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ICRF Heating: The JET Experience and Prospect for ITER

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1. INTRODUCTION

The ITER Ion Cyclotron Resonance Frequency (ICRF) system will comprise two antennas aiming to couple in the long term, 20MW each in ELMy H-mode plasmas with plasma separatrix - antenna distances around 17cm [1]. On JET, the ability to couple ICRF power to H-modes was the main challenge of the past few years. Indeed, the system in place since 1994, could not couple during the fast edge modifications caused by ELMs. The impedance transformers (see fig.1) made of mechanical elements and used to match the 30Ohm transmission line to the plasma acting as a load of typically 2-4Ohm, could not react quickly enough during the associated load changes (typically 400% change in 150μs), leading to excessive power reflection, trips of the generator protection and very low averaged coupled power. The system upgrade started by a modification of the transmission line layout of the A2s antenna [2] between 2004 and 2008 (see Fig.1) that is described in section 2. Secondly, a new ICRF ITER-like antenna (ILA) [3], with a closely packed array of short straps, similar to that foreseen for ITER, was installed in 2007. An outlook of the results obtained both L and H-mode is shown in section 3. In order to maximise the achievable ICRF power at large separatrix-antenna distance, the possibility to inject gas to increase the density in front of the ICRF antennas, was investigated and a brief overview of the results is presented in section 4. Finally, the extrapolation of these results for the ITER ICRF systems is reviewed in section 5.

2. ICRF A2 ANTENNAS SYSTEM UPGRADE USING 3DBS HYBRIDS AND EXTERNAL CONJUGATE-T

3dBs hybrids couplers previously tested in ASDEX-Upgrade [4], were installed in 2005 between antennae A and B (see Fig.2) [5]. By preventing the reflected power arising during ELMs to reach the generator (the reflected power is diverted to a load that is part of the couplers) and avoiding the associated trips, up to 3MW of ICRF power was coupled in H-modes. Secondly, following a successful proof-of principle test in 2007 [6], an External Conjugate T (ECT) system [7][8] was installed in 2008 between the A2 antennae C and D (see Fig.1). In a conjugate-T configuration, the ELM tolerance relies on the adjustment of the impedance at the T-junction Z_T, to a chosen value, typically $Re(Z_T) \cong E$ 3-4 Ohm and $Im(Z_T) \leq 0$. When this val ue is set up correctly (in the case of the ECT, by changing the length of phase shifters), it remains almost constant even during fast, high plasma loading perturbation keeping the reflected power at the generator at acceptable levels. The commissioning of the system was performed beginning of 2009 and proved to be remarkably straightforward [9]. Reliable performance with up to 4MW of ICRF coupled in ELMy H-mode plasmas, was demonstrated. Fig.2 shows typical power levels that could be obtained beginning of 2009. In this pulse, used to compare the performances of H-mode plasmas with different ratios NBI/ICRF [10], 2.9MW were coupled from antennas A and B and 3.6MW from antennas C and D. Overall, the use of ECT and 3dBs hybrids systems, made it possible to increase so far, the total ICRF power coupled in H-mode plasmas by the A2 antennas up to 7MW.

3. THE ICRF ITER-LIKE ANTENNA

The ILA was installed on JET in 2007 (see Fig.1) after preliminary testing on the JET test bed [3].

The commissioning on plasma [11] took place from May 2008 to March 2009 alternating with the JET experimental program. Although the frequencies range available was 30 to 49MHz, the main part of the plasma commissioning was performed at 33, 42MHz and 47MHz in view of its use for the JET experimental program. The main difference between the ILA and the existing A2s is the compactness of straps delivering the power that is relevant to the ITER. The A2s that have a much bigger surface, never reached in L-mode power density above 1.8 MW/m^2 as the ILA has reached up to 6.2MW/m^2 (Pulse No: 73941). Note that the designed 8 MW/m^2 was not reached due to limitation in the available power at the generator. Fig.3 shows an example of a pulse with 4.3MW of ICRF power coupled from the ILA using H minority fundamental heating (the maximum power obtained in L-mode being 4.76MW). A sawtoothing behavior of the electron temperature T_e, characteristic of a central fast ion population, can be observed. In this pulse the central T_e reached ~ 6keV which is similar to value that can be obtained with the A2 antennae when used with similar spectrum. It is also important to note that no impurity production increase that could be linked to the ILA higher power density, was observed [12]. Finally, for the ILA, the ELM-tolerance relies on a T-junction, the main difference with the ECT (see section 2) being that the Z_T value is adjusted by changing the value of capacitors installed in-vacuum just behind the straps (see Fig.1). The maximum power coupled in H-mode was 1.88MW (see Fig.2) from the ILA upper half but further achievements not possible due to a faulty capacitor.

4. GAS INJECTION FOR LOADING IMPROVEMENT AT LARGE ANTENNA – PLASMA SEPARATRIX DISTANCE.

In ITER the foreseen edge density decay in particular in the far scrape-off layer is still subject to lot of uncertainties, and depends on the choice of the ITER scenario and assumption on the outward pinch velocities [13]. Nevertheless, the fast wave launched by the ICRF antenna is evanescent until it reaches a cut-off density $n_{e,cut\text{-}off}$ (10^{18} m^{-3} range) and a small antenna – $n_{e,cut\text{-}off}$ is then essential for a good ICRF loading and to couple the 20MW requested [1]. Although on-going coupling simulations and studies show that the ICRF should meet in most cases its specifications [14] [15], the use of gas injection to ease the operations was investigated on JET in ELMy H-mode with antenna-plasma separatrix distance up to 19cm [16]. The best loading improvement was observed by injecting in the main chamber (top or midplane). Gas injection from a location magnetically connected to the antenna was not found mandatory. The effect of the gas injection on the confinement and coupling improvement was found to vary dramatically with plasma shapes that have different pumping /recycling properties. Finally, these experiments also showed a large reduction in the loading due to ELMs with increasing antenna-separatrix distances.

5. CONCLUSIONS AND PROSPECT FOR ITER

The JET ICRF systems upgrade firstly confirmed that it is indeed possible to design ICRF systems that can couple trip-free power during ELMy H-mode. At the moment both the use 3dBs hybrids and ECT are under consideration for ITER and the presence of these two systems on similar antennas (A2's) has provided a unique set of data to be further analyzed. The ILA because of its design has allowed the testing of much more specific points relevant' for ITER [14]: RF voltages on the antenna structure up to 42kV were achieved routinely (45kV being the choice for ITER) and ITER-relevant power densities were reached. Code (TOPICA[17]) modeling the coupling to be expected in ITER was validated as good agreement was obtained between the coupling predicted for the ILA and the experimental measurements [14]. The feasibility of operating an antenna in the presence of enhanced cross-talk between the straps was also demonstrated although it was found that development of sophisticated control real time software was necessary. Furthermore, as standard protection against arcs cannot fully protect the ICRF systems when operated in ELM tolerant modes, for both the A2s and the ILA, new arc detections, relevant for future design, were tested and implemented [8][18][19]. Finally, injection of gas to improve the ICRF loading in view of ITER worst case scenarios cases was tested. The results obtained emphasized the fact that the edge density profiles, their response to gas injection and modification during ELMs are keys factor to develop our confidence in the ICRF ITER system capabilities.

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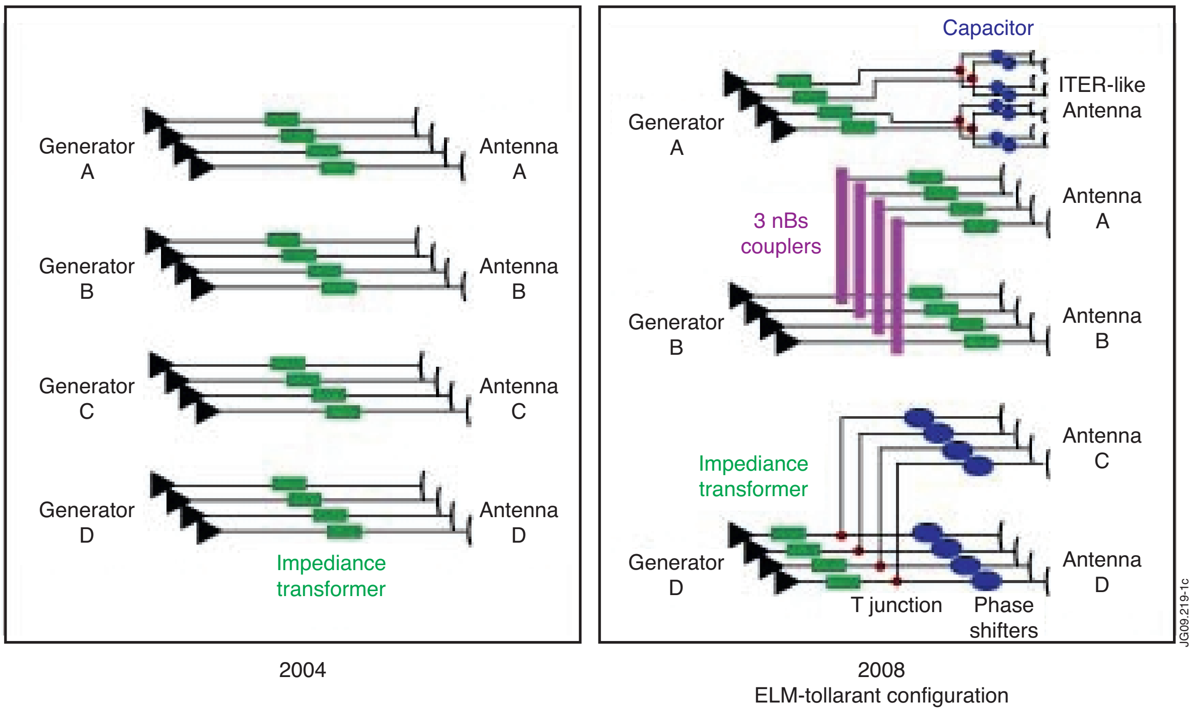

Figure 1: Overview of the JET system in 2004 and after modification in 2008.

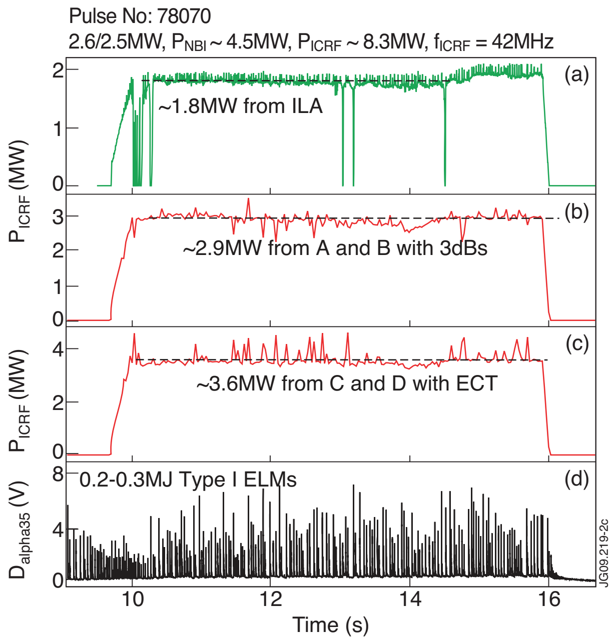

Figure 2: Typical ICRF power levels in ELMy H-mode from (a) the ILA upper half (equipped with in vacuum conjugate-T , (b), antennas A and B (equipped with 3dBs couplers), (c) antennas C and D (equipped with external conjugate T).

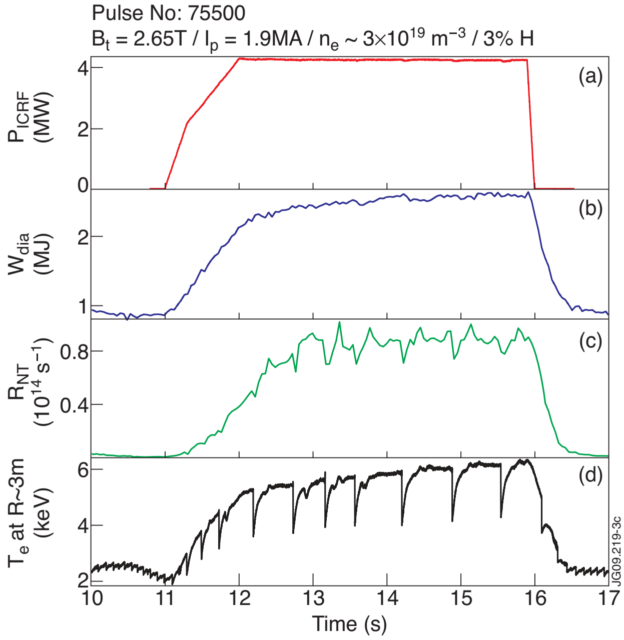

Figure 3: Time evolution of the ICRF power delivered by the ILA, diamagnetic energy, neutron rate and central electron temperature. The heating scheme used was H minority in D.