1 Executive Summary

1.1 OVERVIEW

This report describes the work of the EURATOM/CCFE fusion Association from April 2010 to March 2011. Research at the Culham Centre for Fusion Energy[1] (http://www.fusion.org.uk) is funded jointly by EURATOM and the UK Engineering and Physical Sciences Research Council (EPSRC), which is guided in fusion matters by an independent Fusion Advisory Board.

In Europe, fusion research is co-ordinated by EURATOM with the overall aim of developing power stations that harness on earth the process that powers the sun. Fusion power stations would emit no greenhouse gases and their fuel would be abundant and widespread. The European programme comprises:

a) Work in ‘national’ fusion programmes, via Contracts of Association. Many of these have their own research facilities including MAST (Mega Amp Spherical Tokamak), the centrepiece of the programme of the CCFE Association;

b) Collective physics and technology research under the European Fusion Development Agreement (EFDA, http://efda.org). The largest component is the Joint European Torus (JET) programme at CCFE (http://www.jet.efda.org); JET is presently the world’s leading fusion research facility. CCFE is paid via the JET Operation Contract with EURATOM to operate JET for experiments by Task Forces of scientists from all the Associations (including CCFE). The JET programme is managed by the EFDA Leader and his Close Support Unit, located at CCFE;

c) International collaborations, dominated by ITER (http://www.iter.org), which is being built in Cadarache in France by EURATOM, China, Japan, India, the Russian Federation, South Korea and the US. ITER is mainly being procured by the partners’ ‘Domestic Agencies’, which include for Europe ‘Fusion for Energy’ in Barcelona (F4E, http://fusionforenergy.europa.eu). The aim of ITER is to produce energy from fusion on a power-plant scale (500 MW) and test key technologies for power stations like superconducting coils, remote handling, high heat flux components, and the blankets that will be needed to capture heat from the fusion core to generate electricity in a power station.

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

Chapter 2	Introduction
Chapter 3	CCFE’s role as operator of JET
Chapter 4	CCFE’s role in the JET research programme
Chapter 5	The MAST experiment and the project to upgrade MAST.
Chapter 6	Theory and Modelling of fusion plasmas
Chapter 7	Materials and Technology research
Chapter 8	The design of specialist systems for ITER
Chapter 9	Industry liaison

Chapter 10 lists publications by the Association that appeared in print in 2010/11 and Chapter 11 contains a glossary of technical terms.

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[1] CCFE is the research arm of the United Kingdom Atomic Energy Authority

1.2 INTRODUCTION

In fusion reactions, nuclei of light atoms join together to create nuclei of heavier atoms. The products of the reaction are lighter than the incoming nuclei, and the missing mass is converted to energy via Einstein's famous equation, $E=mc^2$ (where c is the speed of light). The reaction products thus have much more energy than the original nuclei. Deuterium-tritium (D-T) fusion reactions are the easiest to initiate and are illustrated in Figure 1.1; as well as helium nuclei they produce neutrons, and it is the energy of these neutrons that will be used in fusion power stations to generate electricity. To achieve copious fusion reactions requires temperatures exceeding 100 million ^{o}C (routinely reached in JET) at which the hot gas is fully ionised ("plasma") and must be kept away from material surfaces. In JET, MAST and ITER we do this using magnetic fields in the so-called tokamak design; there are other, less developed types of "magnetic bottle", in particular stellarators. In a very different approach, "inertial fusion", the fuel is compressed very rapidly with lasers and the plasma lasts only a tiny fraction of a second. EURATOM maintains a "keep-in-touch" activity in inertial fusion; the UK's contribution, at the Rutherford-Appleton Laboratory, is reported in Chapter 2.

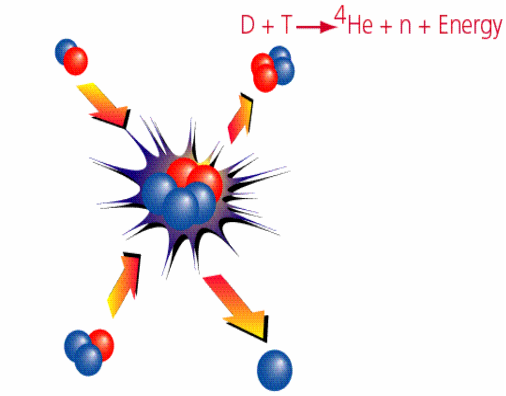

Figure 1.1: *The deuterium - tritium fusion reaction produces a helium nucleus (alpha particle) and a neutron. Deuterium and tritium are 'heavy' and 'super-heavy' hydrogen.*

In a fusion power station the fast helium would remain in the plasma and keep it hot, while the neutron – being neutral – would not feel the confining magnetic field and be captured in a blanket around the plasma. This blanket would (a) get hot - this heat would be used to generate electricity, and (b) contain lithium, which would react with the neutron to create the tritium needed for the fuel (the deuterium is easily extracted from water). The energy released is about ten million times that from a chemical reaction and 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 thirty years. Seventy tonnes of fuel is required to produce this in coal-fired power stations.

1.2.1 EUROPEAN AND UK FUSION RESEARCH

Collective aspects of European fusion research are managed by EFDA and F4E. EFDA is responsible for JET, co-ordination of plasma physics, the development of materials and emerging technologies, power station studies, and training. F4E is responsible for (a) the provision of equipment and other European contributions to ITER (including R&D by CCFE and other fusion laboratories on specialist systems for ITER), and (b) European contributions to the 'Broader Approach' collaboration with Japan which addresses fusion projects needed in addition to ITER (including IFMIF the planned International Fusion Materials Irradiation to qualify materials for a demonstration power station ("DEMO") and a new large superconducting tokamak JT-60SA to be built in Japan).

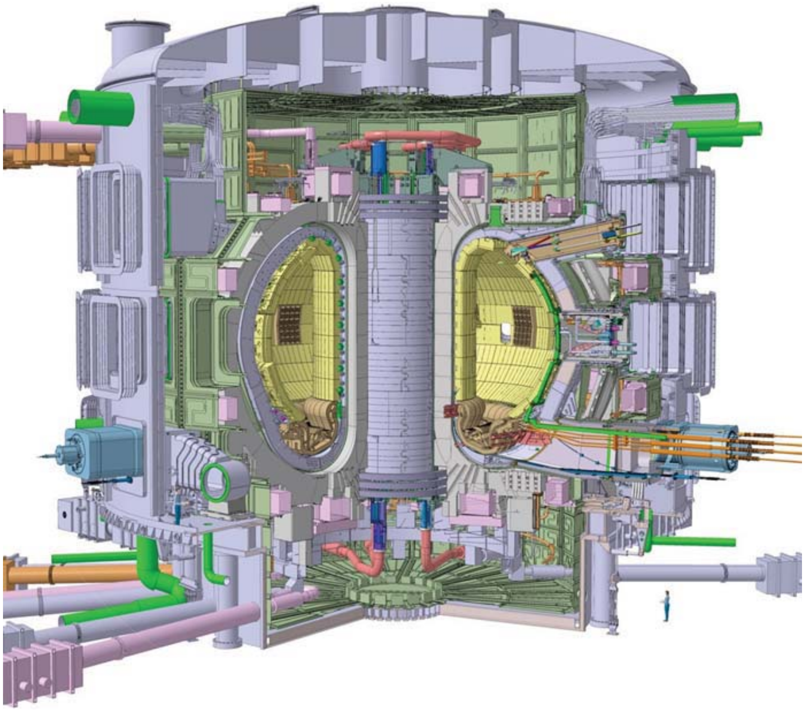

***Figure 1.2:** Cutaway of the ITER machine.*

ITER is scheduled to commence operation at the end of this decade and operate with D-T fuel in about 2027. If IFMIF is built and operated in parallel, then a demonstration power station ('DEMO') could provide electricity to the grid in about 2040. Other facilities will be needed to strengthen the programme and reduce risk. One under consideration is a Component Test Facility (CTF), which might be based on the spherical tokamak (ST) concept pioneered at CCFE through experiments on MAST and its predecessor START. In STs the space through the middle of the plasma is much narrower and so they are more compact than conventional tokamaks like JET and ITER.

JET will be the world's leading fusion machine until ITER is operational, and it is envisaged that JET will run until at least 2015. CCFE's role operating JET is described in Chapter 3, and its participation in the JET science programme is described in Chapter 4. As well as JET, it contributes to studies of key issues in tokamak plasma physics research, often as part of EFDA programmes, through experiments on MAST (Chapter 5), and plasma theory and modelling (Chapter 6). These issues are:

- **Confinement:** how efficiently the tokamak contains energy and particles and whether this can be improved, and how impurities are transported;
- **Stability limits:** how high the current, pressure and density can be in the plasma before it becomes unstable; in large machines like ITER there will be a trade-off between maximising these to optimise performance and keeping the plasma stable to avoid rapid terminations ("disruptions") which would damage 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, use of additional heating to drive currents in the plasma may permit regimes

which allow continuous (steady-state) operation which would avoid cyclic stresses and large energy storage systems and therefore be more attractive to power utilities.

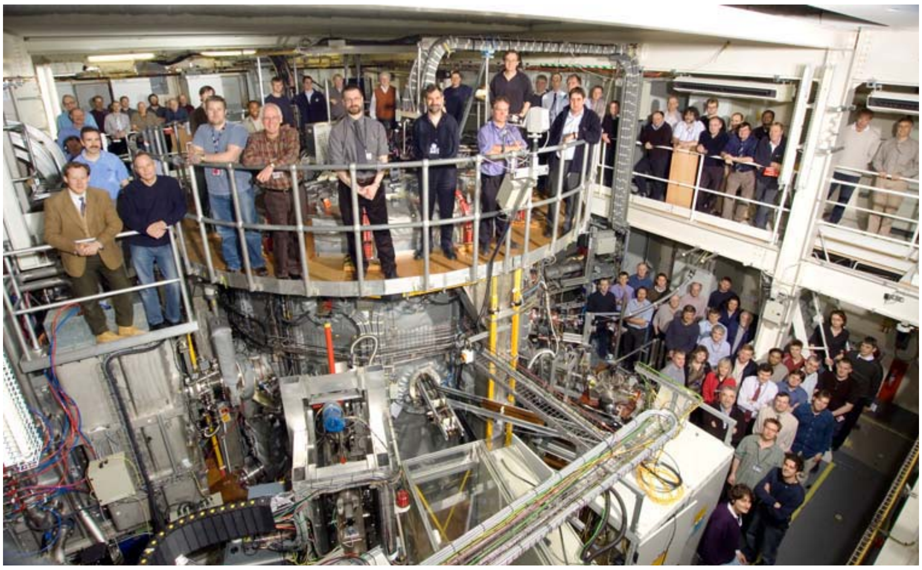

Figure 1.3: *CCFE staff on and around MAST - the vessel has 4 m diameter and 4.4 m height.*

Following a strategic review of fusion by the UK Research Councils[2], EPSRC decided to award CCFE additional funding to help resource a major upgrade of MAST. The project to implement this is under way and is described in Chapter 5. This will mean that when it is completed in 2015 MAST will make stronger contributions to ITER and DEMO physics, including first tests of the promising “Super-X” configuration to handle the high exhaust powers in DEMO, and will allow scientists to study whether the ST approach is indeed suitable for a Component Test Facility.

This review recommended a gradual shift of emphasis from fusion tokamak science to fusion technology. In Chapter 7, we describe our present contributions to understanding and improving the materials and technology needed for fusion power stations, and in Chapter 8 we cover the work we are doing to develop specialist technologies for ITER, which are mainly heating and instrumentation systems.

UK universities make major contributions to the programme, in materials science, plasma physics and engineering. Over twenty now participate in the research, with many having PhD students on fusion projects, either at Culham or at the university. Much of the programme is undertaken in collaboration with other EURATOM Associations (usually via EFDA or F4E programmes) 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. During the year, CCFE had many visits by VIPs, including the local Member of Parliament and the Science Minister, and by schools, universities, professional societies, etc. We held ten open evenings for the general public, with around 100 coming each time. CCFE also staff gave talks and demonstrations to many

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[2] http://www.epsrc.ac.uk/newsevents/news/2010/Pages/energystrategy.aspx

organisations, most notably through our “Sun Dome” outreach facility for schools which is now used by UK universities as well as CCFE.


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Figure 1.4: *The UK Science Minister, David Willetts MP, visited in September and met some of CCFE’s apprentices working on JET.*


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Figure 1.5: *CCFE’s Susan Hayward giving a talk at a local primary school.*

Media interest in fusion and JET and/or MAST was sustained despite both devices having major shutdown periods in the year. Highlights included: the Science Minister David Willetts on BBC Radio’s flagship news programme ‘Today’ supported fusion research and praised the work at Culham; CCFE scientists appeared in a BBC TV ‘Horizon’ documentary on temperature; ‘The Times’ named CCFE Director Steve Cowley as one of the top 100 UK scientists in its ‘Eureka 100 Science List’; and an article by Professor Cowley outlining the case for fusion was published by ‘The Guardian’ in July 2010.

1.2.3 TRAINING

CCFE runs a number of training schemes. We have apprentice technicians and around 40 PhD students, hold the annual Culham Plasma Physics Summer School, award post-doctoral fellowships (some of these also have EFDA Fellowships), and arrange tailored training for new graduates, especially in engineering. CCFE also participates in EFDA “Goal Oriented Training” projects, which are targeted mainly at disciplines needed for ITER.


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Figure 1.6: *In November, CCFE and partner universities held an open day for students considering a PhD in fusion. Over 120 attended. The photo shows CCFE Director Steve Cowley explaining fusion physics to some of the students.*

1.3 JET OPERATIONS

Under EFDA, CCFE has been responsible for the safe operation of JET since January 2000, via the JET Operation Contract which is placed by the European Commission with CCFE and managed by the EFDA Associate Leader for JET, Dr. Francesco Romanelli.

Experiments ceased in October 2009 for a major shut-down for the installation phase of the second JET Enhancement Programme (“EP2”). This EP2 shutdown was completed in May 2011, and therefore spanned the entire period of this report. EP2 comprises 24 projects, ranging from improved diagnostic systems to much larger projects such as the Neutral Beam heating Enhancement and the new all metal (beryllium and tungsten), plasma-facing “ITER-like Wall” (ILW). The ILW will allow experiments with ITER-relevant edge conditions and compatibility with the wall, thus speeding up the early phases of ITER.

The ILW project had two main strands: Engineering Design & Manufacture and Installation Preparation. Because most of the installation was by remote handling the effort involved in tool design and manufacture, procedure preparation, training, etc., was substantial. A feel for the scale of the project can be gained from the facts that 3,360 tiles needed to be installed and that the project received, inspected and accepted 85,273 parts. At the beginning of the reporting year, assembly of tile components into final assemblies was in full swing, and the August deadline for installing the first new tile was met. By the end of 2010, installation was progressing rapidly though a number of anomalies started appearing; the interior of the JET vessel was not exactly as the configuration models showed, which meant tile systems did not fit and needed to be removed for modification. Another major challenge was assembly of the diagnostic conduits which feed thermocouples in the new tiles and need to snake around the machine avoiding existing structures; many modifications were required. Trial assembly was carried out on jig outside the machine, and this paid off with very few installation problems for a complex system of 15 conduit packages and 6 cable looms each with its own remote handling tooling.

Some of the last major items to be delivered were the bulk tungsten tile assemblies. There are fifty modules in all each weighing 60kg. Integration of diagnostics, such as the Langmuir probes, was carried out at JET along with final fit check on a jig.

Figure 1.7: *Trial assembly of diagnostic conduits on a full scale jig.*

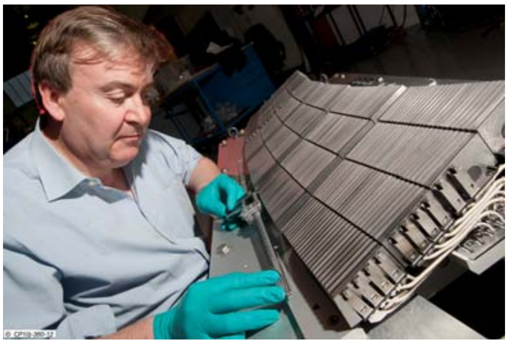

Figure 1.8*: Final fit check of bulk tungsten tiles on a jig.*

The EP2 Shutdown has been the most significant on JET since the early 1990s and required very detailed planning, and sub-division into four Remote Handling and three manual in-vessel phases. The large range of tasks undertaken in these phases is described in Chapter 3. Outside the vessel there were many tasks including installation of EP2 diagnostic enhancements and work associated with the Neutral Beam Enhancement. Aside from the shut-down project, the opportunity was taken to make a number of improvements to the JET facilities. These include a major upgrade to data handling capability, which will be required as the post-shut-down experiments, due to start in late summer 2011, will take much more data than previous JET experiments.

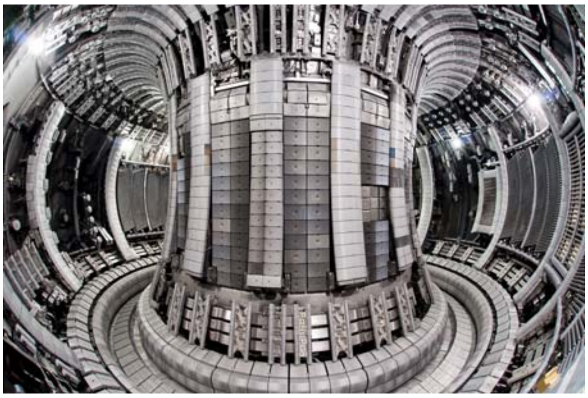

Figure 1.9*: Inside of JET following the shutdown.*

Figure 1.10: *Manual work inside JET.*

1.4 JET STUDIES

The JET research programme is undertaken by staff from all EURATOM fusion Associations working together in the EFDA JET Task Force system. In this section and Chapter 4 we emphasise work where CCFE has had a strong contribution. As JET has been in shutdown for the whole year, the Task Forces have concentrated on analysing and interpreting results from the experimental campaigns before the shutdown, and preparing for operation with the new wall. The analysis has covered a wide range of topics, including plasmas with low power flux to the divertor, development of high performance scenarios for ITER and a power station, other studies for ITER including how to control disruptions, fast particle physics, Edge Localised Modes (ELMs) and their control and RF power coupling. We feature a couple of these in this section.

High power plasmas on JET (and ITER), have the capability to melt metal divertor tiles, even if as in the ILW they are made of tungsten with its high melting point and good thermal conductivity. This means plasmas have to be developed with low power flux at the tiles. A number of techniques can reduce the power on the tiles and several are used on JET. One is seeding the divertor plasma with impurities that radiate energy, to spread the power over a much larger area. Figure 1.11 shows how seeding with neon reduces the load on the outer divertor target. The power between ELMs is reduced dramatically and gives good prospects for handling high power plasmas without damaging the ILW. However, often there is only modest reduction in the heat pulse from ELMs. Therefore these “radiative divertors” will need to be combined on ITER with techniques to mitigate ELMs (being developed on both JET and MAST), and tuning the plasma shape and scenario to find small-ELM even ELM-less regimes. These approaches will be important parts of future JET campaigns. Most of the results to date have used pre-programming of the seeding; future work will use feedback control to improve heat load handling, and probably combine this with sweeping of the strike-points across the divertor targets.

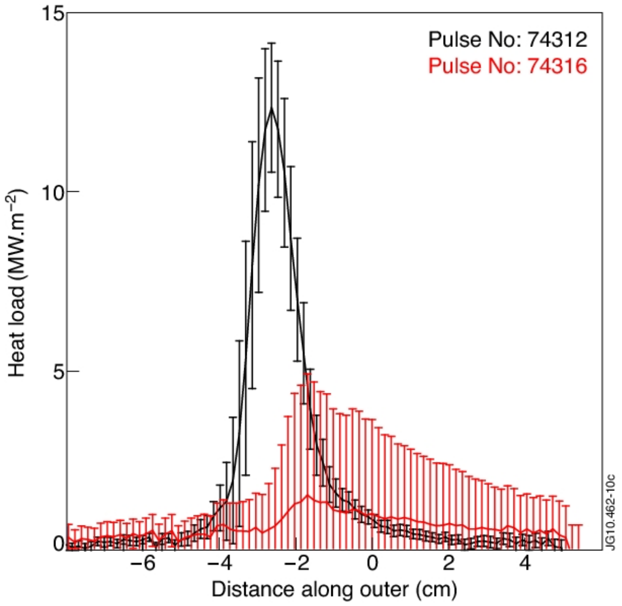

***Figure 1.11:** Use of neon seeding to reduce the power density at the outer divertor target, measured with a high resolution infra-red camera between ELMs. Black: reference discharge. Red: seeded discharge.*

Another way in which plasmas can damage machine components is when they "disrupt" when control of the plasma is lost. Much of the energy (both thermal and electromagnetic) can be deposited on small regions of the machine. In small tokamaks this is of little concern, but in JET damage has occasionally been significant and for ITER it will be more serious still. It is important to understand the most vulnerable areas of the machine and monitor these. Figure 1.12 shows how infra-red pictures reveal where "runaway electrons" hit the wall; these electrons are accelerated to high energy in the disruption process and can leave the plasma in very narrow beams and give hot-spots on the wall. Data like this are used to help the development of mitigation schemes (e.g. by massive gas injection – see section 1.5), and to identify areas to monitor in the ITER-Like Wall.

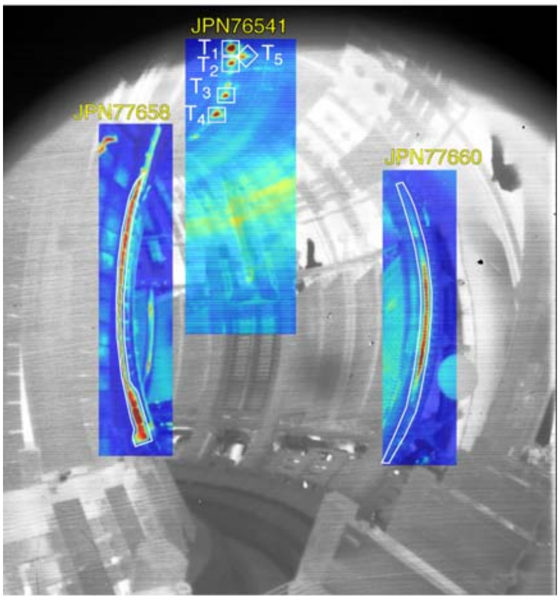

***Figure 1.12**: Plasma facing components in JET as seen by the wide angle view infrared camera. The coloured areas are examples illustrating the regions of interest selected for fast time resolution measurement (1 millisecond): the upper dump plate where runaway electrons cause local hot spots (JET Pulse Number 76541), the inner limiter (JPN 77658) and the outer limiter (JPN 77660).*

1.5 MAST

MAST is one of the two largest spherical tokamaks in the world (the other is NSTX at Princeton, US). Its mission is:

- To explore the long term potential of the spherical tokamak as a fusion component test facility (CTF) and/or ST power plant;
- To advance key tokamak physics for optimal exploitation of ITER and DEMO design optimisation;
- To provide unique insight into underlying tokamak physics.

Much of the work is undertaken in collaboration with other fusion laboratories and universities. Some of the experiments are done in conjunction with similar experiments on other tokamaks around the world, under EFDA and international auspices, to compare and contrast results and thereby strengthen understanding for ITER.

For most of the year MAST was closed to install new equipment and improve existing systems. Additional internal ELM control coils were installed; plasma and neutral beam heating control systems were upgraded; and a controllable high-field-side gas fuelling system was implemented. Several measuring systems (“diagnostics”) were installed or upgraded, many with collaborating organisations, for example: improvements to the neutron detector array (Uppsala University, Sweden); a 2D beam emission spectroscopy system to measure plasma turbulence (RMKI Hungary), electron Bernstein wave imaging to measure the current at the edge of the plasma (University of York); and retarding field energy analysers for ion measurements (Liverpool University). A spark gap impurity injector is also being developed (Dublin City University).

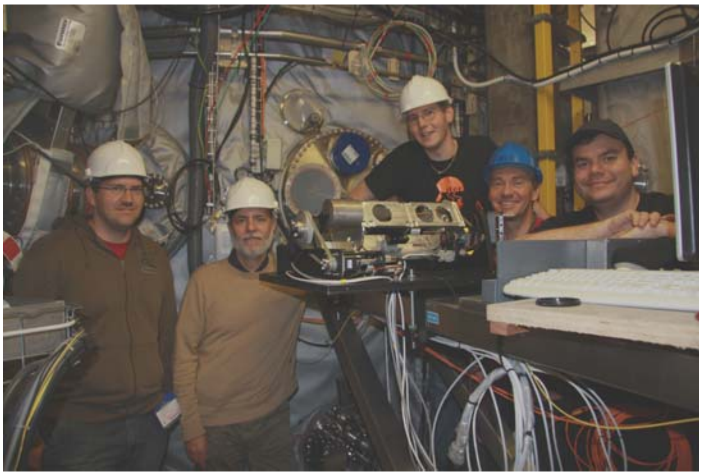

Figure 1.13: *Members of the Hungarian and CCFE team responsible for the new Beam Emission Spectroscopy diagnostic, with the external optical system during installation on MAST in June 2010.*

During the year, the MAST science programme mainly involved analysis of previous experiments. Some highlights follow, with many more described in Chapter 5.

Future devices, such as ITER and a spherical tokamak Component Test Facility, are designed to operate in the high plasma confinement “H-mode” regime, and not the lower confinement “L-mode”. The conditions for entering – and leaving – H-mode are an important area of research. Pellet injection can be more compatible with operating in H-mode than the more usual gas puffing fuelling method. Figure 1.14a shows that raising the plasma density in MAST by injecting pellets from the high magnetic field, inboard side results in a transition into H-mode while the plasma stays in L-mode if the fuelling is by outboard gas puffing.

The favourable effect of pellet fuelling is also seen when the density is increased during H-mode: with pellet fuelling, the plasma remains in H-mode while gas puffing causes a transition to L-mode (Figure 1.14b). This demonstrates that the method of fuelling can be one of the variables controlling H-mode access in contrast to conventional formulae used to calculate the heating power needed to access H-mode in ITER, which do not incorporate this effect.

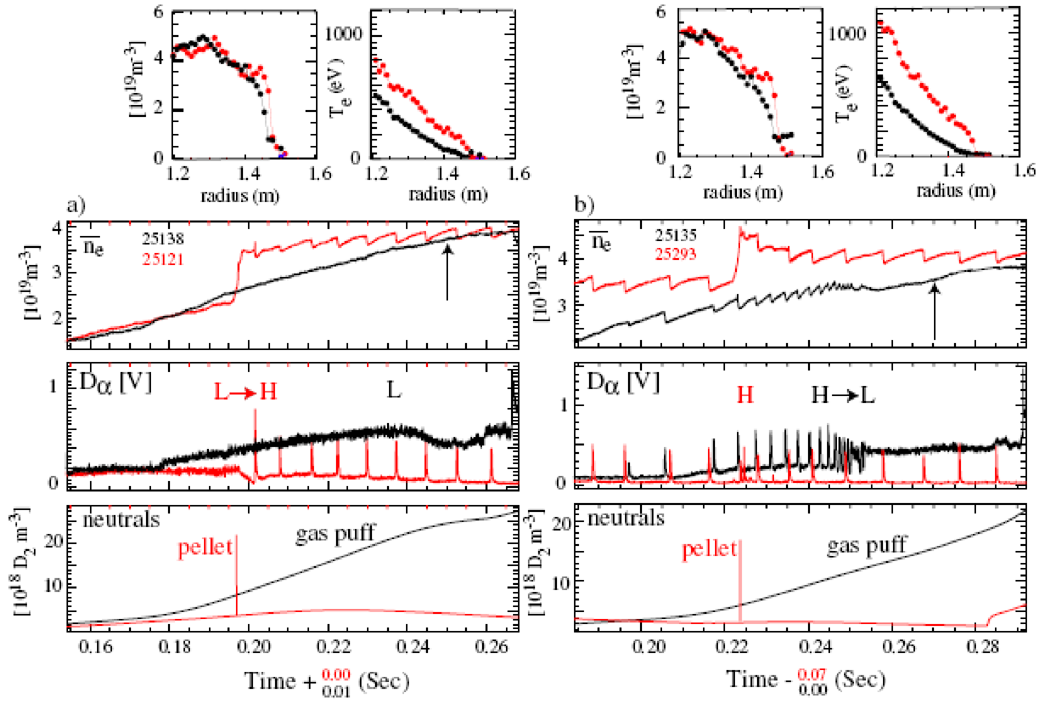

Figure 1.14: *Effect of fuelling method on L-H (a) and H-L (b) transition. High field side pellet (red) and low field side gas puff (black) were used. Top panels show edge electron density and temperature profiles at times indicated by arrows. Note time offsets.*

Presently the most urgent area of tokamak plasma research is investigating how best to reduce the effects of Edge Localised Mode (ELM) instabilities in ITER, where a sophisticated control system will be needed to prevent ELMs damaging expensive components. MAST is one of the best equipped experiments to study this, with excellent diagnostics in the key pedestal region, and a set of internal coils for perturbing the edge magnetic structure and thereby modifying ELM behaviour. A wide range of experiments has been undertaken, reported in Chapter 5, and more will be conducted with the newly installed extra ELM control coils. These have shown that the effect of these coils on the plasma is not straightforward. In particular, it had been thought that how the Chirikov parameter varies across the edge of the plasma was key in determining whether the coils affect ELMs (as the currents in the coils are increased this parameter rises until a threshold is reached when the magnetic field becomes stochastic rather than ordered). MAST experiments have, however, shown that the coils can have very different effects even if the Chirikov parameter profile is the same. Modelling of this is continuing; it is apparent that plasma effects have to be taken into account in predicting the randomising effect of the coils, and that simpler "vacuum" calculations are not adequate.

Experiments with the University of York and FZ Jülich (Germany) have investigated the use of massive gas injection to mitigate plasma disruptions. A mixture of 10% argon and 90% helium has been used, to bring about a controlled termination of the plasma by radiating away the stored energy. Figure 1.15 shows the power arriving at the MAST divertor, measured by infrared cameras, for an unmitigated and a mitigated disruption. The gas injection decreases the peak divertor power load by approximately 60% and the duration of the power load is shorter. Mitigation of disruptions in a range of discharges has shown that around 40% of the energy is radiated and 40% transported to the divertor (the other 20% is thought to be due to other effects, including losses to areas not measured by the cameras). In comparison, in an unmitigated disruption the divertor receives typically 80 to 90% of the total energy. Further experiments are planned injecting different species. A comparison of mitigation time scales and parameters between MAST, JET and TEXTOR (the tokamak at FZ Jülich), is also intended, aided by all three tokamaks using the same type of injection valve supplied by FZ Jülich.

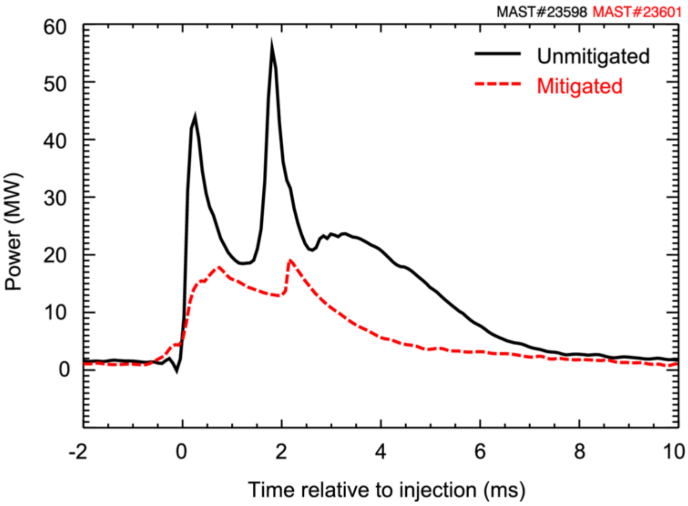

Figure 1.15: *Total power load delivered to the divertor during disruptions on MAST. The dashed red line shows the power load in a mitigated disruption and the solid black line shows the power load in an unmitigated disruption.*

1.51 MAST-UPGRADE

Following the award by EPSRC of extra funding for the purpose, a project to implement Stage 1 of a major upgrade to MAST was formally launched in July 2010 (it is hoped that resources will allow a second stage at a future date). The core scope of this Stage 1 upgrade gives the capability for higher performance, longer pulse plasmas, to allow scientists to address physics validation issues for a Spherical Tokamak Component Test Facility, and undertake more exacting studies of ITER physics and DEMO issues. As well as higher magnetic field and extra heating & current drive capability, the design is capable of fully controlled, closed and pumped, divertor operation, and incorporation of a very long leg divertor to test whether the so-called “Super-X” concept can give enough power dissipation to reduce power loads in DEMO to acceptable values. The main changes to MAST to achieve the Stage 1 upgrade are:

- Load Assembly and Power Systems: (new Central Solenoid, Centre Rod, Toroidal Field power supply, chiller system to enable longer pulses, divertor and inboard Poloidal Field coils for ‘standard’ and ‘Super-X’ divertor configurations and associated power supplies, ‘closed’ divertor with carbon fibre targets in the standard and super-X positions, divertor cryopump and associated gas introduction system).
- Neutral Beam (NB) system (increased heating power – with 2,5MW on-axis and 5MW off-axis – by implementing a new double-PINI NB box and moving one of the existing beam lines for off-axis injection).
- In-vessel, divertor and fast-particle diagnostics.
- Infrastructure (liquid Helium / liquid Nitrogen cryoplant and supply lines).

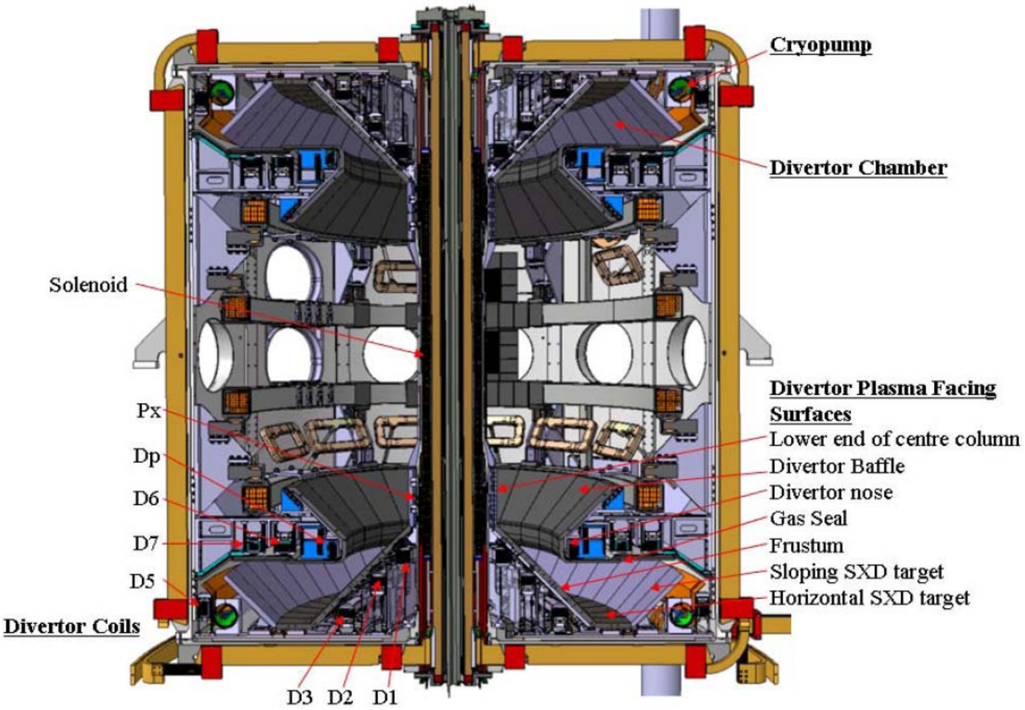

Figure 1.16: *MAST-Upgrade Load Assembly cross-section. The diameter of the vessel is approximately 4 metres.*

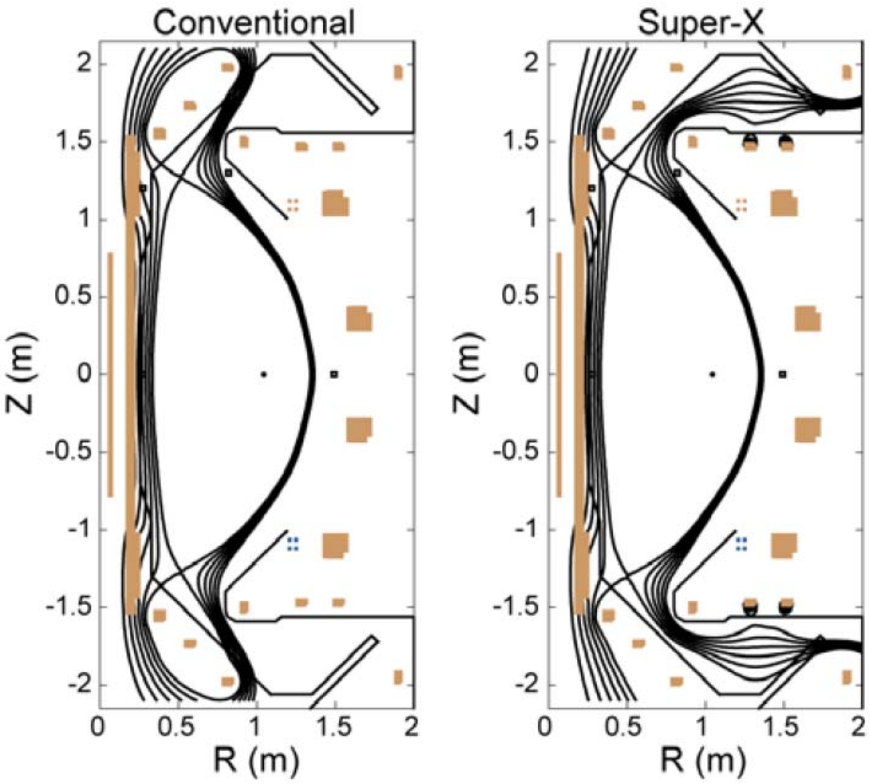

Figure 1.17: *Conventional (left hand side) and Super-X (right hand side) configurations achievable with the upgraded MAST Poloidal Field coil set. In the latter, the divertor coils sweep the divertor plume out to large major radius, resulting in decreased power densities at the divertor target tiles.*

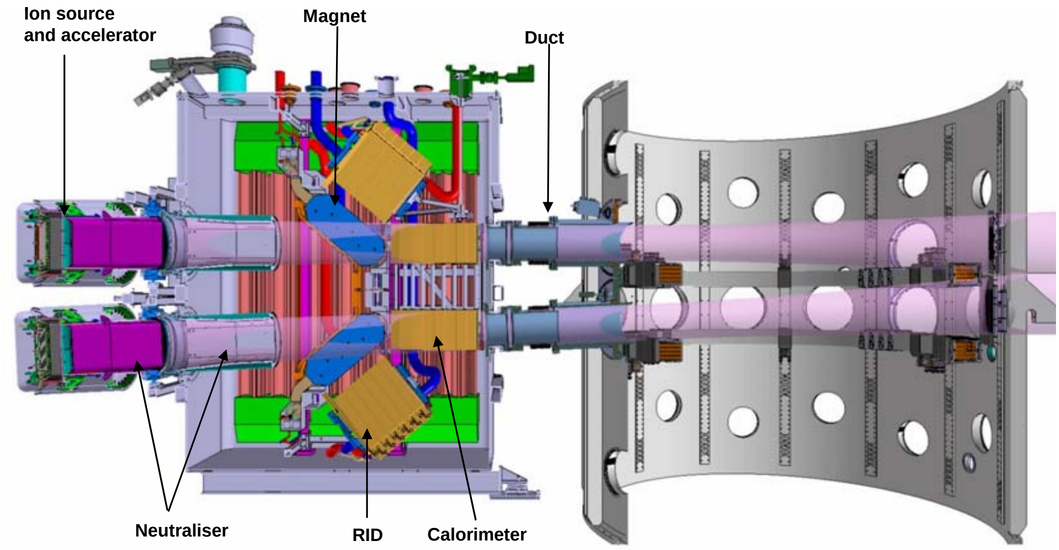

Figure 1.18: *Cutaway elevation of the MAST-Upgrade Double Beam Box design, with MAST vessel.*

The substantial progress with the design is reported in Chapter 5, section 5.5, where the main engineering and physics issues are discussed. In the project schedule, assembly of the many components is due to commence around the end of 2013, with first experiments in 2015. During 2010/11 there have been a number of internal and external project assessments, culminating (in February 2011) in a successful Office of Government Commerce Gateway review.

1.6 THEORY AND MODELLING

The Theory and Modelling Programme provides support to existing devices (e.g. MAST and JET) and contributes to studies of future burning plasma devices such as ITER, CTF and DEMO. It covers many key plasma physics issues that need to be resolved for the successful development of fusion power, in particular: modelling the turbulence mechanisms that underlie the loss of energy from the plasma; avoidance and mitigation of instabilities that can limit plasma performance, or damage the device; and integrated plasma modelling required for developing steady state operational scenarios. The programme benefits from EPSRC and European supercomputers, as well as CCFE's own computers. There are many collaborations, especially with UK universities and other Associations (via EFDA and its Integrated Tokamak Modelling Task Force). Executive Summaries in recent annual reports have concentrated on modelling of turbulence. This year we feature two examples from our work on plasma instabilities.

A resistive wall placed outside the plasma can significantly reduce the growth rate of instabilities which would be stabilized with a perfectly conducting wall. It has been demonstrated theoretically and experimentally that plasma flow can then stabilize the "Resistive Wall Mode" (RWM) completely, allowing higher plasma pressures and thus greater fusion power for a given input cost. We now have codes that can compute the mode stability in present devices under realistic experimental conditions, and to make reasonable predictions for ITER. In particular, the CarMa code can compute RWM growth rates in the presence of both 3D conducting structures (e.g. walls with holes and blanket modules on ITER) and the complicated damping physics in the plasma (due to plasma rotation and kinetic effects induced by mode-particle resonance). Figure 1.19 shows one example of the CarMa computation for an ITER plasma, where the eddy current flow pattern in the inner vacuum vessel, due to the onset of the RWM instability, is plotted. The 3D structures introduce coupling of modes with different toroidal periodicities.

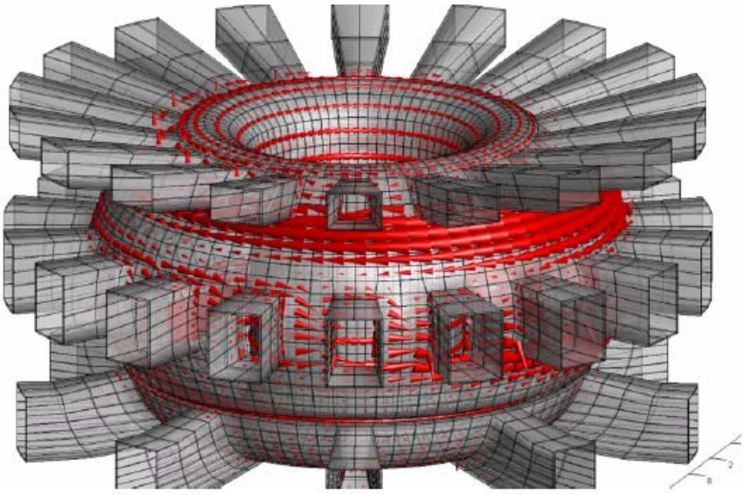

Figure 1.19: *Computation with CARMA of wall eddy currents for an ITER advanced scenario that is unstable to RWMs (work done for F4E in collaboration with the Italian CREATE consortium).*

Today's plasmas heated by neutral beam injection (NBI) can rotate at a significant fraction of the Alfvén speed (the magnetic equivalent of the sound speed), and this rotation can reduce or suppress many plasma instabilities. However, the NBI-driven rotation in ITER and future fusion reactors is likely to be much slower (though the intrinsic plasma rotation is uncertain). Thus, it is important to assess whether the rotation in current devices plays a key role in stability, which may then be absent in ITER. On the other hand, at large rotation velocities as in spherical tokamaks, Kelvin-Helmholtz instabilities can be a concern. Calculations of stability in the presence of strong flows have shown that a spatially varying ("sheared") rotation speed makes the plasma less susceptible to the ideal external kink instability. Since the external kink imposes the ultimate performance limit in tokamaks, optimising the rotation profile to maximise the pressure is attractive for operating future high-performance fusion devices. However, if the toroidal rotation is too high, at a significant fraction of the Alfvén speed, the flow shear drives a Kelvin-Helmholtz global instability, setting an upper limit on the rotation speed for stable plasma operation (an example is given in Figure 1.20). There is therefore an optimum plasma flow speed.

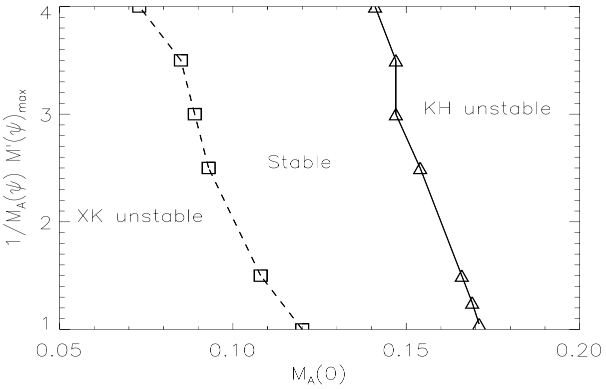

Figure 1.20: *A stable operating space above the no-rotation plasma pressure limits exists in an ITER-like plasma. The external kink (XK) is unstable at low rotation, whilst at very high rotation, Kelvin-Helmholtz (KH) instabilities occur, but there is a window of stable operation at intermediate sheared rotation.*

1.7 MATERIALS AND TECHNOLOGY

CCFE contributes world leading modelling of materials needed for fusion power stations to EFDA programmes, and collaborates extensively with UK universities. It also contributes to EFDA research on the interaction between plasma and materials in the divertor region of JET, and has leading expertise in neutron transport through materials and their activation by neutrons and other radiation. CCFE is making increasing contributions to EFDA power station studies; from 2011 these are being combined into EFDA's Power Plant Physics & Technology programme, which is focused on designing a demonstration plant to follow ITER. Through this decade, CCFE intends to increase its fusion technology contributions, building on work already being undertaken for ITER (Section 1.8). There now follow some highlights from 2010/11; further details are in Chapter 7.

Our **materials** modelling addresses how mechanical properties of structural materials (especially low activation steels) and plasma-facing materials (tungsten and its alloys) are degraded by high energy neutrons from fusion, with validation where possible by experimental work at Oxford University. For example, code calculations, combined with small-scale specimen tests involving ion-irradiated model alloys, provide a way of screening the alloys to determine their suitability for high-temperature applications, and their compatibility with other materials. Extensive simulations of the phase stability of tungsten-tantalum (W-Ta) and tungsten-vanadium (W-V) binary alloys were carried out at CCFE with the Polish and Swiss Associations. Figure 1.21 illustrates some of the findings, related to the phase stability of tungsten alloys and spontaneous formation of vacancy defects at high temperature. It shows that the vacancy formation energy in W-Ta alloys depends sensitively on the lattice site at which a vacancy is formed, whereas in W-V alloys it is almost independent of the position of a vacancy. The results show the possibility of designing alloys where vacancies form within a desired range of temperatures, with potential implications for the development of alloys with improved stability under irradiation.

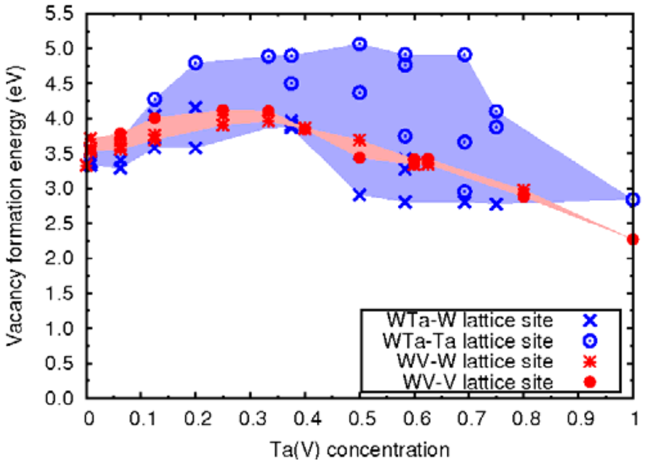

Figure 1.21: *Vacancy formation energies for tungsten-vanadium and tungsten-tantalum alloys derived from* ab initio *density functional calculations.*

In other fusion materials science, "marker" tiles coated with tungsten and beryllium were inserted in JET and exposed to plasmas over many experimental campaigns. Examination of these has been undertaken to ascertain the degree of erosion and deposition. The latest results indicate, *inter alia*, that tungsten coatings on divertor tiles are robust and unlikely to erode unduly when the ITER-like Wall is used in future JET experiments. Also, the shutdown to install the ILW has provided a unique opportunity to collect dust from inside JET. The amount of dust accumulated in different regions of the divertor since 2005 has been calculated by weighing collection containers before and after exposure to plasma.

The results will inform calculations of dust generation in ITER, which is an important issue for the ITER safety case as there can be explosive hazards associated with dust, which can also retain the radioactive fusion fuel, tritium.

In **technology**, CCFE has continued its study of the pros and cons of pulsed and steady-state options for a demonstration ("DEMO") fusion power station. Earlier results from examining the effect of pulsed heat loads suggested there could be a problem with the first wall lifetime. This has been followed up in much more detail and results obtained for three different models of the first wall each using two different coolants. Our calculations have shown that water-cooled versions are likely to achieve lifetimes which can allow operation of pulsed DEMO without the need for too frequent changes of the blanket and first wall, and in this respect are superior to the helium equivalents, which operate at higher temperatures. While this suggests that water is a better option than helium in a pulsed version of DEMO, other important factors influence the choice of coolant – for instance neutron damage to materials, particularly embrittlement, will be more harmful at the lower water-cooled temperatures.

For a steady-state DEMO, a key issue is the choice of technology to sustain the plasma current indefinitely, and how to minimise the power needed for this. The prime candidate is neutral beam heating. A number of effects have been considered including how beam energy and plasma rotation affect performance. At a given rotation speed, the power needed to support the current increases as the energy decreases. Figure 1.22 illustrates this for a particular case and shows how the plasma rotation affects the required power. For instance at a high forward rotation, labelled 0.5, the required power is significantly increased but, if the rotation could be reversed, the power could be decreased. In fact the plasma in DEMO is not expected to rotate at these high speeds, although ways of inducing such rotation are being investigated; however these results are likely to be important for a spherical tokamak Component Test Facility where rotation is expected to be rapid. These results are therefore of more general interest.

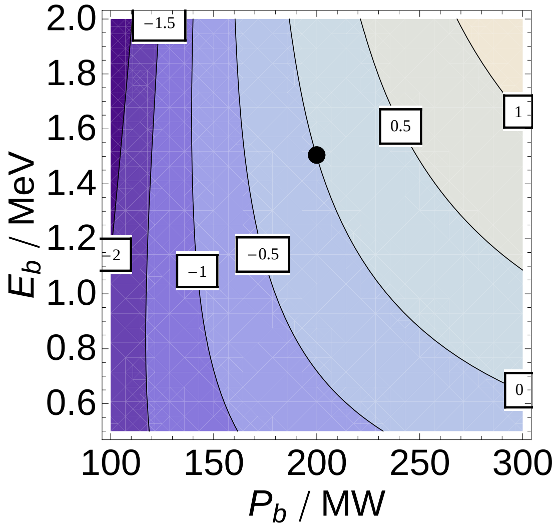

Figure 1.22: *At a given rotation speed, reducing the energy of the neutral beam increases the beam power needed to keep the plasma current flowing (this power drives 56% of 23MA, with the remainder the internal plasma "bootstrap current"). The different contours are at different rotation speeds and show that rotation is an important factor in determining the required neutral beam power (negative contours are for rotation in the opposite direction to the current). If it could be controlled, then current drive would be more easily achieved in a steady-state DEMO. The dot marks the reference point.*

1.8 ITER SYSTEMS

CCFE is developing specialist technology for ITER, mainly via F4E grants[3], where F4E provide approximately 40% of the funding and the remainder comes from EPSRC. CCFE has continued its substantial role in four key ITER systems:

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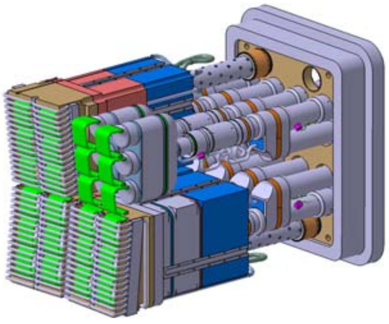
[3] The work by CCFE for F4E is included in this report for completeness, though formally it is not part of the work of the EURATOM/CCFE Fusion Association

- Ion Cyclotron Resonance Frequency heating (ICRF);
- Neutral Beam Injection;
- Core LIDAR Thomson scattering to measure the electron temperature and density profiles;
- Remote handling, in particular the design for the Neutral Beam Hot Cell.

Three of the systems being designed are shown in figures 1.23, 1.24 and 1.25. CCFE is also involved in other F4E grant projects in a more minor way; these and details of the work undertaken for the main projects are provided in Chapter 8. CCFE has also won some fully funded contracts during 2010/11 in first wall design, and control and instrumentation and has continued contract work previously won in areas such as neutronics and radioactive waste analysis.



CATIA Model of the Antenna

Figure 1.23: *Model of the ITER ICRF Antenna design as at March 2011. In 2010/1, development of this 3D CATIA model concentrated on the front housing and the Removable Vacuum Transmission Lines. The antenna straps that will face the ITER plasma are to the left of the picture. CCFE leads the consortium comprising the design team which is located at Culham (the other members are from Belgium and France).*

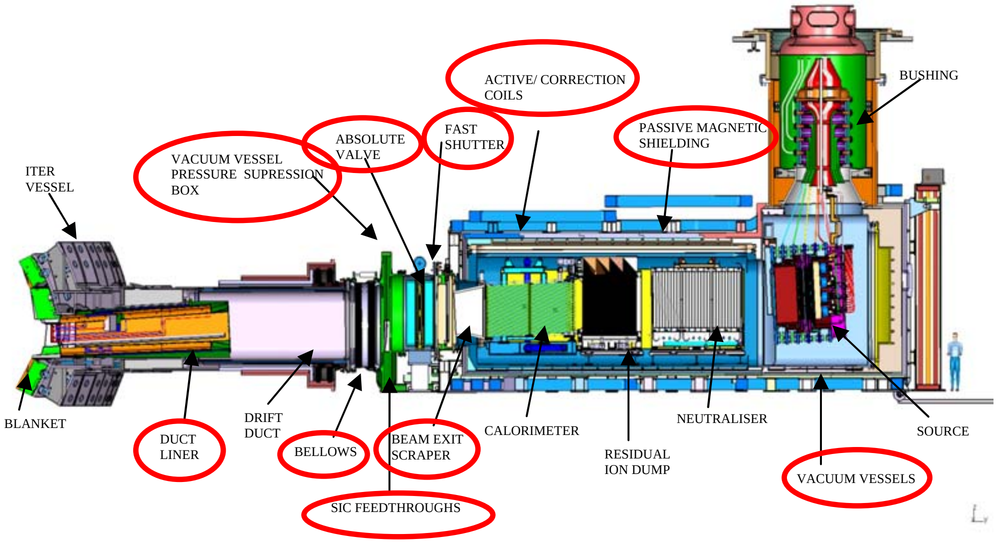


Figure 1.24: *With CIEMAT (Spain) as third party, CCFE has an F4E grant to design the components which will integrate the neutral beam system with the ITER assembly. In this picture of the beam-line, the integration subsystems are highlighted. In other neutral beam work, CCFE is third party to the Italian RFX consortium for the design of components for the MITICA neutral beam test bed to be built in Italy.*

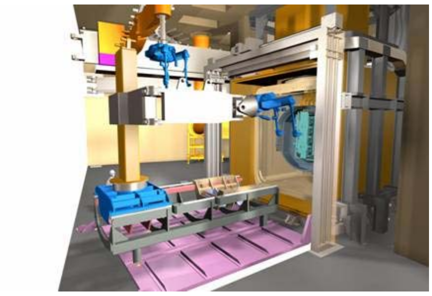


Figure 1.25: *CCFE has an F4E grant to complete the conceptual design of the remote handling equipment of the Neutral Beam Cell in ITER. The image was generated during the Virtual Reality simulations used to validate the maintenance methodology of the accelerator source of the ITER NB heating system.*

1.9 INDUSTRY

The main near-term benefits of fusion research arise from the many high-tech contracts that are placed with industry, particularly for the construction of ITER. For several years, CCFE has had an industry programme to encourage UK companies to consider bidding for ITER contracts, and many have done so – including many new to fusion. To date, we know that at least 150M€ of ITER business has been placed with UK companies, by the ITER International Organisation and Fusion for Energy (F4E, Europe's Domestic Agency); examples are given in Chapter 9. During the year, the UK Science minister, David Willetts MP, met the head of CCFE, Professor Steve Cowley, and stressed the importance of this industrial benefit. When Mr. Willetts later visited Culham, he met directors from four major UK firms with ITER contracts, who emphasised the importance of this work for their companies.

We link to industry in many ways. We have a dedicated website (www.fusion.org.uk/industry) and a database of companies who receive regular 'e-news' of contract opportunities and the electronic newsletter *Fusion Business*. We visit many companies and invite others to Culham to meet our engineers who can explain fusion's and ITER's needs. In September, with support from UK Trade & Investment, we held an event 'Business Opportunities for UK plc from fusion & ITER'. The presentations (at http://www.fusioniteropportunities.org.uk/) were from representatives from the ITER International Organisation and F4E, and from companies with ITER contracts. This event was attended by over 175 people from over 100 companies.

One of our roles is to help UK companies partner with firms from mainland Europe; this is mainly done via the network of European fusion Industry Liaison Officers ("ILOs") who meet regularly with F4E to understand forthcoming opportunities and raise issues from their countries' companies.

During the year, around 30 companies exhibited in our main foyer, where they showed their products to fusion scientists and engineers and to staff from the many high-tech companies also on the Culham site. We also host each year a Technology & Innovation exhibition, which promotes engineering equipment and associated services at nuclear and other sites around the country.

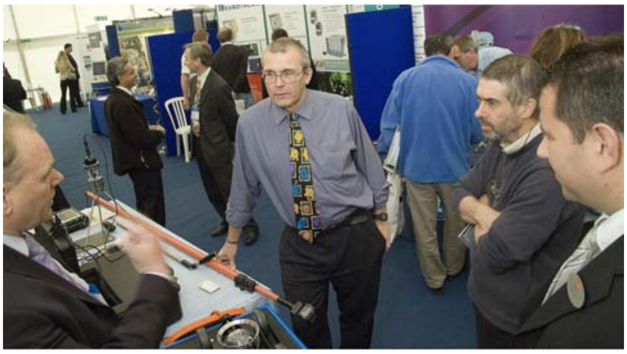


Figure 1.26: *The annual Technology & Innovation Exhibition at Culham attracted a record 350 visitors. Thirty-one companies were on show.*