PECULIARITIES OF PARTICLES AND FIELD DYNAMICS AT CRITICAL INTENSITY OF ELECTROMAGNETIC WAVES (PART II)

V.A. Buts
National Scientific Center « Kharkov Institute of Physics and Technology»,
61108, Kharkov, Ukraine, e-mail: vbuts@kipt.kharkov.ua

Some results of researches of dynamics of particles and fields at such intensity of fields, when the stochastic instability develops, are represented. It was shown that conditions for arising stochastic instability at the wave-particle interaction practically could be always created. It was revealed that the stochastic instability at the wave - wave interaction could be cause of beam instability disruption. Besides the conditions are formulated, at which the non-relativistic charged particles radiate as relativistic.
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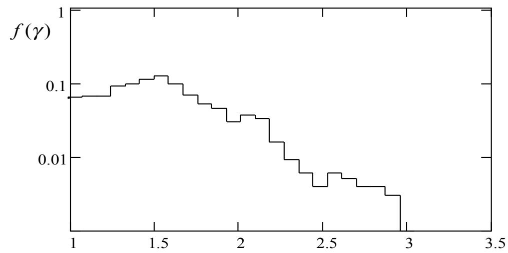
1. WAVE – PARTICLE INTERACTION

The basic processes in physics of plasma and in high-frequency electronics are the processes of interaction of a type a wave - particle and type a wave - wave. Regular dynamics of these processes is well investigated. By us earlier [1-2] the general analytical conditions for transition from regular dynamics of a wave - particle interaction to chaotic for all known resonance's were found. The analysis of these conditions shows that in many practically interesting cases it is difficult to reach a regime of stochastic instability. For example, for overlapping nonlinear cyclotron resonance's, in conditions usually used in experiment (look below), are necessary to have very large intensity of electromagnetic waves. The purpose of the present section is the illustration of fact that conditions for development of local instability practically can be always created. In most cases for achievement of a regime of stochastic instability it is enough to carry out insignificant updating. We used or additional waves (laser heating of solid-state plasma [3]), or low-frequency fields and waves [4,5], or additional spatial modes [6] for necessary updating. As an example we shall represent results on stochastic heating of plasma [6]. Let particles of plasma are moving in a field of a H-wave in round wave-guide with radius a in a constant magnetic field H_0 directed along an axis wave-guide. If the particles of plasma are moving in a field only one $H_{1,1}$ - wave, than for overlapping nonlinear resonance's in wave-guide with radius a=8 ($w/2p=2\ .8$ GHz, and H_0= I kG), are necessary to have $E_0 \approx 300$ kV/cm. If in it wave-guide simultaneously with $H_{1,1}$ to excite a mode $H_{2,1}$, than for development of stochastic instability It is enough to have fields considerably smaller - 24 kV/cm. The distribution function of electron energy at the moment of time $t=200\ p$ is submitted in the figure. The electrons are moving in a field of two spatial modes propagating towards each other.

Experimental researches are in good qualitative, and in many cases and in the quantitative consent with the theory [6]. In experiment the efficiency of heating was 50 %, and average energy of plasma particles ~1MeV. It is necessary to note that in the same experimental conditions without stochastic instability the energy of plasma particles did not exceed 100 eV.



It is useful to compare described above scheme of heating with the schemes of heating, which are used in magnetic traps. The efficiency of plasma heating in a trap is possible to estimate by effective frequency collision $\nu \sim 1/T$, where T - time of passage by particles between mirrors. For stochastic heating it is possible to enter the following frequency $\nu_{eff} \sim 1/T_C$, where - $T_C \sim 1/w \cdot \ln K$ time uncoupling of correlation, K - relation of nonlinear resonance width to distance between them. T_c - is comparable to the period of a high-frequency field. The time, during which the particles pass from one mirror to another in magnetic traps, is about 10^3 periods of a high-frequency field.

2. WAVE-WAVE INTERECTION

The second important process of plasma physics and electronics is the process of nonlinear interaction of waves. Most important and well investigated is the process of regular three-wave interaction. We earlier [7] received the conditions, at which dynamics of three-wave interaction becomes chaotic. Analytical expression of this condition is very simple:. $2\Gamma/\delta > 1$ Here Γ - increment of an initial stage (linear) three-wave interaction. δ - distance (on frequency) up to one of the nearest waves, "not participating" in interaction. In particular, it can be the frequency of a low-frequency wave which take part in three-wave interaction. This last case, as is known, corresponds to the modified disintegration and, as follows from the formulated condition, such disintegration is always chaotic. Chaotic dynamics of three-wave interaction now is investigated a little. It is possible to pint, at least, two potential opportunity uses of this regime. In the first case the originally regular electromagnetic waves after such interaction become chaotic, with a wide spectrum. Such transformation of a spectrum of regular electromagnetic waves in chaotic opens new opportunities in creation of sources intensive noise radiation. The second opportunity is connected with that fact that the presence of such regime of waves interaction can result in break down of beam instability. Seems that this last opportunity is realized in experiments. Therefore we shall describe it in more detail. Schematically process of break down of beam-plasma interaction can be presented as follows. The electron beam excites one of own waves of plasma. When the amplitude of the exited wave will enough large the process of disintegration of this wave into two other own waves arise. At this stage the channel dissipation of the exited wave already has appeared. In some cases, this channel itself can stabilize a level of the waves. The dissipation became large when the process of disintegration becomes chaotic. Really, in this case exited fields have got to a casual component. Well known that such fields quickly and effectively transfers their energy to particles of plasma. The additional channel of dissipation in this case has appeared. To this it is necessary to add, that efficiency of excitation of fields, having a casual component, by electron beam falls.

The presence of these features of nonlinear interaction of waves can result in breakdown of plasma-beam interaction. For the quantitative characteristic described above of the mechanism of breakdown of beam instability, we shall represent some quantitative results.

Let's show that the efficiency of energy transfer from an electronic beam to electromagnetic waves, which have a casual component, is significant less. Let beam interact with an electromagnetic wave in the short resonator. Let wave has got a casual phase $\Delta\Phi$. Let's consider (for simplicity), that this phase δ-correlated: $<\Delta\Phi(\xi)\Delta\Phi(\xi')>= N\delta(\xi-\xi')$. Then it is possible to show that the average energy, which is lost by particles of a beam on excitation of this wave, can be submitted by the formula $<\varepsilon>=\varepsilon\left(\sin\Phi_m/\Delta\Phi_m\right)^2$. Here ε - energy, which the particles of beam lose at interaction with a regular wave; $\Delta\Phi_m$ - maximal value phase fluctuation of a wave. It is visible, that at $\Delta\Phi_m \sim \pi$ a beam practically does not interact with a wave.

Let's estimate, as quickly the casual electromagnetic fields can transfer their energy to particles of plasma. For this purpose we shall consider, that plasma particles are in a field of δ-correlated waves ($\langle E(t_1)\cdot E(t_2)\rangle = A^2\cdot\delta(t_1-t_2)$). In this case from the equations of movement it is easy to find the following expression for an average square increase of energy of particles: $\langle(\Delta\gamma)^2\rangle = \langle(\gamma(\tau)-\gamma(0))\rangle = v^2\cdot A^2\cdot\tau$. From this formula it is visible, that plasma electrons can change the energy from eV up to keV during the time about hundreds periods of a high-frequency field, if the intensity of this field is about ~100V/cm.

3. NON-RELATIVISTIC FEL

In some cases the insignificant changes of properties of environment, in which radiation occur, can considerably changed character of radiation. So in works [8] is shown, that the occurrence even of very small periodic perturbation of permittivity results that non-relativistic particle can radiate as relativistic. So radiation power of oscillator with energy $\gamma = 1.005$ in medium with permittivity $\varepsilon = 1 + q\cos\kappa z$, $q = 10^{-5}$ on 10^3 harmonics is equal to radiation power of oscillator in vacuum only in that case, when his energy is equal $\gamma = 500$.

The maximum of a radiation spectrum at this conditions is at $\omega \approx \kappa\cdot v$ ($\lambda \sim d/\beta$, $\kappa = 2\pi/d$, $\beta = v/c$), where v - is maximal oscillator velocity. Therefore for excitation x-ray radiation by non-relativistic particles it is necessary to have perturbation with the period comparable with the period of crystal lattices. In crystals except the periodic perturbation of permittivity there is a periodic potential. The period of this potential coincides with the period of permittivity. In work [9] was shown, that non-relativistic particles in such potential can radiate as relativistic. And the maximum of radiation coincides wits the maximum of radiation in periodic dielectric. Let's formulate the most important results about radiation non-relativistic particles in periodic potential. Let charged particle are moving in a field of such periodic potential $U = U_0 + g\cdot\cos(\kappa\cdot z)$.

Quantum consideration. The methods of quantum electrodynamics in many cases allow to see many important features of radiation, which are difficult for seeing by classical consideration. If particle is moving in potential with weak periodic heterogeneity, her wave function is possible to present as:

$$\Psi_i = \sum_m \Psi_{i,m} \exp\left[i\left(\vec{k}_i + m\cdot\vec{\kappa}\right)\cdot\vec{r}\right], \qquad (1)$$

where $\Psi_{i,m} \sim g^m \cdot \Psi_{i,0}$

It is visible from (1) , that the wave function has components, which can be identified with particles, which velocity is larger than velocity of a real particles (virtual particles). Such particles themselves do not exist. Analogy to virtual waves in periodically non-uniform medium here is looked through. Only in the latter case we were interested with slow virtual waves. For a case of particles we will be interested with fast virtual particles.

Namely this fast virtual particles give the contribution to radiation. Using a method of perturbation and wave function (1) it is possible to receive the following expression for radiation power of the charged particles, which are moving in periodic potential:

$$P = g^2(e^2V/c^2)(N+1)\int\omega d\omega(1-c^2/v^2) \qquad (2)$$

In the formula (2) $v = 2\cdot\omega/(\vec{\kappa}\cdot\vec{e}_i)$ if photon carries away practically all energy of a particle. If the energy of photon is insignificant part energy of particle, than

$\nu = \omega / (\vec{\kappa} \cdot \vec{e}_i)$. Here $\vec{e}_i$ - unit vector directed along $\vec{v}_i$. If an external electrical field $E(t) = E \cdot \cos(\Omega \cdot t)$ creates an oscillator and this oscillator is moving in periodic potential then for radiation power on frequency $\omega = m \cdot \Omega$ it is possible to receive the following expression:

$$P = \frac{e^2 \Omega^2}{3 \cdot c} \left(\frac{eg}{mc^2} \right)^2 \frac{1}{A^2} \cdot m^2 J_m^2(m)$$

where $A \equiv (eE)/(mc\Omega) = \beta$.

The formula (0) defines radiation only in a maximum of a radiation spectrum. The maximum of radiation is determined by equality of argument of function Bessel to number of this function, i.e. at performance of conditions: $\kappa c A = (2j+1)\Omega = m\Omega$.

Once again we shall note, that the maximums of radiation in periodic potential and in periodic permittivity coincide. If $(eg/mc^2) > (qA^2)$ than the role of periodic potential in radiation will be more significant

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ОСОБЕННОСТИ ДИНАМИКИ ЧАСТИЦ И ПОЛЕЙ ПРИ КРИТИЧЕСКИХ НАПРЯЖЕННОСТЯХ ЭЛЕКТРОМАГНИТНЫХ ВОЛН (ЧАСТЬ II)

В.А. Буц

Изложены некоторые результаты исследований динамики частиц и полей при таких напряженностях полей, когда развивается стохастическая неустойчивость. Показано, что практически всегда могут быть созданы условия, при которых возникает стохастическая неустойчивость взаимодействия типа волна-частица. Найдено, что стохастическая неустойчивость взаимодействия типа волна-волна может быть причиной срыва пучковых неустойчивостей. Сформулированы условия, при которых нерелятивистские частицы излучают как релятивистские.

ОСОБЛИВОСТІ ДИНАМІКИ ЧАСТОК І ПОЛІВ ПРИ КРИТИЧНИХ НАПРУЖЕНОСТЯХ ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ (ЧАСТИНА II)

В.О. Буц

Викладено деякі результати досліджень динаміки часток і полів при таких напруженостях полів, коли розвивається стохастична нестійкість. Показано, що практично завжди можуть бути створені умови, при яких виникає стохастична нестійкість взаємодії типу хвиля-частка. Знайдено, що стохастична нестійкість взаємодії типу хвиля-хвиля може бути причиною зриву пучкових нестійкостей. Сформульовано умови, при яких нерелятивістські частки випромінюють як релятивістські