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Spectroscopic Investigation of Heavy Impurity Behaviour During ICRH with the JET ITER-Like Wall

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Abstract. Magnetically confined plasmas, such as those produced in the tokamak JET, contain measurable amounts of impurity ions produced during plasma-wall interactions (PWI) from the plasma-facing components and recessed wall areas. The impurities, including high- and mid-Z elements such as tungsten (W) from first wall tiles and nickel (Ni) from Inconel structure material, need to be controlled within tolerable limits, to ensure they do not significantly affect the performance of the plasma. This contribution focuses on documenting W and Ni impurity behavior during Ion Cyclotron Resonance Heating (ICRH) operation with the new ITER-Like Wall (ILW). Ni- and W-concentration were derived from VUV spectroscopy and the impact of applied power level, relative phasing of the antenna straps, plasma separatrix – antenna strap distance, IC resonance position, edge density and different plasma configuration, on the impurity release during ICRH are presented. For the same ICRH power the Ni and W concentration was lower with dipole phasing than in the case of $-\pi/2$ phasing. The Ni concentration was found to increase with ICRH power and for the same NBI power level, ICRH-heated plasmas were characterized by two times higher Ni impurity content. Both W and Ni concentrations increased strongly with decreasing edge density which is equivalent to higher edge electron temperatures and more energetic ions responsible for the sputtering. In either case higher levels were found in ICRH than in NBI heated discharges. When the central plasma temperature was similar, ICRH on-axis heating resulted in higher core Ni impurity concentration in comparison to off-axis ICRH in L-mode. It was also found that the main core radiation during ICRH came from W.

Keywords: ICRF heating, plasma impurities.
PACS: 52.50.Qt, 61.72.sd, 52.25.Vy

EXPERIMENTAL ARRANGMENT

In a series of experiments performed in JET with the new ILW that consists of a full W divertor, beryllium (Be) main chamber plasma-facing components (PFCs), and a small fraction of W-coated CFC protection tiles in recessed areas, four A2 ICRH antennas, known as A, B, C and D were in use. Each A2 antenna is a phased array of 4 toroidal straps. Antennas A and B are connected via 3dB splitters and are operated simultaneously. The antenna Faraday screens bars facing the plasma are made of beryllium and the surfaces of the antenna housing and central conductors are coated with Ni. In JET plasmas, low-Z elements such as Be are fully ionized over most of the plasma volume, while the high- and mid-Z elements exist in the partially ionized charge states at the plasma core. For this reason impurities such as W and Ni need to be controlled, to ensure they do not significantly affect the performance of the plasma. Spectroscopic measurements of Ni were obtained by using the VUV spectrometer with the line of sight (l-o-s) along the vessel midplane [1], that record spectra in the wavelength range 10.0–110.0 nm. With the former carbon

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PFCs the VUV spectrum was dominated by different mid-Z metallic impurities like Ni, Fe, Cr from Inconel and Cu [2]. Note that with the ILW and W PFCs, the spectrum also contained intense W features. Furthermore for the low temperature plasma, the most intense Ni lines corresponded to Na-like doublet and Mg-like line. Therefore these transitions were used for determination of Ni impurity densities in the confined plasma region (r/a~0.8-0.9) based on the same method described in [2] that applying the combination of absolutely calibrated Li-like Ni line intensity measurements with the Universal Transport Code (UTC) simulations. The absolute sensitivity calibration factors for Ni lines presented in [3] were used. To provide a quantitative measurement of the W-content in the core plasma, the VUV spectrometer which is set to 5 nm where a quasicontinuum of the W-ions W^{27+} to W^{35+} is emitted [4] was used.

EXPERIMENTAL RESULTS

Effect of Antenna Phasing

In the experiments reported here, dipole (0π0π) and -90° (0 -π/2 -π -3π/2) antenna phasings were used, corresponding to symmetric (dominant k|| ~ 6.6 m^{-1}) and asymmetric (countercurrent, dominant k|| ~ 3.3 m^{-1}) wave spectrum, respectively. The ICRH scheme used was hydrogen minority in D plasmas using an ICRH frequency of 42 MHz. The experiments was performed in L-mode with the magnetic field strength B_T=2.4 T, the plasma current ranging from 1.4 to 2.4 MA and a plasma separatrix - outer limiter distance in the midplane (ROG) in the range of 3 to 7 cm. During the ROG scan 1 MW of total ICRH power was coupled to plasma. Moving the ROG cause changes in decay length of electron temperature and density. Smaller ROG means that hotter ions hitting the outer wall and cause sputtering.

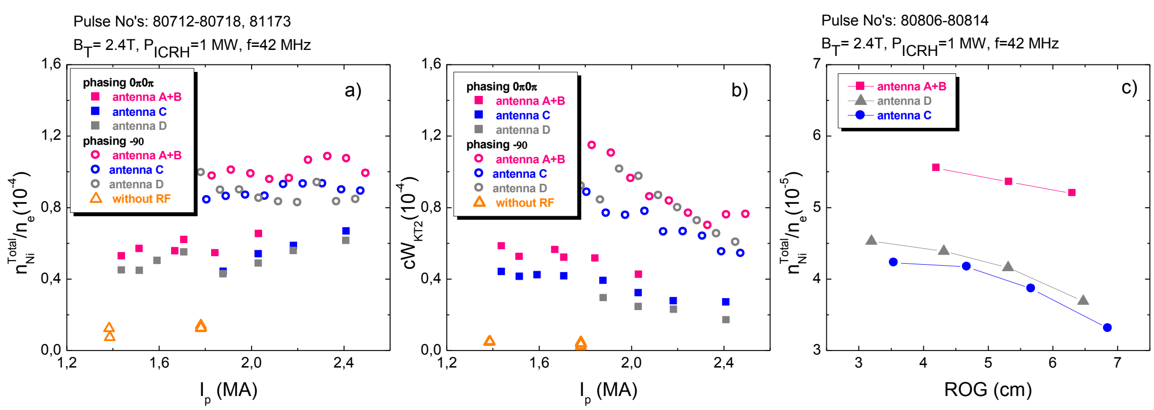

FIGURE 1. Correlation between a) Ni concentration (r/a~0.8-0.9), b) W content and Ip scan for 2 different antenna phasing. c) Ni concentration vs. limiter–separatrix distance ROG for individual ICRF antennas.

As illustrated on Figure 1a, no dependence on the plasma current is observed but for the same ICRH power level, -90° phasing gives a significantly higher Ni concentration than in the case of dipole phasing. This result is similar to the ones obtained in the previous campaigns at JET with C wall where for antenna phasings with higher dominant k||, the Ni impurity concentration was reduced in the central part of the plasma [5]. A similar impact of antenna phasing was observed in the enhanced release of W [6] and Be [7] and points to radio frequency (RF) sheath [8] effects. Indeed, ions accelerated in the (high voltage) sheaths surrounding the ICRH antennas can lead to enhanced sputtering of magnetically connected surfaces and additional heat loads [9]. Ni impurity content decreased with ROG (see Figure 1c). As seen in Figure 1, the Ni content is less pronounced during the operation of antenna C and D than during A+B operation although the same total power level was coupled. This can be due to differences in antenna spectrum (for A and B only 2 over 4 straps are powered) that could result in higher high antenna near fields and higher surface of interaction (two antennas are used).

Effect of Plasma Shape and Edge Density

In ICRH and NBI discharges, the influence of the variations in divertor configuration and main plasma shape by changes in upper δ_U and lower δ_L triangularity on the Ni content was investigated with the ILW. The main purpose of the experiment was to study the influence of the ILW on the L-H power threshold [10]. Figure 2a presents Ni content as a function of auxiliary heating power measured for 0.5 s time range before L-H transition for high triangularity shapes referred as HT3L (δ_U =0.37, δ_L=0.41) HT3R (δ_U =0.38, δ_L=0.35), HT3 (δ_U =0.39, δ_L=0.33) and low triangularity shapes referred as V5 (δ_U =0.19 , δ_L=0.39) and V5L (δ_U = 0.19, δ_L=0.33) (the letter L, R refer to different outer strike point positions). Obtained results show that the Ni concentration increases with the ICRH power and for the same NBI power level (up to 4 MW), ICRH-heated plasmas are characterized by higher Ni content. This comparison is made at the same edge electron density, n_e=2×10^{19} m^{-3}. A similar high Ni content is found in low power H-mode discharges and in limiter configurations indicating the origin of Ni to be the main chamber. The Ni content decreased with increasing line averaged edge plasma density measured by interferometry at the radial location 3.7 m (see Figure 2b).

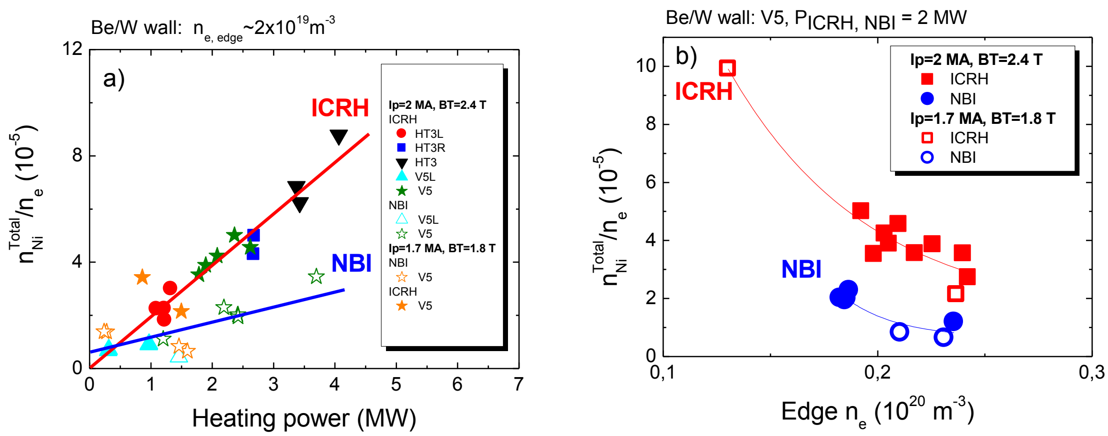

FIGURE 2. Dependence of Ni concentration (r/a~0.8-0.9) measured at L-H transition, B_T=2.4 T, I_p=2 MW, with ICRH and NBI heated plasma for a) different plasma configuration and heating power, b) edge density.

Effect of Resonance Cyclotron Position

For the same power level, central ICRH resulted in higher Ni concentration in the plasma core in comparison to off-axis ICRH as is shown in Figure 3. This effect can be due to the higher central T_e and diamagnetic energy observed with on-axis heating [10], difference in transport or higher impurity influx. It should be also noted that average of Ni and W concentration was taken over a few sawtooth periods that clearly impact on impurities in the plasma center [12]. As larger Ni and W concentrations and higher bulk radiated power ($P_{rad,bulk}$) is measured when using ICRH compared to NBI [12]. From the W and Ni concentrations, the radiated power was derived using the Ni [13] and W [14] cooling factors and the behavior of the W and Ni trend was correlated with the bulk radiated power. It was found that the main core radiation during ICRH came from W. Assuming that the calibration factor presented in [3] has not changed for the ILW, contribution of Ni to $P_{rad,bulk}$ during ICRH (up to 4 MW) was up to 2 %.

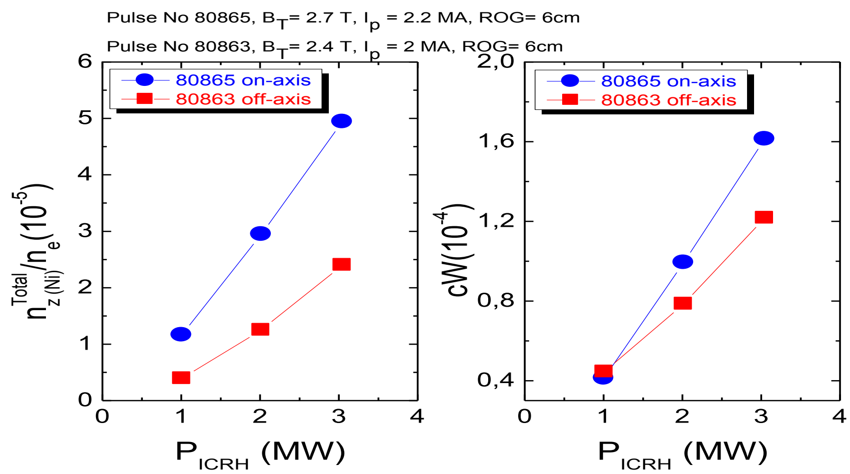

FIGURE 3. Correlation between Ni and W concentration in the plasma core and ICRH power for the on-, and off-axis heating scheme.

SUMMARY

A variety of plasma wall interactions (PWIs) during operation of the auxiliary heating systems is observed in JET with the ITER-like Wall. The application of ICRF power results in higher Ni content in the plasma compared with NBI heating. Differences in plasma wall–interaction for the different plasma shape, antenna phasing, plasma-antenna distance, and the minority cyclotron resonance position shown constitute another factor influencing impurity release. Experimental observations suggest that the Ni source is located in the main chamber. Similarities between W and Ni during ICRH show that W is most likely from W tiles in the main chamber, and not from the divertor. This suggests that the screening in the main chamber is poor in comparison to the divertor. Effectively, this means that the W source in the main chamber can be in magnitude much smaller than the divertor, but more effective to pollute the plasma core, which has been reported also in ASDEX-Upgrade [15].

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