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LARGE-SIGNAL ANALYSIS OF GYRO-TWT WITH APPLICATIONS TO AIRBORNE EARLY-WARNING RADARS

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ABSTRACT

In this paper, the gyro-travelling-wave tube (gyro-TWT) is proposed to be used as the transmitting tube in airborne early-warning radars (AEWRs). Since the gyro-TWT is one of the members of the recently developed gyrotron family that comprises the most powerfull sources of millimeter waves, the radars employing the gyro-TWT will have many significant advantages when compared with the conventional AEWRs. In order to get further insight into the operation and performance of gyro-TWT, the results of a large-signal nonlinear analysis of this device are presented and the effects of the different operating conditions on the performance are investigated.

I. INTRODUCTION

The primary role of airborne early-warning (AEW) radar is the tracking and reporting of low-flying intruders. This provides surveillance cover beyond that available from surface-based sensors. The AEW radar would track bombers, fighter bombers, cruise missiles, at all ranges of interest to the air-defence commanders. To realize full target detection at all ranges in the look-down geometry, a pulse-doppler approach is usually selected in the most AEW radars. All modern AEW radars use the conventional linear-beam tubes for the final transmitter stage. This provides the flexibility in pulse length, pulse-repitition frequency, and the RF power required. The conventional-microwave devices have generally good performance in the centimeter-wave region but their performance in the millimeter-wave region is inferior to that of the more recently developed gyrotron devices. Operation in the millimeter-wave region offers many significant advantages in the AEW radar applications when compared with the centimeter waves . These advantages are :

1. The narrower beam width for the same aperture of the antenna. This provides a better angular resolution and a better ability of detecting and locating small objects. This provides also greater details of the targets, a high tracking and guidance accuracy, a high immunity to jamming and a better quality for area mapping.

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2. Wide frequency-spectrum availability. This provides a greater capability of using the effective ECCM techniques. This provides also a high-information rate capability for obtaining fine structure details of target signature, and a high range-resolution capability for precision tracking and target identification.
3. Low scatter from terrain. This provides reduced multipath interference, and reduced terrain clutter.
4. The smaller size and lighter weight of components.
5. Increased immunity to friendly interference.
6. Increased immunity to hostile ECM.

Because of these advantages, we propose here to operate the AEW radar in the millimeter-wave region. The essential element of such millimeter-wave radars is the transmitting tube that can provide the required power level. The gyrotron is now the most powerfull and efficient millimeter-wave source [1-5]. The travelling-wave version of gyrotrons known as the gyro-TWT is the more suitable version for AEW radars. Hence, in this paper the results of a detailed investigation of the performance of this tube will be presented. These results are obtained using a computer aided analysis and design program developed by the author [5]. This program takes fully into account all the relativistic effects pertinent to the gyro-TWT operation.

II. OPERATION OF GYRO-TWT

The gyro-TWT comprises essentially a relativistic-electron beam (REB) whose electrons are following individual helical orbits under the action of a strong static axial magnetic field inside a waveguide. The REB interacts with a transverse-electric (TE) mode that propagates as a travelling wave in the interaction space. The wave grows both spatially and temporarily at the expense of the rotational kinetic energy of the beam. This growth is attributed to the relativistic dependence of the cyclotron frequency of electrons ω_c on their energy, namely :

$$\omega_c = e B_o / (\gamma m) \qquad (1)$$

where B_o is the static-magnetic field, e and m are the electron charge and mass respectively, γ is the relativistic factor proportional to the beam energy $\mathscr{E}$:

$$\gamma = \mathscr{E} / m c^2 \qquad (2)$$

and c is the velocity of light.

Initially, all the electrons gyrate with the same cyclotron frequency ω_c but their phases in the cyclotron orbits are random. Hence, no effective radiation will be produced. Under the action of the TE mode, some electrons will give up energy to the wave, rotate faster, and accumulate phase lead. Some other electrons gain energy from the wave, rotate slower, and accumulate phase lag. This results in phase bunching of the beam. For the bunching to be effective, the phase velocity of the cyclotron-beam mode must be equal to that of the wave mode. This results in the following synchronism condition :

$$\omega_d = \omega - \beta v_z = S \omega_c \tag{3}$$

where ω_d is the Doppler-shifted frequency, β is the phase-shift factor, ω is the wave frequency, S is the cyclotron-harmonic number, and v_z is the beam axial velocity. Since the electron gyrates faster in a magnetic field when it has lost energy, the electrons tend to bunch in phases where the electric force ahead is accelerating and that behind is decelerating. If ω_d is slightly higher than $S \omega_c$ the electron bunches will slip behind the wave in phase. Hence, these bunches will move under the action of decelerating fields. Therefore, part of the rotational kinetic energy of electrons is given to the wave.

III. BASIC EQUATIONS AND MODEL

In the interaction space of the gyro-TWT, the total force applied to the electron is given by :

$$F = -e [E_t + v_t \times B_t + v_z \times B_t + v_t \times (B + B_z)] \tag{4}$$

where E is the electric field, B is the magnetic field, and the suffix t means transversal and z means axial. The transverse-electric force $- e \times E_t$ gives rise to azimuthal bunching and hence is responsible for the gyro-TWT operation. The force $- e v_t \times B$ is responsible for the circular motion of electrons at ω_c. The force $- e v_z \times B_t$ is an RF-transverse magnetic force. This force usually offsets the transverse-electric force responsible for the gyro-TWT operation [1-3]. The axial force $- e v_t \times B_t$ can give rise to an axial bunching that offsets the azimuthal bunching responsible for the gyro-TWT operation [1-3]. It can be shown that the effects of the deleterious magnetic forces can be reduced by operating the gyro-TWT near the cut-off frequency of the waveguide [1-3].
The electron dynamics in gyro-TWT are governed by the following relativistic equation of motion :

$$d\, m\, u_i / d\tau = \Phi_{ik} S_k / c \tag{5}$$

where u_i's are the components of the 4-velocity vector, τ is the proper time,

S_k's are the components of the 4-current vector given by :

$$\vec{S} = (j_x \quad j_y \quad j_z \quad i c \rho) \qquad (6)$$

ρ is the charge density, and Φ_{ik}'s are the components of the electromagnetic-field tensor :

$$\vec{\Phi} = \begin{bmatrix} 0 & c B_z & -c B_y & -i E_x \\ -c B_z & 0 & c B_x & -i E_y \\ c B_y & -c B_x & 0 & -i E_z \\ -i E_x & -i E_y & i E_z & 0 \end{bmatrix} \qquad (7)$$

This equation can be decomposed into a vector equation and a scalar one. The vector equation is the 3-dimensional equation of motion given by :

$$\frac{\partial m v}{\partial t} = - \frac{e}{m\gamma} [E + v \times B - \frac{v}{c^2} (v . E)] \qquad (8)$$

and the scalar equation is given by :

$$\frac{\partial \gamma m c^2}{\partial t} = - e v . E \qquad (9)$$

The 3-dimensional equation of motion must be solved consistently with the electromagnetic-wave equation in order to obtain the electron velocities, momenta, and positions. Using Eq. (9) which controls the energy exchange between the REB and the electromagnetic wave, the value of γ is updated. During the interaction, the incremental change ΔP_{RF} in the RF power is given by :

$$\Delta P_{RF} = P_{average} \frac{\Delta \gamma}{1 - \gamma_o} \qquad (10)$$

where $\Delta\gamma$ is the incremental change in γ, and γ_o is the initial value of γ.

The incremental change in the electric-field amplitude can be determined from ΔP_{RF}. The efficiency η can be calculated from :

$$\eta = (\gamma_o - \gamma_{av}) / (\gamma_o - 1) \qquad (11)$$

where :

$$\gamma_{av} = \frac{1}{N} \sum_{i=1}^{N} \gamma_i \qquad (12)$$

and γ_i is the final value of the relativistic factor for the i th electron.

IV. RESULTS

Figs. 1 through 3 show the orbital electron radius r_c , the RF power generated P_{out}, and the RF electric field amplitude E_m versus the axial distance travelled for the most efficient electron. It is seen that the value of r_c decreases on the average. This is because as the electron is giving up its energy to the wave the relativistic factor decreases and the cyclotron frequency increases. Consequently, the orbital radius decreases since it is inversely proportional to ω_c.

Figs. 4 and 5 show r_c and E_m for a less efficient electron. It is seen that the average value of r_c decreases firstly then it starts to increase slightly at the end of the tube. Correspondingly, E_m increases firstly rapidly and decreases slightly at the tube end. Hence, this electron is expected to be less efficient which is actually the case.

Figs. 6,7, and 8 show r_c, P_{out} , and E_m for an electron that absorbs power from the wave. It is seen that this electron generates firstly a small amount of power, then it tends to absorb power before reaching the middle of the tube but fortunately its radius increases and it is absorbed in the walls of the waveguide.

Figs. 9, 10, and 11 show the gain G, the electronic efficiency η, and the output power, P_{out} versus the input power P_{in}. The monotonic decrease of G with P_{in} is attributed to the fact that the output power obtainable is limited by the dc power delivered to the REB. The primary increase of P_{out} and η with P_{in} is attributed to the enhancement of the bunching mechanism together with the displacement of the bunches toward the locations of the maximum decelerating fields. If P_{in} is increased excessively, the bunches will be shifted out successively toward smaller decelerating fields and may fall into regions of accelerating fields. The fact that the efficiency increases initially with P_{in} whereas the gain decreases means that the requirements of maximum efficiency and gain are contradictory. This can be explained as follows :

As the electrons are giving up their energy to the field ω_c increases and the synchronism condition becomes violated. This means that the electron cannot give up all its rotational energy to the wave. This implies that a higher efficiency requires a greater difference between the initiall phase velocity of the REB mode and that of the wave. However, an excessive difference between these velocities results in poorer REB bunching at the input section of the tube. Optimum bunching would therefore be recovered through increasing P_{in} and hence the gain decreases.

Fig. 12 shows η versus the dc beam voltage V_o . The shown behavior can be attributed to the increase of the relativistic factor γ with V_o. This has two contradicting effects on the performance. As γ increases, the available beam energy increases, and the relativistic effects become more significant. On the other hand the difference between ω and ω_c increases and the bunching mechanism becomes less effective.

Fig. 13 gives η versus the ratio F/F_c where F is the operating frequency and F_c is given by $\omega_c /2\Pi$. The sharp peak shown is attributed to the fact that there is a definite value of the static magnetic field at which the synchronism condition and the grazing intersection between the REB mode and the waveguide mode are satisfied. At this value also the electron bunches are located at maximum decelerating fields.

Figs. 14 through 16 show G, P_{out} and η versus the tapering ratio dB/B where dB is the incremental increase of the magnetic field along the tube axis. At the optimum value of this ratio the synchronism condition will remain satisfied along most of the interaction space.

CONCLUSIONS

In this paper, the gyo-TWT is proposed to be used as the transmitting tube in AEW radars. Such radars will, therefore, have many significant advantages when compared with the conventional AEW radars These advantages, which are already indicated, are attributed mainly to the inherent capability of gyro-TWT to produce very high power at frequencies much higher than those of conventional tubes. A detailed numerical study of the large-signal operation of gyro-TWT has been undertaken and the results are presented and explained.

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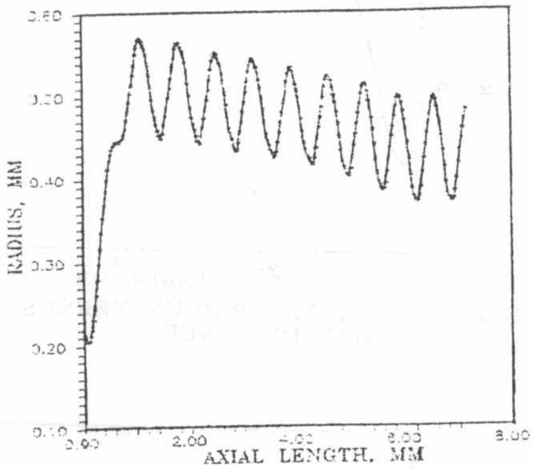

FIG. 1 : ORBITAL RADIUS VERSUS AXIAL DISTANCE.

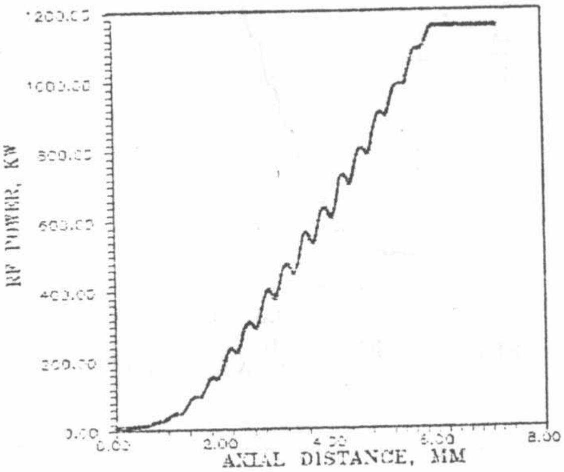

FIG. 2 : RF POWER VERSUS AXIAL DISTANCE.

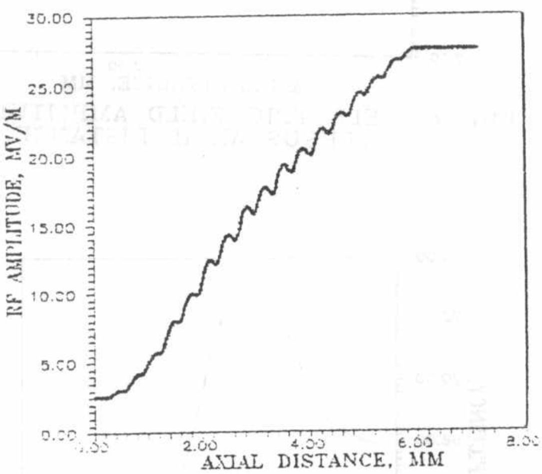

FIG. 3 : ELECTRIC FIELD AMPLITUDE VERSUS AXIAL DISTANCE.

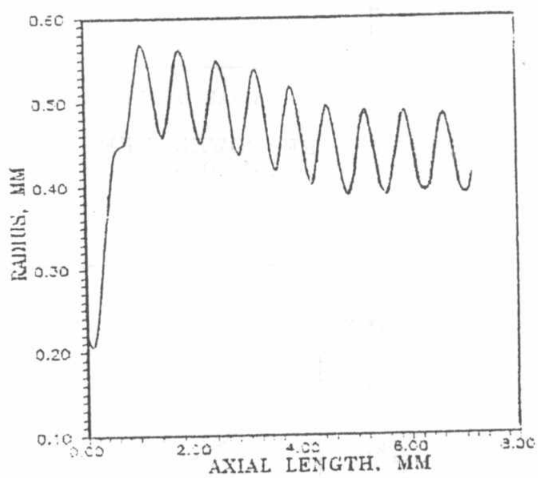

FIG. 4 : ORBITAL RADIUS VERSUS AXIAL DISTANCE.

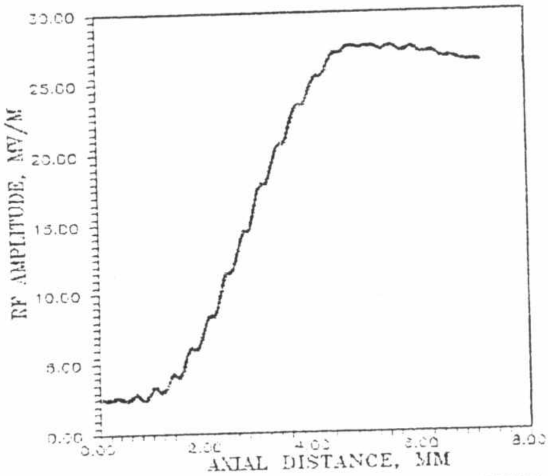

FIG. 5 : ELECTRIC FIELD AMPLITUDE VERSUS AXIAL DISTANCE.

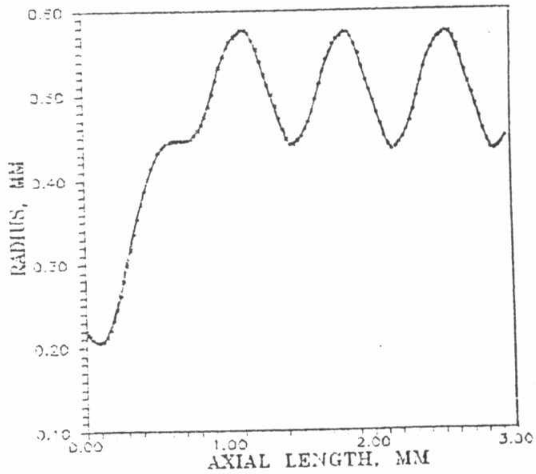

FIG. 6 : ORBITAL RADIUS VERSUS AXIAL DISTANCE.

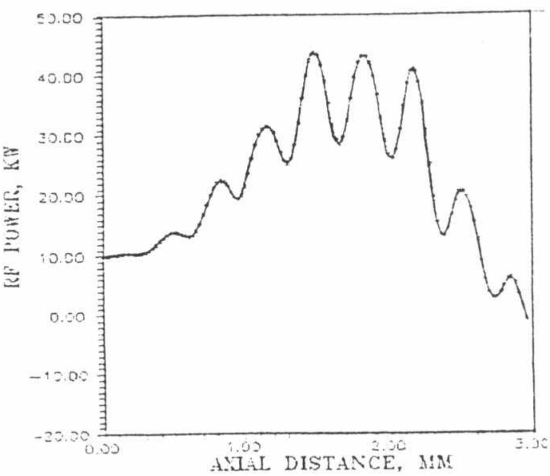

FIG. 7 : RF POWER VERSUS AXIAL DISTANCE.

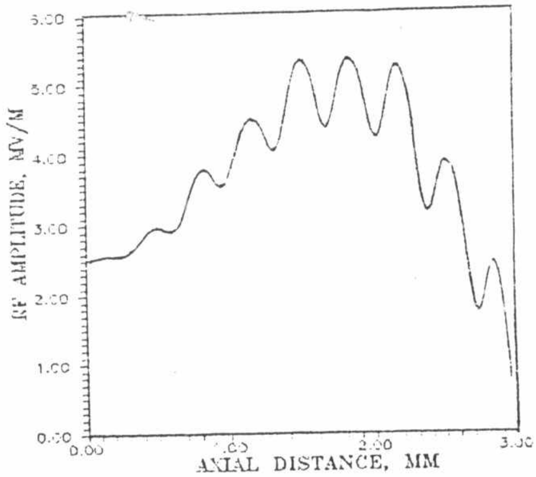

FIG. 8 : ELECTRIC FIELD AMPLITUDE VERSUS AXIAL DISTANCE.

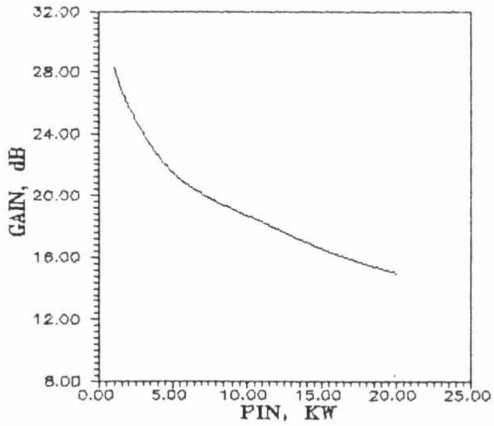

FIG. 9: GAIN VERSUS INPUT POWER.

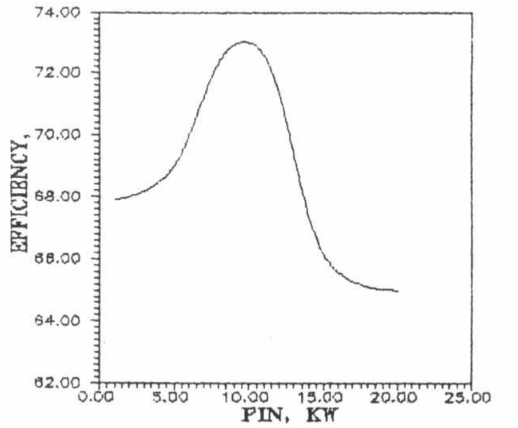

FIG. 10: EFFICIENCY VERSUS INPUT POWER.

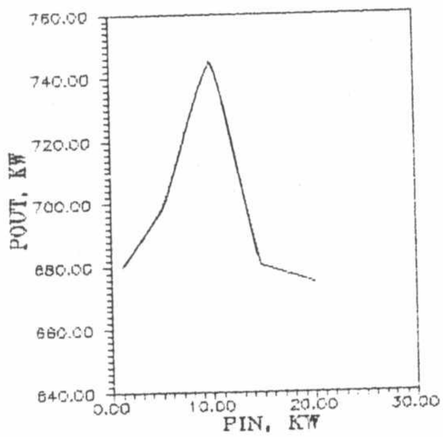

Fig. 11: OUTPUT POWER VERSUS INPUT POWER.

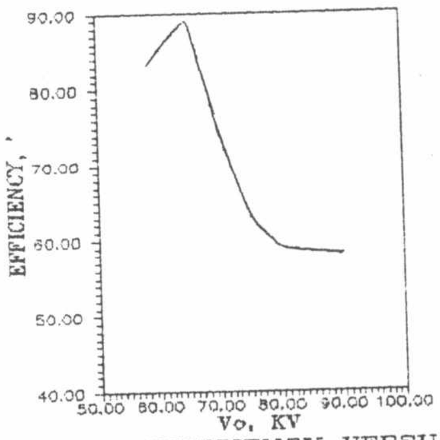

Fig. 12: EFFICIENCY VERSUS DC VOLTAGE.

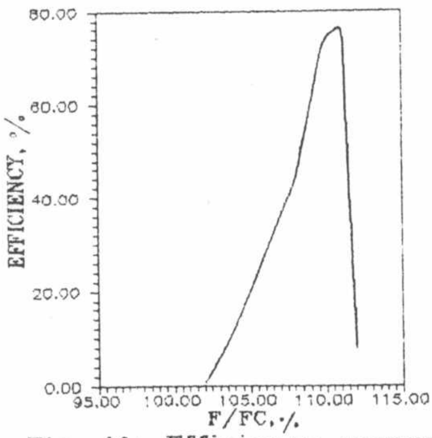

Fig. 13: Efficiency versus F/FC.

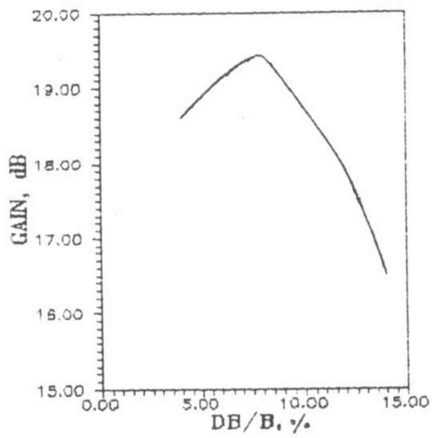

Fig. 14: GAIN VERSUS dB/B.

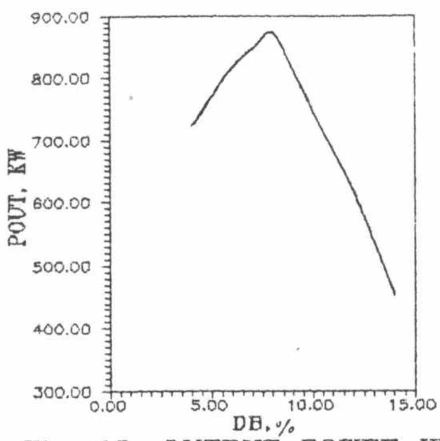

Fig. 15: OUTPUT POWER VERSUS DB/B.

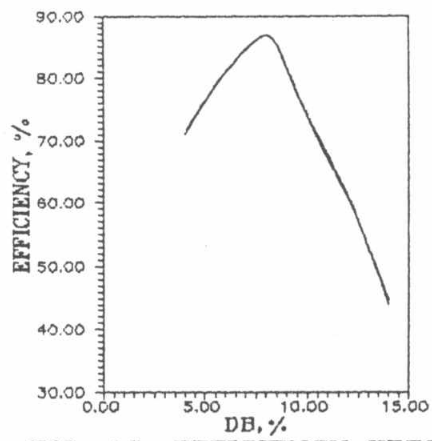

FIG. 16: EFFICIENCY VERSUS DB/B.