A study of RF power absorption mechanisms in JET ICWC plasmas

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Abstract

This paper focuses on further study of the Radio-Frequency (RF) power absorption mechanisms responsible for Ion Cyclotron Wall Conditioning (ICWC) discharge ignition and sustainment in fusion machines in the presence of high toroidal magnetic field. The dominant electron collisional, ion collisional and cyclotron absorption mechanisms are analyzed during local (antenna-near) gas breakdown ($\omega_{pe} < \omega$) and over-torus plasma wave excitation ($\omega_{pe} > \omega$) phases of RF discharge. Optimization of the absorbed RF power in terms of (i) $\tilde{E}_z$-field generation (electric field along B_T-field lines), (ii) antenna phasing and (iii) waves excitation in plasmas with multi-ion species resulted in a successful performance of the JET ICWC experiments (B_T=3.3 T, *f*=25 MHz) using the standard ICRF A2 antennas in a scenario envisaged at ITER full field (B_T=5.3 T, *f*=40 MHz) – i.e. with the fundamental ion cyclotron resonance (ICR) of the deuterons, $\omega = \omega_{cD+}$, on-axis.

Introduction

In ITER and other future superconducting fusion devices, the presence of the permanent, high toroidal magnetic field will prevent using Glow Discharge Conditioning (GDC) between reactor pulses. The alternative ICWC technique, based on discharge ignition and sustainment with conventional ICRF heating antennas in the presence of B_T, was recently demonstrated in present-day tokamaks and stellarators (summarized in Refs. [1,2]). The obtained encouraging results have promoted ICWC to the status of one of the most promising techniques available to ITER for routine inter-pulse/overnight conditioning of the first wall, in particular for recovery after disruptions, isotopic ratio control and fuel removal. The ability to operate in the ICWC mode has recently been confirmed as a functional requirement of the ITER main ICRF heating and current drive system [3]. This paper focuses on ICWC experiments performed at

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JET using the standard ICRF heating A2 antennas and intended to test the ICWC scenario envisaged at ITER full field: on-axis location of the fundamental ICR for deuterium ions, $\omega = \omega_{cD+}$. To enhance the wall conditioning output, the RF discharge ignition and sustaining phases have been optimized in terms of (i) generation of the antenna-near $\tilde{E}_z$-field in vacuum (parallel to the B_T-field), (ii) antenna coupling to low density plasmas (~10^{17} m^{-3}) and (iii) waves excitation/absorption in plasmas containing multi-ion species. Finally, we assess the feasibility of ITER ICRH&CD system operation in the ICWC mode.

Generation of antenna-near E_z-field and local gas breakdown

Electron collisional ionization is the basic process of plasma production in the ICRF band. The electrons oscillate along the static magnetic field lines under the action of the $\tilde{E}_z$-field and acquire energy needed for ionization through random collisions with neutrals [4]. However, in the typical ICRF band (~20–60 MHz), the electromagnetic waves (TM cylindrical modes) cannot propagate along the vacuum torus of *present-day* fusion machines due to small cross-section size: $\kappa_z^2 = \omega^2/c^2 - \kappa_\perp^2 < 0$ (κ_z is the parallel wave-vector) and the initial ionization may only occur locally at the antenna-near *non-homogeneous* $\tilde{E}_z$-field. This process will be efficient if the electrons are trapped in the antenna RF potential wells for many RF periods and the amplitude of the antenna electric field meets the boundary condition: $(2/e)\cdot\sqrt{m_e\varepsilon_i}\cdot\omega\sqrt{(1+\nu_{en}^2/\omega^2)} \le \tilde{E}_z(r) \le (\sqrt{2}m_e/e)\cdot(0.2L_z)\cdot\omega^2\sqrt{(1+\nu_{en}^2/\omega^2)}$. Here ν_{en} is the electron-neutral collision frequency, ε_i is the ionization potential for molecules (atoms), $L_z = \tilde{E}_z/(d\tilde{E}_z/dz)$ is the parallel length scale of the ponderomotive potential. In the radial direction, the antenna-near RF field exponentially decays thus forming radially located breakdown zone with trapped electrons. The impact of JET A2 antenna phasing on formation of the antenna-near gas breakdown region is shown in Fig.1. It clearly illustrates the benefit of the 4-strap antenna operation in monopole phasing (0000) compared to super-dipole phasing (00ππ) for the gas breakdown: more extended breakdown zone (outside the antenna box) traps more electrons into ionization process and gives rise to shorter breakdown time [5].

Standard ICRF antenna coupling to low density ICWC plasmas

The conventional ICRF antenna is designed for dense (n_e>10^{19} m^{-3}) target plasma heating *through excitation of Fast Wave* (FW) with high coupling efficiency (η>0.9). Here we define the antenna-plasma coupling efficiency as a fraction of the generator power coupled to the plasma, $\eta = P_{RF-pl}/P_{RF-G}$. Being operated in the RF plasma production mode with the "plasma heating settings" (high κ_z-spectrum of the radiated RF power), the conventional ICRF antenna gives evidence of poor coupling (η_0~0.2−0.3) to the low density RF plasmas n_e~10^{16}–10^{17} m^{-3}, at which FW is typically non-propagating. The present-day solutions for ICRF antenna enhanced coupling in the ICWC mode are based on the development of scenarios with *FW excitation* in low density plasmas [6]: (i) antenna phasing to low κ_z-spectrum of the radiated RF power, (ii) *FW – Slow Wave (SW) – Ion Bernstein Wave (IBW)* mode conversion (MC) in RF plasmas with two ion species, (iii) operation at High Cyclotron Harmonics (HCH), typically $\omega \approx 10\omega_{ci}$. For the case of JET A2 antenna, the first solution was investigated by changing the antenna phasing from dipole to super-dipole or monopole. A dramatic reduction (about two orders) in the threshold density for FW excitation and coupling enhancement ($\eta/\eta_0 \approx 3$) were achieved with monopole phasing (Fig.2).

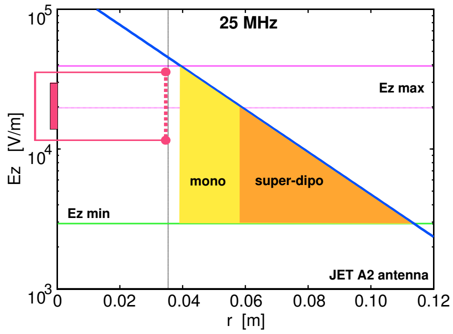

Figure 1. Boundary conditions for H_2 gas breakdown (p_{H2}=2x10^{-3} Pa) in radial direction with JET A2 antenna at monopole vs. super-dipole phasing, *f*=25 MHz, $V_{RF\text{-}ant}$=14 kV.

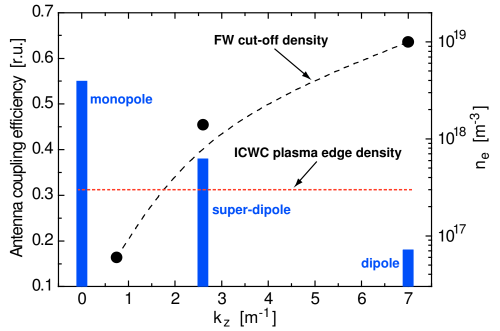

Figure 2. JET A2 antenna coupling to low density ($n_e(0) \approx 1.5\times10^{17}$ m^{-3}) RF plasmas as a function of antenna phasing and FW cut-off density (*f*=25 MHz, deuterium, B_T=3.3 T).

RF power absorption mechanisms in low density/temperature ICWC plasmas

After the first phase of ICWC discharge (gas local breakdown), as soon as the plasma frequency ω_{pe} becomes of the order of the generator frequency ω (this occurs at a very low density ~5×10^{12}–5×10^{13} m^{-3} in the frequency range 20–60 MHz), plasma waves can start propagating in a relay-race regime governed by the antenna κ_z-spectrum, causing further space ionization of the neutral gas and plasma build-up in the torus. Modeling of the absorbed power in ICWC discharge during the plasma wave phase was undertaken with the 1-D full wave RF code TOMCAT [7] accounting for electron (collisional, Landau, TTPM) and ion (collisional, linear cyclotron at *n*=1–3 harmonics) damping mechanisms. An example for the RF power absorption in JET-like ICWC plasmas (D_2 gas injection into the vessel with H_2 preloaded walls [2]) is shown in Fig.3. Because of the very low plasma temperature during the ionization phase (T_i<T_e~5–10 eV [1]), the RF power is predicted to be dissipated mostly collisionally. The electrons absorb the largest fraction of the coupled power, $P_{RF\text{-}e} \approx (0.75–0.9)P_{tot}$, directly from the exponentially decaying antenna $\tilde{E}_z$-field at the LFS and in the widely extended FW-SW-IBW conversion zone from the on-axis ICR ($\omega = \omega_{cD+}$) towards the HFS due to presence of the deuterium-hydrogen ion species. The line-integrated plasma density profile of JET D_2-ICWC shots correlates with the predicted $P_{RF\text{-}e}$ deposition profile thus confirming the basic *e*-ionization mechanism of ICRF plasma production (see Fig.4). The ions absorb a minor fraction of the RF power, $P_{RF\text{-}i} \approx (0.10–0.25)P_{tot}$, mainly collisionally. In addition, linear cyclotron absorption by resonant deuterons and hydrogen molecular ions H_2^+ is predicted at the on-axis fundamental ICR (Fig.3). Interestingly, the NPA diagnostic registered generation of high-energy both, D ($\overline{E}_{\perp(D)}$ ≈5–20 keV) and H ($\overline{E}_{\perp(H)}$ ≈2–15 keV) atoms. The role of the fast particles in the ICWC efficiency and possible acceleration mechanisms for the protons in JET ICWC plasmas (linear fundamental ICR for the H_2^+ ions ($\omega = \omega_{cH2+}$) with their further dissociation and/or direct non-linear ICR for the protons at the first sub-harmonic $\omega = 1/2\,\omega_{cH+}$ [8]) will be the subject of further studies.

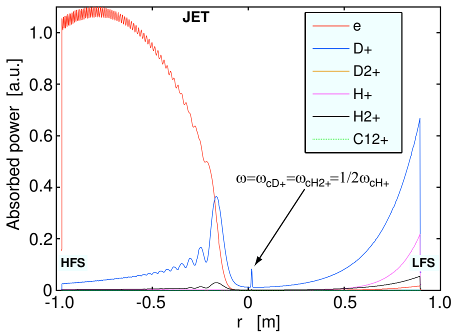

Figure 3. Absorbed power P_{RF-e}(r) and P_{RF-i}(r) simulated for JET-like ICWC plasmas: 60%D^+:37%H^+:0.5%D_2^+:2%H_2^+:0.5%C_{12}^+; $n_e(0)$≈1.5×10^{17} m^{-3}, $k_z(a)$≈0.02 cm^{-1}.

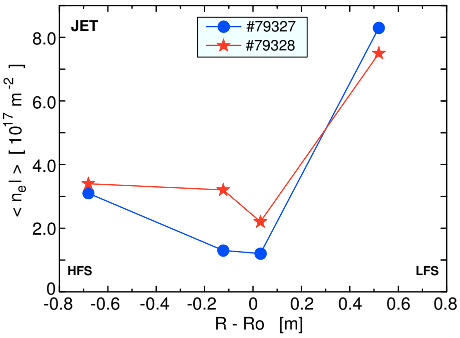

Figure 4. RF plasma density profile measured in JET ICWC conditions: B_T=3.3 T, p_{D2}=2x10^{-3} Pa, A2D and A2C antennas at f=25 MHz, monopole phasing, P_{pl-tot}≈250 kW, $n_D/(n_D+n_H)$≈0.58–0.60.

ICWC discharge extrapolation to ITER

Modeling with the upgraded 0-D plasma [9] and TOMCAT [7] codes predicts that H_2/D_2 ICWC plasmas in ITER-size machine (n_e≈(1–5)×10^{17} m^{-3}, T_e≈1–2 eV, p≈(2–8)×10^{-2} Pa, B_T=2.65 T–5.3 T) may be produced in the reasonable range of the coupled RF power, P_{RF-e} ≈0.5–1.5 MW, depending on the gas pressure. A threshold effect of excitation of vacuum cavity TM mode with on-axis maximum for the $\tilde{E}_z$-field in ITER-like torus was discovered with the 3-D electromagnetic MWS code in the frequency range ≈43–44 MHz which is within the operation frequency band for the ITER ICRF H&CD system (40–55 MHz). The discovered effect may result in simultaneous gas breakdown and initial ionization over the ITER torus if the ICRF H&CD system is tuned to torus Eigen-frequencies, thus facilitating and making safer operation of the ITER antenna in the ICWC mode.

Acknowledgments

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