A METHOD OF MATCHING OF ION AND ELECTRON MOTION EQUATIONS FOR PLASMA MOVING IN A TOROIDAL MAGNETIC FIELD

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A model of the plasma motion in a toroidal magnetic field that quantitatively reflects the real peculiarities of the process is proposed. It is suggested to match the equations of motion for the electron and ion components using some results of the rigid-rotor model along with the guiding centers approximation. The analysis of the ion motion in a toroidal magnetic field with regard for polarization forces results in the conclusion that the drift approximation for ions is valid only under the condition of rather rarefied plasmas or extremely strong magnetic fields. It is shown that the holding of plasma on a curvilinear trajectory is provided by the Lorentz force acting on electrons. Ions are held by polarization forces.

1. Introduction

In the drift models [2–5], it is considered that the transverse and radial velocities of electrons and ions in plasma moving in a toroidal magnetic field are determined by their drift and can be described by the identical equations [2,3]

$$V_\perp = c\frac{E_R}{B} + \frac{mc}{eBR}\left(V_\parallel^2 + \frac{V_{T\perp}^2}{2}\right) + \frac{mc^2}{eB}\frac{d}{dt}\left(\frac{E_\perp}{B}\right), \quad (1)$$

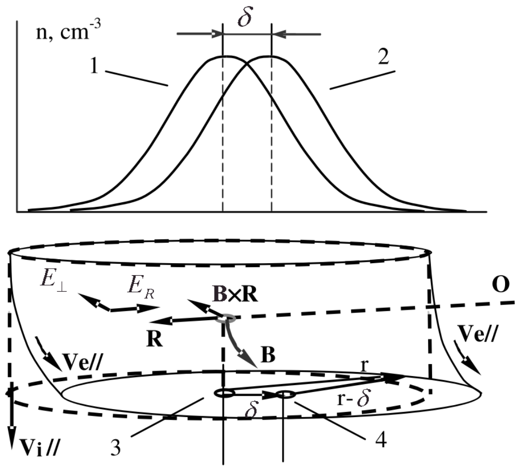
$$V_R = c\frac{E_\perp}{B} + \frac{mc^2}{eB}\frac{d}{dt}\left(\frac{E_R}{B}\right), \quad (2)$$

where R stands for the curvature radius of the magnetic field line, B denotes its intensity, $V_\perp$ is the transverse drift speed of a particle in parallel to $\mathbf{B}\times\mathbf{R}$ (see Figure), whereas V_R is the radial drift speed. According to [2], the plasma must move at the tangent to a magnetic line in the case where its density isn't too small. According to the model proposed in [3], in the presence of short-circuit currents, the plasmoid must move along the toroidal magnetic field shifting both in the direction of the centrifugal drift of ions $-\mathbf{B}\times\mathbf{R}$ and in the direction of $\mathbf{R}$. However, the experiments on the transport of plasmoid [6] and vacuum-arc plasma [7, 8] in curvilinear magnetic fields testify to the inessential shift of the plasma to the opposite side – in the direction of the centrifugal drift of electrons. This disagreement shows that the question requires a further analysis.

The principal differences of the proposed consideration from the drift models proposed in [2–5] are as follows:

1. The initiation of polarization fields is interpreted as a result of the displacement of the electron charge distribution with respect to the ion one rather than as a consequence of the charge density rising on the lateral sides of a plasmoid or the plasma jet with a rectangular cross-section (similarly to [2–4]).

2. The presence of time intervals, during which the electron component validly participates in some kind of



The shift of a thin layer of the electron charge distribution with respect to the ion one at the beginning of a curvilinear trajectory: *1* – Gaussian distribution of the ion density; *2* – Gaussian distribution of the electron density; *3* and *4* – centers of the distributions after the shift; δ – magnitude of the shift; $\mathbf{V}_{i\parallel}$ – vector of the longitudinal ion velocity; $\mathbf{V}_{e\parallel}$ – vector of the longitudinal electron velocity; r – radius-vector of the point inside the plasma cylinder; $\mathbf{R}$ – curvature radius-vector of the lines of the magnetic field $\mathbf{B}$; $\mathbf{O}$ – center of curvature of the magnetic field line drift whereas ions pass only a small part of their Larmor circle, is taken into account. In this case, any force resulting in a displacement of the ion charge distribution will be balanced with polarization forces during the time much less than the Larmor period of an ion. It follows from here that ions can't take part in the drift even in comparatively strong magnetic fields. Respectively, the formulas describing the drift of ions become inapplicable in the equations of their motion.

3. In contrast to [2–5], where the motion equations were first written down separately for the electron and ion components and after that were matched in one way or another, the proposed model deals with the initially self-consistent equations characterizing the relative shifts of the plasma components and the polarization fields arising in this case.

2. Polarization Field in a Plasma Cylinder

According to the conclusions of the rigid-rotor model [1], the plasma density in the cross-section of a plasma cylinder with a constant radius-independent temperature, $T_{e,i}(r) = const$, oriented along the uniform magnetic field is distributed according to the Gaussian law

$$n_{e,i}(r) = n_{e,i}(0)\exp\left[-\frac{r^2}{r_0^2}\right], \tag{3}$$

while the electric field is negative and its absolute value increases proportionally to the radius, $E(r) = -Cr$, where C=const. In the experimental works (see, e.g., [7,9]), it is shown that these parameters are also inherent to the vacuum-arc plasma. Thus, it's more appropriate to simulate the plasma stream exactly in this way rather than in the form of a beam with a rectangular cross-section and a uniform plasma density.

According to the Gaussian law for the electric field

$$\int\limits_S \mathbf{E}d\mathbf{S} = 4\pi\int\limits_V \rho(v)dv, \tag{4}$$

the radial-symmetric field $E(r) = -Cr$ is formed by the uniform density of the negative charge

$$\mathbf{E}(r) = -2\pi e\Delta n\mathbf{r}, \tag{5}$$

where Δn is the excess of electrons as compared to ions (which will be considered one-charged so far). That is, the electron density distribution can be approximated as

$$n_e(r) = n_i(r) + \Delta n. \tag{6}$$

Let's calculate the electric fields formed separately by the ion and electron charge distributions. From (3), (4), and (6), we obtain for the ion and electron distributions, respectively:

$$\mathbf{E}_i = -\frac{2\pi en_i(0)\,r_0^2}{r^2}\left[\exp\left(-\frac{r^2}{r_0^2}\right) - 1\right]\mathbf{r},$$

$$\mathbf{E}_e = \frac{2\pi en_i(0)\,r_0^2}{r^2}\left[\exp\left(-\frac{r^2}{r_0^2}\right) - 1\right]\mathbf{r} - 2\pi e\Delta n\mathbf{r}.$$

The superposition of these fields gives the resulting field (5). As the magnetic field first deviates the guiding centers of electrons on the curvilinear trajectory whereas ions go on moving along the straight line for some time, there takes place a shift of the electron charge distribution with respect to the ion one. If the center of the electron charge distribution shifts with respect to the ion one by the magnitude $\boldsymbol{\delta}$, (see Figure), this distribution becomes symmetric relative to the radius-vector $\mathbf{r}' = \mathbf{r} - \boldsymbol{\delta}$:

$$\mathbf{E}_e = \frac{2\pi en_i(0)\,r_0^2}{(r-\delta)^2}\left(\exp\left[-\frac{(r-\delta)^2}{r_0^2}\right] - 1\right)(\mathbf{r}-\boldsymbol{\delta}) -$$

$$-2\pi e\Delta n(\mathbf{r}-\boldsymbol{\delta}).$$

It's easy to show that the resulting field in this case

$$\mathbf{E} = \mathbf{E}_i + \mathbf{E}_e \approx -2\pi e\Delta n\mathbf{r} -$$

$$-\frac{2\pi en_i(0)\,r_0^2}{(r-\delta)^2}\left(\exp\left[-\frac{(r-\delta)^2}{r_0^2}\right] - 1\right)\boldsymbol{\delta},$$

will be equal to the sum of the radial symmetric field and the polarization field (the first and second terms on the right-hand side, respectively), as the quantity $2\pi e\Delta n\boldsymbol{\delta}$ can be neglected. Assuming $r^2 \cong (r-\delta)^2$ and using the fact that at the center of the stream, where $(r-\delta) \to 0$, the approximation

$$\exp\left[-\frac{(r-\delta)^2}{r_0^2}\right] \approx 1 - \frac{(r-\delta)^2}{r_0^2}$$

is valid, one can find the expression for the polarization field arising in the plasma cylinder due to a relative shift of the Gaussian distributions of the ion and electron plasma components:

$$\mathbf{E} \approx \mathbf{E}_R \approx 2\pi en(0)\,\boldsymbol{\delta}. \tag{7}$$

3. Construction of Self-Consistent Motion Equations of the Electron and Ion Plasma Components

Let's take into account that, during the time interval τ equal to the electron Larmor period by an order of magnitude, plasma ions shift directly under the action of the centrifugal and polarization forces rather than take part in the drift. Let's also assume that the directed velocity of electrons $V_{e\|}$ represents one of the three spatial components of the electron thermal velocity. Moreover, we take $V_{e\|} > V_i$, which is typical of the vacuum-arc plasma [8, 12], and assume

$$V_{T\perp}^2 = 2V_{e\|}^2 \tag{8}$$

in Eq.(1). The self-consistent equations will be formulated for the central part of the plasma stream, where the magnetic field can be considered constant, $B = B_0$, and one can allow only for the polarization field, as the radial field $E_r \to 0$. Since that the ion component shifts directly under the action of the centrifugal and polarization forces, while the electron one moves due to the electric, centrifugal, gradient, and polarization drifts in the coordinate system (see Figure), where the axes are presented by the three vectors $\mathbf{B}$, $\mathbf{R}$, and $\mathbf{B}\times\mathbf{R}$, we can write the following expressions for the shifts of the center of the electron distribution with respect to the ion one along $\mathbf{R}$ and $\mathbf{B}\times\mathbf{R}$:

$$\delta_R = \frac{V_{i\|}}{V_{e\|}}\frac{c}{B}\int_0^\tau E_\perp dt - \frac{V_{i\|}}{V_{e\|}}\frac{m_e c^2}{eB^2}\int_0^\tau \frac{dE_R}{dt}dt-$$

$$-\frac{V_{i\|}^2\tau^2}{2R} - \frac{Ze}{M_i}\int_0^\tau dt\int_0^t E_R dt$$

and

$$\delta_\perp = \int_0^\tau \left[-\frac{c}{B}E_R + \frac{2cm_eV_{e\|}^2}{eRB} - \frac{m_ec^2}{eB^2}\frac{dE_\perp}{dt}\right]\frac{V_{i\|}}{V_{e\|}}dt-$$

$$-\frac{Ze}{M_i}\int_0^\tau dt\int_0^t E_\perp dt.$$

In these equations, it's taken into account that the velocity of the transverse shift of electrons in the reference system moving with the speed of ions along a circular trajectory with radius R will be lower by a factor of $V_{e\|}/V_{i\|}$. Defining $V_{i\|}/V_{e\|} = \eta$ and taking from Eq. (7) that $\mathbf{E}_{R,\perp} = -k\boldsymbol{\delta}_{R,\perp}$, where $k = 2\pi en(0)$, we obtain after simple transformations:

$$E_R\left(1+\eta\frac{km_ec^2}{eB^2}\right) = -\frac{kV_{i\|}^2\tau^2}{2R}-$$

$$-\frac{kZe}{M_i}\int_0^\tau dt\int_0^t E_R dt + \eta\frac{kc}{B}\int_0^\tau E_\perp dt, \tag{9}$$

and

$$E_\perp\left(1+\eta\frac{km_ec^2}{eB^2}\right) = -\frac{\eta kc}{B}\int_0^\tau E_R dt-$$

$$-\frac{kZe}{M_i}\int_0^\tau dt\int_0^t E_\perp dt + \frac{2k\eta cm_eV_{e\|}^2}{eRB}\tau. \tag{10}$$

The coefficient $1+\eta\frac{kmc^2}{eB^2} = 1+\frac{4\pi n_0 mc^2}{B^2}\frac{1}{2}\eta$ evidently represents the part of the plasma dielectric constant conditioned by electrons. It differs from the similar expression in [10] only by the factor $\frac{1}{2}\eta$ that appears due to the Gaussian density distribution (instead of $n =$ const) and the motion of electrons relative to ions. The basic advantage of Eqs.(9) and (10) as compared to (1) and (2) lies in the inherent total self-consistency of the polarization fields and the relative shifts of the ion and electron distributions by virtue of Eq.(7). Having determined the fields E_R and $E_\perp$, we can calculate the *absolute* shifts of each plasma component taking into account that the ion component moves directly under the action of the centrifugal and polarization forces, while the electron one – due to the electric, centrifugal, gradient, and polarization drifts. In this case, the distance between the centers of the electron and ion distributions won't exceed the parameter $\delta = E/k$ providing the quasineutrality of the plasma.

Introducing the notation $D = 1 + \eta kmc^2/eB^2$ and performing simple transformations, we obtain a pair of independent differential fourth-order equations

$$\frac{d^4E_R}{dt^4} + \left[\frac{2k}{D}\frac{Ze}{M} + \left(\frac{k}{D}\right)^2\left(\frac{\eta c}{B}\right)^2\right]\frac{d^2E_R}{dt^2}+$$

$$+\left(\frac{k}{D}\right)^2\left(\frac{Ze}{M}\right)^2 E_R + \left(\frac{k}{D}\right)^2\frac{Ze}{M}\frac{V_{i\|}^2}{R} = 0$$

and

$$\frac{d^4E_\perp}{dt^4}+\left[\frac{2k}{D}\frac{Ze}{M}+\left(\frac{k}{D}\right)^2\left(\frac{\eta c}{B}\right)^2\right]\frac{d^2E_\perp}{dt^2}+$$

$$+\left(\frac{k}{D}\right)^2\left(\frac{Ze}{M}\right)^2E_\perp=0$$

that describe the dynamics of the components of the electric polarization field in the reference system moving with the speed of ions $V_{i\parallel}$ along a circular trajectory with radius R. The approximate solutions have a form

$$E_\perp(t)\approx\left(\frac{M}{eZ}\frac{V_{i\parallel}^2}{R}+\frac{2mV_{e\parallel}^2}{eR}\right)\sin\left(\frac{eZ}{M_i}\frac{B}{\eta c}\right)t+$$

$$+\frac{2mV_{e\parallel}^2}{eR}\sin\left(\frac{k\eta c}{DB}\right)t, \quad (11)$$

and

$$E_R(t)\approx\left(\frac{M}{eZ}\frac{V_{i\parallel}^2}{R}+\frac{2mV_{e\parallel}^2}{eR}\right)\cos\left(\frac{eZ}{M_i}\frac{B}{\eta c}\right)t-$$

$$-\frac{2mV_{e\parallel}^2}{eR}\cos\left(\frac{k\eta c}{DB}\right)t-\frac{M}{eZ}\frac{V_{i\parallel}^2}{R}. \quad (12)$$

In more accurate solutions, the amplitudes include the terms $\frac{2mV_{e\parallel}^2}{eR}\frac{Ze}{M}\left(\frac{B}{\eta c}\right)^2\frac{D}{k}$ and $\frac{D}{k}\left(\frac{B}{\eta c}\right)^2\frac{V_{i\parallel}^2}{R}$ with negative signs that arise due to the polarization drift of electrons and decrease the amplitude of the polarization field. However, the magnitude of this decrease doesn't exceed 0.1% for the typical range of the magnetic field intensity of 150–600 Gs in curvilinear filters.

According to [7, 11, 12], the average parameters of the titanic plasma stream are as follows: the ion mass $M = 7.95\times10^{-23}$ g; the average ion charge $Z = 2.03$; the average ion energy $W_i = 58.9$ eV; the mean electron temperature $T_e = 3.2$ eV; the velocity ratio $V_{i\parallel}/V_{e\parallel} = \eta = 0.022$; the plasma density at the center $n_0 = 10^{12}$ cm^{-3}; the magnetic field strength $B = 160$ Gs; the radius of the plasma trajectory $R = 24$ cm. For such parameters, the magnitudes of the frequencies amount to: $\omega_1 \approx \frac{a}{b} \approx \frac{eZ}{M}\frac{B}{\eta c} \approx 2.72\times10^6$ s^{-1}, and $\omega_2 \approx b \approx \frac{k\eta c}{DB} \approx 2.93\times10^9$ s^{-1}, where $a = \frac{k}{D}\frac{Ze}{M}$, $b = \frac{k}{D}\frac{\eta c}{B}$. Their more accurate values have the form: $\omega_1 \approx \frac{a}{\sqrt{2a+b^2}}$ and $\omega_2 \approx \sqrt{2a+b^2-\omega_1^2}$.

From solutions (11), (12), one can see that the polarization field mainly compensates the centrifugal force acting on the ions. The contribution of the electron component is less by an order of magnitude for the vacuum-arc plasma and by several orders of magnitude for plasmoids, where the electron and ion velocities are equal. The frequency ω_1 is determined by the parameters of the ion component. It's easy to demonstrate that, in the case of a motionless (in the cross-section plane) electron distribution, this frequency would have the maximal value $\sqrt{keZ/2M_i}$. In the presence of the electron response, its magnitude is lower and rises proportionally to the magnetic field strength due to the increase of the "rigidity" of the double oscillatory system. The rigidity evidently increases with decrease in the transversal mobility of electrons, which is mainly determined by both the velocity of their electric drift $V = cE/B$ and the ratio $1/\eta = V_{e\parallel}/V_{i\parallel}$. The frequency ω_2 characterizes electron oscillations and falls with increase in the magnetic field and the ratio $V_{e\parallel}/V_{i\parallel}$ by the same reason (reduction of the transversal electron mobility). The presence of the polarization drift of electrons additionally decreases this frequency by a factor of D, though, in the fields of ~500 Gs and higher, this decrease is already inessential, as $D \to 1$ [at the plasma density $n_0 = 10^{12}$ cm^{-3}; see Eqs. (9) and (10)].

Knowing the fields E_R and $E_\perp$, let's calculate a shift of the central part of the stream from the circular trajectory at some distance S from its beginning. The ion component shifts in the radial direction due to the action of the centrifugal force and the field E_R: $d_{R,i} = \int_0^{\tau(i)} dt \int_0^t \left(\frac{V_{i\parallel}^2}{R}+\frac{eZ}{M}E_R\right)dt$, while the electron one – due to the electric drift in the field $E_\perp$ and polarization drift in the field E_R: $d_{R,e} = \frac{c}{B}\int_0^{\tau(e)} E_\perp dt - \frac{m_ec^2}{eB^2}E_R(\tau_e)$. In the transversal direction, the ions move only under the action of the field $E_\perp$: $d_{\perp,i} = \frac{eZ}{M}\int_0^{\tau(i)} dt \int_0^t E_\perp dt$, whereas the electrons – due to the electric drift in the field E_R, polarization drift in the field $E_\perp$, and the centrifugal and gradient drifts:

$$d_{\perp,e} = -\frac{c}{B}\int_0^{\tau(e)} E_R dt - \frac{m_ec^2}{eB^2}E_\perp\left(\frac{S}{V_e}\right)+\frac{2cmV_e^2}{eRB}\frac{S}{V_e},$$

where $S = V_e\tau(e) = V_i\tau(i)$ denotes the distance passed by the electrons or ions in the circular trajectory. It's easy to show that the equalities $d_{R,i} \approx d_{R,e}$ and $d_{\perp,i} \approx d_{\perp,e}$ hold true to within 2×10^{-6} cm providing the quasineutrality of the plasma. Substituting solutions (11), (12), we obtain

$$d_{R,i} \approx d_{R,e} \approx \frac{M}{eZ}\left(\frac{\eta c}{B}\right)^2\left(\frac{M}{eZ}\frac{V_{i\|}^2}{R}+\frac{2mV_{e\|}^2}{eR}\right).$$

For the parameters of the titanic plasma [7, 11, 12], we obtain that the mean radial deviation amounts only to 0.04 cm, while the amplitude of ion oscillations in the absence of the polarization field $\Delta R \approx \rho^2/R_0$ [3], where $\rho = cMV_{\|}/ZeB$ would exceed 25 cm.

In order to calculate the shift of the central part of the stream in the direction $\mathbf{B}\times\mathbf{R}$, let's use solution (11). Integrating $E_\perp$, we obtain

$$d_{\perp,i} \approx d_{\perp,e} \approx$$

$$\approx \frac{eZ}{M}\frac{1}{\omega_1}\left(\frac{M}{eZ}\frac{V_{i\|}^2}{R}+\frac{2mV_{e\|}^2}{eR}\right)\left(\frac{S}{V_i}-\frac{1}{\omega_1}\sin\frac{S}{V_i}\right).$$

Thus, the shift in the transverse direction, in contrast to that in the radial direction, has the mean velocity $V_\perp \approx \frac{eZ}{M}\frac{1}{\omega_1}\left(\frac{M}{eZ}\frac{V_{i\|}^2}{R}+\frac{2mV_{e\|}^2}{eR}\right)$. Assuming $S = \frac{\pi}{2}R$, one can find the average shift of the center of the plasma beam at the exit of the quarter-torus magnetic duct:

$$d_\perp \approx \frac{\eta c}{B}\frac{\pi}{V_i}\frac{1}{eZ}\left(\frac{MV_{i\|}^2+2ZmV_{e\|}^2}{2}\right)=$$

$$=\frac{c}{B}\frac{\pi}{V_{e\|}}\frac{1}{eZ}\left(W_i+2ZW_e\right),$$

where W_i and W_e denote the kinetic energies of the direct motion of ions and electrons, respectively. Substituting the values of the constants and converting ergs to eVs, we finally obtain

$$d_\perp \approx \frac{7.49[W_i\,(\mathrm{eV})+ZT_e\,(\mathrm{eV})]}{ZB\sqrt{T_e\,(\mathrm{eV})}}. \qquad (13)$$

This expression differs from the one obtained in [13], where the electron temperature was not taking into account. One can see from (13) that the magnitude of plasma beam displacement at the exit of the quarter-torus magnetic duct does not depend on the magnetic field line curvature radius or plasma density (for collisionless plasma). Substituting the titanium plasma and magnetic filter parameters presented in [7, 11, 12] into Eq. (13), we find $d_\perp \approx$ 8.4 mm, which is in a good agreement with 7 mm experimentally obtained in [7]. Analyzing this question in the framework of a two fluid hydrodynamic model, authors of [14, 15] had obtained $d_\perp \sim 25$ cm, which confirms the Schmidt's doubt [2] as to the applicability of the hydrodynamic model to this question.

4. Conclusions

The equations of motion for electrons and ions in the cross-section of the plasma jet moving in the toroidal magnetic field are matched considering the relative shifts of the ion and electron Gaussian density profiles in the self-consisted polarization field. It's shown that the accurate quantitative result for the well-known effect of a plasma beam displacement from the center of a toroidal magnetic duct in the $\mathbf{B}\times\mathbf{R}$ direction can be obtained if one takes into account that ions do not experience the centrifugal drift as the polarization force balances the centrifugal force during the much less time than the ion Larmor period. So, the drift approximation is valid for electrons only. From this, it follows:

1. There's no centrifugal drift in a plasma (except for the causes of extremely strong magnetic fields or low-density plasmas). The same conclusion is valid for other drifts caused by forces resulting in the charge separation.

2. The plasma jet is maintained at a curvilinear trajectory due to the action of the Lorentz force on the electron component, whereas the ions are maintained by polarization forces.

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СПОСІБ УЗГОДЖЕННЯ РІВНЯНЬ РУХУ ЕЛЕКТРОННОЇ ТА ІОННОЇ КОМПОНЕНТ ПЛАЗМИ, ЩО ТРАНСПОРТУЄТЬСЯ В ТОРОЇДАЛЬНОМУ МАГНІТНОМУ ПОЛІ

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Р е з ю м е

Запропоновано модель руху плазми в тороїдальному магнітному полі, яка кількісно відтворює реальні особливості процесу. Рівняння руху електронної та іонної компонентів пропонується узгодити, використовуючи деякі результати твердороторної моделі [1] в поєднанні з наближенням ведучих центрів. Аналіз руху іонів в тороїдальному магнітному полі з урахуванням поляризаційних сил приводить до висновку, що дрейфове наближення для іонів застосовне лише в умовах досить розрідженої плазми або в екстремально сильних магнітних полях. Показано, що утримання плазми на криволінійній траєкторії забезпечується силою Лоренца, яка діє на електрони. Іони утримуються поляризаційними силами.