Isotopic Effect in Experiments on Lower Hybrid Current Drive in the FT-2 Tokamak

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Abstract—To analyze factors influencing the limiting value of the plasma density at which lower hybrid (LH) current drive terminates, the isotopic factor (the difference in the LH resonance densities in hydrogen and deuterium plasmas) was used for the first time in experiments carried out at the FT-2 tokamak. It is experimentally found that the efficiency of LH current drive in deuterium plasma is appreciably higher than that in hydrogen plasma. The significant role of the parametric decay of the LH pumping wave, which hampers the use of the LH range of RF waves for current drive at high plasma densities, is confirmed. It is demonstrated that the parameters characterizing LH current drive agree well with the earlier results obtained at large tokamaks.

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1. INTRODUCTION

The development of noninductive methods for sustaining a quasi-steady current in tokamaks is one of the most important problems in designing fusion reactors. Unfortunately, the most efficient method for sustaining the plasma current by means of lower hybrid (LH) waves can be implemented only at relatively low plasma densities not exceeding a certain density limit \( n_{DL} \). The existence of the density limit for LH current drive (LHCD) was attributed to various mechanisms: linear absorption by ions, which increases as the density tends to the resonance LH value; collision losses; scattering by drift turbulence; parametric instabilities; etc. The density limit effect has been studied and discussed for several past decades; however, it has not received comprehensive physical explanation [1].

For a long time, the interaction of LH waves with plasma has been studied at the FT-2 experimental tokamak with the major radius of the toroidal chamber \( R = 0.55 \) m, the radius of the poloidal limiter \( a = 0.08 \) m, the magnetic field at the center of the chamber \( B_{tor} \leq 3 \) T, the range of the ohmic plasma current \( I_{OH} = 19–40 \) kA, the discharge duration \( \Delta t_{pl} = 50 \) ms, the RF pulse duration \( \Delta t_{RF} = 5–10 \) ms, the pumping wave frequency \( f_0 = 920 \) MHz, and the launched RF power \( P_{RF} < 200 \) kW [2]. Here, we present results of comparative FT-2 experiments with hydrogen and deuterium plasmas intended to reveal the mechanism governing the \( n_{DL} \) value. For this purpose, we employed the influence of the isotopic composition of the working gas on the plasma parameters determining the LHCD efficiency, which is expressed as \( \eta_{CD} = I_{RF}^N \langle n_e \rangle \), where \( \langle n_e \rangle \) is the mean plasma density along the central chord and \( I_{RF}^N = I_{RF}R/P_{RF} \) is the normalized LH-driven current, with \( I_{RF} = (\Delta U_{pl}/U_{pl})I_{OH} \) being the current generated by the RF wave.

The paper is organized as follows. The experimental dependences of the LHCD efficiency \( \eta_{CD} \) on the basic parameters and the data on the density limit for hydrogen and deuterium plasmas are presented in Section 2. In Section 3, the obtained dependences of \( \eta_{CD} \) and \( I_{RF}^N \) on the plasma parameters, as well as the maximum values of these quantities, are compared with results of experiments carried out at large tokamaks and the role of the isotopic factor is analyzed. The main results of the work are summarized in the Conclusions.

2. DEPENDENCE OF THE LHCD EFFICIENCY ON THE MAIN PLASMA PARAMETERS

In order to reveal the mechanism governing the density limit \( n_{DL} \) in LHCD experiments (\( B_{tor} = 2.2 \) T, \( f_0 = 920 \) MHz) with deuterium and hydrogen plas-
mas, we employed the influence of the plasma isotopic composition on the LH resonance density \( n_{LH} \). Above this density, the interaction of the LH wave with electrons is replaced with direct absorption by ions [3]. Estimates show that, under the given experimental conditions, the \( n_{LH} \) value in deuterium plasma (\( n_{LH} \approx 2 \times 10^{20} \text{ m}^{-3} \)) is substantially higher than that in hydrogen plasma (\( n_{LH} \approx 3.5 \times 10^{19} \text{ m}^{-3} \), see Appendix A). Therefore, in hydrogen and deuterium plasmas, one of the mechanisms responsible for LHCD termination—absorption of the LH wave by plasma ions—comes into play at substantially different values of the density.

LHCD termination may be caused by various parametric instabilities. In the literature, two types of instability are discussed. One of them leads to the decay of the pumping wave into a number of satellite waves the frequencies of which are shifted from the pumping frequency \( f_0 \) by a value multiple of the ion cyclotron frequency \( f_{ci} \). The other type of instability leads to the widening of the frequency spectrum of the pumping wave and the excitation of the so-called ionic quasi-mode. In both cases, as a result of parametric instability, satellite waves with longitudinal slow-down factors \( N_\parallel \) greater than that of the pumping wave are excited. These waves can be absorbed at the periphery of the discharge already at relatively low plasma densities [2, 4, 5].

The magnitude of the normalized LH-driven current \( I_{RF}^N = I_{RF} R_0 / \Phi_{RF} \) and the time of its termination in the described experiments depended on the mean plasma density \( \langle n_e \rangle \). Here, \( I_{RF} = (\Delta U_{pl} / U_{pl})I_{OH} \) is the current generated by the RF wave, \( U_{pl} \) is the loop voltage along the plasma column, \( \Delta U_{pl} \) is the reduction in this voltage after supplying the RF pulse, and \( I_{OH} \) is the ohmic heating current. Typical dependences of \( I_{RF}^N \) on the plasma density for hydrogen and deuterium plasmas are shown in Figs. 1 and 2. The data are presented for two magnitudes of the ohmic heating current, \( I_{OH} = 22 \) and 35 kA. It is seen from Figs. 1 and 2 that the normalized LH-driven current \( I_{RF}^N (\langle n_e \rangle) \) behaves according to the theoretically predicted dependence \( I_{RF}^N \sim 1/n [6] \) up to a certain density value \( \langle n_e \rangle^* \), above which it rapidly decreases and vanishes at \( \langle n_e \rangle_{DL} \).

2.1 Hydrogen Plasma

At relatively low values of the discharge current (\( I_{OH} = 22 \) kA), LHCD in hydrogen plasma is suppressed at densities substantially lower than \( n_{LH} \) (Fig. 1). In this case, we observe the cooling of the electron component during LHCD (according to the experimental data, the electron temperature \( T_e \) on the axis of the discharge decreases from ~400 to ~300 eV), which is explained by an increase in the density and a reduction in the ohmic heating power (due the reduction in \( U_{pl} \)) during the LH pulse. The reduction in \( T_e \) and the increase in the plasma density should lead to a reduction in the parametric instability threshold \( P_{th} \sim T_e / n_e \) [7] and, accordingly, the earlier suppression of LHCD. The development of parametric instability is experimentally confirmed by the rise of the first and second satellites in the frequency spectrum of
In deuterium plasma, for the resonance density and the density corresponding to the point of linear conversion (calculated for $N_\parallel = 2.5$, $z_{\text{eff}} = 3$, $T_\perp = 150$ eV, and $T_e = 600$ eV), we have $n_{1\text{H}} \geq n_{1\text{C}} \approx 10^{20}$ m$^{-3}$, i.e., they are substantially higher than in hydrogen plasma [4]. Therefore, it might be expected that, in experiments with a hot deuterium plasma ($I_{\text{OH}} = 35$ kA, $T_{\varphi} = 700$ eV), LHCD would vanish at greater values of the density, close to $10^{20}$ m$^{-3}$. However, the experimental results contradict these expectations. As is seen from Fig. 2, the density limit $n_{\text{DL}} = 4 \times 10^{19}$ m$^{-3}$ is substantially lower than those in hydrogen plasma. The measured dependence $F_{\text{CX}}(\langle n_e \rangle)$ (Fig. 2) is characterized by an appreciable scatter in the experimental points and has no kink. Apparently, under these conditions, it is possible to find the density range at which the sharp increase in the charge-exchange atomic flux begins, if we assume that, at this density, the characteristic density scale of the flux variation, $F_{\text{CX}}/(dF_{\text{CX}}/dn_e)$, is minimal. In addition to $\eta_{\text{CD}}$, Fig. 3 also presents the dependences of $F_{\text{CX}}/(dF_{\text{CX}}/dn_e)$ on the densities of hydrogen and deuterium plasmas obtained from the experimental data approximated by the least-squares method. The arrows mark the minimum values of $F_{\text{CX}}/(dF_{\text{CX}}/dn_e)$. The corresponding values of the plasma density determine the transition to the mode in which the interaction of the LH wave with plasma ions (protons/deuterons) becomes the main mechanism of RF power absorption. However, the density $\langle n_e \rangle_{\text{FN}} = 5 \times 10^{19}$ m$^{-3}$ of fast neutrals (FNs) determined in this way for deuterium exceeds the value $n_{\text{DL}} = 4 \times 10^{19}$ m$^{-3}$, at which LHCD terminates. Apparently, LHCD vanishes due to another mechanism. In particular, it could be caused by a substantial increase in $N_e$ as the LH wave penetrates into the plasma column [3].
However, the observed difference between \( n_{DL} \) and \( \langle n_e \rangle_{FN} \) in deuterium is small and is probably caused by experimental errors. Therefore, in this case, LHCD may vanish due to the interaction of the LH wave with plasma ions.

The reason for such interaction may be the parametric decay of the pumping wave at the periphery of the discharge, which is observed experimentally with the help of an RF probe [2, 4]. The frequency spectra of probe signals measured in deuterium plasma during an RF discharge at densities of \( \langle n_e \rangle = 3 \times 10^{19} \text{ m}^{-3} \) (gray line) and \( \langle n_e \rangle = 4.2 \times 10^{19} \text{ m}^{-3} \) (black line). The arrows mark the positions of satellites. The numbers of satellites are also indicated; for example, 2D + (IH) stands for the second deuterium (the first hydrogen) satellite.

![Fig. 4. Frequency spectra of RF probe signals recorded during LHCD in deuterium plasma: \( I_{pl} = 35 \text{ kA} \), \( \langle n_e \rangle = 3 \times 10^{19} \text{ m}^{-3} \) (gray line) and \( \langle n_e \rangle = 4.2 \times 10^{19} \text{ m}^{-3} \) (black line). The arrows mark the positions of satellites. The numbers of satellites are also indicated; for example, 2D + (IH) stands for the second deuterium (the first hydrogen) satellite.](image)

Another possible explanation of the relatively low density \( \langle n_e \rangle_{FN} = 5 \times 10^{19} \text{ m}^{-3} \) might be the presence in the spectrum of the pumping wave \( f_0 \) of strongly slowed down waves with \( N_\parallel \approx 10 \), as it follows from model calculations performed in [2]. The experimental confirmation of the excitation of slowed down LH waves with \( N_\parallel \gg 2 \) in plasma requires additional studies with the use of diagnostics capable of measuring the spatial and time spectra of LH waves inside the tokamak plasma. One of such diagnostics is that based on enhanced scattering at the lower hybrid resonance [9]. The wavenumbers in this diagnostics are resolved by the time-of-flight [10] and correlation [11] methods. As applied to the study of the propagation of LH waves in a tokamak, the time-of-flight method was used at the FT-1 facility [12] and the first results obtained for the FT-2 tokamak at \( B_{tor} = 1 \text{ T} \) were reported in [13, 14].

The influence of the hydrogen admixture in experiments with deuterium plasma also cannot be excluded. With the help of monitor spectral observations, the presence of hydrogen in deuterium plasma was detected even after a long series of experiments. The content of hydrogen incoming, apparently, from the chamber wall was determined from the ratio of the content of spectral line intensities, Hβ/Dβ. In some cases, in the end of the discharge, the near-wall region contained up to 15–20% of neutral hydrogen. The influence of the hydrogen admixture on the value of \( n_{DL} \) or \( \langle n_e \rangle_{FN} \) in deuterium plasma requires additional studies.

3. VALUES AND FUNCTIONAL DEPENDENCES OF \( \eta_{CD} \) AND \( I_{RF}^N \)

The data obtained in the described experiments were compared with the results obtained at large tokamaks. Such comparison has shown that a number of data characterizing the LHCD effect are in good agreement with the available results. Both the functional dependences of \( \eta_{CD} \) and \( I_{RF}^N \) on the plasma parameters and their values proved to be close to the results obtained at the TORE SUPRA [15] and FTU [16] facilities. For instance, according to Fig. 3, in deuterium plasma at \( I_{pl} = 35 \text{ kA} \) and \( \langle n_e \rangle = 1.6 \times 10^{19} \text{ m}^{-3} \), we have \( \eta_{CD} = 0.4 \times 10^{19} \text{ A m}^{-2} \text{ W}^{-1} \). This value at \( \langle T_e \rangle = 390 \text{ eV} \) and \( Z_{eff} = 2 \) agrees well with the experimental dependence \( \eta_{CD}[12(T_e)/(5 + Z_{eff})] \) presented in [15] and summarizing the result obtained at
As is seen from Fig. 3, within the density range from \( \langle n_e \rangle = 10^{19} \text{ m}^{-3} \) to \( \langle n_e \rangle = 2.5 \times 10^{19} \text{ m}^{-3} \) in deuterium, we have \( \eta_{\text{CD}} \approx 0.4 \text{ A m}^{-2} \text{ W}^{-1} \), whereas, for hydrogen plasma, \( \eta_{\text{CD}} \approx 0.3 \text{ A m}^{-2} \text{ W}^{-1} \).

4. CONCLUSIONS

The results of experiments carried out at the FT-2 tokamak allow us to conclude that the most probable reason for LHCD termination in both hydrogen and deuterium plasmas at a relatively low plasma current of \( I_{\text{OH}} = 22 \text{ kA} \) and, accordingly, a low electron temperature is an additional reduction in \( T_e \) at the periphery of the plasma column during the LH pulse. This results in a lower threshold for the parametric decay (\( \sim T_e / n_e \)) of the pumping wave. The parametric decay satellites, the frequencies of which are down-shifted, \( f_{\text{sat}} = f_0 - k f_c \) (\( k = 1, 2, 3 \), ...), are slowed down more than the pumping wave. Therefore, the plasma density \( n_{\text{LC}} \), at which linear conversion of slowed down satellite waves occurs, is lower than that for the pumping wave; hence, the LH wave after parametric decay can be absorbed by ions even at the plasma periphery, without penetrating into the plasma column.

At a higher plasma current (\( I_{\text{OH}} = 32 \text{ kA} \)) and higher electron temperature (\( T_{e0} = 600 \text{ eV} \)), the density \( n_{\text{DL}} \) at which the LHCD in hydrogen plasma terminates is close to the resonance value \( (n_{\text{DL}} \approx n_{\text{LH}} = \langle n_e \rangle_{\text{FN}} = 3.5 \times 10^{19} \text{ m}^{-3} \)). After the plasma density reaches this value, the interaction of the LH wave with electrons is replaced with direct absorption by ions.

The resonance value of the density for deuterium is substantially higher, \( n_{\text{LH}} \geq n_{\text{LC}} = 10^{20} \text{ m}^{-3} \); however, the obtained value \( n_{\text{DL}} = 4 \times 10^{19} \text{ m}^{-3} \) is smaller by more than one-half. Nevertheless, in contrast to hydrogen plasma, the density at which the sharp increase in the high-energy charge-exchange atomic flux, \( \langle n_e \rangle_{\text{FN}} = 5 \times 10^{19} \text{ m}^{-3} \), takes place proved to be higher than \( n_{\text{DL}} \), i.e., there is an appreciable gap between the values of \( n_{\text{DL}} \) and \( \langle n_e \rangle_{\text{FN}} \). Apparently, the main reason for LHCD termination in this case is the parametric decay of the pumping wave. The experimental results confirm that parametric processes intensify with increasing density during the RF pulse. Nevertheless, we cannot exclude the influence of a substantial slowing down (up to \( N_t \approx 10 \)) of the pumping wave as it propagates into the plasma column. The experimental confirmation of such influence requires special studies.

As a result of the experimental study of the influence of the plasma isotopic composition on the LHCD efficiency, it is established that the efficiency \( \eta_{\text{CD}} \) in deuterium plasma is higher than in hydrogen plasma. As is seen from Fig. 3, within the density range from \( \langle n_e \rangle = 10^{19} \text{ m}^{-3} \) to \( \langle n_e \rangle = 2.5 \times 10^{19} \text{ m}^{-3} \) in deuterium, we have \( \eta_{\text{CD}} \approx 0.4 \text{ A m}^{-2} \text{ W}^{-1} \); whereas, in hydrogen plasma, this value is appreciably smaller, \( \eta_{\text{CD}} \approx 0.3 \text{ A m}^{-2} \text{ W}^{-1} \).

A significant part of the experimental studies were performed at relatively low densities of \( \langle n_e \rangle = 1.6 \times 10^{19} \text{ m}^{-3} \), when an appreciable fraction of
the current in the LHCD mode is transferred by suprathermal and runaway electrons. Under these conditions, the parametric decay of the pumping wave is absent, no fast ions are produced, and the highest LHCD efficiency is observed. It is established that, at relatively large values of the plasma current \( I_{\text{LH}} = 32-35 \text{kA}, P_{\text{RF}} = 100 \text{kW}, T_{e0} \approx 550-600 \text{V} \), the quantities \( \eta_{\text{CD}} \) and \( J_{\text{RF}}^N \) and their dependences on the plasma parameters are close to those obtained at large tokamaks.

**APPENDIX A**

*Plasma Density in the Approximation of Cold LH Resonance*

The permittivity tensor of cold plasma has the form

\[
\tilde{\varepsilon} = \begin{pmatrix} \varepsilon & i g & 0 \\ -i g & \varepsilon & 0 \\ 0 & 0 & \eta \end{pmatrix},
\]

where \( \varepsilon = 1 + \frac{\omega_{pe}^2}{\omega_{Be}^2} \sum_i \frac{\omega_{pi}^2}{\omega_i^2}, \) \( \eta = -\frac{\omega_{pe}^2}{\omega_i^2}, \) and

\[
g = -\frac{\omega_{pe}^2}{\varepsilon \omega_{Be}^2} \quad \text{(under the condition } \omega_{Bi} \ll \omega \ll \omega_{Be}, \omega_{pe}).
\]

Here, \( \omega_{Be} \) and \( \omega_{Bi} \) are the electron and ion cyclotron frequencies, respectively; \( \omega_{pe} \) is the electron plasma frequency; \( \omega_{pi}^2 = \omega_{pe}^2 \left( \frac{c Z_i^2}{M_i m_p / m_e} \right) \), where \( c \) is the relative number density of the \( i \)th ion species; and \( Z_i \) and \( M_i \) are the charge and mass of ions (in units of the proton charge and mass) [3].

The necessary condition for the presence of the LH resonance in plasma is \( \omega_i^2 < \omega_{Be} \omega_{Bi} \). The plasma density corresponding to the LH resonance is determined from the condition \( \varepsilon = 0 \), i.e.,

\[
\omega_i^2 = \omega_{LH}^2 = \sum_i \omega_{pi}^2 \left( 1 + \frac{\omega_{pe}^2}{\omega_{Be}^2} \right)^{-1}.
\]

At \( z_{\text{eff}} = 1 \), the resonance LH density is \( n_{\text{LH}} = 2.3 \times 10^{19} m_f f^2 \), where \( f \) is in GHz and \( B \) is in kG [17].

Therefore, for hydrogen and deuterium, we have \( n_{\text{LH}} = 3.5 \times 10^{19} \text{ m}^{-3} \) and \( n_{\text{LH}} = 2 \times 10^{20} \text{ m}^{-3} \), respectively.

**APPENDIX B**

*Plasma Density at the Point of Linear Conversion*

When the finite plasma temperature is taken into account, the “cold” LH wave propagating into the plasma column does not reach the LH resonance surface, because, at \( n_{\text{LH}} < n_{\text{LH}} \), it undergoes linear conversion into the warm plasma mode. For the inner plasma regions of ordinary tokamaks, we have \( \omega_{pe}/\omega_{Be} \sim 1 \); therefore, near the point of linear conversion (under the condition \( \omega \ll \omega_{pe} \) or \( N_f \gg 1 \)), the transverse refractive index is described well by the approximate “warm” dispersion relation

\[
\alpha_T N_f^4 - (\varepsilon + \alpha_T \eta) N_f^2 - \eta (N_f^2 - \varepsilon + g^2) = 0,
\]

with the thermal correction

\[
\alpha_T = \frac{3}{8} \left( \frac{\nu_{Te} \omega_{pe}}{c \omega_{Be}^2} \right)^2 + \frac{3}{2} \sum_i \left( \frac{\nu_{Ti} \omega_{pi}}{c \omega_i} \right)^2.
\]

The plasma density at the point of linear conversion, \( n_{\text{LH}} \), is found from the vanishing of the discriminant of this biquadratic equation (in this case, the roots corresponding the “cold” and “warm” modes coincide). It is easy to see that, with allowance for all above-mentioned conditions, we have \( \alpha_T \eta \ll \varepsilon \ll N_i^2 \) near the point of linear conversion. Therefore, \( n_{\text{LH}} \) is determined with a high accuracy by the following relationship:

\[
\varepsilon^2 = 4 \alpha_T \left( \eta |N_f^2 - g^2| \right).
\]

The calculations performed for \( T_e = 500 \text{ eV}, T_i = 150 \text{ eV}, B_{\text{tor}} = 2.2 \text{ T}, z_{\text{eff}} = 3 \), and \( N_f = 2.5 \) yield the values \( n_{\text{LH}} = 3.4 \times 10^{19} \text{ m}^{-3} \) and \( n_{\text{LH}} = 1.1 \times 10^{20} \text{ m}^{-3} \) for hydrogen and deuterium, respectively. For \( N_f = 10 \) (at \( T_e = 500 \text{ eV}, T_i = 150 \text{ eV}, B_{\text{tor}} = 2.2 \text{ T}, \) and \( z_{\text{eff}} = 3 \)), the corresponding values are \( n_{\text{LH}} = 2.2 \times 10^{19} \text{ m}^{-3} \) for hydrogen and \( n_{\text{LH}} = 4.5 \times 10^{19} \text{ m}^{-3} \) for deuterium.

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