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EXPERIMENTAL STUDY OF A HIGH FREQUENCY MEGAWATT GYROTRON OSCILLATOR

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A detailed experimental study of the efficiency and output power of a pulsed gyrotron operating in the $TE_{16,2,1}$ mode at 148 GHz has been conducted. A peak efficiency of 30% was achieved at 80 kV and 20 A for an output power of 480 kW. The highest output power of 925 kW, corresponding to an efficiency of 19%, was measured at 120 kV and 40 A. Two cavities with different interaction lengths (6.0λ and 4.2λ) were investigated. In both cases, agreement was found between the theoretical and experimental efficiency for beam currents up to 15-20 A. At higher currents, the experimental efficiency saturated between 20% and 25%, well below the 35% to 40% predicted by theory. No increase was obtained for modest positive or negative linear tapering of the cavity magnetic field. Measurements indicate that the beam velocity ratio decreases as beam current increases, partially explaining the reduced efficiency at higher currents. Operation in different azimuthal rotations of the cavity modes was also observed. The measured rotation was found to be consistent with the theoretical coupling between the beam and RF field.

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1. Introduction

Progress continues on the development of novel, high power sources of millimeter and submillimeter radiation. A variety of applications exist for these sources, including high resolution radar, isotope separation, particle acceleration, and plasma diagnostics. At present one of the strongest motivations for millimeter sources is the need for high powers for electron cyclotron resonance heating (ECRH) of fusion reactors. Recent tokamak experiments[1] indicate efficient heating with localized deposition of the power is possible with ECRH. The required frequencies for fundamental heating range from 140 GHz for TFTR (toroidal field of 5 T) to 280 GHz for the Compact Ignition Tokamak (10 T).

A large variety of experiments over the past ten years have demonstrated the viability of the gyrotron as a high power, high frequency source. Early work at Varian Associates, Inc.,[2] led to cw tubes at 28 and 60 GHz. The recent emphasis has been at frequencies above 100 GHz. Varian has developed a 100 kW, cw gyrotron that can operate at 140 GHz in the $TE_{0,3,1}$ mode,[3] and has operated a short pulse tube up to 820 kW at this frequency in the $TE_{15,2,1}$ mode.[4] Experiments at M.I.T.[5] have demonstrated high power, step tunable operation between 120 and 240 GHz. Extensive international gyrotron research efforts also exist with impressive results reported at 100 GHz,[6,7] 120 GHz,[8] and 150 GHz.[9] Gyrotrons have operated at frequencies as high as 600 GHz, both with fundamental and harmonic[10] operation. Although most gyrotron research has been based on the cylindrical waveguide cavity, results have also been obtained with a quasi-optical cavity.[11]

At M.I.T., the present research goal is to demonstrate that megawatt power levels can be generated in a single high order mode of a cylindrical cavity. Our first experiments utilized a 10 T Bitter copper magnet and a single, tapered cavity. In addition to demonstrating step tunability over a large frequency range, we also found that mode stability and suppression of nearby competing modes persisted even for operation in very high order modes with severe mode competition. We observed single mode emission at 243 GHz with output powers of 470 kW from a gyrotron cavity with a diameter of twelve wavelengths. A peak power of 645 kW was measured in the $TE_{15,2,1}$ mode at 140.8 GHz at 80 kV and 35 A, corresponding to an efficiency of 23%. At lower powers, a peak efficiency of 25% was measured.

One concern that resulted from these experiments was the relatively low efficiencies that were measured at higher currents. Figure 1 compares our earlier experimental results with self-consistent nonlinear theory[12] assuming a velocity ratio $\alpha = \beta_\perp/\beta_\parallel$ of 1.93, where $\beta_\perp = v_\perp/c$ is the beam perpendicular velocity, and $\beta_\parallel = v_\parallel/c$ is the parallel velocity. Good agreement is found for beam currents up to 15 A. At higher currents the efficiency saturates while nonlinear theory predicts efficiencies of 44% at 35 A. Optimization of operating parameters did increase the efficiency to 23% and the output power to 645 kW at 35 A, still well below theory. The disagreement between theory and experiment was not observed in our previous 100-200 kW experiments[13] at 140 GHz in the $TE_{0,3,1}$ mode using a 65 kV, 5 A electron gun. In those experiments, a peak efficiency of 36% was obtained, consistent with theoretical predictions. In this paper we will describe possible reasons for the lower efficiencies of the MW gyrotron, and report on various attempts to improve its performance.

This paper is organized in the following manner. In Section 2, the nonlinear theory and criteria used to design our experiment will be outlined. In Section 3 the experimental results with a cavity having a long interaction length will be presented. This will include the effects of magnetic tapering, as well as the observed coupling to different rotating modes. In Section 4, operation with a cavity having a short interaction length will be described, including operation at cathode voltages up to 120 kV. A discussion of these results and conclusions will be presented in Section 5.

2. Design of Experiment

Our gyrotron is an oscillator that operates at 4 Hz with 3 μsec pulses, but is designed so that it can be scaled by industry to cw operation. The interaction between the beam and RF field occurs in a weakly tapered cavity with an oscillation frequency ω given by

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

where $k_\perp = \nu_{mp}/R_o$, R_o is the cavity radius, and ν_{mp} is the pth zero of $J'_m(x)$. Numerical simulations of the open resonators used in our experiments indicate that $k_\parallel \approx 2/L$, where L

is determined by fitting the Gaussian $exp(-2z/L)^2$ to the axial field profile. For a gyrotron operating near cutoff, the resonance condition can be approximately written as

$$\omega \approx \nu_{mp} c/R_o \approx \omega_c = eB_o/\gamma m_e \tag{2}$$

where $\gamma^{-2} = 1 - \beta_\perp^2 - \beta_\|^2$ and B_o is the cavity magnetic field.

Extensive studies of the nonlinear fundamental interaction of the gyrotron[14,15] based on a fixed Guassian profile of the axial RF field have been conducted. These show that the amount of perpendicular beam energy converted into RF power is a function of three parameters:

$$\begin{aligned} F &= \frac{E_o}{\beta_\perp^3 B_o c} J_{m\pm1}\left(k_\perp R_e\right) \\ \mu &= \pi \left(\frac{\beta_\perp^2}{\beta_\|}\right)\left(\frac{L}{\lambda}\right) \\ \Delta &= \frac{2}{\beta_\perp^2}\left(1 - \frac{\omega_c}{\omega}\right) \end{aligned} \tag{3}$$

where E_o is the RF field amplitude, λ is the free space wavelength, and R_e is the beam radius. The choice of sign depends on the azimuthal rotation of the mode. Typically, Δ is adjusted by varying B_o. The parameters F and μ are determined by the cavity equilibrium, which is a function of the cavity characteristics, including the cavity Q and L, as well as the beam parameters. Nonlinear studies show that high efficiency is possible either with larger F and smaller μ, or vice versa. The results reported in this paper include a study of both of these options. The above nonlinear theory is useful for preliminary cavity designs. The final design of our cavities, and the theoretical results presented in this paper, are based on a nonlinear theory with a self-consistent axial RF field profile.[12]

The configuration of the present experiment is similar to that used in our earlier experiments,[5] except that the cavity magnetic field is produced by a superconducting (SC) magnet instead of a Bitter magnet. The magnetron injection gun, which was built by Varian,[16] produces a beam with a theoretical $\beta_\perp/\beta_\|$ of 1.93 and a spread in $\beta_\perp$ of 4% at 80 kV and 35 A. The superconducting magnet has a six inch warm bore and is capable of fields up to 6.5 T and linear tapers up to 4% per inch. There is also a small gun coil centered at the cathode for optimizing the beam quality. The radiation produced is transmitted via a copper waveguide to a fused quartz window and broadcast into a shielded box where measurements of the power, frequency, and far field pattern can be made.

Our primary emphasis has been the study of surface modes, in particular the $\mathrm{TE}_{m,2,1}$ modes. These modes provide good coupling between the RF field and the electron beam, reduced mode competition, and allow the beam to be placed relatively close to the wall to minimize voltage depression by the space charge field. The cavities and gun were optimized to generate 140 GHz radiation in the $\mathrm{TE}_{15,2,1}$ mode. In our experiments on the SC magnet, the best results were in fact obtained with the $\mathrm{TE}_{16,2,1}$ mode at 148.0 GHz, and it will be these results that will be presented in this paper.

A list of the main parameters of the experiment is given in Table 1. Multiple entries indicate the parameters of two different cavities that were tested. These cavities consisted of straight cylindrical sections terminated at each end by linear tapers. The long cavity had an L of 6.0λ, while for the short cavity L was 4.2λ. The cavities were designed to operate at the minimum diffractive Q,[17] given by $4\pi(L/\lambda)^2$. The cavity current density is well below thresholds at which efficiency degradation would be expected.[18,19] The radial thickness of the beam is also sufficiently small that good coupling to the RF field is expected. Although the operating current of 35 A is well below the maximum current I_{max} of 85 A, the effects of voltage depression are still expected to be present. The design efficiency goal of 38% was conservative compared to the theoretical prediction of 48% at 35 A.

3. Experiments with Long Cavity

Figure 2 shows results with the long cavity in the SC magnet for an 80 kV beam. For each beam current I and cavity magnetic field B_o, the cathode magnetic field B_k has been optimized. As I increases, the B_o that produces the highest power decreases. This is consistent with theory, which predicts that Δ increases as the beam current becomes larger. This figure also shows the efficiency saturating and then decreasing at higher currents, similar to the behavior observed in the earlier Bitter magnet experiments. In fact the efficiency remains relatively constant (between 20% and 30%) over a broad range of currents (5A to

30A). There was an improvement in the peak efficiency, from 24% in the early experiments on the Bitter magnet to 30% on the SC magnet, but this peak continues to occur at low currents.

Measurements of the far field were made in order to determine the purity of the output mode. Results for the $TE_{16,2,1}$ mode are shown in Fig. 3. The theory is based on scalar diffraction from a circular waveguide.[20] The agreement between theory and experiment is quite good. The measured pattern is slightly asymmetric, suggesting a small amount of mode conversion may be occurring in the uptaper and output waveguide. The excitation of more than one mode in the cavity was monitored with a frequency system consisting of a harmonic mixer and a SAW filter that processes the IF signal. Cavity emission at a single frequency was always observed when the gyrotron was optimized for high power operation.

A comparison of the optimum efficiency with self-consistent nonlinear theory is shown in Fig. 4. Two theory curves are shown, one based on an α of 1.93, and the other on beam velocities as measured by our capacitive probe.[21] The theoretical efficiency has been reduced by a total of 12% to account for a calculated ohmic loss of 7% in the cavity, uptaper, and output waveguide, and a calculated 5% dielectric loss in the output window. Both theory curves indicate that the efficiency should peak at 30-35 A, in contrast to our observations of a peak at lower currents. Although gun simulations indicate that our gun should produce a 35A beam with an α of 1.93 and low spread, our capacitive probe indicates that α decreases from 2.0 at 5A to 1.55 at 35A. This reduction is consistent with our experimental observation that, for fixed beam voltages, it is necessary to raise B_k as I is increased in order to achieve high power, stable operation. According to adiabatic theory,[22] which approximately describes the behavior of a magnetron injection gun,

$$\beta_\perp = \left(\frac{E_k}{B_k c}\right)\sqrt{\frac{B_o}{B_k}} \tag{4}$$

where E_k is the electric field at the emitter. For fixed E_k, this theory indicates that a higher B_k produces a lower α. Figure 4 indicates that a reduction in α partially explains the lower efficiencies at higher currents.

Various attempts were made to increase the output power beyond the 645 kW generated at 80kV and 35A. These included operating in $TE_{m,2,1}$ modes other than the $TE_{16,2,1}$, tuning the cathode power supply to produce a flatter pulse, using windows of different thicknesses, and running at higher beam voltages and currents. It was hoped that operating in other modes at different B_o would result in better coupling between the beam and RF field, or improve the beam quality due to the change in cathode magnetic field. In particular we varied the magnetic field from 4.6T to 6.3T, exciting the $TE_{12,2,1}$ (119.5 GHz) through the $TE_{18,2,1}$ (162.1 GHz). It was found that the $TE_{16,2,1}$ produced the highest powers. It was hoped that flattening the voltage pulse would allow us to tune farther into the hard excitation region and reach higher efficiencies. By adjusting the pulse forming network of the modulator, the ripple was reduced to ±0.7%, but no improvement resulted. Fused quartz windows of various thicknesses were tried in order to determine if partial reflections back to the cavity were affecting the operation of the cavity. Again no improvement was observed. Only by running at higher voltages and currents could the power be increased. In general, increasing the voltage produced better results than increasing the current. The highest power achieved was 765 kW at 96kV and 36A, yielding an efficiency of 22%.

Tapering of the magnetic field in the cavity was also investigated. Magnetic tapering can lead to higher efficiencies.[23] In particular, a positive linear taper of 5-10% produces a tighter electron bunch with less energy spread at the beginning of the cavity, leading to greater energy extraction. Tapering becomes more difficult at higher frequencies because of the higher magnetic fields required and the need to taper over a shorter axial distance. The SC magnet consists of a Helmholtz pair of coils, each operated independently. This allows a positive or negative linear taper of up to 4% per inch in the cavity region. For the long cavity, a modest total taper of ±1.5% was possible. Both positive and negative tapers were tried with the $TE_{16,2,1}$ mode, and in both cases the efficiency dropped about 10% compared to the uniform field results. One possible explanation is deleterious effects on the gun performance when the SC magnetic field is tapered. When the taper is introduced, it is not localized to the cavity region, and the entire axial field profile is modified. The resulting changes of the field in the cathode region could be lowering the beam quality and producing the lower efficiencies.

The efficiency can also be reduced if the electron beam couples to different rotations of the same mode, resulting in mode competition. Gyrotron theory indicates that the electron beam can couple to either azimuthal rotation of the $\mathrm{TE}_{m,p,1}$ mode depending on the radial location of the beam in the cavity. The coupling strength is given by[14]

$$S_{mp}^{\pm} = \frac{J_{m\pm1}^{2}(k_{\perp}R_{e})}{(\nu_{mp}^{2} - m^{2})J_{m}^{2}(\nu_{mp})} \tag{5}$$

where the choice of signs depends on the azimuthal rotation of the mode. The rotation with the highest coupling strength will typically be excited first and prevent the excitation of the other rotation. We were able to measure the azimuthal rotation by fabricating two Vlasov couplers,[24] each designed for a different rotation, and by measuring their efficiencies. The rotation of the $\mathrm{TE}_{m,2,1}$ modes with $12 \leq m \leq 16$ was determined, and the results are given in Table 2. It was found that while the $\mathrm{TE}_{12,2,1}$ through the $\mathrm{TE}_{14,2,1}$ modes were coupled to the positive rotation, the $\mathrm{TE}_{15,2,1}$ and $\mathrm{TE}_{16,2,1}$ modes had switched to the negative rotation. This observed switch was found to be in agreement with the coupling factor S_{mp} between the beam and modes in our gyrotron. The change in coupling as B_o increases is due to a reduction in beam radius resulting from the higher magnetic compression, and the shift of the rf field pattern closer to the cavity wall as $\mathrm{TE}_{m,2,1}$ modes with higher m are excited.

4. Experiments with Short Cavity

As noted in Fig. 2, the efficiency of the $L = 6.0\lambda$ cavity peaks at about 15-20 A, and decreases at higher currents. One possible explanation is a diffractive Q, Q_D, that is higher than the value predicted by theory. This would cause the cavity RF field to be too strong, resulting in overbunching of the electrons and a reduction in the efficiency. Since the cavity was designed to operate at close to the minimum Q_D of $4\pi(L/\lambda)^2$, it is necessary to shorten L in order to lower Q_D. A short cavity with $L = 4.2\lambda$ and Q_D=300 was designed and constructed. A larger output taper angle was used (6° versus 4° for the long cavity) in order to keep Q_D sufficiently high to achieve megawatt powers at 35 A. In addition to avoiding electron overbunching, another advantage of the short cavity is its higher theoretical starting current of 6.4 A, compared to 1.5 A for the longer cavity. Recent studies of mode competition[25] indicate that excitation of parasitic modes can occur if the ratio of the operating current to the starting current becomes too large, and that this can prevent access to the high efficiency region. For our cavity this ratio is 5.5, well below the threshold for parasitic oscillations as indicated by these studies. A recent mode competition study[26] also shows that short cavities can reach stable operation in the high efficiency region. Other changes were also made to improve the performance of the experiment, including additional vacuum pumping and the elimination of an electrical break in the collector. These changes reduced mode conversion and RF breakdown in the output waveguide.

Experimental results with the short cavity are shown in Figs. 5 and 6. All experiments involved an untapered cavity magnetic field. In Fig. 5 a comparison between the optimum experimental efficiency and self-consistent nonlinear theory is shown. As with Fig. 4, the efficiency at each beam current has been optimized by varying the cathode and cavity magnetic field. The behavior of the short cavity is similar to the long cavity. The efficiency peaks at about 26% at a beam current of 15 A, and remains between 20% and 26% at higher currents. Agreement with theory is generally good up to 15-20 A. The theoretical efficiency in Fig. 5 includes a reduction due to ohmic and dielectric losses. The variation of α with electron beam current was not determined during these measurements. A reduction in efficiency due to lower α at higher currents, similar to that shown in Fig. 4, would be expected. A minimum starting current of 4.6 A was also measured, which is consistent with the 6.4 A predicted by theory.

A careful study of the dependence of the gyrotron's output on operating parameters was conducted. In particular, we varied the anode and cathode voltages as well as the cathode and cavity magnetic fields. One such scan is shown in Fig.6. This graph indicates that the efficiency was insensitive to the anode voltage as long as the cathode magnetic field was adjusted to optimize output power. Slightly better performance was achieved at higher anode voltages. As with the long cavity, increasing the cathode voltage was generally more productive than increasing the beam current. This study led to a peak output power of 0.815 MW at 90 kV and 44 A, corresponding to an efficiency of 21%.

For both cavities, the discrepancy between theory and experiment becomes larger as the beam current increases. This suggests that space charge effects within the beam may be playing a role. Such effects may be more prevalent in the megawatt experiments, which are operated at 41% of the limiting current,[27] compared to 10% in the 100 kW experiments. Of particular concern is voltage depression of the beam, which reduces the parallel kinetic energy of the beam and increases the likelihood of mirroring. In practice this effect may require us to operate with lower α at higher currents in order to maintain a minimum $\beta_{\|}$ through the cavity. As mentioned earlier, capacitive probe measurements indicate this reduction in α is occurring. Therefore, increasing the perpendicular energy of the beam by raising the cathode voltage should lead to higher output powers. A study of cathode voltages between 80 and 120 kV was conducted to verify this approach. The optimum cavity magnetic field was found to be an increasing function of voltage. This is expected based on the resonance condition (Eq.(2)). An improvement in output power was achieved, with 0.925 MW being generated at 120 kV and 40 A for an efficiency of 19%. The efficiency remained relatively constant at about 20% as the cathode voltage was varied. The beam $\beta_{\perp}$ was calculated using adiabatic theory from the anode voltage and magnetic fields (Eq. (4)). It was found to increase as the cathode voltage was raised, as expected.

5. Discussion

In these experiments we have confirmed that high efficiencies can be achieved at power levels up to 0.5 MW in the $TE_{16,2,1}$ mode at 148 GHz. For example, 30% total efficiencies are reached at 80 kV and 20 A, which is consistent with self-consistent theory. Our main concern has been the divergence between theory and experiment at higher currents. Many factors could explain this discrepancy, and in this section we will explore some possibilities. It is noteworthy that Varian Associates has virtually duplicated these results in their short pulse experiments,[4] so the likely explanations should apply to both the M.I.T. and Varian experiments.

Operation with a highly overmoded cavity suggests that mode competition may be preventing access to the high efficiency region. Certainly the mode density in this cavity is higher than in the cavity used in the 100 kW experiments. However, the spacing between the $\mathrm{TE}_{16,2,1}$ mode and its main competing mode, the $\mathrm{TE}_{12,3,1}$, is 2.9%, which is comparable to the spacing between the $\mathrm{TE}_{0,3,1}$ mode excited in the 100 kW experiments and the competing $\mathrm{TE}_{2,3,1}$ (2.0%). In the latter experiments, an efficiency of 30% was achieved at the design current of 5 A, indicating competition was not a limiting factor. Our step tuning study[5] also suggests that competition may not be the problem. This scan from 126 to 243 GHz shows the maximum output powers to be relatively constant over this range, even though competition at the highest frequencies should be much more severe.

In general, we found that modes with strong coupling to the beam can be excited over a wide range of parameters, again suggesting that mode competition is not a critical factor. One example is shown in Fig. 7, which was generated as part of our earlier study of the $\mathrm{TE}_{15,2,1}$. Changing the cavity magnetic field changes the cyclotron frequency and therefore the resonance condition. Changing the cathode magnetic field B_k primarily affects $\beta_\perp$; Eq.(4) shows that $\beta_\perp$ increases as B_k decreases. This is consistent with the observation of arcing at low B_k, suggesting that mirroring may be occurring because $\beta_\perp$ is too large. The shapes of the resonance regions can be understood in terms of the detuning parameter Δ. In general a mode is excited over a region bounded by $0 \lesssim \Delta \lesssim 0.5$. As B_o is increased, it is necessary for $\beta_\perp$ to decrease in order for Δ to remain within this range. This explains why the resonance region shifts to higher B_k as B_o increases.

Figure 7 also provides indirect information about the electron beam. For example, this figure shows that three modes covering a 7.2 GHz range can be excited at the same cavity magnetic field. Only large changes in $\beta_\perp$ can change Δ enough to cover such a large frequency range, indicating that $\beta_\perp$ is sensitive to B_k. Beam measurements with a capacitive probe[21] support this finding. Figure 7 also shows that the highest powers occur along the boundary between the $\mathrm{TE}_{15,2,1}$ mode and its main competing mode, the $\mathrm{TE}_{11,3,1}$. It is noteworthy that the highest powers do not occur at the lowest B_k (highest $\beta_\perp$). This suggests that as α

increases, the beam quality may be deteriorating and reducing the efficiency.

The present experimental evidence suggests that the electron beam may be primarily responsible for the lower efficiencies at high currents. This is supported by the observation that the measured α decreases as the beam current increases, as shown in Fig. 4. Attempts to operate at higher α lead to unstable operation or arcing, and no increase in RF power. This suggests that the beam quality deteriorates under these conditions. The beam may also be indirectly affecting the tube performance during the startup phase as the beam voltages are raised to their final values. The variation of α during this phase could be preventing access into the hard excitation region where the highest efficiencies are normally achieved. Further studies of these effects, as well as measurement of the beam velocity and spatial characteristics, are now in progress. We are also investigating novel cavities that may be less susceptible to the beam quality.

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TABLE 1

Design parameters for the 1 MW gyrotron operating at 148 GHz. Multiple entries are for separate cavities.

Mode	$TE_{16,2,1}$
Current(A)	35
Voltage(kV)	80
η_T(%)	38
Velocity ratio	1.93
Beam radius(cm)	0.53
Cavity radius(cm)	0.75
Cavity length(L/λ)	6.0/4.2
Diffractive Q	420/300
Magnetic compression	30
Cavity current density(A/cm^2)	384
Beam thickness(r_L)	3.85
Starting current(A)	1.5/6.4
Maximum current(A)	85
Voltage depression(kV)	3.3

TABLE 2

Comparison of theoretical and observed coupling to different azimuthal rotations of $\mathrm{TE}_{m,2,1}$ modes

m	B_o (kG)	S^+_{mp} ($\times 10^3$)	S^-_{mp} ($\times 10^3$)	Observed Rotation
12	46.0	8.49	0.80	Positive
13	48.6	7.78	1.67	Positive
14	51.2	6.06	4.24	Positive
15	53.8	4.41	6.56	Negative
16	56.5	3.30	6.59	Negative

Figure Captions

Fig. 1 Measured power and efficiency compared with self-consistent nonlinear theory. The cavity and cathode magnetic fields have been optimized at each beam setting.

Fig. 2 Maximum measured efficiency as a function of beam current for the $TE_{16,2,1}$ mode. The beam voltage is 80 kV.

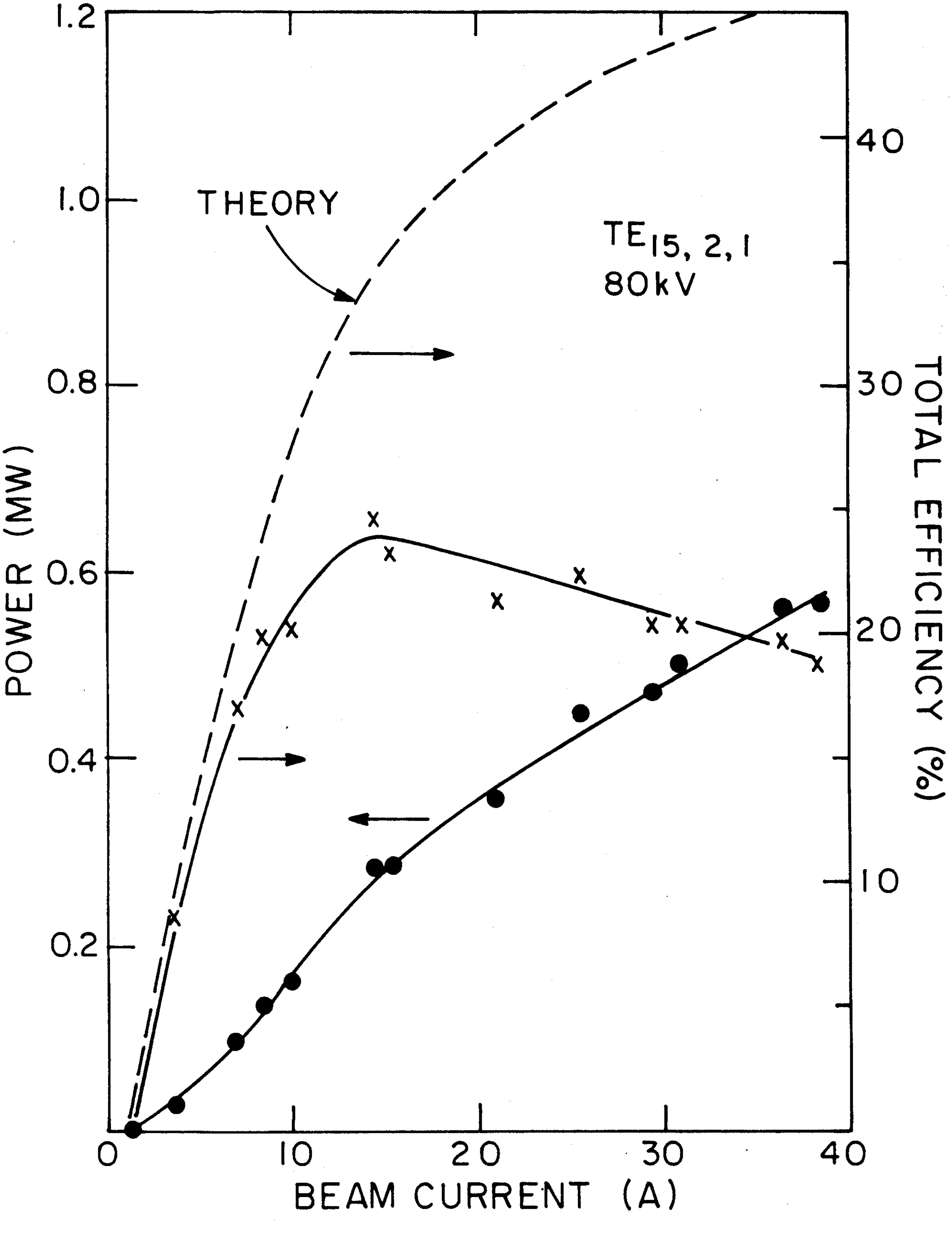
Fig. 3 Measured and calculated far field pattern from the output cylindrical waveguide of the gyrotron.

Fig. 4 Comparison of the measured efficiency of the 6.0λ cavity with self-consistent theory based on the design velocity ratio of 1.9, and with measured ratios. The cavity and cathode magnetic fields have been optimized at each current setting.

Fig. 5 Comparison of the measured efficiency of the 4.2λ cavity with self-consistent nonlinear theory for optimized cavity and cathode magnetic fields.

Fig. 6 Maximum measured efficiency of the 4.2λ cavity for various anode voltages. The cathode magnetic field has been optimized at each setting.

Fig. 7 Regions of excitation for the $TE_{15,2,1}$ and neighboring modes for an 80 kV, 35 A electron beam.



1.2
1.0
0.8
0.6
0.4
0.2
POWER (MW)
0
10
20
30
40
BEAM CURRENT (A)
40
30
20
10
TOTAL EFFICIENCY (%)
THEORY
TE15, 2, 1
80kV

Figure 1

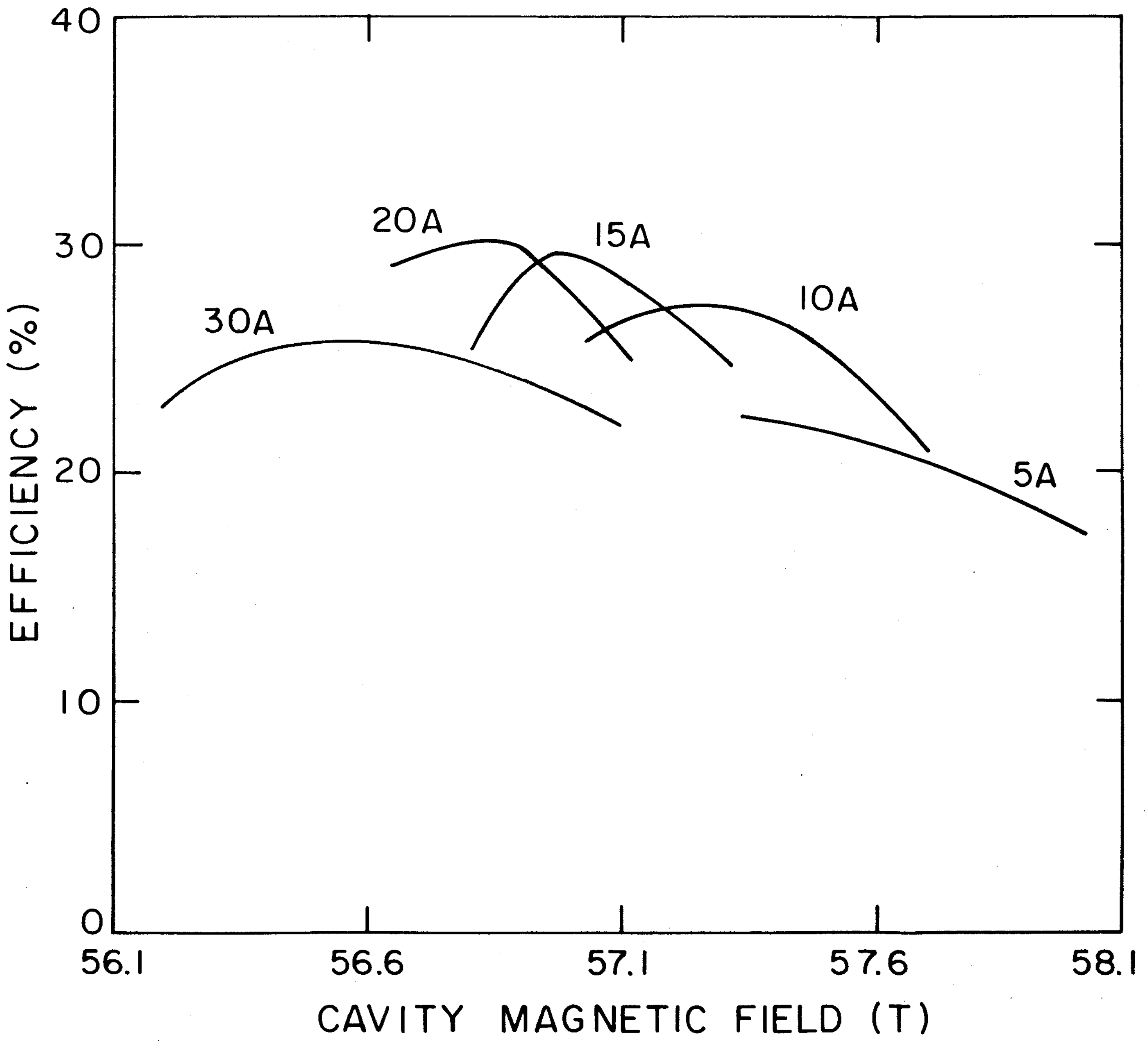

EFFICIENCY (%)
40
30
20
10
0
56.1
56.6
57.1
57.6
58.1
CAVITY MAGNETIC FIELD (T)
30A
20A
15A
10A
5A

Figure 2

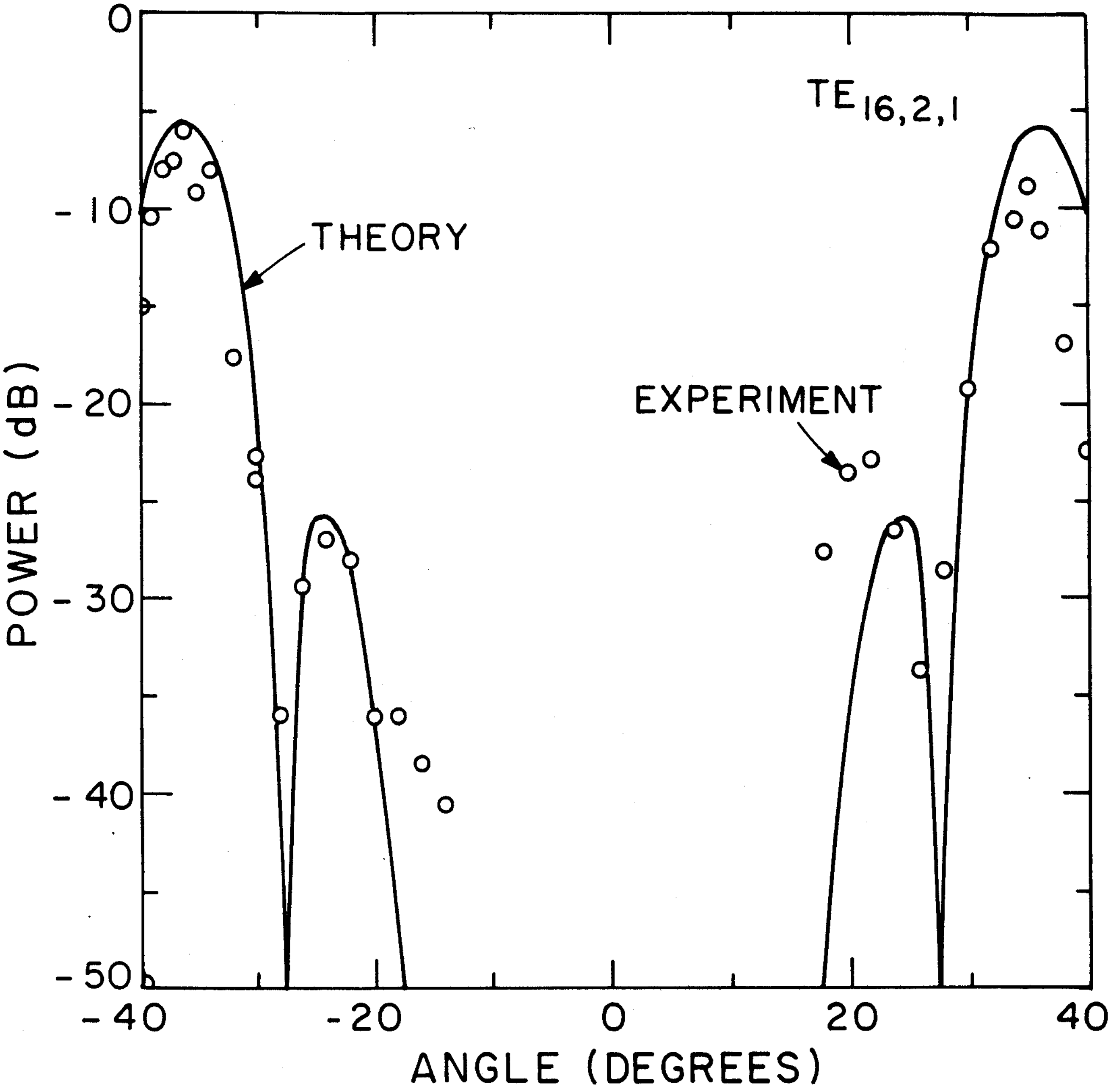

TE$_{16,2,1}$
THEORY
EXPERIMENT
POWER (dB)
0
-10
-20
-30
-40
-50
-40
-20
0
20
40
ANGLE (DEGREES)

Figure 3

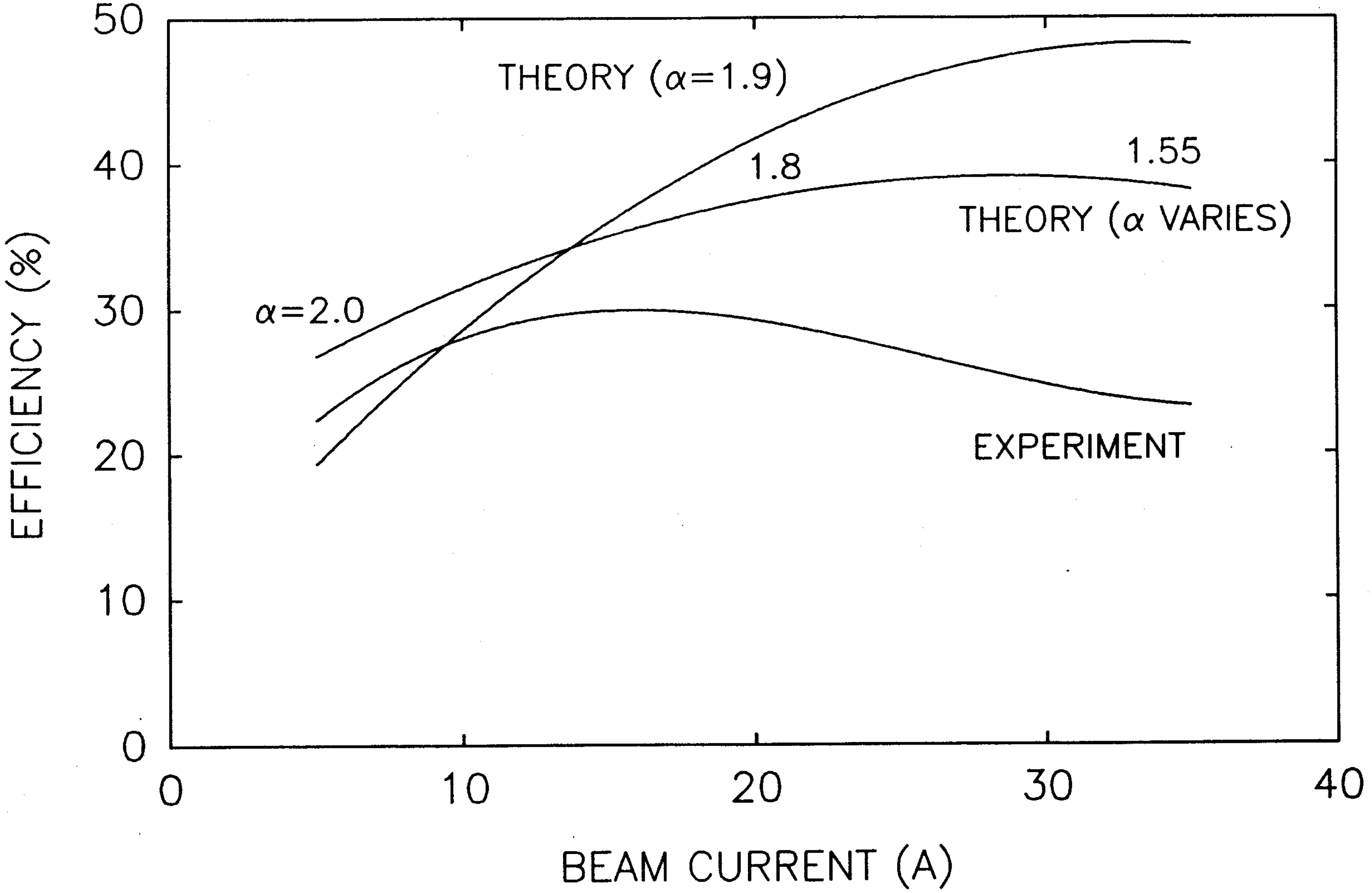

THEORY (α=1.9)
1.8
1.55
THEORY (α VARIES)
α=2.0
EXPERIMENT
50
40
30
20
10
0
EFFICIENCY (%)
0
10
20
30
40
BEAM CURRENT (A)

Figure 4

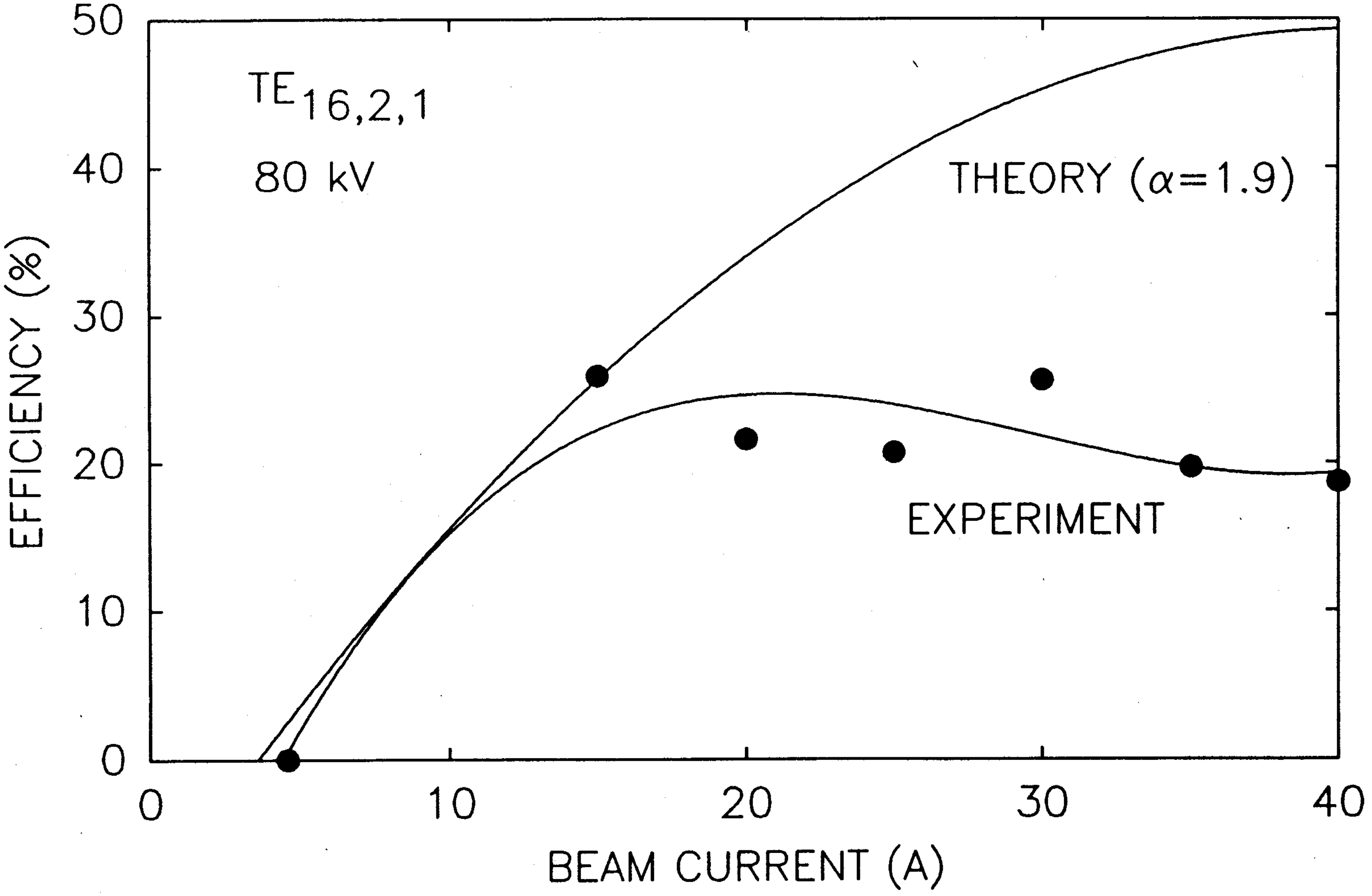

50
40
30
20
10
0
EFFICIENCY (%)
0
10
20
30
40
BEAM CURRENT (A)
$TE_{16,2,1}$
80 kV
THEORY (α=1.9)
EXPERIMENT

Figure 5

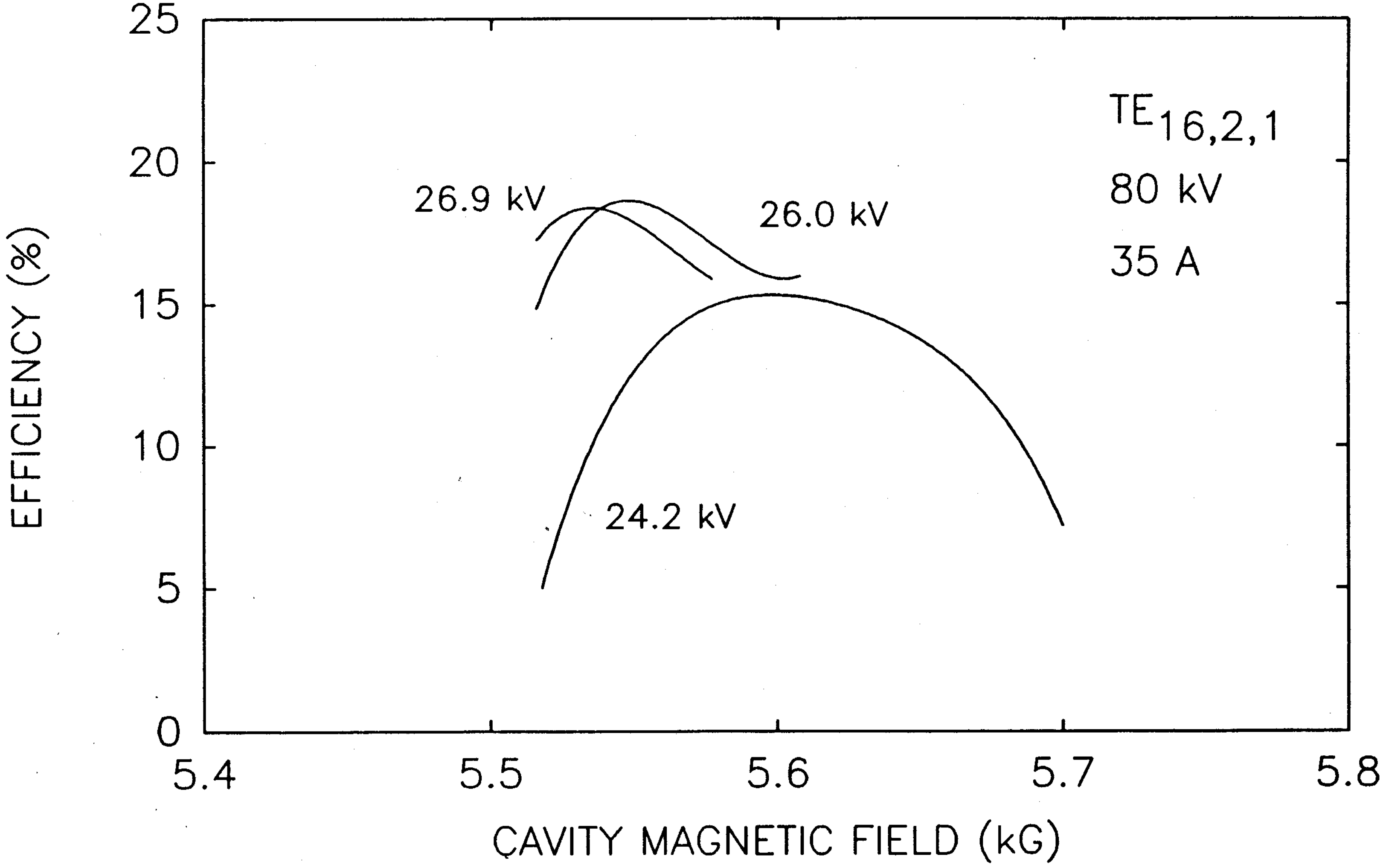

25
20
15
10
5
0
EFFICIENCY (%)
5.4
5.5
5.6
5.7
5.8
CAVITY MAGNETIC FIELD (kG)
26.9 kV
26.0 kV
24.2 kV
$TE_{16,2,1}$
80 kV
35 A

Figure 6

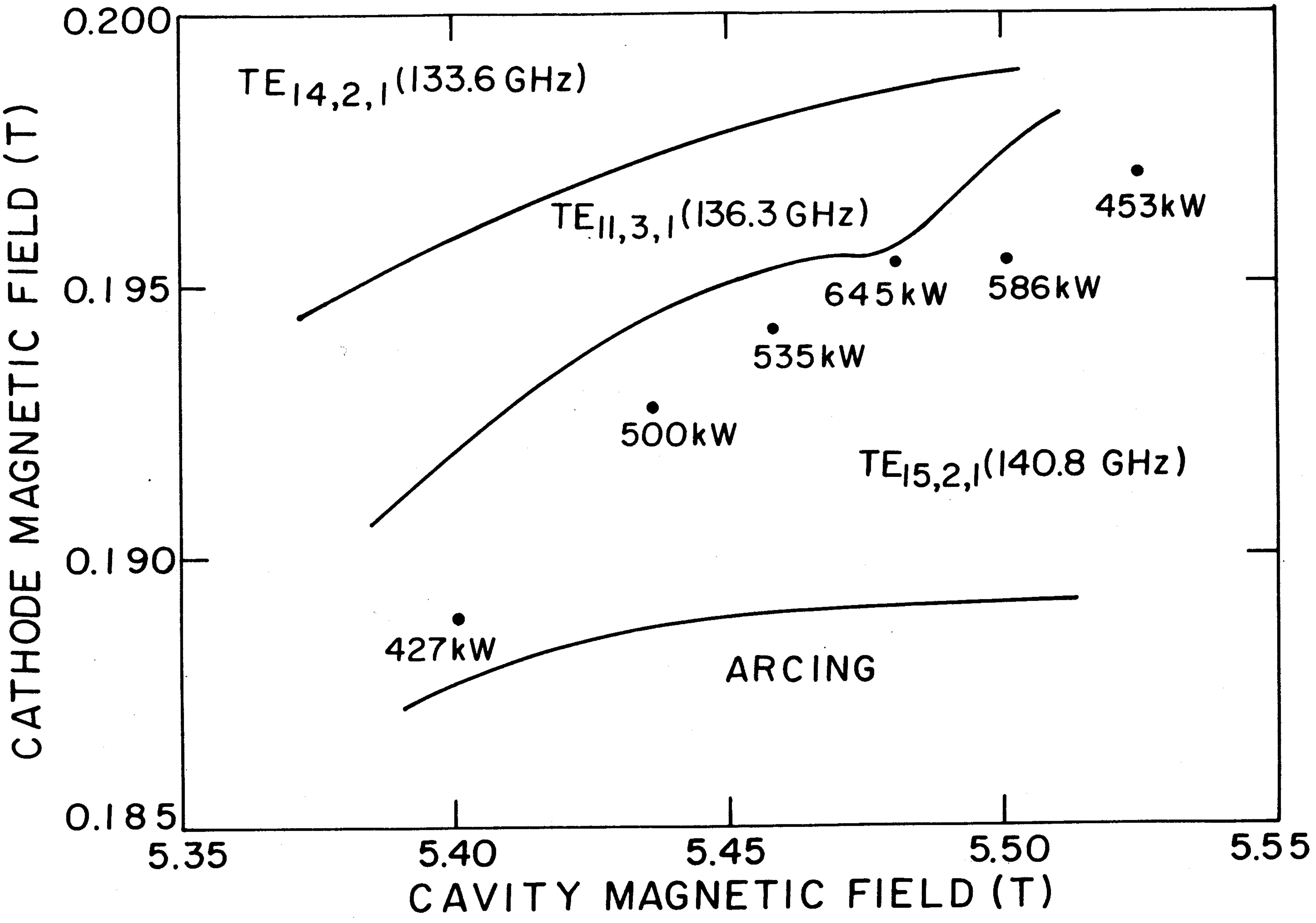

0.200
0.195
0.190
0.185
CATHODE MAGNETIC FIELD (T)
5.35
5.40
5.45
5.50
5.55
CAVITY MAGNETIC FIELD (T)
$TE_{14,2,1}$ (133.6 GHz)
$TE_{11,3,1}$ (136.3 GHz)
$TE_{15,2,1}$ (140.8 GHz)
ARCING
453kW
645kW
586kW
535kW
500kW
427kW

Figure 7