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The aim of this work is the development of a procedure for the characterization of a collisionless plasma using the current–voltage characteristic of a cylindrical probe perpendicular to the plasma flow at an arbitrary

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ratio of the probe and reference electrode current-collecting areas. Using familiar theoretical and experimental ion and electron current vs. probe potential relationships, a mathematical model of current collection was constructed for a probe system with cylindrical electrodes. The model includes the calculation of the reference electrode equilibrium potential as a function of the probe bias voltage. Based on this theoretical model of the current-voltage characteristic of a cylindrical probe in a supersonic flow of a low-temperature nonisothermal collisionless plasma, a procedure was developed for kinetic plasma parameter extraction using a priori information on the plasma properties and the experimental conditions. The procedure is based on the determination of the values of the charged particle temperature and density, the flow velocity, and the ion mass such that the theoretical current-voltage characteristic best fits the experimental one. The a priori information on the plasma properties and the experimental conditions is specified as restrictions on the parameters of the theoretical current-voltage characteristic.

The sensitivity of the current-voltage characteristic of cylindrical probe to small variations of the unperturbed plasma parameters was studied as function of the ratio of the probe and cylindrical reference electrode current-collecting surface areas. Quantitative characteristics of the effect of the area ratio on the current-voltage characteristic of a cylindrical probe were obtained. Probe measurements in the ionosphere were numerically simulated. The operability of the kinetic plasma parameter extraction procedure was demonstrated. The effect of probe measurement errors on the extraction of the plasma parameters was numerically studied. Within the adopted assumptions, the reliability of unperturbed plasma parameter extraction was estimated as a function of the current-voltage characteristic measurement accuracy. The results obtained may be used in ionospheric plasma diagnostics.

**Keywords:** nonisothermal collisionless plasma flow, Cylindrical Langmuir probe, reference electrode, characterization, a priori information, plasma characterization reliability.

( )

[1]

( ) ( ) ,

$S_z \quad S_{pz}$

: ( $S_z \ll S_{pz}$ )

( $S_z \approx S_{pz}$ ) [1 - 3].

, ( ) ,

$S_z \ll S_{pz}$

[4]

[4]

$( \dots ) r_{pz} , r_z ,$   
 $( \dots ) ,$   
 $T_e , T_i , m_i , n ,$   
 $S_i = V/u_i ,$   
 $\xi = r_c/\lambda_d ,$   
 $\mu = m_e/m_i , \beta = T_e/T_i , u_i = \sqrt{2kT_i/m_i}$   
 $, k - , r_c -$   
 $, \lambda_d -$   
 $\varphi , m_e -$

[4],

[5],

[6] [4, 7, 8].

[4] (

):

$$\bar{I}_c(\varphi) = \bar{I}_e(\varphi) + \bar{I}_i(\varphi), \tag{1}$$

$$\bar{I}_e(\varphi) = \begin{cases} 2/\sqrt{\pi} \cdot \sqrt{\pi/4 + \varphi}, & \varphi > 0; \\ \exp(\varphi), & \varphi \leq 0 \end{cases} \tag{2}$$

$$\bar{I}_i(\varphi) = \begin{cases} -\sqrt{\mu/\beta} \sqrt{2/\pi} \exp(-\beta\varphi + S_i^2), & \varphi \geq S_i^2/\beta; \\ -\sqrt{\mu/\beta} \sqrt{2/\pi} \sqrt{1/2 + S_i^2 - \beta\varphi}, & \varphi < S_i^2/\beta \end{cases}, \tag{3}$$

$$\bar{I}_c = I_{e,0} = j_{e,0} \cdot S_c, \quad j_{e,0} = enu_e / 2\sqrt{\pi} -$$

$$, \quad u_e = \sqrt{2kT_e/m_e} - , \quad S_c =$$

$$, \quad \mathbf{e} - \quad i$$

$$I_c$$

$$U$$

$$\bar{I}_c : I_c(U) = j_{e,0} \cdot S_c \cdot \bar{I}_c(eU/kT_e). \quad (4)$$

$$\xi \leq 1 \quad [2, 7], \quad (2)$$

$$S_i \geq 4 \quad (3)$$

$$\xi \leq 10 \quad [4, 8, 9, 10].$$

$$(1) - (3) \quad ( S_i \geq 4, \xi \leq 10. - \xi \leq 1. )$$

$$r_z \quad r_{pz}$$

$$\xi. \quad [4, 10], \quad (1) - (3)$$

$$(\quad 3-5) \% \quad S_i \geq 4, \quad \xi \leq 10,$$

$$\varphi \geq -50.$$

$$I_z \quad " \quad - \quad - \quad " \quad (U_{iz} = U_z - U_{pz},$$

$$U_{iz} \quad U_z, \quad U_{pz} \quad - \quad - U_z = U_{iz} + U_{pz}.$$

$$).$$

$$[1]. \quad ($$

$$U_{iz})$$

$$, \quad U_{iz}$$

$$U_{pz},$$

$$\bar{I}_c(\varphi_{pz}) \cdot S_s + \bar{I}_c(\varphi_{pz} + \varphi_{iz}) = 0, \quad (5)$$

$$S_s = S_{pz} / S_z -$$

$$\bar{I}_c(\varphi_{pz}) \quad \bar{I}_c(\varphi_{pz} + \varphi_{iz}) -$$

$$(1) - (3). \quad (5)$$

$$- \varphi_{pz} = \Phi(\varphi_{iz}).$$

$$U_{pz}(U_{iz}) = \Phi(eU_{iz}/kT_e) \cdot kT_e/e.$$

$$\bar{I}_z(\varphi_{iz}) = \bar{I}_c(\Phi(\varphi_{iz}) + \varphi_{iz}),$$

$$I_z(U_{iz}) = j_{e0} \cdot S_z \cdot \bar{I}_c(\Phi(eU_{iz}/kT_e) + eU_{iz}/kT_e). \quad (6)$$

$$\beta, S_i \quad (1) - (3) [4],$$

$$\Phi(\varphi_{iz}) \quad (5)$$

$$\varphi_{iz}$$

$$(6) \quad (1) - (5),$$

$$\mu, \beta, S_i, S_s, \varphi_{iz},$$

$$m_i, T_i, T_e, n, V, S_z, S_{pz}, U_{iz}.$$

$$\bar{I}_z(\varphi_{iz})$$

$$S_s ($$

$$)$$

$$)$$

$$)$$

$$)$$

$$\varphi_{pz}$$

$$\varphi_{iz}$$

$$S_s.$$

$$S_i = 4,8,$$

$$\mu = 3,7 \cdot 10^{-5} \quad \beta = 1,27,$$

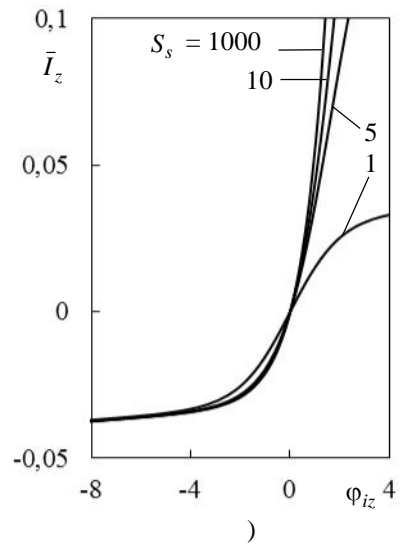
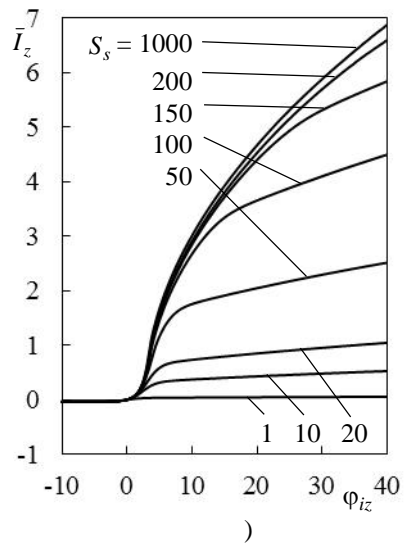
$$700 \quad [4].$$

$$S_{pz},$$

$$S_s \approx 10,$$

$$. 1, ).$$

$$n$$



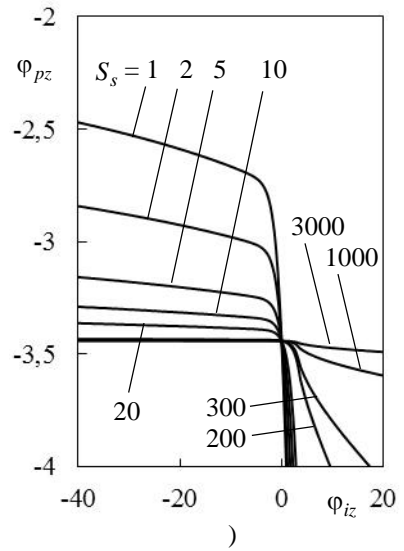
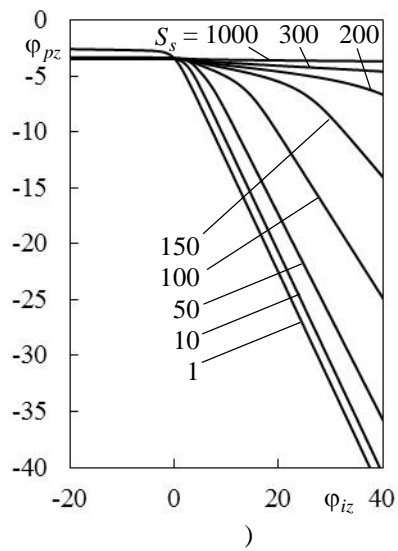
.1

,  
 $S_s^*$   
 :  $S_s < S_s^*$   
 ;  $S_s > S_s^*$  -  
 ( .1).  
 $S_s^*$ .

.2, )

$S_s$ ,

$\varphi_{iz}$



.2

$$\varphi_{iz} < 200 - S_s^* \approx 9,5, \quad \varphi_{iz} < 40, \quad S_s^* \approx 18, \\ [1 - 3], \quad -$$

$$S_s \geq 10^4, \quad -$$

$S_s$ .

(1) – (6)  
[4],

$$\mu, \beta, T_e, n, V, S_s. \quad (7)$$

$$P \quad (7), \\ (6), \quad (1) - (5),$$

:

$$I_z(U_{iz}, P) = j_{e0}(P) \cdot S_z \cdot \bar{I}_c(\varphi_z(U_{iz}, P), P),$$

$$\varphi_z(U_{iz}, P) = eU_{iz}/kT_e + \Phi(eU_{iz}/kT_e, P),$$

$$\varphi_z(U_{iz}, P) - \Phi(\varphi_{iz}, P) - ,$$

$$(7), \quad \varphi_{iz} \quad P \\ (5). \quad I(U_{iz}) -$$

$$I_z(U_{iz}, P) \quad (7), \quad I_3(U_{iz}). \\ (7)$$

[4]:

$$P^* : F(P^*) = \min_{P \in D} F(P), \quad F(P) = \|I_z(U_{iz}, P) - I(U_{iz})\|_{M_{iz}}. \quad (8)$$

$$\|f(U_{iz})\|_{M_{iz}} - f(U_{iz}), \\ M_{iz}, D -$$

$$P : P^{\min} \leq P \leq P^{\max}, \quad P^{\min}, P^{\max} - \\ (7). -$$

(7)

[4].

$$(1) - (4), (6), \quad (5), \quad U_{iz} \quad (7). \\ - , -$$

$$U_{iz} + U_{pz}(U_{iz}, P) = 0, \quad U_{iz} + U_{pz}(U_{iz}, P) = m_e / e \cdot V^2 / 2\mu.$$

$$(U_{iz}, P), \quad I_z(U_{iz}, P) \quad -$$

$$\quad \quad \quad D \quad I_z(U_{iz}, P) \quad -$$

$$\quad \quad \quad (8) \quad \quad \quad -$$

$$\quad \quad \quad \quad \quad \quad F(P) \quad -$$

$$\quad \quad \quad \quad \quad \quad \rho \quad -$$

$$(7). \quad \quad \quad I_z(U_{iz}, P) \quad -$$

$$P_0 = (\mu_0, \beta_0, T_{e0}, n_0, V_0, S_{s0}) \quad -$$

$$\rho: \quad \quad \quad -$$

$$\bar{I}_{z,p}(U_{iz}, P_0) = \frac{p_0}{j_{e0} \cdot S_z} \frac{\partial I_z(U_{iz}, P_0)}{\partial p}.$$

$$(7) \quad p = p_0(1 + \varepsilon_p), \quad P_0$$

$$\bar{I}_z(U_{iz}, P) \approx \bar{I}_z(U_{iz}, P_0) + \sum_p \varepsilon_p \bar{I}_{z,p}(U_{iz}, P_0). \quad (9)$$

(7)

$S_s$  700 .  $P_B$  (7)

[4]. (1) – (6) [4]

(1) – (6) [4] " " (5).  $T_e$

$U_{pz}$   $n$ , -

$T_e$ , (1) – (6) [4]

"  $n, \mu, \beta, V$  "  $S_s > 200$  -

" [4] " -

"  $n$ ,  $\mu$  -



$\beta$

$S_s > 500$

$V$  -

$T_e$

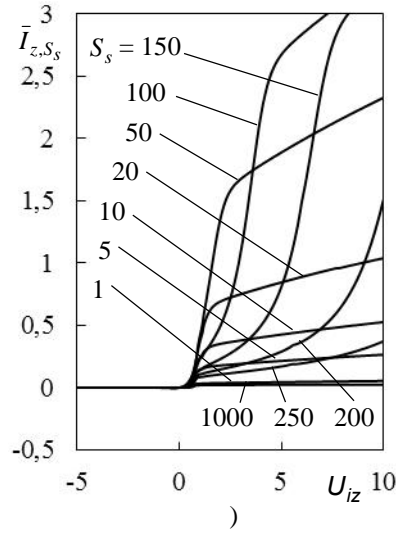
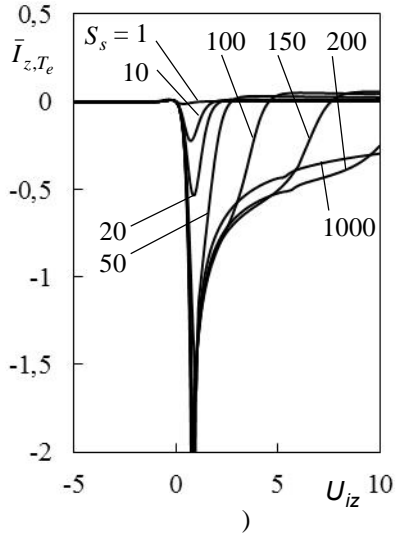
.3

(1) - (6)

$T_e ( )$

$S_s ( )$

$U_{iz}$



.3

$S_s$  .

(7).

.3

$P_B$

$T_e$

$S_s$  .

$S_s > 100$

$S_s$

$T_e$

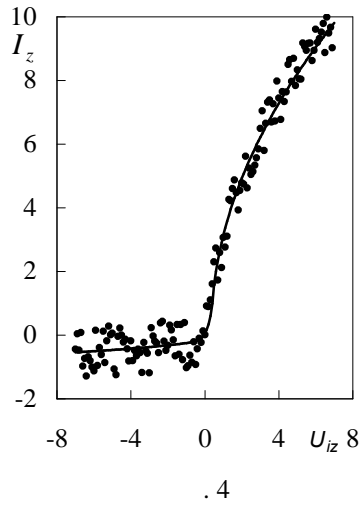
$U_{iz}$  .

$S_s > 300$

$T_e$

(7)

$S_s = 1000$ .



(7)

$I_z$  20%

(7),

.4 (

$U_{iz}$

[4],

(9)

-10 +10 ~100

$$|\tilde{p} - \bar{p}| \leq \Delta_p \approx \delta_p \cdot |\bar{p}|, \quad |\bar{p}| \gg 0$$

$$|\tilde{I} - \bar{I}| \leq \Delta_I \approx \delta_I \cdot M_I, \quad M_I > 0.$$

$p$  -

(7);  $\Delta$  -

$\delta$  -

$M_I$  -

(7);

"

"

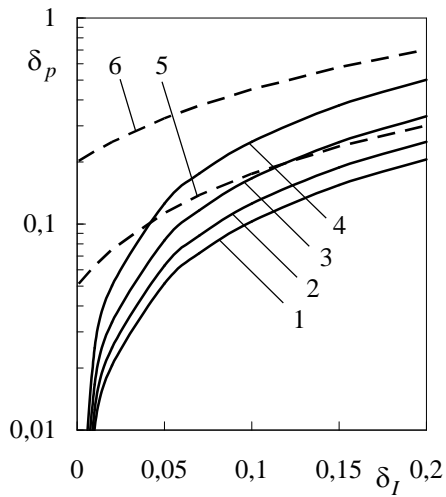
"

"

,

.5

$\delta_p$



(7)

$\delta_I$ :

1

$n$ ; 2 -

$V$

$\delta_\mu = 0$ ; 3 -

$T_e$ ;

4 -

$\mu$

$\delta_V = 0$ ; 5 -

$V$

$\delta_\mu = 0, 1$ ; 6 -  $\mu$

$\delta_V = 0, 1$ .

.5

(9)

(1) – (6)  
[4].

:

$$M_I = \begin{cases} I_{\max} & |I_{\text{э}}| > I_{\text{э}0}, \\ I_{\text{э}0} & |I_{\text{э}}| < I_{\text{э}0}, U_{\text{из}} > U^*, \\ 0,025 \cdot I_{\text{э}0} & |I_{\text{э}}| < I_{\text{э}0}, U_{\text{из}} \leq U^*, \end{cases}$$

$I_{\max}$  –

;  $I_{\text{э}0}$  –

;  $U^*$  –

(

$U^* = -1$  ).

1. . . . . 1971. . 506–538. / . . . . .
2. . . . . 1978. 201 .
3. . . . . , 1969. 291 .
4. . . . . 2018. 1. . 107–120. <https://doi.org/10.15407/itm2018.01.107>

