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The JET Technology Program in Support of ITER

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ABSTRACT
This paper presents an overview of the current and planned technological activities at JET in support of ITER operation and safety. The scope is very broad and it ranges from analysis of components from the ITER-like Wall (ILW) to determine material erosion and deposition, dust generation and fuel retention to neutronics measurements and analyses. Preliminary results are given of the post mortem analyses of samples exposed to JET plasmas during the first JET-ILW operation in 2011-12, and retrieved during the following in-vessel intervention. JET is the only fusion machine capable of producing significant neutron yields, up to nearly 10^{19} n/s (14.1MeV) in DT operations. Recently, the technological potential of a new DT campaign at JET in support of ITER has been explored and the outcome of this assessment is presented. The expected 14MeV neutron yield, the use of tritium, the preparation and implementation of safety measures will provide a unique occasion to gain experience in several ITER relevant technological areas. A number of projects and experiments to be conducted in conjunction with the DT operation have been identified and they are described in this paper.

1. INTRODUCTION

JET is the largest operating fusion device and its scientific program is fully devoted to supporting the preparation of ITER operation. Recently, the JET plasma-facing wall made of carbon fibre composites (JET-C) was replaced by the so called ITER-like Wall (JET-ILW), using the same material combination as in ITER [1]. In the ILW solid Be or Be-coated tiles are used on the walls, and a combination of bulk W and W-coated CFC tiles in the divertor. This major enhancement was performed by remote handling during one intervention and completed in May 2011. JET-ILW experiments are now focused on studies of plasma-wall interaction processes, including low fuel retention, and on the compatibility of the ITER materials with high power operation [2]. After the first ILW campaign in 2011-12 and the following first intervention, the reference scenario for the JET program includes a deuterium campaign, started already in July 2013 and continuing up to early 2014 (including ~ 1 month of Hydrogen operation), and a full performance deuterium operation in 2015 eventually finished with helium operation envisaged at the end of the campaign. After a preparatory shutdown in 2016, operation with tritium is planned in 2017 with a full deuterium-tritium campaign followed by a clean-up deuterium campaign (Fig.1).

In parallel to, and in close collaboration with the scientific program, a technology focused program is carried out at JET in support of ITER operation and safety. The scope is very broad and ranges from detailed analysis of components from the JET-ILW to determine material erosion, deposition, dust production and tritium retention by post mortem analyses, to neutronics and activation measurements and analyses for neutron detector calibration and code validation.

A range of post mortem technologies are being deployed on samples and diagnostics which are exposed to JET-ILW plasmas in the main chamber and in the divertor, and also in divertor remote areas to collect deposited material. The fuel retention by post mortem analysis in samples is critical for determining the true retained amount because the experimentally determined retention with the ILW during plasma operation using the active gas handling system is very low and can only be regarded as an upper limit due to long term outgassing [3]. First results from ion beam analysis show a dramatic reduction in overall deposition as compared to the carbon wall and low levels of retained deuterium with very little residual carbon. Post-mortem analysis also provide the total amount of eroded materials, the overall erosion deposition patterns in the main chamber and in the divertor, the characteristics of deposits and the dust formation rate which are of great importance for ITER safety. First results have also been obtained from special diagnostic mirror samples located in the main chamber and divertor which are critical for determining the design and the materials used for the first mirrors in ITER. In Section 2 the erosion/deposition studies by post mortem analyses are presented, with the preliminary results from the first JET-ILW campaign, as well as the future plans.

JET has full capability of operating with tritium and it is the only fusion machine capable of producing significant neutron yields, typically $\approx 10^{16}$ n/s (2.5 MeV) in DD and up to nearly 10^{19} n/s (14.1MeV) in DT operations. The present option for the DT experiments in 2017 (DTE2, after DTE1 performed at JET in 1997) is to use the full 14MeV neutron budget of 1.7×10^{21} still available to JET according to the Joint Implementing Agreement. This proposed 14MeV neutron budget is nearly an order of magnitude higher than any previous DT campaigns (JET or TFTR). The DTE2 will require using 60g of T in the T plant, while the total releasable T inventory allowed outside the T plant is limited to 11g T on the various cryo-panels and to 4 g on the mobile in-vessel inventory. The calculated neutron fluence on JET first wall at the end of DTE2 will be up to10^{20} n/m^2, that is hardly achievable at existing 14 MeV neutron generator. Moreover, such fluence can be obtained on large surfaces thanks to the volumetric plasma neutron source. At P_{fus} = 14MW, the neutron flux on the first wall is $>10^{17}$ n/s·m^2, comparable with that expected in ITER between the blanket and the vacuum vessel.

The operation with T, and the production of an unprecedented 14MeV n-source, together with the preparation and implementation of the safety measures, would offer an unique opportunity for gaining experience in several technological areas especially those related to the nuclear aspects. Recently, the technological potential of a DT campaign at JET in support of ITER has been explored and a number of projects and experiments to be conducted in conjunction with the DT operation have been identified. These activities are described in Section 3, together with the preparatory experiments already on going at JET.

2. EROSION AND DEPOSITION STUDIES BY POST MORTEM ANALYSES

Before the start of ILW operation, a number of samples and diagnostics had been installed both in the main chamber and in the divertor (Fig.2). They include: marker tiles which can either contain ^{10}Be isotope marker or special sub-surface marker layers of Mo on W or Ni on Be that allow precise determination of erosion rate; sachet samples inserted in the vessel cladding tiles; rotating collectors (that provide a time-resolved deposition pattern on the surface of a rotating Si disc); first mirrors on outer wall and in the divertor; passive diagnostics in divertor remote areas (rotating collectors, sticking monitors, louvre clips, quartz micro-balance) that collect deposited material for post mortem analyses [4]. During the intervention following the first ILW campaign a total of 57 tiles and samples, 20 mirrors and several other diagnostics have been removed and replaced by remote handling. The retrieved samples are being analyzed by surface profiling, Ion Beam Analyses (IBA), Proton Induced X-ray Emission (PIXE), SIMS, SEM and X-ray techniques to obtain a measurement of the modification of the tiles surface after plasma exposure, the thickness and the chemical composition of deposits and the fuel content.

The first results available so far are presented in the following and compared with those obtained in the JET Carbon wall (JET-C). For such comparison, it should be noted that the total plasma time has been about a factor of 2 lower in the first ILW campaign (19h) as compared to the last two JET-C campaigns (35h in 2005-07, 45 in 2007-09) and that the proportion of limiter phase for the ILW is slightly higher (6 h) than for the same JET-C campaigns (8h, 12h respectively). This is due to a number of dedicated limiter plasma experiments performed in JET-ILW to test the operating limits of the Be first wall in the main chamber, and for gas balance experiments in limiter configuration. The main erosion mechanism in JET-ILW is due to physical sputtering in Be that has a threshold energy for incident D ions or neutrals at about 10 eV (lower than for C). It is known that there may be a contribution of chemical assisted sputtering a lower ion energies and a contribution of Be self sputtering at higher energies associated with low density operation [5]. Moreover, the physical sputtering yield is higher for Be than for C. For these reasons, it is expected that significant erosion occurs during the limiter plasma phase, when the plasma is in contact with the limiter materials, and re-deposition also occurs in the main chamber creating an overall balance. However there is no chemical erosion in the case of Be, as it is the case of C at low incident particle energy, and for this reason much less erosion is expected on the wall by low energetic ions or neutrals in the far SOL during the divertor phase, and therefore much reduced migration of Be from the wall to the divertor. These expectations have been confirmed by experiments during ILW campaign by spectroscopic measurements [6], but the total amounts of eroded material and the distributions of deposits can only be accurately determined by post mortem analyses. The erosion rate has been estimated on the inner limiter at the mid-plane by tile surface profiling and by IBA [7]: the results show that erosion is found on the central part of the tile while very little deposition is found on the lateral areas of the tile, as it was the case in the carbon wall. Considering just one row of tiles from the mid-plane and extrapolating to all Be inner limiters the net erosion in JET – ILW is higher ($\sim 2.3\times 10^{19}$ atoms/s) than for JET-C ($\sim 1.4\times 10^{19}$ atoms/s). This results has been obtained by just normalizing to the total plasma time in limiter configuration, while other parameters influencing the erosion rate have not been considered yet, such as incident ion flux, power and variations in the point of contact of the plasma with the inner limiters. Another area of strong erosion has been identified on the outer poloidal limiters, but further analysis is required to complete picture of erosion and deposition pattern in the main chamber.

In the divertor, very thin deposits, with thickness of the order of 1 μm, have been found on Tiles 4 and 6 on the divertor base, which were characterised by very thick deposits in the previous JET-C [8]. The only significant amount of deposit has been found on the apron and top part of Tile 1 in the inner divertor (Fig.3), although significantly smaller than in JET-C. These deposits consist mainly of Be but with an increasing W fraction with depth. The C content is very low. In JET-C thick deposition was found on the divertor base and in the divertor remote areas. In JET-ILW the volume of deposit on Tiles 4 and 6 is two orders of magnitude lower than JET-C. There is also about an order of magnitude reduction in deposit formation in the remote divertor areas. These results indicate a much reduced erosion of the wall during the divertor phase, as expected. First analyses on samples retrieved from the vessel cladding tiles could confirm this picture. In JET-C, the C deposited on Tile 1 was either re-eroded and migrated to Tile 4 and the remote areas resulting in thick spalling deposits or was directly spalling or flaking from the apron region. In the JET-ILW the stepwise transport of hydrocarbons does not occur since there is no chemical sputtering at Tile 1 to initiate migration of the Be to Tile 4 and to the rest of the divertor.

Dedicated experiments were performed to measure the long term fuel retention with the ILW by gas balance [3]. These experiments have shown that the long term D retention rate normalised to the divertor phase drops by more than one order of magnitude with the full metallic wall as compared to JET-C. The main mechanisms for the long-term retention are implantation in Be and co-deposition of fuel with Be. Implantation is responsible for the dynamic retention during the discharge which is released after the discharge and saturates with impinging ion flux while co-deposition increases linearly with ion flux and operational time. Co-deposition of fuel with Be is therefore the dominant process for long term fuel retention. Preliminary analyses in these deposits show that the D retention is not dissimilar to that in JET-C, although this has to be confirmed by analyzing more samples from the divertor and the main wall. However, the observed much reduced volume of the deposits in the divertor is already in line with the reduction in the long term retention observed by gas balance experiments, and provides confirmation of a very positive result for ITER.

During the first intervention following the ILW campaign the dust from the divertor tile surfaces was collected by vacuuming and the amount of collected dust (<1g) was dramatically reduced compared with much larger amount collected from JET-C after 2008-9 operations (277g). By comparing that amount of dust with the weight of the observed deposits, the conversion rate of deposited materials into dust for JET-C was estimated in the frame of an ITER contract and was found to be about ~45% [9]. As many divertor tiles in JET-C were in the vessel since 1998 the dominant mechanism for producing dust and flakes in the divertor for JET-C was from spalling deposits that have reached a critical thickness. In the ILW the deposits forming in the divertor are still very thin and have not reached a stability limit where spalling occurs resulting in only a small amount of dust and flakes being collected. Dust quantities and layer growth in the divertor will continue to be monitored in future JET interventions to build up an accurate picture of dust production. On the basis of the preliminary results, it is however expected that it will take longer in the JET-ILW to come to a steady state condition for the production of dust from deposits.

Metallic mirrors will be essential components of all optical systems for plasma diagnosis in ITER. A comprehensive first mirror test has been carried out in the JET-C and is now continuing in JET-ILW. The mirrors are exposed in carriers both on the outer wall and in the divertor, and are characterized before and after their exposure by optical and surface analysis methods. In the JET-C it has been observed that reflectivity of all tested mirrors is degraded either by erosion or by the form of thick deposits. The preliminary results of JET-ILW [10] show that mirrors in the main wall are generally shiny and clean after exposure**.** The reflectivity of Mo mirrors is retained in Vis-IR range (400–1600 nm), but is reduced in UV range (250–400nm), whereas the reflectivity of Rh-coated mirrors is reduced in the whole range (250–2500nm). All mirrors exposed in the divertor have lost reflectivity due to the presence of deposits (up to 700nm) containing Be, C and W. Plasma and laser cleaning techniques will be tested on exposed mirrors for these ITER-relevant deposits.

Samples and diagnostics will be collected and replaced in all future JET interventions and analyzed through post mortem analysis to build up an accurate picture of material migration, fuel retention and dust production in support of ITER safety. Post mortem analysis of JET-ILW samples after the DT campaign will provide accurate measurements to validate models of tritium retention, outgassing and removal efficiency in bulk materials, deposits and dust.

3. TECHNOLOGICAL EXPLOITATION OF DT OPERATION

Recently, the technological potential of the DTE2 in support of ITER has been reviewed in collaboration with experts from the ITER, F4E and the European fusion laboratories. A number of activities and projects to be performed in conjunction with DTE2 have been identified and include:

- Studies on tritium retention, outgassing and airborne tritium
- Neutron detector calibration at 14MeV neutron energy
- Experiments for the validation of neutronics and activation codes
- Activation measurements for ITER material characterization and data validation
- Validation of calculations of activation corrosion products (ACP) generation
- Studies of irradiation damage on functional materials
- Collection of operational experience on occupational dose
- Studies on waste production and characterization
- DEMO-relevant studies

In order to fully exploit the nominal neutron budget available, and to obtain a full scientific return for the investment into the DT campaign, an accurate calibration of JET neutron detectors (^{235}U and ^{238}U fission chambers and the in-vessel activation system) at 14MeV neutron energy will be performed using a DT neutron generator deployed inside the vessel by remote handling. The calibration, that will take advantage of the experience gained with the recent calibration of JET neutron detectors at 2.5MeV neutron energy [11], will also benchmark the calibration procedure envisaged in ITER where neutron detectors have to provide not only the fusion power but also the amount of tritium burnt for tritium accountancy. For this reason an accuracy better that 10% is required [12]. JET calibration will assess the achievable accuracy and provide guidance to improve it.

The validation of neutronics codes will also be addressed with *ad hoc* experiments. The calculations for neutron fluxes and consequent nuclear responses in ITER far from the plasma source are very complex because they involve large and complex geometries, with the presence of narrow penetrations in thick shields and of many materials involved. The errors associated to these calculation cannot be easily quantified mainly because of the lack of experimental data for calculation validation in real fusion environment [13]. Experiments will be carried out with the fusion relevant conditions in JET, with the appropriate neutron source and environmental complexities to validate the codes used in ITER design to predict quantities such as neutron flux along streaming paths, activation of materials, shutdown dose rates. Shutdown dose rates are now measured at each intervention at JET in different locations and compared with values predicted by the numerical codes used in ITER design [14] which involve coupling of neutron and gamma transport calculations with activation calculations. Recently, a streaming experiment has been started in which the neutron fluence has been measured at increasing distances from JET machine, on the walls of the Torus Hall and also in penetrations of the Torus Hall such as the South West labyrinth access and the South East chimney containing large air ducts. The neutron fluence, which varied over more than four orders of magnitude, was measured in only two weeks of JET campaign using very sensitive thermo-luminescent detectors calibrated in terms of neutron fluence [15]. The measurements and the calculation tools are being optimized in current DD campaigns in view of completing the experiments during the DT campaign in presence of 14MeV neutrons.

The 14MeV neutron fluxes at JET will also be used to irradiate samples of real ITER materials used in the manufacturing of the main in vessel components, and to measure the neutron induced activation. ITER-grade W, Be, CuCrZr, 316L(N)-IG will be considered, but also functional materials used in diagnostics and heating systems that, if strongly activated, may release high dose levels to critical components. Large neutron flux and fluence, as well as large irradiation surface, will allow to expand significantly the activation detection range achievable at existing 14 MeV neutron sources (Fig.4).

During the DT campaign, experiments can also be carried out to validate the calculations of the generation of activation corrosion products (ACP) in ITER cooling water. The estimate of ACP is very important in assessing the ITER plant Occupational Radiation Exposure, and the activity released in case of a loss-of-coolant accident. No experimental data for fusion neutron spectrum and materials exist to validate these calculations. The feasibility of a test loop has been investigated with a test head made of AISI 316L or CuCrZr and exposed to JET neutrons during DTE2 in a vertical port, with circulating water at 1.3 m/s and 200°C. ACPs generated in the pipes are captured in mixed beds of ion exchange resins. The analysis of the experiment has shown that that ACP are generated in sufficient amount in JET cooling loops for validating calculation predictions of ACPs in ITER [16].

Finally, at neutron fluence levels achievable on the JET first wall at the end of DTE2, i.e. at

~10^{20} n/m^2, the degradation of physical properties of functional materials can be observed. As an example, Fig.5 shows the case of the degradation of the thermal conductivity of window grade diamond irradiated in fission reactors as a function of the neutron fluence [16].

Experimental and theoretical data show that 14MeV neutrons produce between 1.5 and 2 times as many point defects as fission reactor neutrons [17], hence irradiating window grade diamond in a fusion spectrum in JET would enable an upper dose limit to be established and to validate simulation modeling. At ionizing radiation dose rates of ≥100 Gy/s, occurring at neutron flux ≥3×10^{17} n/s·m^2, changes in radiation induced conductivity (RIC), dielectric loss, as well as radioluminescence are readily visible. Related to the use of optical fibres, the radioluminescence from the visible to the IR could be monitored during the JET pulses. In the same way, the Radiation Induced Electromotive Force (RIEMF) in mineral insulated cables could be easily monitored. RIC could be measured for various candidate alumina materials and compared with available in reactor data.

CONCLUSION

A strong technological program is being carried out and is planned to continue at JET in support of ITER. First results from post-mortem analyses of the JET- ILW have been described, that provide very positive input to ITER operation and safety. These analyses will continue in the future to establish the overall erosion deposition patterns, and to provide ITER with a reliable figure for the the dust formation rate and for the long term fuel retention. A number of technological projects have been identified to exploit the potential of JET DT operations. These will provide validation of current assumptions made for preparing ITER plant safety and operation, in areas such as neutronics, activation, diagnostics, safety and waste. Its implementation will provide important data to validate assumptions used in ITER safety and operation, and will stimulate facilities and the capabilities in EU to handle Be and activated samples for testing and analyzing ITER relevant materials.

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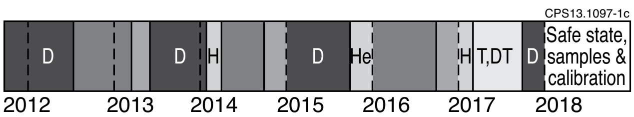

Figure 1: Reference JET Schedule with ILW operations.

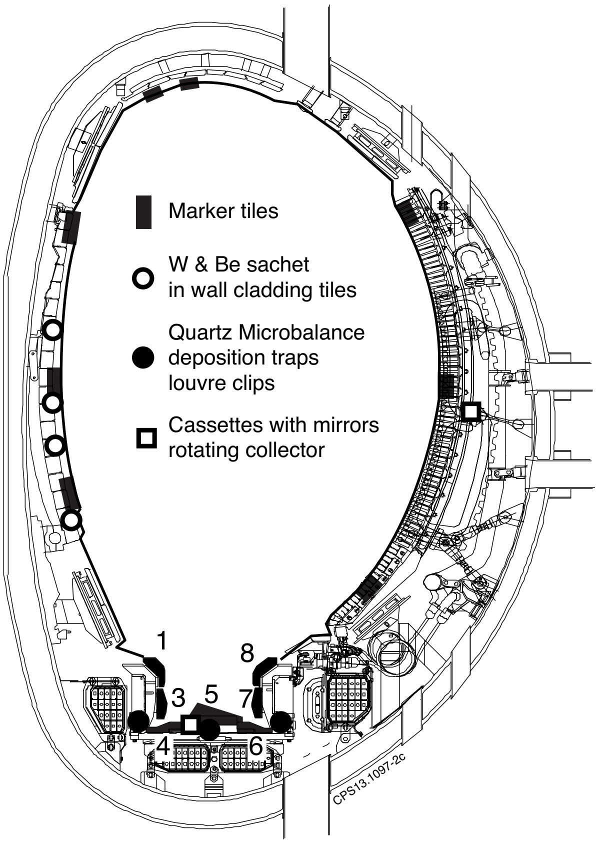

Figure 2: Erosion/deposition diagnostics in JET-ILW.

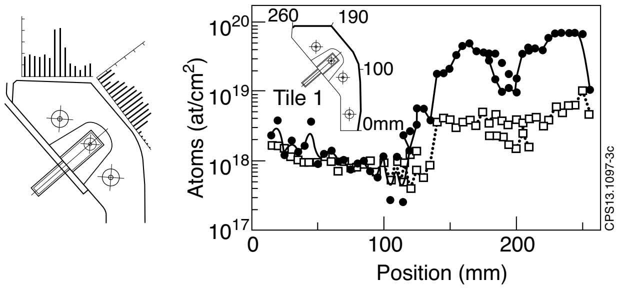

Figure 3: Left: Thickness profile of deposits on top of Tile 1, from tile profiling. Right: Be and D content in the same deposits from IBA analyses [8].

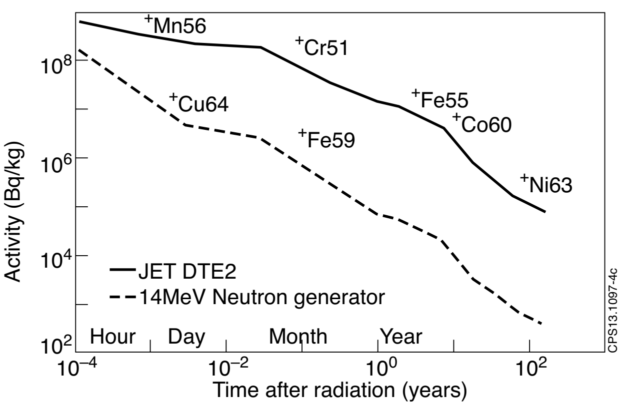

Figure 4: Neutron induced activity in AISI 316(LN) after irradiation in JET first wall. during DTE2 and at a neutron generator producing $5x10^{10}$ n/s on average for 30h.

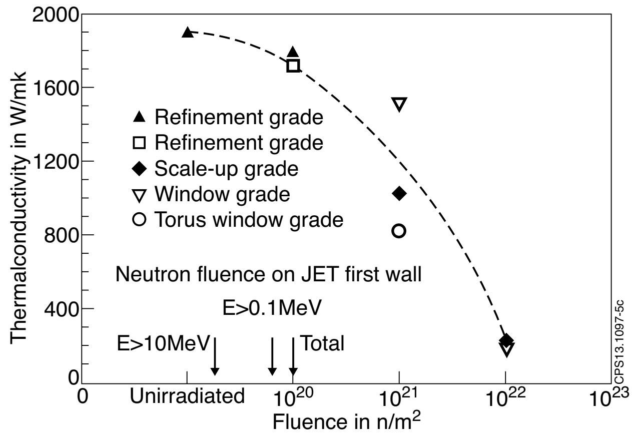

Figure 5: Degradation of thermal conductivity in high grade CVD diamond window due to neutron irradiation [16]. Arrows show the neutron fluence on JET first wall at the end of DTE2.