The Electron Cyclotron Maser—An Historical Survey

J. L. HIRSHFIELD AND V. L. GRANATSTEIN

Abstract—**It has taken nearly twenty years for practical development of the electron cyclotron maser. The initial theoretical notions were put forward by R. Q. Twiss in 1958, but the first clear experimental demonstration did not take place until 1964. Today, in the USSR, these devices are being built which deliver kilowatt-level CW power at submillimeter wavelengths with high efficiency. This paper traces these developments. After the first decade, Western device development became rather somnolent, and the initiative passed to the Soviet scientists. But a healthy resurgence of interest is now growing universally, due to a number of factors including device potential in practical systems. It has been shown recently that the cyclotron maser mechanism can explain a wide range of observations on intense relativistic electron beams, including the generation of gigawatt bursts. Furthermore, theoretical interest is again growing, especially as regards the nonlinear behavior of the interaction.**

Early Theoretical Developments

IT SEEMS THAT the brilliant astrophysicist R. Q. Twiss was the first to recognize an amplifying mechanism for free-electron gyroradiation [1]. He derived the general formula for the absorption coefficient α_ω for monochromatic radiation of angular frequency ω traversing an ionized medium undergoing free-free electronic radiative transitions.

$$\alpha_\omega = -(\hbar\omega)^2 \int dE Q_\omega(E)\, \partial F(E)/\partial E. \qquad (1)$$

Here $F(E)$ is the energy distribution function for the ensemble of electrons and $Q_\omega(E)$ is the effective transition probability for stimulated emission. Equation (1) is valid for $\hbar\omega \ll \bar{E}$, where $\bar{E}$ is the mean energy. In (1), $\hbar$ is Planck's constant over 2π.

Twiss showed that the two necessary conditions which had to be simultaneously satisfied to produce negative absorption (i.e., amplification) are

$$\text{(I) } \partial F/\partial E > 0 \qquad \text{and} \qquad \text{(II) } \partial Q_\omega/\partial E < 0$$

over some joint range of the energy E. Condition (I) is the familiar population inversion requirement; condition (II) can be traced to a requirement for either an energy-dependent level width or an energy-dependent level spacing for the quantized free electron states.

While Twiss did not actually evaluate (1) for conditions appropriate to an amplifying device, he did point out that the formula predicts amplification for Cerenkov radiation and for cyclotron radiation, but not for bremsstrahlung in a fully ionized plasma.

Then in 1959, evidently without knowledge of Twiss's work, Schneider [2] and Gaponov [3] each published calculations which specifically treated the stimulated emission of relativistic monoenergetic electrons in a magnetic field; Schneider's approach was quantum mechanical, while Gaponov's was classical. Schneider's result allowed one to estimate the experimental conditions required for stimulated emission to exceed absorption, albeit for monoenergetic electrons not drifting along the magnetic field.

But how can one understand physically the mechanism discovered by these workers which underlies the cyclotron resonance maser? If one takes a quantum-mechanical view, the free electron in a uniform static magnetic field B behaves as an anharmonic oscillator with quantized energy levels

$$W_n = mc^2[1 + 2(n + \tfrac{1}{2})\hbar\Omega_0/mc^2]^{1/2} - mc^2 + p^2/2m$$

neglecting spin, where Ω_0 is the rest electron gyrofrequency eB/m and where p is the unquantized momentum along the magnetic field. Transitions between states $n + 1$ and n will occur at frequency $\omega_n = (1 - n\hbar\Omega_0/mc^2)\Omega_0$ for $n\hbar\Omega_0 \ll mc^2$; we note that ω_n decreases as n increases. Now, if a system is prepared with a higher population in state $n + 1$ than in state n, photons at frequency ω_n will induce a greater number of downward transitions $n + 1 \rightarrow n$, than upward ones $n \rightarrow n + 1$. It is the unequal level spacing which reduces the probability for absorptive transitions $n + 1 \rightarrow n + 2$, since $\omega_{n+1} < \omega_n$, thus allowing stimulated emission to exceed absorption, with a concomitant increase in the photon number. A similar effect can occur if the width of the level $n + 1$ exceeds that of level n; this can be brought about if the radiating electrons suffer (elastic) phase-interrupting collisions (say with neutral atoms) with a sufficiently strong energy-dependent cross section [4].

The classical picture of cyclotron maser action emerges by considering the phases of electrons rotating about the magnetic field. The orbiting charge radiates as an individual electric dipole (and as a higher order multipole when relativistic effects are properly included). For a system of monoenergetic electrons, originally distributed randomly in phase, the essential question for explaining coherent emission is to find a phase bunching mechanism, since N dipoles rotating in phase will give radiation which is about N more intense than for N dipoles with random phases. For even slightly relativistic electrons this bunching does in fact occur. Electrons absorbing radiation will become more

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massive and slip back in phase; electrons emitting radiation will become less "massive" and advance in phase. The ultimate phase distribution is such as to favor emission over absorption, thus enhancing the intensity of the incoming wave. Detailed trajectory calculations by Coccoli [5] have reinforced this view. The classical picture holds for the orbiting electron as a soft-spring oscillator in a general theory of the maser developed by Lamb [6], and as discussed in an extensive review by Gaponov *et al.* [7].

Perhaps a better view of the theoretical requirements for achieving amplification is afforded by study of the detailed form of (1), as analyzed by Bekefi *et al.* [4] and by Wachtel [8]:

$$-\alpha_\omega = \frac{2\pi(2m)^{3/2}\omega_p^{\,2}}{3\Omega_0^{\,2}c} \cdot \int dE \frac{\partial F}{\partial E}\{E^{3/2}\Omega(E)\ \mathrm{Im}\,[\Omega(E) - \omega + i\nu]^{-1}\} \quad (2)$$

where $\omega_p^{\,2} = Ne^2/m\varepsilon_0$ is the plasma frequency squared, $F(E)$ is only a function of energy and is thus isotropic in momentum, and the aforementioned quantity $Q_\omega(E)$ is that part of the integrand in braces. For $\nu(E)$ the collision frequency taken as constant, $\partial Q_\omega/\partial E < 0$ only via $\Omega(E)$ and negative absorption is possible for $\omega < \Omega_0$. For $F(E) \sim \delta(E - E_0)$, the case discussed by Schneider, $\alpha_\omega \sim (1 + x^2)^{-2}(1 + x^2 + ax)$ where $x = [\omega - \Omega(E_0)]/\nu$ and $a = 4E_0\Omega(E_0)/3mc^2\nu$; amplification results for $a > 2$. The presence of a phase-randomizing collision frequency ν requires sufficient relativistic phase bunching in a time ν^{-1} so that the attendant collisional absorption can be overcome by the stimulated coherent emission.

The possibilities for amplification when $\bar{E}$ is totally negligible with respect to mc^2, but when $\nu = \nu(E)$, was referred to above and discussed in [4] and [8]. Experimental verification of this collision-induced cyclotron maser action has been obtained [9] when low-energy electrons undergo elastic collisions in low-pressure xenon. But further discussion of this fascinating subject would carry us too far afield in this review.

In 1964–1965, Hirshfield *et al.* [10], [11] developed a theory for the interaction which closely paralleled the experimental devices then being studied. In this theoretical model, an axisymmetric beam with anisotropic velocity distribution $f_0(w,u)$ drifted along the axis of a TE_{011} cylindrical microwave cavity, coaxial with the uniform static $\boldsymbol{B}$ field. The velocity components along and across $\boldsymbol{B}$ were u and w, respectively. One result of the calculation was a general expression for the linearized power flow from the cavity fields (which were assumed known) to the electrons:

$$P_{RF} = \frac{\pi}{2}\frac{\rho e^2 E_0^{\,2}}{mk_\parallel^{\,2}}\int_0^\infty dww \cdot \int_{-\infty}^{\infty} duf_0(u,w)u^{-1}G_\omega(x)[1 + (k_\parallel w^2/\omega u)H_\omega(x)] \quad (3)$$

where $G_\omega(x) = (1 - x^2)^{-2}\cos^2(\pi x/2)$, $2H_\omega(x) = 2x - (\omega^2/k_\parallel^{\,2}c^2 - x^2)\ d[\ln G_\omega(x)]/dx$, $x = [\Omega(u,w) - \omega]/k_\parallel u$,

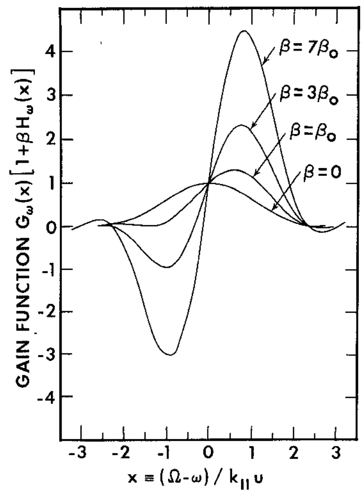

Fig. 1. Gain function $G_\omega(x)[1 + H_\omega(x)]$ versus $x = (\Omega - \omega)/k_\parallel u_0$ for the cyclotron maser in a TE_{0nm} cylindrical cavity, where $k_\parallel = m\pi/L$. The linear emission (negative values) or absorption (positive values) is proportional to this function. The parameter $\beta = k_\parallel w_0^{\,2}/\omega u_0$, and $\beta_0 = -H_\omega^{-1}(-1)$.

$k_\parallel = \pi/L$ with L the axial length of the cavity, and $\rho = 2\pi\int_0^R drrJ_1^{\,2}(k_\perp r)N(r)$ is the line density of the beam weighted by the RF electric field squared in the cavity of radius R. Negative values of P_{RF} are required to sustain oscillations.

Equation (3) can be used to find the start oscillation condition, and it can be used to estimate the oscillator efficiency, if the steady-state magnitude of E_0 is provided by the appropriate nonlinear theory. For the TE_{011} mode cavity, the start oscillation condition is

$$-P_{RF} = 0.0407(\pi R^2 L)(\omega\varepsilon_0 E_0^{\,2}/2Q)$$

where Q is the cavity quality factor.

While (3) can be used for any distribution function $f_0(u,w)$ in order to understand the effects of finite parallel and perpendicular velocity spread, it is instructive (and much simpler) to describe its predictions for a cold beam, i.e., $f_0(u,w) = (2\pi u_0 w_0^{\,2})^{-1}\ \delta(u - u_0)\ \delta(w - w_0)$. Then we find the oscillation threshold condition to be

$$\frac{Q}{4\pi}\frac{\omega_p^{\,2}}{k_\parallel u_0\omega}\ G_\omega(x_0)[1 + \beta H_\omega(x_0)] < -1$$

where $\omega_p^{\,2} = (\rho e^2/m\varepsilon_0)(0.0407\pi a^2)^{-1}$ is the modified plasma frequency for the beam, and where $\beta = k_\parallel w_0^{\,2}/\omega u_0$. A plot of the gain function $G_\omega(x_0)[1 + \beta H_\omega(x_0)]$ is shown in Fig. 1 for various values of β/β_0, where β_0 is the β value which must be exceeded in order for gain to occur. One sees, incidently, that maximum gain occurs when $x_0 = -1$, i.e., $\omega = \Omega(u_0,w_0) + k_\parallel u_0$. This condition is rather general and would apply for a TE_{0nm} cavity mode as well, provided $k_\parallel$ is taken as $m\pi/L$. The condition corresponds to an approximate matching between the beam drift velocity u_0 and the axial group velocity $d\omega/dk_\parallel$ for one of the component axial waves making up the cavity standing wave.

To give an illustrative example, let us pick $\omega/k_\parallel c = 4$, $\omega/k_\parallel u_0 = 40$, and $w_0^{\,2}/u_0^{\,2} = 20/3$. These conditions are typical for experiments, corresponding to a cavity with $L/R = 3.18$, a parallel beam energy of 5 keV, and a perpendicular beam energy of 33 keV. Since $G_\omega(-1) = G_\omega'(-1) = \pi^2/16$ and since our conditions correspond to $\beta/\beta_0 = 1.417$, we find $Q\omega_p{}^2/\omega^2 > 1.22$ for oscillations.

To estimate the efficiency η achievable in this device, we compared the RF power transferred from the beam to the cavity, with the transverse beam power $mu_0w_0{}^2\rho/2$. This ratio reduces to $\eta = -0.5(v_{osc}/w_0)^2(\omega/k_\parallel u_0)^2G_\omega(x_0)[1 + \beta H_\omega(x_0)]$ which, at $x = -1$ and for the conditions chosen above gives $\eta = 206(v_{osc}/w_0)^2$. Our approximate nonlinear analysis showed that v_{osc}/w_0 would have to exceed $u_0{}^2/c^2$ in order for nonlinear saturation of the distribution function to set in. If we pick $v_{osc}/w_0 \sim 3u_0{}^2/c^2$ then, for the example discussed above, we find a transverse efficiency of 19 percent. This value is only to be considered approximate, in view of the many simplifications which went into its derivation. It may be compared with the value of 41 percent published by Gaponov *et al.* [7].

Early Experimental Developments

Early experimental studies of the interaction of radiation with orbiting electrons in a static magnetic field were a natural outgrowth in the development of the traveling-wave tube, in all its variations. But since the interaction we have been discussing does not involve space-charge waves in any form, one may eliminate slow-wave interactions altogether in examining the early experiments. It was probably R. H. Pantell who, in 1959, reported the first results with a fast-wave cyclotron resonance interaction [12]. He described a device which oscillated at frequencies between 2.5 and 4.0 GHz, as the magnetic field into which a 3-μA electron beam at 1000 V drifted was varied. The radiation propagated along an *S*-band waveguide, and Pantell claimed that the radiation arose from synchronism between the backward cyclotron wave and the waveguide TE_{11} mode. These results were later extended by Chow and Pantell [13] who showed, in fact, how axial bunching could result from the combined forces due to the RF electric and RF magnetic fields. The axial bunching mechanism has been discussed in depth by Gaponov *et al.* [7] as a companion, sometimes a competitor, for the orbital phase bunching mechanism of the cyclotron maser.

In 1964, I. B. Bott of the Royal Radar Establishment reported the generation of radiation [14] between 2.2 and 0.95 mm using a 10-kV 50-mA beam in a spatially converging pulsed magnetic field of up to 100 kG. Bott's radiation propagated within a 0.5-in-diam internally silvered glass tube, was coupled out through a quartz end window, and was detected with an InSb detector. The gain mechanism briefly mentioned as being responsible for the emission was an axial bunching, similar to that discussed by Chow and Pantell; a cyclotron radiation mechanism was stated to only give incoherent emission. At a later date, a device similar to Pantell's was built by Schriever and Johnson [15]. Using a more powerful electron beam, they managed to generate about 800 W at *S* band.

These first experiments studied steady-state oscillators,

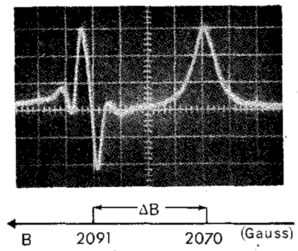

Fig. 2. Evidence for negative cyclotron resonance absorption, showing TE_{011} cavity loading at 6500 MHz for 5-keV electrons in a ~2-kG magnetic field. The absorption line at 2070 G was due to cold electrons; the line at 2091 G from the energetic electrons. Negative absorption is seen at the low ***B***-field side of the resonance. The 21-G shift is due to the relativistic mass shift of about 1 percent. At higher electron beam currents, oscillations appeared at 2090 G.

where presumably nonlinear effects have entered to saturate the gain, and thus to put the interaction out of reach of the linear theory which was outlined earlier. Moreover, the unknown mode properties of Bott's waveguide, and the clear possibility of coupling to the transverse RF magnetic fields in Pantell's devices, both left open questions as to whether cyclotron maser action had in fact been observed. (To be sure, neither author had claimed this.) For, in either case, had an axial synchronism condition been satisfied, it was demonstrably possible to explain the results without appeal to the cyclotron maser interaction [7].

In order to unequivocally establish the validity of the cyclotron maser mechanism, an experiment was needed satisfying at least two requirements: 1) the apparatus should operate below the start oscillation condition, so that the predictions of linear theory could be checked in detail, 2) the RF fields in the interaction region should be such that any axial bunching or axial synchronism would be prevented.

Both of these requirements were met in an experiment reported in 1964 [16], in which 5-keV electrons drifted along an axial magnetic field through a concentric high-Q TE_{011} cylindrical cavity. The beam was prepared using a low-perveance gun and a combination of a twisted transverse static magnetic field ("corkscrew") and a magnetic hill; the electrons could then be injected into the cavity with most of their energy transverse to the magnetic field. Near the cavity axis negligible axial bunching is predicted, since the transverse RF magnetic field vanishes there. The beam current was kept below the value where the cavity would break into oscillations, and the external magnetic field was swept over a narrow interval about the cyclotron resonance value. Under appropriate conditions cavity loading curves (proportional to the change in reciprocal Q) were observed with a shape as predicted above, namely, $G_\omega(x)[1 + \beta H_\omega(x)]$. A typical cavity loading curve for this experiment is shown in Fig. 2. When the beam current was increased oscillations occurred just where the negative loading had previously been observed. It would seem that this experiment provided the first clear test of the validity of the cyclotron maser mechanism, and resulted in the first publication in which the moniker "electron cyclotron maser" was applied. Later, a two-cavity experiment was reported [17] which

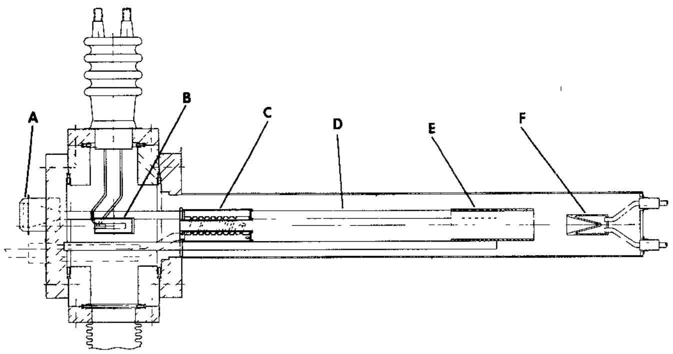

Fig. 3. Outline drawing of the cyclotron maser built in 1968 [19], which provided up to 100 mW in the range 5.82–0.725 mm and, at the second harmonic, measurable power at 0.488 mm. A—output horn and window; B—thermionic cathode; C—water-cooled magnetic corkscrew; D—output waveguide; E—overmoded open resonator; F—collector.

showed that an amplifier configuration was possible based fundamentally on the same phase bunching mechanism, only here the bunching is allowed to pile up between cavities as the electrons move on free-streaming orbits. A theoretical efficiency of 34 percent was shown to be possible for this type of amplifier.

Then in 1965 Bott published a second letter [18] describing experiments with an apparatus similar to that described earlier in [16], but with a 50-kG superconducting magnetic field. In these experiments continuous oscillations at watt levels were observed from 2 to 4 mm. Even second harmonic radiation of about 10 mW was seen down to 1.06 mm. Although Bott took note of the cyclotron maser mechanism in this paper, the uncertainties discussed above would still make an unequivocal identification of the gain mechanism difficult. Still, it seems unlikely that axial bunching could have occurred in this apparatus due to the overlap of several axial waveguide modes in Bott's waveguide.

In 1968, L. C. Robinson [19] placed a tube built by Hirshfield into the high-magnetic-field facility at the Francis Bitter National Magnet Laboratory at MIT. An outline drawing of this device is shown in Fig. 3. An overmoded resonator was used so that, as in Bott's device, continuous tuning could be achieved by adjusting the magnetic field. Radiation at power levels up to 100 mW was observed in the wavelength range 5.82 mm–725 μm. Second harmonic power of about 2 μW was detected at 488 μm. The cyclotron maser had penetrated the submillimeter regime.

Recent Developments

Improvements are currently accumulating in experimental realizations of cyclotron maser devices and in theoretical understanding of the ultimate limitations to efficiency and power output. It would be premature to attempt a definitive review of this topic now. It is important, however, to mention briefly three areas of important contribution which have set the tone for the present-day resurgence.

TABLE I
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	24
2	350	2.6	40	23
0.8	8	0.6	15	21
0.4	2	0.6	15	21

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. Giant microwave bursts were first reported in 1970 by J. A. Nation [20] 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 [21]–[24], a nonadiabatic convergence of the magnetic field lines [25], and a nonadiabatic divergence of the magnetic field lines [26], [27]. 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 [26], [27] that the modal structure of the microwaves corresponded to that expected in the cyclotron maser instability. Secondly, it was demonstrated [21] 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 I displays the maximum attained peak power levels produced with intense relativistic electron beams through the cyclotron maser process. It is especially noteworthy that these very high peak powers were produced at millimeter wavelengths as well as in the more usual microwave bands.

In addition to the high power levels in these intense beam experiments, it was also demonstrated [27] that the emission possessed a high degree of temporal and spatial coherence. Furthermore, the cyclotron maser was operated as a distributed interaction amplifier [28] which could be tuned magnetically over a wide frequency range. The amplifier configuration is shown in Fig. 4. It should be noted that a distributed-interaction device allows dissipation of far greater power as compared with a short resonator, and thus its realization has considerable practical importance.

Experimental research on cyclotron masers using intense realtivistic electron beams is summarized in review papers

TABLE II
REPORTED GYROTRON OPERATING CONDITIONS AND OUTPUT PARAMETERS [34]

model no.	mode of oscillation	wavelength mm.	cw or pulsed	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

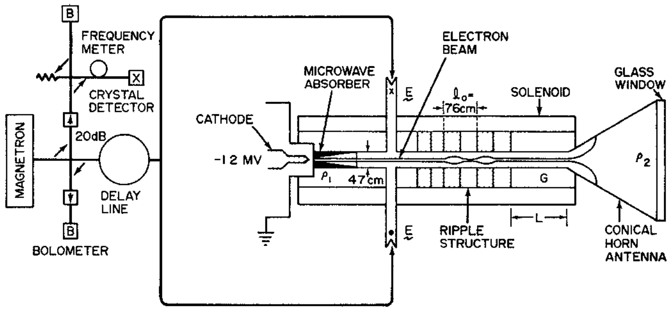

Fig. 4. Cyclotron maser distributed-interaction amplifier using an intense relativistic electron beam. Input signal from magnetron was coupled into the drift tube in the TE_{01} mode. The ripple structure consisted of alternating iron and aluminum rings which perturbed the magnetic field lines and imparted large transverse energy into the growing TE_{01} wave. The length of the system from cathode to output window was about 3 m.

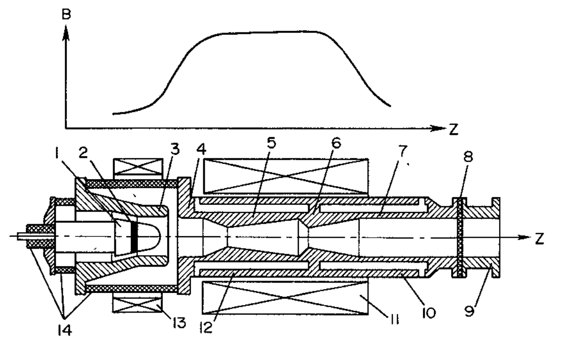

Fig. 5. Outline drawing of Soviet gyrotron prototype. 1—cathode; 2—emitting strip; 3—first anode; 4—second anode; 5—cavity; 6—output coupling aperture; 7—beam collector; 8—output window; 9—output waveguide; 10 and 12—water jackets; 11—main solenoid; 13—electron gun solenoid; 14—insulators. Overall length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

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.

The lead in development of practical cyclotron masers using such conventional electron beams 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 U.S.A. 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. Results have been published of the development of magnetron injection guns in nonuniform magnetic fields which produce annular beams of nearly 1 A at up to 60 keV, with a large component of the electron energy in transverse motion. These guns employed thermionic cathodes for CW and long-pulse operation. Further 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 II summarizes the results published to date on tubes of the first class [34]. Fig. 5 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-percent efficiency, and pulsed power of 30 kW at 43-percent efficiency.

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 [36], nonuniform electromagnetic fields of the resonator structure in a full nonlinear treatment [37], and of gyroharmonic operation [38].

For the future, major systems requirements, such as electron cyclotron resonance heating in magnetically confined fusion research, will stimulate development of millimeter-wave sources characterized by the megawatt power levels of Table I together with the high efficiencies of Table II. The combined analytical and numerical nonlinear theory of Sprangle and Drobot [33] has been applied to assaying these possibilities, and has predicted that the desired combination of power and efficiency is achievable.

CONCLUSIONS

We have surveyed a 20-year evolution of the cyclotron maser from a fleeting theoretical idea and a small-scale laboratory curiosity, to a powerful and efficient gyrotron which already competes favorably with conventional generators in the millimeter and submillimeter wavelength ranges. Its future promise in extending this parameter range is very high. Important applications are already at hand, including plasma heating [39] and millimeter-wave radars.

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