8 ITER Systems

8.1 OVERVIEW

For ITER to achieve its goals it needs high performance heating and current drive systems to drive the plasma, and very effective and reliable measurement systems (‘diagnostics’) to measure, control and thus optimise the plasma. These systems are based on many years experience built up in the fusion laboratories around the world, and as a result it has been decided that the development and design of the specific systems for ITER should be done in these same laboratories, before the systems or components are procured from specialist industries. The various ITER parties have been allocated these specialised systems to be delivered ‘in kind’. Europe has a large number of them. This work was managed by EFDA, but is now the responsibility of the new ‘Fusion for Energy’ agency (F4E) in Barcelona. Our participation is mainly via F4E grants (funded 40% by F4E, 60% by our UK funding agency EPSRC) but some work will also be undertaken via contracts (funded 100% by F4E). Note that 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.

UKAEA has substantial roles in four systems, two diagnostics and two heating systems:

- core LIDAR Thomson scattering to measure the electron temperature and density profiles;
- core charge exchange recombination spectroscopy to measure the helium (ash) content, the ion temperature and flow;
- ion cyclotron resonance heating (ICRH) system;
- neutral beam injection system.

As part of the work on the LIDAR system, where UKAEA hopes to be the Lead Party for integrating other diagnostics into the relevant ‘Diagnostic Port Plug’, the Association has been active in a substantial engineering activity on the port plug structure (note that the ICRH antenna is also installed in a Port Plug). In order to support our proposed work on LIDAR, UKAEA are therefore aiming to perform engineering design on the ‘generic’ aspects of Diagnostic Port Plugs, although it is not our aim to take this further and become a ‘supplier’ of Port Plug services. The status and progress on all these studies is described in the rest of this chapter.

As indicated above, the control of this work passed from EFDA to F4E in this reporting year, and the work on our last EFDA ITER study contracts came to a close. During this year UKAEA was also awarded F4E Grants. One of these was as a third party to a Grant for which Consorzio RFX (Italy) was the principal beneficiary, for work on design of components for the Neutral Beam Test Facility to be built in Padua. UKAEA has produced the design of the Beamline Calorimeter, following on from the work for EFDA described in the 2007/08 Annual Report. This work was presented to a Design Review at F4E at the end of this reporting period.

Another grant awarded to UKAEA and Consortium Partners at the end of this reporting period involves nuclear data production, and in particular, the updating and maintenance of the European Activation File. This work has hitherto been part of EFDA’s responsibilities, and the work done at Culham as part of this programme is described in Section 7.1 in the Materials chapter of this report.

UKAEA's leading position in this work has been recognised by being the Lead Association for the F4E Grant work on this topic which started in April 2009.

It is also the UKAEA Association's aim to grow its participation in other areas of ITER Systems work. The full realisation of this will require more budget for this area, and UKAEA intends to bid for more funding from EPSRC specifically for this purpose. One of the areas where UKAEA can deploy its strengths is in neutronics work, and the Association has been awarded two F4E Contracts towards the end of this reporting period. One concerns: integrating the ATTILA programme more completely in the ITER neutronics assessment; developing a faster reference source with better angular resolution for both ATTILA and the Monte Carlo MCNP; and developing a suitable algorithm for the conversion of the ITER reference source to ATTILA. The second contract is for a series of simulations to validate the neutronics calculations for various systems and components for ITER. These contracts are for one year in the first instance, but may be renewable.

In previous years, UKAEA has participated in some of the EFDA-led R&D for IFMIF. As IFMIF is now pursued as part of the 'Broader Approach' projects by in-kind contributions of particular EURATOM partners to joint work with the Japanese, and as the UK is not part of the Broader Approach, the work on IFMIF has been discontinued.

8.2 CORE LIDAR THOMSON SCATTERING

8.2.1 INTRODUCTION

Thomson scattering (TS) systems are being designed to be integrated to ITER to use laser scattering to measure electron temperatures substantially higher than in any existing tokamak. This diagnostic technique is needed for a wide range of physics studies, and some real-time plasma control, so high accuracy and, especially, high reliability is needed. The specified errors in such systems are generally between 5% and 10%. Their successful deployment requires that all components maintain adequate performance throughout the lifetime of the experiment or some other appropriate time-scale. This time-scale can be different for different parts of the system; where immediately accessible components can in principle have short maintenance intervals (as little as weeks for out of machine areas), while less accessible components may be required to have very long intervals (~5-10 years for some in-machine components). The parameters accessed by ITER will lead to very different operating conditions from present devices. Amongst the new challenges are the high dose neutron environment, in-vacuum mirrors and the extremely long plasma discharges.

The main systems being considered for ITER include the mid-plane core TS system (to be provided to ITER by the EU) using two general techniques to get spatial information – LIDAR using time-resolved detection of backscattered light from very short laser pulses, and imaging systems where the laser beam is viewed from an angle. It is Culham's intention to lead a Consortium for F4E to design, supervise procurement, and commission the ITER Core LIDAR system.

Detailed measurement requirements are given in the ITER Diagnostics Table of Requirements. To support the measurements at the highest temperatures, work to examine the robustness of TS theory for ITER operating scenarios has been carried out. Key items in all the systems will be the lasers used to illuminate the plasma and the efficiency of light collection and detection. For the light collection, the first mirror must endure challenging conditions. A generic approach to this problem is being addressed in Russia. For the light detection, suitable detectors with demanding bandwidth are required. The design of these systems for ITER requires urgent R&D in many areas.

8.2.2 CORE TEMPERATURE AND DENSITY MEASUREMENTS

The limited access in ITER means that the laser and collection optics need to be in the same port, see Figure 8.1. The laser entry is positioned to ensure that the critical input window is well clear of the plasma environment. The performance goals are demanding and require a fully integrated approach to the design. For example the core LIDAR system measures backscattered light which is strongly blue-shifted at the high temperatures. This has led to a long wavelength laser (e.g. Nd:YAG at 1,064 nm) being favoured, and even this requires the collection optics to transmit into the near UV (~300 nm ideally). This very wide spectral range has a critical effect on the optical system and the detectors, which can be met with the use of rhodium or equivalent material for the first collection mirror, and development of fast high efficiency detectors in the near infra-red (850-1,300 nm). At shorter wavelengths efficient fast detectors exist and need only modest improvement (some are already well proven from use on the JET LIDAR systems). State of the art detectors in the >850 nm near-infrared spectral region have many of the physics attributes required for use in the LIDAR system (sensitivity, area) but these are not presently developed enough for use on ITER. Two types of detectors are required for this spectral range but for use in ITER LIDAR TS both require some technology advancements. The first is based on the technology of the present night vision image intensifiers: by carefully controlling the composition of the ternary alloy $In_xGa_{1-x}As$ it appears possible to produce NIR photocathodes with a quantum efficiency (QE) of the order of 5% up to a cut-off wavelength of ~1,000 nm. The second is based on the technology of the transferred electron (TE) detector. These devices use an active, externally biased, InGaAsP/InP photocathode with a QE in excess of 25% up to λ=1,330 nm, but require substantial improvements to the speed and active area to achieve the required characteristics.

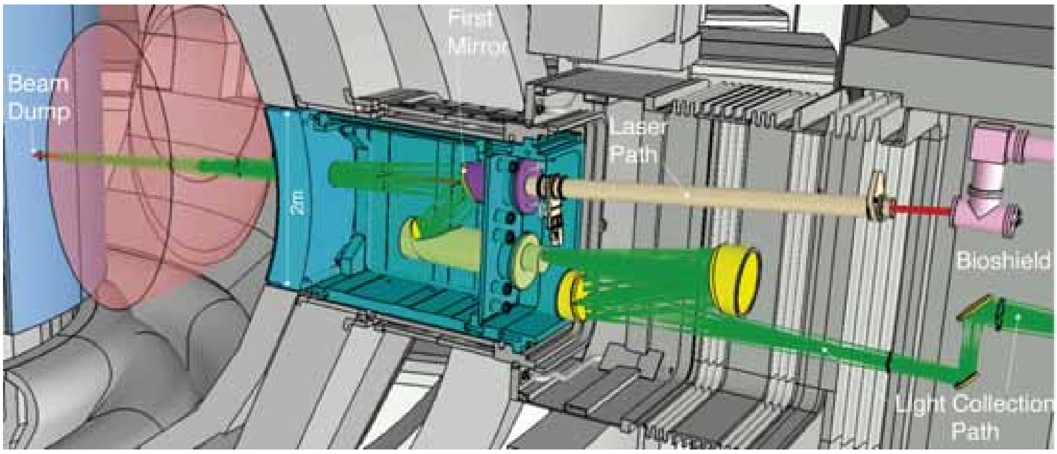

Figure 8.1: *Core LIDAR TS system showing the laser launcher and the light collection path from the plasma*

Special tools have been developed to analyse the performance of the complete system from laser to detector, with all the spectral and transmission characteristics utilised. A Monte Carlo technique is used to estimate the resultant accuracy, and an example is shown in Figure 8.2 for the core LIDAR where a combination of a 5 J, 250 ps laser pulse, ~250-300 ps response time detectors of 4-5 types to cover the spectral range, and an optimised 6-8 channel polychromator allows the target accuracy and space resolution to be met. The ITER specification of 10 ms time resolution is based on several arguments (e.g. instability and transport analysis, same order as the actuator time) is a challenging target for such a high energy laser. At present, the plan is to achieve the specification by utilising a number of lasers. Estimations suggest that 15 Hz versions could be realisable; hence seven lasers would be required. For the core LIDAR system, reliability is of paramount importance and redundancy in design must be incorporated where possible. Typical operation of a multi-laser system on the MAST device has shown that out of four lasers, at least one laser was available almost 100% of the time while all four lasers were available >70% of the time (this corresponds to an individual laser availability of about 92% per plasma shot). Translating this simply to ITER would give five or more lasers available more than 98% of the time, but all seven lasers only 56% of the time.

It has been shown by detailed neutronics studies, backed up by irradiations, that even with many years of ITER operation, silica (e.g. the Russian-developed KU-1 material) retains good transmission across the spectral band for the core LIDAR, and adequately low absorption to be used as a laser window.

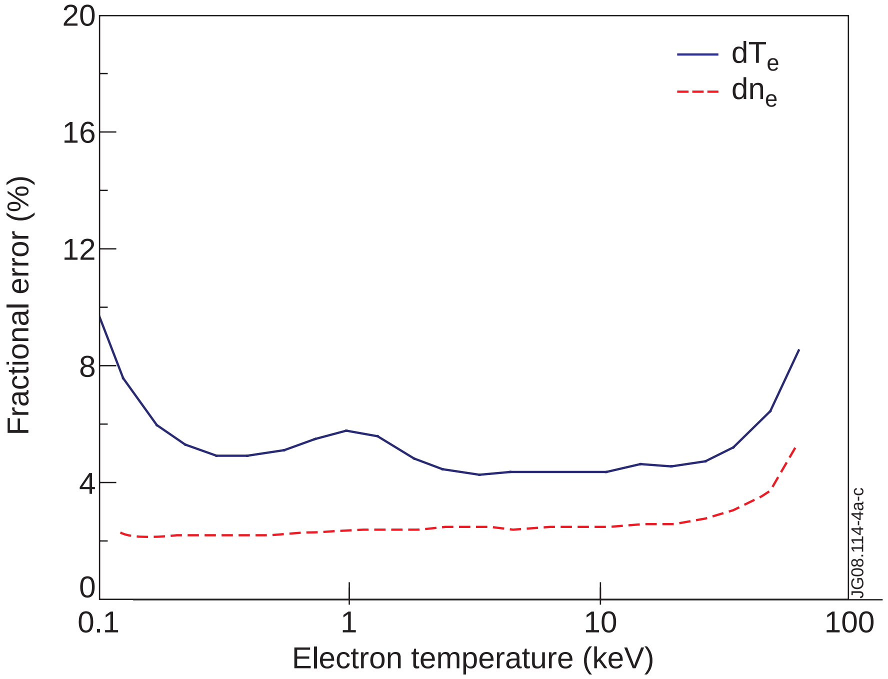

Figure 8.2: *Fractional error in temperature and density as a function of temperature in the ITER plasma (electron density,* $n_e=3x10^{19}m^{-3}$*). The system comprises of a 5 J, 250 ps laser pulse, ~250-300 ps response time detectors of 4-5 types to cover the spectral range (including IR TE detectors). The spectrometer is optimised for 6-8 channels*

8.2.3 GENERAL

To maintain successful continuously calibrated measurements in ITER, all the TS systems will require a range of techniques from mirror surface recovery and deposition prevention to wide-band in-situ calibrations. For example, an issue common to TS and several other optical diagnostics on ITER is the plasma facing mirror. While rhodium (as a coating) has the required spectral range for the core LIDAR, it is, like any material, subject to erosion and deposition by the plasma, causing its reflectivity and spectral response to change in time. A combination of in-situ calibration, deposition prevention and optics cleaning techniques needs to be developed. While the core TS system is expected to use a dielectric laser mirror, this is not possible in all of the TS systems. An assessment of in-vessel metallic mirror materials for the transmission of the laser beam used in the ITER edge Thomson scattering diagnostics has also been studied. For candidate mirror materials a comparison has been made between the numerical calculation and data relevant to the laser-induced damage threshold. Successful deployment of the TS systems in ITER will require significant offline testing to ensure an efficient transfer from the build to the tokamak.

Significant progress has been made in several areas of the TS diagnostic development for ITER. This includes theory, laser, detector and many aspects of the system design. The modelling shows that, based on present estimates of the performance of individual components, in principle the systems can achieve the measurement accuracy and spatial resolution required, but with relatively little margin. Further work, backed up by testing is required in the areas indicated to ensure that reliable systems can be deployed. Critical areas such as first mirrors, calibration, lasers and detectors need further work relatively urgently.

UKAEA currently holds the Chair of the ITPA Thomson Scattering Working Group. During 2008, a review of all the Thomson scattering systems proposed for ITER, looking from the system performance perspective, was carried out. This work was presented at the 2008 IAEA Fusion Energy Conference in Geneva.

8.2.4 NEXT STEPS

The next critical steps in this project are to set up the Consortium agreement with the other interested European fusion organisations and prepare for the official F4E Grant bid call for proposals. Hitherto, a draft Consortium agreement has been circulated and a date for detailed discussions has been set. An F4E Grant call is expected to arrive towards the end of 2009, and the Consortium will need to make a detailed bid for this work.

8.3 CHARGE EXCHANGE RECOMBINATION SPECTROSCOPY

ITER will be equipped with a diagnostic neutral beam (DNB), injecting 100 keV hydrogen atoms. Electron transfer (charge exchange) from these hydrogen atoms to impurity ions in the plasma results in light emission from these impurities. Spectroscopic analysis of this emission yields measurements of the plasma ion temperature and flow speed. The intensity of the spectral emission is dependent on the quantity of impurity in the plasma and on the intensity of the neutral beam. The beam undergoes strong attenuation as it travels through the plasma and so an independent measurement of the beam density is necessary for the interpretation of charge exchange signals in terms of impurity concentrations. This measurement comes from the Doppler shifted D_α emission from the moving beam particles and dedicated spectrometer channels will be used for this measurement. The motion of the beam particles through the ITER magnetic field causes a splitting and polarisation of the emission line. It is necessary to understand the processes affecting the spectrum shape both to design the optimum detection system and (ultimately) to interpret the data coming from ITER.

Work on this system is led by German (FZJ) and Dutch (FOM) laboratories. UKAEA is participating in some of the physics studies. A simulation code, originally developed for the design of the MAST Motional Stark Effect diagnostic, has been used to make detailed predictions of the beam emission spectrum from the ITER DNB. This code is able to model the effects on the spectrum due to a number of influences. The most important are those due to the large range of velocity vectors of particles in the beam and to any voltage ripple on the electrical power supplies operating the DNB. Simulated spectra from this code are shown in Figure 8.3. Results of this work indicate that the diagnostic performance will not suffer even if the voltage ripple on the DNB power supplies is as much as 15%, which will allow ITER to use relatively low specification power supplies, resulting in a cost saving for the project.

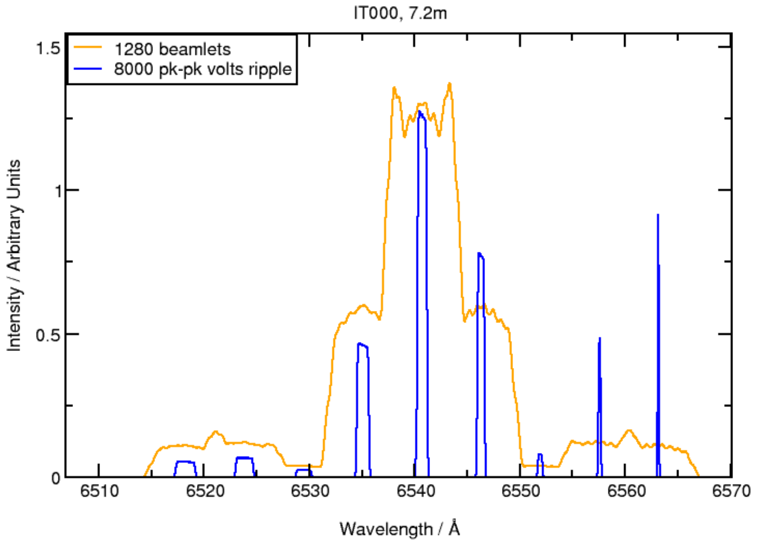

Figure 8.3: *Numerical simulation of the emission spectrum from the ITER diagnostic neutral beam showing the effect of two particular line broadening mechanisms. In orange the combined emission due to all of the 1,280 beamlet apertures. In blue, the spectrum from a single beamlet with broadening due to an 8 kV ripple on the beam power supply*

8.4 ITER ION CYCLOTRON RESONANCE HEATING (ICRH)

ICRH involves the launching of high power radio waves, at frequencies in the tens of MHz, that are primarily absorbed by minority ion populations in the plasma, which are heated and then lose their energy in collisions with the majority plasma ion population and electrons, thus heating the plasma.

UKAEA has been involved in key upgrades to the JET ICRH system (Chapters 3 and 4), and as a result has developed a leading position in Europe in ICRH design and build. In previous years (as reported in the 2005/06, 2006/07 and 2007/08 Annual Reports), UKAEA and collaborators have performed many EFDA Design Tasks on the ITER ICRH antenna proposal. The ICRH Antenna will be part of the EU contribution to ITER. During 2008/09, UKAEA has continued to develop the concept design, primarily in the area of mechanical engineering, and played a major role in completing the process of forming a consortium to bid for antenna design tasks.

8.4.1 ITER ANTENNA DESIGN ACTIVITIES

A significant slowdown in design activities applied throughout 2008-09 due to delays in funding for the next phase of the design and R&D.

Despite this slowdown, the UKAEA team was able to advance the design in the following areas:

- the geometries of the RF straps/feeders and the service stubs within the Removable Vacuum Transmission Lines, proposed by UKAEA during 2007, were further developed in conjunction with the Ecole Royale Militaire in Brussels. The outcome of this collaborative design effort was much-improved relative power coupled from the antenna shown in Figure 8.4 (the green and red curves show the predicted coupled power prior to and post optimisation respectively). This optimisation has raised the power reaching the plasma significantly, and has considerably flattened the coupled power across the design frequency range of 40 to 55 MHz;

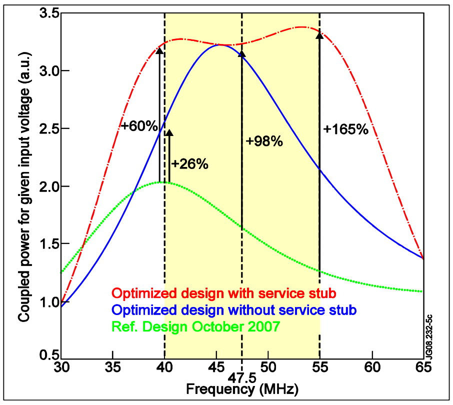

Figure 8.4: *Predicted Coupled Power Before and After Strap and Service Stub Optimisation (Figure provided by Dumortier et al, ERM)*

- UKAEA has continued to assess the use of titanium on the ICRH vacuum window, leading to further definition of the required R&D programme;
- UKAEA played a significant role in proposing an updated design to ITER and F4E at a meeting in Cadarache in June 2008. The resultant design is shown in Figures 8.5 to 8.7;

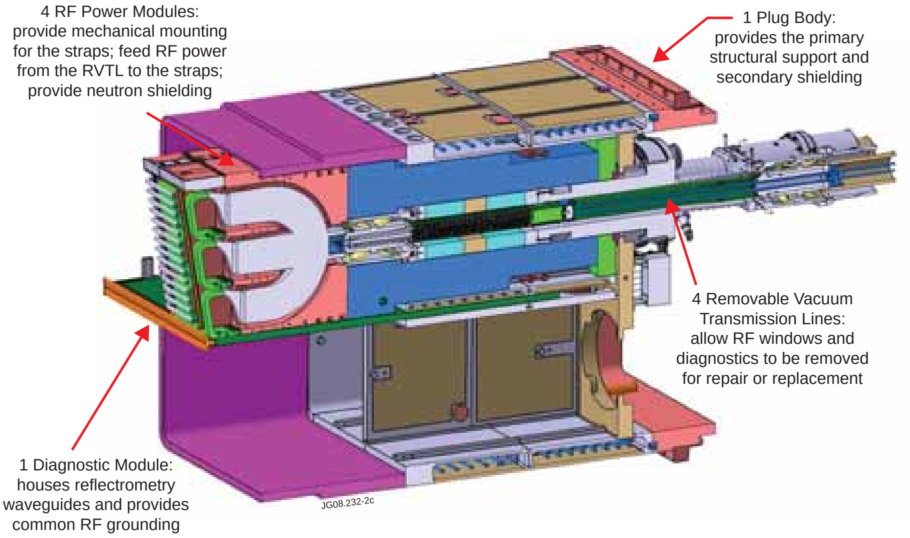

Figure 8.5: *June 2008 Antenna: section through the ITER ICRF Antenna with one RF Power Module (and RVTL) installed*

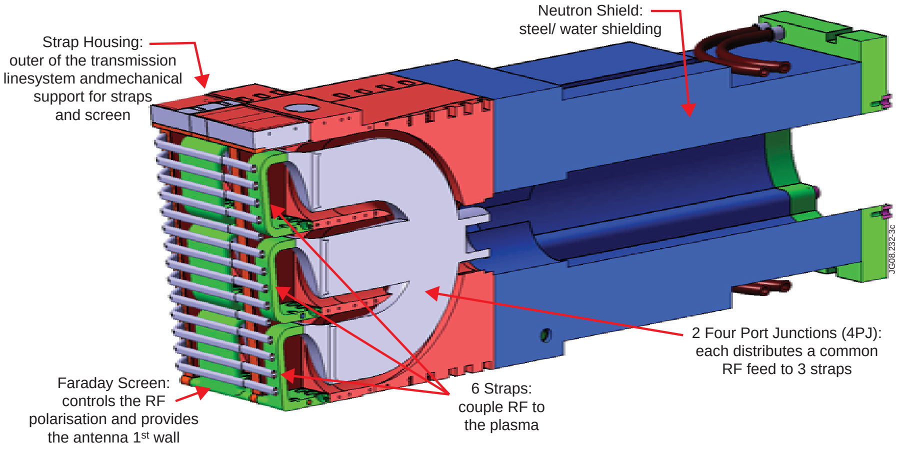

Figure 8.6: *June 2008 Antenna: section through one RF Power Module (RVTL removed)*

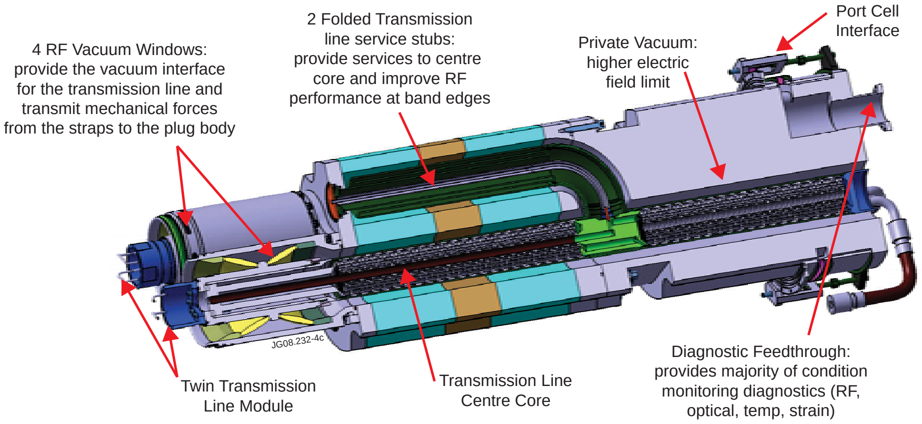

Figure 8.7: *June 2008 Antenna: Section through one Removable Vacuum Transmission Line (RVTL)*

- a proposal for a revised front face design has been put forward to the wider design team (including the ITER Organisation). This has been added to a number of proposed geometry changes that will be considered at the start of the next contractual design contract;
- an initial cooling assessment in March 2007 concluded that it should be feasible to cool the antenna at the expected thermal loads. Further, more detailed, modelling during late 2008 and early 2009 has concluded that achieving the required cooling at acceptable pressure drops could well prove very challenging. Analytic and computer modelling of the flows and pressure drops within the proposed structures is ongoing;
- the use of stripline geometries for the strap feeds and four port junctions has been proposed to the design team in order to overcome fabrication issues foreseen with these components. Optimisation of such designs, to allow a final feasibility decision, is ongoing with the Ecole Royale Militaire in Brussels.

8.4.2 ANTENNA CONCEPTS R&D

Two urgent areas of R&D have been initiated directly with industry to feed into the next round of antenna design reviews.

One contract has been placed to test two potential uses of honeycomb structures within the proposed antenna. In the first case, the feasibility of using a honeycomb design to provide robust straps whilst minimising disruption forces is being tested. In particular, use of such a honeycomb will lead to voids within the straps that need to be evacuated during torus pump down. The present tests will confirm the likely pump-down timescales for such structures. A second use of honeycomb to provide lightweight port plug body panels with high radiation shielding using boron carbide-filled honeycomb is being tested. In this case, the main aim is to establish the feasibility of achieving the required brazing in the presence of boron carbide powder.

A second contract will test the feasibility of using diffusion-bonded structures to achieve a water-cooled shielding system containing a high water fraction that can operate with the water temperatures and pressures up to 150 ° C and 50bar (62.5 bar test pressure). Figure 8.8 shows the output from ANSYS modelling of a small section of the proposed geometry.

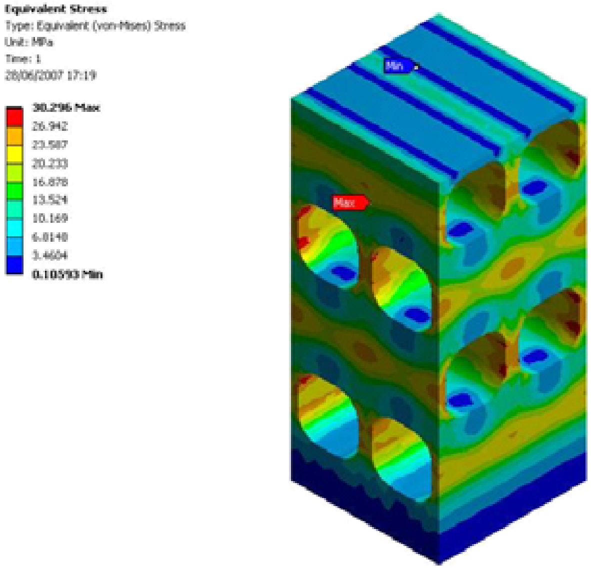

Figure 8.8: *ANSYS Model of stresses in the proposed shielding technology*

8.4.3 NEUTRONICS MODELLING

Neutronics analyses continued on the proposed ITER ICRH antenna during 2008/09. Radiation transport models were created for the MCNP code, in order to perform neutron and photon transport calculations. The nuclear inventory code FISPACT was used to calculate subsequent neutron activation of the ICRH model. The key parameter calculated was the 14-day shutdown gamma ray dose at the rear of the ICRH Port Plug, which was found to be below the ITER stipulated limits after one year of D-T operation. Another parameter of interest was the so-called ‘onload’ nuclear heating which was determined to be 3.46 MW. Also calculated was the fast neutron fluence across the vacuum windows, which was determined to be significantly less than the ITER recommended guidelines. Further work will include improvement of the neutron transport model via automated CAD to MCNP conversion techniques, and further analyses of the shutdown gamma ray dose.

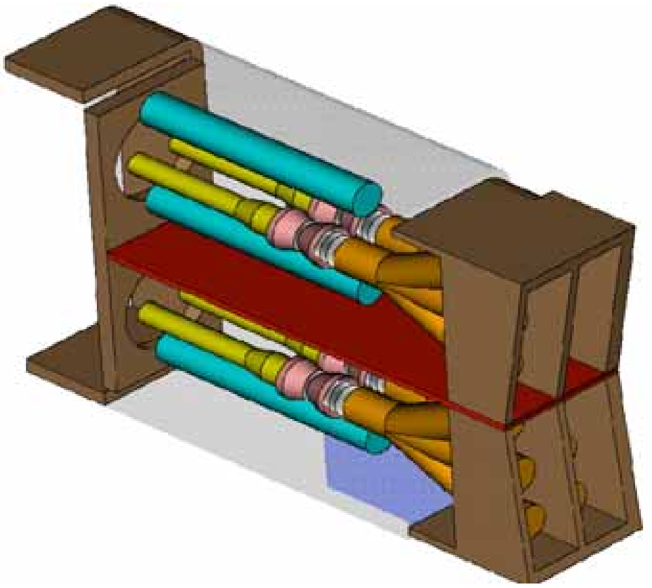

***Figure 8.9:** Neutron Transport model of half of the ICRH system, showing how detailed the model is.*

8.4.4 CYCLE CONSORTIUM

As discussed in previous Annual Reports, UKAEA and several other EU fusion organisations have been in a process of negotiating the formation of a Consortium which would bring together the best EU expertise in order to provide Design and R&D effort for the EU's ICRH contribution to ITER.

The negotiations to form this European consortium have now been completed and an agreement was signed between UKAEA, ERM, Commissariat a l'Energie Atomique (CEA, France), Max Planck Institut fur Plasma Physik (IPP, Germany) and Politecnico di Torino (Italy) in January 2009. It was agreed that UKAEA should be the Lead party in this Consortium. At the time of writing, the Consortium has answered a Design Grant call from F4E, for the first stages of the ITER RF Antenna design. Should the consortium be successful in winning the Grant for the next phase of antenna design, the work will be led by UKAEA.

8.5 ITER NEUTRAL BEAM DUCT LINER DESIGN

As reported in the 2007/08 Annual report, UKAEA received a contract from EFDA in September 2007 for the study of the existing ITER Heating Neutral Beam (HNB) duct liner design and to propose improvements where necessary. This was an urgent ITER Task resulting from the Working Group reviews of Spring 2007. The study involved:

- specifying duct liner requirements by originating a Functional Specification and circulating to F4E and ITER for comment and approval;
- assessment of thermo-mechanical performance of the existing design;
- assessment of the Remote Handling (RH) compatibility of the existing design;
- development of RH features, procedures and tooling for alternative liner design (see below);
- review of relevant documentation, including a check on the potential for copper alloy embrittlement and erosion due to excessive neutron flux;
- physics assessment of the power loading on the Duct Liner, including validation of the 'BTR' trajectory code used.

The work on the first, fifth and sixth bullets was largely completed in the 2007/08 period. Work on the remaining topics was started and completed in 2008/09 and is briefly discussed below.

An alternative concept was developed for the ITER HNB duct liner which satisfies the key thermo-mechanical requirements and incorporates features, procedures and tooling to ensure a level of remote maintainability suitable for its ITER classification.

From a thermo-mechanical perspective, the alternative ‘tapered duct liner’ presented by UKAEA (see Figure 8.10) shows a significant improvement when compared to the reference design. Where it was previously limited to a maximum vertical beam steering of 6 mrad (equivalent to a total of 10 mrad when considering worst case beam misalignment), this new duct concept can fulfil the ITER steering requirement of 9 mrad, with an adequate fatigue Safety factor of 4.25 on the beam facing panels. The modified neutron shield, which is water cooled and protected by copper plates on the side walls, shows a high fatigue Safety factor of 21.

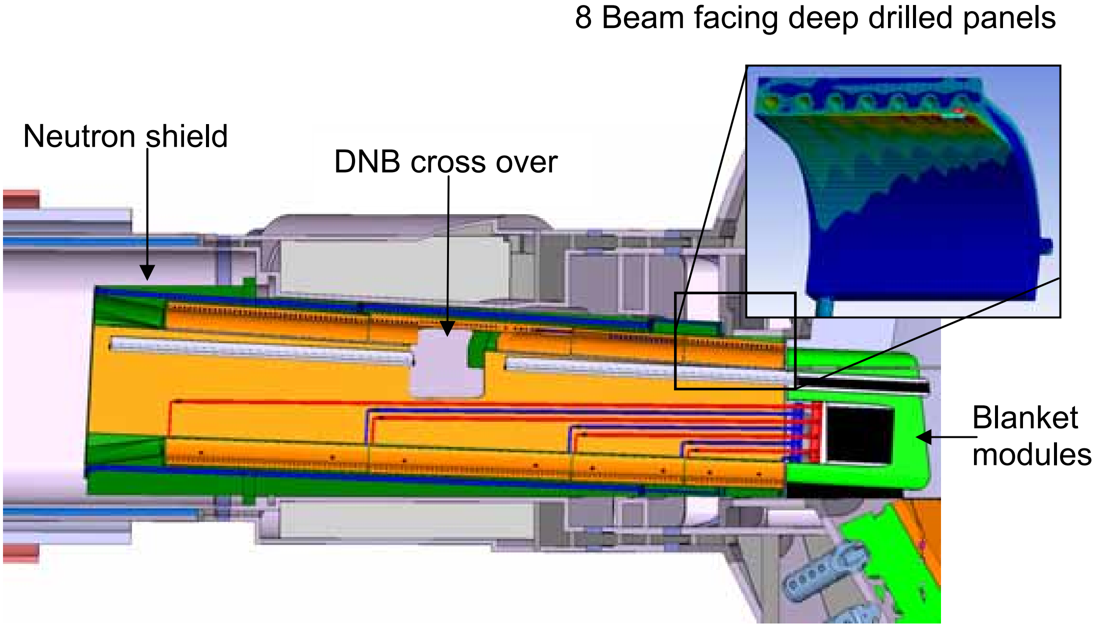

Figure 8.10: *ITER HNB duct assembly*

In addition, Remote Handling (RH) compatibility was considered throughout the design process ensuring realistic maintenance procedures could be developed and proposed to ITER. Specifically, this has been made possible by incorporating a modular duct segmentation and by limiting the number of panels and RH operations. The proposal relies on an in-vessel maintenance strategy whereby the in-vessel transporter coupled with an end effector is used to carry a duct liner module transporter and chassis structure to a specific position adjacent to the NB port (see Figure 8.11).

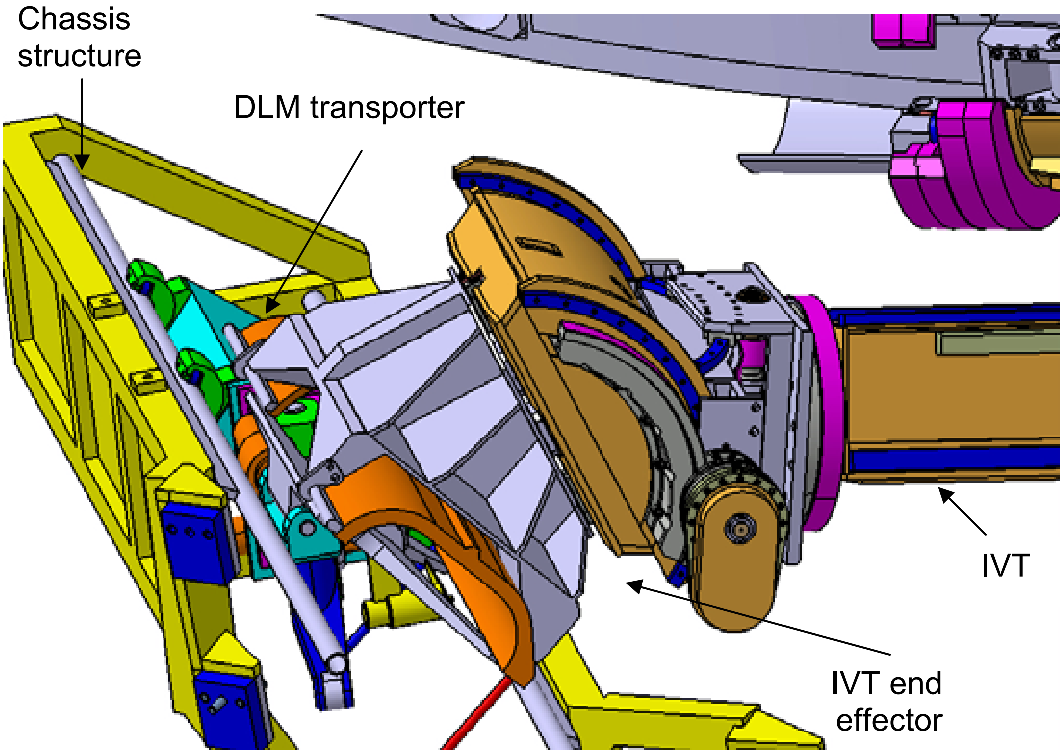

Figure 8.11: *Remote Handling compatibility of the duct liner*

Once in position, this will enable the installation and removal of any of the duct liner panels. Due to the difference in loading and safety margins, the UKAEA study has proposed that the RH classifications for the beam facing panels and the neutron shield should be different. It is suggested that the beam facing panels and feed pipes are RH class 2 whilst the neutron shield and the rest of the structure will remain RH class 3. In the ITER classification [10], RH class 2 components are those classified as *likely* to require repair or replacement, whilst RH class 3 are *not expected* to require repair maintenance or replacement during the lifetime of ITER, but would need to be replaced remotely should they fail. Thus the duct beam-facing panels and feed pipes are in the same ITER category as Blanket Modules and some Diagnostics.

A selective depressurisation system is also proposed, adapted from methods currently used on the JET tokamak, which might help to pin-point any significant water leak (e.g. $1x10^{-3}$ mbar.l.s^{-1}) to a particular panel within the duct. Using permanently installed non-return valves and inverting the water flow within the duct liner, this method should allow successive isolation of each panel. A residual gas detection technique can then be used to detect changes in background pressure, indicating the likely position of the failure. Subsequently, a more conventional and precise in-situ Helium leak detection method would be used to confirm which panel required replacement (detects leak down to 5.10^{-8} mbar.l.s^{-1}).

During this task, it was found that the existing blanket modules surrounding the HNB ports would be exposed to direct beam interception and subjected to power densities of up to 1.8 MW/m^2 when the beam is at its vertical steering limit (this is true for both the reference and alternative duct liner designs). This is unacceptably high and will need to be resolved during the next phase of design (see below).

The UKAEA duct liner concept proposal has been accepted by the ITER Organisation to become the new reference baseline design. Therefore, taken through to the scheme phase of design, a number of outstanding issues will have to be resolved at an early stage. These include consideration of beam blocking scenarios and adequate interlock systems to protect the duct structure integrity, resolving the key interface with the blanket modules and ELM coil system, modifying the design to take account of the new DNB position and examining in more detail the potential for incorporating an ‘early’ leak detection system (such as the proposed depressurisation system). The ITER Korean partner, which will be responsible for the provision of this component, is now in the process of carrying out mock-up trials of some of the manufacturing techniques which are proposed in the UKAEA design, which has aimed everywhere at using robust, industrially-available processes.

8.6 Nb_3Sn SUPERCONDUCTING STRANDS FOR ITER MAGNETS

Superconductivity is the main enabling technology for the ITER fusion tokamak. Without superconductors, more energy would be required to sustain the magnetic fields that confine the plasma than would be produced in the nuclear burning process. About one third of the cost of ITER is the superconducting magnets. Because the high magnetic fields required are as large as ~ 13 Tesla, a brittle superconductor must be used which leads to challenges associated with the strain tolerance and fatigue performance of the composite superconducting strands.

At Durham University, there is a long-standing programme measuring the current density (J_C) that brittle ITER superconducting strands can carry as a function of strain (ε) temperature (T) and magnetic field (B) up to 28 Tesla in Grenoble (Grenoble High Magnetic Field Laboratory) and in-house at Durham up to 15 Tesla. The $J_C(B,T,\varepsilon)$ datasets are parameterized and analysed using a general one-dimensional scaling law which incorporates both microscopic Bardeen-Cooper-Schreiffer and phenomenological Ginzburg-Landau theory. There are interesting issues still to be resolved – for example how to incorporate the inhomogeneities that are inevitable in polycrystalline materials and how to include the three-dimensional nature of strain. Nevertheless, as can be seen in Figure 8.12, $J_C(B,T,\varepsilon)$ is accurately parameterised using the scaling law. Consistency tests have shown that the variable-strain J_C data are homogeneous (±5%) along the length of the strand, and that there is a good agreement between different samples measured in Durham and other European laboratories (at zero applied strain). Limited strain-cycling (fatigue) tests demonstrate that there is no significant degradation in the critical current density in the strands after a small number of cyclic mechanical loads.

By making measurements in magnetic fields up to 28 Tesla in Grenoble, we have measured the upper critical fields of Nb_3Sn strands directly at a temperature of 4.2 K. In Figure 8.13, the normalized effective upper critical field at $T = 0$ ($B^*_{C2}(0,\varepsilon_I)$) as a function of intrinsic strain is displayed for many doped Nb_3Sn strands. The strain dependence of $B^*_{C2}(0,\varepsilon_I)$ for the bronze-route strand (Vac) in Figure 8.13 was found to be less marked than for the advanced strands (OKSC). This is consistent with the higher value of $T^*_C(\varepsilon)$ for the bronze-route material and theoretical considerations that show that as the critical temperature of binary Nb_3Sn is reduced by doping, $B^*_{C2}(0,\varepsilon_1)$) $B^*_{C2}(0,\varepsilon_I)$ becomes more strain sensitive. These results open the possibility that in future, detailed knowledge of the composition or fabrication route for the Nb_3Sn strand will lead to reliable extrapolation of partial $J_C(B,T,\varepsilon)$ data sets and hence better characterisation and optimal utilisation of all types of Nb_3Sn superconducting material.

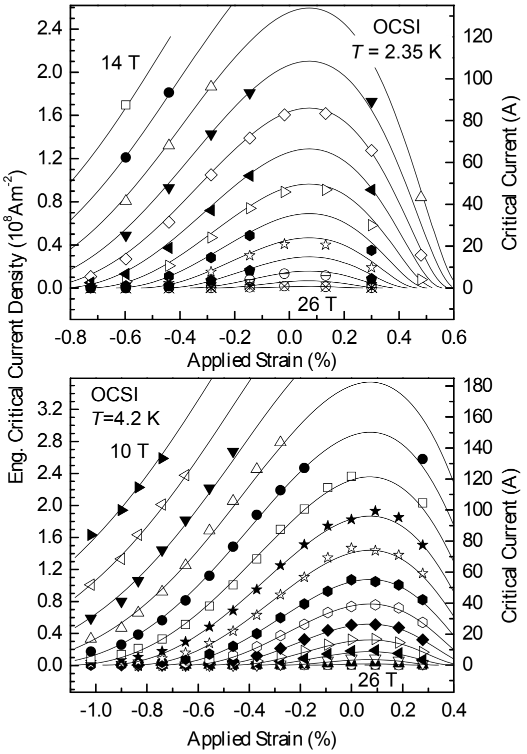

Figure 8.12: *Engineering critical current density (and critical current) as a function of applied strain at temperatures 2.35 K and 4.2 K for a Nb_3Sn strand. The lines are provided using the Durham scaling law.*

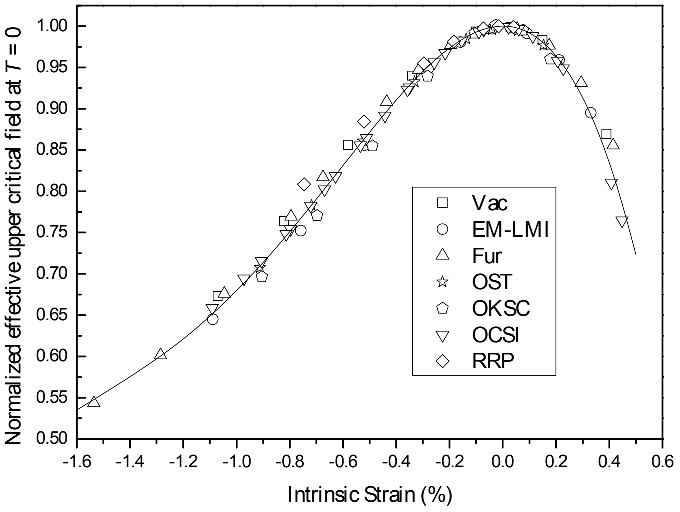

Figure 8.13: *The normalized effective upper critical field at $T = 0$ as a function of intrinsic strain for a large range of doped Nb_3Sn superconducting strands.*