NEW CONCEPTIONS OF OSCILLATION MECHANISMS IN THE ACCELERATOR WITH CLOSED DRIFT OF ELECTRONS

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Abstract

Here is an analysis of the basic oscillation types in ACD: "ionization", "transit-time", "electron-drift". The disadvantages of the models proposed before are considered. The general view on these problems is suggested and justified, which allows to explain such phenomena as; anomalous erosion, conductivity and diffusion crosswise magnetic field etc. The fruitfulness of this approach to the development of new ACD's is marked.

Introduction

Plasma oscillations are of first importance in the ACD (accelerator with closed drift of electrons). Finally, they are responsible for: kind of electron distribution function, conductivity and diffusion crosswise magnetic field, distribution of concentrations and temperatures in plasma, flows of particles and energy on the walls etc. All this defines the quality of ACD, it's efficiency, capacity, erosive processes, resource, reliability. So, not having clear outlines of oscillations in ACD one cannot distinctly comprehend the processes taking place there. And, therefore, continue further development of ACD technique.

By convention, it's taken that the plasma oscillations may be separated [1] into "ionization" (10¹...10⁵ Hz), "transit-time" (10⁵...10⁶ Hz), "electron-drift" (10⁶...10⁷ Hz), electron-cyclotron (10⁸ Hz) and Langmuir (10⁹, 10¹⁰ Hz) ones.

The two last mentioned oscillation types are inherent in magnetized plasma and their mechanism is clear. The three first are characteristics of ACD plasma in itself, and so they are very important for the researchers of ACD.

The mechanisms of these oscillations proposed just after the development of the first ACD's, in the seventieth, have some principal errors in physical models and they are not compatible with experimental data, in particular:

1) In the existing models of ionization oscillations in gas discharge the necessary conditions for their realization are either the availability of electric field as a source of energy for electrons, or atoms metastabilities [2].

In the model of ionization oscillations in ACD [3], where not magnetized ions serve as a plasma charged component, one cannot find both of these conclusions. So, the statement of getting oscillations of the required frequency under this model is rather strange. Naturally, that the generally known dependence of ionization oscillations on magnetic field in ACD remained outside the frames of this model (in particular: the existence of oscillations threshold).

2) The commensurability of the ion transit time of the ACD's channel with reverse frequency of MHz oscillations, which are registered in it, led to the declaration of "time-transit" oscillation mechanism [4]. The absurdity of the basic idea of the model, that ions, going through the ACD channel are initiator of oscillations is in: firstly; under existing plasma parameters in channel ions cannot excite any oscillations (the velocity of ion is lower than the velocity of any wave) [5] and secondly: for generation in the system of time-transit

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oscillations, in the classical sense of this word, there must be sufficiently "hard" connection between its boundaries [6], but there are no such circumstances in ACD.

3) The mechanism of electron-drift wave [1], running along the azimuth on the whole length of the channel with the velocity in several times less than with $c \frac{E_0}{B}$ [7], was very weakly justified only for the acceleration zone, where $E_0 \neq 0$, but there was no numerical accordance with experiment. The mechanism of wave excitation in the zone of ionization ($E_0=0$) has not been clear up to the recent time [8]. As a result, a very interesting situation in the comprehension of transfer mechanism of electrons to anode turned out: the process was considered as one, stimulating by oscillations [1], but how they arise, or their influence on the transfer of electrons remained enslaving task.

Unfortunately, during the last 20 years, there was a stagnation in researching of plasma physics processes in ACD. That found a reflection in invariability of the first ACD's, let alone the process of "engineer finishing".

The researches carried out recently in NIITP, allowed to develop and to justify mechanisms of these oscillations, which adequately describe processes, taking place in the ACD and allow to change the construction of ACD. The purpose of the present work is not only total review of new oscillation mechanisms [9 - 11], but detailed consideration of common universal oscillations mechanism in ACD and method of operation with it.

Nomenclature

- $r, \varphi, z$ - cylindrical coordinates;
- $n_e, n_i, n_0, V_e, V_i, V_0$ - electrons, ions, atoms concentrations and their velocities, accordingly;
- $V_e^0, V_i^0$ - electrons, ions, atoms flow velocities;
- $\omega_e, \omega_i, \Omega_e, \Omega_i$ - plasma and Larmor frequencies of electrons and ions;
- $m, M, \mu$ - masses of electron and ion and their ratio;
- $E, E_0, B$ - total electric field, its stationary $z$-component, magnetic fields;
- $\omega, k$ - wave vector and length of the wave ($k = \frac{2\pi}{\lambda}$);
- $\omega, \omega_e, \omega_i$ - oscillation frequency, its effective and imaginary parts;
- $T_e$ - temperature of electrons;
- $e, c$ - electron charge, velocity of light;
- $\nu, D$ - frequency of collisions and coefficient of electrons diffusion;
- $l_a, l_i$ - length of acceleration and ionization zones;
- $\Phi$ - electric potential;
- $\alpha$ - ionization parameter;
- $G$ - the parameter of gas flow (gas supply);
- $W$ - velocity of the wave.

Initial equations and method of their solution

The system of equations, describing the dynamic of three-component plasma (electrons, ions and atoms) in ACD channel, involves equations of continuity and motion for every component and Poisson equation.
\[
\begin{align*}
\frac{\partial n_e}{\partial t} + \nabla(n_e V_e) &= \alpha n_e n_i; & \frac{\partial V_e}{\partial t} + V_e \nabla V_e &= -\frac{e}{m} E - \frac{e}{m c} [V_e B] - \nu V_e - \frac{T_e}{m} \nabla n_e; \\
\frac{\partial n_i}{\partial t} + \nabla(n_i V_i) &= \alpha n_i n_e; & \frac{\partial V_i}{\partial t} + V_i \nabla V_i &= \frac{e}{M} E; & \Delta \Phi &= -4 \pi e (n_i - n_e); \\
\frac{\partial n_o}{\partial t} + \nabla(n_o V_o) &= G - \alpha n_e n_i; & V_o &= \text{const}; & E &= -\nabla \Phi.
\end{align*}
\]  

It is assumed that ions are "cold", not magnetized and don't change their impulse during collisions.

The solution of the system is carried out by the standard method. First, the solution of stationary system is found, i.e. all $\partial / \partial t = 0$, that gives stationary values $A^0$ ($A^0$ - any of the variables). Then, the solution of the initial non-stationary system is given as $A = A^0 + A'$, where $A'$ is a small one. Then, in the assumption of a small one heterogeneity ($\nabla n_i = 0$), the solution of nonstationary system for $A$ is found as $A \exp\{ -i(\omega t - k\xi) \}$. To find oscillation thresholds, the assumption of small heterogeneity is quite reasonable. Finally, we have a dispersion equation $F(\omega, k) = 0$, where the necessary condition for oscillations excitations is $\omega > 0$.

Under wide heterogeneity it's necessary to take $k(\tau)$ instead of "$k$".

Here, the efficiency of application of this system to the plasma processes in ACD channel is considered. Consideration is separated for acceleration zone ($E_0 \neq 0$) and ionization zone ($E_0 = 0$), analyzing all frequencies, from the highest to the lowest, following the hierarchy.

The moving is considered only by coordinates "$\varphi$", and "$z$".

Special attention should be drawn to the most important and delicate aspects of the stating approach.

1. In spite of the advantages in completeness of facts description in plasma of kinetic model in comparison with hydrodynamics one, the latter is preferred, because of:
   - in kinetics model, the detailed knowledge of the aspect, nature and electrons distribution function are necessary. But relating to ACD, this problem is only arising;
   - for comprehensive understanding of the facts (and that's the purpose of our work), hydrodynamic description of magnetized plasma in double-liquid model is more obvious;
   - the oscillations with frequencies less $\omega_c$ are analysed.

2. To avoid unjustified losses of solutions under consideration of certain range of frequencies, the restrictions connected with it are introduced mostly not in the initial equations, but in the getting answer.

3. The lack of correlation between velocities and coordinates of electrons in ACD plasma allows to determine the velocity of electron flow by averaging of particles ensemble (not by time). Hence we can introduce into consideration the drift velocity $(c E_0 / B)$ for enough small time $\Delta t \approx \Omega_e^{-1}$.

2. Acceleration zone

Plasma is defined completely ionized and homogeneous and $E_0, B$ are unvariable under "$z$".
2.1. For \( \omega \), commensurable with \( \omega_i \), and bigger than it, and presuming that azimuthal drift electrons velocity is bigger than the thermal one, the system (1) takes the following from:

\[
\begin{align*}
\frac{\partial n_e}{\partial t} + \nabla (n_e V_e) &= 0; \\
\frac{\partial V_e}{\partial t} + V_e \nabla V_e &= -\frac{e}{m} E - \frac{e}{mc} [V_e B]; \quad E = -\nabla \Phi; \\
\frac{\partial n_i}{\partial t} + \nabla (n_i V_i) &= 0; \quad \frac{\partial V_i}{\partial t} + V_i \nabla V_i = \frac{e}{M} E; \quad \Delta \Phi = -4 \pi e (n_i - n_e).
\end{align*}
\]

(2)

Not changing the essence of the facts, it is supposed, that ions move through the acceleration zone with unvariable rate \( V_i^0 \). Then, from (2) we get dispersion equation in the form:

\[
\frac{\omega_i^2}{(\omega - k_z V_i^0)^2} + \frac{\omega_e^2}{(\omega - k_\phi V_e^0)^2 - \Omega_e^2} = 1,
\]

(3)

where \( V_e^0 = cE_0/B \).

For big \( \omega \) in moving with \( V_e^0 \) velocity system of coordinates, considering \( \omega_i^2/\omega_e^2 = \mu = 10^{-3} \), from (3) comes a trivial solution

\[\omega = \sqrt{\omega_e^2 + \Omega_e^2},\]

(4)

that's the upper hybrid frequency.

For \( \omega < k_\phi V_e^0 \) it's better to take the solution in the following form

\[\omega = k_\phi V_e^0 \pm \sqrt{(k_\phi V_e^0)^2 - \Omega_e^2}/(\Omega_e^2 - \omega_e^2 - \Omega_e^2),\]

(5)

The increase of oscillations will occur, if \( \frac{\Omega_e^2}{V_e^0} < k_\phi < \sqrt{\frac{\Omega_e^2 + \omega_e^2}{V_e^0}} \) or, for \( \Omega_e \approx 2 \cdot 10^6 \text{ c}^{-1} \), \( \omega_e \approx (3...5) \cdot 10^{16} \text{ c}^{-1} \), which are typical for ACD, we finally get

\[0.3 < \lambda_\phi < 3 \text{ (mm)}.\]

As \( k_\phi \gg k_z \), it's easy to convince, that perturbations will distribute mostly along the "z" axis (the angle of perturbation inclination to the "z" axis comes arctg \( k_z/k_\phi \)). Note, that (4) and (5) are all four solutions of the equation (3) (in (4) missed a sign \( \pm \)). Thus, in the acceleration zone steady periodical special plasma structure forms. The presence of this structure is shown in the experiments by erosive structure on ACD walls.

2.1.1. It's not difficult to understand, that with due regard to \( B \) heterogeneity (and hence \( E_0 \) varies along "z") will cause to appearance additional member \( \nabla V_e^0 \) in the dispersion equation. This will give rise to some interesting effects. In particular, an area with magnetic field, abating from the channel cut to outside, will become the zone of instabilities.
It's necessary to stress, that not the change of sign at $\nabla B$ serves as a criterion of this effect (as mentioned in reference [1]), but $\nabla V_e^0$, and that is not the same.

2.2. For $\omega \leq \Omega_e$ the system turns into

$$
\begin{cases}
\frac{\partial n_e}{\partial t} + \nabla (n_e v_e) = 0; \quad 0 = -\frac{e}{m} E - \frac{e}{mc} [V_e B] - v n_e - \frac{T_e}{m} \frac{\nabla n_e}{n_e}; \\
\frac{\partial n_i}{\partial t} + \nabla (n_i V_i) = 0; \quad \frac{\partial V_i}{\partial t} + V_i \nabla V_i = \frac{e}{M} E; \quad n_i = n_e.
\end{cases}
$$

(6)

For azimuthal motion, the system of equations (6) gives the following dispersion equation

$$
\omega^2 + i \mu \left( \frac{\Omega_e^2}{\nu} + \nu \right) (\omega - k_v V_e^0) - k_v^2 \frac{T_e}{M} = 0.
$$

(7)

The condition of the oscillations excitation $V_e^0 > \left( \frac{T_e}{M} \right)^{\nu^2}$ (10) for typical circumstances of ACD is always implemented, i.e. (that is) in case of need, electron-drift wave is aroused along the azimuth in the acceleration zone.

The frequency of the wave ranges $\mu \frac{\Omega_e}{\nu} < \omega < k_v V_e^0$. For $B = 10^3$ Gc, $\nu = 10^6$ s$^{-1}$, $E_0 = 300$ V/cm from (7) comes $\omega_z \approx \omega_s \leq 10^4$ s$^{-1}$, and the wave velocity is $W = \omega_z / k_v \approx 10^7$ cm/s. The experimental fact explains that: the velocity of electron drift wave is several times less than drift velocity $c E_0 / B$. It could not be differently, as the condition of its initiation $V_e^0 = c E_0 / B > W$.

2.2.1. Here there is a mechanism of electrons conductivity intensification crosswise magnetic field to anode, initiated by electron drift wave.

The condition $V_e^0 > W$ is produced in the following form $V_e^0 = W + \gamma$ ($\gamma > 0$).

Not breaking the essence of the fact, - $\gamma$ is considered a small quantity. Electrons, moving practically simultaneously with the wave, will assemble in the area, where the field of the wave is equal 0 (in the area where the field changes from accelerating to braking one). And as $\gamma > 0$, the electrons, outrunning the wave, will group in braking phase of the wave. So in any moment, the number of electrons, moving against field $E_0$ (i.e. to anode), in crossed fields-external magnetic and azimuthal electric of the wave, will exceed the number of electrons displacing along the field $E_0$. The suggested mechanism is reliable even if $\nu \rightarrow 0$.

3. Ionization zone

Plasma is considered heterogeneous under $\nu$ and $E_0 = 0, B = \text{const}$.

3.1. For $\omega < \Omega_e$ the system (6) and the dispersion equation (7), coming out of it, are justified, as in azimuthal direction plasma is homogeneous.

Only now we have

$$
V_e^0 = -\frac{T_e}{m} \frac{\nabla n_e^0}{n_e^0} \frac{\Omega_e}{\Omega_e^2 + \nu^2}.
$$

(8)
All the calculations p.2.2 for acceleration zone remain correct, but with following differences [10]:
- electron-drift wave is arouse by azimuthal current of electrons, following in heterogeneous magnetized plasma ($E_0$ field analog);
- $\omega \equiv \omega_r \equiv \omega_s \geq 10^7 \text{ s}^{-1}$.

3.1.1. The mechanism of electron diffusion amplification to anode crosswise magnetic field, stimulating by electron-drift wave, is analogous to the mechanism in p. 2.2.1.

Hence, missing qualitative analysis of the mechanism, there is it's numerical estimation. Energy, required for wave swing, is selected from the energy of azimuthal electrons moving.

Let's introduce average effective tension $E_{ef}$ of the wave field. This tension characterizes the process of energy selection and can be found.

Due to $\omega_r = \omega_s$, the energy, loss during oscillation period is comparable with amount of energy in itself and equal $mV_0^2$. If the space period $l$ of oscillations equal $l = V_0/\Omega_e$ [9], we'll get

$$E_{ef} = \frac{\Phi}{l} \frac{\Phi}{V_0} \Omega_e = \frac{mV_0}{e} \Omega_e = -\frac{T_e}{e} \frac{\nabla n_0}{n_e}$$

let's assume, that electron is drifting to anode in $E_{ef}$ and $B$ crossed fields. Then it's velocity is $V_d = cE_{ef}/B$ or $V_d = -c\frac{T_e}{eB} \frac{\nabla n_0}{n_e}$; or in the diffusion terms (with an accuracy to constant)

$$D = cT_e/eB.$$

The $V_d$ estimation is $\approx 5 \cdot 10^6 \text{ cm/s}$.

Thus, even in weakly heterogeneous, non-collision, magnetized plasma, electron diffusion crosswise magnetic field is in proportion to $1/B$.

3.1.2. The advantage of the previous result is important, because of the uncapability of classical diffusion ($D = 1/B^2$) to consider current flowing in ACD, through ionization zone. Another advantage of the obtaining result, is that transit-time oscillations mechanism become obvious.

Supposing plasma under coordinate "z" weekly heterogeneous, we appreciate dispersion equation (7) to longitudinal motion ("z" axis). Considering, that

$$V_0 = -c\frac{T_e}{eB} \frac{\nabla n_0}{n_e},$$

we have $\omega_r \approx \omega_s \approx 6 \cdot 10^6 \text{ Hz}$. Therefore, longitudinal oscillations rise due to electrons current, flowing to anode. But without azimuthal electron-drift wave, their existence would be impossible.

3.2. For frequencies $\omega \leq v$ the ions are adjusted to electrons moving, and system (1) turns into:

$$\begin{align*}
\frac{\partial n_e}{\partial t} + \nabla (n_e V_e) &= \alpha n_e n_a; 0 = \frac{e}{mc} [V_e B] + vV_e + \frac{T_e}{m} \frac{\nabla n_e}{n_e}; \\
\frac{\partial n_a}{\partial t} + \nabla (n_a V_a) &= G - \alpha n_a n_a; V_a = \text{const}.
\end{align*}$$

(9)

From the electrons moving equation ($\Omega_e \gg v$)

$$V_e^0 = -\frac{T_e}{m\Omega_e^2} \frac{\nabla n_0}{n_e}.$$
Missing the cumbersome dispersion equation, we reduce condition of the oscillations excitation to supposition of their long-waving, i.e. to $kI<1$ [11]

$$V_a^2 > \frac{(n_o^0 - n_a^0)^2}{n_o^0} D\alpha.$$  \hspace{1cm} \text{(10)}

Or in some other form $V_a > \frac{\alpha}{B^2} f(n_o^0; n_a^0); B > \text{const}.$

From the conditions (10), it's possible to state the following:
- atoms flow velocity must be higher than the certain velocity, defining by ionization and removing of electrons;
- the presence of oscillations threshold on both of these results are confirmed by experiment [11].

\section*{Conclusion}

The general view on oscillation processes in plasma of ACD channel is suggested, allowing:
- to give true interpretation of experimental fact, incomprehensible before;
- to find interdependence between various oscillations types;
- to search successfully new oscillation branches;
- to indicate new methods of their control.

\section*{References}


