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Demonstration of the Technique of Central Lower Hybrid Heating of High-Density Plasma at the FT-2 Tokamak

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The method of central low-hybrid heating of the ion component of dense tokamak plasma based on theoretical concepts has been experimentally demonstrated. The experiments were performed on the FT-2 tokamak, a compact tokamak with a large aspect ratio and a strong toroidal magnetic field $B_T \leqslant 3.5$ (large toroidal radius $R = 0.55\,\mathrm{m}$, small $a = 0.08\,\mathrm{m}$). The maximum increase in ion temperature from $T_i(0) = 200$ to $500-600\,\mathrm{eV}$ as a result of additional central low-hybrid heating ($f_0 = 920\,\mathrm{MHz}$, $P_{\mathrm{RF}} = 100\,\mathrm{kW}$) was obtained in deuterium plasma at a reduced the value of $B_T = 1.7-1.9\,\mathrm{T}$

Keywords: HF ion heating, modeling, RF wave longitudinal slowdown spectrum, diagnostics of plasma ion temperature.

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It was widely believed in the 1970s and 1980s that intermediate-frequency waves (of the decimeter wavelength range) should help heat the ion component of plasma in devices with magnetic confinement. Slow waves with a lower hybrid resonance corresponding to them in plasma, where the wavelength in the direction transverse to the magnetic field decreases abruptly and wave absorption at ions should proceed by the stochastic mechanism, were used in experiments on heating [1]. The following signs of interaction of lower hybrid (LH) waves with the ion component of plasma were observed in numerous experiments at medium- (PLT, ASDEX, Alcator C) and small-sized (Petula B, Vega, FT-1, DITE, FT-2) [1,2] tokamaks: ion acceleration and the production of high-energy „tails“ of the ion distribution function. The thermalization of these tails may induce, under favorable conditions, plasma heating. However, the actual effect of heating of plasma ions was reported in very few experiments [2]. Improper confinement of high-energy ions in a tokamak, their weak thermalization in insufficiently dense plasma, and the excitation of nonlinear processes (most particularly, parametric decay instabilities in the periphery of plasma) were named among the reasons for failure [1,2]. This lack of experimental success has dampened the interest in lower hybrid heating (LHH) of ions, and intermediate-frequency waves have long been used primarily for maintaining non-inductive current in tokamak plasma [3]. Considerable advances were made in this field [4]. In recent years, the studies into LHH of ions have been resumed at the FT-2 tokamak, where the possibility of simultaneous suppression of all three above-mentioned effects reducing the efficiency of LHH of ions and the possibility of central LHH of ions in plasma of an ITER density level ($n_e \leqslant 10^{20}\,\mathrm{m}^{-3}$) were demonstrated. Specifically, it was reported in [5] that the efficiency of LHH of ions in dense plasma should be reconsidered with allowances made for the specific features discovered in the study of the isotopic effect of interaction between LH waves and plasma. In the present study, a method for central efficient LHH of dense plasma is proposed and verified experimentally. This method utilizes the strong dependence of density at which the lower hybrid resonance (LHR) occurs on the magnetic field of a tokamak and the heating wave frequency:

$$n_e|_{\mathrm{LHR}} = (m_i/4\pi e^2)\big(\omega^2/(1-\omega^2/\omega_{ce}\omega_{ci})\big). \qquad (1)$$

In Gaussian units, m_i in dependence (1) is the ion mass, ω is the heating wave frequency, and $\omega_{ce} = eH/m_e c$ and $\omega_{ci} = eH/m_i c$ are the electron and ion cyclotron frequencies, respectively. Although this expression was derived for two-component plasma, it still provides fine accuracy in the conditions typical of the center of tokamak plasma with light impurities. According to (1), the density at which the LHR occurs and sufficient slowdown of a pump wave becomes possible increases abruptly if the wave frequency tends to the geometric mean of electron and ion cyclotron frequencies: $\omega \to \sqrt{\omega_{ce}\omega_{ci}}$. This trend persists in the analysis of thermal effects, where the slowdown of a pump wave in the direction transverse to the magnetic field occurs near the line conversion point (LCP) that is close to the lower hybrid resonance point. The magnetic-field dependence of plasma density n_{LC} at the LCP point of a wave with a frequency of 920 MHz was used in the present study, which is focused on the efficiency of LHH of the ion component of a deuterium discharge at the FT-2 tokamak in various magnetic fields ensuring that condition (1) is satisfied approximately at high densities in the central discharge region. In other words, we used magnetic fields ensuring that pump wave frequency $f_0 = 920$ MHz is approximately equal to the geometric mean of electron and ion cyclotron frequencies. Experiments were performed at the FT-2 tokamak with a large aspect ratio (large toroidal radius $R = 0.55$ m, small radius $a = 0.08$ m) and a strong toroidal magnetic field $B_T \leqslant 3.5$ T [5]. Additional LHH of ions was examined in the high-density regime (HDR; $n_e \leqslant 10^{20}\,\mathrm{m}^{-3}$) in deuterium plasma.

A detailed analysis of the LHH region localization was performed by varying both phase relation $\Delta\varphi$ between two grill waveguides and the value of B_T. This required, first, calculating the spectrum of longitudinal slowdown factor for a pump wave $N_\parallel = N_z$ (N_z is the projection of refraction index N onto toroidal axis z [1]) as a function of phase relation $\Delta\varphi$ between waveguides and, second, calculating the position of the point of line conversion of a „cold" LH wave into a „warm" plasma mode (i.e., the n_{LC} density value) at various B_T values. Longitudinal slowdown spectra of an RF wave $N_z = N_\parallel$ were calculated in GRILL3D [6] with the plasma impedance taken into account (by solving the wave equation numerically). They are characterized by bidirectionality (with respect to the plasma current) and the presence of several maxima in the distribution of high-frequency (HF) power $P(N_z)$ over the spectrum. In asymmetric spectra (e.g., at $\Delta\varphi \approx \pi/2$), the maxima correspond to slowdowns $N_z \approx -9$, -3, 4, and 20. At $\Delta\varphi = 0$ and π, the spectra are symmetric with maxima at $N_z \approx \pm 5$ and $N_z \approx \pm 4, \pm 12$, respectively. The N_z spectrum specifies the conditions of propagation and absorption of an LH wave [1]. Although a direct influence of phase shift $\Delta\varphi$ on the efficiency of ion heating could not be identified in experimental runs with a complex N_z spectrum, the effect of variation of localization of additional heating with B_T was demonstrated.

Figure 1 presents the dependences of density n_{LC} at antiphase ($\Delta\varphi = \pi$) excitation of waveguides of a two-waveguide grill on toroidal magnetic field B_T for various values of projection N_z of the wave refraction index onto the magnetic field direction (at effective plasma charge $z_{eff} = 2$) calculated for deuterium plasma (D-plasma). It is evident that the region of absorption of LH power shifts toward lower densities n_{LC} (i.e., to the periphery of a plasma filament) as B_T increases. For example, the density at LCP is $n_{\mathrm{LC}} \approx (5-4) \cdot 10^{19}\,\mathrm{m}^{-3}$ at the value of $N_z = 5-7.5$, which is achieved in the case of antiphase excitation of waveguides in toroidal field $B_T = 2.2-2.3$ T. A 20–25% reduction in the toroidal field strength (to $B_T \approx 1.7-1.9$ T), which is permissible as far as the plasma discharge stability is concerned, shifts the line conversion point into the zone with higher density $n_{\mathrm{LC}} \sim 10^{20}\,\mathrm{m}^{-3}$ that may be achieved only in the central HDR region. The heating region should then be positioned closer to the discharge center.

When B_T is reduced further, LCP shifts out of the plasma region. The interaction of an RF wave with ions should then switch to absorption in the electron component. In addition to thermal ion profiles $T_i(r)$ (r is the magnetic surface radius), „effective temperature" $T_{i\_tail}(r)$ profiles of

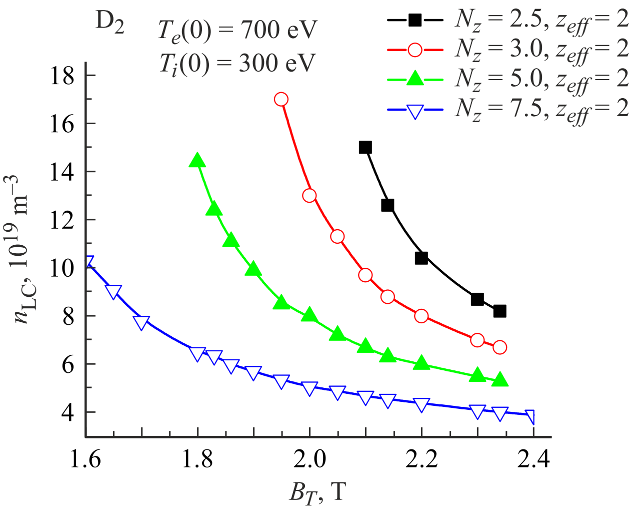

Figure 1. Dependences of density n_{LC} at antiphase ($\Delta\varphi = \pi$) excitation of waveguides of a two-waveguide grill on B_T for various values of N_z (at $z_{eff} = 2$) calculated for deuterium plasma. Modeling was performed for plasma with $T_e(0) = 700$ eV and $T_i(0) = 300$ eV.

fast „tail" ions produced directly in the interaction of an RF wave with plasma ions (see Fig. 7 in [5]) were examined in order to localize the site of additional heating. Chord profiles $T_i(y)$ and $T_{i\_tail}(y)$ were measured with a five-channel neutral particle analyzer (NPA) [7] by scanning the fluxes of charge-exchange atoms from plasma in the vertical direction (here, y is the impact parameter of the observation chord with respect to the chamber axis). In contrast to $T_{i\_tail}(r)$ for the central plasma region at $\langle n_e \rangle > 5 \cdot 10^{19}\,\mathrm{m}^{-3}$, direct measurements of T_i with the NPA were unfortunately infeasible. This is attributable to the effect of screening of charge-exchange atom fluxes by HDR plasma, which introduced a significant error into T_i measurements. Therefore, experimental T_i values determined by the NPA in the central regions were corrected in accordance with the results of model calculations with the DOUBLE MC-2 code [5,7]. Two experimental runs at $P_{\mathrm{RF}} = 100$ kW are compared here: (1) #071222D with a strong field at $B_T = 2.2-2.3$ T (plasma discharge current $I_{pl} = 34$ kA, RF pulse duration $\Delta t_{\mathrm{RF}} = 30.1-36.3$ ms, and $\langle n_e \rangle = 7 \cdot 10^{19}\,\mathrm{m}^{-3}$); (2) #111721D with the same parameters, but lower values of $B_T = 1.9-2.0$ T, $I_{pl} = 27$ kA, and $\Delta t_{\mathrm{RF}} = 27.2-32.5$ ms. According to the results of interferometric measurements, the deuterium plasma density increased from $\langle n_e \rangle = 6.9 \cdot 10^{19}$ to $8.3 \cdot 10^{19}\,\mathrm{m}^{-3}$ in the course of additional LHH. Additional heating of principal plasma ions from $T_i(y = 0\,\mathrm{cm}) = 200$ to 350 eV (by $\Delta T_i(y = 0\,\mathrm{cm}) \approx 150$ eV) was noted in both cases, but the profiles of ion temperature $T_i(y)$ at $B_T = 1.9-2.0$ T were „more peaked" (Figs. 2, *a* and *b*). A more substantial difference in heating localization was observed in the profiles of temperature $T_{i\_tail}(y)$ of „fast" ions produced directly by an LH wave. Here, $T_{i\_tail}(y = 0\,\mathrm{cm}) \approx 600-700$ eV

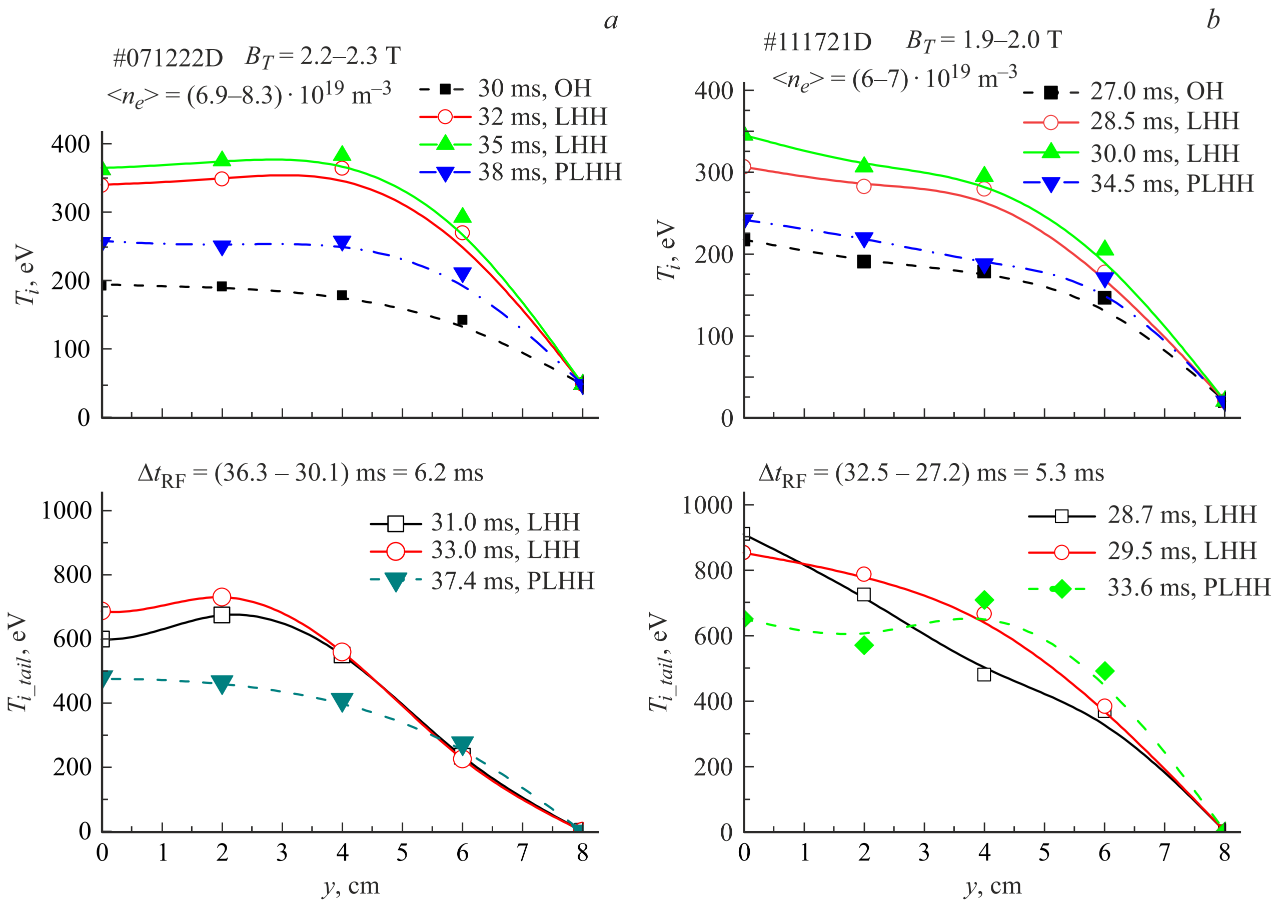

Figure 2. Chord profiles $T_i(y)$ and $T_{i\_tail}(y)$ under additional LHH, $P_{\mathrm{RF}} = 100$ kW (y is the impact parameter). *a* — $B_T = 2.2{-}2.3$ T, $\Delta t_{\mathrm{RF}} = 30.1{-}36.3$ ms; *b* — $B_T = 1.9{-}2.0$ T, $\Delta t_{\mathrm{RF}} = 27.2{-}32.5$ ms. OH stands for ohmic heating, LHH is lower hybrid heating, and PLHH is the profile obtained after switching off the lower hybrid heating.

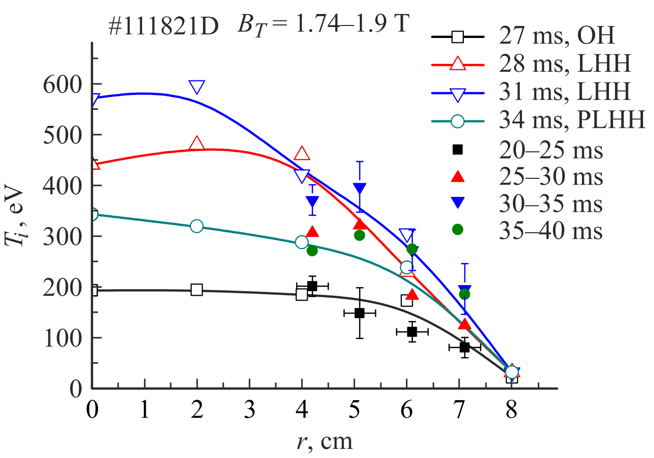

Figure 3. Ion temperature profiles in the case of additional LHH; $P_{\mathrm{RF}} = 100$ kW, $\Delta t_{\mathrm{RF}} = 27{-}32$ ms. Open and filled symbols represent the results of NPA measurements and spectral measurements for the CIII line (464.75 nm), respectively.

at $B_T = 2.2{-}2.3$ T and $T_{i\_tail}(y = 0\,\mathrm{cm}) \approx 1000$ eV at $B_T = 1.9{-}2.0$ T. This suggests that central heating is more efficient when B_T decreases. The maximum magnitudes of additional LHH of thermal ions from $T_i^{\mathrm{OH}}(0) \approx 200$ eV to $T_i^{\mathrm{LHH}}(0) \approx 500{-}600$ eV were obtained in experiment (#111821D) with a minimally reduced value of $B_T = 1.74{-}1.9$ T (Fig. 3). The NPA data were verified partially via spectral measurements. Figure 3 presents the values of $T_i(r)$ measured by the NPA and determined from broadening of the CIII line (464.75 nm) of doubly ionized carbon C^{2+} in the outer half of plasma cross section at $4 \leqslant r \leqslant 8$ cm. The measurements of T_i with a relatively „cold" CIII line ($E_{ion} = 60$ eV) were made possible by the inflow of working gas D_2, which exerted a significant influence on the concentration profile of ion C^{2+} $n_{C^{2+}}(r)$shaped by the processes of ionization, charge exchange, and recombination, in the same cross section. Particle fluxes and recombination processes shifted the maximum of the observed radiation profile $I_{\mathrm{CIII}}(r)$ deeper into the plasma filament (down to $r \geqslant 4$ cm, where $T_e \leqslant 200$ eV). According to the results of laser measurements of $T_e(r)$ and $n_e(r)$

performed during LHH, $T_e(r)$ becomes „peaked" with a rise at the center from $T_e(0) = 500$ to $550\,\mathrm{eV}$ and slight cooling in the periphery. In addition, a U-shaped $n_e(r)$ profile (a profile with steep gradients) forms by the end of an RF pulse in the course of additional LHH, and the D_β glow fades, which is typical of an L–H transition [5].

Thus, it was demonstrated that additional central lower hybrid heating of ions with a high efficiency on the order of

$$\eta^{\mathrm{D}}_{\text{FT-2}} = \Delta T_i \langle n_e \rangle / P_{\mathrm{RF}} \sim (2-3)\cdot 10^{14}\,\mathrm{eV}/(\mathrm{kW}\cdot\mathrm{cm}^3),$$

which is comparable to record-high parameters achieved recently at modern thermonuclear machines with the use of other ion heating methods [8], may be induced by varying (selecting) the B_T magnitude.

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Conflict of interest

The authors declare that they have no conflict of interest.

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