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Implementation and Exploitation of JET Enhancements at Different Fuel Mixtures in Preparation for DT Operation and Next Step Devices

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In the framework of the ITER Physics Department of the EUROfusion Consortium, JET mission is focused on preparing for the next step devices by developing high performance scenarios and testing reactor relevant techniques and technologies. In terms of scenario development, a complete scan in isotopic composition has already started and, according to the present schedule, should include full T operation and culminate in a 50/50 DT campaign by 2020. In DD, significant increases in input power and various adjustments in fuelling have allowed matching the IPBp8y2 scaling up to 3 MA. A complete set of diagnostic upgrades is being implemented to support operation and to guarantee adequate scientific exploitation of the experiments. With regard to the technology, the main enhancements and specific tests are focused on maximizing the returns from the unprecedented 14 MeV neutron field and the tritium fuel cycle.

Keywords: JET, DT operation, burning plasma, diagnostics, fuel cycle, tritium blanket module.

1.JET a unique nuclear Tokamak

JET is the only nuclear operational Tokamak in the world and presents some unique capabilities, which render the experiment the most relevant for the future generation of machines. The most important specificities are the use of the reactor fuel D-T, the plasma facing components of ITER (W divertor and Be main chamber first wall) and the plasma parameters to confine the alpha particles. The fuel scan experiments, leading to the next JET T-T and D-T experimental campaigns, now scheduled for the period 2019-2020, are expected to provide an important contribution to fill major physics and technological gaps for the development of fusion energy, mainly regarding the isotopic effects on various plasma aspects such as confinement, the threshold to access the H mode and ELM behaviour. From a technical point of view, the total yield of the final D-T phase is expected to be 10^{13} n/s·cm^2, about a factor of six higher than the previous main D-T campaign on JET, DTE1. Therefore, the radiation field will be quite relevant for next step devices, since the neutron flux at the first wall (~10^{16}n/cm^2), for example, will be similar to the one in ITER behind the blanket, the closets position to the plasma where it is conceivable to locate any equipment. With respect to the technological enhancements, for many years JET systems have been upgraded in order to support the scientific exploitation during the fuel mixture scan leading to a full D-T campaign. In this context, the main efforts have concentrated on improving three main aspects of JET capability: 1) the heating and ancillary systems to develop scenarios and improve performance 2) the quality of the measurements to maximize the scientific exploitation and investigate the fusion products in reactor relevant

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radiation fields 3) testing specific technologies relevant for ITER and DEMO.

2. Scenario development toward ITER

With regard to scenario developments and the increase in performance, in deuterium the confinement predicted by the IPB98y2 scaling has been reproduced up to a plasma current of 3 MA. The main plasma parameters of one of these discharges are reported in Figure 1; if run in 50/50 DT the discharge in the figure would have produced about 8 MW of fusion power for a couple of seconds. Such results have been obtained by properly tuning the fueling, to prevent excessive impurity generation at the edge by operating at high densities but not to the point of affecting the pedestal. In this direction, impurity seeding, particularly with N, has also proved to be quite helpful. Essential to the progress has obviously been also the improvement in power and reliability of JET neutral beams. Even if the number of operational days was limited in 2016, 68 discharges with NB power in excess of 28 MW for at least 1 s have been produced, more than in all the previous years combined. On the basis of these results, various simulations support the ambition of achieving 15 MW of fusion power for 5 s in full DT operation, with an additional heating power of about 40 MW. It is to note that such simulations are conservative because they do not consider neither the effects of the isotopic composition nor the contribution of the alpha particles. Moreover, it is worth mentioning that the developed plasma configurations are fully compatible with the wall properties, from melting to retention and dust production (less than 2 g in the last set of campaigns). In particular post mortem analysis indicates that retention with the ILW is less than 0.5%, including the effects of the more than 170000 castellations.

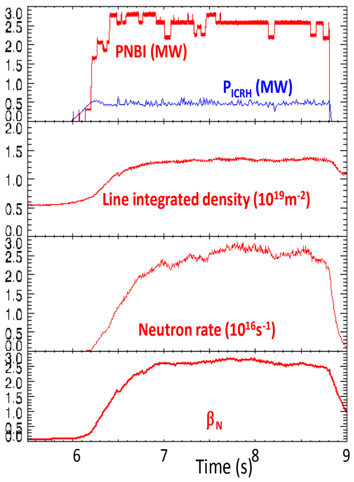

Fig. 1. Discharge 92398 which would produce about 8 MW of fusion power if run in DT. Similar performances have been obtained for the baseline scenario.

A systematic scan of the isotopic composition has already started with a series of dedicate hydrogen and deuterium campaigns. These first experiments seem to indicate that the mass dependence of the energy confinement time is $A^{0.4}$, significantly higher than the one $A^{0.2}$ predicted by the IPB98(y,2). In preparation for high current operation, very significant efforts have also been devoted to investigate disruptions, from mitigation and avoidance to prediction. Two new DT compatible fast valves for massive gas injections (MGI) have been systematically used to assess the potential of this mitigation scheme. Fine tuning of the MGI use has allowed to increase the radiation emitted during the current quench at levels comparable to JET with the carbon wall but it has not be possible to reach ITER requirements and to suppress the runaways beams. A new shatter pellet injector, just installed, will allow further studies of these very delicate issues. The development of disruption predictors has also continued at high pace. In particular adaptive machine learning predictors, capable of operating from scratch i.e. after being trained with a single disruptive and a single safe discharge, have been applied to practically all the campaigns with the ILW, for a total of thousands of discharges. They reach about 98% of success rate and a few percent of false alarms. Since their performance never fall below 90% of success rate and 5 % of false alarms, they have to be considered good options of next step devices, particular at the beginning of their operation.

3. Diagnostic upgrades

In preparation for DT operation, diagnostic upgrades are essential not only for optimizing operation and performance but also for maximizing the scientific exploitation of the experiments. In this perspective, for many years JET diagnostics have been upgraded, with particular attention to the experimental and operational conditions expected during deuterium-tritium campaigns. Diagnostic capabilities relevant for burning plasmas conditions have been specifically targeted with the focus mainly on fast ions, instabilities, neutron, gamma, ion temperature and operations support [1].

During last shutdown, a full calibration of the diagnostics for the measurement of the total neutron yield, particularly three couples of fission chambers and activation foils, has been performed. A neutron generator, consisting of a deuterium beam on a tritiated target providing about 2 10^8 neutrons per second, was located in about 40 different toroidal positions with the help of the remotely handling system [2]. The results have been very positive. The calibration factors of the fission chambers have been derived with an estimated accuracy of the order of 10%, meeting ITER requirements. This new calibration complements the one performed in 2014 for the 2.45 MeV neutrons. Since the calibration factors for the two neutron energies are very similar (within 10%), it is believed that JET now can provide very accurate estimates of the total neutron yield

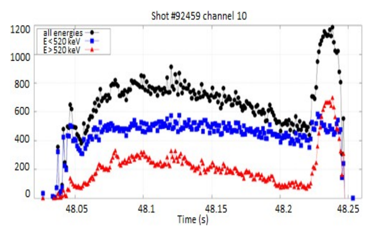

Fig.2 Measurements of runaway eelctrons emission with the gamma ray detectors.

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for all the various isotopic compositions, including full TT operation.

On JET, a horizontal and a vertical neutron/γ camera provide information on the radial profile of the respective emission source. The neutron cameras use NE213 liquid scintillators for the simultaneous measurement of 2.5MeV and 14MeV neutrons as well as Bicron BC418 plastic scintillators for 14MeV neutron detection with only very low sensitivity to gamma radiation. A new data acquisition system has been tested, showing good linearity of recorded counts versus reference neutron yield monitor (up to ~10 MCps for BC418 and ~7MCps for NE213) and therefore proving the effectiveness of the pile-up count rate correction with the firmware up to the target count rate requirements. This system has already been used under real plasma conditions with the BC418 acquiring data on the tritium burn up 14 MeV neutrons. With regard to the measurements of the fast particles, on JET the α-particle diagnostic is based on the nuclear reaction $^{9}Be(\alpha,n\gamma)^{12}C$ between confined α-particles and Be impurity ions present in the plasma. Besides the α-particles, which will be the dominant suprathermal species on ITER, there will be also other minority energetic ions produced by the auxiliary heating systems. These non-fusion born supra-thermal particles must also be diagnosed and studied, as their confinement affects performance, as well as to avoid the serious damage they might cause to the tokamak first wall if lost from the plasma. To fulfil the requirements for high count rate γ measurements, a new set of detectors based on $LaBr_3$(Ce) have replaced the existing scintillators. Initial results with a prototype detector have provided measurements of runaway electrons (see Figure 2) [3] in good agreement with other diagnostics (plasma current, neutron emission, hard X-rays). Instabilities in the Alfvén frequency range can be driven by fast ions (including fusion generated alpha particles) and can lead to their spatial redistribution and eventually fast radial transport that can affect the fusion performances and could damage the first wall of future fusion reactors. The understanding of the mechanisms of the mode stability is therefore of paramount importance for ITER and can also be used to control the alpha particle population itself. AEs can be excited by means of in-vessel antennas and fast ions can be produced by additional heating like ICRH or NBI injections. A unique, state of the art, detection system allows real-time detection of TAEs of specific toroidal mode number(s) in the range n=0-15, the measurement of their damping rate and amplitude and their tracking. A new generation of amplifiers allows a more reliable operation and provides the diagnostic with the potential to further increase the antenna current, hence TAE modes excitation (see Figure 3)[4].

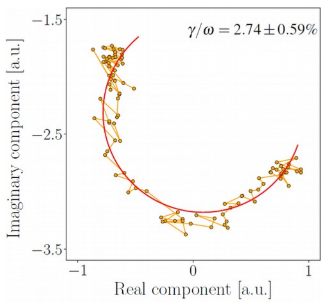

Fig.3 Resonance measured after the NBI phase of a divertor pulse in the complex plane.

With regard to upgrades for operation, the imaging systems at JET have become essential and now more than 30% of the first wall is monitored by cameras. Unfortunately the neutron yield during 50-50 D-T operation is likely to cause irreversible damage to the cameras or, in the best case scenario, white out the images during plasma operation. Shielding these cameras from the neutrons is the only way to keep these diagnostics functional during D-T operations. This has been achieved by relocating the cameras to a low radiation environment behind the biological shield by relaying the emitted light out of the torus hall (which involves path lengths of the order of 40 m) through a carefully designed optical system. This has been done for a wide-angle view and one divertor view from the top of the machine, carrying information in the visible, near-Infrared and mid-Infrared wavelengths. A wide angle view image, obtained using this optical relay and acquired by a visible camera, can be seen in Figure 4. This is a new capability which was not available in DTE1. In ITER several optical diagnostics will have relays with similar lengths making the operation of such system on JET especially relevant.

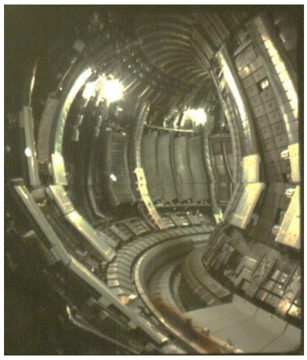

Fig.4 JET visible wide angle view acquired using the newly installed optical relay.

4. The technology programme on the route to ITER and DEMO

JET technological programme is mainly meant to take full advantage of JET operations with tritium and of the unprecedented level 14 MeV neutron production in the planned DT campaign. The most relevant topics explicitly addressed are the validation of neutronics and activation codes for ITER, the irradiation effects on materials, the fuel cycle and tritium breeding blanket.

The validation of neutronics codes is addressed with *ad hoc* experiments in JET in fusion relevant conditions, to validate the codes used in ITER design to predict quantities such as the neutron flux along streaming paths, the activation of materials, as well as the resulting shutdown dose rates. In this respect in 2015-2017, several experimental and computational activities have been carried out on Neutron Streaming and Shutdown dose rate measurements around the JET machine [5]. These measurements were performed using thermoluminescent dosimeter (TLDs) and activation foils placed in several positions inside and outside the Torus Hall (TH). These studies

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will allow optimising the parameters of the ADVANTG code, as well as refining the available MCNP models, which is essential in order to be better prepare for the TT and DT campaigns. The agreement of the simulations with experimental results is very good, especially for locations close to the machine, while at locations further away from the plasma, the calculations tend to be higher than the measurements. To further exploit the neutron yield expected in the next full DT campaign, various samples are going to be located very close to the plasm edge in the specifically developed Long Term Irradiation Stations (LTIS). The main objectives of the studies are the assessment of the degradation of functional materials and the activation of structural materials.

One of the objectives of the Test Blanket Modules (TBMs) programme in ITER is to provide the experimental validation of numerical predictions on tritium production and recovery. However, this will require nuclear instrumentation for on-line measurement of neutron/gamma fluxes and tritium production, capable of withstanding the harsh working conditions expected (high temperatures, up to 400°C, magnetic field and high level of radiation fluxes). For this purpose, a mock-up of TBM is ready for installation on JET and several detectors have been developed; their testing on JET is of paramount importance, since at JET it would be possible to simultaneously have the relevant fusion environment, i.e. high temperatures (up to 250 °C), magnetic field (up to 3 T), as well as, high level of radiation fluxes (neutrons and gammas). Using the Frascati Neutron Generator (FNG), which is able to provide 14 MeV neutrons irradiation, it has been possible to successfully test two prototypes of diamond detectors, which are now ready to be installed at JET. One detector is only a diamond device, while the second detector is a diamond coated with a 2 micron thin layer of ^{6}LiF. The bare diamond detector exploit the nuclear reaction $^{12}C(n,\alpha)^{9}Be$, thus measuring the number of neutrons arriving at a certain location, whereas the second detector coated with ^{6}LiF, exploit the nuclear reaction $^{6}Li(n,\alpha)^{3}H$. That means that the comparison of the two corresponding peaks provides information about the tritium production rate.

The DEMO Fuel Cycle (DFC) sub-project, aims to test comp[...]O. In the Direct I[...]osed by KIT, it is[...] unburnt fuel fron[...]. 80% of the exha[...]lly very significa[...]eduction in the [...] process ('KArlsr[...]cess for fusion R[...]alization of the D[...]tion is a liquid ri[...]patibility reasons, uses mercury as working fluid. As this approach is new and no operation experience is available on a Tokamak, JET provides a unique opportunity to test and validate this scheme under fusion relevant conditions. This brand new pumping system, will be integrated into the Active Gas Handling System at JET and be operational during the TT and DTE2 campaigns.

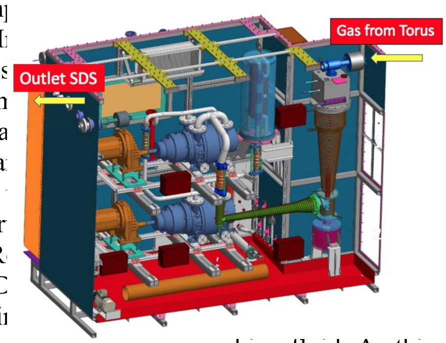

Fig.5 Overview of the system implementing the KALPUREX process for JET

5. Conclusions

In preparation for DT operation, JET is pursuing an aggressive experimental programme and the installation of a series of ambitious enhancements. The results obtained so far in DD and the first scans in isotopic composition are very promising for the achievement of about 15 MW of stable fusion power. The major upgrades, from diagnostics to ancillary systems and fusion technology studies, guarantee good scientific exploitation of this unique opportunity of tritium operation before ITER. Significant efforts are also planned in support of DEMO, since and entire EUROfusion department is devoted to the design of this future device, in preparation for the commercial reactor.

Acknowledgments

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