1 Executive Summary

1.1 OVERVIEW

The objective of fusion research around the world is generation of electricity using as a heat source the process that powers the sun and other stars. There would be major advantages with such an energy option; virtually unlimited and widely available fuel resources and no emission of environmentally damaging gases. In Europe, the research is co-ordinated by EURATOM and comprises:

a) work in 'national' fusion programmes, via EURATOM Contracts of Association – including, for the UK, the EURATOM/UKAEA Association at the Culham Science Centre in England (http://www.fusion.org.uk). Many Associations have their own experiments; UKAEA's is called MAST (Mega Amp Spherical Tokamak);

b) collective activities within Europe managed by EFDA (the European Fusion Development Agreement, http://efda.org). By far the largest of these activities is the Joint European Torus (JET) at Culham (http://www.jet.efda.org). JET is presently the world's leading fusion research facility;

c) international collaborations, presently dominated by the ITER project (http://www.iter.org), construction of which has started in Cadarache in southern France. Along with EURATOM, the partners are China, Japan, India, the Russian Federation, South Korea and the US. ITER will mainly be procured by 'Domestic Agencies' in the seven parties; Europe's is in Barcelona and known as 'Fusion for Energy' (F4E, http://fusionforenergy.europa.eu). The aim of ITER is to produce energy from fusion on a power-plant-relevant scale (500 MW) and test key technologies needed for a power plant.

Research at Culham is jointly funded by EURATOM and the UK Engineering and Physical Sciences Research Council (EPSRC), which is guided in fusion matters by an independent Fusion Advisory Board. UKAEA also has a contract from EURATOM to operate JET, for a programme of experiments by Task Forces of scientists from all EURATOM fusion Associations (including UKAEA). This programme is managed by the EFDA Associate Leader for JET and his 'Close Support Unit', located at Culham.

This report covers the activities of the EURATOM/UKAEA Association in the period April 2008 to March 2009. In this Executive Summary each section corresponds to a chapter of the main report:

Chapter 2	General introduction
Chapter 3	UKAEA's role operating JET
Chapter 4	UKAEA's role in the JET science programme
Chapter 5	Results from MAST
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 lists publications by the Association that appeared in print in 2008/09 and Chapter 11 contains a glossary of technical terms.

1.2 INTRODUCTION

In fusion reactions, which only happen at high temperatures, nuclei of light atoms join together to create nuclei of heavier atoms and neutrons with much more energy than the original atoms. The deuterium-tritium reaction is easiest to initiate and is illustrated in Fig 1.1. This requires laboratory temperatures exceeding 100 million °C (conditions which are routinely reached in JET).

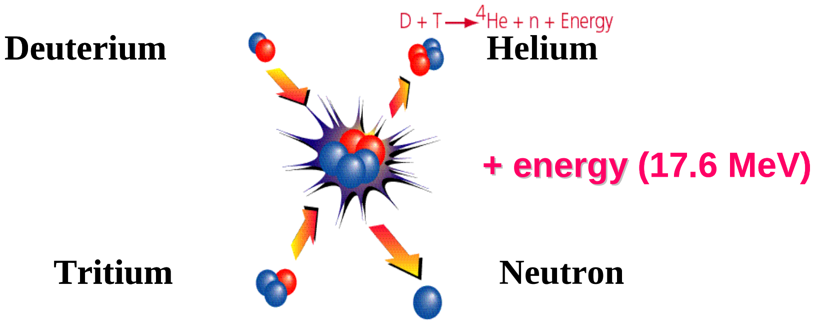

Figure 1.1: *Schematic of the deuterium - tritium fusion reaction which produces a helium nucleus (alpha particle) and a neutron. Deuterium and tritium are 'heavy' and 'super-heavy' hydrogen*

In the most developed approach to fusion, magnetic fields keep the very hot (but very low density) gas away from material surfaces (the gas is ionised and therefore a 'plasma'). There are different designs of this 'magnetic bottle'; the most developed is the 'tokamak' (JET, ITER and MAST are all tokamaks). In a fusion power station the helium from the fusion reaction would remain confined by the magnetic bottle and so keep the plasma hot, while the neutron – being neutral – would escape and be captured in a blanket surrounding the reacting plasma. This blanket would (a) get hot, and the heat would be used to generate electricity as in today's power stations, and (b) contain lithium, which would react with the neutron to create the tritium needed for the fuel. The other component of the fuel, deuterium, is easily extracted from water. 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 provide the fuel for around 200,000 kiloWatt-hours of electricity, equal to the UK's per capita electricity consumption for 30 years. 70 tonnes of fuel is required to produce this in coal-fired power stations.

In a different approach to fusion, *inertial fusion*, fuel is compressed very briefly to high densities. This approach is the subject of a 'keep in touch' watching brief by the Association via work at the Rutherford-Appleton Laboratory – see Section 2.5.

1.2.1 EUROPEAN AND UK RESEARCH

The collective aspects of the EURATOM fusion programme are managed by EFDA and the F4E agency. 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 other European contributions to ITER (including commissioning from organisations like UKAEA the R&D needed for specialist systems), and (b) European contributions to the 'Broader Approach' collaboration with Japan, that comprises fusion projects needed in addition to ITER (including IFMIF the planned International Fusion Materials Irradiation Facility).

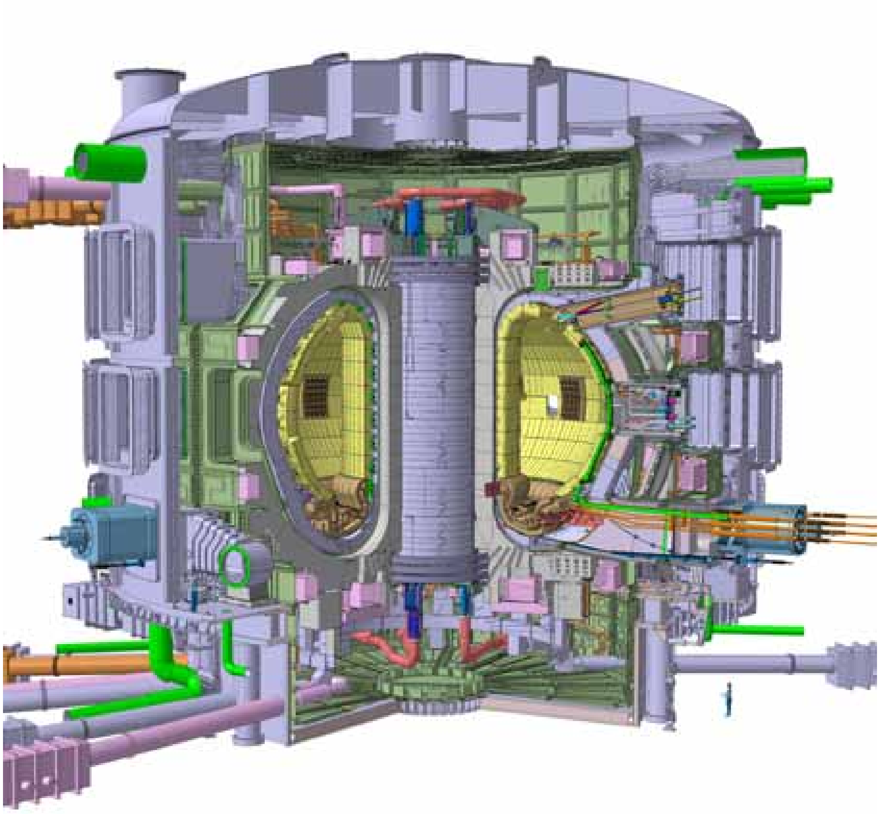

Figure 1.2: *The ITER design – the size is shown by the person at the bottom right*

It is intended that ITER and IFMIF will operate in parallel (the so-called 'fast track' approach to fusion development) and a subsequent demonstration power station ('DEMO') could provide electricity to the grid within around thirty years. Other facilities may be needed to help strengthen the programme and reduce risk, including a Component Test Facility (CTF) which might be based on the spherical tokamak concept.

In 2008 an independent panel reviewed the facilities in the European fusion programme (http://ec.europa.eu/research/energy/fu/fu_pubs/article_1256_en.htm) and ranked these. It concluded that the most important was JET and it is therefore expected that JET will remain operational until at least 2014, and probably longer. ASDEX-Upgrade (Germany) was ranked second, and then MAST third equal. A long-term forward programme for MAST is therefore envisaged. Plans for an upgrade to enhance MAST's contributions to ITER and to the basis for a CTF are well-advanced but at the time of writing the extent to which these can be funded is not yet clear.

Figure 1.3: *The MAST tokamak (the vessel has 4 m diameter and 4.4 m height)*

The EURATOM/UKAEA Association contributes to all the key areas of study in tokamak plasma physics research, as part of EFDA co-ordinated programmes, through experiments on MAST (Chapter 5), participation in the JET programme (Chapter 4), and fusion plasma theory and modelling (Chapter 6). These key areas are:

- **confinement:** how well energy and particles are retained in the plasma and how this can be improved;
- **stability limits:** how high the current, pressure and density can be in the plasma before it becomes unstable; in large machines like ITER it is important to stay within stable operating regimes to avoid potentially major damage to components;
- **plasma exhaust:** the properties of the edge of the plasma, the size of steady and transient heat loads on material surfaces (especially bursts from ‘ELMs’ – Edge Localised Mode instabilities), and the influx of impurities into the main plasma;
- **steady-state operation:** while the tokamak is naturally a pulsed device, there are regimes with the potential for continuous (steady-state) operation which while more difficult to attain would avoid cyclic stresses and large energy storage systems and therefore be more attractive for a power station;
- **optimum configuration:** the JET/ITER design is the most developed system, but other magnetic configurations have advantages including the more compact spherical tokamak developed at Culham most recently on MAST, and stellarators studied in Germany, Spain and other countries.

As well as plasma physics research, there is a major activity worldwide on the **technology and materials** (Chapters 7 and 8) needed for ITER and fusion power stations. UKAEA contributes to these areas, particularly to specialist heating and measurement systems needed for ITER, to studies of fusion power stations including DEMO, and to the science of materials needed for power stations with the aim of minimising their activation and their deterioration when exposed to the very fast neutrons from the fusion reactions.

Over recent years, the contributions of UK **universities** to the programme, in materials science, plasma physics and engineering, have increased markedly. Around twenty-five now make contributions to research and/or to student training.

The programme also benefits from collaborations with many other EURATOM Associations and with fusion institutes in the rest of the world.

1.2.2 PUBLIC UNDERSTANDING AND EDUCATION OUTREACH

There is a strong and varied programme of public information and education, some of which is undertaken with the EFDA JET programme under Host Support. Culham has many visits by VIPs. Recently we introduced Open Evenings for around a hundred members of the public – at first there were four a year, but they are so popular that now there is one in most months. In addition, there are visits by schools and universities, professional institutions, etc.; demand for these exceeds our capacity to take them. There are also talks and demonstrations away from Culham by our staff, particularly at schools and local and national science events including the British Association for the Advancement of Science Festival, which this year generated a lot of press interest in our materials research which has applicability beyond fusion. Many television and radio production companies have visited from the UK and farther afield, most notably BBC2 for its *Horizon* programme 'Can we build a star on earth?' which attracted two million viewers.

We are increasingly using 'new media' to reach out to new audiences by developing a series of video podcasts available on YouTube, and making use of social networking websites including Facebook and Twitter.

The Sun Dome outreach activity, aimed at primary school-age children (10-11 years old), remains in great demand following its launch in March 2007. Developed with the aid of an EPSRC Partnership for Public Awareness grant and EURATOM funding, the Sun Dome uses a large portable dome which is inflated in the school hall and comprises movies and interactive role-play activities. There continues to be excellent feedback from teachers and pupils and the number of Sun Dome shows has been increased, with almost 5,000 children attending in 2008/09. During the year, the original EPSRC funding expired, but the medium-term future of the Dome has been secured with new funding. This enables the Dome to continue to be offered as a free resource to local primary schools and will allow for expansion to new secondary school shows.

Figure 1.4: *Schoolchildren in front of the Sun Dome with Chris Warrick and Joana Silva from Culham*

1.2.3 TRAINING

UKAEA Culham has a number of training initiatives targeted at specific disciplines, especially in areas of shortage. There is an apprentice scheme to train technicians, the annual two-week Culham Plasma Physics Summer School for post-graduates, the Culham Fusion Research Fellows (some of these post-docs also have EFDA Fusion Researcher Fellowships), a training programme for new graduates, and around 40 PhD students from nearly twenty universities. Culham sponsors the Institute of Physics prize for the best PhD in plasma physics; the winner gives a lecture at the annual IoP meeting on plasma physics (Fig 1.5). UKAEA also participates in two EURATOM Fusion Training Schemes, including EFDA's 'Goal Oriented Training', which are targeted mainly at engineering disciplines needed for ITER.

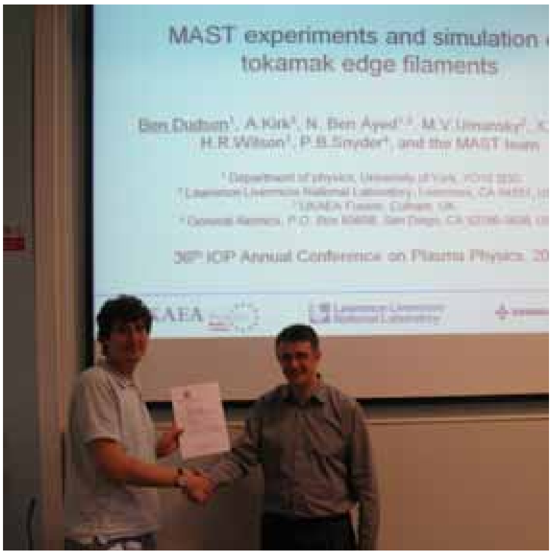

Figure 1.5: *This year's Culham thesis prize, for the best PhD in plasma physics in the UK, was for a fusion project, by Ben Dudson of Oxford University, seen here receiving his award from Richard Buttery from Culham*

1.3 JET OPERATIONS

Under EFDA, UKAEA has been responsible for the operation and safety of the JET facilities since January 2000. UKAEA's costs are reimbursed by the JET Operation Contract placed by the European Commission and managed by the EFDA Associate Leader for JET, Dr. Francesco Romanelli.

The JET Restart in early 2008 followed the planned 2007 major shutdown, and marked the end of the installation of the final elements of the first Enhanced Performance programme ('EP1'). These included new and improved plasma diagnostic systems and a new high-power ITER-like antenna (ILA) to launch RF waves to heat the JET plasma.

The EFDA experimental campaigns resumed in April 2008. Eight campaigns were conducted in 46 operational weeks to 7 April 2009. Much of this time was dedicated to the commissioning of the ILA, and substantial progress has been made towards meeting its objectives, especially in demonstrating tolerance to Edge Localised Modes (ELMs). Many key JET sub-systems, such as the power supplies, the plasma heating and current-drive systems and over 80 diagnostic systems, have operated at very high levels of performance and availability throughout 2008. For example the neutral beam heating system delivered its highest ever power level (>23 MW) and energy injected in a single pulse (192 MJ).

The second ‘EP2’ enhancement programme comprises many projects; new and upgraded diagnostics, upgrades to the neutral beam heating system, a new high frequency continuous pellet injector and biggest of all the replacement of the plasma-facing tiles in the vacuum vessel. Procurement from industry is via contracts placed by the European Commission. Most projects are undertaken by the Associations (including UKAEA), with UKAEA as JET operator responsible for installing, commissioning and operating the equipment. In its role as an Association, UKAEA is leading several projects (notably the neutral beam upgrade) and is involved in several others. The exception to these arrangements is the ITER-like Wall (ILW) project to replace the carbon fibre composite tiles presently in JET with a beryllium wall and a tungsten divertor, the planned material configuration for the deuterium-tritium phase of ITER. For the ILW, UKAEA as JET Operator has overall responsibility for the project and performs the vast majority of the project tasks. The ILW project covers design and procurement of all the new components required inside JET. Installation of the ILW using Remote Handling, and the substantial preparation required (including new tooling, a lengthened RH boom and inspection facilities – Figure 1.6) are part of the EP2 Shutdown project. Apart from technical issues associated with the tungsten coatings used in the divertor, which required a change of manufacturing technique to one developed by the Romanian Association, there have not been any significant technical issues with the procurements and deliveries of components have commenced. The complexity of the project is illustrated by the fact that a database with a bar code based interface has been developed to manage storage and assembly of the 86,000 parts for the new wall.

The installation of the ILW, which will take more than one year, will be the most significant shutdown and enhancement of JET since the early 1990s. There will be four Remote Handling and three Manual in-vessel phases, and many ex-vessel tasks including installation of the remaining EP2 diagnostics and the neutral beam enhancement project. The shutdown is due to start in autumn 2009.

Figure 1.6: *Left: The new lengthened Remote Handling boom during commissioning. Right: Inspection of the carriers for the Upper Dump Plate tiles in the Beryllium Inspection Facility*

1.4 JET STUDIES

The collective use of JET is the responsibility of the EFDA Associate Leader for JET, who co-ordinates the JET research programme, which is carried out by Task Forces of visiting scientists from the EURATOM Associations. UKAEA plays a full role, with the participation of some UK university staff and students.

The year was a period of intensive experiments, exploiting the highest heating power and the best ever set of plasma measurement systems (diagnostics). Operation will continue until the major EP2 installation shutdown that starts towards the end of 2009. There has been increased focus on issues directly relating to the finalisation of the design of ITER components, and the understanding needed for detailed planning of ITER plasma scenarios and determining the operational capability. On both physics and technology there has been notable progress in many areas (in almost all, it has been joint work with, and often led by, other Associations):

- the ‘pedestals’ in density and temperature at the edge of high performance plasmas (illustrated in Figure 1.7). These have a strong influence on the core temperature and density in ITER and hence the fusion power;
- methods to reduce the power flowing to the divertor and thereby lessen the challenging demands on plasma facing components in ITER and DEMO, and indeed JET when the ILW is installed. The impact of ELMs on the first wall and the divertor, and how to reduce this, again a key issue for ITER and DEMO;
- substantial performance improvements in ‘advanced tokamak’ regimes, being developed to allow very long pulse or steady state in ITER / DEMO, and detailed experimental studies of confinement behaviour and formation of transport barriers;
- improved understanding of plasma stability at high pressure, especially the theory of fast particle and flow effects, which affects the performance range on ITER and DEMO;
- achievement of the technical objectives of the new ITER-like ICRH antenna – dynamic matching of the impedance, operation in ELMy plasmas and attainment of the target voltage on the antenna straps. The power coupled is lower than expected, so the power target has not been reached (a wave-plasma physics issue). These results are invaluable for the design of the ITER launcher. Significant progress has also been made with other ELM-resilient ICRH coupling schemes;
- delivery and commissioning of all four new power supplies for the heating upgrade. Delivery of a new power supply to improve control of the plasma position to allow reliable operation at high current, high performance;
- completion of an upgrade to the edge LIDAR diagnostic, using ITER-relevant detector technology (LIDAR uses laser back-scatter from the plasma to measure the temperature and density of the electrons – Figure 1.7). Good progress on other diagnostics projects.

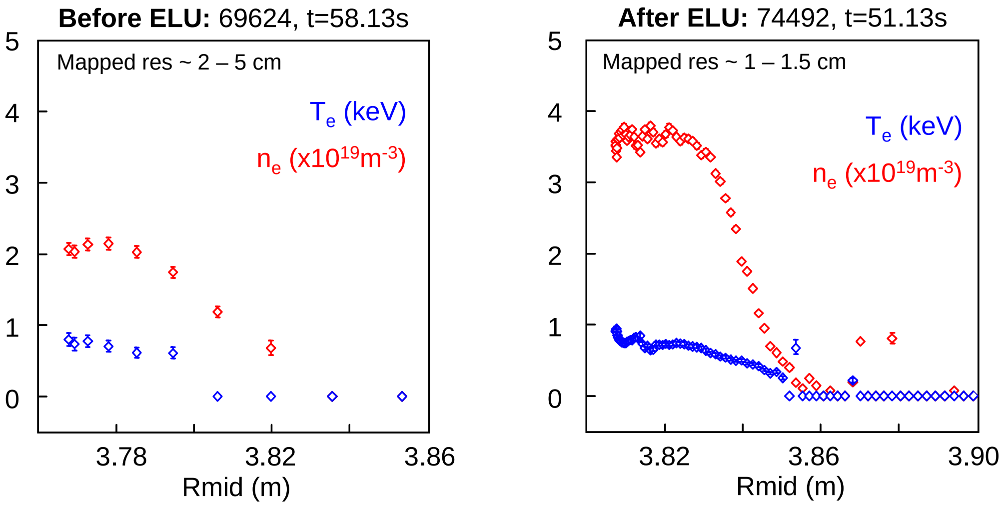

Figure 1.7: *Measurements before and after the edge LIDAR upgrade (“ELU”), showing the much greater spatial accuracy now achievable for both the electron density and electron temperature. Measurements of these quantities are key to understanding (a) the properties of the pedestal in high performance plasmas, and (b) ELMs and their effects*

1.5 MAST

MAST is one of the two largest spherical tokamaks in the world (the other, of similar size but differing design, is NSTX at Princeton, US). The MAST programme is guided by an international Programme Advisory Committee. The main aims of the MAST programme are twofold:

- to address key physics issues for ITER, complementing and extending data from conventional aspect ratio tokamaks, via experiments co-ordinated by EFDA Topical Groups and Task Forces and by expert groups of the ITPA (International Tokamak Physics Activity – a global effort addressing the main plasma physics issues for ITER). There are many joint experiments with other European and non-European tokamaks;
- to explore the potential of the spherical tokamak (ST) as a basis for a compact, low tritium usage fusion component test facility (CTF) and possibly an ST power plant. International ST research is co-ordinated via the International Energy Agency's Implementing Agreement on Spherical Tori.

The 2008 European Fusion Facilities Review stated that 'MAST provides important contributions to the physics understanding of toroidal plasmas in domains not accessible by larger aspect ratio devices' and acknowledged its valuable contributions to ITER physics and to the possible development of a CTF. An important forward programme for MAST is therefore envisaged as part of the ongoing EURATOM programme, with the experiments increasingly involving, via EFDA, scientists from other Associations.

MAST experiments have made progress on many fronts, with highlights including:

- improved understanding of how confinement scales in ST plasmas, this work is linked closely to theoretical modelling (Section 1.6);
- measurements of how ions rotate in the poloidal direction, showing this is consistent with theory based on inter-particle collisions and not affected strongly by plasma turbulence;
- use of MAST's world-leading diagnostics to study the density and temperature pedestal at the edge of high performance plasmas in ITER-relevant configurations, and also the electric field and toroidal rotation in this region (these quantities have roles in pedestal formation and sustainment). The pedestal is key in ITER as it will determine the central plasma pressure and therefore the fusion power output;
- first use of the new in-vessel control coils to address how magnetic perturbations can be used to limit ELMs – these instabilities at the edge of the plasma are very important as they will damage plasma-facing components in ITER unless they are kept to tolerable levels;
- use of MAST's unique diagnostic capabilities to increase understanding of the 3D filamentary eruptions from the plasma boundary in ELMy and turbulent conditions (Figure 1.8). Code simulations by UKAEA and York University scientists have added to this understanding;
- studies of sawtooth, fast particle and other instabilities in beam-heated plasmas; these can limit performance in both ITER-like and ST plasmas;
- high-quality data from the new multi-chord Motional Stark Effect (MSE) system for diagnosis of the plasma current profile are evidence for off-axis neutral beam current drive – an essential ingredient of steady-state scenarios for both conventional and spherical tokamaks which will be a key area for study in the future MAST programme.

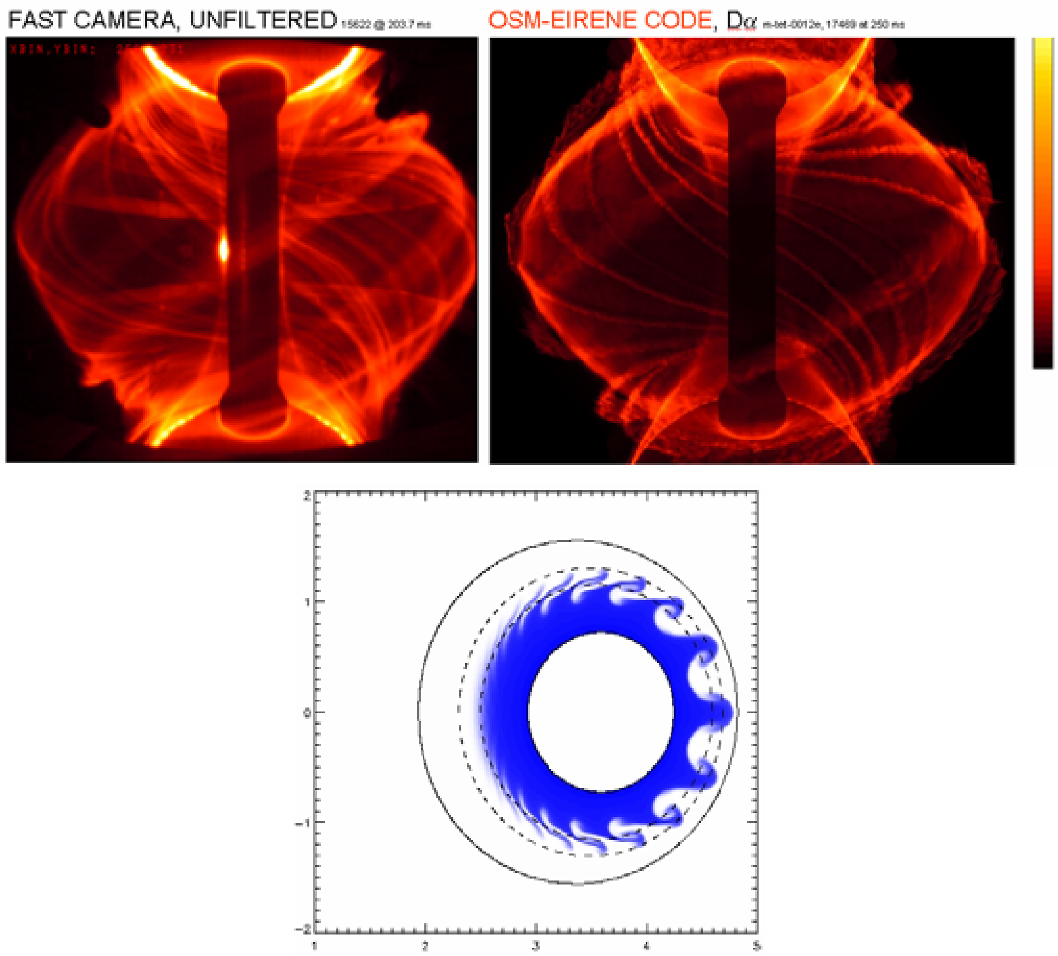

Figure 1.8: *Above: Left: Measured (fast camera) and Right: simulated edge filamentary structures. Below: 2D cross-section of the start of ELM filaments predicted by the BOUT++ code (nonlinear simulation by the University of York). The cross-section shown corresponds to the right-hand half of the plasma in the upper pictures.*

There have been many other technical developments on MAST. The upgrade of the neutral beam heating system to JET-style ‘PINI’ sources is close to completion; two PINIs have been operated simultaneously into MAST for the first time. The first of two stages of a major upgrade to the Thomson scattering system (part funded by York University) was completed on schedule, doubling (from four to eight) and increasing the energy (1 J to 1.5 J) of the lasers and implementing a new ‘event triggering’ system. Several other diagnostic improvements have included long wavelength infra-red (IR) imaging system for better measurements of divertor power loading during ELMs and other transient events (Figure 1.9). A divertor science facility has been installed to allow tests of plasma-material interactions and transport studies of injected material (gas and dust). There has been progress on projects undertaken with other Associations: a disruption mitigation system (with FZJ Jülich, Germany); 2D beam emission spectroscopy for measuring long wavelength turbulence (KFKI, Hungary); and a collimated neutron emission detector array (Uppsala University, Sweden).

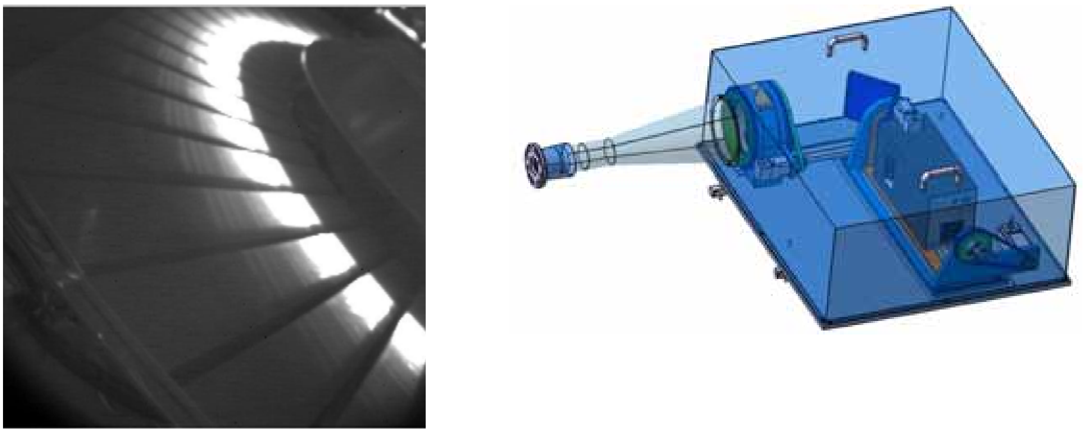

Figure 1.9: *MAST diagnostics are being continually improved. Left: Observation of filamentary structures on the divertor target plate in L-mode plasmas using the new fast long-wave IR camera. Right: ex-vessel opto-mechanical components of the 2D turbulence imaging system being developed with the Hungarian Association, comprising the view-port mounted optics, filter cell with field lenses and the Avalanche Photo Diode camera*

Longer-term it is important that MAST is upgraded to give higher performance, longer pulse plasmas. This requires increased heating power and major modifications to the machine. Such an upgrade would enable more exacting tests of ITER physics and allow key questions to be answered concerning the feasibility of an ST-based Component Test Facility (CTF). In recent years a design of such an upgrade has been developed covering a wide range of physics and engineering. A plan for how the upgrade could be staged has also been formulated, as it is unlikely that funding could be secured for implementation of the full upgrade in one stage. An important addition to the design in 2008/09 has been the ‘Super-X divertor’. Coping with continuous high heat loads is one of the biggest challenges for future fusion machines, especially a DEMO power station and CTF. In the Super-X, the power density striking material surfaces is reduced by increasing the radius and therefore area of the target; which also allows much higher radiative cooling before the plasma ever gets to the target. Unlike other tokamaks, MAST’s vacuum vessel is much larger than its plasma, meaning it is the only existing facility that can be adapted to test the concept.

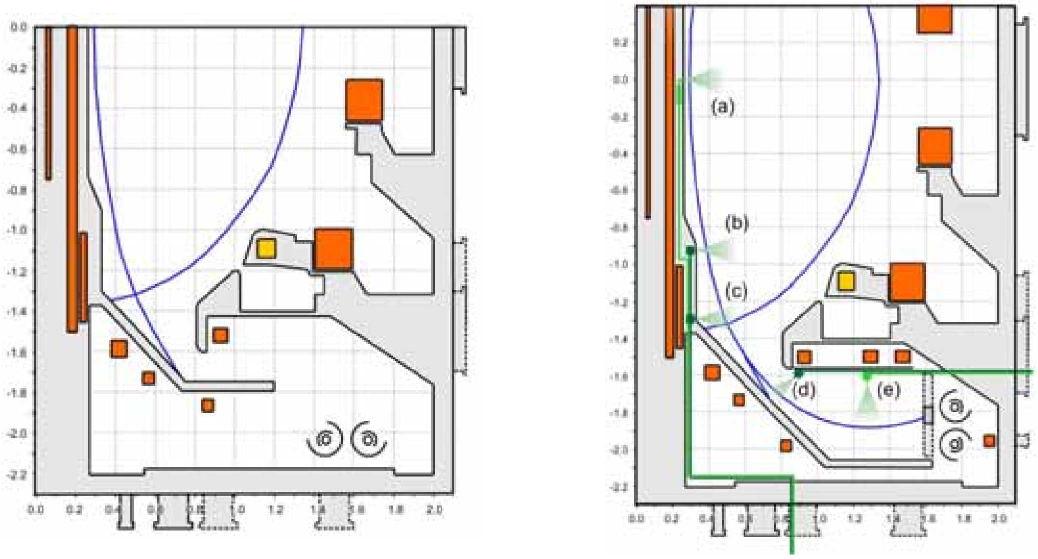

Figure 1.10: *Comparison of previous (left) and “Super-X” (right) MAST upgrade divertor design with magnetic field coils (orange) and boundary of the bottom half of the plasma (blue). The much longer exhaust region with Super-X is apparent. Also shown are proposed gas puff locations (green, labelled a-e)*

1.6 THEORY AND MODELLING

This programme's activities cover many of the key plasma physics issues that need to be resolved for the successful development of fusion power, in both ITER-like and spherical tokamak devices:

- confinement and transport, with an emphasis on modelling the turbulence mechanisms that underlie the loss of energy from the tokamak plasma. Much of this work has substantial participation from UK university experts, and also involves collaborations with overseas institutes;
- the avoidance or mitigation of instabilities that can limit plasma performance or damage the device;
- the integrated plasma modelling required for developing steady state operational scenarios. This is a priority for future development.

These topics have been addressed by exploiting the Association's traditional strengths in analytic theory and by its rapidly increasing capability in computational modelling. The latter benefits from EPSRC and European high performance computers, and Culham's own parallel computers. The programme works in close contact with UKAEA experimentalists on MAST and JET; this both stimulates the development of models and provides the opportunity to validate these, a crucial element in providing a reliable predictive capability. Participation in the International Tokamak Physics Activity (ITPA) is a priority, in particular hosting and managing the ITPA Profile Database.

A wide range of topics were addressed in 2008/09. Highlights include:

- a range of calculations of the short-scale turbulent fluctuations responsible for energy leakage from the plasma, using a variety of codes. For example, ORB5 - a global gyrokinetic particle-in-cell code – has been used to study Ion Temperature Gradient (ITG) driven turbulence in MAST (Figure 1.11 – a collaboration with Warwick University, German and Swiss scientists). The ITG instability was shown to be unstable and therefore perhaps responsible for energy transport across the MAST plasma. Further work is exploring the effects of spatially-varying plasma rotation ('shear') which is expected to affect this;
- 'Resistive Wall Modes' (RWMs) which grow because the metal wall of the tokamak (which stabilises many gross plasma instabilities) is not a perfect conductor. Calculations have shown that resonances with ions rotating in the plasma contribute to stabilising the instability;
- many contributions to the EFDA Integrated Tokamak Modelling (ITM) Task Force, with codes developed for equilibrium reconstruction, RWMs, edge physics and electromagnetic turbulence. UKAEA provided one of the ITM Deputy Leaders, and intends to increase its contributions with scenario modelling for ITER a priority.

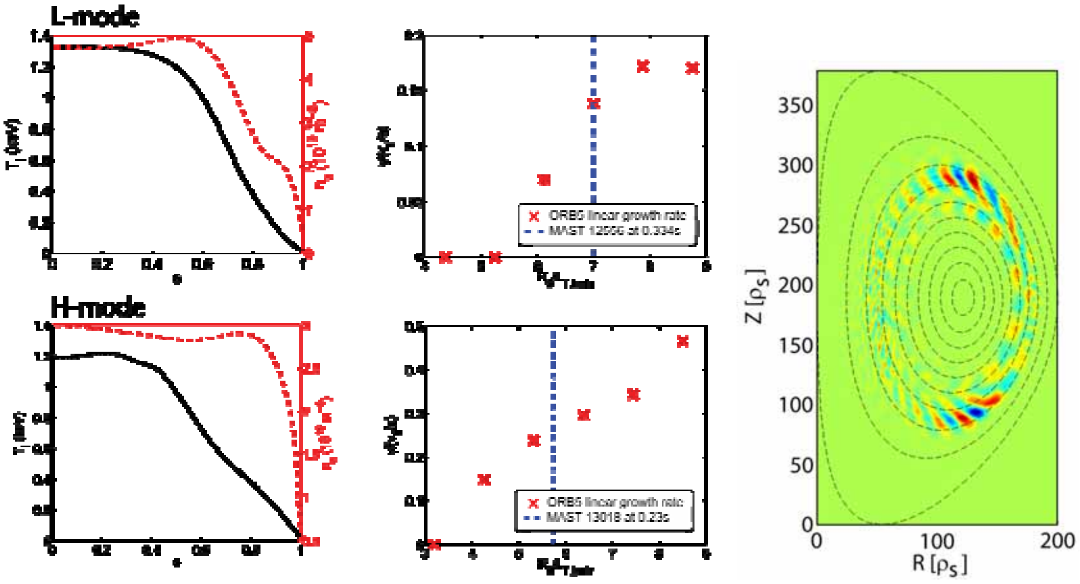

Figure 1.11: Calculation with the ORB5 turbulence code for MAST plasmas. Calculations have been made for both low confinement (L-mode) and high confinement (H-mode) plasmas. Left: the plasma temperature (black) and density (red) profiles in these two confinement modes. Centre: how the ITG growth rate (γ) varies with the temperature gradient scale length (L_T) – the blue dashed line indicates the MAST value and it can be seen that the ITG is unstable (i.e. $\gamma > 0$). Right: the electrostatic potential variation for an ITG mode in MAST

1.7 MATERIALS AND TECHNOLOGY

UKAEA participates in EFDA programmes on the materials needed for fusion power stations, and collaborates extensively with UK universities on this topic. There are also studies of conceptual designs of power stations (including a DEMOnstration plant), and analyses of their socio-economic, environmental and safety attributes; all as part of EFDA and international programmes. Resources permitting, UKAEA will with UK universities grow its contributions to DEMO and power plant technology, building on the expansion that is well under way for ITER technology (Section 1.8).

Materials research addresses (a) how mechanical properties of structural materials – especially low activation steels – are degraded by high energy neutrons from fusion, (b) how these and other materials used in fusion are made radio-active by neutrons, and (c) how surfaces are affected by exposure to fusion plasmas (at the moment the studies are focused on JET as part of work in the EFDA JET Fusion Technology Task Force). Highlights include:

- development of techniques for modelling high-temperature properties of iron and steels and the phase stability of binary iron-chromium alloys in the high-temperature limit, with significant progress in understanding certain fundamental defects in body-centred cubic metals (‘screw dislocations’);
- prediction of ‘pile-ups’ of dislocations in steel. As the strength of interaction between individual dislocations decreases (for example, in iron at high temperature), calculations show that dislocation sources generate more dislocations, in this way accelerating plastic deformation of the material. Electron microscope images (Figure 1.12) show that dislocation pile-ups formed at higher temperatures are more compact, and that they contain many more dislocation lines, in agreement with the solution of the problem of interacting dislocations in a pileup;

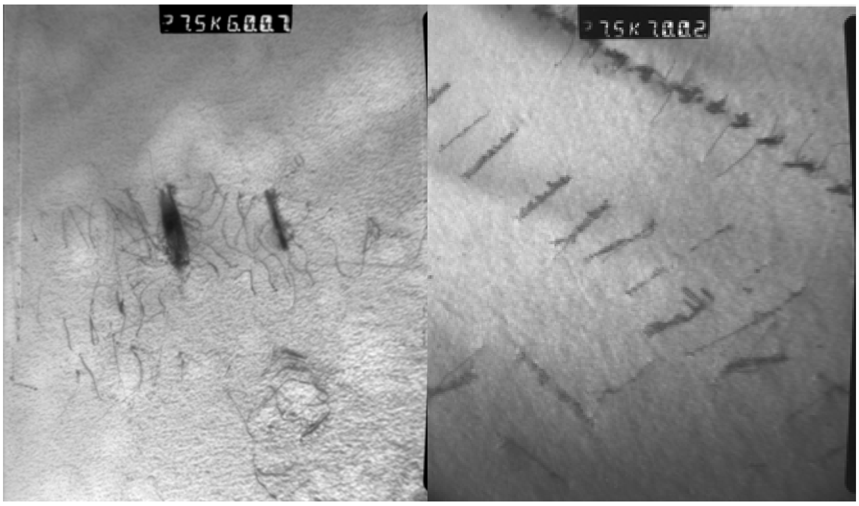

***Figure 1.12**: Electron microscope images of dislocation microstructures formed in pure iron deformed at elevated temperatures. Left: 530°C, right: 713°C. Note the more compact structure of pile-ups formed at the higher temperature. Work by Oxford University funded by the Association*

- Ion Beam Analysis measurements of how erosion, deposition and hydrogen-isotope retention vary with the location of JET tiles. In particular, the behaviour of beryllium (already present in JET) has been studied. There has been a change in deposition pattern with different divertor configurations, which is thought to arise from differing "strike-point" locations, the effects of ELMs, etc. These studies are providing valuable information for future experiments with the JET ITER-like Wall (ILW), which will be mainly beryllium.

In **technology**, we have looked at the desirable attributes of a demonstration fusion power station ('DEMO'). There are several clear advantages in a steady-state device; however the potential simplification in a pulsed device of greatly reducing the need for current drive gives it a significant counter-advantage. The choice between the two options depends to a large extent on whether DEMO must be prototypical of a power station – it would clearly be easier to demonstrate pulsed electricity production if fatigue life of the plant or the resulting cost of electricity were not a concern. The most important questions for DEMO are not only technical. Where it should lie in the range between ITER and a full power station is a matter of judgement, though if it were to fall too close to ITER then another intermediate step could be required, possibly delaying rather than advancing fusion power. However, in an international DEMO programme which included several facilities, an early DEMO could certainly be considered for one of these. Providing the technical and economic background to a decision as to whether an early DEMO should primarily demonstrate electricity production, or whether it must also be prototypical of a full power station, remain key topics for much ongoing work. In the light of the crucial importance of these questions, a new area of work has been started looking in more detail at the scientific and technical detail of the facilities and development programme needed to achieve fusion power. New and more detailed work on DEMO has already started whilst work on the roles of a Component Test Facility (CTF) and materials development is soon to begin.

Conceptual design studies of a CTF based on the spherical tokamak have continued. A big challenge for any fusion system is dealing with the large exhaust power from burning plasmas. One promising option, for both DEMO and CTF, and which we intend to study on MAST, is the 'Super-X' expanded divertor – cf. Section 1.5. This reduces the power per unit area impinging on plasma-facing tiles by increasing the radius of the target and allowing much higher radiative heat loss before the plasma gets to the tile. Studies show that the CTF design can be adapted to include the 'Super-X', and adequate shielding provided for the extra coils that it needs, including one that needs to be in the vessel. Other studies have examined another key issue, how the CTF plasma can be started; while there is no room for a neutron-shielded central solenoid, one option is to have a solenoid that can be lowered out of the machine once the plasma has been established (Figure 1.13).

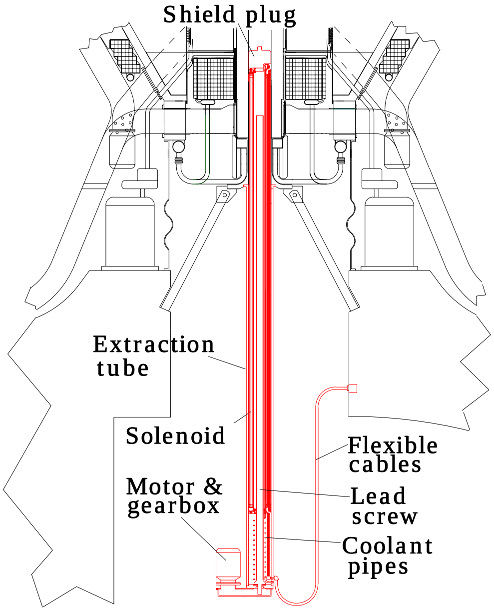

Figure 1.13: *In the design of the CTF, the solenoid for plasma start-up can be retracted once the plasma has been established*

1.8 ITER SYSTEMS

The many specialist systems required for ITER are allocated to the various ITER parties and mainly comprise the heating equipment and many measuring systems ("diagnostics"). Before these systems can be built, further research, development and design is needed. The European ITER Domestic Agency, F4E, is allocating this work to consortia of fusion laboratories, mainly funded by grants (supported 60:40 by national and F4E funds)[1], with some 100% funding via F4E contracts. Before F4E was established, this work was managed by EFDA, and during the last year our contributions have mainly been the completion of EFDA contracts. Apart from the systems in which we take major roles, detailed in the following paragraphs, UKAEA is involved at a relatively small level in some areas, like Charge Exchange Recombination Spectroscopy (to measure ion temperature and flows, led by German and Dutch laboratories). In addition we have recently been awarded two F4E contracts to provide neutronics services for the ITER design. Other work, by Durham University, is on the characterisation of the superconducting strand to be used in the ITER magnets.

UKAEA has substantial roles in three systems. It leads the **core LIDAR Thomson scattering**, with contributions from several other Associations. Significant progress has been made in several areas, including the theory, laser, detector and many aspects of system design. The modelling shows that, based on present estimates of the performance of individual components, in principle

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[1] The work by UKAEA for F4E is included in this report for completeness, though formally it is not part of the work of the EURATOM/UKAEA Fusion Association.

the systems can achieve the measurement accuracy and spatial resolution required, but with relatively little margin. Further work, backed up by testing is required to ensure that reliable systems can be deployed. Critical areas such as first mirrors, calibration, lasers and detectors need further work. As part of the support for this LIDAR work, UKAEA is bidding for an F4E grant for design work on generic aspects of engineering of the Diagnostic Port Plugs within which the interfaces and transmission systems of diagnostics like LIDAR will enter the ITER vacuum vessel.

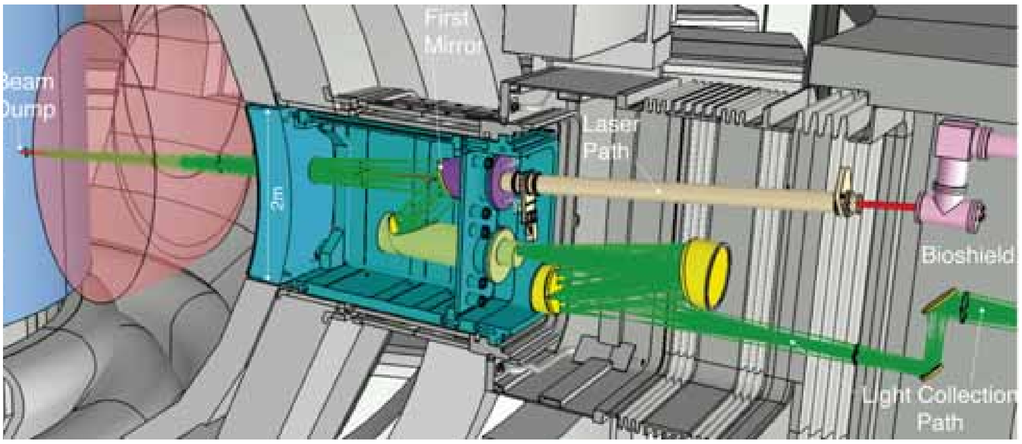

__Figure 1.14:__ Core LIDAR TS system showing the laser launcher and the light collection path from the plasma (shown in pink, to the left)

The Ion Cyclotron Resonance Heating antenna consortium is led by UKAEA with Belgian, French, German and Italian partners; the formal agreement for this ‘CYCLE’ consortium was signed in January 2009. With its partners, UKAEA has continued to develop the concept design of this very challenging component. The geometries of the RF straps/feeders and the service stubs within the Removable Vacuum Transmission Lines (RVTLs), previously proposed by UKAEA, were further developed with Belgian engineers; the outcome being much-improved power coupled to the plasma, and over a wider frequency range. Other important areas studied included cooling requirements and manufacturing options.

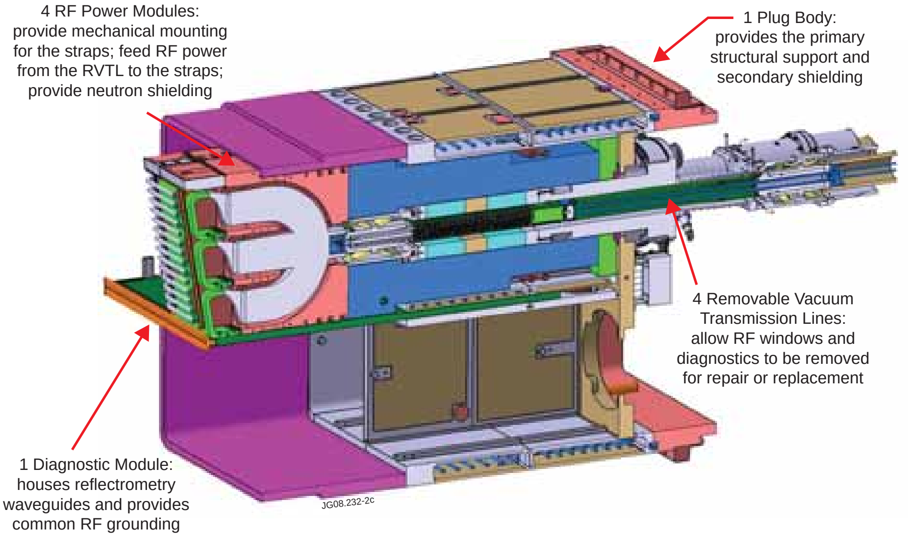

__Figure 1.15__ Section through the ITER ICRF Antenna with one RF Power Module (and RVTL) installed

Europe is responsible for most of **the ITER Neutral Beam Injection system**. UKAEA participates in a grouping led by RFX (Italy) to establish an ITER Neutral Beam Test Facility (NBTF) in Padua; UKAEA has produced the design of the beam-line calorimeter. For a contract not connected with the NBTF, UKAEA studied the design of the Heating Neutral Beam duct liner, and proposed a number of improvements. Work in 2008/09 has concentrated on assessment of the thermo-mechanical performance and Remote Handling (RH) compatibility of the existing design, and development of RH features, procedures and tooling for an alternative liner concept with improved characteristics. This alternative has been accepted by ITER as the new reference design.

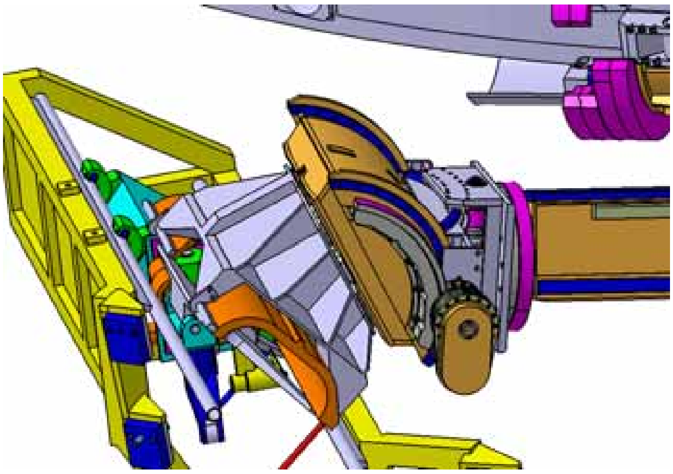

Figure 1.16: *Remote Handling compatibility of the duct liner which relies on an in-vessel maintenance strategy. The In-Vessel Transport to the right coupled with its end effector carries a Duct Liner Module Transporter attached to the Chassis structure (yellow)*

1.9 INDUSTRY

The main purpose of our industry liaison is to encourage UK companies to bid for contracts from the international fusion programme, especially ITER. We have a dedicated website (www.fusion.org.uk/industry) and a database of companies who receive regular 'e-news' updates and the electronic newsletter *Fusion Business*. We collaborate with Government organisations including UK Trade & Investment and a Knowledge Transfer Network, which has as part of its remit the objective of increasing the involvement of UK industry in 'big science' projects at home and overseas.

Increasingly we work as part of the network of Industry Liaison Officers in Europe, established by F4E, particularly on facilitating pan-European consortia of high-tech companies that could bid for ITER contracts. We have accompanied UK companies on trade missions to both ITER in Cadarache and F4E in Barcelona. During the year UKAEA facilitated the establishment of two UK consortia, which have the objective of bidding for high value ITER contracts in the vacuum vessel and magnetic field coil areas. Several UK companies have won sizeable contracts for ITER work, and for JET, and examples are given in Chapter 9.

During the year many companies have exhibited their products and services to scientists and engineers from both the fusion programme and the many high-tech companies on the Culham site. In May or June each year there is an exhibition by companies in a marquee (Figure 1.17).

Figure 1.17: *Exhibitors and visitors at the annual Technology & Innovation Exhibition at Culham*

A secondary objective of the industry programme is to facilitate technology transfer from fusion to other markets. Our main vehicle for this is the technical support that we provide to half-a-dozen small companies at the Culham Innovation Centre working in sectors including aeronautics, plasma devices and magnetic resonance imaging.

1.10 FUTURE PLANS

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

The remainder of the EFDA **JET** 2009 campaign will concentrate on commissioning and exploiting the improved vertical position control system for qualification of integrated operating scenarios for ITER, together with experiments in hydrogen and helium to provide information for the lower activation campaigns on ITER before D-T operation. Preparations for the ITER-like Wall campaigns will continue, and its installation will begin toward the end of 2009 with first experiments scheduled for 2011. Longer-term there may be further upgrades of JET, and an experimental campaign using D-T fuel.

The **MAST** Thomson scattering upgrade will be completed, and a high power 28 GHz gyrotron (loaned by Oak Ridge National Laboratory, US), will be installed and used for plasma start-up studies. Diagnostic projects with other Associations, some under EFDA auspices, will be completed. Near-term experiments will exploit these and other developments, especially improved neutral beam heating, and will maintain a two-pronged approach addressing key ITER physics issues and exploring the potential of the spherical tokamak. University, EFDA and international collaborations will continue to expand. The main physics themes will be: ELMs and their control; fuelling and exhaust physics; power loading and disruption mitigation; optimisation of performance and stability; plasma transport including turbulence and pedestal physics and scalings for ITER; and neutral beam current drive and fast ion physics. Resources permitting, an upgrade of MAST will proceed, if necessary in stages.

In the **plasma theory** programme collaborations with universities will increase further, with a concerted effort on improving understanding of energy losses caused by plasma turbulence in MAST and other tokamaks. Support for European and international activities will increase, particularly as part of the EFDA Integrated Tokamak Modelling Task Force (including in the area of ITER scenario modelling). Instability studies will concentrate on ELMs, fast particle effects, and modes that limit plasma pressure and current, and will address the implications for ITER.

In **materials** research, activities will continue to concentrate on steels and other alloys needed for structural components in fusion power stations, within the framework of university, European and wider international collaborations: we will continue to lead the EFDA Materials Task Force. Universities, particularly Oxford, will carry on providing world-leading contributions, particularly in experimental aspects, while UKAEA staff will concentrate on the theory and modelling that is an essential complement to these experiments. On JET, as part of the EFDA-JET Fusion Technology Task Force, there will be preparations for studies with the ITER-like Wall, including erosion measurements and tile analysis.

UKAEA intends to expand its involvement in fusion **technology** as part of European programmes. This has already commenced with **work for ITER**, via first EFDA and now F4E grants and contracts; we expect to sign further consortia agreements with other fusion institutes in Europe, and retain leading roles in the LIDAR, ICRH and Neutral Beam systems. Smaller, but still important contributions will be made to other ITER systems. Beyond ITER, DEMO will get particular attention as will routes to fusion power and the facilities that may be needed, e.g. a Component Test Facility. An initiative has started to increase the involvement of UK university experts in fusion technology projects, and university-led bids to EPSRC have already been made to seek funding, in areas such as neutral beam source options for machines after ITER.

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 schools, the latter using the Sun Dome facility which is being upgraded to be suitable for secondary as well as primary school children. Other outreach, including our very popular Open Evenings, will continue.