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The JET Programme in Support of ITER

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ABSTRACT.
As part of its mission to prepare the operation of ITER, a major programme of enhancements has just been completed on the JET tokamak. These enhancements include a complete replacement of the plasma-facing components in JET, from carbon-based to the combination of beryllium and tungsten foreseen for ITER, an upgrade of the neutral beam heating available on JET from 20MW/short pulse to 30MW/long pulse operation, the installation of a high frequency pellet injection system for plasma fuelling and ELM control studies, an upgrade to the JET vertical stability system and a suite of new diagnostics.

The future JET programme is foreseen to proceed progressively from a test of fuel retention in the standard regimes of ITER operation towards more aggressive, high performance experiments that will demonstrate the operating space limits with the new wall. Depending on the results of the earlier experiments, the exploitation of the enhancements is foreseen to be completed with a deuterium-tritium experiment. This would represent the most integrated test of ITER operational scenarios possible before ITER itself.

JET is a cooperative programme funded and exploited in collaboration by all of the European fusion laboratories. As such, JET is a test bed for multi-national use of a single fusion facility, as is foreseen for ITER. Opportunities for broadening the participation in JET to other ITER Parties are presently being explored. If these opportunities can be implemented, JET would provide not only an integrated test of ITER regimes of operation but also a demonstration of how ITER will be operated, even to the extent of including significant numbers of the same team who will eventually operate ITER.

1. INTRODUCTION

Research at the Joint European Torus (JET) is strongly focused on preparations for the exploitation of ITER. The "Programme in Support of ITER" is aimed at developing the operating scenarios required to meet the ITER goals, supporting the development and testing of technologies that need not be frozen early in the ITER construction phase, preparing burning plasma physics on ITER and developing integrated tokamak modelling tools for ITER [1]. As part of this mission, a major programme of enhancements has just been completed on the JET tokamak. These enhancements include a complete replacement of the plasma-facing components in JET, from carbon-based to the combination of beryllium and tungsten foreseen for ITER, an upgrade of the neutral beam heating available on JET from 20 MW/short pulse to 30 MW/long pulse operation, the installation of a high frequency pellet injection system for plasma fuelling and ELM control studies, an upgrade to the JET vertical stability system and a suite of new diagnostics.

The experimental programme at JET can be seen as part of a programme of mitigation of risk to ITER operation. Indeed, the ITER Research Plan (IRP) [2] contains a list of top operational risks that should be addressed by the world-wide fusion programme in parallel to ITER construction. This list of risks is reproduced in summary form in Table 1. These risks are not viewed as showstoppers but rather as issues which may affect the ITER schedule for achieving quickly its goal of Q = 10 operation. There is significant potential leverage in this regard as the annual operation cost for ITER is expected to be approximately five times greater than that for JET.

The JET research programme makes contributions to mitigating all of the risks listed in Table 1, with emphasis placed on areas where JET's contribution is unique. In this paper, the recent JET enhancements will be introduced in Section 2 using the list of ITER operational risks as motivation. The JET forward programme, which is designed to exploit these enhancements and to make optimum use of JET's capabilities, will be described in Section 3 before a short summary and discussion is given in Section 4.

2. JET CONTRIBUTION TO MITIGATING ITER OPERATIONAL RISKS

2.1 HIGH LEVELS OF TRITIUM RETENTION

Carbon has been the preferred material for plasma-facing components (PFCs) in the magnetic confinement devices since the 1970s due to its resistance to transient events and the low core dilution and radiation levels associated with low Z plasma impurities. On the other hand, the long-term retention of hydrogen fuel in carbon tokamaks is typically 10–20% of that introduced into the machine (see, for example, [3] where this was measured for tritium). Such a rate of retention in DT operation of ITER would lead to the requirement for frequent periods of dedicated fuel removal and thus to reduced progress in the main experimental programme. ITER's solution to this problem is to operate with a combination of beryllium and tungsten as first wall materials. Beryllium will be used in the main chamber whilst the divertor will be armoured with tungsten. This combination of materials is predicted to reduce the trapping of tritium in re-deposited layers to an acceptable level [4] and to provide an acceptably low level of core plasma contamination while meeting ITER's strict power handling requirements. This material combination, though, has never been tested in a tokamak and for that reason the main component of the present JET enhancement programme is to install and test an ITER-like Wall (see figure 1).

The main chamber the largest source of impurities in present tokamaks and thus the largest source of fuel retention as this is dominated, at least for low Z PFCs, by co-deposition of the fuel with impurities. Fuel retention in beryllium layers will tested in JET using both gas balance measurements and post-mortem analysis of tiles removed from the machine. Depending on the results, time will also be given in the programme to developing reliable methods for removal of retained fuel from the tokamak.

2.2 TUNGSTEN PFCS

High Z PFCs are desirable to reduce erosion and thus increase the lifetime of in-vessel components. The reduced erosion also is expected to lead to lower dust production and tritium retention. Indeed, tungsten armour is the primary candidate for PFCs in fusion reactors. The main concern with high Z impurities is that they radiate strongly also at high plasma temperature, thus potentially quenching fusion in the hot plasma core. Experience at ASDEX Upgrade [5] suggests that this can be overcome by controlling plasma-wall interaction and increasing core diffusive transport so that the core high Z concentration is kept very low. Values of a few times 10^{-5} are required for the fractional tungsten content of a fusion reactor plasma and have been achieved in ASDEX Upgrade in combination with good performance. The remaining concerns for ITER are that these positive results scale favourably to larger machines, in particular with regard to transient and off-normal events and that there are no unfavourable effects due to material mixing between beryllium and tungsten. Both of these issues will be addressed in the JET programme.

The JET enhancement programme also includes a significant upgrade to the machine's diagnostic capabilities. In all, 18 separate projects have been launched. These include diagnostic upgrades specifically in support of experiments with the new wall such as thermocouples and near-IR cameras to measure tile bulk and surface temperatures, erosion / deposition monitors as well as a wide range of improvements to JET's spectroscopic systems. The field of view of a new endoscope designed to make high-resolution measurements of the light emission from the new tungsten divertor is shown in figure 2.

2.3 H-MODE POWER THRESHOLD

There is considerable uncertainty in the scaling to ITER of the power required to access high confinement regimes of operation. The IRP considers optimistic and pessimistic scalings that result in more than a factor of two difference in the predicted threshold power. This could be particularly an issue for ITER in the non-active phase of operation when its heating systems are still being commissioned and the fusion alpha heating will not be available. Similarly, operation of JET at its highest performance, i.e. in conditions as close as possible to those of ITER, also requires input power at or near to the maximum available. In these conditions, the energy confinement is lower than what is expected from the scaling laws used to predict ITER performance [6]. One of the candidates for this observed rollover of JET performance is the lack of available input power. Proving this in JET would have implications for prediction of the required input power on ITER.

In order to address these issues and to open the JET operation space at the highest current, the JET neutral beam heating system has been enhanced. The goal of the project is to increase the maximum power and pulse duration of the system from 24 MW, 10 s to 34 MW, 20 s, while also increasing system reliability (so that the routinely-available power is increased from 20 MW to 30 MW). Initial tests prior to the shutdown to install the new wall have shown that the individual ion sources do meet the project's specifications. Following the installation of upgrades to internal cooling components, the system will now be brought up to full power and energy gradually (see figure 3) with the pace likely to be dictated more by the requirements of the programme than by the availability of the heating system.

2.4 ELM MITIGATION

The power and energy deposited by Edge Localised Modes (ELMs) on the ITER divertor and PFCs represent a potential threat due to the very localised loads. Projections suggest that the size of unmitigated ELMs on ITER will have to be reduced by a factor of 10-20 in order to guarantee an acceptable divertor lifetime. ITER foresees two methods for ELM mitigation or suppression: the injection of repetitive deuterium pellets and the application of Resonant MagneticPerturbations (RMPs) to the plasma edge.

Pellet injection has been shown as a reliable tool for ELM mitigation on ASDEX Upgrade [7] where, at sufficiently high injection frequency, each pellet triggers an ELM and the ELM energy drops in inverse proportion to the ELM frequency. In ASDEX Upgrade the dynamic range of this technique (the ratio of the driven to natural ELM frequency) is limited to about a factor of two due to technical limits in the injector itself on maximum frequency and minimum pellet size and the relatively high natural ELM frequency. This frequency decreases with machine size (this is one of the reasons why ELMs become such an issue in ITER) so that more dynamic range can be achieved with the same technology. In addition, the performance of larger machines will be less affected by the fuelling provided by the pellet pacing as this fuelling will be smaller relative to the plasma particle inventory. A high frequency pellet injector has been installed on JET and, after an upgrade during the recent shutdown to improve the performance of its small pacing pellets, it is planned to test ELM control and mitigation in JET up approximately ten times the natural ELM frequency, extending the results from ASDEX Upgrade to the range required for ITER.

2.4 VERTICAL STABILITY CONTROL

In JET, as in ITER, the maximum plasma performance can be limited by the vertical stability of the plasma column. This is particularly a concern for ITER, where maximum performance is the primary project mission, but also affects JET's ability to approach as closely as possible to the plasma conditions of ITER by operating a maximum plasma current and toroidal field. Again, ELMs are a key issue, this time with respect to the disturbance they cause to the plasma vertical position and to the magnetic sensors used to measure this position. The largest ELMs in JET can lead to vertical displacement events (VDEs) and disruptions of the plasma (see figure 4). For this reason, an important part of the JET enhancement programme was the provision of a new vertical stabilisation system [8].

The new system consists of an enhanced radial field amplifier with ~20% higher voltage and a factor of two higher current capacity than its predecessor as well as a new digital real-time controller with a much improved response time. The amplifier was installed during a seven-week intervention in 2009 and the new system fully commissioned before the shutdown to install the ITER-like Wall. In the time available, control of ELMs > 1 MJ was demonstrated and modelling validated. This modelling indicates that the project goal of recovering from ELMs of 2 MJ at 4 MA could be easily met. Indeed, these simulations suggest that ELMs up to 5 MJ may be survivable for medium growth rate plasmas.

3. JET FORWARD PROGRAMME

The Reference Scenario for JET exploitation foresees full exploitation of the present enhancements covering the period of approximately 2011-15 (figure 5). The scenario is divided into three phases, the first of which is focused on the full characterisation of the ITER-like Wall and its compatibility with the ITER reference H-mode operating regime. This phase has just begun and is expected to continue until mid-2012. The key deliverables for this phase are: a demonstration of sufficiently low fuel retention of the ITER-like Wall; an assessment of the wall power handling; an investigation of beryllium & tungsten erosion, migration, deposition and mixing; and development of the ITER regimes of operation compatible with the wall at moderate input power.

The second phase of the Reference Scenario will be devoted to developing operating scenarios for ITER and exploring their limits in JET. The key deliverables of this phase are the definition of the heating, control and fuelling requirements to achieve high confinement regimes and the achievement of high energy confinement plasmas whilst maintaining acceptable steady-state and transient (ELM) loads on the PFCs. This second phase is expected to last throughout 2013 and 2014. Depending on the progress made in the scenario development, optional additional objectives could be a deliberate melt experiment and/or dedicated campaigns to prepare ITER non-active operation in hydrogen and helium.

Phase 3 of the Reference Scenario is a demonstration in DT plasmas of the scenarios developed earlier. A final decision on whether or not to proceed to DT will be taken only once initial results with the ITER-like Wall are available. Even in this case, two options are being considered: a low neutron budget DT campaign whose primary goal is to definitively confirm previous results on tritium retention and removal and a high neutron budget DT campaign that would also allow optimisation in DT of ITER regimes of operation. This would represent the most integrated test of ITER operational scenarios possible before ITER itself. In this Reference Scenario, JET operation would cease in the middle of this decade.

The Alternative Scenario for the future JET programme (figure 5) is based on the concept of testing all of the control tools foreseen for ITER in one machine and in the conditions as close as possible to those foreseen for ITER. In this scenario, it would be necessary to launch one or two further upgrades to JET, to be ready in time for installation before DT operation. To match ITER control capabilities, these upgrades should be an RMP system for ELM mitigation and/or suppression and an ECRH system for plasma current profile control including for stabilisation of Neoclassical Tearing Modes (NTMs). Full exploitation of the new control tools is expected to require three to five years and so, in the Alternative Scenario, JET operation would be extended to the end of this decade. The post-upgrade phase would still include DT operation but in this case interleaved with operation without tritium in order to more efficiently commission and learn how to benefit from the new control tools.

The extension of JET operation in the Alternative Scenario would provide greatly increased scope for other ITER parties to contribute to and benefit from JET in advance of ITER operation.

An Alternative Scenario is predicated on a strong international contribution, not only in terms of financial support but also in providing manpower to exploit the machine. The situation would closely mirror what is expected in ITER – multinational teams operating and exploiting one device. Operation of JET with strong participation of other ITER parties (and of the ITER IO) would allow the modalities of multi-national operation of a tokamak to be tested with the same people who will be operating ITER.

SUMMARY AND DISCUSSION

The JET tokamak has just completed a major enhancement programme as part of its mission to support efficient ITER operation. While conceived before the ITER Research Plan was developed, the JET enhancement programme can be seen to address the main operational risks identified by ITER with particular emphasis on the unique capabilities of JET: machine size and capability to use both beryllium and tritium.

JET's "Programme in Support of ITER" has been elaborated along three main axes [1]:

(i) Experimentation with an ITER-like wall;
(ii) Development of plasma configurations and parameters towards the most ITER-relevant conditions achievable today;
(iii) Integrated experimentation in deuterium–tritium.

In a Reference Scenario to complete this programme, JET operation would continue until the middle of this decade. An Alternative Scenario based on integrating all of the control tools foreseen for ITER in the closest possible plasma conditions would continue for a further three to five years.
JET is a cooperative programme funded and exploited in collaboration by all of the European fusion laboratories. As such, JET is a test bed for multi-national use of a single fusion facility, as is foreseen for ITER. Opportunities for broadening the participation in JET to other ITER Parties are presently being explored.

If these opportunities can be implemented, JET would provide not only an integrated test of ITER regimes of operation but also a demonstration of how ITER will be operated, even to the extent of including significant numbers of the same team who will eventually operate ITER.

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REFERENCES

[1]. J. Paméla et al., The JET Programme in Support of ITER, Fusion Engineering and Design **82** (2007) 590-602.
[2]. D.J. Campbell et al., ITER Research Plan, private communication.

[3]. P. Andrew et al., Tritium Recycling and Retention in JET, Journal of Nuclear Materials **266-269** (1999) 153-159.
[4]. J. Roth et al., Recent Analysis of Key Plasma Wall Interaction Issues in ITER, Journal of Nuclear Materials **390-391** (2009) 1-9.
[5]. O. Gruber et al., Compatibility of ITER Scenarios with Full Tungsten Wall in ASDEX Upgrade, Nuclear Fusion **49** (2009) 115014.
[6]. I. Nunes et al., Confinement and Edge Studies towards Low ρ* and ν* at JET, IAEA Fusion Energy Conf. (2010, Daejeon) Paper EXC/P8-03.

1	Inadequate disruption mitigation
2	H-mode power threshold at high end of uncertainty range
3	Inadequate ELM mitigation schemes
4	Inadequate vertical stability control
5	Lack of reliable high power heating during non-active phase of programme
6	Unacceptable "divertor" performance with tungsten PFCs
7	Level of toroidal field ripple degrades plasma performance
8	Lack of plasma rotation leads to a degradation of plasma performance
9	High levels of tritium retention require more frequent tritium removal procedures than foreseen
10	Incompatibility of core plasma requirements for Q=10 with radiative divertor operation
11	Inability to achieve densities near Greenwald value required for Q=10
12	Inadequate particle control to sustain high-Q plasma scenario

Table 1: Top 12 risks to the ITER scientific programme as listed in the ITER Research Plan [2].

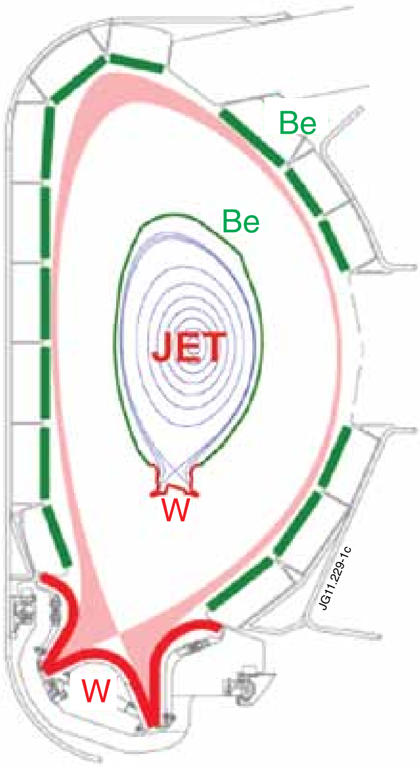

Figure 1: Schematic showing the use of beryllium and tungsten in JET and ITER.

Figure 2: Field-of-view of the new divertor endoscope, showing the tungsten divertor, composed of tungsten-coated CFC tiles on its vertical surfaces and a solid tungsten module on the divertor floor.

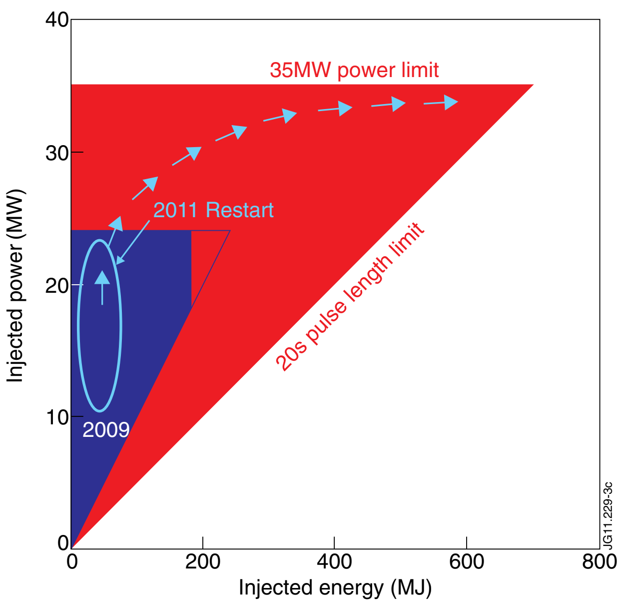

Figure 3: Operating space of the JET neutral beam heating system before and after the recent enhancement. The oval shows the operating space being commissioned during the present restart while the arrows indicated the expected performance trajectory as the 2011/12 experimental campaigns progress.

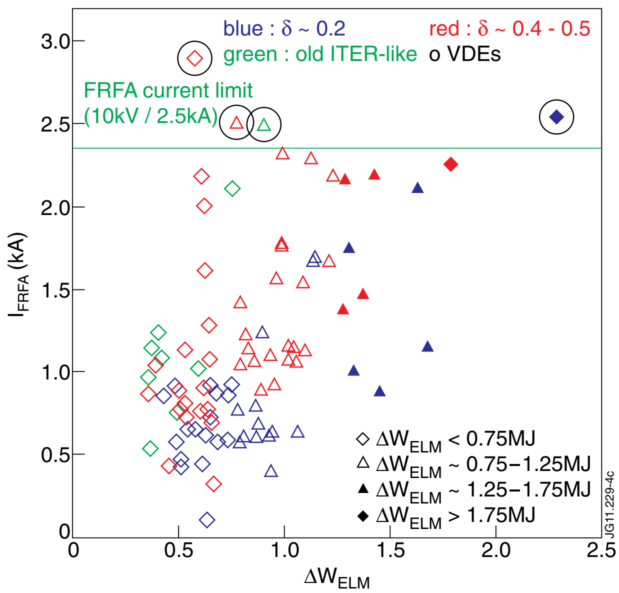

Figure 4: Maximum current required from the old JET vertical stabilisation system in response to the disturbance caused by an ELM as a function of ELM size in MJ. Currents above the system limit (the horizontal line) led to vertical displacement events and disruptions of the plasma column (from [8]).

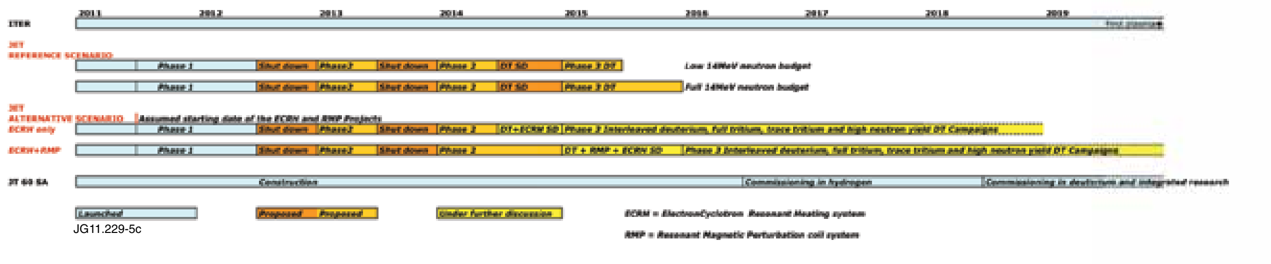

Figure 5: Timeline for the JET Reference and Alternative Programme Scenarios.