SPACE PLASMA

# DYNAMICS OF NONQUASINEUTRAL CURRENT FILAMENTS ON DIFFERENT SPACE – TIME SCALES

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The earlier obtained results on the equilibrium and dynamics of the nonquasineutral current filaments for the size scale on the order of 1 μm and the time on the order of 1 ps are being applied to the objects in the atmosphere, the ionosphere and in the interstellar space. The main feature of the equilibrium for the electron current filament consists in the presence of the strong electric field that appears as a result of the charge separation at the magnetic Debye radius $r_B$. The numerical calculations of the ion dynamics due to the electric field of the filament are performed. It was obtained that the same equations can describe the equilibria and dynamics of the filaments from the micron size scale to the length of about millions km. Some arguments are presented in order to introduce a new approach for the lightning phenomena, where the magnetic field of the current in the lightning channel may play a decisive role.

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## INTRODUCTION

By the investigations of the laser pulses and the large currents in high density plasmas the appearance of the current filaments is a commonplace [1,2]. Therefore the analysis of the structures of the current filaments and their dynamics in high density plasmas is a very important direction of the contemporary investigations [3,4]. In this case the generation of the current filaments in the magnetic field range $4\pi n_e m_e c^2 << \vec{B}^2 << 4\pi n_i m_i c^2$ results in the charge separation at the magnetic Debye scale $r_B \sim |\vec{B}|/(4\pi e n_e)$ and the appearance of a very high radial electric field that leads to the ion acceleration in the radial direction. Such phenomena, which are connected with the appearance of the current filament in the laser and the Z-pinch plasmas displayed at a very small size scale on the order of 1μm and a time scale on the order of 1 ps. However, it is obvious that these phenomena can occur also in some another space-time scales, where there exist the diverse plasma densities and the magnetic field's magnitudes. The appearance of the current filaments on different space-time scales is connected with the presence of the magnetic field everywhere in our planetary system and in the cosmic space. One can show that in definite ranges of the magnetic field and the plasma density, the same equations can describe equilibria and dynamics of the filaments with the size scales from $10^{-4}$ cm to $10^6$ km. As a very interesting object for the possible application of the nonquasineutral current filament presents the lightning phenomenon in the Earth atmosphere, where already at the dart leader phase the current magnitude of about 11 kA is registered in the last measurements [5]. The simultaneous appearance of the x-ray emission in the 30-250 keV range and also the gamma-ray burst with the energies extending up to more than 10 MeV in the dart leader stage of the lightning may be explained within the framework of the present approach. In addition, the return stroke phase of the lightning may be interpreted as a reflected magnetic self-insulation wave [6].

## PHYSICAL MODEL AND MAIN EQUATIONS

By the describing of the nonquasineutral current filament structure in the limit of the relativistic electron equations the plasma dynamics can be considered in the following range of the magnetic field

$$4\pi n_e m_e c^2 << \vec{B}^2 << 4\pi n_i m_i c^2 \qquad (1)$$

The l.h.s. of this inequality corresponds to the nonquasineutrality of the electron filament at the Debye magnetic radius $r_B \sim |\vec{B}|/4\pi e n_e$ and the r.h.s. of the inequality (1) results in the appearance of the quasistatic approximation for electrons as the small parameter $\varepsilon = \omega_{pi} r_B/c << 1$. Taking into account the quasistatic approximation for electrons and introducing the dimensionless quantities

$$B_{\theta,z}=b_{1,2}\sqrt{4\pi m_e c^2 n_{e\infty}},\ v_{ez,\theta}=v_{1,2}c,\ n_e=\nu n_{e\infty},$$

$$n_i=n\frac{n_{e\infty}}{Z},\ I_1=4\pi e i_1,\ I_2=i_2\sqrt{\frac{4\pi m_e c^2}{n_{e\infty}}},$$

one can obtain the system of the equations, which describes the quasistatic electron filament structure in accordance with the earlier constructed theory [3,4]

$$\gamma\frac{\partial v_1}{\partial\rho}=(1-v_1^2)(\rho\nu i_1-b_1)+v_1 v_2(\nu i_2-g_2),$$
$$-\nu v_1=\frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho b_1) \qquad (2)$$

$$\gamma\frac{\partial v_2}{\partial\rho}=-(1-v_2^2)(\nu i_2-g_2)-v_1 v_2(\rho\nu i_1-b_1),$$
$$\nu v_2=\frac{\partial b_2}{\partial\rho},\quad g_2=b_2-\frac{\gamma v_2}{\rho}, \qquad (3)$$

$$\nu=\frac{\gamma n+2v_1 v_2 b_1 g_2+\gamma^2 v_2^2/\rho^2+(1-v_1^2)b_1^2+(1-v_2^2)g \ldots}{1/\gamma+\rho i_1[v_1 v_2 g_2+(1-v_1^2)b_1]+i_2[v_1 v_2 b_1-\gamma v_2/\rho+(1- \ldots}, \qquad (4)$$

$v_1 v_2 > 0.$

In such a setting of the problem the filament dynamics is determined only by a relatively slow ion motion in the electric field of the filament. In this case, block of the nonstationary dimensionless equations, that describes the dynamics of the current structure by the account of the ion motion and the slow filament dynamics, takes the form

$$\frac{\partial n}{\partial t}+\frac{1}{\rho}\frac{\partial}{\partial \rho}(\rho n u)=0,$$

$$\frac{\partial u}{\partial \tau}+u\frac{\partial u}{\partial \rho}=e_r-\frac{1}{n}\frac{\partial p}{\partial \rho}-\alpha u, \quad (5)$$

$$\frac{\partial i_{1,2}}{\partial \tau}+\left(\frac{n}{v}u+\frac{1}{v}\frac{\partial e_r}{\partial \tau}\right)\frac{\partial i_{1,2}}{\partial \rho}=0\ ,$$

$$e_r=v_1 b_1-v_2 g_2\ , \quad (6)$$

where the dimensionless radial electric field $e_r$ is introduced according to $E_r=e_r\sqrt{4\pi n_{e\infty} m_e c^2}$ , and $\alpha=v_{in}/\omega_{pi}$ takes into account the possible ion-atom collisions with the ion-neutral frequency $\nu_{in}$ .

Here the dimensionless length ρ, time τ, and ion radial velocity u and the dimensionless pressure p with the isentropic exponent equal 2 are introduced

$$r=\rho\sqrt{\frac{m_e c^2}{4\pi e^2 n_{e\infty}}}, t=\tau\sqrt{\frac{m_i}{4\pi e^2 Z n_{e\infty}}}, v_{ir}=uc\sqrt{\frac{Z m_e}{m_i}},$$

In addition, the initial conditions n(τ=0) =1 and u(τ =0)=0, and the boundary conditions n(ρ=∞)=1 and u(ρ =0)=u(ρ=∞)=0 will be used.

One should stress that because of the absence of the ion trajectory's bending the introduced values $n_{e\infty}$ and $n_{i\infty}$ correspond to the radius $r_\infty$ ~ $c/\omega_{pi}$ , which is in accordance with r.h.s. of the inequality (1).

## ESTIMATES FOR FILAMENTS WITH DIFFERENT SPACE –TIME SCALES

Earlier on, the filament equilibrium was obtained, where one bears in mind the typical parameters of the plasma with electron density $n_e$ ~ $10^{20}$ $cm^{-3}$. And though all the equations were presented in the dimensionless form, it follows from the main inequality (1) that the magnetic field is on the order of $|\vec{B}|$ ~ $10^7$- $3{\cdot}10^7$ G. However, some another ranges of the parameters can also exist by the fulfillment of the inequality (1). Of course, the existence of such parameter "windows" does not prove the real appearance of the equilibrium, however, this gives a possibility to search such equilibria. The simplest way to obtain the physical equivalent of the earlier obtained nonquasineutral current filaments for other space and time scales is the introduction of the three scale factors in order to connect the previous values [3,4] with subscript "0"and the values for new filaments with subscript "1". After some transformation according to formulae

$$B_0=\lambda_1 B_1, \quad n_0=\lambda_2 n_1, \quad E_0=\lambda_3 E_1 \quad (7)$$

and by the account of the approximate relation $\lambda_1^2\approx\lambda_2$ according to (1) one can obtain that for the ionosphere with $B_1\approx$ 1G and $n_1\approx 10^5$ $cm^{-3}$ the characteristic space and time scales are $r_1\approx 10^2$ m and $t_1\approx 3\cdot 10^{-5}$ s. The analogous calculations for the interstellar space results in $r_1\approx 10^6$ km and $t_1\approx$ 1s.

It is obvious that the current filaments may be considered also in a media with the only partial degree of the ionization. As an example of the application of the considered approach one can try to investigate the lightning phenomena in the Earth atmosphere by the initiation of the electric discharge between the charged clouds and the Earth surface. According to the recent concept of the lightning propagation in the Earth atmosphere, this phenomenon is based on the streamer breakdown at the very front of the lightning dart leader. In such an approach the value of the electric field is a critical point of the existing theory. In the present approach the main effect that allows to resolve this problem consists in the taking into account the magnetic field which arises because of the current flow in the lightning channel. According to the above presented theory by $c/\omega_{pe} \ll r_B$ a very strong radial electric field appear as a result of the charge separation at the magnetic Debye radius $r_B$. In addition, when one assumes that the channel radius is equal to $r_0\approx c/\omega_{pe}$ and one considers the l.h.s. of the inequality (1) on the verge of the applicability $\vec{B}^2\approx 4\pi n_e m_e c^2$ , so from B = $2J/(r_0 c)$ one can obtain that the current is equal to $J_{cr}\approx J_{Ae}$ = 8.5 kA, which is independent of the plasma density in the lightning channel. This Alfven current value is very close to the current in the dart leader phase of the lightning, which was measured in the initial stage of the rocket-triggered lightning [5]. In this case, the estimate of the Hall potential in the filament $U_{Hall}$ = $\vec{B}^2/(4\pi e n_e)$ by the account of the above-mentioned approximate relation $\vec{B}^2\approx 4\pi n_e m_e c^2$ gives the relativistic value $U_{Hall}\approx$ $m_e c^2/e$ = 0.511 MeV. This means that already for the electron density greater than $n_e > 10^{12}$ $cm^{-3}$ the radial electric field in the current channel is greater than 1 MV/cm. In the filament with the strong radial electric field $E_r$ and the azimuth magnetic field $B_\theta$, the electron drift velocity is on the order of the light velocity c. The calculation of the maximum relativistic factor of the drifting electrons at the axis within the framework of the presented theory gives for the measured current value J ≈ 11kA in the dart leader stage $\gamma_0$ ~ 2. This value is in a reasonable accordance with the measured x-ray emission in the 30 – 250 keV. By the domination of the collision term in the second Eq. (5) the characteristic time of the filament dynamics connected with the neutralization of the electric potential is about $t_0$ ~ 0.1 μs what is in accordance with the characteristic time of the x-ray bursts in [5]. One can calculate the total energy of the filament related to the unit length. This value is about $10^{-2}$ J/cm for the above-mentioned dart leader phase of the lightning and can increase up to 1 J/cm for the main phase with the current about 100 kA. The dissipation of this energy depends on the collision of the relativistic electron with the neutral component and can be neglected by $\nu_{en} t_0 \ll 1$, where $\nu_{en}$ – the electron-neutral collision frequency. This condition may by fulfilled by $t_0$ ~ 0.1 μs. Here one should stress that the total energy of such a filament is on the order of the several hundred keV by the current J = 100 kA for the clouds remote from the Earth surface on the several km, however, this energy constitutes only a small fraction of the total energy of the charged cloud. Also it is useful to mention the return stroke stage of the lightning phenomena, when the inverse propagation of the lightning occurs. It is known that by the investigation of the lightning propagation one can consider the processes in the current channel within the framework of the telegraph equation. Now, in the introduced approach the wave processes in the current channel correspond rather to the propagation of the magnetic self-insulation wave [6]. In the presented approach, the return stroke phase of the lightning must be the reflected magnetic self-insulation wave that propagates in the reversed direction from the Earth surface as the surface potential is equal to zero. Therefore, in the propagation of the reflected magnetic self-insulation wave the potential difference of the filament essentially diminished or disappeared, so the filament energy is released in the filament plasma. This energy deposition must result in the radiation from the filament plasma and in the forming of the shock waves.

## CONCLUSIONS

The conducted investigations reveal the existence of the filament equilibria with the different space - time scales, where the magnetic field plays a decisive role. In addition, in this equilibrium the current flow is carried out by the relativistic electrons. The full similarity of the physical processes for the nonquasineutral current filaments in the different space-time scales at the definite ranges of the magnetic field and the plasma density is obtained. Estimates within the framework of the current filament model show that the account of the magnetic field, connected with the current of the lightning channel, results in the appearance of the strong electric field and the relativistic electrons, which energy and life time increase with the current and the radius of the channel, respectively.

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## ДИНАМИКА НЕКВАЗИНЕЙТРАЛЬНЫХ ТОКОВЫХ ФИЛАМЕНТОВ НА РАЗЛИЧНЫХ ПРОСТРАНСТВЕННО-ВРЕМЕННЫХ МАСШТАБАХ

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Полученные ранее результаты по равновесию и динамике неквазинейтральных токовых филаментов для пространственного масштаба порядка одного микрона и временного масштаба порядка одной пикосекунды применяются к объектам в атмосфере, ионосфере и в межзвёздном пространстве. Основной чертой нового равновесия для электронного токового филамента является присутствие электрического поля, которое появляется как результат разделения зарядов на магнитном дебаевском радиусе $r_B$. Произведены численные расчёты ионной динамики, связанной с электрическим полем филамента. Получено, что одни и те же уравнения могут описывать равновесие и динамику филаментов от микронного масштаба до длины порядка миллиона км. Представлены аргументы, которые вводят новый подход для феномена молнии, где магнитное поле в канале молнии может играть решающую роль.

## ДИНАМІКА НЕКВАЗІНЕЙТРАЛЬНИХ ТОКОВИХ ФІЛАМЕНТІВ НА РІЗНИХ ПРОСТОРОВО-ТИМЧАСОВИХ МАСШТАБАХ

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Отримані раніше результати по рівновазі і динаміці неквазінейтральних токових філаментів для просторового масштабу порядку одного мікрона і тимчасового масштабу порядку однієї пікосекунди застосовуються до об'єктів в атмосфері, іоносфері й у міжзоряному просторі. Основною рисою нової рівноваги для електронного токового філамента є присутність електричного поля, що з'являється як результат поділу зарядів на магнітному дебаєвському радіусі r. Зроблено чисельні розрахунки іонної динаміки, зв'язаної з електричним полем філамента. Отримано, що ті ж самі рівняння можуть описувати рівновагу і динаміку філаментів від мікронного масштабу до довжини порядку мільйона км. Представлено аргументи, що вводять новий підхід для феномена блискавки, де магнітне поле в каналі блискавки може відігравати вирішальну роль.