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BEAM - PLASMA GENERATORS OF STOCHASTIC MICROWAVE OSCILLATIONS USING FOR PLASMA HEATING IN FUSION AND PLASMA - CHEMISTRY DEVICES AND IONOSPHERIC INVESTIGATIONS

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ABSTRACT

The results of theoretical and experimental investigations of generator of stochastic microwave power based on beam-plasma inertial feedback amplifier is discussed to use stochastic oscillations for heating of plasma.

The efficiency of heating of plasma in the region of low-frequency resonance in the geometry of "Tokomak" is considered theoretically. It is shown, that the temp of heating is proportional the power multiplied by spectra width of noiselike signal.

The creation and heating of plasma by stochastic microwave power in oversized waveguide without external magnetic field is discussed to plasma-chemistry applications. It is shown, that efficiency of heating have been defined by the time of phase instability of stochastic power.

1. STOCHASTIC MICROWAVE OSCILLATORS BASED ON HYBRID BEAM-PLASMA SYSTEMS

The high-power beam-plasma generators of stochastic microwave signals are considerable interest for both pure and applied research. On the one hand, they can contribute to the study of fundamental problems of the stochastic dynamics of nonlinear dynamic systems with distributed parameters. On the other hand, they have wide applications in controlled nuclear fusion (as a radiation source for stochastic plasma heating), in nonequilibrium plasma chemistry (stochastic microwave discharge techniques), in charged particle stochastic acceleration, etc.

The nonlocality of the electron beam interaction in travelling wave systems in conjunction with the nonequilibrium and broad-band character of this interaction leads to an unstable system behaviour in the presence of a delayed feedback circuit. At certain nonequilibrium parameter values, the system instability regarding automodulation processes at the nonlinear interaction stage can result in a stochastization of the microwave oscillations accompanied by the formation of broad noise-type spectra. Numerous papers were devoted to the purely physical and applied aspects of this problem [1-6]. The generator of stochastic microwave oscillations based on a hybrid beam-plasma amplifier with an external delayed feedback circuit belongs to such systems.

In [3], the evolutionary partial differential equations pertaining to the nonstationary model of the electron beam-wave interaction were reduced to an integral equation of the form

$$F(\tau+\theta) = \Psi\{ |G_o(F(\tau)|, \nu(\tau)\} \cdot exp\{arg(G_o F(\tau))\} \quad (1)$$

Here, F represents the dimensionless complex signal amplitude; τ denotes the dimensionless time; θ is the delay time; G_o is a difference kernel operator:

$$G_o F(\tau) = \int_{-\infty}^{\tau} G(\tau - \tau')F(\tau')d\tau'$$

which defines the interaction linear stage; and $\Psi\{|GF(\tau)|, \nu\}$ is a nonlinear function describing the nonlinear stage and depending on the instantaneous values of signal level $x=|GF(\tau)|$ and frequency $\nu(\tau)$ at the end of the linear interaction stage. Equation (1) explicitly defines the generator signal current value according to the totality of past signal values, i.e., it transforms the solution process into a certain functional mapping iteration. This equation, in contrast to the partial differential equations, can be analytically analysed for stability rather easily. The disruption of monochromatic regimes [1-6] followed by automodulation and signal stochastization occurs (for example, at some point of beam current growth) if either of these conditions is satisfied:

$$|a(\nu)|\left|\frac{\partial}{\partial x}|\psi|\right| > 1 \quad (2)$$

$$\frac{d^2}{d\nu^2}|a(\nu)| - |a|\cdot|\Psi|\cdot\frac{d^2}{d\nu^2}\arg(a)\cdot\frac{d}{dx}\arg(\Psi) > 0 \quad (3)$$

Here, $a(\nu)$ represents the device frequency response in a linear amplification regime and is equivalent to the Fourier transform of function $G(\nu)$. The first condition connects the disruption of monochromatic generation regimes with a steepening of the dropping part of the amplifier amplitude characteristic. The second condition is related to the amplifier frequency response. Therefore, the first mechanism of stability loss is called the amplitude mechanism, and the second, the phase mechanism.

The identification of the mechanism responsible for the oscillation stochastization is very important, because it determines the signal spectral characteristics and the scenario of the transition from a regular to a stochastic generation mode. Here are the characteristic features of the amplitude mechanism: transition via a chain of period doubling bifurcations; and low probability of large signal amplitudes, and, consequently, a rather small electron efficiency. The phase mechanism involves an intermittent turbulence and a high electron efficiency when the amplitude nonlinearity is weak.

As shown above, the deep amplitude nonlinearity mode involves a significant current deposition onto the slow-wave structure, which is undesirable in high-power CW devices.

The noted advantages of the phase stochastization mechanism were decisive in our choice of our stochastic oscillator scheme.

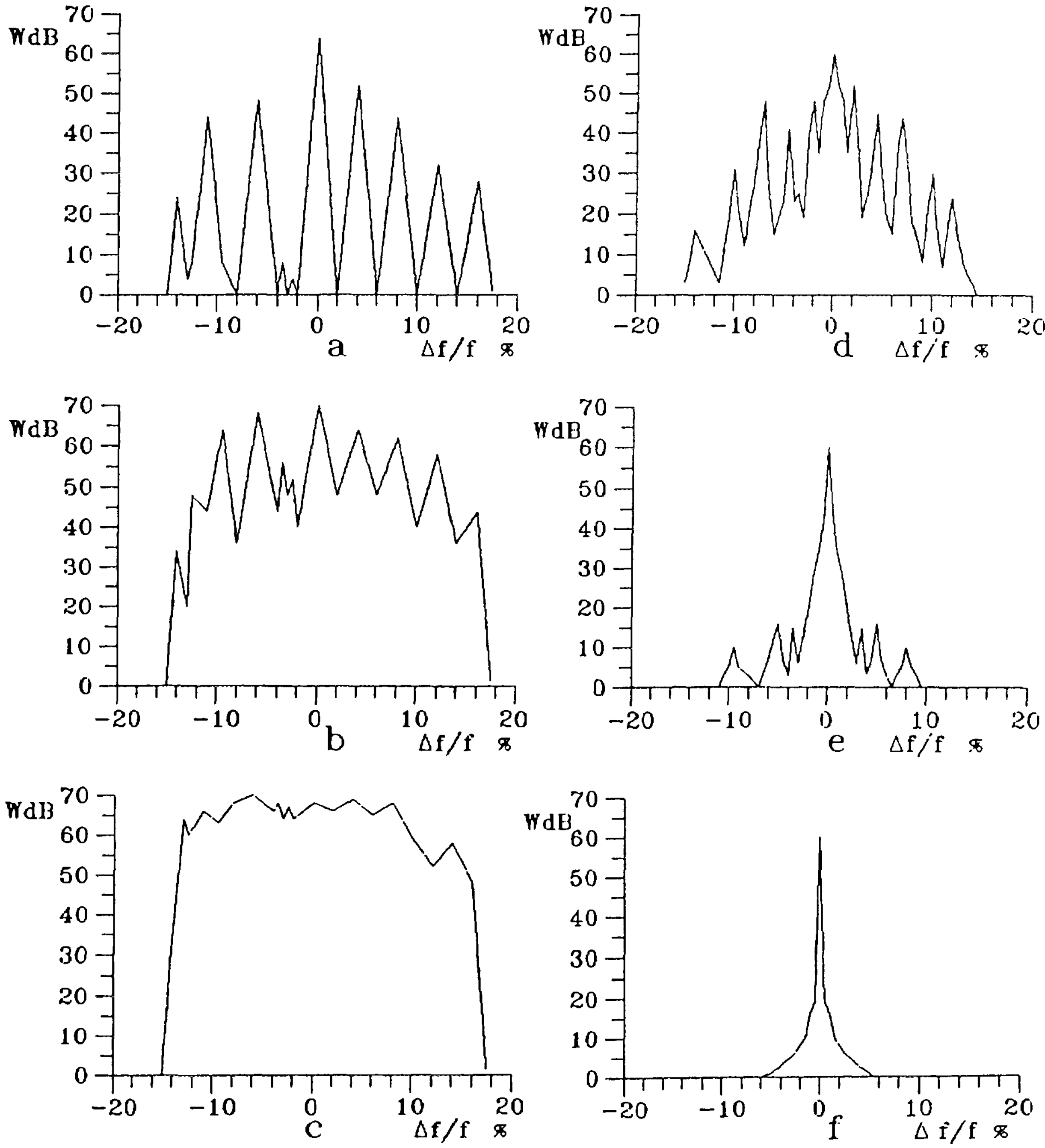

Fig.1.
Oscillation spectra for different power levels of feedback circuit signal:
(a) 0.5, (b) 0.8, and (c), 1.2 mW; (d), (e), and {f), in the presence of control signal of 0.2, 0.8, and 1.2 mW, respectively.

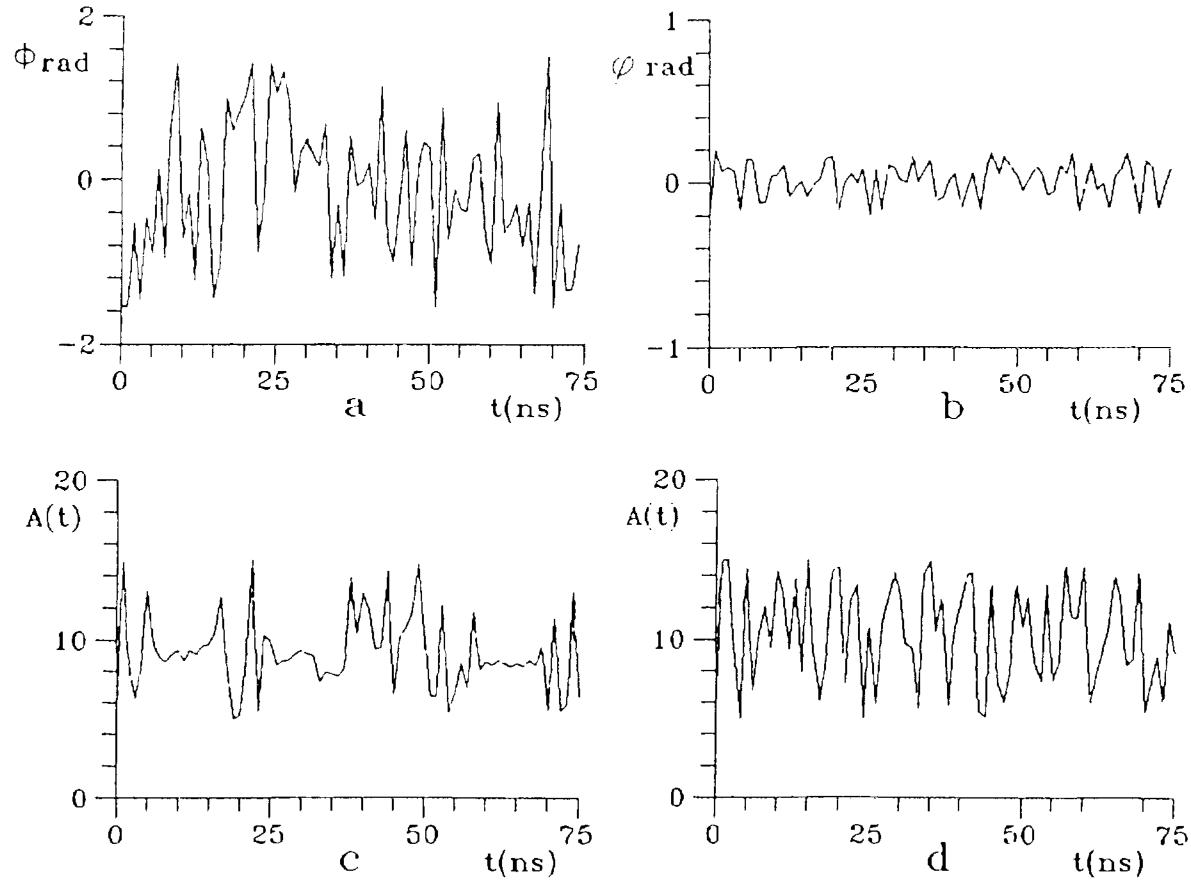

Fig.2.
Time dependence of (a) phase of stochastic signal with a wide frequency bandwidth, (b) phase of output signal in the spectrum compression regime, (cl output signal amplitude at 1.8 A electron beam current, (d) output signal amplitude at 3 A electron beam current.

The experiments were carried out for the same electron beam parameter set, as before, in the amplification regime. Figures 1a-1c present the generated oscillation spectra at various power levels of the feedback signal. As the feedback signal increased, the system passed through a multifrequency generation regime toward stochastic oscillation spectra covering the whole bandwidth defined by the dispersion characteristic. The maximal output power obtained in this regime was 20 kW. In a 30 % relative frequency bandwidth, the spectrum of oscillations was flat within 3 dB. Figures 2a, 2d show the signal phase and amplitude (signal envelope) as functions of time. One sees that in the wide-band generation regime the signal is random character both in oscillation amplitude and phase. The phase mechanism of transition to a stochastic behaviour is confirmed by the signal realisations recorded at different beam currents (Figs. 2c and 2d). One clearly discerns quasi-monochromatic zones peculiar to the intermittent turbulence regime. They disappeared when the electron beam current was increased.

The wide-band generation mode is hard to control. In addition, it is energetically unprofitable. Therefore, it is not desirable in many applications, unless one needs wide microwave oscillation spectra. In this connection, we realized and studied the regime of frequency spectrum compression by means of an external control signal. The control signal was fed to the input of the travelling wave tube, being a part of the feedback circuit. Figures ld-lf present the dependence of the generated spectra on the control signal power. For a 1 mW signal power at the travelling wave tube input (100 W at the beam-plasma amplifier input), the spectrum bandwidth was reduced by two orders of magnitude. At the same time, the integral output microwave power remained unchanged at the level of 20 kW. Figure 2b presents the time dependence of the signal phase in the spectrum compression mode. Note that the signal is still a noiselike one, although the phase dispersion is small. It was possible to retune the generated frequency over a bandwidth of about 25 %, where the spectrum nonuniformity was within 3 dB.

2. THE PLASMA HEATING AND THE ARTIFICIAL IONIZED LAYER (AIL) CREATION BY STOCHASTIC ELECTROMAGNETIC RADIATION

By way of example, consider the Earth's ionosphere plasma heating by stochastic electromagnetic radiation. The interaction of the powerful electromagnetic radiation with the Earth ionosphere is one of few accessible methods of active influence on the space plasma. Among different effects connected with powerful electromagnetic radiation the local thermal instability is one of the essential because it leads to the most marked changing of ionospheric parameters. The efficiency of plasma heating by monochromatic electromagnetic radiation is determined by electron collision frequency , which in the ionosphere is rather small ($\nu \leq 10^3\ s^{-1}$ on the height about 300 km).

In the case of stochastic signal, as it was shown in [7,8], the efficiency of energy transference to plasma electron component is determined by the reciprocal correlation time τ^{-1} Its value may be much larger than collision frequency ($\tau^{-1} >> \nu$). It allows to reduce the radiation source power and to increase the frequency. The latter makes accessible on influence all ionosphere, including the region above F-layer.

In [9,10] was shown that the growth rate of particle average kinetic energy is determined by following expression:

$$\frac{d}{dt}\left(\frac{m|V|^2}{2}\right) = \frac{e^2}{m}\frac{(|E|^2)}{(w^2+\tau^{-2})\tau} \tag{4}$$

were w is the carrier frequency of a electromagnetic radiation.

As follows from comparison (4) with the analogous formula for plasma heating by monochromatic radiation [11], the role of collision frequency in (4) plays the value τ^{-1}. It means, that the efficiency of the plasma heating by stochastic radiation is greater than heating by monochromatic radiation in ratio of $1/\nu\tau$. In ionosphere the value $1/\nu\tau$ may be very large and it allows to use signals with $w >> w_{pm}$ (w_{pm} is the maximal value of plasma frequency in the region of F-layer), which can warm thoroughly the whole width of the ionosphere. For this case the dependence of heating rate and the electron steady temperature as functions of height will be discussed further.

Taking into account the angular diverging and the loss of energy it is possible to obtain the following expression for dependence of steady electron temperature T_∞, on height:

$$\frac{\Delta T}{T_o} \equiv \frac{T_\infty - T_o}{T_o} \sim \frac{e^2 P_{eff}\,\Delta f}{mcw^2 h^2 \nu(h)\delta T_o(h)} \cdot \exp\left(-\frac{3}{4}\frac{\Delta f}{c}\int_0^h dh' \frac{w_p^2(h')}{w^2}\right) \tag{5}$$

Here T_0 is ionospheric heavy component temperature, $\delta \sim m/M \sim 10^{-3}$-$10^{-4}$ is the part of energy losses due to collisions of electrons with ions or neutrals, P_{eff} is an effective power of the radiation source, Δf is radiation spectrum width: $\Delta f \sim \tau^{-1}$.

Let us consider as an example the ionospheric plasma heating by stochastic electromagnetic radiation with following parameters: $f \sim 10 f_p \sim 50$ MHz, $\Delta f \sim 5$ MHz, $P_{eff} \sim$ 10 MW

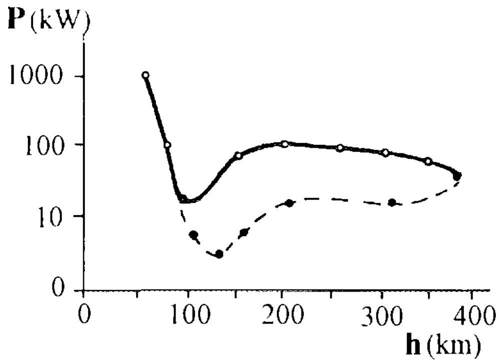

Fig.3. The dependence *P(h)* of ground-based radiation source power that is necessity for AIL creation on the height h. The carrier frequency is chosen about 1 GHz, the spectrum width is 10% and the antenna growth coefficient is 10^3. Solid and dotted lines correspond to day and night ionosphere.

To height about 1000 km the loss of power may be neglected and dependence $T_e(h)/T_0$ is determined by function $\varphi(h)=h^2 \nu(h)$ which has a sharp maximum on the height of F-layer. It means that the largest value of the relative temperature growth is to be expected on the heights more and less than F-layer height. This fact illustrated the essential difference between heating by monochromatic and stochastic signals.

The value $\Delta T/T_0$ for above mentioned parameters is about 1 on the height 200 km and higher. The transition time to a steady state is about 10 s.

Formula (5) allows to assess radiation power P_{eff} (i), which is necessary for neutral component ionization. Dependence $P_{eff}(i)$ is determined by function $\varphi(h)$. The minimal power $P_{eff}(i)$ is essential for an AIL creation on the height 150-250 km. The dependence of assess for AIL creation power *P(h)* of ground-based source of electromagnetic radiation, that was obtained using standard Earth's ionosphere parameters, is shown on Fig. 3. If the radiation power is not very large than changed in a random manner wave amplitude exceed threshold of gas discharge only during short time intervals. In this case the discharge has pulse character that is favourable for ozone production. The point is that in the stationary air discharge the ozone formation is intensive only during initial stage. After that the ozone formation is decreased and some unhealthy nitrogen compounds appear [12]. High efficiency of ionosphere heating and pulse character of discharge make possible to use stochastic electromagnetic radiation for ozone reproduction, for example, in the regions of ozone "holes" that appear during space missiles launching.

The stochastic radiation can be used for long-distance transporting of electromagnetic radiation in the ionosphere. High efficiency of plasma heating make possible to use sources with relatively small power for wave-guide channel creation, where plasma density drop prevent the wave beam divergence. As an example, for the stochastic radiation with carrier frequency ~ 1 GHz and spectrum width ~100 MHz the power that is necessary for wave-guide channel creation in the F-layer region is about some kW. Corresponding power of mono-chromatic radiation with frequency ~1 GHz is about 105 kW. Such high difference between powers is connected with very low collision frequency ν in the ionosphere ($\nu \sim 10^3\ s^{-1}$) that make non-effective heating by monochromatic radiation.

3. THE HEATING IN THE FIELD OF STOCHASTIC POTENTIAL WAVE IN MAGNETIZED PLASMA

In the homogeneous waves fields the heating rate is determined only by their correlation time τ_c. But in the case of non-homogeneous wave created, for example, by localized source (antenna), the heating of plasma electrons is defined not only by temporary but by space correlation characteristics as well. In the dispersive media which plasma is, this characteristics change according to removal from radiation source. The plasma heating efficiency changes according to this one. Below the magnetized plasma heating by localized source of stochastic potential waves is considered. The interest to this wave type is connected with investigation of possibility of stochastic radiation sources using for plasma additional heating in Tokomaks. In the presence the regular low and high hybrids waves are applied particularly. The results about stochastic signal propagation, which are described in this report, can represent also a special interest for Earth's ionosphere physics and removal sensing.

The dispersion of potential magnetized plasma waves connects frequency with direction of wave propagation only. In [13] was shown that on large distance from localized source (antenna) of such waves the correlation time τ determines only a wave beam width, but not the correlation parameters in it. The correlation length in transversal direction and correlation time in a wave beam do not depend on τ.

The constancy of transverse to wave beam direction correlation length $l_\perp$ when mean beam radius increases is a consequence of specific property of considered wave in anisotropic media: their frequency determines only direction of the wave vector but not its modulus. Therefore each spectral harmonic, which propagates at corresponding angle with respect to anisotropy direction (magnetic field), "carries" the source image as a whole. Because in the stationary stochastic processes the spectral components are statistically independent, the space correlation vanishes when two points of observation are separated one from another at distance greater than source size a. So, on the great distance from antenna the transverse correlation length is determined by source dimension only: $l_\perp \sim$ a.

The independence of correlation time τ_* in the wave beam on τ may be explained by following. The signal harmonics from source with a size a may come to the removal observation point only if they are contained in frequency interval $\Delta w \sim a/z$ (z is the distance between observation point and antenna). If $\Delta w << \tau^{-1}$ then signal spectrum in the observation point is much smaller than initial spectrum width $\sim \tau^{-1}$. The media at issue acts as a frequency filter, which bandwidth decreases as z^{-1} when z increases. The correlation time τ_* of stochastic signal which passes through narrow-band filter is determined not by initial correlation time τ, but by frequency band width Δw: $\tau_* \sim \Delta w$.

Now we shall estimate the electron heating rate. The field that acts on a moving electron has a correlation time τ_e which is determined by expression:

$$\tau_e^{-2} \sim \frac{v_o^2}{l_\perp^2} + \tau_*^{-2} \quad . \tag{6}$$

First term in the right part of (6) connects with transversal stochastic space structure of wave beam, and the second one - with stochastic time variations of the field. According to (3) the temperature T grow rate is described by the following expression:

$$\frac{dT}{dt} \sim \frac{e^2}{m}\frac{\langle E^2 \rangle}{w^2 \tau_*} \sim \frac{e^2}{m}\frac{E^2}{w^2}\sqrt{v_o^2 / l_\perp^2 + \tau_o^{-2}} \ .$$

A particle crosses the region with dimension R during the time interval $\Delta t \sim R/v_0$, so the total particle energy charge[1] during one pass through whole wave beam is

$$\Delta T \sim \frac{e^2}{m}\frac{\langle E^2 \rangle}{w^2}\sqrt{v_0^{2}/l_c^2 + \tau_c^{-2}} \cdot \frac{R}{v_0} \tag{7}$$

As it following from (7), the slow particles acquire greater energy during one crossing of a wave beam than fast ones. This circumstance may be very important, because such "priority" of slow particles prevent the formation of high-energy "tails" in the electron distribution function and it leads to more uniform energy distribution in the plasma electron component.

Let us compare now the expression for ΔT with similar ones for monochromatic signal[2]. In this case the particle energy changing occurs only at the moment when particle crosses a beam boundary[3], and the value ΔT is determined by the squared oscillation velocity in the wave field:

$$\Delta T \sim \frac{e^2}{m \cdot w^2}. \tag{8}$$

Note, that the expression (5) is the upper boundary for ΔT value and is satisfied for beams with sharp boundaries and uniform intensity distribution across the beam. If the intensity smoothly decreases toward boundary then the particle energy increasing may by much smaller.

In the considered media the radiation of antenna represents the conic shell with axis that is parallel to anisotropy direction. Let us define D as a diameter of cone and R as a shell width in the observation point (for regular radiation $R \cong a$ in the considered approximation). The formulas (7) and (8) expressed in terms of radiation source power P may be rewritten in the form:

$$\Delta T_S \sim \frac{e^2}{mc}\frac{P}{Dw^2 a}\sqrt{1 + a^2/(v_0^2 \cdot \tau_c^2)}, \tag{9}$$

$$\Delta T_l \sim \frac{e^2}{mc}\frac{P}{D\,w^2 a}, \tag{10}$$

where $\Delta T_{S,T}$ are the particle energy changing for stochastic and regular radiations, respectively.

As it follows from comparison (9) and (10), the heating efficiency for "slow" electron in the stochastic wave beam's field exceeds the heating efficiency by regular wave with the same power and created by the same source, and for "fast" particles these efficiencies are equal.

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[1] It is assumed here that energy change is small: $\Delta T \ll T$.

[2] Here only stochastic mechanism of energy exchange between regular wave and particles is considered. Resonance interaction may be more effective but it affects only small group of particles.

[3] It is assumed that the electron collision frequency ν in a media is small enough: $\nu \ll v_0/R$.

4. CONCLUSION

As it was shown mentioned above examples, the stochastic radiation interaction with plasma may be in some conditions more strong as for regular one. It is possible to say that in the general case the stochastic heating is more effective than heating in the regular fields if the collision frequency is smaller compare to reciprocal correlation time τ_e. Such condition may be fulfilled in the plasma with low density (Earth's ionosphere) or in the high temperature plasma (thermonuclear plasma).

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