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JET Experiments with Tritium and Deuterium-Tritium Mixtures

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Extensive preparations are now underway for an experiment in the Joint European Torus (JET) using tritium and deuterium-tritium mixtures. The goals of this experiment are described as well as the progress that has been made in developing plasma operational scenarios and physics reference pulses for use in deuterium-tritium and full tritium plasmas. At present, the high performance plasmas to be tested with tritium are based on either a conventional ELMy H-mode at high plasma current and magnetic field (operation at up to 4 MA and 4 T is being prepared) or the so-called improved H-mode or hybrid regime of operation in which high normalised plasma pressure at somewhat reduced plasma current results in enhanced energy confinement. Both of these regimes are being re-developed in conjunction with JET's ITER-like Wall (ILW) of beryllium and tungsten. The influence of the ILW on plasma operation and performance has been substantial. Considerable progress has been made on optimising performance with the all-metal wall. Indeed, operation at the (normalised) ITER reference confinement and pressure has been re-established in JET. In parallel with the physics development, extensive technical preparations are being made to operate JET with tritium. The state and scope of these preparations is reviewed, including the work being done on the safety case for DT operation and on upgrading machine infrastructure and diagnostics. A specific example of the latter is the planned calibration at 14 MeV of JET neutron diagnostics.

Keywords: JET, deuterium, tritium, 14 MeV neutrons.

1. Introduction

As the final phase of its Programme in Support of ITER [1.1], JET is presently preparing for a set of experimental campaigns using tritium and deuterium-tritium mixtures as the plasma fuel. The goal of these experiments is to gain the maximum possible operational experience of a nuclear tokamak as well as a fusion science knowledge base in preparation for ITER.

The fusion science experiments will focus on the effect of fuel isotope on plasma transport and confinement, the physics of fusion alpha particles, ion cyclotron resonance heating schemes in the presence of tritium and the impact of fuel isotope on the evolution of plasma discharges and access to high-performance conditions (so-called scenario development). Comparing DT and T results with those obtained previously in hydrogen and deuterium plasmas will inform the interpretation of ITER results during its non-active phase of operation and their extrapolation to active operation.

Technological objectives associated with nuclear operation include: validation of neutron transport and activation codes; tests of neutron damage to functional materials; gaining experience with tritium handling, retention and recycling; gaining experience with safety in a nuclear fusion environment; and collecting data on waste production and characterisation. A key element of all of these studies will be to provide training and generate know-how in the European fusion community for later application to ITER.

The first use of tritium in JET was in 1991 – the Preliminary Tritium Experiment (PTE) [1.2] – during which tritium was injected into the machine using two of JET's 16 positive ion neutral injectors in two separate discharges. Peak fusion power of 1.7 MW

**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, St. Petersburg, Russia*
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was achieved transiently with an integrated fusion yield of 2 MJ. During PTE, the neutron yield was deliberately limited in order to permit timely modification of the machine and further deuterium experiments. The first extensive use of tritium on JET – Deuterium-Tritium Experiment 1 (DTE1) [1.3,1.4] – was carried out in 1997. At that time, varying DT mixtures from pure deuterium to pure tritium were tested and compared, maximum transient (16 MW) and steady (4 MW) fusion performance was demonstrated and a range of physics studies was undertaken. Most recently, a trace tritium experiment (TTE) was carried out in JET in 2003 [1.5]. At that time, the physics of thermal and fast particle transport in various scenarios and of heating and current drive was studied using plasmas with tritium concentrations of up to 3%.

In addition to the experiments with tritium on JET, TFTR carried out an extensive set of experiments over the full range of DT mixtures from 1993 until the machine's closure in 1997 [1.6,1.7]. As no other machine has had or does have the capability of operation with tritium, these results, supplemented by future DT experiments on JET will be the only experience of nuclear tokamak operation prior to the active phase of ITER operation. Given the long time between the high power DT experiments in JET and TFTR in the 1990s and the foreseen first DT experiments in ITER, an important goal of a further DT experiment on JET (DTE2) is to train scientists and engineers in the operation and exploitation of a nuclear tokamak.

Following the trace tritium experiment, it was decided to dedicate JET operation almost exclusively to the preparation of ITER operation and, in particular, to test the compatibility of high performance regimes of plasma operation with the wall material combination to be used in ITER. For this reason, the plasma-facing components of JET were changed from predominantly carbon-based to a combination of beryllium in the main vacuum chamber next to the hot fusion plasma and tungsten in the divertor. The installation of the new wall was done almost entirely using JET's remote handling system and took place during a shutdown from October 2009 to May 2011 [1.8]. This new configuration is referred to as the ITER-like Wall (ILW). Since that time, considerable progress has been made in characterising operation with the new wall [1.9] and in expanding the range of operation [1.10]. The planned DT experiment will be the culmination of this effort to provide experiments in conditions as close as possible to those foreseen for ITER and thus the best possible preparation and training for ITER. The scope of DTE2 for physics and technology studies is much greater than for previous tritium experiments at JET. The 14 MeV neutron budget for DTE2 is $1.7\text{x}10^{21}$, which is seven times the budget for PTE, DTE1 and TTE combined. The on-site tritium inventory will be increased to 60 g, three times the amount available for DTE1.

2. Objectives of the JET DT Experiment

The objectives of the proposed experiment can be divided, somewhat arbitrarily, into three categories: plasma physics and fusion plasma performance related to operation with tritium; nuclear technology; and operational experience. More details of the plasma physics and fusion performance related goals can be found in [2.1] whilst the technological objectives are described in [2.2]. Highlights of all three sets of objectives are given below.

2.1 Plasma Physics Objectives Related to Operation with Tritium

A key aspect of the JET DT experiment will be to integrate the various aspects of plasma physics and plasma-wall interactions so as to produce a scenario as close as possible to that foreseen for use on ITER. In this regard, since ITER will have to operate at or near to its plasma and wall limits, it is crucial to test the feasibility of this requirement by demonstrating the extent to which JET can be pushed towards its operational limits whilst maintaining compatibility with constraints imposed by the ITER-like Wall. As a figure-of-merit, it is proposed to target operation in ELMy H-mode operation at or near JET's maximum toroidal field and with the safety factor (q_{95}=3), the normalised confinement ($H_{98(y,2)}$=1 [2.3]) and normalised plasma pressure (β_N=1.8) foreseen for ITER Q=10 operation. With these choices, it is predicted that JET should produce 12-13 MW of fusion power. In a similar manner to ITER, JET will test integrated high performance not only with conventional q_{95}=3 ELMy H-modes but also in improved H-mode or hybrid regimes in which the benefits of operating at high poloidal beta will be traded against lower plasma current.

The goal of the integrated performance experiment includes demonstration that this fusion performance is stationary on energy confinement time scales. In the foreseen conditions, both the energy confinement time and the alpha particle slowing down time would be ~0.4 s. Allowing for three confinement times to reach steady conditions and three more in these conditions already requires a high power heating phase of 2.5 s. For comparison, the original target duration with constant conditions in DTE1 was five energy confinement times [2.4]. Subsequent experience from the preparation for DTE1 showed that there was a need for longer heating pulses. For conditions of marginal input power such as those at maximum toroidal field, back transitions from H- to L-mode can take place even several seconds after the high power heating is initiated [2.5]. For these reasons, it is proposed to target flat top high power heating waveforms of at least 5 s in duration, in line with what was done in DTE1 [1.4].

Note that the primary goal is not to achieve a certain fusion power or energy *per se* but rather to demonstrate that the necessary integrated performance, appropriately normalised, can be achieved in conditions as close as possible to those in ITER. Such a discharge would indeed represent a significant step forward in fusion performance as compared to that achieved in DTE1, with an increase in long-pulse fusion power of a factor of three, close to the levels achieved only transiently in previous experiments.

All this needs not only to be achieved in JET but understood well enough to allow confident, model-based extrapolation of the results to ITER. For this reason, an important aspect of all the deuterium-tritium and tritium experiments is validation of physics-based models. For the performance target, key models to be validated include those for core and edge transport, edge stability, impurity transport and power balance, and for first wall power and energy loads, both steady-state and transient.

In addition to the integrated performance objective, an important DTE2 plasma physics objective is the assessment of the effect of fuel isotope composition on energy, particle, impurity and momentum transport and stability. Here the goal is to build on the DTE1 results, which were limited in terms of the number of shots available, the absence of hybrid H-mode data and by the diagnostic capabilities at the time. It was, nonetheless, clear from DTE1 that there are important differences in the dependence of core and edge transport and stability on fuel isotope. DTE2 objectives include:

- Providing an accurate resolution of confinement into core and pedestal contributions; Validation of corresponding transport and stability models.
- Providing high quality confinement and transport data in T, DT for ITER scenario extrapolation.
- Assessing ELM behaviour and mitigation in T and DT; Validation of non-linear ELM models.
- Characterising H-mode access in T & DT
- Testing of tritium-specific ion cyclotron heating schemes
- Assessing fuelling & mixture control in T and DT

This experiment is part of a broader study including pulses in deuterium and hydrogen. The experiment will assess high performance plasmas as well as plasmas in a wide range of operating conditions.

Another DTE2 experiment will be focused on alpha particle physics and heating. Generating fusion powers at the level described above would provide sufficient central alpha heating so as to significantly alter the core pressure and electron power balance. Important by-products of this will be the study of the efficiency of alpha heating in controlling central tungsten accumulation, a job that is done in JET deuterium plasmas primarily by central ion cyclotron resonance heating (ICRH) and the validation of theoretical predictions that the alpha particle pressure leads to stabilisation of ITG turbulence in the plasma core and thereby to improved confinement [2.6-2.8].

Measuring and understanding alpha particle transport and slowing down is crucial to the understanding of plasma self-heating. The goal in DTE2 will be to demonstrate alpha heating in stationary conditions. For this purpose, high temperature ($T_i \geq 10$ keV), high pressure ($\beta_N \geq 2$) and high performance ($P\alpha$=1-3 MW) plasmas are required for a duration of 2-3 seconds, corresponding to 3 alpha particle slowing down times. Such conditions remain to be achieved with the ITER-like Wall and demonstration of this capability in deuterium is a key programme goal in the JET 2015/16 experimental campaigns. Such a plasma would also allow investigation of the anomalous ion heating reported in transient conditions in DTE1 [2.9, 2.10] and, in particular, discriminating between radiative transfer from alpha particles to thermal ions [2.11, 2.12] and fast alpha electromagnetic stabilisation of turbulence [2.6, 2.7] as possible mechanisms for this observation.

The interaction of fusion alpha particles with Alfvén eigenmodes (AEs) will also be studied. For most plasma conditions foreseen for DTE2, AEs are predicted to be stable even in the presence of the (de-stabilising) fast alpha population. JET's active TAE antenna can be used in these circumstances to probe the underlying Alfvén wave spectrum and to assess damping and drive (using opposite toroidal mode numbers). If AEs can be driven unstable in certain plasma conditions, it will be possible to validate energetic particle mode models in fusion-specific conditions. Options for generating such plasma conditions to be tested first in deuterium include internal transport barriers, 'afterglow' experiments in which the alpha drive remains after the stabilising beam fast ions are removed (as used in TFTR [2.13]), mild RF heating of T or D neutral beam injection (NBI) ions to compensate slowdown such as to maintain their energy around 120 keV for maximum beam-thermal fusion reactivity, and bulk ion heating.

A variety of tritium- and DT-specific ion cyclotron heating schemes are required for ITER [2.14, 2.15], have been tested in previous DT experiments in TFTR [2.16] and JET [2.17, 2.18] and will be deployed in DTE2. A crucial element in DTE2 with the ITER-like Wall will be the control of central tungsten accumulation. Along with impurity control, optimised ion heating with ICRH is expected to be an ingredient in the DTE2 high performance scenarios. For the ITER reference heating scheme of second harmonic tritium / minority ^{3}He heating, a DTE2 objective will be model validation in conditions similar to those expected in both ITER start-up and flat-top phases. In both conditions, the minimum ^{3}He concentration necessary for high fusion performance will be determined.

Several alternative ICRH schemes are being considered for use in ITER. Fundamental D heating in T-rich plasmas was used in DTE1 to generate the record steady-state fusion Q [2.17]. Such a scheme may be used in early phases of ITER discharges as it could provide easier access to H-mode due to isotope scaling of the H-mode power threshold and extra fusion power from this scheme's ability to provide ion heating (thus providing additional alpha power). In DTE2, testing this idea in ITER scenario simulation discharges is being considered.

Three-ion heating schemes (two majority and one minority) such as (Be)-D-T may also be attractive for ITER and avoid the need for (expensive) ^{3}He [2.19]. The (Be)-D-T scheme could be tested in JET with its ITER-like Wall to understand whether the intrinsic level of beryllium impurity in the plasma is compatible with high absorption and bulk ion heating (modelling suggests that lower levels than the observed 2-3% Be are optimum for this purpose).

2.2 Technology Objectives Related to Operation with Tritium

Operation of JET with tritium and in conditions producing high 14 MeV neutron flux and fluence provide a unique opportunity to study a range of technological issues in preparation for ITER and a demonstration fusion reactor. A key element of this programme is the calibration at 14 MeV of the JET neutron detectors (^{235}U fission chambers and a in-vessel activation system) using a DT neutron generator deployed on JET's remote handling system. This 14 MeV calibration will be based on the success of a calibration for 2.5 MeV (DD) neutrons using a ^{252}Cf source [2.20]. The 14 MeV calibration will allow full exploitation of the JET neutron budget and will provide a benchmark of the calibration procedure foreseen for ITER [2.21], where precise measurements of the neutron rate are necessary not only for fusion yield and gain calculations but also as input to tritium particle balance calculations.

As with the plasma physics-related objectives, validation of models is a central theme in JET DT technology programme. Validation of neutronics codes has already begun based on deuterium experiments [2.22, 2.23]. These codes are important for predicting dose to sensitive machine components but also for dose rates in areas where hands-on maintenance may be required.

The fluence of 14 MeV neutrons generated in the DTE2 experiments will also be used to measure the activation of a range of ITER materials in a real fusion neutron spectrum. This will allow validation of assumptions made in ITER activation codes. Functional materials so irradiated will be tested for signs of changes to their physical properties. It may, for example, be possible to measure effects such as radiation-induced conductivity, dielectric loss, radioluminescence and radiation-induced absorption.

In addition, experiments are designed to test detectors that have been developed for ITER test blanket modules in a real fusion environment in presence of high magnetic field, high temperature and radiation level.

The neutronics studies described above will be supplemented by the collection of operational experience on occupational dose and studies of waste production and characterisation during and following tritium operation. Again, the primary goal will be to validate codes and assumptions made in the preparation for ITER operation.

Finally, the technology programme also includes the test of a continuously operating, non-cryogenic pumping system for a demonstration reactor [2.24]. A prototype liquid metal (mercury) roughing pump will be installed and tested in the JET Active Gas Handling System (AGHS).

2.3 Gaining Operational Experience with Tritium

The JET DTE2 experiment will be the first high power experiment with deuterium-tritium mixtures since the 1990s. Refreshing operational experience of a nuclear tokamak is a key strategic goal of the EU fusion programme. In the same way that installation of the metallic ITER-like Wall has implied significant changes in the JET operational procedures and strategy, nuclear operation will require training of scientific and engineering staff and will be used to prepare these staff in the best way possible for ITER operation. This training has already begun – it takes several years to fully qualify a JET engineer-in-charge or session leader.

A key element in this preparation will be a rehearsal, in deuterium, of operation in DT conditions, which is planned for five weeks in autumn 2015. The main aim of the rehearsal is to exercise technical systems and test operational procedures to gain experience and make recommendations for the preparation of the DTE2 campaign. The scope of the rehearsal includes:

- Testing operation of one of the two neutral injection boxes (NIBs) with gas feed from the AGHS;
- More generally exercising the AGHS, including supply of gas to one NIB and one gas introduction module, using the cryogenic fore vacuum pumps to evacuate NIBs and torus, and carrying out emergency exercises;
- Testing procedures specific to operation with tritium, including for neutron budget and tritium usage accounting;
- Operating in DT-like conditions including with torus hall depression and oxygen depletion, with restricted access to certain operational areas, with a DT-like operational pattern of cryogenic pump regeneration and with additional firewall restrictions for access to online computers.
- Training, both prior to and during the rehearsal (staff rotation schemes will be implemented to maximise the benefit of the rehearsal).

The results of the DT rehearsal will be used to guide optimisation of procedures and training in the period running up to tritium operation.

3. Preparation for Operation with Tritium

3.1 Delivering JET DT Capability Project

The Culham Centre for Fusion Energy (CCFE) operates the JET Facilities under contract from the European Commission and is thus responsible for making available, maintenance and running of the facilities so as to support the JET component of EUROfusion work programme. As is normally the case at CCFE, the activities required to deliver operation of JET with tritium and deuterium-tritium mixtures are being managed in a formal project structure. The mission of the Delivering JET DT Capability (DTE2) Project is "To safely prepare the JET Machine, its Ancillaries and Personnel for Operations using Tritium in a DT Experimental Campaign, with the capability to carry out essential machine maintenance and recovery during the Campaign, and the post-DT Campaign Clean-up and In Vessel Sample Removal phases". This project is currently the single largest project activity being undertaken by CCFE as JET Operator with the focus expected to continue to grow as the DT experiment approaches.

The DTE2 Project scope has been developed using a formal requirements analysis based on the Operational and Technology Case for DT Operation that was agreed by the EU fusion committee system. The project scope touches virtually all aspects of JET operation including plasma fuelling, heating and exhaust systems, diagnostics, machine infrastructure and shielding, remote handling, tritium systems, machine control, and personnel training. Detailed scope has been defined 'bottom-up' at a work package level with a formal link between the work to be done and the defined project requirements. Recently achieved high-level milestones include completion of the provisional DT safety case (see below), of the concept design for the Diagnostic Vacuum Crown (for centralised fore vacuum pumping of diagnostics connected to the torus), of the scheme design of tritium-compatible torus gas introduction modules, and of the draft fitness-for-purpose review of the torus hall shielding as well as the order commitment to purchase the additional 55 g of tritium needed for the planned experiments. Project completion is defined by issuance of the Authority to Operate in DT.

A key element in planning DT operation on JET is the level of expected machine activation and its impact on the Operator's ability to maintain the facilities. The planned neutron budget for DTE2 is roughly six times that of DTE1 and will result in no manned access to the inside of the machine and significant ex-vessel access limitations. Predictive radiation dose maps have been produced as guidance for planning ex-vessel activities both post-DTE2 and at intermediate stages during the campaign, if necessary. An example of such a dose map is given in figure 3.1, where the predicted dose five months after the last high power DT pulse is shown for a torus hall elevation through Octants 1 and 5 of machine. These dose maps will be validated by dose surveys; indeed validation of this type of predictive mapping is one of the technological deliverables of the experiment. For the purposes of the present project, such mapping is a useful tool for focusing the ex-vessel shielding activities and other tasks and ensuring that they are in line with the project requirements.

3.2 Safety Case for DT Operation

The Authority to Operate (ATO) is a CCFE management system to ensure that facilities are operated safely. In this system, an annual ATO certificate (license to operate) is issued by the CCFE Site Safety Working Party with the ATO Holder accountable for safe delivery of all the activities covered by the ATO. One of the conditions of the ATO is that a Safety Case is prepared; this is a top-level demonstration that a facility and its operations/activities are safe. This ATO and Safety Case structure is modelled on proven systems developed when the UK Atomic Energy Authority (CCFE's parent body) managed nuclear licensed systems. Although JET is not classed as a nuclear licensed facility, the same rigorous systems are adopted.

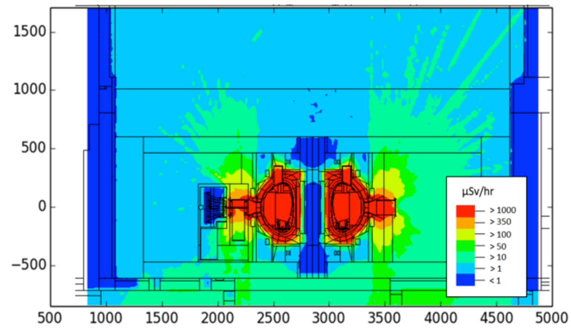

Fig.3.1 Calculated dose rate in the JET torus hall 3 months after the end of the DD clean-up phase and thus 5 five months after the end of the last high power DT discharge. Elevation at Octants 1 and 5 of the machine.

JET is presently being operated under a Torus ATO and Safety Case that apply to operation without tritium. (The JET tritium plant operates under a separate Safety Case and Authority to Operate.) A key element of preparing for DTE2 is the preparation of the corresponding torus safety case for operation with tritium [3.1]. The safety case determines the necessary safety controls to ensure that both occupational and accident doses to operators and members of the public will be ALARP and below the Basic Safety Limits as defined by the UK nuclear regulator. In particular, at JET Key Safety Related Equipment (KSRE) and Key Safety Management Requirements (KSMR) are identified to ensure that potential accident doses cannot exceed the Basic Safety Limits of 20 mSv for workers and 1 mSv for the public. For the JET torus, the safety case has identified 21 KSRE systems and 15 KSMRs.

Having identified the key systems and management requirements, Fitness for Purpose reviews and Human Factor Analyses have been carried out to demonstrate the existing equipment and procedures are adequate to fulfil the corresponding safety functions. These reviews and analyses identified no showstoppers for the DT Safety Case and have been distilled down into a small number (29) of implementation actions, which must be completed prior to adoption of the safety case and a significant number of improvement actions. In addition, a range of reliability risk reduction actions was identified. Together, the safety case improvement and reliability actions number about 400. Completion of all of these actions is likely to be challenging on the present JET schedule and a programme of prioritisation is presently underway.

3.3 Active Gas Handling System and Tritium Preparations

In JET, tritium is supplied to the tokamak and to the neutral beam injection systems and recovered from both by an Active Gas Handling System (AGHS). As noted above, the AGHS operates with a Safety Case and Authority to Operate separate from that of the torus hall. The AGHS Safety Case, which includes tritium operation, was issued in 2009 following a complete re-write and review. It is valid for ten years and applied up to a total inventory of 90 g of tritium – the plant design capacity. For AGHS, the safety case process generated twenty implementation actions and twenty improvement actions. Of these, five implementation actions remain to be completed but are planned as part of the commissioning in preparation for DTE2 and five improvement actions related to document revision are still in progress.

Details of the AGHS can be found in [3.2]. Significant upgrades in preparation for DTE2, in particular to the process control systems, are now nearing completion. Indeed, the first batch of tritium for DTE2 was delivered to site in spring 2015 and it is expected that all of the additional 55 g, bringing the total inventory up to the required 60 g, will be on site by early 2016.

In contrast to DTE1, during which the tritium fuelling to the torus was limited to one mid-plane gas introduction module, a much more flexible system is foreseen for DTE2. This is based on the need for higher gas flow rates (and durations) in DTE2 and the findings that:

- Main chamber fuelling is favourable for impurity compression in the divertor [3.3, 3.4] and provides more efficient plasma fuelling [3.5, 3.6]
- Divertor fuelling can be used in some divertor geometries to control the symmetry between the inner and outer divertor legs [3.5]
- Fuelling near to or at least magnetically connected to ion cyclotron resonance heating antennae can significantly improved the antenna coupling and thus the power delivered to the plasma [3.7, 3.8]
- Main chamber fuelling near a neutral beam injection duct can lead to beam trips

3.4 Risk & Reliability Studies

Machine reliability will be important in the execution of a future JET DT experiment because the number of 14 MeV neutrons that may be produced is limited (the remaining budget after DTE1 is 1.7×10^{21}), because access to the machine, both in-vessel and ex-vessel, becomes much more difficult once these levels of neutron production are approached and because reaching the DTE2 programme goals will require operating the machine at its limits.

The usage of the expected lifetime of the toroidal field coils (set by the mechanical and thermal shear stresses on the coil tails) and of the vacuum vessel (set by the strain on the root welds of the main vertical ports) are monitored carefully. To date, approximately 60% of the assumed TF lifetime has been consumed and about 15% of the vacuum vessel lifetime. Both limits are thought to be appropriately conservative and the remaining assumed lifetimes sufficient to carry out the foreseen JET programme.

In order to better understand and mitigate the risk of failures in other components during DT operation, a series of reliability studies have been undertaken. These studies were divided into: torus hall systems; diagnostics; KSRE and IOPS (Integrated Operation Protection Systems); and auxiliary systems. All studies produced lists of recommendations, which were filtered for priority by the JET Engineering Analysis Group and the high priority items then reviewed by senior management. The result is a list of more than 500 tasks that have been allocated either to the DTE2 Project or to individual departments for implementation. The accepted tasks cover a wide range of systems and activities including: ensuring primary vacuum integrity including valves and windows; checking shielding and penetrations of the biological shield; removing sensitive instrumentation from areas of high neutron flux; developing remote-handling and portable shielding schemes for planned work and repairs; timely execution of system maintenance; completing commissioning procedures; training; and completion of as-built drawings. At the time of writing, the implementation of these tasks was being further reviewed in light of project schedule and budget.

3.5 Planning and Restart Requirements

Experimental campaigns using tritium and deuterium-tritium mixtures must be carefully prepared. On the other hand, generating a pool of staff trained in operation of a nuclear tokamak will be of benefit to both ITER and to Europe's participation in ITER. On JET, the long pause between periods of operation with tritium means that less than 100 staff have any practical DT experience. In some key areas, such as vacuum, cryogenics and neutron diagnostics, DT operation will be new to all staff.

Training matrices have been developed in preparation for DTE2. In all, it is expected that over 150 people will require training, including engineers-in-charge, active gas handling staff, neutral beam operational staff, vacuum and cryogenics group staff, shift technician and incident response officers, session leaders and other staff specifically involved in tritium operations such as certain diagnosticians, computer experts and operational engineers.

All experimental campaigns on JET are preceded by a restart phase in which the machine systems are brought up to a pre-agreed set of targets so that subsequent 'physics operation' can make maximum use of scientists travelling to JET from other European fusion laboratories. The restart in 2015 will be modified to include a rehearsal of DT operation (see Section 2.3), which will extend into the first weeks of the campaign so that it serves as rehearsal also for that purpose. The restart prior to DTE2 will also require special procedures and planning. Following a restart similar to what occurs normally at JET, a two-week period will be dedicated to expanding the tritium boundary in a controlled manner. In this period, there will be puffs of tritium into the JET main vacuum chamber, both with and without plasma. Tests with plasma will be used for a first check of the 14 MeV neutron calibration. The physics programme will then proceed via operation with hydrogen, tritium, deuterium-tritium mixtures and some combination of hydrogen and deuterium operation for tritium removal from the machine. The hydrogen campaign, while useful as a last chance to obtain reference discharges for isotope studies, is necessary in order to reduce to a minimum the deuterium content in the plasma and thus the 14 MeV neutron yield during full tritium experiments. Obtaining a neutron yield in tritium that is dominated by T-T reactions requires a deuterium concentration in the plasma of less than 1%.

Another important aspect of full tritium operation will be validation of the power available from tritium neutral beam injection. The present predicted power is based on calculations of the extracted ion source species, the known cross-sections for collision processes in the neutraliser and estimates of the neutraliser target density variation with beam power (which are expected to be similar to that observed when operating with deuterium). Present expectations are that each of the sixteen sources will inject between 2.1 and 2.5 MW when operating in tritium, i.e. at or slightly above the power available in deuterium.

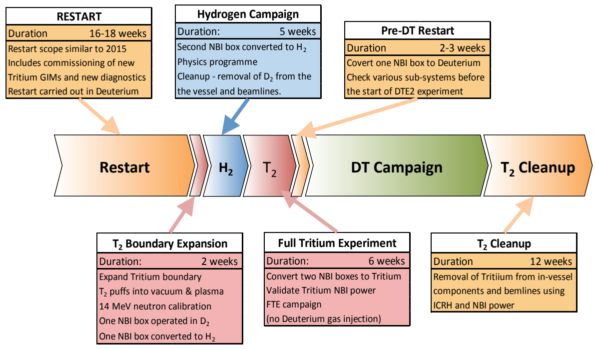

Fig.3.2 Schematic timeline showing the stages preceding and after the planned DTE2 experiment. Details of the durations of each of these stages will depend on detailed physics objectives and the plasma purity that can be obtained when operating in tritium.

4. Measurement Requirements

JET is equipped with an extensive set of diagnostics. Typically ~50 GB of data are collected after each JET discharge, two orders of magnitude more than was the case as the time of last high power DT experiments in 1997. Since that time, new techniques and capabilities have been deployed. Indeed, a priority at the time of launching the Programme in Support of ITER was to enhance JET's diagnostic capability in preparation for DT experiments and as a test-bed for ITER diagnostics.

Measurements of the electron fluid have been greatly improved, with a factor of ten higher spatial and temporal resolutions and much better accuracy. Careful calibration has resulted in agreement to within 5% of three independent measurements of the electron temperature profile and two of the electron density profile.

As tritium and deuterium-tritium operation has always been foreseen at JET, the vast majority of the diagnostic systems will be available also during the DT experiment. Nonetheless, a few diagnostic upgrades for DT are necessary to fully benefit from the experiments and are presently being undertaken:

- Upgrading JET low-energy Neutral Particle Analyser for isotopic composition
- Cameras for DT operations (IR and Visible)
- JET Neutron Camera Upgrade: spatial emissivity
- Vertical Neutron Spectrometer
- Upgrade of the JET Gamma Ray Camera: spatial emissivity
- JET Horizontal Gamma-Ray Spectrometer Upgrade for the alpha-Particle Diagnostic
- Upgrade of the scintillator based Fast-Ion Loss Detector (FILD)
- Correlation Reflectometer and Doppler reflectometer
- Upgrade of the JET Toroidal Alfvén Eigen-mode (TAE) system

Several of these diagnostic upgrades will become available only immediately prior to the presently scheduled tritium and deuterium-tritium experiments. Of particular concern are the upgrade to the JET viewing system, which is required for machine operation as well as for physics studies, and the upgrade of the TAE diagnostic, which is expected to require some time to develop a good physics understanding and which is planned to be used already in the deuterium preparation experiments in 2015/16 to probe stable modes.

Two particular measurements have been identified as being of particular concern in the run-up to DTE2 due to their central nature and the fact that they have become more difficult since the installation of the ITER-like Wall.

Measurements of the ion temperature, rotation and density on JET rely on charge exchange recombination spectroscopy (CXRS) [4.1, 4.2] in which an electron is exchanged from an injected beam to an excited state of an impurity ion in the thermal plasma. Emission from this impurity as it relaxes to its ground state is then a probe of the impurity's velocity distribution and density. Prior to the installation of the ILW, the main impurity in JET plasmas was carbon and many years of experience were acquired in interpreting the carbon CXRS spectrum at 529 nm. Since the installation of the new wall, the level of carbon in the machine has decreased by about a factor of 20 [4.3] and nuisance lines, thought to be coming from tungsten emission, have appeared in the spectrum. This has made the interpretation of the data much more difficult. Analysis is available for more than half of the requested ILW discharges, sometimes using the beryllium spectrum instead of carbon. A particular problem is that the push to high performance is expected to be accompanied by increased current and density, increased beam attenuation and thus worse signal-to-noise especially in the plasma core.

Strategies for improving the situation include neon seeding (the neon spectrum is known to be easier to analyse than either the beryllium or the present carbon spectrum), beam modulation, combining data from different spectra in one integrated fitting package and augmenting CXRS data with X-ray measurements of the core ion temperature. These strategies will be tested in the 2015 restart and the most promising incorporated in the subsequent development of high performance scenarios for use with tritium.

Another diagnostic concern for DTE2 is the partial lack of high frequency magnetic measurements due to an increased rate of coil failures since the installation of the ILW. In-vessel inspection during the recent JET shutdown has shown that there at least two different failure modes and that both are internal to the coils rather than at feed-throughs or connections to in-vessel conduits. One failure mode is thought to be due to embrittlement of the hot titanium wire by exposure to high-pressure hydrogen or nitrogen (used for divertor protection) and possibly chafing. The other failure mode appears to be due to overheating of the coil but is not yet understood. For the 2015/16 campaigns, three of the failed fast coils have been replaced by a proven design based on mineral insulated cable, which have sufficient bandwidth to be used for plasma control but not for MHD applications. Two prototype coils using a glidcop® winding and with liquid ceramic applied so as to reduce chafing have also been installed. These coils have their 3 dB point at 400 kHz and can thus be used for MHD analysis. If these coils are proven sufficiently robust, a similar design will be installed in other locations inside the machine, depending on time and resources available.

5. Operational Issues

The DTE2 objectives require operation of JET simultaneously at or near multiple performance limits. Indeed, mapping these limits is the key deliverable of the present phase of operation with deuterium in view of further experiments with other hydrogen isotopes and an integrated demonstration with deuterium-tritium mixtures. This need to operate simultaneously at several limits, which is shared with ITER, is driving the study of several operational issues. Three are of particular importance: the mitigation or avoidance of disruptions, the achievement of maximum additional heating power from the NBI and ICRH systems, and the power and energy handling of the in-vessel components.

The frequency, causes and dynamics of disruptions in JET have changed substantially since the installation of the ITER-like Wall [5.1,5.2]. A large part of this is directly a result of increased plasma purity, resulting in higher temperature post-disruptive plasmas, slower current quenches and higher impulse on the vacuum vessel and heat loads on the plasma-facing components (PFCs). For both impulse and heat load, levels normal for operation with carbon PFCs can be re-obtained by the injection of massive amounts of gas mixtures; in JET typically 10%Ar in D is used. As a result, use of the JET disruption mitigation system is now mandatory for all discharges with maximum plasma current above 2 MA or internal stored energy (poloidal magnetic plus kinetic) above 5 MJ. In order to guarantee that disruption mitigation will be reliably available in DTE2, a second tritium-compatible disruption mitigation valve has been installed on the machine (there will then be three valves in total but one is not tritium-compatible and will be removed before DTE2).

The need to go to maximum plasma performance in DTE2 implies that disruption forces on the machine will be high, even with mitigation. Furthermore, while some melt damage in an individual disruption may be tolerable, forces beyond machine limits must be avoided even in fault conditions leading to a lack of mitigation. For this reason, magnetic configurations intended for high current use have been re-optimised so that their predicted unmitigated force on the vacuum vessel stays within the agreed operating limit of

8.5 MN [5.3]. In this way, while mitigation will be active at all times to reduce the impact of any disruptions, credit for this mitigation is not taken in the safety case.

At the time of DTE1, the JET NBI system was capable of supplying 20.5 MW in deuterium and up to 23 MW in DT with one of the two NIBs operating in tritium. Since then, the system has been upgraded twice [5.4, 5.5], the second time as part of the enhancement programme including the ITER-like Wall. The system is now capable in principle of providing 34 MW in either deuterium or tritium. Commissioning of the new system has been more difficult than anticipated and the full design performance has not yet been reached. That said, individual sources have been operated at or very close to the required power of 2.13 MW so it is clear that the system is capable of reaching its design specifications. The remaining issues, bar one, are to do with reliability and conditioning, the latter made more difficult by two major incidents in the system that resulted in water leaks. When dealing with reliability, every effort, within the available budget, has been made to try to permanently resolve problems. For example, all of the injector back plates and grids have renewed.

The one remaining major issue with the upgraded NBI system is the failure of an actively cooled component that exhausts the heat load from non-dissociated D_2^+ ions. These components, which are called J-plates due to their shape, failed during the commissioning of the NBI system for a hydrogen campaign, having been operated previously at very close to maximum power in deuterium. The reason for the failure in hydrogen is not understood but subsequent analysis has shown that the plates must have been much closer to their limit in deuterium than had been assumed. A re-design of the system is underway with the expectation that the heat handling capability of the plates can be significantly increased, perhaps doubled. New plates will be installed in JET during a shutdown scheduled to take place in 2016. Experiments in 2015/16 will use the old J-plate design (there were two spares for the plates that were damaged). Some limitation in allowed beam power is still being considered. This will be based on in situ thermal measurements that have now been installed. Given that the peak power load on the J-plates can be reduced by a factor of two for a reduction in total available power of 1 MW, this possible additional restriction is not thought to be a fundamental problem for the programme.

JET is equipped with an ICRH system based on four in-vessel ‘A2’ antennae [5.6, 5.7], which will be complemented in the coming experimental campaigns by a refurbished and re-commissioned ITER-like Antenna [5.8]. Maximising the ICRH power coupled to the plasma is crucial in order to provide the maximum possible control of tungsten transport and thus the widest possible operating space without central accumulation of tungsten as other methods of tungsten control typically come with a confinement penalty.

Considerable progress has been made in optimising the A2 antenna-plasma coupling and thus the delivered power [3.8]. In optimised discharges at the mid-band frequency of 42 MHz, it is now possible to deliver 6 MW. The remaining challenge in preparing for DTE2 is to scale this result to higher toroidal field operation, which will require operation at a different frequency operation and/or using a different heating scheme, whilst also including heating from the ITER-like Antenna, which it is hoped might deliver up to 4 MW in optimised plasma conditions. For this purpose, it is likely that a combination of different heating schemes will be required, due to the different technical limitations on the individual antennae. In DT, a combination of minority H and second harmonic tritium / minority ^{3}He is thought most likely to provide maximum power, albeit with somewhat reduced total power compared to operation at mid-band frequencies (8.5 MW is being targeted rather than 10 MW). Developing and optimising this solution (using ^{3}He) is a key programmatic goal of the 2015/16 experimental campaigns.

The power and energy handling limits of JET’s ITER-like Wall are explained in [5.9, 5.10]. The surface temperature of the bulk beryllium limiters is controlled to less than 900°C so as to avoid melting. Dedicated tests have shown the melt limit to be consistent with the simple estimated limit in $Pt^{1/2}$ of 19 MW m^{-2} $s^{-1/2}$ [5.10]. The bulk tungsten component of the divertor [5.11] has an energy limit of 60 MJ on each of its four stacks of lamellae, due to a temperature limit of 330°C on the pre-loaded springs which are used to maintain the alignment of the lamellae, and a soft surface temperature limit so as to avoid recrystallization. The latter limit is controlled administratively; some operation up to surface temperature of 2200°C is possible. Finally, the tungsten-coated CFC tiles used in the remainder of the divertor are limited to a surface temperature of less than 1200°C so as to avoid carbidisation of the coating and brittle failure [5.12].

Guaranteeing that these plasma-facing component limits are not exceeded is the purpose of significant upgrade to the JET control system, the Protection of the ITER-like Wall (PIW) project [5.13]. This new control system relies on an array of pyrometers and robust, near infrared cameras [5.14] and a suite of real-time temperature monitoring and alarm generation software [5.15]. Considerable operational experience has been gained with this new system and its functionality and value proven. Upgrades in the most recent JET shutdown include the first rigorous in-vessel calibration of the sensors, permitting proper focusing with the necessary filters in place, and the development of greatly improved logging and analysis tools, which are intended to speed control room interpretation.

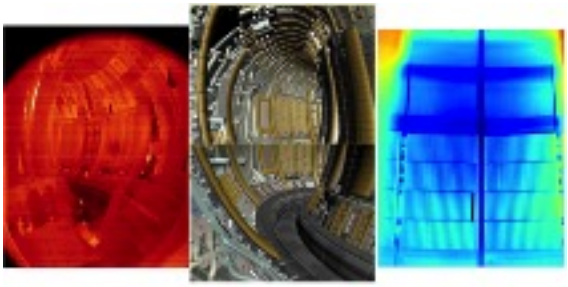

Fig.5.1 The three views of the inside the JET machine, from left to right: wide angle IR, wide angle visible and divertor IR, for which optical relays are being designed so that the corresponding cameras will continue to function during high power DT operation.

During the high fusion power pulses in DTE2, cameras that are close-coupled to the machine will not provide useful data due to high neutron background levels. Even use between pulses is not expected to continue through the campaign, due to neutron and gamma damage to the camera's electronics. For that reason, a key diagnostic upgrade in preparation for DTE2 is to install remote optical links so as to bring three of the in-vessel view outside the biological shield so that they can continue to be used for both machine protection and physics applications. The corresponding views are shown in figure 5.1.

Despite the careful and successful use of the new protection system, some damage to the new plasma-facing components has been observed. Melting of beryllium in disruptions is difficult to completely avoid due to the much-changed disruption dynamics. Some delamination of tungsten coated divertor tiles has also been observed. This delamination is so far almost exclusively on the outer, more highly loaded divertor tiles and is correlated with a particular batch of tiles that is known to have had sub-optimal preparation prior to coating. It remains to be seen whether and when this delamination appears more generally on 'good' tiles. For now, the exposed area of carbon is small, consistent with the lack of any clear signs that the carbon content of JET plasmas has started to increase.

6. Status of plasma scenarios and performance predictions for DT

Development of the high performance scenarios for DTE2 is focusing on the conventional ELMy H-mode, here referred to as the baseline ELMy H-mode, and the so-called improved H-mode [6.1] or hybrid H-mode [6.2], the two primary candidates for application towards ITER's Q=10 mission. Due to the limitations of the present JET schedule, it has been decided not to pursue development of (potentially) fully non-inductive regimes of operation as might be used in Phase 2 of ITER operation [6.3].

Operation with the ITER-like Wall has required re-optimisation of the standard regimes of operation. This has been due not only to the additional constraints on the available operating space due to the new wall but also due the changes in plasma behaviour following the change in wall material and the resulting change in plasma composition. To a large extent, the techniques being used in this re-optimisation are common to the baseline and hybrid regimes of operation. In the following the status and plans for further development of both regimes are presented, with the common items described in the baseline sub-section.

6.1 Baseline ELMy H-mode

Use of tungsten as a plasma-facing material can result in the accumulation of this heavy impurity in the centre of the confined plasma and very high levels of central radiation [6.4]. Gas fuelling, which increases the ELM frequency and thus the flushing of tungsten from the edge of the confined plasma, can be used to avoid central accumulation but reduces the overall confinement. This is a useful tool when a conservative route to developing high current configurations is required.

Central electron heating, in ASDEX Upgrade primarily by Electron Cyclotron Resonance Heating (ECRH) [6.5], can be also used to control central tungsten peaking and thus to widen the available operating space with less impact on confinement. The same technique but using ICRH has been applied to JET with its ITER-like Wall [6.6] with the result that central ICRH is now a ubiquitous component of scenario development. It is found that, at moderate plasma current (2.5 MA), about 4 MW of central ICRH is required in order to control tungsten transport. In order to provide confidence that it will be possible to do so also at higher current and field, JET's ITER-like Antenna is being recommissioned.

In addition to controlling tungsten accumulation by central heating and thus control of core impurity transport, control of the plasma edge and, in particular, of the ELM frequency, also has the potential to provide a wider operating space [6.7]. While there are error field correction coils on JET that can and have been used for ELM control experiments [6.8], these coils are not designed for this purpose and not compatible with high performance operation. The main ELM control tool on JET is a high frequency pellet injector [6.9], which unfortunately has not yet been able to provide strings of pellets into the plasma with sufficient reliability so as to be used in scenario development. Following optimisation of the injector itself, the limitation in this regard has been the pellet track system and as a consequence the injector has been relocated during the most recent JET shutdown so that it will be available in a configuration that should provide much more reliable pellets in 2015/16 experiments. In this regard, development of a real-time system for ELM control that allows optimal sharing of pellet and gas fuelling [6.10] is expected to provide a key ingredient in future scenario development.

Considerable progress has been made in optimised ELMy H-modes at moderate current and field. It is important to note that discharges with the nominal

ITER confinement ($H_{98(y,2)}$ = 1) and pressure (β_N=1.8) have been achieved with the ITER-like Wall (figure 6.1). This has been obtained by combining central ICRH with optimised divertor pumping [6.11].

Experiments in the 2015/16 experimental campaigns will focus on extending the range of good confinement in the baseline ELMy H-mode to higher current. This has not been possible to date, as it will require use of maximum input power. The combination of increased input power and higher current, which leads to narrower scrape-off layers [6.13], will require further efforts to develop integrated scenarios within wall power and energy limits. In addition to deploying the newly available tools (ITER-like Antenna and relocated pellet injector), two main strategies are being planned: sweeping of the divertor strike points to spread the power and energy loads and addition of extrinsic impurities to enhance radiative losses and thus diminish the total power transported to the divertor. The issue with strike point sweeping is whether the required amplitude can be achieved whilst maintaining the improved confinement observed when the strike point is placed in the pump throat. Nitrogen seeding has been used in AUG [6.14] and later in JET [6.15] to reduce divertor power load with, in some cases, a beneficial effect on confinement. Nitrogen seeding is not compatible with the JET Active Gas Handling System and thus with tritium operation and so recycling alternatives must be found. Neon and argon or some combination of the two are under assessment and will be tested in future experiments. At the highest currents and input powers, it may be that both sweeping and radiation from extrinsic impurities are required.

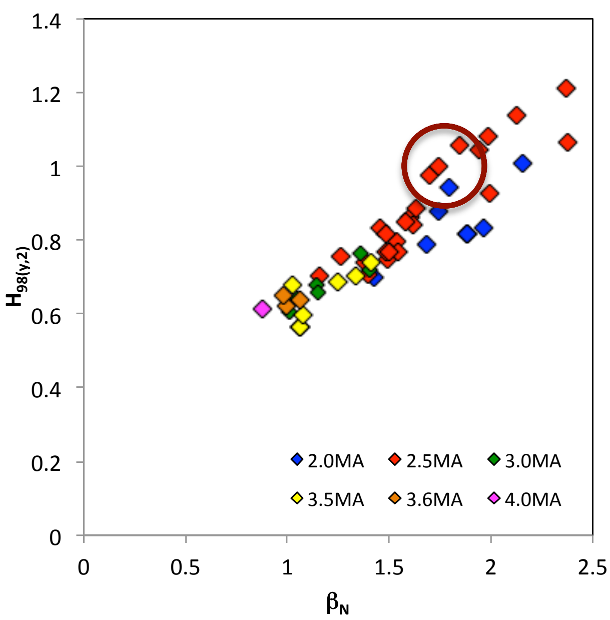

Fig. 6.1 Confinement enhancement factor $H_{98(y,2)}$ versus normalised plasma pressure for JET ELMy H-mode discharges with the ITER-like Wall. The nominal ITER operating point of $H_{98(y,2)}$=1 and β_N=1.8 is indicated with the open circle (from [6.12]).

6.2 Hybrid H-mode

Several experiments have observed that the confinement in ELMy H-modes can in some circumstances depend (decrease) more weakly on normalised pressure than implied by the standard $H_{98(y,2)}$ scaling [6.16, 6.17]. This behaviour has recently been observed also with the ITER-like Wall [6.18]. This suggests an alternative route to maximum fusion performance in JET, in which the plasma β is maximised perhaps even at the expense of maximising the plasma current. Indeed, with the limited input power so far available, the highest equivalent (in deuterium) fusion powers have been obtained in these hybrid conditions even though lower plasma current has been used as compared to the baseline ELMy H-mode.

Hybrid operation is even more susceptible to divertor over-heating than the baseline mode of operation, since operation at lower current implies operating at lower density and thus typically with a hotter divertor plasma. Added to this is the observation of a complex interplay between plasma stability and impurity transport, which is not yet fully understood [6.19]. As a result, the highest performance hybrid discharges so far developed with the ITER-like Wall are limited to durations of about 1 s.

Development plans for the hybrid scenario are focussed around obtaining maximum input power as high β is essential for obtaining the high confinement conditions. Tungsten control and divertor heat load mitigation will be integrated using the same tools as foreseen for the baseline ELMy H-mode with the addition of plasma current profile optimisation to mitigate deleterious MHD.

6.3 Fusion performance predictions

In order to understand what present JET results imply for operation in DT and, more importantly, what they imply for ITER, it is essential to accompany the experimental programme with a strong interpretative and predictive modelling effort. This modelling effort has been launched as part of the EUROfusion 2015 work programme with the results expected to provide key input to the final decision to proceed with DTE2.

Interpretation of existing JET results in deuterium and predictions for DTE2 are being done using a combination of a spread sheet-based tool (JETFUSE [2.1]), supported by a variety of one-dimensional modelling using TRANSP [6.20], JETTO [6.21], CRONOS [6.22] and ASTRA [6.23].

Modelling of existing discharges provides benchmarks for extrapolation towards DT plasmas, which involve higher power, higher toroidal field, higher plasma current and likely higher densities than in the current ILW operational database. The predictions are sensitive to uncertainties in the core power balance, especially at the higher densities expected at the higher currents, due to the reduced NBI penetration together with a tendency for higher core radiation.

Modelling using TRANSP of existing baseline discharges tends to over-predict the measured DD neutron rate [6.24]. Neutron rates in existing hybrid discharges, on the other hand, are close to expectations from modelling. These 'neutron deficits' are not understood. Explanations based on erroneous fuel dilution measurements [6.24] or on anomalous fast particle transport due to 3D effects and particle-wave interactions [6.25] have so far not been able to quantitatively reproduce the observations. Overall, there is an anti-correlation between plasma normalised confinement and the deficit. Thus, for 'good' baseline discharges with $H_{98(y,2)}$~0.8, interpreted neutron rates are ~20-30% above those measured.

Modelling of existing hybrid discharges has also produced a reasonable benchmark. However, non-linear gyrokinetic modelling indicates stronger core transport reduction compared with present linear simulations due to effect of fast particle pressure and electromagnetic effects and weaker core transport reduction compared with present linear simulations due to ExB effects. The relative role of fast particle pressure and ExB effects has yet to be clarified but provides source of uncertainty for extrapolation to DT where the α-particle pressure may modify core turbulence.

For both baseline and hybrid, an important input is the model for the edge transport barrier. At present, two approaches are being followed: the EPED model [6.26] and an empirical scaling developed for the JET carbon wall [6.27] and which has been shown to be consistent with more recent power scans with the ITER-like Wall. This work is still in progress and it is expected that numerical results, both interpretative and predictive, will continue to vary.

Application of these tools to DT plasmas gives an achieved equivalent fusion power of 3.2 MW for the best baseline ELMy H-mode and 5.5 MW for the best hybrid discharge. Extrapolations to full power, full toroidal field and optimum plasma current suggest that up to 7.5 MW might be achievable in the baseline regime at the confinement enhancement factor of the reference discharge ($H_{98(y,2)}$ = 0.8). Similarly, extrapolations of the best hybrid discharge give a DT performance at full input power of 10-13 MW. Considerable improvement in the baseline performance is expected if H=1 can be achieved at maximum plasma current, such that the fusion power from a baseline discharge would be similar to that from a hybrid discharge.

There are three principle sources of uncertainty in this modelling: measurement uncertainties in reference plasmas; models and scalings used for projection; and the validity of projection assumptions, in particular successful control of MHD and impurities and compatibility with divertor heat load constraints. For this reason, modelling will continue in parallel with scenario development so as to progressively reduce the uncertainty by minimising the extrapolation distance. It is to be noted that DT-specific uncertainties such as isotope scaling, α-particle effects and ICRH heating schemes will still remain; resolving these is a key objective of the DTE2 experiment itself. While there are indications from DTE1 that these isotope effects may be positive, no credit for them has been taken in the fusion power projections described above.

7. Summary

The JET programme is now focusing on preparation for a further set of experiments using tritium. These experiments will form the final step in JET's Programme in Support of ITER and will provide a unique proof of the extent to which plasma performance can be integrated with nuclear tokamak operation and the use of the plasma-facing materials foreseen for ITER. Supported by a strong modelling programme, this will provide the best possible predictions for ITER performance and mitigation to the extent possible in present machines of the risk of encountering surprises as ITER operation moves from its non-active to nuclear phase. The performance goal of the experiment is not designed to set records *per se* but is rather targeted at a demonstration of integrated performance in conditions as close as is presently possible to ITER. The extent to which the experiment is a success will be in the level of additional understanding that is obtained and in how applicable that understanding is to ITER.

The JET DT experiment is a key deliverable of the EUROfusion work programme and to guarantee its success resources are being allocated on other machines in support of the JET DT preparation. ASDEX Upgrade, in particular, is expected to make an important contribution to both scenario development and improving physics understanding in the areas of ELM pacing by pellets, tungsten control by ICRH, divertor heat load control and pedestal / core confinement integration, amongst others.

The preparation for DTE2 includes not only further experimental campaigns but also a large programme in support of operational readiness and of risk mitigation. Operational experience with tritium is being systematically gathered throughout this process and will be provided to ITER so as to inform work in a wide range of areas such as occupational dose, remote maintenance and waste management.

The present schedule for JET foresees completion of the phase of performance optimisation in a set of deuterium campaigns in 2015-2016 and then the tritium and deuterium-tritium experiments in 2017. A recent review of readiness for DT has recommended that this schedule be extended to provide more preparation time in deuterium and a pause between a dedicated isotope experiment (H, D and T) and a final DT experiment so that maximum benefit can be taken of supporting modelling. If this extended programme is agreed, the isotope experiment will take place in early 2018 and the DT experiment in 2019.

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