The Gyrotron

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Abstract—**This paper describes the genealogical tree of the gyrotron, stimulated emission of cyclotron radiation in microwave electronics from magnetron to gyrotron, and arrangement of the gyrotron. The structure of the alternating field in the gyrotron is also given, along with motion and bunching of electrons near cyclotron resonance, equations of the gyrotron, and varieties of the gyrotron. A review of experimental studies is discussed, with problems of utilization of stimulated emission cyclotron radiation.**

I. Genealogical Tree of the Gyrotron

The prehistory of the gyrotron began early in the twentieth century with attempts to produce electromagnetic waves by radiation of oscillating electrons. Among progenitors of the gyrotron are the Barkhausen–Kurz oscillator and the cyclotron resonance magnetron (magnetron with the smooth cylindrical anode). Numerous references to early work are found in the review paper [1]. The nearest relatives of the gyrotron are the strophotron, helitron, ubitron, and similar devices based on interaction of electromagnetic waves with electrons oscillating in macroscopic static fields, that is, on stimulated emission. The electrons here behave as excited classical oscillators. Therefore, we may call these devices "classical" electron masers (CEM's).

The CEM's are distantly related to quantum mechanical devices (masers and lasers) and to conventional microwave electron beam tubes (klystron, TWT, etc.).

As in the quantum devices, in CEM's electromagnetic waves interact with oscillating electrons satisfying a resonance condition

$$\omega - \boldsymbol{k} \cdot \boldsymbol{v}_0 \simeq n\omega_0, \qquad n = 1,2,\cdots \tag{1}$$

where ω_0 and $\boldsymbol{v}_0$ are the oscillation frequency and drift velocity of the electrons, and ω and $\boldsymbol{k}$ are the frequency and wave vector for the electromagnetic wave. The Doppler shift $\boldsymbol{k} \cdot \boldsymbol{v}_0$ will be shown below to be of great importance for the gyrotron. Since the resonance condition may be satisfied even for fast waves in CEM's (as in quantum devices), in contrast to conventional microwave tubes, ordinary waveguides with smooth walls, as well as open waveguides and open cavities, may be employed.

As in conventional microwave tubes (and in contrast to quantum devices), in CEM's one electron is able to radiate a great number of quanta at the signal frequency. Therefore, by proper design of a system it is possible to make use of an intense high-energy (in particular, relativistic) electron stream for electromagnetic wave generation with high efficiency.

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Since CEM's possess the merits of both quantum and conventional devices, the natural frequency range of CEM's is, not surprisingly, located between the natural ranges of both related classes, viz. the domain of CEM's is expected to be found in the millimeter and submillimeter-wave region.

Generally speaking, there are many ways to provide macroscopic oscillatory motion of electrons, i.e., to make them travel along periodic trajectories. For this purpose one may use either homogeneous fields, fields inhomogeneous in the direction transverse to the electron drift, or periodic static fields. Accordingly, the various types of CEM's are rather numerous. Among them, the CEM's with homogeneous static fields seem to be most attractive because of their simplicity and because of the possibility to confine intense electron streams with uniform parameters in large volumes (by analogy with an active medium in lasers). The main objective of this paper is to survey the theoretical and experimental work which has led to the development of the gyrotron.

II. Stimulated Emission of Cyclotron Radiation in Microwave Electronics—From Magnetron to Gyrotron

In crossed uniform static electric and magnetic fields $\boldsymbol{E}_0$ and $\boldsymbol{B}_0$, a free electron moves along a toroidal trajectory with a built-in periodicity (provided $E_0 < cB_0$). There exists a unique frame of reference where the static field is purely a magnetic field, of strength B_0', and in which the electron orbit is circular at the cyclotron (or gyro-) frequency

$$\omega_H' = eB_0'/m'$$

where primed quantities are in this unique frame. In the laboratory frame the corresponding frequency is

$$\omega_0 = \omega_H = \omega_H'[1 - (v_0/c)^2]^{1/2}$$

where $\boldsymbol{v}_0$ is the relative velocity between the laboratory frame and the unique frame. This frequency ω_0 is the cyclotron resonance frequency in the laboratory frame.

In order to provide coherent emission of electromagnetic waves by the electrons, it would seem enough to impart to them a gyration energy. However, any electron gun forms a stationary electron beam which creates by itself only a static field. The influence of an electromagnetic wave on the beam gives rise to alternating currents which can lead to stimulated emission and absorption, thereby either increasing or decreasing the wave energy.

One way to arrange for stimulated emission to exceed stimulated absorption in an ensemble of gyrating electrons is to extract the absorbing electrons from the interaction space. This idea was exploited in the smooth anode magnetron (see, e.g., [2]) and in phasochronous devices [3]–[5] where the walls of the electrodynamic systems functioned as extractors for electrons of unfavorable phases. But the electron bombardment of the walls places obstacles on high-power generation by those devices.

From this viewpoint, a device with an unintercepted electron beam would be preferable. However, any physical mechanisms which could provide for the prevalence of stimulated cyclotron radiation over stimulated absorption in systems without extraction of unfavorably phased electrons were unknown for a long time. Mechanisms were revealed in 1959 [6]–[8]. The first of these is associated with the relativistic dependence of the cyclotron frequency upon the electron energy and the second with inhomogeneity of the alternating electromagnetic field. The first mechanism leads to azimuthal bunching of gyrating electrons, the second one gives rise to their longitudinal bunching. An excellent introduction to both mechanisms may be found in a pioneering work on electromagnetic waves in non-equilibrium magnetoactive relativistic plasma [9].

The devices based on the induced cyclotron radiation of transiting electron beams are called cyclotron resonance masers (CRM's). This term was introduced in [12], [13]. The energy dependence of the gyrofrequency can also be found in semiconductors with the nonparabolic energy surfaces; this led to suggestions for solid-state CRM's [12].

The number of possible types of CRM's is rather great [1], [14] but, not surprisingly, only the most promising of these has been investigated in detail. A great change in the history of CRM's occurred in 1965–1966 when CRM's with crossed $\boldsymbol{E}_0$ and $\boldsymbol{B}_0$ fields and trochoidal electron beams achieved 1 kW of continuous wave power at 8 mm [1]. This suggested that it may be possible to build CRM's with pure magnetic field and helical electron beams. The fact is that in the crossed field CRM's the drift electron velocity $v_0 = E_0/B_0$ decreases as the wavelength shortens, the electric field is limited by breakdown, and the magnetic field increased since $\omega \simeq n\omega_H \simeq neB_0/m$. The drift velocity reduction is accompanied by the drop of electron current. On the contrary, in helical beams the electron drift velocity $v_0 = v_\parallel$ is not limited and the electron current increases with the beam voltage.

However, at first, the obvious energetic advantage of helical beams seemed to be offset by a large drift velocity dispersion inherent to any practical method of high-current electron beam formation. Therefore, the cyclotron resonance line would be severely Doppler broadened and, hence, would make it impossible to satisfy the resonance condition (1) for all electrons.

A way out was found by the use of electromagnetic waves with phase velocity along $\boldsymbol{B}_0$ which is much greater than the velocity of light

$$\omega/k_\parallel \gg c. \tag{2}$$

(A wave of this sort is a superposition of uniform plane waves propagating in directions almost perpendicular to $\boldsymbol{B}_0$.) Such an arrangement may be realized in a waveguide of gently varying cross section at a frequency close to cutoff, for example, in a quasi-optical open resonator. The resonance condition (1) taking account of (2) may be written as

$$\omega \simeq n\omega_H. \tag{3}$$

It should be noted at once that the condition (2) only applies for systems where electron velocities v are small compared to the velocity of light

$$\beta^2 = v^2/c^2 \ll 1. \tag{4}$$

In this case the gyrofrequency

$$\omega_H = (m_0/m)\omega_{H0} = \omega_{H0}(1 - \beta^2/2) \tag{5}$$

is close to that of cold electrons

$$\omega_{H0} = eB_0/m_0 \tag{6}$$

(m and m_0 are the relativistic mass and the rest mass of an electron). However, in systems with ultrarelativistic electrons ($c - v \ll c$), a high efficiency is most likely to be reached in practice even if the condition (2) is not fulfilled [15].

The CRM's in which the interaction of helical electron beams with electromagnetic waves takes place in nearly uniform waveguides near their cutoff frequencies were called gyrotrons [16].

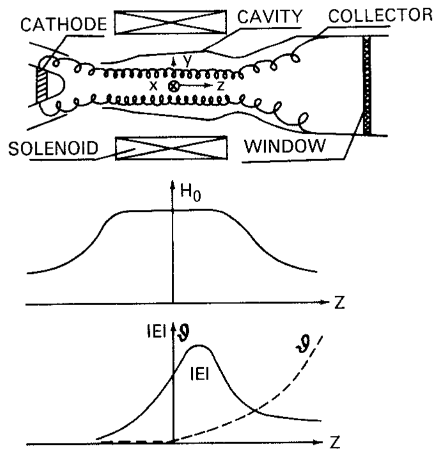


Fig. 1. Arrangement of the gyrotron. Distribution of static H_0 and alternating $E = |E| \operatorname{Re}(e^{i\omega t - i\phi})$ fields.

III. Arrangement of the Gyrotron

Fig. 1 shows the most popular configuration of the gyrotron, namely, the axisymmetric gyrotron. The symmetry originates with the solenoid creating the magnetic field. Due to this symmetry, the cathode with a large emitting surface is able to produce an intense flow of electrons with rather small velocity dispersion. The flow undergoes compression by the magnetic field which increases in the direction from the cathode to the interaction space. The compression section represents a reversed magnetic mirror ("corkless magnetic bottle") where the initial cathode orbital velocity of electrons $v_\perp$ grows according to the adiabatic invariant $v_\perp{}^2/B_0$ = constant, the orbital energy being drawn from that of longitudinal motion and from the accelerating electrostatic field. In the interaction space the electrons are guided by quasi-uniform magnetic fields. Escaping it, they enter the region of the decreasing field (the decompression section) and then settle on the extended surface collector.

If axial symmetry is given to the electrodynamic system, all electrons interacting with the RF field are found with nearly equal conditions. This favors the possibility of obtaining high efficiency. As to the longitudinal profile, the electrodynamic system has a gently varying cross section, with different sections functioning as the interaction space (open cavity), output, and input apertures.

The diffraction output aperture for the RF power (through the end of the open cavity) allows mode selection, thus keeping the RF loading on the output window at a moderate level.

IV. Structure of the Alternating Field in the Gyrotron

Under the conditions (2)–(4), as follows from simple arguments, supported by calculations [17], the electron beams interact with TE waves much more effectively than with TM waves. The electromagnetic field of a TE mode in a waveguide of slowly varying cross section near cutoff is given by the equations [18]

$$\boldsymbol{E}(x,y,z,t) = \mathrm{Re}\,[F(z)\boldsymbol{E}_s \exp{(i\omega t)}]$$
$$\boldsymbol{H}(x,y,z,t) = \mathrm{Re}\,[F(z)\boldsymbol{H}_s \exp{(i\omega t)}] \tag{7}$$

where $\boldsymbol{E}_s = \hat{z} \times \nabla_\perp \Psi_s$ and $\boldsymbol{H}_s = i(\omega/c)\hat{z}\Psi_s$. The field structure is close to that of the corresponding mode of the uniform waveguide [18]. The membrane function $\Psi_s(x,y,z)$ satisfies the equation $\nabla_\perp{}^2\Psi_s + k_\perp{}^2\Psi_s = 0$, with the boundary condition $\partial\Psi_s/\partial n = 0$ on the wall of the waveguide, where $\hat{n}$ is the normal to the surface. The eigenvalue $k_\perp{}^2(z)$ of the membrane equation (the square of the transverse wave number) is involved in the nonuniform string equation

$$\frac{d^2F(z)}{dz^2} + k_\parallel{}^2F(z) = \frac{1}{N_s}\int \boldsymbol{j}_\omega \cdot \boldsymbol{E}_s{}^*\, dx\, dy \tag{8}$$

satisfied by $F(z)$. Here $k_\parallel{}^2(z) = k^2 - k_\perp{}^2$, $k = \omega/c$, $N_s = (\omega/4\pi)\int|\Psi_s|^2\, dx\, dy$, $\boldsymbol{j}_\omega = (1/2\pi)\int_0^{2\pi} \boldsymbol{j}(t)e^{-i\omega t}\, d(\omega t)$ is the fundamental harmonic of the electron current density $\boldsymbol{j}$.

The action of the alternating force upon a gyrating electron results, generally, in the change both of the radius and position of the gyration axis. Analyzing a short impulse acting upon an electron (any arbitrary force may be represented as a set of such impulses), it is easy to conclude that both of these changes are of the same order of magnitude. Hence the shift of the gyration axis does not exceed the radius

$$r = v_\perp/\omega_H \tag{9}$$

of the electron orbit. Therefore, in accord with (2), the shift is small compared to the scale of the transverse inhomogeneity of the field, i.e., to the wavelength $\lambda = 2\pi c/\omega$. Equivalently, one may neglect a weak dependence of Ψ_s on the coordinate z.

When analyzing the action of the electromagnetic wave upon the orbital motion of an electron, it is convenient to use the polar coordinate system (r,θ) with the origin on the gyration axis and to expand the function $\Psi_s(x,y)$ into the Fourier series in the angular variable θ

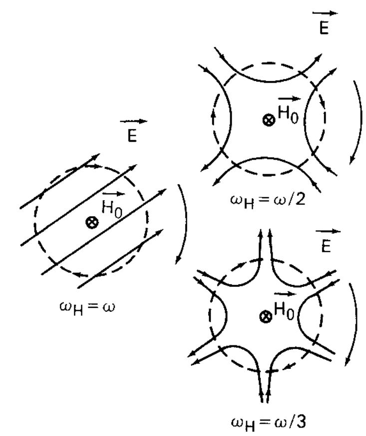


Fig. 2. Resonance near harmonics of gyrofrequency. A dotted line shows the initial trajectory of electrons.

$$\Psi_s = \sum_l \psi_l(r) \exp{(-il\theta)}.$$

The lth harmonic of this series describes the field rotating with an angular frequency ω/l. The greatest cumulative action upon the electrons is caused by the nth azimuthal harmonic

$$E_{\mathrm{synch}} = \mathrm{Re}\,\{FE_{s,\mathrm{synch}}e^{i\omega t}\} \quad E_{s,\mathrm{synch}} = \hat{z} \times \nabla_\perp \Psi_n \tag{10}$$

rotating synchronously with them.

In a region small compared to λ, the function $\Psi_n = \psi_n \exp{(-in\theta)}$ satisfies approximately the Laplace equation $\nabla^2\Psi_n = 0$ and may be written as

$$\Psi_n = A_n r^n \exp{(-in\theta)} = A_n(R^*)^n, \qquad R = x + iy.$$

Correspondingly, the synchronous field has a quasi-static structure

$$\boldsymbol{E}_{s,\mathrm{synch}} = -iA_n\nabla(R^*)^n \tag{11}$$

and represents the field of a rotating nth order multipole (see Fig. 2).

V. Motion and Bunching of Electrons Near Cyclotron Resonance

Under the conditions (2)–(4), as shown in [17], the longitudinal bunching of electrons is negligible compared with the azimuthal. This is not difficult to understand observing a set of gyrating electrons which, at the initial state, form a uniform ring beam (Fig. 2) and are resonantly affected by the alternating field during a time interval corresponding to the transit time of electrons in an interaction space of a gyrotron. Let us consider, for the sake of definiteness, the case of the fundamental gyroresonance ($n = 1$). The position of the particles and the orientation of the synchronous component of the alternating field will be shown in a plane perpendicular to the static magnetic field (Fig. 3) at the moments of time which are multiples of the period $2\pi/\omega_H{}^{(0)}$ of unperturbed gyration of electrons (all the parameters of electrons at the input of the interaction space will be written with the index$^{(0)}$).

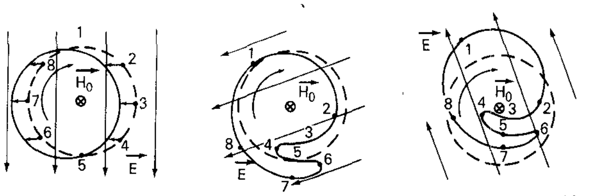


Fig. 3. Motion of relativistic electrons near cyclotron resonance. A dotted line describes the initial distribution of electrons.

If the electron energy is assumed to be weakly relativistic (2), at the first stage of their interaction with the alternating field [Fig. 3(a)] the gyrofrequency energy dependence (5) has no essential effect upon their motion and bunching. Since the nonrelativistic motion of electrons is described by the linear equations, the set of gyrating electrons is equivalent to an ensemble of linear oscillators. In Fig. 3(a) this stage is described by the displacement of the ring of electrons, as a whole, towards the region of the accelerating field where $\boldsymbol{v} \cdot \boldsymbol{E} < 0$. The figure shows that the energy of some of the electrons decreases and that of others increases. On the average, the energy increases so that the electrons absorb the energy of the alternating field.

When the electrons are acted upon for a sufficiently long time by the alternating field, namely, for

$$\beta_\perp{}^2 N \gtrsim 1 \tag{12}$$

where N is the number of turns made by electrons in the alternating field $\beta_\perp = v_\perp/c$ the dependence of the gyrofrequency on the electron energy (5) becomes essential and gives rise to the additional bunching of electrons. If

$$\omega > \omega_H \tag{13}$$

the bunch occurs in the decelerating phase of the field where $\boldsymbol{v} \cdot \boldsymbol{E} < 0$ [Fig. 3(b)]. As a matter of fact, in this case for electrons which first enter the decelerating phase, their angular velocity relative to the RF field $|\omega_H - \omega|$ decreases due to the energy loss and they remain in this phase; on the contrary, for electrons which first enter the accelerating phase, their relative angular velocity increases due to the energy increase, and they readily shift to the decelerating phase.

At the final stage [Fig. 3(c)], the bunch is decelerated so that the electrons give up their energy to the alternating field.

In terms of the quantum theory, an electron placed in the magnetic field has a discrete energy spectrum (Fig. 4). The distance between two neighboring energy levels (Landau levels) equals approximately $\hbar\omega_H$. Since the gyrofrequency decreases with increasing energy, the energy levels are unequally spaced ($\varepsilon_k - \varepsilon_{k-1} > \varepsilon_{k+1} - \varepsilon_k$). Therefore, elementary acts of induced radiation (transitions $k \to k - 1$) and induced absorption (transitions $k \to k + 1$) occur at slightly different frequencies. Correspondingly, the system of relativistic electrons possesses the same absorption curve as a three-level quantum object (Fig. 5). The condition (12) requires a sufficiently strong nonuniform spacing of Landau levels relative to the linewidth of stimulated emission and absorption. The condition (13) defines tuning of the frequency of the electromagnetic field to correspond to that of stimulated emission (transition $p \to p - 1$). Strictly speaking, the linewidth determined by the lifetime of electrons in a classical system exceeds considerably the difference between frequencies $\omega_{p,p+1}$ and $\omega_{p,p-1}$. Therefore, the induced radiation and induced absorption cannot be observed separately. One may speak only about the predominance of one of these processes.

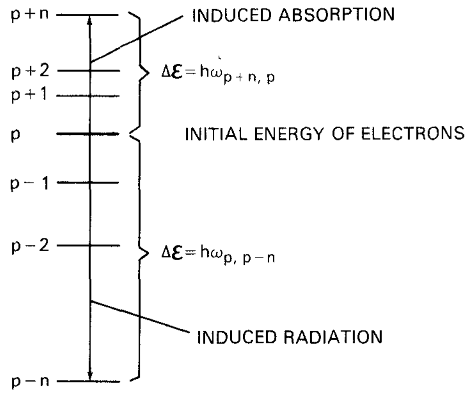


Fig. 4. Energy spectrum and induced radiation processes in a system of gyrating relativistic electrons.

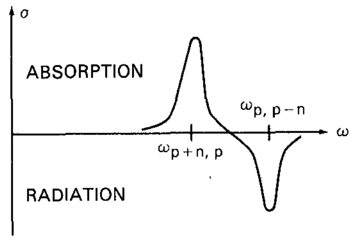


Fig. 5. Absorption line for a system of gyrating relativistic electrons.

Whether one analyzes this process from the viewpoint of classical or quantum theory, it is not difficult to estimate the optimal parameters of the gyrotron without using a mathematical apparatus any more complex than the first four rules of arithmetic. For example, for the simplest type of the gyrotron, namely, a gyrotron autogenerator with one cavity, the optimal combination of the parameters is [14]

$$\beta_\perp{}^{(0)2} N \sim 1 \tag{14a}$$

$$\omega - \omega_H{}^{(0)} \sim \omega_H{}^{(0)}/N \tag{14b}$$

$$e|\boldsymbol{E}_{\text{synch}}|(2\pi r^{(0)})N \sim m v_\perp{}^{(0)2}/2 \tag{14c}$$

$$\eta I_0 U Q = \omega W. \tag{15}$$

Here $N = (L/\lambda)/\beta_\parallel$, $\beta_\parallel = v_\parallel/c$, L is the length of the cavity, Q is its quality factor, $W = (1/8\pi)\int|\boldsymbol{E}|^2\,dx\,dy\,dz$ is the RF energy stored in the cavity, I_0 and U are the current and voltage of the electron beam, and η is the fraction of the electron's energy given up to the RF field, i.e., the efficiency of the gyrotron. When $\beta_\parallel \lesssim \beta_\perp$, in the optimal parameter region the efficiency may amount to several tens of percent.

The condition (14a) is the compromise between the relation (12) and the requirement that the resonance is not to be disturbed even if the electron has lost a considerable part of its initial energy. Under the condition (14b) the field frequency is tuned to the middle of the negative absorption region [see (13) and Fig. 5]. Under the condition (14c) the work of the RF field on the electrons is comparable with their initial energy. The relation (15) describes a dynamic balance between the RF power carried by the electron beam into the cavity and the power drawn from the cavity into the load.

For given parameters of the electron beam, the relation (14a) determines the cavity length and (14b) the magnetostatic field adjustment. The combination of (14c) and (15), taking into account the relation between $\boldsymbol{E}_{\text{synch}}$ and $\boldsymbol{E}$ for the operating mode, determines the Q factor of the cavity.

However, a more reliable basis for the design of experimental devices is undoubtedly the use of exact quantitative methods.

VI. Equations of the Gyrotron

A full set of the equations of the gyrotron consists of (8) of a nearly uniform waveguide and the equation of motion of electrons

$$d\boldsymbol{p}_\perp/dt + \omega_H \boldsymbol{p}_\perp \times \hat{z} = -e\boldsymbol{E} \tag{16}$$

where

$$\boldsymbol{p}_\perp = m\boldsymbol{v}_\perp$$

is the transverse momentum of an electron.

Let the electron beam be of infinitesimal cross section. Then the wave excitation factor in the right-hand side of (8) is

$$\int dx\, dy\, \boldsymbol{j}_\omega \cdot \boldsymbol{E}_s^* = \langle \rho \boldsymbol{v}_\perp \cdot \boldsymbol{E}_s^* e^{-i\omega t}\rangle_{\omega t} = \langle \rho \boldsymbol{v}_\perp \cdot \boldsymbol{E}_s^* e^{-i\omega t}\rangle_{\omega t_0}$$

where $\rho = -I_0/v_\parallel$ is the linear charge density of the beam, t_0 is the time at which the electron enters the interaction space, and

$$\langle\cdots\rangle_\phi = \frac{1}{2\pi}\int_0^{2\pi} d\phi(\cdots).$$

Taking into account that at the resonance condition (3) only the synchronous component (10), (11) of the alternating electric field (7) interacts effectively with the electrons, and neglecting the difference between m and m_0 everywhere but in the cyclotron frequency ω_H involved in the left-hand side of (16), we may write the system (8) and (16) as

$$\frac{dP}{dt} - i\omega_H P = \xi F e^{i\omega t}(P^{n-1})^*$$

$$\frac{d^2F}{dz^2} + k_\parallel^2 F = \chi\langle P^n e^{-i\omega t}\rangle_{\omega t_0}$$

where

$$P = p_x + ip_y \qquad \xi = \frac{i^n enA_n}{(m\omega_H)^{n-1}} \qquad \chi = -i\,\frac{\rho n\omega_H A_n^*}{N_s(im\omega_H)^n}.$$

Introducing a slow variable $P = pe^{-i(\omega/n)t}$, we have

$$\frac{dP}{dt} + i\left(\frac{\omega}{n} - \omega_H\right) P = \xi F(P^{n-1})^*$$

$$\frac{d^2F}{dz^2} + k_\parallel^2 F = \chi\langle P^n\rangle_{\omega t_0}.$$

If we introduce the dimensionless quantities

$$q = \frac{P}{|P^{(0)}|} \qquad f = -i\xi|P^{(0)}|^{n-2}F$$

$$\Delta = \frac{2}{\beta_\perp^{(0)2}}\,\frac{\omega - n\omega_H^{(0)}}{\omega} \qquad \gamma = \frac{2}{\beta_\perp^{(0)2}}\,\frac{k_\parallel v_\parallel}{\omega_H^{(0)}}$$

$$I = \frac{4eI_0 v_\parallel}{N_s \beta_\perp^{(0)4}\omega_H^{(0)2}}\, n^2|A_n|^2 (r^{(0)})^{2(n-1)}$$

this system of equations is

$$q' + iq(\Delta + |q|^2 - 1) = if(q^*)^{n-1}$$

$$f'' + \gamma^2 f = I\langle q^n\rangle_\gamma \tag{17}$$

where the prime denotes the derivative with respect to the dimensionless coordinate

$$\zeta = \frac{\beta_\perp^{(0)2}}{2}\cdot\frac{\omega_H^{(0)}z}{v_\parallel}. \tag{18}$$

The boundary condition for an electron is

$$q^{(0)} = e^{i\phi}. \tag{19}$$

Various types of the gyrotron differ according to the profile of their electrodynamic system [characterized by the function $\gamma^2(\zeta)$], the distribution of the weakly inhomogeneous magnetostatic field [characterized by the function $\Delta(\zeta)$], and input and output conditions for the function $f(\zeta)$ proportional to the RF field.

The efficiency of the gyrotron is determined by the relative energy lost by electrons due to their interaction with the RF field

$$\eta = \frac{1}{1 + (\beta_\parallel/\beta_\perp^{(0)})^2}\,\eta_\perp \tag{20}$$

where

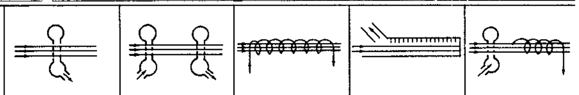
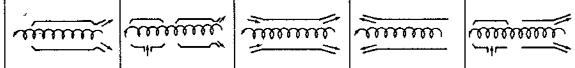
$$\eta_\perp = 1 - \langle|q|^2_{\text{out}}\rangle_\phi = \frac{2}{I}\,\text{Im}\,\{(f'f^*)_{\text{in}} - (f'f^*)_{\text{out}}\} \tag{21}$$

is the so-called transverse (orbital) efficiency.

Essentially, the position of the gyration axis of an electron is characterized by a single parameter, namely, $|A_n|$. Hence (17) may be directly used to describe the interaction of an electromagnetic wave with a set of electron beams if all of them are characterized by the same $|A_n|$. The important particular case of this kind is the axially symmetric gyrotron (Fig. 1). Here the equality of $|A_n|$ for different elementary subbeams of the electron stream is provided either by the axial symmetry of the operating mode field or by the fact that, due to the gyrotropy of the electron stream, the modes with nonzero azimuthal index have a rotating field structure [1].

It should be noted that the electron motion equation in the form (17) coincides with the equation which describes the interaction between the alternating field and an ensemble of weakly nonlinear oscillators with one degree of freedom [1]. Therefore (17) is applicable not only to gyrotrons but also to a number of other classical electron masers.

TABLE I

"0" TYPE DEVICE					
	MONOTRON	KLYSTRON	TWT	BWO	TWYSTRON
TYPE OF GYROTRON					
	GYRO-MONOTRON	GYRO-KLYSTRON	GYRO TWT	GYRO BWO	GYRO-TWYSTRON
RF FIELD STRUCTURE					
ORBITAL EFFICIENCY	0 42	0 34	0 7	0 2	0 6

VII. Varieties of the Gyrotron

Bunching of electrons in the gyrotron discussed in Section V has much in common with that in conventional 0-type electron beam devices, namely, klystron, TWT, monotron, etc. In both cases the primary energy modulation of electrons gives rise to bunching (azimuthal or longitudinal, respectively) which is inertial. The bunching continues even after the primary modulating field is switched off (at the drift section of a klystron-type device). This analogy suggests the correspondence between 0-type devices and various types of the gyrotron (as well as of the other classical electron masers).

Table I presents schematic drawings of devices of both classes and the orbital efficiency calculated on the basis of (17) for the simplest modifications of the gyrotron at the fundamental gyroresonance ($n = 1$). A uniform approximation for the longitudinal structure of the RF field [1] was used for the gyromonotron. For the gyroklystron, the calculation was made in the narrow-gap approximation of the RF field in the input and output cavities. The electrodynamic system of the gyroTWT and gyroBWO, as well as the output section of the gyrotwystron, was assumed to have the form of a uniform waveguide [1], [19]. In all these cases the magnetic field is assumed to be homogeneous.

According to the calculations, the gyrotrons can have a high efficiency not only at $n = 1$ but also at the high harmonics of the gyrofrequency ($n \geq 2$). The corresponding data for the gyromonotron with the uniform approximation of the longitudinal structure of the RF field are presented in Table II [1].

The efficiency of any type of gyrotron may be increased above the magnitudes given in Tables I and II by optimization of the electrodynamic system profile and of the longitudinal distribution of the magnetic field [1]. In particular, as follows from calculations given in [20], a rather high efficiency (0.79 at $n = 1$ and 0.76 at $n = 2$) may be achieved by the use of one of the simplest types of open cavities, namely, a beer-barrel cavity [21] (with a Gaussian longitudinal field distribution). Utilizing the multiparameteric functions for Δ and γ^2 and optimizing them in the parameter space, one may compute a higher efficiency [22].

It should be borne in mind, however, that we have discussed an idealized model for the gyrotron without allowance for the dispersion of electron velocities, ohmic losses, and many other factors which decrease the efficiency of experimental gyrotrons.

TABLE II

n	1	2	3	4	5
$\eta_\perp$	0.42	0.30	0.22	0.17	0.14

VIII. Review of Experimental Studies

As was noted in Section II, the experimental beginnings of gyrotrons started when CRM's with trochoidal electron beams generated ~1-kW output CW power in the millimeter-wave range [1]. In addition, investigations of the CRM's of other types have been conducted up to the present (the total number of possible versions of CRM's is estimated to be about 100 [14]). From 1959 till 1976 there have appeared more than 20 papers concerning experimental investigations of CRM's excluding gyrotrons and CRM's with relativistic electron beams formed by high-current accelerators (the total number of theoretical works on CRM's excluding semiconductor CRM's approaches 200).

The experimental studies of gyrotrons started with checking the effects by which gyrotrons have advantages over other types of CRM's. First of all, one should be sure that the generator in which the nonuniform waveguide is excited near its cutoff frequency is stable with respect to the electron velocity dispersion. For this purpose a generator with an open-end rectangular cross-section cavity [23] was made. The length of the cavity was much greater than the wavelength. The TE_{011} mode (with one longitudinal variation of the RF field) should be excited in the generator. As for the formation of the electron beam with a large velocity dispersion, it has not ever been a difficult problem. The experimental characteristics of the generator were in agreement with the theory and, though its output parameters were rather poor (the efficiency was as low as 1 percent since a low-power gun allowed one to work only close to the self-excitation threshold of the generator), the attractiveness of the direction chosen was evidenced [24].

After this, a second-harmonic gyrofrequency generator was designed, the TE_{021} mode being excited in the open cylindrical cavity [23]. The gun, more powerful than in the first case, allowed an output efficiency of 3 percent but the output power, as followed from cold and hot measurements accounted for only a small part of the power which was extracted from the electron beam by the RF field, since the output waveguide coupled the cavity with the load very loosely.

The way out of the situation has been found by using the cavity with a diffraction output for the RF field. In the first tests a generator of this type allowed one to obtain the efficiency of 30 percent at the fundamental gyroresonance ($n = 1$, the TE_{011} mode) and by corresponding adjustment of the magnetic field 15 percent at the second harmonic of the gyrofrequency ($n = 2$, the TE_{021} mode). Some time later it became possible to achieve an efficiency up to 50 percent at the fundamental by the choice of the cavities and up to 19 percent at the second harmonic of the gyrofrequency [20]. This was the first generator which was named the gyrotron.

The subsequent experiments [25]–[32] were carried out in several directions: the cavity profile optimization [25], [26], the elimination of the parasitic oscillation in the high-current regime [27], the wavelength shortening [28]–[30], and the development of frequency tunable generators with a high-directivity output radiation [32]. (The sequence of the papers [20], [25]–[32] reflects not so much the chronology of the experimental research as the promptness of their authors.)

By the proper choice of the cavity profile (the appropriate calculations are mentioned, particularly, in [1]), it has become possible to increase the efficiency of gyrotrons at the second harmonic of the gyrofrequency [25] (viz. up to 40 percent), as well as to shift the efficiency saturation to the higher current range at the fundamental gyroresonance [26].

One of the ways to eliminate the parasitic oscillations in the enlarged cross-section gyrotrons was found to be, in particular, the use of the "whispering gallery" modes [27], [30].

The short-wave gyrotrons were investigated in two versions: with pulsed [28] and superconducting [29], [30] solenoids. The latter proved to be more convenient in the work and, mainly, were capable for the continuous-wave generation. Their output power was 22 kW at $\lambda = 2$ mm ($n = 1$, the TE_{021} mode) [30] and 1.5 kW at $\lambda = 0.92$ mm ($n = 2$, the TE_{031} mode) [29], respectively.

The split quasi-cylindrical cavities have been used in the frequency tunable gyrotrons. The frequency tuning was performed by shifting of mirrors and by the appropriate adjustment of the magnetic field. The gyrotrons of this type found application in spectroscopic devices with high resolution of weak lines [33].

One of the ways to form a narrow radiation directivity pattern at the output of the gyrotron is the use of the wave transformer in the form of the corrugated waveguide. Such a transformer was used in a gyrotron with the TE_{131} mode for the transformation of the output wave to the TE_{11} wave [32]. This generator was used for investigation of nonlinear self-focusing of the intense electromagnetic wave in plasma [34].

Finally, it may be said that the gyrotrons have lived up to expectations (Sections I, II) and really represent effective sources of the millimeter and submillimeter electromagnetic wave radiation.

IX. Problems of Utilization of Stimulated Cyclotron Radiation

At present, the theoretical and experimental investigations of the weakly relativistic gyrotrons have reached almost the same stage as that for conventional vacuum microwave devices. In the course of time the development of high-current electron guns, effective collectors, rugged output windows, and so on becomes more central for gyrotrons. Problems of this kind may be classified as technical. In the solution of them, wide experience has already been gained. Certainly, the efforts in the considerable advance of the gyrotrons give birth to sophisticated physical problems, but the underlying principles of the gyrotron remain as originally conceived.

On the other hand, the question of utilization of the stimulated cyclotron (synchrotron) radiation of relativistic (in particular, ultrarelativistic) electron beams for microwave power generation is less developed. Interest in this problem [35]–[39] has been aroused with the advent of high-current electron accelerators [40], [41]. The results of many theoretical works (especially in the linear approximation) being free of limitation of electron energy (see, particularly, reviews [1], [14], [42]) are applicable to relativistic CRM's.

Now it is clear that the devices based upon the stimulated emission of electrons, moving in the uniform magnetostatic field (as well as the devices based upon other types of stimulated emission of electrons [42]) retain, in principle, high efficiency at any large electron energies [15]. The experiments in which the megaelectronvolt electron beams are used [35]–[37], [39] seem to agree with this concept.

It is rather evident that in the ultrarelativistic range the cyclotron resonance maser should degenerate (remaining a device with high efficiency) into a synchrotron generator where every electron would give up its energy to the electromagnetic wave during a period of time not exceeding on the order of a cyclotron period. This tendency is illustrated by relation (14a) (see also [15]). Yet, which of the possible versions of the synchrotron generators would prove to be more viable remains to be seen.

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