AD-A046 793 NAVAL RESEARCH LAB WASHINGTON D C F/G 20/7
DEVELOPMENT OF HIGH-POWER, MILLIMETER-WAVE, CYCLOTRON MASERS AT--ETC(U)
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NRL Memorandum Report 3493

Development of High-Power, Millimeter-Wave, Cyclotron Masers at NRL and its Relevance to CTR

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July 1977

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NRL Memorandum Report 3493

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER (9)

4. TITLE (and Subtitle): (6) DEVELOPMENT OF HIGH-POWER, MILLIMETER-WAVE, CYCLOTRON MASERS AT NRL AND ITS RELEVANCE TO CTR.

5. TYPE OF REPORT & PERIOD COVERED: Interim report on a continuing NRL problem.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): (10) W.M. Manheimer [redacted] V.L. Granatstein

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, D.C. 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NRL Problem R08-59; (17) ~~Subtask~~ RR0110941

11. CONTROLLING OFFICE NAME AND ADDRESS: (12) 29p.

12. REPORT DATE: (11) July 1977 (61531N)

13. NUMBER OF PAGES: 28

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (14) NRL-MR-3493

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited. (16) RR01109

(18) SBIE (19) AD-E000 008

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

- Gyrotron
- Cyclotron maser
- Tokamaks
- r.f. heating
- ECRH

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

The purpose of this memorandum is to make the CTR community aware of the relevance of ongoing research and development of a new class of high-power, millimeter-wave generators at NRL. The generators have been called "electron cyclotron masers" in the U.S. and "gyrotrons" in the Soviet Union. In the near future (~ 1 year), cyclotron masers could be available that have immediate applicability in tokamak research for such purposes as the following: local heating experiments; preionization; test wave launching; and measurement of trapped-electron collision frequency. On a

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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20. Abstract (Continued)

longer timescale, advanced cyclotron masers could be developed which would be useful in bulk plasma heating, and in the measurement of tokamak ion temperature.

CONTENTS

DEVELOPMENT OF HIGH-POWER, MILLIMETER-WAVE, CYCLOTRON MASERS AT NRL AND ITS RELEVANCE TO CTR

I. INTRODUCTION

It is rare that basic research in plasma physics leads to a practical device; it is rarer still when the device itself finds application in a plasma development program. This unexpected double play has occurred for the electron cyclotron maser, a device based on a negative-mass instability in a relativistic electron beam that promises to provide powerful and efficient generation of radiation at millimeter and submillimeter wavelengths. Applications are at hand for this novel generator in the diagnostics and heating of CTR plasmas as well as in extensions of conventional microwave systems (radars etc.).

NRL is currently pursuing the development of a pulsed, distributed-interaction amplifier capable of generating 300 kW peak power at $\lambda = 8$ mm with 50% efficiency. The improved understanding of cyclotron maser physics, the expertise in relevant numerical analysis, and the basic experimental facility which are being accumulated in the course of this program can be made available for the cost effective development of cyclotron masers with quite different characteristics. For example, a CW maser with 10's of kilowatts of power at $\lambda = 3$ mm would appear to be feasible, and would present an interesting scientific and technological departure from the first NRL device.

Such a maser could be used in a number of salient CTR studies including test wave launching, preionization and local electron cyclotron resonance heating. Another type of cyclotron maser susceptible to short term development would produce a single 50 ns pulse at megawatts of peak power at 1 mm $< \lambda <$ 3 mm and would be useful in measuring trapped electron collision frequency. On a longer time scale, cyclotron masers

Note: Manuscript submitted June 20, 1977.

could be developed which would be useful in measurement of tokamak ion temperature and in bulk plasma heating. The CTR applications are discussed briefly in Secs. II thru VII while the NRL cyclotron maser research and development work is described in Sec. VIII.

II. TOKAMAK PLASMA HEATING AT THE ELECTRON CYCLOTRON RESONANCE

The most obvious, albeit long term, application of gyrotrons is in electron cyclotron heating (ECH). Except for ohmic heating and ECH, every other auxiliary heating means has difficulty in depositing the energy in the center of the tokamak. For instance neutral beams are deposited roughly one charge exchange mean free path from the edge, while microwave power at the lower hybrid frequency or at harmonics of the ion cyclotron frequency generally has not propagated to the center of the discharge in auxiliary heating experiments. Electron cyclotron heating is different in this respect. Since the energy is deposited either near[1,2] $\omega = \Omega_c$ or $\omega = 2\,\Omega_c$, it is possible to deposit the energy at the center of the discharge simply by selecting the frequency.

Electron cyclotron heating has been successfully done on TM3 in the Soviet Union at both the first and second harmonic of the electron cyclotron frequency.[3] Typically 60 kW of RF power is applied for about 750 μsec. The electron temperature increases from about 400 eV to about 600 eV during the duration of the pulse. In Fig. 1a is shown the electron temperature profile in TM3 before and after the heating pulse. Combination of laser scattering and diamagnetic measurements indicate that the heating is in the body of the electron distribution function, and not in an energetic nonthermal tail.

Perhaps as interesting, not only do the electrons heat, the electron energy confinement time increases as a function of temperature. Figure 1b shows the electron energy confinement time in microseconds as a function of central electron temperature.

In order to do electron cyclotron heating in present day tokamaks, the power output of the gyrotron (or gyrotrons) must at least equal the ohmic power, and the frequency must equal the electron cyclotron frequency. Given below is a short table which enumerates the characteristics necessary for ECH of various American Tokamaks.

Machine	Field	Wavelength	Power
PLT	35 kG	0.3 cm	⩾ 1 MW
ALCATOR	50 kG	0.2 cm	⩾ 300 kW
VERSATOR (MIT)	10 kG	1.0 cm	⩾ 100 kW
MACROTOR (UCLA)	5 kG	2.0 cm	⩾ 100 kW

III. LOCAL HEATING OF LARGE TOKAMAKS

While gyrotrons necessary for heating of the entire tokamak plasma will not be developed for sometime, gyrotrons sufficient for local heating could be developed in the near term (~ 1 year). There are two basic types of local heating experiments that could be done. First, one could deposit a large amount of energy at one point in the torus very quickly and watch it diffuse away. Secondly, one could continuously heat an interior region of the plasma and examine the new steady state which is established.

In either case, the power of the gyrotron (or gyrotrons) must be larger than the energy in the localized region divided by the containment time of that region. Also the total energy deposited should be comparable to the energy in that region of the tokamak. Experiments on PLT[4] show that the electron confinement time is relatively insensitive to radius and is between about 30 and 50 msec. However, when a region is locally heated, its confinement is almost sure to drop greatly. Let us arbitrarily consider a confinement time of 1 msec. Then if the plasma temperature is 1 keV, the density is 5×10^{13} cm^{-3} and the major radius is 135 cm (PLT), the electron energy content of the inner centimeter radius is about 20 J. Therefore, a gyrotron with a power of 20 kW at a wavelength of 3 mm and a pulse time ⩾ 1 msec is needed to do local heating experiments on PLT.

IV. PREIONIZATION

One of the principle problems which plagues tokamak research is the large number of impurities in the plasma. Experimental work in TFR has shown that roughly half of the impurities enter the plasma during the initial breakdown.[5] This is only natural since the breakdown starts at the walls of the tokamak.

If the breakdown could be initially localized near the center of the plasma, impurities could not enter via this route. One way to initialize the plasma near the center is to use electron cyclotron breakdown. If millimeter wave radiation is focused (for instance by microwave lenses or reflectors) to a small region in the center of the vacuum vessel where $\omega = \Omega_c$, the initial breakdown should be strongly localized in this region. Roughly a millisecond or two after the breakdown is produced, the hydrogen ions will travel once around the torus and provide a closed current path. At this time, the main capacitor banks can be activated, and the discharge should spread from the inside to the outside rather than visa versa.

Microwave sources with power in excess of $\sim$ kW (the more power the better) are required for preionization.[6] The microwave frequency should of course be chosen for electron cyclotron resonance ($\lambda \approx 3$ mm in PLT).

V. WAVE LAUNCHING

It is currently believed that drift and trapped electron instabilities may be responsible for anomalous transport in tokamaks. Many turbulence theories relating to such instabilities start with an examination of the propagation of a test wave in a turbulent background.[7] One very interesting possible experiment would be to actually launch such a test wave in a plasma and observe its propagation. This can be done in a low temperature plasma by focusing the outputs of 2 mm wave sources into the same region and thereby launching a wave at the difference frequency ($\omega = \Omega_1 - \Omega_2$) and wave number ($\underline{k} = \underline{\kappa}_1 - \underline{\kappa}_2$) as shown in Fig. 2.

If $\Omega_{1,2} \gg \omega_{pe}, \omega_{ce}$, the 2 mm waves exert a pondermotive potential[8] on the electrons. If the drift wave is characterized by a potential φ, the electron density perturbation of the electrons is

$$n_e = n_o \left(\frac{e\varphi}{T_e} + \frac{e^2 \langle E_1 E_2 \rangle}{2\, m\Omega^2 T_e} \right) , \qquad (1)$$

where we have assumed E_1 and E_2 are parallel. Above, $\langle\ \rangle$ means an average over rapid (time $\sim \Omega^{-1}$) temporal variations. Assuming that the ion velocity is the $E \times B$ drift velocity and that $n_e = n_i$, the ion continuity equation reduces to

$$\frac{\partial}{\partial t} \left(\frac{e\varphi}{T_e} + \frac{e^2 \langle E_1 \cdot E_2 \rangle}{2\, m\Omega^2 T_e} \right) + V_D \frac{\partial}{\partial y} \frac{e\varphi}{T_e} = 0 , \qquad (2)$$

where

$$V_D = - \frac{cT}{eBn} \frac{\partial n}{\partial x} .$$

Thus the volume rate of production of $\frac{e\varphi}{T_e}$ is $\frac{e^2 \langle E_1 E_2 \rangle}{2\, m\, \Omega^2 T_e}$, while the rate of convection out through the surface is $V_D \frac{e\varphi}{T_e}$. If the depth of the intersection region of the two beams is ℓ (shown in Fig. 2), then in steady state,

$$\frac{e\varphi}{T_e} = k\ell \frac{e^2 \langle E_1 E_2 \rangle}{2\, m\omega^2 T_e} . \qquad (3)$$

If $|\varkappa_1| = |\varkappa_2| = 10\,\pi\ \text{cm}^{-1}$ the power in each beam is 3 kW/cm^2 and ℓ = 2 cm, then

$$\frac{e\varphi}{T_e} = \frac{6 \times 10^{-2}}{T_e} . \qquad (4)$$

Thus for temperature less than about 10 eV (i.e. in spherators or Q machines), strong coherent, test waves can be launched in the plasma and their propagation in a turbulent medium can be studied.

Gyrotrons with $f_o \approx 150$ GHz frequency stabilized to 1 part in 10^5 with CW power of 10 kW should be suitable for this application.

VI. ION TEMPERATURE MEASUREMENTS

One of the most important measurements to do on a tokamak is a measurement of the ion temperature. Unfortunately this is also one of the most difficult, particularly if the neutral hydrogen mean free path is not longer than the minor radius. One possible approach is to scatter off of electron density fluctions which move with the ions.[9,10] Then from an examination of the doppler broadening of the scattered signal, one can untangle the ion temperature and even the ion distribution function as long as the scattering wave number k_s is much less than k_D. Assuming that $k_s \sim k_i$ where k_i is the incident wave number, the condition for the wave to propagate through the plasma with $k = |\underset{\sim}{k}_i - \underset{\sim}{k}_s| \leqslant k_D$ can be written roughly as

$$\frac{\omega_{pe}}{c} < k < \frac{\omega_{pe}}{V_e} . \qquad (5)$$

For densities below about 10^{14} cm^{-3}, millimeter waves satisfy Eq. (5).

In order to do the scattering experiment, powers on the order of 1 MW[9] are needed and the coherence, $\nabla\omega/\omega$ must be less than V_i/c, or less than one tenth of one percent. Efficient, thermionic-cathode, cyclotron masers are under development at $\lambda = 3$ mm. They are expected to be highly coherent but megawatt power levels will not be available for some time.

Another possible way to generate a suitable microwave pulse is with cyclotron masers based on cold-cathode, intense-electron-beam technology.[11,12] The conversion efficiency in such devices has been small (typically $\leqslant$ 1%) but millimeter-wave output at the level of many megawatts has been produced. In particular, we note that with a 50 nsec electron beam at 450 kV and 7 kA (such a beam could be furnished by relatively small, portable, electron accelerator) 2MW has been generated at λ=4mm.

Two megawatts of microwave power at 4 mm wavelength were produced at NRL.[13] The coherence time was not measured. However, experiments on the same microwave generation mechanism at $\lambda = 3$ cm showed a coherence time limited only by the finite time of the pulse[11] (i.e., 50 nsec). In the near future, microwave generation experiments with intense-electron-beams are planned at $\lambda = 2$ mm. It may be possible to perform coherence measurements on these signals.

VII. MEASUREMENTS OF THE EFFECTIVE COLLISION FREQUENCY OF TRAPPED ELECTRONS

One of the most important parameters appearing in both the theory of trapped electron modes and also in neoclassical transport theory is the effective collision frequency as a function of velocity $\nu_{ef}(V)$. That is, the frequency at which electrons are detrapped. As long as the bounce $\omega_b(V)$ frequency is sufficiently larger than the $\nu_{ef}(V)$, $\nu_{ef}(V)$ can be measured[9,14] by echo techniques using millimeter waves.

The idea is that a pulse of duration τ, with $\omega_b(V)\tau \ll 1$, is absorbed by ECH in the outer region of the tokamak where there are the maximum number of trapped particles. A time t_r later, where $t_r = \pi m/\omega_b(V)$, a second pulse is absorbed. Then for times nt_r, later where n is any integer, the trapped particle with velocity V will reassemble in phase and emit an echo at the incident microwave frequency. The decay of these echoes as a function of n then gives a measurement of $\nu_{ef}(V)$. The bounce frequency of a trapped particle of velocity with velocity V is given by

$$\omega_b(V) = \sqrt{\frac{\varepsilon}{2}}\ \frac{V}{Rq}\,, \qquad (6)$$

where R is the major radius of the torus, q is the safety factor and $\varepsilon = r/R$, r being the minor radius. For electrons in PLT, $\omega_b \sim 2 \times 10^6$. Thus two 50 nsec pulses of several megawatts should be sufficient to measure $\nu_{ef}(V)$. It seems as though mm wave generators based on intense, relativistic, electron beams are suitable for this measurement. As previously noted, power levels in excess of 2 MW at 4 mm wavelength have already been demonstrated. Also the coherence requirements on the microwave power may be less stringent than they were for the application discussed in the previous section.

VIII. ELECTRON CYCLOTRON MASERS (GYROTRONS)

(a) Description of the Process and Early Developments:

The electron cyclotron maser ideally consists of a cloud of monoenergetic electrons in a fast wave structure such as a metallic tube or waveguide, with electron velocity transverse to an applied axial magnetic field. Such an electron ensemble can react unstably with a fast microwave signal propagating through the waveguide. Initially, the phases of the electrons in their cyclotron orbits are random, but phase bunching can occur because of the relativistic mass change of the electrons. Those electrons that lose energy to the wave become lighter and accumulate phase lead while those electrons that gain energy from the wave become heavier and accumulate phase lag. This can result in a phase bunching such that the electrons radiate coherently and amplify the electromagnetic wave. Energy transfer from the electrons to the wave is optimized when the wave frequency is just slightly higher than the electron cyclotron frequency (or its harmonics). Early descriptions of this maser process are to be found in the works of Twiss,[15] Schneider,[16] and Gapanov.[17]

From the above description, it is clear that the cyclotron maser emits radiation at a wavelength determined by the strength of an applied magnetic field, and not by the dimensions of some resonant structure. Thus, unlike other microwave generators, the internal dimensions of the device may be large compared to the wavelength, and high power handling capability (up to megawatts) becomes compatible with operation at millimeter wavelengths. Indeed, the highest recorded millimeter-wave power, both peak and average have been achieved with cyclotron masers.

The first unequivocal experimental demonstration of the cyclotron maser mechanism was made in 1964 by Hirshfield and Wachtel.[18] Their 5 kV, 200 μA electron beam was passed through a combination of a "corkscrew" static magnetic field and a magnetic hill; the electrons were then injected into a high-Q cylindrical cavity resonant at 5.8 GHz with most of their energy transverse to the axial magnetic field. Later a two cavity "gyro-klystron" experiment was reported[19] which showed that an amplifier configuration was possible based on the same transverse bunching mechanism, only now the bunching is allowed to continue ballistically between input and output cavities. Other early work extended frequency into the millimeter wave and even the submillimeter wave regime; an extensive description of this early work is contained in the review by Hirshfield and Granatstein.[20] However, in all of the early experiments, the promise of exceptionally large millimeter wave power was not realized, the best result being that of Bott who generated several watts of power at $2\ \mathrm{mm} \leq \lambda \leq 4\ \mathrm{mm}$.[21]

(b) <u>Intense Relativistic Electron Beam Studies (Realization of High Peak Power Millimeter Waves)</u>:

New impetus to the study of the cyclotron maser mechanism itself came from research into microwave emission from intense relativistic electron beams, with beam power in the range 10^9 - 10^{12} W. The electron beams are generated from cold, field-emission cathodes typically as a single pulse with duration ~ 50 nsec. Giant microwave bursts were first reported in 1970 by J. A. Nation[22] when he caused an intense beam to interact with a long periodic structure inserted into the electron drift tube. Subsequent experiments, mainly at the Naval Research Laboratory, demonstrated that intense microwave radiation could also be produced by eliminating the periodic wall structure, but instead perturbing the externally applied magnetic field which guided the electron beam.

This magnetic field perturbation took a number of forms, viz. a periodic magnetic ripple of limited length,[13,23-26] a nonadiabatic convergence of the magnetic field lines,[27] and a nonadiabatic divergence of the magnetic field lines.[11,28] A definitive identification of the cyclotron maser mechanism as the major source of microwave generation in these experiments was made through two salient observations. First, it was established[11,28] that the modal structure of the microwaves corresponded to that expected in the cyclotron maser instability. Secondly, it was demonstrated[13] that wave growth took place in a region of uniform magnetic field after the electron beam had encountered the magnetic perturbation. The perturbation in the magnetic field provided the required distribution of transverse kinetic energy, much as the magnetic corkscrew functioned in the early low power level experiments.

Table 1 displays the maximum attained peak power levels produced with intense relativistic electron beams through the cyclotron maser process. It is especially noteworthy that these record peak powers were produced at millimeter wavelengths as well as in the more usual microwave bands.

Table 1 - Peak power levels from cyclotron masers driven by intense relativistic electron beams.

Wavelength (cm)	Peak Microwave Power (MW)	Accelerating Voltage (MV)	Diode Current (kA)	Reference
4	900	3.3	80	26
2	350	2.6	40	25
0.8	8	0.6	15	13
0.4	2	0.6	15	13

In addition to the high power levels in these intense beam experiments, it was also demonstrated[11] that the emission possessed a high degree of temporal and spatial coherence. Furthermore, the cyclotron maser was operated as a distributed-interaction amplifier[12] which could be tuned magnetically over a wide frequency range. The amplifier configuration is shown in Fig. 3. It should be noted that a distributed-interaction device has the advantage of tunability over a wide frequency range, and in addition, allows dissipation of far greater power as as compared with a short resonator. Thus, its realization has considerable practical importance.

Experimental research on cyclotron masers using intense relativistic electron beams is summarized in review papers by Hammer, et al.[29] and by Granatstein, et al.[30] Equally important as the experimental results was the stimulation they provided for theoretical studies.[31-33] We note especially the nonlinear analysis of the saturation of the cyclotron maser instability by phase trapping,[32] and the subsequent self-consistent analysis,[33] which generalized the first result to include saturation by energy depletion as well as by phase trapping. The latter work is useful not only in interpreting intense relativistic electron beam experiments but also in developing practical cyclotron maser tubes driven by electron beams with more conventional parameters.

(c) Studies in the USSR Using Magnetron Injection Guns (Realization of High Average Power Millimeter Waves):

The lead in development of practical cyclotron masers using electron beams with conventional voltage and current values has been taken by a group working at the Gork'ii State University (USSR), where the device has been given the name "gyrotron". In contrast to the cyclotron maser work in the USA after 1970 which centered around the intense relativistic electron beam technology outlined above which was very much in the nature of a basic laboratory study, the Soviet work comprised a very intense development effort leading to practical power tubes at millimeter and submillimeter wavelengths. The key element in achieving practical devices characterized by high efficiency was in careful design of the electron gun. In the Gork'ii studies a crossed field, or so-called magnetron injection gun was used to launch an annular beam with a large fraction of energy transverse to the axis and with minimum energy spread. These guns employed thermionic cathodes for CW and long-pulse operation. Experimental work on nonuniform cross section open resonators to optimize beam coupling for high efficiency has also taken place. All together, these developments have led to the announcement of the operation of two classes of devices, those operating in high (superconducting) magnetic fields, and those operating in lower conventional fields. Table 2

Table 2 - Reported gyrot[illegible]g conditions and output parameters.[34]

Model No.	Cavity Mode of Oscillation	Wavelength mm	CW or Pulsed	Cyclotron Harmonic Number	B-field kG	Beam Volts kV	Beam Amps	Output Power kW	Measured Eff., %	Theoretical Eff., %
1	TE_{021}	2.78	CW	1	40.5	27	1.4	12	31	36
2	TE_{031}	1.91	CW	2	28.9	18	1.4	2.4	9.5	15
	TE_{231}	1.95	pulsed	2	28.5	26	1.8	7	15	20
3	TE_{231}	0.92	CW	2	60.6	27	0.9	1.5	6.2	5

summarizes the results published to date on tubes of the first class.[34] Figure 4 is a drawing of a device of the second class, built by Kisel', et al.[35] This latter device in a magnetic field of only 6 kG, produced 9 mm CW power of 10 kW with 40% efficiency, and pulsed power of 30 kW at 43% efficiency. Recent reports from Soviet scientists who use the gyrotrons for RF heating of tokamak plasmas indicate that millimeter wave gyrotrons are now available with power at the level of hundreds of kilowatts.[36]

In parallel with the device development work there has been a strong Soviet theoretical effort. In the corpus of this work account has been taken of the electron space charge,[37] nonuniform electromagnetic fields of the resonator structure in a full nonlinear treatment,[38] and of gyro-harmonic operation.[39]

(d) The Current NRL Program in Advanced Development of High Power Millimeter Wave Cyclotron Masers (Gyrotrons):

The success achieved in the USSR in realizing high efficiency gyrotrons has now stimulated parallel work in the USA. Under ERDA sponsorship, Varian Associates are currently developing a tube at 28 GHz with a CW power level of 200 kW for use in microwave-generated plasma studies at the Oak Ridge National Laboratory. This device is of the gyroklystron type[19] employing resonant cavities separated by drift spaces.

The work at NRL is concentrating on millimeter wavelengths and on addressing scientific and technical issue at the limits of the technology. Currently studies are underway with the aim of demonstrating efficient generation of 1 MW peak power at = 8 mm within 3 years. The device configuration which is the major forces of this effort is the distributed, traveling-wave amplifier (gyro-TWA) similar to that shown in Fig. 3 because of its advantages in handling high power; the field strengths encountered for a given power level will be much lower in a traveling wave device than in a device employing resonant cavities. Among the scientific issues to be addressed are the effect of self-fields of the electron beam, and suppression of spurious mode generation in overmoded waveguide.

As a first stage in this program, a device designed for peak power of 300 kW at $\lambda = 8$ mm is currently under development. The advanced nonlinear theory of Sprangle and Drobot[33] has been adapted to cylindrical geometry[40] and used in obtaining a device design optimized for maximum efficiency. In this theory,[33] it is shown that a threshold for the cyclotron maser instability exists at low energy (typically 10 - 20 keV transverse kinetic energy); at energies just above the threshold the process becomes saturated because the growth rate goes to zero as the transverse energy is depleted and approaches the threshold value. At higher energies, on the other hand, a quite different saturation mechanism occurs. As energy is removed from the electrons the cyclotron frequency increases until the gyrating electrons are trapped in a phase such that energy transfer ceases. Competition between the two mechanisms leads to a peak in efficiency as a function of beam transverse energy. The plot of efficiency vs transverse energy which was used in designing the 300 kW distributed amplifier at $\lambda = 8$ mm is shown in Fig. 5. Efficiency is seen to reach a peak value of 74% in these beam frame calculations, the corresponding efficiency of transferring beam energy to wave energy in the laboratory frame is 53% for the design value of $V_\perp/V_\parallel = 1.6$.

Realization of this high efficiency requires spread in electron velocity no larger than a few percent, and thus, very exacting design of the electron gun. A numerical code for tracing electron trajectories has been developed at NRL[41] and used in the design of a magnetron injection gun for the 300 kW $\lambda = 8$ mm maser. The optimized electrode configuration together with some representative electron trajectories is shown in Fig. 6. For this gun design the spread in transverse energy as calculated by the numerical code is 2% and the spread in streaming energy is 6%.

An overall sketch of the traveling wave amplifier in which this electron gun will be employed is shown in Fig. 7. In essence, it combines the magnetron injection gun which characterized the Soviet work (see Fig. 4) with the input wave launcher and traveling wave interaction of the NRL intense beam amplifier (see Fig. 3). It is expected that this approach will lead to devices which are characterized by the megawatt peak power levels of Table 1 combined with the high efficiencies of Table 2.

Lastly, it should be noted that a superconducting magnet is being employed in the λ = 8 mm device in Fig. 7. This will allow for future experiments at higher frequency. Specifically there is DoD interest in devices which o[illegible] λ = 3 mm and λ = 1 mm. Preliminary design is in progress for a [illegible]er which would generate tens of kilowatts at λ = 3 mm at the fu[illegible] of the cyclotron frequency and kilowatts at λ = 1 mm at the 3rd cyclotron harmonic. The choice of pulse length, repetition rate, and CW operation are as yet open options and depend on sponsor interest.

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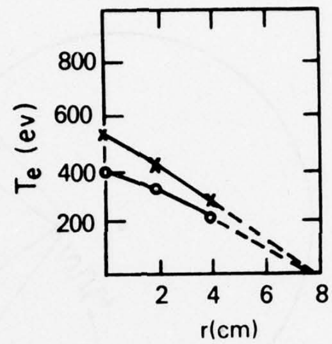
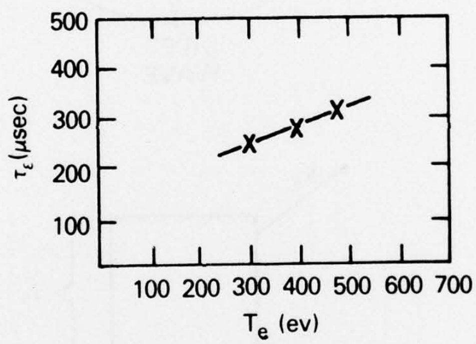


(a)



(b)

Fig. 1 — (a) Radial distribution of electron temperature at the end of a heating pulse (-x--x-) and in its absence (-0--0). (b) Dependence of average energy containment time τ_ϵ on the maximum electron temperature (-x--x).

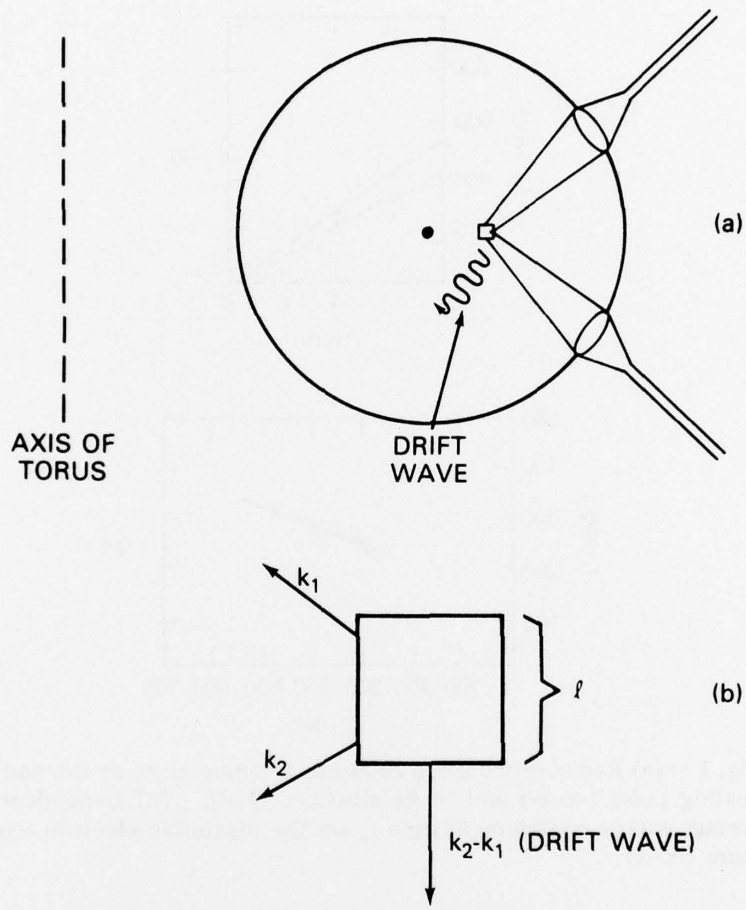


Fig. 2 — (a) Configuration for launching drift waves, and (b) the interaction region

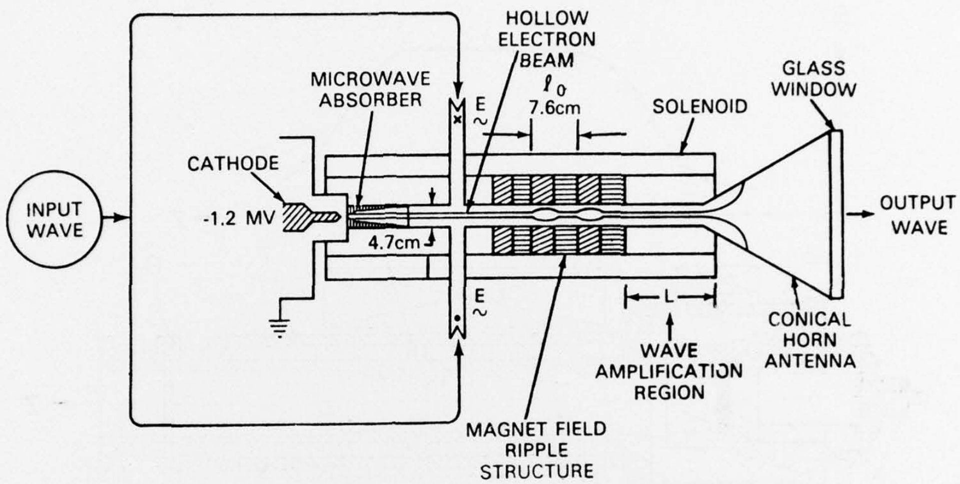


Fig. 3 — Cyclotron maser distributed-interaction amplifier using an intense relativistic electron beam. Input signal from magnetron was coupled into the drift tube in the TE_{01} mode. The ripple structure consisted of alternating iron and aluminum rings which perturbed the magnetic field lines and imparted large transverse energy into the growing TE_{01} wave. The length of the system from cathode to output window was about 3 meters.

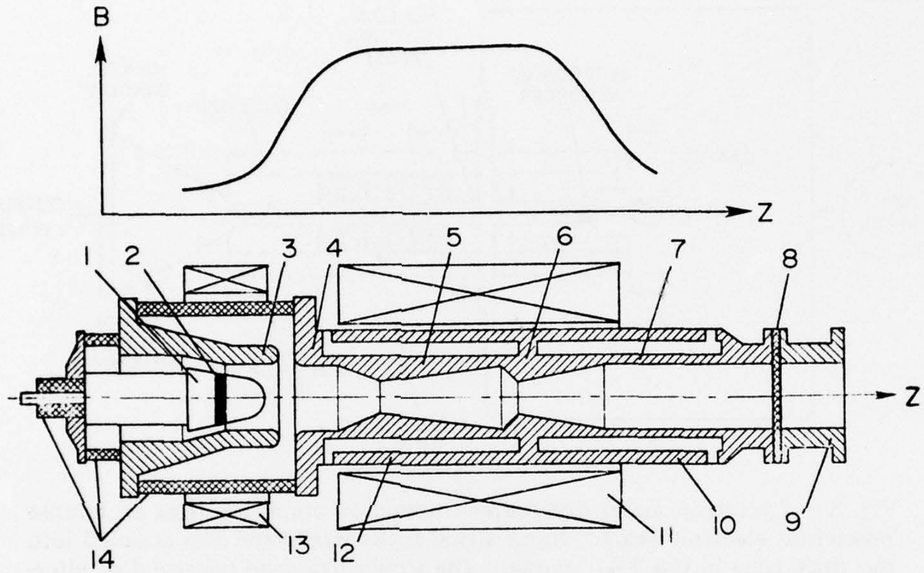


Fig. 4 — Outline drawing of Soviet gyrotron prototype. 1 — cathode; 2 — emitting strip; 3 — first anode; 4 — second anode; 5 — cavity; 6 — output coupling aperture; 7 — beam collector; 8 — output window; 9 — output waveguide; 10 and 12 — water jackets; 11 — main solenoid; 13 — electron gun solenoid; 14 — insulators. Overall length of this device is approximately 20 cm.

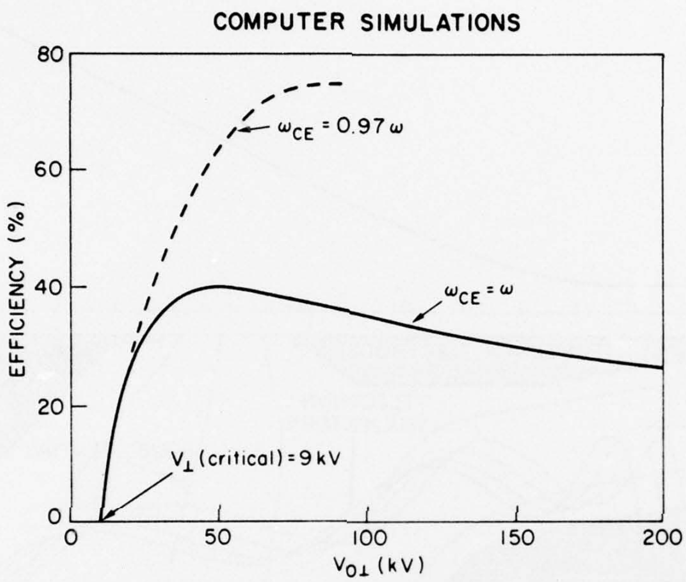


Fig. 5 — Calculated efficiency of cyclotron maser amplifier vs initial transverse electron energy, expressed in kilovolts, for beam current of 10 amps (from calculations based on theory in Ref. 33 and 40). Solid curve: cyclotron frequency = input wave frequency (TE_{01} mode); dashed curve: cyclotron frequency detuned by 3% by reducing magnetic field. The calculations shown here have been used to design a highly efficient 35 GHz distributed amplifier at the 300 kW level.

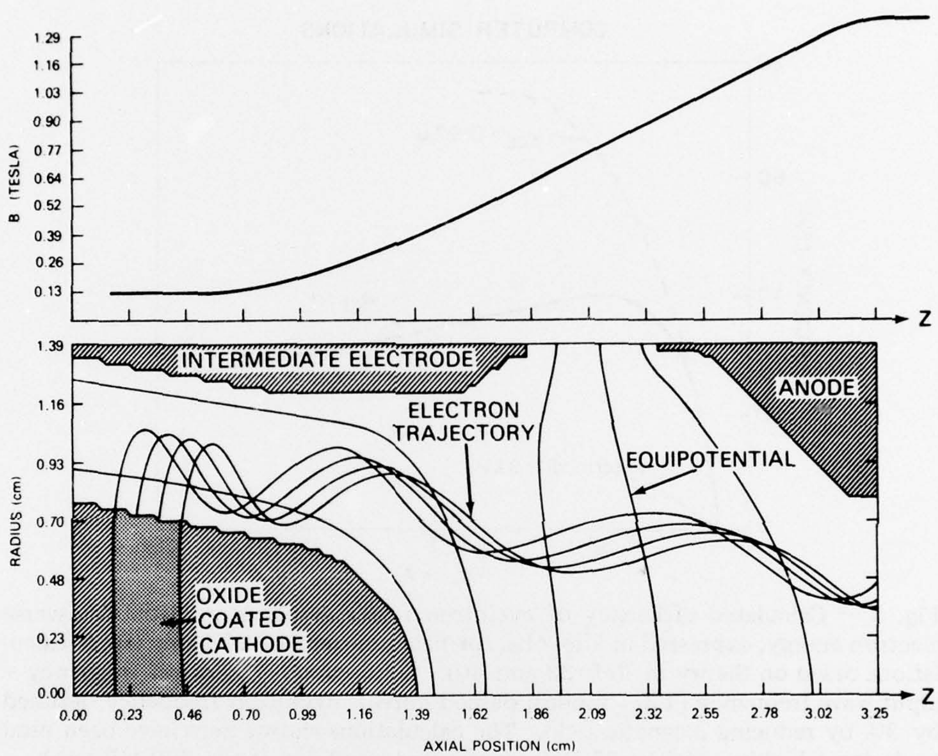


Fig. 6 — Computer design of electron gun for 35 GHz distributed amplifier at 300 kW level

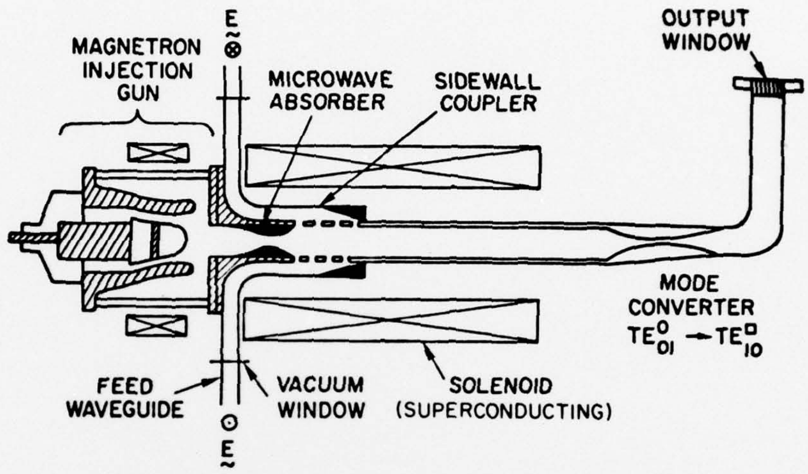


Fig. 7 — NRL Gyro-Traveling Wave Amplifier (TE$^{\circ}_{01}$ mode 35 GHz operating at the fundamental of the cyclotron frequency)