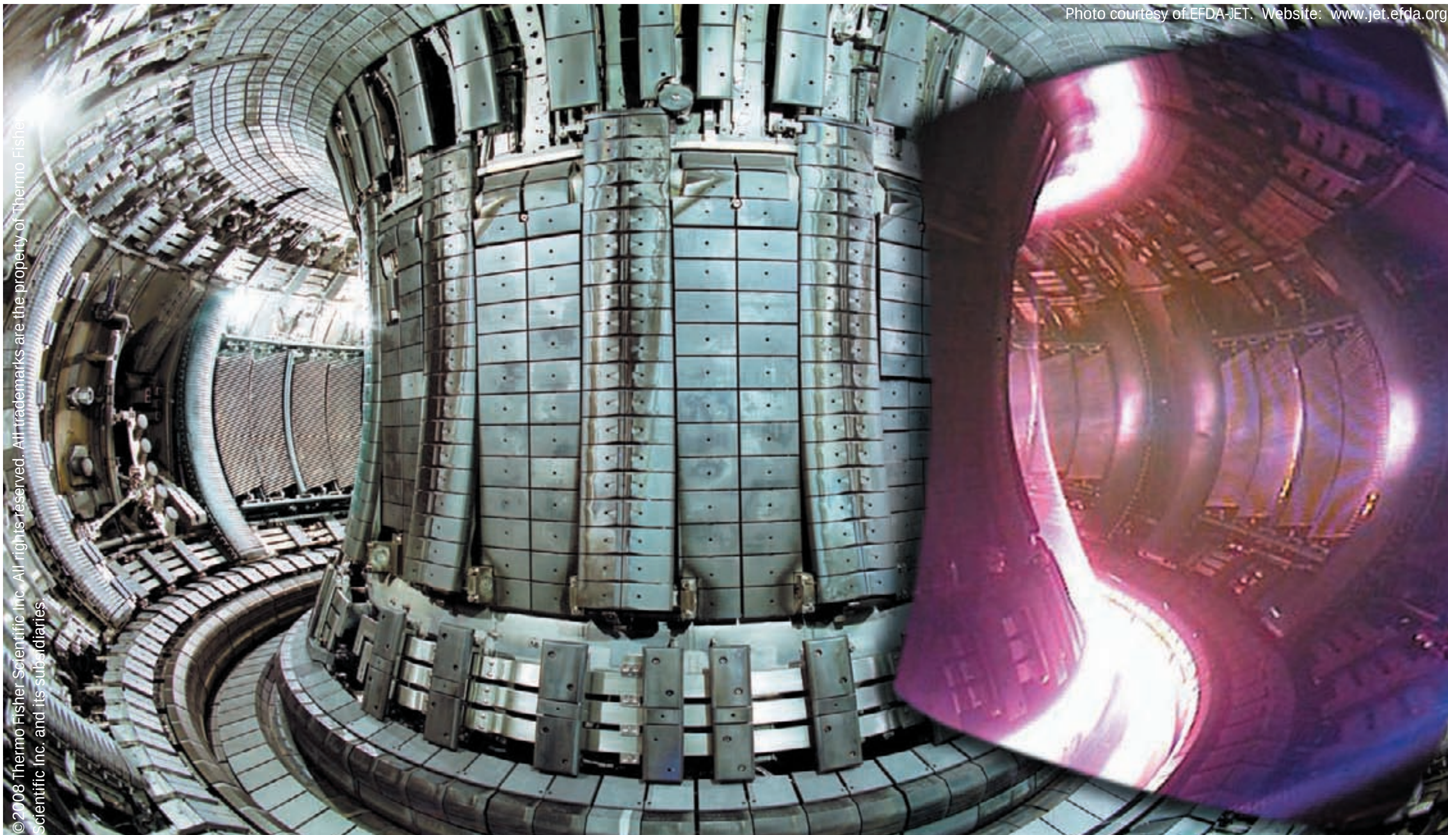
EFDA-JET

December 2009

Fusion challenges and solutions

"The governments of the world have made a substantial investment in fusion research; the time has come to begin to capitalize on this." This is the battle-cry of Stephen O Dean, president of the research and education foundation Fusion Power Associates. He feels that now is the time for the fusion community to pull together to make fusion power a reality (p14). Key to that goal is the success of the ITER project, but until it is constructed, the Joint European Torus (JET) based at the Culham Centre for Fusion Energy holds the world record for power output. A €60m upgrade could, however, see JET break its own record, and provide valuable information for the ITER team in the process (p5). Getting the best out of ITER is not just a case of building the best reactor, it is also essential to be able to predict the conditions inside the plasma itself. Help is now at hand with the switch-on of a new supercomputer dedicated to the study of magnetically confined fusion plasmas. The High Performance Computer for Fusion, based at Jülich in Germany, is the first of its kind and should make plasma modelling easier for researchers (p11). But it is not just magnets that hold the key to fusion power, laser-driven inertial-confinement fusion may also play a role. The European High Power Laser Energy Research Facility (HiPER) may only be a feasibility study at the moment, but the lessons learned along the way will be vital for this alternative approach (p7). Whether it be ITER or HiPER, the future of fusion power will rely on talented scientists and engineers to drive the technology forward. Two innovative UK postgraduate training programmes in fusion energy aim to equip the next generation of fusion leaders (p9). Hopefully, they will take Stephen O Dean's plea to heart and help make electricity from fusion a reality.

Contents



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JET set to break own fusion record

The €60m upgrade to the Joint European Torus (JET) will let it mimic the design of the ITER experiment in France. Andy Extance reports.

Monitoring the development of fusion technology is not a pursuit for the impatient. After a 10-year building phase that started in 2007, fusion experiments at the ITER project in Cadarache, France, are not set to begin until 2018. And with reports of construction delays, fusion enthusiasts would be forgiven for craving developments elsewhere to boost their morale.

Such a lift could be provided by the Joint European Torus (JET) near Oxford, UK, which is the only fusion device currently in operation using the same deuterium–tritium (D–T) fusion reaction that will be used at ITER. Physicists at the site will use €60m contributed by the European Commission and a consortium of national atomic-energy research bodies for JET's revamp – its most significant since 1993 – to make it even more like ITER.

After the upgrade, JET's neutral-beam injector will reach a test power of 34 MW.

The first signs of change are already noticeable. Although JET was only shut down for the upgrade in late October, many of the visiting scientists have returned to their home laboratories, being partly replaced by a team of engineers that will upgrade JET by November 2010. After experiments restart in spring 2011, researchers aim to recommence D–T fusion reactions in 2014. They believe that JET will beat its own 16 MW fusion-power-output world record, which was set in 1997.

If reached, this achievement will be a direct consequence of replacing more than 4500 carbon-fibre tiles that were previously lining the inner wall of JET's torus, and enhancing its neutral-beam heating system – one of several techniques used to raise the plasma to fusion temperatures. "Carbon fibres have this annoying property in that they act like a sponge, absorbing deuterium and tritium," explains Fernanda Rimini, deputy leader of JET's support unit. As a result, the inner wall is contaminated with radioactive hydrogen isotopes, and the high-temperature plasma where the fusion reaction occurs needs more D–T fuel. ITER plans to reduce these problems by using mainly beryllium and tungsten metal components instead, although initially it plans to keep some carbon-fibre components. JET will install a wall made completely of beryllium and tungsten as part of its upgrade, which may even accelerate the development of ITER. "If this wall is successful, then ITER might use it from the outset, rather than going through an intermediate stage that uses carbon," says Rimini.

With beryllium being used to tile most of the main chamber, a shortage of the metal proved a significant challenge for JET's planners. As a result, they recycled four tonnes of their own used beryllium from redundant components from JET's past experiments. Although it should help to improve fusion performance through its limited absorption of deuterium and tritium, beryllium will also pose challenges to JET and ITER's physicists. It has a comparatively low melting point of 1287 °C, so JET scientists will therefore need to study how best to integrate the new tiles and the 10^6 K plasmas that the chamber is set to contain.

Tungsten is more robust but is no less problematic. It melts at 3422 °C – much higher than beryllium – but it contaminates the deuterium and tritium in the plasma. To avoid this, JET and ITER will both limit its use to only the hottest area at the bottom of the vessel – the divertor – that takes exhaust heat and impurities away from the plasma and out of the tokamak. Unfortunately, melted beryllium forms an alloy with tungsten that has a melting point of just 2247 °C, which accelerates the process of eroding the tungsten. "Beryllium and tungsten form little droplets and damage the divertor," Rimini explains, "so we really need to rehearse the mitigation of the heat exhaust from the plasma."

As well as a wall material that should help maintain high fuel concentrations for longer, JET's similarities with ITER will be increased by upgrading its plasma-heating capabilities. JET's plasma is heated in several ways, but the upgrade will focus on improving the beam of highly energetic, but uncharged, tritium and deuterium fuel atoms, known as the neutral beam. JET's neutral-beam power will increase from 25 to 34 MW for up to 20 s pulses, or half this power for up to 40 s. Consequently, the overall power that JET can use to heat the plasma to the temperatures needed for fusion will increase to 45 MW, allowing access to what Rimini calls "ITER-relevant conditions". "The enhancement of the input power will have a big impact on performance," she says. "With a machine with a metal wall and with significant auxiliary heating power, we can improve on the results from 1997."

As D–T experiments at JET will not begin until 2014, physicists are careful not to overstate what it can achieve. JET's ultimate target is to produce more power than it consumes – one of the main challenges in fusion-energy research. "We cannot say how close we will be to breakeven, but we definitely know that there will be progress," says Rimini.

Andy Extance is a science writer based in Exeter, UK

Laser fusion shifts into HiPER drive

Ignition will be a fusion milestone, but what happens next? Margaret Harris looks at how a laser project called HiPER could lead to a practical fusion power plant.

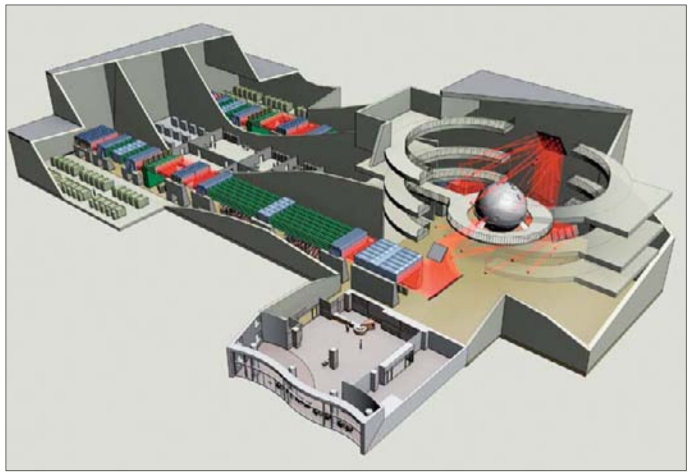
Something very big is about to happen in the world of laser fusion. At some point in the next two years, the US National Ignition Facility (NIF) should reach "ignition" – the moment at which a fusion device produces more energy than is required to start the reaction. When that happens, it will be the culmination of more than 50 years of research. Yet in many ways, ignition will be just the beginning. Releasing energy is one thing; releasing it in a form that could actually add a few gigawatts to a country's electrical grid is another.

One project that aims to help bridge this gap is the European High Power Laser Energy Research Facility, or HiPER. Led by the UK's Science and Technology Facilities Council and backed by researchers from 26 institutions in 10 countries, HiPER's mission is to carry out proof-of-principle research into energy generation from laser-driven inertial-confinement fusion. The project is currently one year into a three-year, €63m feasibility study, with construction slated to begin in about 2014, following a €100m prototype-development phase. The full facility, if built, is expected to cost at least €1bn and would be operational by the end of the coming decade, with a commercial laser-fusion power plant perhaps a further 20 years off.

Such estimates place laser fusion on a similar timetable to the €10bn ITER facility that is currently being built in southern France. But unlike ITER, which will use magnetic fields to contain deuterium–tritium plasmas at relatively low densities for several minutes, the idea behind HiPER is to hold fuel capsules at extremely high pressures for a few picoseconds (10^{-12} s) using lasers. As a laser beam heats the outer surface of the capsule, the surface expands outwards, causing the centre of the capsule to implode. Within 10^{-11} s of this implosion, a second "fast ignition" laser then heats this dense core to a temperature of about 10^{8} K, forcing the nuclei to fuse and releasing excess energy (in the form of neutrons) that could, in principle, be used to produce electricity.

"Think of HiPER as being like a car engine," says project director Mike Dunne, a physicist at the Rutherford Appleton Laboratory in Oxfordshire and head of the UK's Central Laser Facility (CLF). "You inject some fuel – in this case a small ball-bearing full of deuterium and tritium – and the laser acts like a piston, compressing the fuel to the point at which the atoms fuse to form helium, and ignite a fusion burn wave. Lots of energy is given off, the fuel is exhausted and the process is repeated."

The technological challenges are far from trivial. Igniting the fuel will require a laser capable of delivering a few petawatts (10^{15} W) of power – more than 10 000 times the entire capacity of the UK National Grid – in less than a picosecond. Repeating the fusion cycle quickly enough to generate significant amounts of power may be an even bigger barrier. A large conventional power station typically produces a few gigawatts. To match this, a commercial laser-fusion power plant would need to fire five times a second. Such a high repetition rate is "about a factor of 10 from where we are now in the laser world", Dunne acknowledges. The laser system at NIF, for example, can only fire every 2–4 hours. However, he adds that lasers develop quickly, and he believes that the required technology is only three or four years away.



An artist's impression of the HiPER facility.

Developing laser technology to the point where it meets HiPER's needs is a key part of the ongoing feasibility study. In particular, France's Petawatt Aquitaine Laser (PETAL) is being developed as a forerunner to HiPER, with the specific goal of studying the fast-ignition process. In the UK, existing lasers at the CLF provide possible templates for achieving higher-power regimes. The titanium–sapphire-driven Astra-Gemini laser, for example, is capable of firing once every 20 s, while the flashlamp-driven Vulcan laser is one of the world's highest power systems, having recently received an upgrade to 10 PW. None of these lasers will be direct blueprints for the high-repetition-rate system HiPER needs, but Dunne notes that such world-class facilities do provide a huge talent pool for meeting the experiment's technological challenges.

HiPER's is also expected to allow academic researchers to explore fundamental science at the extremes. A laser-fusion facility could be used to study solar physics, as well as "laboratory astrophysics" like supernovae evolution. Exploiting HiPER's ability to create a "star in the lab" will be a challenge for scientists, Dunne says, but he thinks the community is up to it. "There is a very large capability base out there," he notes. "We would like to see part of that capability and capacity turn to this problem."

• Watch an interview with HiPER director Mike Dunne online at *physicsworld.com*.

***Margaret Harris is Reviews and Careers editor for* Physics World**

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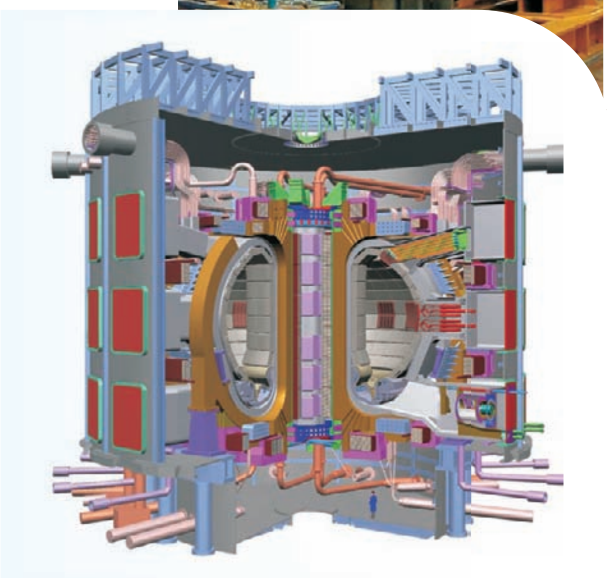
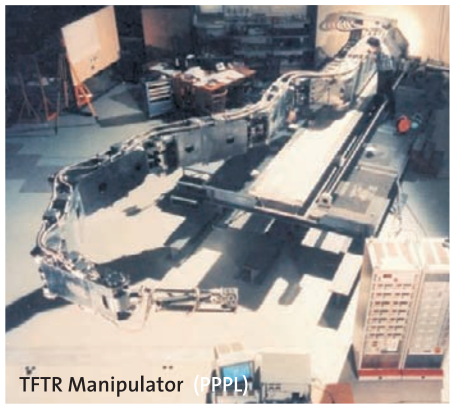
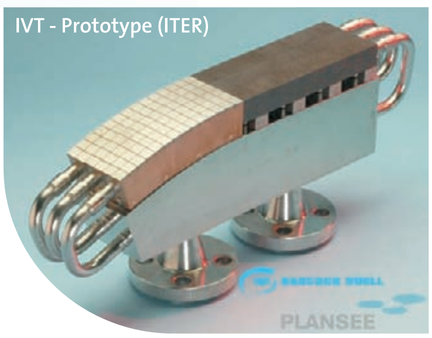
Non Planar Coil (Wendelstein 7-X)



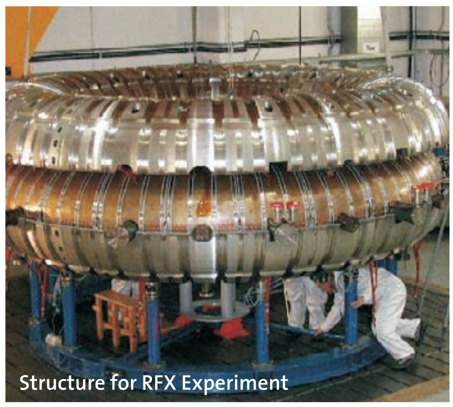

TARM (JET)


TFTR Manipulator (PPPL)



IVT - Prototype (ITER)


Trim Coil (Wendelstein 7-X)


Structure for RFX Experiment

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Building career prospects in fusion

Greg Tallents and Howard Wilson describe two innovative new postgraduate training programmes in fusion energy.

Research into nuclear fusion has long offered the hope of a carbon-free source of power using cheap, plentiful fuel. It is now reaching a critical stage, with a series of major new developments around the world. Experiments will begin soon at the recently completed National Ignition Facility (NIF) in the US, while the massive, €10 bn ITER project is currently being built in France. Next year, NIF is expected to exceed "breakeven" – the point at which more energy is generated from fusion than is used to heat the fuel to fusion conditions. ITER is designed to demonstrate that breakeven can be exceeded in reactor-relevant scenarios.

As interest grows in the potential offered by nuclear-fusion research, the Department of Physics at the University of York in the UK has launched a Masters (MSc) degree in fusion energy. The department has also developed a Doctoral Training Network (DTN) in fusion energy, in collaboration with the universities of Durham, Liverpool and Manchester, as well as the Culham Centre for Fusion Energy (CCFE), the Rutherford Appleton Laboratory (RAL) and AWE Aldermaston. Students on the DTN, which is part-funded by the UK's Engineering and Physical Sciences Research Council, focus during their first six months on the fundamentals of fusion physics with the Masters students before spending the rest of their three-year course doing research. A total of 13 students are taking the MSc course this year, with a further eight on the DTN.

Nuclear fusion, which powers the Sun, occurs when light elements such as hydrogen combine to form heavier elements. Fusion reactions generate lots of energy but require atomic nuclei to be forced together at very high temperatures in conditions that are difficult to reproduce here on Earth. "Inertial confinement" facilities, such as NIF, aim to achieve fusion by compressing deuterium and tritium together to very high densities for short periods using lasers. ITER, in contrast, uses "magnetic confinement", in which magnetic fields confine lower densities of deuterium and tritium for much longer periods of time. The inherent efficiency of magnetic confinement makes it the approach more likely to produce the first commercial fusion reactor, although inertial confinement is likely to be the first to achieve breakeven.

In the UK, several universities have offered PhDs in fusion-energy research for some years, often based around facilities at the CCFE or at the Central Laser Facility (CLF) at RAL. However, the number of postgraduate students in fusion energy must increase – and that training must incorporate more taught material – if the UK is to remain competitive in the rapidly growing international fusion programme. It is for this reason that the MSc and DTN in fusion energy have been set up. The formal taught part of both courses is delivered at York and includes lectures on a diverse range of topics in fundamental plasma physics, fusion technology and the scientific measurements required in a fusion plasma.

Koki Imada

The Fusion Learning Studio at the University of York.

In a dedicated new Fusion Learning Studio, also at York, all students attend laboratory sessions on magnetic- and inertial-confinement fusion and learn basic techniques for computational simulation of plasma phenomena. Masters students complete their training with a three-month research project over the summer. Some projects are associated with the UK's Mega Amp Spherical Tokamak (MAST) national facility at the CCFE or at the CLF. After completing six months of formal training in fusion at York, the DTN students then carry out research projects at one of the participating universities. Some projects use the Joint European Torus (JET) and MAST tokamaks or, for inertial fusion, the CLF. Potential research projects for the doctoral students are broad, covering everything from plasma eruptions and instabilities in tokamaks to opacity measurements for inertial-fusion experiments.

Students also benefit from a week-long fusion-technology workshop in York in January with invited expert lecturers from the CCFE and RAL, while a "frontiers and interfaces" workshop will take place in May featuring seminars and discussion sessions with leading researchers in the field. The latter will include core fusion subjects, but also related disciplines such as astrophysics, advanced instrumentation, nuclear materials and technological plasmas used in industry.

The MSc and the DTN in fusion energy both give students high-level technical knowledge of particular aspects of fusion research, but are also made aware of work in related fields and industries. The experience and training will ensure that students are well equipped for a range of exciting career options. Those students who choose to stay in fusion research and development will be well prepared to build on their comprehensive training to become the next generation of international leaders who will make electricity from fusion a reality.

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Fusion supercomputer starts up

Sibylle Günter explains how a new high-performance computer will help to get the best out of the ITER project.

Forschungszentrum Jülich

The High Performance Computer for Fusion is now up and running in Jülich, Germany. It has 1080 computing nodes.

On 1 August a new supercomputer was turned on at the Forschungszentrum Jülich Supercomputing Centre in Germany. The High Performance Computer for Fusion (HPC-FF), which is dedicated to the study of magnetically confined fusion plasmas, will help physicists to make reliable predictions of the conditions inside fusion reactors – including ITER, which is currently being built in Cadarache, France.

The supercomputer consists of 1080 computing nodes, each equipped with two Intel Quad Core processors, and can achieve a peak performance of about 100 teraflops per second. A high-level support team has been created to improve the performance of existing computer codes and bring new numerical techniques to the fusion community. The core of the team is at the Max-Planck Institute for Plasma Physics and the Garching Computer Centre of the Max Planck Society, which both have extensive expertise in computational plasma physics. The other members are at various European fusion institutions and the team's activities are partly funded by the European Union. The team's work is co-ordinated by the European Fusion Development Agreement (EFDA), which comprises various leading fusion research institutions and the European Commission.

ITER is expected to begin experiments in 2018, and in 2026 it should achieve its ultimate goal of using magnetic fields to confine a high-temperature plasma of deuterium and tritium. When that happens, some nuclei in the plasma should undergo fusion reactions that convert a portion of their rest mass into energy. Physicists hope that ITER will be the first such reactor to generate substantially more power than is supplied to the plasma from the outside for heating.

To achieve this goal, the complex behaviour of such plasmas is being studied in experimental devices worldwide – ranging from large facilities like the Joint European Torus (JET) in the UK to smaller university-based experiments. At the same time, advances in computing, along with the development of more elaborate physics models and their implementation in complex computer codes, have driven plasma modelling to a new level of realism. These models are tested continuously against experiments and form an integral part of the preparations for the operation of ITER.

Among the first physics problems to be tackled by HPC-FF will be the simulation of turbulence in plasmas, which can degrade the performance of a reactor. The primary aim of this research is to gain a better understanding of turbulence in current experiments and extrapolate this knowledge to a reactor such as ITER. HPC-FF will allow physicists to perform numerical simulations that cover larger computational domains (up to an entire reactor) and to include more physical effects than had been possible in the past.

A new effect that must be investigated for ITER is "thermonuclear self heating", whereby charged fusion products (energetic ions with MeV energies) are expected to transfer their energy via Coulomb collisions to the thermal plasma particles (of keV energy) – heating the plasma in the process. These energetic ions can resonate with and possibly destabilize plasma waves in the reactor. This could lead to energetic ions being expelled from the plasma, bombarding the surrounding walls and reducing the lifetime of the plant. Numerical investigations of the non-linear interactions between plasma waves and energetic particles are therefore of utmost practical relevance to the design of ITER and other reactors.

A further focus of the HPC-FF is to gain a better understanding of how materials used within a reactor deteriorate when exposed to neutrons created in fusion reactions. This is a complex process beginning with the formation of tiny defects during collision events and culminating in macroscopic changes in material properties over the lifetime of a reactor. As a result, such models must bridge the range from nanometres to metres and from picoseconds to years.

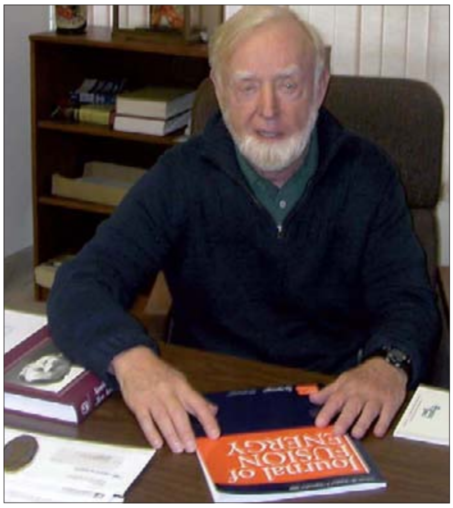
The ultimate goal of such modelling is to provide physicists with the tools to simulate all relevant processes in a magnetic fusion device, just as a flight simulator helps aeroplane pilots to fly. This goal is not yet achievable, even with the most powerful computers available today. Europe and Japan have therefore agreed to join forces to provide fusion researchers with a next-generation high-performance computer. This system will start operating by 2012 in Rokkasho – Japan's candidate site for ITER – and is expected to have a peak performance of a few petaflops per second.

Sibylle Günter is a director at the Max-Planck Institute for Plasma Physics in Garching, Germany, e-mail sig@ipp.mpg.de

FPA president predicts bright future

Stephen O Dean, president of Fusion Power Associates, discusses how we must all work together to make fusion a success.

Fusion Power Associates (FPA) is a not-for-profit research and education foundation providing information about the development of fusion energy and other applications of plasma science and fusion research. Its membership includes institutions, individuals and small businesses. FPA was formed 30 years ago and its aim, then and now, is to ensure the timely development and acceptance of fusion as a socially, environmentally and economically attractive source of energy. Stephen O Dean co-founded FPA in 1979 and has been its president ever since. He trained as a physicist and spent 14 years managing fusion programmes for US government agencies.



Stephen O Dean believes that fusion's time has come.

What is FPA's role?
FPA's members are heavily involved in all aspects of fusion development and play a key role in a number of international collaborations, including the ITER project. The foundation consolidates information and news on fusion developments from around the world on its website and also distributes this information to its members, the media and government officials via its electronic newsletter *Fusion Program Notes*. It provides lay-level materials and expert advice on plasma physics and fusion energy to the general public and runs an awards programme to honour leaders in the fusion community. It also publishes a more extensive bimonthly newsletter, *Fusion Power Report*, which is available on subscription.

How would you assess the current state of fusion science?
Globally, there is an increased urgency to develop new, environmentally friendly sources of energy. Fusion should play a key role in the long term. With the recent completion of the laser-based National Ignition Facility (NIF) in the US and the start of construction of ITER in France, fusion is entering a new era – one that involves the actual production of fusion energy, though not yet on a commercial scale. Thus there will necessarily be a growing technology base required for the eventual practical application of fusion energy. Industry will be heavily involved in manufacturing the components for ITER and this experience will be essential if commercial applications are to follow.

What do you see as the main challenges facing those involved in fusion science?
There are many scientific and technological advances that are still required for fusion to become a successful commercial power source. I think these advances will come in the normal flow of gaining experience from ongoing R&D. But the major issue, I think, is the high cost of fusion facilities and their associated development. Will governments be prepared to foot the bill for this over the next 20 years? Can we find a way to reduce the cost of fusion development with new discoveries?

How can FPA's programmes help to address these challenges?
One of FPA's primary functions is public education, to help everyone realize the potential of fusion. Fusion is an energy source for which the fuel is readily available to all nations and that poses essentially no adverse effects on the environment. However, it does require difficult, advanced technology and that will not come quickly. Thus, a significant, dependable source of financial support for fusion development is essential for an extended period of time. The foundation works with the managers of fusion-research programmes, through annual meetings and symposia, to focus their attention on the benefits of working together towards a common goal.

How does FPA plan to develop?
When it started out, FPA was primarily an industry association with the aim of bringing the private sector into fusion development. As interest in energy research waned in the 1980s and 1990s, it lost many of its industrial members, but it did retain and grow its membership among universities and government labs. Now, as we enter what is hopefully a fruitful new era of energy research, FPA hopes to attract industry back so that firms can work hand-in-hand with researchers to forge a path towards commercial fusion applications. Industrial participation in ITER is key to such an evolution.

What are your predictions for the future of fusion science?
First, we must get ITER built. The project is very ambitious and expensive. It is also on an extremely long timescale. One hopes, however, that the experience gained from the construction and operation of the project – combined with complementary efforts in materials development, smaller innovative experiments and parallel developments in theory – will allow a global effort to begin construction of the first demonstration fusion power plant. The governments of the world have made a substantial investment in fusion research; the time has come to capitalize on this.

Stephen O Dean is president of Fusion Power Associates (http://fusionpower.org)

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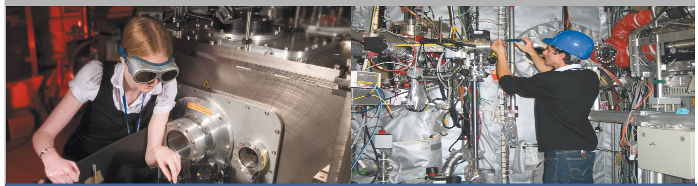

PhD studentships
Fusion Energy Science and Technology

Fusion Energy is entering an exciting new era

World-leading facilities in the UK, including JET, MAST and the Central Laser Facility, offer opportunities for scientists and engineers, while for the future, construction of ITER has begun and NIF should demonstrate ignition next year.

The Universities of Durham, Liverpool, Manchester and York, with Culham Centre for Fusion Energy, the Central Laser Facility and AWE have formed the Fusion Doctoral Training Network with EPSRC support, offering science and engineering graduates:

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