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GENERATION OF SPONTANEOUS MAGNETIC FIELDS IN STRONGLY INHOMOGENEOUS FULLY IONIZED PLASMA

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This paper investigates the spontaneous generation of magnetic fields in a fully ionized plasma with collinear density and temperature gradients. It is shown that the magnetic field generation is caused by the development of thermomagnetic (TM) instability in a strongly inhomogeneous plasma. In the long-wavelength limit of TM perturbations, the inhomogeneous region is approximated by a sharp discontinuity in density and temperature. Analytical expressions for the growth rates of magnetic field and temperature perturbations are derived in this regime. The criteria for the onset of TM instability are obtained by taking into account both convective heat transfer and thermomagnetic effects, which determine the conditions for magnetic field generation.

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INTRODUCTION

With the development of laser technologies, the field of laser-driven thermonuclear fusion actively emerged. In experiments involving laser radiation interaction with matter, powerful magnetic fields up to several $\sim 10^2$ T spontaneously arose in plasma within fractions of a second ($\sim 10^{-9}$ s) [1]. This magnetic field generation negatively affects the hydrodynamics of thermonuclear target compression, deteriorating compression and plasma heating regimes [2]. The primary mechanism for strong magnetic field excitation is related to thermoEMF in plasma with intersecting density and temperature gradients − the Biermann battery effect [3]. This mechanism is based on charge imbalance due to plasma property inhomogeneities: in the presence of temperature or pressure gradients, electrons and ions experience different forces, creating an electric current that generates a magnetic field. The Biermann battery effect is important in astrophysics for explaining magnetic field generation in the early Universe and near black holes. In turbulent plasma, an analogous process is called the cross-helicity effect, where the role of pressure gradient is played by the gradient of turbulent stresses [4, 5]. Magnetic fields significantly influence heat transfer and plasma hydrodynamics through thermomagnetic instability [6]. When the equilibrium temperature gradient is disturbed, the Biermann battery generates a magnetic field that amplifies temperature perturbations by affecting plasma thermal conductivity. In laser heating of spherical targets, the most probable mechanism for magnetic field generation is magnetothermal instability with parallel density and temperature gradients. Analysis of non-magnetized plasma showed that hot plasma $T = 10^8$ K with density 10^{17} m^{-3} becomes magnetized at just 0.03 T [7].

Upon transition to magnetized plasma, the instability character changes: transverse thermal conductivity causes instability with opposite density and temperature gradients, however the growth rate becomes significantly lower. Under strong magnetic field conditions, thermal convection begins to dominate over thermal conductivity, while the Hall effect provides additional system stabilization. Thermomagnetic instability represents a mechanism for converting part of the heat flux into magnetic field energy in non-uniformly heated plasma. This mechanism finds wide application in astrophysics, explaining the generation of strong magnetic fields in neutron star surface layers [8], hot massive stars [9], and radioactive plasma [10]. The physical basis of this instability type lies in the feedback between the Nernst effect and transverse heat fluxes (Righi-Leduc effect).

In the papers mentioned above, the mechanisms of generation of magnetic fields in a high-temperature plasma were considered when “skew” heat fluxes became significant in heat transfer. In this case, the scales of the generated fields are small compared to the characteristic scales of plasma inhomogeneity in temperature and density. In our previous paper [11], we investigated the initial stage of magnetic field generation considering thermomagnetic (TM) effects and convective heat transfer in fully ionized plasma with smooth temperature and density gradients. Based on Braginskii's equations for electron gas, the fundamental equations describing the evolution of both magnetic and thermal perturbations were derived. Taking into account thermomagnetic phenomena and convective heat transfer, criteria for TM instability development were established. Applying the geometrical optics approximation, we derived the dispersion equation for short-wavelength TM perturbations. Detailed analysis of this equation revealed that in low-temperature plasma, TM perturbations decay due to electron gas thermal conductivity.

In this regard, the aim of this work is to investigate the possibility of magnetic field generation by convective flows in strongly inhomogeneous low-temperature plasma.

STATEMENT OF THE PROBLEM

In our previous work [11], we demonstrated that in a low-temperature plasma, when convective heat flows dominate over the “skew” components of electron heat transfer, the instability growth rate at $kL \gg 1$ cannot exceed the thermal losses due to electron heat conductivity. Moreover, in the calculation of the instability growth rate for low-temperature plasma, the effect of the thermal force was neglected because the short-wavelength approximation was applied. Given these limitations, there is significant interest in exploring the possibility of magnetic field generation in a low-temperature, unmagnetized plasma under long-wavelength perturbations $kL \ll 1$. In this regime, the geometrical optics approximation is not applicable, and the system of equations governing the evolution of thermomagnetic (TM) perturbations

$$(B_1, T_1) = (B_1(x), T_1(x))e^{\gamma t + iky} \qquad (1)$$

takes the following form:

$$(\nu_m + \gamma r_d^2)\frac{d^2 B_1}{dx^2} - \left(\gamma K_N r_d^2 + \frac{3}{2}\nu_m K_T\right)\frac{dB_1}{dx} -$$

$$-(1+k^2 r_d^2)(\gamma - \gamma_B + \gamma_\beta^{'})B_1 = \frac{c}{e} ikK_N T_1 ; \qquad (2)$$

$$\frac{2}{3}\chi_\perp^{(0)}\frac{d^2 T_1}{dx^2} + \frac{5}{3}\chi_\perp^{(0)} K_T \frac{dT_1}{dx} -$$

$$-\left[\gamma + \gamma_\chi - \frac{5}{3}\chi_\perp^{(0)}\left(\frac{1}{T_0}\frac{d^2 T_0}{dx^2} + \frac{3}{2}K_T^2\right)\right]T_1 =$$

$$= -\frac{cT_0}{4\pi e N_0}\left(\left(1 + \frac{2}{3}\beta_\perp\right)K_T - \frac{2}{3}K_N\right)ikB_1 . \qquad (3)$$

It is evident that the differential equations (2), (3) form a coupled system only in an inhomogeneous plasma. In a homogeneous plasma, these equations become decoupled. In this case, equation (2) describes the decay of magnetic field perturbations due to magnetic viscosity, while equation (3) accounts for the decay of temperature perturbations caused by electron thermal conductivity. In the wavelength range $L \ll \lambda$, the plasma inhomogeneity can be approximated by a sharp discontinuity in electron density and temperature at the point $x = 0$:

$$N_0(x) = N_{01} + \Theta(x)\cdot(N_{02} - N_{01}) = N_{01} + \Theta(x)\cdot \Delta N_0 ,$$

$$T_0(x) = T_{01} + \Theta(x)\cdot(T_{02} - T_{01}) = T_{01} + \Theta(x)\cdot \Delta T_0 ,$$

where $\Theta(x)$ is the Heaviside step function, defined as $\Theta(x) = 0$ for $x < 0$ and $\Theta(x) = 1$ for $x \geq 0$. Thus, a discontinuity in electron density and temperature is localized within an infinitesimally thin layer (Fig. 1).

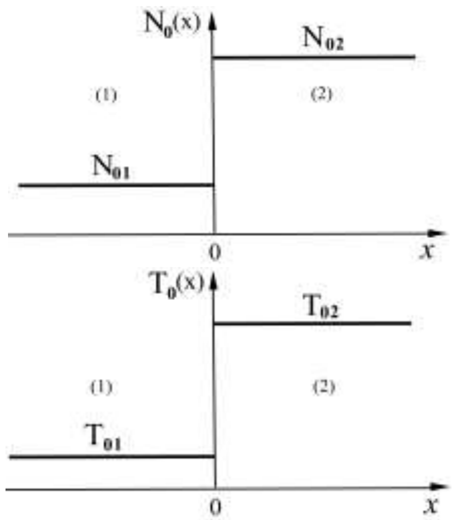

Fig. 1. The scheme shows the jump in the density and temperature of electrons at the boundary between two media: (1) and (2)

The hydrodynamic description of plasma that we use is applicable if the characteristic times of the processes γ^{-1} are much longer than the times of collisions of electrons with ions ν_{ei}^{-1}: $\nu_{ei} \gg \gamma$. In the considered long-wave limit, we also neglect the inertia of the electrons $kr_d \ll 1$. The perturbations decrease according to exponencial law in regions of the plasma that are far from the transition layer, i.e., where the plasma is homogeneous:

$$B_1(x) = A_{B_1} e^{-k_{\nu_m}|x|},\ T_1(x) = A_{T_1} e^{-k_\chi |x|},\ k_{\nu_m}, k_\chi > 0 . \qquad (4)$$

The expressions (4) are damped solutions of the system (2), (3) for a homogeneous plasma. The coefficients $k_{\nu_m}^{(1,2)}$ and $k_\chi^{(1,2)}$ corresponding to the regions $x < 0$ (1) to the left of the boundary of two media) and $x \geqslant 0$ (2) to the right of the boundary of two media) have the form:

$$k_{\nu_m}^{(1,2)} = k\sqrt{1 + \frac{\gamma}{\gamma_H^{(1,2)}}} , \qquad k_\chi^{(1,2)} = k\sqrt{1 + \frac{\gamma}{\gamma_\chi^{(1,2)}}} ,$$

$$\gamma_H = 0.51\nu_{ei}\left(\frac{k^2 c^2}{\omega_{pe}^2}\right). \qquad (5)$$

The indices (1.2) mean that in carrying out the calculations, one should take the corresponding values of the electron density and temperature at the jump of these plasma parameters. The derivatives dB_1/dx, dT_1/dx are discontinuous at the point $x = 0$. The boundary conditions relating the values of these derivatives to the left and right of the plasma inhomogeneity parameter jump are found by integrating the equations (2), (3) over a thin layer $(-\varepsilon, +\varepsilon)$ at $\varepsilon \to 0$:

$$\left\{\frac{dB_1}{dx}\right\} = \lim_{\varepsilon\to 0}\left(\left(\frac{dB_1}{dx}\right)_{x=+\varepsilon} - \left(\frac{dB_1}{dx}\right)_{x=-\varepsilon}\right) -$$

$$-\left(\frac{\gamma \Delta N_0}{0.51\nu_{ei}(0)N_0(0)} + \frac{3}{2}\frac{\Delta T_0}{T_0(0)} +\right.$$

$$\left. +0.81\frac{\tau(0)\Delta T_0}{m\nu_m(0)}\right)\left(\frac{dB_1}{dx}\right)_{x=+0} = \frac{ikc\Delta N_0 T_1(0)}{e\nu_m(0)N_0(0)} , \qquad (6)$$

$$\left\{\frac{dT_1}{dx}\right\} = \lim_{\varepsilon\to 0}\left(\left(\frac{dT_1}{dx}\right)_{x=+\varepsilon} - \left(\frac{dT_1}{dx}\right)_{x=-\varepsilon}\right) =$$

$$-\frac{3/2}{3.16}\frac{ikmc}{4\pi e N_0(0)\tau(0)} \times$$

$$\times\left[\left(1 + \frac{2}{3}\cdot 0.71\right)\frac{\Delta T_0}{T_0(0)} - \frac{2}{3}\frac{\Delta N_0}{N_0(0)}\right]B_1(0) . \qquad (7)$$

Here the curly brackets indicate a break at $x = 0$. Boundary conditions (6), (7) are supplemented by the condition of continuity of perturbations inside the transition layer:

$$\{B_1\} = 0,\ \{T_1\} = 0 . \qquad (8)$$

After deriving the linearized equations and representing the perturbations in the form of wave modes (4), solutions are obtained in each region on either side of the interface (5), decaying exponentially away from the boundary. These solutions are then matched by applying physical boundary conditions (6)-(8) that ensure the continuity of the relevant temperature and magnetic disturbances. This procedure leads to a dispersion relation that determines the spectrum of admissible perturbations propagating along the interface in a plasma with spatially varying temperature and density.

DISPERSION EQUATION

Using the boundary conditions (6), (7) and solutions (4), we obtain a system of equations for finding the amplitudes of the disturbances $B_1(0) = A_{B_1}$ and $T_1(0) = A_{T_1}$. The condition for the existence of a nontrivial solution of the resulting system of equations leads to the dispersion equation:

$$\left[(1-\Pi)\sqrt{1+\frac{\gamma}{\gamma_H^{(2)}}}+\sqrt{1+\frac{\gamma}{\gamma_H^{(1)}}}\right]\times$$
$$\times\left[\sqrt{1+\frac{\gamma}{\gamma_\chi^{(2)}}}+\sqrt{1+\frac{\gamma}{\gamma_\chi^{(1)}}}\right]-\Lambda=0, \quad (9)$$

where

$$\Pi=\frac{\gamma\Delta N_0}{0.51\nu_{ei}(0)N_0(0)}+\frac{3}{2}\frac{\Delta T_0}{T_0(0)}+0.81\frac{\tau(0)T_0(0)}{m\nu_m(0)}\frac{\Delta T_0}{T_0(0)},$$

$$\Lambda=\frac{3/2}{3.16\cdot 0.51}\left[\left(1+\frac{2}{3}\cdot 0.71\right)\frac{\Delta T_0\Delta N_0}{T_0(0)N_0(0)}-\frac{2}{3}\left(\frac{\Delta N_0}{N_0(0)}\right)^2\right]$$

are the parameters of magnetic field generation. In the dispersion equation (9), the damping decrements $\gamma_H^{(1,2)}$ and $\gamma_\chi^{(1,2)}$ are calculated for the electron density and temperature values from regions (1) and (2), respectively. The expression for Π includes new effects that contribute to the generation of the magnetic field. The first term in Π describes the excitation of electronic vortex motions due to the electron density gradient. However, due to the fulfillment of the hydrodynamic description $\gamma \ll \nu_{ei}$, this term can be neglected since the ratio $\Delta N_0 / N_0(0)$ does not exceed unity. The second term is related to taking temperature fluctuations into account in the thermal conductivity; and finally, the third term is due to the influence of thermal force. The parameter Λ is an analogue of the quantity $(c/e)k_y^2 K_N G$ [11] for the case of short-wave disturbances and describes the occurrence of instability due to convective heat transfer, taking into account the work of pressure forces.

1. Generation of a magnetic field in a temperature-inhomogeneous plasma

Let us consider the case when there is no jump in the electron density $N_{01} = N_{02}$. Then the parameter $\Lambda = 0$ in the dispersion equation (9) is equal to zero, and the nontrivial solution takes the following form:

$$\gamma=\frac{\Pi_T(\Pi_T-2)\gamma_H^{(1)}\gamma_H^{(2)}}{\gamma_H^{(2)}-\gamma_H^{(1)}(\Pi_T-1)^2}, \quad (10)$$

where

$$\Pi_T=\frac{3}{2}\frac{\Delta T_0}{T_0(0)}+\left(\frac{0.81}{0.51}\right)R_{TM}\frac{\Delta T_0}{T_0(0)}=\frac{3}{2}\frac{\Delta T_0}{T_0(0)}(1+1.05R_{TM}).$$

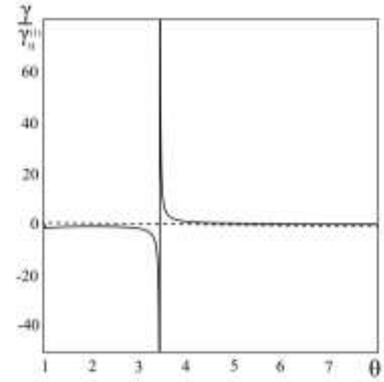

Fig. 2. Dependence of the increment instability $\gamma/\gamma_H^{(1)}$ on the temperature jump θ at a fixed value of the parameter $R_{TM} = 0.3$

Using the relationship between ω_{pe}^2 and ν_{ei} with the electron density and temperature

$$\omega_{pe}^2(1)\sim N_{01},\quad \omega_{pe}^2(2)\sim N_{02},$$
$$\nu_{ei}(1)\sim N_{01}T_{01}^{-3/2},\quad \nu_{ei}(2)\sim N_{02}T_{02}^{-3/2}$$

we can write the expression for the instability increment γ in a more convenient form:

$$\frac{\gamma}{\gamma_H^{(1)}}=\frac{3}{2}\left(1-\frac{T_{01}}{T_{02}}\right)(1+1.05R_{TM})\times$$
$$\times\frac{\frac{3}{2}\left(1-\frac{T_{01}}{T_{02}}\right)(1+1.05R_{TM})-2}{1-\left(\frac{T_{02}}{T_{01}}\right)^{3/2}\left(\frac{3}{2}\left(1-\frac{T_{01}}{T_{02}}\right)(1+1.05R_{TM})-1\right)^2}. \quad (11)$$

It is clear that the relative growth rate $\gamma/\gamma_H^{(1)}$ of perturbations depends on the value of the temperature jump T_{02}/T_{01} at the interface between two media. If there is no temperature jump, i.e., $T_{01}=T_{02}$, then the magnetic field generation is zero, as the increment (11) equals zero. The behaviour of the relative growth rate $\gamma/\gamma_H^{(1)}$ with respect to T_{02}/T_{01} is examined by fixing the parameter $R_{TM}=0.3$ for the case of low-temperature plasma. Fig. 2 shows a graph of the dependence of $\gamma/\gamma_H^{(1)}$ on T_{02}/T_{01}, from which a sharp increase in the growth rate, and hence the magnetic field, is clearly visible in the vicinity of a certain critical value of the temperature jump $\theta_{cr}=(T_{02}/T_{01})_{cr}$: $\gamma/\gamma_H^{(1)}\approx 1067.28$ at $\theta_{cr}\to 3.428$. Moreover, for jump values T_{02}/T_{01} less than θ_{cr}, the instability increment has a negative value $\gamma/\gamma_H^{(1)}<0$ and even a zero value at $T_{02}/T_{01}=1$. For $T_{02}/T_{01}>\theta_{cr}$, a decrease in the instability increment is observed, so, for example, if the ratio is $T_{02}/T_{01}\approx 4$, we obtain $\gamma/\gamma_H^{(1)}\approx 1$. A further increase in the ratio $T_{02}/T_{01}\gg 1$ leads to a decrease in the instability increment $\gamma/\gamma_H^{(1)}\ll 1$, and therefore, in this case, no magnetic field is generated. Indeed, this conclusion can be reached by analyzing expression (10) for $T_{02}/T_{01}\gg 1$, and taking into account the relation

$\gamma_H^{(2)}/\gamma_H^{(1)} = (T_{01}/T_{02})^{3/2}$, we can derive an estimate for the growth rate of the instability, $\gamma \cong \gamma_H^{(2)} \sim N_{02}T_{02}^{-3/2} \ll 1$. A similar dependence of the growth rate $\gamma/\gamma_H^{(2)}$ on the temperature jump θ is shown in Fig. 3.

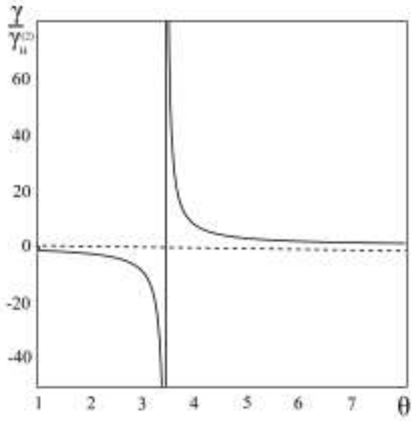

Fig. 3. Dependence of the increment instability $\gamma/\gamma_H^{(2)}$ on the temperature jump θ at a fixed value of the parameter $R_{TM} = 0.3$

2. Generation of a magnetic field in a strongly inhomogeneous plasma

Let us now find out under what conditions the generation of a magnetic field occurs in a strongly inhomogeneous plasma when there is a jump in the density $N_{02}/N_{01} = n > 1$ and temperature $\theta > 1$ of electrons. The relationship between the relative change in temperature and density at the stability boundary is found from equation (9) at $\gamma = 0$ and has the following form:

$$\frac{\Delta T_0}{T_0(0)} = \frac{2+\frac{1/2}{3.16\cdot 0.51}\left(\frac{\Delta N_0}{N_0(0)}\right)^2}{\frac{3/4}{3.16\cdot 0.51}\left(1+\frac{2}{3}\cdot 0.71\right)\frac{\Delta N_0}{N_0(0)}+\frac{3}{2}(1+1.05R_{TM})}. \quad (12)$$

The minimum jump in electron density

$$n_{min} = \left(\frac{N_{02}}{N_{01}}\right)_{min} \approx 25$$

at which the development of instability can begin is determined by expression (12), and the minimum temperature jump corresponding to this value n_{min} is

$$\theta_{min} = \left(\frac{T_{02}}{T_{01}}\right)_{min} \approx 7.69, \text{ at } R_{TM} = 0.3.$$

Using the relation between the decrements $\gamma_\chi/\gamma_H \cong R_{TM} \ll 1$, one of the positive solutions of the dispersion equation (9) has the form

$$\gamma \approx \frac{\gamma_\chi^{(2)}}{1+(\gamma_\chi^{(2)}/\gamma_\chi^{(1)})}\times$$

$$\times\left[\frac{0.93}{1-\frac{\Pi_T}{2}}\left(1.47\frac{\Delta T_0}{T_0(0)}\frac{\Delta N_0}{N_0(0)}-\frac{2}{3}\left(\frac{\Delta N_0}{N_0(0)}\right)^2\right)-4\right]. \quad (13)$$

Expression (13) for the TM instability increment in a plasma with a sharp boundary has a similar structure as expression for the TM instability increment in a weakly inhomogeneous plasma [11]. As can be seen from (13), a necessary condition for the development of instability, as in the case of the short-wavelength approximation, is the parallelism of the density and temperature gradients of the electrons. For definiteness, we assume $\Delta N_0 > 0$ and $\Delta T_0 > 0$. For convenience, we write solution (13) in terms of the jump parameters n and θ, i.e.,

$$\Gamma \approx \left[\frac{0.93}{1-\frac{\Pi_T}{2}}\left(1.47(1-n^{-1})(1-\theta^{-1})-\frac{2}{3}(1-n^{-1})^2\right)-4\right],$$

where $\Gamma = \gamma(\gamma_\chi^{(1)}+\gamma_\chi^{(2)})/\gamma_\chi^{(2)}$ is the dimensionless instability increment. It is clear that the generation of a magnetic field occurs at positive $\gamma > 0$, which implies the necessary conditions for density and temperature jumps satisfying the following inequality:

$$1.47(1-n^{-1})(1-\theta^{-1})-\frac{2}{3}(1-n^{-1})^2 > 4.3\times$$

$$\times(1-0.75(1-\theta^{-1})(1+1.05R_{TM})). \quad (14)$$

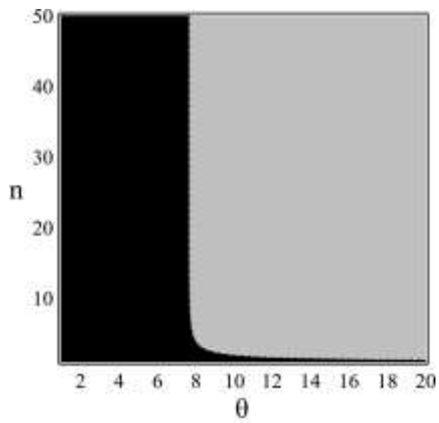

Fig. 4. The gray region indicates the range of parameters for the density n and temperature θ jump where the magnetic field generation takes place

Using inequality (14), we determine the area of development of instability, which is highlighted in gray in Fig. 4. The black color in Fig. 4 shows the area of parameters (n,θ) where there is no magnetic field generation. In other words, for these values of n and θ, the convective transfer is not sufficient to excite the instability. Instability arises at sufficiently large differences in density and temperature. It should be noted that the theory of magnetic field generation in a strongly inhomogeneous plasma developed in this section is extended to the range of parameters n and θ, where the approximation of a low-temperature fully ionized plasma is fulfilled. Such conditions can be realized at the contact interface between two media during the expansion of the plasma torch in the plasma or gas. The validity of the results obtained may be compromised due to partial ionization of the gas at the contact boundary by the radiation of the plasma torch or diffusing electrons. As a result, the use of a fully ionized plasma description in a region with a lower electron density, as done in this study, is not entirely accurate if the frequency of electron-atom collisions is greater than that of electron-ion collisions. Another restriction is related to the ratio between the time of development of instability $t_0 = \gamma^{-1}$ and plasma expansion t_p. The solution is applicable only if $t_p > t_0$. If this condition is not met, the assumption of constancy of the absolute values of the jump in density ΔN_0 and temperature ΔT_0 of electrons during instability development will not hold.

CONCLUSIONS

In this study, a linear theory of spontaneous magnetic field generation driven by thermomagnetic effects and convective heat transfer is developed for a strongly inhomogeneous, low-temperature, fully ionized plasma. The analysis focuses on a configuration with a sharp discontinuity in density and temperature, where the gradients of these quantities are collinear. A set of ordinary differential equations is derived to describe the dynamics of small magnetic field perturbations near the interface. The analysis of these equations showed that there is a region of density and temperature jump parameters in which spontaneous magnetic field generation occurs near the interface where a sharp change in plasma parameters occurs.

The developed theory can be applied to explain spontaneous magnetic field generation in plasma plumes and similar media.

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ГЕНЕРАЦІЯ СПОНТАННИХ МАГНІТНИХ ПОЛІВ У СИЛЬНО НЕОДНОРІДНІЙ ПОВНІСТЮ ІОНІЗОВАНІЙ ПЛАЗМІ

М.Й. Копп, В.В. Яновський

Досліджується спонтанна генерація магнітних полів у повністю іонізованій плазмі з колінеарними градієнтами густини та температури. Показано, що виникнення магнітного поля зумовлене розвитком термомагнітної (ТМ) нестійкості в сильно неоднорідній плазмі. У довгохвильовій межі ТМ-збурень неоднорідну область апроксимовано як різкий розрив густини та температури. У цьому режимі отримано аналітичні вирази для темпів зростання збурень магнітного поля та температури. Критерії виникнення ТМ-нестійкості визначаються з урахуванням як конвективного теплообміну, так і термомагнітних ефектів, які разом задають умови для генерації магнітного поля.