

Experimental Examination of the Enhancement of Gyrotron Efficiencies by Use of Profiled Magnetic Fields

MICHAEL E. READ, KWO RAY CHU, AND ALAN J. DUDAS

Abstract—An experiment in which the enhancement of the efficiency of gyrotron oscillators through profiling of the magnetic field at the cavity is discussed. Electronic efficiencies to 65 percent were obtained, with power levels of 1–100 kW at 35 GHz. Satisfactory agreement with theory was found.

I. INTRODUCTION

THE GYROTRON has become a very promising source for high power millimeter-wave radiation. To date with gyrotron oscillators (gyromonotrons) a power of 212 kW has been obtained on a CW basis at 28 GHz [1], and 1 MW on a pulsed basis at 100 GHz [2]. Extrapolations to CW megawatt operation at ≥ 100 GHz appear possible [3]. For the primary application presently foreseen for this type of device (electron cyclotron heating in magnetically confined fusion devices) [4], [5] substantial work on the optimization of the efficiency has been performed [1], [2], [6]–[11]. Profiling of both the cavity [1], [2], [6] and dc magnetic field contours [7]–[10] has been proposed. Perpendicular efficiencies (i.e., the efficiency of extraction of the energy associated with the electron motion perpendicular to the dc magnetic field) of up to approximately 80 percent have been predicted for the cavity profiling [6], although the highest efficiencies require long cavities which will produce relatively low powers. Perpendicular efficiencies of 60–70 percent are predicted to be possible with high power devices. (Current electron beam generating capabilities allow total efficiencies of about 0.80 of the perpendicular efficiencies.) With magnetic profiling, perpendicular efficiencies of up to 77 percent have been predicted by Kurayev and Shestakovich [7], [8], and more recently, 85 percent has been calculated by Sprangle and Smith [9] and by Chu *et al.* [10].

Of the methods proposed utilizing profiling of the magnetic field, the linear ramp suggested by Chu *et al.* appears to be the easiest to realize, and has the highest predicted efficiency.

We report in this paper a series of experiments which

can examine this. We note that in a previous work [11] unknown to the authors at the time these experiments were performed, experiments in which more complex field profiles were examined. Efficiency enhancements similar to those given in this paper were reported there.

II. DESCRIPTION OF THE EXPERIMENT

The experiments were performed at a frequency of 35 GHz, using the apparatus shown in Fig. 1. The configuration was similar, with the exception of the provisions for tapering the magnetic field, to other gyrotron oscillators [1], [2], [12]. The cavity was right circular, and supported the TE_{011} (circular) mode. In order to thoroughly examine the theory, four cavities of different lengths [6] were tried in the experiments. Their parameters are shown in Table I.

The electron gun used had a nominal operating voltage of 70 kV, producing an essentially monoenergetic beam with a theoretically predicted [13] perpendicular to parallel velocity ratio (α) of 1.5–1.8. We note that only the energy associated with electron motion perpendicular to the magnetic field is accessible for transfer to the output waves. Therefore, α will determine the ultimate maximum efficiency. For $\alpha = 1.8$, the maximum efficiency achievable is 63 percent [10].

Measurement of the output power was performed by converting the TE_{01} circular output into the TE_{10} rectangular mode, employing a commercial mode transducer [14], and using a calibrated directional coupler and precision attenuator to reduce the power level to where it could be sensed with a calibrated crystal. This method has been previously checked using a calorimeter, and found to be accurate to ± 5 percent. The frequency was measured using a conventional wavemeter.

The main (unperturbed) applied magnetic field was produced by a system of superconducting solenoids, and on axis had a profile as shown in Fig. 1. The unperturbed field over the length of the cavity was uniform to better than ± 0.5 percent.

The profiling of the applied magnetic field in the cavity region was accomplished by either shaped collars of steel (Fig. 2) or active coils. (The collars were used for the short cavities where strong gradients were required.) Typical field perturbations produced by these methods are shown in Figs. 2 and 3. (The profile shown in Fig. 3 was produced

Manuscript received December 29, 1980; revised July 30, 1981. This work was supported by the Department of Energy, under Contract DEAI01-79ET52053.

M. E. Read and K. R. Chu are with the Naval Research Laboratory, Washington, DC 20375.

A. J. Dudas is with JAYCOR, Inc., Alexandria, VA.

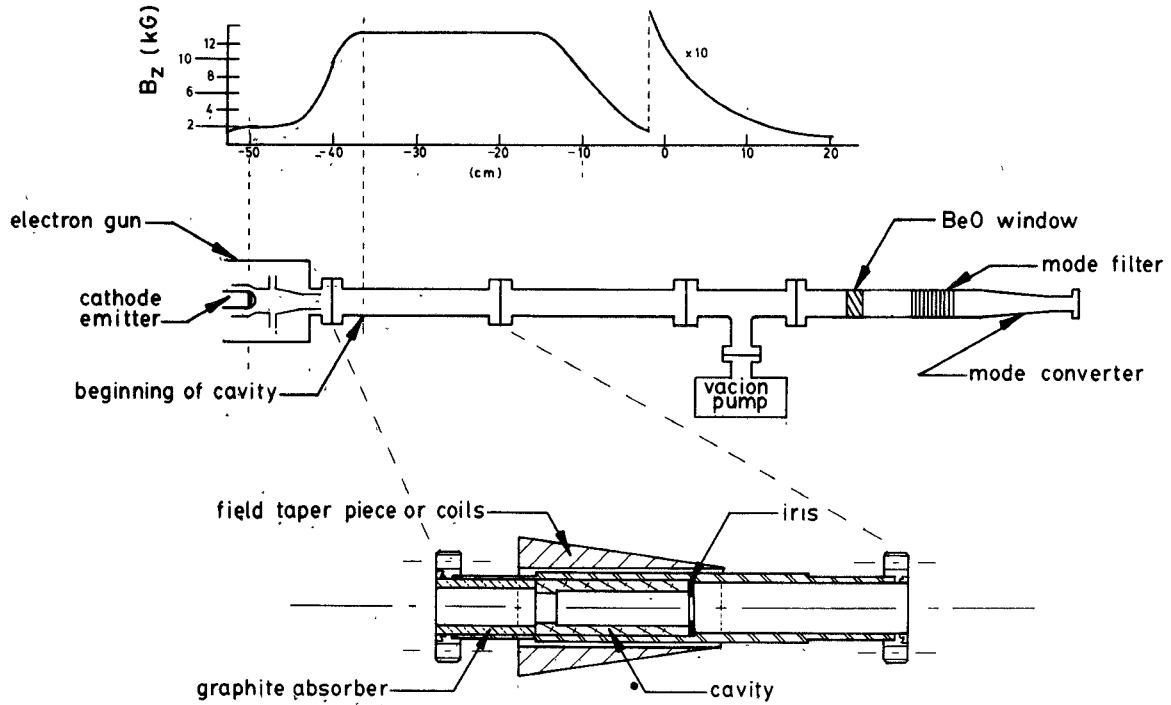


Fig. 1. Apparatus of the experiment.

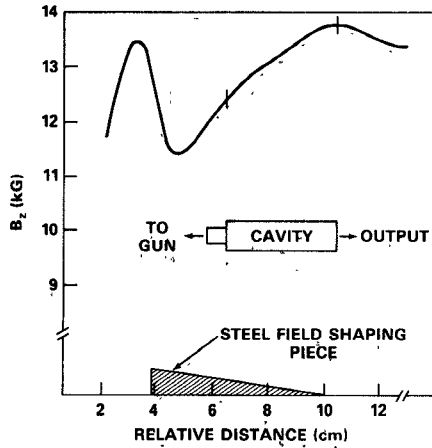


Fig. 2. Drawing of the field shaping steel collar and the magnetic field resulting from its insertion in the field of the superconducting magnet.

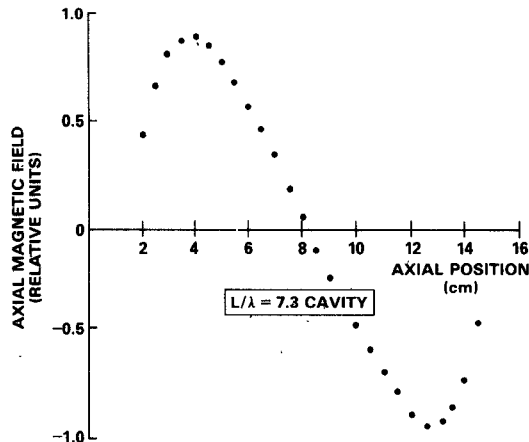

 Fig. 3. Field perturbation produced by the active coils. The coils comprised a solenoid in which the current reversed at the center. $\Delta B/B$, for those cavities of different length L . $\lambda = 8.6$ mm.

 TABLE I
CAVITY PARAMETERS

L/λ	Measured Total Q	Ohmic Q
3.3	2000	10^4
4.9	2900	10^4
4.9	450	10^4
7.3	1300	10^4
9.2	3500	10^4
$\lambda = 8.57$ mm.		

by a coil in which the direction of winding was reversed at the center.) For most of the experiments the total applied magnetic field in the cavity region increases approximately linearly along the direction of the electron beam propagation.

III. CALCULATION OF THE ELECTRONIC EFFICIENCY

In order to compare unambiguously with the theory, which assumes the RF field profile of a closed-end cavity, the reflection at the output end of the cavity was made large, resulting in a relatively large output Q and consequently low radiated power. Thus ohmic losses in the circuit become substantial factors in inferring the electronic efficiency (η_e), defined as the fraction of beam power deposited to the wave, from the measured efficiency (η_m), defined as the ratio of the measured wave power to the beam power. Since the measured power is the deposited power less the circuit losses, we may write

$$\eta_e = \eta_m \left[A \left(1 - \frac{Q_L}{Q_\Omega} \right) \right]^{-1}$$

where η_m is the measured value of the output power

normalized to the beam power. Q_L is the loaded (total) Q , Q_Ω is the ohmic Q of the cavity, and A accounts for the loss in the output guide and mode converter. A was determined by measurement to be 0.8, and typically $(\eta_m/\eta_e)^{-1}$ ranged from approximately 0.5 to 0.7 depending on the cavity used. The details of the cavity measurements are given in Table I.

IV. RESULTS

All of the cavities oscillated in the TE_{011} mode, identifiable by the frequency of the radiation. The nearest competing mode was found in the longest cavity, where the frequency of the TE_{012} mode was found to be 35.13 GHz, as opposed to 34.97 GHz for TE_{011} .

Of primary interest was the behavior of the efficiency as a function of $\Delta B/B$, defined as the percent increase in B over the length of the cavity. This is shown in Fig. 4, along with the theoretically predicted behavior. The following observations can be made: 1) electronic efficiencies of up to 65 percent were obtained; 2) enhancements of the efficiency and power (from the uniform field cases) of up to 1.9 were obtained; and 3) the agreement of experiment and theory is good for $\Delta B/B \leq 7$ percent.

It is recognized that the calculations required to extrapolate from the measured energies to the electronic efficiencies make the absolute values for the efficiency somewhat open to question. To give confidence in our observations we note that the degree of enhancement is independent of the correction factors. Further, there is good agreement of experiment and theory for the results without magnetic profiling, and these levels of efficiencies have been achieved by other groups. Finally, similar agreement of theory and experiment was found for the one low Q case tried ($Q=450$, $L/\lambda=4.9$), in which the correction factor was small. A summary of the results is given in Table II.

The reason for the fall-off of the efficiency prematurely with $\Delta B/B$ (evident for the shorter cavities) is most likely caused by a degradation in the electron beam due to the influence on the electron gun of the residual fields from the taper producing coils or iron pieces. The influence of small (on the order of one percent) changes in the gun fields cannot be simply predicted, as the electron beam parameters are complicated functions of these fields. Studies are in progress to examine the problem. Restraints on the length of the distance from the cavity to the gun made it impossible to reduce the fields at the gun in the present experiment. These restraints do not appear to be fundamental, and should be able to be eliminated in future designs.

There has been some conjecture that a field profile with negative slope also produces an enhancement of efficiency, since the change in field could potentially restore losses of coherence between the beam and waveguide modes caused by reduction in the beam energy as it traverses the cavity. (The coherence is given by $\omega - k_{11} \cdot u_{11} - (\Omega_c/\gamma)$, where k_{11} is the axial wavenumber, u_{11} the axial electron velocity, Ω_c the classical cyclotron frequency, and γ the relativistic mass factor.) However, our calculations indicated little support

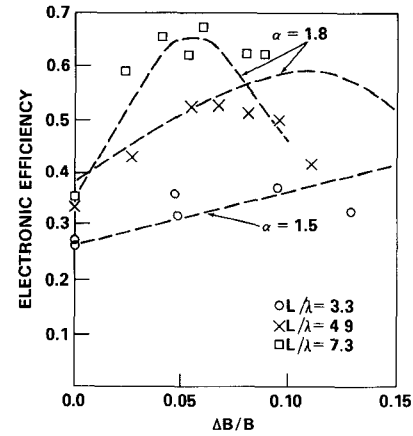


Fig. 4. Electronic efficiency as a function of the magnetic profile strength, $\Delta B/B$, for those cavities of different length L . $\lambda = 8.6$ mm.

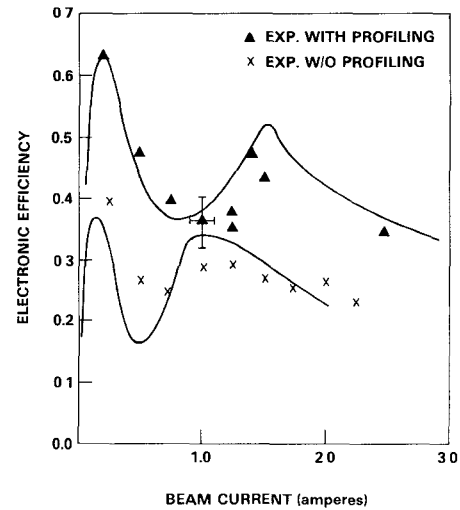


Fig. 5. Electronic efficiency as a function of the beam current for the cavity with $L/\lambda=9.2$. Experimental and theoretical points for the efficiency with and without optimal magnetic profiling are given.

TABLE II
SUMMARY OF RESULTS

L/λ	Q	Maximum Efficiency			Enhancement	Power (kW)		
		TE_{10}	TE_{01}	Electronic		TE_{10}	TE_{01}	Electronic
3.3	2000	0.24	0.27	0.38	1.35	34.0	38.0	53.0
4.9	2900	0.29	0.33	0.53	1.5	8.1	9.2	15.0
4.9	450	0.39	0.44	0.51	1.5	82.0	92.0	107.0
7.3	1300	0.42	0.52	0.67	1.9	15.0	18.0	23.0
9.2	3500	0.33	0.36	0.63	1.7	2.3	2.5	4.4

for this conjecture. Subsequent experiments also indicate only slight improvement in the efficiency with this type of profile.

During the experiments another phenomenon, of use in understanding the basic physics of the cyclotron maser, was observed. The effect is illustrated in a plot of efficiency versus beam current for the cavity with $L/\lambda=9.2$ (Fig. 5). Both the experimental points and theoretical curves are given. Qualitative agreement between theory and experiment is evident. Initial investigations indicate that the lack of good quantitative agreement in the magnitude of the

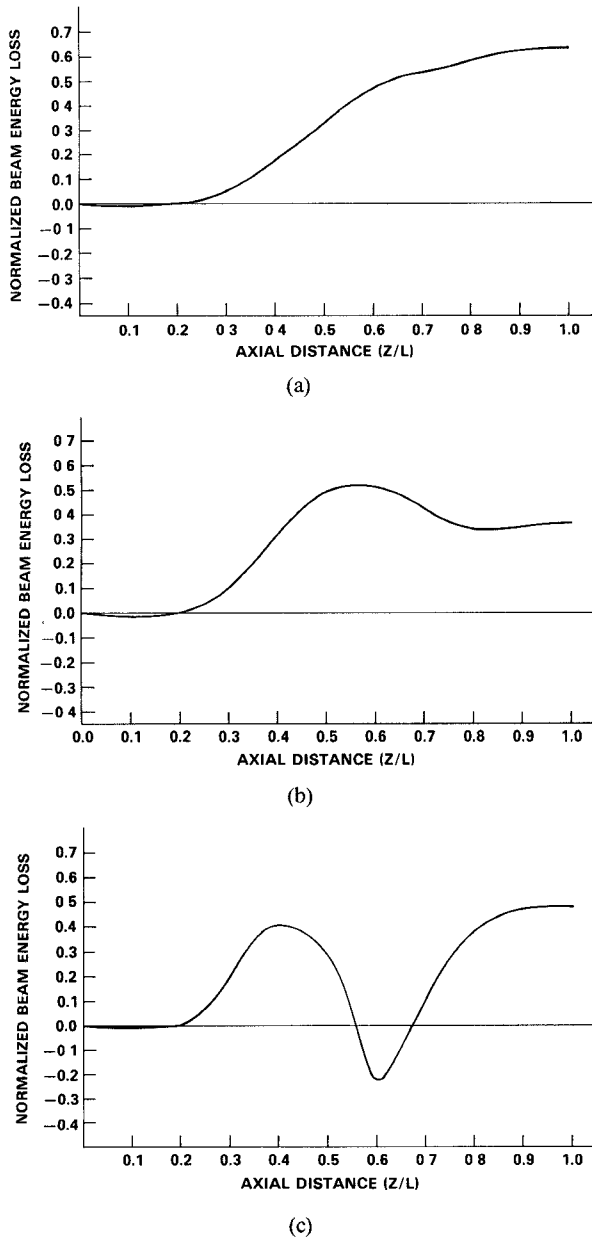


Fig. 6. Calculated plots of the average energy loss (normalized to the initial energy) of electrons in the beam as they traverse a cavity with $L/\lambda = 9.2$. (a) Beam current = 0.1 A. (b) $I_b = 1.0$ A. (c) $I_b = 1.5$ A. A ratio of the perpendicular to parallel electron velocities of 1.8 was used in the calculations.

efficiency for currents $\gg 0.1$ A is due to velocity spread on the beam. Both theory and experiment show the efficiency as a double peaked function of the current. This is apparently due to the trapping of the electron bunches, a phenomenon predicted by Sprangle and Drobot [15]. Trapping is the dominant limit on the efficiency of the cyclotron maser. It occurs as the RF fields becomes strong enough to “pull” some of the electrons out of the phase where they give up energy to the wave. With further increased RF fields (produced by increased beam current) the electrons undergo a 360° phase change as they traverse the cavity and, subsequently, a substantial fraction of their energy is transferred to the waveguide mode.

This is shown more clearly in Fig. 6(a), (b), and (c).

These figures are computer calculated plots of the average electron energy loss (normalized to the initial electron energy) as a group of electrons traverses a cavity with predetermined RF fields. The value of this normalized loss at the end of the cavity is then the efficiency. Fig. 6(a) is for the case for $I = 0.1$ A, while Fig. 6(b) is for $I = 1.0$ A, and Fig. 6(c) is for $I = 1.5$ A. For $I = 0.1$ A, we note that the energy loss is monotonic as the particles drift through the cavity. Trapping occurs at the end of the cavity. At $I = 1.0$ A, the RF fields are stronger, and trapping occurs earlier, causing some of the electrons to regain energy. The resulting efficiency is therefore much lower. At $I = 1.5$ A, the RF fields are strong enough such that the electrons go through a complete cycle—losing, gaining, then losing again their energy. The resulting efficiency is similar to that with $I = 0.1$ A. Although previous theoretical predictions of this phenomena have been made [6], [15], to the authors’ knowledge this is the first time that this phenomenon has been reported to have been observed in the cyclotron maser oscillator, and appears to confirm an important element of the theory which explains the saturation mechanism for this instability.

V. COMMENTS

For the cavities with $L/\lambda = 7.3$ and $L/\lambda = 9.2$, we note that the 65-percent overall (electronic) efficiency means that, with an α of 1.8, 85 percent of the power in the beam available to the interaction has been extracted. (Only the power associated with the perpendicular motion of the electrons is accessible.) Further improvement in the efficiency can come from improving this figure, or by increasing the velocity ratio α . Refinement of the magnetic profile may help to achieve the former although attempts at this by other workers have not appeared successful [11]. As to the latter, the present state of the art in gun design appears to yield $\alpha \approx 2$ [13], [16], [17]. If guns with an α of 2.5 can be produced, calculations [10] show that a gyrotron with an efficiency of 78 percent should be possible.

The cavities used in this study produced relatively low powers (1–100 kW), due to the large output Q ’s chosen. In order to produce substantially higher powers, it will be necessary to use lower output Q ’s and/or higher order cavity modes [3], [10]. Both of these methods can reduce cavity losses to the order of a few percent of the output power. Studies of these methods are currently in progress.

The usefulness of magnetic tapering for efficiency enhancement at higher frequencies will be limited by the field gradients that can be produced. The required gradient, dB/dz , scales as f^2 (assuming operation at the fundamental cyclotron frequency). For high power devices, cavity lengths on the order of $L/\lambda = 5$ are desirable [10]. The 10-percent value for $\Delta B/B$ which appears to be necessary requires a gradient of 300 G/cm at 35 GHz, and 3.0 kG/cm at 100 GHz. Gradients to approximately 3–5 kG/cm appear feasible with present generation superconducting magnets. Therefore, the use of this method appears feasible in the frequency regime of interest for many fusion devices. The method can be used at even higher frequencies

if cyclotron harmonic interaction is employed since the magnetic field required for these cases is reduced by the inverse of the harmonic number.

VI. CONCLUSIONS

We have shown that magnetic field profiling can enhance the efficiency by a factor of 1.5–1.9. As a result, an electronic efficiency of 67 percent has been demonstrated. The method should be feasible to frequencies of 110–150 GHz for the first cyclotron harmonic and 220–300 GHz for the second cyclotron harmonic, using presently available superconductor magnet technology.

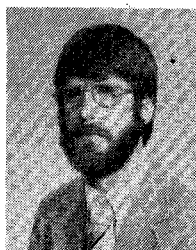
It is expected that this method can in some cases be extended to higher power devices by use of the lower Q cavities and higher order modes.

ACKNOWLEDGMENT

The authors would like to thank Dr. B. Arfin, Dr. V. L. Granatstein, and Dr. J. Vomvoridis for their helpful comments.

REFERENCES

- [1] J. F. Shively, P. Ferguson, H. R. Jory, J. Moran, and R. S. Symons, "Recent advances in gyrotrons," in *Conf. Dig., IEEE Int. Microwave Symp.*, p. 99, May 1980.
- [2] A. V. Gaponov, V. A. Flyagin, A. Sh. Fix, A. L. Gol'denberg, V. I. Khizhnyak, A. G. Luchinin, G. S. Nusinovich, M. I. Petelin, Sh. Ye. Tsimring, V. G. Usov, S. N. Vlasov, and V. K. Yulpatov, "Some perspectives on the use of powerful gyrotrons for the electron cyclotron heating in large tokamaks," in *IV Int. Conf. Infrared and Near Millimeter Waves*, Dec. 1979.
- [3] M. E. Read, K. R. Chu, and K. J. Kim, "Power limits in cylindrical gyromonotrons using TE_{01} modes," submitted to *Int. J. Infrared and mm Waves*.
- [4] R. M. Gilgenbach, M. E. Read, K. E. Hackett, R. Lucey, B. Hui, V. L. Granatstein, K. R. Chu, A. C. England, C. M. Loring, O. C. Eldridge, H. C. Howe, A. G. Kulchar, E. Lazarus, M. Murakami, and J. B. Wilgen, "Heating at the electron cyclotron frequency in the ISX-B tokamak," *Phys. Rev. Lett.*, vol. 44, no. 10, pp. 647–650, Mar. 1980.
- [5] V. V. Alikhaev et al. *Fiz. Plasma*, vol. 2, p. 390, 1976; also, *Sov. J. Plasma Phys.*, vol. 2, p. 212, 1976.
- [6] G. S. Nusinovich and R. E. Erm, "Efficiency of a CRM monotron with a longitudinal Gaussian distribution of high frequency fields," *Elektronnaia Tekhnika*, no. 8, 1972.
- [7] A. A. Kurayev and V. P. Shestakovitch, "Triggering conditions for gyroresonance devices with an arbitrary cavity profile and a slightly nonuniform magnetostatic field," *Radio Eng. Electronic Phys.*, vol. 22, no. 2, pp. 150–152, 1977.
- [8] A. A. Kurayev and V. P. Shestakovitch, "Optimization of the cavity profiles and magnetostatic field distributions in gyromonotrons in terms of efficiency while ensuring the conditions of soft self-excitation," *Radio Eng. Electronic Phys.*, vol. 22, no. 2, pp. 152–155, 1977.
- [9] P. Sprangle and R. A. Smith, "The non linear theory of efficiency enhancement in the electron cyclotron maser," *NRL Memo. Rep.* 3983, 1979.
- [10] K. R. Chu, M. E. Read, and A. K. Ganguly, "Methods of efficiency enhancement and scaling for the gyrotron oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 318–325, Apr. 1980.
- [11] V. N. Glushenko, S. V. Koshevaya, and V. A. Prus, "Improved efficiency of a gyrotron at the fundamental gyroresonance by means of a corrected distribution of magnetostatic fields," *ISV. V.U.Z. Radioelectron.*, vol. 13, no. 1, pp. 12–17, 1977.
- [12] M. E. Read, R. M. Gilgenbach, R. Lucey, K. R. Chu, A. T. Drobot, and V. L. Granatstein, "Spatial and temporal coherence of a 35 GHz gyromonotron using the TE_{01} circular mode," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 875–878, Aug. 1980.
- [13] J. L. Seftor, K. R. Chu, and A. T. Drobot, "An investigation of a magnetron injection gun suitable for use in cyclotron resonance masers," *IEEE Trans. Electron Devices*, vol. ED-26, pp. 1609–1616, Oct. 1979.
- [14] Hitachi Denishi, LTD, Model R6414.
- [15] P. Sprangle and A. T. Drobot, "The linear and self consistent nonlinear theory of the electron cyclotron maser instability," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 528–544, June 1977.
- [16] J. Shively, C. Conner, H. Jory, D. Stone, R. Symons, G. Thomas, and G. Wendell, Quarterly Rep. #2, 60 GHz and 110 GHz Development Program, Varian Assoc. (ORNL/Sub-21453/2), 1980.
- [17] K. W. Arnold, J. J. Jancredi, M. Caplan, K. W. Ha, D. N. Birnbaum, and W. Weiss, Quarterly Rep. 1, Development Program for a 200 kW, CW, 110 GHz Gyrotron, Hughes Aircraft Co., (ORNL/Sub-33200/1), 1979.
- [18] K. R. Chu, "Theory of electron cyclotron maser interaction in a cavity at harmonic frequencies," *Phys. Fluids*, vol. 21, no. 12, pp. 2354–2364, 1978.



Michael E. Read received the B.S., M.S., and Ph.D. degrees, all in electrical engineering, from Cornell University, Ithaca, NY. His graduate work was in physics and applications of intense relativistic electron beams, including the problems of beam transport, microwave production, and collective ion acceleration.

He is currently with the Naval Research Laboratory, Washington, DC, where he is Head of the Gyrotron Oscillators and Plasma Interactions Section of the High Power Electro-

magnetic Radiation Branch. His work includes research on gyrotrons and their use in electron cyclotron heating and air breakdown experiments.



Kwo Ray Chu received the B.S. degree in physics from National Taiwan University in 1965, the M.S. degree in physics from the University of Massachusetts, Amherst, in 1968, and the Ph.D. degree in applied physics from Cornell University, Ithaca, NY, in 1972. He specializes in microwave theory, relativistic electronics, plasma physics, and controlled thermonuclear fusion.

From 1973 to 1977, he was a research physicist with Science Applications, Incorporated. Since September 1977, he has been with the Naval Research Laboratory, presently serving as Head of the Advanced Concepts Section in the High Power Electromagnetic Radiation Branch.



Alan J. Dudas received the B.S. degree from Case Institute of Technology in 1974 and the M.S. degree from Cornell University, Ithaca, NY, in 1978. He has degrees in electrical engineering supported with background work in electron beam and microwave generation.

He is currently a member of JAYCOR's NRL support staff and is engaged in work on optimizing the efficiency of the short pulse high power gyrotron. Prior to joining JAYCOR, he was employed as a Klystron Engineer at the Stanford

Linear Accelerator Center (SLAC). At SLAC, he had primary responsibility for coordinating and managing microwave cold tests for S-band high power klystrons, high power RF loads, 500 kW PEP storage ring klystrons and various microwave components. He redesigned the gun portion of an S-band high power klystron, and assisted in the design of a "Triotron"—a new type of RF amplifier. He also redesigned the RF input of an S-band high power klystron to produce better match and lower drive requirements. At Cornell, he conducted research on the generation of high power microwaves using a relativistic electron beam via the cyclotron maser interaction.