Sideband Mode Competition in a Gyrotron Oscillator

W. C. Guss, M. A. Basten, K. E. Kreischer, and R. J. Temkin
Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

T. M. Antonsen, Jr., S. Y. Cai, G. Saraph, and B. Levush
Laboratory for Plasma Research, University of Maryland, College Park, Maryland 20742
(Received 1 July 1992)

We report the first observation of sideband mode competition in a gyrotron with an overmoded open waveguide resonator. Experiments were conducted in a gyrotron operating in the $TE_{16,2}$ mode at 146 GHz. Up to 600 kW of power was generated in 3-μs pulses at 80 kV beam voltage and up to 40 A beam current. A pair of sidebands was excited corresponding to the $TE_{15,2}$ and $TE_{17,2}$ modes offset by ± 5 GHz. A multimode, multifrequency, self-consistent time-dependent code predicts the excitation of the sidebands with good accuracy.

PACS numbers: 42.52.+x, 52.35.−g, 52.40.Db, 84.40.Cb

Gyrotron oscillators are widely used for plasma heating at the electron cyclotron resonance (ECRH) frequency. As plasma devices increase in size and magnetic field, higher power and higher frequency (ω) operation of the gyrotron are required. Power levels of at least 1 MW at frequencies above 100 GHz are now under investigation worldwide [1–3]. As the gyrotron power increases, the constraints of cooling due to Ohmic loss in the cavity require an increase in the parameter D_0/λ, where D_0 is the (cylindrical) cavity diameter and $\lambda = 2\pi c/\omega$ is the free space wavelength, where c is the speed of light. Typical values of D_0/λ are in the range of 5 to 15 for megawatt power level gyrotrons at frequencies of 100 to 150 GHz. These values may be compared with $D_0/\lambda \approx 0.6$ for a TE_{11} mode cavity operating near cutoff.

Although mode competition has been observed in devices with small D_0/λ values [4,5], this paper reports the first experimental observation of mode competition in an overmoded gyrotron oscillator under conditions relevant to the production of high average power.

Operation of gyrotron oscillators in highly overmoded cavities raises many issues of mode competition and mode stability [6–9]. Generally, operation of such gyrotrons will occur under conditions where linear theory predicts several modes to be unstable, that is, to have gain. Single-mode operation is still possible under these circumstances provided the desired mode is able to nonlinearly suppress its competitors [6–8]. If the desired mode is not effective in suppressing its competitors, they may grow also and cause a reduction in device efficiency, essentially by spoiling the quality of the beam.

The modes of a weakly tapered gyrotron cavity can be approximated as TE_{mpq} modes of a circular cylinder cavity where m, p, and q are the azimuthal, radial, and axial mode indices, respectively. The oscillation frequency ω is given by

$$\omega^2/c^2 = k^2 = k_\perp^2 + k_\parallel^2 , \tag{1}$$

where $k_\perp = \nu_{mp}/R_0$ (the cutoff frequency is $k_\perp c$), R_0 is the cavity radius, and ν_{mp} is the pth zero of $J_m'(x)$. The axial wave number, $k_\parallel$, is given by $q\pi/L$ for a uniform, closed cylinder of length L, where q is an integer. However, for an open cylinder, with a wall radius tapered with axial distance to allow efficient coupling of the radiation out of the cavity, the axial structure must be determined self-consistently in the presence of the beam. To understand possible forms of mode competition, consider the condition for excitation of the cyclotron maser instability,

$$\omega - k_\parallel v_\parallel = \Omega_e = eB/\gamma_0 m , \tag{2}$$

where $v_\parallel, v_\perp$ are the axial and transverse electron velocity components, $\beta_\parallel = v_\parallel/c$, $\beta_\perp = v_\perp/c$, $\gamma_0^{-2} = 1 - \beta_\parallel^2 - \beta_\perp^2$, B is the axial magnetic field, Ω_e is the electron cyclotron frequency, and e,m are the electron charge and mass. The linear theory of the gyrotron indicates that Eqs. (1) and (2) apply exactly in the limit of vanishingly small electron beam density.

Equations (1) and (2) are plotted in Fig. 1 for the case of the $TE_{16,2}$ mode, which was studied experimentally, and the nearby $TE_{15,2}$ and $TE_{17,2}$ modes. Values of key parameters in Fig. 1 are $R_0 = 0.764$ cm, $B = 5.73$ T, $\beta_\parallel = 0.255$, and $\gamma = 1.157$ (80 kV). Figure 1 indicates that excitation of the desired mode, $TE_{16,2}$, can occur with simultaneous excitation of an unwanted mode such as $TE_{15,2}$ since the beam line [Eq. (2)] intersects the waveguide curve [Eq. (1)] for both the $TE_{16,2}$ at $k_\parallel > 0$ and $TE_{15,2}$ modes at $k_\parallel < 0$. The simulation of Ref. [9] (in particular, those described in Sec. 4) predicted that mode competition with a backward-wave $TE_{15,2}$ mode should be expected in the present cavity. This prediction motivated the present experimental study. The beam line does not intersect the $TE_{17,2}$ mode curve. Nevertheless, the $TE_{17,2}$ can still be excited via a nonlinear, four-wave mixing process [7] at a frequency ω_{+1} where

$$2\omega_0 - \omega_{+1} - \omega_{-1} \equiv \delta\omega \approx 0 . \tag{3}$$

Here, ω_0 and ω_{-1} are the frequencies of the $TE_{16,2}$ and $TE_{15,2}$ modes, respectively, and $\delta\omega$ is the four-wave beat

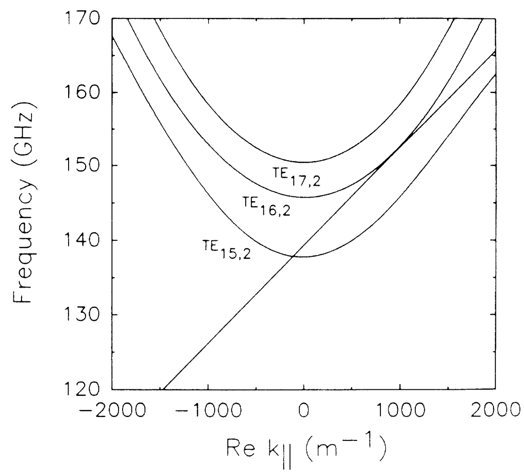

FIG. 1. Oscillations are possible at intersections of the cavity dispersion line (parabola) and the Doppler-shifted beam line. The assumed physical parameters are those of the cavity proper.

frequency mismatch. In addition, the azimuthal mode numbers must satisfy a similar matching condition, viz. $m_{+1}=2m_0-m_{-1}$, where $m_{+1}=17$, $m_0=16$, and $m_{-1}=15$. The frequency ω_{+1} may be displaced somewhat from the normal frequency of the $TE_{17,2}$ mode. For a high-Q cavity, this displacement should be less than the resonance width ω_{+1}/Q. However, for the relatively low-Q cavity under consideration, where the beam is able to significantly alter the axial structure of the modes, the four-wave resonance condition can be satisfied as will be shown.

The power and efficiency were calculated via computer simulation for the tapered gyrotron resonator shown in Fig. 2. For this cavity, the cutoff frequencies of the lowest-order axial modes are 138.28 GHz for the $TE_{15,2}$ mode, 145.29 GHz for the $TE_{16,2}$ mode, and 152.27 GHz for the $TE_{17,2}$ mode. The multimode, multifrequency, time-dependent code used for these calculations has been described in detail elsewhere [9]. In this code, the transverse dependence of the radiation field is expanded as a set of waveguide modes. Each of the modes has a time-dependent axial profile which is determined self-consistently by the response of the electrons and which satisfies appropriate boundary conditions at both ends of the cavity. We have also included the effects of ac space charge and electron beam energy and velocity spread.

Figure 2 shows a typical electric field amplitude profile for the $TE_{15,2}$, $TE_{16,2}$, and $TE_{17,2}$ mode triplet. The backward-wave $TE_{15,2}$ mode is excited in the downtaper that leads to the beam tunnel. Because the taper cuts off this mode, backward-wave power is reflected toward the gyrotron output window. The forward-wave mode ($TE_{17,2}$) is cut off in the gyrotron cavity and must be excited at a larger radius corresponding to a location in the uptaper, and propagates directly to the output window. A key feature which allows for the excitation of the

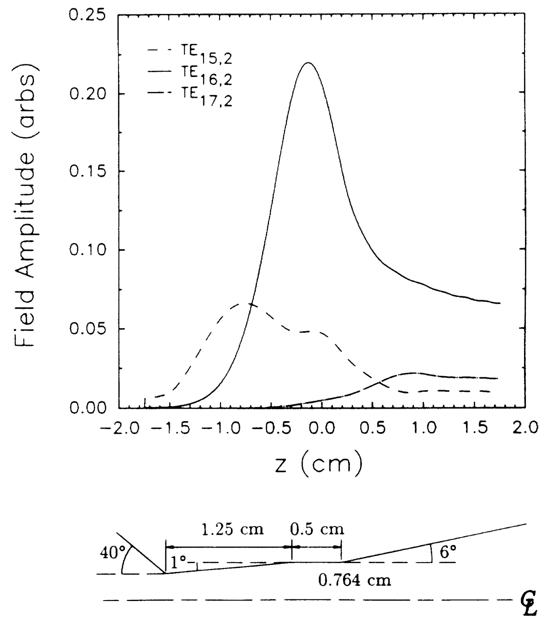

FIG. 2. Electric field amplitude as a function of axial distance for the $TE_{15,2}$, $TE_{16,2}$, and $TE_{17,2}$ mode triplet. The beam enters from the left and exits toward the gyrotron window on the right. The middle of the 0.5-cm cavity is located at $z=0$.

$TE_{15,2}$ in the presence of the $TE_{16,2}$ is the fact that the axial locations for the maximum of the electric field of the two modes do not coincide. The $TE_{15,2}$ mode is able to access the free energy of the beam first and thus it can grow. If the two modes are forced to exist at the same axial location, simulations indicate that the $TE_{16,2}$ suppresses the $TE_{15,2}$ [9]. For typical beam voltages (80 kV) and currents (40 A), and a magnetic field of 5.7 T, the theoretical frequency values of the $TE_{16,2}$ mode and the sideband $TE_{15,2}$ and $TE_{17,2}$ modes are shown in Fig. 3 as a function of α $(=\beta_\perp/\beta_\parallel)$. Theory indicates that the $TE_{16,2}$ mode power is about 0.5 MW for these experimental conditions.

The experiments were conducted on a gyrotron optimized for operation in the $TE_{16,2}$ mode at 146 GHz [10]. Electrons are produced from a thermionic cathode in a magnetron injection gun (MIG) and are accelerated to 80 kV. The control-anode voltage was 24.5–25.0 kV. The average electron velocity ratio $\langle\alpha\rangle=\langle v_\perp\rangle/\langle v_\parallel\rangle$ was measured using a capacitive probe [11]. In the cavity, the beam radius was $r_b=0.53$ cm. The cavity had a straight section length $L_c=0.50$ cm. The diffractive Q_D was ≈ 310. The pulse length was about 3 μs.

Two diagnostics were used to measure the frequency and power of the emitted microwaves. Initial measurements were made with a 5-cm-diam Fabry-Pérot etalon using 50-line/cm wire meshes. The reflectance at ≈ 140 GHz was measured [12] to be 0.966 and the resulting theoretical intensity resolution $I_{max}/I_{min}\approx 3.3\times 10^4$ or about 35 dB. Frequency measurements were made using a calibrated wavemeter at the output of the Fabry-Pérot etalon. The output of the etalon was sent through a calibrated attenuator to the detector diode. The attenuator setting was adjusted to maintain a constant diode voltage to minimize effects of possible diode nonlinearities. This system gave relative intensity measurements to within 3 dB and frequency measurements to within 0.1 GHz. In addition, independent measurements were made using a single-ended mixer and yttrium iron garnet (YIG) tuned filter. The sideband modes were beat against the $TE_{16,2}$ primary mode and the difference frequency was sent through the YIG filter. After calibration, relative powers of about 45 dB were detectable. This system gave frequency separations to an accuracy of about 0.05 GHz. Intensity and frequency measurements from these two independent systems were generally in very good agreement.

Figure 3 indicates the frequency measured for the $TE_{15,2}$, $TE_{16,2}$, and $TE_{17,2}$ modes measured as a function of the beam velocity ratio $\langle\alpha\rangle$. The data were taken at 80 kV and 40 A. The experimentally measured frequencies are equally spaced. The largest measured value of the frequency offset $\delta\omega/2\pi$ is about 100 MHz. Both the theory and experimental data show the frequencies of the $TE_{15,2}$ and the $TE_{17,2}$ shifted from their cold-cavity values (138.28 and 152.27). The upshift of the $TE_{15,2}$ is consistent with the backward-wave interpretation. The simulated field profiles for the sideband modes shown in Fig. 2 are distorted significantly from what would be found in an empty cavity.

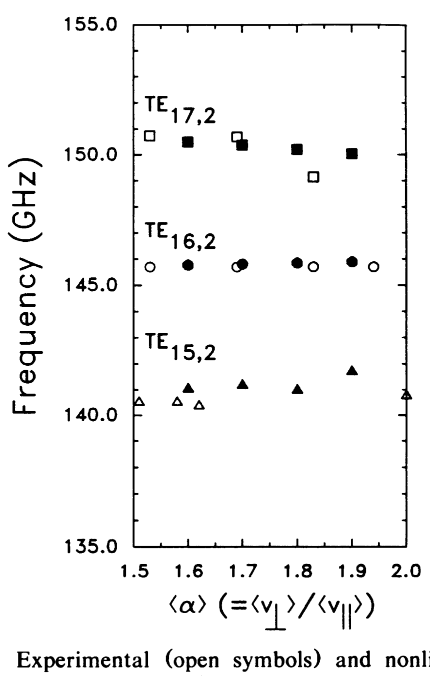

FIG. 3. Experimental (open symbols) and nonlinear self-consistent code (solid symbols) frequencies for the $TE_{16,2}$ (circles) main mode and the sidebands, $TE_{15,2}$ (triangles) and $TE_{17,2}$ (squares).

Figure 4 indicates the power in the $TE_{15,2}$ and $TE_{17,2}$ modes relative to that in the $TE_{16,2}$ mode. Theory also predicts very weak power levels in the sideband modes. However, the theoretical values have been found to be very sensitive to the form of the assumed distribution of pitch angles of the injected electrons in the simulation. For example, the results shown in Fig. 4 apply to the case of a triangular-shaped distribution function suggested by measurements [13] of the distribution of average parallel electron velocities. The power in the $TE_{16,2}$ mode was about 600 kW for the experimental conditions of Fig. 4.

The present experiments are the first observation of equally spaced sideband mode generation in a waveguide gyrotron oscillator. Theory predicts the existence of such sideband modes and also predicts the correct frequency and power in the modes with good accuracy. The excitation of sideband modes is dependent on the exact cavity shape [9]. We have completed the design of a higher-Q cavity (≈ 900) in which, in initial experiments, no sideband modes have been observed to the limits of the diagnostic sensitivity, and a significantly higher microwave efficiency has been measured.

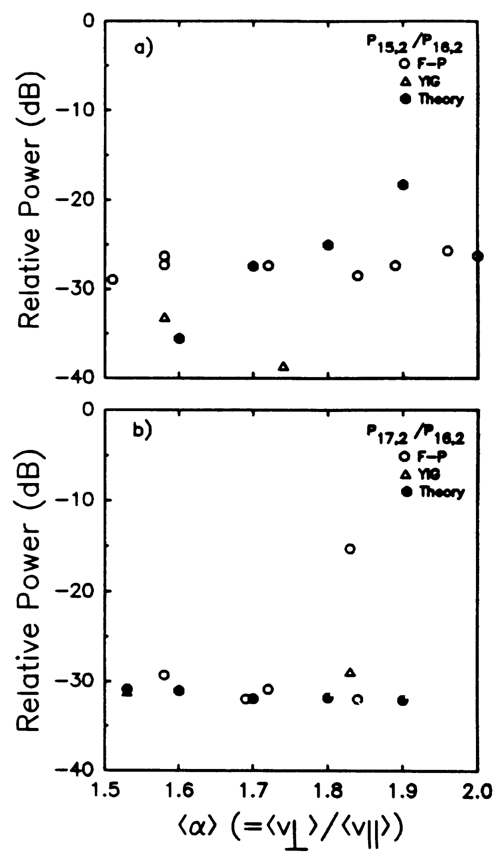

FIG. 4. Experimental power relative to the $TE_{16,2}$ mode (open circles) measured by the Fabry-Pérot etalon and the calibrated YIG filter system for the (a) $TE_{15,2}$ and (b) $TE_{17,2}$ modes. The computational predictions (solid circles) were made using the multimode code.

The power levels observed in the sideband modes are low and one might consider that these modes would have a minimal effect. However, sideband mode generation is potentially of great importance in gyrotron oscillators. First, the power measured outside of the cavity is indeed low in the sideband modes. However, the field amplitude and stored energy inside the cavity, as shown in Fig. 2, are quite large. This can lead to heating of the cavity walls and leakage of power toward the gun end of the gyrotron ($-z$ direction). The $TE_{15,2}$ mode in Fig. 2 is at the cavity entrance. After the beam passes through the large amplitude $TE_{15,2}$ mode field, it develops an energy spread which can reduce the oscillator efficiency in the $TE_{16,2}$ mode, the desired mode. Another potential problem with sideband modes is that they may affect the temporal evolution of the oscillator. They may cause the oscillator to reach a different final state than the state that would be achieved in a single-mode excitation. Sidebands must also add spectral components which can interfere with some applications of gyrotrons such as plasma scattering.

Gyrotron oscillators in much higher-order modes, such as the $TE_{42,7}$ mode at 280 GHz, are under investigation for higher-frequency gyrotrons. The problem of sideband mode excitation in such oscillators will be far more severe than in the present experiment. The present results will be useful in carrying out those experiments.

This research is supported by the Department of Energy Contracts No. DE-AC02-78ET51013 and No. DE-FG05-87ER52147, and under appointment to the Magnetic Fusion Science Fellowship program administered by Oak Ridge Associated Universities for the U.S. Department of Energy. Parts of this experimental program were conducted using the facilities at the Francis Bitter National Magnet Laboratory, Cambridge, MA. We also gratefully acknowledge helpful discussions with T. Grimm, M. Blank, and G. Nusinovich and the computational assistance of W. Menninger. W. Mulligan and G. Yarworth assisted in the experimental fabrication.

[1] V. A. Flyagin and N. S. Nusinovich, Proc. IEEE **76**, 644 (1988).

[2] K. E. Kreischer and R. J. Temkin, Phys. Rev. Lett. **59**, 547 (1987).

[3] J. Neilson, K. Felch, J. Feintstein, H. Huey, H. Jory, R. Schumacher, and M. Tsirulnikov, Proc. SPIE Int. Soc. Opt. Eng. **1576**, 120 (1991).

[4] K. E. Kreischer, R. J. Temkin, H. R. Fetterman, and W. J. Mulligan, IEEE Trans. Microwave Theory Tech. **32**, 481 (1984).

[5] P. Muggli, M. Q. Tran, and T. M. Tran, in *Proceedings of the Fifteenth International Conference on Infrared and Millimeter Waves, Orlando, Florida, 1990*, edited by R. J. Temkin, SPIE Proceedings Vol. 1514 (SPIE–International Society for Optical Engineering, Bellingham, WA, 1990), p. 413.

[6] I. G. Zarnitsina and G. S. Nusinovich, Izv. Vysh. Uchebn. Zaved., Radiofiz. **17**, 1858 (1974) [Sov. Radiophys. **17**, 1418 (1974)]; D. Dialetes and K. R. Chu, in *Infrared and Millimeter Waves*, edited by K. J. Button (Academic, New York, 1983), Vol. 7, p. 537; O. Dumbrajs, G. S. Nusinovich, and A. B. Prevalyev, Int. J. Electron. **64**, 137 (1988); A. W. Fliflet, R. C. Lee, S. H. Gold, W. M. Manheimer, and E. Ott, Phys. Rev. A **43**, 6166 (1991).

[7] G. S. Nusinovich and V. Ye. Zapevalov, Radioteckh. Electron. **3**, 563 (1985); A. Bondeson, W. M. Manheimer, and E. Ott, in *Infrared and Millimeter Waves* (Ref. [6]), Vol. 9, p. 310.

[8] B. Levush and T. M. Antonsen, Jr., IEEE Trans. Plasma Sci. **18**, 260 (1990).

[9] S. Y. Cai. T. M. Antonsen, Jr., G. Saraph, and B. Levush, Int. J. Electron. **72**, 759 (1992).

[10] K. E. Kreischer, T. L. Grimm, W. C. Guss, A. W. Mobius, and R. J. Temkin, Phys. Fluids B **2**, 640 (1990).

[11] W. C. Guss, T. L. Grimm, K. E. Kreischer, J. T. Polevoy, and R. J. Temkin, J. Appl. Phys. **69**, 3789 (1991).

[12] Paul Woskoboinikow, John Machuzak, and William J. Mulligan, IEEE J. Quantum Electron. **21**, 14 (1985).

[13] W. C. Guss, T. L. Grimm, K. E. Kreischer, and R. J. Temkin, in *Proceedings of the Fifteenth International Conference on Infrared and Millimeter Waves, Orlando Florida, 1990* (Ref. [5]), p. 416.