COAXIAL GYRO-BWO.
1. LINEAR THEORY. STARTING CURRENTS

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UDC 621.372.8
‰ 2004

The analytical investigation of the backward wave oscillator operating at the resonance of a relativistic electron beam (REB) with a backward wave on the normal Doppler effect (gyro-BWO) in a coaxial tube is developed. The linear theory of exciting process is presented. The dependence of starting current values upon the coaxial waveguide length, electron beam energy, magnetic field strength, and ratio of the initial transversal momentum of REB to its initial longitudinal one is investigated.

The gyro-BWO is a HF oscillator in which a REB coupling with a backward wave on normal Doppler effect is used. The first research of gyro-devices was proposed in [1]. The recent experimental investigations of gyro-BWO are published in [2¯6]. The state of the art of the gyro-BWO program is represented in reviews [7¯9]. Gyro-BWO allows one to generate HF radiation power (up to ~ 1GW at 10 GHz in short pulse [4] and 340kW at 28 GHz in CW regime [9, 10]). Possible applications of the HF radiation of obtained levels are the following: electron cyclotron resonance heating of plasma for controlled fusion, communication, spectroscopic researches, high-resolution radars, etc.

Analytical investigations for gyro-BWO in linear [11¯13] and nonlinear [14] approximations have been carried out only for circular and rectangular waveguides. In this paper, the case of a coaxial waveguide is investigated for gyro-BWO elaboration. The choice of it is conditioned by a more value of the vacuum limiting current of REB for a coaxial waveguide comparatively to other types of waveguides. In addition, in some recently appeared numerical and experimental researches of coaxial gyrotrons [15], it was shown that a coaxial device possesses the additional capability of increasing its efficiency by applying independently an appropriate constant voltage to outer and inner cylinders.

In the first part of the coaxial gyro-BWO investigation presented in this paper, the results of the linear approximation are presented. Starting currents and eigen frequencies of HF-generation in dependence on the coaxial waveguide length, electron beam energy, magnetic field strength, and ratio of the initial tranversal momentum to the longitudinal one are obtained.

The electron beam and waveguide support the oscillations which can be described by

$$\omega = k_{||} V_{||} + n\, \Omega_H / \gamma, \quad (1)$$

$$\omega^2 = c^2 k_\perp^2 + c^2 k_{||}^2, \quad (2)$$

where $\Omega_H = \dfrac{eH_0}{mc}$ is the nonrelativistic gyro-frequency of electrons with energy $E = m_0 c^2 (\gamma - 1)$, γ ¯ relativistic factor, $n = 0, \pm 1, \pm 2$` An operating mode for gyro-BWO (see Fig. 1) is near to the interception of a straight line (1) and parabola (2) in the coordinate plane $(\omega, k_{||})$ (for the gyro-BWO, the longitudinal wave number $k_{||} < 0$). We note that, for the gyro-BWO, the phase velocity and group velocity have the same direction, while for a Cherenkov backward-wave oscillator (BWO), the phase velocity and group velocity have opposite directions.

The Basic Equations

Let’s consider the coaxial waveguide formed by two coaxial cylinders of length L and radii a and b $(a > b)$. At the input $z = 0$, there is the annular monoenergetic REB with the initial distribution function

$$f_0 = \frac{n_b}{\pi}\, \delta(p_\perp^2 - p_{\perp 0}^2)\, \delta(p_{||} - p_{||0}),$$

where n_b is the electron beam density, $p_\perp, p_{||0}$ ¯ initial transversal and longitudinal momenta, accordingly. The system is placed into a constant longitudinal magnetic field H_0. As is well known, for the considered case, the most effective coupling of the electron beam and the eigenmode of the waveguide takes place under the electron cyclotron resonance condition $\omega - k_{||} V_{||} \approx n\, \Omega_H / \gamma$. For obtaining the set of equations describing the given coupling of the beam and backward wave TE_{01} of the coaxial waveguide, we use the Maxwell equations for the nonzero component of the electromagnetic field,

$$\frac{\partial H_r}{\partial z} - \frac{\partial H_z}{\partial r} = \frac{1}{c}\frac{\partial E_\varphi}{\partial t} + \frac{4\pi}{c} j_\varphi,$$

$$\frac{\partial E_\varphi}{\partial z} = \frac{1}{c}\frac{\partial H_r}{\partial t},$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rE_\varphi) = -\frac{1}{c}\frac{\partial H_z}{\partial t}, \quad (3)$$

and the equations of motion for REB electrons in Lagrangian variables

$$V_{||}\frac{d\vec{p}}{dz} = -eE_\varphi\vec{e_\varphi} - \frac{e}{c}H_z\vec{V}\times\vec{e_z} - \frac{e}{c}H_r\vec{V}\times\vec{e_r} -$$

$$-m\,\Omega_H\vec{V}\times\vec{e_z}, \quad (4)$$

where $\vec{e_r}, \vec{e_\varphi}$ and $\vec{e_z}$ are unit vectors along the axes r, φ and z,

$$j_\varphi = -e\int V_\varphi f\,d^3p.$$

The set of equations (3) is reduced to an equation of second order for the azimuthal components of the electrical field E_φ

$$\frac{\partial^2 E_\varphi}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E_\varphi}{\partial t^2} + \frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}(rE_\varphi) = \frac{4\pi}{c^2}\frac{\partial j_\varphi}{\partial t}, \quad (5)$$

We choose the dependence of E_φ upon r, t and z as

$$E_\varphi(r, z, t) = \frac{1}{2}(\tilde{E}_\varphi(z, t)\,e^{-i(\omega t - k_{||}z)} +$$

$$+\tilde{E}^*_\varphi(z, t)\,e^{i(\omega t - k_{||}z)})\,R_1(k_\perp r), \quad (6)$$

where $\tilde{E}_\varphi(z, t)$ is the amplitude of an excited wave that slowly changes with z and t,

$$\left|\frac{1}{\tilde{E}_\varphi(z, t)}\frac{\partial\tilde{E}_\varphi}{\partial z}\right| << k_{||}; \quad \left|\frac{1}{\tilde{E}_\varphi(z, t)}\frac{\partial\tilde{E}_\varphi}{\partial t}\right| << \omega,$$

$R_1(k_\perp r)$ is the function describing the radial structure of the excited field in the coaxial waveguide

$$R_\perp(k_\perp r) = J_1(k_\perp r) - \frac{J_1(k_\perp a)}{N_1(k_\perp a)}N_1(k_\perp r),$$

$J_1(x)$ and $N_1(x)$ are cylindrical Bessel and Neumann functions of the 1st order, $k_\perp$ is the eigen transverse

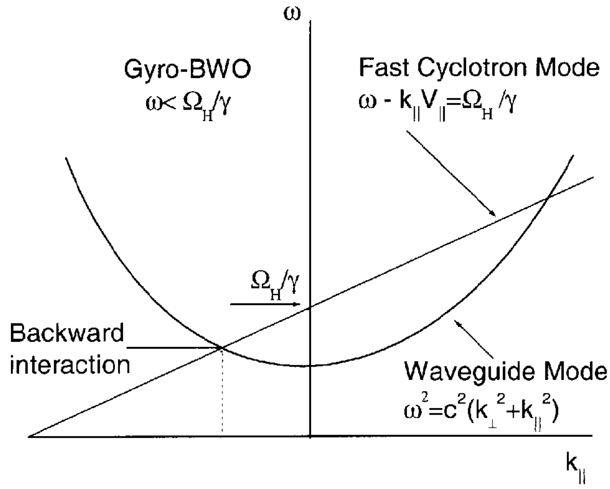

Fig. 1. REB-backward wave interaction in a gyro-BWO device

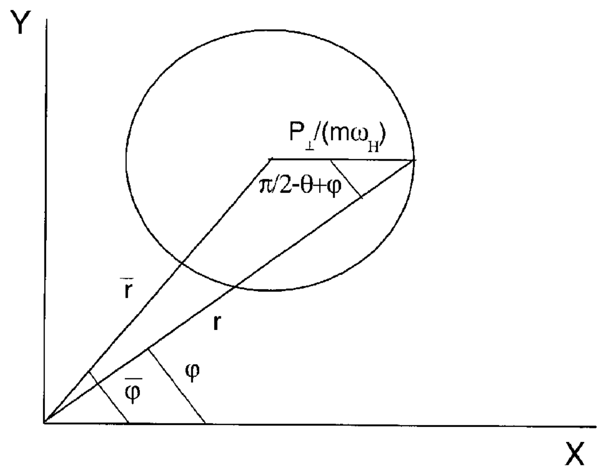

Fig. 2. Orbit of an electron in gyro-BWO

wave number that can be found from the solution of the dispersion equation for TE_{01}-mode,

$$J_1(k_\perp b) - \frac{J_1(k_\perp a)}{N_1(k_\perp a)}N_1(k_\perp b) = 0.$$

Substituting (6) into (5) and (4), we pass from the variables r and φ to variables $\bar{r}$ and $\bar{\varphi}$, the guiding center radius of a Larmor orbit of electrons and the azimuthal angle of the Larmor orbit center, respectively (see Fig. 2). They are related by the expressions

$$r^2 = \bar{r}^2 + \frac{p_\perp^2}{m^2\omega_H^2} + \frac{2p_\perp\bar{r}}{m\,\omega_H}\sin(\theta - \bar{\varphi}),$$

$$\varphi = \bar{\varphi} - \frac{p_\perp}{m\,\omega_H \bar{r}} \cos(\theta - \bar{\varphi}), \qquad (7)$$

where θ is an angle in the momentum space

$$\mathrm{tg}\,\theta = \frac{p_x}{p_y}, \quad p_\perp = (p_x^2 + p_y^2)^{1/2}.$$

For further calculations, we use the formula for summation of cylindrical functions

$$e^{is\beta} Z_s(w) = \sum_{n=-\infty}^{\infty} Z_{s+n}(U)\, J_n(u)\, e^{in\varphi}$$

where the variables w, U, u, β, φ are connected by the relation

$$U - u\cos\varphi = w\cos\beta,$$

$$u\sin\varphi = w\cos\beta,$$

$Z_s(w)$ are Bessel and Neumann functions of the s-order, and the Liouville theorem on phase volume conservation reads

$$f\, d^3 p d^3 r = f_0\, d^3 p(0)\, d^3 r(0),$$

where $f_0\, d^3 p(0)\, d^3 r(0)$ is the initial phase volume of beam particles in the injection plane $z = 0$.

We get the equation for the excited field amplitude

$$\left(\frac{\partial}{\partial t} - \frac{|k_{||}|\, c^2}{\omega}\frac{\partial}{\partial z}\right)\tilde{E}_\varphi = \frac{ie V_{||} n_b}{2\pi ||R^2||} \times$$

$$\times \int_0^{2\pi} d\Psi(0) \int_{r_b}^{r_b+\Delta} \bar{r}(0)\, d\bar{r}(0) \frac{V_\perp}{V_{||}} e^{i\Psi} R_1(k_\perp \bar{r}), \qquad (8)$$

and the equation of motion for beam electrons

$$V_{||}\frac{d\bar{r}}{dz} = \frac{ek_\perp p_\perp}{2m^2\omega_H^2}\left[\left(1 - \frac{k_{||}V_{||}}{\omega}\right) - \frac{dR_1(\bar{k}_\perp r)}{d(\bar{k}_\perp r)} - \right.$$

$$\left. - \frac{\omega_H R_0(\bar{k}_\perp r)}{\gamma\omega}\right] \frac{1}{2i}(\tilde{E}_\varphi e^{-i\Psi} + \tilde{E}_\varphi^* e^{i\Psi}),$$

$$V_{||}\frac{dp_{||}}{dz} = -\frac{eV_\perp k_{||}}{4i\omega} R_1(k_\perp r)(\tilde{E}_\varphi e^{-i\Psi} - \tilde{E}_\varphi^* e^{i\Psi},$$

$$V_{||}\frac{dp_\perp}{dz} = -\frac{e}{4i}\left(1 - \frac{k_{||}V_{||}}{\omega}\right)\times$$

$$\times R_1(k_\perp \bar{r})(\tilde{E}_\varphi e^{-i\Psi} - \tilde{E}_\varphi^* e^{i\Psi}),$$

$$V_{||}\frac{d\gamma}{dz} = -\frac{ep_\perp}{4i\gamma} R_1(k_\perp \bar{r})(\tilde{E}_\varphi e^{i\Psi} - \tilde{E}_\varphi^* e^{i\Psi}),$$

$$V_{||}\frac{d\Psi}{dz} = \omega - k_{||}V_{||} - \frac{\omega_H}{\gamma} + \frac{e}{4p_\perp}\times$$

$$\times\left(1 - \frac{k_{||}V_{||}}{\omega}\right) R_1(k_\perp \bar{r})(\tilde{E}_\varphi e^{-i\Psi} + \tilde{E}_\varphi^* e^{i\Psi}),$$

where $\omega_H = \Omega_H/\omega$, $\Psi = \omega t - k_{||} z - \theta + \bar{\varphi}$.

We introduce the dimensionless variables and parameters

$$C_\varphi = \frac{e\tilde{E}_\varphi}{m\,c\,\omega}, \quad a_\perp = \frac{p_\perp}{mc}, \quad a_{||} = \frac{p_{||}}{mc},$$

$$\xi = z\frac{\omega^2}{c^2 k_{||}}, \quad \bar{\rho} = k_\perp \bar{r}, \quad \tau = \omega t,$$

$$\bar{k}_{||} = \frac{k_{||}c}{\omega}, \quad \bar{k}_\perp = \frac{k_\perp c}{\omega}, \quad \alpha = \frac{\omega_b^2 V_{||}(0)}{4\pi c\,\omega^2 k_\perp^2 ||R^2||},$$

where

$$||R^2|| = \int_b^a r\,dr\,R_1^2(k_\perp r), \quad \omega_b^2 = \frac{4\pi e^2 n_b}{m}.$$

In such variables, the set of equations (8), (9) has the following view:

$$\left(\frac{\partial}{\partial\tau} - \frac{\partial}{\partial\xi}\right) C_\varphi = -\frac{i\alpha}{2\pi}\int_0^{2\pi} d\Psi(0)\times$$

$$\times \int_{\rho_b}^{\rho_b+\Delta} \bar{\rho}(0)\, d\rho(0) \frac{a_\perp}{a_{||}} e^{i\Psi} R_1(\bar{\rho}) \qquad (10)$$

and

$$\frac{d\bar{\rho}}{d\xi} = -\frac{\bar{k}_\perp^2 \bar{k}_{||}\gamma}{2\omega_H^2 a_{||}}\left[\left(1 - \frac{\bar{k}_{||}a_{||}}{\gamma}\right)\frac{dR_1(\bar{\rho})}{d\bar{\rho}} - \right.$$

$$\left. - \frac{\omega_H R_0(\bar{\rho})}{\gamma}\right]\frac{1}{2i}(C_\varphi e^{-i\Psi} - C_\varphi^* e^{i\Psi}),$$

$$\frac{da_{||}}{d\xi} = \frac{a_\perp k_{||}^2}{4i\,a_{||}} R_1(\bar{\rho})(C_\varphi e^{-i\Psi} - C_\varphi^* e^{i\Psi}),$$

$$\frac{da_\perp}{d\xi} = -\frac{\bar{k}_{||}\gamma}{4i\,a_{||}}\left(1 - \frac{\bar{k}_{||}a_{||}}{\gamma}\right) R_1(\bar{\rho})(C_\varphi e^{-i\Psi} - C_\varphi^* e^{i\Psi}),$$

$$\frac{d\gamma}{d\xi} = \frac{a_\perp \bar{k}_{||}}{4i\,a_{||}} R_1(\bar{\rho})(C_\varphi e^{-i\Psi} - C_\varphi^* e^{i\Psi}),$$

$$\frac{d\Psi}{d\xi}=\frac{\gamma|\bar{k}_{||}|}{a_{||}}\left(1-\frac{\bar{k}_{||}a_{||}}{\gamma}-\frac{\omega_H}{\gamma}\right)+$$
$$+\gamma\frac{|\bar{k}_{||}|}{4a_{||}a_{\perp}}\left(1-\frac{\bar{k}_{||}a_{||}}{\gamma}\right)R_1(d\bar{\rho})(C_\varphi e^{-i\Psi}+C_\varphi^{*}e^{i\Psi}), \quad (11)$$

where $\rho_b=r_b k_\perp$, Δ – normalized depth of a beam.

Let's supplement Eqs. (10) and (11) by boundary conditions for the phase and momenta of REB particles and the excited wave amplitude

$$\Psi|_{\xi=0}\in[-\pi,\pi],\ a_\perp|_{\xi=0}=a_{\perp 0}=\frac{p_{\perp 0}}{mc},$$

$$a_{||}|_{\xi=0}=a_{||0}=\frac{p_{||0}}{mc},\quad C_\varphi|_{\xi=\bar{L}}=0,$$

where $\bar{L}=\omega L/(-\bar{k}_{||}c)$ – normalizing length.

While obtaining the set of equations (10) and (11), we supposed that the condition $p_\perp/m\,\omega_H \ll \bar{r},\ k_\perp^{-1}$ is satisfied.

Linear Theory

To obtain the value of the starting current I_{st}, we linearize the set of equations (10), (11), supposing that the perturbations of the field amplitude and momenta and phase of electrons are small. Introducing the functions

$$W_1=\frac{1}{2\pi}\int_0^{2\pi}d\Psi_0\int_{\rho_b}^{\rho_b+\Delta}\bar{\rho}(0)\,d\bar{\rho}(0)\,\delta\bar{\rho}\,R_0(\bar{\rho})\,e^{i\Psi(0)},$$

$$W_2=\frac{1}{2\pi}\int_0^{2\pi}d\Psi_0\int_{\rho_b}^{\rho_b+\Delta}\bar{\rho}(0)\,d\bar{\rho}(0)\,\delta a_\perp\,R_1(\bar{\rho})\,e^{i\Psi(0)},$$

$$W_3=\frac{1}{2\pi}\int_0^{2\pi}d\Psi_0\int_{\rho_b}^{\rho_b+\Delta}\bar{\rho}(0)\,d\bar{\rho}(0)\,\delta a_{||}\,R_1(\bar{\rho})\,e^{i\Psi(0)},$$

$$W_4=\frac{1}{2\pi}\int_0^{2\pi}d\Psi_0\int_{\rho_b}^{\rho_b+\Delta}\bar{\rho}(0)\,d\bar{\rho}(0)\,\delta\Psi\,R_1(\bar{\rho})\,e^{i\Psi(0)}, \quad (12)$$

we obtain a set of differential equations for the linear approximation of the coupling of the electron beam and TE_{01} mode,

$$\frac{dW_1}{d\xi}=\frac{\bar{k}_\perp^2\bar{k}_{||}}{4i\omega_H a_{||}}C_\varphi G_1,$$

$$\frac{dW_2}{d\xi}=\frac{\bar{k}_{||}\omega_H}{4ia_{||}}H_z G_2,$$

$$\frac{dW_3}{d\xi}=\frac{a_\perp\bar{k}_{||}^2}{4ia_{||}}C_\varphi G_2, \quad (13)$$

$$\frac{dW_4}{d\xi}=\frac{\bar{k}_{||}\omega_H}{4a_{||}a_\perp}C_\varphi G_2-\frac{\bar{k}_{||}}{a_{||}}\left(\frac{a_{||}}{\gamma}-\bar{k}_{||}\right)W_3-\frac{a_\perp\bar{k}_{||}}{\gamma a_{||}}W_2,$$

$$\left(\frac{\partial}{\partial\tau}-\frac{\partial}{\partial\xi}\right)C_\varphi=$$
$$=-\frac{i\alpha}{2\pi}\left[W_1+\frac{1}{a_{||}}W_2-\frac{a_\perp}{a_{||}^2}W_3+i\frac{a_\perp}{a_{||}}W_4\right],$$

$$G_1=\int_{\bar{\rho}_b}^{\bar{\rho}_b+\Delta}R_0(\bar{\rho})R_1(\bar{\rho})\,d\bar{\rho},\quad G_2=\int_{\bar{\rho}_b}^{\bar{\rho}_b+\Delta}R_1^2(\bar{\rho})\,\bar{\rho}\,d\bar{\rho},$$

$$R_0(\bar{\rho})=J_0(\bar{\rho})-\frac{J_1(k_\perp a)}{N_1(k_\perp a)}N_0(\bar{\rho})$$

with the boundary conditions

$$W_i|_{\xi=0}=0,\quad C_\varphi|_{\xi=\bar{L}}=0. \quad (14)$$

Supposing the dependence of values in (13) in the form $\sim e^{\chi\xi-i\nu\tau}$, we obtain the dispersion equation

$$\chi^3+i\nu\chi^2+A_1\chi+A_2=0 \quad (15)$$

where

$$A_1=\alpha\left(-\frac{\bar{k}_\perp^2\bar{k}_{||}a_\perp G_1}{4\omega_H a_{||}^2}-\frac{\bar{k}_{||}\omega_H G_2}{2a_{||}^2}\left(1-\frac{\bar{k}_{||}a_\perp^2 a_{||}^2}{2\omega_H}\right)\right),$$

$$A_2=-i\alpha\frac{a_\perp^2\bar{k}_{||}^2\omega_H}{a_{||}^3}\left(1+\frac{\bar{k}_{||}a_{||}}{\omega_H}-\frac{\bar{k}_{||}^2\gamma}{\omega_H}\right)G_2,$$

$$\nu=(\omega-\omega_{o.f})/\omega,$$

$\omega_{o.f}$ – operating frequency.

Equation (15) yields three possible branches of oscillations $\chi_i(\nu)$. Therefore, the excited field can be represented by the series

$$C_\varphi=\sum_{i=1}^{3}C_i e^{\chi_i\xi-i\nu\tau}, \quad (16)$$

where C_i are arbitrary constants.

Substituting (16) in (14) and (15), we obtain nonzero solutions under the condition

$$S\equiv e^{\chi_1\bar{L}}\left(\frac{1}{\chi_2\chi_3^2}-\frac{1}{\chi_3\chi_2^2}\right)+e^{\chi_2\bar{L}}\left(\frac{1}{\chi_3\chi_1^2}-\frac{1}{\chi_1\chi_3^2}\right)+$$

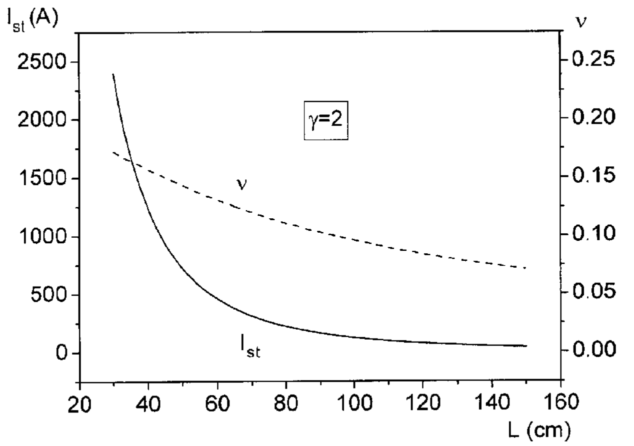

Fig. 3. Dependence of the starting current I_{st} (solid line) and detuning ν (dashed line) on the coaxial waveguide length L at eigen frequency $\omega = 62.8 \cdot 10^9$ rad/s, fixed ratio $P_{\perp 0} / P_{\| 0} = 0.3$, magnetic field $H_0 = 12.6$ kOe ($\Omega_H = 222 \cdot 10^9$ rad/s), and total energy of REB $E = 511$ keV ($\gamma = 2$)

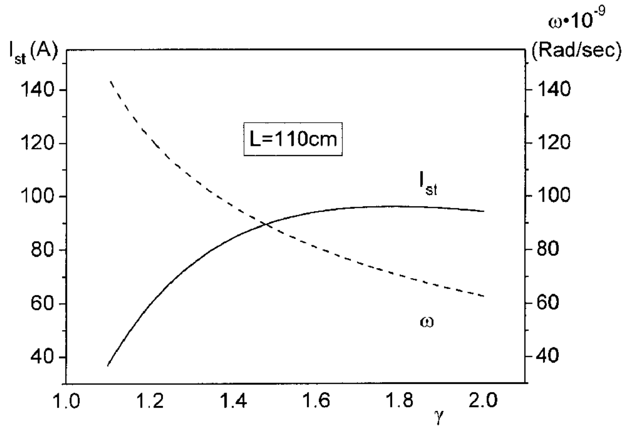

Fig. 4. Dependence of the starting current I_{st} (solid line) and frequency ω (dashed line) on the relativistic factor γ at the coaxial waveguide length $L = 110$ cm, magnetic field $H_0 = 12.6$ kOe, and fixed ratio $P_{\perp 0} / P_{\| 0} = 0.3$

$$+ e^{\chi_3 L}\left(\frac{1}{\chi_1 \chi_2^2} - \frac{1}{\chi_2 \chi_1^2}\right) = 0. \quad (17)$$

Equating the determinant to zero, we get the spectrum of oscillations. The values of ν and α in (11) are proportional to the starting current.

As a result, we obtain the condition for the starting current I_{st} of gyro-BWO

$$\mathrm{Re}\,(S) = 0, \quad \mathrm{Im}\,(S) = 0.$$

From the obtained analytical expressions, the plots for starting current I_{st} ($I = e n_b V_{\|} S_b$, S_b – cross-section of the beam, $V_{\|}$ – longitudinal velocity) and detuning ν in dependence on the system length L, electron beam energy E, magnetic field H_0, and ratio of initial transversal to longitudinal momentum of beam electrons $P_{\perp 0}/P_{\| 0}$ were calculated.

The inner radius of the coaxial waveguide was taken $b = 0.5$ cm, outer radius $a = 5$ cm, the inner radius of the annular electron beam is $R_{bi} = 3$ cm, its outer radius is $R_{be} = 3.2$ cm.

In Fig. 3, the starting current I_{st} and detuning ν are shown in dependence on the coaxial waveguide length L at the fixed ratio of initial transversal to longitudinal momenta $P_{\perp 0} / P_{\| 0} = 0.3$, constant magnetic field $H_0 = 12.6$ kOe (nonrelativistic cyclotron frequency $\Omega_H = 222 \cdot 10^9$ rad/s), energy of REB $E = 511$ keV and eigen frequency $\omega = 2\pi f = 62.8 \cdot 10^9$ Rad/s. As follows from Fig. 3, the increase of length L from 30 to 150 cm results in decreasing the starting current I_{st} from 2395 to 40 A and decreasing the detuning modulus ν from 0.017 to 0.0071.

The dependences of the starting current I_{st} and eigenfrequency ω on the relativistic factor γ for the coaxial waveguide length $L = 110$ cm, fixed ratio $P_{\perp 0}/P_{\| 0} = 0.3$, and constant longitudinal magnetic field $H_0 = 12.6$ kOe ($\Omega_H = 222 \cdot 10^9$ rad/s) are shown in Fig. 4. Under increasing the relativistic factor $\gamma = (1.1 \div 2)$, increasing starting current $I_{st} = (36 \div 94)$ A, decreasing the circular frequency $\omega = (145 \div 62.8) \cdot 10^9$ rad/s, and changing detuning $\nu = -0.0014 \div -0.009$ take place.

In Fig. 5, the dependence of the starting current I_{st} and frequency ω on magnetic field H_0 (nonrelativistic cyclotron frequency Ω_H) at the electron beam energy $E = 511$ keV, length $L = 110$ cm and $P_{\perp 0} / P_{\| 0} = 0.3$ are shown. As a result of increasing magnetic field twice $H_0 = (6.3 \div 12.6)$ kOe ($\Omega_H = (111 \div 222) \cdot 10^9$ rad/s), we can see increasing the starting current $I_{st} = 48 \div 94$ A, increasing the eigenfrequency $\omega = (34.6 \div 62.8) \cdot 10^9$ rad/s, and changing the detuning $\nu = (-0.015 \div 0.009)$.

The dependence of the starting current I_{st} and frequency ω on the ratio of initial transversal to initial longitudinal momentum of REB $P_{\perp 0}/P_{\| 0}$ at the coaxial waveguide length $L = 110$ cm, constant longitudinal magnetic field $H_0 = 12.6$ kOe ($\Omega_H = 222 \cdot 10^9$ rad/s), and total energy of electron beam $E = 511$ keV are shown in Fig.6. Increasing the ratio $P_{\perp 0}/P_{\| 0} = 0.1 \div 0.5$ results in decreasing the starting current $I_{st} = 230 \div 39$ A and changing the detuning $\nu = -0.0025 \div -0.01$ and eigen frequency $\omega = (61.8 \div 64.5) \cdot 10^9$ rad/s.

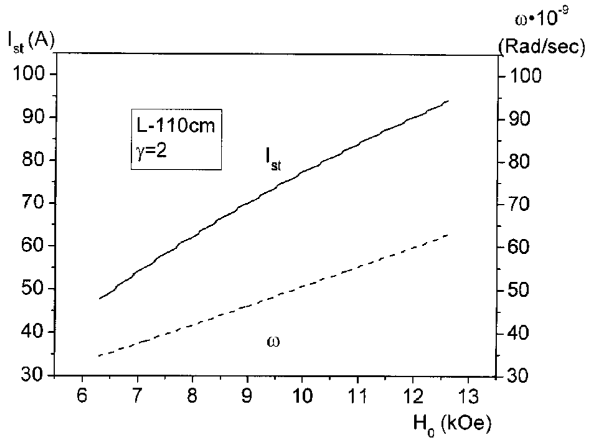

Fig. 5. Dependence of the starting current I_{st} and frequency ω on magnetic field H_0 at the coaxial waveguide length L = 100 cm, relativistic factor $\gamma = 2$, fixed ratio $P_{\perp 0} / P_{|| 0} = 0.3$, and electron beam energy E = 511 keV

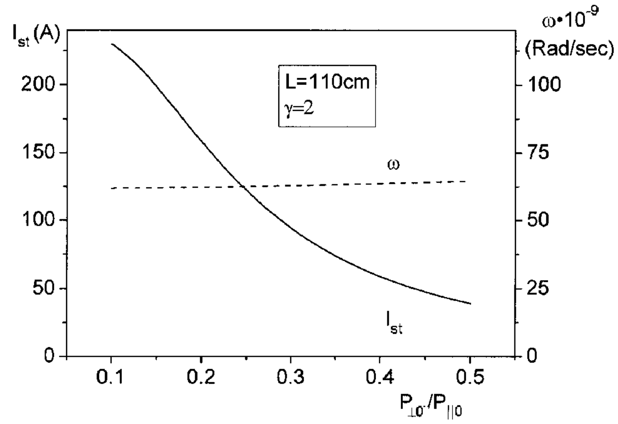

Fig. 6. Dependence of the starting current I_{st} and frequency ω the ratio of initial transversal momentum of a beam to initial longitudinal one $P_{\perp 0} / P_{|| 0}$ at the coaxial waveguide length L = 110 cm, magnetic field H_0 = 12.6 kOe, and total electron beam energy E = 511 keV

The obtained expressions for the starting current I_{st}, eigenfrequency ω and detuning ν demonstrate their essential dependence on the system length L and electron beam energy E. The obtained results in a linear approximation enable us to formulate the specific requirements to the electron beam current, length of the coaxial waveguide, and constant magnetic field for the operation of powerful gyro-BWO at a given frequency ω.

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Received 12.03.03