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ABSTRACT.

The first series of experiments with the ITER-like wall (ILW) will start mid-2011 with D plasmas and will continue through 2012-13 with H, ^{4}He and D plasmas, and up to 2014-15, when a DT campaign is proposed. In this paper, the previous experience at JET is reviewed to set the scene for the future challenges of ICRF operation including change in the ICRF coupling, W impurity production and evaluation of localized power loads due the RF sheaths. development in a Beryllium/ Tungsten environment of ICRF heating schemes for the non activated and the DT phases of ITER.

1. INTRODUCTION

JET reached, mid-May 2011, the end of an extensive shutdown during which all the carbon fiber composite (CFC) plasma facing components were replaced by bulk beryllium (Be) tiles (main chamber), tungsten (W) - coated CFC tiles (main chamber high heat flux areas and part of the divertor), Be-coated Inconel (main chamber) and bulk W components (divertor) [1]. During this process, all the components around the A2 ICRF antennas [2] were replaced, with the exception of the antennas screen bars already made of Be (see FIG. 1 and 2). The horizontal bars on the top and bottom of the A2 antennas now consists in 5 Inconel carriers each supporting 22 bulk Be slices (previously there was 1 CFC block per carrier). The antenna septum (private vertical limiter in the middle of the A2 antennas), now consists of 5 Inconel carriers each supporting 2 bulk Be bricks (previously it was 1 CFC block per carrier). The new septa are recessed by 8 mm with respect to the main poloidal limiters (previously it was 4 to 7 mm before) with a slightly modified shape aimed at reducing the thermal loads. Newly designed flux excluders in Cu-coated Inconel have been fitted in between the antennas and the poloidal limiters to provide a path for mirror currents of the antenna straps. The new outer poloidal limiters consist of an assembly of 23 Be tiles with an Inconel carriers and up 7 vertical Be blocks (previously horizontal CFC slices on carriers).

2. ICRF OPERATION WITH A METALLIC WALL

Experimental campaigns in Deuterium (D) alternated with restart phases will start mid-2011 allowing a gradual expansion of the performance. The ICRF heating program aims at applying the ICRF power safely and reliably using a high single-pass absorption scheme (H minority heating) and includes:

- The characterization of any arcing issues that could arise from the changes made on the component surrounding the antennas.
- The evaluation of the power loads due to the RF sheath effect on the new Be ICRF septa.

Preparatory work based on measurements of the CFC septum temperature, showed that power density up to 5MW/m^2 along the flux tube (2MW/m^2 projected onto tile surface) can be expected in the worst case scenarios (1.5MW per antenna, asymmetric spectra, plasma-limiter distance ~ 4cm) [3][4]. This value indicates that operational limits should not be necessary as the power handling capability of the Be tiles was estimated to 6MW/m^2 for 10s with a cold start (200°C) and 4MW/m^2

with a hot start (400°C). Nevertheless, the temperature of the antenna septa will be monitored by a real time wall protection system, ensuring that they do not reach critically high temperature (i.e. temperature near the Be melting point of 1356°C).

- The monitoring of RF sheaths enhanced sputtering of the W-coated CFC divertor tiles. Indeed for some commonly used plasma configurations, the antennas and the divertor baffle are magnetically connected and any increase in the central W concentration must be assessed.
- The characterization of any modifications in the ICRF antenna coupling. Indeed, the recycling properties of the Be wall are expected to be different compared to the C-wall [5] leading to difference in the Scrape-Off-Layer density profiles hence in ICRF coupling.

3. ITER ICRF SCHEME DEVELOPMENT WITH THE ILW

3.1. DEVELOPMENT OF ICRF SCHEME FOR ITER NON ACTIVATED PHASE

After the initial characterization and exploration of the ITER operating scenarios with the ILW, a program with H and ^{4}He plasmas aiming at consolidating the ITER non-activated phase is envisaged (2013-14). In Table 1, the possible ICRF heating schemes for this phase are detailed as their main characteristic when tested on JET. From this list, the inverted minority schemes for full field H plasmas operations i.e. (^{3}He)H and (D)H, that are affected by mode conversion parasitic absorption (sensitive to C levels) [8][9] are to be re-tested in priority. The effect that the dilution of ^{4}He plasmas by H pellets fuelling, could have on the H(^{4}He) scheme, must also be investigated experimentally. Preliminary modeling for ITER shows that the degradation in the single-pass absorption when the H level is increased could be compensated by using higher toroidal mode number n_ϕ (for example with $0\pi0\pi$ with $n_\phi = 60$ instead of $0\pi\pi0$ with $n_\phi = 34$) [7].

3.2. DEVELOPMENT ICRF HEATING SCHEMES FOR THE ITER DT PHASE

Recently, the preparation of a scientific case for performing a DT campaign at JET in 2015, was started. Table 2 summarizes the ICRF schemes foreseen in ITER DT phase. The main scenarios (2nd T & ^{3}He)DT and (D)T were tested in the 1999 JET DT campaign, but further experiments in a Be/W environment using enhanced diagnostics capabilities (high resolution gamma-ray diagnostics, fast ions loss detectors, neutral particles analyzer), real-time control of the ^{3}He level, Break-In-Slope power deposition techniques [15], would allow the completion of their characterization focusing on issues like:

- for the (2nd T)DT scheme: the absorption at the 2nd T layer for the end of the current ramp-up and transition to H-mode in ITER (conditions similar to JET flat-top) and for the ITER flat-top (to be achieved at JET using T beam injection); the influence of possible parasitic absorption due to mode conversion near the D fundamental layer.
- for (2nd T & ^{3}He)DT: the minimum ^{3}He level required for effective ion heating.
- for (D)T: the D concentration level up to which this heating scheme is usable starting with

T-rich plasmas; the parasitic mechanism involved (mode conversion, parasitic absorption by alphas particle and Be).

In a DT campaign, the T removal efficiency by D2 - Ion Cyclotron Wall Conditioning discharges, must also be fully studied, knowing that this scheme, foreseen for the ITER full-field operation (40 MHz, 5.3T, D resonance layer on axis), can only be reproduced at JET (25MHz and 3.3 T, see [16] [17]). Finally, as the frequencies to be used are equal or below 37 MHz (see Table 2) a modification of the External Conjugate-T system [18] layout that presently does not give full ELM-tolerance at 37MHz and below 30 MHz should be assessed. Futhermore, as for the ICRF antennas coupling capabilities starts to degrade for frequencies below 37MHz, the repair of the ITER-like antenna [19] is suggested in order to provide 3 to 5MW of additional power.

CONCLUSIONS

The “JET programme in support for ITER” launched in 2007 [25] is entering one of his more challenging phase i.e. the start of experimentation with a Be/W wall. This first phase will be followed by the development of integrated plasma scenarios towards ITER-relevant conditions using D, H, ^{4}He and DT plasmas. From an ICRF perspective, this long term program will be a unique opportunity to characterize the plasma edge – RF field interaction, focusing on the possible W divertor sputtering and characterization of heat loads on Be tiles. The effect that reduced C level and increased level of Be and W will have on the ITER ICRF heating schemes will be studied. New experiments on ICRF scenarios for DT plasmas should allow to create a much more solid and targeted database with relevance for ITER.

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		ITER ICRF scheme	**ITER f_{ICRF}/ B_t ***	**JET f_{ICRF} / B_t***	**Comments**
H plasmas	Half field operation	Fund. H	40-44 MHz @ 2.65 T	42 MHz @ 2.65 T	Fundamental H heating -Low single pass absorption increasing with electron temperature and density. Tested on JET in 2009, see [6][7].
		(2nd ^{3}He)H	50-55 MHz @ 2.65 T	51 MHz @ 2.65 T	2nd harmonic ^{3}He heating -Low single pass absorption increasing with ^{3}He level. Tested on JET in 2009, see [6][7].
	Full field operation	**(^{3}He)H**	**50-55 MHz @ 5.3 T**	**28 MHz @ 2.6-2.9 T 33 MHz @ 3.1-3.4 T 37 MHz @ 3.5-3.8 T**	**Inverted minority heating**. Good single pass absorption if ^{3}He < 2% when transition to mode conversion occurs. Tested on JET in 2003 and 2009, see [8][9].**
		(D)H	40-44 MHz @ 5.3T	28 MHz @3.4-3.9T 33 MHz @ 4T	Inverted minority heating**. Strongly affected by the presence of C (~2-3%) leading to mode conversion. Tested on JET in 2003, see [8]
^{4}He plasmas	Half field operation	**(H)^{4}He**	**40- 44 MHz @ 2.65 T**	**42 MHz @ 2.65 T**	**H minority high single pass absorption scheme . Commonly used on JET**
		(2nd ^{3}He)^{4}He	50-55 MHz @ 2.65 T	51 MHz @ 2.65 T	2nd harmonic ^{3}He heating - Low single pass absorption – Not tested on JET
	Full field operation	**(^{3}He) ^{4}He**	**50-55 MHz @ 5.3 T**	**28 MHz @ 2.6-2.9 T 33 MHz @ 3.1-3.4T 37MHz @ 3.5 -3.8T**	**Minority ^{3}He heating - High single pass absorption scheme. Commonly used on JET for ^{3}He level up to mode conversion [10][11].**
		Fund. ^{4}He	40-44 MHz @ 5.3T	28 MHz @3.4-3.9T 33 MHz @ 4T	Fundamental H heating Low single pass absorption. Equivalent scheme, D fundamental in D plasmas tested in JET on 2007, see [12][13]

* *for central heating i.e.* $|R - R_{0\text{-}ITER}|$ *~ 0.5m for ITER and* $|R - R_{0\text{-}JET}|$ *~ 0.25m for JET*

** *the term inverted minority is used when the charge to mass ratio of the minority ions is smaller than the one of the majority ions*

TABLE 1. Overview of the ICRF heating schemes for ITER non-activated phases (see [14]) and possible ICRF frequency f_{ICRF}, *and magnetic field Bt to test them at JET. The more promising schemes are highlighted in bold . Note that any remark that apply to* ^{4}*He plasmas are valid for latter planned D plasmas.*

ITER ICRF scheme	ITER f_{ICRF}/ B_t *	JET f_{ICRF} / B_t *	Comments
(2^{nd} T) DT & (^{3}He) DT	53 MHz @ 5.3T	28 MHz @ 2.6-2.8 T 33 MHz @ 3.1-3.3 T 37 MHz @ 3.5-3.7 T	2^{nd} harmonic T scenario that can be combined with ^{3}He minority heating to increase ion heating - main heating scenario for DT phase – tested on JET in 2007, see [20][21][22]
(D)T	40 MHz @ 5.3 T	28 MHz @ 3.7T	Minority D heating in T plasmas. Tested on JET in 2007, see [19][20]. Record Q=0.22 obtained with 6MW of ICRF. Parasitic absorption for increased D levels.
FWCD	55 MHz @ 5.3 T	28 MHz @ 2.6-2.8 T 33 MHz @ 3.1-3.3 T 37 MHz @ 3.5-3.7 T	Fast wave current drive (on-axis) – Direct damping on electrons weak in JET due too low target electron temperature, tested on JET in 2003 featured strong parasitic damping by residual ^{3}He ions, see [23]
(^{3}He) DT	45 MHz @ 5.3T	28 MHz @ 3.1-3.3 T 33 MHz @ 3.5-3.7T	Sawtooth control with ^{3}He minority resonance layer near q = 1 surface (outboard) – Tested at JET in 2008 with D plasmas and the ^{3}He resonance on the inboard, see [24]

** for central heating i.e.* $|R - R_{0\text{-}ITER}| \sim 0.5m$ *for ITER and* $|R - R_{0\text{-}JET}| \sim 0.25m$ *for JET*

TABLE 2. Overview of the ICRF heating schemes for ITER DT plasmas (see also [14]) and possible ICRF frequency f_{ICRF}, *and magnetic field Bt to test them on JET*

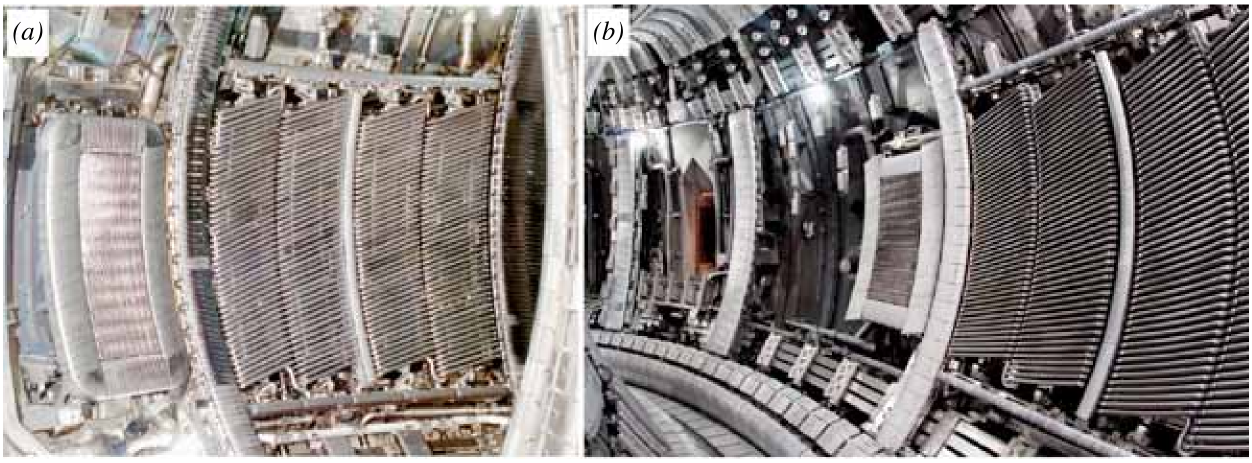

Figure 1: Inside view of the JET vessel (a) before 2011; from left to right: LHCD launcher, A2 antenna B and (b) in 2011; from left to right (Oct.4 beam duct, LHCD launcher, A2 antenna B)

Figure 2: Close view of an A2 antennas lower part showing Be-screen bars, part of the new Be septa and horizontal bars.