ICRH OPERATIONS DURING THE JET TRITIUM AND DTE2 CAMPAIGNS

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The JET-ILW pure tritium and Deuterium-Tritium (DTE2) experimental campaigns took place in 2021-2022. T and D-T operations present challenges not encountered in present day tokamaks [1]. This contribution focuses on Ion Cyclotron Resonance Heating (ICRH) operations in tritium and D-T plasmas, starting with a summary of the program of improvements to the ICRH system which spanned over few years prior to DTE2. Procedures were implemented to address specific constraints from tritium and deuterium-tritium operations (tritium safety and reduced access to the RF generator area) and increase the system reliability and power availability during plasma pulses. Operation of the upgraded Real Time RF power control system that maximises the launched power while taking into account limitations from the system or antenna coupling is described. We also report on the result from dedicated pulses performed to assess the impact of the 2nd harmonic tritium resonance in the plasma, close to the inner wall, when using the standard central hydrogen minority ICRH scheme. During DTE2, the ITER-Like Antenna (ILA) was not used because water leaked from an in-vessel capacitor into the vessel on day-2 of the experimental campaign. The lessons learnt from this incident are highlighted.

Introduction: Experimental campaigns with pure tritium and Deuterium-Tritium (D-T) plasmas were run on JET-ITER-Like Wall (JET-ILW) in 2021-2022. These campaigns were a unique opportunity to address essential questions for magnetic fusion development, and in particular to prepare for ITER operations and experiments [1,2,3]. To deliver these objectives, ICRH was used in most DTE2 and tritium plasmas (see Fig. 1) to provide electron heating for central impurities chase out and discharges stationarity [4]. ICRH was also used for bulk heating of fuel ions and boost fusion power [5,6]. Specific experiments were performed to study the impact of isotopes on RF induced Plasma Wall Interactions (PWI) [7]. The demonstration of ITER D-T ICRH scenarios was one of the items of the JET-DTE2 program [8].

Preparation prior to T and D-T operations: In preparation for the pure tritium and D-T campaigns a program of improvement of the JET ICRH system [9,10] was implemented over several years. This was driven essentially by:

(a) Tritium safety constraints: we verified the integrity and effectiveness of the systems used to prevent tritium permeating through the vacuum windows from accumulating into the transmission lines.

(b) Radiological safety constraints: the generators area could not be accessed when JET was running in D-T; hence, a number of projects were conducted to improve the reliability of the plant and enhance capabilities to control and monitor the ICRH plant remotely.

Operation and maximization of launched power: To maximize the outcomes of the T and D-T campaigns while not exceeding the allocated T and neutron budgets, the procedure to prepare the system before a discharge was also improved. The target was to get the required coupled ICRH power on the first pulse of the day. Each frequency change was systematically followed by test load pulses to verify the state of the generators and identify limits if any, so that appropriate actions can be taken before an actual plasma pulse is performed. Reference pulses (with adequate plasma conditions) to set the position of the matching elements were systematically used. The real time control system that handles the output power of the RF generators was improved as recommended in [11]. The revised algorithm automatically maximizes the RF plant coupled power capabilities in conditions of variable plasma loading of antenna straps by intelligently redistributing the power request between individual generators depending on known (for example maximum transmission line voltage before breakdown) and emerging hardware limitations. An example is shown in Fig. 2. The implemented approach substantially improved the reliability of high-power performance ensuring predictable outcome without dedicated RF set-up plasma pulses.

Lessons learnt from water leak in the ILA: In September 2020, one of the ITER Like Antenna (ILA) [12] in-vessel matching capacitor filled-in with water after a micro-leak developed in the bellow between the water-
cooling circuit and the capacitor (see Fig. 3). In the autumn 2020 a differential pumping system was installed to evacuate the upper row capacitors water cooling circuits. Operations with the ILA lower row resumed in January 2021, but in August 2021 a second fault developed on day-2 of the DTE2 campaign. Some water was still being retained in the capacitor; during a pulse, a crack developed either in the capacitor ceramic or in the brazing joint, and the water was released to the JET vacuum vessel. It took three weeks to identify the origin of the leak into the JET torus, to fully evacuate the water and recondition the machine before JET operations could resume. As a precaution, the ILA was not run during the DTE2 campaign; but the lower row of the antenna has been operated again afterwards. The ability to drain, fill, inject marker gases and isolate/pump the different ILA water cooling circuits separately was crucial to localize the faulty cooling circuit. The differential pumping system installed in the autumn 2020 presently mitigates the effect of this double fault in the capacitor and allows JET to run.

**Proving safe operation with \( \omega=2\omega_{c,T} \) resonance close to inner wall:** When using the hydrogen minority ICRH scheme in presence of tritium (scheme most commonly used in JET D, T and D-T plasmas to provide central electron heating), the 2\(^{nd}\) harmonic tritium resonance \((\omega=2\omega_{c,T})\) is also located in the plasma close to the inner wall (see Fig. 4). Dedicated pulses with hydrogen minority ICRH in the plasma core were performed, in H-mode tritium plasmas and with tritium NBI, and we have verified experimentally that the \( \omega=2\omega_{c,T} \) inner wall resonance did not cause adverse heat-loads to the JET-ILW wall. Configurations with an ICRH resonance near the outer wall (in particular inside the antenna box where hot spots or arcs would be difficult to detect) are still not allowed on JET.

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**REFERENCES**

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FIGURE 1: ICRH launched power plotted as a function of frequency during the DTE2 campaign. Typical ICRH scheme usage in DTE2 vs frequency is also indicated.

FIGURE 2: Example showing real time optimization of RF voltages in the transmission lines feeding the A2 antennas to maximize the ICRH launched power. Pulse 99633 with $I_p=2.3\, \text{MA}$, $B_T=3.45\, \text{T}$, $^3\text{He}$ minority ICRH with $f_{\text{RF}}=32.5\, \text{MHz}$.
(a) RF-Voltages in the 8 transmission lines feeding antennas A&B (fed via 3dB-hybrid couplers). RF amplifiers power is adjusted so RF-voltages reach the maximum permissible, 30 kV. (b) RF-Voltages in the 8 transmission lines feeding antennas C&D (fed via ECTs). (c) power launched by antennas A&B, and C&D. (d) total ICRH power.
FIGURE 3: Simplified diagram of ILA capacitors cooling circuit and vacuum arrangement showing the suspected location of the faults leading to a water leak into the JET vessel.

FIGURE 4: Illustration of the 2nd harmonic tritium resonance on the inner wall when using hydrogen minority ICRH.