One Century of Cyclotron Radiation

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(Invited Tutorial)

***Abstract*—During the one century after the theoretical prediction of the cyclotron radiation, this effect was found to contribute to many phenomena in nature and now delivers the highest powers at the shortest microwaves.**

***Index Terms*— Classical oscillators, high power microwaves, stimulated coherent radiation.**

I. Introduction

IN 1898, one year after the discovery of electron by Thomson [1], Lienard noted [2] that the electron circulating in the magnetic field should radiate electromagnetic waves.

At later studies, the cyclotron component was found to be present in the radiation of the Sun, planets, and other nebular objects [3], [4]. The asymptotic ultra-relativistic form of the cyclotron radiation, namely the synchrotron one, accompanies the particle motion in cyclic accelerators [5].

As for the cyclotron radiation of collective type, microwave generators based on this effect could not compete with devices based on Cherenkov and transition radiations for many decades. It would seem surprising, because the Cherenkov devices, e.g., the traveling wave tube (TWT), need slow wave structures and the transition radiation devices, e.g., the klystron, need structures of a strong irregularity, whereas the cyclotron radiation represents a partial case of the Bremsstrahlung which can take place in electrodynamic systems of a much wider class. However, to realize the latter advantage in devices fed with stationary electron beams, it is necessary to provide conditions when the stimulated radiation prevails over the absorption. The first relevant methods of the sort appeared already in 1920's, but those which allowed one to create cyclotron resonance devices of really high power and efficiency were proposed only in 1950's and 1960's.

This survey does not present a real history of the research and only describes evolution of main ideas in the field. The historical truth (which can be traced with reviews [6]–[12]) is sacrificed here to simplicity of models and symmetry of analysis. In particular, for the sake of "unification" of electron vacuum microwave generators with "conventional" lasers, the quantum approach is used symmetrically to the classical one.

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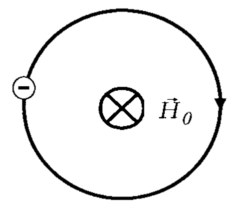
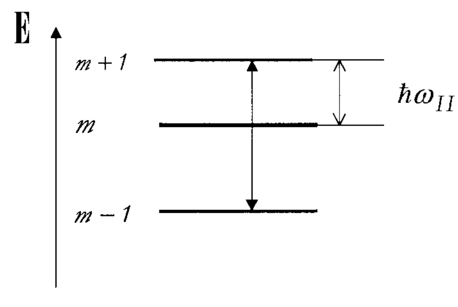


(a)



(b)

Fig. 1. Electron in (a) magnetic field and (b) Landau levels.

II. First Approximation: Electron in Magnetic Field as an Oscillator With One Degree of Freedom

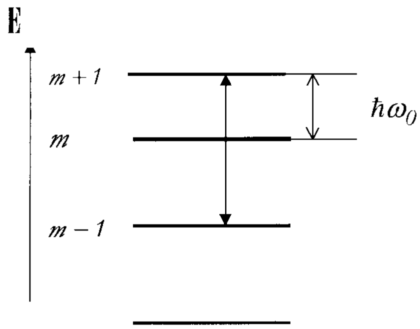
A. Classical and Quantum Models of Oscillating Electron

In the frame of classical description, the electron situated in the homogeneous static magnetic field is assumed to gyrate along a circular trajectory [Fig. 1(a)], whereas from the quantum viewpoint it represents an object with a discrete spectrum of energies (Landau levels [13]) separated with distances $\hbar\omega_H$, where ω_H is the cyclotron resonance frequency and $\hbar$ is the Planck constant [Fig. 1(b)]. Such an electron may be regarded as equivalent to a particle oscillating in a potential well [Fig. 2(a)] and characterized with a discrete spectrum of energies separated with distances $\hbar\omega_0$ [Fig. 2(b)], where ω_0 is the classical oscillation frequency. To transit from the model shown in Fig. 2 to that shown in Fig. 1, it is sufficient to change ω_0 for ω_H. As ω_0 and ω_H may depend on the electron energy, the spectrums shown in Figs. 1(b) and 2(b) may be nonequidistant.

B. Interaction Between an Electron Oscillator and a Photon

Interacting with an alternating electromagnetic field, the particle in Figs. 1(b) or 2(b) can transit from one energy level to another [13], [14].

(a)



(b)

Fig. 2. Electron in (a) potential well and (b) its energy levels.

- Transition from level of number m to the nearest lower level of number $m-1$ reduces the electron energy by $E_m - E_{m-1}$ and is accompanied with emission of a photon with frequency

$$\omega_{m,\,m-1} = (E_m - E_{m-1})/\hbar \approx \omega_0 \tag{1}$$

- absorption of a photon with frequency

$$\omega_{m+1,\,m} = (E_{m+1} - E_m)/\hbar \approx \omega_0 \tag{2}$$

enlarges the electron energy by $E_{m+1} - E_m$ and causes its transition from level of number m to the nearest upper level of number $m+1$.

The radiation transitions $m \rightarrow m-1$ are of two kinds: spontaneous and stimulated. In the latter case the stimulating photon should have the frequency determined by (1).

C. Interaction of a Monochromatic Electromagnetic Field with Monoenergetic Ensemble of Oscillators

Let a number of photons with frequency $\omega \approx \omega_0$ be injected into a homogeneous medium composed of electrons situated in the potential well [Fig. 2(a)] at the same energy level of number p. A part of these photons will be absorbed by electrons and stimulate transitions $p \rightarrow p+1$, another part will stimulate electron transitions $p \rightarrow p-1$ followed with emission of additional photons. If the stimulated radiation prevailed over the absorption, a chain reaction of the photon multiplication would take place, which could be used to amplify or generate a coherent electromagnetic radiation.

The averaged electron-photon interaction effect can be characterized with the medium RF conductivity [14]

$$\sigma = \frac{ie^2N}{\hbar}\left\{\frac{\omega_{p,\,p-1}|x_{p,\,p-1}|^2}{\omega - \omega_{p,\,p-1} - i\nu_{p,\,p-1}} - \frac{\omega_{p+1,\,p}|x_{p+1,\,p}|^2}{\omega - \omega_{p+1,\,p} - i\nu_{p+1,\,p}}\right\} \tag{3}$$

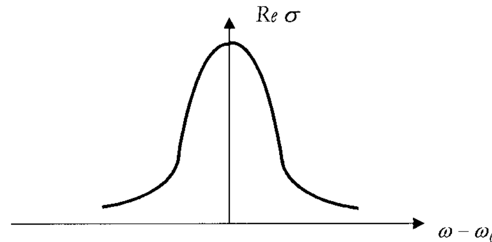


Fig. 3. Absorption line of stationary ensemble of energy independent lifetime linear oscillators.

(the electron oscillation scale being assumed negligible compared with that of the RF field inhomogeneity). In (3), N is the electron density, e is the electron charge, $x_{m,\,n}$ is the element of the electron coordinate matrix, $1/\nu_{m,\,n}$ is the $m,\,n$ transition lifetime.

In the quasi-classical limit $\hbar \rightarrow 0$, (3) reduces to [7]

$$\sigma \approx e^2N\omega_0 \frac{d}{dE}\left(\frac{\omega_0|x_1|^2}{i\Delta\omega + \nu}\right) \tag{4}$$

where x_1 is the complex amplitude of the first harmonic of electron oscillation, $\Delta\omega = \omega - \omega_0$ is the resonance mismatch. The formula (4) can be derived from classical electron motion equations as well [7].

D. Absorption of the RF Field Energy by Stationary Ensemble of Linear Oscillators with Energy Independent Lifetime

If an oscillator is linear, its energy spectrum is equidistant and the oscillation frequency

$$\omega_0 = \omega_{p,\,p-1} = \omega_{p+1,\,p} \tag{5}$$

does not depend on the particle energy. If, in addition, the oscillator lifetime $1/\nu$ is also energy independent, formulas (3), (4) reduce to

$$\begin{aligned}\sigma &= \frac{e^2N\omega_0}{\hbar}\cdot\frac{|x_{p+1,\,p}|^2 - |x_{p,\,p-1}|^2}{i\Delta\omega + \nu}\\ &\approx \frac{e^2N\omega_0^2}{i\Delta\omega + \nu}\cdot\frac{d|x_1|^2}{dE}\\ &= \frac{e^2N/2m}{i\Delta\omega + \nu}.\end{aligned} \tag{6}$$

This formula represents the usual Lorentian resonant absorption line (Fig. 3). So, the active part $\mathrm{Re}\,\sigma$ of the conductivity (6) is positive independently of the initial electron energy and at any mismatches of the cyclotron resonance. As a matter of fact, according to (5) both the photon absorption (transitions $p \rightarrow p+1$) and stimulated radiation (transitions $p \rightarrow p-1$) happen exactly at the same frequency ω_0 and, so, cannot be separated; the probability of stimulated radiation determined by $|x_{p,\,p-1}|^2$ is proportional to p, whereas the probability of absorption determined by $|x_{p+1,\,p}|^2$ is proportional to $p+1$ [13].

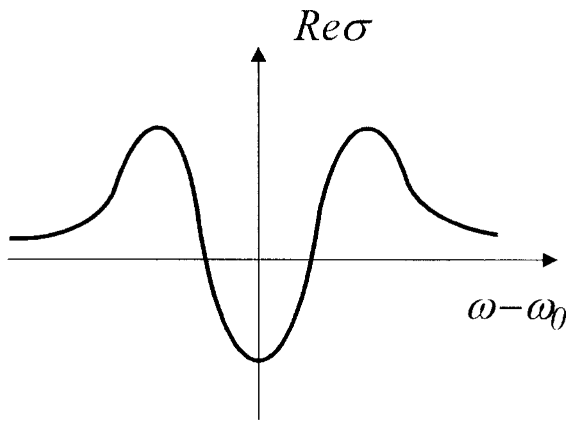


Fig. 4. Absorption line of stationary ensemble of linear oscillators with energy dependent lifetime.

E. Negative Reabsorption of RF Field Energy by Stationary Ensemble of Oscillators with Energy Dependent Lifetime

If oscillators are linear, but their lifetime $1/\nu$ is energy dependent and sufficiently long

$$\left|\frac{d\nu}{dE}\right| \gg \frac{\nu}{2m\omega_o^2|x_1|^2} \tag{7}$$

formulas (3), (4) reduce to

$$\sigma \approx -\frac{d\nu}{dE} \cdot \frac{e^2 N\omega_0^2|x_1|^2}{(i\Delta\omega + \nu)^2}. \tag{8}$$

Accordingly, in a part of the resonant band (Fig. 4) the active component of conductivity is negative. For the cyclotron resonance case a formula similar to (8) was derived in [15], [16] and confirmed by an experiment with a non-Maxwellian collisional plasma [16].

The negative conductivity effect illustrated with (8) and Fig. 4 was used in cyclotron resonance microwave generators and amplifiers where the unperturbed motion of electrons proceeded near a metallic wall [17]–[19]. In such a device (Fig. 5)

- "wrong phase" electrons, those which are accelerated by the RF field at the first cyclotron loop, enlarge their gyration radius and, so, are immediately captured by the wall, whereas,
- "right phase" electrons, those which are decelerated by the RF field at the first cyclotron loop, reduce their gyration radius and, so, remain able to give their energy to the RF field during a large amount of subsequent RF periods.

The cyclotron resonance magnetron with smooth (nonsplit) cylindrical anode [17][1], whose simplified scheme is shown in Fig. 5, could be called, according to the general definition of masers (microwave amplification by stimulated emission of radiation), the first cyclotron resonance maser (CRM), though the latter term was introduced only three decades later [23], [24].

[1]The magnetron of Zacel [17] was neither first nor last electron device named the magnetron: the magnetron of Hull [20] was a low frequency (nonresonant) valve and the famous present day magnetron [21] is a product of gradual evolution from the cyclotron resonance [17] to a wave—particle synchronism of Cherenkov type. In spite of the change of synchronism, the classical magnetron with corrugated cylindrical anode [21] still uses the extraction of "wrong phase" electrons by walls of the RF interaction space. The latter effect contributes also (along with the electron oscillation nonisochroneity discussed in the next section) to the operation of the Barkhausen–Kurtz microwave generator [22] and its modern version: the vircator [10], [12].

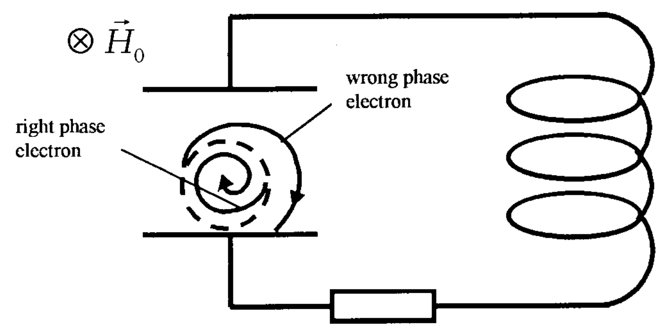


Fig. 5. A scheme of microwave generator based on extraction of "wrong phase" electrons and deceleration of "right phase" ones.

F. Negative Reabsorption of the RF Field Energy by Stationary Ensemble of Nonisochronous Oscillators

If the potential well in Fig. 2(a) is nonparabolic, electron oscillations are nonisochronous: the oscillation frequency ω_0 depends on the particle energy ($d\omega_0/dE \neq 0$). Accordingly, the oscillator energy spectrum is nonequidistant and frequencies of radiation and absorption transitions (1), (2) are different

$$\omega_{m,\,m-1} \neq \omega_{m+1,\,m}. \tag{9}$$

This effect is essential for usual quantum masers and lasers [14]. In classical microwave devices the difference between frequencies $\omega_{m,\,m-1}$ and $\omega_{m+1,\,m}$ is small compared with the width of the absorption line, but, nevertheless, may be sufficient to provide, at some band of frequencies ω, the prevalence of stimulated radiation over absorption. Indeed, assuming the oscillator lifetime independent on the particle energy, formulas (3), (4) reduce to

$$\sigma \approx \frac{A_1}{i\Delta\omega + \nu} + \frac{iA_2}{(i\Delta\omega + \nu)^2} \tag{10}$$

where

$$A_1 = e^2 N\omega_0 \cdot \frac{d\left(\omega_0|x_1|^2\right)}{dE}$$
$$A_2 = e^2 N\omega_0^2|x_1|^2\,\frac{d\omega_0}{dE}. \tag{11}$$

For the medium composed of nonisochronous $(d\omega_0/dE \neq 0)$ oscillators, the resonant curve (Fig. 6) consists of two adjacent parts: one with prevailing absorption, another with prevailing radiation.

Dependence $\sigma(\omega)$ equivalent to (10) and Fig. 6 was obtained at first for the strophotron [25] where electrons oscillate in a nonparabolic potential well and later for other microwave generators with periodic curvilinear electron trajectories (Fig. 7): the helitron, the ubitron etc; see review [7]. In particular [26], [23], [27], [28], the formula (10) and Fig. 6 are applicable to the stationary ensemble of electrons in the homogeneous magnetic field with account of relativistic

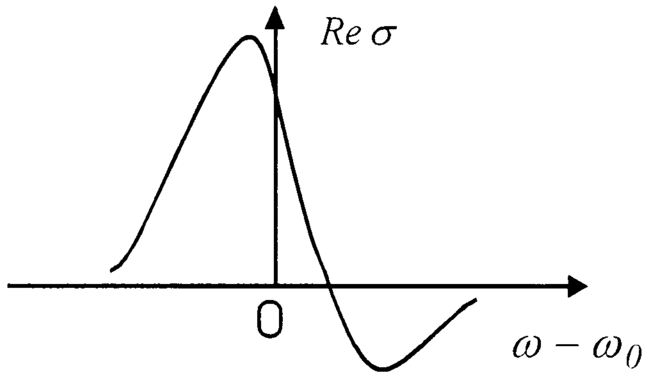


Fig. 6. Absorption line of stationary ensemble of nonisochronous $(d\omega_0/dE < 0)$ oscillators.

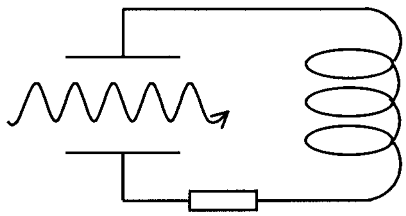


Fig. 7. A scheme of microwave generator based on interaction of RF field with a flow of nonisochronous electron oscillators.

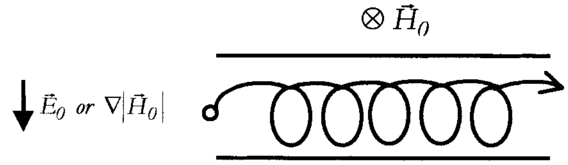


Fig. 8. A scheme of microwave generator based on interaction of electromagnetic wave with trochoidal electron beam guided either: 1) with crossed electric and magnetic fields or 2) with a transverse inhomogeneous magnetic field. The electron oscillations are nonisochronous due to either: 1) the relativistic effect or 2) the transverse of magnetic field inhomogeneity.

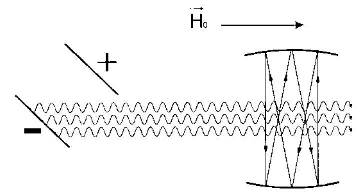


Fig. 9. A scheme of the gyrotron. A flow of oscillating electrons interacts with a wave flow propagating (quasi-) perpendicular to the static magnetic field, which excludes Doppler broadening of the cyclotron resonance line and is favorable for effective mode selection, thus providing coherence of radiation from strongly oversized quasi-optical cavities.

dependence of the cyclotron resonance frequency on the electron velocity v

$$\omega_H = \frac{eH_0}{mc}\sqrt{1-\frac{v^2}{c^2}}. \tag{12}$$

In the frame of classical description, Fig. 6 for relativistic electrons is explained in the following way [7].

- The quasi-resonant RF field changes the electron energy, and, as the change depends on the phase of electron relative to the RF field, the particles begin to gyrate with different frequencies (12) and gather into a bunch.
- If $\omega < \omega_H$, the bunch gyrates faster then the RF field, shifts to the accelerating phase, and finally absorbs the RF energy ($\sigma > 0$).
- If $\omega > \omega_H$, the bunch gyrates more slow then the RF field, shifts to the decelerating phase, and finally gives its energy to the RF field ($\sigma < 0$).

The relativistic effect resulting in the negative conductivity of the medium (electron beam) is used in a number of cyclotron resonance masers [29]–[34], [24][2] (Fig. 7), in particular, in the trochotron [32] (Fig. 8) and the gyrotron [34] (Fig. 9).

Obviously, the effective conductivity of a stationary ensemble of classical oscillators may be negative due to dependence of the oscillation frequency not only on the electron energy, but on some other parameter as well. In particular, if the static magnetic field is inhomogeneous, the cyclotron frequency and the electron drift velocity depend on the transverse position of the orbit center (Fig. 8), which provides amplification of the resonant electromagnetic wave even if the relativistic effect is negligible [7], [35].

III. Cyclotron Resonance Interaction of Electrons with Tranverse Inhomogeneous RF Fields

To take into account the RF field inhomogeneity at the electron cyclotron orbit, it is convenient to use polar coordinates r, ϑ with the origin in the orbit center and expand the RF field into the Fourier series

$$\vec{E} = -\mathrm{Re}\left\{ e^{i\omega t}\,\vec{H}_0 \times \nabla \sum_{l=-\infty}^{+\infty} A_l r^l e^{-il\vartheta} \right\}. \tag{13}$$

In (13), any summand, with an index l, describes a field rotating with angular velocity ω/l. Due to its inhomogeneity, the RF field can interact with electrons not only at the fundamental cyclotron resonance, but at harmonics of the cyclotron frequency as well

$$\omega \approx n\omega_H, \qquad n = 1, 2, 3, \cdots. \tag{14}$$

In the frame of quantum description, under the condition (14) the electron absorbs and emits photons with energies close to $n\hbar\omega_H$, jumping over n steps at the Landau ladder. The interaction of the transverse inhomogeneous RF field with electrons may be of two kinds.

A. Cyclotron Harmonic Gyrotron

If in (13) the RF field summand with the index n is nonzero, its interaction with the synchronous gyrating electron is the dominant effect and can be characterized with the conductivity (10), where $\Delta\omega = \omega - n\omega_H$ and coefficients A_k are calculated basing on the RF field expansion (13), the coefficient A_2 providing the negative conductivity effect (Fig. 6) is due to the relativistic dependence of the cyclotron frequency on the electron energy (12) [7].

[2]Authors of the "simpletron" [29] scarcely suspected that their 1 GHz generator operated due to a relativistic effect.

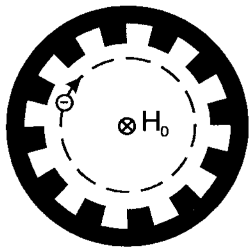


Fig. 10. A scheme of the peniotron. Electrons gyrate faster than the cyclotron resonant wave.

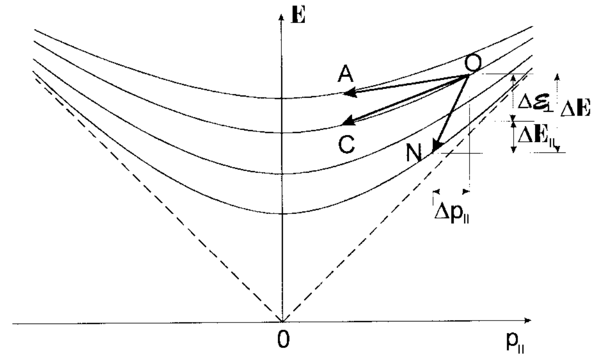


Fig. 11. Energy and momentum loss by an electron due to a photon radiation.

B. Peniotron

If the RF field (13) at the electron orbit is distributed so that the synchronous harmonic is absent: $A_n = 0$, the electron remains coupled (though not as strong as in the gyrotron case) with nonsynchronous $(l \neq n)$ angular harmonics. In the latter case the effective electron beam conductivity is negative, if the angular velocity of electrons exceeds that of the RF field resonant harmonic $(l = n + 1)$. Microwave generators of the sort (peniotrons [36], [37]) are exemplified with a scheme shown in Fig. 10 [36], where frequencies ω of the cavity coupled to a stationary circular electron beam satisfy equation

$$(\omega - n\omega_H)(\omega - \omega_s) = -D^2. \tag{15}$$

If the cavity eigen-frequency ω_s tends to the nth harmonic of the cyclotron frequency $n\omega_H$, (15) has complex conjugate roots, one of them corresponding to the instability.

Note that the peniotron effect can be derived from nonrelativistic equations and has much in common with the negative conductivity effect for the stationary ensemble of one-dimensional linear oscillators (Fig. 2) whose velocity exceeds the phase velocity of a wave propagating in a background medium [7]. However, this analogy is not very profound, because in the peniotron the electron motion is essentially two-dimensional: the resonant RF field effects the motion of the electron orbit center.

IV. Effects of Electron Motion Longitudinal to Magnetic Field

In the above analysis of the photon-electron interaction, the electron motion perturbation longitudinal to the static magnetic field was ignored, which is valid, if the RF field longitudinal inhomogeneity scale is much larger than the free space wavelength. Otherwise the electron, emitting the photon, loses not only a part of its energy, but also undergoes the recoil: loses a part of its longitudinal momentum, as illustrated with Fig. 11. This figure representing a modification of Fig. 1(b) shows the electron energy E as a continuous function of the translational momentum p_{II} and a discrete function of the gyrational state of the particle; the vertical distance between two neighboring Landau curves being equal to $\hbar\omega_H$. If the electron emits a photon and, accordingly, transits from point O to point N, the electron energy loss represents a sum

$$\Delta E = \Delta E_{II} + \Delta E_{\perp} \tag{16}$$

one part of energy

$$\Delta E_{\perp} = n\hbar\omega_H$$

is lost by the electron, because it has jumped down by n Landau steps, another part

$$\Delta E_{II} = \frac{\partial E}{\partial p_{II}} \Delta p_{II} = V_{II} \Delta p_{II}$$

is lost together with the electron translational momentum. As the losses of the electron energy and of its longitudinal momentum are equal to the energy and longitudinal momentum of the emitted photon

$$\Delta E = \hbar\omega, \quad \Delta p_{II} = \hbar k_{II}$$

the formula (16) reduces to the Doppler shifted cyclotron resonance equation

$$\omega = k_{II} V_{II} + n\omega_H. \tag{17}$$

In the elementary radiation event:

- if the electron does not change its gyrational state and loses only its longitudinal momentum ($n = 0$, transition $O \rightarrow C$ in Fig. 11), the radiation is of the *Cherenkov type*;
- If the electron loses both its oscillatory energy and longitudinal momentum ($n > 0$), transition $O \rightarrow N$ in Fig. 11), the *cyclotron resonance* condition is of the *normal Doppler* type;
- If the electron loses its longitudinal momentum, but enlarges its oscillatory energy ($n < 0$, transition $O \rightarrow A$ in Fig. 11), the *cyclotron resonance* condition is of the anomalous Doppler type. The anomalous Doppler cyclotron radiation [38] can take place if the wave phase velocity is less compared to the longitudinal velocity of electron $\omega/k_{II} < v_{II}$, which is possible only in a slow wave medium.[3]

As the Cherenkov effect is outside the scope of this review, let us concentrate on the wave-electron interaction of the cyclotron resonance type ($n \neq 0$).

[3] Under the anomalous Doppler condition, in the laboratory reference frame the radiated wave represents a wake behind the electron. In the moving reference frame, where the initial electron velocity is zero, the same effect is seen as consumption of the energy by electron from the radiated wave; the latter propagating from the electron in the medium motion direction has energy of the negative sign.

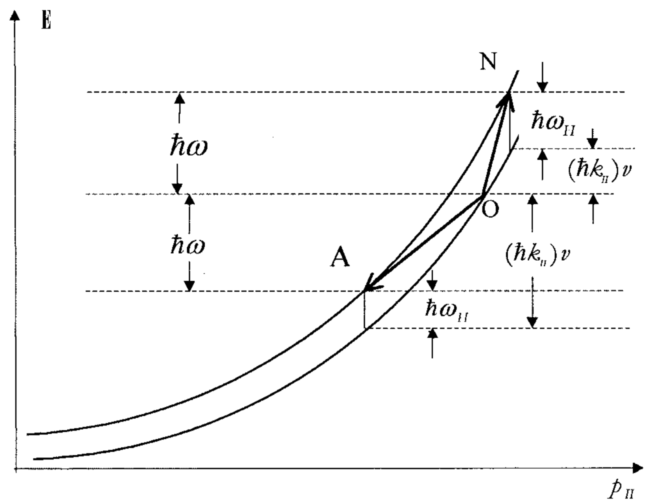


Fig. 12. Energy and momentum changes for electron interacting with a fast or slow wave.

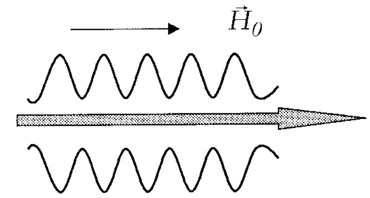


Fig. 13. A scheme of an anomalous Doppler cyclotron resonance microwave amplifier.

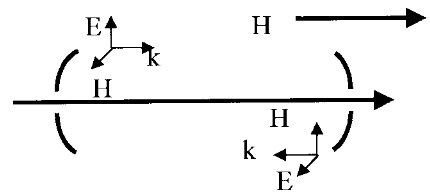


Fig. 14. A scheme of microwave generator where a mode of a two-mirror cavity interacts with a rectilinear electron beam near to the cyclotron resonance.

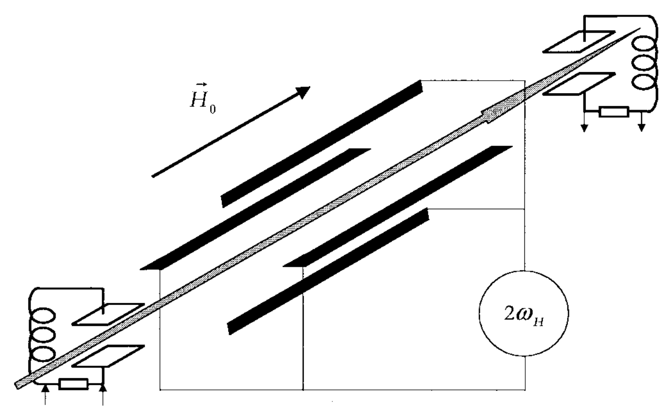


Fig. 15. A scheme of parametric cyclotron resonance microwave amplifier.

A. Cyclotron Resonance Interaction of Electromagnetic Waves with Rectilinear Electron Beams: Anomalous Doppler and Parametric Amplifiers

If the electron is situated at the lowest Landau curve (point O at Fig. 12), it can:

- absorb the photon of energy $\hbar\omega$ and transit to point N, which is described by the normal Doppler cyclotron resonance condition [$n = 1$ in (17)] and corresponds to the fast cyclotron wave of the rectilinear electron beam; or
- emit the photon of energy $\hbar\omega$ and transit to point A, which is described by the anomalous Doppler cyclotron resonance condition [$n = -1$ in (17)] and corresponds to the slow cyclotron wave of the rectilinear electron beam.

According to Fig. 12, the energy of the fast cyclotron wave is positive and that of the slow cyclotron wave is negative.

As the slow cyclotron wave energy is negative, its coupling to any "usual" slow electromagnetic wave (Fig. 13) results in an instability [39]–[41] described with equation

$$(k_{II} - h_s)(\omega - k_{II}v_{II} + \omega_H) = B^2 \tag{18}$$

where h_s is the electromagnetic wave propagator. However, RF amplifiers bases on this effect do not seem able to compete with usual Cherenkov amplifiers providing higher gain at the same electron current. Inexplicit forms of the anomalous Doppler cyclotron radiation are present in some theoretical models of nonslow-wave microwave generators [42] (Fig. 14) where the effective electron beam conductivity is related to slow RF field Fourier components satisfying condition (17) with $n = -1$.

As the energy of the fast cyclotron wave [$n = 1$ in (17), transition $O \rightarrow N$ in Fig. 12], is positive, its coupling to the "usual" electromagnetic wave does not result in an instability and, so, cannot be used to amplify electromagnetic waves. However an amplification can be provided with a parametric pumping [43] (Fig. 15). The cyclotron resonance RF signal introduced into the electron beam through the resonant cavity makes the beam gyrate with nonzero radius and couples it with the tranverse quadrupole RF field of the doubled cyclotron frequency. Due to the pumping, the electron gyration radius increases exponentially. Then the beam enters the output cavity where the electrons give their enhanced gyration energy to the RF field in the frame of cyclotron resonance interaction. In a modified version of such a RF amplifier, the second harmonic RF pumping is replaced with a space periodic static one [44].

B. Cyclotron Resonance Interaction of Electromagnetic Waves with Helical Electron Beams: CARM and Magnicon

Under the normal Doppler condition [$n \geq 1$ in (17)], the photon radiation is accompanied with the loss of electron energy and momentum (Fig. 12), that is, with increase of the cyclotron frequency and decrease of the electron longitudinal velocity. Thus, in (17) changes of terms $k_{II}V_{II}$ and $n\omega_H$ have opposite signs.[4] The changes can be mutually compensated

[4] If the wave phase velocity is small compared with the velocity of light ($\omega/k_{II} \ll c$), the recoil (or, which is the same, the effect of the RF field inhomogeneity in the direction perpendicular to electron oscillations [7]) dominates over that of the relativistic nonisochroneity of electron oscillations and can provide the wave amplification by the stationary helical electron beam even in the frame of nonrelativistic theory. This possibility was discussed in a number of papers published in 1950's (see review [6]).

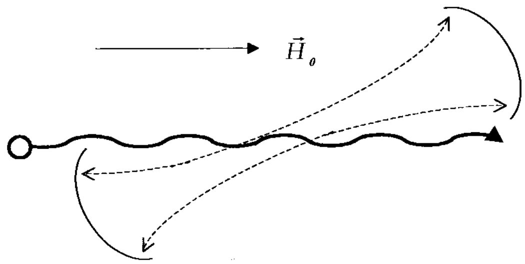


Fig. 16. A scheme of cyclotron autoresonance maser. A helical electron beam interacts with a wave whose phase velocity in the static magnetic field direction slightly exceeds the velocity of light.

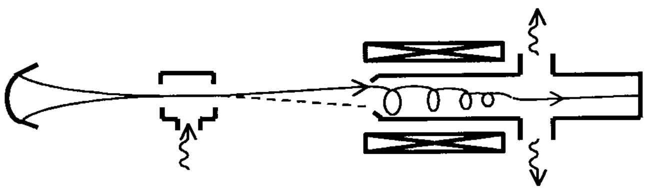


Fig. 17. A scheme of magnicon: microwave amplifier with circular deflection of electron beam in the input cavity and cyclotron resonance deceleration of electrons in the output section.

if the wave phase velocity ω/k_{II} is close to the velocity of light. This compensation (the cyclotron autoresonance [45], [46]) provides a deep deceleration of electron beam at any large, ultra-relativistic, electron energies. Let us note that microwave devices based on this effect, cyclotron resonance masers (CARM's [47], [48], Fig. 16), can be efficient only if the pitch angle dispersion in electron beams is sufficiently low.

By analogy with other microwave generators and amplifiers, the cyclotron resonance devices may be sectioned. Moreover, there are hybrid versions where different sections operate at different synchronisms or resonances. One of the most perspective devices of the sort is the magnicon [49] (Fig. 17). In this microwave amplifier, a rectilinear electron beam is deflected in an input cavity by a rotating RF field and drifts downstream in a field-free space along a conical surface of enlarging radius. Then electrons enter an output section where they move in a homogeneous static magnetic field and give their energy to the RF field in the frame of distributed cyclotron resonance interaction.

V. Practical Aspects of Cyclotron Resonance Devices

Though the stimulated cyclotron radiation is an interesting and broad field of physical research, only a very small part of relevant devices is really a perspective for practical applications.

First, at low powers any vacuum RF devices yield to semiconductor ones. Maybe the only exception is the use of overloading-proof electron vacuum amplifiers (e.g., electrostatically pumped cyclotron resonance amplifier [44]) at the front end of radars [50], [51]. With this exception, the vacuum microwave sources make sense only if they produce sufficiently high powers [10], [12].

Second, at medium and high powers the band of frequencies below 10 GHz represents the natural domain of microwave generators and amplifiers based on the stimulated Cherenkov and transition radiations [10], [12]. The power capabilities of these devices are exemplified with the famous X-3030 klystron [52].

However, the klystron, the magnetron, the TWT, etc., use slow wave structures or cavities whose dimensions are commensurable with the wavelength. Such components are compatible with the high power, till the wavelength is large, but if the latter shortens, the power decreases inevitably and steeply. Beginning with ~10 GHz, the Cherenkov and transition radiation devices yield to fast wave Bremmstrahlung devices where intense beams of oscillating electrons are canalized with homogeneous or space-periodic static magnetic fields.

Devices with the space-periodic electron beam focusing, ubitrons [53] (or free electron lasers (FEL's) [10], [12]), have already reached the ultraviolet band due to the Doppler upshift of the radiation frequency relative to the electron oscillation one. Such upshifts are realized by use of short-pulse multi-megavolt electron beams. However, as the magnetic field period being down-limited for a number of practical reasons, reduction of the electron energy results in a steep decrease of both the radiation frequency and the output power. At operating voltages within ~1 MV the ubitron (FEL) proves to be unable to compete with Bremssstrahlung microwave sources of the cyclotron resonance type.

The cyclotron resonance masers (the gyrotron family including the high harmonic gyrotron, the gyroklystron, and the gyroTWT; the CARM and the magnicon) are not devices to beat power records in short pulses. Instead, using moderate, (10^3–10^6) V, they are capable of producing the highest powers in the CW and long, (10^{-6}–10) s, pulses at frequencies over 10 GHz . Presently these microwave generators and amplifiers [54]–[76] developed by various research laboratories and industrial firms deliver 10^3–10^5 W in the CW mode of operation, $\sim 10^6$ W in ~1 s pulses and 10^7 W in pulses of $\sim 10^{-6}$ s duration. For devices with radiation frequencies ~(10–30) GHz, necessary magnetic fields are produced with permanent magnets and water cooled solenoids. Cryomagnets produce homogeneous static magnetic fields up to 10–15 T in volumes of ~10 cm diameter, which provides radiation of millimeter and submillimeter waves from strongly oversized interaction spaces. Still higher magnetic fields and, correspondingly, higher radiation frequencies are available with pulse solenoids.

Thus, the promised land for the cyclotron resonance masers is, certainly, the region of high power millimeter and submillimeter waves.

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