Scientific preparation for future D-T campaigns at JET in support of ITER

A.C.C. Sips[1,2], C.D. Challis[3], H. Weisen[1,4], P. Batistoni[5], J. Bizarro[6], F. Crisanti[5], L-G Eriksson[2], J. Garcia[7], I. Jenkins[3], X. Litaudon[7], R. Neu[8], I. Nunes[6] and JET EFDA Contributors*, *JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK.*

[1]*EFDA Close Support Unit, Culham Science Centre, Abingdon, OX14 3DB, UK.*
[2]*European Commission, Brussels, B-1049, Belgium.*
[3]*Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK.*
[4]*Ecole Polytechnique Fédérale de Lausanne, Centre de Recherches en Physique des Plasmas, Association EURATOM – Confédération Suisse, 1015 Lausanne, Switzerland.*
[5]*Associazione EURATOM/ENEA sulla Fusione, Centro Ricerche Frascati, 00044 Frascati, Italy*
[6]*Euratom/IST Fusion Association, Instituto de Plasmas e Fusao Nuclear, Lisboa, Portugal*
[7]*CEA, IRFM, F-13108 St-Paul-Lez-Durance, France*
[8]*Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748, Garching, Germany.*

E-mail contact of main author: george.sips@jet.efda.org

Abstract

JET is preparing for deuterium-tritium operation in 2015 with the newly installed ITER-like Wall, neutral beam enhancements (35MW, 20s) and diagnostics upgrades, as part of a phased approach to the full exploitation of JET. Performance projections for stationary ITER scenarios predict Q~0.16-0.20 for ELMy H-mode plasmas at 4.5MA/3.6T, Q~0.3-0.5 for hybrid plasmas at 3.5MA/3.45T to 4.1MA/4.0T and Q~0.1-0.4 for advanced scenario plasmas at 1.8MA/2.7T to 2.3MA/3.45T. Key physics studies would concentrate on isotope mass dependence of the edge pedestal, ELM size and ELM mitigation as well as the access to H-mode. ICRH schemes for ITER could be tested, while sufficient alpha particles would be available for heating and instability studies. The tritium retention (using the Active Gas Handling Systems at JET) and cleaning methods for tritium removal could be assessed in addition to testing D-T diagnostics and 14 MeV neutron calibration techniques.

Introduction

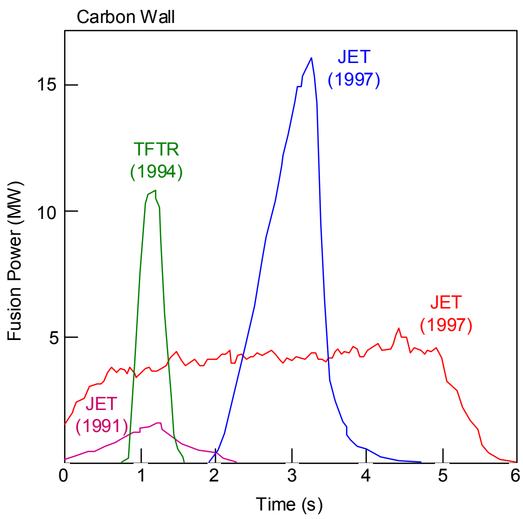

Figure 1. *Overview of the fusion power obtained in previous D-T experiments in JET and TFTR.*

JET has unique capabilities such as operation with tritium, confining alpha particles produced in D-T fusion reactions, use of beryllium as a first wall material, and remote handling systems for maintenance and refurbishments of the interior of the device.

Previous D-T campaigns at JET in 1997 (DTE1, [1]) produced up to 16.1MW of fusion power transiently, in an ELM free H-mode at Q~0.6, and 4MW in stationary ELMy H-mode conditions at Q=0.18, producing 22 MJ of fusion energy in a single pulse ([1] and Figure 1). These experiments also showed that the fuel mixture impacts strongly on performance. During 2003, a third period of JET D-T operation was carried out in which trace levels of tritium (~1-3%) in deuterium plasmas were used to study the fundamental processes for plasma transport and test specialised diagnostics at low fusion power. JET has maintained its D-T capability and after more than 15 years of development of ITER regimes of operation, the impact of using a D-T fuel mix will need to be assessed on JET in advance of ITER operations.

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

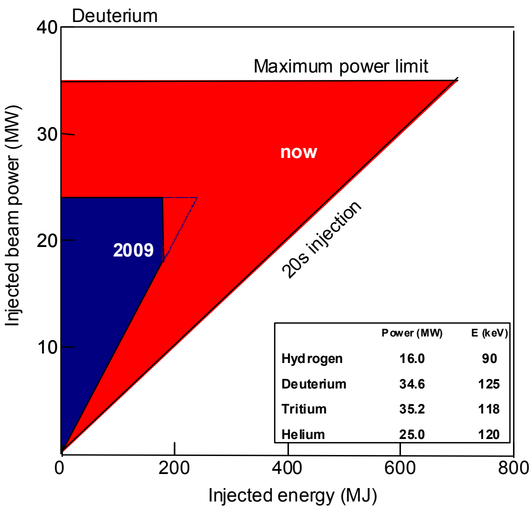

Figure 2. *The enhanced neutral beam capabilities in JET for hydrogen, deuterium, tritium and helium.*

Over the last few years, significant investments have been made on JET, primarily to replace the plasma facing components of JET with a combination of beryllium and tungsten (the ITER-Like Wall), reproducing for the first time in a fusion device the plasma facing materials planned for the deuterium-tritium phase of ITER operation [2].

A substantial upgrade of the neutral beam heating system [3] has provided JET with an increase in heating pulse length at full power from 10s to 20s, an increase in heating power in deuterium from 24MW to 35MW and a unique capability for the injection of high power particle beams of hydrogen, deuterium, tritium and helium (see Figure 2). Moreover, JET diagnostics for profile measurements have been substantially upgraded in spatial and temporal resolution for the core and pedestal region, along with improved diagnostics for fusion products that are of direct relevance to ITER.

With these enhancements the JET programme has a phased approach over the next five years:

- *Phase 1 (2011-2012):* Characterisation of the ITER-like wall, with experiments carried out at moderate input power to reduce the risk of an early damage of the wall, while protection systems are still being commissioned, followed by an intervention to remove tiles for post-campaign analyses of the ITER-Like Wall;
- *Phase 2 (2013-2014):* Expansion of the ITER regimes of operation. Develop plasma operation towards high performance, fully exploiting the recent enhancements, and approaching conditions closest to ITER; and
- *Phase 3 (2015):* D-T campaigns with both full tritium and deuterium-tritium operation. Deuterium-tritium experiments in JET with the ITER-Like Wall would address key aspects of the ITER research needs. Compared to previous D-T campaigns, significant new data would be obtained in the area of scenario development, isotope effects, H-mode physics studies, and tritium retention/removal techniques. High performance D-T experiments in stationary conditions may yield several MW of alpha power for heating studies and MHD instability studies. Moreover, JET can give a 14 MeV neutron flux in excess of 10^{12} n/s·cm^2 and fluence in excess of 10^{14} n/cm^2 on the first wall. Results obtained would be used for code validation and modelling in preparation for ITER.

Fusion performance projections

For the next D-T campaign, JET aims to operate at high fusion performance in stationary conditions. Fusion performance projections are based on existing deuterium experiments using: (1) TRANSP, conserving the plasma profiles, (2) a spreadsheet based, single time-slice fusion yield calculator, which has been benchmarked against experimental data and TRANSP runs and (3) CRONOS and JETTO simulations using density profiles and temperature pedestal values scaled from the reference plasmas, with the temperature profiles calculated using a Bohm-GyroBohm transport model, coupled with an internal transport barrier (ITB) model using a threshold condition for magnetic shear and ω_{ExB} flow shear [4].

ELMy H-modes provide a robust basis for extrapolation with recent experiments [5] in deuterium at 4.5MA/3.6T (Figure 3). The increased neutral beam heating power available opens the prospect for a significant increase in the steady fusion power up to 8 MW. The fusion gain is rather insensitive to the heating power applied, with Q~0.2.

It is considered that the hybrid scenario [6] gives the best prospect for steady high Q operation in JET, provided that the improved confinement and good stability achieved during the 2008/9 experimental campaigns (i.e. $H_{98}(y,2)$~1.3 and β_N~3 at I_P~1.7MA/2.4T) can be extended and maintained to high plasma current and magnetic field (reduced q_{95}~3). A key uncertainty concerns the density dependence of confinement, but taking a range of assumptions for the extrapolation up to 4.1MA/4.0T, the predictions give a range of uncertainty for Q (spreadsheet calculations, Figure 4). The $\tau_E \propto n^{0.41}$ dependence in the IPB98(y,2) scaling would predict a significant increase in fusion gain with plasma current (higher plasma density). At 3.5MA/3.45T CRONOS simulations indicate that Q~0.44 could be obtained at moderate density ($6\times10^{19}m^{-3}$), while at higher density the fusion yield in the simulations is substantially reduced due to the loss of ion temperature peaking resulting from poor beam penetration.

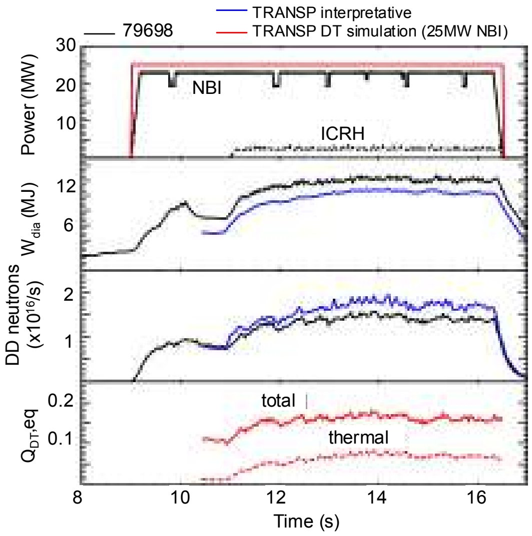

Figure 3. A recent ELMy H-mode discharge at 4.5MA/3.6T (#79698) compared with TRANSP D-D interpretative simulations (blue) and TRANSP D-T predictions (red).

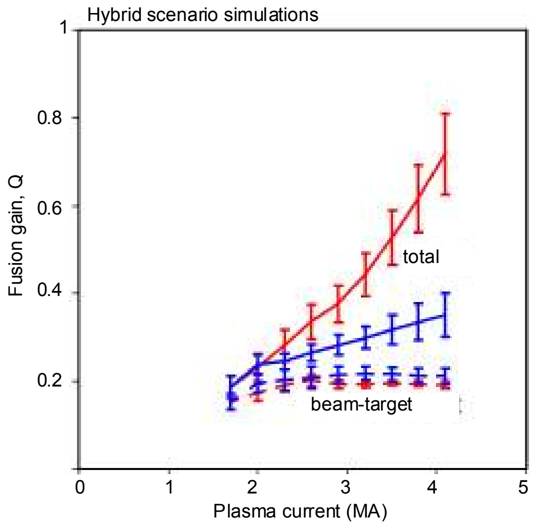

Figure 4. Hybrid scenario projections in D-T as function of the plasma current (I_p) and $n \propto I_p$. Used are $\tau_E \propto n^{0.41}$(red) or $\tau_E \propto n^0$ (blue) for the energy confinement scaling.

For advanced tokamak (AT) scenarios, existing discharges at 1.8MA/2.7T would extrapolate in D-T to Q~0.10-0.14. At 2.3MA/3.45T with 45MW input power, Q~0.27-0.38 could be obtained at β_N~3, provided the high input power available produces ITBs at large plasma radius (ρ~0.7) giving access to H_{98}~1.7 [7].

Key elements for the extrapolation need to be investigated prior to a D-T campaign to validate the assumptions made: Such as the compatibility of operation at high input power with the ITER-Like Wall using impurity seeding, strike point sweeping, ELM mitigation techniques, or divertor detachment and the potential for high confinement at high plasma current and high density, together with control of the impurity content and q-profile.

Physics and technology program with deuterium-tritium plasmas

Isotope scaling experiments are important in future D-T campaigns in JET. The scalings of the pedestal, ELM size, and L to H threshold require renewed experimental evidence as the pedestal in the DTE1 experiments was poorly resolved. Experiments with up to 100% tritium experiments during DTE1 [1] did indicate that, compared to deuterium and hydrogen discharges, the lowest ELM frequency was observed in pure tritium plasmas, with the largest ELMs expelling up to 18% of the total stored energy (Figure 5). The pedestal height was reported to scale linearly with isotope mass, whereas global confinement only weakly scales with mass. The effectiveness and impact of ELM mitigation techniques remains to be studied

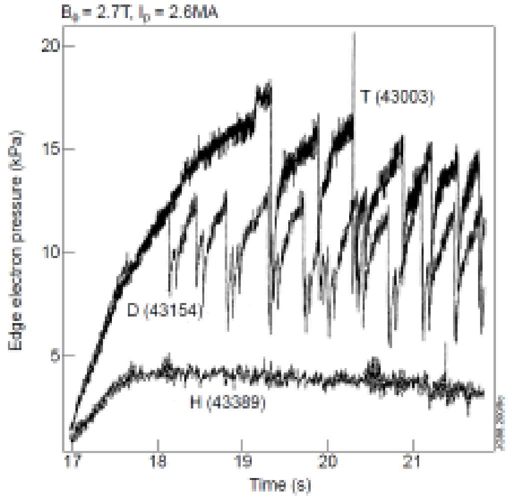

Figure 5. *Evolution of the pedestal pressure for tritium, deuterium and hydrogen discharges.*

in D-T plasmas as well as the isotope dependence of performance in hybrid scenarios and advanced scenarios.

ICRH scenarios in D-T for plasma heating in ITER can only be demonstrated and quantified at JET. As highest priority the experiments should provide a full characterisation of the 2^{nd} harmonic tritium scheme providing electron heating together with a documentation of the minimum level of ^{3}He required for ion heating. JET discharge conditions during flat top offer absorption conditions for ICRF similar to the ITER ramp-up phase. By using tritium beam injection, the absorption conditions for the flat top phase of ITER can be reproduced.

High performance D-T experiments in stationary conditions may produce up to 4MW of alpha power (hybrid scenario at 40MW input power) to provide a detailed assessment of alpha particle heating, including electron heating, possible direct ion heating through “alpha channelling”, as well as the effect of alpha heating on core impurity and particle transport. Measurements of TAE spectra and alpha particle drive on TAE modes will be made for code validation. The alpha-driven AEs could exhibit bursting evolution of the amplitude causing significant fast ion-redistribution, especially in advanced modes with q_0~2 [8].

An extensive fusion technology programme can be implemented in parallel with a D-T programme, covering:

1. Tritium retention with the ITER-like wall, including retention by co-deposition with beryllium, formation of (tritiated) dust, validation of tritium accountancy methods and the study of long term retention by removing tiles from the first wall.
2. The assessment of tritium removal using cleaning techniques proposed for ITER, such as clean-up discharges, bake-out of the first wall (Be, 320^{o}C) and divertor (W and W-coated, 200^{o}C), Ion Cyclotron Wall Cleaning (ICWC) in deuterium to remove the retained tritium, hot and cold temperature venting of the vessel and laser de-tritiation in the divertor area.
3. Test/rehearsal of ITER calibration procedures for neutron diagnostics in the D-D, T-T and D-T neutron energy ranges; and
4. Irradiation tests of ITER relevant material samples by 14 MeV neutrons, for testing ITER diagnostic components and validation of neutron transport codes in realistic geometries/materials.

Acknowledgments - This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Jacquinot J. and the JET Team, 1999, Plasma Phys. Control. Fusion **41** A13
[2] Pamela J. et al, 2007, JNM **363 - 365** 1
[3] Ciric, D. et al, 2010, 26th Symposium on Fusion Technology (SOFT), Porto, Portugal.
[4] Tala T. et al, 2006, Nucl. Fusion **46** 548.
[5] Nunes I. et al, 2010, 23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea.
[6] Hobrik J. et al, 2011, submitted to Plasma Physics and Controlled Fusion, EFD-P(10)65
[7] Litaudon X. et al, 2007, Nucl. Fusion **47** 1285
[8] Sharapov S.E.. et al, 2011, this conference.