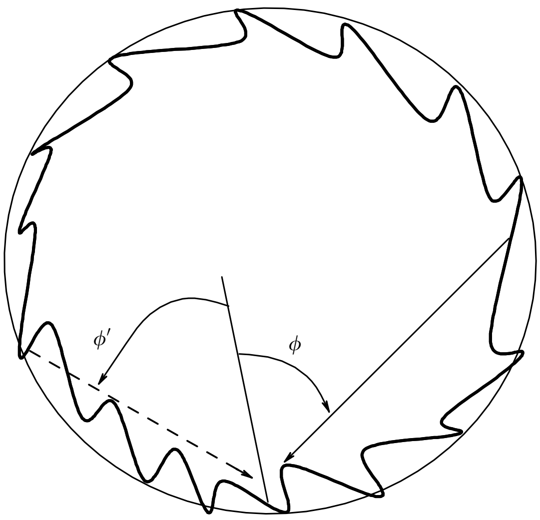

Figure 3. Detailed balance violation in the Knudsen gas in a chiral cylinder.

emphasizes) the chirality of biological molecules in his story of how he stayed interested in biology for 50 years [11]. Furthermore, he mocks at theoretical biologists who invoke a priori schemes and are preoccupied with them. He believes that evolution, or 'The Blind Watchmaker,' as referred to at the suggestion of the English pop biologist R Dawkins [16], is far from different schemes: an accident is more important. The blind watchmaker is seated in a chair in a field over which the wind is carrying parts of a watch. He is assembling a mechanism. He does not contemplate anything, he just fumbles about under the chair, finds something, inserts into the mechanism, and waits: will that do or not, will the Mechanism start going or not? Most likely, he chanced upon the left spiral and the mechanism started going, and all the remaining parts that fitted the mechanism also turned out to be left spirals. But the watchmaker could have chanced upon the right spiral or no spiral at all!

However, if spirals live longer, owing to the violation of the principle of detailed balance, they are to be in the 'initial broth,' from which the watchmaker picks up the components. Maybe therein lies, at least in part, the reason for the emergence of the chirality of biomolecules.

However, all this is speculation, of course.

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Fast moving radiators and their use in high-frequency electronics

V L Bratman

In 1946, when discussing the possibilities for mastering the then hard-to-reach region of millimeter- and submillimeter waves, Ginzburg considered several generation techniques, which turned out to be highly efficient for a substantially broader spectrum of electromagnetic radiation. In Ref. [1], he proposed the use of Doppler frequency conversion of fast moving electron oscillators as "the most interesting and promising method."

Let an electron move with a translational velocity $\mathbf{v}_{\|} = \boldsymbol{\beta}_{\|} c$ and oscillate in the transverse direction with a frequency Ω in an electric field varying harmonically in time (Fig. 1). Then, at an angle θ to the direction of translational motion, the electron radiates at the frequency

$$\omega = \frac{\Omega}{1 - \beta_{\|} \cos\theta} \,. \tag{1}$$

For an ultrarelativistic velocity $\beta_{\|} \approx 1$, when the Lorentz factor γ of the electron is large, the Doppler frequency gain for the low-angle radiation is proportional to the squared particle energy, $\omega \sim \gamma^2 \Omega$, and may be quite high. For instance, for energies 5 MeV and 5 GeV, we obtain Doppler gains of the order of 10^2 and 10^8, respectively.

Ginzburg [1] also considered the possibilities that open up when the cyclotron and synchrotron radiation of an electron

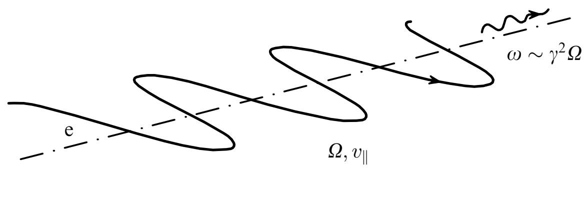

Figure 1. Idea of a 'dopplertron': an oscillating and rapidly moving charge radiates forward at frequencies that are many times higher than its oscillation frequency.

following a circular path in a uniform magnetic field is used. We note that in this case, too, the 'dopplertron' is easy to obtain by imparting to the electron a relativistic translational velocity along with the rotational one, such that the electron describes a helical trajectory (Fig. 2a). At the fundamental cyclotron resonance, its radiation frequency is given by formula (1), in which the oscillation frequency is equal to the relativistic electron cyclotron frequency $\Omega_B = \Omega'_B/\gamma$, where $\Omega'_B = eB/m$. In a strong magnetic field, it is easy to obtain a high Ω'_B frequency, but for large γ, because of a decrease in Ω_B, this method ranks in frequency below the dopplertron, for which the oscillation frequency is independent of the energy. At the same time, as emphasized in Ref. [1], the synchrotron radiation of a particle describing a circular path, which had just been discovered at that time, furnishes a peculiar example of a dopplertron with a very high frequency conversion ratio (Fig. 2b). As we now know, this dopplertron is highly important for different realms of physics and technology. In this case, the combined action of three effects — the relativistic angle transformation, which contracts the instantaneous radiation pattern to a narrow cone with the angle $\sim \gamma^{-1}$; the rotation of this pattern, which leads to a pulsed temporal structure of the radiation in a given direction; and the compression of a generated pulse by a factor of γ^2 due to the electron approaching the point of observation (the longitudinal Doppler effect) — has the consequence that the radiation peaks at a very high cyclotron harmonic with a frequency $\sim \gamma^3 \Omega_B$.

Along with the radiation of electrons rapidly moving in a vacuum, Ginzburg [1] also proposed the use of the radiation of electrons moving above a dielectric or in a dielectric channel (Cherenkov radiation and the Doppler effect in the presence of a decelerating medium). In these cases, obtaining short-wave radiation requires substantially lower particle energies.

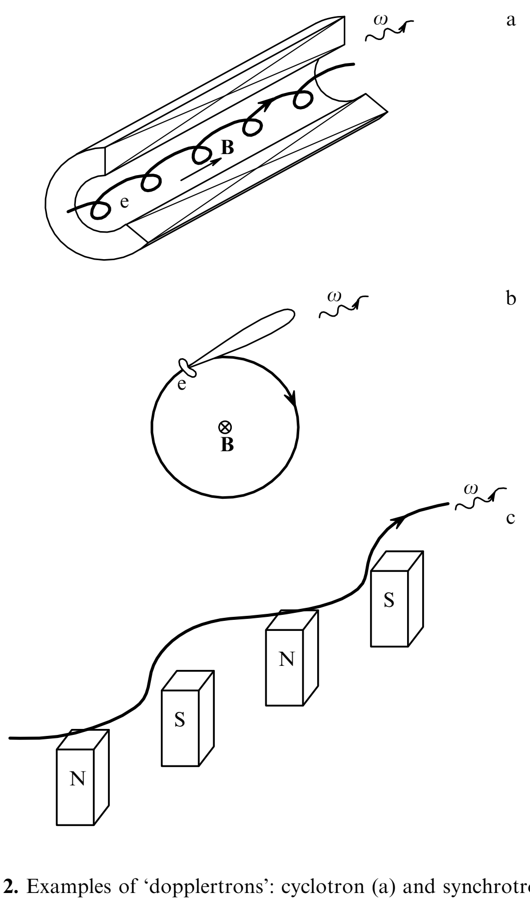

Figure 2. Examples of 'dopplertrons': cyclotron (a) and synchrotron (b) dopplertrons in a uniform magnetic field, an ondulator dopplertron in a spatially periodic magnetic field (c).

It is pertinent to note that several years later, the British physicist Motz [2] also proposed, independently of Ref. [1], the use of the Doppler effect for the emission of short-wave radiation. Furthermore, Motz proposed a highly efficient technique of particle oscillation buildup in a spatially periodic magnetic system producing a field transverse to the direction of particle motion — a static magnetic wave (Fig. 2c). These devices, which impart a periodic shape to a thin electron beam, have come to be known as ondulators (from the French onde — wave). It was not long before the Doppler-converted emission of isolated particles was discovered in diverse situations and different frequency regions. For instance, coherent Bremsstrahlung radiation was discovered in crystals, which emerges in the particle motion at a specific angle in an electrostatic ondulator produced by the fields of periodically located atoms. More recently, a discovery was made of a highly directional X-ray and gamma radiation of ultrarelativistic positrons and electrons related to another type of motion in crystals, channeling, which is accompanied by relatively low frequency transverse oscillations in the averaged atomic field.

Devices relying on frequency conversion in the photon backscattering by electrons (the inverse Compton effect), in which the pump wave field is used as the ondulator, may also be classed with dopplertrons. Another important example is provided by the Smith – Purcell radiation of particles moving rectilinearly above a periodic structure. The simplest interpretation of this effect is commonly given also in the spirit of a dopplertron and consists in considering an oscillating and rapidly moving dipole made up of the charge and its (quasistatic) image in the structure. The radiation of a charge penetrating through a periodic plate stack allows a similar explanation.

All the methods considered above involve individual (spontaneous) emission by particles or prepared compact bunches with dimensions smaller than the radiation wavelength. Preparing these bunches was a highly intricate problem, and much effort was mounted to do it in the 1950s. At the same time, these years saw the rapid development of electric vacuum microwave devices such as klystrons, magnetrons, traveling-wave tubes (TWTs), and backward-wave oscillators (BWOs), in which electrons are automatically[1] grouped in compact bunches, resulting in their collective (stimulated) emission. All these devices enabled generating radiation in the millimeter range for relatively low voltages, and it has even been possible to attain a wavelength of 0.2 mm with the help of a BWO. It is significant that the synchronous interaction (the Cherenkov or the transition interaction, which reduces to it) of particles with slow waves, which for low voltages requires electrodynamic systems with small-scale elements, is realized in these devices. The electrons must then travel at a very small distance from the decelerating systems (instead of the dielectrics proposed in Ref. [1], periodic metal structures are typically used) or through narrow gaps. Owing to wall overheating or the risk of a microwave breakdown, this leads to a rapid lowering of the output power P of the

[1] The operation of high-frequency charged-particle accelerators is also based on particle self-bunching.

above devices with decreasing the radiation wavelength λ: $P \propto \lambda^2$ at best.

Entirely new opportunities opened up when ensembles of electron oscillators were used as the active medium in short-wave vacuum devices [3]. To realize the stimulated (Bremsstrahlung) particle radiation in these electron lasers and masers, the fast eigenmodes of resonators and waveguides with smooth walls can be efficiently used. This is possible, in particular, in highly selective open large-volume electrodynamic systems where electrons can move away from the walls (and even in open space). Following a prehistory [2] rich in ideas and inventions (see Ref. [3]), the 1950s saw the introduction of two versions of electron masers, which are under active development at the present time: ubitrons [4] and cyclotron-resonance masers (CRMs, see, Ref. [3]).

Ubitrons (derived from 'undulated beam interaction') are a direct result of the elaboration of Ginzburg's and Motz's ideas towards obtaining stimulated emission from an electron beam propagating through a magnetostatic ondulator and interacting with the field of a waveguide or a resonator. In the 1970s, ubitrons took a leap into the 3 – 10 μm wavelength range [5, 6] to obtain a more spectacular name — free-electron lasers and masers (FELs and FEMs). This was the first and so far the only classical generator of coherent electromagnetic radiation that encroached so deep into the realm of quantum devices and was capable of competing with them in many cases (in what follows, we use the terms FEL and FEM in reference to all devices based on the Doppler-converted stimulated emission of rapidly moving electron oscillators).

We consider the principle of operation of an FEL ubitron (Fig. 3) in greater detail. In this device, an electron moves with a translational velocity $v_{||}$ lower than the phase wave velocity, but its transverse oscillations under the action of the ondulator field occur in phase (at resonance) with the wave. This signifies the proximity of the phase $\omega t - k_{||} z(t)$ of particle oscillations in the wave to the phase $\Omega_{\rm u} t$ of oscillations in the ondulator field, which gives resonance condition (1). Here, $\Omega_{\rm u} = 2\pi v_{||}/d$ is the frequency of electron 'collisions' with field periods. The electric field of the wave works on the oscillating electron, while the magnetic wave field acts on its transverse motion and produces a resonance longitudinal force, which groups the particles as this occurs under the action of a longitudinal electric field of the slow wave in a TWT. This analogy becomes even more transparent when relation (1) is represented in the equivalent form of the

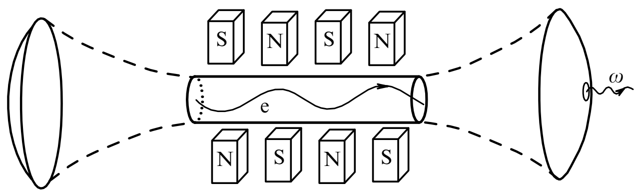

Figure 3. Scheme of a free-electron laser with an ondulator and an open resonator. Electrons are grouped in the longitudinal direction (as in a traveling-wave tube) under the action of the combination wave produced by the radiated wave and the spatially periodic ondulator field (magnetostatic wave).

[2] Interestingly, the first electron maser (a triode with a positive grid — a Barkhausen – Kurtz oscillator) was realized shortly after Einstein introduced the notion of spontaneous and stimulated emission of quantum systems, i.e., long before the advent of the 'laser era.'

synchronism condition for the electron and the field of a slow combination wave produced by the high-frequency wave and the ondulator field (magnetostatic wave with a wavenumber $k_{\rm u} = 2\pi/d$ and a zero frequency):

$$\omega = (k_{||} + k_{\rm u})\, v_{||}\,. \tag{2}$$

In this case, the frequency, the wavenumber, and the phase velocity of the combination wave are respectively equal to the high-frequency wave frequency ω, $k_{||} + k_{\rm u}$, and $\omega/(k_{||} + k_{\rm u})$, while the amplitude is proportional to the product of the amplitudes of the high-frequency and magnetostatic waves. According to relation (2), the phase velocity of the combination wave in the ubitron is therefore equal to the translational particle velocity (more precisely, should be close to it). Under the action of the wave, a part of the electrons is decelerated and a part of them is accelerated in the longitudinal direction. This process, which is responsible for particle grouping in compact bunches like ordinary TWTs and klystrons, is inertial in character and may continue even in regions where the high-frequency field is absent. This approach and the analogy with a TWT are also easily extended to the motion and stimulated emission of electrons in the field of a pump wave with a frequency $\omega_{\rm i}$ and the longitudinal wavenumber $k_{\rm i}$, i.e., to the scattering of a wave (photons) by electrons:

$$\omega - \omega_{\rm i} = (k_{||} + k_{\rm u})\, v_{||}\,. \tag{3}$$

The backscattering from an ultrarelativistic charge exemplifies the reflection of a wave by a mirror moving fast towards it, which was considered by Einstein.

For a relatively small variation in the energies of particles, their grouping under the action of the wave and the energy exchange with it in an FEL are described by precisely the same equations as in a TWT. In particular, for the stationary regime of an FEL oscillator with a high-Q resonator, in which the wave amplitude may be considered constant, the equations of motion of the beam electrons are brought to the form [7]

$$\frac{{\rm d}w}{{\rm d}\zeta} = \varkappa\, {\rm Re}\, a \exp({\rm i}\vartheta)\,, \quad \frac{{\rm d}\vartheta}{{\rm d}\zeta} = \mu w + \delta\,, \tag{4}$$

which coincides with the equations for the oscillator version of a TWT. Here, w and ϑ are the relative energy variation of a particle and its phase relative to the combination wave, ζ is the dimensionless coordinate, $\varkappa$ is the electron – wave coupling coefficient proportional to the transverse particle velocity, a is the dimensionless amplitude of the combination wave, $\mu \approx \gamma_0^{-2}$ is the nonisochronity parameter of particle oscillations in the wave, and δ is the dimensionless detuning from the exact synchronism described by relations of type (1) – (3). By differentiating the equation for the electron phase ϑ with respect to ζ and using the equation for the energy w, it is easy to verify that the nonlinear system of equations (4) is equivalent to the equation of a mathematical pendulum.

A stationary electron beam in which particles are uniformly distributed in the initial phase ϑ_0 from 0 to 2π is normally fed to the oscillator input. For a negligibly small particle energy spread, this corresponds to the initial condition

$$w(0) = 0\,, \quad \vartheta(0) = \vartheta_0\,. \tag{5}$$

Integrating system of equations (4) with boundary conditions (5) for a small amplitude a up to second-order terms and averaging the result over the initial particle phase, we obtain the efficiency of energy exchange between the electron oscillators and the wave in the small-signal approximation as

$$\eta_{\text{s.s.}} = (\varkappa a)^2 \mu \xi^3 \varphi'(\psi)\,, \tag{6}$$

where $\varphi(\psi) = (1 - \cos\psi)/2\psi^2$ is the function proportional to the intensity of the spectrum of the high-frequency force (in this case, 'a stopped sinusoid') acting on an electron in its transit through the resonator, $\psi = \delta\xi$ is the particle transit angle relative to the wave, and ξ is the dimensionless length of the interaction space. According to expression (6), the electrons transfer their energy to the wave in the main zone of transit angles $-2\pi < \psi < 0$, where the particle velocities exceed the phase velocity of the combination wave and $\varphi'(\psi)$ is positive.

Asymptotic nonlinear equations (4), as well as their generalization to the case of a variable-amplitude high-frequency wave, apply to all kinds of FELs and other devices based on various mechanisms of inertial particle grouping (see Ref. [8]). The possibility of a common approach on the basis of universal equations significantly simplifies comparison of different devices with each other.

The question of the efficiency attainable in an FEL is significant for applications. In the approximation of a low particle energy variation, the efficiency is found by integration of Eqns (5) in the regime of a relatively large signal. Here, we restrict ourselves to simple estimates that can be derived from the equations themselves or from their corresponding phase plane (Fig. 4), or directly from the conditions that particles come out of resonance (1) with the wave. All these methods give the following estimates for the energy exchange between electrons and a fixed wave, as well as for the admissible particle energy spread:

$$\eta \sim \frac{\Delta\gamma}{\gamma} \sim \frac{1}{2N}\,, \tag{7}$$

where N is the number of particle oscillations in the ondulator. Similar estimates are obtained for the frequency band generated in the FEL and the optimal detuning from resonance:

$$\frac{\Delta\omega}{\omega} \sim \delta \sim \frac{1}{2N}\,. \tag{8}$$

For very high N, the requirements on the spread become quite stringent, while exciting the resonator for small N requires very high currents. In all FELs, the interaction length and the number of particle oscillations are therefore rather high and the efficiency in the simplest scheme is rather low.

However, there are several ways to radically increase the efficiency up to quite high values of several dozen percent, which was achieved in experiment. The basic idea of this improvement [9] was obtained by inverting the principle of operation of high-frequency accelerators; it was also proposed in papers on TWTs [10]. Unlike in the above method involving the 'conventional' regime of inertial particle grouping, whereby saturation occurs at the exit of the electron bunches from synchronism with the wave (Fig. 4a), in this method a substantial fraction of electrons is captured into the potential well formed by the wave (a 'bucket' formed by separatrices, Fig. 4b), and then the particles remain in synchronism with the wave due to the FEL parameter profiling lengthwise to the system and are smoothly decelerated together with the bucket. Also proposed, as a development of this trick, was the 'blowing-up bucket' technique [11] (Fig. 4c), which permits, according to calculations, using a beam with a wide parameter spread and obtaining wide amplification bands.

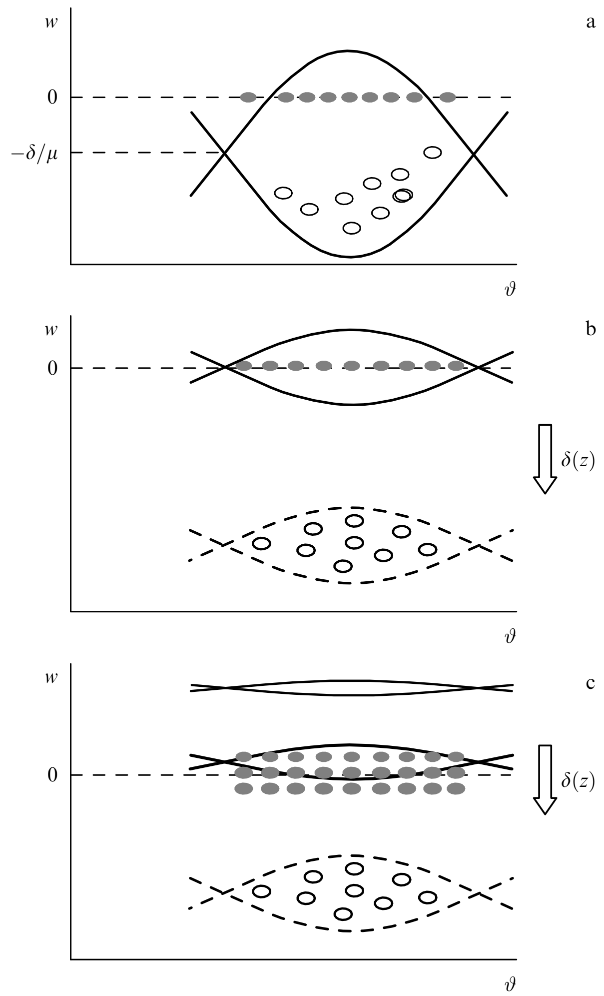

Figure 4. Comparison of free-electron lasers with constant or lengthwise-varied ondulator parameters in the phase plane 'relative energy variation — electron phase'. For constant parameters (a), particles assemble in a bunch, which sinks to the bottom of the 'bucket' formed by the wave with a relatively low amplitude and imparts a small energy fraction to it (the conventional low-efficiency regime of inertial particle grouping). For slowly varying parameters (b, c), the particles are captured into the bucket and adiabatically decelerated with it to donate a substantial energy fraction to the wave (the capture regime with a high efficiency). For a high-current electron beam and a rapid wave amplification on reaching particle – wave resonance (c), the blowing-up bucket is able to capture different beam fractions with a wide velocity spread.

Quite interesting regimes were realized in FELs, which were previously unknown in vacuum electronics. In particular, the first infrared generator [5] already involved longitudinal resonator mode locking via periodic injection of virgin electron bunches in time with the circulation of a short electromagnetic pulse (the 'slice' of the electromagnetic field formed by a large number of modes) in the resonator. Vinokurov and Skrinskii [12] proposed and later realized a version of an FEL in the form of a so-called optical klystron, in which particle energy modulation and the energy extraction from the bunches occur in short ondulator sections and the transverse magnetic field in a gap between these sections is used to speed up the electron bunching. Several FELs use highly selective large-volume electrodynamic systems, which enable exciting a single mode at a high power level and at the same time using one of the main FEL virtues, the capability of radiation frequency tuning over an extremely wide range.

To date, a large number of FELs of different types have been realized, from the millimeter range to the vacuum ultraviolet range (see Ref. [13]); several of them have been in successful operation for many years, enabling the pursuit of diversified research. A high-power terahertz FEL was recently developed in Russia [14]. In the 1980s, FELs were considered essential elements of the so-called Strategic Defense Initiative. Today, the most ambitious projects are aimed at producing coherent X-ray radiation (see, e.g., Ref. [15]). Among its stated fantastic potentialities are, in particular, shooting chemical reactions and the response of materials and biomolecules with atomic resolution. Owing to the absence of sufficiently strong input signal sources, the planned X-ray FELs are to use the intrinsic e-beam noise amplification self-narrowing in frequency — the mode of self-amplified spontaneous emission (SASE) demonstrated in the long-wavelength ranges. Producing radiation in the X-ray range requires electron energies of several gigaelectronvolts. Such beams with pulsed kiloampere currents are produced in linear accelerators several kilometers long, and the particle oscillation is effected in ondulators several hundred meters long.

It should be remembered that the field in the simplest ondulator (Fig. 2c) decreases exponentially with the distance from the magnets. To weaken this effect, two slightly spaced parallel magnet systems (Fig. 3) or helical current ondulators with a double winding or more complex systems are used. It has been possible to make ondulators with periods down to several millimeters or even shorter; in practice, however, ondulators with periods less than several centimeters are infrequently employed. Accordingly, beams with particle energies above 1 MeV are used to obtain lasing in the short-wavelength part of the millimeter range. Ondulators in the form of a pump wave permit forming transversely uniform fields with a short period; however, obtaining particle oscillations with a sufficiently high amplitude requires very high pump powers. It is much simpler to obtain short periods of curvilinear particle motion for producing lasing in the millimeter and submillimeter ranges by using a uniform magnetic field for pumping and the stimulated cyclotron radiation of electron beams for the radiation mechanism. This Doppler version of a CRM is called a cyclotron autoresonance maser (CARM) [8, 16].

The cyclotron autoresonance effect [17, 18] consists in the exact resonance condition (1), if initially satisfied, being automatically maintained for an electron that travels in a uniform magnetic field and the field of a wave propagating along the magnetic field in a vacuum. Indeed, in each event of elementary interaction with the wave, the energy and translational momentum of the electron change by fixed values $\hbar\omega$ and $\hbar\omega/c$. For finite variations in the quantities, we therefore obtain $\Delta E/\Delta p_{||} = c$. This implies the conservation of the left-hand side of the relation

$$\gamma\,(1-\beta_{||})\,\omega = \Omega_B'\,, \tag{9}$$

which is equivalent to condition (1), and the possibility for unlimited (for a constant wave amplitude) electron acceleration. Under these conditions, however, the nonisochronity due to the relativistic dependence of the cyclotron frequency on the particle energy (the nonequidistance of Landau energy levels in the quantum interpretation), which is responsible for the azimuthal particle displacement in the Larmor circle, is exactly compensated by the nonisochronity of longitudinal particle oscillations under the action of the magnetic field of the wave (recoil in the emission of a photon) [19]. An electron ensemble therefore behaves as an ensemble of linear oscillators. Accordingly, the stimulated absorption in it prevails over emission.

For the emission to prevail, the above cancellation should be slightly disturbed [16] by using a fast wave in whose field the particle oscillation nonisochronity parameter $\mu = (c^2 k_{||}^2/\omega^2) - 1$, which includes both mechanisms, is nonzero. In this case, the deviation from resonance may be small even for appreciable variations in the cyclotron frequency and translational particle velocity, which allows obtaining a high efficiency even for a large length without profiling the parameters of the system [20]. However, this is possible only for a very narrow particle velocity spread and a high selectivity of the electrodynamic system. Each of these goals is rather hard to achieve considering that the non-isochronity parameter in a CRM strongly depends on the phase velocity of the eigenwave of the electrodynamic system. Among these waves, the occurrence of 'parasitic' waves, which propagate almost transversely to the magnetic field and accordingly have high phase velocities in the direction of particle motion, is practically inevitable. However, the operation by precisely these waves is extremely attractive and they are very efficiently employed in another, much more widely used and highly efficient CRM version, the gyrotron [3, 21].

The longitudinal Doppler effect is practically absent in the gyrotron (Fig. 5), which deprives this device of oscillation frequency conversion but in return affords it its main virtue — the high nonsensitivity to particle velocity spread, which in most cases outweighs the above drawback. Even for a low particle energy, gyrotron operation is entirely based on the relativistic effect discussed in the foregoing, the nonisochronity of electron cyclotron rotation. Owing to the nonisochronity, the particles group in compact bunches in

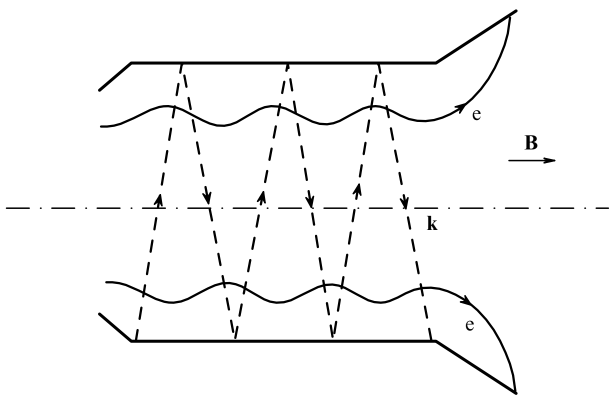

Figure 5. Schematic of a gyrotron with an open resonator in the form of a leg of a weakly irregular cylindrical waveguide with a tubular electron beam. The partial waves that make up the field of the working mode propagate almost transversely to the magnetic field, which leads to a small Doppler correction and a high nonsensitivity to the particle energy spread. Under the action of the wave, electrons group in azimuthal bunches owing to the relativistic nonisochronity of cyclotron rotation.

the Larmor circles under the action of a 'seed' signal, and then the bunches impart their rotational energy to the wave. The effectiveness of these processes may be so high that modern gyrotrons range up to 50% in efficiency.

For the electrodynamic systems in gyrotrons, selective resonators in the form of sections of weakly irregular cylindrical waveguides are typically used (see Fig. 5), with the highest-Q oscillations being those with one longitudinal variation and with the frequencies closest to the cut-off waveguide frequencies. These modes correspond to the least values of the longitudinal wavenumber and the Doppler correction to the frequency, and are therefore least sensitive to electron velocity spread. To provide the optimal value of the force acting on the particles, as well as to reduce the risk of a high-frequency breakdown at the walls and decrease their heating, high-power gyrotrons involve resonators that are many times greater in diameter than the working wavelength and working modes with a complex transverse structure. It is remarkable that using the resonance in a magnetic field with a high degree of uniformity and injecting the electron beam into the domain with a high effective mode field, it has been possible to excite these modes with only a small admixture of undesirable waves.

Gyrotrons intended for plasma heating are broadly used in controlled thermonuclear fusion facilities to provide enormous power, of the order of 1 MW, in a cw oscillation mode at frequencies 30 – 170 GHz. Furthermore, lower-power 5 – 300 GHz gyrotron oscillators and amplifiers find technological applications, as well as applications in radars, spectroscopy, and diagnostics of various media. Recently, in the prototypes of pulsed gyrotrons, it has been possible to obtain oscillation at the frequency 1 THz. Obtaining this frequency requires a hard-to-attain magnetic field, 36 T when operating at the fundamental cyclotron resonance. In recent years, efforts have been intensified to obtain generation at higher harmonics, which requires lower magnetic fields.

Reverting to the beginning, we note that the millimeter wavelength range and, to a large extent, the submillimeter range are presently mastered by electronic devices based on various principles. In accordance with Ginzburg's predictions [1], the role of devices that rely on the emission of electron oscillators is great in these ranges. True, the stimulated radiation of previously unphased particles resulting from their self-bunching but not the radiation of preformed electron bunches immediately considered in Ref. [1] has turned out to be most efficient. The devices based on the stimulated radiation of electron oscillators already provide coherent high-power radiation not only in the above ranges but also up to the vacuum ultraviolet range, and may allow obtaining coherent X-ray radiation in the near future. The analysis of elementary mechanisms of emission by 'free' electrons and the new ideas advanced in Ref. [1] have had an impact on the development of all high-frequency electronics.

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Cosmic accelerators for ultrahigh-energy particles

E V Derishev, V V Kocharovsky,
Vl V Kocharovsky

1. Introduction

Ginzburg made a significant contribution to solving the problem of the origin of cosmic rays, in particular, by analyzing the synchrotron radiation of their constituent high-energy electrons, developing the concept of the galactic cosmic ray halo, and investigating several other problems (see his review Ref. [1] and the works of his school, e.g., Refs [2, 3]). Many questions still remain open in this area; however, as before, according to Ref. [1], "the most important problem yet to be solved in cosmic ray astrophysics is the origin of cosmic rays of ultrahigh energy." This problem is discussed in our report, which is based on previously published works [4 – 6].

The cosmic ray composition is dominated by positive-charged ions, primarily protons, while the particle distribution function over energies, dN/dE, is described with a high degree of accuracy by a power-law dependence with a break (a knee): $dN/dE \propto E^{-2.7}$ for energies below $\approx 3 \times 10^{15}$ eV and $dN/dE \propto E^{-3}$ for higher energies (see, e.g., review Ref. [7]). The properties of cosmic rays with energies up to 10^{17} eV, which have galactic origin and are produced primarily in