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The JET ITER-Like Wall Experiment: First Results and Lessons for ITER

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** See annex of F. Romanelli et al, "Overview of JET Results",
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ABSTRACT.

The JET Programme in Support of ITER has entered its second phase, in which the boundaries for safe plasma operation with an ITER-like Wall are being explored. A key element of these studies is the benchmarking of the codes that are being used for ITER to predict plasma-wall interactions and, more generally, the influence of wall material on plasma performance and regimes of operation. Studies have focused on material migration and erosion, disruptions and runaway electron beams, and optimisation of plasma and divertor performance. In addition, a dedicated tungsten divertor melt experiment was carried out and provided key information for the ITER decision to begin operation with an all-W divertor. Initial results underline the strong influence that the wall material has on plasma performance and regimes of operation but show that there is significant scope for optimisation by careful discharge design. The future JET programme will concentrate on completing this optimisation and demonstrating the resulting performance in deuterium-tritium plasmas, thus providing the best possible preparation of ITER operation.

1. INTRODUCTION

The JET Programme in Support of ITER has completed its first phase, in which operation with the new ITER-like Wall (ILW) showed the expected reduction in retention of fuel gas and the baseline operating regimes for JET and ITER were re-established [1].

The second phase of the exploitation of the ILW has begun with the aim of exploring the limits of operation compatible with the new wall materials. This paper reports highlights from the experimental results so far in this second phase of experiments, carried out between July 2013 and September 2014. The paper then concludes with a summary and a description of future plans for JET.

2. MATERIAL MIGRATION AND EROSION

First ex situ analyses of tiles removed during the JET 2012/13 shutdown have confirmed that the amount of deposition during the operation with the ILW has decreased at least by an order of magnitude when compared to operation with a carbon wall [2]. In addition to this large reduction, the pattern of deposition has changed significantly since the change of wall material from carbon (JET-C) to beryllium and tungsten (JET-ILW). The predominant area of (Be) deposition is now on the top of the inner divertor (see figure 1) with negligible migration of material to recessed areas. This is consistent with the picture developed for JET-C of re-erosion and transport of deposited carbon, leaving behind beryllium-rich deposits [3] and the very low carbon content of plasmas in JET-ILW.

The main mechanism for material migration to the JET divertor is believed to be sputtering of beryllium from the main chamber and limiters by low energy (<10eV) neutrals during diverted plasma operation [4]. Spectroscopic measurements confirm that the primary material source has been reduced by a factor 4–5, consistent with lower Be sputtering yields (as compared to C). The sputtering material is then preferentially transported to the inner divertor due to SOL flows.

In order to understand quantitatively the material migration and thus be able to make predictions

for future devices such as ITER, a programme of modelling of the JET results has been launched, employing the same codes that are used for ITER predictions and planning.

Global impurity migration and fuel retention is studied using the WALLDYN code [5]. Not only is the profile of Be deposition reproduced in the code, the absolute level of fuel retention matches results obtained in both JET-C and JET-ILW once long term outgassing is taken into account.

Modelling of local material migration with the ERO code is being used to quantify the rates of beryllium and tungsten erosion and deposition during and between ELMs [6]. These ERO results are furthermore being used as input to calculations of transport to remote areas using the 3D-GAPS code, allowing quantitative comparisons to be made to measurements using quartz micro-balances and rotating collectors [7]. At present, the modelled rate of beryllium deposition in remote areas is a factor of 5–150 larger than experiment, suggesting that the assumed primary flux of beryllium into the divertor is too high [6].

3. TUNGSTEN MELT EXPERIMENT

First priority in the 2013/14 experimental campaigns was a dedicated test of the effect of shallow melting of one lamella of JET's solid tungsten divertor. This was in response to a concern expressed by the ITER IO that shallow melting during the commissioning of plasma protection systems might compromise subsequent operation and thus the strategy of installing the ITER all-W divertor on day one.

Following careful setup to guarantee transient melting due to ELMs without bringing the divertor lamella temperature above melting between ELMs (figure 2), melting was achieved in a series of seven identical discharges with very little impact on the plasma performance and no disruptions [8]. A photo showing the state of the lamella after these seven discharges is given in figure 3.

As with the material migration studies, application of these JET melt results to ITER requires a physics-based understanding and a primary goal of the JET experiment is to benchmark the code that is being used to model melt dynamics in ITER [9]. Indeed, the experimental results can only be reproduced in the model when the power flux to the exposed side of the offset lamella is reduced by a factor of 0.4. When this is done, the code then reproduces the location and size of the melt as well as the dynamics of the molten material. To further investigate this issue, a new JET melt experiment is being planned in which the offset lamella will be chamfered so that the power flux on the leading edge can be resolved by the (top-down) infra-red camera measurements.

4. DISRUPTIONS AND RUNAWAY ELECTRON BEAMS

The dynamics of disruptions are very different in JET-ILW due to the higher plasma purity and thus lower radiation losses during the disruption [10]. As a result, active mitigation using massive gas injection (MGI) is required for all JET pulses with a predicted plasma current $> 2\text{MA}$ or total internal (poloidal magnetic + kinetic) above 5MJ. In practice, this means that such mitigation is required for almost the entire JET programme and, as a result a second, tritium-compatible injector has been installed on JET [11-12]. Disruption mitigation, which done routinely with 10% Ar / 90% D₂, has

been largely successful – of the 143 pulses in the 2014 high current development programme, 35 disrupted and only three were unintentionally unmitigated and all of those at $\leq 2\text{MA}$ [13].

In ITER, an additional concern during disruptions is the generation of very high-energy beams of electrons. In JET, these runaway electron beams are normally not observed during disruptions but they can be produced and studied using massive argon injection above some threshold value. Runaway avoidance and mitigation experiments have been carried out using a second MGI system [14]. It has been found that runaway beams can be avoided by a second massive injection of deuterium provided that the gas reaches the plasma before the mixing phase induced by the thermal quench of the plasma. This transition is very sharp with a transition from no observed high-energy electrons to a fully developed beam (figure 4). Thereafter, it has not been possible to mitigate the beam, even using high-Z species (Ar and Kr) in the injection.

5. PROGRESS TOWARDS MAXIMUM PLASMA PERFORMANCE

The replacement of the JET carbon wall by the ITER-like Wall has affected plasma energy confinement in two ways [15]:

- i. By the effect of the wall materials on key plasma parameters, e.g. through plasma composition and wall recycling; and
- ii. By operational techniques necessary to avoid damage to plasma facing components (PFCs) and maintain stable plasma conditions, e.g. gas injection to avoid tungsten accumulation.

Techniques to minimise these effects and to maximise plasma performance are being developed. For central tungsten accumulation in particular, it has been possible to show that central ion cyclotron resonance heating (ICRH) can be used to widen the operating space [16]. Combining this with optimised divertor pumping, impurity injection both to reduce conducted power and to improve edge confinement [17], and judicious sweeping of the divertor strike points to control the divertor plate temperature, it has been possible to re-establish JET operation at the foreseen ITER operating point of $H_{98(y,2)} = 1$ and $\beta_N = 1.8$ (figure 5).

On the other hand, studies have shown that the degradation of energy confinement with input power is weaker than that given by the $H_{98(y,2)}$ scaling [15]. While this is attractive for advanced mode of operation that will operate at higher normalised plasma pressure, it does present issues for control of burning plasmas. A primary goal of JET experiments in 2015 will be to explore confinement at high β .

The range of operation of ELMy H-modes with the ILW has been extended to 4.0MA, limited by the available input power. At 3.5MA, optimisation of confinement continued up to the end of deuterium experiments (in September 2014) [18]. While the level of performance obtained in JET-C has not yet been achieved, considerable progress has been made. It remains to be confirmed whether the undoubtedly increased constraints of JET-ILW operation can be completely overcome. Indeed, the need to optimise confinement in JET-ILW is driving the selection of upgrades to be performed in the 2014/15 shutdown:

- Re-installation of the JET ITER-like Antenna, with the goal of providing more central electron heating; and
- Relocation of the High Frequency Pellet Injector so as to allow efficient delivery of pellets for ELM pacing (in a geometry relevant for future fusion devices [19]).

Both systems have the potential to decrease the present constraints on a minimum gas-fuelling rate in JET-ILW, which remains considerably higher than that used in JET-C.

6. MAXIMUM RADIATED POWER FRACTION

The use of a conventional divertor solution in a demonstration fusion power plant will require a large fraction of the input power (external plus alpha) to be radiated away rather than conducted to the divertor plates. Options for a DEMO being considered by the EU fusion programme require $f_{\text{RAD}} = P_{\text{RAD}}/P_{\text{IN}}$ to be greater than 90%.

Dedicated experiments in JET-ILW have explored the maximum achievable f_{RAD} as function of extrinsic impurity (or impurity mix) used to generate the radiation and of input power. The maximum radiated power fraction is found to be $\sim 75\%$ (figure 6), based on experiments with a variety of extrinsic impurities (N_2 , Ne and Ar) as well as an initial test of species mixes (N_2/Ne) [20]. This is particularly disappointing at high input power, where it is hoped that more margin to either the H-mode threshold or to divertor power starvation would result in higher fractions, i.e. that the limit would be on a net minimum conducted power to the SOL or divertor. So far in JET, however, this does not appear to be the case.

It must be said, however, that it has not yet been possible to generate a radiating mantle in the core plasma, rather an evolution towards a strong radiating blob near the X-point is observed. Further experiments are planned for the next JET campaigns, possibly using a higher Z extrinsic impurity.

7. SUMMARY AND FUTURE PLANS

The JET programme is presently in the second phase of its Programme in Support of ITER [21]. Results from the most recent set of campaigns indicate that, while there are significant additional constraints on operation with an ITER-like Wall, performance optimisation is possible with careful design of the discharge scenarios. While it is unlikely that the full range of operation possible with a carbon wall will be recovered, there is still considerable scope for further optimisation and it remains to be seen what is the maximum plasma performance that can be achieved with the new wall materials. This process of optimisation underlines the importance of learning how to operate with the ITER first wall materials.

The reference, future JET programme is to complete the phase of performance optimisation in a set of campaigns in 2015–2016 and then to complete the qualification of JET-ILW operation with a set of tritium and deuterium-tritium experiments in 2017. The D-T experiments will concentrate on long pulse, ITER regimes of operation, addressing also the physics associated with fuel isotopes and alpha particle heating. Performance predictions based on JET-C operation range from a fusion gain

of 0.3–0.5 in the so-called hybrid mode of operation, something that has never been tested in D-T. If the present JET-ILW results can be extrapolated to the highest possible current and power and if problems of tungsten accumulation can be overcome, it still seems possible that these predictions can be realised.

A strong technology programme will accompany JET tritium and deuterium-tritium experiments, covering areas such as [22]:

- Neutron detector calibration at 14 MeV neutron energy
- Experiments for the validation of neutronics & activation codes
- Tests on neutron / tritium detectors for TBMs
- Activation measurements for ITER material characterization & data validation
- Studies of irradiation damage on functional materials
- Studies on tritium retention, outgassing and airborne tritium
- Collection of operational experience on occupational dose
- Studies on waste production and characterization
- DEMO-relevant studies

A start has already been made on the preparation for these experiments. As an example, the JET neutron diagnostics (fission chambers and activation system) have been calibrated for 2.5MeV (D-D) neutrons using a ^{252}Cf source deployed on the JET remote handling boom [23, 24]. With careful planning and a strong supporting modelling effort, it was possible to achieve the target precision of 10% (the same precision required for ITER) (figure 7). The resulting neutron yield calibration factor has as a result been increased by 16% (this is the first calibration of the JET neutron diagnostics since the 1980s).

It is planned as part of the JET D-T experiments to calibrate the neutron diagnostics for 14MeV neutrons using a D-T neutron generator, again deployed on the JET RH boom. Preparation for this new calibration has already begun with an extensive set of neutronics calculations.

In addition to planning to complete the exploitation of the ITER-like Wall in the so-called Reference Scenario for JET exploitation, discussions are underway to extend and broaden the use of JET by inviting other ITER Parties to participate in and contribute to the programme. Feasibility studies have been successfully completed for both an ECRH [25] and an ELM Coil System on JET [26]. More recently, an ELM coil conceptual design has been completed in collaboration with colleagues from the Institute of Plasma Research in India. A decision on whether or not to proceed with this Alternative Scenario for JET exploitation is expected in the next few months.

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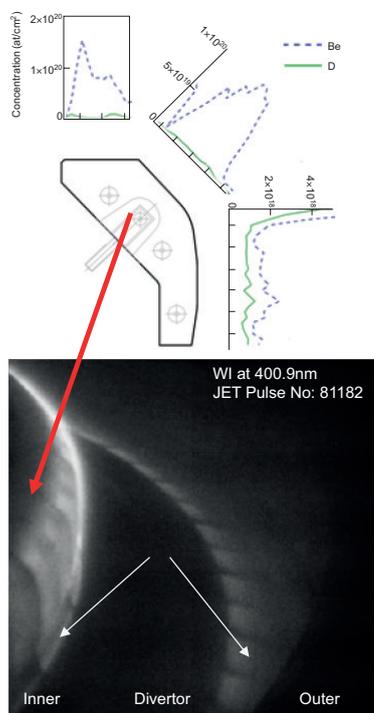


Figure 1: (above) Measured pattern of beryllium deposition on the JET inner divertor after the first set of experimental campaigns in 2011/12 (adapted from [2]) as well as (below) the divertor tungsten emission showing a lack of emission from the region where Be coatings have been observed.

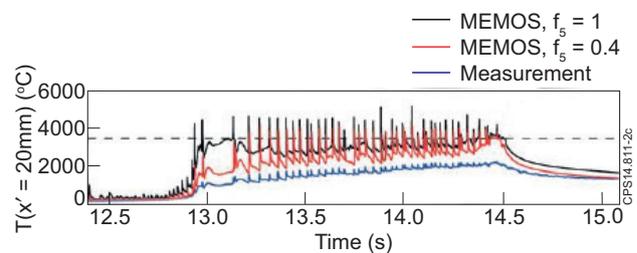


Figure 2: Time evolution of the offset divertor lamella temperature during one of the melt discharges, showing that melting occurred only during ELMs. To match the observed melt characteristics, the measured temperature must be corrected in the model (see text).

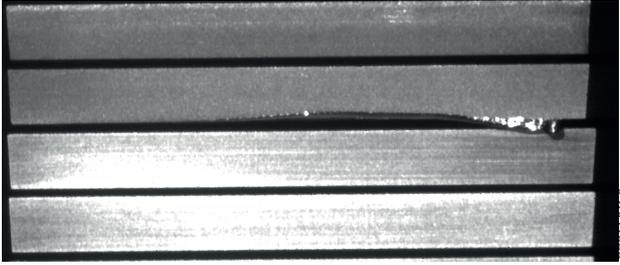


Figure 3: Photo of the JET offset divertor lamella after a series of seven identical discharges in which the lamella edge was repeatedly melted by ELMs. Each lamella is 5.5mm thick.

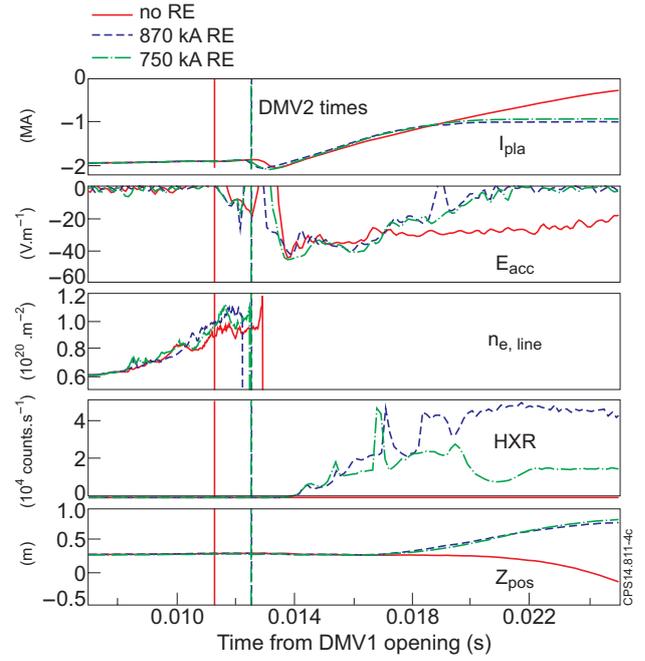


Figure 4: Runaway electron beam avoidance experiments showing the sharp transition from no to a fully developed beam depending on the timing of the massive gas injection (a) plasma current, (b) electric field, (c) line-integrated density, (d) hard X-ray counts as a high energy electron monitor, and (e) vertical plasma position [14].

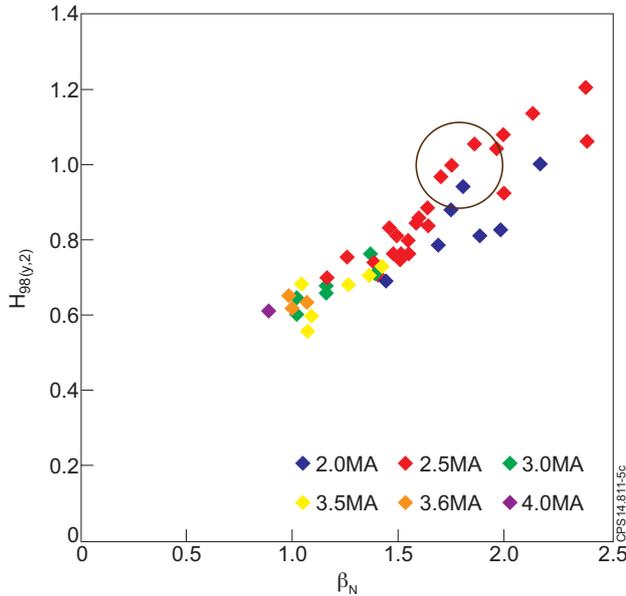


Figure 5: Confinement enhancement factor $H_{98(y,2)}$ versus normalised plasma pressure for JET ELMy H-mode discharges with the ITER-like Wall. The nominal ITER operating point of $H_{98(y,2)} = 1$ and $\beta_N = 1.8$ is indicated with the open circle.

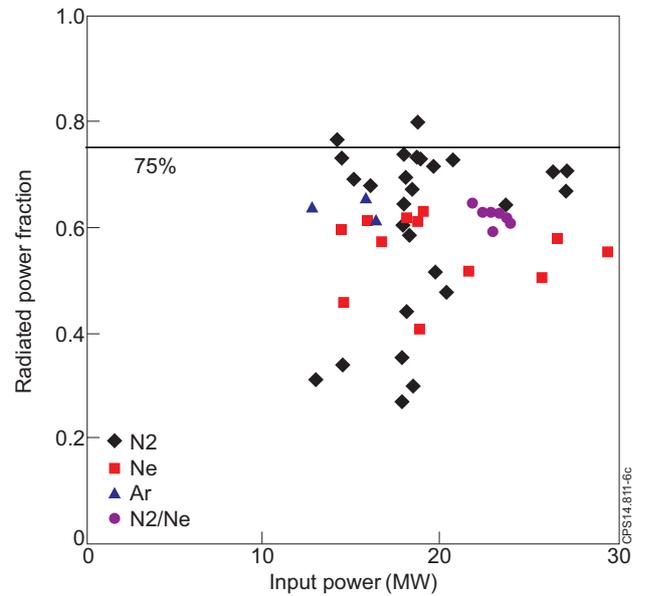


Figure 6: Radiated power fraction as a function of input power for a series of discharges exploring the maximum achievable radiation by the injection of impurities.

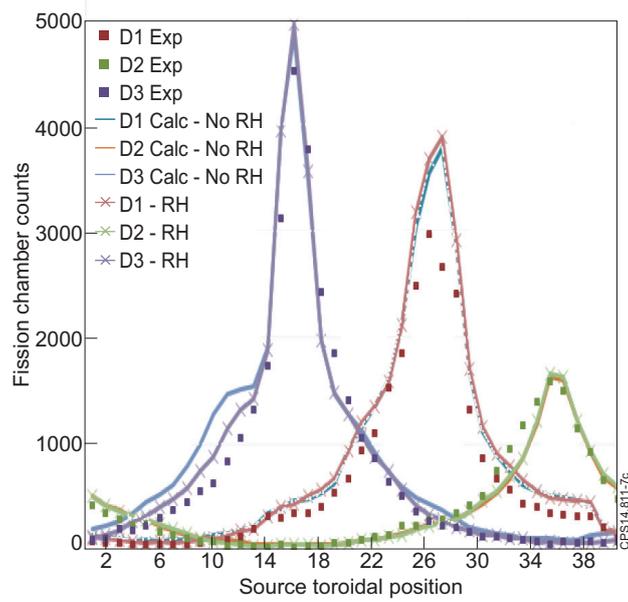


Figure 7: Response of the JET fission chamber diagnostics to a ^{252}Cf source deployed inside vacuum vessel using the remote handling boom (points) and calculations of the expected response, with and without the additional shielding and scattering generated by the boom (lines).

