Influence of distance between coils with current on the effect of cascade plasma heating in flows injected from the QSPA

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Abstract. Research of the interaction of high-speed dense plasma flows generated by the quasi-stationary plasma accelerator with the magnetic field of the set of ring current-carrying conductors located at different distances from each other is presented. The study was based on the model of radiation magnetic gas dynamics, taking into account electrical conductivity, thermal conductivity and radiation transport. It was found that a decrease in the distance between the coils with a current leads to the disappearance of the effect of step-by-step or cascade transformation of kinetic energy into thermal energy of the plasma.

1. Introduction

New approach to solving the problem of the controlled thermonuclear fusion (CTF) was proposed and formulated in [1] as a result of research conducted in the framework of the model of radiation magnetic gas dynamics (RMHD). New approach is based on the revealed effect of the step-by-step or cascade increase in the plasma temperature during the heating and deceleration of high-speed flow in the magnetic field of the set of ring current-carrying conductors located at a certain distance from each other. The influence of various ways of setting currents in coils on cascade plasma heating in the injected flows was considered in [2], where the optimal mode for plasma heating in the flows was presented, in particular.

In the present work, the influence of the distance between ring conductors on the effect of cascade step-by-step plasma heating is studied. Obviously, too large distance between the coils eliminates the possibility of cascade heating in the injected plasma. The very small distance between the coils corresponds to the magnetic field of the solenoid. Numerical studies [3] have shown that injection of high-speed plasma stream into the magnetic field of the solenoid is not accompanied by heating of the plasma inside the volume of the solenoid. In this case, the plasma is heated only in the region where the flow enters the magnetic barrier created by one ring conductor [4] or a number of coils with a current. Most studies that reveal cascade plasma heating [1, 2] have been carried out under the condition that the distance between the ring conductors exceeds their radius. The results of numerical studies of the injection of plasma flows into the set of ring current-carrying conductors, the distance between which is of the order of the radius of the coils, are presented in this paper.

The quasi-stationary plasma accelerator (QSPA) is proposed to be used as an injector of high-speed dense plasma flows into the set of ring current-carrying conductors in accordance with figure 1. The conditions for generation of deuterium-tritium plasma flows with thermonuclear parameters and ion energy at the outlet from the QSPA at a level of 30 keV, necessary for the subsequent fusion reaction in the promising thermonuclear installations, were determined and presented in [5]. In modern and earlier experimental studies on the QSPA, the ion energy is within 1 keV [6-10].

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It should be recalled that the processes in the simplest plasma accelerators occur in the presence of the main azimuthal magnetic field, which is generated by the electric current passing along the internal electrode. Mainly radial plasma current flowing between the electrodes and the azimuthal magnetic field provide the plasma acceleration behind the ionization front due to the Ampere force \( \frac{1}{c} j \times H \), where \( j \) is the current in the plasma. According to experiments, the QSPA in the full configuration is two-stage installation [6-10]. A number of small plasma accelerators, in which the incoming gas is ionized [11, 12] and the plasma is pre-accelerated, forms the first stage. The second stage of the QSPA is a large accelerator connected to a separate power circuit. Here, the final acceleration of the plasma is carried out again due to the Ampere force. Theoretical and numerical researches in new-generation plasma accelerators are aimed at studying plasma flows in the presence of an additional longitudinal magnetic field [13-15]. It can be useful for preventing near-electrode irregularities [16, 17] and for organizing the coordinated flow from accelerators to magnetic traps. Some problems of plasma dynamics in the QSPA in the presence of a longitudinal magnetic field were considered in [18, 19].

New approach being developed to solve the CTF problem involves the joint use of the QSPA and a number of coils with a current for sufficiently dense plasma, in contrast to the multi-mirror traps [20-21], which are used for the rarefied plasma. The problem of the interaction of dense plasma flows with the magnetic field of ring conductors with a current is considered on the basis of the non-stationary RMHD model for two-dimensional axisymmetric plasma flows in three-component magnetic field. The developed model implements one of the possible ways to include ring conductors into the model. Formulation of the problem is generally similar to previous studies [1-4].

2. Equations and formulation of the problem

Stationary The axisymmetric plasma flow is considered in the channel between two coaxial profiled electrodes and at the outlet from the accelerator, where the plasma volume is limited by the cylindrical surface of the insulator, which is a continuation of the external cylindrical electrode. The flow occurs in the presence of three components of the magnetic field \( \mathbf{H} = (H_z, H_r, H_\phi) \) and velocity \( \mathbf{V} = (V_z, V_r, V_\phi) \) in the presence of a longitudinal magnetic field, which is additional to the main azimuthal field in the accelerator channel, as well as in the presence of a longitudinal field created by ring conductors with a current. The model is based on the equations of magnetic gas dynamics in the one-fluid approximation (\( \mathbf{V}_e = \mathbf{V}_i = \mathbf{V} \)) taking into account the electrical and thermal conductivity

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \text{div} \rho \mathbf{V} &= 0, \\
\rho \frac{d \mathbf{V}}{d t} + \nabla P &= \frac{1}{c} \left[ j, \mathbf{H} \right], \\
\frac{\partial}{\partial t} (\rho \varepsilon) + \text{div} (\rho \varepsilon \mathbf{V}) + P \text{div} \mathbf{V} &= \frac{j^2}{\sigma} - \text{div} \mathbf{q} - \text{div} \mathbf{W}, \\
\frac{\partial \mathbf{H}}{\partial t} &= \text{rot} \left[ \mathbf{V}, \mathbf{H} \right] - c \text{rot} \frac{j}{\sigma}, \\
\frac{d}{d t} &= \frac{\partial}{\partial t} + \left( \mathbf{V}, \mathbf{V} \right), \\
\rho &= m_i n, \\
P &= P_i + P_e = 2 k_B n T, \\
\varepsilon &= 2 c_v T.
\end{align*}
\]
Here, the variables have the usual meaning. The electrical conductivity of the medium is equal to
$$\sigma = e^2 n_e \tau_e / m_e,$$
where $\tau_e$ is the characteristic time of collisions of electrons with ions. The vector $\mathbf{q} = -\kappa \nabla T$ corresponds to the heat flux, where $\kappa$ is the thermal conductivity coefficient. The density of the radiation energy flux $\mathbf{W}$ in the equation for internal energy, as well as the radiation energy density $U$, are determined by the radiation intensity $I_v(r, \Omega)$ with a frequency $\nu$ along the selected direction of the solid angle $\Omega$ at the point with the coordinate $\mathbf{r}$. The solution of the radiation transport problem is presented in [12].

Numerical modeling is carried out in dimensionless variables. Dimensionless parameters are the ratio of the characteristic gas pressure to the magnetic one $\beta = 8 \pi P_o / H_o^2$ ($P_o = 2 k n_o T_o$), magnetic viscosity $\nu = 1 / \text{Re}_m = \sigma_0 / \nu L$, and also the dimensionless value of the thermal conductivity $\kappa$. In the case of the Spitzer dependence of conductivity on temperature, we have $\text{Re}_m = \sigma_0 T^{3/2}$, where the value $\sigma_0$ is expressed in terms of the initial dimensional parameters and physical constants. As the units of measurement, we choose the channel length $L$, the characteristic values of concentration $n_o$ or density $\rho_o = m_i n_o$, temperature $T_o$, and the azimuthal component of the magnetic field at the inlet to the channel $H_o = 2 J_d / c R_o$, where $R_o$ is the characteristic radius and $J_d$ is the discharge current in the plasma accelerator. Then the unit of time is the characteristic time of collisions of electrons with ions.

Using the vector potential $\mathbf{A}$ of the magnetic field so that $\mathbf{H} = \nabla \times \mathbf{A}$, we have in the axisymmetric case ($\partial / \partial \phi = 0$)
$$H_r = -\frac{\partial A_\phi}{\partial z}, \quad H_z = \frac{1}{r} \frac{\partial (r A_\phi)}{\partial r},$$
where $A_\phi$ is the azimuthal component of the vector potential. Relations (2) under the condition of axial symmetry ensure the exact implementation of the equation $\text{div} \mathbf{H} = 0$. The MHD equations (1) in the axisymmetric case can be written in dimensionless form in terms of the component $A_\phi$ of the vector potential and the component $H_\phi$ of magnetic field. The corresponding equations (see e.g. [15]) contain seven independent variables $\rho$, $T$, $V_z$, $V_r$, $V_\phi$, $H_\phi$, $A_\phi$, as well as the azimuthal current
$$j_\phi = \frac{\partial H_r}{\partial z} - \frac{\partial H_z}{\partial r} = -\Delta A_\phi + \frac{A_\phi}{r^2}, \quad \Delta A_\phi = \frac{\partial^2 A_\phi}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial A_\phi}{\partial r} \right).$$

Formulation of the problem includes the following boundary conditions. At the inlet to the channel ($z=0$), we assume that the plasma is supplied with the known values of density $\rho(r) = f_1(r)$ and temperature $T(r) = f_2(r)$, and the current is kept constant, and $j_z = 0$ at $z=0$ or $r H_\phi = t_o = \text{const}$ ($t_o = R_o / L$). In the presence of a longitudinal magnetic field in the QSPA channel, we assume that the plasma does not rotate in the inlet section and the azimuthal velocity is zero $V_\phi = 0$. In addition, a value $H_z \neq 0$ should be set at the inlet. We have $H_z(r) = H^o = \text{const}$ and $\psi(r) = r A_\phi = 0.5 H^o r^2$ at $z=0$ under the condition of the inflow balanced in the radial direction [13].

The boundary conditions at the electrodes of the plasma accelerator for $r = r_c(z)$ and $r = r_a(z)$ determine their equipotentiality ($E_z = 0$) and surface impermeability ($V_n = 0$). The additional relation $H_n = 0$ is natural condition at plasma–conductor boundary in the presence of longitudinal magnetic field in the accelerator channel. It ensures the conservation of magnetic flux along the channel.
It is known that in the middle part of the channel there is a transition of the flow velocity through the speed of a fast magnetosonic wave. Accordingly, we have a supersonic flow at the outlet from the accelerator channel.

The insulator is the boundary between the plasma volume and the vacuum magnetic field created by ring conductors with a current. The boundary conditions on the cylindrical surface of the insulator, which is a continuation of the external cylindrical electrode of the accelerator at \( z > 1 \), have the following form: \( V_n = 0 \), \( j_n = 0 \), \( A_{\varphi} = A(z) \). The values of the azimuthal component of the vector potential \( A_{\varphi} \) and the magnetic flux function \( \psi = r A_{\varphi} \) are determined along the insulator based on the solution of the problem of the vacuum magnetic field created by ring conductors with a current [22].

In dimensionless variables, the azimuthal component of the vector potential for one ring conductor with a current \( J_k \) is equal to

\[
A_{\varphi}^k = 2 \frac{J_k}{J_p} \frac{R_k}{F} \sqrt{\frac{R_k}{r}} \left[ 1 - \frac{1}{2} F^2 \right] G - U ,
\]

where \( G \) and \( U \) are complete elliptic integrals of the first and second kind:

\[
G = \int_0^{\pi/2} \frac{d \theta}{\sqrt{1 - F^2 \sin^2 \theta}} , \\
U = \int_0^{\pi/2} \sqrt{1 - F^2 \sin^2 \theta} d \theta , \\
F^2 = \frac{4 r R_k}{(R_k + r)^2 + (z - z_k)^2} ,
\]

\( R_k \) is radius of the ring with a current, \( z_k \) is position of the ring with a current in the cylindrical coordinate system, for which \( z = 0 \) corresponds to the inlet to the channel of the plasma accelerator.

The total value of the azimuthal component of the vector potential is equal to \( A_{\varphi} = \sum_{k=1}^{K} A_{\varphi}^k \) in the presence of several conductors with an index \( k = 1, \ldots, K \). This sum, taking into account relation (4), allows us to determine the value of the function \( A(z) \) on the insulator for several rings.

The domain of numerical modeling in variables \((z,r)\) is presented in the figure 2. The numerical model includes the mapping of the curved region onto the rectangle in the plane \((z,y)\) using relation

\[
r = (1 - y) r_c(z) + y r_d(z) .
\]

The hyperbolic part of the MHD equations is calculated using the difference scheme with flux correction [23]. Magnetic viscosity and thermal conductivity were taken into account using the flux variant of the back-substitution method presented in [12], for example. Quasi-stationary flows are calculated by the method of establishing in the process of numerical solution of the non-stationary MHD problem. The 3D formulation of the radiation transport problem and the used method of long characteristics are also presented in [12].

3. Simulation results and discussion

The Figure 1 schematically shows the geometry of the region for the numerical study of plasma injection into the set of four ring conductors located outside the calculation domain that allows us to avoid the simulation of the plasma flow around individual conductors. The lines with arrows show mainly radial currents in the plasma \( j \) within the accelerator channel, as well as currents in ring conductors \( J_k \).

This work is devoted to the study of the influence of the distance between the coils with a current on the detected effect of the step-by-step or cascade temperature increase in the injected plasma streams with parameters that correspond to modern experimental studies with the ion energy at the outlet of the QSPA at the level of 1 keV. The distance between the coils in the previous studies [1, 2] is equal to \( \Delta z = 0.75 \) in dimensionless units for the unit of length \( L = 60 \text{ cm} \). At present, the calculations have been carried out for \( \Delta z = 0.5 \) when the coils are located at \( z = 1.5, 2, 2.5 \) etc. The optimal mode of the cascade plasma heating, identified and presented in [2], is observed under the condition of increasing ring currents from one coil to another. In this case, the step-by-step increase in temperature occurs most effectively.
Figure 2. Distributions of (a) density, (b) temperature, (c) velocity vector field and azimuthal velocity, (d) plasma current and vector magnetic field, (e) radiation energy density and vector field of radiation energy flux density in the plasma flow interacting with magnetic field of four coils with the increasing values of currents for $n_o = 10^{15} \text{ cm}^{-3}$, $T_o = 2 \text{ eV}$, $J_d = 450 \text{ kA}$, and $\Delta z = 0.5$.

Figure 2 demonstrates the quasi-stationary plasma flow generated by the QSPA and interacting with the magnetic field of four ring conductors for $\Delta z = 0.5$ and with the increasing values of the ring currents during the transition from one coil to another. The calculation of the flow was carried out in the presence of the additional longitudinal field $H_z^o = 0.02$ at the inlet to the channel for the following parameters of the problem $J_d = 450 \text{ kA}$, $n_o = 10^{15} \text{ cm}^{-3}$, $T_o = 2 \text{ eV}$, $L = 60 \text{ cm}$, $R_o = 20 \text{ cm}$, $\sigma_o = 580$ and $\beta = 0.004$. The ion mass is equal to $m_i = 2.5 \cdot m_p$ for the deuterium-tritium plasma.

The geometry of the accelerator channel corresponds to the analytical studies of two-dimensional plasma flows [15]. In the analytical model in the cold plasma approximation, the density at the inlet to the channel changes according to the law $\rho(z=0,r) = r_o^2 / r^2$. Assuming the isentropicity of the incoming plasma ($S = c_v \ln P / \rho^y = \text{const}$), we have $T = \rho^{y-1}$ at $z=0$. We assume that the density and temperature in the calculations are determined at the inlet according to the indicated laws.
The scale of the vectors in the figures 2(c) and 2(d) are determined by the values $H_\phi = 0.3 \cdot H_o$ and $V_\phi = V_o$. Here, the unit of velocity is equal to $V_o = 1.97 \cdot 10^7 \text{ cm/s}$, and the unit of the magnetic field is the characteristic value of the azimuthal component $H_o = 4.5 \text{ kOe}$ determined by the discharge current $J_d$. Figure 2(d) shows four ring conductors located outside the computational domain. These conductors are at the same distance $\Delta z = 0.5$ starting from the first ring conductor in cross section $z = 1.5$. The radius of the ring conductors is the same and equal to $R_o = 1.5 \cdot r_o$ where $r_o = R_o / L = 0.33$. The insulator limiting the computational domain is additionally marked for all distributions of the MHD variables presented in the figure 2 at the outer boundary at values $z > 1$.

The currents in the ring conductors increase sequentially and have the following values: $J_1 = 0.075 \cdot J_d$, $J_2 = 0.09 \cdot J_d$, $J_3 = 0.105 \cdot J_d$, $J_4 = 0.12 \cdot J_d$, $J_5 = 0.135 \cdot J_d$, $J_6 = 0.135 \cdot J_d$ in the considered version of the flow. Accordingly, the currents in the magnetic coils in the figure 2 increase linearly within the calculation domain. In this case, the function $\psi = r A_\rho$ shown in the figure 3(a) by the solid curve 1 is determined on the insulator at the values $z > 1$ by means of relations (4) for six ring conductors, two of which are located outside the calculation region.

A number of trends identified and presented earlier in [1-5] remain. Transonic flow is formed in the nozzle-like part of the accelerator channel. The conical shock wave is formed at the outlet of the accelerator, and the gradually increasing rotation of the plasma is observed in the presence of the weak longitudinal magnetic field equal to $H^L_\phi = 0.02$ at the inlet to the channel. According to the figure 2(d), the magnetic field of the ring conductors penetrates deep into the plasma volume along the entire length of the insulator, but the longitudinal field is more uniform in the vicinity of the insulator as compared to the flows presented in [1, 2] for value $\Delta z = 0.75$. As before, the magnetic field of ring conductors has a significant effect on the high-speed plasma flow, primarily in the vicinity of the insulator. Here, a strong magnetic field pushes out the plasma that also leads to the significant rarefaction observed in the figure 2(a) along the entire length of the insulator. In this case, the rarefied plasma practically does not move in the longitudinal direction in the vicinity of the insulator, and the plasma rotation in the region of a strong magnetic field and in the main stream occurs in different directions in accordance with the figure 2(c). The initial flow structure associated with the conical shock wave is deformed. Only two local maxima in the distribution of density and temperature in the figures 2(a) and 2(b) are observed at $z \approx 1.7$ and $z \approx 2.6$ in the vicinity of the axis of the installation behind the compression region corresponding to $z \approx 1$. The first maximum is a consequence of the flow around the region with a strong magnetic field in the process of flowing into the magnetic barrier. The second maximum is due to the reflection of the plasma flow from the region of a strong field and the secondary convergence of the flow on the axis. The cascade step-by-step heating of the plasma after passing through each ring conductor is not observed in this case for $\Delta z = 0.5$. Cascade plasma heating presented in [1, 2] occurs when the coils with a current are more distant from each other. This means that for the emergence of cascade heating, the distance between the coils should provide a noticeable periodic change in the longitudinal field $H_z$ along the insulator, provided that the amplitude of the field change is significant. In this case, the plasma dynamics in the set of ring conductors with a current is accompanied by the cascade plasma heating and the formation of several compression regions corresponding to each of the coils with a current, not counting the compression region in the vicinity of the axis at the outlet from the profiled part of the accelerator channel. At the same time, all the considered examples with cascade heating of the plasma relate to streams with ion energy at the outlet from the QSPA within 1 keV in accordance with modern experiments.

If you use a number of coils that are close enough and the currents in them increase from one coil to another, then the longitudinal field in such installation also increases and the azimuthal current $j_\phi$ determined by relation (3) is present, but its value is not significant. The maximum values of the azimuthal current will be in the vicinity of individual ring conductors. In the framework of the new approach being developed, the mechanism of step-by-step or cascade plasma heating in quasi-
stationary flow is caused by the Joule heating $j^2/\sigma$ due to the azimuthal current $j_\phi$, which takes maximum values in the vicinity of ring conductors located at sufficient distance from each other.

Figure 2(c) demonstrates the distribution of the radiation energy density $U$ and the vector field of the radiation energy flux density $\mathbf{W}$ corresponding to the given density and temperature distributions. The radiation transport was calculated under conditions of local thermodynamic equilibrium (see e.g. [12]). The figure shows the level lines of the function corresponding to the dimensionless value $c\bar{U}$ associated with the radiation energy density $U$ by the relation $\bar{U} = 10^6 c \cdot U / W_o$, where

$$W_o = V_o H_o^2 / 4 \pi = 3.85 \cdot 10^{13} \text{ erg} / \text{cm}^2 \text{s}$$

is the unit of the radiation energy flux density for the above initial parameters $n_o$, $T_o$, $J_d$ and $L$. The scale of the vectors $\mathbf{W}$ is determined by the modulus of the vector $W_s = 10^{-6} W_o$, which is indicated in the figure. Relatively high values of density and temperature in the vicinity of the axis correspond to relatively large values of the radiation energy density. The most significant radiation energy flux is observed in compression region at $z \approx 1$, as well as in the region of the first and second temperature maximum in the vicinity of the axis at $z \approx 1.7$ and $z \approx 2.6$. The radiation energy flux has predominantly radial direction in the axisymmetric plasma flow, and the recombination part of spectrum makes the main contribution to the total radiation field.

Figure 3(b) presents one-dimensional graphs of temperature changes along the axisymmetric plasma flow, and the vector field of temperature in the vicinity of the axis correspond to relatively large values of the radiation energy density. The most significant radiation energy flux is observed in compression region at $z \approx 1$, as well as in the region of the first and second temperature maximum in the vicinity of the axis at $z \approx 1.7$ and $z \approx 2.6$. The radiation energy flux has predominantly radial direction in the axisymmetric plasma flow, and the recombination part of spectrum makes the main contribution to the total radiation field.

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Numerical experiments carried out for the flows of sufficiently dense plasma have shown once again that the processes proceed according to a scenario which is different from the traditional theoretical representations of the dynamics of the individual particles in the magnetic field of the classical multi-mirror trap for the rarefied plasma.

4. Conclusion
The study of the injection of axisymmetric dense plasma flows generated by the QSPA into the set of ring current-carrying conductors has been carried out under the condition that the distance between the coils with a current is sufficiently small to provide the effect of cascade plasma heating. Numerical studies have been carried out on the basis of two-dimensional model of radiation magnetic gas dynamics taking into account electrical conductivity, thermal conductivity and radiation transport. It is shown that the magnetic field of coils with a current isolates ring conductors from high-speed plasma flows. In this case, a region of the rarefied plasma is formed and separates the main stream from coils with a current. It has been established that cascade step-by-step plasma heating does not occur if the distance between the coils with a current is less than or equal to the radius of the ring conductors.

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