THE EFFECT OF GAS PUFFING AT THE LH GRILL ON THE EFFICIENCY OF THE CENTRAL DENSE PLASMA ION HEATING AT THE FT-2 TOKAMAK

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1. INTRODUCTION

Additional heating of plasma ion component using radio-frequency (RF) waves in the lower hybrid (LH) frequency range was actively developed in the late 1970s. However, its application in small tokamaks did not perform relevant positive results [1]. The efficiency of this heating method depends on numerous parameters, including the constructive arrangement of the RF antenna relative to the neutral gas source. This paper describes an effective LH heating (LHH) scenario for high-density deuterium plasma $<n_e>_{OH} \geq 5 \cdot 10^{19}\text{m}^{-3}$ [2], presenting experimental results on heating with varying arrangements of the gas puffing valves versus LH grill position. High efficiency of central ion heating is observed, which depends significantly on these arrangements. Additionally, the LHH scenario with gas puffing in front of the grill shows plasma displacement from the RF antenna, that grows with the RF power. This phenomenon is attributed to the ponderomotive mechanism of interaction between LH wave and plasma. Furthermore, the formation of a highly non-monotonic plasma density profile is observed, supposing the formation of an internal transport barriers (ITB).

2. EXPERIMENTAL APPROACH

In this paper we perform high-density deuterium discharges in the FT-2 tokamak ($a = 0.08$m, $R = 0.55$m, 30kA < I_{pl} <35 kA, 2T < B_T < 2.3T, q_{95} ~ 3-4; $<n_e>$ ~ (5-7)$\cdot 10^{19}$ m^{-3}). The effect of pulsed gas puffing on the efficiency of central ion heating in dense plasma is studied. Two discharge scenarios were compared: gas puffing in front of the LH grill position (valve PV2) versus gas puffing in a neighboring section (valve PV1), toroidally shifted by $\pi/2$ relative to the PV2 valve.

In the later scenario application of LH heating (P_{LHH} = 100 kW, f_{LH} = 920 MHz) resulted in central ion heating $T_{i\ cent}$ from 200eV up to 350 eV (see Fig. 1). Thomson scattering (TS) profiles indicated a density increase with slight peaking of the electron temperature $T_e(r)$ [3]. The formation of a Π-shaped density profile with a steep density gradient at the plasma periphery was accompanied by a reduction in D_β line emission.

The first scenario was performed under the same plasma parameters with gas puffing in the vicinity of the grill horn aperture (PV2). More efficient additional ion heating was observed here with $T_{i\ cent}$ increasing from 200 eV up to 450 eV (see Fig. 1). Notably, when using the PV2 valve in both the lower hybrid current drive (LHCD) mode and ion heating (LHH) mode, the suppression of parametric decay instability (PDI) was observed, previously reported in [4].

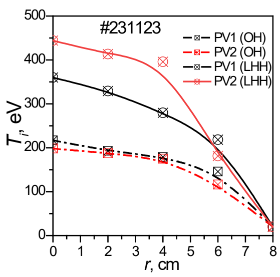

Fig. 1. Ion temperature: comparison of ion heating at pulsed gas puffing via valves PV1 and PV2

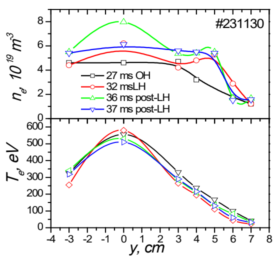

Fig. 2. PV2 case. $T_e(r)$ and $n_e(r)$ profiles during LHH. RF pulse duration: Δt_{RF}=28 ÷ 35ms

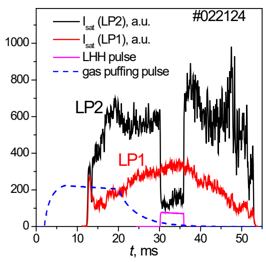

Fig. 3. Comparison of the ion saturation current I_{sat} measured simultaneously by Langmuir probes LP2 (near PV2) and LP1 (shifted by $\pi/2$ toroidally).

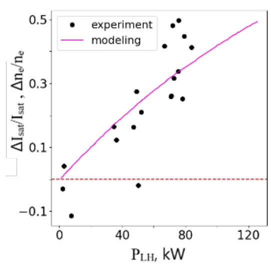

Fig. 4. Dependence on the LH-power of the experimental values of $\Delta I_{sat}/I_{sat}$ (points) and the modelling results of $\Delta n_e/n_e$ (line)

A significant difference was also observed in the PV2 case in the density profiles measured by Thomson scattering (TS). These profiles became non-monotonic at mid-radii ($r = \pm 4$–5 cm, $q \approx 2$), presenting density "dip" and an additional secondary maximum formation during LH heating (Fig. 2). Several possible causes for such non-monotonic profiles are considered: 1) plasma displacement/compression within the resonant cone of the LH wave due to the ponderomotive force; 2) formation of an internal transport barrier (ITB).

3. PONDEROMOTIVE EFFECTS AT THE LH HEATING

The hypothesis regarding the significant influence of the ponderomotive force on the plasma arose from the probe measurements, which presented a plasma density drop in the SOL (scrape-off layer) near the grill during LHH. Figure 3 shows the behavior of the ion saturation current $I_{sat} \sim nT_e^{1/2}$ during the RF power application. Notably, a probe located far from the grill horn, conversely, showed an increase in plasma density (fig. 3). The dependence of this density drop on the RF power magnitude is shown in Fig. 4 in comparison with theoretical predictions [5]. One can see that the RF power application aligns with theoretical expectations, leading to plasma displacement away from the grill and local steepening of the density profile. According to [6], this is also accompanied by a modification of the plasma rotation profile at the periphery in the grill poloidal cross-section. These factors may be responsible for the plasma transition into an improved particle confinement mode as well as for the density profile evolution in the inner plasma radii.
According to theoretical predictions, quasi-electrostatic LH waves form a "resonant cone-like structure" far from the HF antenna. As this structure gradually penetrates deeper into the plasma, it reaches the point of linear conversion into a warm electrostatic mode, namely the LH resonance. Simulations of the two-dimensional plasma density profile were conducted, accounting for ponderomotive forces [5] during the propagation of the LH wave in the cone. The simulation performs a density "dip" at $r = \pm 4$ - 5cm, $q \approx 2$ in a section toroidally shifted by 180° from the HF antenna. It is assumed that gas puffing via PV2 valve results in higher parallel wavenumber components N_z^{max} in the pump wave spectrum compared to the case of PV1 puffing, which, according to [5], amplifies the influence of ponderomotive forces.

4. ITB MODELING

Measured density profile with a central dip and a peripheral maximum demands some propriate explanation, so the hypothesis supposing the formation of a particle transport barrier in the inner plasma radii was explored under the natural assumption of neutral particle influx from the plasma boundary. The modelling was performed by widely accepted codes (ASTRA) as well as by special ones. Particularly, the ASTRA code solved a diffusion equation to directly simulate electron transport in a quasi-stationary approximation [7]. As a result, to describe the experimentally measured electron density at $t = 27$ ms (OH phase), it was sufficient to use a diffusion coefficient profile with an internal transport barrier (ITB) at the normalized minor radius $\rho = r/a = 0.6$ at $q \approx 2$. For $t = 36$ ms, a diffusion coefficient profile with two ITBs was applied at $\rho = 0.3$, ($q \approx 1$) and $\rho = 0.8$, ($q \approx 2$). When modeling the density dip at $t = 32$ ms, an additional module describing a particle pinch velocity linearly increasing toward the plasma periphery had to be incorporated alongside the ITB diffusion profile. As a result, this pinch velocity significantly exceeded the neoclassical Veer pinch velocity.

ACKNOWLEDGEMENTS

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REFERENCES

[1] V.E. Golant, V.I. Fedorov. High-frequency methods of plasma heating in toroidal fusion devices (in Russian), (Energoatomizdat, M., 1986), pp. 69–96, 116–141
[2] S.I. Lashkul, A. B. Altukhov, A. D. Gurchenko et al., Plasma Physics Reports, (2020), Vol. 46, No. 9, pp. 863–873
[3] S.I. Lashkul, A.B. Altukhov, A.D. Gurchenko, et al., Technical Physics Letters, (2024), Vol. 50, No.3. pp. 73-76
[4] C. Castaldo, A. Di Siena, R. Fedele et all. Nuclear Fusion 56 (2016) 016003
[5] A.G. Litvak, in Reviews of Plasma Physics, edited by M. A. Leontovich (Consultants Bureau, New York) (1986), vol. 10, p. 293.
[6] A.B. Altukhov, V.V. Bulanin, L.A. Esipov et al. 31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.28G, P-1.174
[7] D.V. Kouprienko, A.D. Gurchenko, E.Z. Gusakov et al., Nuclear Fusion, v.62, 6, (2022) 066045