

COMPUTER INVESTIGATION OF EFFICIENCY ENHANCEMENT IN COAXIAL GYROTRON BACKWARD WAVE OSCILLATORS

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Abstract

An efficiency enhancement for a gyrotron backward-wave oscillator (gyro-BWO) through local variation of guiding magnetic field by special law is investigated using computer simulation. As result, more number of bunched beam electrons take up position in energy-losing phase for chosen gyro-BWO's parameters or other gyro-devices. An accelerator device buncher provides analogous effect for accelerated particles of bunched beam nearly synchronous phase.

INTRODUCTION

The gyro-BWO is a HF powerful oscillator for cm and mm band of wavelength, where relativistic electrons beam (REB) is used for coupling with a backward wave on normal Doppler effect. The first research of gyro-devices was published in 60th[1]. The state of the art of gyro-BWO program is represented in Ref. [2],[3]. In our paper the case of coaxial waveguide is investigated for gyro-BWO elaboration. Results of the linear and non-linear analytical investigation of coaxial gyro-BWO operation are presented in Ref. [4], [5]. An electron beam and waveguide support the oscillations with circular frequency ω , which can be described by the expressions for normal Doppler effect, accordingly

$$\omega = k_z V_z + n\Omega_H / \gamma \quad (1)$$

$$\omega^2 = c^2 k_\perp^2 + c^2 k_z^2 \quad (2)$$

, where $\Omega_H = \frac{eH_z^g}{mc}$ is non-relativistic gyro-frequency of electrons with energy $W = m_0 c^2 (\gamma - 1)$, H_z^g -guiding magnetic field, γ -relativistic factor, k_z, V_z -longitudinal wave number and velocity, $n=0, \pm 1, \pm 2 \dots$. An operating mode for gyro-BWO is near to interception of a straight line (1) and hyperbola (2) in coordinate plane (ω, k_z) (for gyro-BWO the longitudinal wave number $k_z < 0$). An ordinary efficiency value for coaxial gyro-BWO is $\sim 10\%$ for homogenous guiding magnetic field H_z^g .

The efficiency of the gyro-BWO is relatively lower than one of other gyro-devices. Confinement of as many electrons as possible in energy-losing phase takes place due to phase shift under optimal bunched beam formation. It is aim of our investigations. Other investigation results of efficiency enhancement in gyro-BWO were papered in Ref. [6-14]. In Ref. [6-9], the efficiency of the gyro-BWO has been found to be

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significantly improved by tapering the magnetic field. Results found revealed that the magnetic field tapering with a positive gradient tended to increase the initial frequency mismatch leading to the efficiency enhancement. In Ref. [10-12] a tapered interaction structure (the reduction of the waveguide radius along the interaction region) was proposed and used in the experiment. The gyro-BWO with a tapered magnetic field and waveguide wall radius was analyzed in Ref. [13, 14].

COMPUTER SIMULATION

We investigated in our paper efficiency enhancement in coaxial gyro-BWO through profiling of guiding magnetic field $H_z^g(z)$ at longitudinal direction z as

$$H_z^g(\xi) = H_{z0}^g (1 + \alpha(\xi/\bar{L})^j \cos^m(\pi\xi/2\bar{L}))^{1/2} \quad (3)$$

comparatively to homogenous case $H_z^g = H_{z0}^g$, where α is non-homogeneity amplitude, $\xi = z\omega/c$ is normalizing longitudinal coordinate, $\bar{L} = L\omega/c$ is normalizing waveguide length, $\xi/\bar{L} = z/L$, $j > 0$, $m > 0$. A corresponding transversal component one is

$$H_r^g(z) = -\frac{r}{2} \frac{\partial H_z^g}{\partial z},$$

where r is transversal coordinate.

We considered waveguide exciting mode TE_{01} with components of an electromagnetic field E_ϕ, H_r, H_z under satisfy conditions (1, 2). For computer simulation we used equations for electrons motion and exciting field TE_{01} from Ref. [5].

We investigated coaxial gyro-BWO with oscillation frequency $f_0 = 7.7 \text{ GHz}$ for satisfying expressions (1, 2), homogenous guiding magnetic field $H_{z0}^g = 6.1 \text{ kOe}$, inner radius of the coaxial waveguide gyro-BWO $b = 3 \text{ cm}$, outer radius one is $a = 5 \text{ cm}$, inner beam radius is $r_b = 3.9 \text{ cm}$, outer beam radius is $r_a = 4.1 \text{ cm}$, energy of injected electron beam is $W_0 = 511 \text{ keV}$ ($\gamma_0 = 2$), an initial ratio transversal momentum to longitudinal one $\mu = 1$, length of system is $L = 60 \text{ cm}$, cut off frequency $f_c = 7.5 \text{ GHz}$, starting current $I_{st} = 3.7 \text{ A}$, limiting vacuum current $I_{lim} = 6.6 \text{ kA}$ for coaxial waveguide. Maximal efficiency $\bar{\eta}_{max} \approx 0.11$ is under input beam current $I_b = 0.6 \text{ kA}$ for

homogenous guiding field and cited above gyro-BWO parameters [5].

Computer simulation of optimal regime gyro-BWO performance time averaged efficiency $\bar{\eta}$ was carried out for determination values α, m and j of profiling guiding magnetic field (3) under the same input electron beam current $I_b = 0.6kA$. We determined location, amplitude and width values of profiling guiding magnetic field for our gyro-BWO parameters. In our case optimal process for bunching of input electron beam takes place under

$$m=6, \alpha=2.9, j=1 \quad (5)$$

for expression (3). In Figure 1 we can see longitudinal distribution of guiding magnetic field for parameters (5).

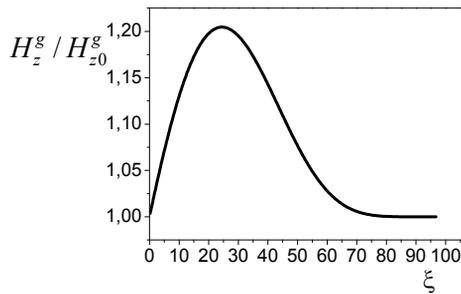


Figure 1: Dependence normalized magnetic field amplitude $H_z^g(\xi)/H_{z0}^g$ on dimensionless longitudinal coordinate ξ .

Then we used computer simulation for investigation efficiency $\bar{\eta}$ dependence on injection beam current I_b under fixed parameters of guiding field α, m and j (5).

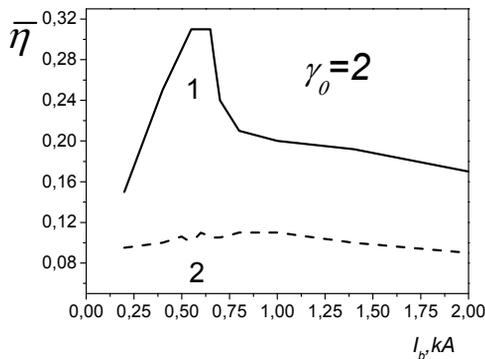


Figure 2: Dependence time averaged efficiency $\bar{\eta}$ from injection beam current I_b (curve 1 is for profiling guiding magnetic field (3), curve 2 is for homogenous one $H_z^g(z) = H_{z0}^g$).

For given injection energy $\gamma_0 = 2$ efficiency $\bar{\eta} \geq 0.25$ is for $0.7kA \geq I_b \geq 0.4kA$ (see Figure 2). An

efficiency $\bar{\eta}$ for profiling guiding field has essentially more value than efficiency $\bar{\eta}$ for homogenous case.

We suggested non-homogenous distribution (3) for creation the most optimal conditions during process bunch formation of input electron beam. In Figure 3-5 you can see difference between bunch formation for homogenous guiding magnetic field and non-homogenous one on phase plane energy-phase for various fixed values of longitudinal coordinate ξ ($I_b = 0.6kA, \gamma_0 = 2$). For all of Figures circles correspond to homogenous case, black points correspond to non-homogenous one.

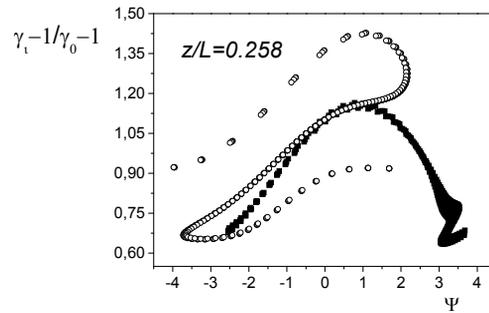


Figure 3: Dependence normalized energy of the particles beam $\gamma_i - 1/\gamma_0 - 1$ on helical (total) phase Ψ for $z/L = 0.258$ (black points correspond profiling field, circles correspond homogenous field).

The majority particles for profiling guiding magnetic field have energy-losing phase from the beginning bunch formation process comparatively homogenous one (see Figure 3).

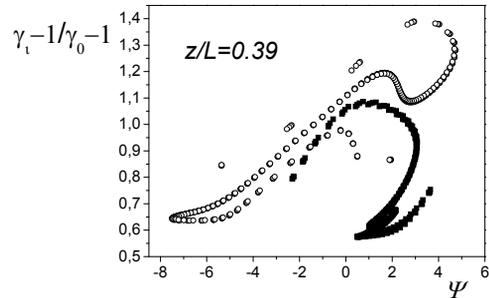


Figure 4: Dependence normalized energy of the particle beam $\gamma_i - 1/\gamma_0 - 1$ on helical (total) phase Ψ for $z/L = 0.39$.

An effective bunch formation process takes place along further increasing longitudinal coordinate (Figure 4, 5).

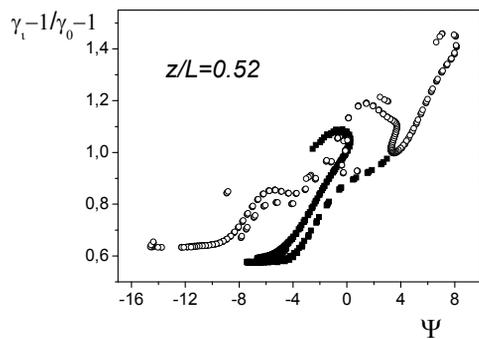


Figure 5: Dependence normalized energy of the particles beam $\gamma_i - 1 / \gamma_0 - 1$ on helical (total) phase Ψ for $z/L=0.52$.

As result phase portrait of bunched beam along longitudinal coordinate is more compact in comparison with homogenous guiding magnetic field. An effective formation of bunched beam in energy-losing phase leads to most electrons can be confined in the losing energy phase even after completion a compact bunching process (Figure 5).

CONCLUSIONS

In our paper we obtained enhancement of gyro-BWO's efficiency from 11% (homogenous distribution of guiding magnetic field) up to 32% (non-homogenous one) through profiling of magnetic field (3). Oscillation frequency has fixed value under satisfying equations (1),(2). As a result of effective process bunch formation under special conditions most electrons can be confined in the energy-losing phase. The obtained efficiency is closely to gyrotron's efficiency (without single stage depressed collector (SDC) for energy recovery).

The current mechanism can also be applied to interpret the efficiency enhancement in other gyrotron oscillators (for example, cyclotron autoresonance maser in Ref. [15]) with profiling guiding magnetic field.

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