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ABSTRACT.
Ion Cyclotron Wall Conditioning (ICWC) discharges, in pulsed-mode operation, were carried out in the limiter tokamak TEXTOR and the divertor tokamaks ASDEX Upgrade (AUG) and JET to simulate the scenario of ITER wall conditioning at half-field (TEXTOR, AUG) and full-field (JET). ICWC-plasma and antenna coupling characterization results obtained during the ICRF-Wall Conditioning experiments performed in helium-hydrogen mixture in TEXTOR, AUG and helium-deuterium mixtures in JET are presented here. Safe operational regimes for the experimental parameters could be explored for possible ICWC in ITER at different magnetic fields. Satisfactory antenna coupling in the Mode Conversion scenario along with reproducible generation of ICRF plasmas and reliable wall conditioning were achieved by coupling RF power from one or two ICRF antennas at single (TEXTOR) and at two (AUG, JET) different ICR frequencies, in agreement with the predictions of 1-D TOMCAT code. The plasma breakdown results obtained in the TEXTOR tokamak have been compared with the predictions of a 0-D RF plasma production model. The present study of ICWC emphasizes on the beneficial effect of application of an additional (along with toroidal magnetic field) stationary vertical ($B_V << B_T$) or oscillating poloidal magnetic field ($B_P << B_T$) on antenna coupling and plasma parameters.

1. INTRODUCTION

Wall conditioning is not only essential for initial cleaning and tokamak start up but also important in between tokamak discharges to ensure reproducible plasma breakdown. Wall conditioning based on RF plasma production in the Ion Cyclotron Range of Frequencies (ICRF) is envisaged as an effective tool in the presence of high permanent magnetic field in present and next generation superconducting fusion devices to control the in-vessel impurity content and tritium retention [1]. It is a functional requirement on the ITER ICRF heating and current drive system [2]. Therefore further development of ITER relevant ICWC discharges with conventional ICRF antennas was performed in limiter (TEXTOR) and divertor (AUG and JET) tokamaks to simulate the scenario of ITER wall conditioning at half-field (TEXTOR, AUG) and full-field (JET).

According to the theory of ICRF plasma production with poloidal ICRH antennas, the antenna $E_{||}$-component (along the toroidal magnetic field B_T), induced by the RF voltage difference between the antenna box and strap, initiate working gas breakdown and ionization near the antenna [3]. When the plasma density becomes high enough ($\omega_{pe} \geq \omega$), the plasma waves can start propagating in a relay-race regime governed by the antenna parallel wavenumber ($k_{//}$) spectrum, causing further ionization/plasma build-up along the torus. During the experiments carried out in TEXTOR, AUG and JET, the RF voltage/power at the antenna straps and the torus gas pressure were so chosen as to avoid any deleterious effects due to arcing and plasma formation inside the antenna box.

ICRF antennas are generally designed for the heating of high density target plasma ($n_e > 10^{19}$ m^{-3}) by coupling fast magnetosonic waves to the target plasma. In ICWC discharges ($n_e > 10^{17}$ m^{-3}), Fast magnetosonic Waves (FW) are generally non-propagating. Since ICWC experiments are carried out in the mentioned tokamaks with the conventional ICRF antennas, without any modification in hardware, the coupling efficiency in the ICWC mode of operation is an important experimental parameter to be characterized concomitantly with wall conditioning output (removal rates). It reflects the ability of the plasma to propagate RF waves and to absorb the power and is therefore an indicator of the RF plasma production physics processes in action. A low coupling efficiency implies that most of the RF power is lost in heating the antennas and transmission lines and even maybe in other parasitic processes, a situation which should be avoided in ITER and even more in a reactor. This means that this parameter is also of practical operational importance. The antenna-plasma coupling efficiency is characterized by the ratio $\eta = R_p/(R_p + R_v)$ (R_v is the antenna resistance in vacuum and R_p is the resistance due to plasma loading). Former information about this parameter in ICWC experiments can be found in [4]. Recent ICWC experiments provide information about this important parameter, which gives an indicative measure of RF performance along with removal rates of marker masses for the study of wall conditioning effect in tokamaks [4].

Several schemes have been proposed and applied individually in various tokamaks to improve the antenna-plasma coupling during ICWC mode of operation. A mixture of gases can lead to the presence of a mode conversion layer near ion-ion hybrid resonance which results in more homogeneous plasma formation in the vessel [5, 6]. The presence of the fundamental ion cyclotron resonance (ICR) layer (or its first harmonic) in the plasma may improve wall conditioning because of the generation of fast ions [3, 5, 6]. Antenna-plasma coupling can also be improved by reducing the width of the FW evanescent layer near the edge by reducing the magnitude of toroidal magnetic field (B_T) at given ICR frequency (regime of High Cyclotron Harmonics, HCH). Thus, operation in the HCH regime also facilitates higher density near the antennas which further aids in reducing the width of the evanescent layer near the antennas. Application of a stationary vertical magnetic field ($B_V \ll B_T$) or oscillating poloidal magnetic field ($B_p \ll B_T$) during ICWC experiments also results in a significant improvement of antenna-plasma coupling in high toroidal field (fundamental or first harmonics ICR) as well as in low toroidal field (HCH regime) [5].

Present study of ICWC plasmas, performed at different gas pressures in different machines, emphasizes on the simultaneous application of the above mentioned proposals in the scenario of ITER wall conditioning at half-field (TEXTOR, AUG) and full-field (JET) and the resulting improvement of the antenna-plasma coupling observed in respective machines. Advantageous effect of monopole phasing over dipole phasing (mostly suited for heating applications) of ICRH antennas during ICWC operation, on the antenna-plasma coupling efficiency, as observed in TORE SUPRA [7], are also discussed for TEXTOR, AUG and JET.

2. EXPERIMENTAL SETUP AND DIAGNOSTICS

The ICRF-discharge cleaning and wall conditioning experiments in TEXTOR, AUG and JET have been performed under the following conditions:

In TEXTOR (plasma major radius R_0 = 1.75m and minor radius a = 0.46m) single pulse-mode

(6-8sec) operation were performed at 29MHz, in presence of $B_T = 2.3T$ ($\omega \approx \omega_{cH}+$) and 0.23T ($\omega \approx 10\omega_{cH}+$), for comparison of ICWC in fundamental and higher harmonic regime and 1.92T (on-axis $\omega \approx \omega_{cH}+$) to simulate ITER ICWC operation at half field (40MHz, 2.65T). The TEXTOR ICRF system [8, 9] has two antennas. The first one consists of two straps, each made of three poloidal parallel tubes (TEXTOR-A1), while the second one has two solid poloidal current straps (TEXTOR-A2). The system was operated either (a) with TEXTOR-A1 alone, powered with $P_{RF/ant} = 80kW$ (in π-phase) at $B_T = 2.3T$ or (b) with both antennas powered with $P_{RF/ant} = 60kW$ each to A1 (in 0-phase) and TEXTOR-A2 (in π-phase) at $B_T = 1.92T$. ICWC experiments were performed in a continuous Helium (He) flow ($3x10^{-4}$mbar) along with feedback controlled Hydrogen (H_2) injection ($2x10^{-4}$mbar) after the ICRF ignition. For the study of isotope exchange by ICWC in reproducible surface conditions, the walls of the vessel were preloaded with Deuterium (D_2) during a standard Glow Discharge. Stationary vertical (B_V = 10-30 mT << B_T) and rotating poloidal B_p =1 mT/1-10Hz (resultant of vertical and radial oscillating components) magnetic field were applied during few ICWC discharges. Plasma parameters (n_e, T_e) have been measured by Thermal Lithium beam, Langmuir probe diagnostics (at r = 0.45m) on low field side and line-average density (averaged over all the chords) multichannel (vertical) HCN interferometer.

In AUG (Torus radius, R_0 = 1.65m, minor radius a = 0.5m and elongation k = 1.6) up to 4 double strap ICRF antennas were used for ICWC operation. AUG antennas operate in pairs which contain antennas 1 and 2 and antennas 3 and 4 respectively. Thus there are either 2 or 4 antennas operating at a time. The antennas-12 (antenna 1 in pair with antenna 2) powered with 100kW at 36.5MHz, in single pulse mode (0-6)sec, and antennas-34 (antenna 3 in pair with antenna 4) powered with (100-400)kW at 30MHz, in multi pulse mode (1.9Sec On, 0.1Sec Off), former in π or π/2-phase and the latter in π-phase, at B_T = 2.3T. Antenna operation at 30MHz, in presence of B_T = 2.3T simulates ITER ICWC operation at half field (40MHz, 2.65T). ICWC experiments were performed in presence of continuous He flow in the pressure range of P_{He} = (0.3-1.0) $x10^{-4}$mbar with adjunction of H_2 ($0.6x10^{-4}$mbar) flow. Electron cyclotron resonance heating (ECRH) was also used with 100kW power at frequency *f* = 140GHz, in single pulse mode for (0.1-0.5)sec along with ICRF power during few ICWC discharges. A stationary vertical magnetic field (B_V = 10-30 mT) in a 3 step pulse or continuous pulse (0-6s) was applied during few discharges. Line averaged plasma density (n_e) and electron temperature (T_e) have been measured by the multichannel DCN interferometer and ECE (radial) diagnostics respectively. The density results are given as average densities based on a chord length of 1 m for all channels.

In JET (R_0 = 2.96m, a = 0.9m and k = 1.6) two ICRF antennas (A2 antenna arrays C and D, each with four poloidal current straps) were used for ICWC operation, both powered with (100-400) kW, at 26.06MHz for antenna C and 25.21MHz for antenna D, in 2 step pulse (5.5 + 4.5)s, in 0000 phase, at B_T = 3.3T. Antenna operation at 25.21MHz in presence of B_T = 3.3T simulates ITER ICWC operation at full field (40MHz, 5.3T). In order to minimize the risk of arcing inside the antenna box, the ICWC experiments were commenced with RF power in vacuum, followed by a gas mixture of (50%He +

50%D_2), puffed after approx. 1s. After the initial puff, a continuous flow of D_2 was maintained with adjunction of He puffed during ICWC discharges, in the pressure range (2-7) x10^{-5}mbar. The initial gas mixture of (50%He + 50%D_2) was gradually changed to pure He or pure D_2 (in presence of H_2 desorbed from the wall) during progressive ICWC discharges. A stationary vertical magnetic field (B_V = 10-30 mT) in three step pulse or continuous pulse (up to 9s) was applied during few discharges. The line integrated density was measured by the multichannel (vertical) FIR interferometer.

3. EXPERIMENTAL AND MODELLING RESULTS

3.1. NEUTRAL GAS ICRF BREAKDOWN

Since the gas breakdown phase of the ICRF discharge is considered critical due to fast transition from vacuum to plasma conditions, RF power was applied prior to gas injection during JET-ICWC experiments, in order to avoid gas breakdown inside the antenna box. It was necessary to pre-match the antenna to a vacuum-near load typical to ICRF antenna operation in the low density plasma condition. Further JET-ICWC optimization resulted in a single RF pulse (up to 9s), with a two-step RF power wave-form operation. The transition from the RF breakdown phase to the ICRF discharge phase (at t=3.75s) in JET is shown in Fig.1. Here the *RF Power*, *Antenna Resistance* and *RF Voltage on Antenna Straps* are shown for antennas C (*blue*) and D (*red*). The gas breakdown event shows up as a drop in the antenna RF voltage, increase in antenna resistance and in a burst in the $H_{\pm}$ emission (measured away from the antenna). This correlation, obtained during ICWC-operation in JET, is an indication of successful RF discharge initiation and subsequent plasma streaming along the magnetic field lines [10].

During ICWC experiments in TEXTOR, breakdown of neutral gas and discharge initiation were identified experimentally from the concomitant drop in antenna (TEXTOR-A1) voltage, rise in antenna resistance and increase in the $H_{\pm}$ signal (Fig.2a). RF plasma formation (gas breakdown) in present scenario has been simulated using a set of energy and particle balance equations for the electrons, ions and atoms, solved numerically in a homogeneous 0-D model based on RF power coupled to the electrons and the electron collisional excitation, ionization and recombination of atomic Hydrogen [11]. Typically, only a fraction of the generator RF power is coupled by plasma ~ (40-60) % and the electrons absorb ~80% of the coupled power. Therefore the code has been run for the electron coupled RF power ≈ 5kW at gas pressure ≈ 5x10^{-4}mbar, according to the experimental conditions as depicted in Fig.2a. The breakdown time ≈ 14ms, ionization degree ($n_e/(n_e+n_{atoms})$) ≈ 0.05, breakdown density = 6x10^{16} m^{-3} and T_e ≈ 1.4eV obtained from the simulation (Fig.2b) are found in reasonable agreement with the breakdown time (≈10ms) and plasma parameters measured during the experiments. This implies that the breakdown time is reproducible by solving the power and particle balance equations taking into account the atomic reactions. It is to be noted that only atomic H neutrals were considered in the model and that T_e ≈ 3eV has been imposed artificially at the beginning of the simulation to avoid excessive T_e excursions. Balance obtained between the losses due to electron ionization and electron-ion collisions at the moment of neutral gas breakdown, typical for weakly ionized plasmas, is also shown in Fig.2b (bottom).

Study of gas breakdown during ICWC at $B_T = 2.3T$ in AUG revealed the better performance of $\pi/2$-phasing, somewhat similar to the monopole phasing during the ICWC experiments in other tokamaks, over π-phasing. In the same conditions, breakdown time was longer in presence of an additional stationary vertical magnetic field. This phenomenon observed in AUG could be attributed to the possible fast drift of charged plasma particles along the vertical field lines during initiation of ICWC plasma formation.

3.2. ICWC DISCHARGE CHARACTERIZATION

3.2.1. Comparison of antenna coupling during ICWC in fundamental and high harmonic regime

During ICWC experiment in TEXTOR, a total RF power of 80kW was applied to the two strap TEXTOR-A2 antenna (in Conjugate T-scheme, CT) [8, 9] at 29MHz, in dipole (π) phase in presence of $B_T = 2.3T$. The coupling efficiency of the ICRF antenna was $\Sigma \sim 60\%$ during the formation of RF plasmas with low density ($n_e \sim 10^{16}$-10^{17} m^{-3}). The factor Σ obtained in present experiment is in agreement with the earlier database of TEXTOR and TORE SUPRA [3, 10]. At such low density ($n_e \sim 8x10^{16}$ m^{-3}) fast magneto-sonic waves (FW) are non-propagating. More homogeneous plasma formation in the vessel was obtained in the mode conversion scenario ($He+H_2$ gas mixture). A possible explanation is that conversion of non-propagating FW into a propagating slow or ion Bernstein wave in the two ion species plasma may have increased the RF power absorption by the electrons [5, 6]. The radial line averaged density profile, obtained during ICWC operation in fundamental regime ($B_T = 2.3T$), is asymmetric with large density gradients near the vessel centre and then near the antenna, shown in Fig.3.

During the ICWC discharges performed with the TEXTOR-A2 antenna at $B_T = 0.23T$ (HCH), the coupling efficiency was further improved ($\Sigma \geq 70\%$). Analysis of the plasma waves dispersion relation, for the radial line averaged density profile obtained experimentally, showed that the higher antenna coupling, observed along with higher $H_\pm$ intensity, in the HCH regime, could likely be attributed to the slow wave excitation at the plasma edge and strongly reduced evanescence or even access to the propagation of fast wave. However, only small increase in plasma density could be noted during ICWC in HCH regime, in comparison to that obtained during ICWC operation in fundamental ICR regime. The radial density profile essentially remained the same during ICWC in HCH regime ($B_T = 0.23T$), unlike earlier studies in TEXTOR [3] and TORE SUPRA [10]. The density profile flattens, essentially due to redistribution of plasma, during application of an oscillating poloidal magnetic field at B_T=2.3T (Fig.3). Although antenna-plasma coupling during ICWC at high cyclotron harmonics (HCH, at $B_T = 0.23T$) has been observed to be better than that in the fundamental MC scenario (at $B_T = 2.3T$), the latter might benefit from the IC generation of fast ions [4, 5].

3.2.2. Influence of gas mixture and frequency dependence on Antenna Coupling

The equivalent of an ITER full field ICWC scenario was tested in JET (ITER: 40MHz/5.3T, JET:

25MHz/3.3T). Although operating frequencies were chosen on the basis of ITER f/B_T ratio, in JET impedance matching of A2 antennas for optimization [12] of neutral gas RF breakdown [3], led to minor deviation from $f = 25$MHz. During these experiments, two JET A2 antennas have been used, A2 antenna C at 26.06MHz and A2 antenna D at 25.21MHz at $B_T = 3.3$T with stationary vertical magnetic field $B_V = 10$-30mT. Monopole phasing of antennas was proposed in view of the encouraging results (strong increase in antenna coupling and decrease of the breakdown time) obtained recently in TEXTOR, AUG and TORE SUPRA. On JET, for the simulation of ITER full field scenario, the fundamental resonance for deuterium ($\omega_{cD}+$) was on axis, unlike the ICWC experiments in TEXTOR, TORE SUPRA [7] and AUG, discussed so far, where $\omega = \omega_{cH+} = 2\omega_{cD+}$ was on axis. He and D_2 were chosen as gases to be injected to condition the H_2-preloaded wall. The 1-D RF code predicted [13, 14] that power is transferred to the electrons via Mode Conversion (MC) when a resonant species is present in the gas mixture, like shown for a He+D_2 mixture in Fig.4. The injected gas was changed from pure He to pure D_2 and intermediate mixtures during JET-ICWC study. The 0-D plasma/transport code predicted that Deuterium plasma with parameters $n_e \sim 2\times10^{17}$ m^{-3}, $T_e \sim 2$ eV, ionization degree $\gamma_i \sim 18$-20% might be produced by coupled RF power $P_{RF} \sim 55$kW in JET vessel in (1-8) x 10^{-5} mbar pressure range [13]. The comparison of antenna-plasma coupling efficiency for dual frequency (25.21 MHz, 26.06 MHz) operation in mode conversion scenario and for single frequency ICWC at 25.21 MHz, B_T=3.3 T, D_2/(He+D_2)~0.2–0.3) is discussed below.

For JET A2 antennas, the antenna coupling resistance during ICWC discharges (R_p) is calculated from the characteristic line impedance (Z_0), forward (+) and reflected (−) voltages in the Main Transmission Line (MTL) and Outer Transmission Line (OTL) as $R_p = Z_0\,[{V^+_{OTL}}^2 - {V^-_{OTL}}^2]/[V^+_{MTL} + V^-_{MTL}]^2$, for each discharge. The coupling improved by (10-15)% during switch over from single antenna operation (25.21MHz) to double antennas operation (25.21MHz, 26.06MHz), all operating in monopole (0000) phasing. This type of operation also aided in improving the density from 10^{16}m^{-2} to 10^{17}m^{-2} measured near the antenna by the multichannel (vertical) FIR interferometer and the electron temperature T_e up to 50eV. The density increase close to the antenna further increased the coupling and improved the radial homogeneity of ICWC plasma. On the contrary, the coupling at 26.06MHz was poor. The 1-D TOMCAT code also shows no propagating wave in this case. Since in the 25.21MHz scenario, the RF field was expected to decay exponentially from the antenna inwards (Fig.4b), monopole (0000) phasing was suggested to increase the fast wave decay length and increase the field strength at the vessel center (at MC layer location). Operation above 25MHz shifts the MC layer towards high field side (at $B_T = 3.3$T) and is expected to lead to a reduction of the power being mode converted at the MC layer and hence to poorer plasma production. However, this dual frequency operating (25.21MHz + 26.06MHz, $B_T = 3.45$ T in $D_2/(D_2$+He) ~ 0.85) improves the plasma condition. During the ICWC discharges in (He+D_2) gas mixture or in pure D_2, the torus pressure declined sharply due to fast losses of He or D_2 to the plasma facing components. A strong dependence of the coupling and the torus fill pressure on the applied RF power could be observed.

Antenna coupling improved with pressure for both the operating frequencies (25.21MHz, 26.06MHz). Safe RF breakdown of the neutral gas and discharge initiation in JET led to reliable and reproducible production of ICRF plasma, suitable for isotope exchange study and ICRF assisted tokamak start-up scenario at ITER relevant low inductive $E_{||}$-field.

3.2.3. Effect of antenna phasing on coupling and plasma characterization during ICWC

On the basis of modeling with TOMCAT code [14] and experience from earlier ICWC experiments [5], further studies of ICWC scenario were conducted in AUG. Present ICWC experiments have been carried out in mode conversion scenario (high ratio of hydrogen in helium and hydrogen gas mixture) at dual frequency (30MHz and 36.5MHz), in presence of ITER simulated half field (B_T = 2.3T) and stationary vertical magnetic field (B_V = 10-30mT). The vessel wall was preloaded with Deuterium in preparation of H-D isotopic exchange experiments. Experiments were performed in (H_2+He) gas mixture, at pressure (P_{tot}) ~ $1x10^{-4}$ mbar, in presence of B_T = 2.3T, in dual frequency regime (30+36.5) MHz. The CCD cameras monitoring RF discharges in toroidal and poloidal directions indicated that ICRF plasmas were toroidally uniform but poloidally shifted towards the top of vessel. A repetitive pulse mode has many advantages above CW operation in order to avoid re-ionization or re-deposition of the wall-released gases due to the ICWC-plasma itself. During the single frequency operation of the antenna pair-3 and 4 at 30MHz in presence of B_T = 2.3T (in π-phasing) and B_T = 1.97T (in π/2 phasing), in multi-pulse mode (1.9s on, 0.1s off) during 6sec, the antenna-plasma coupling was poor (~10%) and showed insignificant improvement with higher applied RF power pulses. However, the coupling measured at 30MHz in presence of B_T = 2.3T in π/2 phasing, was four times higher than that measured during π-phasing and it further increased up to (50-60)% in multi-pulse mode operation during subsequent higher applied RF power pulses. This observation of increase of coupling with RF power is in agreement with the coupling study performed in TEXTOR. Significant improvement (by approx. 3 times) of antenna-plasma coupling could be observed during the shift of fundamental resonance ($w = w_{cH+}$) from the vessel axis (B_T = 1.97T) towards the antenna side (B_T = 2.3T). This observation is in agreement with earlier results [5] obtained in AUG. Generally, during high frequency ICRF operations the width of evanescent layer for FW is smaller which increases the antenna-plasma coupling. However, in present experiments, during simultaneous operation of antennas-12 (36.5MHz) and antennas-34 (30MHz), former in π phasing and the latter in π/2 phasing, the antenna coupling of antennas-12 indicated saturation with RF power and antenna coupling of antennas-34 declined during high power pulse (Fig.5a). The line average density measured in AUG by the DCN interferometer revealed a strong dependence on applied RF power. It increases monotonously with the antenna-plasma coupling (estimated for three different levels of RF-pulse scheme) during the operation of antennas-34 at 30MHz, with or without the antennas-12 (36.5MHz), in presence of B_T = 2.3T, as shown in Fig.5b. Although, during the ICWC operation in AUG, the gas pressure, initially at ~1×10^{-4}mbar, slumped to ~2×10^{-5}mbar, the antenna-plasma coupling and the line average density followed the rise in RF power during subsequent pulses. Density measurements indicate that a relatively high density (~10^{18} m^{-3}) plasma forms in the vicinity of ICRH antennas. The ECE radiation temperature shows a peak (max. 5eV) in the vicinity of the resonance layer $\omega = \omega_{cH+}$ during $\pi/2$-phasing whereas this is less pronounced for π-phasing, consistent with the lower coupling.

In JET, higher antenna-plasma coupling and better radial/poloidal homogeneity of ICWC plasma was achieved during monopole (0000) phasing (Fig.6a) in comparison to 00ππ phasing (Fig.6b) in the same physical conditions during the ICWC experiments. Reliable and reproducible ICWC discharges with high substantial coupling (~50%) and density (~$10^{17}m^{-2}$ measured near antenna), was obtained at $B_T = 3.3T$ along with vertical magnetic field $B_V \approx$ (15-30) mT, in D_2 discharge (with H_2 desorbed from the wall). Sporadic tripping during antenna operation, as observed during previous ICWC experiments in JET [15], was avoided due to safe regime of operation chosen during the present ICWC experiments. A correlation between the coupling efficiency of the antenna operating at 25.21MHz, in monopole phasing, and applied RF power was observed (Fig.7) during ICWC.

During another ICWC experiment performed in TEXTOR with both the antennas TEXTOR-A1 and TEXTOR-A2 ($B_T = 1.92T$, $\omega \approx \omega_{cH+}$), an RF power of 60kW was applied to each antenna. The TEXTOR-A1 antenna was operated in dipole phasing and TEXTOR- A2 antenna was operated in monopole phasing. The latter had better performance. Since the radial decay of E|| towards the high field side of TEXTOR vessel for monopole phasing is much more gradual than for dipole strap-phasing, former phasing couple much better to IC-resonant layers. Comparison of edge line average density (0.5-1×10^{17} m^{-3}) measured during 0-phasing of TEXTOR-A2 antenna, at $B_T = 2.3T$ and the edge density measured by Li-beam diagnostic during π-phasing of TEXTOR-A2 at $B_T = 1.92T$ (0.4-0.9×10^{17} m^{-3}), does not show any significant change due to antenna phasing. However, a strong dependence of antenna-plasma coupling on the gas pressure was observed. Higher density and lower electron temperature (n_e = 0.8-1×10^{17} m^{-3}, T_e = 6-8eV) were obtained at the edge at higher gas pressure (5×10^{-4} mbar) as compared to low gas pressure (1×10^{-4} mbar) regime (n_e = 0.3-0.5×10^{17} m^{-3}, T_e = 10-12eV).

3.2.4. Influence of stationary and oscillating poloidal magnetic fields on Antenna Coupling

In TEXTOR, although the application of a stationary (B_V = 10-30 mT << B_T) vertical or an oscillating poloidal B_p (vertical and radial) magnetic field, during ICWC discharge at $B_T = 2.3T$, demonstrated effective and promising results for wall conditioning [5] due to improvement of vertical and radial homogeneity of plasma, antenna coupling did not improve during this condition. The absence of improvement could be attributed to the asymmetric location (with respect to the equatorial plane) of the antennas in TEXTOR which make them insensitive to the expansion of plasma expansion in the presence of B_V [5]. However, application of oscillating B_P in HCH regime induces concomitant improvement of η (≥ 78%), H_α line intensity and line average density (n_e~1×10^{17} m^{-3}). Application of oscillating B_P allowed better poloidal distribution of plasma, partly due to improved ionization by inductively induced toroidal electric field which also increased the interaction of the plasma with the vessel surface. Fig.8 shows the concomitant oscillations of the line average density and of B_P.

During experiments performed in TEXTOR with both the antennas at B_T = 1.92T ($\omega \approx \omega_{cH}$+), application of an oscillating poloidal field (10mT/1-10Hz) improved the antenna coupling for monopole as well as dipole phasing of ICRH antenna. Antenna coupling was insensitive to the frequency of oscillation (1-10Hz) of the poloidal magnetic field. Another ICWC experiment was performed in similar conditions, but after hydrogen preload and puffing deuterium (2×10^{-4}mbar) after powering the ICRF antennas. A significant dependence of the antenna coupling on gas pressure and the superposition of oscillating magnetic field (10-30mT/1-10Hz) were also observed in this case. The plasma parameters obtained during the experiments mentioned above, were in agreement with the earlier TEXTOR database [3]. The thermal Lithium beam diagnostic in TEXTOR was recently updated for measurements of the electron density n_e and temperature T_e at the edge of ICRF plasmas. The electron temperature and density data derived from the characteristic Lithium radiation intensity ratios and atomic database were found in a reasonable agreement with the edge Langmuir probe data. An interesting observation was that the T_e decreased when the additional poloidal magnetic field was increased from 10mT to 100mT which indicates that a minor adaption of the additional vertical field could provide an extra control over T_e. An increase in the floating potential measured by the edge Langmuir probe in TEXTOR was also observed during ICWC experiments in presence of stationary vertical magnetic field.

In AUG, stationary vertical magnetic field (B_V) of varying magnitude was applied as a stepwise waveform (B_V = 10-30mT) during the continuous pulse ICWC operations. Although an improvement in the antenna-plasma coupling efficiency by about 10% was observed in the presence of an additional vertical magnetic field, at the initiation of ICWC discharge (t = 1Sec), it gradually deteriorated with increasing magnitude of the vertical magnetic field. Higher coupling could not be obtained during continuous application at lower values for the vertical magnetic field (B_V = 10mT, 0-6s). The line average density, measured near the antennas by the DCN interferometer, also followed the same trend as the antenna-plasma coupling which could be attributed to the fast decay of torus pressure during ICWC discharges in AUG (Fig.9). Density (~10^{18} m^{-3}) obtained at the initiation of ICWC discharge (t=1sec) gradually decreased to as low as (~1×10^{17} m^{-3}) although B_V was increased from 10mT up to 30mT during the discharge. However, constant high density (~10^{18} m^{-3}) could be obtained when the vertical magnetic field (B_V = 10mT, 0-6s) was applied continuously instead of a stepwise waveform, for a similar coupled RF power. The above observations of antenna coupling and edge density, in presence of a stationary vertical magnetic field, are contrary to the earlier ICWC results [5] obtained in AUG. Although a significant upward shift of ICWC plasma could be observed during application of an additional vertical magnetic field, no clear vertical expansion of ICWC plasma was observed, contrary to expectations.

A stationary vertical magnetic field B_V = (10, 20, 30)mT was applied during ICWC discharges in JET with $D_2/(D_2+He)$ ~ 0.85 gas mixture and during pure Helium gas discharge. Application of an additional vertical magnetic field (≤15mT) led to the concomitant improvement of plasma density (near the antennas) and antenna-plasma coupling (~12%). However, further increase of vertical magnetic field led to a decrease of plasma density near antenna as well as to degradation of coupling, as shown in Fig.10a and Fig.10b respectively. The density measured (~2×10^{17} m^{-2}) during discharges in (D_2+He) or pure D_2 was higher than that (9×10^{16} m^{-2}) in pure Helium discharges.

3.2.5. Influence of ECRH on Antenna Coupling

Advantageous effects of application of Electron Cyclotron Resonance heating (ECRH) on plasma-antenna coupling have been observed in TEXTOR [16] during ICWC discharges. Low power ECR assistance during ICWC proved beneficial in enhancing poloidal homogeneity by providing seed-plasma in the centre of torus to which ICRF waves can couple. However, ECR pulse (100kW/140GHz), applied for ~ 0.5 sec during ICWC discharges in AUG, lead to no significant change in coupling. Further, the line average density, measured near the antenna, has been observed to decline in presence of ECR. This difference in behaviour is not yet understood.

3.3. STUDY OF ANTENNA-PLASMA COUPLING DURING ISOTOPE EXCHANGE IN JET

After the ICWC discharge optimization in JET, as discussed above, proper wall preloading with hydrogen was done. Optimal physical parameters/conditions, thus identified, were chosen for the study of hydrogen to deuterium isotope exchange in presence of B_T = 3.3T along with constant B_V = 30mT at pure deuterium gas pressure p_{tot}~2×10^{-5}mbar. The RF-power waveform was tailored after breakdown (within safe boundaries) in order to achieve optimum T_e for isotope exchange rate. Hydrogen, removed from the wall during ICWC discharges, was pumped out regularly. Better coupling efficiency of the antenna operating at 25.21MHz over the other antenna operating at 26.06MHz was evident during ICWC-isotope exchange experiments. Almost 230kW of RF power could be coupled to obtain ICWC plasma density n_e~1×10^{18} m^{-2}, measured near the antenna. Both antenna coupling and the density measured near antenna varied more or less proportionally to each other during hydrogen desorption (Fig.11). The radial density profile, obtained from the multichannel (vertical) FIR interferometer, is similar to that obtained in TEXTOR ICWC discharges in (He + H_2) [12], as shown in Fig.12. The plasma density profile is also seen to change shape while the concentration of hydrogen is changing. The appreciable coupling obtained in case of pure D_2 ICWC (≥50%), owing to the H_2 desorbed from wall, is comparable to that obtained during ICWC in (He + H_2) gas mixture (≥60%) in TORE SUPRA [7], TEXTOR, AUG. From the present study of isotope exchange during JET-ICWC experiments one can see that the coupling efficiency might be a rough indicative measure of ICRF-Wall Conditioning performance as it shows a rough correlation with the removal rates of marker masses that characterize isotope exchange [4, 7] i.e. in parallel with the progress of the isotope exchange process. ICWC-DC and study of isotope exchange in JET revealed that at such low pressure, high power ICWC discharges maximize H out-gassing and minimize D retention.

CONCLUSIONS

Advances have been made in the characterization of RF produced plasmas during ICWC experiments in various tokamaks. Major dependences of the antenna-plasma coupling on the plasma parameters, measured during ICWC experiments, have been identified. Evolution of antenna-plasma coupling during isotope exchange experiment in JET shows a rough correlation with the completeness of the exchange process. Safe parameter regimes of operating pressure, RF voltage on ICRH antennas straps and antennas phasing, have been explored for possible ICWC experiments in ITER at different magnetic fields. First simulation of ICWC operation in ITER full field scenario was successfully demonstrated in the largest present-day tokamak. Both vertical and poloidal homogeneity of the ICWC plasma and better antenna-plasma coupling could be achieved by the application of additional vertical/poloidal magnetic fields in different operational regimes during ICWC studies. Poloidal field components, added to the pure toroidal field, aided to guide the ICWC-plasma towards the wall on high field side. It was observed that monopole phasing of ICRH antennas is more favorable than p-phasing, as it provides fast breakdown, higher density and higher coupling efficiency in some machines. Similar beneficial properties could be observed for π/2 phasing with respect to π-phasing in AUG. The dual frequency operation in various gas-mixtures (depending on magnetic field) with mode conversion mechanisms has been demonstrated to be a promising scenario to enhance ICWC plasma homogeneity inside the machines. Further study is required in different machines to better understand the link between the RF plasma and the conditioning efficiency.

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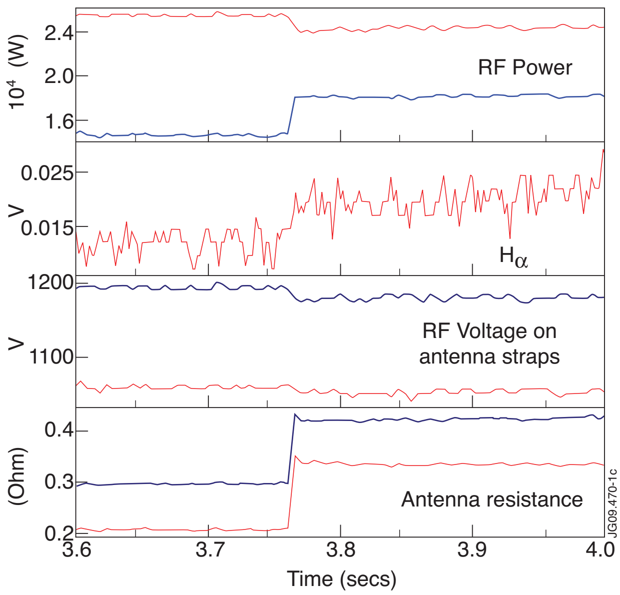

Figure 1: Experimentally observed indications of gas breakdown during ICWC in JET (Pulse No. 79322); concomitant rise in H_α signal, drop in antenna RF voltage and rise in antenna resistance for antennas C (blue) and D (red).

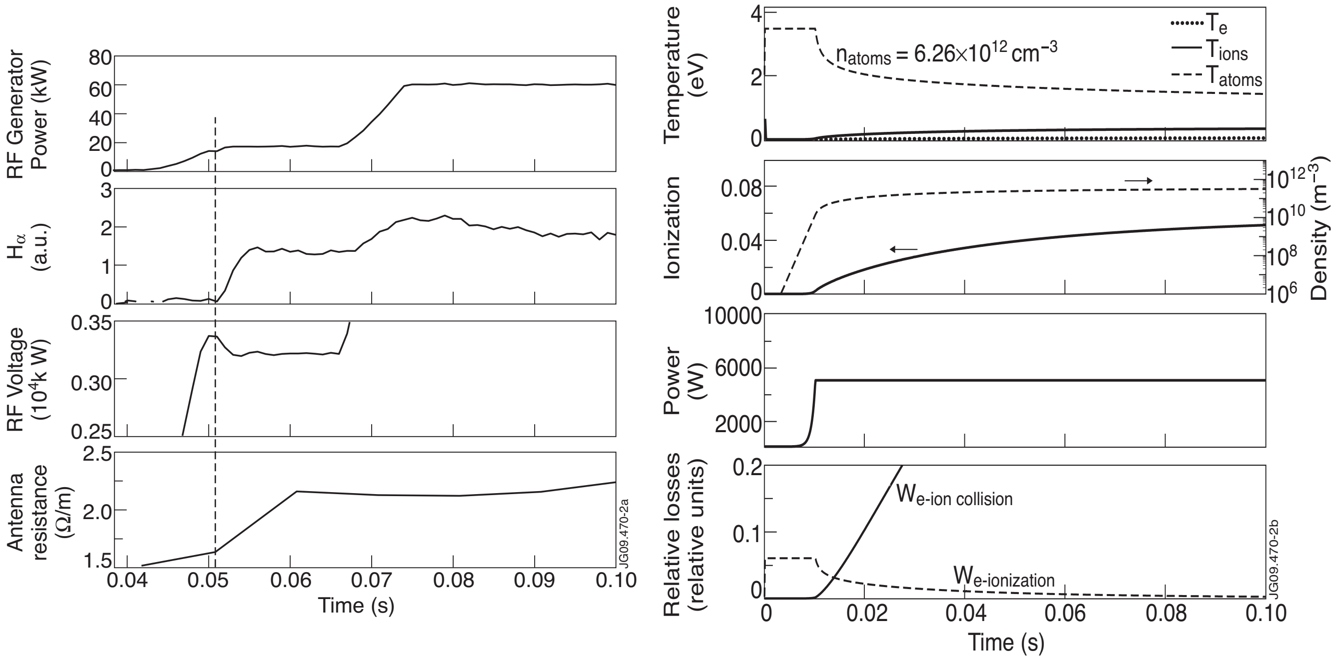

Figure 2: Comparison of (a) Experimentally observed indications of gas breakdown during ICWC in TEXTOR (Shot No. 110504); concomitant rise in $H_{\pm}$ signal, drop in antenna RF voltage and rise in antenna resistance, indicated by the dotted line, with the (b) 0-D code prediction. In addition to the usual quantities, curves are given for T_{atoms} the atom's temperature, η_i the ionization fraction, radiative losses due to $W_{e\text{-}ionization}$ ionization and $W_{e\text{-}ion\ collision}$ electron-ion collisions.

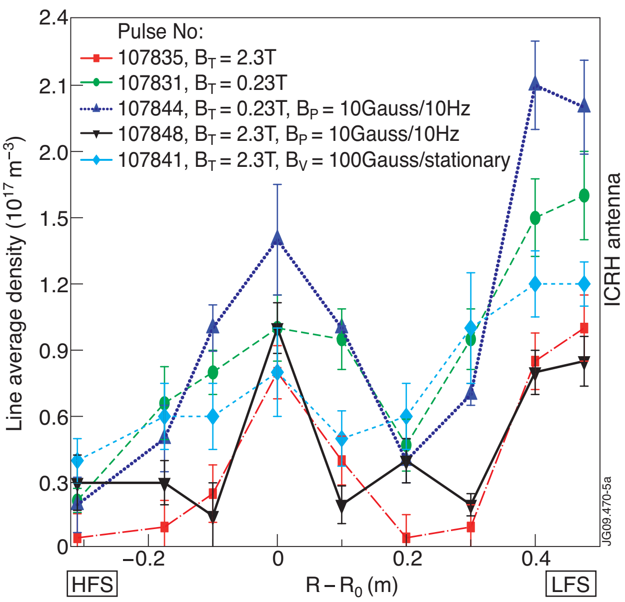

Figure 3: Comparison of radial line averaged density profiles obtained during the ICWC-DC experiments in TEXTOR, in presence of stationary vertical magnetic field or rotating poloidal magnetic field with B_T = 2.3T and B_T = 0.23T.

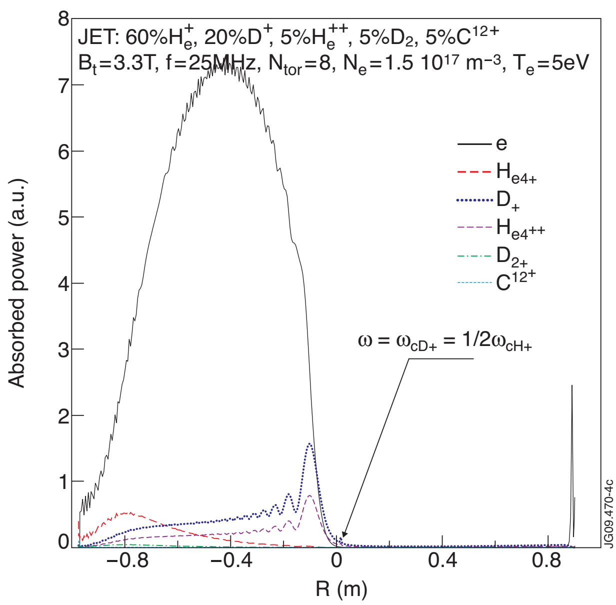

Figure 4: The RF- power absorbed by the various particle fluids according to the TOMCAT-code for MC scenario in JET ICWC-plasma in (He+D_2) gas mixture, at the following parameters: a≈1.62 m, R_0=2.96 m, B_T=3.3 T, n_{e0}=1.5×10^{17} m^{-3} and single frequency of 25 MHz and particle composition: 60%He^{4+}, 20%D^+, 5%D_2^+, 5% He^{4++}, 5%C^{12+}.

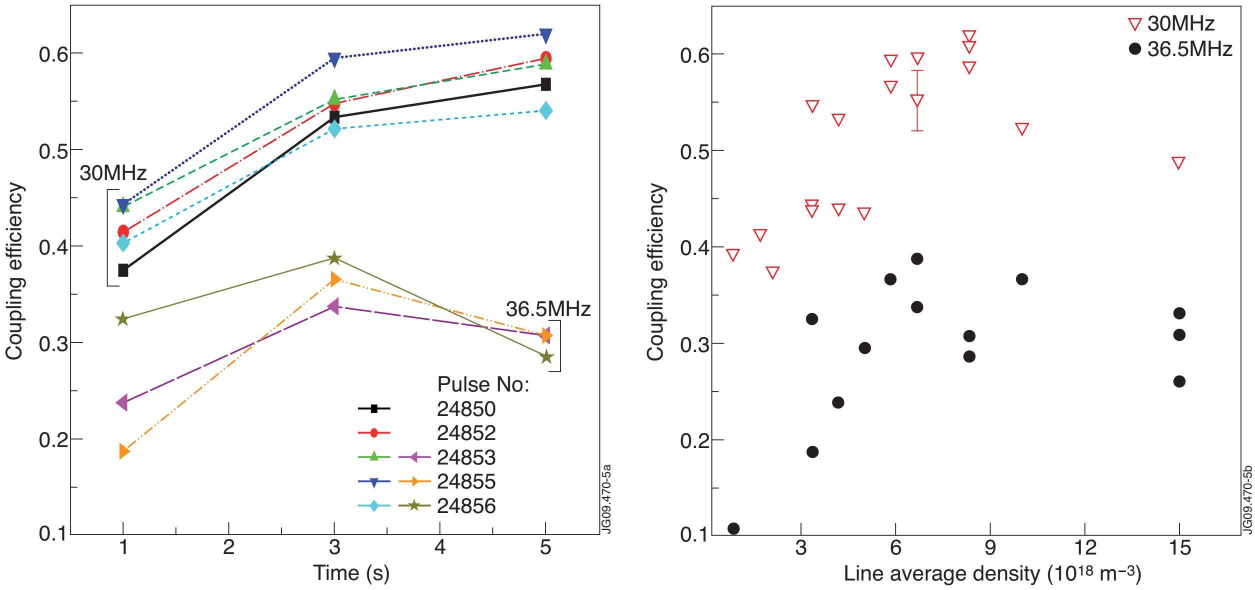

Figure 5: (a) Coupling efficiency estimated for the antennas operating at 30MHz and 36.5MHz at different instants of time (fordifferent input power levels) during ICWC experiments in AUG. (b) Correlation between antenna-plasma coupling, obtained for the AUG antennas operating at 30MHz and 36.5MHz,with and without B_V, at three different coupled power levels (for repeated pulse scheme) and the plasma density (measured near the antenna centre).

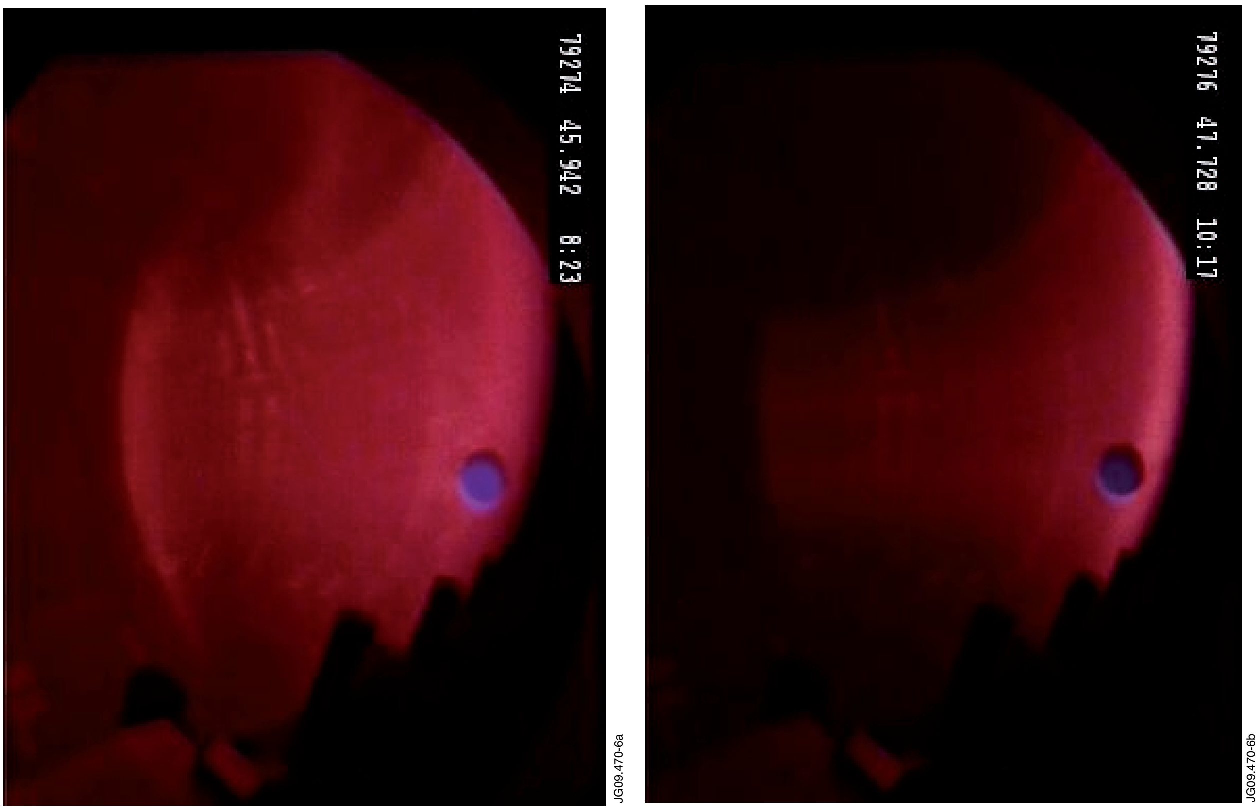

Figure 6: Comparison of the plasma profiles obtained by the broad view camera during JET ICWC in (a) 0000-phasing, at coupled power of 230kW (Pulse No. 79274)and (b) 00ππ-phasing, at coupled power of 65kW (Pulse No. 79276)

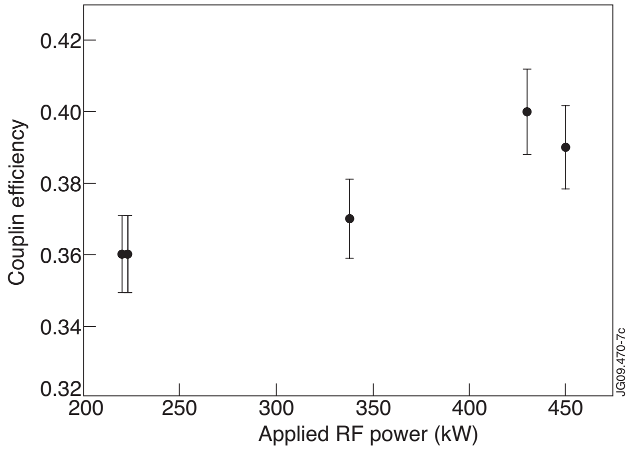

Figure 7: Correlation between the antenna-plasma coupling efficiency and the applied RF power (in monopole phasing) observed during discharge optimization for the study of isotope exchange experiment during ICWC in JET.

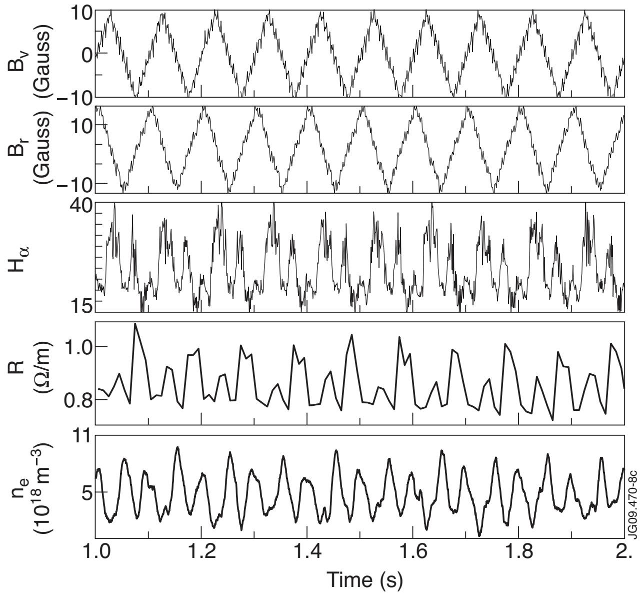

Figure 8: Concomitant oscillations of H-alpha (H_α), antenna resistance (R) and line average plasma density (n_e) with the additional poloidal magnetic field (resultant of vertical B_V and radial B_r components, with a phase difference of $\pi/2$) applied in presence of B_T=0.23T (HCH regime) during the TEXTOR Shot No.107844.

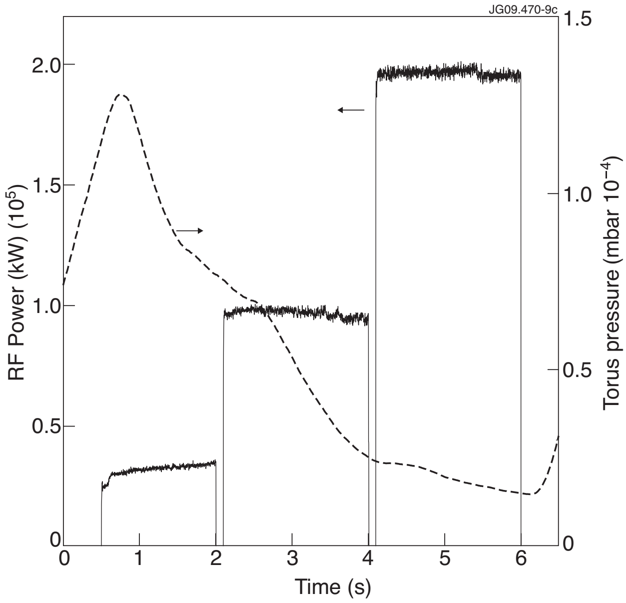

Figure 9: Coupled RF power during an ICWC discharge (Pulse No. 24850) in repeated power pulse scheme, in AUG and evolution of torus pressure during the discharge.

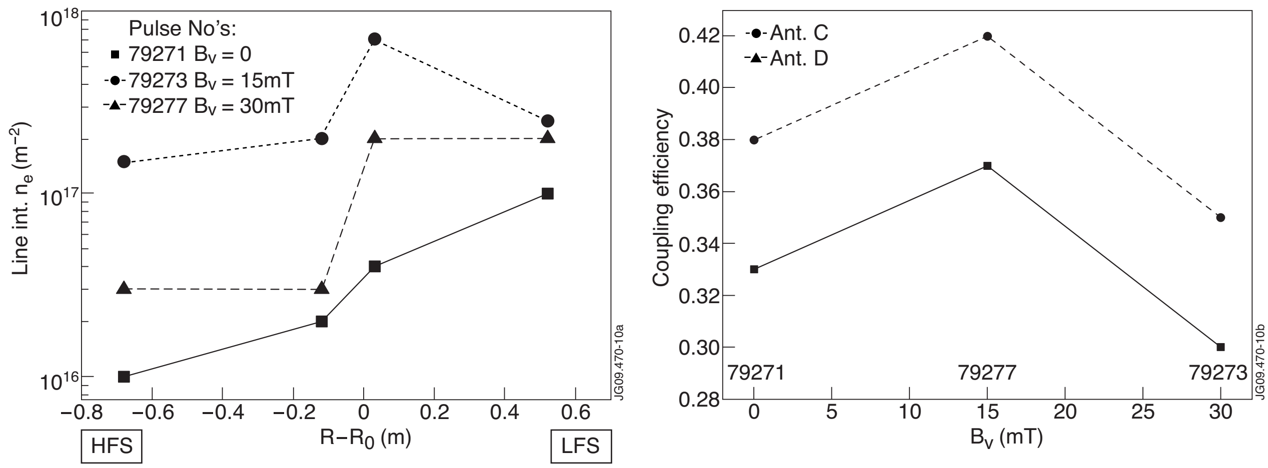

Figure 10: Application of additional vertical magnetic field (B_V ≤15mT) during ICWC in JET lead to improvement of (a) plasma-antenna coupling and (b) line integrated density, measured near the antenna. However, concomitant degradation of coupling and density could be observed on increasing the B_V to 30mT.

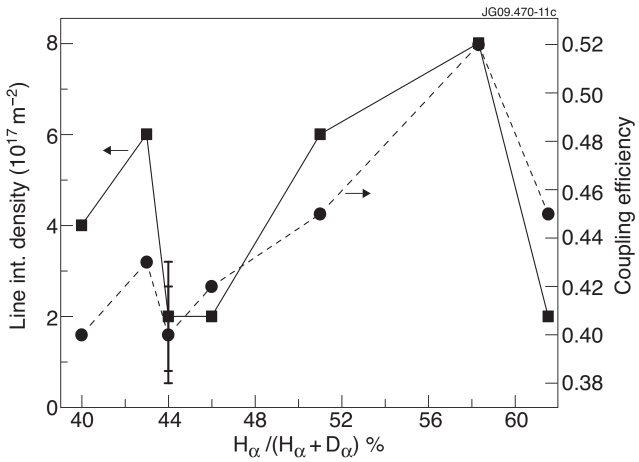

Figure 11: Correlation between hydrogen concentration, antenna-plasma coupling efficiency and density (measured near antennas) observed during isotope exchange experiment in JET-ICWC.

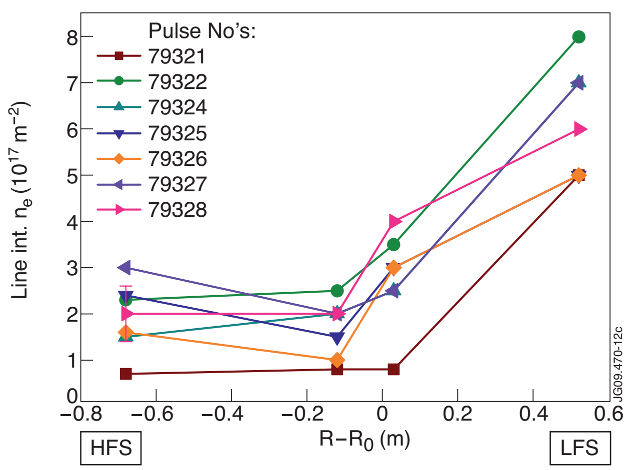

Figure 12: Radial density profiles obtained in isotope exchange experiment during the ICWC discharge in JET in presence of stationary B_T = 3.3T and additional vertical magnetic field B_V = 30mT.