SIMULATION OF A 160kW, 32GHz GYROTRON USING AN ELECTROMAGNETIC PIC CODE

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Abstract

A simulation study with experimental parameters of a 32GHz gyrotron operating in the TE_{021} mode is presented. Beam electrons with typical energy of 40 keV and transverse-to-axial velocity ratio ranging from 0.8 to 2.0 are injected into the cavity to drive electromagnetic oscillations from noise. On the basis of an electromagnetic PIC code, a parameterization study is carried out to determine how sensitive the output power is to change in pitch ratio and beam current.

Introduction

The remarkable capabilities of the gyrotron in producing megawatt powers at frequencies up to 140GHz have represented a technological breakthrough in high-power microwave generation for RF plasma heating applications [1] . Being a fast device, the gyrotron's distinguished attribute is its operation in a higher-order cavity mode which allows wall heating and beam interception problems to be greatly alleviated in comparison with other microwave tubes. Gyrotrons are meeting expanding requirements in different application areas such as material processing and plasma chemistry [2] .

From the mathematical point of view, the study of the cyclotron resonance interaction of the cavity fields with a relativistic electron beam in the gyrotron has largely been carried out by means of two analytical approaches, namely, via a dispersion equation based on plasma physics, and through ballistic methods considering equations of motion and particle trajectories [3] . The first method lies in the analysis of a dispersion equation for the beam eigenmodes and the corresponding search for instabilities in the form of a complex solution, that may be interpreted as a growing space-charge wave in the beam, which is in synchronism with the surrounding electromagnetic structure. Although velocity spread and space-charge effects can be adequately accounted for, this method is an example of perturbation procedure as the starting point is the linearized Boltzmann equation, and further nonlinear extensions are a second-order approximation in nature. In the ballistic approach, the equation of motion for the beam electrons – thus combined with Maxwell's equations for self-consistency of the solutions to be achieved – is integrated to give the particle trajectories. The energy exchange term $\vec{v} \cdot \vec{E}$ is then calculated and averaged over the beam to solve for the problem of power transfer between the fields and the electrons. This technique is most general regarding nonlinear analysis, since all possible geometry variations of the fields and injection schemes of the particles can be taken into consideration. However, this approach involves a vast amount of numerical calculation which is not so illuminating during the early stage of the discussion.

Nevertheless, with the advent of high-speed computers, particle simulations can offer insights that complement and enlarge those gained by traditional approaches, thus adding feedback for improvement in theory. Gyrotron simulations using particles have begun since the 1980's, either making relativistic predictions of the saturated RF output characteristics of a gyrotron amplifier [4] or examining the scaling of the transient growth rate with the beam current [5] Being fully nonlinear, simulation is then capable of handling growth in time and space from linear through large amplitudes. In the particle model [6, 7] , the motion of a large assembly of charge particles is followed in their self-consistent electric and magnetic fields. Although this approach sounds simple and straightforward, practical computational limitations require the use of sophisticated numerical methods that provide sufficient accuracy and stability to make the simulations useful for many characteristic cycles of the beam.

In this paper, we report on a simulation study of a high-power, pulsed gyrotron operating in the TE_{021} mode at 32 GHz. Simulations have been carried out on a $2\frac{1}{2}$ dimensional, fully relativistic electromagnetic particle code [6] and are aimed at the identification of the physical process which determine the nonlinear saturation and the efficiency of the radiation production. Beam equilibrium parameters are based on experimentally observed values [8], and in all the computer runs a monoenergetic annular electron beam with guiding centers located on the second radial maximum of the TE_{021} mode is injected into the cavity to drive the electromagnetic oscillations from noises. Beam currents of 5 and 10A with pitch angle $\alpha = v_\perp/v_\parallel$ varying from 0.8 to 2.0 have been considered. For each value of current, optimization of the conversion efficiency with respect to the external magnetic field has given 40% efficiency at α=1.1 and 10A, while for the low-current case the maximum efficiency has been 32% at α=1.3. Results of the simulation are detailed in the second section and followed by discussion in the final section.

Results of the Simulation

Fig. 1 illustrates the elements of the particle modeling.

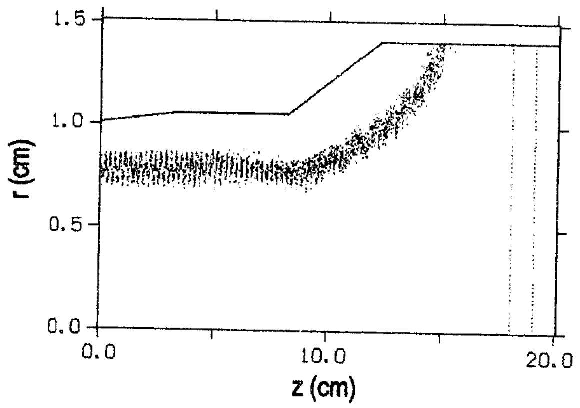

Fig. 1. Real-space (r-z) diagram of the simulated beam at t=48 ns

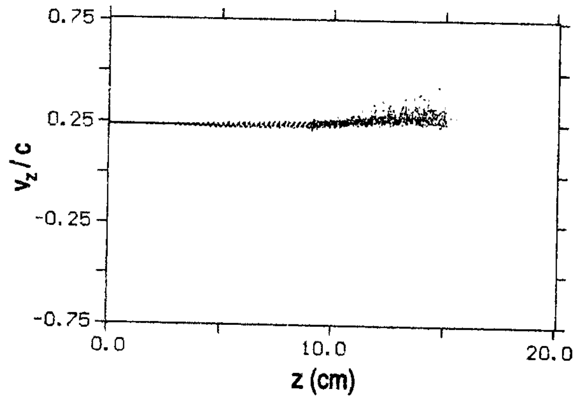

Fig. 2. Axial velocity vs. axial distance of the electron beam at t=48 ns

Simulations are initiated by continuously injecting the beam electrons with prescribed parameters into the cavity. The inlet is at the beginning of a downtapered section that ensures cutoff for the operating mode. Thus little or no radiation propagates toward the left boundary, which is assumed to be a perfect conductor in the simulation. In the output waveguide is inserted a conducting disk having a resistance per unit square equal to the characteristic impedance Z_{TE} of the outgoing traveling wave that propagates to the right, that is, $Z_{TE} = 1/d\sigma$, where σ =0.2S/m and d =1.0cm are the conductivity and thickness of the absorbing disk. The absorber is placed a quarter-wavelength from the shorted waveguide end, since for perfect conductor, the shorted end quarter-wave guide represents an infinite impedance in parallel with the matching resistance.

In this sense, the output guide acts as an ideal calorimeter that absorbs all the radiation from the quasi-stationary fields in the cavity, otherwise reflections at the right boundary could have a significant impact on the dynamics of the wave growth process. The axial component of the applied guiding magnetic field is constant over the distance $0 \leqslant z \leqslant 9.0$cm and decreases linearly to reach a zero value at z=17.5cm, so that the spent beam is dumped beyond the output taper, where the electrons are no longer in resonance with the wave. We have used over ten thousand particles to simulate the beam and a mathematical spacial grid, having dimensions 0.2mm$\times$0.3mm, which is fine enough to resolve a Larmor radius in order to measure the charge density and then calculate the self-consistent electric and magnetic fields. The simulations proceed discontinuously in time step by step, and at time t=48ns an injected 44-keV, 5-A beam with pitch ratio of 1.4 has clearly become modulated as shown in Fig. 1. The corresponding plots of the axial and transverse velocities vs. the axial distance are given in Fig.

2 and Fig. 3 at a time t=48ns when the RF fields have saturated into the simulation. The azimuthal bunching (Fig. 3) is seen to result in dense groups of electrons with decelerated transverse velocities. In spite of the electron axial velocity has been accelerated (Fig. 2), the overall result is a net transfer of energy from the beam to the cavity fields as a majority of the beam electrons become confined inside the initial guiding center circle (Fig. 4).

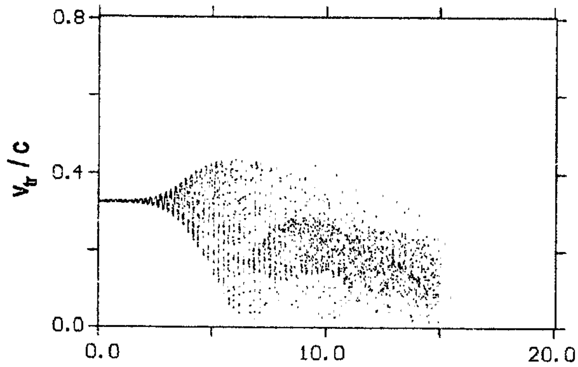

Fig. 3. Transverse velocity vs. axial distance of the beam at t=48 ns

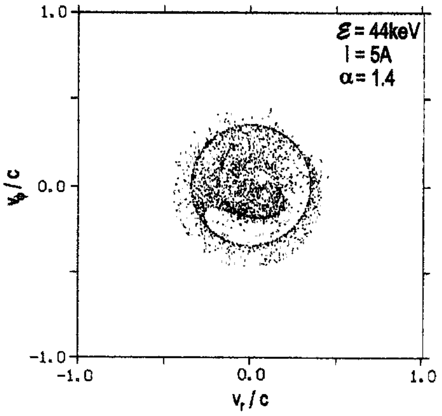

Fig. 4. Particle positions in the normalized velocity space

The simulated self-consistent axial profile of the operating TE_{021} mode is shown in Fig. 5 for $\Omega_B/\omega_c = 0.97$ where Ω_B is the relativistic cyclotron frequency and ω_c is the waveguide cutoff frequency. We can distinguish the quasi-stationary cavity field confined in the region 0⩽z⩽9.0cm and a pure outgoing traveling wave that propagates to the right. This indicates the effectiveness of the conducting disk in absorbing all the output radiation, thus preventing the wave from reflecting back to the cavity.

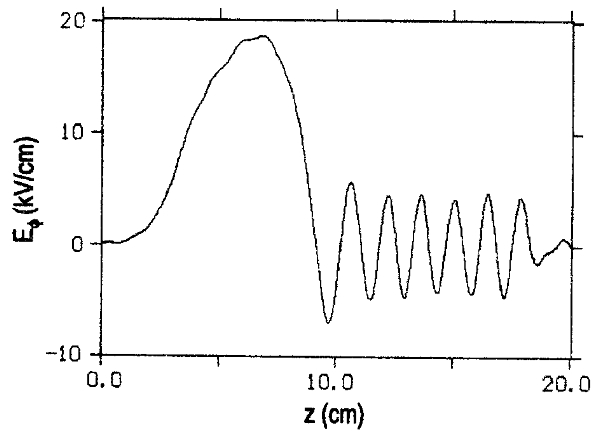

Fig. 5. Self-consistent TE_{021} electric field profile after the time of saturation

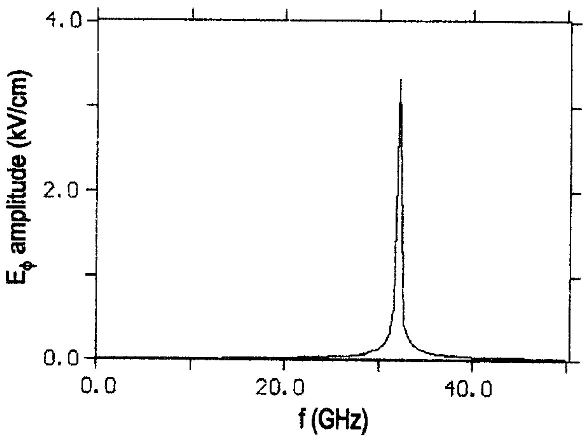

Fig. 6. Frequency spectrum at the point r=1cm, z=17cm in the output guide

The associated frequency spectrum of the electric field at r=1.0cm, z=17.0cm is given in Fig. 6, which is characterized by a single-frequency component peaked at 32.03GHz, being slightly above the 31.90GHz cutoff frequency of the regular section of the waveguide cavity with radius 1.05cm. Fig. 7 shows the time history of the output power as determined by integration of the Poynting flux across the observation section at z=17.0cm. We see that the production of RF power saturates at a time around 48ns, reaching a peak value of 110kW which translates into a conversion efficiency of 50% for a 44-keV, 5-A beam with injection pitch-ratio of 1.4. A parameterization of the gyrotron's settings were carried out to determine how sensitive the output power is to changes in pitch ratio and beam current. The results of this study are presented in Fig. 8 which shows the output power as function of the pitch ratio with the beam current as a parameter. The output power was optimized with respect to the applied magnetic field, and we see that the maximum values of both output power and efficiency increase with beam current.

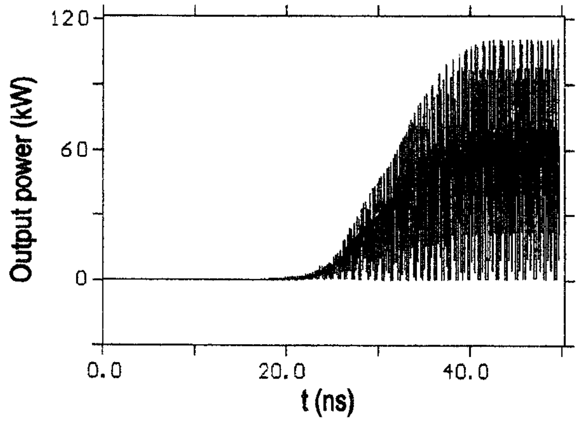

Fig. 7. Time history of the output power measured at the section z=17.0cm

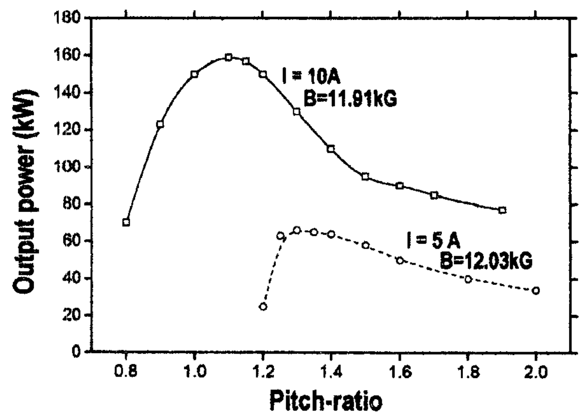

Fig. 8. Simulated pitch-ratio parameterization of the 32GHz gyrotron

Conclusion

The operation of 32GHz gyrotron was examined using an electromagnetic PIC code that provided a comprehensive picture of cyclotron resonance interaction of TE-mode cavity fields with a helical electron beam. That the relativistic angular bunching dominates over the axial bunching (that originates with the RF magnetic force) can best be seen by evaluating the ratio of axial to relativistic angular bunching rates which may be expressed as $(f_R/f_B)(1 - f_c^2/f_R^2)$, where $f_B = 2.8B(kG)/\gamma_0$, f_R is the cavity resonance frequency, and f_c is the TE_{02}-mode cutoff frequency. Taking $f_R = 32.03$GHz, $f_c = 31.90$GHz, $f_B = 31.10$GHz (B=12.03kG, injection energy =44keV) the bunching ratio is of the order of 10^{-3}, and therefore the relativistic mass shift is responsible for the gyrotron interaction mechanism.

Acknowledgment

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