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Probe diagnostics in helium plasma, generated by a volume source of fission fragments

Abstract. In the present paper experimental results of probe measurements in nuclear induced helium plasma are presented and analyzed. Both parts of volt–ampere characteristics (VAC) of the probe are used to get the density of electrons and positive ions in plasma. Plasma is formed by products of the reaction $^3He + n \to p + T + 0.76Mev$ and studied under the pressure to be equal 760 torr and neutral flux about 10^{13-14} cm^{-2} s^{-1}. The linear part of VAC and its slope might be used to evaluate density and temperature of the studied plasma. In some special cases like plasma diagnostics in the core of active of nuclear reactor the probe diagnostic methods is the only one possible experimental technique which makes possible to extract nuclear induced plasma property information. Electrostatic probe represents substantially a metal electrode placed in the diagnostic cell, inserted in the active zone of nuclear reactor and within which the tested mixture is uploaded.

Key words: helium, plasma, nuclear induced plasma, flux of thermal neutrons, volt ampere characteristics.

Introduction

Commonly known that electrostatic probe is used as a primary diagnostic tool in the measurement of the local parameters of the ionized gas in a variety of medium [1], such as the electrical discharge and afterglow, the ionization boundary region behind the shock waves, flames, MHD generators, plasma jet, as well as atmospheric and space plasmas. Despite its limited area of application the probe techniques of experimental measurements are very successful and rapidly developed in recent years. The probe diagnostics experimental set in nuclear reactor is schematically presented on the figure 1.

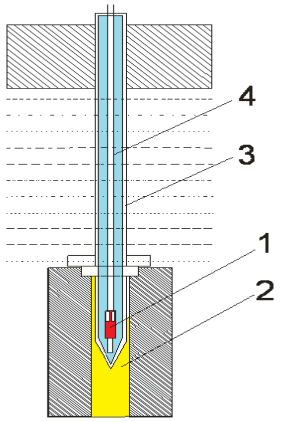
The plasma apparatus [3,7] is relatively simple, however, the theory of electrical probes complicated by the fact that the probe is boundary surface to the nuclear induced plasma, and the equations describing the behavior of the plasma near the interface are nonlinear [2]. The plasma created in the active zone of a nuclear reactor has a number of specific features. These include, in particular, inseparably related problems: chemical aggressiveness and toxicity of raw materials, the impossibility of direct contact with the experimental set due to induced radioactivity, making all of the experimental apparatus is only a one-time use as well as the obligatory remote control of the experiment set due to the irreversible structural changes in the measurement and diagnostic devices connected with strong radiation [3]. Plasma, created by fission fragments was initially described in the following papers by Leffert C.B. Reese D.B., Nguyen D. H., Grossman L.M. and Guyot J.C., Miley G.H., Verdeyen J.T. [4–6]. But direct probe measurement was undertaken in the present paper and the experimental studied in [3].

Experimental volt ampere characteristics analysis

The test ampulla of the ^{3}He gas was inserted in the flux of thermal neutrons absorbs thermal neutrons creating highly energetic particles, which cause in its own turn the ionization of the working medium through the following channel:

$$^3He + n \to p + T + 0.76MeV, \qquad (1)$$

where n – neutron, p – proton, T – tritium.



1 –Vial of the test mixture; 2 – the reactor core; 3 – Diagnostic channel; 4 – signal wires.

Figure 1 – Experimental setup for probe diagnostics of the plasma gas mixtures in the radiation field of a stationary nuclear reactor.

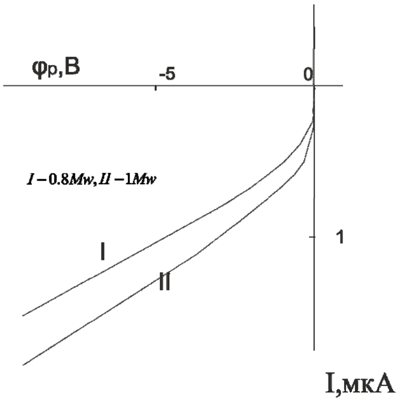
Reaction cross section (1) for thermal neutrons is 5400 barns and increases as its energy varies proportional to $E^{-0.5}$. The energy released distributed among the proton and triton as follows: the nucleus of tritium $-578\ kev$ and $198\ kev$ proton energy. The input power of the reaction ^{3}He (n, p) T per unit volume, estimated by the following expression:

$$P = 1.65 * \Phi * [^3He] \frac{W}{cm^3}, \qquad (2)$$

where Φ – neutron flux density.

The diagnostic channel into which the test cell inserted is made of steel pipe. The diagnostic cell has the shape of a cylinder with a diameter of 40 mm. At the bottom of the cell special tips are made to fill the gas mixture that is to be studied. In the center of the upper base of the cell the probes of different geometry configurations are welded, sealed and mounted to the signal wires. The probes are mounted on a ceramic holder. Non–operating part of the probe is protected from contact with plasma by insulator made of the quartz tubes. Pumping, heating and filling cells with gas mixture carried out with a high–vacuum unit [8].

In the present paper, the detailed quantitative consideration of this problem is made and compared with experimental data realized by one of the authors [7]. On the figure 2 and figure 3 the VAC of ion and electron branch are presented at different neutron fluxes and different geometry of probe in tested plasma.



Ion branches of the probes VAC in nuclear induced helium plasma

Power input 10^{-2} W/cm^3	Diffusion coefficient	Probe	10^{-7} A	n^+ 10^{10} см $^{-3}$	σ 10^{-6}	b_e см^2/V	n_e 10^{10} см $^{-3}$	n_i calculated
1.5	1.1	Spherical	0.7	1.7	36.57	13900	1.6	1.8
		plane	0.4	1.8	35.14		1.5	
3.0	1.2	Spherical	1.8	2.9	66.13	14334	2.9	2.8
		plane	0.8	2.7	64.23		2.8	
5.0	1.4	Spherical	4.6	5.2	87.14	15276	3.6	3.7
		plane	2.5	5.5	90.35	-	3.7	
7.5	1.6	Spherical	7.0	6.4	115.0	16382	5.0	4.2
		plane	3.8	6.6	107.9		5.3	

Figure 2 – Ion branches of VAC of probe in helium plasma.

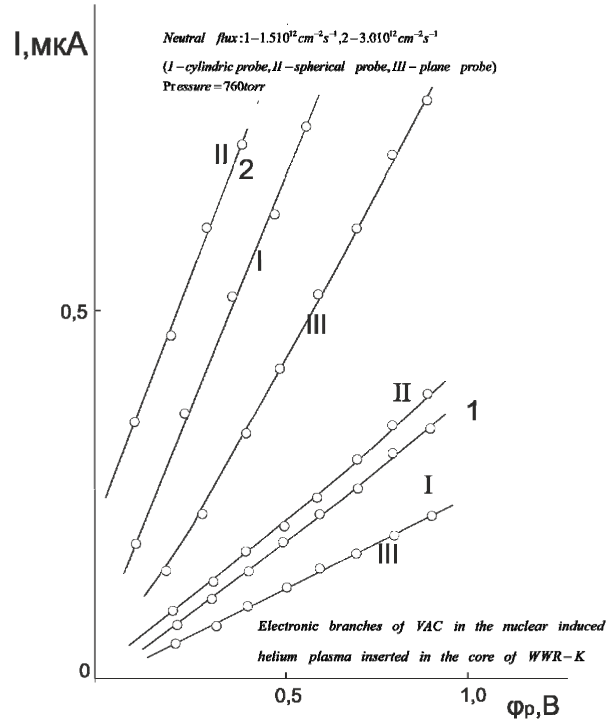


Figure 3– Electronic branches of VAC of probe in nuclear induced helium plasma.

At any surrounding probe surface we have:

$$\oint \overrightarrow{J^+}\, d\vec{s} = I_p^+, \qquad (3)$$

where I_p^+– current of positive ions on the probe.

$$\oint \overrightarrow{J^e}\, d\vec{s} = I_p^e, \qquad (4)$$

where I_p^e– current of electron on the probe.

We also accept that at any point:

$$I^e + I^+ = I_p. \qquad (5)$$

From experimental curve, we may notice that ion and electron branches of VAC at some definite region are linear and the slope might be exactly taken out from the experimental VAC.

In the charged volume layer, we may state that:

$$divJ^+ = S, \qquad (6)$$

and the radius of the layer is equal to:

$$r_0^+ = r_p\left(1 + \frac{I_p^+}{4\pi e S r_p^3}\right)^{\frac{1}{3}}, \qquad (7)$$

where e – electron's charge.

From this we may obtain, that:

$$I_p^+ = 4\pi e r_0^+ n^+ b^+ \varphi_p^{negative}, \qquad (8)$$

where $\varphi_p^{negative}$ – probe's potential, b$^+$– mobility coefficient, r_0^+– length charge layer.

To get concentration of positive ions in plasma we come to the following:

$$n^+ = \frac{\tan\alpha^+}{4\pi e b^+ r_0^+}, \qquad (9)$$

where

$$\tan\alpha^+ = \frac{\Delta I^+}{\Delta\varphi^{negative}}. \qquad (10)$$

Then we also may evaluate the electron's temperature:

$$T_e = \frac{\lambda_e m_i}{\lambda_i m_e}\left(\frac{\tan\alpha_i}{\tan\alpha_e}\right)^2 \left(\frac{1+\beta I_p{}^e}{1+\beta I_p{}^i}\right)^{\frac{2}{3}}, \qquad (11)$$

Where λ_e – electron mean free path in nuclear induced plasma, λ_i – ions mean free path in nuclear induced plasma. The coefficient β is equal:

$$\beta = \frac{3}{4\pi e S r_p^3}$$

On the VAC in figure 4 it is shown how the estimation might be done.

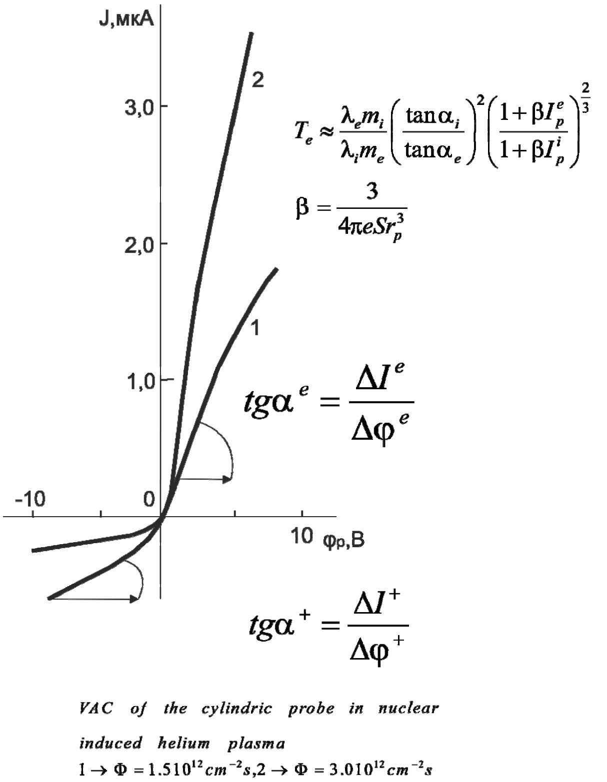


Figure 4– The ion and electronic branchesof experimentally measured current–voltage characteristics for plane and spherical probes.

Preceding our evaluations for positive values of the probe potential then for electronic part of the probe VAC we get:

$$I_p^e = 4\pi e r_0^e n^e \varphi_p^{positive}. \tag{12}$$

From (6) and Poisson equation for charged layer the potential obeys to the following differential equation:

$$\varepsilon\omega^+\theta[\frac{\partial^3\Psi}{\partial\xi^3}\frac{\partial\Psi}{\partial\xi}+[\frac{\partial\Psi}{\partial\xi}]^2]=1, \tag{13}$$

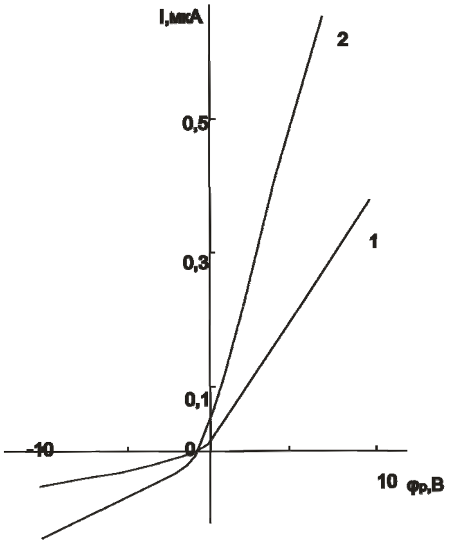
where

$$\xi = \frac{r}{r_p}, \theta = \frac{T^e}{T^+}, \omega^+ = \frac{D^+ n_\infty^+}{S}, \varepsilon = (\frac{r_d}{r_p})^2, \Psi = \frac{\phi}{\frac{kT^e}{e}}.$$

Boundary conditions are as follows:

$$\Psi(1) = \Psi_p, \Psi''(1) = 0. \tag{2.14}$$

The solution of (2.13) gives the confirmation of the linear dependence of experimental probe's VAC in this part of applied electric potential (Figure 5).



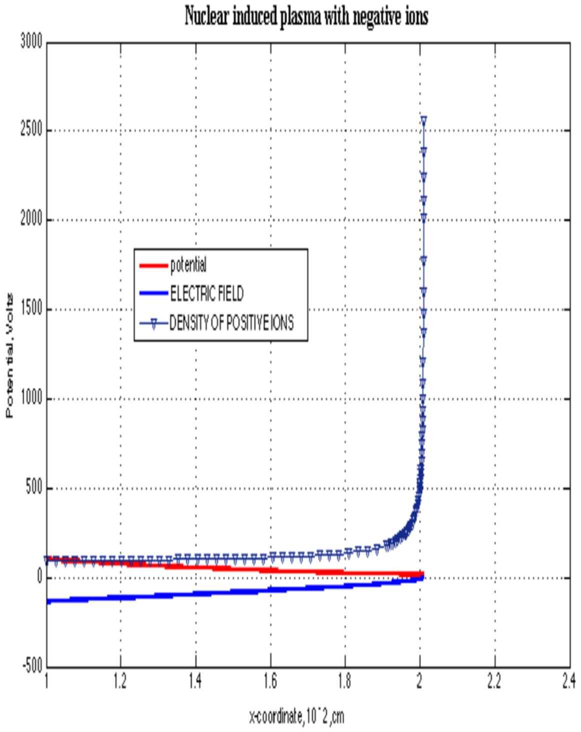


Figure 5 – Numerical solution of the equation (2.13–2.14) shows the drop of probe potential within one probe's size.

Electric field in the charged layer

$$\frac{\partial\phi}{\partial r}=\sqrt{\beta}r_0(1-\xi^2{}_0)^{\frac{1}{2}},\beta=\frac{4\pi eS}{b^+},\quad(15)$$

where

$$r_0 = r_p + (\frac{36}{25}\frac{\varphi_p^2}{\beta})^{\frac{1}{4}}.\quad(17)$$

Results and conclusion

The balance equations for particles of He^+, He^{+2}, He^{+3} and the electron energy balance equations were composed, which take into account all sources of primary electrons [10]. It is assumed that the cooling of electrons occurs due to elastic collisions with helium atoms. System of these equations were solved for the case of quasi–stationary numerical method. At rates of ion formation at 10^{15}–10^{16}cm^{-3}s^{-1}, the electron temperature of the plasma close to the temperature of heavy particles.

Table 1 – The concentrations of electrons and ions derived from experimentally measured current–voltage characteristics.

W, kWh	He^+, sm^{-3} x10^7	$He_2{}^+$, sm^{-3} x10^7	$He_3{}^+$, sm^{-3} x10^{11}
200	3.7	1.3	1.7
500	9.3	3.2	2.8
800	14.9	5.0	3.6
1000	18.6	6.2	4.3

Primary ions, formed by the interaction of high–energy fission products ^3He are intermediate He^+ ions and electrons. In plasma at high pressure (760 torr) in an inert gas the conditions are favorable for the formation of molecular ions He^{+2}. He^{+2} recombination time is large, and time conversion to He^{+3} ions is small, so the of molecular ions He^{+2}. He^{+2} recombination time is large, and time conversion to He^{+3} ions is small, so the ions He^{+2} are also negligible.The ratio of the concentration of ions He^{+} and He^{+2}, He^{+3} concentration is around of 10^{-3}– 10^{-2}. In connection with the above, the main channel for electron loss is a reaction of dissociative recombination with ions He3 +. The results of these calculations are presented in Figure 6.

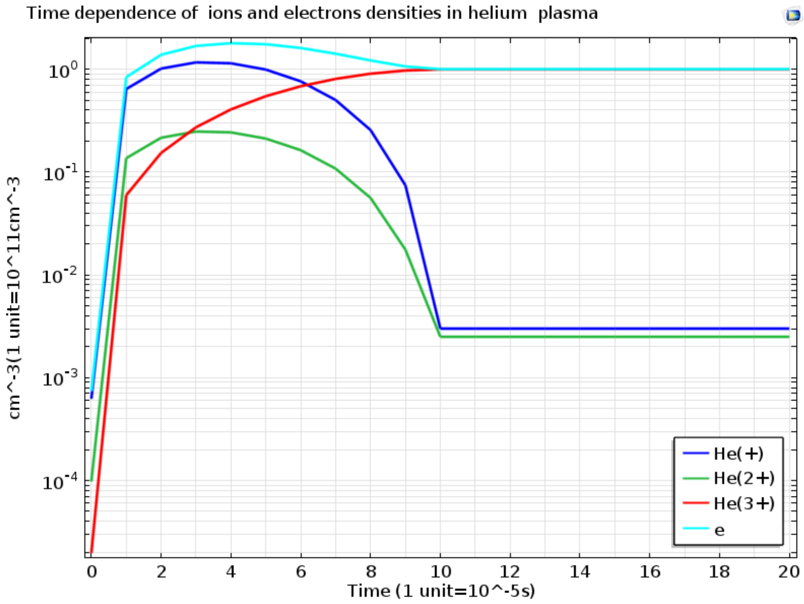


Figure 6 – Time dependence of ions and electrons density in nuclear induced helium plasma.

The concentrations of electrons and ions derived from experimentally measured current–voltage characteristics are shown in Table 1. The results are in good agreement, both among themselves and with the results of numerical calculations.The experimental VAC in some regions is linear from probe potential and the slopes of the curve might be used to evaluatethe density and temperature of electrons in nuclear induced plasma.

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