THE TRANSPORT PHENOMENA IN NON-ISOTHERMAL MULTISPECIE PLASMA.

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The study of multispecie plasma properties is important for practically all modern plasma applications. The multispecie plasma with hot electrons is considered. It is obtained that the separation of the plasma into the regions with different ion composition is a universal property of such a plasma.

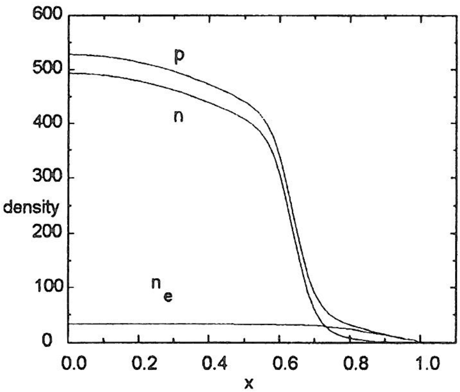

Fig. 1. Density profiles in positive column of dc dicharge in electronegative gas, the product of attachment frequency and difusion time ($L^2/(b_i T_e)$)equals to 10, the same product for detachment equals to 1.

The detailed analysis of the transport problems for multispecie non-isothermal plasma was performed recently for discharges in electronegative gases. The positive column [1-3], and capacitively coupled RF discharge [4-6] were investigated. The obtained profiles of ion densities consisted of two regions of different ion composition. The first one is situated near the discharge boundary; negative ion density (n) is small here compared with electron (n_e) and positive ion (p) densities (see fig. 1). The second region is situated in the discharge center, and n_e values are small here compared with n, p ones. These regions are divided by narrow transition region where ion density profiles have a very steep slope; practically ion density shocks are formed in this region.

It is well known that shocks are formed in systems, which are described by non-linear transport equations, where the signal propagation velocity depends non-linearly on ion density [7]. For current carrying multispicie plasma the shock formation was demonstrated in [7]. In plasma with two different species of positive ions (n_1 and n_2) electric field is $E = j / b_e(n_1 + n_2)$, where j - current density, b_e - electron mobility. The ion flux is $\Gamma_i = jb_i n_i / b_e(n_1 + n_2)$, i=1,2, b_i - ion mobility and $\Gamma_i(n_1, n_2)$is nonlinear function so that shocks of ion densities can be formed [7]. Moreover if $\Gamma_i(n_1, n_2)$ is nonmonotonic function the stationary shocks are possible.

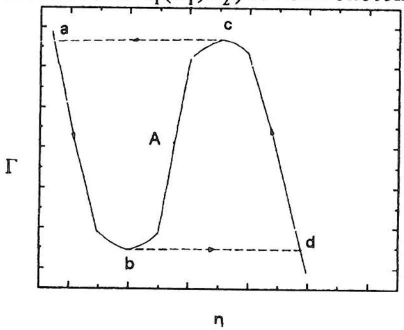

Fig. 2.
The N-type dependenceof flux Γ(n).

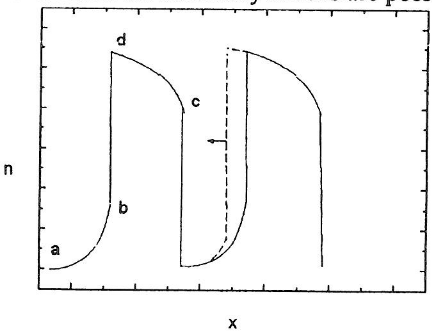

Fig.3
The density profile in periodical structure.

The periodical structure with shocks was proposed in [8]. The necessary conditions of this structure formation is N-type dependence of Γ(n) function and instability of equilibrium point A (which must be in region (bc), see fig. 2,3).
It should be mentioned that this structure is unstable. A slight shift of the shock leads to further displacement from the stationary position, and in a result the shocks collide and dissappeare.

In currentless plasma the dependence of ion fluxes on ion densities is much more complicated. So let's study the signal propagation in non-isothermal currentless multi-species plasma. We shall consider collisional situation, where charged particles fluxes are described by diffusion and drift in electric field:

$$\frac{\partial n_\alpha}{\partial t} + \frac{\partial}{\partial x}(-D_\alpha \frac{\partial n_\alpha}{\partial x} - Z_\alpha e b_\alpha n_\alpha \frac{\partial \phi}{\partial x}) = 0 \qquad (1)$$

We assume, that Debye radius is small, and a qusineutrality condition is hold:

$$\sum Z_\alpha n_\alpha = 0 \ , \qquad (2)$$

where n_α- density of charged particles of specie α; D_α, b_α- diffusion and mobility coefficients, $D_\alpha = b_\alpha T_e$; Z_α - particles charge number. We shall neglect temperature gradient and assume that T_α is constant (x). If the electron density is not too small compared with ion ones: $b_e n_e >> b_i n_i$, from equations (1) and (2) it follows that due to large electron mobility electrons are trapped by electric field and Boltzmann distribution $n_e = n_o \exp(e\phi / T_e)$ is fulfilled. In the gas discharge plasma usually electron temperature is large compared with ion ones. So the drift in electric field is the main mechanism of ion transport. For plasma with two ion species of ions with density p (with charge number equals to unity) and n (with charge number Z= ±1), there are two transport equations and quasinetrality condition:

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial x}\left(\frac{d_n Z n}{n_e}\frac{\partial n_e}{\partial x}\right) = 0\ ,\ \frac{\partial p}{\partial t} - \frac{\partial}{\partial x}\left(\frac{d_p p}{n_e}\frac{\partial n_e}{\partial x}\right) = 0,\ n_e = p + Zn, \qquad (3\ a,b,c)$$

where $d_\alpha = b_\alpha T_e$. Let's analyse the small signal propagation in non-homogeneous plasma: $\partial n_e^o / \partial x = \mathrm{const}(x)$, $n^o / n_e^o = \mathrm{const}(x)$. The ion and electron density variations n_α are taken in the form: $n_\alpha = \delta n_\alpha \exp(-i\omega t + ikx)$. The solution of the equations system (3) (for kL>>1, $L = [\partial \ln n_e^o / \partial x]^{-1}$) splits into two modes with frequencies:

$$\omega_1 = -D_{ef} i k^2,\ \ D_{ef}(n^o/n_e^o) = (d_n n^o + d_p p^o) / n_e^o \qquad (4a)$$

$$\omega_2 = u_{ef} k,\ \ u_{ef}(n^o/n_e^o) = Z d_n d_p n_e^o / (L(d_n n^o + d_p p^o)) \qquad (4b)$$

The first mode is analogous to ambipolar diffusion. The combination of equations (3) gives the diffusion equation for n_e:

$$\frac{\partial n_e}{\partial t} - \frac{\partial}{\partial x}\left(D_{ef}\frac{\partial n_e}{\partial x}\right) = 0 \qquad (5).$$

For $n^o/n_e^o = 0$ or $d_n = d_p, Z = 1$, the equation (5) is usual ambipolar diffusion equation. If $n^o/n_e^o >> 1$, D_{ef} is large compared with ambipolar diffusion coefficient. The physical description of the second mode is more complicated. If $n^o/n_e^o << 1$, u_{ef} coincides with the drift velocity of ions n. If $n^o/n_e^o >> 1$, u_{ef} is small compared with drift one. It is result of coupling of equations in system (3). Under our conditions $\omega_2 << \omega_1$, and divergence of effective electron flux $\Gamma_e = -D_{ef}(n,p)\partial n_e / \partial x$ is small for the second mode. So Γ_e is practically const(x). Substituting $\partial n_e^o / \partial x$ from expression for effective electron flux Γ_e, equation (3a) takes a form :

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial x}\Gamma_n = 0\ ,\ \Gamma_n(n/n_e) = Z d_n n \Gamma_e / (d_n n + d_p p) \qquad (6)$$

The plot of $\Gamma_n(n/n_e)$is shown in Fig. 4. Linearisation of equation (6) results in expression (4b) for u_{ef}. Signal propagation velocity $u_{ef}(n/n_e)$ depends on ion density n. It means that during the non-linear evolution of plasma inhomogeniety the

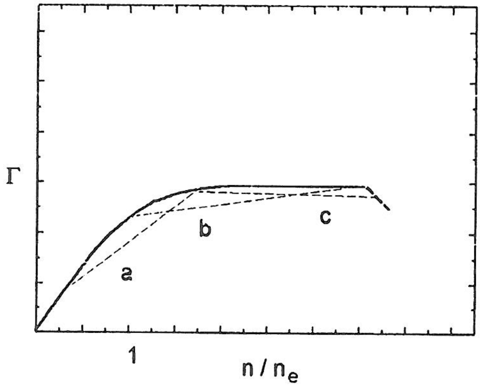

Fig. 4. The dependence of $\Gamma_n(n/n_e)$.

shock formation of ion density is possible [6]. The evolution of plasma profiles are shown in Fig. 5,6; the shock formation is clearly seen. The shock velocity is determined by flux conservation

$$V_{1,2} = (\Gamma(n_2) - \Gamma(n_1))/(n_2 - n_1)$$

(see Fig. 4). The width of shock is determined by ion diffusion and is proportional to T_i/T_e. The expressions for velocity and width of these shocks are obtained in [6]. The equations (5) and (6) are valid for analysis of non-linear stage of evolution also, because in the place of shock formation n_e changes are small. The duration of shock formation is proportional to $(\partial u_{ef}/\partial n)^{-1}$. The maximum $(\partial u_{ef}/\partial n)^{-1}$ is at n=0. It means that shocks are formed preferably in regions where initial values of n are small (see Fig.5,6). Even if such regions were absent initially, they arise during an evolution [6].

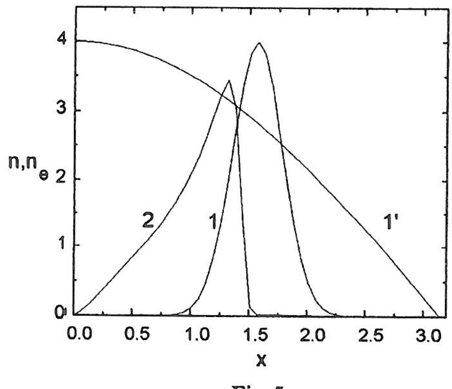

Fig.5

Profiles of negative ions density n and electrons density n_e. Initial profiles of densities: 1 - negative ions $n(x,0)=4\exp(-11(x-p/2)^2)$; 1' - electrons $n_e(x,0)=2(1,1+\cos x)$; 2 - profile n at t=5;

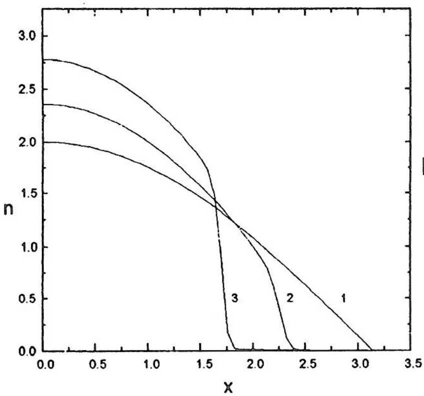

Fig.6 (a)

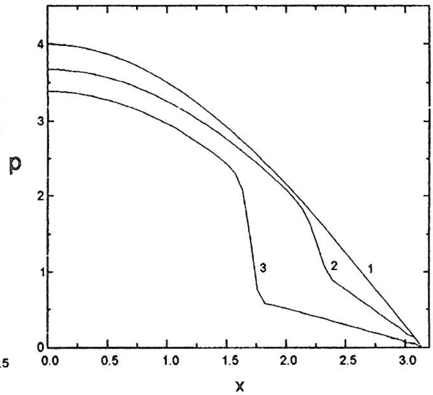

Fig.6 (b)

Fig.6 (a) Profiles of negative ions density. Initial profiles of density: negative ions n(x,0)=(1+cosx); positive ions p(x,0)=2(1+cosx); mobility ration D=0,5; zero boundary conditions at x=3.14 were used. Profiles of negative ions density correspond to: 1 - t=0; 2- t=1; 3 - t=5. $T_i = 0$

Fig.6 (b) Profiles of positive ions densities; conditions are the same as in Fig 6(a).

Such plasma separation into regions of different ion composition is a sort of self-organisation process. For constant ion mobilities, Z=-1 and fixed n_e the flux $\Gamma_n(n)$ is monotoncus function. It means that at moderate n/n_e only moving shocks are possible in this system (see Fig.4. line a). But $\partial \Gamma_n/\partial n \rightarrow 0$ for $n/n_e \rightarrow \infty$ and asymptotic stationary shocks can be formed, which divide regions of electron-ion ($n/n_e<1$), and ion-ion ($n/n_e>>1$) plasmas [1-3] (see Fig.4. line b). If ion mobilities depend on ion density (f.e. due to ion-ion coulomb collision) and stationary shocks can be formed.

The derived formalism is applied for analysis of spatial structures of positive column of dc discharge and of RF discharge with negative ions. The received analytical formulae agree with numerical modelling and allow to understand the complicated spatial structure of these discharges.

In the bounded plasma he electric field drags the negative ions from periphery region to the centre. If in plasma centre $n >> n_e$ the shock of ion densty arises. They usually occur in plasma close to the plasma - sheath boundary. If the place of ion density growth coincides with the place where electric field diminishes rapidly to zero (in plasma centre or at the end of sheath region in RFC discharge) the peaks of ion density can be formed. In Fig. 1 the typical profiles in dc discharge are shown, where the shock arises near the plasma boundary.

So the conception of shocks in plasma composition is very useful and powerful approach for solution of problems in non-stationary inhomogenious multispiece plasma.

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