

Study of LHCD efficiency dependence on main parameters of hydrogen/deuterium plasmas of the FT-2 tokamak

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Development of quasi-stationary non-inductive plasma current drive methods in a tokamak is critically important for a thermonuclear reactor. Current drive by lower hybrid waves (LHCD) is the most effective method to keep the plasma current, but it is feasible only at the plasma density not exceeding some density limit n_{DL} . In spite of the fact that the density limit effect has been studied for a few decades, its mechanisms did not obtain a comprehensive physical explanation. In the present work the main attention is paid to the investigation of this effect on the FT-2 tokamak ($R=0.55$ m, $a=0.08$ m, $B_T \leq 3$ T, $I_p=19\div 40$ kA, $f=920$ MHz, where a large experience in the observation of plasma–LH wave interaction has been accumulated and the long-continued experimental run on LHCD efficiency study has been realized [1]. The dependence of LHCD efficiency on isotopic plasma content (hydrogen/deuterium) is studied. Results of comparative experimental studies of the

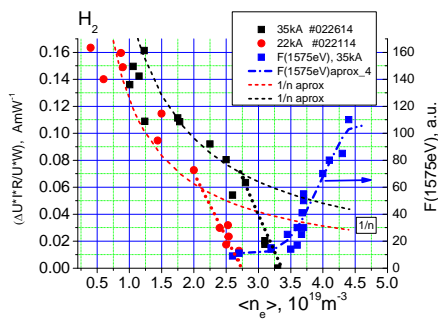


Fig. 1. I_{RF}^N as functions of the hydrogen plasma density for $I_{OH}=22$ kA and 35 kA. High energy CX neutral particle fluxes F_{CX} with energies $E_{CX} = 1575$ eV as functions of plasma density are shown only for $I_{OH} = 35$ kA.

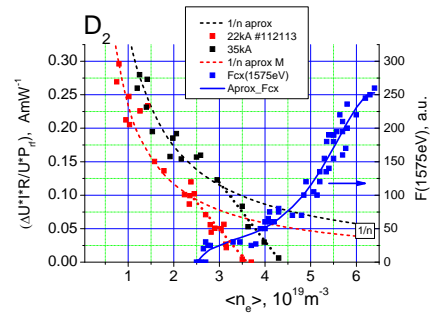


Fig. 2. I_{RF}^N as functions of the deuterium plasma density for $I_{OH}=22$ kA and 35 kA. High energy CX neutral particle fluxes F_{CX} with energies $E_{CX} = 1575$ eV as functions of plasma density are shown only for $I_{OH} = 35$ kA.

normalized $I_{RF}^N = I_{RF}R/P_{RF}$ LHCD generation (efficiency $\eta_{CD} = I_{RF}^N <n_e>$) and of the density limit n_{DL} in both hydrogen and deuterium plasmas are presented.

A characteristic feature of such an experiment is the strong influence of isotope plasma composition on the LH resonance density n_{LH} [2]. For hydrogen plasma ($B_T=2.2T$) $n_{LH} \sim 3.5 \cdot 10^{19} \text{ m}^{-3}$, while for deuterium $n_{LH} \sim 2 \cdot 10^{20} \text{ m}^{-3}$. The suppression of the LHCD and beginning of the interaction of LH waves with ions is controlled by the plasma density rise. Experimental data for hydrogen and deuterium plasmas are presented in Fig. 1 and 2, where I_{RF}^N are shown as functions of plasma density for $I_{pl} \sim 22\text{kA}$ and 35 kA . In both cases the LHCD (up to some density $\langle n_e \rangle^*$) was inversely proportional to the density, which corresponds to the theoretical predictions $1/n$ [3]. Experiments carried out in the FT-2 tokamak in the hydrogen plasma revealed that parametric processes can suppress LHCD at densities much lower than the LH resonance density, n_{LH} . In discharges with a relatively low current, $I_{pl} = 22 \text{ kA}$, the launch of LH waves was accompanied by a decrease of the central electron temperature $T_e(0)$ from $\approx 400\text{eV}$ to 300 eV , which was attributed to the reduction of the ohmic heating power due to a decrease of the loop voltage and an increase of the plasma density during the RF pulse. The cooling of the plasma column (and also drop of the edge electron temperature) led to a reduction of the power threshold for the pump wave parametric decay ($\sim T_e/n_e$) and resulted in the earlier suppression of LHCD [1, 4]. In the hot hydrogen

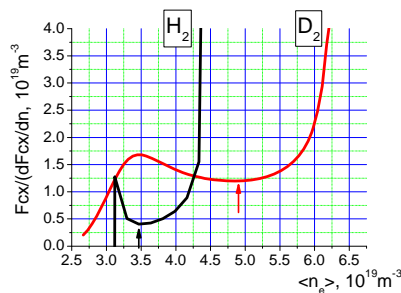


Fig. 3 The meaning of $F_{CX}/(dF_{CX}/dn_e)$ for hydrogen and deuterium plasmas. $I_{OH} = 35\text{kA}$.

plasma ($I_{pl} = 35\text{kA}$, $T_e(r=0\text{cm}) \approx 700\text{eV}$) the density limit n_{DL} of LHCD is approximately equal to the resonance value n_{LH} at which the interaction of the LH wave with the electron component is replaced by direct absorption by plasma ions ($n_{LH} \approx n_{LC} = 3.5 \cdot 10^{19} \text{ m}^{-3}$, where n_{LC} is the point of linear conversion (LC)), which was accompanied by fast neutral (FN) flux

$F_{CX}(1575\text{eV})$ rise shown in the Fig. 1 only for hot plasma case ($I_{pl} = 35\text{kA}$). The increase in the fast charge-exchange neutral flux $E_{CX} = 1575\text{eV}$ indicates at the appearance of extremely slowed down LH waves ($N_{\perp} \approx 600$), which are completely absorbed by the ions [4, 5]. In the hot deuterium plasma ($I_{pl} = 35\text{kA}$, $T_e(r=0\text{cm}) \approx 700\text{eV}$) one could expect an increase of n_{DL} because of a much higher value of $n_{LH} \geq n_{LC} \approx 10^{20} \text{ m}^{-3}$ [2]. However it appeared that the observed density limit for LHCD generation $n_{DL} \approx (3.5 \div 4) \cdot 10^{19} \text{ m}^{-3}$ is not determined by n_{LH} . As shown in Fig. 2, a more intensive rise of the fast deuterium neutral $F_{CX}(1575\text{eV})$ generation is located near $\langle n_e \rangle \approx 5 \cdot 10^{19} \text{ m}^{-3}$. The minimal value of $F_{CX}/(dF_{CX}/dn_e)$ (as typical density scale of F_{CX} variation) was used to define formally the plasma density value at which

the direct absorption of LH wave by plasma ions becomes a dominant process of LHW absorption. As one can see in Fig. 3, the position of the minimum of that ratio (labeled by arrows) for deuterium is shifted to a larger density ($\langle n_e \rangle_{FN} \approx 5 \cdot 10^{19} \text{ m}^{-3}$) in comparison with the hydrogen case ($\langle n_e \rangle_{FN} \approx 3.5 \cdot 10^{19} \text{ m}^{-3}$). From the data obtained in the hot deuterium plasma case, where there is a density gap between LHCD suppression and beginning of fast neutral generation, one can conclude that the switch-off of LHCD with the density rise does not depend on direct resonance absorption by ions. It could depend on the parametric decay of the pumping wave or else be the result of some other processes. So, the role of parametric instabilities in CD switch-off has to be considered in both cases. In these experiments, the presence or absence of parametric decay of the pump wave was detected by an RF probe placed in the scrape off layer on the low field side of the torus [1, 2]. Figure 4 demonstrates the comparison of the frequency spectra of the RF probes for two deuterium plasma densities. On the one hand, the formation of slowed down “daughter” waves in deuterium plasma could

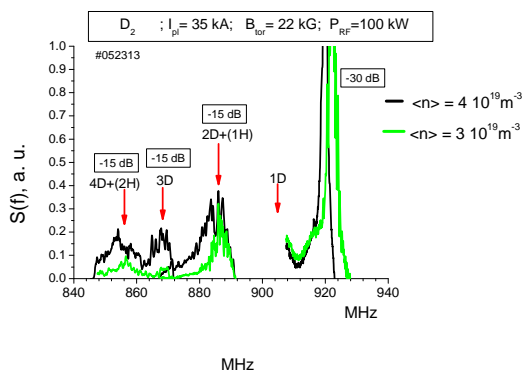


Fig. 4. Frequency spectrum of the RF probe measured in an LHCD deuterium plasma discharge with $I_{pl} = 35 \text{ kA}$ at (a) $\langle n_e \rangle = 3 \cdot 10^{19} \text{ m}^{-3}$ (green line) and (b) $\langle n_e \rangle = 4.2 \cdot 10^{19} \text{ m}^{-3}$ (black line). Positions of the deuterium (hydrogen) satellites are indicated by arrows. For instance, 2D + (1H) identify second

occur at $f_0 - nf_{Ci}$ ($n = 1, 2, 3, \dots$), where $f_{Ci} \approx 15 \text{ MHz}$ is the ion cyclotron (IC) frequency at $B_{tor} = 2.2 \text{ T}$. On the other hand, the broadening of the LH pump wave and IC sidebands could result from scattering of LHW by low frequency evanescent mode (quasi-modes) of the thermal background density fluctuations [6]. Presented spectra demonstrate significant increase and broadening of the second, third and fourth satellites of the pumping wave in the frequency spectrum at $\langle n_e \rangle = 4.2 \cdot 10^{19} \text{ m}^{-3}$ in

comparison with $\langle n_e \rangle \approx 3 \cdot 10^{19} \text{ m}^{-3}$. The first satellite is not shown. The start of the FN generation at $\langle n_e \rangle_{FN} = 5 \cdot 10^{19} \text{ m}^{-3} < n_{LC}$ can be the result of a parametric decay of the pumping wave also due to increasing density and cooling plasma periphery during the RF pulse. As for some other reasons influencing n_{DL} and n_{FN} , it is necessary to take into account the presence of some residual hydrogen in deuterium after the change of the working gas, some traces of which appear in different spectral data. Monitoring hydrogen/deuterium percent content of the working gas is performed using the relation of $H\beta/D\beta$ spectral lines intensity. Usually one register about (15÷20)% of hydrogen in the deuterium plasma near the wall of the vacuum chamber. This idea needs further discussion after obtaining new detailed experimental data.

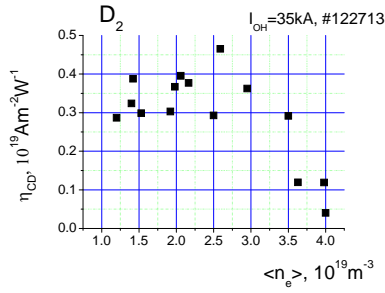


Fig. 6. Efficiency $\eta_{CD} = I_{RF}^N / \langle n_e \rangle$ of LHCD at $I_{pl} = 35kA$

$\langle n_e \rangle = 1.6 \cdot 10^{19} \text{ m}^{-3}$ revealed the relation $I_{RF} \sim \Delta P_{RF}^\alpha$, where $\alpha = 0.66$ for hydrogen and $\alpha = 0.5$ for deuterium plasmas. These data are in a good accordance with data obtained on [8].

To explain a relatively good efficiency of LHCD obtained at the small FT-2 tokamak a thorough modeling of experimental data has been performed [1]. The spectrum of the parallel refractive index $N_{//} = N_z$ of LH waves excited in the plasma by the two waveguides antenna was determined using the GRILL3D code [9]. The spectra of the waves $P(N_z)$ are bidirectional (with respect to the plasma current) and have several maxima. For $\Delta\varphi = \pi/2$ (asymmetric excitation) there are maxima at $N_z \approx -9; -1,7; 3$ and 20 . Using the Fast Ray Tracing Code (FRTC) [10] with the calculated spectrum $P(N_z)$ of LH waves and with the measured plasma parameters, we found the value and direction of LHCD. The magnetic equilibrium of the plasma column was calculated using the ASTRA code. FRTC modeling revealed the important role of the synergetic effect caused by the interaction of different spectral components of the excited RF waves for bridging of spectral gap. An LH wave with the slowing down factor $N_z = -1.7$ efficiently drives the current only in the presence of even slower waves with $N_z = -9$.

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Functional dependence and values of η_{CD} and I_{RF}^N

turned out to be close to those obtained in larger tokamaks [7, 8]. Accordingly Fig. 6, for deuterium plasma at

$I_{pl} = 35kA$, $\eta_{CD} \approx 0.4 \cdot 10^{19} \text{ Am}^{-2} \text{ W}^{-1}$ (at $\langle T_e \rangle = 390 \text{ eV}$ and $Z_{eff} \approx 2$), which correlates with relation shown in Fig. 6(a)

of [7]. The study of I_{RF}^N dependence on main plasma parameters revealed the increment of I_{RF}^N with increase of

I_{pl} , T_e and P_{RF} . For instance, the relationship between I_{RF} and $\Delta P_{RF} = P_{Rf_{inp}} - P_{Rf_{refl}}$ measured at $I_{pl} = 35kA$ and