Displacement of the electron-cyclotron heating region in the L-2M stellarator and the related effects

G.M. Batanov, V.D. Borzosekov, S.E. Grebenshchikov, N.K. Kharchev, L.V. Kolik, E.M. Konchekov, A.A. Letunov, V.P. Logvinenko, D.V. Malakhov, A.I. Mesheryakov, A.E. Petrov, K.A. Sarksyan, A.S. Sakharov, N.N. Skvortsova, V.D. Stepakhin, M.A. Tereshchenko, and I.Yu. Vafin

A.M. Prokhorov General Physics Institute RAS, Moscow, Russia

Electron-cyclotron (EC) heating of plasma in toroidal magnetic traps (tokamaks and stellarators) is accompanied by a number of nonstationary processes occurring in the plasma column and in the wall region. EC heating leads to the formation of transport barriers, suppresses sawtooth oscillations and tearing instability, changes the level of short-wavelength turbulence, and, as a consequence, modifies the processes of plasma–wall interaction. As a result, both the value and the radial profile of the plasma density change. This process to a certain extent affects the refraction of the heating microwave beam and, therefore, may lead to a change in the distribution of the energy deposited in plasma. Changes in the distribution of the energy deposition, in turn, affect transport processes and energy balance in the plasma column. Thus, the experiments carried out at the Heliotron-E stellarator have shown that the radial displacement of the EC heating region results in a change of the radial temperature profile from the bell-shaped to a hollow one [1]. The radial displacement of the heating region from the center of the plasma column during auxiliary EC heating at the DIII-D tokamak causes a change in the profile of the electron temperature and the growth of short-wavelength density fluctuations, which is interpreted as a consequence of the increase in the growth rate of the electron temperature gradient (ETG) mode [2]. In the 3D geometry of the L-2M stellarator, the increase in the plasma density during EC heating can lead to the radial displacement of the EC heating region due to the refraction of the microwave beam and, hence, to the effects similar to those observed in the Heliotron-E and DIII-D devices. Therefore, it is of interest to study how the increase in the plasma density during EC heating affects the shift of the EC heating region and the characteristics of short-wavelength density fluctuations at high heating power densities (~2.4 MW/m3) currently achieved at L-2M.

The rotational transforms on the magnetic axis and at the boundary magnetic surface are $\iota(0)/2\pi = 0.18$ and $\iota(a)/2\pi = 0.78$, respectively. The magnetic axis of the unperturbed plasma magnetic configuration is shifted inward the torus by Δr = 2.6 cm relative to the minor axis of the vacuum chamber with a major radius of R = 100 cm. The average radius of the boundary magnetic surface is a = 11.5 cm. EC heating in these experiments was performed using two GIKOM gyrotrons (Russia) with a total power of 700 kW (the specific heating power density being 2.4–2.8 MW/m^3) and frequency of f_0 = 75 GHz (the second harmonic of the electron gyrofrequency). The gyrotron beams were injected in different cross sections of the vacuum chamber. The magnetic field on the axis of the vacuum chamber was 1.29–1.34 T. The average value of the plasma density along the central chord was in the range of (1.4–3.0)×10^{13} cm^{-3}. Before the experiments, the chamber wall was cleaned by thermal heating and a glow discharge, after which boronization was performed.

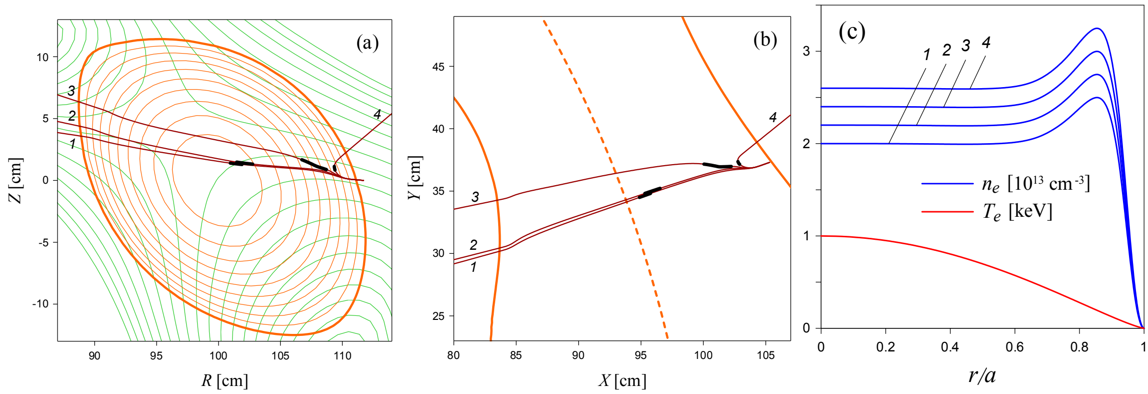

Fig. 1. Propagation and absorption of the extraordinary wave in plasma columns with different densities. (a) Toroidal projections of the ray paths for four density profiles; the bold portions correspond to the efficient microwave absorption (a decrease in the microwave power from 95% to 5% for profiles *1–3* and 70% for profile *4*). Also shown are the cross sections of the magnetic surfaces in the base cross section (red contours) and the contour of the absolute value of the magnetic field (green lines). (b) The same as the top view; the red lines show the minimum and maximum overall radii of the plasma column (bold solid lines) and its axis (dashed line). (c) Radial profiles of the electron density (blue curves) and temperature (red line) used in the calculations.

Figure 1 shows the results of calculations of the ray trajectories corresponding to the axis of the microwave beam injected into the plasma for several density profiles close to the experimental ones. In the injection cross section, the magnetic field at the plasma axis is 1.34 T, which corresponds to the nonrelativistic resonant value for the 75-GHz gyrotron frequency. The calculations were performed using the TRUBA numerical code with the weakly relativistic approximation for the plasma dispersion tensor [3]. As can be seen from Fig. 1, the growth of the plasma density causes a deflection of the beam upward in the poloidal cross section and away from the injection cross section in the top view. This is accompanied by the displacement of the power deposition region from the magnetic axis. Thus, when the maximum plasma density in the outer part of the density profile approaches 3.5×10^{13} cm^{-3} (the cutoff density), the EC heating region shifts toward the plasma periphery. Note that the total effect is not only due to the shift of the position of the beam intersection with the 1.34-T surface, but also due to an increase in the longitudinal component of the wave vector. The latter effect leads to a tiny shift of the EC resonance region toward a lower magnetic field; nevertheless, the small angle between the beam axis and the 1.34-T surface makes the effect of the geometric displacement of the EC resonance region quite appreciable.

The position of the reflection region in plasma with an evolving average density was determined from the measured value of the phase shift of the beam reflected from the resonant layer (see [4]). The extraordinary (X) wave is not only absorbed in the EC resonance region, but also partially reflected from it. The change in the phase shift $\Delta\varphi_X$ of the reflected wave relative to the reference wave (separated from the gyrotron radiation before it enters the plasma) during EC heating was measured using a quasi-optical directional coupler. This allowed us to determine the distance from the plasma boundary to the EC heating region. Figure 2 shows the signals recorded during the experiment. The detected signal is a result of the interference of three signals: the reference, rapidly oscillating, and quasi-constant ones. The rapidly oscillating component corresponds to the wave scattered from density fluctuations. The wavenumber of fluctuations is determined by the Bragg condition $k_s = 2k_0 \approx 30$ cm^{-1}, where k_0 is the wavenumber of the incident wave. The quasi-constant signal corresponds to the wave reflected from the EC heating region. The change in the phase of the reflected wave $\Delta\phi_x$ was determined from the positions of the maxima and minima of the quasi-constant components of the signal. The results of processing the experimental signals are shown in Table 1. Here, x_0/l_0 is the ratio between the distance from the plasma boundary to the reflection region and the length of the central horizontal chord, R_{res} is the major radius of the resonance region, and $\overline{R}^2$ is the coefficient of reflection (in terms of the power) of the X-wave from the EC resonance region. These values are close to theoretical predictions [4].

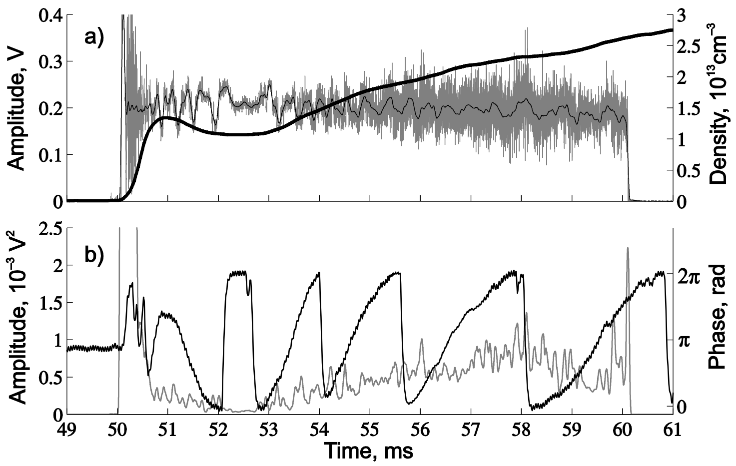

Fig. 2. (a) Backscattered signal (gray curve) and its average over a 100-ms time interval (thin black line) and the line-averaged density of the plasma (bold black curve); (b) interferometer phase shift (black curve) and square of the rapidly oscillating component of the scattered signal averaged over a 100-ms time interval (gray curve).

Table 1

Interval, ms	53.0–53.4	54.5–54.9	59.1–59.4
$<N_e>$, 10^{13} cm^{-3}	1.3	1.85	2.8
x_0/l_0; R_{res}, cm	0.46; 99.3	0.33; 102.3	0.2; 105.3
$\overline{R}^2$	2.5×10^{-4}	0.45×10^{-4}	0.73×10^{-4}
P_{ECRH}, kW	370	370	330

We calculated the Fourier spectra of the rapidly oscillating components for different positions of the absorption region. The shift of the EC heating region toward the plasma boundary at the end of the heating pulse due to the increase in the density causes a sharp increase in the turbulence energy. The continuous growth of the density after 53 ms and the progressive increase in the displacement of the heating region toward the periphery of the plasma column causes an increase in the turbulence energy by an order of magnitude as compared to its value within the time interval of 52–53 ms.

CONCLUSIONS

(i) We have studied reflection of the extraordinary wave used for EC plasma heating at the second harmonic of the electron gyrofrequency in the 3D magnetic configuration of the L-2M stellarator at an oblique incidence of the microwave beam onto the EC resonance layer.

(ii) Analysis of the geometry of the surfaces of the constant magnetic field in the L-2M cross section in which EC heating is performed shows that, as the plasma density grows, the refraction of the heating microwave beam leads to the progressive shift of the heating region from the center of the plasma column toward the periphery.

(iii) It is found that the growth of the plasma density leads to a decrease in the reflection coefficient of the heating microwave beam from the cyclotron resonance region, the tenfold increase in the energy of short-wavelength turbulence, and the appearance of high-power spectral components of density fluctuations in the frequency range of 0.3–1.5 MHz.

This work was supported by RFBR grant № 14-02-00589.

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