Analysis of a proposed high microwave power ion gyromonotron

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This paper presents a proposed ion gyromonotron capable of generating extremely high microwave power. The essential feature of this device is the use of an ion beam as the intermediary agent in converting the dc energy into microwave energy. The performance of the proposed device is analyzed based on the numerical solution of the relativistic electrodynamics equations governing the device operation. All the physical effects pertinent to operation are fully taken into account. The results are displayed, discussed, and interpreted.

تعرض هذه الورقة مقترحا لجيرومونوترون أيونى قادر على توليد قدرة ميكروموجية شديدة العلو، والسمة الأساسية لهذه النبيطة هى أستخدام حزمة أيونية كعامل وسيط لتحويل طاقة التيار المستمر (الطاقة المستمرة) إلى طاقة ميكروموجية. ولقد تم تحليل أداء هذه النبيطة باستخدام الحل العددى للمعادلات الكهروديناميه النسبية الحاكمة لعمل النبيطة حيث أخذت كل التأثيرات الفيزيائية المتعلقة بعمل النبيطة فى الاعتبار، ثم تم عرض النتائج ومناقشتها وتفسيرها.

Keywords: Gyromonotron, Super high-power microwave generator, Relativistic hydrodynamics

1. Introduction

The proposed gyromonotron comprises a relativistic helical ion beam (RIB), an electrodynamics (ED) system, a superconducting solenoid to produce an axial static magnetic field B_o and an output assembly. The ED system can be an open-ended cavity of rectangular or circular cross section. The essential feature of the proposed gyromonotron is the use of an ion beam (IB) rather than the conventional electron beam (EB) for converting the dc energy into microwave energy. The kinetic energy acquired by the IB can be three orders of magnitude higher than that of the corresponding EB. Consequently, the microwave output power of the proposed device is expected to be almost three orders of magnitude higher than that of a corresponding device using an EB [1]. This means that tens of gigawatts are expected to be generated by using the proposed device. Evidently, this necessitates a corresponding increase of the static electric and magnetic fields required for operation. Therefore, the expected output power will be limited by the achievable values of these fields. The simplest ion beam is a proton beam. Hence, the results that will be presented here are for a proton-beam gyromonotron. The proposed device can find many wide applications in directed energy weapons and super-high-power radar systems [1].

In the proposed device, the interaction that leads to the microwave power generation is based on the cyclotron-maser instability [1-4]. This instability is attributed to a relativistic effect; namely, the dependence of the cyclotron frequency ω_c of ions on their energy $\Im$. This dependence is given by:

$$\omega_c = \frac{q\ B_o}{\gamma\ m}, \tag{1}$$

where q and m are the ion charge and rest mass, respectively, and γ is the relativistic factor proportional to the particle energy given by:

$$\gamma = \frac{\Im}{m\,c^2} = \frac{1}{\sqrt{1-(\frac{v}{c})^2}}, \tag{2}$$

where c is the velocity of light and v is the ion velocity. This dependence gives rise to phase bunching of ions under the action of a properly chosen cavity transverse-electric (TE) mode. Through this bunching a coupling is established between the cavity mode characterized by the dispersion relation:

$$\omega^2 - k_z^2\ v_z^2 - \omega_{co}^2 = 0, \tag{3}$$

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and the fast-cyclotron beam mode given by:

$$\omega - k_z v_z - \omega_c = 0 , \qquad (4)$$

where ω is the operating frequency, k_z is the axial-wave number, v_z is the axial-velocity of the beam, and ω_c is the cut-off frequency. For efficient interaction to occur, the two modes are required to propagate in synchronism with each other, i.e., the phase velocity v_{ph} of the cavity mode must be equal to the phase velocity of the beam mode. This requires that the Doppler-shifted frequency ω_d be equal to ω_c or one of its harmonics. The Doppler-shifted frequency is given by:

$$\omega_d = \omega - k_z v_z . \qquad (5)$$

For the exchange of energy to be from the RIB to the microwave, ω_d should be slightly higher than s ω_c ,i.e.,

$$\omega_d \geq s\,\omega_c , \qquad (6)$$

where s is the harmonic number.

Since an ion gyrates faster in a magnetic field when it has lost energy, the ions tend to bunch in phases where the electric field ahead is accelerating and that behind is decelerating. If condition (6) is satisfied, the ion bunch will slip behind the wave in phase and the bunch will be developed and remain in the favorable phase as long as condition (6) is satisfied. The formation of the bunch will be efficient since the forces of repulsion between the ions cannot disturb considerably the motion of the ions.

2. Modeling of the gyromonotron

The gyromonotron is very difficult to model analytically because the equations describing its operation must be solved using the full rigor of relativistic electrodynamics [1-5]. Therefore, our model is based on the numerical solution of the gyromonotron equations. In the gyromonotron, the ion dynamics are governed by the four-dimensional equation of motion:

$$\frac{d\vec{P}}{d\tau} = \vec{F} , \qquad (7)$$

where τ is the proper time, $\vec{P}$ is the four-momentum given by:

$$\vec{P} = (\gamma m \bar{v} , \; i m \gamma c), \qquad (8)$$

$\bar{v}$ is the three-dimensional velocity, (i) is the imaginary number, $\vec{F}$ is the Minkowski four-force given by:

$$\vec{F} = (\gamma \bar{f} , \; i \frac{\gamma}{c} \bar{f} . \bar{v}). \qquad (9)$$

The force acting on the ion is due to the electromagnetic-field tensor, $\vec{\Psi}$, which is given by:

$$\Psi_{ik} = c \left(\frac{\partial \Phi_k}{\partial x_i} - \frac{\partial \Phi_i}{\partial x_k} \right), \qquad (10)$$

where x_i are the components of the four-position vector, $\vec{R}$:

$$\vec{R} = (\bar{r} , \; i c t) , \qquad (11)$$

$\bar{r}$ is the three-dimensional position vector and $\vec{\Phi}$ is the four-potential given by:

$$\vec{\Phi} = (\bar{A} , \; \frac{i}{c} \phi), \qquad (12)$$

where $\bar{A}$ is the magnetic potential and ϕ is the electric potential.

Equation (7) can be rewritten as:

$$\frac{d m u_i}{d\tau} = \Psi_{ik} \frac{S_k}{c} , \qquad (13)$$

where u_i are the components of the four-velocity given by:

$$\overrightarrow{u} = (\gamma \overline{v}, i m \gamma c). \quad (14)$$

Note that the Einstein summation convention is used in Eq. (13). In this equation, S_k are the components of the four current given by:

$$\overrightarrow{S} = (\overline{J}, i c \rho), \quad (15)$$

where ρ is the charge density, and $\overline{J}$ is the current density.

Equation (7) can be decomposed into a vector equation and a scalar one. The vector equation is:

$$\frac{\partial \overline{v}}{\partial t} = \frac{q}{m\gamma} [\overline{E} + \overline{v} \times \overline{B} - \frac{\overline{v} \cdot \overline{E}}{c^2}], \quad (16)$$

And the scalar equation is:

$$\frac{\partial}{\partial t} \gamma m c^2 = -e\, \overline{v} \cdot \overline{E}. \quad (17)$$

In Eqs. 16 and 17, E is the electric field intensity.

The electrodynamics equations must be solved consistently with the electromagnetic wave equation given by:

$$(\nabla^2 - \frac{\partial^2}{c^2 \partial t^2}) \Phi_k = - \mu_o S_k, \quad (18)$$

where μ_o is the free-space permeability, and k = 1,2,3, and 4.

Since the ion beam will be very tenuous, its space-charge effect can be neglected and the normal mode configuration of the electromagnetic field in the cavity will not be significantly modified. If a dominant TE_{101} mode is assumed, the field components are:

$$E_y = E_m \sin(k_x x) \sin(k_z z) \cos(\omega t) \quad (19a)$$

$$B_x = B_{xm} \sin(k_x x) \cos(k_z z) \sin(\omega t) \quad (19b)$$

$$B_x = -B_{zm} \cos(k_x x) \cos(k_z z) \sin(\omega t) \quad (19c)$$

where:

$$B_{xm} = k_z \frac{E_m}{\omega}, \quad (20a)$$

$$k_z = \frac{\pi}{L}, \quad (20b)$$

$$k_x = \frac{\pi}{a}. \quad (20c)$$

In the above equations, (a) is the width of the rectangular waveguide, L is its length, E_m is the amplitude of the electric field and B_{xm} and B_{zm} are the magnitudes of the respective components of the magnetic field.

In order to save computational time, a steady state is assumed to be established. This means that the average power lost by the RIB is equal to the power diffracted out of the cavity. In this case the RIB sustains a constant amplitude normal-mode oscillation.

A computer-aided design and analysis program is developed in order to solve numerically the above set of equations. The first part of the program serves to design the gyromonotron. This design must ensure a grazing intersection in the ω- k_z plane of the dispersion relations characterizing the cavity mode and the fast-cyclotron frequency mode [2]. At the grazing intersection, the efficiency is maximized and the sensitivity of operation to small changes in ω_o or k_z is minimized. More details concerning the gyromonotron design are given elsewhere [6-13]. The second part of the program computes the ion trajectories, the efficiency, and the microwave output power as functions of the following parameters:

1. The initial-relativistic factor γ_o or equivalently the beam energy V_o since they are related by:

$$\gamma_o = (1 + \frac{e V_o}{m_o c^2}) \quad (21)$$

2. The transverse-to-axial velocity ratio α which is given by:

$$\alpha = \frac{v_t}{v_z} \qquad (22)$$

where v_t is the transverse velocity.

3. The ratio of the operating frequency to the cyclotron frequency f/f_c.
4. The operating frequency F.
5. The amplitude of the RF electric field E_m.

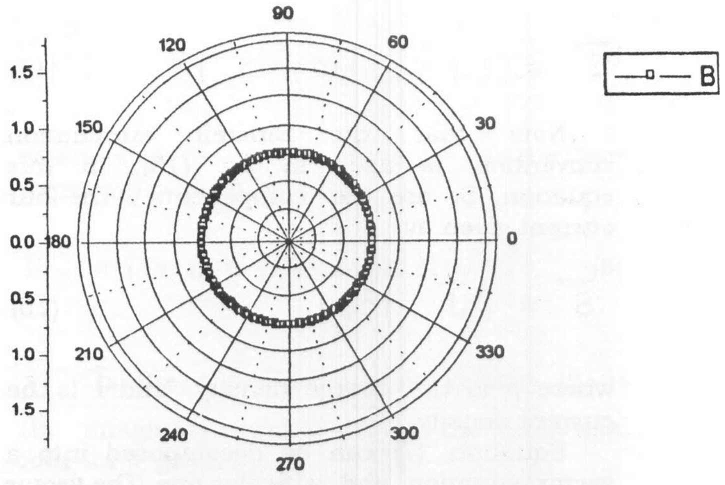
3. Results

The results that will be presented here are for a gyromonotron that is designed to operate at a frequency of 3 GHz. The ED system is a rectangular cavity operating at the TE_{101} mode. The results of computer simulation of the ion gyromonotron operation are presented in Figs. 1 through 6.

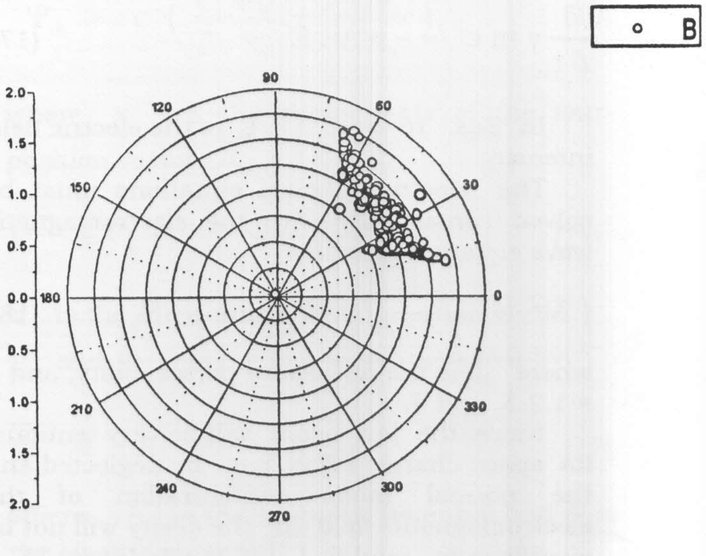
Figure 1 shows the distribution of the ions of the RIB at the entrance of the ED system and at its end. It is seen that the ions that were initially distributed uniformly are bunched.

Figure 2 shows the efficiency η versus γ_o. It is seen that η increases firstly rapidly with γ_o and then it decreases sharply. This is because increasing γ_o has two competing effects on the performance. As γ_o increases, the available beam energy increases and the relativistic effects become more significant. On the other hand, the size of the instability responsible for gyromonotron operation decreases.

Figure 3 gives the effect of α on the performance. It is seen that there is an optimum value of α at which η is maximum. This is because increasing α has two contradicting effects on the performance. As α increases, the available transverse kinetic energy that can be transformed into microwave energy increases. On the other hand, the relativistic factor γ_o increases with α and the size of the cyclotron-maser instability decreases.



(a)



(b)

Fig. 1. The distribution of ions (a) at the entrance and (b) at the end of the ED system.

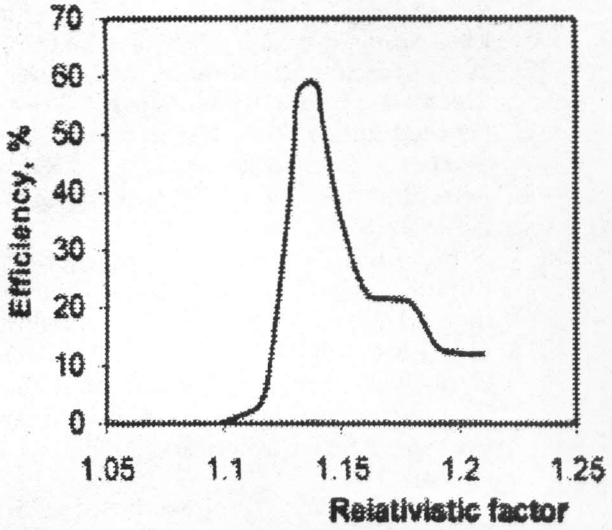


Fig. 2. Efficiency versus relativistic factor.

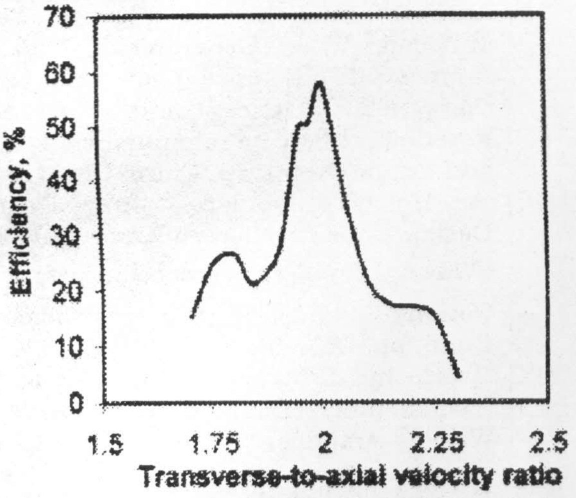


Fig. 3. Efficiency versus transverse-to-axial velocity ratio.

Figure 4 shows the effect of varying the ratio f/f_c on the performance. The variation of this ratio is equivalent to the variation of the static magnetic field B_o. It is seen that there is an optimum ratio at which η is maximum. This because it is the static magnetic field that essentially imposes the operating frequency. At the optimum value of B_o the synchronism condition is fulfilled and the grazing intersection between the cavity mode and the beam mode is ensured.

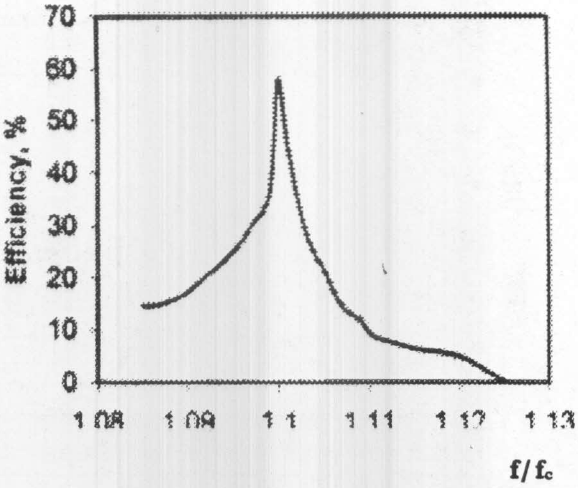


Fig. 4. Efficiency versus f/f_c.

The effect of the RF field E_m on the performance is shown in Fig. 5. It is seen that E_m has two competing effects on the performance. If E_m is increased, the ability of the wave to decelerate the ion bunches is enhanced. However, if E_m is excessively increased, these bunches may fall in the accelerating half cycle of the wave. Consequently, the performance will be degraded.

Figure 6 gives the effect of the operating frequency on the performance. It is clear that the bandwidth is very narrow which is expected since the ED system used is a cavity resonator.

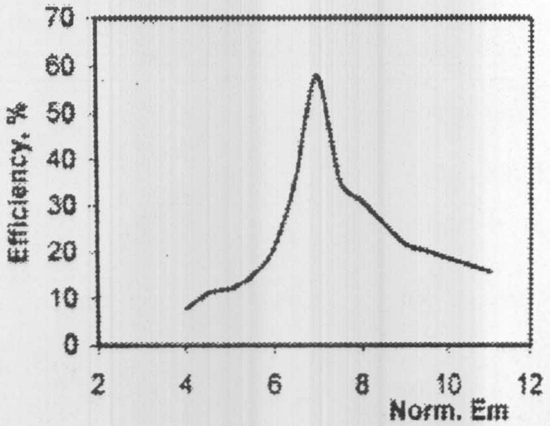


Fig. 5. Efficiency versus the RF field E_m.

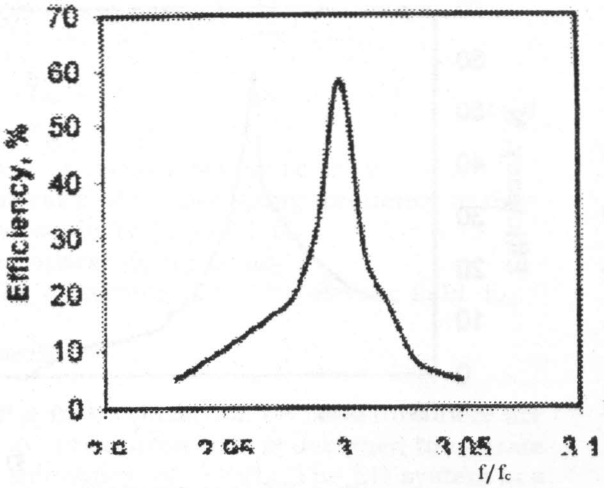


Fig. 6. Efficiency versus the operating frequency .

4. Conclusions

In this paper, a proposed super high-power microwave generator is presented. This is a gyromonotron using a helical relativistic ion beam as the intermediary agent for converting the transverse kinetic energy of the beam into microwave energy. The principle of operation of this generator is explained. A computer aided design and analysis program is developed and used to analyze the performance of this gyromonotron. The program is used to investigate the effects of some important parameters on the gyromonotron operation. The results of this investigation are presented and explained. The proposed device can be used in directed-energy weapons and in super-high-power radar systems.

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