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The role of JET for the preparation of the ITER exploitation

Francesco Romanelli[a], Martin Laxåback[a,b,*], Frédéric Durodié[c], Lorne Horton[a,d], Michael Lehnen[e], Andrea Murari[a,f], Fernanda Rimini[a,d], George Sips[a,d], Klaus-Dieter Zastrow[g], JET EFDA contributors[1]

[a] JET-EFDA, Culham Science Centre, Abingdon OX14 3DB, UK
[b] Association EURATOM-VR, EES, KTH, SE-10044 Stockholm, Sweden
[c] Association Euratom – Belgian State, ERM/KMS, TEC Partners, Brussels, Belgium
[d] European Commission, B-1049 Brussels, Belgium
[e] Institut für Energieforschung-Plasmaphysik, Forschungszentrum Jülich, Association EURATOM-FZJ, 52425 Jülich, Germany
[f] Associazione EURATOM-ENEA per la Fusione, Consorzio RFX, 4-35127 Padova, Italy
[g] EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK

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ABSTRACT

The JET programme is devoted to the consolidation of ITER design choices and the qualification of ITER integrated regimes of operation. During the experimental campaigns carried out in 2008 and 2009 attention focussed on the test of the ITER-like ICRH antenna, the ITER scenario preparation, the verification of the adequacy of the ITER poloidal field coil design and the test of disruption mitigation methods such as massive gas injection. From 2011 the new ITER-like wall with all beryllium and tungsten plasma facing components, the neutral beam power upgrade and the enhanced control and diagnostic capability will allow key questions on plasma-wall interactions, fuel retention and plasma impurity control with the foreseen ITER wall materials to be addressed. Finally, feasibility studies have confirmed the option of installing an ITER-technology based 170 GHz/10 MW electron cyclotron resonance heating system for the control of MHD activity and the development of advanced tokamak scenarios, and 32 in-vessel coils for ELM control capable of producing magnetic perturbation spectra with a Chirikov parameter above unity for plasma currents up to 5 MA. During the ITER construction phase, JET will be the only device of its class in operation and will therefore play a key role in the preparation of ITER operations – saving time and reducing risk from the ITER programme.

1. Introduction

The efficient exploitation of ITER will depend crucially on the scientific and technical preparatory work performed in present day devices to optimize those aspects of the ITER design that are not yet frozen and to develop safe and effective operating scenarios. The Joint European Torus, JET, is ideally positioned to advance the state of ITER preparations by virtue of its size, ITER-like geometry, large plasma current and unique capability to operate with tritium fuel and beryllium plasma facing components. In the last couple of years, these features have allowed significant progress in the understanding of key ITER physics issues and in testing and validating the performance of new technologies. As examples of this work, this paper presents results from studies on the ITER integrated scenario preparation and ITER-like Ion Cyclotron Resonance Heating (ICRH) antenna and on the effect and mitigation of disruptions.

To take full advantage of the scientific opportunities offered by the JET facilities a series of strategic upgrades are an integral part of the ongoing JET programme in support of ITER [1] and will also be reported on here. The JET ITER-like wall (ILW) [2] will provide the first experience of tokamak operation with a beryllium (Be) first wall and tungsten (W) divertor, as is planned for the activated phase of ITER. Compared to carbon, the new wall materials should demonstrate a major beneficial impact on fuel retention and on the lifetime of plasma facing components (PFCs). The Neutral Beam Injection (NBI) system is being upgraded with the routinely available total injected power in deuterium being increased from the present 20 MW to 30 MW, while the maximum NBI pulse length is doubled to 20 s, or 40 s at half power [3]. Finally, to address the limitations of the JET Vertical Stabilisation (VS) system in controlling high current plasmas at the ITER-relevant collisionalities (ν^*) that will be achievable with the increased heating power [4] the JET plasma control system has recently been upgraded and success-

* Corresponding author at: EFDA Close Support Unit, Culham Science Centre, Abingdon OX14 3DB, UK. Tel.: +44 1235464518.
E-mail address: martin.laxaback@jet.efda.org (M. Laxåback).

[1] See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA FEC 2010, Daejeon, Korea.

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fully commissioned on plasma [5], using a model-based approach to minimise the time and risk to the main JET programme. A number of new diagnostics have also come to fruition.

With these enhancements, the JET programme in the coming years will provide an unequalled opportunity for advancing ITER preparations in conditions as close to those foreseen in ITER as is possible in any present fusion device. The main objectives of the JET programme now being elaborated for the 2011–2014 period are to:

- Demonstrate sufficiently low fuel retention for a Be/W wall to meet ITER requirements.
- Study the formation of Be–W mixed layers, their impact on W erosion, material migration and resistance to melting damage.
- Develop control strategies for detecting and limiting damage to Be and W plasma facing components by steady state and transient heat loads.
- Develop fully integrated scenarios for an all-metal machine, demonstrating the required confinement for ITER with impurity seeding strategies to replace the intrinsic carbon radiation and active mitigation of Edge Localised Modes (ELMs) for acceptable wall and divertor power loads.

The possibility of further improving the JET capability of preparing ITER operation has also been investigated. Specifically, two feasibility studies have been conducted for a 170 GHz/10 MW Electron Cyclotron Resonant Heating (ECRH) system and a set of Resonant Magnetic Perturbation (RMP) coils.

2. ITER integrated scenario preparation

The ITER poloidal field (PF) coils must be able to safely control the plasma during the current ramp up to 15 MA, current flat top, and current ramp down phases of the discharge. The plasma internal inductance should be kept between $0.7 < l_i(3) < 1.0$ during the current ramp up phase and excessive increases of the inductance must be avoided during the current ramp down to maintain vertical stability while avoiding additional flux consumption from the central solenoid.

JET has performed ITER scenario demonstration discharges in deuterium in 2008 [6]. These results contributed to the modification of the ITER coil design and have been used as a reference for the helium discharges carried out in 2009 for the assessment of the ITER non-active phase performance [7]. For the helium campaign the neutral beam system was fully converted to He injection, using the technique of argon frosting to ensure He pumping.

Good control of the internal inductance is achieved with both gasses during the current ramp-up using a full bore plasma shape with early X-point formation at 0.8 MA, equivalent to forming a diverted plasma at 4.5 MA in ITER. In this scenario early heating is required to keep l_i below 0.85 when using the fastest current ramp rate available (0.36 MA/s), still maintaining an MHD stable plasma up to $q_{95} = 3$ (2.65 MA/2.36 T) with a transition to H-mode that in deuterium JET discharges occurs at 7–9 MW of input power and in helium at similar power levels (8–11 MW).

During the current ramp-down to half the flat-top current the plasma inductance increases monotonically but can be maintained within the ITER limits by remaining in H-mode, Fig. 1. If heating is not available simultaneous control of the internal inductance and avoidance of flux consumption can be achieved by combining an appropriate ramp-down rate with a strong reduction in plasma elongation to reduce the vertical instability growth rate.

Apart from higher flux consumption for helium discharges during plasma initiation deuterium and helium discharges are very similar with respect to key requirements for ITER plasma control. Studies in helium during the ITER non-active phase should there-

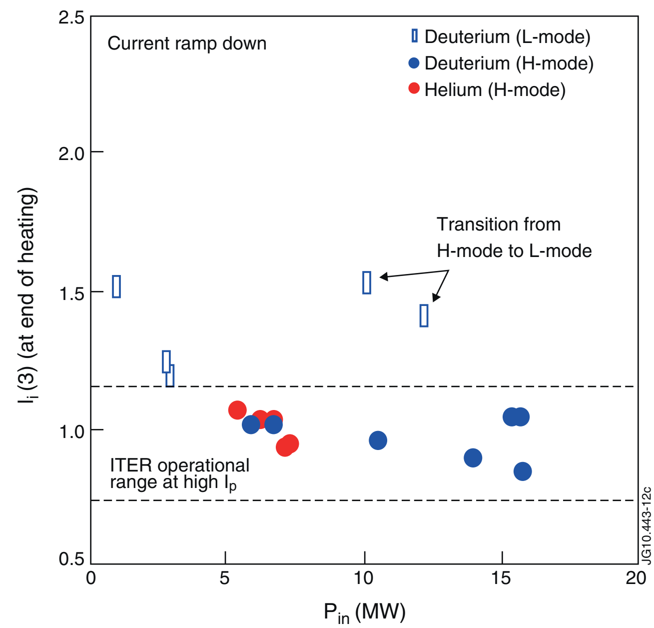

Fig. 1. Plasma internal inductance after current ramp down to half the flat-top current.

fore provide a good test of the operational space available in the current ramp-up and ramp-down phase of the discharge.

3. Disruption studies

Plasma disruptions are a key issue for all large tokamaks due to the electromechanical and thermal loads they can place on the tokamak structure. For ITER, and to a lesser degree also for JET with the ITER-like wall, a thorough understanding of disruptions and how they can be avoided or mitigated is critical. The JET disruption studies in support of ITER make use of a comprehensive set of recently upgraded diagnostics, including enhanced magnetic diagnostics capable of measuring asymmetries in the poloidal halo- and toroidal plasma current in four positions 90° apart [8] and improved infrared thermal imaging for power load studies [9]. Additionally, a fast Disruption Mitigation Valve (DMV) has been installed for disruption studies by Massive Gas Injection (MGI) [10].

3.1. Electromagnetic loads

Disruptions cause electromagnetic loads by forces from halo currents, currents with a composite path, partially in the plasma column and partially in the plasma facing conductive structure and the vessel wall, and forces from eddy currents induced by the rapidly varying magnetic fields during the current quench.

During asymmetric Vertical Displacement Event (VDE) disruptions the plasma current and vertical current moment are $n = 1$ toroidally asymmetric, leading to sideways forces of up to 4 MN in JET [11]. Scaled with Noll's formula the equivalent forces are an order of magnitude larger in ITER [12,13], which is designed for 48 MN. The possibility of a rotating asymmetry at the 8 Hz ITER fundamental mechanical vessel resonance frequency is a concern. Results from JET [13] however indicate that large asymmetries (∼10%) are observed only for short to moderate current quench times (up to 50 ms, corresponding to ∼250 ms in ITER if scaled with the plasma cross section area [14]) and that the asymmetries are significantly smaller for longer quench times. This implies that, at the ITER vessel resonance frequency, large asymmetries will only