Plasma density fluctuations and turbulent thermal fluxes in the transient process at ECH in the L-2M stellarator

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Studying of anomalous heat transport and plasma turbulence role in it is still of interest to magnetic confinement devices. In the paper the measurements of short-wavelength ($k_\perp = 30\ \mathrm{cm}^{-1}$) and long-wavelength density fluctuations ($k_\perp = 1\ \mathrm{cm}^{-1}$) at a transient process in the L-2M stellarator are presented. Such process in the L-2M stellarator is usually attributed to electron cyclotron heating (ECH) switch on/off and it is accompanied by density pump-out effect [1,2] and missing power effect [3,4].

The major radius of the L-2M stellarator R = 100 cm, average radius of the last closed flux surface a_0 = 11.5 cm, rotational transform angle at the magnetic axis $\iota(0) = 0.17$ and at the last closed flux surface (LCFS) $\iota(a_0) = 0.8$. The ECH system consists of two gyrotrons with frequencies f = 75 GHz. The implemented heating scenario is X2 (heating with extraordinary wave at the second harmonic of electron gyrofrequency) with microwave power injected in two adjacent standard external ports of toroidal vacuum vessel. By varying gyrotrons switch on/off time it is possible to achieve pedestal-like form of ECH power time evolution. It should be noted that one gyrotron is used both for heating and microwave scattering diagnostics. Thus gyrotrons switching sequence does matter for density fluctuations measurements.

Short-wavelength density fluctuations were measured using backscattering of gyrotron radiation [5]. Long-wavelength density fluctuations were studied using small-angle scattering of gyrotron radiation [6]. Both diagnostics are based on homodyne detection. Core electron electron temperature T_e was measured by 2^{nd} harmonic ECE (electron cyclotron emission) diagnostics f = 76 GHz. Average electron density n was measured by a central chord microwave interferometer f = 141 GHz. Discharges with different ECH power, electron density time evolution and ECH absorption region location (central, non-central heating) were investigated.

Plasma density fluctuations are routinely characterized by their mean square value $\langle \tilde{n}^2 \rangle$ (angle brackets mean averaging herein). However, turbulent heat and particle fluxes also depend on particle temperature. Let us assume that the turbulence has drift-wave nature. Then electron heat flux will be:

$$q_e = c k_\perp T_e^2 \langle \tilde{n}^2 \rangle (\langle n \rangle e B_0)^{-1} \cdot \xi(t),$$

here c — speed of light, e — charge of an electron, B_0 — magnetic field, T_e — electron temperature, $\xi(t)$ — function of phase shift between density and potential fluctuations. The fact that plasma oscillations speed in wave depends on T_e $\tilde{v} = c\tilde{E}/B_0 = ck_{\perp}T_e(\langle\tilde{n}\rangle/\langle n\rangle)(B_0 e)^{-1}$ was taken into account in the expression of heat flux q_e. Since focus of this paper is to investigate dependence of turbulent heat flux on ECH power then further in the paper time evolution of $\langle\tilde{n}^2\rangle$ and $T_e^2\langle\tilde{n}^2\rangle/\langle n\rangle$ will be used to characterize change of the flux.

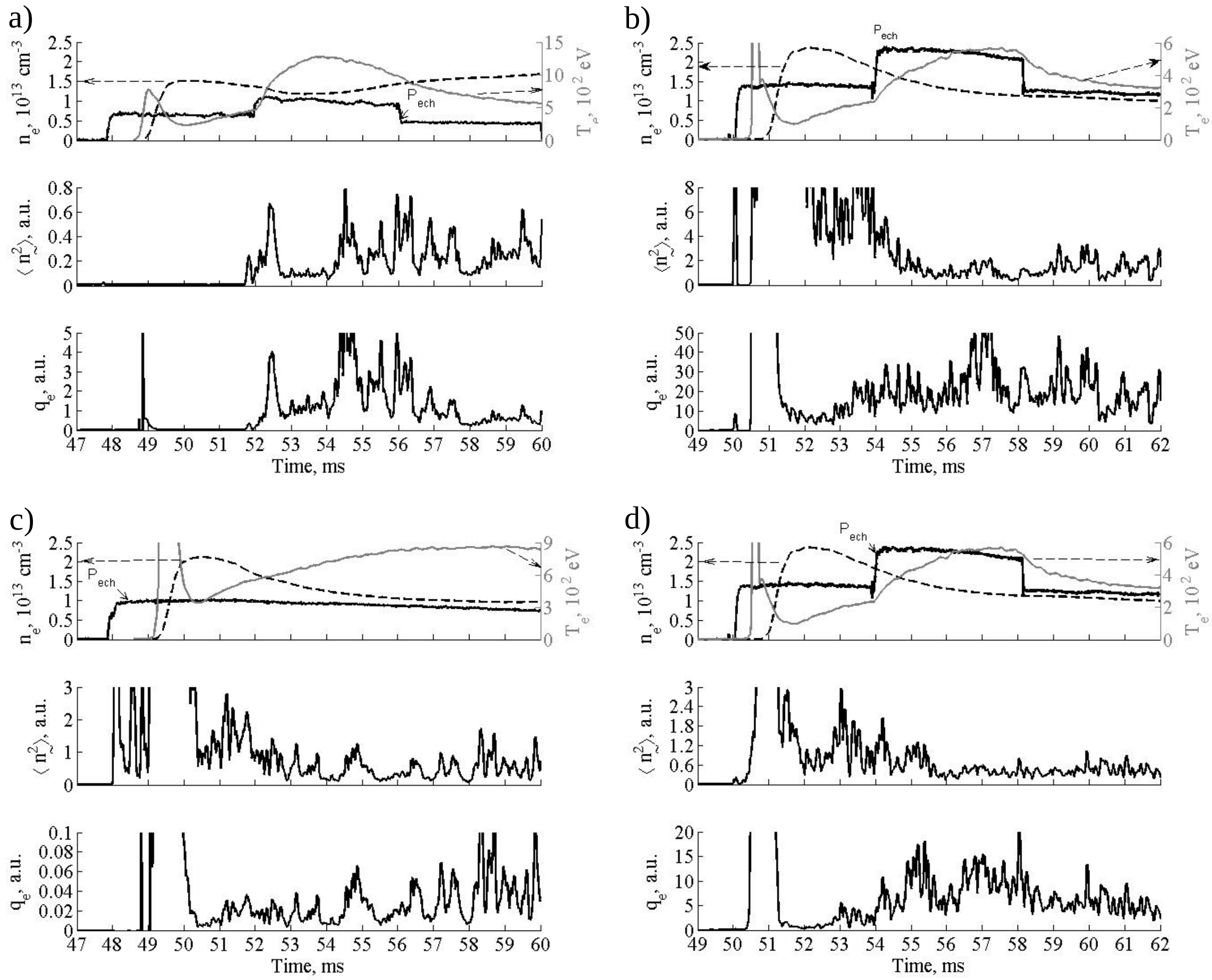

Fig.1. For each case: upper graph — electron density n_e, electron temperature T_e and microwave heating power P_{ech} time evolution; middle graph —density fluctuations energy $\langle n^2_{\sim}\rangle$; lower graph — turbulent heat flux q_e. a) Central ECH, short-wavelength density fluctuations, b) non-central ECH, short-wavelength density fluctuations . c) reference case, short-wavelength density fluctuations, d) Non-central ECH, long-wavelength density fluctuations.

Measurements results for central ECH case are presented in fig.1(a). Here each gyrotron has power of 130—150 kW. Short-wavelength density fluctuations level $\langle\tilde{n}^2\rangle$ was measured by backscattering diagnostics. At second (first and second is related to switching on time sequence herein) gyrotron switch on (52 ms) there is already high level of density fluctuations in plasma that was created and heated by first gyrotron. Fluctuations level increase appears with a time delay 2—2.5 ms, which is comparable with energy confinement time, after second gyrotron switch on at 52 ms and further the level remains increased even after first gyrotron switch off (56 ms). Turbulent heat flux (related to short-wavelength fluctuations) changes synchronously with electron temperature change. Thus turbulent heat flux after doubling the ECH power is increased up to 4 times at a central heating.

Measurements results for non-central ECH case (at magnetic field B_0 = 1.29 T absorption region is shifted towards inner wall on $a_0/4$) are presented in fig.1(b). In this case each gyrotron has microwave power 400 kW. The gyrotron which also used for giagnostics worked during all discharge length, thus density fluctuations measurements are available for full ECH length. Second gyrotron had only short pulse from 54 ms till 58 ms. As can be seen from fig.1(b) minimum of ECE signal is at 52 ms, when electron density is maximal. This minimum correspond to T_e = 100—200 eV. At this time short-wavelength density fluctuations level is maximal. Then the level is decreased almost by an order to 55 ms, when second gyrotron already heats the plasma for 1 ms. After second gyrotron switch off at 58 ms fluctuations level is increased up to 1.5—2 times. Thus, time delay of density fluctuations level increase, after second gyrotron switch on, is 4 ms at non-central ECH. The level remains increased till the end of heating (62 ms), despite of second gyrotron switch off at 58 ms. Electron temperature increase determines electron heat flux increase in this case too. It appears that turbulent heat flux is maximal at the end of the second gyrotron pulse.

A discharge with constant ECH power is presented in fig.1(c) as a reference case. Here ECH power P_{ECH} = 400 kW and electron density time evolution close to that of previous case. It can be seen that time evolution of the fluctuations level is similar to the non-central heating case with one exception: after decrease in the beginning of the discharge the level is not increased, as it was with some delay after second gyrotron switch on, but remains constant till the ECH pulse end. The turbulent heat flux evolves accordingly to electron temperature evolution.

Time evolution of long-wavelength density fluctuations level was investigated for the case of non-central heating at pedestal-like form of ECH power time evolution. These measurements, which are presented in the fig.1(d), were carried out simultaneously with the short-wavelength fluctuations measurements from fig.1(b). Therefore density and temperature time evolutions are the same as in fig.1(b). Time evolution of the long-wavelength density fluctuation level resembles time evolution of short-wavelength density fluctuations level in the reference case: highest fluctuations level is observed at the time period of plasma breakdown and sharp density increase (50.5—51.5 ms); the level is decreased till the time of minimal electron temperature and further it remains approximately constant. However, turbulent heat flux is increased after second gyrotron switch on at 54 ms and is decreased after second gyrotron switch off at 58 ms till the ECH end at 62 ms. Thus the heat flux increase after doubling ECH and decrease after it ends is typical both for long-wavelength density fluctuations and for short-wavelength density fluctuations

Another important issue to mention is a high value of the fluctuations amplitude $\tilde{a} = \tilde{v}/\omega$ that means non-linearity of the observed phenomena. This fact was pointed out in [7] for density fluctuations with $k_\perp = 6\,\text{cm}^{-1}$ and it was shown that Reynolds number $R_E = k_\perp r_n(e\tilde{\varphi}/T_e) > 1$ (r_n— density gradient scale length, $\tilde{\varphi}$ — potential fluctuations level). $R_E > 1$ is a condition for excitation of drift wave vortices [8]. For the case of non-central ECH presented in this paper estimation of relative density fluctuations level yields $\langle\tilde{n}\rangle/\langle n\rangle = 10^{-3}$. At T_e = 600 eV it gives $\tilde{v} \approx 10^5$ cm/s. Taken into account that approximately 50% of $\langle\tilde{n}^2\rangle$ is in the 25 kHz frequency range [9] then, given that $\omega = 10^5\ \text{s}^{-1}$, fluctuations amplitude $\tilde{a} = \tilde{v}/\omega = 1$ cm, i.e. amplitude higher than wavelength more than an order magnitude. Unlikely that in such case linear or quasilinear approach will be reliable. For our case dispersive spreading of drift waves is damped by nonlinearity at $r_n > 33$ cm (for $R_E > 1$ condition). Such density profile flattening is typical for L-2M stellarator currentless plasmas created and sustained by ECH.

To conclude this short paper we should emphasize factors responsible for enhancing of anomalous transport: electron temperature increase itself, fluctuation speed increase (caused by temperature increase) and density fluctuations level increase. All that is enhanced by a strong turbulence case which suppose drift wave vortices formation.

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