NON-STATIONARY ELECTRIC PROBE FOR PLASMA DIAGNOSTIC OF ELECTRIC PROPULSION ENGINES

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Abstract

In classical Langmuir probe the characteristic probe potential change time T is much greater then the pertubat zone relaxation time τ. The reverse limiting case is considered in this work when $T < \tau$. In this conditions the electric probe was called non-stationary.

The problem about non-stationary probe in the molecular mode is connected with the common solution of the kinetic equations and Maxwell equations. At continually mode the equations of magnetic hydrodinamics and the Maxwell equations are solved. The solution methods of this equations systems are considered in (1).

The probe current change curve was received in the result of the solutions. The results of the numerical experiments modeling the work of the non-stationary probe in different modes are presented. The method of the probe experiment founded on unification of stationary and non-stationary approach is proposed. In the result of this the probe method gives the supplementary possibility, for exemple, to measure the temperature of the heavy plasma components, that is, ion.

Nomenclature

n_i - ion concentration,
m_i - ion mass,
T_i - ion temperature,
T_e - electron temperature,
k - Boltzmann conctant,
e - electron charge,
r_p - probe radius,
r_D - Debye radius,

$r_0 = r_p / r_D$

φ_p - probe potential,

$M_\varphi = kT_i / e$

$\varphi_0 = \varphi_p / M_\varphi$

$\varepsilon = T_i / T_e$

I - current,
τ - characteristic time of relaxation,
$t_з$ - undimentsional time of the relaxation,
t_p - potential impulse growing time,
ε_0 - electric constant.

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In classical Langmuir probe the characteristic probe potential change time T is much greater then the pertubat zone relaxation time τ . The reverse limiting case is considered in this work when $T < \tau$. In this conditions the electric probe was called non-stationary. Assume for definition that probe potential changes impulsively with infinitely steep front of growing and then becomes constant.

The problem about non-stationary probe in molecular mode is connected with the common solution of Vlasov and Poisson equations system. In the simple case of cylindrical and sperical probes without magnetic fields, drift velocity of plasma and electron emission this sistem can be written

$$\begin{aligned}
&\frac{\partial f_{i,e}}{\partial t} + \vec{v}\frac{\partial f_{i,e}}{\partial \vec{r}} + \frac{F_{i,e}}{m_{i,e}} \cdot \frac{\partial f_{i,e}}{\partial \vec{v}} = 0 \\
&\operatorname{div} \vec{E} = -\frac{1}{\varepsilon_0}\rho , \quad \vec{E} = -\vec{\nabla}\varphi \\
&\rho = e(n_i - n_e) \\
&n_{i,e} = \int f_{i,e}\, d\vec{v}_{i,e} \\
&F_{i,e} = q_{i,e}\vec{E}
\end{aligned} \qquad (1)$$

where $f_{i,e}$ - ion and electron distribution function, φ - potential of electric field, $\vec{E}$ - strength of electric field. Another meaning is generally accepted. Equations system (1) supplemented by the system of initial and boundary conditions was solved by method of sequental iterations in the time, and what's more Vlasov equation was solved by the method of the large-sized particles and Poisson equation was solved by Furje method.

The characteristic graph of change of probe current is shown in figure 8, where

$$\hat{\varphi} = e\varphi / kT_i , \quad \hat{I} = I / M_I ,$$
$$\varphi_0 = e\varphi_p / kT_i , \quad t_3 = \tau / M_t$$

There you can see two maximums. First maximum ($t = t_1$) corresponds to the displacement current and second maximum ($t = t_2$) corresponds to the conductivity current. The time of completion of transitional process in wall plasma we can consider as one more characteristic time ($t = t_3$). All these times $t_{1,2,3}$ can be found in numerical experiment and can be measured in phisical experiment, that allow to determine supplementary dependence between the parameters of plasma and probe.

At continually mode the non-stationary probe problem comprised the equations of continuity for ions and electrons, energy equation for electrons and Poisson equation. This system can be written

$$\frac{\partial n_{i,e}}{\partial t} + \mathrm{div}\,\vec{J}_{i,e} = \varkappa_{i,e}$$

$$\vec{J}_{i,e} = -D_{i,e}\left(\frac{1}{T_{i,e}}\frac{\partial n_{i,e}T_{i,e}}{\partial \vec{r}} \mp \frac{q_{i,e}\, n_{i,e}}{k\, T_{i,e}}\vec{E}\right)$$

$$\rho_e \frac{\partial H_e^{\circ}}{\partial t} + e n_e \frac{\partial \varphi}{\partial t} + (\rho_e \vec{V}_0 + \vec{j}_e)\frac{\partial}{\partial \vec{r}} H_e^{\circ} - \qquad (2)$$

$$-\frac{\partial P_e}{\partial t} - \frac{\partial}{\partial \vec{r}}\left(\Lambda \frac{\partial T_e}{\partial \vec{r}}\right) = J_{em} + \vec{J}_{em}\cdot V_0$$

$$\mathrm{div}\,\vec{E} = -\frac{1}{\varepsilon_0} e\,(n_i - n_e)$$

Equations system (2) supplemented by the system of initial and boundary conditions was solved by method of sequental iterations in the time, and what's more continuity and energy equation was solved by the method of the large-sized particles and Poisson equation was solved by Furje method.

In figure 1-7 you can see some results of numerical experiments to determine characteristic relaxation time versus $r_0 = r_p/M_r$, $\varepsilon = T_i/T_e$, B_0, U_0, K_n, $\varphi_0 = \varphi_p/M_\varphi$, where

r_0 - undimentsional probe radius,
φ_0 - undimentsional probe potential,
ε - ratio of the ion temperature to the electron temperature,
t_3 - undimentsional time of the relaxation,
K_n - Knudsen number,
B_0 - undimentsional magnetic induction,
U_0 - drift velocity of plasma,

$$M_r = r_D = \left(\frac{\varepsilon_0 k T_i}{n_i e^2}\right)^{1/2}, \quad M_\varphi = {}^{kT_i}/_{e},$$

$$M_t = \begin{cases} \left({}^{\varepsilon_0 m_i}/_{2 n_i e^2}\right)^{1/2} & \text{- at molecular mode} \\ r_D^{\,2}/D_i & \text{- at continually mode} \end{cases}$$

D_i - ion diffusion coefficient.
All another meaning is generally accepted.

The measurement of the plasma relaxation time in probe experiment allow to determine supplementary dependence between the parameters of the plasma and the probe. In molecular mode this dependence can be written

$$t_3 = \tau / M_t , \quad M_t = \left(\frac{\varepsilon_0 m_i}{2 n_{i\infty} e^2} \right)^{1/2} , \quad n_{i\infty} = \frac{t_3^2 \varepsilon_0 m_i}{2 e^2 \tau^2}$$

where t_3 can be received from figure 1, and τ can be received from probe experiment.
In continually mode this dependence can be written

$$t_3 = \tau / M_t \approx 25 , \quad M_t = \tilde{r}_D^2 / D_i$$

where t_3 can be received from figure 2, and τ can be received from probe experiment.
In the result of this the probe method gives supplementary possibility to measure the temperature of the heavy plasma component, that is, ion (2).

The experimental probe equipment has been elaborated (2). This equipment allow to chenge the probe potential slowly and impulsively.

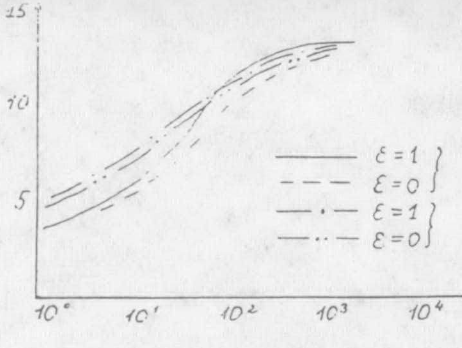
Conclusions

The results of this work may be used in theoretcal and experimental investigations having to do with ion engine conctruction and other fields of plasma research.

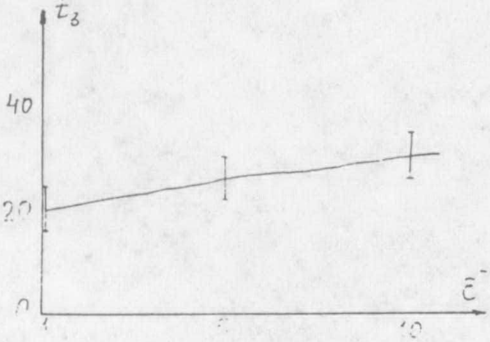
References

(1). Alexeev B.V., Kotelnikov V.A.
" Probe method of plasma diagnostics "
Moscow, Energoatomizdat, 1988 (in Russian)

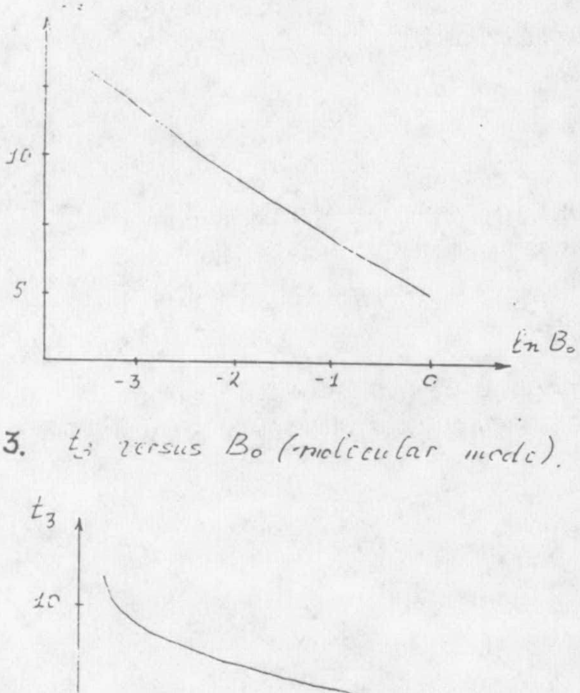
(2). Report about scientific-research work.
"Elaboration of theory and method of non-stationary probe"
Moscow Aviation Institute, phisics depatment, 1994



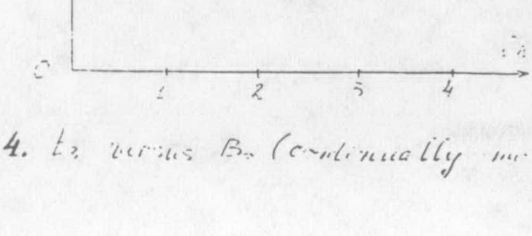
1. t_3 versus τ_0, ε (molecular mode)



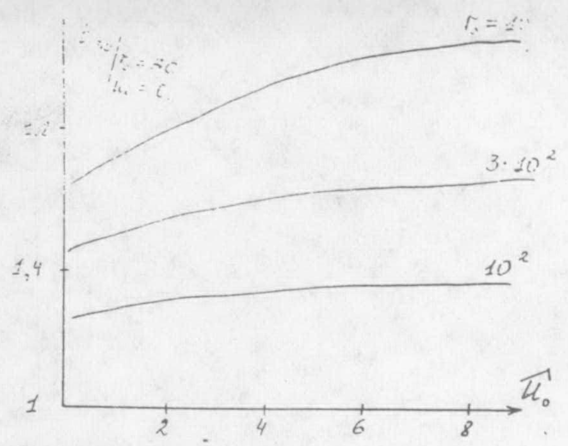
2. t_3 versus ε (continually mode).



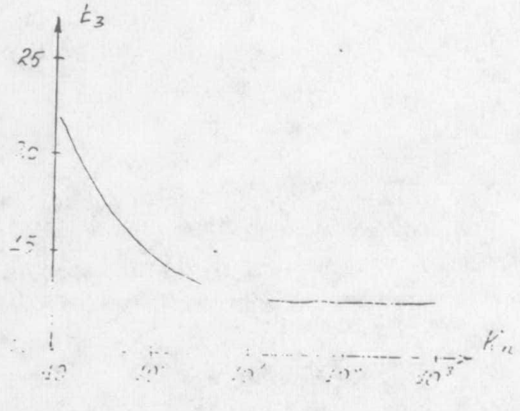
3. t_3 versus B_0 (molecular mode).



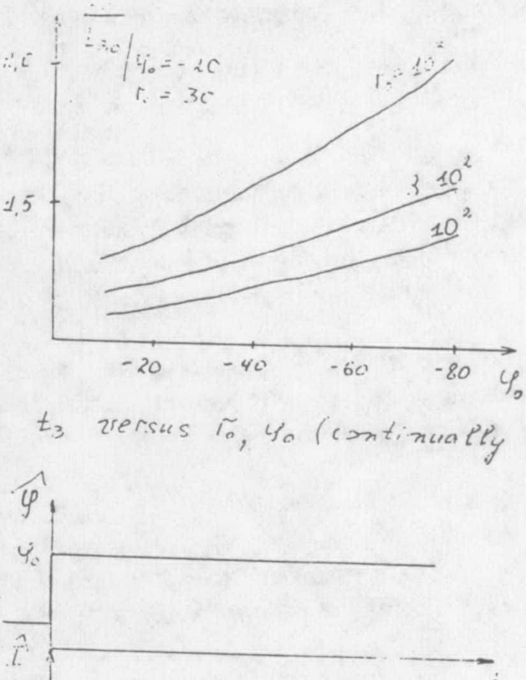
4. t_3 versus B_0 (continually mode).



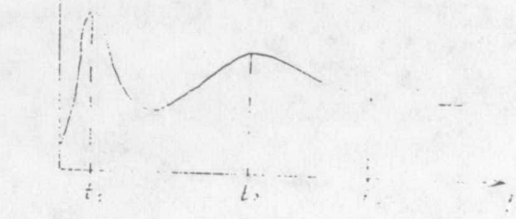
5. t_3 versus u_0 (continually mode



6. t_3 versus K_n (spherical mode)



7. t_3 versus τ_0, φ_0 (continually mode)



8. φ versus t and T versus t