1 Executive Summary

1.1 OVERVIEW

If fusion – which powers the sun and other stars - can be harnessed on earth it could provide the world with large-scale electricity generation with virtually unlimited fuel resources and without the emission of environmentally damaging gases. Fusion research is undertaken in many countries around the world, with much of it in Europe, co-ordinated by EURATOM. This report summarises research between April 2007 and March 2008 by the EURATOM/UKAEA Association at the Culham Science Centre in England (http://www.fusion.org.uk). This research is jointly funded by EURATOM and the UK Engineering and Physical Sciences Research Council (EPSRC). UKAEA also has a contract from EURATOM to operate the world's leading fusion research facility, the Joint European Torus (JET, also sited at Culham, http://www.jet.efda.org), for a collective programme of experiments by Task Forces of scientists from all EURATOM fusion Associations. The JET programme is managed as part of the European Fusion Development Agreement (EFDA).

During the year, the team to build the multi-billion Euro international ITER experiment in Cadarache, France, has been assembled and a pre-construction design review held. ITER will mainly be procured by 'Domestic Agencies' in the seven parties; Europe[1] will provide the most components and its Agency, known as 'Fusion for Energy' or 'F4E', was established in Barcelona in June. A main focus of the EURATOM/UKAEA programme is dedicated experiments and design of specialist equipment for ITER.

In this Executive Summary each section corresponds to a chapter of the main report:

Chapter 2	General Introduction
Chapter 3	UKAEA's role in the JET science programme
Chapter 4	UKAEA's role operating JET
Chapter 5	The MAST spherical tokamak, the centrepiece of the EURATOM/UKAEA programme.
Chapter 6	Theory and Modelling of fusion plasmas
Chapter 7	Materials and Technology research
Chapter 8	Contributions to the design of specialist heating and measurement systems for ITER
Chapter 9	Industry Liaison

Chapter 10 contains a glossary of technical terms and Chapter 11 lists publications by the Association that appeared in print in 2007/08.

1.2 FUSION ENERGY RESEARCH

In fusion reactions, nuclei of light atoms fuse together at high temperatures to create nuclei of heavier atoms and neutrons; these reaction products are much more energetic than the reactants. Tapping into this energy source offers the prospect of a long-term, large-scale safe way to generate electricity to help meet

---

[1] The other ITER partners are China, India, Japan, the Russian Federation, South Korea and the US.

the energy needs of a growing and developing world population without the emission of greenhouse gases.

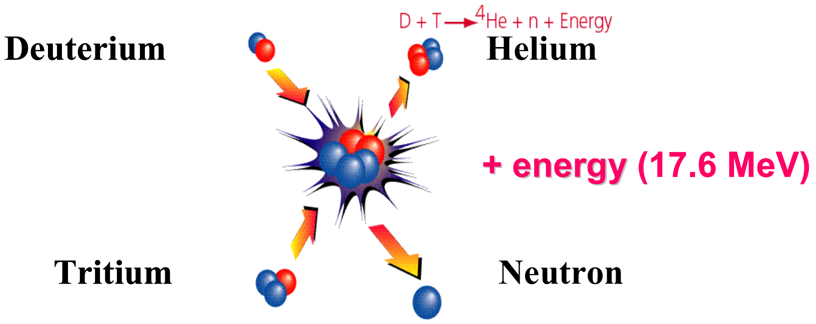

Figure 1.1: *Schematic of the deuterium - tritium fusion reaction*

The easiest fusion reaction to initiate is between deuterium and tritium (‘heavy’ and ‘super-heavy’ hydrogen – Figure 1.1), which produce a helium nucleus (‘alpha-particle’) and a neutron. Deuterium can be extracted from water, and tritium could be made in a fusion power station from neutrons hitting lithium. As the energy released is about ten million times that from a chemical reaction, the amount of fuel required is correspondingly less; half a bath of water plus the lithium in one laptop battery would produce around 200,000 kiloWatt-hours of electricity – the same as 70 tonnes of coal, and equal to the UK’s per capita electricity consumption for 30 years.

On earth, temperatures of at least 100 million°C are required to give sufficient fusion reactions. This temperature is routinely achieved in JET by using magnetic fields to keep the very hot, low density, ionised gas (‘plasma’) from contact with material surfaces. (An alternative approach, *inertial fusion*, is the subject of a ‘keep in touch’ watching brief by the Association – see Section 2.5.) The most developed magnetic confinement system is the tokamak: JET and ITER are tokamaks and MAST, the experimental facility of the UKAEA programme, is a more compact version known as a ‘spherical tokamak’.

1.2.1 EUROPEAN AND UK RESEARCH

All European Union countries, plus Switzerland, collaborate in a single European research programme, co-ordinated by the European Commission acting for EURATOM.

The collective aspects of this programme are organised under the European Fusion Development Agreement (EFDA) and the new agency Fusion for Energy (F4E) in Barcelona. EFDA is responsible for the JET programme, co-ordination of fusion plasma physics, the development of emerging technology, and training. F4E is responsible for (a) the provision of equipment and staff to ITER, commissioning research, development and design from organisations like UKAEA on specialist technology for ITER (including heating systems and measurement devices known in fusion research as ‘diagnostics’), and (b) European contributions to the ‘Broader Approach’ projects with Japan (see below).

Figure 1.2: *The MAST tokamak (the vessel has 4m diameter and 4.4m height)*

The EURATOM/UKAEA Association contributes to all the key areas of study in tokamak plasma physics research, increasingly as part of EFDA co-ordinated programmes, through experiments on MAST (Chapter 5), participation in the JET research programme (Chapter 3), and fusion plasma theory and modelling (Chapter 6). These key areas are as follows.

- **Confinement:** Losses of energy and particles from the plasma must be minimised for an effective system – the confinement efficiency determines how large a system needs to be to produce more energy from fusion than is needed to keep the plasma hot.
- **Stability limits:** When the plasma current, pressure or density are raised too high the plasma can become unstable. Unless mitigating action is taken, plasma performance is degraded or control of the plasma is lost and plasma-facing equipment can be damaged.
- **Plasma exhaust:** The edge of the plasma must be sufficiently cool where it meets material surfaces to ensure that damage to these surfaces and pollution of the plasma by impurities are minimal. Very high transient heat loads must also be avoided.
- **Steady-state operation:** Ideally, a fusion power station would operate continuously (in ‘steady-state’) to avoid cyclic stresses and large energy storage systems. Research is conducted into advanced operating modes of the tokamak which might allow this.
- **Optimum configuration:** The JET/ITER-like tokamak is the most developed system, though other magnetic configurations have advantages including the spherical tokamak developed at Culham most recently on MAST. Non-tokamak systems, notably stellarators, are studied in some countries but not the UK.

As well as plasma physics research, there is a major activity worldwide on the technology and materials needed for ITER and fusion power stations. The UKAEA Association contributes to these areas, particularly to the development of specialist systems for ITER (Chapter 8), and to EFDA research on the characteristics of fusion power stations and on understanding how to choose or design materials used in a power station to minimise their deterioration when exposed to the highly energetic neutrons streaming from the burning plasma (Chapter 7).

The programme benefits from collaborations with many other research organisations including about twenty-five UK universities, most of the other EURATOM Associations (particularly as part of EFDA and F4E programmes), and fusion institutes in the rest of the world. In one such collaboration, UKAEA and EURATOM have donated the small, ITER-shaped tokamak COMPASS-D to the Czech fusion Association.

Figure 1.3: *The COMPASS-D tokamak at the start of its journey from Culham to Prague, September 2007*

1.2.2 ITER, THE BROADER APPROACH AND IFMIF

In ITER (http://www.iter.org/), scientists will study plasmas in conditions similar to those expected in an electricity-generating power station. The machine is designed to produce plasmas of volume ~1,000m^3, with temperatures exceeding 100 million^{o}C, conditions which should result in around 500 MW of fusion power being released, ten times greater than the energy input needed to keep the plasma hot. Key technologies for fusion power stations will be tested, including superconducting coils, the blankets surrounding the plasma which will breed tritium and absorb the neutrons' energy, heating and current drive systems and remote maintenance.

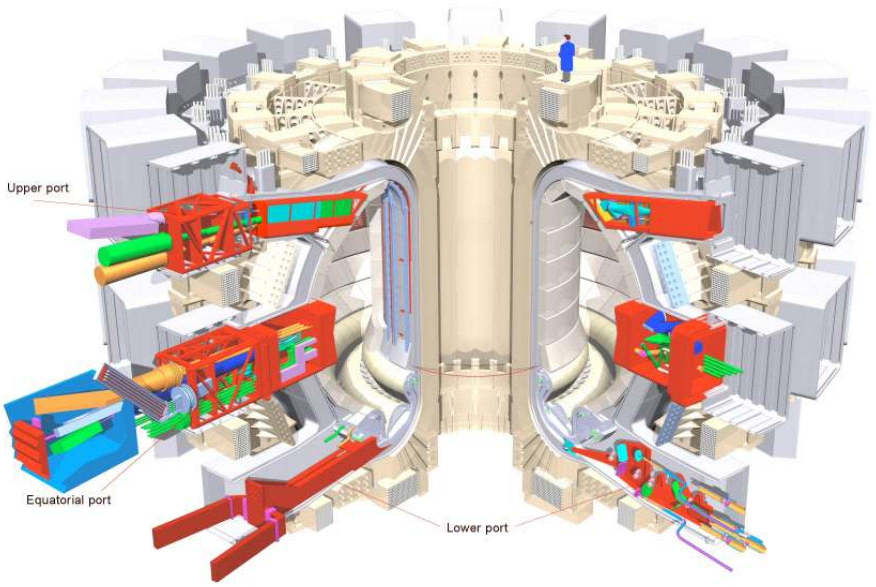

Figure 1.4: *The ITER design – the size is shown by the person at the top*

As part of the ITER site decision, it was agreed that Europe and Japan will take forward ‘Broader Approach’ projects, for example a new large, superconducting tokamak in Japan (JT-60SA), completion of the design of the International Fusion Materials Irradiation Facility (IFMIF), and a centre in northern Japan to house supercomputers and work on a demonstration power station to follow ITER (DEMO). European contributions to the Broader Approach will largely be voluntary contributions from France, Germany, Italy, Spain and Switzerland.

IFMIF is the main facility other than ITER that is needed before a demonstration, electricity-generating power station can be built. Its purpose is to test samples of candidate materials for power stations under sustained bombardment by neutrons with similar energies to those produced in fusion reactions, to ascertain how long they maintain their un-irradiated mechanical properties.

In the so-called ‘fast track’ approach to fusion development, which is increasingly favoured internationally, ITER and IFMIF would operate in parallel and a subsequent demonstration power station could be providing electricity to the grid within thirty years. UKAEA and EFDA are also investigating facilities that would help reduce remaining risks, such as a Component Test Facility.

1.2.3 PUBLIC UNDERSTANDING AND EDUCATION OUTREACH

The Association has a strong programme of public information and education, some of which is undertaken under Host Support for the EFDA JET programme at Culham. In any one year there are many visits from VIPs, several hundred members of the public (most during the half a dozen Open Evenings held each year), schools and universities, professional institutions, etc. UKAEA staff also give talks and demonstrations away from Culham, particularly at schools and science festivals, including this year at the British Association for the Advancement of Science meeting in York. During the year a number of television and radio production companies have visited, not only from the UK but also from other European countries and from as far afield as South Korea.

Figure 1.5: *The House of Lords Select Committee on Science and Technology visiting the MAST experiment at Culham. Other VIP visitors in the year included the then Science Minister Malcolm Wicks MP*

A particularly focus in recent years has been schoolchildren, where the aim is to encourage them to consider careers in science and technology in general, and fusion in particular. This has been the first full year of use of our new ‘Sun Dome’ facility (funded by a special EPSRC grant and EURATOM). Over 2,500 children, generally aged around ten, have had presentations in the sun-dome, mainly in the UK but also in Germany and the US. It is intended to increase the number of presentation videos that are projected inside the dome to include ones designed for older children.

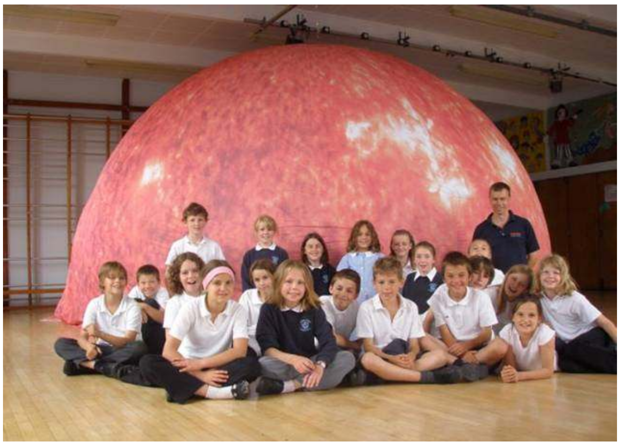

Figure 1.6: *Schoolchildren in front of the Sun Dome, with Chris Warrick of UKAEA at the back right*

1.2.4 TRAINING

The fusion programme needs a steady input of ‘new blood’, both to replace departing scientists, engineers and technicians and to be able to adapt to changing priorities and emphases in the programme. In recent years our range of training schemes has expanded and as well as long-established activities such as the annual two-week Culham Plasma Physics Summer School for post-graduates, we now have an apprentice scheme, five Culham Fusion Research post-doctoral Fellows and a training programme for new graduates, as well as over 40 PhD students from nearly twenty universities working with us on fusion research at any one time. UKAEA participates in two EURATOM Fusion Training Schemes, on engineering aspects of plasma diagnostics and radio-frequency (ICRF) heating.

Figure 1.7: *Some of the participants, lecturers and organisers of the 44th Culham Plasma Physics Summer School, July 2007*

1.2.5 INDEPENDENT REVIEWS OF THE PROGRAMME

The Association programme is mainly funded by the UK Engineering and Physical Sciences Research Council. EPSRC has a Fusion Advisory Board (FAB), which meets twice a year to advise on the strategic direction of the programme (FAB is supplemented by a MAST Programme Advisory Committee and a forum on materials research). Typically every two years a major review is held, and one was undertaken in autumn 2007 by a panel comprising some of the members of FAB and other UK and international experts under the chairmanship of a member of EPSRC's Council. The Review was broadly very complimentary about the programme, supported the need for a major upgrade of MAST (see below) and, *inter alia*, agreed with UKAEA‘s proposal that it was timely to grow a major fusion technology programme at Culham. While at the moment there is insufficient funding to both take forward the upgrade and make a strong start on growing a technology programme, longer-term plans that incorporate both are in preparation. EPSRC has subsequently agreed that the upgrade of MAST should proceed, probably in stages determined by the availability of funding, provided that it is supported by the EURATOM fusion programme.

During 2008, an independent panel is reviewing the facilities needed to develop fusion power, to inform decisions about the European programme in the coming years. The panel comprises non-fusion members from Europe, and fusion experts from outside Europe. As well as ITER and IFMIF, a range of plasma and technology facilities are likely to be required; many will be existing facilities, perhaps upgraded, while there will be a need for some new facilities. The UKAEA Association has proposed a major upgrade to MAST to (a) strengthen its contributions to ITER and DEMO physics, and (b) determine, from a plasma physics standpoint, whether the spherical tokamak would be a feasible basis for a Component Test Facility (CTF), a machine that could test whole power station components in a proper fusion environment. If, after, the Facilities Review, it is clear that an upgrade to MAST is needed, then UKAEA intends to make a detailed proposal for consideration by EFDA. More information on the aims and scope of the upgrade are given in Chapter 5.

1.3 JET STUDIES

The collective use of the JET facilities is the responsibility of the EFDA Associate Leader for JET, Dr. Francesco Romanelli. The JET research programme is carried out by Task Forces of visiting scientists from the Associations, including UKAEA (in addition, some UK university staff and students participate via UKAEA). During the year JET was closed for improvements – see Section 1.4 – and research therefore concentrated on analysis of previous experiments and preparation of the 2008 campaigns; some of the main contributions by UKAEA scientists are summarised in this section.

A main thrust of the JET programme is refining and understanding plasma operation regimes for ITER, especially the high confinement 'H-mode', and also more advanced regimes that have the potential for continuous operation which would be advantageous in a power station. Progress has been made in a number of areas, including unravelling the dynamics of the L-to-H mode (low-to-high confinement) transition, and demonstrating how advanced regimes become less stable if the current is distributed too far away from the centre of the plasma.

JET has two heating and current drive methods that use electromagnetic waves in very different frequency ranges; Lower Hybrid and Ion Cyclotron Resonance Heating. Both rely on coupling wave energy via an antenna close to the plasma and in each the power transferred to the plasma is sensitive to the distance from the edge of the plasma and to its density. When both systems are used simultaneously, each can adversely affect the other's coupling efficiency. Use of both systems has been improved by controlled puffing of gas close to the LH antenna, to give record values of joint power input to the plasma. Of key importance for ITER is how to couple waves to H-mode plasmas with Edge Localised Mode (ELM) instabilities – the efficiency of ICR heating of these plasmas has been improved substantially using gas puffing techniques.

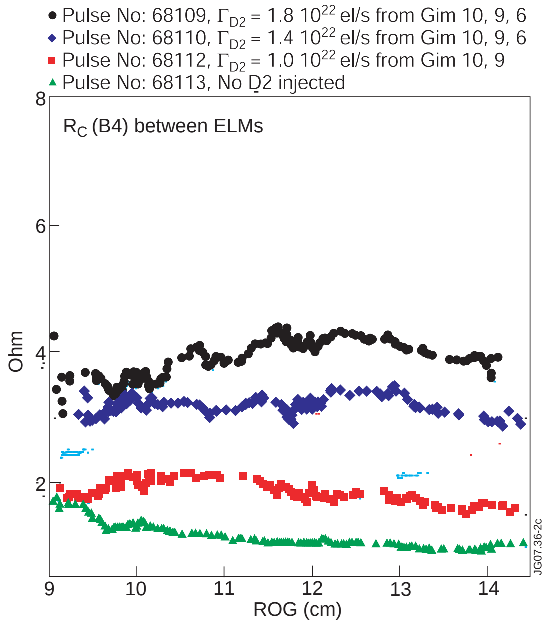

***Figure 1.8:** Improvement (i.e. a rise) in the ICRH antenna coupling resistance on JET by injection of deuterium gas*

UKAEA scientists have contributed to other studies on topics such as: plasma stability, including control of instabilities such as 'sawtooth' and ELMs; understanding the edge transport barrier in H-mode plasmas (through joint experiments with other tokamaks including Alcator C-Mod in the US); plasma-wall interactions including erosion of and deposition on tiles; and fast ion physics.

The UKAEA Association has also been involved in several projects in the two major JET Enhancement programmes (‘EP1’ and ‘EP2’). The EP1 projects are now largely complete (see next section for the installation of the largest of these, the ITER-like ICRH antenna). The EP2 projects are ongoing, for installation in 2009/10. The largest being undertaken as an Association project is managed by UKAEA; the Neutral Beam Heating upgrade. During the year, major progress has been made, with the ‘PINI’ injector sources upgraded, new power supplies delivered to new buildings, and much of the necessary electrical infrastructure installed. Part of the project involves upgrading the two beam-lines have been upgraded to handle higher powers – see Figure 1.8.

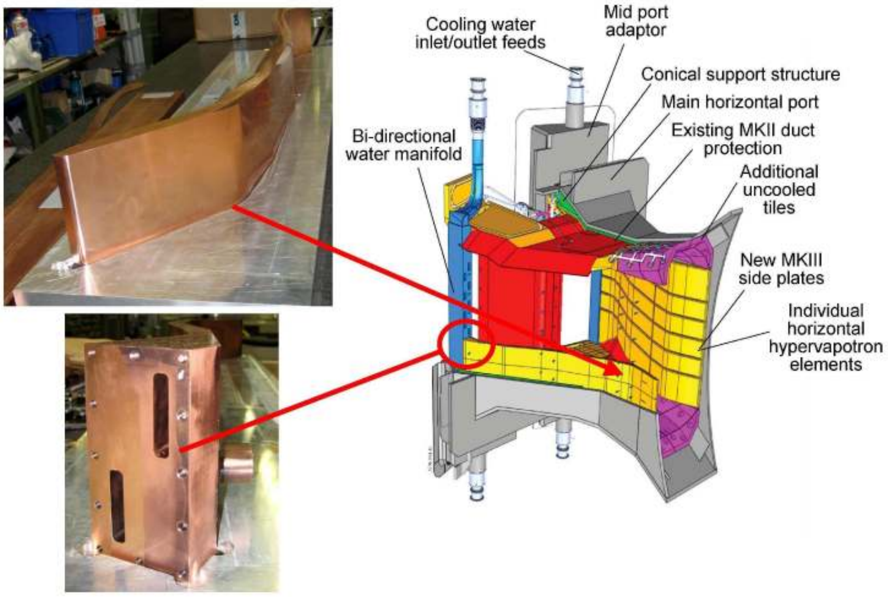

Figure 1.9: *Part of the JET EP2 neutral beam upgrade project: schematic diagram of the new duct protection and photographs of one of the horizontal actively cooled elements, ready for e-beam welding onto the vertical manifold section*

1.4 JET OPERATIONS

UKAEA has been responsible for the operation and safety of the JET facilities since January 2000 under the European Fusion Development Agreement (EFDA) via the JET Operation Contract between the European Commission and UKAEA. During 2007 JET was not operating, to enable the remaining tasks of the first JET Enhanced Performance programme (‘EP1’) to be completed. The initial activities of the second EP programme, EP2, were also undertaken. In addition extensive maintenance and refurbishment activities were performed. The machine including its new systems was then re-commissioned to allow experiments to resume in April 2008.

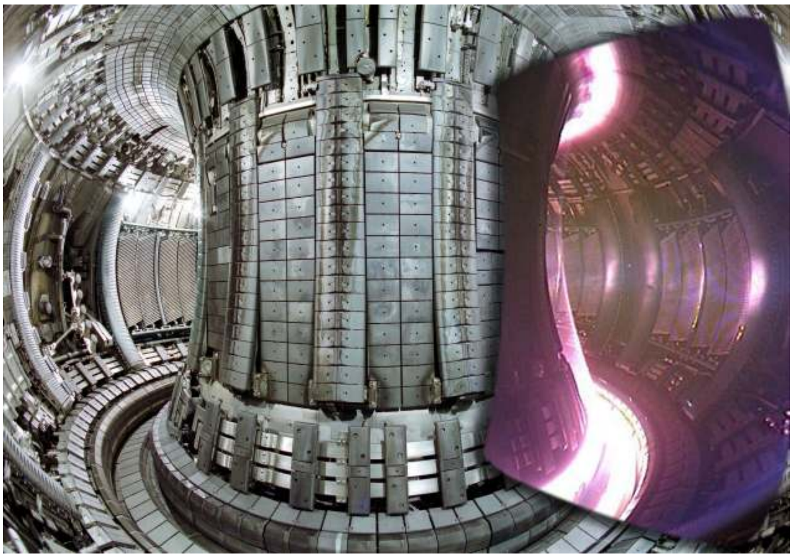

Figure 1.10: *Picture of the inside of the JET torus with a picture of the plasma superimposed on the right-hand side*

A list of the major installations in the 2007 shutdown is given in Chapter 4. These included the EP1 ITER-like Ion Cyclotron Resonance Heating antenna, a range of diagnostics (both new systems and changes to existing ones), a new High Frequency Pellet Injector to mitigate ELM instabilities and for deep fuelling studies, and preparations for the two largest EP2 projects, the ITER-like Wall (see below) and the Neutral Beam heating upgrade.

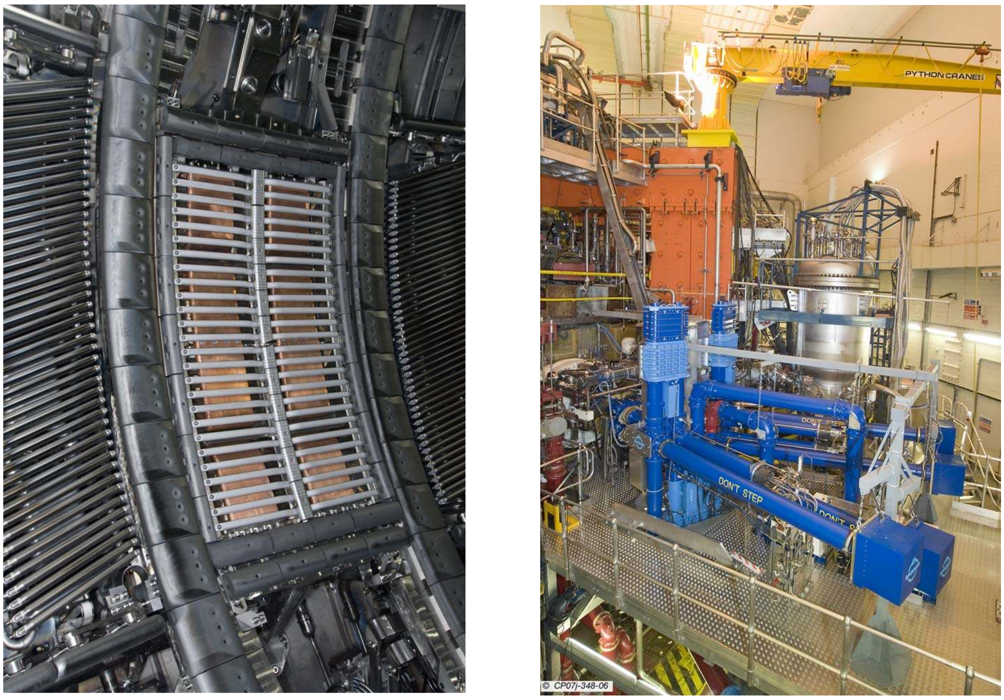

Figure 1.11: *The ITER-like ICRH antenna inside the JET torus, and its blue transmission line assembly outside the torus at Octant 2*

A wide range of maintenance activities was undertaken, the most major of which included repair of a water leak in the very large Centre Support Column of one of the two Neutral Beam Heating (NBH) systems, installation of new pumps and a new Rotary High Vacuum Valve for the NBH, replacement of a major motor in the plant used to heat the JET vessel to its operating temperature of up to 320°C, and repairs/maintenance to major systems including the site cooling water and electrical circuit breakers and switchgear.

After the shut-down, the process of restarting JET began at the end of November. After some minor problems of the type normally encountered in restart after a major shutdown, the vessel was baked and the vessel conditioned using Glow Discharge Cleaning. Good vacuum conditions were rapidly achieved allowing operation at high plasma density within two weeks of first plasma. As well as the tokamak, the main auxiliary systems including the ICRH and NBH, the new Pellet Injector and the many diagnostics were commissioned, although in some cases not yet to full operational performance.

Most of the EP2 projects are (until the installation phase) the responsibility of Associations under EFDA co-ordination (UKAEA is responsible for the NBH upgrade and a number of smaller projects). The exception is the **ITER-like Wall project**, most of which UKAEA undertakes as part of the JET Operation Contract. Its objective is to install in JET a beryllium wall and tungsten divertor, as these materials are expected to erode less and trap less tritium than the carbon used at present. The project involves a total of around 80,000 parts and the replacement of the present around 5,000 Carbon-Fibre-Composite tiles. The new materials require more complex tile designs than the CFC, which complicates their manufacture and installation. The latter is to be done with remote handling, and an additional RH boom will be used, otherwise the installation time would be unacceptably long. The RH installation, due to start in 2009, has to be planned in detail using virtual reality simulations.

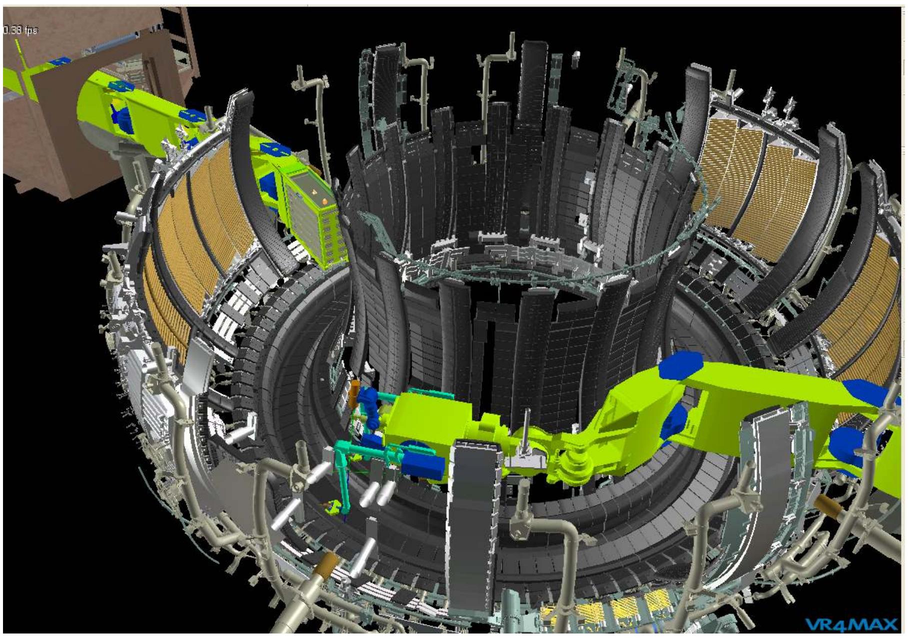

Figure 1.12 *Virtual reality simulation of remote handling, showing the new extended JET boom (on the left, in green) bringing a package of tiles and tools into the torus for delivery to the Mascot manipulator, shown at the end of the right hand boom (also green)*

1.5 MAST

MAST is, with NSTX a complementary experiment at Princeton, one of the world’s two leading spherical tokamaks (STs). In STs, the centre column through the middle of the toroidal plasma is much narrower than in other tokamaks like JET, meaning that plasmas resemble a cored apple rather than a doughnut. Experiments on MAST are important for two reasons. Firstly, they test ITER physics in new regimes, thereby providing exacting tests of plasma theories and scalings. Secondly, they help determine the long-term potential of the ST, which may eventually be suitable as the basis for a power station and, nearer-term, may be suitable for a compact Component Test Facility (CTF), which could reduce risk and potentially accelerate the development of commercial fusion power. Many experiments on MAST are collaborative: with UK universities; with other EURATOM Associations; and with non-European fusion laboratories. Several are joint experiments with other tokamaks usually under the auspices of International Tokamak Physics Activities (ITPA) expert groups.

For much of 2007/08 MAST was shut-down for improvements to the tokamak and its auxiliary systems. The most important of these were:

- the second neutral beam heating system has been upgraded to have an improved JET-like ‘PINI’ injector;
- an array (2x6) of internal coils has been installed to study control of ELMs (Edge Localised Modes, of concern for ITER) and ‘TAE’ fast particle instabilities;
- control and data acquisition systems have been upgraded;
- a divertor science facility has been installed to allow tests of plasma-material interactions;
- the MAST control room has been refurbished and remote participation facilities installed for the benefit of our increasing number of collaborating scientists.

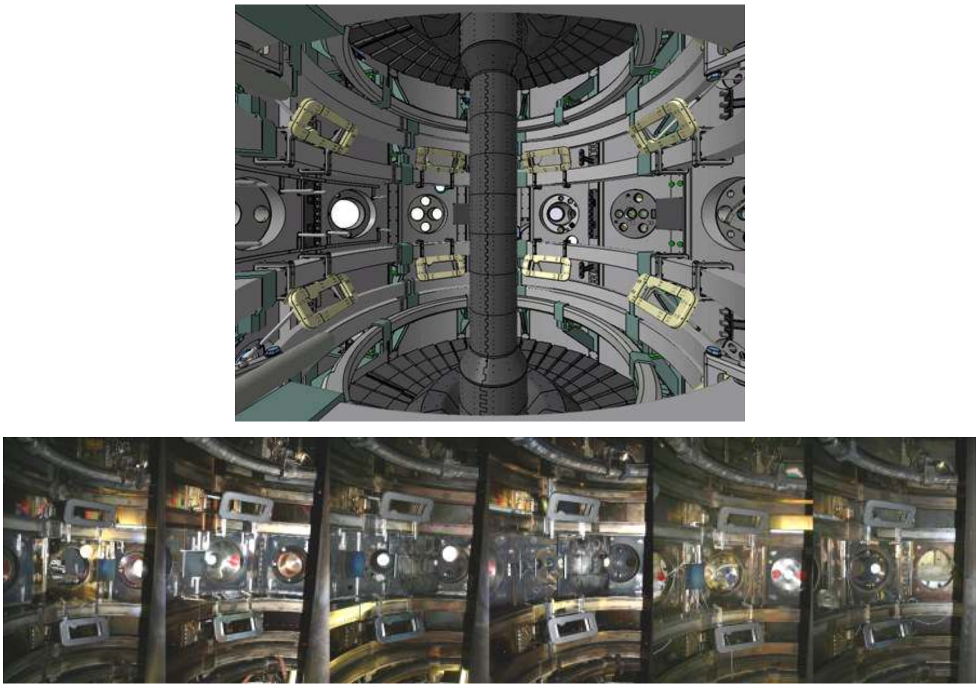

Figure 1.13: *The 12 ELM control coils installed in MAST in 2007: schematic (above) and composite of photographs of the coils*

Several diagnostics have had major improvements. In particular the number of lasers has been doubled in our world-leading Thomson Scattering system that measures the detailed spatial dependence of electron density and temperature (this project, which is ongoing, is partly funded by the University of York). Following tests of a prototype system, our Motional Stark Effect diagnostic that is used to deduce the distribution of current across the plasma, has been upgraded to a multi-chord system. Other diagnostic developments have involved collaborations with HAS (Hungary) and IPP Greifswald (Germany).

In 2007/08, the MAST research programme made good progress in several areas of importance for ITER and/or STs, namely: energy confinement scaling with plasma current and magnetic field; particle transport and fuelling by pellet injection; the characteristics of ELMs and their effects on the plasma; the structure of the temperature and density 'pedestals' at the edge of H-mode plasmas, and instabilities in this region; plasma-wall interactions; instabilities associated with having significant fast particle populations present; and current drive methods that do not use solenoid action (Electron Bernstein Waves for plasma start-up and off-axis Neutral Beam current drive). The results of all these experiments are reported in Chapter 5; two highlights are now summarised.

The transition of the plasma to a high confinement H-mode regime is accompanied by a sharp increase in the plasma pressure at the edge, forming a pedestal which periodically weakens when edge instabilities ELMs occur. As described in previous reports, the excellent imaging and other diagnostics on MAST have led to it being a world-leading facility for studying both the pedestal and the ELMs. In 2007/08 studies have continued, with a focus on small ELM regimes, which are attractive as these ELMs might not give unacceptable heat loads on plasma-facing materials in machines like ITER. Fast camera images reveal that small ELMs have a much more complicated filament structure than large ELMs. The pedestal conditions that give rise to small ELMs have been investigated. Generally small ELMs do not occur at high pedestal temperature, low pedestal density but recently a new regime with small ELMs has been accessed under such conditions.

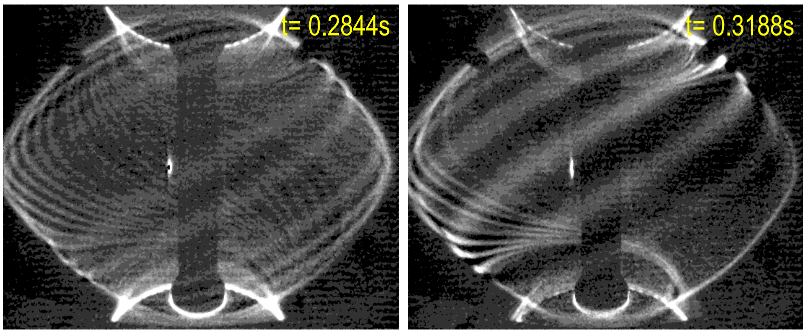

Figure 1.14: *Filament structure of a small ELM (left) and a large ELM (right)*

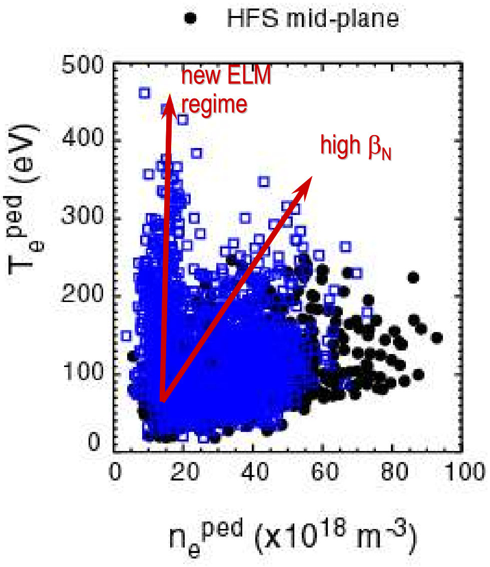

Figure 1.15: *Pedestal temperature versus pedestal density for MAST ELMy H-modes showing the new small ELM regime at high pedestal temperature and low pedestal density (low collisionality)*

In the spherical tokamak, plasma densities comparable to those in other tokamaks are achieved with lower magnetic field. The low field means that the Alfvén speed (the magnetic sound speed, which is proportional to the field) is less than the speed of the ions that are created in the plasma when fast neutrals are injected in Neutral Beam heating. This is analogous to the case in ITER, when the alpha-particles (i.e. helium nuclei) created from fusion reactions will move faster than the Alfvén speed. MAST is therefore an important experiment for studying the effects of 'super-Alfvénic' ions, which can interact with the plasma to give a range of fast ion, Alfvénic modes, some of which may degrade plasma performance. The spectra of these modes can also be investigated using coils inside MAST. An analysis of the plasma response to perturbations applied up to 500 kHz with three trial coils revealed modes in the 'Toroidal' and 'Ellipticity'-induced classes of Alfvénic instability, and calculated their damping rates. Further studies will be undertaken with the new ELM/TAE coils installed in 2007/08, as well as with Neutral Beam Heating to create fast ion populations.

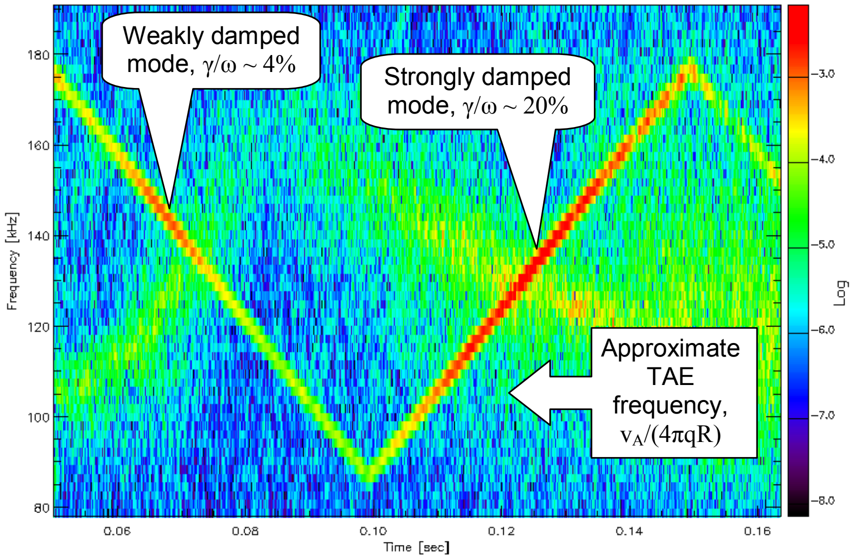

Figure 1.16: *Coils in MAST have been used to stimulate Alfven Eigenmodes at different frequencies*

The improvements to MAST outlined above mean that experiments in the coming two to three years will benefit from an advanced set of diagnostics and more reliable heating power. However, for the longer term, a major upgrade of MAST is needed to allow scientists to study high performance, longer pulse plasmas, both for ITER and for the development of the ST towards a CTF. The design of such an upgrade is now well advanced. The Upgrade has been supported in principle by Culham's Fusion Advisory Board, and the UK component for funding a substantial part of the Upgrade has been agreed. If, after the 2008 Facilities Review, it is clear that an upgrade to MAST is needed, UKAEA will put forward a detailed proposal for preferential support to EFDA in early 2009 and if the project is approved it will then be implemented, probably in stages, in the following years. The main features of the Upgrade are: a more than doubling of neutral beam heating power to over 10 MW; an improved centre column and central solenoid, allowing higher magnetic field and more volt-seconds capability to sustain the plasma current; pulse lengths around five seconds, long enough to test regimes in which the plasma has reached steady-state; a new 'Poloidal Field' coil system to give better plasma shaping and control and a range of divertor configurations; and better control of plasma conditions including cryo-pumping for density control.

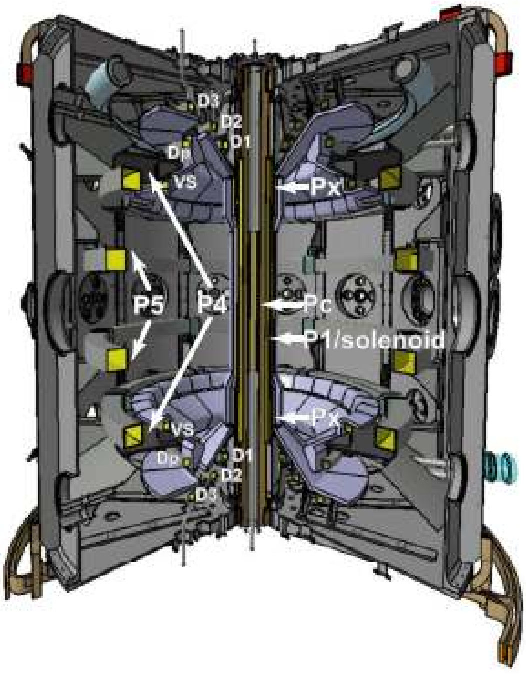

Figure 1.17: *Proposed layout of coils in the MAST vessel following the upgrade*

1.6 THEORY AND MODELLING

The purpose of this programme is to use analytic theory and sophisticated computer codes to support the tokamak experiments, and to make reliable predictions of the performance of future fusion devices, such as ITER, a spherical tokamak Component Test Facility and a demonstration power station. The models developed are tested where possible by comparisons with data from MAST, JET and other tokamaks. Parallel computing facilities at Culham and EPSRC (and in the future European and international) supercomputers are used for some simulations, many of which are undertaken in collaboration with universities and with other fusion Associations as part of EFDA's Integrated Tokamak Modelling Task Force.

The programme covers many of the key topics in fusion plasma physics; confinement physics, especially the turbulence that is largely responsible for energy transport; plasma instabilities – what causes them and how they can be tamed to allow controlled, high performance plasmas; the physics of fast particles (as alpha-particles will be important in burning plasma devices); and integrated scenarios with the potential for continuous ('steady-state') operation. Many examples of work undertaken in the year are reported in Chapter 6; this section only has room for two examples.

Different codes are used to study different aspects of turbulent transport. Codes which resolve very fine details of the underlying physics can only simulate relatively small parts of the plasma, as otherwise the computing requirements would be prohibitive. On the other hand, codes with a more 'broad-brush' treatment can simulate the whole plasma. For example, using EPSRC's HECTOR supercomputer in Edinburgh, we have used the gyrokinetic code GS2 to make an initial study of how the spatial variation ('shear') of plasma flow affects the turbulence in a small region of the MAST plasma. It is found that the flow shear can break up turbulent structures thus aiding the formation of good confinement regions in the plasma and reducing the radial loss of heat from the plasma core.

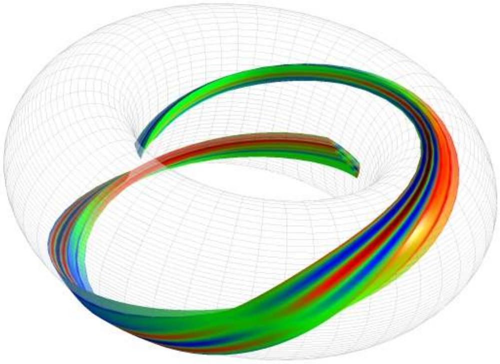

Figure 1.18: *Plot showing electrostatic potential perturbations predicted by the GS2 code used to simulate a narrow region ('flux tube') of the MAST plasma*

A plasma instability currently of significant concern is the ELM (Edge Localised Mode) as it could result in unacceptably high heat loads on plasma facing materials. The trigger for ELMs is thought to be the 'peeling-ballooning' instability, the theory of which has been developed by UKAEA with collaborators, especially the University of York. However, recent code calculations had suggested that this instability should be stabilised in many tokamak plasmas due to the influence of the 'X-point' in the divertor region of the boundary of the plasma. A theoretical technique has been used to treat this complicated plasma boundary shape. The results both confirm and explain the modelling predictions, correctly predicting how the growth of the instability weakens as the shape of the boundary changes and approaches a true separatrix with an X-point.

1.7 MATERIALS AND TECHNOLOGY

UKAEA participates in EFDA programmes on the development of materials suitable for attractive fusion power stations, the conceptual design of these power stations (most recently a DEMOnstration plant), and analyses of their socio-economic, environmental and safety attributes.

In recent years, UKAEA with major contributions from UK universities, has established a world-leading modelling programme that addresses how materials properties are affected by bombardment from fusion plasmas. The ab-initio modelling reported in previous years is now being incorporated in million-atom simulations elucidating materials physics at a larger scale. This along with other work, including experimental studies at Oxford University, has led to major advances in several areas including: understanding the magnetic origin of the loss of strength of structural steels at temperatures well below their melting points; elucidating the formation and migration of defects in body-centred cubic metals (the class of metals of most applicability to fusion); expansion of atomistic modelling to include electronic effects.

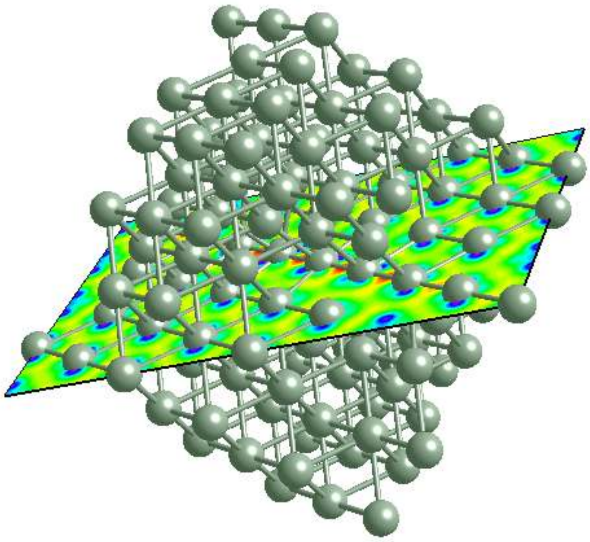

Figure 1.19: *A three-dimensional structure illustrating the approach used in ab-initio calculations. Positions of atoms define the distribution of the electronic "liquid" that in a self-consistent way drives atoms towards the structure corresponding to the minimum total energy of the system*

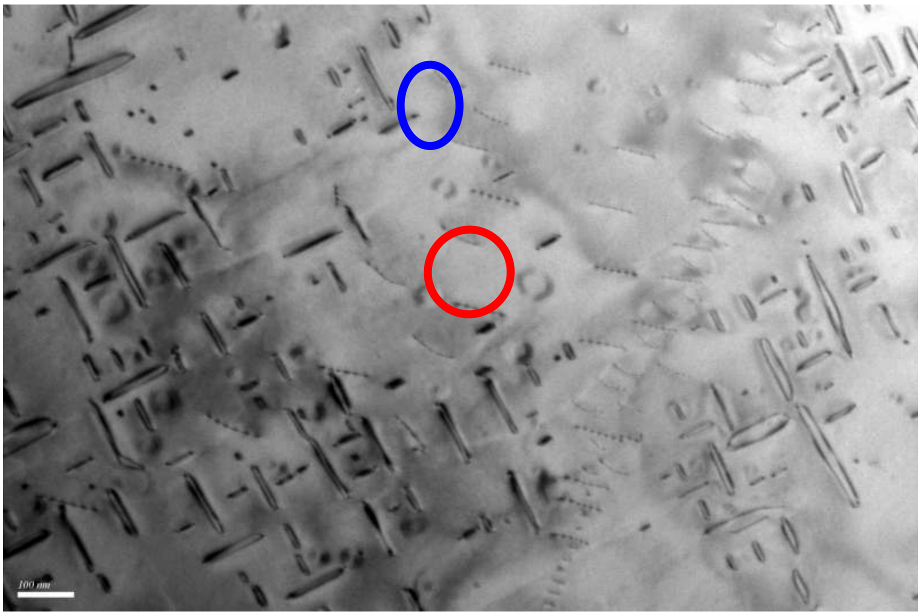

Figure 1.20: *Electron microscope image showing dislocation loops formed in pure iron under ion irradiation at 500°C. Images like these are used to help validate computational models of defect formation and migration. Work undertaken by Oxford University using facilities at Argonne National Laboratory, US*

In other work, UKAEA has revised its conceptual design of a spherical-tokamak-based Component Test Facility, produced an extensive Validation Report for the European Activation System (EASY) that we manage for EFDA and F4E, and contributed to EFDA studies of DEMO, including options for hydrogen production showing that substantial economies of scale might be achieved in combined electricity and hydrogen generating power stations.

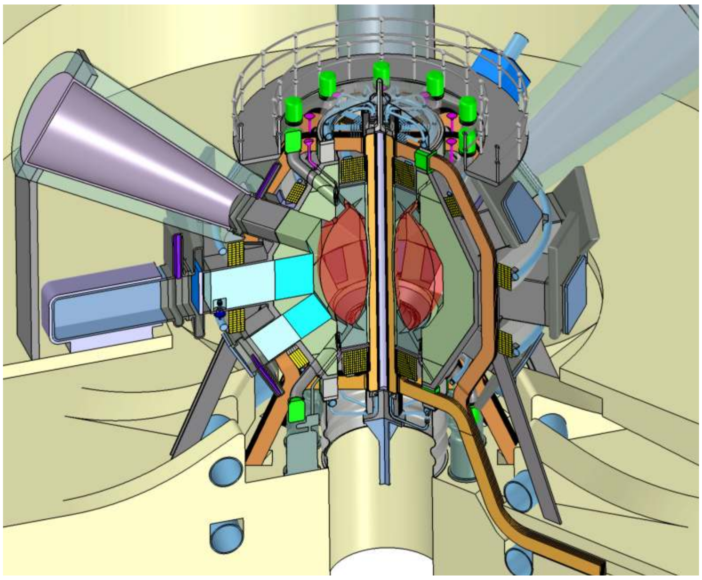

Figure 1.21: *3D view of a conceptual design of a Component Test Facility based on the spherical tokamak. The plasma is about the same size as the MAST plasma, though the magnetic field and current are much higher so that much higher performance can be achieved*

1.8 ITER SYSTEMS

ITER will need high performance heating systems and very effective and reliable plasma measurement instruments (‘diagnostics’). Each is the responsibility of one of the ITER parties, and more than one party is involved in the more complicated systems, including the heating systems. Europe is responsible for many and groupings of EURATOM fusion Associations are undertaking the R&D before the detailed design can be set; formal consortia agreements are expected to be signed in the coming year, as the R&D programmes expand and the detailed design stage approaches. Central management of this activity was the responsibility of EFDA but this has now been transferred to F4E. UKAEA has substantial roles in three systems:

- **core LIDAR Thomson scattering** (UKAEA leads, with contributions from six other Associations). Back-scattering from the plasma of a laser pulse is measured to give the spatial variation (‘profiles’) of electron temperature and density across the plasma. There is now an outline design of a system that appears to meet the performance requirements. There are a number of areas that need further attention as several components are at the limits of existing technology. Recent activity has focused on the technical aspects of the system and on generating the structure of a project to build and deliver the complete system to ITER. There is now almost enough information for a full end-to-end conceptual design to be assembled and reviewed. Most of the ingredients for a planning and costing exercise have been assembled and some preliminary estimates have been generated;

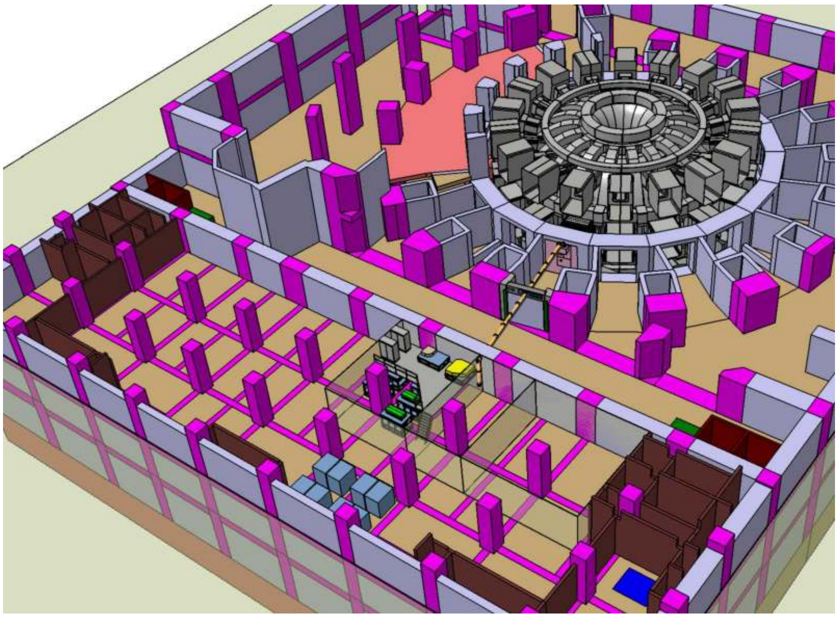

Figure 1.22: *Location of major components of the LIDAR system in relation to the tokamak and diagnostic room*

- **the Ion Cyclotron Resonance Heating antenna** (a Belgian, French, UK grouping), building on work done for the ITER-like antenna recently installed on JET (Section 1.4). It is expected that UKAEA will lead this consortium. The Belgian-UK ex-vessel design has now been adopted (Figure 1.23) and work has been undertaken on more detailed aspects including optimum layout, ‘maintainability’ (making the most vulnerable components easily replaceable), reduction in weight, improvements to the RF window design, and more detailed neutronics modelling;

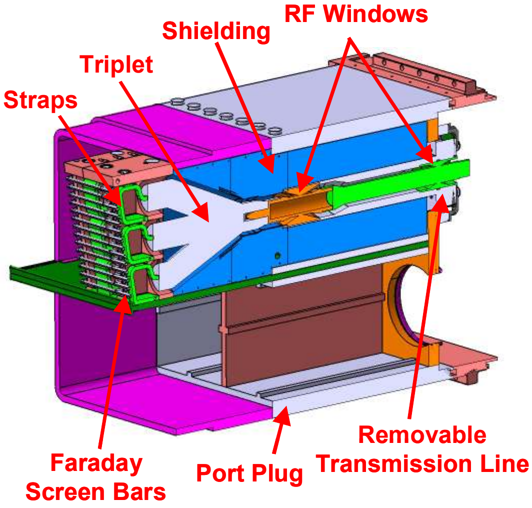

Figure 1.23: *2007 ICRH antenna design*

- **the Neutral Beam Injection system**, most of which is a European responsibility (Italy, UK, Germany, France and Spain). UKAEA has completed the detailed design for the neutraliser and its electron dumps, assessed the operating conditions for the Electrostatic Residual Ion Dump (showing these are acceptable for the heating beam but not the diagnostic beam) and produced a design for an alternative Magnetic Residual Ion Dump (MRID) which is combined with the NBI calorimeter (Figure 1.24).

With Swiss and UK companies UKAEA has developed concepts for the NBI system for an absolute valve (Figure 1.25) and for remote handling maintenance respectively. UKAEA has also undertaken an urgent ITER engineering and physics evaluation and design task on the Neutral Beam duct and liner protection, deploying expertise gained from the operation and enhancement of the JET NB Injectors;

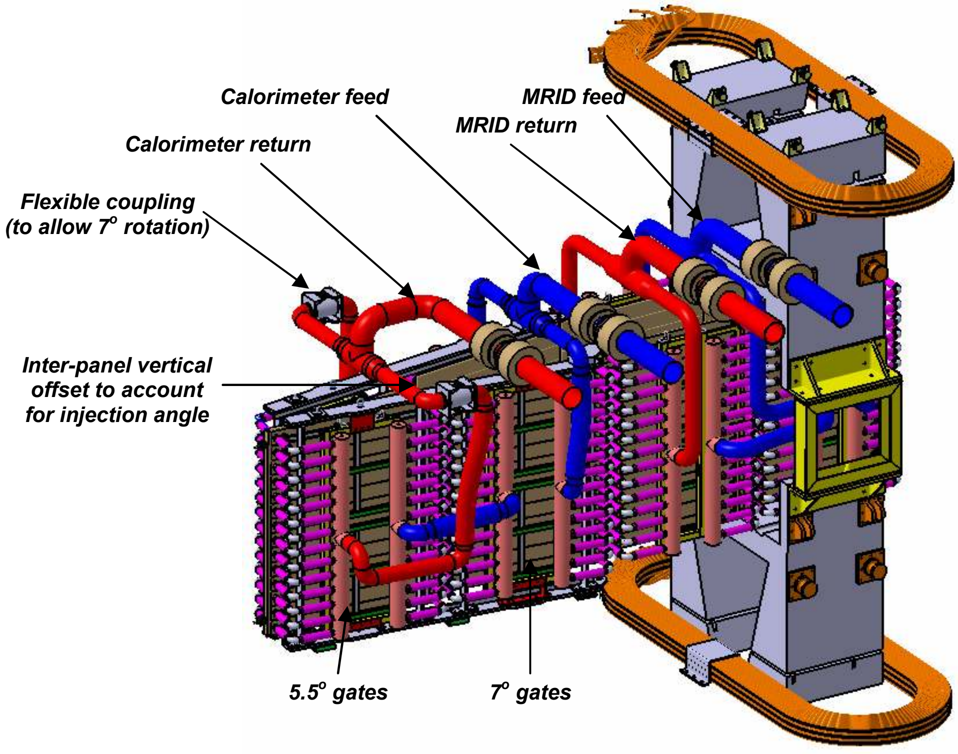

Figure 1.24: *Isometric view of an Alternative Combined MRID / Calorimeter Concept for the ITER Neutral Beam Injection system*

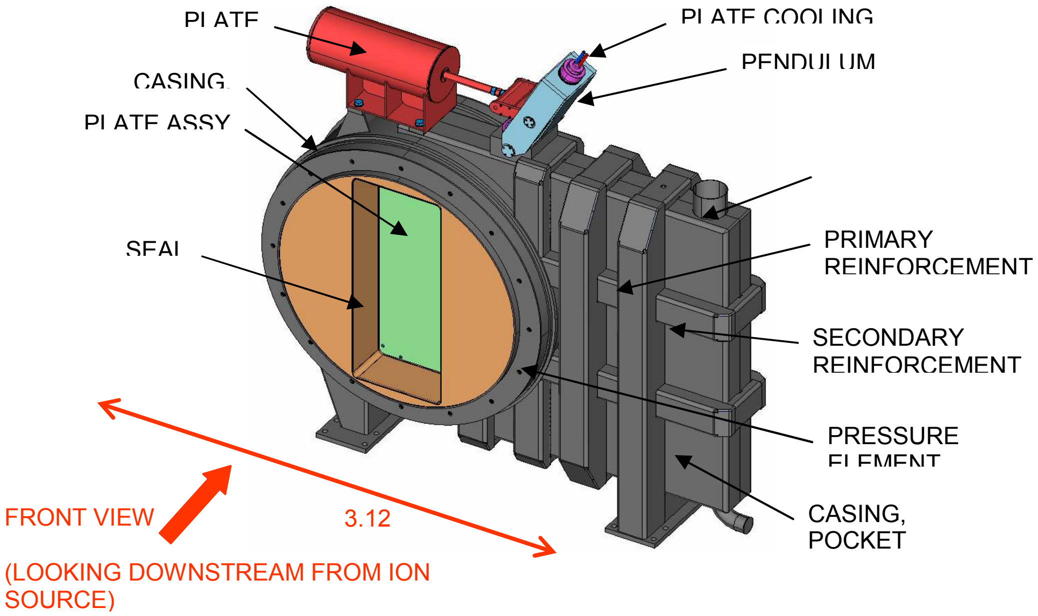

Figure 1.25: *General Assembly of NNBI Absolute Valve*

- jn addition, UKAEA has a modest, but pivotal, role in **Core Charge Exchange Recombination Spectroscopy** which will measure the ion temperature and rotational flow of the plasma, and the helium ash content (led by Dutch and German laboratories);
- UKAEA has also taken a leading role in the conceptual engineering design of the **diagnostic port plugs**. This has provided underlying support for our projects which involve installation in port plugs, such as the core LIDAR and ICRH antenna;
- other work for ITER has included development of specifications for **diagnostic windows**, assessing **vacuum vessel welding techniques** (by Cranfield University) and **characterising the properties of superconducting strand** for the ITER magnets (by Durham University);

1.9 INDUSTRY

Our industry liaison work has two main tasks: to encourage UK companies to bid for contracts from the international fusion programme, especially ITER; and to facilitate technology transfer from fusion to other markets. We have a website (www.fusion.org.uk/industry), electronic newsletter and database all dedicated to industry liaison. Some of our work is in conjunction with UK Government organisations including UK Trade & Investment (with whom we took a trade mission to visit F4E) and a Knowledge Transfer Network, part of the remit of which is to increase the involvement of UK industry in ‘big science’ projects at home and overseas, recognising that many technologies are common to fusion, particle physics, astronomy and neutron and synchrotron facilities. We also work with Industry Liaison Officers in other EURATOM Associations on facilitating pan-European consortia of high-tech companies that could bid for ITER contracts.

The number of companies on our database continues to grow, and many of these we have put forward for tender lists for JET and ITER contracts. Several UK companies won high-tech contracts for the JET EP2 enhancement programme, which were placed by the European Commission during the year. A number have also had ITER-related R&D contracts, and now that the project has commenced some are getting contracts from the construction project, from both ITER itself and the European agency F4E.

In June 2007, we held an event attended by 150 representatives from UK industry that focused on near-term ITER contract opportunities (civil engineering and long-lead time items i.e. the magnets and vacuum vessel) and on specialist system projects in which UKAEA is involved and would like the participation of industry. UKAEA also, with UKTI, took a delegation of UK industrialists to the major ITER Business Forum held in Nice, France, in December.

Fig 1.26: *Akko Maas from the ITER International Organisation describes ITER procurement to delegates at the ITER Event at Culham, June 2007*

On the technology transfer front our main activity is the Technical Support Package whereby start-up companies in the Culham Innovation Centre have access to specialist skills and equipment deployed on the fusion programme. Companies in markets including Magnetic Resonance Imaging, aerospace and battery development benefit from this assistance much of which concerns manufacturing techniques utilised in our specialist workshop.

1.10 FUTURE PLANS

The future programme will continue to focus on scientific and technological contributions to ITER and DEMO, spherical tokamaks, fusion power station concepts, and materials science.

For much of 2008/09, **JET** will operate, with experiments concentrating on commissioning and exploiting the new ITER-like ICRH antenna and on contributions to ITER on several key physics issues. UKAEA will play a full role in the Task Forces undertaking the experiments. Then a major shutdown is due to commence in the second half of 2009 for installation of the ITER-like Wall and other EP2 enhancements, including some led by UKAEA.

The **MAST** programme will continue to have two main focuses; tokamak science for ITER and developing the spherical tokamak concept. The major improvement to the Thomson Scattering system will be completed allowing improved spatial and temporal measurements of plasma density and temperature, improving a number of experiments, including instability and transport barrier studies. Operation with both neutral beam heating systems upgraded will now be possible. A priority in the programme will be use of the new coils to control ELMs as this is a key issue for ITER. It is intended that collaborations with universities and with other fusion Associations will continue to increase, and that MAST will participate fully in experiments co-ordinated by both EFDA and under ITPA auspices.

If, after, the Facilities Review, it is clear that an upgrade to MAST is needed, in early 2009 UKAEA intends to submit to EFDA a proposal for a major **upgrade to MAST** comprising a range of improvements to the facility's heating, magnetic field, shaping, exhaust, and control capabilities. These will allow higher plasma performance for longer, better controlled pulses, and be of great benefit to MAST experiments for both ITER and the development of the spherical tokamak towards a component test facility.

The **plasma theory** programme will continue its contributions to modelling ITER-like and spherical tokamaks. Collaborations with universities will increase, as will work with other Associations via EFDA mechanisms. The main topics for study will be turbulence calculations and other modelling of plasma transport, fast ion instabilities (where UKAEA has a particular strength), and large- and small-scale instabilities in the core and edge of the plasma. The programme will continue to have a close involvement in experimental programmes, particularly those on MAST and JET.

In **materials and technology** research, activities will continue to be undertaken within the framework of university, European and wider international collaborations. Work is expected to concentrate on the design of a demonstration power plant, conceptual design of a Component Test Facility, and neutronics and activation modelling of fusion systems. Our materials modelling programme will be extended to more complex alloys and phenomena, including investigating whether the loss of strength of structural steels at high temperatures can be mitigated by alloy design. Where possible we will take opportunities to expand our work on fusion technology, as supported by the review of the programme held by EPSRC in autumn 2007, if possible securing an involvement in Europe’s Test Blanket Module programme for eventual testing on ITER.

On **ITER** technology, it is expected that UKAEA will soon sign consortium agreements with other Associations in the main systems in which it is participating in the R&D; the LIDAR diagnostic and ICRF Antenna projects, which we expect to lead; the neutral beam system; and the Charge Exchange diagnostic. As the volume of work on these systems is expected to expand, other contributions, for example to port plug design, may need to reduce, but UKAEA will maintain a watching brief and be ready to undertake important engineering studies of limited duration where these activities help to reduce the technical risks associated with our core activities. The Port Plug engineering and Neutral Beam Remote Handling design are examples of areas where suitably-deployed effort could provide significant benefits. 2008/09 will be the first year in which the R&D is undertaken directly for the F4E agency in Barcelona, rather than for EFDA.

Finally, the programme will continue its **outreach activities**, both to industry where the emphasis will still be on encouraging the involvement of UK companies in work for ITER, and to the public and schools the latter using the Sun Dome facility which we intend to upgrade to be suitable for a wider range of ages.