2 General Introduction

2.1 FUSION ENERGY RESEARCH

2.1.1 FUSION FOR ENERGY PRODUCTION

Fusion is the fundamental energy source of the universe, the process that powers the sun and the stars. In a fusion reaction, light atoms fuse together at extremely high temperatures, releasing huge amounts of energy. Fusion research aims to reproduce this process here on earth, and to use fusion as a safe way of producing large-scale energy, without the emission of greenhouse gases.

The fusion reaction that is easiest to accomplish on earth is the reaction between deuterium and tritium, two isotopes of hydrogen. As shown in Figure 2.1, a deuterium and a tritium nucleus can combine to form a helium nucleus, and a neutron. The helium and particularly the neutron carry a large amount of energy, and it is this energy that would be used to heat water and drive turbines in a fusion power station.

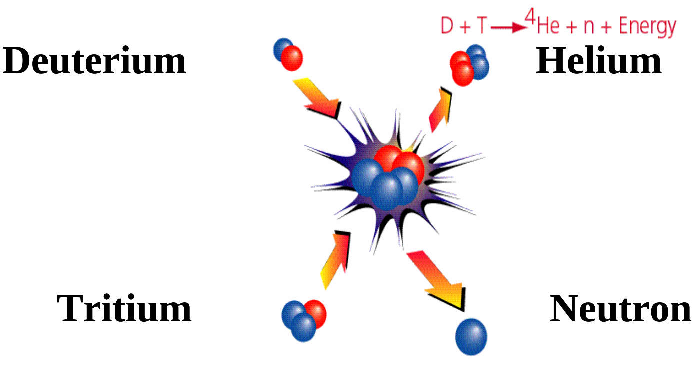

Figure 2.1: *Schematic of the deuterium – tritium fusion reaction.*

Deuterium is readily extracted from seawater and tritium would be made in a fusion power plant from neutrons striking lithium, which is widely available in the earth's crust. In a fusion reaction, the amount of energy released is about ten million times as high as the amount of energy released in an ordinary chemical reaction, such as the burning of coal. That enormous difference means that a fusion power plant only needs a very small quantity of fuel. The lithium from one laptop battery, combined with half a bath of water, would provide the fuel for 200,000 kW-hours of electricity – the same as 70 tonnes of coal, and equal to the UK's per capita electricity consumption for 30 years.

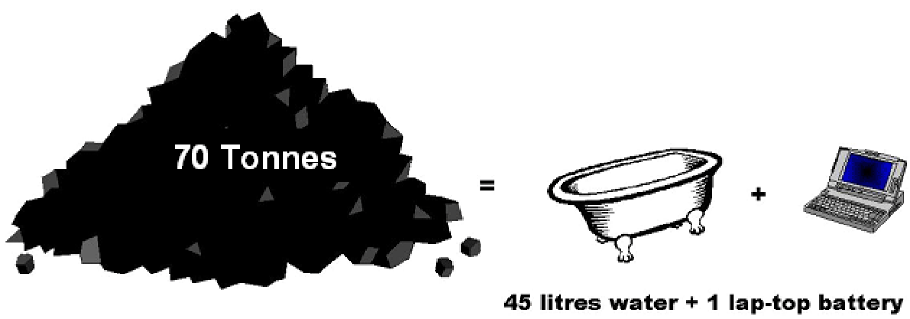

Figure 2.2: *Half a bath of water plus the lithium in one laptop battery would provide the fuel needed for the same amount of electricity as 70 tonnes of coal.*

Fusion reactions occur naturally at the middle of the sun (Figure 2.3) at temperatures of 15 million $^{\circ}$C. The sun keeps the hot plasma together by gravity, which causes a very high pressure in the centre of the sun. On earth gravity is much too weak, so a different technique needs to be used. One practical approach on earth is *magnetic confinement,* where strong magnetic fields are used to control and confine a much lower density plasma, which is heated to a higher temperature (over 100 million $^{\circ}$C).

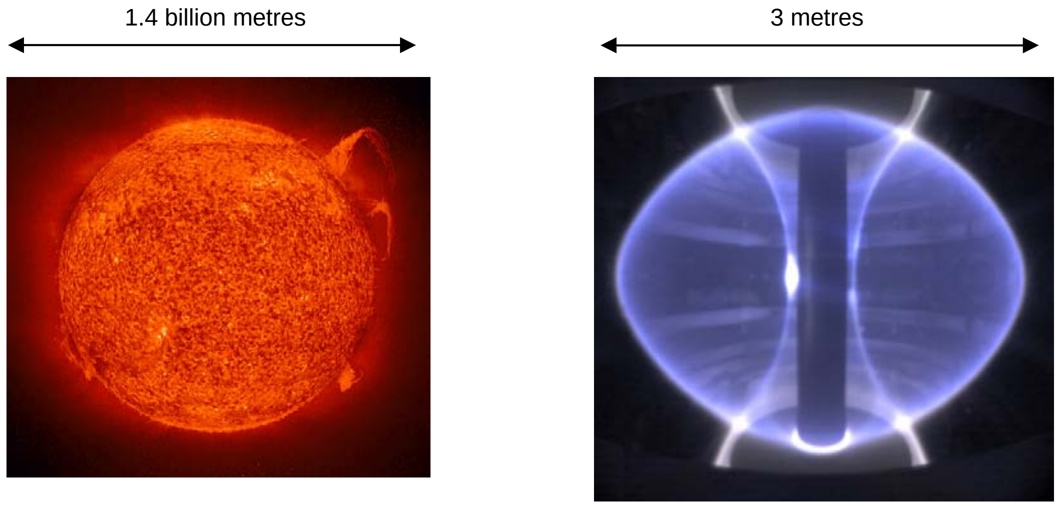

Figure 2.3: *Hot plasmas with copious fusion reactions occur naturally in the sun (left) and at Culham we create plasmas just as hot in MAST (right).*

With climate change and the need for increasing energy resources at the top of the world's governmental agendas, fusion is one of the key options that could contribute to a solution to this global challenge, with almost unlimited supplies of fuel, produced in devices that have low levels of stored and potential energy and can therefore be operated safely. Fusion R&D programmes are carried out in about 50 member countries of the International Atomic Energy Agency.

Other information about fusion research is available on CCFE's fusion website: http://www.ccfe.ac.uk and a glossary of fusion terms is provided in Chapter 11.

2.1.2 OVERVIEW OF EUROPEAN AND UK RESEARCH

Fusion research in Europe is aimed at demonstrating that nuclear fusion is a viable future energy option. It is fully integrated at the European level, with 26 EURATOM fusion Associations in European Union Member States and Switzerland contributing to the programme. The research activities in the various Member States are co-ordinated and complementary, and make it possible to undertake projects that would be on too large a scale for any individual member.

The collective aspects of the European physics activities, the management of the research on the Joint European Torus (JET) at Culham (Section 2.1.4) and on emerging technologies and training are all organised under the European Fusion Development Agreement (EFDA, http://www.efda.org/). Fusion for Energy – F4E, http://fusionforenergy.europa.eu/ – a EURATOM Joint Undertaking located in Barcelona, Spain, manages and provides Europe's contribution to the ITER project and to the Broader Approach projects agreed with Japan (Section 2.1.3).

The programme is focused on the tokamak approach to the development of magnetic confinement of fusion, whereby the plasma is confined by a magnetic field with two main components. The biggest (so-called *toroidal*) field is produced by external coils, and keeps the plasma away from the walls. However, by itself this field is not enough to confine the plasma. A second (so-called *poloidal*) field is added to reduce particle drifts and to counteract the natural pressure inside the plasma which tries to make it expand. In a tokamak, the poloidal field is generated by a strong electrical current which flows through the plasma, and which is also used to heat the plasma.

Other important ingredients are high vacuum conditions, powerful additional heating systems (using high energy beams of neutral atoms, radiofrequency waves and microwaves) and, to measure the plasma performance, a wide range of instrumentation ('diagnostics').

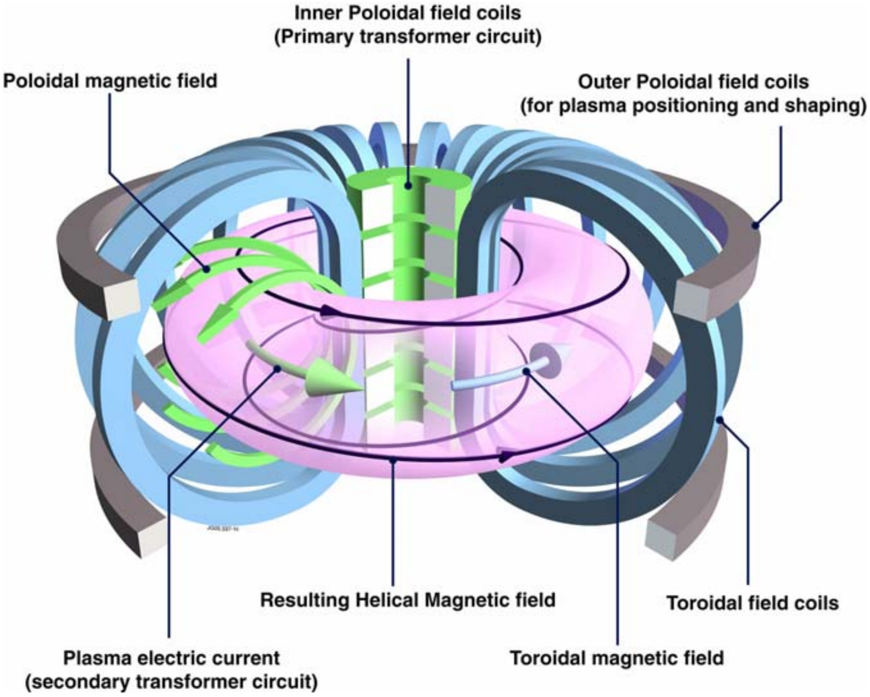

Figure 2.4: *Schematic of the tokamak approach to magnetic confinement fusion; the magnetic field is produced by a combination of external coils and the plasma current.*

The EURATOM/CCFE Fusion Association is a world leader in the study of a variant of the tokamak called the spherical tokamak (ST), currently represented by the Mega Amp Spherical Tokamak (MAST) device at Culham (Chapter 5). In STs the plasma is much more compact (resembling a cored apple) than in the more conventional JET-like plasmas (which have the shape of the inner tube of a truck tyre).

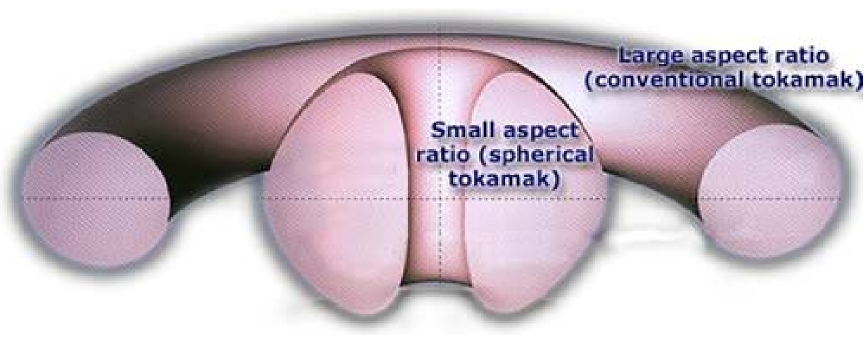

Figure 2.5: *The ST has more compact plasmas than the conventional large aspect ratio tokamak.*

MAST can address key ITER-relevant issues by testing ITER physics in new regimes, checking scaling laws and makes many contributions to ITER physics results co-ordinated by the International Tokamak Physics Activities collaboration.

Experimental and theoretical evidence suggest that the ST has a number of attractive properties, which if confirmed on MAST and other machines, would position it as a promising candidate for a Component Test Facility (a machine that could test whole power station components in a proper fusion environment) and perhaps, in the longer term, for a cheaper fusion power plant. These properties include good plasma stability and confinement, high pressure capability and the potential for continuous operation. A project to carry out a major upgrade to MAST is now underway. (See Chapter 5)

An alternative to the magnetic confinement approach is inertial confinement, in which extremely intense laser or particle beams are used to compress and heat small fuel pellets to densities and temperatures high enough for fusion to occur for a very short time. The European programme maintains a ‘keep-in-touch’ watching brief on this research, some of which is carried out at the Central Laser Facility based at the Rutherford-Appleton Laboratory in the UK (Section 2.5).

The EURATOM/CCFE research programme is jointly funded by EURATOM and the UK Engineering and Physical Sciences Research Council (EPSRC, http://www.epsrc.ac.uk).

2.1.3 ITER

ITER is an international project that aims to demonstrate the scientific and technical feasibility of fusion power, and will constitute the largest international scientific project bringing together countries representing over one-half of the world’s population. The partners in the project – the ITER Parties – are the People’s Republic of China, the European Union (represented by EURATOM), the Republic of India, Japan, the Republic of Korea, the Russian Federation and the United States of America. ITER is being constructed in Europe, at Cadarache, in the South of France.

The heart of ITER will be a superconducting tokamak facility, similar in shape to JET, but twice its size. Its design builds on the success of a very wide range of fusion experiments around the world as well as theory and modelling of tokamak plasmas, and developments in fusion technology.

In ITER, scientists will study plasmas, with a major radius of six metres, in conditions similar to those expected in an electricity-generating fusion power plant. Its goal is to release 500 MW of fusion power for extended periods of time, ten times the power input needed to keep the plasma at the right temperature. It will therefore be the first fusion experiment to produce net power. It will also test a number of key technologies for fusion power stations, including the superconducting coils, the blankets surrounding the plasma which will breed tritium and absorb the neutrons’ energy, and remote maintenance.

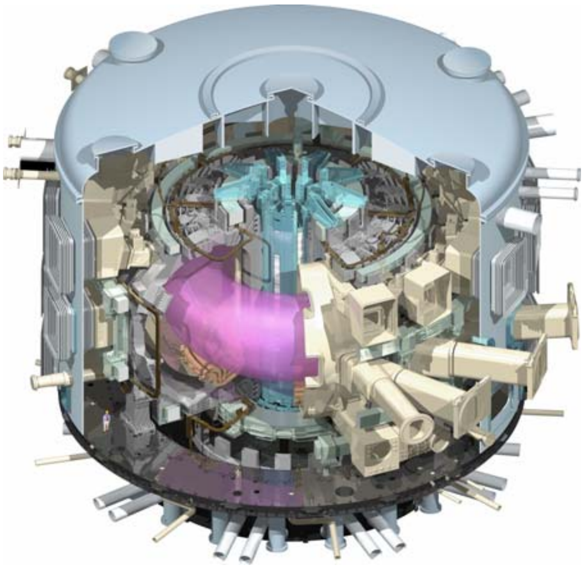

Figure 2.6: *Cutaway of the ITER machine.*

CCFE has been pursuing work on ITER in a number of areas of significance to the ITER diagnostic and heating systems in particular. Work so far has mainly been funded via F4E grants, where F4E provide approximately 40% of the funding, and the remaining 60% comes from the EPSRC block grant. CCFE has also pursued 100% F4E funded contracts together with 100% funded contracts from the central ITER Organisation (IO) itself, and intends to increase this contract work. CCFE has continued its substantial role in key ITER systems (Chapter 8):

- Ion cyclotron resonance heating (ICRH) system;
- Neutral beam injection system;
- Core LIDAR Thomson scattering to measure the electron temperature and density profiles;
- Core charge exchange recombination spectroscopy (CXRS) to measure the helium (Ash) content, ion temperature and flow;
- Remote handling, in particular the design for the Neutral Beam Hot Cell.

As part of the ITER site decision it was agreed that Europe and Japan would participate in 'Broader Approach' projects to complement the ITER project and accelerate the development of fusion energy. The projects include:

- A new fusion machine in Japan: the JT-60U tokamak is being converted to an advanced superconducting fusion machine known as JT-60SA, to act as a 'satellite' to ITER to develop operating scenarios and address key physics issues in support of ITER and the future DEMO power plant;
- Completion of the design and prototyping of IFMIF, a facility to test and qualify advanced materials for use in a future fusion power plant;
- An International Fusion Energy Research Centre in Rokkasho in the north of Japan to house the core of the Broader Approach activities, including the project team for IFMIF, supercomputing facilities and work on a demonstration power station (DEMO) to follow ITER.

In a 'fast track' approach to fusion development, ITER and IFMIF would operate in parallel and a demonstration power station could be providing electricity to the grid within thirty years.

Other information on ITER can be found on the ITER website: http://www.iter.org/ and on the Broader Approach on the Fusion for Energy website, http://fusionforenergy.europa.eu/.

2.1.4 THE JET FACILITIES

JET, the Joint European Torus, is the flagship of the EURATOM Fusion Programme and is the largest and most powerful fusion experiment in the world. It has operated for over 25 years and holds the current world record for fusion power (16 MW – a value comparable to the power needed for heating one thousand households in a cold winter) and fusion energy (21 MJ) released in one shot. However, JET cannot produce more energy than it consumes and can produce fusion power for only a few tens of seconds because it does not have the superconducting coils that will be used in ITER and fusion power plants.

Figure 2.7: *Graphic of the JET machine.*

The plasmas in JET have a very similar shape to those planned for ITER, but with half of their linear dimension. The JET facilities include plasma heating systems capable of delivering over 30 MW of power, an Active Gas Handling System and a Beryllium Handling Facility providing JET with unique tritium and beryllium capability, respectively. The UK Atomic Energy Authority, through its fusion arm, CCFE, is responsible for the safety, maintenance and operation of the JET facilities for a collective European programme of experiments. The work is carried out under the auspices of EFDA and its JET Implementing Agreement, with the Authority's costs reimbursed via the JET Operation Contract (Chapter 3). The UK is responsible for the eventual dismantling of the facilities.

In addition to operating the facilities and providing support to the EFDA Close Support Unit at Culham, which co-ordinates the JET programme, CCFE plays a full role in the Scientific and Technical Task Forces (described further in Chapter 4). As well as undertaking fusion plasma physics experiments, the Task Forces examine technology issues such as the conditioning of plasma-facing materials (tritium retention and dust removal being particular concerns) and machine activation. Non-EURATOM countries (the USA, Japan, the Russian Federation and China) also participate in the exploitation of the JET facilities under International Energy Agency (IEA) and other auspices.

Other information on JET can be found at: http://www.jet.efda.org.

2.2 THE EURATOM/CCFE PROGRAMME

2.2.1 COMPONENTS OF THE PROGRAMME

The overall aim of the EURATOM/CCFE programme is to maximise the UK's contribution to the 'fast track' development of fusion power. The main themes are: (a) ITER science – improving the ITER science base through experiments on MAST and JET, and related Theory & Modelling; (b) ITER technology – developing specialist equipment for deployment on the machine; (c) developing the spherical tokamak (ST) concept which has the potential to play a key role in fusion development; and (d) work on the science of materials and other aspects of fusion power technology.

The programme benefits from collaborations with many other research organisations, including UK universities, most of the other EURATOM Associations, and fusion institutes in the rest of the world.

The main components constituting this programme are shown in Table 2.1. The substantial activity in relation to JET operations is described in Chapter 3.

Chapter	Main objectives
4. JET Studies	• Participate in the EFDA Science and Technical programme on JET to improve the physics and technology understanding for ITER and their translation to future power plants
5. Tokamak Development (MAST)	• Contribute to the optimisation of the design and operating scenarios of ITER • Explore the potential of the spherical tokamak as a basis for a Component Test Facility (CTF) and as a future fusion power plant
6. Theory	• Address key physics issues for ITER and spherical tokamaks, by developing theories and codes validated by experimental data
7. Materials & Technology	• Improve understanding of the behaviour of materials in the fusion environment, particularly their tolerance to neutron bombardment • Improve understanding of the safety, environmental and socio-economic attractiveness of fusion power • Examine the spherical tokamak route to CTF and a fusion power station • Participate in DEMO and other studies in the international Fast Track to fusion
8. ITER Projects	• Contribute to the development of specialist equipment for ITER, e.g. heating and current drive systems, diagnostics, port plugs, plasma control, plant control and data acquisition systems
9. Industry	• Encourage companies to tender for fusion procurement and consultancy contracts arising from the national and international programmes • Facilitate technology transfer from fusion research

Table 2.1: *Main components of the EURATOM/CCFE programme*

The largest component of the programme relates to the experiments for ITER and the development of the ST using the MAST facility. MAST is one of the two largest and most advanced STs in the world, the other being NSTX at Princeton Plasma Physics Laboratory in the USA. The ST is a very promising line of research, pioneered at Culham, which now features in fusion programmes around the world (USA, Japan, Brazil, the Russian Federation, Italy and China); devices of this type are the subject of an IEA Implementing Agreement.

The ST has been proposed as the basis of a Component Test Facility (CTF), which would be desirable for the development of fusion power. A CTF could provide the necessary conditions to test and develop reliable fusion reactor components and structures in an environment which combines a realistic fusion neutron spectrum and all the other relevant tokamak stress fields.

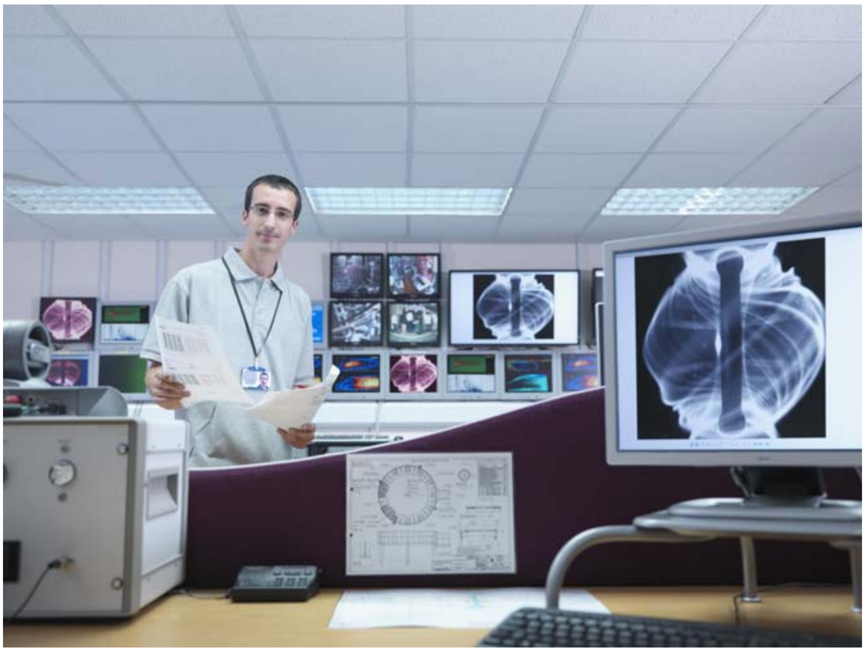

Figure 2.8: *The MAST control room.*

Participation in the JET scientific and technical programme, when combined with work on MAST and other tokamaks, provides the best possible data for the development of ITER operating scenarios and their translation to a fusion power plant. In addition to the development of reacting plasmas, the exploitation of JET contributes to the performance characterisation of plasma-facing materials, tritium technology and the development of ITER equipment. The UK contributions to JET are co-ordinated with all others by the Culham-based EFDA Close Support Unit.

The MAST and JET programmes have inter-dependent links with the development of the theoretical physics understanding of plasmas and their modelling, using state-of-the art, sophisticated codes. The work in this area is targeted on the key issues for ITER and spherical tokamaks, and is evolving in response to the future development needs of these concepts. The models developed are tested where possible by comparing with results from MAST, JET and other tokamaks.

The technology work promotes the cost-effective accelerated development of fusion as a safe, environmentally benign and economically attractive source of energy. This is achieved through work on a number of 'fast track' and longer-term technology issues. The development of robust structural and plasma facing materials is on the critical path to fusion power, and the programme concentrates on the development and characterisation of suitable materials needed for fusion power plants and DEMO.

The programme on ITER projects focuses on securing the most appropriate ITER specialist equipment projects for the UK. Leading roles in partnerships of European fusion laboratories on certain diagnostic systems and heating and current drive projects have already been established. A related issue is the UK participation in ITER procurement and construction activities, and the Culham industry liaison programme concentrates on ITER and encourages UK companies, both big and small, to bid for contracts. UK companies have already won some important ITER contracts.

The results of the research and development work are published in journals, presented at international conferences and workshops, and at meetings of the international tokamak physics activity (ITPA) Topical Groups, which co-ordinate work on the various topics. A list of publications in 20010/11 is available in Chapter 10, and a Glossary in Chapter 11.

2.2.2 INTERNATIONAL COLLABORATIONS

The EURATOM/CCFE Association undertakes collaborative work with many laboratories and institutes in the framework of the European and international fusion programmes. Much of this is within EFDA-co-ordinated programmes – CCFE staff are among the EFDA Task Force Leaders - or under the auspices of the IAEA and the IEA. These include: the EFDA, F4E and ITER Teams; ERM Brussels (Belgium); IPP Hefei (China); Institute of Plasma Physics (Czech Republic); Risø (Denmark); TEKES and Helsinki University of Technology (Finland); CEA Cadarache and CEA Saclay (France); Institute of Plasma Physics (Garching, Berlin and Greifswald), FZ Jülich, FZ Karlsruhe, (Germany); Hong Kong Polytechnic University; Hungarian Academy of Sciences (Hungary); Dublin City University and University College Cork (Ireland); ENEA Frascati and Consorzio RFX (Italy); University of Toyko, NIFS and JAEA (Japan); Taegu University (Korea); FOM and University of Eindhoven (the Netherlands); Institute of Plasma Physics and Laser Microfusion (Poland), Instituto Superior Tecnico Lisbon (Portugal); MEdC (Romania); the Kurchatov and Ioffe Institutes, Moscow State University, St. Petersburg State Technical University (Russian Federation); CIEMAT, University of Alicante and University of Seville (Spain); Vetenskapsrådet (VR) (Sweden); CRPP Lausanne, University of Basle and Paul Scherrer Institute (Switzerland); General Atomics in San Diego, Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory, Stanford University, Massachusetts Institute of Technology, University of California (San Diego, Los Angeles and Davis), University of Wisconsin, Lawrence Livermore National Laboratory, University of Maryland (all USA).

2.2.3 UNIVERSITY COLLABORATIONS

There are collaborations and other links with UK universities, many of which have post-graduate and other students working at Culham.

Over 40 students from many UK (and a few overseas) universities work on fusion with CCFE, with about half based at Culham and half at their universities. The topics studied span theoretical and experimental plasma physics, materials science, technology and engineering. Many are 'EPSRC Industrial CASE' students of which Culham has an annual quota of six. In addition to collaborations involving students, there is work with university staff on a range of research projects, many of which are featured in this report. And in some cases Culham staff contribute lectures to university courses.

Universities with which there were active collaborations in 2010/11, some of which have their own fusion-related EPSRC grants, include: Birmingham, Bristol, Brunel, Cambridge, Cranfield, Durham, Edinburgh, Glasgow, Heriot Watt, Imperial College London, Liverpool, Loughborough, Manchester, Oxford, Queens Belfast, Salford, Sheffield, St. Andrews, Strathclyde, University College London, Warwick and York.

2.3 EXTERNAL RELATIONS

2.3.1 PUBLIC UNDERSTANDING OF FUSION

A busy and varied programme of public engagement has continued at Culham during 2010/11, led by the CCFE Communications Group.

A Public affairs and media

Media interest in fusion and JET and/or MAST has been steady despite both devices having major shutdown periods throughout the year. Immediately following the nuclear accident at Fukishima in March 2011, there was intense media interest, with CCFE asked to provide comments on fission safety and future development - all politely declined. A renewed interest in fusion as a long-term energy option has been observed since the incident.

Notable media items have included:

- An interview with Science Minister David Willetts on BBC Radio's flagship news programme 'Today' in July 2010, in which he endorsed fusion and praised the work being done at Culham;
- An appearance by Culham scientists in a BBC TV 'Horizon' documentary on temperature, January 2011;
- 'The Times' newspaper named Culham Director Prof Steve Cowley as one of the top 100 UK scientists in its 'Eureka 100 Science List' in October 2010;
- An article by Prof Cowley outlining the case for fusion, which was published by 'The Guardian' in July 2010;
- Culham and UK fusion research have been featured in journals including Physics World, Nature, Science, The Engineer, Laboratory News, Power Technology, Chemistry World, Industrial Fuels & Power and The Chemical Engineer. Also in the international media: Finland, Germany, India, Russia, Spain, and the United States.

The Communications Group offers continued support to the CCFE Director in building up and maintaining contacts with key parliamentarians and staff in the UK and European Parliaments. A notable recent example was the organisation of a visit to CCFE in September 2010 by the new Science Minister, David Willetts MP, following the change of Government in the 2010 General Election.

Figure 2.9: *David Willetts MP (right) meeting a CCFE apprentice during his visit to Culham.*

B Public outreach

The series of popular Culham Visit Evenings allowed almost 1,000 members of the public to view the JET and MAST experiments and find out more about fusion. Culham also actively supported local outreach events such as the Abingdon Schools Science Fair and the opening event of the annual Oxfordshire Science Festival. Communications staff, aided by volunteers from within the Culham programme, also gave a large number of external talks during 2010/11.

In addition, CCFE has launched a new six-monthly newsletter, 'InFusion', available via the website www.ccfe.ac.uk. The newsletter will provide an informative and accessible mix of feature articles and news to update readers on the research at Culham.

Figure 2.10: *New CCFE 'InFusion' magazine.*

C EFDA-JET CSU support

The EFDA-JET Close Support Unit is responsible for the management and co-ordination of the JET experimental programme, for analysis and dissemination of the results and for monitoring of UK Atomic Energy Authority's implementation of the JET Operation contract.

The CCFE Communications Group continued to provide through 'Host Support' strong support for EFDA-JET's communications activities and also its EIROforum activities throughout the year. It provides one of the core members of the Outreach and Education group, which links the public and schools around Europe to the work at the EIROforum laboratories (the other members being CERN, ESRF, ILL, ESA, ESO and EMBL). CCFE's Chris Warrick and Jennifer Hay co-chaired this group from July 2010, with responsibility for EIROforum's involvement in various events (European Contest for Young Scientists, Science on Stage teachers festivals, Euroscience Open Forum).

D Education outreach

This activity remains a key priority for CCFE's Communications Group. School visits are organised at the rate of four to six per month – with almost 2,000 students coming to Culham during the year. Unfortunately this does not meet demand and visits are normally fully booked at least six months ahead.

The Sun Dome schools activity continues to be utilised in local primary schools for Year 5/6 groups, with new secondary school shows now employed on some occasions. Capitalising on CCFE's strong links with several universities, students from the Oxford University Materials department are starting to help with shows in Oxfordshire and the Dome has toured the York area, with shows being conducted by plasma physics students at the University there.

Figure 2.11: *CCFE's Susan Hayward giving a talk at a local primary school.*

2.3.2 CULHAM SUMMER SCHOOL

The 47th annual Plasma Physics Summer School took place at Culham Science Centre over two weeks in July. The 2010 School was attended by 57 students of whom the majority came from outside the United Kingdom. Lecturers are drawn from research and academic institutions across Europe, providing a broad-based curriculum. The Culham Plasma Physics Summer School is committed to offer training in plasma physics suitable for a wide scientific community.

Figure 2.12: *Students at the 2010 Culham Summer School.*

2.3.3 CULHAM THESIS PRIZE

Each year CCFE sponsors through the UK Institute of Physics a prize for the best thesis in the field of plasma physics submitted through a UK or Irish University. The 2011 Culham Thesis Prize was awarded to Dr Stefan Kneip for his thesis entitled 'Laser Plasma Accelerator and Wiggler', submitted to Imperial College, London. He received his prize at the annual IOP plasma physics conference in North Berwick.

2.4 INTERNAL INITIATIVES AND CONTROL

2.4.1 SAFETY

CCFE continued to maintain a low accident rate which compared well with industry standards. Injury related accidents increased – this is deemed to be due to the intensive engineering work involved in the JET shutdown rather than an increase in unsafe practices – but remained within the site target set for 2010/11. All accidents were relatively minor in nature, with few lost days and causes fully investigated.

The JET and MAST experimental devices operate at very high voltages and currents, and electrical safety is therefore of critical importance to the organisation's overall safety performance and is arguably the most significant day-to-day safety hazard at Culham. Over recent years, significant resources have been directed towards ensuring installations (some of which are more than 20 years old) meet modern standards. One example of this involves a project to survey and upgrade over 2,000 electrical cubicles. Following an independent review of electrical safety arrangements further work has been undertaken to ensure working practices meet the highest standards.

A behavioural safety programme has seen an increase in the reporting of safety related incidents. This indicates that a positive incident reporting culture exists at Culham, as the increase is in the reporting of near miss incidents and this ensures that the majority of risks can be addressed prior to any loss or personal injury occurring.

The Authority Board and Senior Management team display visible, strong commitment to improving safety on the Culham site, which has been key to the successes this year.

2.4.2 QUALITY AND MANAGEMENT SYSTEMS

In 2010/11 CCFE maintained its certification to the national and international standards ISO9001, ISO14001, BS OHSAS18001 and ISO17025 (for Quality, Environmental, Occupational Health & Safety management and Health Physics testing respectively).

During the year, operating to the international standards provided the organisation with a strong base from which to meet the demanding requirements set by Fusion for Energy when commissioning work in relation to ITER. As part of the continual improvement process a revised Project Management system and toolbox was developed and launched to facilitate the delivery of major projects.

2.4.3 ENVIRONMENT

Culham's Environmental Management System retains certification under ISO14001:2004, and as part of this system has progressed with a programme of continual improvement.

In support of the development of an operational Integrated Waste Strategy, as required by the Environment Agency, a Best Available Techniques study was successfully completed; this engaged key local stakeholders in the decision making processes to determine the best practical environmental options for all radioactive wastes. Furthermore, significant improvements were taken to reduce waste management holdings, with new waste routes being established and a large amount of historic material sent off site during the year.

2.4.4 TRAINING

A Culham Research Fellowships

The scheme offering Fellowships for outstanding researchers in an early stage of their career (typically immediately after their PhD, or after a short post doctoral position elsewhere) is in its fifth year. These two-year Culham Fusion Research Fellowships are open to anyone, to research on any topic within the research programme of the EURATOM/CCFE Association. Candidates are invited to propose their own research project, and a period working in another laboratory is encouraged to provide wider experience. One or two are selected each year. Several past fellows have also been awarded EFDA Fusion Research Fellowships, and all have been selected for posts in fusion research at Culham or elsewhere at or before the end of their fellowship.

Further details on the Culham Fusion Research Fellowships can be found at: http://www.ccfe.ac.uk/fellowships.aspx.

B Culham Apprentice Scheme

CCFE runs an advanced apprentice scheme, in order to maintain the engineering skills base at technician level.

The scheme continues to grow in popularity, with another strong set of applications in the latest recruitment round. There are currently 17 apprentices under training at CCFE – ten electrical and seven mechanical. Five of the electrical apprentices are due to graduate in September 2011.

Two apprentices are sponsored by Reaction Engines, a company based on the Culham site. CCFE hopes to expand the number of ‘sponsored apprentices’ further in future.

C Culham Graduate Scheme

Currently there are eight people on the CCFE graduate training programme. There has been a decrease in the number of new entrants to the programme during 2010/2011, due to government restrictions on recruitment. During the year, the Graduate Handbook has been updated to conform to IMechE, IET and IOP ‘accreditation standards’ and IMechE accreditation has been sought.

More details on the scheme and its objectives are available at: http://www.culhamgraduatescheme.com.

D Power Academy

The Power Academy is a scheme run by the IET that supports power engineering students through their studies at one of the member universities. A total of six university, sixteen industry and two institution partners work together to further power engineering and ensure a healthy pool of talent for all power engineering needs. Culham can sponsor up to two Power Engineering undergraduates each year. CCFE currently has two Power Academy students, and two candidates have already been identified for 2012. Further details on the Power Academy can be found at: http://www.theiet.org/about/scholarships-awards/power-academy/partners.cfm.

E EFDA Goal Orientated Training Scheme

CCFE is taking part in a number of projects in the Goal Orientated Training Scheme, which was initiated to provide a structured programme to develop staff with particular expertise in areas identified as being of significant relevance to the future fusion programme, but where there was currently limited expertise. The projects CCFE is currently involved in are on fusion blankets, tokamak theory, neutral beams, tritium technology, tokamak operation, power supply engineering and quality assurance. CCFE both provides staff to be trained and gives some of the training courses.

2.5 KEEP-IN-TOUCH WORK ON INERTIAL FUSION ENERGY

The work that is undertaken in the UK on Inertial Fusion Energy (IFE) takes place at the Central Laser Facility (CLF) at the STFC Rutherford Appleton Laboratory (RAL, http://www.clf.stfc.ac.uk). This work receives some EURATOM funding as part of its keep-in-touch inertial fusion programme. Much of the research performed at the Central Laser Facility in energy research over the past year has been devoted to investigations of the concept of fast ignition inertial fusion. Central hot-spot Inertial Confinement Fusion works by compressing fusion fuel (deuterium and tritium) to ultra-high density using nanosecond duration laser beams.

The control of the divergence of MeV fast electrons entering the target is necessary to minimise the petawatt laser energy requirement. The idea of using two laser pulses was suggested by Robinson, Sherlock and Norreys in 2008 as a method of generating an artificial magnetic field in the first pulse to guide the fast electrons generated in the second pulse. This has now been successfully demonstrated on the Vulcan PW laser facility at CLF by physicists from across Europe.

Another way of controlling the divergence of the fast electron beam has been to impose a materials mismatch. The gradient of resistivity across the boundary between the two materials allows a large magnetic field field to grow there. Proof-of-concept experiments led by Queens University Belfast were constrained to planar geometry. As described in last year's report, these studies were extended to radial symmetric targets. The successful confinement of the fast electron beam was demonstrated in the most recent experiment on the Vulcan PW facility and has now been fully published in *Physical Review Letters*.

The University of Strathclyde has used proton emission imaging to infer the degree of filamentation that fast electrons undergo as they propagate through foil targets. In combination with hybrid modeling this has been used to constrain the possible resistivity curves (as a function of temperature) for various materials. Interesting results that may well be highly relevant to fast ignition have emerged. For example, recent work showed that diamond must be much less resistive (by a factor of 10-100) than glassy carbon in the 1-20eV region. This was in fact confirmed by very detailed calculations performed at Sandia National Laboratories in the US.

In an extension to the idea of staff at CLF have been developing a new, currently theoretical concept, for magnetic guiding of fast electrons in Fast Ignition. This will require an insert that will sit inside the cone, but does not require any structures that would sit in the fuel assembly region, i.e. outside the cone. Recent calculations suggest that this should lead to substantial improvements in coupling efficiency even with highly divergent fast electron beams.

Fundamental energy transport studies have been made by imaging of fast electrons transport in foam targets using the technique of proton radiography by Queens University Belfast. Interesting new features were observed in experiments undertaken in the CLF and are currently under analysis. Equally interesting spectroscopic methods have been used to study the anisotropy of the electron distribution function by the Universities of York and Oxford.

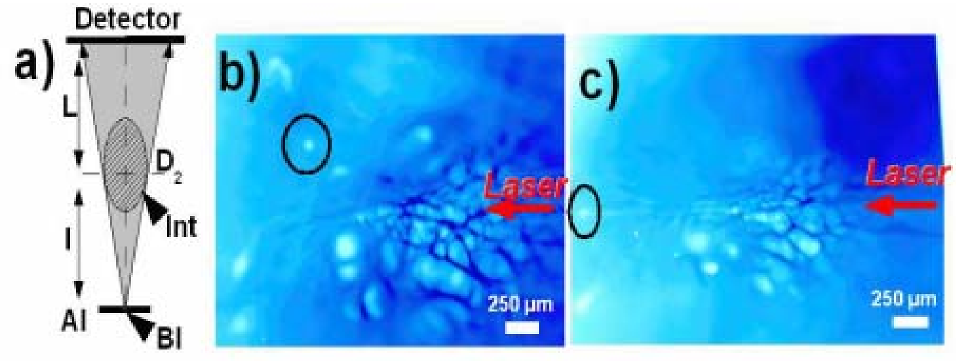

Figure 2.13: *Post-solitons observed in proton radiography/deflectometry. They resulted from channel formation in under-dense plasma driven by a relativistic intense, 30-ps duration laser pulse. These images were formed by protons being deflected by self-generated electric and magnetic fields about 100ps after the interaction.*

An alternative to the idea of cone-guided fast ignition inertial fusion is to use a 100ps intense laser pulse to drill a channel in the coronal plasma surrounding the compressed fuel at peak compression. This allows the petawatt laser pulse to propagate and deliver its energy close to the compressed fuel. Finally, proof-of-concept experiments showing that channels can be formed in under-dense plasmas have been undertaken (Figure 2.13); interesting non-spherical bubble-like structures were observed at higher densities and were successfully modelled using 3D simulations.