SIMULATION OF ITER ICWC SCENARIOS IN JET

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Encouraging results recently obtained with alternative ion cyclotron wall conditioning (ICWC) in the present-day tokamaks and stellarators have elevated ICWC to the status of one of the most promising techniques available to ITER for routine interpulse conditioning in the presence of the permanent high toroidal magnetic field. The paper presents a study of ICWC discharge performance and optimization of the conditioning output in the largest tokamak JET using the standard ICRF heating antenna A2 in a scenario envisaged at ITER full field, B_T=5.3 T: on-axis location of the fundamental ICR for deuterium, $\omega=\omega_{cD+}$. The perspective of application of the alternative technique in ITER is analyzed using the 3-D MWS electromagnetic code, 1-D RF full wave and 0-D plasma codes.

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1. INTRODUCTION

In ITER and future superconducting fusion devices, the presence of the permanent, high toroidal magnetic field will prevent using glow discharge conditioning technique (GDC) between reactor pulses. An alternative technique, Ion Cyclotron Wall Conditioning (ICWC), based on Radio-Frequency (RF) discharge ignition with conventional ICRF heating antennas in the presence of B_T, was recently demonstrated in present-day tokamaks and stellarators (summarized in Ref. [1] and Refs. herein). The obtained encouraging results have promoted ICWC to the status of one of the most promising techniques available to ITER for routine interpulse conditioning of the first wall, in particular for recovery after disruptions, isotopic ratio control and fuel removal. The ability to operate in ICWC mode has recently been confirmed as a functional requirement of the ITER main ICRF heating and current drive system [2].

This paper focuses on a study of ICWC in the largest current tokamak JET using the standard ICRF heating A2 antennas in a scenario envisaged at ITER full field: on-axis location of the fundamental ICR for deuterium, $\omega = \omega_{cD^+}$. To enhance the wall conditioning output, ignition and sustainment phases of the ICRF discharge have been optimized in terms of (i) antenna-near $\widetilde{E}_z$ -field generation (parallel to the B_T-field) responsible for the discharge ignition, (ii) antenna coupling to low plasma density ($\sim 10^{17}$ m^{-3}) and (iii) plasma wave excitation/absorption over the torus in the low density plasmas. Finally, the application of this alternative technique in ITER is assessed using the 3-D MWS electromagnetic code, 1-D full wave RF and 0-D plasma codes.

2. JET A2 ICRF ANTENNA OPERATION IN PLASMA PRODUCTION MODE

2.1. GENERATION OF ANTENNA-NEAR E_Z-FIELD

The ICRF discharge initiation in the presence of B_T-field results from the absorption of RF energy mainly by the electrons. The RF $\widetilde{E}_z$ -field is considered to be responsible for this process [3]. However, in the typical ICRF band (~20–60 MHz) in the *present-size* fusion devices, for most of the antenna κ_z -spectrum, the RF waves (cylindrical modes) cannot propagate in the vacuum torus: $\kappa_\perp^2 = \omega^2/c^2 - \kappa_z^2 <0$, where $\kappa_\perp$ is the perpendicular wave-vector, $\omega = 2\pi f$, f is the RF generator frequency. Even the RF waves with the longest toroidal wavelength (κ_z =1/R_0, R_0 is the torus major radius) or with infinite wavelength (κ_z =0), which satisfy the propagation condition $k_\perp^2 > 0$, can only oscillate locally in the cross-section in front of the antenna but not propagate

See the Appendix of F. Romanelli et al., Proc. 22nd Int. FEC Geneva, IAEA (2008).

along the torus. The perpendicular wavelength of such waves is still larger than the *present-day* torus size.

Hence, the neutral gas breakdown and initial ionization may only occur locally at the antenna-near $\tilde{E}_z$-field.

In the general case of a poloidal loop-type ICRF antenna with a tilted Faraday shield (FS), the RF $\tilde{E}_z$-field in vacuum can be induced *electrostatically* and *inductively*. The *electrostatic* mechanism results from the RF potential difference between the central conductor and the side parts of the antenna box (side protection RF limiters). The *inductive* mechanism results from the RF voltage induced between the FS rods by the time-varying magnetic flux [4]. Such a simplified description of the antenna-near $\tilde{E}_z$-field in vacuum was found in a good agreement with numerical simulations done for the real antenna configurations (JET A2 antenna [5]) using the 3D MWS electromagnetic code [6] as shown in Fig. 1.

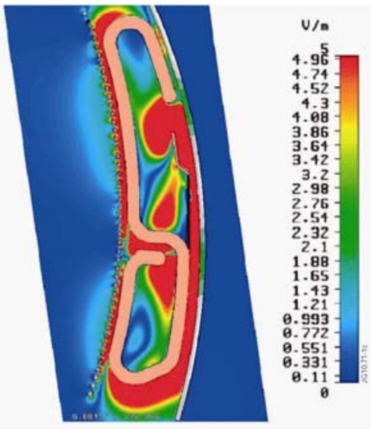

Fig.1. E_z-field simulation for the JET A2 antenna with 3-D MWS code (f=30 MHz, antenna straps in dipole-phasing, $P_{RF\text{-}input}$=1 W) [7]

The basic process leading to the neutral gas breakdown and initial ionization is the oscillation of the electrons along the static magnetic field lines under the action of the <u>*non-homogeneous*</u> antenna-near $\tilde{E}_z$-field. An analysis of the parallel equation of motion for electrons in terms of the Mathieu equation [8] revealed that the electrons perform complex motions: linear fast oscillations under the action of the Lorentz force $F_{Lor} = (e/m_e)\left|\tilde{E}_z\right| exp(i\omega t)$ and non-linear slow motions under the action of the RF ponderomotive force $F_{pnd} = -(e^2/4m_e\omega^2)\nabla_z(\left|\tilde{E}_z\right|^2)$. The RF energy can be transferred to the electrons only through random collisions with gas molecules, atoms or ions. If the oscillation energy of the electrons exceeds the ionization potential for molecules $m_e v_{ez}^2/2 \geq \varepsilon_i$, gas ionization can proceed. This inequality provides a *lower limit* to the $\tilde{E}_z$-field required for neutral gas RF breakdown. The RF ponderomotive potential does not vanish near the antenna surface if the RF waves do not propagate in the torus. For the electrons, this potential may have two different effects: keep them trapped in the RF potential wells for many RF periods helping the ionization process or just repel them out from the antenna area preventing the ionization. The latter regime is typical for very high amplitude of the antenna RF field, when the *stability parameter* for the Mathieu equation $\varepsilon = e\tilde{E}_z/m_e\omega^2 L_z$ meets the condition for *unstable solutions* [8, 9]: $\varepsilon \geq 1/4 - 2\varepsilon^2$ or $\varepsilon > (\sqrt{3}-1)/4 \approx 0.183$. Here $L_z = 2\tilde{E}_z/(d\tilde{E}_z/dz)$ is the parallel length scale of the ponderomotive potential.

The stability threshold for the Mathieu equation

$$e\tilde{E}_z/m_e\omega^2 L_z \approx 0.183 \qquad (1)$$

may be considered as a more refined *upper limit* to the $\tilde{E}_z$-field above with which the concept of a "ponderomotive force" becomes broken. Thus, the neutral gas breakdown and initial ionization will be efficient when the electrons are trapped in the antenna RF potential wells for many periods and when the amplitude of the antenna electric field meets the boundary condition:

$$(\omega/e)(2m_e\varepsilon_i)^{1/2} \leq \tilde{E}_z(r) \leq 0.183 m_e\omega^2 L_z/e\,. \qquad (2)$$

It should be noted that the definition of the upper limit in terms of the Mathieu equation stability parameter (1) lowers the $\tilde{E}_z$-field threshold with a factor of ~5 compared to the alternative condition of balance between the ponderomotive and Lorentz forces, $F_{pnd}=F_{Lor}$ [4] and looks more correct having in mind that F_{pnd} is derived by means of a Taylor-expansion which is only valid for cases where $F_{pnd} \ll F_{Lor}$.

2.2. ANTENNA SAFETY CONSIDERATIONS AND ICWC OPERATIONAL WINDOWS

The major concern for ICRF antenna operation in plasma production mode is to prevent the occurrence of deleterious arcing events and plasma ignition inside the antenna box. Let's analyze the problem in terms of radial location of the boundary ignition condition (2). In the non-propagating case, the amplitude of $\tilde{E}_z$-field exponentially decays in the antenna-near region: $\tilde{E}_z(r) = \tilde{E}_z(0)exp(-k_z\Delta r)$. Here k_z represents the inverse decay-length of the near-field. The $\tilde{E}_z$-field pattern for 4-stap antenna as a function of the phase in the current straps is shown in Fig. 2.

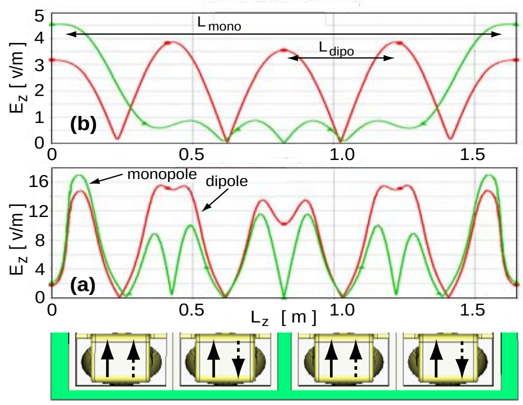

Fig.2. E_z-field pattern simulated with the MWS code for 4-strap antenna at r= 5 cm (a) and r=21 cm (b) from the current strap surface for monopole (green) and dipole (red) phasing, f=40 MHz, $P_{RF\text{-}input}$=1.0 W

It is clearly seen that operation of the 4-strap antenna in the monopole phasing enlarges toroidal size of the

antenna-near RF potential well compared to the dipole phasing. As a result, the $\tilde{E}_z$-field amplitude decays in the radial direction with larger decay-length.
The impact of this effect on formation of the gas breakdown region in the radial direction is illustrated for the JET A2 antenna in Fig. 3.

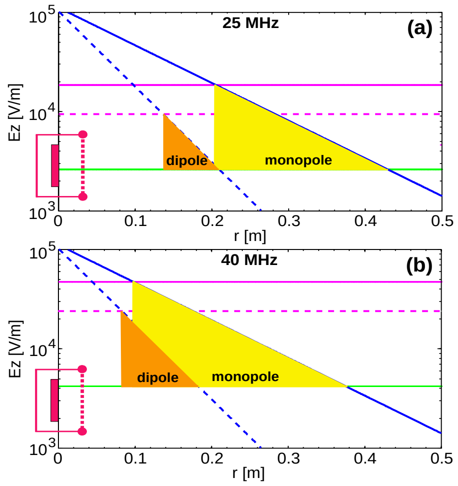

Fig.3. Boundary conditions for gas breakdown (He) in the radial direction for JET A2 antenna for monopole/dipole phasing at f=25 MHz (a) and f=40 MHz (b), both at at $V_{RF\text{-}ant}$*=10 kV*

Several features should be mentioned: (i) safe operation at both low (25 MHz) and high (40 MHz) frequencies may be possible: updated condition (2) indicates breakdown zone formation outside of the antenna box, (ii) the monopole phasing at any frequencies should be considered as a high priority operation regime: larger breakdown area (in the (E_z-r)-parameter space) is more remote from the antenna surface compared to the dipole phase, (iii) operation at lower frequency (25 MHz) may be beneficial: ignition area is more shifted away from the antenna box.

Taking into account (i) the ITER IO request to demonstrate the ICWC feasibility in conditions similar to the ITER full field operation (B_T=5.3 T and 40–55 MHz frequency band for the ITER ICRF system) and (ii) the JET safety aspects and operational constraints, the following JET operational window for ICWC has been elaborated and successfully tested.

1. $25MHz/3.3T\big|_{JET} \approx 40MHz/5.3T\big|_{ITER}$ for on-axis resonance condition $\omega=\omega_{cD+}$. The selected frequency f=25 MHz satisfied also the safety aspects of the A2 antenna operation: (i) shifted the ignition area far away from the antenna box (Fig.3) and (ii) allowed to avoid low voltage arcing at the vacuum transmission line (VTL) bellows.
2. The main transmission line (MTL) RF voltage was limited to 20 kV.
3. In order to be sure that the RF generator can register arcs, the RF power was applied to vacuum before the gas was injected.
4. To avoid antenna cross-coupling, we operated 2 of the four JET A2 antennas (C and D) at mixed frequencies (f_{A2C}=26.06 MHz, f_{A2D}=25.21 MHz) but not at mixed phasing. The highest priority phasings for the antenna straps were *monopole* (0000) and *super-dipole* (00ππ).
5. Working gas was ^4He and D_2 injected simultaneously or independently. This was allowed only at pressures up to 2×10^{-5} mbar to avoid arcing inside the antenna box and vacuum transmission line (VTL).
6. To extend the RF conditioning plasma in vertical direction and push it down towards the divertor area [10], an additional vertical magnetic field B_V between 3 and 30 mT in the "barrel" shaped configuration was also applied.

2.3. ANTENNA COUPLING TO LOW DENSITY ICWC PLASMAS

After the first (gas local breakdown) phase of the RF discharge, as soon as ω_{pe} becomes of the order of ω (it occurs at a very low density ~ $(5\times10^{12})\ldots(5\times10^{13})$ 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 (plasma phase). Because of the very low plasma temperature during the ionization phase (T_e~3…5 eV [1]), the RF power is expected to be dissipated mostly collisionally either directly or through conversion to ion Bernstein waves (IBW) if $\omega > \omega_{ci}$ or by conversion at the Alfvén resonance if $\omega < \omega_{ci}$. Such a non-resonant coupling allows RF plasma production at any B_T.
The described plasma production scheme is aimed on performance of a sustained ICWC discharge and assumes that ICRF antenna couples the RF power to plasma with high enough efficiency during all phases of the discharge. Here we define the antenna-plasma coupling efficiency as a fraction of the generator power coupled to the plasma, $\eta = P_{RF-pl}/P_{RF-G}$. 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). 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 (η_0~0.2…0.3) to the low density RF plasmas n_e~$10^{16}\ldots10^{17}$ m^{-3}, at which FW is typically non-propagating [11]. The present-day solutions for ICRF antenna enhanced coupling in the ICWC mode are based on the development of scenarios with *FW close to propagation or propagating* in low density plasmas [7]: (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 $\omega \approx 10\omega_{ci}$. It should be noted that the density threshold for the FW excitation is determined by the LFS cut-off for FW ($\kappa^2_{\perp_{FW}} = 0, \omega > \omega_{ci}$) [12]:

$$\omega_{pi}^2 = \left(\frac{\kappa_z^2 c^2}{\omega^2} - 1\right)\left(1 + \frac{\omega}{\omega_{ci}}\right)\omega_{ci}^2 . \qquad (3)$$

For the case of JET A2 antenna (f=25 MHz, B_T=3.3 T, deuterium), it results in a dramatic reduction (about two orders) in the threshold density for FW excitation on changing the phase between RF current in the antenna straps from *dipole* to *monopole* (Fig. 4). The recent ICWC experiments have clearly demonstrated that indeed antenna coupling efficiency strongly increased with monopole phasing ($\eta/\eta_0 \approx 3$) at which FW excitation was possible (Fig.4).

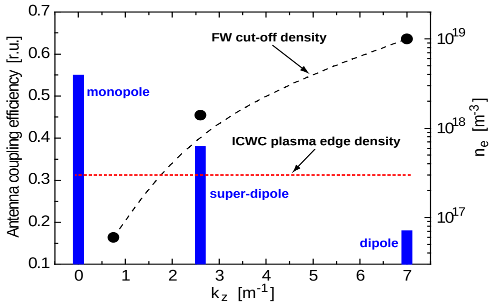

Fig.4. JET A2 antenna coupling to low density ($n_e(0) \approx 1.5\times10^{17}$ m^{-3}) RF plasmas as a function of antenna phasing and threshold density for FW excitation (f=25 MHz, deuterium, B_T=3.3 T)

3. ICWC PLASMA PERFORMANCE AND OPTIMIZATION OF WALL CONDITIONING OUTPUT

By operating the JET A2 antennas in plasma production mode in the MC scenario [7] at the monopole phase we obtained reliable ignition of the working gas (D_2, He or their mixtures) and ICWC discharge formation with improved homogeneity ($\bar{n}_e \approx (1\text{-}3)\times10^{17}$ m^{-3}) in conditions relevant to ITER full field, i.e. on-axis resonance $\omega = \omega_{cD^+}$ (Fig. 5). It is clearly seen from the FIR interferometer signals that RF plasma was detected in all interferometer channels, showing that the created RF plasma was present through the total cross-section of the vessel, from LFS (antenna side, channels 4-3) towards HFS (channels 2-1).

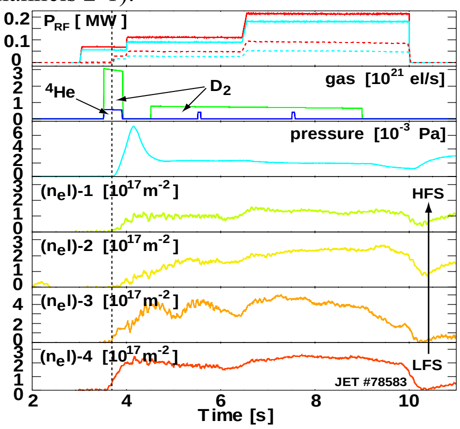

Fig.5. Typical performance of ICWC discharge in JET with two A2 antennas operated in monopole phasing in conditions similar to ITER full field: f=25 MHz, $P_{RF\text{-}G\text{-}max} \approx 400$ kW, $\eta \approx 0.6$, B_T= 3.3 T, p_{tot}=2×10^{-3} Pa, gas composition - D_2 : He ≈0.85 : 0.15

The conditioning output was studied by measuring the overall outgassing rate of several *marker gases* using mass spectrometry, spectroscopy in the main vessel and optical penning gauges in the divertor. We define the outgassing rate of given species as the quantity [7]:

$$Q_{RR}(t) \sim V(dp/dt) + p\cdot s + V(k_d + k_i)pn_e\,. \quad (4)$$

Here V is the volume, p and s are the partial pressure of the given mass and its pumping speed, respectively, k_d and k_i are the dissociation and ionization rates and n_e is the electron density. The pressure and RF coupled power were adjusted to optimize the efficiency of D_2-ICWC discharges for fuel removal by isotopic (D-H) exchange. The best conditions to maximize the ratio between outpumping (H) and retention (D) atoms without lowering the H release were found to be high coupled power (~ 250 kW) achieved with the monopole phasing for both antennas and low pressure (≈ 2×10^{-3} Pa). The efficiency for fuel removal by isotopic exchange was assessed using the following procedure: two hours H_2-GDC was operated to preload the walls with ≈ 4×10^{23} H-atoms, after which the JET cryopumps were regenerated. Then, 8 identical D_2-ICWC discharges (p = 2×10^{-3} Pa, B_T = 3.3 T, B_V = 30 mT, 9 s duration) have been repeated, the cryopumps were again regenerated and the gas released from the regeneration of cryopumps was analyzed by gas chromatography [13]. The evolution of the isotopic ratio is given on Figure 6 as a function of the cumulated ICWC discharge time. A noticeable increase of the isotopic ratio D/(D+H) between 40% and 60% in a cumulated discharge time of 72 s was achieved in the main vessel and in the divertor chamber. The following averaged isotope exchange efficiency was achieved: $H_{autgassed}/D_{implanted} \approx 1/3$.

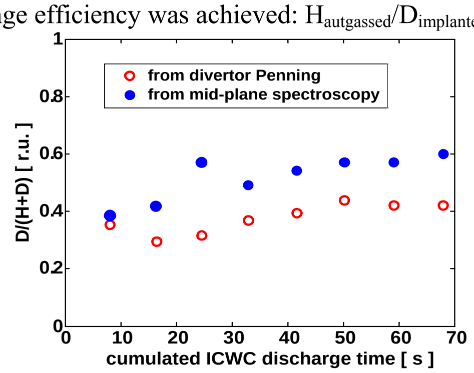

Fig.6. Isotopic ratio as measured by optical penning gauges in the divertor and from midplane spectroscopy as a function of the cumulated D_2 ICWC discharge time in JET [13]

4. ICWC EXTRAPOLATION TO ITER

As was mentioned in Section 2, the electromagnetic waves can not propagate along the vacuum vessel in the present-day tokamaks or stellarators in the typical ICRF band (~20…60 MHz) due to small cross-section size. It results in locally occurring neutral gas breakdown and initial ionization at the antenna-near $\tilde{E}_z$ -field.

Modeling of the electromagnetic wave propagation in ITER-like D-shaped vacuum vessel was undertaken with the 3-D MWS code. The eigenmode solver predicts that a threshold frequency for the propagation and eigenmode formation of the E-wave (containing $\tilde{E}_z$ -field in the direction of propagation) are within the frequency range ≈43…44 MHz. Remarkably, the found frequencies suit well to the settled frequency band for the ITER ICRF H&CD system. Further analysis showed that the predicted frequency for continuous field distribution (f=42.9807 MHz, Fig.7) corresponds to a threshold frequency of the E_{010}-mode propagation along the cylindrical waveguide [14]: $f_{c-E_{010}}(\text{MHz}) = 114.7/r_{w-eff}(\text{m})$. Here r_{w-eff} is the effective radius of a circle with the area equivalent to the given D-shaped cross-section: $r_{w-eff} \approx 0.91\sqrt{r_v r_h}$, where

r_v ≈3.94 m and r_h ≈2.2 m are the ITER vessel vertical and horizontal radii, respectively. The discovered effect indicates that the gas breakdown and initial ionization may occur in the ITER vessel simultaneously over the torus if ICRF H&CD system is tuned to torus eigenfrequncies, thus facilitating and making safer the operation of ITER antenna in the ICWC mode.

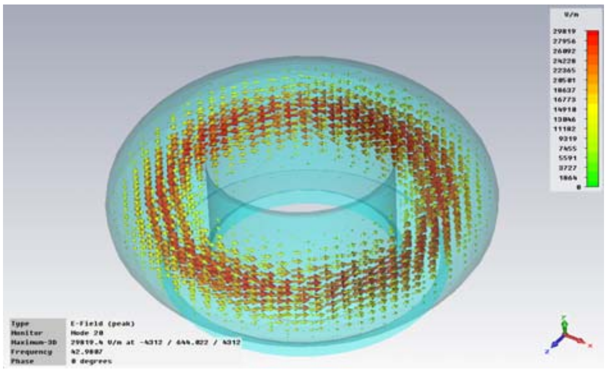

Fig.7. 3-D MWS eigenmode solver: E_z-field distribution along the torus in ITER-like vacuum vessel at a cut-off frequency for the E_{010}-mode propagation (f_{E010}=42.98 MHz, all eigenmode solutions are normalized to 1 Joule total stored energy)

An 0-D plasma code [15] was used to simulate a scale of the RF power necessary to produce and sustain ICWC hydrogen/deuterium plasmas in ITER-size machine ($\overline{a}_{pl}$ ≈2.4 m, R_0=6.2 m) in the presence of B_T=5.3 T in the pressure range $p \approx (2…8)\times10^{-2}$ Pa. The code predicts that RF plasmas with density of $n_e \approx (1…5)\times10^{17}$ m^{-3}, temperature $T_e \approx$ 1…2 eV and ionization degree γ_i≈0.05…0.10 can be produced with the RF power coupled to the electrons in the range $P_{pl\text{-}ITER}$≈ 0.3…1.5 MW depending on the gas pressure. Assuming an "optimistic" antenna coupling efficiency η≥0.5 at the monopole-phasing, this corresponds to the generator power range $P_{G\text{-}ITER}$ ≈ 0.6…3.0 MW. The empirical direct extrapolation from the TEXTOR and JET ICWC data (coupled power $P_{pl\text{-}TEXTOR}$≈12…30 kW, $P_{pl\text{-}JET}$≈230 kW, similar power density scaling and antenna coupling) gives a power of $P_{pl\text{-}ITER}$≈1…2 MW and $P_{G\text{-}ITER}$≈2…4 MW, respectively.

The TOMCAT 1-D RF code [16] predicts that a more homogeneous power absorption by the electrons over the ITER vessel may be achieved in the MC scenario at intermediate B_T=3.6 T with two different frequencies (f_1=40 MHz and f_2=48 MHz) and low k_z-spectrum (π/3-, π/6- or monopole-phasing between the RF currents in the toroidally adjacent antenna modules). Performance of the MC scenario at half-field (B_T=2.65 T) or at full field (B_T=5.3 T) may result in less homogeneous ICWC discharge. However, plasma production with the antenna phased to low k_z-spectrum of the radiated RF power looks beneficial: (i) FW is already propagating in low density plasmas; (ii) better antenna coupling is foreseen; (iii) larger fraction of the coupled RF power may be transported to the antenna distant (>2 m) mode conversion layer.

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МОДЕЛИРОВАНИЕ НА JETе СЦЕНАРИЕВ ВЧ-ЧИСТКИ ДЛЯ РЕАКТОРА ITER

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Обнадёживающие результаты по альтернативной ионно-циклотронной (ИЦ) чистке поверхностей вакуумной камеры, полученные недавно на современных токамаках и стеллараторах, выдвинули этот метод в число наиболее вероятных технологий, планирующихся использовать в ITERе между импульсами в присутствии постоянного сильного тороидального магнитно поля. В настоящей работе представлены результаты исследований ВЧ-разряда и его оптимизаци по усилению эффекта чистки в крупнейшем из ныне действующих токамаке JET с использованием стандартных ИЦ А2 антенн. Эксперименты по ВЧ-чистке на JETе были осуществлены в режиме, моделирующем сценарий ИЦ-разряда в токамаке-реакторе ITER, при работе на полном магнитном поле B_T=5.3 T и при расположении фундаментального ИЦ-резонанса для дейтерия $\omega=\omega_{cD+}$ в центре вакуумной камеры. Перспективы применения альтернативной ВЧ-чистки в ITERе анализируются с помощью численных кодов: 3-D MWS- электромагнитного кода, 1-D ВЧ-кода и 0-D плазменного кода.

МОДЕЛЮВАННЯ НА JETі СЦЕНАРІЇВ ВЧ-ЧИСТКИ ДЛЯ РЕАКТОРА ITER

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Обнадійливі результати з альтернативної іонної циклотронної (ІЦ) чистки поверхонь вакуумної камери, отримані останнім часом в сучасних токамаках і стелараторах, висунули цей метод до числа найбільш вірогідних технологій, які планується використовувати в ITERі між імпульсами в присутності постійного сильного тороїдального магнітного поля. В роботі представлено результати дослідження ВЧ-розряду та його оптимізації щодо підсилення ефекту чистки в найбільшому з нині діючих токамаці JET з використанням стандартних ІЦ А2 антен. Експерименти по ВЧ-чищенню на JETі були здійснені в режимі, що моделює сценарій ІЦ-розряду в токамаці-реакторі ITER, при роботі на повному магнітному полі B_T=5.3 T та при розміщенні фундаментального ІЦ-резонансу для дейтерію $\omega=\omega_{cD+}$ в центрі вакуумної камери. Перспективи застосування альтернативної ВЧ-чистки в ITERі аналізуються за допомогою числових кодів: 3-D MWS- електромагнітного коду, 1-D ВЧ-коду і 0-D плазмового коду.