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 (\(E_\parallel \approx 0.3 \text{ V/m)}\) in ITER) [4].
• Target dense RF plasma production (\(n_e \geq 10^{19} \text{ m}^{-3}\)) 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 plasma core on build-up of the target dense (~10^{19} \text{ m}^{-3}) plasmas in stellarators and on performance of more homogeneous conditioning plasmas (~10^{18} \text{ 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\(_2\), D\(_2\), He\(_2\)), 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 \(E_\perp\)-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 \(E_\perp\)-field (evanescent in vacuum). Analytical study and 3D simulations show that, in general case, ICRF antenna can generate the RF \(E_\perp\)-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]:

\[
(\omega/e)(2m_e e_V)^{1/2} \leq E_{\perp}(r) \leq 0.2m_e \omega^2 L_c/e .
\]

Here \(L_c = 2E_{\perp}/(dE_{\perp}/dz)\) is the parallel length scale of the ponderomotive potential.

As soon as the electron plasma frequency \(\omega_{pe}\) becomes of the order of \(\omega\) (it occurs at a very low density ~10^{12}−10^{14} \text{ m}^{-3}\) in the frequency range 10−100 MHz), plasma waves can start propagating in a relay-race regime governed by the antenna \(\kappa\)-spectrum, causing further
2.2. 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).

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 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 $E_z$-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 $\omega_{ci} > \omega$ is already fulfilled.

3. ICRF PLASMA CHARACTERIZATION

3.1. NEUTRAL GAS BREAKDOWN

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 ($n_{ci}$~$5\times10^{16}$–$3\times10^{18}$ m$^{-3}$) were reliably produced in a wide range of the toroidal magnetic field $B_T$=0.20–2.24 T (2$\omega_{ce} \leq \omega \leq 20\omega_{ci}$) and gas pressure ($10^{-8}$–$10^{-11}$ 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, $\eta_i=n_i/(n_e+n_i)<0.1$.

3.3. ANTENNA-PLASMA LOADING

The antenna-plasma coupling efficiency is defined as a fraction of generator power coupled by the plasma, $\eta=\frac{P_{RF,pl}}{P_{RF,G}}$ [9]. For the standard ICRH antenna, this factor becomes rather low ($\eta_i=20–40\%$) in the regime of low-density ($n_i<10^{17}$ m$^{-3}$) helium ICRF plasma in contrast to the heating scenarios applied for target dense plasmas ($\eta_i>290\%$ at $n_i>10^{19}$ 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 $\eta_i$ 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 ($n_i/n_B=1.6\sim 2.0$) [11,15];
- ECRF pre-ionization/assistance for the ICRF plasma production ($n_i/n_B=1.4$) [16];
- Mode conversion in plasmas with two ion species ($n_i/n_B=2.0\sim 3.0$) [15];
- Antenna “magnetic tilting” towards $B_{ic}=B_T+B_n$ by superposing an additional vertical magnetic field $B_{ic}=\omega B_T$ ($n_i/n_B=1.2$) [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 (He+H)+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 $\omega=\omega_{ci}=2\omega_B$ layer in the plasma cross-section [11];
- Heating at the first cyclotron harmonic ($\omega=2\omega_B$) creates a 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)-plasmas (circles)](attachment)

Fig. 4 shows typical $H$ and $D$ atom spectra observed in the AUG ICRF discharge in pure He (a) and in (He+H)-plasmas when the Ion Cyclotron Resonances (ICR), $\omega=4\omega_n,\omega_D=2\omega_B$ 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: $P_{ICRF}=150\ kW$, $f=110\ GHz$, $P_{ECRF}=60\ kW$, $f=32.5\ MHz$, $B_T=2.0\ T$, $P_{He}=2.5\times 10^4\ Pa$](attachment)

Very optimistic results with ICRF-DC were achieved in the limiter tokamaks. The hydrogen removal rate in the resonance condition $\omega=\omega_{ci}=4\omega_B$ 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 ($\omega=2\omega_B$) 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 (N₂+H₂)-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(NH₃), NH₅(NH₄) produced in the (N₂+H₂)-plasmas. Chemical erosion of the C containing amorphous a-C: H films with the nitrone 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 \( (l_{Te} = 2.6 \) m, \( R_0 = 6.2 \) m, \( B/I = 5.3 \) 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, \( P/N = 13 \) kW/(Pa·m³), and the high power-per-particle, \( P/N \approx 200 \) kW/(Pa·m³), 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)) and high power-per-particle, \( P/N \approx 200 \) kW/(Pa·m³).

In the first case (Fig.6), the code predicts that weakly ionized (\( \gamma_e \approx 1.4\%) \) low temperature \( (T_e = 1 \) eV) and low density \( (n_e = 4 \times 10^{11} \) cm⁻³) plasma may be produced in ITER-size machines coupling relatively low power with the electrons \( (P_{RF\text{-G}} = 850 \) 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 \( (p_{He} = 8 \times 10^{-2} \) 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 \( (p_{He} = 2 \times 10^{-2} \) Pa) and the increased RF power \( (P_{RF\text{-G}} = 3.4 \) MW, \( P_{RF\text{-G}} = 6.8 \) MW) and is characterized by the increased ionization degree, \( \gamma_e \approx 16\%\). 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 \( (P_{RF\text{-G\text{-TEXTOR}}} = 50 \) kW \( \& \) \( P_{RF\text{-G\text{-ITER}}} = 3.5 \) MW). Wall conditioning at \( P_{RF\text{-G\text{-TEXTOR}}} = 200 \) kW/(Pa·m³) may become economically disadvantageous \( (P_{RF\text{-G\text{-ITER}}} > 10 \) MW) and inefficient for pumping out the adsorbed gas species (\( \gamma_e > 16\%\)).

5. ICRF ASSISTED TOKAMAK START-UP

For the present ITER start-up scenario, the inductive electric field is limited to \( E_i = 0.3 \) V/m, to prevent a quench in the superconducting coils. Therefore, to perform the tokamak start-up at \( E_i = 0.3 \) 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 2α, scenario to produce pre-heated RF plasmas prior applying the inductive electric field. The target helium RF plasma with density \( n_e = (0.2–7.0) \times 10^{17} \) m⁻³ was reliably produced in the gas pressure range \( P = (1.5–7.0) \times 10^{-3} \) 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 \( E_0 = 0.32 \) V/m, which met the ITER requirements (Fig.7).

Fig.7. ICRF-assisted low loop voltage start-up in TEXTOR: \( B/I = 2.25 \) T, \( p_{He} = 3.5 \times 10^{-3} \) Pa, \( T_e \approx 1.5 \) eV, \( \gamma_e \approx 1.4\%\) low temperature \( (1.5–7.0) \times 10^{-3} \) 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 \( E_0 = 0.32 \) V/m, which met the ITER requirements (Fig.7).

Without assistance, start-up at \( E_i = 0.45 \) 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 \( (E_i = 0.32 \) V/m) could only be successful when the following requirements have simultaneously been achieved [25]:

- Low resistance of the target plasma, \( R_{se} \leq 0.4 \) mΩ;
- Low value of the compensated stray field, \( |B_{str}| \leq 10 \) 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 \( (T_e \geq 260 \) 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 70s using Frame-Type antennas (FTA) [5].

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The ability of antenna to produce plasma can be characterized by the parameter \( \rho = R_p/n_e \) (\( R_p \) 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 \( \rho \text{-} \text{const} \) 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] (\( n_e = 2 \times 10^{19} \text{ m}^{-3} \)) or when the Crankshaft antenna operated alone (\( n_e \leq 10^{19} \text{ m}^{-3} \)) [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 \( \rho \text{-} R_p/n_e \) vs. plasma density for U-3M Crankshaft and THT antennas](image)

### REFERENCES


**ПРИМЕНЕНИЕ ВЧ-ПЛАЗМЫ В ТЕРМОЯДЕРНОМ РЕАКТОРЕ**

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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) Ассилирование старту токамака в режиме слабого вихревого электрического поля \( (E_o = 0,3 \text{ Вм} \text{ в ITERe}) \); (iii) Создание плотной нейтронной плазмы \( (n_e \geq 10^{19} \text{ м}^{-3}) \) в стеллаторах. Сделан обзор ВЧ-метода создания плазмы и его применения в современных токамаках и стеллаторах. В рамках моделирования 0-D плазменным кодом проведен анализ перспективности использования данного метода в ITERе.

**ЗАСТОСОВАНИЕ ВЧ-ПЛАЗМИ У ТЕРМОЯДЕРНОМУ РЕАКТОРУ**

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ВЧ-метод уширения плазмы (ICRF) разглядывается как перспективный альтернативный инструмент для таких заслуживаний у сущих и майбутних надвордных термоядерных установках: (i) ВЧ-чистка стек в присутствии постоянного сильного магнитного поля; (ii) Ассилирование старту токамака у режиме слабого вихревого электрического поля \( (E_o = 0,3 \text{ Вм} \text{ в ITERe}) \); (iii) Створение густейшей вихревой плазмы \( (n_e \geq 10^{19} \text{ м}^{-3}) \) в стеллаторах. Зроблено огляд ВЧ-метода створення плазми та його заслужування у сущих токамаках й стеллаторах. В рамках моделювання 0-D плазменним кодом проведено аналіз перспективності використання даного метода в ITERе.