Single-Mode Operation of a High-Power, Step-Tunable Gyrotron

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A gyrotron oscillator with a single cylindrical cavity has produced output powers up to 645 kW and efficiencies up to 24% at 140.8 GHz, and step-tunable single-mode operation between 126 and 243 GHz. Mode stability and suppression of nearby competing modes are found to persist even for operation in very high-order cavity modes with severe mode competition. These results greatly improve prospects of developing cw megawatt gyrotrons relevant to the heating of fusion plasmas.

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In recent years, intensive research has been conducted on novel sources of high-power radiation at millimeter wavelengths. Important advances have been reported in research on electron cyclotron masers such as the gyrotron,[1-4] Cherenkov sources,[5] free-electron lasers,[6-8] and other novel devices.[9] For application to plasma heating at millimeter wavelengths, which requires cw or long-pulse operation, the gyrotron has achieved the most impressive results, with 100-kW, cw operation at 140 GHz[4] and 200-kW, cw operation at 60 GHz.[10]

The extension of gyrotron operation to high frequencies, at least 250 GHz, and megawatt power levels will be required for future applications in electron-cyclotron-resonance heating, such as for the proposed compact ignition tokamak, a 10-T device, or for a fusion reactor. One major obstacle to increasing the power and frequency of gyrotrons is the need to operate in high-order modes.[11] An important physics issue is the stability of operation of an oscillator in a highly overmoded cavity with minimal mode separation. Although stable, single-mode operation may be possible under such conditions as a result of mode suppression,[12] previous experimental evidence for this has been lacking in highly overmoded gyrotrons.

This Letter reports a major advance in gyrotron research with the achievement of power levels of over 0.5 MW at frequencies up to 243 GHz in short-pulse operation. These results were obtained with a gyromonotron utilizing a single, tapered cavity. Only one previous gyrotron device (of moderate voltage) has achieved such high power levels, a Soviet 2.1-MW, 100-GHz gyrotron;[3] however, no details have been reported of the nature of that device or its operating mode. The present results, although obtained in short-pulse operation, indicate that the gyrotron is very promising for further development as a cw, megawatt-power-level source for application to plasma heating in future plasma machines.

The tapered cavity has been previously questioned with regard to its ability to maintain single-mode operation at high power and frequency. As a result, a number of innovative approaches to mode control have been suggested, such as the complex cavity (or step cavity),[2] which has proven successful at lower frequencies, and quasioptical cavities, particularly Fabry-Perot cavities.[13] Our experiments indicate that the tapered cavity is, in fact, remarkably effective in providing efficient, single-mode emission even when the cavity is highly overmoded. Single-mode operation has been achieved in the $TE_{22,4,1}$ mode, the 377th transverse mode of a circular waveguide, corresponding to a cavity diameter of 12λ (λ is the free-space radiation wavelength). The tapered cavity is also easily fabricated, and can be step tuned by variation of the applied cavity magnetic field.[14,15] Such step tuning may be useful during plasma heating when the magnetic field applied to the plasma is varied, or for reasons of controlling the plasma.

The mode of a weakly tapered gyrotron cavity can be approximated as a TE_{mpq} mode of a circular cylinder cavity, where m, p, and q are the azimuthal, radial, and longitudinal 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 $k_\perp = \nu_{mp}/R_0$ and $k_\parallel = q\pi/L$, R and L are the cavity radius and length, and ν_{mp} is the pth root of $J_m'(x) = 0$. The condition for excitation of the cyclotron instability is

$$\omega - k_\parallel \beta_\parallel c = n\omega_c = n\omega_{c0}/\gamma, \tag{2}$$

where $\omega_{c0} = eB_0/m$ is the cyclotron frequency, $\gamma^{-2} = 1 - \beta^2$, and β is the total beam velocity normalized by c. The velocity components parallel and perpendicular to the magnetic field B_0 are given by $\beta_\parallel$ and $\beta_\perp$ respectively. Only fundamental operation ($n=1$) will be considered in this paper. For a gyrotron operating near cutoff, $k_\perp \gg k_\parallel$ and $\omega \approx \nu_{mp}c/R_0 \approx \omega_c$. For a given γ and R_0, a mode represented by ν_{mp} and oscillating at ω is only excited over a narrow range in B_0. By variation of the magnetic field, a sequence of discrete modes can be excited.

The excitation region for each mode can be determined by combining the linearized equations of motion[16] with the equilibrium condition within the cavity. This results in the following threshold condition for the beam current:

$$I_{\mathrm{th}}(A)=2190\frac{\gamma\beta_{\parallel}^{2}}{Q_T}\frac{\lambda}{L}\frac{\exp(2x^2)}{\mu x-1}S_{mp}^{-1}, \tag{3}$$

where

$$S_{mp}\equiv\frac{J_{m\pm1}^{2}(k_{\perp}R_e)}{(\nu_{mp}^2-m^2)J_m^2(\nu_{mp})},$$

$\mu=\pi(\beta_{\perp}^2/\beta_{\parallel})(L/\lambda)$, and $x=L(\omega-\omega_c)/4c\beta_{\parallel}$. The total cavity Q, Q_T, includes diffractive and Ohmic losses. A Gaussian axial-field profile has been assumed. The choice of sign depends on the azimuthal rotation of the rf field. Figure 1 shows I_{th} for modes in our cavity between 135 and 144 GHz, indicating the high density of modes present.

In our tapered resonator, single-mode operation is the result of three factors: beam quality, cavity attributes that reduce the number of competing modes, and mode suppression. Beam quality is important because a spread in γ, $\beta_{\perp}$, or $\beta_{\parallel}$ can cause some electrons to become resonant with competing modes[12] as well as reduce the efficiency. The density of competing modes has been reduced by designing the resonator output taper to reflect $q=1$ modes more strongly, increasing the diffractive Q of these modes relative to the $q>1$ modes, and allowing the $q=1$ modes to dominate. Further mode selection was achieved by choice of the electron-beam radius that results in preferential coupling to the desired transverse TE_{mp} mode structure. As a result, the number of competing modes in our cavity scales approximately as λ rather than λ^3.

Mode suppression in tapered cavities has been extensively modeled in the past.[12,17,18] These simulations indicate that once a mode becomes established within a cavity, the nonlinear perturbation of the beam increases the threshold conditions for other modes, especially when the established mode interacts efficiently with the beam.

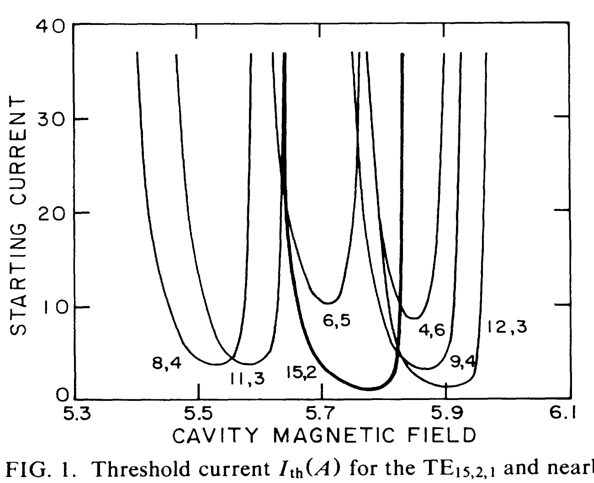

FIG. 1. Threshold current $I_{\mathrm{th}}(A)$ for the $\mathrm{TE}_{15,2,1}$ and nearby modes.

Therefore, the desired mode must be excited before unwanted modes are excited as the gun voltage is raised to its steady-state value.[19] Although nearby modes can be excited by the sideband generation mechanism, which is called nonlinear parasitic mode excitation in gyrotrons,[20,21] this effect has been previously shown to be relatively weak in gyrotron oscillators.[21] A numerical simulation of our experiment would be of great interest but is beyond the scope of this paper. However, our experimental results agree qualitatively with previous simulations. In fact, the degree of success of mode locking in the present experiments is remarkable and can probably be even more effective in cw operation.

The design of the present experiment consisted of first identifying specific modes, such as $\mathrm{TE}_{15,2,1}$, which have a relatively wide separation from nearby modes. The cavity and high-quality electron beam were then designed to excite the desired mode first, as the voltage was raised, while avoiding parasitic modes and sideband-generated modes. Suppression of nearby modes in saturated operation then assured single-mode operation. The cavity was also designed to satisfy certain technological constraints, such as maintaining an Ohmic wall loss of less than 2 $\mathrm{kW/cm^2}$.

A schematic of our experiment is shown in Fig. 2. The gyrotron operates at 4 Hz with 3-μsec pulses. The magnetron injection gun, which was built by Varian Associates, produces a beam with theoretical $\beta_{\perp}/\beta_{\parallel}=1.93$ and a spread in $\beta_{\perp}$ of 4% at 80 kV and 35 A.[22] The beam has been placed relatively close to the wall to minimize voltage depression by the space-charge field. The cavity magnetic field is provided by a Bitter copper magnet capable of fields up to 9.7 T. There is also a small gun coil centered at the cathode for optimizing the beam quality. The cavity, which consists of a straight cylindrical section terminated at each end by linear tapers, has an effective L of 6λ, and a diffractive Q of 415. The radiation produced is transmitted via a 2.54-cm-i.d. copper waveguide to a broad-band moth-eye window,[23] and broadcast into a shielded box where measurements of the power, frequency, and far-field pattern can be made.[1]

In the first set of experiments, stable operation was achieved in the $\mathrm{TE}_{15,2,1}$ mode at 140.8 GHz. Output powers up to 645 kW were measured at 80 kV and 35 A with single-mode emission. The efficiency peaked at 24% at 15 A, and remained between 20 and 24% at higher currents. This contrasts with self-consistent nonlinear theory, which suggests that the efficiency should continue to increase to 38% at 35 A. The observed degradation of efficiency at higher currents may be due to several effects, including mode competition from the $\mathrm{TE}_{11,3,1}$ mode, which was observed at 136.4 GHz. The highest $\mathrm{TE}_{15,2,1}$ powers occur along the boundary with the $\mathrm{TE}_{11,3,1}$ oscillation region. The optimum cavity magnetic field at 5.48 T at 35 A agrees with predictions based on nonlinear theory. It was found that the gyrotron was

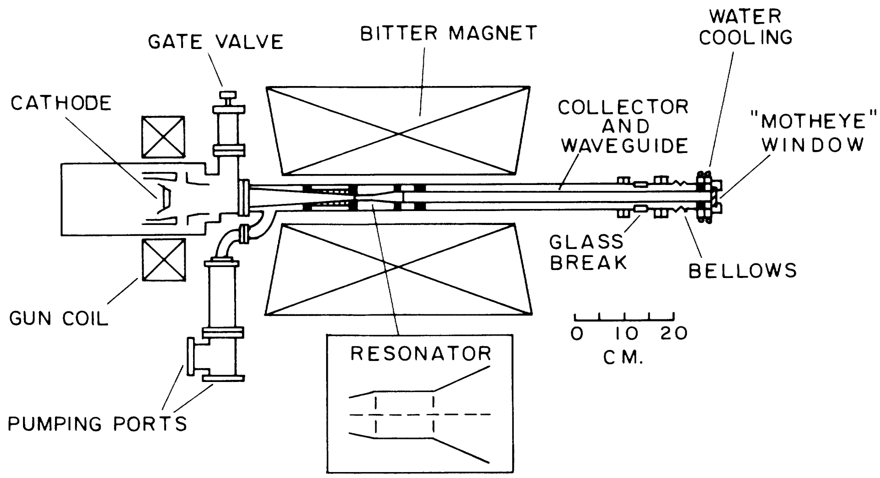

FIG. 2. Schematic of the gyrotron.

sensitive to the magnetic field settings. Minimal second-harmonic ($n=2$) emission was observed, probably because of suppression by the dense fundamental spectrum.

The tuning of our gyrotron was investigated as the magnetic field was varied from 4.8 to 9.7 T. The results are shown in Fig. 3. The dominant modes observed corresponded to the $p=2$, 3, and 4 radial modes. For each series, high-power single-mode emission was detected at discrete frequencies separated by about 7 GHz corresponding to a sequence of azimuthal (m) modes with $q=1$. In the highest-order mode observed ($TE_{22,4,1}$ with $D=12.2\lambda$), 470 kW was generated at 243 GHz in a single mode. These data indicate that the gun, although designed for operation at 140 GHz, produces a high-quality beam over the entire range from 126 to 243 GHz. It also appears that high powers could be achieved at even higher frequencies if magnetic fields above 9.7 T were available.

The normalized current[16] I is also plotted in Fig. 3 for the observed modes using the actual beam radius, and including the effect of higher-magnetic compression at higher frequencies. This parameter is defined as

$$I \equiv 0.59\times 10^{-4}\frac{Q_T I(A)}{\lambda \beta_\perp^4}\frac{\lambda}{L}S_{mp}. \qquad (4)$$

In Fig. 3, only the maximum value of S_{mp} for the two rotating modes is plotted. This graph indicates that the output power scales approximately as I, as would be expected from nonlinear theory.[16] The curves for I also predict a transition from the $p=2$ to the $p=3$ modes at about 165 GHz, and from the $p=3$ to the $p=4$ modes at about 225 GHz, in agreement with our observations.

The step-tunable behavior of the gyromonotron can be understood by analysis of the coupling strength S_{mp} between the beam and rf field. A plot of S_{mp} is shown in Fig. 4 for the $TE_{15,2,1}$ mode and neighboring parasitic modes. The beam is located between R_e/R_0 of 0.69 and 0.72, ensuring good coupling to the $TE_{15,2,1}$ and suppression of the competing modes. A plot of S_{mp} for other nearby $TE_{m,2,1}$ modes would show a similar functional dependence. For example, the inner maximum occurs at $R_e/R_0=0.70$ for the $TE_{13,2,1}$ and at 0.75 for the $TE_{18,2,1}$ mode. Thus, choosing R_e for strong coupling to the $TE_{15,2,1}$ mode automatically leads to strong coupling to nearby $TE_{m,2,1}$ modes, resulting in strong emission from these modes.

In summary, single-mode, step-tunable operation of a gyromonotron with powers up to 645 kW has been demonstrated between 126 and 245 GHz. These results make the cylindrical cavity highly competitive with alternative approaches, such as the complex cavity and quasioptical gyrotron. Additional mode suppression

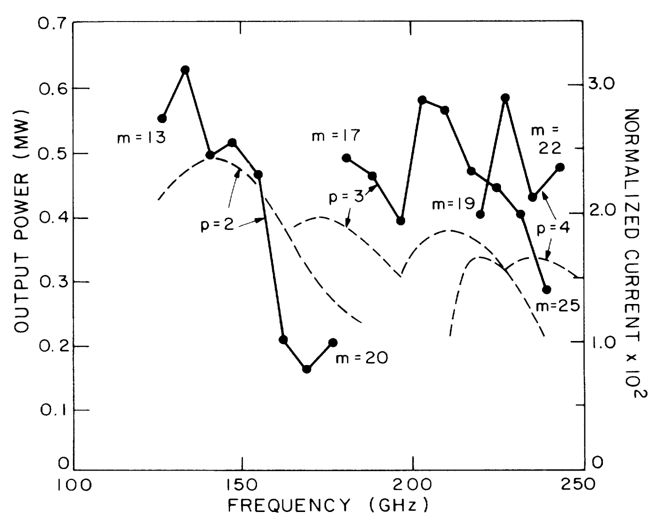

FIG. 3. Measured output power for $TE_{m,p,1}$ modes at 80 kV and 35 A (solid lines), and the theoretical normalized current I for these modes (dashed lines).

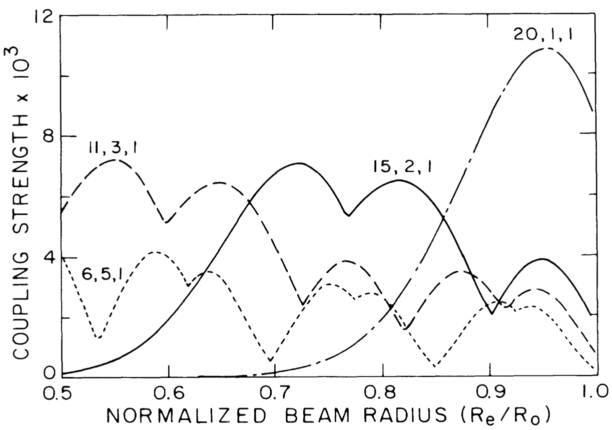

FIG. 4. Coupling strength S_{mp} [see Eq. (3)] vs the normalized beam radius. The beam is centered at 0.71.

techniques, such as the coaxial insert,[24] could make the gyromonotron even more attractive. These results suggest that megawatt gyrotron sources at frequencies relevant to the heating of fusion plasmas should be feasible.

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