Microwave Reflection from the Region of Electron Cyclotron Resonance Heating in the L-2M Stellarator*)

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(Received 9 December 2013 / Accepted 15 May 2014)

In experiments on electron cyclotron resonance (ECR) heating of plasma at the second harmonic of the electron gyrofrequency in the L-2M stellarator, the effect of partial reflection of high-power gyrotron radiation from the ECR heating region located in the center of the plasma column have been revealed. The reflection coefficient is found to be on the order of 10^{-3}. The coefficient of reflection of an extraordinary wave from the second-harmonic ECR region is calculated in the one-dimensional full-wave model. The calculated and measured values of the reflection coefficient are found to coincide in the order of magnitude.

Keywords: stellarator, plasma heating, microwave, gyrotron, electron-cyclotron resonance, full-wave equation

DOI: 10.1585/pfr.9.3402128

1. Introduction

In studying the interaction of microwave radiation with a weakly inhomogeneous high-temperature plasma in toroidal magnetic confinement systems, reflection of microwaves from the electron cyclotron resonance (ECR) region, where the heating radiation is absorbed, is usually ignored. When the plasma is heated at the second harmonic of the electron gyrofrequency, the absorption region is much shorter than the characteristic inhomogeneity scale lengths of the electron density and magnetic field, whereas microwaves in many cases are almost completely absorbed over a distance comparable with the radiation wavelength. Strong nonuniformity of the absorption coefficient should result in a partial reflection of microwaves from the region of ECR heating [1, 2]; however, this effect has not been studied experimentally as of yet.

In our experiments on ECR heating of plasma in the L-2M stellarator (see, e.g., [3]), we have revealed microwave reflection from the region of the resonance at the second harmonic of the electron gyrofrequency ($\omega_0 \approx 2\omega_{ce}$, where ω_0 is the angular frequency of heating radiation and ω_{ce} is the electron gyrofrequency) by analyzing backscattered gyrotron radiation [4, 5].

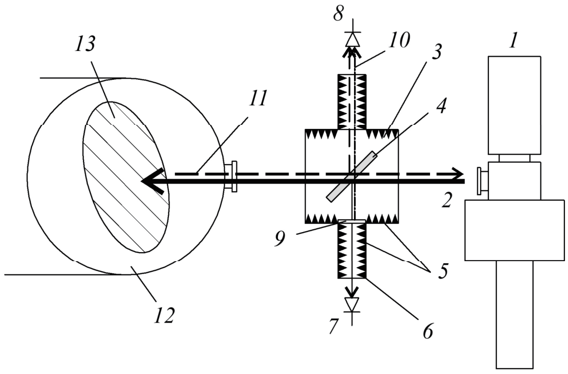

Fig. 1 Scheme of the experiment on the detection of backscattered gyrotron radiation in the L-2M stellarator: (1) gyrotron, (2) gyrotron radiation, (3) quasi-optical coupler, (4) mica splitter, (5) absorber, (6) radiation collimator, (7) detector of the gyrotron radiation power, (8) detector of scattered radiation, (9) polarization grid, (10) reference beam, (11) backscattered radiation, (12) cross section of the vacuum chamber, and (13) cross section of the plasma column.

2. Experiment: Measurement Technique and Results

The scheme of the experiment is shown in Fig. 1. The linearly polarized gyrotron radiation with the frequency $f_0 = \omega_0/2\pi = 75$ GHz splits near the plasma column boundary into elliptically polarized extraordinary (X) and ordinary (O) waves. The X-wave is absorbed in the ECR region located in the center of the plasma column and heats plasma electrons. The O-wave passes through the plasma practically without absorption. The input radiation power was 200 - 350 kW. About 15% of the input power was transformed into the O-wave. The average plasma density was $(1.7 - 1.8) \times 10^{13}$ cm^{-3}, and the central electron temperature $T_e(0)$ reached 0.7 - 1.0 keV.

Figure 2 (a) shows signals from the detectors of the

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*) This article is based on the presentation at the 23rd International Toki Conference (ITC23).

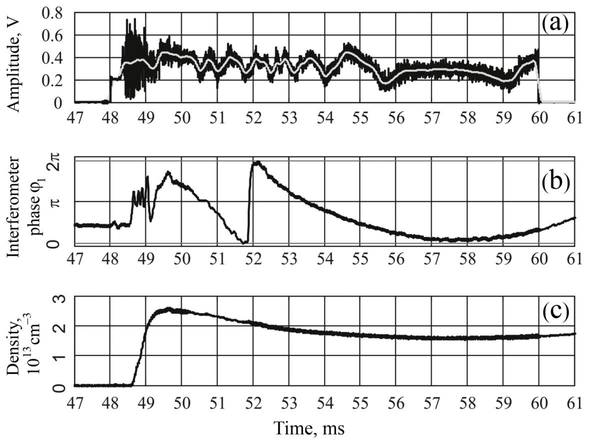

Fig. 2 (a) Signal of the homodyne detector before and after averaging over the time interval of 300 μs (1500 readings) and the time dependences of (b) the phase increment of the interferometer measuring the plasma density along the central horizontal chord and (c) the average plasma density.

quasi-optical directional coupler recorded during one of the L-2M discharges. The backscattered signal was recorded using the homodyne detection scheme. By turning the receiving rectangular waveguide by $\pi/2$, two mutually orthogonal components of the backscattered radiation could be recorded—the Y component collinear with the field of the incident wave and the Z component orthogonal to the field of the incident wave. Thus, the backscattered X- and O-waves could be recorded separately.

The shape of the detected signal shown in Fig. 2 (a) is a result of the interference of three signals: the reference signal, the fast oscillating signal, and the signal with a slowly varying phase. The fast oscillating signal can be attributed to gyrotron radiation backscattered from small-scale plasma fluctuations with wavenumbers $k_s \approx 2k$, where k is the wavenumber of the scattered wave. The signal with a slowly varying phase is quite natural to interpret as a wave reflected from some obstacle or a quasi-steady perturbation. Hereinafter, we will call this signal quasi-steady.

If the quasi-optical coupler is calibrated, then it is easy to determine the reflection (backscattering) coefficients of both the fast oscillating and quasi-steady components. After averaging over the fast oscillating component, the result of the interference of the reference signal and the signal with a slowly varying phase is retained. The location of the plasma region that is the source of the quasi-steady signal can be determined by analyzing variations in the phase of this signal. The change in the phase of the quasi-steady signal is apparently caused by a change in the average plasma density on the path of the incident and reflected radiation. If gyrotron radiation is reflected from the rear wall of the vacuum chamber, then its phase increment should correspond to the doubled length of the central chord of the cross section of the last magnetic surface. If reflection takes place inside the plasma column, then the phase increment should be smaller. Since the resonance at the second harmonic of the electron gyrofrequency is located on the magnetic axis, the phase increment of X-wave in the case of reflection from the ECR region should correspond to the length l_0 of the central chord. Note that the X-wave is almost completely ($\approx$ 99%) absorbed in the ECR region. Therefore, it is hard to expect that reflection of the X-wave from the rear wall of the chamber could be detected.

Reflection from the ECR region is confirmed by the calculation of the length over which the recorded phase increment φ_0 of the quasi-steady signal at the gyrotron radiation frequency f_0 takes place. To calculate this length, it is necessary to have information on the change in the average plasma density over a given time interval. This information can be obtained by analyzing variations in the phase of the signal from the interferometer operating on the O-wave with the frequency $f_1 = \varphi_1/2\pi = 141$ GHz and measuring the average plasma density along a horizontal chord passing through the center of the plasma column. Figure 2 (b) shows the time evolution of the interferometer phase φ_1 for the same discharge in which the backscattered signal was recorded, and Fig. 2 (c) shows the time evolution of the average plasma density recovered from the interferometer signal.

The change in the phase of the quasi-steady signal over a certain time interval Δt can be written as

$$\Delta\varphi_0 = 2k_0 \int_0^{x_0} \Delta N_X \mathrm{d}x \approx 2k_0 \int_0^{x_0} \frac{\partial N_X}{\partial v} \Delta v \mathrm{d}x, \qquad (1)$$

where $k_0 = \omega_0/c$ is the wavenumber of gyrotron radiation in vacuum, $N_X = ((1-v)^2 - u)/(1-u-v))^{1/2}$ is the refractive index of the X-wave propagating perpendicular to the magnetic field, $u = (\omega_{ce}/\omega_0)^2$, $v = (\omega_{pe}/\omega_0)^2$, and ω_{pe} is the plasma electron frequency. The factor 2 in formula (1) accounts for the double passage of radiation from the plasma boundary ($x = 0$) to the point of reflection ($x = x_0$) and back.

The change in the interferometer phase $\Delta\varphi_1$ is

$$\Delta\varphi_1 = k_1 \int_0^{l_0} \Delta N_O \mathrm{d}x \approx k_1 \int_0^{l_0} \frac{\partial N_O}{\partial v_1} \Delta v_1 \mathrm{d}x, \qquad (2)$$

where $N_O = (1-v_1)^{1/2}$ is the refractive index of the O-wave propagating perpendicular to the magnetic field, $k_1 = \omega_1/c$, $v_1 = (\omega_{pe}/\omega_1)^2$, and integration is performed over the entire length of the central chord ($l_0 = 23$ cm).

Taking into account that

$$\frac{\partial N_X}{\partial v} = -\frac{1-u-2v+2uv+v^2}{2\left((1-v)^2-u\right)^{1/2}(1-u-v)^{3/2}}, \qquad (3)$$

$$\frac{\partial N_O}{\partial v_1} = -\frac{1}{2(1-v_1)^{1/2}}, \qquad (4)$$

Table 1 Position of the reflection region and reflection coefficient of the X-wave as functions of time.

Δt, ms	x_0/l_0	R_X^2
52.1 - 52.8	0.40	1×10^{-3}
52.4 - 53.2	0.55	1×10^{-3}
52.8 - 53.6	0.58	8.2×10^{-4}
53.6 - 54.6	0.58	2.5×10^{-3}
54 - 55.6	0.49	2.7×10^{-3}
54.5 - 55.6	0.49	2.7×10^{-3}

for the conditions of our experiment ($u \approx 0.25$, $v \approx 0.25$, $v_1 \approx 0.07$), we can approximately write

$$\Delta\varphi_0 \approx 2k_0 x_0 \frac{\partial \bar{N}_X}{\partial v}\Delta\bar{v} \approx -2.2k_0 x_0 \Delta\bar{v}, \quad (5)$$

$$\Delta\varphi_1 \approx k_1 l_0 \frac{\partial \bar{N}_O}{\partial v_1}\Delta\bar{v}_1 \approx -0.52k_1 l_0 \Delta\bar{v}_1 \approx -0.28k_0 l_0 \Delta\bar{v}, \quad (6)$$

where the upper bar stands for the averaging over the central chord.

Thus, for the known values of $\Delta\varphi_0$ and $\Delta\varphi_1$, the distance x_0 from the plasma boundary to the point of reflection can be found by the formula

$$\frac{x_0}{l_0} \approx 0.125\frac{\Delta\varphi_0}{\Delta\varphi_1}. \quad (7)$$

The Table 1 presents the values of x_0/l_0 calculated by formula (7) and the measured values of the power reflection coefficient R_X^2 in the quasi-steady component of the backscattered X-wave for several time intervals during the L-2M discharge illustrated in Fig. 1.

It can be seen from the table that the x_0 positions determined from the measured change in the phase of the quasi-steady component of the backscattered X-wave lie close to the center of the plasma column. The average values of R_X^2 and x_0/l_0 (with allowance for their root-mean-square deviations from their average values) over the time interval 52 - 56 ms are $(1.8 \pm 0.8) \times 10^{-3}$ and 0.52 ± 0.06, respectively.

3. Discussion of the Results

We performed numerical calculations of the coefficient of reflection from the ECR region for the conditions corresponding to the experiments on ECR plasma heating at the second harmonic of the electron gyrofrequency in the L-2M stellarator [3]. Let us consider a plane X-wave propagating along the x axis and polarized in the (x, y) plane perpendicular to the external magnetic field $B_0(x)\boldsymbol{e}_z$. The propagation of such a wave near the resonance $\omega_0 = 2\omega_{ce}$ is described by the following set of one-dimensional full-wave equations [1,6]:

$$\frac{d}{dx}\left(f\frac{dE_x}{dx}\right) + i\frac{d}{dx}\left(f\frac{dE_y}{dx}\right) + SE_x - iDE_y = 0, \quad (8)$$

$$-i\frac{d}{dx}\left(f\frac{dE_x}{dx}\right) + \frac{d}{dx}\left((1+f)\frac{dE_y}{dx}\right) + iDE_x + SE_y = 0. \quad (9)$$

Here,

$$S = k_0^2\frac{1-u-v}{1-u}, \quad D = k_0^2\frac{v\sqrt{u}}{1-u},$$

$$f = \frac{v}{2u}F_{7/2}\left(\frac{\omega_0 - 2\omega_{ce}}{\beta\omega_0}\right),$$

where $\beta = T_e/m_e c^2$ and $F_{7/2}(x)$ is the Dnestrovskii function [7], which accounts for the thermal effects near the resonance at the second harmonic of the electron gyrofrequency in weakly relativistic ($\beta \ll 1$) Maxwellian plasma,

$$\mathrm{Re}F_{7/2}(\xi) \approx \frac{1}{\xi} \text{ for } |\xi| \gg 1,$$

$$\mathrm{Im}F_{7/2}(\xi) = \begin{cases} 0 & \text{for } \xi > 0 \\ -\frac{8}{15}i\sqrt{\pi}|\xi|^{5/2}e^{\xi} & \text{for } \xi < 0 \end{cases}. \quad (10)$$

Set of equations (8) and (9) possesses the energy integral

$$\frac{d}{dx}P + W = 0. \quad (11)$$

Here,

$$P = \frac{c^2}{8\pi\omega_0}\mathrm{Im}\left(E_y^*\frac{dE_y}{dx} + (E_x^* - iE_y^*)\frac{d}{dx}\left(E_x + iE_y\right)f\right) \quad (12)$$

is the power flux density (where the first and second terms in parentheses correspond to the Poynting flux and the kinetic power flux, respectively) and

$$W = -\frac{c^2}{8\pi\omega_0}\left|\frac{d}{dx}\left(E_x + iE_y\right)\right|^2 \mathrm{Im}f > 0 \quad (13)$$

is the power density absorbed by the plasma.

Since set of equations (8) and (9) consists of two second-order differential equations, it describes two types of waves. In a uniform plasma, the spatial dependence of the electrical fields of these waves can be represented as $\sim\exp(ikx)$, where the wavenumber k satisfies the following biquadratic dispersion relation:

$$fk^4 - (S + 2(S+D)f)k^2 + S^2 - D^2 = 0. \quad (14)$$

Far from the resonance ($|\omega_0 - 2\omega_{ce}|/\omega_0 \gg \beta$, $f \to 0$), the solutions to dispersion relation (14) correspond to the left- and right-propagating X-waves,

$$k_X \approx \pm\sqrt{(S^2 - D^2)/S}, \quad (15)$$

as well as Bernstein (B) modes at the second harmonic of the electron gyrofrequency,

$$k_B \approx \pm\sqrt{S/f}, \quad |k_B| \gg |k_X|. \quad (16)$$

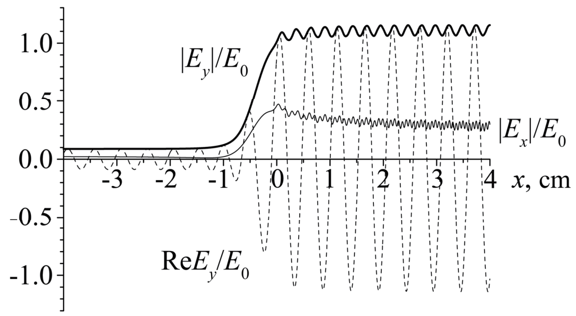

Fig. 3 Calculated profiles of $|E_y|$ (heavy solid line) and $|E_x|$ (light solid line) near the resonance $\omega_0 = 2\omega_{ce}$. The dashed line shows ReE_y as a function of x at a certain instant of time. The fields are normalized to the amplitude E_0 of the incident wave in vacuum.

The B-modes are propagating at $\omega_0 - 2\omega_{ce} > 0$ (Im$k_B = 0$) and evanescent at $\omega_0 - 2\omega_{ce} < 0$ ($|\mathrm{Im}k_B| \gg |\mathrm{Re}k_B|$).

In a nonuniform magnetic field, the X- and B-modes turn out to be coupled. The coupling is the strongest in the ECR region, where the dispersive properties of the medium vary most rapidly, and gradually weakens with increasing distance from the resonance region. As a result, a fraction of the X-wave energy can transform in the resonance region into the energy of the B-mode propagating toward the lower magnetic field.

Set of equations (8) and (9) was solved for the conditions close to the experiment on ECR plasma heating in the L-2M stellarator. It was assumed that the X-wave with the frequency $f_0 = 75$ GHz ($\lambda_0 = 0.4$ cm) was incident from the right (from the low-field side) and propagated along the x axis toward negative values of x (toward the major axis of the vacuum chamber). The magnetic field was directed along the z axis. The resonance point $\omega_0 = 2\omega_{ce}$ was at $x = 0$. The gradient of the magnetic field along the x axis was assumed to be constant and equal to its value on the minor axis of the stellarator chamber, $|\mathrm{d}B_0/\mathrm{d}x|/B_0 \equiv L^{-1} \approx 0.0116\,\mathrm{cm}^{-1}$. The plasma density and temperature were assumed to be constant and equal to $n_e = 1.75 \times 10^{13}\,\mathrm{cm}^3$ ($v \approx 0.25$) and $T_e = 1$ keV, respectively.

The problem was solved numerically by the sweep method [8] with a spatial step of $\Delta x = 0.004$ cm. The boundary condition at the right boundary corresponded to the superposition of the incident X-wave with a given amplitude, the reflected X-wave, and the outgoing (right-propagating) B-wave. The boundary condition at the left boundary corresponded to the transmitted (left-propagating) X-wave. The heavy solid line in Fig. 3 shows the amplitude of the transverse component of the electric field $|E_y|$. The dashed line in Fig. 3 shows ReE_y as a function of x at a certain instant of time. The light solid line shows the amplitude of the longitudinal components of the electric field $|E_x|$. It is seen that the X-wave experiences strong damping in the resonance region over a length comparable with its wavelength. The coefficient of power transmission through the resonance region is $T^2 = 0.59 \times 10^{-2}$, which is very close to its value calculated for the same parameters in the geometrical optics approximation [9] ($T^2 = 0.57 \times 10^{-2}$).

In the region $x > 0$, the profile of the amplitude of the transverse field $|E_y|$ exhibits spatial oscillations with the period equal to one-half of the wavelength of the X-wave, which corresponds to the presence of a wave reflected from the resonance region. The power reflection coefficient of the X-wave in this case is $R_X^2 \approx 1.56 \times 10^{-3}$. Thus, the result of numerical calculation of the reflection coefficient of the X-wave from the set of full-wave equations (8) and (9) turns out to be close to the values obtained in the above-described experiment.

To be assured that spurious reflection from the boundaries of the computation region was negligibly small, we performed a test calculation in which the magnetic field was reduced by 10%, so that there was no longer a resonance at the second harmonic of the electron gyrofrequency in the computation region (i.e., the entire computation region was in the zone of the weak magnetic field). In this case, the power reflection coefficient of the X-wave was at a level of $\sim 10^{-15}$.

Small-scale oscillations observed in the profile of the amplitude of the longitudinal field $|E_x|$ (see Fig. 3) are a result of the interference between the longitudinal electric fields of the X-wave and the B-wave propagating toward the region of the weak magnetic field. In this case, the coefficient of X-B transformation (in terms of the power) is $R_B^2 = 0.12 \times 10^{-3}$.

4. Conclusions

In experiments on ECR heating of plasma at the second harmonic of the electron gyrofrequency in the L-2M stellarator, the effect of partial reflection of high-power gyrotron radiation from the ECR heating region located in the center of the plasma column has been revealed. The reflection coefficient is found to be on the order of 10^{-3}, which agrees with the results of full-wave numerical calculations.

To conclude, we note that microwave reflection from the ECR heating region can contribute to the low-frequency modulation of the gyrotron power caused by the reflected wave. Since the reflection coefficient depends strongly on the electron temperature, this effect can, in principle, be used to estimate the electron temperature in the ECR region.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research, project nos. 11-08-01129a and 12-02-31522.

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