THE IONIZATION OSCILLATIONS MECHANISM IN ACD

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Abstract

The mechanism of the ionization oscillations in partly ionized plasma without electric field was proposed and developed in this paper. The oscillations excitation conditions were found. The comparison of the theory with the experiment results is given as well.

Introduction

The low frequency (10-100 kHz) ionization oscillations are essential matter of the ACD operation and one of the main obstacle for improving its efficiency, because oscillations periodically break plasma discharge.

Despite of importance of this problem there was no adequate theory up to date. Thus, for example, in the ionization oscillations model suggested in [1] the unmagnitized ions was taken as the main charged plasma component, therefore the well known from experiments the oscillations amplitude dependence on the magnetic field stayed outside the frames of this model.

In the other model [2] the dropping dependence of the ionization oscillations intensity on magnetic field was received, but this result is not in agreement with the experiments. Besides in the both model the presence of the external electric field is necessary, but in the ionization zone it is practically absent.

Nomenclature

\( n_a, n_m, n_e, n_{a0}, n_{m0}, n_{e0} \) - atoms, metastable atoms, electrons densities and its stationary values;
\( D_e, T_e \) - electrons diffusion coefficient and temperature;
\( v_a \) - atoms velocity;
\( \alpha, \beta, \gamma \) - excitation and ionization coefficients;
\( G \) - parameter of the mass flow;
\( \omega, k \) - frequency and wave vector;
\( v_e \) - electrons collisions frequency;
\( B \) - magnetic density;
\( l_i \) - ionization zone length;
\( U \) - voltage.

The oscillations mechanism in the partly magnetized plasma

Magnetized electrons were taken as the main charged plasma component and the excitation and ionization processes were investigated with taking in account metastable levels of xenon.

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The electrons flow in the ionization zone was supposed as diffusion. Discontinuity equations set in the one dimension case can be written as

\[
\frac{\partial n_1}{\partial t} - v_a \frac{\partial n_1}{\partial x} = G - (\alpha + \beta)n_1n_e
\]

\[
\frac{\partial n_m}{\partial t} - v_a \frac{\partial n_m}{\partial x} = \alpha n_1 n_e - \gamma n_m n_e
\]

\[
\frac{\partial n_e}{\partial t} - \frac{\partial}{\partial x} \left( D_e \frac{\partial n_e}{\partial x} \right) = \beta n_1 n_e + \gamma n_m n_e
\]

where "x" axis is directed to anode and \( v_a > 0 \).

This set (1) was solved by disturbance method under following suggestions:
- disturbances are proportional to \( \exp\{-i(\omega t - kx)\} \);
- \( k(x) \) is smooth function;
- disturbances are long wave (\( kl_1 > 1 \)).

Then we can obtain dispersion equation whence the oscillations excitation conditions were found. To avoid unnecessary complexity and to save the matter of problem we give these conditions without taking in account the presence of metastable atoms

\[
(D_e^r - v_a)^2 > \frac{(n_1^0 - n_e^0)^2}{n_1^0} D_e \beta.
\]

From this inequality we immediately obtain (making allowance for dependence \( D_e \sim B^{-2} \) and monotonous magnetic field) following results:
- the presence threshold value of the magnetic density for oscillations and the excitation condition as \( B > \text{const} \);
- the oscillation frequency as \( \omega \approx kv_a \), which for \( l_1 \approx 1 \text{cm} \) give \( \omega \approx 130 \text{ kHz} \);
- reducing the threshold value in the case if the magnetic field decreased from anode \( (D_e^r < 0) \).

To summarize we can say that the reason of ionization oscillations excitation in plasma is magnetized electrons and the presence of metastable atoms decreases the oscillations threshold value of magnetic field.

**Ionization oscillations in ACD**

To investigate more detail the condition (2) in ionization zone of accelerator with closed drift (ACD) fulfill following simplifications:

\[
n_e^0 \sim x, \quad \frac{\partial n_e^0}{\partial x} = -\frac{n_e^0}{l_1}, \quad \frac{\partial n_1^0}{\partial x} = \frac{n_1^0}{l_1}
\]

which are qualitatively valid. Then we can write the stationary values of densities from (1)

\[
n_a^0 = \frac{D_e^r}{\beta l_1}, \quad n_e^0 = \frac{G l_1 + v_a}{D_e^r \beta l_1}
\]

Substituting (3) in (2) we obtain oscillations excitation condition:
\[(D^*_e - v_a)^2 > \frac{D_e^*}{D_e^*!} (D^*_e - v_a - \frac{G\beta l^2}{D_e^*})^2\]  \hspace{1cm} (4)

For ACD the factor \(D_e/D_e^!\) in the right part of the inequality (4) can be evaluated as

\[
\frac{D_e^*}{D_e^!} \approx \frac{D_{e,\text{max}} - D_{e,\text{min}}}{D_{e,\text{max}} + D_{e,\text{min}}} = \alpha \leq 1 \quad (B_{\text{max}} = 90 \text{G}, B_{\text{min}} = 50 \text{G})
\]

whence from (4) finally obtain

\[y_1 = D_e^* (D^*_e - v_a) < 2G\beta l^2 = y_2\]  \hspace{1cm} (5)

We will analyze the dependence of the inequality (5) on changing of the external discharge parameters of ACD:

a) magnetic field;

b) mass flow;

c) voltage.

a) Here and further we suppose the values in (5) as following \(v_a = 2 \times 10^4 \text{cm/s}, \ G = 5 \times 10^3 \text{cm}^2\text{s}^{-1} \) (mass flow 4 mg), \(b = 2 \times 10^{-7} \text{cm}^3\text{s}^{-1}, \ I = 1 - 2 \text{cm}, \ T_e = 10 \text{eV}, \)

\[\Delta B = B_{\text{max}} - B_{\text{min}} = 40 \text{G}, \ v_e = 10^6 \text{s}^{-1}, \ D_e = B^{-2}, \] then inequality (5) gives two conditions for excitation of the oscillations (fig. 1)

\[30 \pm 10 \text{G} < B_1 < 60 \pm 10 \text{G}, B_2 > 100 \pm 20 \text{G}.\]

Note that the boundaries of two instability zones \(B_1\) and \(B_2\) draw together if mass flow is increased.

b) The influence of the mass flow on the excitation conditions is shown on fig 2. Unlike the dependence oscillations threshold from magnetic field here we have the one continuous region, even though the dependencies \(G\) from \(B\) in the neighborhood of boundaries \(B_1\) and \(B_2\) differ.

c) The influence of the external voltage can be followed on qualitative level through dependence \(T_e \sim (U/B)^2\), where \((U/B)\) characterize the drift velocity. In its turn the electrons diffusion is determined through \(T_e\), and diffusion coefficient can be written as [3]

\[D_e = \left(10^{-3} T_e^{-1/2} + 1.4 \times 10^{-7} T_e^{5/2} \frac{n_0}{n_e^0}\right) B^{-2}\]  \hspace{1cm} (6)

where first term in the right part describes the electron-ion collisions and second - electron-atom collisions. In the region where the magnetic density is high (zone \(B_1\) ) we have from (3) \(n_0^0 < n_e^0\), then \(D_e \approx 10^{-2} T_e^{-1/2} B^{-2}\) and \(D_e^* \sim \left(1/U^3 + 1/UB^3\right)\) \((T_e, B \Rightarrow \text{const})\). In this case inequality (5) gives

\[D_\text{e*} < \text{const or} \ B^2 > \{U(\text{const} - U^{-1})\}^{-1} \]
In the region with low magnetic density (zone $B_2$) on the contrary $n_e^0 < n_e^0$ and then
\[ D_e = 1.4 \cdot 10^{-5} T_e^{-1/2} \frac{n_e^0}{n_e^0} B^{-2} \text{ and } D_e' = \frac{U}{B^2}. \]
Inequality (5) is written here as $v_e - D_e' < \text{const or } U/B^2 > \text{const.}$

Qualitative view of obtained conditions is shown in fig. 3.

**Comparison with experiments**

Experimental investigations of the oscillations threshold dynamic and their characteristics in ACD was carried out on the accelerators of T-100 type in the different regimes. As a result it was found that:
- there is the region in the values of the magnetic density where oscillations are absent (analogy for $B_1$, $B_2$);
- oscillations threshold exists for mass flow and its exceeding leads to the generation of ionization oscillations (fig. 2);
- when magnetic density is not high the voltage increasing leads to the excitation of the oscillations (fig. 3);
- oscillations frequency is equal approximately 30 kHz (theory gives 20 kHz).

**Conclusion**

The ionization oscillations mechanism is suggested which permits correct description of the oscillations thresholds and their dependence's from the main external characteristics: magnetic field (its value and form), mass flow and voltage.

The knowledge of these dependence's allows effective fight with ionization oscillations in ACD without using additional elements both in the discharge chamber and in the external circuit and even to exclude some using now elements. The developed new ACD has more high efficiency and less mass volume characteristics.

**References**