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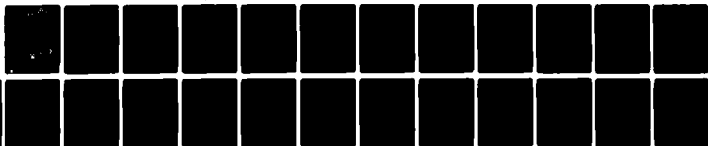
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Design of a High Power 240 GHz Gyromonotron

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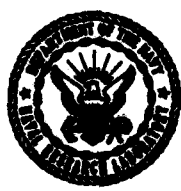
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November 4, 1980

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DESIGN OF A HIGH POWER 240 GHz GYROMONOTRON

I. Introduction

During the past several years the gyrotron¹ has been shown to be an efficient source (4 to 45 percent) of high power radiation (1 kW to 1MW) at wavelengths less than 1 cm. Although a number of such devices have been operated successfully in the U.S. in the 8 to 10 mm range,^{2,3} the only devices operating in the near-millimeter wave range (≈ 3 mm) are those built in the Soviet Union.^{4,5}

This paper describes results of the design phase of the first known effort in the U.S. to build an efficient, high-power gyrotron oscillator operating with a wavelength near 1 mm. Specifically, the design goals for this gyromonotron (i.e., single-cavity cyclotron resonance maser (CRM)) were 1 to 10 kW (peak) at 1.3 mm and an overall efficiency of 10 to 15 percent. It was to operate at the second harmonic of the cyclotron frequency ($\omega = 2\omega_c$) and with a cavity mode of TE_{051} . Although these last two facts allow operation at reduced magnetic field and higher power than would be possible with the fundamental and lower order modes, they greatly increase the problem of mode competition; the circumvention of this complication is one of the main considerations in this design.

II. Design Considerations

A schematic of the device is shown in Fig. 1. The design utilized both analytical and numerical methods. For the beam-wave coupling and oscillation start conditions, the linear theory of Chu⁶ was used. Calculation and optimization of the device efficiency required the use of a code initially developed by Drobot,⁷ and modified by the authors.

The desired output of the device was 1 to 10 kW at the frequency of 240 GHz. An operating mode of the class of TE_{onl} was considered desirable because of the ease with which other modes can be preferentially damped.⁸ In addition, these modes are well suited to a high power device, since wall losses in the cavity and output waveguides are minimal for modes without azimuthal variations. The value of n was chosen to be 5 to allow a large enough cavity radius to minimize breakdown or heating problems and reduce perturbations caused by machining errors, while allowing operation near cutoff. (The latter is necessary for optimum CRM coupling.¹) It is desirable to operate at as low a cyclotron harmonic as possible in order to minimize mode competition. Since the maximum magnetic field available was 60 kG, the minimum possible cyclotron harmonic, 5, and the one chosen, was 2.

The initial ratio of perpendicular to parallel electron momentum, α , is important because only the perpendicular energy is available to the cyclotron resonance maser interaction, has an upper limit fixed by present electron-gun technology. A reasonable estimate for this limit, without knowledge of the exact gun design, appeared to be 1.5.⁹ Finally, the beam voltage was chosen to be $V = 30$ kV, a value deemed to be practical for non-laboratory devices.

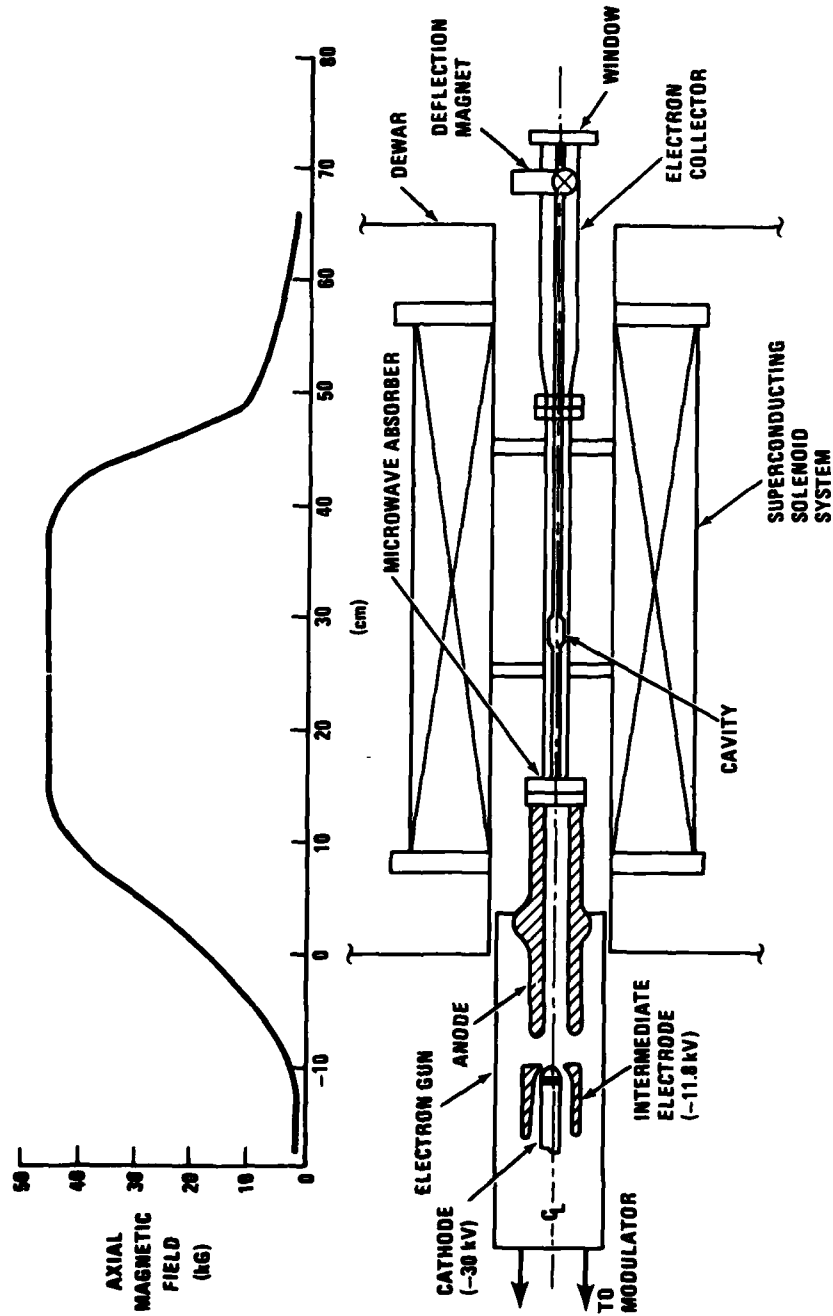


Fig. 1 - Schematic of 240 GHz gyrotron oscillator and plot of axial magnetic field

The linear theory allowed calculation of the beam-wave coupling, which is inversely proportional to the product of electron beam power P , and cavity Q required for an oscillation to start. The parameters varied in these calculations were L (cavity length), r (mean beam radius), and ℓ (axial eigen-number of the cavity mode). There are several locally optimum values of r . The strongest coupling occurs for the smallest of these values,⁶ $r = 0.19b$, where b is the cavity wall radius. This value therefore requires the lowest starting current and, despite the small beam radius, yielded the smallest spread in velocities due to space charge. As seen in Fig. 2, the mode $\ell = 1$ has stronger coupling than modes for which $\ell > 1$, and the choice for that parameter was so determined.

III. Efficiency Optimization

The optimization of the device efficiency was then carried out by varying the remaining parameters, L , I (beam current), Q_L (leakage Q) and B (external magnetic field), with the boundary conditions as follows:

$$Q_L > 4\pi(L/\lambda)^2, \quad (1)$$

$$I_{th} < I < 2 \text{ A}, \quad (2)$$

$$\delta\Delta = \delta[(\omega - kv_{ph} - \frac{S\Omega}{\gamma}c)_{\tau}] \ll 2.5\pi, \text{ and} \quad (3)$$

$$Q_L < Q_{ohmic}. \quad (4)$$

The authors' output power requirement meant that

$$10^3 \text{ W} < VI < 10^4 \text{ W}. \quad (5)$$

The condition in Eq. (1) states that the leakage Q has a lower limit, usually termed the diffraction Q . The condition in Eq. (2) states that I must exceed the minimum current required for start of oscillation and be less than 2 A. The latter upper limit on I is imposed by the predicted dependence of electron

velocity spread on current density at the cathode of the electron gun.¹¹ In the present case this upper limit is less than the maximum allowed by voltage depression due to space charge in the cavity. Eq. (3) is the criterion given by Chu⁶ on the maximum allowed spread in the phase shift, Δ , between cyclotron and electromagnetic (cavity) modes. In this equation $\tau = L/v_{||}$, $v_{||}$ is the velocity parallel to the magnetic field, $k = \pi/L$, ω and Ω_C are the radiation and relativistic cyclotron frequencies, respectively, and γ is the normalized electron energy. Finally, the condition in Eq. (4) must be satisfied in order for the ohmic losses to be small.

The code used for the optimization integrates the electron energy loss along its orbit. It is a single particle, 3 dimensional code, and calculations are made with steady-state cold cavity field profiles. Optimization was accomplished in a three parameter space, the parameters being L , B and QI . The parameters L and B determine the phase shift, Δ , in Eq. (3), and the parameter QI , when combined with η_{CRM} (CRM efficiency) and the cavity mode and geometry, yields a measure of the magnitude of electromagnetic fields in the cavity.

The results of the optimization runs for CRM efficiency, η_{CRM} , versus QI , with Δ as parameter and $L = 8b$ are shown in Fig. 3. We note that the variation of η_{CRM} with field amplitude predicted by the code for small amplitudes is in excellent agreement with that given by the linear theory. The threshold values, $(QI)_{th}$, from the linear theory are indicated by the vertical lines in Fig. 3.

$(QP)_{TH}$ VS L/b

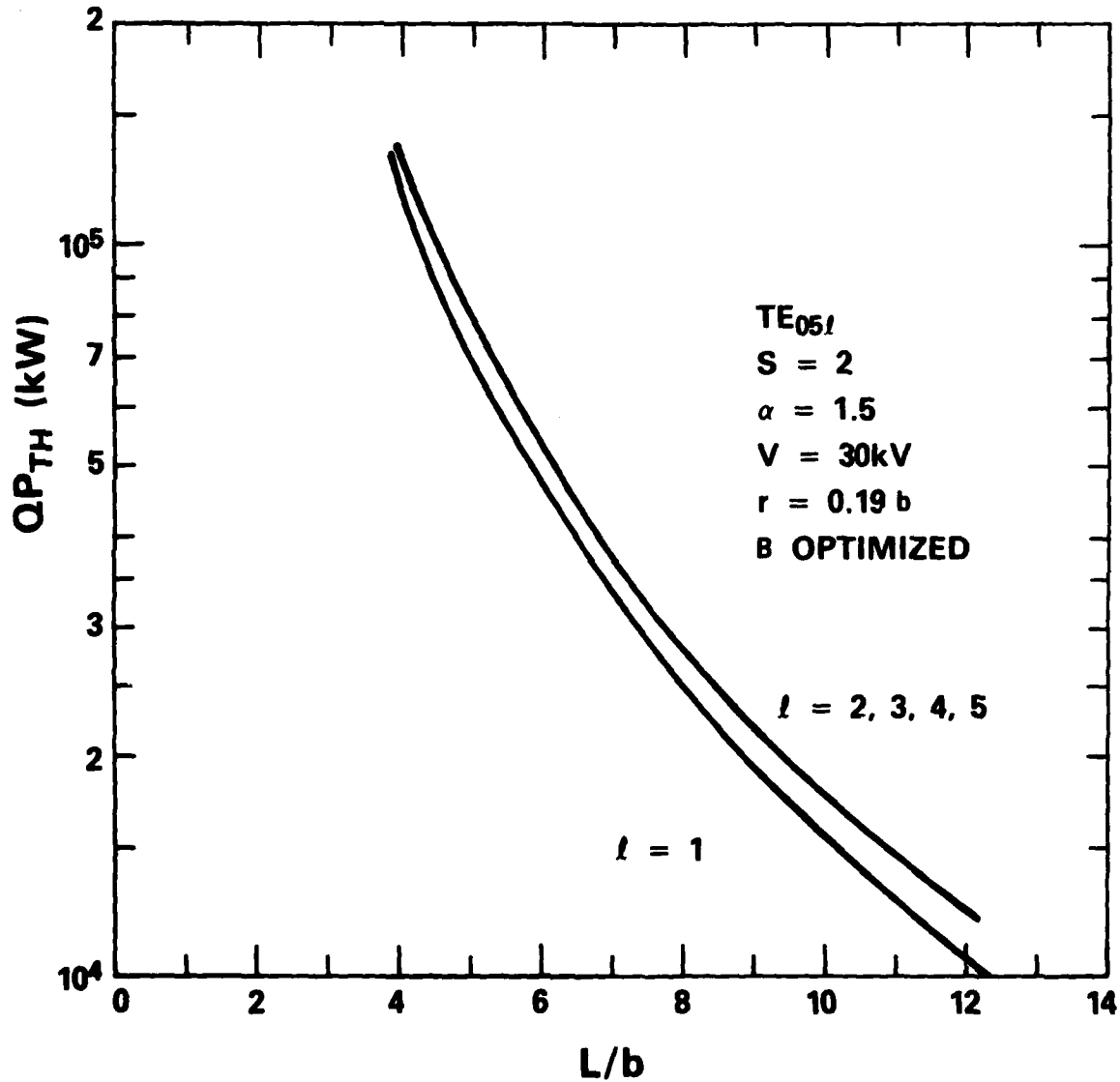


Fig. 2 — Threshold QP for gyrotron oscillator vs. cavity length-to-radius ratios from gyrotron cavity theory. $(QP)_{th}$ for $l = 2, 3, 4, 5$ have nearly the same value so they are represented by the same curve.

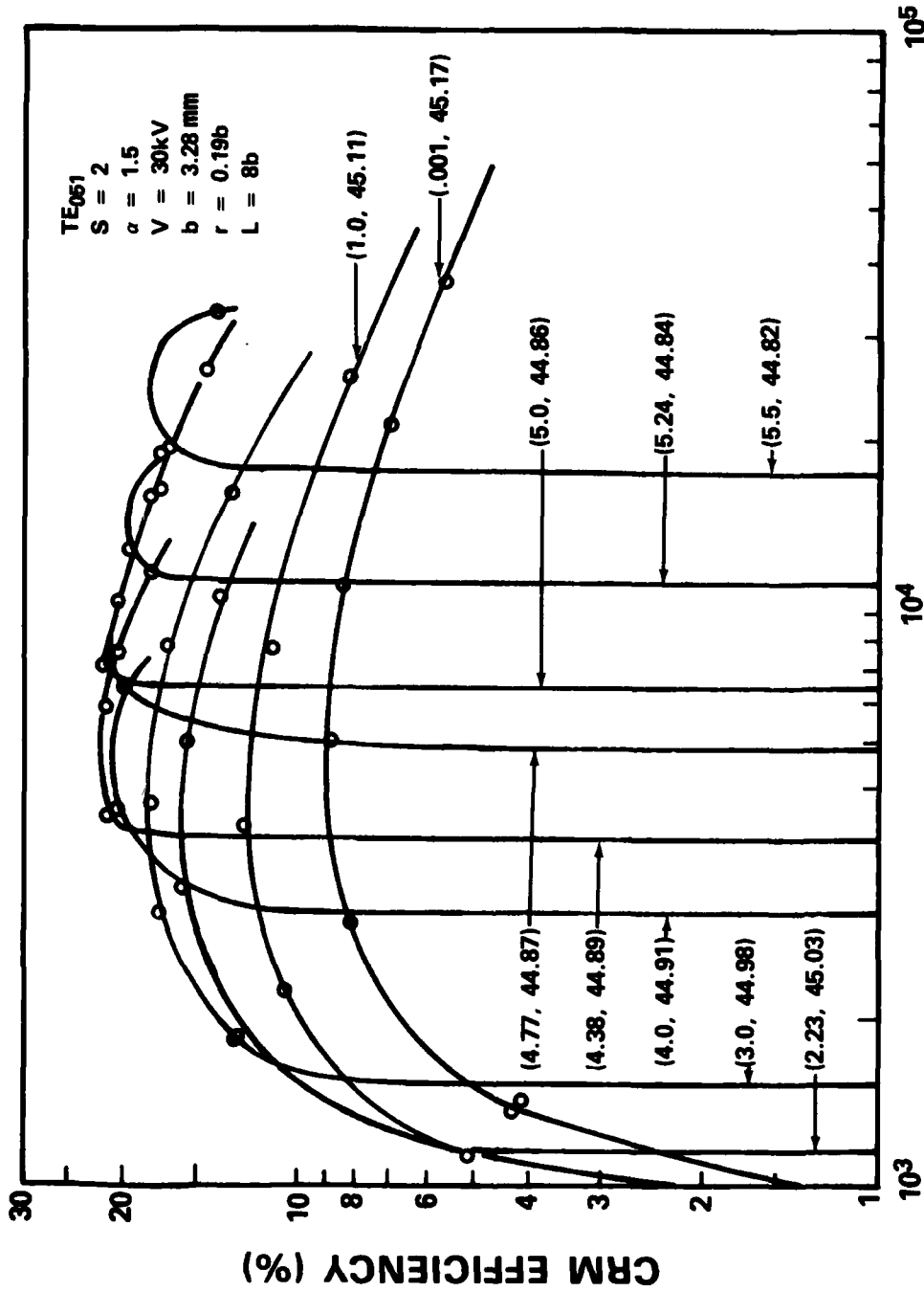


Fig. 3 — CRM efficiency vs. QI from electron orbit computer code. The two numbers in the parentheses are, respectively, Δ in radians and B in kG.

The results for maximum CRM efficiency $\eta_{\text{CRM}}^{\text{max}}$, obtained by varying B and QI for various fixed values of L, are shown in Fig. 4. It can be seen that $\eta_{\text{CRM}}^{\text{max}}$ has a value of 30 percent for a cavity length $L = 4b$. However, the overall (loaded) efficiency, η_L , unlike η_{CRM} , depends on wall losses. It is therefore limited by the boundary conditions (1) through (5) and the maximum achievable ohmic Q of 20,000 in a copper cavity at room temperature. The result is that the highest value of η_L is achieved with a cavity length $L = 8b$, even though $\eta_{\text{CRM}}^{\text{max}}$ for this cavity length is only 22 percent. This cavity length was therefore chosen for the design. From Fig. 3, a QI value of 8.0×10^3 amperes maximizes η_{CRM} . Assuming an achievable Q_L of 7300 (1.3 times the diffraction Q), the total Q of the cavity is 5300, resulting in a required beam current of 1.5 A; η_L is then 16 percent.

Our predictions of efficiency versus QI for this gyrotron have been compared with those based on data from the theory of Nusinovich and Erm.¹⁰ This theory assumes that the rf electric field in the cavity has a Gaussian dependence on axial distance. Such a field shape is known to result in a higher efficiency than the purely sinusoidal shape of a straight cylindrical cavity. The lowest QI for which a comparison could be made by extrapolating the Nusinovich and Erm data is 1.55×10^4 A. Assuming an ohmic Q of 20,000 as above, a total Q of 7000, and therefore, a current of 2.2 A, those data predict an η_L of 16 percent whereas our simulation code predicts an η_L of 11 percent.

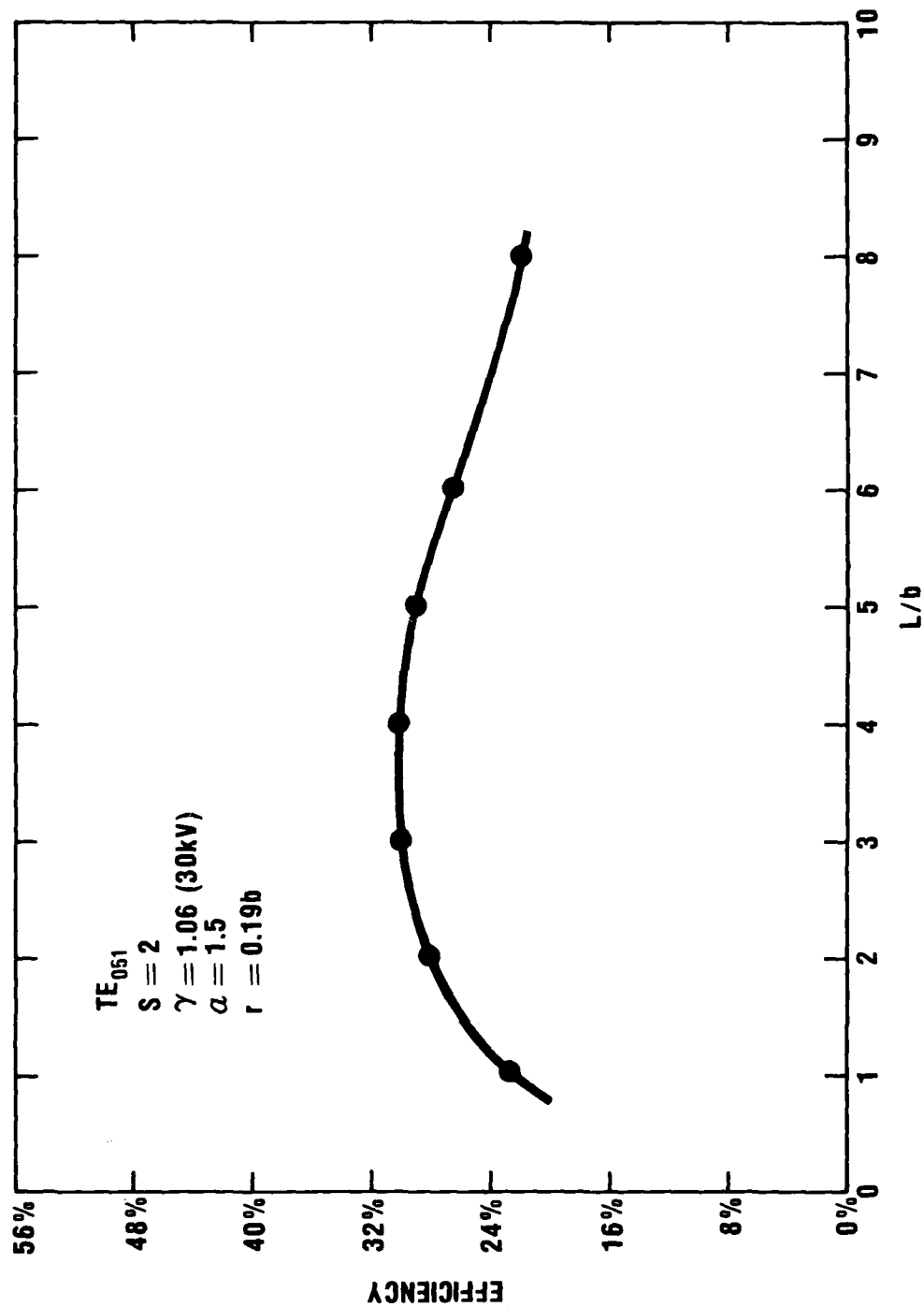


Fig. 4 — Maximum CRM efficiency vs. cavity length-to-radius ratio from electron orbit code

The geometry, beam parameters, and magnetic field determine the phase shift, Δ , given by equation (3). Figure 3 shows that the mechanism is "strong" for $0 < \Delta < 4.5$. This agrees with the analytical theory⁶ that strong coupling occurs within the range $-\pi/2 < \Delta < 2\pi$. It is clear that for the stable operation of a device, the phase shift associated with any electrons should not be outside this range. Preferably, the range should be much less than 2.5π . This puts a limit on the inhomogeneity in the static magnetic field and on the electron gun-dependent beam temperature.

The computer code results of Fig. 3 show that in order for this device to operate within 10 percent of its maximum efficiency, spread in the magnetic field should be no greater than 0.2 percent. Other runs with the computer code were made in which the electron velocity components were varied, with the electron energy, applied magnetic field, and rf field amplitude held constant. Based on these runs, the 22 percent CRM efficiency for zero spread in v_{\parallel} would be reduced to 21 percent for a 10 percent spread in v_{\parallel} , and to 20 percent for a 20 percent spread in v_{\parallel} .

IV. Mode Competition

Until now it has been assumed that the cavity can only oscillate in the TE_{051} mode. In order to assess the effects of mode competition, $(QI)_{th}$ for other $TE_{on\ell}$ modes was calculated by means of the linear theory at values of Δ for those modes corresponding to the range in Δ for the TE_{051} , $S=2$ mode in Fig. 3. Values of S ranging from 1 through 3 were scanned. As was expected, $(QI)_{th}$ for a number of $TE_{on\ell}$, $S=1$ modes was less than that for the TE_{051} , $S=2$ mode due to the stronger coupling at the first cyclotron harmonic than at the second. However, due to the rather strong dependence of Δ on resonant frequency (see eq. (3)), the only modes with $S=1$ for which the requirement $-\frac{\pi}{2} < \Delta < 2\pi$ was satisfied were those with rather large axial mode number, ℓ . Assuming a coupling scheme in which Q_L has the previously stated value of 7300 for TE_{051} , the value of Q_L for modes with larger ℓ is correspondingly smaller.⁸ The result is

that for the entire range in Δ or B over which the gyrotron would be operated for oscillations in the TE_{051} , $S=2$ mode, the lowest $S=1$ mode threshold power, which occurs for the TE_{028} mode, is still about ten times that of the TE_{051} , $S=2$ mode. The only modes whose threshold power is comparable to that of the TE_{051} , $S=2$ mode are other $TE_{05\lambda}$, $S=2$ modes.

The results for P_{th} vs Δ or B are shown in Fig. 5. It is seen that while the TE_{051} mode has the lowest threshold for high magnetic fields, the TE_{052} mode has a lower threshold for $B = 44.86$ kG, the field for which the TE_{051} mode is most efficient, as is evident from Fig. 3. In order to assure stable operation in this mode, a reasonable operating point is probably 44.86 kG. Fig. 3 then shows that η_{CRM} is reduced from 22 percent to 18 percent, leading to a reduction in η_L from 16 percent to 13 percent.

The device parameters resulting from the design are given in Table I.

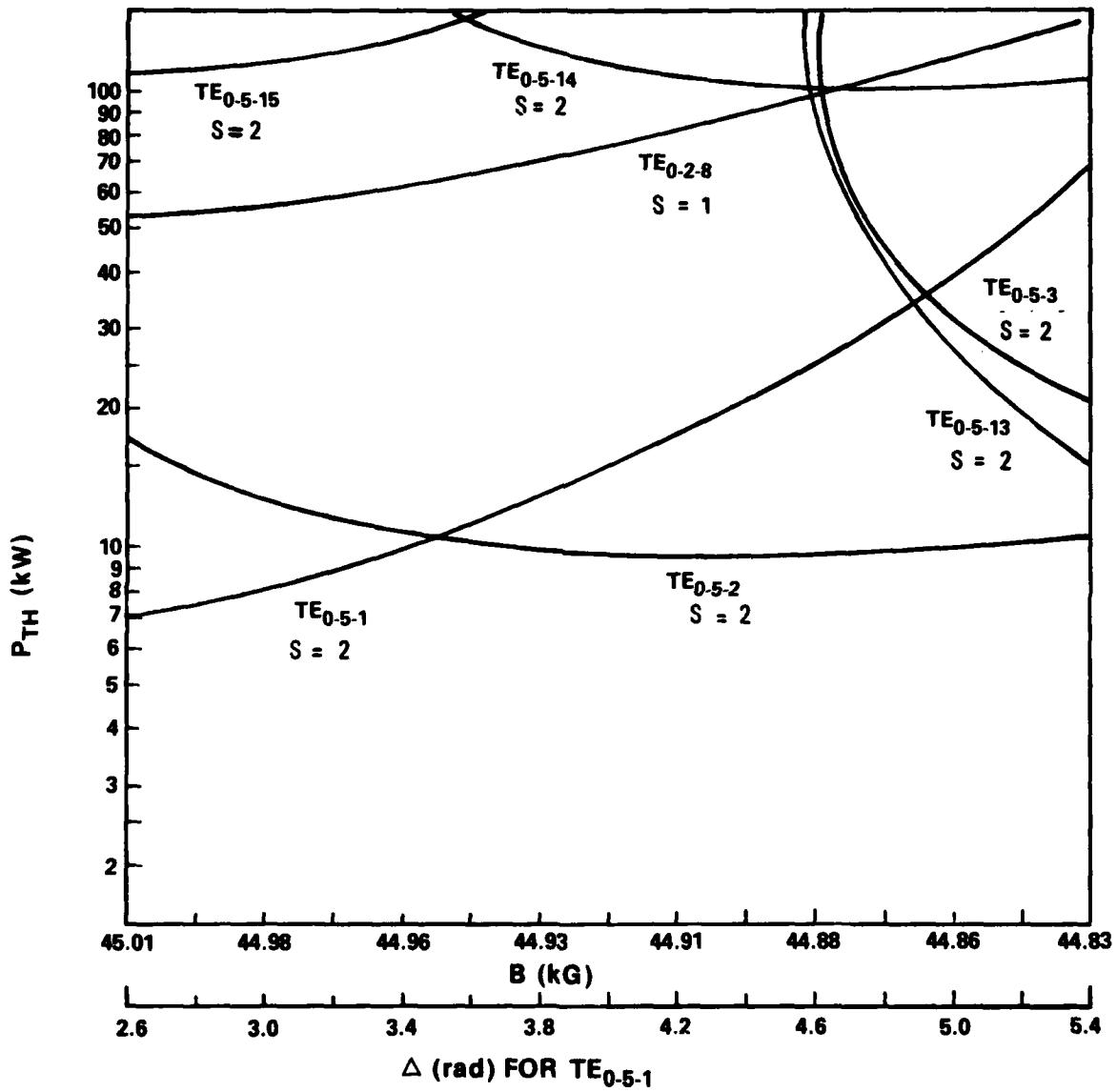


Fig. 5 — Threshold power for gyrotron oscillation in various $TE_{0n\ell}$ modes vs. B from gyrotron cavity theory. $Q_L = 7300$ for the TE_{051} mode.

TABLE I
GYROMONOTRON PARAMETERS

Frequency	240 GHz
Cavity mode	TE ₀₅₁
Output power	3.5 kW
Cavity diameter x length	6.6 x 26.2 mm
Beam voltage	30 kV
Beam current	0.9 A
Beam geometry	annular
Mean beam diameter	1.2mm
Initial ratio of electron perpendicular to parallel momentum in cavity	1.5
Beam thickness	0.2mm
Magnetic field	45 kG
Magnetic field homogeneity in cavity	0.2%
Beam temperature:	
Axial component	10%
Transverse component	5%

Acknowledgment

The authors acknowledge the many useful suggestions from and discussions with A. T. Drobot and V. Granatstein during the design of this device.

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