THE EFFECT OF LOW-DENSITY BACKGROUND PLASMA ON FREQUENCY AND ENERGY CHARACTERICTICS OF COAXIAL GYROTRON CAVITY

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The effect of low density background plasma on the electromagnetic field energy density in the ITER relevant coaxial gyrotron cavity is studied. The model of cold collisionless magnitoactive plasma is used. The dispersion relation and expression for the density of RF energy in plasma-filled coaxial gyrotron cavity are derived in the analytical form and analyzed numerically. It is shown that presence of low density plasma in coaxial gyrotron cavity leads to downshift of the operational frequency and to decreasing Ohmic loads of both the outer and inner conductors of coaxial gyrotron cavity.

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INTRODUCTION AND MOTIVATION

Gyrotrons are seen as the most promising configurations for high-power Electron Cyclotron Resonance Heating (ECRH) and current drive in tokamaks and stellarators [1, 2]. New generation of millimeter-wave gyrotrons developed for plasma heating utilize coaxial cavities operating in high-order modes. The choice of modes is dictated by the mode selection requirements and the admissible level of the heat load on the cavity walls. These devices can deliver microwave power more than 2 MW and have potentials for further increasing power-handling capabilities. For example, 170 GHz coaxial cavity gyrotrons with 2 MW output power are regarded as potential ECRH sources in ITER [3, 4]. Low density background plasma appears in the coaxial gyrotron cavity in the long pulse regimes and can influence gyrotron operation.

The main goal of the work is to study the effect of low-density background plasma on electromagnetic properties of the ITER relevant coaxial gyrotron cavity.

For illustration of the results we use parameters of the 170 GHz, 2 MW, CW coaxial-cavity gyrotron (relevant to the ITER requirements), which is developed in Karlsruhe Institute of Technology (KIT), Forschungszentrum Karlsruhe, Germany.

1. MODEL OF A COAXIAL GYROTRON CAVITY FILLED WITH PLASMA

Due to significant difficulties of the direct analysis of the plasma-filled coaxial gyrotron cavity we assume several idealizations. First, instead of the cavity we consider infinitely long coaxial waveguide with perfect conducting walls. Second, we assume that the inner rod is smooth (in reality it is corrugated). Also it is assumed that the waveguide is filled by a homogeneous cold magnetized plasma with the tensor of dielectric permittivity (1).

We have started our study, considering plasma effect on cutoff frequencies of the cavity ($k_z = 0$).

$$\varepsilon = \begin{pmatrix} \varepsilon_1 & i\varepsilon_2 & 0 \\ -i\varepsilon_2 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix}, \qquad (1)$$

where $\varepsilon_1 = 1 - \left(\xi^2 / 1 - \tau^2\right)$, $\varepsilon_2 = -\left(\xi^2 \tau / 1 - \tau^2\right)$ and $\varepsilon_3 = 1 - \xi^2$, $\xi = \omega_p / \omega$, $\tau = \omega_H / \omega$, $\omega_p = \sqrt{n_e e^2 / m_e \varepsilon_0}$, $\omega_H = eB_0 / m_e$.

Using Maxwell equations and the dielectric tensor of plasma (1) we derived the equation for H_z in the form

$$\left(\Delta_\perp + k_\perp^2\right) H_z = 0, \qquad (2)$$

$$\left.\left[\varepsilon_1 \frac{\partial H_z}{\partial r} + \frac{m}{r}\varepsilon_2 H_z\right]\right|_{r=R_0} = 0,$$
$$\left.\left[\varepsilon_1 \frac{\partial H_z}{\partial r} + \frac{m}{r}\varepsilon_2 H_z\right]\right|_{r=R_i} = 0, \qquad (3)$$

where $k_\perp = k\sqrt{\varepsilon_1^2 - \varepsilon_2^2 / \varepsilon_1}$ and $k = \omega\sqrt{\varepsilon_0 \mu_0}$. Boundary conditions express that tangent electric field at the outer and inner conductors should be equal to zero.

The solution of (2) with boundary conditions (3) is

$$H_z(r) = A(J_m(k_\perp r) + \alpha Y_m(k_\perp r)) \equiv AZ_m(k_\perp r), \qquad (4)$$

where

$$\alpha = -\left[J_m'\left(\frac{\chi}{C}\right) + \frac{\varepsilon_2 mC}{\varepsilon_1 \chi} J_m\left(\frac{\chi}{C}\right)\right] \Big/ \left[N_m\left(\frac{\chi}{C}\right) + \frac{\varepsilon_2 mC}{\varepsilon_1 \chi} N_m\left(\frac{\chi}{C}\right)\right]$$

$\chi = k_\perp R_o$ and $C = R_0 / R_i$. The other components of electromagnetic fields are expressed using H_z.

The dispersion relation for determination the cutoff frequencies for $TE_{m,n}$ mode is

$$Z_m'(\chi) + \left(\varepsilon_2 m / \varepsilon_1 \chi\right) Z_m(\chi) = 0. \qquad (5)$$

It should be noted that in the case considered cut-off frequencies of co-rotating (m>0) and counter-rotating (m<0) modes are different. Assuming $\varepsilon = 1$ and $\varepsilon_2 = 0$ we come to the dispersion relation for a vacuum coaxial waveguide.

2. NUMERICAL RESULTS

The dependence of the normalized cutoff frequency versus the plasma density for the operational mode is presented in Fig. 1. Calculational parameters are presented in the Table. As it can be seen, background plasma leads to decrease of the cutoff frequency.

The effect of plasma on eigenvalues of competing modes (two triplets {TE$_{35,19}$; TE$_{34,19}$; TE$_{33,19}$} and {TE$_{-33,20}$; TE$_{-32,20}$; TE$_{-31,20}$}) is demonstrated in Fig. 2.

Parameters of the Coaxcial Gyrotron Cavity

Parameters	value
Frequency, *GHz*	$f = 170$
Magnetic field, *T*	$B = 6.72$
Operational mode	$TE_{34,19}$
Inner radius (middle cross-section), *cm*	$R_i = 0.8$
Outer radius(middle cross-section) , c*m*	$R_o = 2.955$

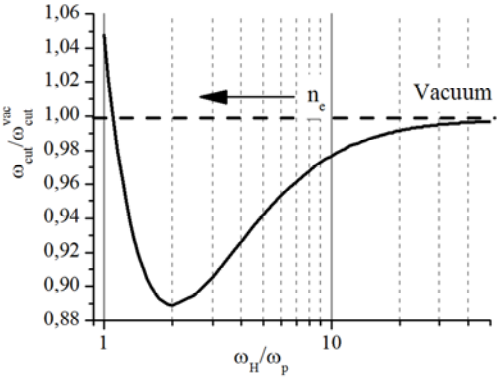

Fig. 1. Dependence of the cut-off frequency for operational modeon plasma density

Fig. 2 shows that for 'plasma' case the pair of modes (TE$_{-33,20}$; TE$_{35,19}$) become closer, as well as (TE$_{-32,20}$; TE$_{34,19}$) and (TE$_{-31,20}$; TE$_{33,19}$). Besides, co-rotating and counter-rotating modes show different behavior versus plasma density. For co-rotating modes the positive slope becomes larger and for counter-rotating smaller.

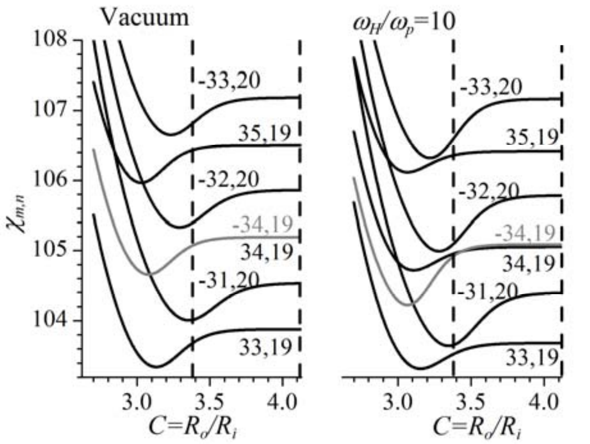

Fig. 2. The effect of plasma on eigenvalues of the most dangerous competing modes

The effect of plasma density on eigenvalues of TE$_{34,19}$ and TE-$_{34,19}$ modes is demonstrated in the Fig. 3 for fixed value of C, which corresponds to the middle cross-section of the coaxial gyrotron cavity. One can see that for co-rotating mode (*m > 0*) the eigenvalue shift is negative, and for counter-rotating mode (*m<0*) the eigenvalue shift is positive. In contrast, in the vacuum case eigenvalues for these modes coincide.

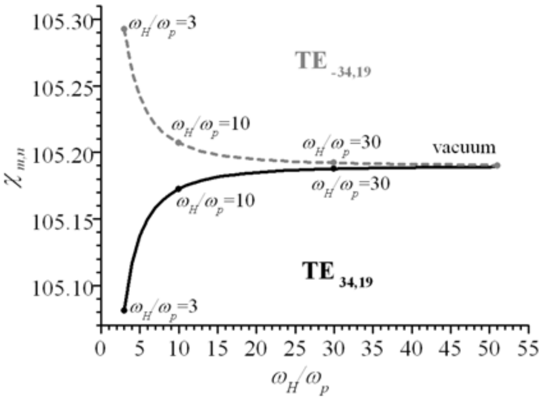

Fig. 3. The effect of plasma density on eigenvalues of TE$_{34,19}$ and TE-$_{34,19}$ modes

In conclusion, we present the plasma influence on energy characteristics of the coaxial gyrotron cavity. For this purpose, analytical expression for the energy density was derived

$$W = \frac{\pi\mu_0}{4}\left\{\frac{k^2\left(\omega\varepsilon_1\right)'_{\omega}}{2k_\perp^2}\left[\left(\varepsilon_1+\varepsilon_2\right)^2 I_1+\left(\varepsilon_1-\varepsilon_2\right)^2 I_2\right]+I_3\right\}, \quad (6)$$

where $I_1 = \int_{R_i}^{R_0} Z_{m-1}^2\left(k_\perp r\right) r dr$, $I_2 = \int_{R_i}^{R_0} Z_{m+1}^2\left(k_\perp r\right) r dr$,

$$I_3 = \int_{R_i}^{R_0} Z_m^2\left(k_\perp r\right) r dr .$$

Using expression (6) the dependence of the linear energy density (energy per unit length of coaxial gyrotron cavity) on the plasma density was calculated for fixed value of radiuses ratio, which corresponds to the middle cross-section of the coaxial gyrotron cavity (Fig. 4). One can see that energy increases with increasing plasma density. The values on Fig. 4 are normalized with the vacuum value of the linear energy density for which the axial magnetic field on the outer conductor is the same.

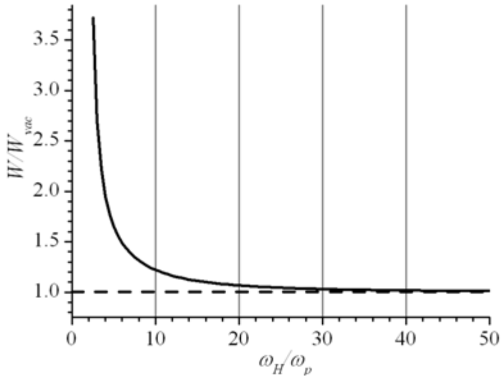

Fig. 4. The energy content versus plasma density

In order to estimate the effect of the background plasma on Ohmic losses in the inner conductor we calculated the axial magnetic field on the inner conductor and compared it with the vacuum value at the same linear energy density. The results are presented in Fig. 5. Calculations were made for the middle cross-section of the coaxial gyrotron cavity.

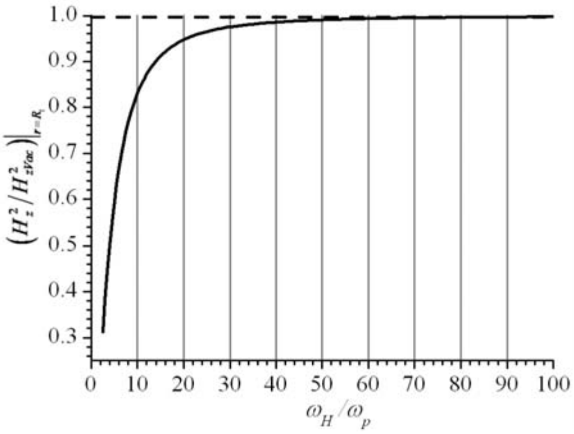

Fig. 5. The dependence of axial magnetic field on the inner rod on plasma density

Since the density of Ohmic losses is proportional to $|H_z|^2$ one can conclude that the background plasma lead to decreasing of Ohmic losses in the inner rod of the coaxial gyrotron cavity.

SUMMARY

The analytical model of the plasma-filled coaxial gyrotron cavity is developed. The effect of the low-density plasma on the cutoff frequencies and the RF energy density of the coaxial gyrotron cavity are studied. It is assumed that the inner rod is smooth and the coaxial gyrotron cavity is filled uniformly by a cold low-density magnetized plasma.

The dispersion relation (5) for cutoff frequencies (k_z=0) is derived taking into account the effect the background plasma. It is shown that plasma leads to downshift of cutoff frequency of the operational mode and consequently to the downshift the operational frequency of $TE_{34,19}$ coaxial cavity gyrotron. The effect of plasma on frequencies of the triplets of competing modes $\{TE_{35,19};\ TE_{34,19};\ TE_{33,19}\}$ and $\{TE_{-33,20};\ TE_{-32,20};\ TE_{-31,20}\}$ is shown as well (see Fig. 2).

The analytical expression for the RF energy linear density was derived. Using this expression the dependence of the linear energy density on the background plasma density was calculated. Also influence of plasma on Ohmic losses in the outer and inner conductors of coaxial gyrotron cavity is investigated. It is showed that plasma lead to increasing the energy density in the coaxial gyrotron cavity (due to the additional energy of plasma electrons oscillating in RF field) and decreasing Ohmic losses in both outer and inner conductor of coaxial gyrotron cavity (due to plasma influence on transverse distribution of field in the coaxial gyrotron cavity).

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ВЛИЯНИЕ ФОНОВОЙ ПЛАЗМЫ НИЗКОЙ ПЛОТНОСТИ НА ЧАСТОТНЫЕ И ЭНЕРГЕТИЧЕСКИЕ ХАРАКТЕРИСТИКИ КОАКСИАЛЬНОГО ГИРОТРОНА

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Изучено влияние фоновой плазмы низкой плотности на плотность энергии электромагнитного поля в коаксиальном резонаторе гиротрона ITER. Используется модель бесстолкновительной, магнитоактивной плазмы. Дисперсионное соотношение и выражение для плотности СВЧ-энергии в плазмонаполненном коаксиальном резонаторе гиротрона получены аналитически и исследованы численно. Показано, что наличие плазмы низкой плотности в коаксиальном резонаторе гиротрона приводит к уменьшению рабочей частоты и уменьшению омических потерь на внешней стенке и внутреннем проводнике резонатора коаксиального гиротрона.

ВЛИВ ФОНОВОЇ ПЛАЗМИ НИЗЬКОЇ ГУСТИНИ НА ЧАСТОТНІ ТА ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ КОАКСІАЛЬНОГО ГІРОТРОНА

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Вивчено вплив фонової плазми низької щільності на густину енергії електромагнітного поля в коаксіальному резонаторі гіротрона ITER. Використовується модель беззіткненної, магнітоактивної плазми. Дисперсійні співвідношення та вираз для густини НВЧ-енергії в плазмонаповненому коаксіальному резонаторі гіротрона отримані аналітично та досліджені чисельно. Показано, що наявність плазми малої густини в коаксіальному резонаторі гіротрона призводить до зменшення робочої частоти та зменшення омічних втрат на зовнішній стінці та на внутрішньому провіднику резонатора коаксіального гіротрона.