4. Conclusions

Presented in this report is a study, within a unified research framework, of the critical properties of a 3D diluted Ising model with canonically distributed nonmagnetic impurities and of a modified *xy*-model supposed to describe the peculiarities of iron – vanadium superlattices (Fe/V).

(1) Our data indicate that at low impurity concentrations ($p \geqslant 0.8$), the nonmagnetically-doped Ising model forms a new universality class different from that of the pure Ising model ($p = 1.0$).

(2) Strongly diluted systems ($p \leqslant 0.7$) are characterized by a different set of critical exponents and form a universality class of their own.

In this case there are also two crossover regions:

(1) between a pure system ($p = 1.0$) and weakly diluted ($p \geqslant 0.8$) systems, and

(2) between weakly diluted ($p \approx 0.8$) and strongly diluted ($p \leqslant 0.7$) systems.

Possibly, it is the existence of the crossover and the large extent of these regions which explains the inconsistent and sometimes conflicting results the study of this model has produced.

The results obtained with the modified *xy*-model provide insight into how and when a magnetic superlattice makes a transition from the three-dimensional behavior to the quasi-two-dimensional. The critical exponents show dependence on the ratio of the interlayer-to-intralayer exchange interaction. At the same time, the values of the critical exponents obey scaling relations for values of r up to a threshold value of $r = 0.01$.

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Relativistic multiwave oscillators and their possible applications

V A Cherepenin

This report is a brief review of advances in a rapidly developing realm of science — relativistic high-frequency electronics. The term relativistic high-frequency electronics is presently used in reference to that area of vacuum electronics which harnesses electron beams with energies of 0.2 – 100 MeV and currents up to 10^4 A. The resultant microwave oscillators (MOs) range up to $10^9 - 10^{10}$ W in power for a pulse duration of $10^{-9} - 10^{-7}$ s. The wavelengths utilized in this field lie in the interval from several dozen centimeters to values belonging to the visible range, i.e., span six orders of magnitude. Naturally, the family of the devices employed in these ranges is highly diversified. However, it turns out that many of them are well known in conventional microwave electronics. In this connection, of interest is the advancement of new ideas of vacuum electronics, aimed at raising the generated- or amplified-signal power and at mastering new wavelength ranges. The present report is concerned with this aspect of relativistic high-frequency electronics. It is pertinent to note that there are excellent reviews dedicated to relativistic high-frequency electronics and its application (see, for instance, Ref. [1]). Here, we endeavor to call attention to those aspects of the development of this area, which for several reasons have not been adequately discussed in the foregoing and other reviews.

The first vacuum devices — grid electron tubes — date back to the beginning of the 20th century and, having undergone a series of modifications, are employed to the present day. The shortest-wavelength devices can operate in the decimetric wavelength range. The output power of these devices can be quite high and some of their other characteristics, for instance, radiation resistance, give promise that they will, despite the rapid development of semiconductor devices, also find use in the future, at least in special-purpose tasks. The physical principles of the operation of grid electron tubes are well known even from school textbooks and do not call for analysis. We only mention the relatively recent ideas of employing them to produce high-power radiation by incorporating a great number of these devices into a transmission line. Broadly speaking, methods for making a high-power device out of many lower-power devices are vigorously being developed and sometimes come to fruition. Naturally, the last mentioned remark pertains to devices of any kind.

The 1920s – 1940s saw the advent of microwave devices of a new type, in which the 'intrinsic' properties of the electron beam had profound significance: the time of electron transit through the interaction region, electron bunching, the space charge, etc. The electrodynamic notions of the quasistationary theory, like the induced current theorem or coupled transmission lines, were sufficient for their description and design. It was then that the vacuum devices which still enjoy wide use were invented and fabricated. It will suffice to mention klystrons, traveling-wave tubes (TWTs), backward-wave tubes (BWTs), and magnetrons.

Initially, work in the area of microwave electronics, as a rule, was unrelated to the self-radiation of charged particles (usually, electrons), which was viewed from the application standpoint and studied primarily with reference to measurements of high-energy particle characteristics (Cherenkov counters, accelerators and so forth). However, even in the late 1940s ideas were conceived to produce short-wavelength electromagnetic radiation with the aid of relativistic electrons due to Doppler frequency conversion [2]. The magnitudes of beam currents obtained at that time and, hence, the density of the working material of the active medium were moderate, and preliminary electron bunching was therefore proposed in order to increase the radiation intensity. The spontaneous radiation of electron bunches could thus become partly coherent, provided the electron concentration were made sufficiently high on a scale much smaller than the operating wavelength. Unfortunately, the technical difficulties encountered in reaching this goal are enormous, even now. The advent of masers and lasers in the 1950s, which employ excited atoms or molecules as the working medium, hindered to some extent the development of relativistic high-frequency electronics because the problem of obtaining coherent short-wavelength radiation was solved. Modern semiconductor electronics has also successfully mastered the microwave and even visible wavelength ranges. Electron-beam devices nevertheless remained dominant in those applications where high output power is required. For instance, semiconductor devices are hardly employed in radar for an output power of a single device above 1 kW. The endeavor to increase the power of electronic devices naturally led to the ideas of relativistic electronics; moreover, at the new stage of its development it was possible to produce electron beams with currents that exceeded the beam currents employed in the 1950s by many orders of magnitude. With the aid of high-current direct-action electron accelerators it is nowadays possible to produce with relative ease 0.1 – 2-MeV electron beams with a current of 1 – 30 kA suitable for generation. The voltage pulse duration (and, hence, the beam energy) may significantly vary, depending on the accelerator type, and range from several hundred picoseconds to several microseconds [3, 4]. It should be emphasized that the potential to raise the power of high-frequency accelerators is quite high and has been realized to only a small degree by contemporary relativistic high-frequency electronics. In particular, the power of high-current accelerators amounts to 10^{13} W, whereas the output power of microwave oscillators does not exceed 10^{10} W. Therefore, relativistic high-frequency electronics is above all the electronics of high (quite frequently termed superhigh) powers.

Another feature of relativistic electronics is that the same principles may be invoked for the generation of both microwaves and substantially shorter-wavelength electromagnetic oscillations, for instance, light waves. In particular, the microwave device proposed back in the 1960s with a curvilinear beam formed by a periodically nonuniform magnetic field — a ubitron — by its principle of operation is the prototype of modern free-electron lasers (FELs).

The necessity of generating higher-power short-wavelength electromagnetic radiation fosters research into relativistic devices with spatially developed electrodynamic structures. In nonrelativistic electronics, devices (for instance, an orotron) spatially developed in the orthogonal direction relative to the translational electron motion are the exception rather than the rule. In particular, a high-Q quasioptical resonator in the orotron ensures only the high frequency stability of the oscillator. By contrast, in the historically first relativistic electronic device employing the inherently relativistic properties of the electron beam — a cyclotron-resonance maser (or its most successful modification, a gyrotron [5]) — the increase in the transverse dimensions of the electrodynamic structure is related mainly to the increase in the output power of the device.

The developers of an oscillator or an amplifier usually endeavor to select the working mode in a 'cold' electrodynamic structure (void of electrons) in order that the beam generates coherent single-frequency oscillations when it interacts with the structure [6]. In this case, it is assumed that the electron beam has only a slight effect on the spatial structure of the electromagnetic field. Naturally, there is no way to completely eliminate this effect. In oscillators, account should be taken of the electron-induced frequency shift. In amplifiers, the electron load may wholly change the character of the interaction, especially in Cherenkov devices operating near the passband edge of the electrodynamic structure. However, in the design of single-mode (single-wave) devices all these effects are taken into account merely as corrections to the basic regime: most often the amplified field in the device is hardly different in spatial structure or frequency from the input signal. In a single-mode oscillator, as in an amplifier, the mode is defined primarily by the electrodynamic structure. Single-mode devices are traditional both for nonrelativistic and relativistic electronics.

Passing to relativistic electron velocities changes the properties of the electron stream as an active medium. The specific character of relativistic electronics in single-mode devices shows up only in the increase in the optimal length of the interaction region, $L \approx \lambda \gamma^2$ (λ is the wavelength, $\gamma = 1/\sqrt{1-\beta^2}$, $\beta = v/c$, and v is the particle velocity), and in the lowering of the optimal amplitude $\alpha \approx 1/\gamma$ [$\alpha = eE/(mc\omega)$, $\omega = 2\pi c/\lambda$] of the high-frequency field E with an increase in particle energy $\varepsilon = mc^2$ [7]. The physical significance of this change is related to the increase in so-called longitudinal electron mass. However, for relativistic electrons not only the character of their motion but also their radiation becomes substantially different. This circumstance may be employed in multiwave relativistic sources of coherent radiation.

In multiwave interaction, unlike the single-mode (single-wave) one, the electron beam interacts at a fixed frequency simultaneously with several or many modes of the electrodynamic structure. The spectrum of interacting modes may be continuous as well. This situation is typical for open electrodynamic systems and empty space. The output of a multiwave device exhibits the coherent sum of modes that interact with the electron beam. The radiation frequency is common, as in single-mode devices, and therefore this mode mixture can be efficiently converted into a wave beam of any structure, for instance, Gaussian beam. We advance some elementary reasoning which explains the mechanism of operation of multiwave devices.

The interaction of an electron flux with an electromagnetic field in microwave electronics is due to several physical mechanisms. However, it is possible to mark out several features common to microwave devices. This is, above all, the finite length of the interaction region. In the simplest case, the device length is determined by the cathode – collector spacing. Another important characteristic of the system is the use of the conditions for the synchronism (resonance) between the electromagnetic field and the electron flux, which may be written in the following form

$$\omega - \mathbf{kv} \approx n\Omega\,, \qquad (1)$$

where ω is the field frequency, $\mathbf{k}$ is the wave vector, $\mathbf{v}$ is the electron velocity, $n = 0, \pm 1, \pm 2, \ldots$, and Ω is the characteristic electron oscillation frequency which depends on the emission mechanism. For instance, for $\Omega = \omega_H \equiv \omega_0/\gamma$, $\omega_0 = eH_0/(mc)$ (γ is the relativistic factor) synchrotron radiation occurs; for $\Omega = (2\pi/l)\, v_{||}$, where $v_{||}$ is the velocity of translational electron motion, and l is the period of the electrodynamic structure, diffraction radiation occurs; for $\Omega = (2\pi/l_H)\, v_{||}$, where l_H is the period of the nonuniform magnetic field, ondulator radiation occurs, and so forth. It is easily seen that condition (1) applies, strictly speaking, only to the interaction of the electron beam with plane electromagnetic waves, for which it is possible to introduce the notion of a wave vector $\mathbf{k}$. This condition is nevertheless possible to apply also to nonuniform waves whose isophase surface is plane, for instance, to waveguide modes, because relationship (1) is phase (kinematic) in nature. As noted above, in microwave electronics it is usually endeavored to fix the direction and magnitude of the wave vector $\mathbf{k}$ by making a specific electrodynamic structure. In this case, the beam interacts with one wave (mode). These systems are naturally termed single-wave devices. Among the multiwave devices are those in which the electron flux interacts with several uniform or nonuniform propagating waves at a fixed frequency of the electromagnetic field. It would be natural to associate the single-wave interaction with the notion of stimulated emission because the photon of stimulated emission is by its definition indistinguishable in frequency and wave vector from the incident photon. In multiwave devices, the emission of photons with different wave-vector directions is possible, which differ from the wave-vector direction of the incident wave (see Fig. 1). We explain the emergence of multiwave problems by the simplest example. Let a plane electromagnetic wave ($\mathbf{k}$, ω) be incident on the region where an electron stream exists (the interaction region), then the width of the angular spectrum of the waves scattered at a frequency ω is defined by the relationship

$$\Delta k_i\, \Delta x_i \approx 1\,,$$

where Δk_i and Δx_i are the projections of the wave vector and the dimensions of the interaction region on the axes of the Cartesian coordinate system.

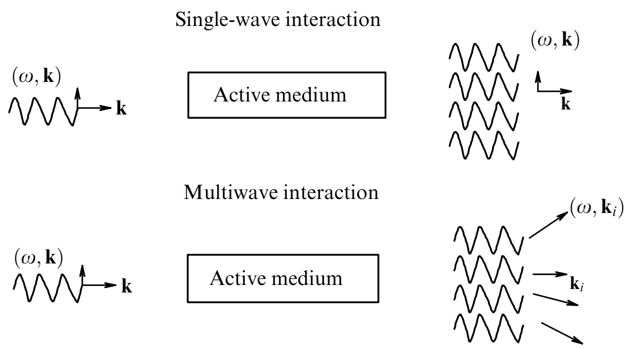

Figure 1.

Therefore, the mere limited nature of the interaction region ensures the finite width of the angular spectrum of the interacting waves. Under certain conditions, both the incident and scattered fields are amplified, and at the output of the corresponding device there forms a field distribution with a directivity pattern substantially different from that of the field at the input. The amplification mechanism depends on the specific realization of the system and may be classified either according to the kind of beam instability or with the help of relationship (1). As a rule, the electron beam during its interaction with electromagnetic waves breaks up into bunches with characteristic dimensions smaller than the emission wavelength λ. The separation between the bunches in the direction of primarily translational beam motion is, in the majority of cases, equal to the quantity $\lambda_e = (2\pi/\omega)\, v_{||}$ referred to as the electron wavelength. The radiation of electrons becomes coherent and occurs at a frequency ω and, provided the grouping is sufficient, at the harmonics $n\omega$ ($n = 1, 2, \ldots$). When resonance condition (1) is not fulfilled at the harmonic frequencies, the harmonic radiation is weak and physical processes take place only at the frequency of the field that was fed to the device. The electron stream becomes similar to a traveling wave antenna. In this case, the directivity pattern of coherent electron radiation depends on the beam shape, the lifetime (range) of the bunches, and the properties of individual electron emission, determined by the interaction mechanism. For instance,

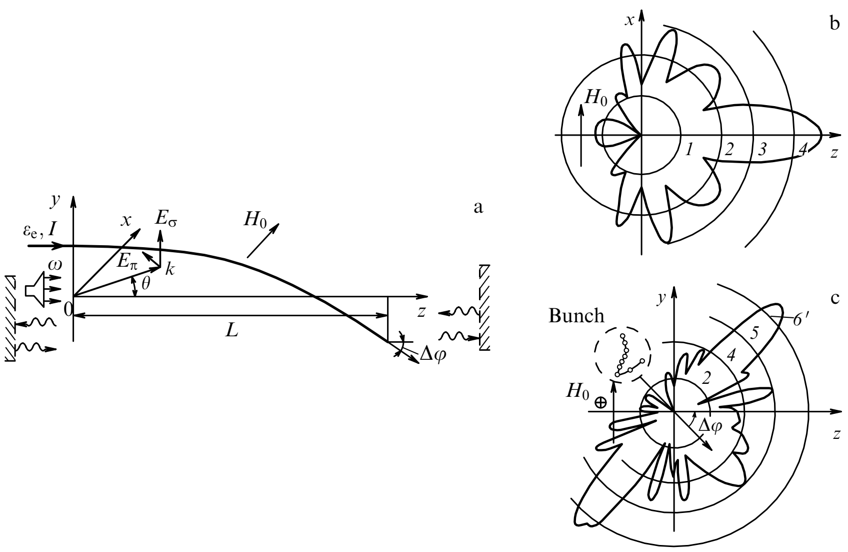

Figure 2. (a) Interaction scheme. (b, c) Directivity patterns of coherent beam radiation for low (b) and high (c) currents.

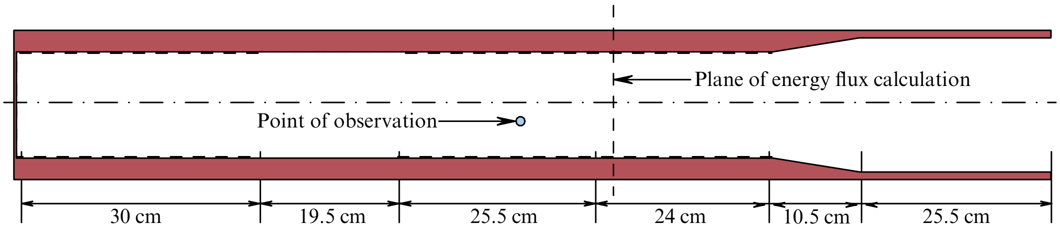

Figure 3. A schematic representation of the multiwave Cherenkov generator. Main parameters of the electrodynamic structure: the total length is 135 cm, the diameter 14 cm, the period 1.5 cm, the nonuniformity height 0.3 cm, the number of periods in the first section 20, and the number of periods in the second section 17. Electron beam characteristics: the diameter is 9.8 – 12.0 cm, the voltage 1.8 – 2.1 MV, the current 20 kA, and the magnetic field 19 – 21 kG.

coherent synchrotron radiation possesses a narrow (searchlight-like) directivity pattern. Multiwave systems are easiest to realize (at least in principle) in the amplification regime, and multiwave oscillators can also be made. Feedback may be applied by feeding a part of the output radiation to the input of a device. For a single-frequency oscillator, mode selection should be provided in the feedback path. When the gain is high enough, the bulk of output radiation energy is transferred to the output bypassing the feedback path, which is of importance in making high-power devices.

Of course, the above qualitative considerations must be rendered concrete when considering different schemes for the production of multiwave coherent radiation. Virtually all the main mechanisms have been theoretically treated: the Cherenkov, diffraction, and synchrotron mechanisms; masers reliant on the normal and anomalous Doppler effects, and so forth [8]. It turned out that under essentially nonlinear operating regimes the output radiation is determined by the intrinsic radiation of electron bunches resulting from grouping. Furthermore, multiwave devices were shown to have a higher electron efficiency than single-wave ones, because on exit from the optimal regime of interaction with one wave, the electrons begin to interact with another wave.

For an illustrative methodical example we outline the results of an investigation of a multiwave synchrotron radiation device [9].

Here, the interaction takes place in the curvilinear portion of the electron trajectory (Fig. 2a). When the beam current is relatively low, its coherent radiation in directions different from the incident wave direction is rather weak (Fig. 2b). When the current increases, the collective electron emission just barely depends on the incident wave direction and is determined by the character of electron grouping (Fig. 2c).

We now outline the latest results of numerical simulation of a multiwave Cherenkov generator (MWCG) which has ranked highest in power for almost 20 years [10]. The MWCG is diagrammed in Fig. 3.

The dimensions indicated in Fig. 3 give an idea of the size of the experimental device. The transverse dimensions of the electrodynamic structure were equal to $3-10\,\lambda$, depending on the operating wavelength range — the three-centimeter or eight-millimeter range. The thickness (about 1 mm) of the tubular electron beam was much smaller than the wavelength. The period of periodic structure sections and the height of nonuniformity elements were so selected that the beam–field interaction occurred near the short-wavelength edge of the passband (Fig. 4).

Figure 4 illustrates the multiwave interaction mechanism in surface-wave oscillators. Forward and backward waves near the edge of the passband are coupled and make up oscillations with a finite diffraction Q, which ensures that several modes can be simultaneously excited.

The section lengths were on the order of the structure diameter, thus ensuring that electrons interacted concurrently with several modes of the sections. The sections were coupled by way of diffraction, via the radiation of electron bunches.

A complete three-dimensional analysis of the physical processes in a MWCG has not been carried out so far. Only the data obtained within two- and 2.5-dimensional models are available.

Some results of numerical simulations (obtained jointly with V N Kornienko) are given in Fig. 5. These results lend support to the following interaction picture. The field distributions in the lateral and longitudinal directions correspond to multiwave interaction. The amplitude of the field synchronous with the electron stream increases toward the end of a device, in the second section. Single-frequency oscillation is imposed by selecting the electrodynamic system parameters and is stable enough.

It is pertinent to note that similar oscillator designs have also been realized in the higher-order zones of passbands of periodic systems, for instance, in relativistic diffraction radiation generators.

Experiments with MWCGs were carried out back in the mid-1980s at the Institute of High-Current Electronics (IHCE), Siberian Branch of the Russian Academy of Sciences. The voltage across the high-current accelerator diode was varied from 1.5 to 2.2 MV. The current ranged from 10 to 20 kA. The guiding magnetic field intensity was varied between 15 and 30 kOe. By selecting the section lengths and the beam parameters it was possible to obtain an output power of 15 GW in the three-centimeter wavelength range for

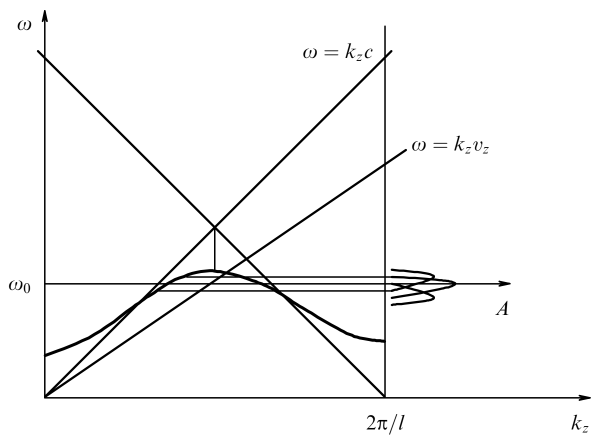

Figure 4.

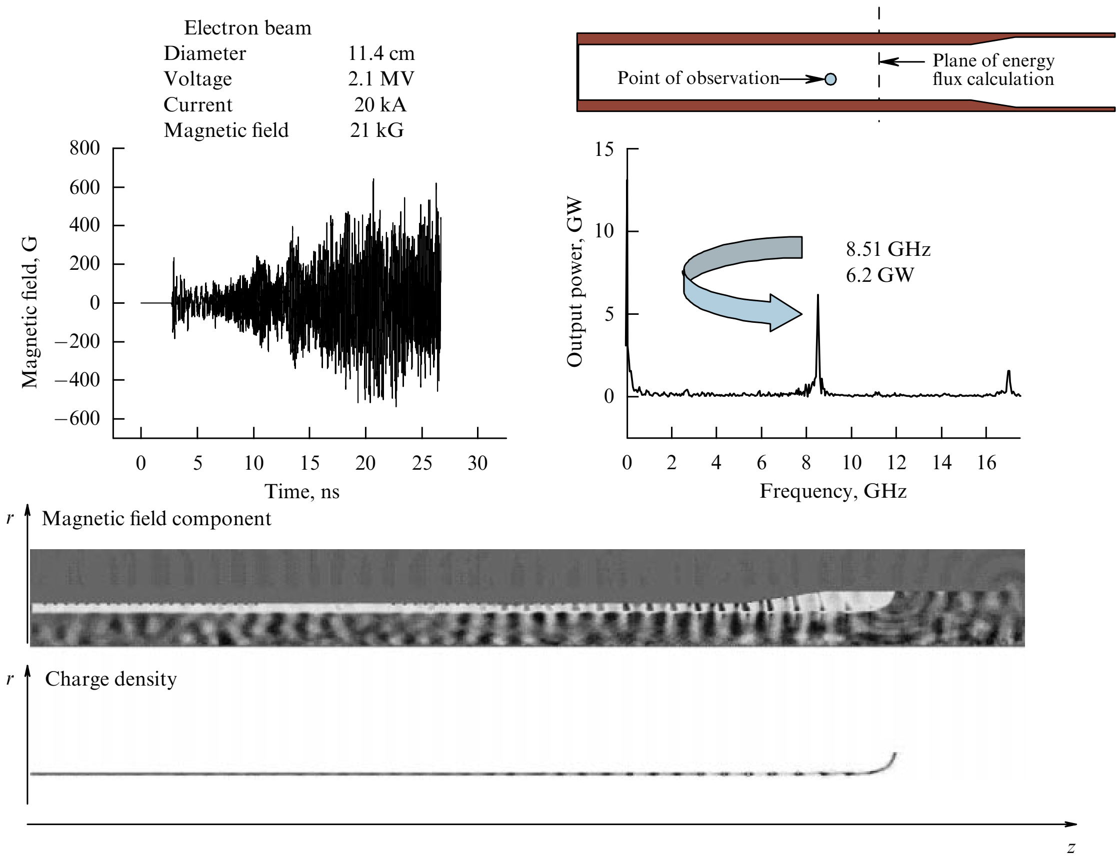

Figure 5.

an electron efficiency of about 50%. In the millimeter wavelength range, the output power ran as high as a gigawatt. The spatio – temporal coherence of the MWCG was verified: it turned out to be high and corresponded to the spectrum of the radio-frequency pulse produced. These results still remain unrivaled.

In the early 1990s, intensive research in this area was terminated in Russia. However, its resumption seems possible and important for practical ends in connection with the recent development of short-pulse radar research, charged-particle acceleration, high-power electronic warfare, the nonthermal action of high-power electromagnetic pulses on natural and artificial media, etc. We briefly consider only the last-mentioned application.

The nonthermal action of electromagnetic radiation on various media has been studied for a relatively long time. It will suffice to mention work on the action of millimetric waves on acupuncture points in the human body, the results of which are applied in medicine [11]. However, a start on the investigation into the nonthermal action of high-power electromagnetic pulses was made relatively recently, primarily due to the progress in relativistic high-current electronics [12]. Remark should be made here of Refs [13 – 16] related to biomedical applications, in which attempts were made to take advantage of the high electric intensities in microwave pulses in order to exert an influence on living organisms. However, these pioneering works were not systematic in character and thus far have not brought about appreciable results. Here, we consider the data relating to the nonthermal action of high-power electromagnetic pulses on gold-bearing rock [17 – 20].

We give some consideration concerning the formulation of the problem. From the electrophysical viewpoint, gold-bearing rock may be represented as an inhomogeneous mixture of metals, dielectrics, and semiconductors, which contains small (about 1 μm in size) gold particles. The modern technology of gold extraction in ore mining and processing enterprises involves dissolving gold in cyanides in rock preliminarily ground to particles measuring 50 μm and less. However, the gold extraction efficiency depends heavily on the kind of rock. Furthermore, there are ore types, termed stubborn ores, from which the extraction of gold in this way is inefficient and, therefore, economically not advantageous. The situation with used minerals (reject material) is the same. The aim of the nonthermal action consists in forming the conditions for efficient gold extraction.

Recently, at the Institute of Radioengineering and Electronics (IRE), Russian Academy of Sciences, and at the Institute of Electrophysics (IEP), Ural Branch of the Russian Academy of Sciences, a start was made on research in this direction.

To disintegrate gold ore in the work pursued at the IEP [21], advantage is taken of a hydroblow produced in spark water breakdown. Experiments are carried out in a water cell which also contains a dredge of the constantly agitated ore. The application of a nanosecond high-voltage source has been proposed to improve the extraction efficiency. Unlike the work performed at the IEP, in IRE experiments carried out jointly with the Research Institute of Comprehensive Exploitation of Mineral Resources, Russian Academy of Sciences, conditions were purposefully formed whereby the interelectrode spark breakdown in a dry or slightly wet gold ore either was only minor or did not occur at all.

We give below the definition of the conditions accompanying nonthermal high-power pulsed action, namely:

(i) the temperature T of the medium is hardly changed, $T_{\rm mean}$ (prior to interaction) $\sim T_{\rm mean}$ (after interaction);

(ii) the amplitude E of the electric field intensity of a pulse is much higher than the amplitude of the static medium breakdown, $E_{\rm peak\,pulse} \gg E_{\rm static\,breakdown}$;

(iii) the pulse duration Δt is much shorter than the time of thermal medium relaxation, $\Delta t \ll \Delta t_{\rm therm.\,medium\,relax}$.

It is pertinent to note that the term *nonthermal action of electromagnetic oscillations* is frequently used in reference to the dependence of the changes occurring in the medium on the electric field intensity. We believe that the definition introduced in the present work is, on the one hand, broad enough and, on the other hand, corresponds more closely to the physics of the nonthermal action of high-power electromagnetic pulses, whereby the energy contribution hardly changes both the temperature of the medium as a whole and the temperature of its relatively homogeneous characteristic elements subjected to the action. In this case, naturally, the local temperature during the action may be high for a short time which is much shorter than the characteristic settling times of the thermophysical properties of the materials that make up the medium.

The idea of the nonthermal action of high-power electromagnetic pulses on gold-bearing rock, put forward by Yu V Gulyaev, consists in the following. The action of a high-intensity electric field on an inhomogeneous mixture of metals, semiconductors, and dielectrics gives rise to a family of nonlinear effects: ponderomotive forces, microbreakdowns near inhomogeneities, and so forth. These effects to a greater or lesser extent foster the disintegration of gold particles and, consequently, their more efficient washing out by cyanides.

These processes are extremely complicated and have not been adequately studied, which is especially true of their combined action. The data outlined below, which were experimentally obtained proceeding from this rather simple physical model, still invite a detailed theoretical description.

It should be noted that the gold particles in the ore are quite small (≈ 1 μm), and the action can be effected by video pulses and microwave radio pulses alike. The application efficiency of one kind of pulse shape depends on the technical conditions of applying the method under consideration. In particular, it is conceivable that the application of radio pulses will be efficient with the availability of industrially made superhigh-power microwave oscillators (over 1 GW) with a long service life (several tens of thousands of hours) and a relatively high efficiency. Such devices have not been made, although there supposedly exist no fundamental difficulties in making them.

Table 1. Effect of high-power electromagnetic pulsed irradiation on cyanide-assisted extraction of gold and silver from the stubborn gravity concentrate from the Nezhdaninsk deposit (the slash '/' separates the data obtained for 500- and 50-μm particles, respectively).

Number of pulses, $N \times 10^{-4}$	Extraction efficiency A, %		Efficiency gain δA, %	
	Gold	Silver	Gold	Silver
Without irradiation (reference experiment)	51.2/77.0	21.8/43.2	—	—
1.75	70.7/80.6	42.1/76.3	19.5/3.6	20.3/33.1
2.50	81.8/84.0	65.5/68.7	30.6/7.0	43.7/25.5
3.75	82.3/83.4	68.9/73.7	31.1/6.4	47.1/30.5

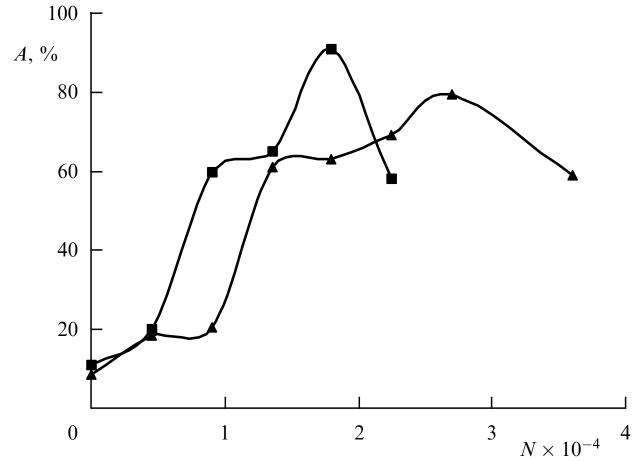

Figure 6.

The data on the nonthermal action of high-power electromagnetic video pulses on stubborn gold ore are collected in Table 1. It might be well to point out that the relatively small number of requisite video pulses are easily realized by one or several radio pulses.

Figure 6 portrays the results of pulsed nonthermal action on the gold-bearing reject material of two mineral processing industrial complexes. The gold yield rose by nearly a factor of 10.

Therefore, high-power relativistic electronics, including multiwave electronics, can well be applied in civilian areas as well.

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