AN INVESTIGATION INTO THE EFFECT OF MASS-TRANSFER PROCESSES AND THE FORCES OF RESISTANCE ON THE ELECTRODYNAMIC ACCELERATION OF A PLASMA

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We examine the mass-transfer processes brought about by the physical phenomena of plasma recombination, ambipolar diffusion, and electrode erosion. We investigate the effect of resistance forces in their various relationships to the parameters of the accelerated plasma.

An investigation into the effect of various physical processes on the process of electrodynamic acceleration is of considerable interest and is being actively discussed in the periodical literature [1-41].

The very first attempts at electrodynamic acceleration of a plasma demonstrated the deviation of the characteristics of the resulting plasma from the theoretical calculations based on the familiar idealized model of a current "jumper" [1]. This resulted in a number of papers which carefully examined the effect of the individual factors and physical processes on the electrodynamic acceleration of a plasma.

Electrode erosion as a result of ion bombardment of the electrode surfaces and as a result of evaporation due to Joule heating was studied in [2-16]. It was demonstrated that the eroding electrode mass is comparable to the mass of the plasma formed and accelerated on breakdown, or it may even exceed it. The velocities and efficiency in erosion acceleration are comparatively low; however, because of the increase in the accelerated mass the developed momenta may be greater than in acceleration without erosion.

The various resistance forces of the moving plasma exert a negative effect on its characteristics. Some of the relationships involving the resistance forces were studied in [5, 17, 18], and they were compared in [19]; however, no combined effect of such forces, in conjunction with other factors, was found to affect the plasma characteristics.

In [20-23] we find an investigation into the effect of the passage of current through the discharge gap; in [23-27] there is a study of the unique regimes involved in plasma acceleration; in [28-29] the role of electrode polarity is investigated; the appearance of various types of instabilities in a plasma was investigated in [30-34], while the pinch effect on plasma acceleration was studied in [32, 34]; in [35-37] we find an investigation into the energy balance on acceleration, and a study of the efficiency of energy conversion is described in [38-40], etc.

An important physical process leading to intensive mass transfer in the working zone is the process of plasma diffusion. The study of this process was begun in [17, 41]; however, it is in need of further development. Diffusion results in losses in the accelerated mass and leads to a reduction in the developed momenta. This same effect is achieved by the phenomena of recombination, overcharging, and surface adsorption; the effect of these phenomena on plasma acceleration has not been investigated. Nor has the effect of the processes of volume ionization, surface ionization, etc., been examined as yet in the theory of plasma acceleration.

In this paper we study the effect of mass-transfer processes brought about by diffusion and recombination of the particles from the accelerated plasma, as well as the increase in the plasma mass as a result of electrode erosion. Moreover, here we make clear the relative role of the friction and resistance forces which hinder the plasma acceleration.

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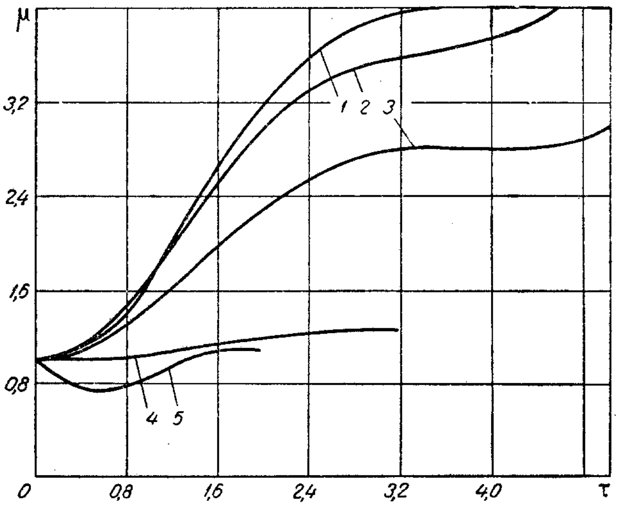

Fig.1

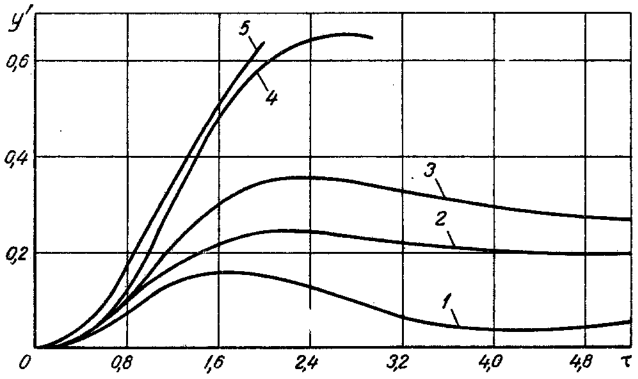

Fig.2

Fig.1. Change in mass μ during time τ for the following parameters of system (13)-(17) ($q = 1$; $\alpha = 0.1$): 1) $\gamma_1 = 0$, $\gamma_2 = 0$, $\gamma_3 = 1$, $\gamma_4 = 1$, $\delta_1 = 0$, $\delta_2 = 1$, $\delta_3 = 0$, $\delta_4 = 0$; 2) $\gamma_1 = 0$, $\gamma_2 = 0$, $\gamma_3 = 1$, $\gamma_4 = 1$, $\delta_1 = 0$, $\delta_2 = 0.1$, $\delta_3 = 0$, $\delta_4 = 0$; 3) $\gamma_1 = 0$, $\gamma_2 = 0$, $\gamma_3 = 1$, $\gamma_4 = 0.1$, $\delta_1 = 0$, $\delta_2 = 0.1$, $\delta_3 = 0$, $\delta_4 = 0$; 4) $\gamma_1 = 0$, $\gamma_2 = 0$, $\gamma_3 = 0.1$, $\gamma_4 = 0.1$, $\delta_1 = 0$, $\delta_2 = 0.1$, $\delta_3 = 0$, $\delta_4 = 0$; 5) $\gamma_1 = 1$, $\gamma_2 = 0$, $\gamma_3 = 1$, $\gamma_4 = 1$, $\delta_1 = 0$, $\delta_2 = 0.1$, $\delta_3 = 0$, $\delta_4 = 0$.

Fig.2. Change in the velocity of the center of inertia y' for the plasma mass during time τ (the parameters and notations correspond to those of Fig.1).

The basic equations describing the process of electrodynamic acceleration in approximation of the motion of the center of inertia are taken in conventional form.

The equation of motion for the center of inertia is

$$\frac{dmv}{dt} = \frac{b}{2} I^2 - F. \tag{1}$$

The electrical processes are described by the following electric-circuit equations:

$$I = -C_0 \frac{dV}{dt}, \tag{2}$$

$$\frac{dLI}{dt} + RI - V = 0, \tag{3}$$

$$L = L_0 + bz. \tag{4}$$

The change in the mass m is described by an equation of the continuity-equation type

$$\frac{dm}{dt} = S(t, v, z, I), \tag{5}$$

where S is a function characterizing the processes of mass transfer on acceleration of a plasma.

Let us examine some of the processes which lead to a change in a mass in motion. The mass balance is governed by various competing processes. The entry of the mass into the acceleration volume proceeds as a result of the ionization of the neutral gas and because of the entrainment of the charged particles during the course of the acceleration process, the erosion of the electrodes, and in the processes of thermal and self-emission of electrons and ions which are brought about by the introduction of the plasma from without or through the "piston" scraping of the neutral gas by the moving plasma. The mass losses are caused by the diffusion of the particles, with the ambipolar diffusion, as a rule, predominating because of plasma recombination, and because of the processes of adhesion and particle overcharging, which result in the formation of neutral particles; moreover, the losses can be attributed to the departure of the particles from the acceleration process and to similar "elementary" processes. The effect of certain of these processes on plasma acceleration was examined in the above-cited references. It is assumed that the entry of the mass results exclusively from electrode processes with relatively slight effect exerted by other processes of mass formation, and considering only the competing processes of diffusion and recombination, we can write the mass-balance equation (5) in the approximate form

$$\frac{dm}{dt} = -a_1 m - a_2 m^2 + a_3 |I| + a_4 I^2, \tag{6}$$

where the first term in the right-hand member describes the reduction in mass as a result of diffusion, with the second term describing the mass reduction due to particle recombination; the third and fourth terms describe the increase in mass as a result of electrode erosion as a consequence of ion bombardment and Joule fusion of the electrodes, respectively; a_1, a_2, a_3, a_4 are proportionality factors determined experimentally or theoretically on the basis of the kinetics of the elementary processes. The expressions for a_1, a_4, and a_3 were treated in [5, 15, 17]. Let us examine the coefficient of particle recombination. The reduction in ion concentration n as a result of recombination is described [42] by the kinetics equation

$$\frac{dn}{dt} = -\rho n^2, \tag{7}$$

where ρ is the recombination factor which is a function of the properties exhibited by the recombining material. For example, for a helium plasma $\rho \sim 10^{-15}$ m^3/sec. If we introduce the plasma mass $m = m_i n$ as the product of the ion mass m_i and the ion concentration n, the mass recombination factor a_2 is determined from the relationship

$$a_2 = \frac{\rho}{m_i}. \tag{8}$$

At this point a comment is appropriate with regard to the first term in (6). A change in the mass according to the law

$$\frac{dm}{dt} = -a_1 m \tag{9}$$

may be described not only as resulting from particle diffusion, but also as a result of overcharging and electron adhesion [42], causing the neutral particles to leave the accelerated plasma. It therefore becomes possible to account for these phenomena through the variation in the coefficient a_1.

The resistance force **F** in the equation of motion (1) can be presented in the following form:

$$\mathbf{F} = b_1 \cdot \mathbf{v} + b_2 \mathbf{v} \cdot m + b_3 |I| \cdot \mathbf{v} + b_4 \cdot v^2 + \cdots. \tag{10}$$

It is governed by the friction of the moving plasma against the electrode, and this is accounted for by the first term in the right-hand member of (10) [15]; in addition we have the processes of friction in mass transfer which are accounted for by the second and third terms [17, 18], and by the resistance of the external medium, which is accounted for by the fourth term [5]. The proportionality factors b_1, b_2, b_3, and b_4 can be evaluated theoretically; however, their exact determination under specific conditions is possible only through experimentation.

For the solution of Eqs. (1), (2), (3), and (6), in conjunction with (4) and (10), for selected values of the system parameters, we specify the initial conditions in the following form:

$$\text{when } t = 0 \quad z = v = I = 0; \quad V = V_0, \quad m = m_0. \tag{11}$$

The solution of the system of equations (1)-(3) and (6) is conveniently achieved in dimensionless variables which we introduce on the basis of the formulas

$$\begin{gathered} \tau = \frac{t}{\sqrt{L_0 C_0}}, \quad y = \frac{b}{L_0} z, \quad y' = b\sqrt{\frac{C_0}{L_0}}\, v, \\ \varphi = \frac{V}{V_0}, \quad \mu = \frac{m}{m_0}, \quad \varphi' = \sqrt{\frac{L_0}{C_0}}\, \frac{I}{V_0}. \end{gathered} \tag{12}$$

In dimensionless variables the indicated system, reduced first to canonical form, assumes the form

$$\frac{dy}{d\tau} = y'; \tag{13}$$

$$\frac{dy'}{d\tau} = \frac{q}{\mu}\varphi'^2 - \frac{y'}{\mu}(\delta_1 + \delta_2\mu + \delta_3|\varphi'| + \delta_4 y') - \frac{y'}{\mu}(-\gamma_1\mu - \gamma_2\mu^2 + \gamma_3|\varphi'| + \gamma_4\varphi'^2); \tag{14}$$

$$\frac{d\varphi}{d\tau} = -\varphi'; \tag{15}$$

$$\frac{d\varphi'}{d\tau} = \frac{\varphi - \alpha\varphi' - y'\varphi'}{1 + y}; \tag{16}$$

$$\frac{d\mu}{d\tau} = -\gamma_1\mu - \gamma_2\mu^2 + \gamma_3|\varphi'| + \gamma_4\varphi'^2, \tag{17}$$

where q, δ_1, δ_2, δ_3, δ_4, γ_1, γ_2, γ_3, γ_4, and α are the dimensionless parameters which in terms of the parameters of the system of equations (1)-(6) are expressed in the following manner:

$$\begin{gathered} q = \frac{b^2C_0^2V_0^2}{2m_0L_0}, \quad \alpha = R\sqrt{\frac{C_0}{L_0}}, \\ \gamma_1 = a_1\sqrt{L_0C_0}, \quad \gamma_2 = a_2m_0\sqrt{L_0C_0}, \\ \gamma_3 = \frac{a_3C_0V_0}{m_0}, \quad \gamma_4 = \frac{C_0^2V_0^2}{\sqrt{L_0C_0}}\,\frac{a_4}{m_0}, \\ \delta_1 = \frac{b_1}{m_0}\sqrt{L_0C_0}, \quad \delta_2 = b_2\sqrt{L_0C_0}, \\ \delta_3 = \frac{1}{2}\,\frac{m_iC_0V_0}{em_0}, \quad \delta_4 = \frac{b_4L_0}{m_0b}. \end{gathered} \tag{18}$$

The initial conditions (11) in dimensionless variables assume the following form:

$$\text{when } \tau = 0 \quad y = y' = \varphi' = 0, \ \varphi = 1, \quad \mu = 1. \tag{19}$$

The physical significance of the dimensionless parameters in (18) is the following. The parameter q represents the ratio of the characteristic magnitude of the force of magnetic pressure on the plasma to the characteristic magnitude of the inertial forces of the accelerated plasma.

The parameters δ_i (i = 1, 2, 3, 4) represent the ratio of the characteristic resistances to the characteristic inertial force, and here it is not difficult to see the physical significance of each individual value of δ_i. Thus, for example, δ_1 is the ratio of the characteristic force of friction against the electrode to the characteristic inertial force; δ_4 is the ratio of the forces of gas-dynamic resistance to the characteristic inertial forces, and finally; δ_2 and δ_3 represent the ratios of the characteristic viscosity forces due to the processes of mass transfer and current to the characteristic inertial forces.

The parameters γ_i (i = 1, 2, 3, 4) represent the ratio of the change in mass brought about by a certain "elementary" process in the kinetics of mass transfer to the characteristic magnitude of the time-change of mass as a result of the unsteadiness of the process. Consequently, the parameter γ_1 describes the effect of diffusion (or of overcharging, or of the adhesion of the particles to each other, with mutual neutralization), while the parameter γ_2 describes the effect of particle recombination, with the parameters γ_3 and γ_4, finally, making it possible to take into consideration the processes of erosion as a result of ion bombardment and the Joule heating of the electrodes, respectively.

The magnitude of the parameter q is determined exclusively by the characteristics of the external circuit, with the values of the remaining parameters depending strongly on the acceleration regimes and the characteristics of the plasma. Under certain conditions one of the processes may predominate over another; a complete examination, however, requires that consideration be given to the combined effect of all phenomena.

We see from (14) that the resistance force of viscous friction with the parameter δ_2 exhibits precisely the same structure as the "reactive" term by means of which we take into consideration the diffusion process. There is therefore complete justification for referring to the second term in (10) as the frictional force of diffusion mass transfer. Analogously, we note that the third term in (10) is a result of an erosion process of mass transfer under the action of electrode bombardment by an ion current. In analogy with the right-hand member of (14), expression (10) for the frictional force can be complemented through consideration of the frictional forces which arise in mass transfer as a result of recombination,

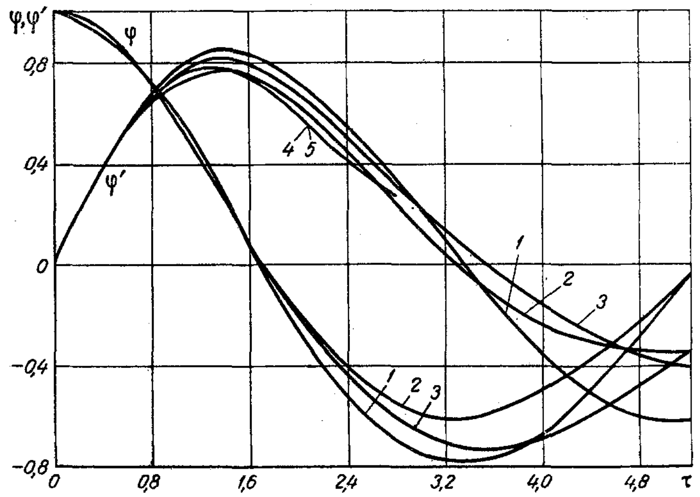

Fig. 3. Change in the current φ' and in the voltage φ during time τ (the parameters and notations correspond to those of Fig. 1).

$$F_{\mathrm{rec}} = b_5 v m^2, \tag{20}$$

and with consideration of the frictional force resulting from the transfer of mass on Joule fusion of the electrodes,

$$F_{\mathrm{Jf}} = b_6 v I^2. \tag{21}$$

The frictional forces which arise during the processes of mass transfer can therefore be taken into consideration by appropriate changes in the coefficients γ_1, γ_2, γ_3, and γ_4 in Eq. (14). This remark does not pertain to such external resistances as the wave drag developed by the unperturbed gas, etc.

To evaluate the role and relative effect of the various physical processes on the electrodynamic acceleration of the plasma, we repeatedly solved the system of equations (13)-(17), given the initial conditions (19), with the variable parameters of (18). The calculation was accomplished numerically by the Runge–Kutta method, with an integration interval of $\tau h = 0.2$. The results of the calculations are shown in Figs. 1-4. For convenience of comparison, one of the figures shows the change in identical quantities during the process of acceleration for various parameter values. The parameter values corresponding to a given curve are shown in the keys to the figure.

Figure 1 shows the change in mass as a result of erosion and plasma diffusion, with consideration given to the "diffusion" friction force. Curve 1 corresponds to an intensive process of electrode erosion as a result of Joule fusion of the electrodes and as a result of electrode bombardment by an ion current, in conjunction with pronounced influence on the part of the forces of diffusion friction. The mass in this case increases by a factor of approximately 4 during the acceleration time $\tau = 3.2$. Curve 2 (Fig. 1) enables us to evaluate the role of diffusion friction. The tenfold reduction in the magnitude of the latter leads to a time delay in mass release and, naturally, it results in increased velocity (see Fig. 2). By comparing curve 3 with curve 2 we are able, at any instant of time, to evaluate the relative effect of mass release as a result of Joule electrode fusion. The tenfold reduction in the parameter γ_4 reduces the mass at the instant $\tau = 3.4$ by a factor of only 1.28, which suggests a more intensive release of mass with the selected parameters as a result of ion bombardment of the electrodes. Indeed, we see from curve 4 that the reduction in the parameter γ_3 by means of which we account for the ion bombardment reduces the mass release at $\tau = 3.4$ by a factor of 2.28. To clarify the role of diffusion, here we present curve 5 showing the change in mass as a result of intensive diffusion. All other conditions relative to variant 2 being equal, intensive diffusion leads to a pronounced reduction in mass; diffusion with these parameters almost completely offsets the influx of mass due to erosion, and in the initial segment of acceleration actually is greater than the mass release.

The effect of these processes on the velocity of the center of plasma inertia is shown in Fig. 2. The reduction in mass release is naturally going to lead to an increase in velocity; however, the total momentum, equal to the product of the mass and the velocity, may diminish in this case, and we can see this from the

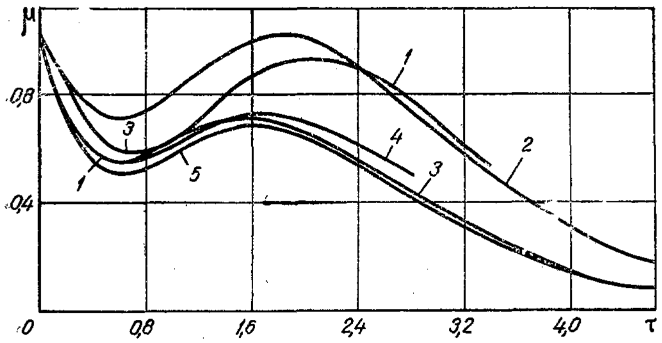

Fig. 4. Change in mass μ during time τ for the following parameters of system (13)-(17): 1) $q = 0.24$, $\alpha = 0.1$, $\gamma_1 = 1$, $\gamma_2 = 1$, $\gamma_3 = 1$, $\gamma_4 = 1$, $\delta_1 = 0$, $\delta_2 = 0.1$, $\delta_3 = 0$, $\delta_4 = 0$; 2) $q = 1$, $\alpha = 0.1$, $\gamma_1 = 1$, $\gamma_2 = 0.1$, $\gamma_3 = 1$, $\gamma_4 = 1$, $\delta_1 = 0$, $\delta_2 = 0.1$, $\delta_3 = 0$, $\delta_4 = 0$; 3) $q = 1$, $\alpha = 0.1$, $\gamma_1 = 1$, $\gamma_2 = 1$, $\gamma_3 = 1$, $\gamma_4 = 1$, $\sigma_1 = 0.1$, $\sigma_2 = 0.1$, $\sigma_3 = 0.1$, $\delta_4 = 0.1$; 4) $q = 1$, $\alpha = 0.1$, $\gamma_1 = 1$, $\gamma_2 = 1$, $\gamma_3 = 1$, $\gamma_4 = 1$, $\delta_1 = 0$, $\delta_2 = 0$, $\delta_3 = 0$, $\delta_3 = 0$, $\delta_4 = 0$; 5) $q = 1$, $\alpha = 0.1$, $\gamma_1 = 1$, $\gamma_2 = 1$, $\gamma_3 = 1$, $\gamma_4 = 1$, $\delta_1 = 0.1$, $\delta_2 = 0.1$, $\delta_3 = 0$, $\delta_4 = 0$.

following figures. Thus, for example, at the instant $\tau = 2.0$, when the velocities for all of the cited cases approach their maximum, the corresponding momenta are equal to:

$$P_2 = \mu y' = 2.9696 \cdot 0,2447 \simeq 0,767;$$
$$P_3 = 2.2947 \cdot 0.34965 \simeq 0.803;$$
$$P_4 = 1.1916 \cdot 0.6021 \simeq 0.714;$$
$$P_5 = 1.0845 \cdot 0.6493 \simeq 0.670.$$

The reduction in velocity on attainment of maximum magnitude is explained by the reduction in the forces of magnetic pressure and the increase in the forces of diffusion friction.

The effect of the processes of mass transfer on the electrical characteristics can be evaluated for the corresponding conditions from the curves in Fig. 3.

The effect of the recombination process on the plasma acceleration process is shown in Fig. 4 where the change in the mass is presented for the case of intensive recombination, given a recombination parameter $\gamma_2 = 1$. Comparison of curve 5 in Figs. 1 and 4 shows that recombination leads to an intensive reduction in accelerated mass. Thus, at $\tau = 0.6$ we have a reduction by a factor of 2.5 in the mass, due to recombination. The curve showing the change in mass with time exhibits a characteristic maximum at the time interval $\tau = 1.4$-2.4, so that the acceleration time is best limited to this interval if we are to achieve maximum momenta in the acceleration of the plasma.

Let us note that curve 3 corresponds to the solution of the complete system of equations (13)-(19) for the cited parameters. To evaluate the role of the parameter on the phenomena studied here, we offer curve 1. As usual, the reduction in q leads to a substantial reduction in the developed velocity; however, this parameter has little effect on the magnitude and nature of the time change in mass.

NOTATION

m	is the accelerated mass;
m_0	is the initial mass of the accelerated plasma;
m_i	is the ion mass of the accelerated plasma;
e	is the electron charge;
z	is the coordinate of the inertial center;
t	is the time;
I	is the current;
V	is the voltage;
V_0	is the initial voltage at the capacitor;

F	is the force resisting the motion of the plasma;
C_0	is the battery capacitance;
R	is the total ohmic resistance of the circuit;
L_0	is the inductance of the supply leads and of the capacitor;
b	is the distributed inductance per unit length of the coaxial;
$\alpha_1, \alpha_2, \alpha_3, \alpha_4$	are the mass coefficients of diffusion, recombination, and electrode erosion under the action of ion bombardment, and electrode erosion as a result of Joule fusion of the electrodes, respectively;
n	is the particle concentration;
ρ	is the coefficient of particle recombination;
$b_1, b_2, b_3, b_4, b_5, b_6$	are the proportionality factors which account, respectively, for the friction of the moving plasma against the electrodes, the processes of friction in mass transfer (b_2, b_3), the effect of the resistance of the external medium (b_4), the processes of friction in mass transfer as a result of recombination (b_5), and the processes of friction as a result of mass transfer in the case of Joule fusion (b_6);
$\tau, y, y', \varphi, \mu, \varphi'$	are, respectively, time, path, velocity, voltage, mass, and current;
$q, \delta_1, \delta_2, \delta_3, \delta_4, \gamma_1, \gamma_2, \gamma_3, \gamma_4, \alpha$	are dimensionless parameters.

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