ICRF PLASMAS FOR FUSION REACTOR APPLICATIONS

A. Lyssoivan[1], R. Koch[1], D. Van Eester[1], M. Van Schoor[1], G. Van Wassenhove[1], M. Vervier[1], R. Weynants[1], J. Buermans[2], T. Matthys[2], H.G. Esser[3], O. Marchuk[3], O. Neubauer[3], V. Philipps[3], G. Sergienko[3], V. Bobkov[4], H.-U. Fahrbach[4], D.A. Hartmann[4], A. Herrmann[4], J.-M. Noterdaeme[4,5], V. Rohde[4], B. Beaumont[6], E. Gauthier[6], G.P. Glazunov[7], A.V. Lozin[7], V.E. Moiseenko[7], N.I. Nazarov[7†], O.M. Shvets[7], K.N. Stepanov[7], E.D. Volkov[7], I.L. Beigman[8], L.A. Vainshtein[8], TEXTOR Team, ASDEX Upgrade Team, TORE SUPRA Team and U-3M Team

[1] LPP-ERM/KMS, Association EURATOM-BELGIAN STATE, 1000 Brussels, Belgium[*];
[2] Royal Military Academy, ERM/KMS, 1000 Brussels, Belgium;
[3] Institut für Plasmaphysik FZ Jülich, EURATOM Association, D-52425 Jülich, Germany[*];
[4] Max-Planck Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany;
[5] Gent University, EESA Department, B-9000 Gent, Belgium;
[6] Association EURATOM-CEA, CEA Cadarache, 13108 St Paul lez Durance, France;
[7] Institute of Plasma Physics, NSC KIPT, 61108 Kharkov, Ukraine;
[8] P.N.Lebedev Physical Institute of Russian Academy of Sciencies, 119991 Moscow, Russia

The ICRF plasma production technique is considered as a promising alternative tool for the following applications in the present and next generation *superconducting* fusion devices: (i) Wall conditioning in the presence of permanent high magnetic field; (ii) Assistance for the tokamak start-up at low inductive electric field (E_0 ~ 0.3 V/m in ITER); (iii) Target dense plasma production ($n_e \geq 10^{19}$ m^{-3}) in stellarators. The paper presents a review of the ICRF plasma production technique and its applications in the present-day tokamaks and stellarators. The perspective of the alternative technique applications in ITER is analyzed in the frame of 0-D plasma modeling.

PACS: 52.25.Jm, 52.35.Hr, 52.40.Fd, 52.40.Hf, 52.50.Qt

1. INTRODUCTION

The plasma production technique based on absorption of the radio-frequency power in the Ion Cyclotron Range of Frequencies (ICRF) is becoming an indispensable tool for present and next generation *superconducting* fusion devices because of its high potential for solving several basic problems of reactor oriented machines:

- Wall conditioning (tritium retention, surface isotope exchange, wall cleaning/coating) with ICRF plasmas in the presence of permanent high magnetic field in stellarators [1,2] and tokamaks [3].
- Assistance with the ICRF pre-ionization for the tokamak start-up at low inductive electric field ($E_0 \approx$ 0.3 V/m in ITER) [4].
- Target dense RF plasma production ($n_e \geq 10^{19}$ m^{-3}) in the stellarators [5,6].

The paper presents a review of the alternative ICRF plasma production technique developed earlier for routine use in the stellarators [5] and successfully adapted later for the tokamak applications. The concept of the ICRF plasma production based on absorption of the RF power mainly by the electrons via collisions is described. The main plasma parameters achieved in different scenarios are characterized and compared with those predicted by newly developed 0-D Plasma code [7]. The crucial effect of the RF power deposition to the *electrons* in the plasma core on build-up of the target dense (~10^{19} m^{-3}) plasmas in stellarators and on performance of more homogeneous conditioning plasmas (<10^{18} m^{-3}) in large-size divertor tokamaks was predicted numerically and successfully demonstrated in the experiments [8,9]. The main results on ICRF discharge conditioning (ICRF-DC) achieved in the present fusion machines in the gas mixtures of ($He+H_2$), (D_2+H_2), ($He+O_2$), and (H_2+N_2) are analyzed in terms of the gas species removal rate. The results on ICRF assisted tokamak start-up (TEXTOR) are presented and compared with the non-assisted start-up. The antenna ability to produce target dense plasma in stellarator (U-3M) is analyzed in terms of the plasma production rate.

Finally, we discuss a perspective on the feasible applications of the new technique in ITER for wall conditioning in between shots and for tokamak start-up assistance.

2. BASIC PRINCIPLES OF ICRF PLASMA PRODUCTION

The initiation of ICRF discharge in a toroidal magnetic field B_T results from the absorption of RF energy mainly by electrons [10,11]. The RF $\tilde{E}_z$-field (parallel to the B_T-field) is considered to be responsible for this process. However, the electromagnetic waves in the typical ICRF band (~10–100 MHz) cannot propagate in vacuum in the present-size fusion devices [12]. Therefore, the neutral gas breakdown and initial ionization may only occur locally at the antenna-near $\tilde{E}_z$-field (evanescent in vacuum). Analytical study and 3D simulations show that, in general case, ICRF antenna can generate the RF $\tilde{E}_z$-field in vacuum *inductively* and/or *electrostatically* [11]. Further analysis of the parallel equation of motion of the electrons revealed that the neutral gas breakdown and initial ionization will be efficient when the electrons will be trapped in the antenna RF potential wells for many periods and the amplitude of the antenna electric field will meet the boundary condition [10]:

$$(\omega/e)(2m_e\varepsilon_i)^{1/2} \leq \tilde{E}_z(r) \leq 0.2m_e\omega^2 L_z/e\,. \qquad (1)$$

Here $L_z = 2\tilde{E}_z/(d\tilde{E}_z/dz)$ is the parallel length scale of the ponderomotive potential.

As soon as the electron plasma frequency ω_{pe} becomes of the order of ω (it occurs at a very low density ~10^{12}–10^{14} m^{-3} in the frequency range 10–100 MHz), plasma waves can start propagating in a relay-race regime governed by the antenna κ_z-spectrum, causing further

[*]Partners in the Trilateral Euregio Cluster (TEC)

Problems of Atomic Science and Technology. 2007, № 1. Series: Plasma Physics (13), p. 30-34

space ionization of the neutral gas and plasma build-up in the torus. Because of the very low plasma temperature during the ionization phase (T_e~2–5 eV [3,11]), 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 (AR) if $\omega < \omega_{ci}$. *Such a non-resonant coupling allows RF plasma production at any* B_T.

3. ICRF PLASMA CHARACTERIZATION

3.1. NEUTRAL GAS BREAKDOWN

On applying RF voltage/power at the antenna straps, the neutral gas breakdown occurs after some time-delay characterized by the breakdown time t_{bd} [9].

Data for the neutral gas breakdown time obtained from the RF discharges with similar RF power per strap (30–50 kW) and frequency (~30 MHz) were found in a good agreement for three European tokamaks TEXTOR, JET and AUG in the measured gas pressure range (Fig.1).

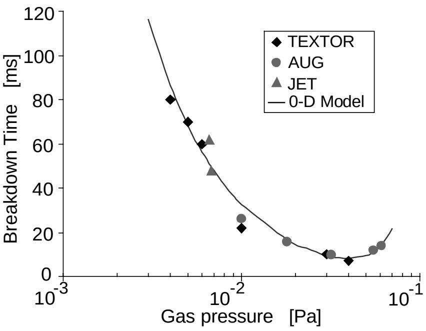

Fig.1. Pressure dependence of the RF breakdown time as derived from the H_α emission analysis ($P_{RF/Ant.strap}$≈30–50 kW, f≈30 MHz, $\omega=4\omega_{cHe+}=2\omega_{cD}=\omega_{cH}$) and compared with 0-D modeling

Further analysis of the neutral gas breakdown phase was performed with a recently developed 0-D Plasma code [7], which solved numerically a set of differential particle and energy balance equations for the atoms, electrons and ions. The following atomic reactions with the updated reaction rates have been considered: electron collisional excitation and ionization of the atoms, radiative, dielectronic and three-body recombination and charge-exchange recombination. The predicted gas breakdown time, t_{bd}, derived from the balance of the power losses between the electron impact ionization and the electron-ion Coulomb collisions was found in an agreement with the experimental data (Fig.1). It might be an indication that:

- Collisional ionization by the electrons is the principal mechanism of gas ionization in the ICRF band;
- For the fixed RF power density (antenna $\tilde{E}_z$-field), the breakdown time is independent on the machine size;
- Plasma waves contribute to the gas ionization in torus starting from the breakdown phase, at which the condition $\omega_{pe} > \omega$ is already fulfilled.

3.2. ICRF PLASMA BUILD-UP

The plasma production process has been studied on TEXTOR under various conditions as summarized in Fig.2. Helium ICRF plasmas with central line averaged density (n_{e0} ≈5×10^{16}–3×10^{18} m^{-3}) were reliably produced in a wide range of the toroidal magnetic field B_T≈ 0.20–2.24 T ($2\omega_{ci} \le \omega \le 20\omega_{ci}$) and gas pressure (~$10^{-3}$–$10^{-1}$ Pa) without changing the RF generator frequency (f=32.5 MHz). The RF plasma density was proportional to the injected RF power (a sign of weakly ionized plasma) and increased with the torus pressure. The ionization degree roughly estimated from the averaged density/pressure measurements was found to be rather low, $\gamma_i=n_e/(n_e+n_0)<0.1$.

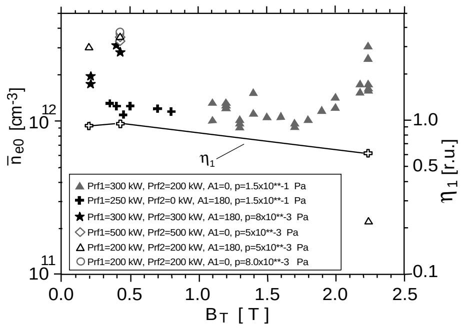

Fig.2. B_T-dependence of the central line-averaged density of the He-plasmas (symbols) and the coupling efficiency of the A1-antenna (solid line) at different gas pressure, RF power and antenna phasing

Analysis of the exterior D_α line-integrated emission measured in different sections of the torus vessel showed that the distribution of ICRF plasmas in the toroidal direction was uniform. The electron temperature (deduced from the spectroscopic and electric probe measurements) varied in the range 3-30 eV, increasing in the low gas pressure case [11] or in the presence of FW-IBW mode conversion [9]. For the latter case, 1-D RF code [13] predicts an enlargement of the RF power fraction absorbed by the electrons from 34 to 64 % on increasing the H^+-concentration in the ($He+H_2$)-plasmas from 2 to 10% [14]. The promising mode conversion scenario performed at two different frequencies (30 and 36.5 MHz) was used later during the ICRF wall conditioning experiments in ASDEX Upgrade (AUG) for further plasma extension towards HFS (Fig.3).

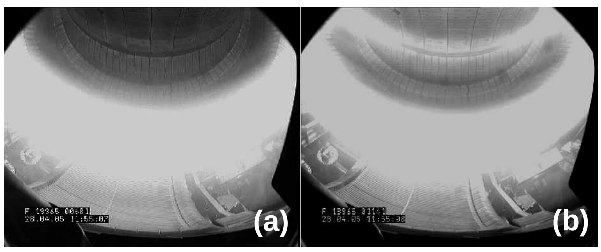

Fig.3. The CCD top view of ICRF plasmas produced in AUG at f=30 MHz (a) and at f=36.5 MHz (b) under the similar other conditions: P_{RF-pl}≈50 kW, B_T=2.4 T, gas mixture $H_2/(He+H_2)$~0.1-0.3, p≈4×10^{-2} Pa

3.3. ANTENNA-PLASMA LOADING

The antenna-plasma coupling efficiency is defined as a fraction of generator power coupled by the plasma, $\eta=P_{RF-pl}/P_{RF-G}$ [9]. For the standard ICRH antenna, this factor becomes rather low (η_0≈20–40%) in the regime of low-density (n_e~10^{17} m^{-3}) helium ICRF plasma in contrast to the heating scenarios applied for target dense plasmas (η≥90% at $n_e>10^{19}$ m^{-3}). Such difference is caused by the antenna polarization. The standard antenna is optimized to couple the RF power efficiently to fast wave (FW), which propagates usually in the high-density plasmas only. To achieve an improved coupling efficiency η_1 of the standard ICRF antenna during low-density RF plasma production, several recipes have been found and successfully tested:

- Lower B_T or higher frequency operation ($\eta_1/\eta_0 \approx 1.6–2.0$) [11,15];
- ECRF pre-ionization/assistance for the ICRF plasma production ($\eta_1/\eta_0 \approx 1.4$) [16];
- Mode conversion in plasmas with two ion species ($\eta_1/\eta_0 \approx 2.0–3.0$) [15];
- Antenna “magnetic tilting” towards $B_{tot}=B_T+B_V$ by superposing an additional vertical magnetic field $B_V<<B_T$ ($\eta_1/\eta_0 \approx 1.2$) [17].

3.4. GENERATION OF HIGH-ENERGY *H* AND *D* ATOMS

All ICRF-DC experiments performed until now reported on the generation of high-energetic fluxes of *H* (with energies up to 60 keV) and of *D* atoms (up to 25 keV) detected by a neutral particle analyzer in deuterium or helium RF plasmas [3]. Detailed study of the phenomenon revealed that *ion cyclotron absorption mechanism* plays a fundamental role in the generation of the high-energy H and D atoms:

- Intensity of the locally collected flux of CX neutrals strongly correlated with the position of the $\omega=\omega_{cH}=2\omega_{cD}$ layer in the plasma cross-section [11];
- Heating at the first cyclotron harmonic ($\omega=2\omega_{ci}$) creates tail in the H-atom spectra at higher energy than fundamental heating, in line with the fast particle distributions caused by RF quasilinear diffusion [18].

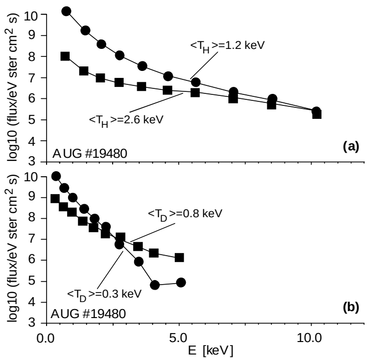

Fig.4. Hydrogen (a) and Deuterium (b) atom spectra observed with NPA in He-plasmas (squares) and in ($He+H_2$)-plasmas (circles) ($P_{RF} \approx 60$ kW, f=30 MHz, $p \approx 4.0\times10^{-2}$ Pa, $B_T=2.4$ T)

Figure 4 shows typical *H* and *D* atoms spectra observed in the AUG ICRF discharge in pure He (a) and in ($He+H_2$)-plasmas when the Ion Cyclotron Resonances (ICR), $\omega=4\omega_{cHe+}=2\omega_{cD}=\omega_{cH}$ were present in the plasma cross-section. (Minor concentrations of the protons/deuterons in helium plasmas were present due to hydrogen/deuterium outgassing from the walls.) It is clearly seen that increasing the H_2/He-ratio (from 0 to ≈0.2) causes the decrease in the averaged energy of both, H and D atoms. The phenomenon observed in the ICRF plasmas was predicted from modeling of the power deposition profiles for plasma species of variable concentrations using the TOMCAT code [13] and looks similar to the well-known transition in plasma heating scenarios from dominant ion cyclotron heating of the minority ions to heating of the electrons via mode conversion process when concentration of the minority ions goes up.

4. ICRF WALL CONDITIONING

In future reactor-scale *superconducting* fusion devices such as ITER, the presence of permanent high magnetic field will prevent the use of conventional *Glow Discharge Conditioning* (G-DC) in between shots due to a short-circuit occurring between anode and cathode along the magnetic field lines. The need of controlled and reproducible plasma start-up and tritium removal, e.g. from the co-deposited carbon layers, will require applying an *alternative* wall conditioning technique compatible with the presence of magnetic field.

4.1. WALL CONDITIONING IN THE PRESENT-DAY MACHINES

ICRF Discharge Conditioning (ICRF-DC) was initially developed in stellarators [1] and successfully applied in tokamaks later [3] using the present generation ICRF antennas without any modifications in hardware.

The discharge conditioning is attributed to the removal of adsorbed gas species from the wall so that they may then be pumped out of the system. The adsorbed atoms may be removed by electronic excitation, chemical interaction and momentum/energy transfer [19]. For the latter mechanism, the rate of desorption increases with the impact energy of the ions and their masses [20]. ICRF discharges generate high-energetic fluxes of ions and neutrals due to presence of cyclotron mechanism (Fig.4) and may be considered promising for wall conditioning.

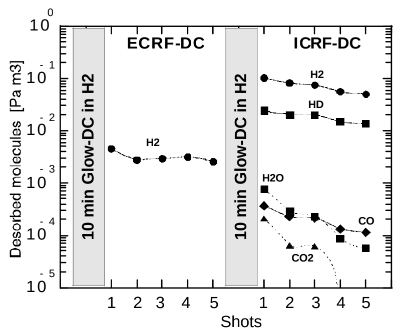

Fig.5. Desorption of the gas species after a set of helium ECRF-DC and ICRF-DC in TEXTOR: $P_{ECRF}=150$ kW, f=110 GHz, $P_{ICRF}=60$ kW, f=32.5 MHz, $B_T=2.0$ T, $p_{He} \approx 2.5\times10^{-2}$ Pa

Very optimistic results with ICRF-DC were achieved in the limiter tokamaks. The hydrogen removal rate in the resonance condition $\omega=\omega_{cH}=4\omega_{cHe+}$ was found to be about 10-20 times higher than in the typical G-DC [3] and about 20 times higher than in the ECRF-DC ($\omega=2\omega_{ce}$) produced by a focused microwave beam [3]. In the latter case (Fig.5), better homogeneity of the ICRF discharge and generation of the energetic neutrals bombarding the wall could contribute to the achieved result.

The oxidation of amorphous tritiated carbon layers by plasma-assisted technique is considered as one of the most promising techniques to solve the problem of tritium retention in fusion reactor [21]. A set of successful experiments on O-treatment with ICRF discharges in the ($He+O_2$)-mixtures or in pure oxygen has recently been performed on tokamaks HT-7 [22] and TEXTOR [14]. Compared to ICRF-DC in He, the ICRF oxidation demonstrated a higher removal rate for the C-atoms by a factor of 20 and for the H-atoms by a factor of six [22]. However, post-oxidation wall cleaning (consequence of the residual O-retention) and inevitable phase of the tokamak recovery to the normal plasma operation (accompanied by contamination caused disruptions) look at the moment as time consuming and painful procedures: from ten to several tens disruptive shots are needed for tokamak recovery [14,22].

The encouraging result with ICRF-DC in (N_2+H_2)-mixture has recently been obtained in the URAGAN-3M (U-3M) stellarator [23]: surprisingly high removal rate of hydrogen. This effect was explained by increased interactions of the adsorbed hydrogen with neutrals and different radicals like NH(NH^+), NH_2(NH_2^+) produced in the (N_2+H_2)-plasmas. Chemical erosion of the C containing amorphous a-C: H films with the nitride ions followed by the formation of volatile hydrocarbons could be another probable mechanism responsible for the enhanced hydrogen removal [24].

4.2. MODELING OF ICRF CONDITIONING PLASMAS IN *ITER*

The simulation of hydrogen conditioning plasmas with the low T_e≈1 eV and ionization degree (1.0–16%) was done for the ITER-like case ($\overline{a}_{pl}$ ≈2.6 m, R_0=6.2 m, B_T=5.3 T) using recently developed 0-D plasma code based on the electron collisional ionization with the updated reaction rates [7]. Two extreme cases with the low power-per-particle, $P/N \approx 13\,\mathrm{kW/(Pa\cdot m^3)}$, and the high power-per-particle, $P/N \approx 200\,\mathrm{kW/(Pa\cdot m^3)}$, have been analyzed.

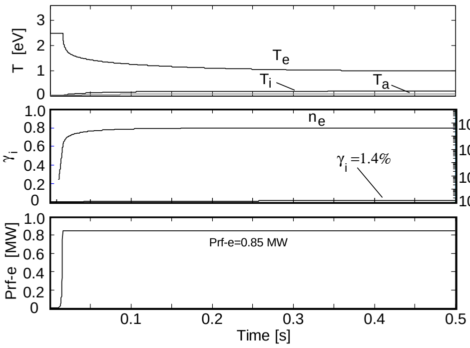

Fig.6. 0-D simulation of the hydrogen conditioning plasma in ITER for the low power-per-particle case (P/N~13 kW/(Pa·m³)

In the first case (Fig.6), the code predicts that weakly ionized (γ_i ≈1.4%) low temperature (T_e≈1 eV) and low density (n_e≈4×10^{11} cm^{-3}) plasma may be produced in ITER-size machines coupling relatively low power with the electrons ($P_{RF\text{-}e}$≈850 kW). Assuming that coupling efficiency of the ICRF system is about 50%, a relatively low power at the RF generator ($P_{RF\text{-}G}$≈1.7 MW) will be necessary. This regime may be achieved operating at high gas pressures (p_{H2}≈8×10^{-2} Pa) and looks reasonable for the starting phase of wall conditioning. The second simulated regime with T_e≈1.4 eV may be achieved at the reduced gas pressure (p_{H2}≈2×10^{-2} Pa) and the increased RF power ($P_{RF\text{-}e}$≈3.4 MW, $P_{RF\text{-}G}$≈6.8 MW) and is characterized by the increased ionization degree, γ_i ≈16%. The RF power predicted for this regime was found in a good agreement with direct extrapolation to ITER from TEXTOR data assuming similar power density ($P_{RF\text{-}pl(TEXTOR)}$ ≈ 50 kW à $P_{RF\text{-}pl(ITER)}$ ≈ 3.5 MW). Wall conditioning at P_{RF}/N>200 kW/(Pa·m^{-3}) may become economically disadvantageous ($P_{RF\text{-}G}$>10 MW) and inefficient for pumping out the adsorbed gas species (γ_i>>16%).

5. ICRF ASSISTED TOKAMAK START-UP

For the present ITER start-up scenario, the inductive electric field is limited to E_0≈0.3 V/m, to prevent a quench in the superconducting coils. Therefore, to perform the tokamak start-up at E_0≈0.3 V/m in a safe, prompt and reliable manner, non-inductive pre-ionization, target plasma production and pre-heating are desirable.

5.1. *TEXTOR* START-UP WITH ICRF PRE-IONIZATION

ICRF-assisted tokamak start-up has successfully been tested on tokamaks TEXTOR and HT-7. In the case of TEXTOR [4,25], two pairs of the ICRF double-loop antennas without FS, driven in π phase, have been used in the standard 2ω_{ci} scenario to produce pre-heated RF plasmas prior applying the inductive electric field. The target helium RF plasma with density n_e≈(0.2–7.0)×10^{17} m^{-3} was reliably produced in the gas pressure range p≈(1.5–7.0)×10^{-3} Pa with the total RF power about 300 kW, applied to both antennas. ICRF-assisted start-up was achieved at the central inductive electric field $E_0 \approx 0.32$ V/m, which met the ITER requirements (Fig.7).

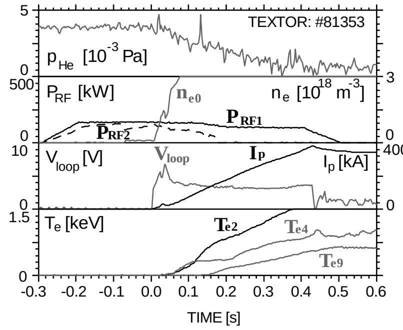

Fig.7. ICRF-assisted low loop voltage start-up in TEXTOR: B_T=2.25 T, p_{He}≈3.5×10^{-3} Pa. T_{e2}, T_{e4}, T_{e9} is resp. T_e(ECE) at R=1.75, 1.56, 2.08 m

Without assistance, start-up at E_0≈0.45 V/m was possible. ICRF-assisted start-up has been found to be more prompt and robust than a non-assisted one and has resulted in a significantly broader (about four times) pressure range for current initiation, with ≈22% higher current ramp-up rates.

5.2. MODELING OF ICRF PRE-IONIZATION IN *ITER*

The experiments performed on TEXTOR clear indicated that the assisted tokamak start-up at low inductive electric field (E_0≈0.32 V/m) could only be successful when the following requirements have simultaneously been achieved [25]:

- Low resistance of the target plasma, R_{pl} ≤0.4 mΩ;
- Low value of the compensated stray field, |B_V| ≤10 G;
- Low content of the low-Z impurities.

Considering the mentioned requirements, simulations with the 0-D Plasma code predicted that fully ionized hydrogen plasma with high enough temperature (T_e ≥60 eV) might be produced in ITER-like machine with the power coupled to the electrons less than 2 MW. However, presence of 3% C-impurity increased the needed power by ≈54%.

6. TARGET ICRF PLASMA PRODUCTION IN STELLARATORS

To operate in a current-free regime, fusion machines based on the stellarator concept usually use the non-inductive auxiliary heating systems for target plasma production. The plasma production technique in the ICRF band was originally developed to achieve this goal in Kharkov stellarators in the early 70th using Frame-Type antennas (FTA) [5].

The ability of antenna to produce plasma can be characterized by the parameter ρ $=R_{pl}/n_e$ (R_{pl} is the antenna-plasma loading resistance), which is proportional to the plasma production rate. The constancy of the parameter in time provides exponential growth of the plasma density with the same increment. Based on the ‘ρ=const’ concept, compact Three-Half-Turn (THT) and Crankshaft-like antennas were proposed for Alfvén Resonance plasma production and heating in U-3M [26] (Fig.8). Target dense plasmas have successfully been produced when the THT antenna sequentially operated with FTA [6] ($n_e \approx 2\times10^{19}$ m^{-3}) or when the Crankshaft antenna operated alone ($n_e \leq 1\times10^{19}$ m^{-3}) [8], in a good agreement with predictions from modeling [26]. Numerical optimization of the Crankshaft antenna for the RF plasma production in the U-2M stellarator is under progress using self-consistent modeling with 1-D Plasma and 1-D RF codes [27].

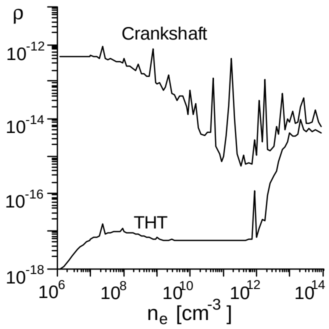

Fig.8. Calculated dependence of plasma production rate index ρ*=Rpl/ne vs. plasma density for U-3M Crankshaft and THT antennas*

REFERENCES

1. N.I. Nazarov et al.// *Sov. J. Plasma Phys*. 1987, v.13, p. 871-873.
2. R. Brakel et al.// *Journal of Nuclear Materials.* 2001, v. 290-293, p. 1160-1165.
3. E. de la Cal, E. Gauthier// *Plasma Phys. Control. Fusion.* 2005, v. 47, p. 197-218.
4. R. Koch et al.// *26th EPS Conf. Contr. Fusion and Plasma Phys.*, Maastricht, 1999/ ECA, 1999, v. 23J, p. 745-748.
5. O.M. Shvets et al.// *4th Int. Symp. on Heating in Toroidal Plasmas,* Roma, 1984/ ENEA, Frascati, 1984, v.1, p. 513-528.
6. A. Lyssoivan et al.// *Fusion Engineering and Design.* 1995, v. 26, p. 185-190.
7. J. Buermans and T. Matthys // *Diploma Thesis,* ERM/KMS, Brussels, 2006.
8. V.E. Moiseenko // *7th Int. Conf. on Plasma Phys. and Control. Fusion*, Alushta, 1998, Paper I-5.
9. A. Lyssoivan et al.// *Journal of Nuclear Materials.* 2005, v. 337-339, p. 456-460.
10. A.I. Lyssoivan et al.// *Nuclear Fusion.* 1992, v. 32, p. 1361-1372.
11. A. Lyssoivan et al.// *Final Report on ITER Design Task D350.2*. LPP-ERM/KMS Laboratory, Brussels, 1998, Report N114.
12. A. Lyssoivan et al.// *Problems of Atomic Sci. and Technol. Series “Plasma Physics”* (10). 2005, N 1, p. 44-48.
13. D. Van Eester, R. Koch// *Plasma Phys. Control. Fusion* . 1998, v. 40, p. 1949.
14. A. Lyssoivan et al.// *17th Int. Conf. Plasma Surface Interactions*, Hefei, 2006, Paper P2-72.
15. A. Lyssoivan et al.// *16th Topic. Conf. on Radio Frequency Power in Plasmas,* Park City, 2005/ AIP, 2005, v. 787, p. 445-448.
16. A. Lyssoivan et al.// *14th Topic. Conf. on Radio Frequency Power in Plasmas,* Oxnard, 2001/ AIP 2001, v. 595, p. 146-149.
17. A. Lyssoivan et al.// *26th EPS Conf. Contr. Fusion and Plasma Phys.*, Maastricht, 1999/ ECA, 1999, v. 23J, p. 737-740.
18. R. Koch // *Transactions of Fusion Science and Technology.* 2004, v. 45, p. 203.
19. P.C. Stangeby, G.M. McCracken// *Nuclear Fusion.* 1990, v. 30, p. 1225-1379.
20. J. Winter // *Plasma Phys. Control. Fusion.* 1996, v. 38, p. 1503-1542.
21. J. Davis, A.A. Haasz // *Phys. Scripta.* 2001, v.T91, p.33-35.
22. J.S. Hu et al.// *17th Int. Conf. Plasma Surface Interactions,* Hefei, 2006, Paper I-16.
23. G.P. Glazunov et al. // *Problems of Atomic Sci. and Technol. Series “Plasma Physics” (10).* 2005, N1, p.33-35.
24. V.S. Vojtsenya et al. // *Problems of Atomic Sci. and Technol. Series “Plasma Physics” (12).* 2006, N6, p.141.
25. R. Koch et al.// *16th Int. Conf. on FusionEnergy,* Montreal, 1996/ IAEA, 1997, v.1, p. 633-641.
26. V.E. Moiseenko et al.// *21st EPS Conf. on Contr. Fusion and Plasma Phys.,* Montpellier, 1994/ ECA, 1994, v.18B, p. 980-983.
27. V.E. Moiseenko et al.// *Problems of Atomic Sci. and Technol. Series “Plasma Physics” (12).* 2006, N 6, p. 62.

ПРИМЕНЕНИЕ ВЧ-ПЛАЗМЫ В ТЕРМОЯДЕРНОМ РЕАКТОРЕ

А. Лысойван, Р. Кош, Д. Ван Истер, М. Ван Скоор, Ж. Ван Вассенхов, М. Вервъе, Р. Вейнантс, И. Буэрманс, Т. Маттис, Х.Г. Эссер, О. Марчук, О. Нойбауэр, Ф. Филлипс, Г. Сергиенко, В. Бобков, Г.-У. Фарбах, Д.А. Хартманн, А. Херрманн, Ж.-М. Нотердам, Ф. Родэ, Б. Бомон, Э. Готье, Г.П. Глазунов, А.В. Лозин, В.Е. Моисеенко, Н.И. Назаров†, О.М. Швец, К.Н. Степанов, Е.Д. Волков, И.Л. Бейгман, Л.А. Вайнштейн, команды TEXTOR, ASDEX Upgrade, TORE SUPRA и U-3M

ВЧ-метод создания плазмы (ICRF) рассматривается как перспективный альтернативный инструмент для следующих применений в современных и будущих сверхпроводящих термоядерных установках: (i) ВЧ-чистка стенок в присутствии постоянного сильного магнитного поля; (ii) Ассистирование старту токамака в режиме слабого вихревого электрического поля (E_0 ~ 0.3 В/м в ITERe); (iii) Создание плотной исходной плазмы ($n_e \geq 10^{19}$ $м^{-3}$) в стеллараторах. Сделан обзор ВЧ-метода создания плазмы и его применений в современных токамаках и стеллараторах. В рамках моделирования 0-D плазменным кодом проведен анализ перспективности использования данного метода в ITERe.

ЗАСТОСУВАННЯ ВЧ-ПЛАЗМИ У ТЕРМОЯДЕРНОМУ РЕАКТОРІ

А. Лисойван, Р. Кош, Д. Ван Істер, М. Ван Скоор, Ж. Ван Вассенхов, М. Верв’є, Р. Вейнантс, І. Буерманс, Т. Маттіс, Х.Г. Ессер, О. Марчук, О. Нойбауер, Ф. Філліпс, Г. Сергієнко, В. Бобков, Г.-У. Фарбах, Д.А. Хартманн, А. Херрманн, Ж.-М. Нотердам, Ф. Роде, Б. Бомон, Е. Готьє, Г.П. Глазунов, О.В. Лозін, В.Є. Моісеєнко, М.І. Назаров†, О.М. Швець, К.М. Степанов, Є.Д. Волков, І.Л. Бейгман, Л.А. Вайнштейн, команди TEXTOR, ASDEX Upgrade, TORE SUPRA и U-3M

ВЧ-метод утворення плазми (ICRF) розглядається як перспективний альтернативний інструмент для таких застосувань у сучасних й майбутніх надпровідних термоядерних установках: (i) ВЧ-чистка стінок в присутності постійного сильного магнітного поля; (ii) Асистування старту токамака у режимі слабого вихрового електричного поля (E_0~ 0.3 В/м в ITERi); (iii) Створення густої вихідної плазми ($n_e \geq 10^{19}$ $м^{-3}$) в стелараторах. Зроблено огляд ВЧ-метода створення плазми та його застосування у сучасних токамаках й стелараторах. В рамках моделювання 0-D плазмовим кодом проведено аналіз перспективності використання даного метода в ITERi.