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A Study Of RF Power Absorption Mechanisms In JET ICWC Plasmas

ABSTRACT
This paper focuses on further study of the 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 and also 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 (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): on-axis fundamental ICR for deuterons, $\omega = \omega_{cD+}$.

1. 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) technique between reactor pulses. An alternative ICWC technique, based on Radio-Frequency (RF) 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 a study of operation of the JET standard ICRF heating A2 antennas in the ICWC mode in a 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.

2. GENERATION OF ANTENNA-NEAR E_z-FIELD AND LOCAL GAS BREAKDOWN

The 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: $K_z^2 = \omega^2 / c^2 - k_\perp^2 < 0$ (k_z is the parallel wave-vector). Hence, the initial ionization may only occur locally at the antenna-near *non-homogeneous* $\tilde{E}_z$-field and 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: $(2/e).\sqrt{m_e\varepsilon_i} \cdot \omega\sqrt{(1+\nu^2_{en}/\omega^2)} \le \tilde{E}_z\,(\mathrm{r}) \le (\sqrt{2}m_e/e) \cdot (0.2L_z)\cdot\omega^2\sqrt{(1+\nu^2_{en}/\omega^2)}$. Here ν_{en} is the electron-neutral collision frequency, ε_i the ionization potential for molecules (atoms), $L_z = \tilde{E}z\,/(d\tilde{E}_z/\mathrm{d}_z)$ 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 is clearly seen the benefit for operation of the 4-strap antenna in monopole phasing compared to super-dipole phasing: more extended breakdown zone (outside the antenna box) gives rise to shorter breakdown time [5].

3. 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, $\eta = P_{RF\text{-}pl}$ / $P_{RF\text{ - }G}$. Being operated in the RF plasma production mode with the "plasma heating settings" (high k_z -spectrum of the radiated RF power), the conventional ICRF antenna gives evidence of poor coupling ($\eta_0 \sim$ 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 k_z- spectrum of the radiated RF power, (ii) FW-SW-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 (f=25 MHz, B_T=3.3 T, deuterium), the first solution results in a dramatic reduction (about two orders) in the threshold density for FW excitation and coupling enhancement ($\eta/\eta_0 \approx 3$) on changing the RF current phase in antenna straps from *dipole to monopole* (Fig.2).

4. 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 (it 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 k_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 the 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 (deuterium gas injection into the vessel with hydrogen 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, $P_{RF\text{-}e}\approx(0.75\text{–}0.9)P_{tot}$: directly from the exponentially decayed antenna $\tilde{E}_z$-field at LFS and dominant absorption in the widely extended FW-SW-IBW conversion zone from the on-axis ICR ($\omega = \omega_{cD+}$) towards HFS due to presence of the deuterium-hydrogen ion species. The line-integrated plasma density profile for set of JET D_2-ICWC shots is in a qualitative agreement with the predicted $P_{RF\text{-}e}$ deposition profile thus confirming the basic e-ionization mechanism of ICRF plasma production (Fig.4). The ions absorb minor fraction of the RF power, $P_{RF\text{-}i}\approx(0.10\text{–}0.25)P_{tot}$, also mainly collisionally. In addition, the linear cyclotron absorption by the resonant deuterons and hydrogen molecular ions H_2^+ is predicted at the on-axis fundamental ICR (Fig.3). To our surprise, the NPA diagnostic registered generation of high-energy both, deuterium ($\bar{E}_{\perp(D)}\approx$5-20 keV) and hydrogen ($\bar{E}_{\perp(H)}\approx$ 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 hydrogen molecular 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.

5. ICWC DISCHARGE EXTRAPOLATION TO ITER

Modeling with the upgraded 0-D plasma [9] and TOMCAT [7] codes predicts that hydrogen/ deuterium ICWC plasmas in ITER-size machine ($n_e\approx(1\text{–}5)\times10^{17}$ m^{-3}, $T_e\approx1\text{–}2$ eV, $p\approx(2\text{–}8)\times10^{-2}$ Pa, B_T=2.65 T–5.3 T) may be produced in the reasonable range of the coupled RF power, $P_{RF\text{-}e}\approx0.5\text{–}1.5$ MW, depending on the gas pressure. The new effect was predicted with the 3-D electromagnetic MWS code: vacuum cavity TM mode excitation in ITER-like torus in the frequency range ≈43–44 MHz that 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.

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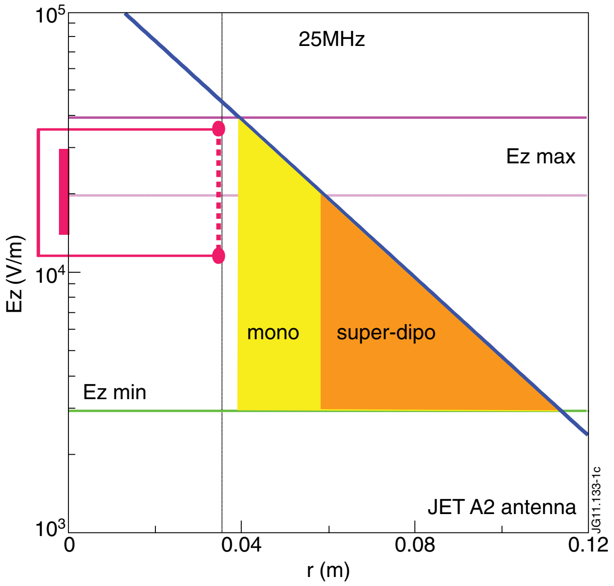

Figure 1: Boundary conditions for H_2 gas breakdown (p_{H2} = 2×10^{-3} Pa) in radial direction with JET A2 antenna at monopole vs. super-dipole phasing, f = 25MHz, $V_{RF\text{-}ant}$ = 14kV.

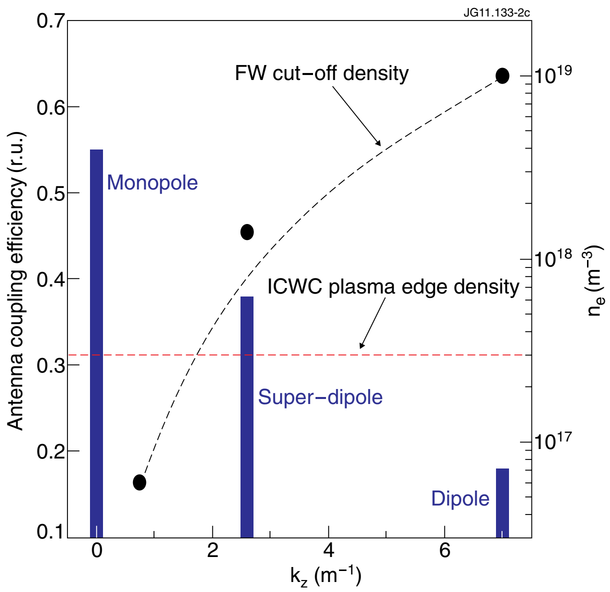

Figure 2: JET A2 antenna coupling to low density ($ne(0)\approx 1.5\times10^{17}\,m^{-3}$) RF plasmas as a function of antenna phasing and FW cut-off density (f = 25 MHz, deuterium, B_T = 3.3 T).

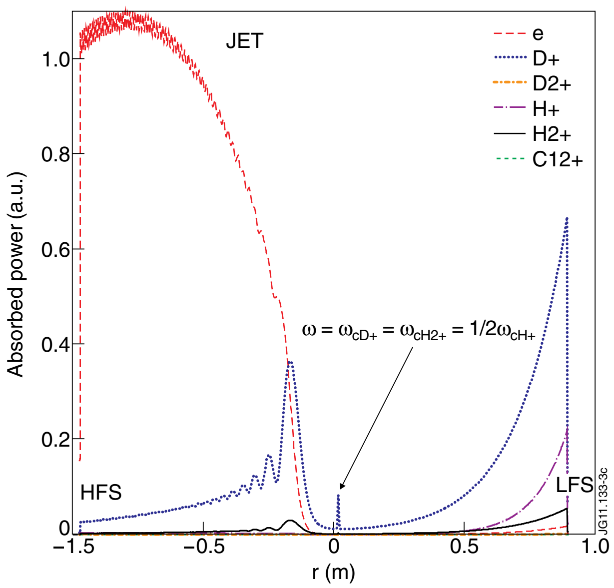

Figure 3: Absorbed power $P_{RF\text{-}e}(r)$ and $P_{RF\text{-}i}(r)$ simulated for JET-like ICWC plasmas: 60%D+:37%H+:0.5%D_2^+: 2%H_2+:0.5%C_{12}^+; $n_e(0)\approx1.5\times10^{17}\,m^{-3}$, $k_z(a)\approx0.02\,cm^{-1}$.

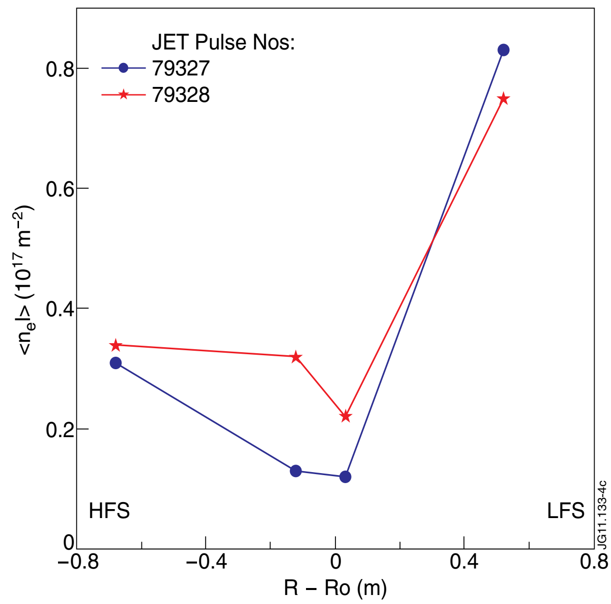

Figure 4: RF plasma density profile in JET ICWC conditions: B_T = 3.3T, p_{D2} = 2×10^{-3} Pa, A2D and A2C antennas at f = 25MHz, monopole phasing, $P_{pl\text{-}tot}\approx250$kW, $n_D/(n_D+n_H)\approx 0.58–0.60$.