INFLUENCE OF THE ION VISCOSITY ON THE CURRENT SHEET FORMATION AND PLASMA HEATING

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This paper deals with the problem of the ion viscosity influence on the current sheet formation and plasma heating, in the experiments performed on "Current sheet" facility (Prokhorov General Physics Institute, Russian Academy of Sciences). On the basis of magnetohydrodynamic theory one can see that pressure force and viscid tension force can bring considerable contribution to the formation and heating of the current sheet plasma. The estimations obtained show that the effect of the ion viscosity is comparable with other effects which were taken into account previously.

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INTRODUCTION

The experimental investigation of phenomenons in two-dimensional current sheet (Fig. 1), which was generated by means of fast magnetoacoustic waves in the zero line zone, were carried out in Prokhorov General Physics Institute, Russian Academy of Sciences [1-4].

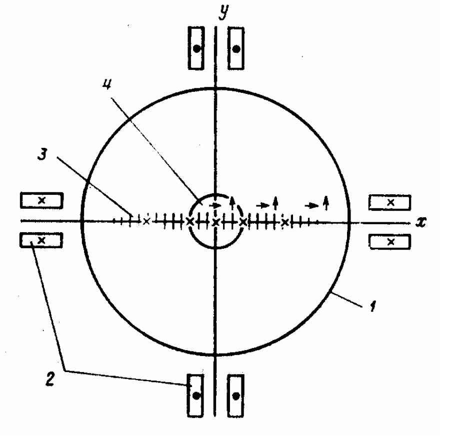

Fig. 1. Cross section of the "Current Sheet" device [1]: 1 – vacuum chamber; 2 – conductors to produce quadrupole magnetic field with the null line which is combined with the vacuum chamber axis ($B_{x0}=hy$, $B_{y0}=hx$, $B_{z0}=0$); 3 – current sheet ($2\Delta y\sim0.6$ cm, $2\Delta x\sim6\ldots7$ cm); arrows at layer's surface show position and orientation of the magnetic probes; 4 – the central area where plasma radiation is registered

The alternating electrical current in plasma $J_z(t)$ was directed along the zero line of the magnetic field. It was driven by activating pulse voltage between two electrodes (Fig. 2). These electrodes were inserted in plasma from the sides of the chamber end faces

$$J_z(t)=J_0\sin(\omega t)e^{-\delta t}\ .$$

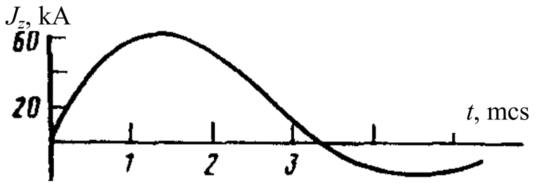

Fig. 2 Alternating electrical current in plasma from Ref. [1]

The start phase of current sheet formation ($\Delta t\sim1$ mcs) is considered. In this phase the temperature of Ar^+ ions comes up to 80 eV (Fig. 3) and plasma density increases from initial $10^{14}\ldots10^{15}$ to 10^{16} cm^{-3} [1].

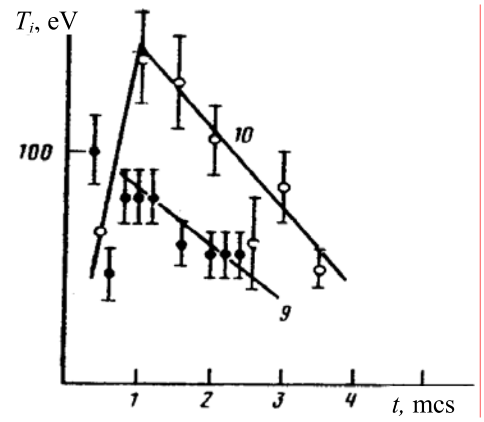

Fig. 3 Measured temperature of ions Ar^+ (9) and C^{++} (10) from Ref. [1]

The magnetic field component, which is tangential to sheet's surface, shows considerable increasing in the interval t=0.5…1.0 mcs. When x=0 and y=0.6 cm, B_x=5 kG and $B_x/B_{x0}\sim3.6$; going away from zero line, the B_x-component shows the decreasing. At first it diminishes smoothly to 3 kG by x=2 cm and then much more sharply. There is simultaneous decreasing of perpendicular, relative to sheet, B_y-component relatively its initial value of B_{y0} [1].

AN ANALYSIS OF VISCOSITY INFLUENCE ON THE CURRENT SHEET FORMATION AND HEATING

The evaluations for a region near the zero line are carried out at $\Delta t\sim1$ mcs, $B_x\sim5$ kG, $T_i\sim80$ eV, $T_e\sim10$ eV, $n\sim10^{16}$ cm^{-3}.

The estimation of Ampere force value which is responsible for plasma acceleration, allows to establish the velocity of Y-motion

$$f_y=\frac{j_zB_x}{c}\sim\frac{B_x}{4\pi}\frac{B_x}{2\Delta y}\sim10^6\,dyn/cm^3,$$

$$v_y \sim \frac{f_y \Delta t}{m_i n_i} \sim 1.6 \cdot 10^6\, cm/s.$$

The force due to pressure gradient and Ampere force have the same order-of-magnitude

$$f_{y\ pressure} = -\frac{\partial p}{\partial y} \sim \frac{n_i T_i}{2\Delta y} \sim 2.1 \cdot 10^6\, dyn/cm^3.$$

The estimation of the viscosity force was obtained taking into account a significant distinction between sheet's thickness and its width $\Delta y/\Delta x \sim 1/10$

$$f_{y\ visc} \approx -\frac{\partial \pi_{yy}}{\partial y},$$

where tensor of viscid tension, which takes into account the effects of finite Larmor radius is equal [5]:

$$\pi_{yy} = -\eta_0^i W_{0yy} - \eta_1^i W_{1yy} - \eta_2^i W_{2yy} + \eta_3^i W_{3yy} + \eta_4^i W_{4yy},$$

and values of η depend on parameter $\xi = \omega_{ci}\tau_i \sim 1.3$, where $\omega_{ci} \sim 1.2 \cdot 10^6\, s^{-1}$, $\tau_i \sim 1.1 \cdot 10^{-6}\, s$:

$$\eta_0^i = 0.96 n_i T_i \tau_i\ ,$$

$$\eta_1^i = n_i T_i \tau_i \frac{24/5\xi^2 + 2.23}{16\xi^4 + 16.12\xi^2 + 2.33}.$$

The terms with W_{2yy}, W_{3yy}, W_{4yy} are negligible since B_y and B_z components are small as compared with tangential to layer surface component B_x,

$$\begin{aligned} W_{0yy} \approx \left(h_y^2 - \frac{1}{3}\right)\Bigg[&(3h_x^2 - 1)\frac{\partial v_x}{\partial x} + (3h_y^2 - 1)\frac{\partial v_y}{\partial y} + \\ &+ 3h_x h_y\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) + 3h_x h_z \frac{\partial v_z}{\partial x} + \\ &+ 3h_y h_z \frac{\partial v_z}{\partial y}\Bigg] \sim \frac{1}{3}\frac{\partial v_y}{\partial y}, \end{aligned}$$

$$\begin{aligned} W_{1yy} \approx\ &(h_x^2 h_y^2 - h_z^2)\frac{\partial v_x}{\partial x} + (1 - h_y^2)^2 \frac{\partial v_y}{\partial y} - \\ &- h_x h_y (1 - h_y^2)\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) + \\ &+ h_x h_z (1 + h_y^2)\frac{\partial v_z}{\partial x} - h_y h_z (1 - h_y^2)\frac{\partial v_z}{\partial y} \sim \frac{\partial v_y}{\partial y}, \end{aligned}$$

where $\vec{h} = \vec{B}/B$, $h_x \sim 1$, $h_y << 1$, $h_z << 1$.

The adopted assumptions allow us to get an estimation for the tensor of viscid tension and viscosity force at $\xi \sim 1.3$

$$\pi_{yy} = -n_i T_i \tau_i \left(\frac{0.96}{3} + \frac{(24/5)\xi^2 + 2.23}{16\xi^4 + 16.12\xi^2 + 2.33}\right)\frac{\partial v_y}{\partial y},$$

$$f_{y\,visc} = \frac{\partial}{\partial y}\left(0.45\, n_i T_i \tau_i \frac{\partial v_y}{\partial y}\right) \sim$$

$$\sim \frac{0.45\, n_i T_i \tau_i v_y}{(2\Delta y)^2} \sim 3 \cdot 10^6\, dyn/cm^3.$$

An evaluation of ions heating velocity was obtained by means of entropy production [5] $dQ/dt = T_i\, dS_i/dt$

$$\frac{dQ_{visc}}{dt} = \frac{1}{2}\left(\frac{\partial v_y}{\partial y}\right)^2 \left(\frac{\eta_0^i}{9} + \eta_1^i\right) \sim$$

$$\sim \frac{0.12 n_i T_i \tau_i v_y^2}{(2\Delta y)^2} \sim 1.3 \cdot 10^{12}\, erg/s.$$

Thereby an estimation of heating time was obtained and this value coincides with measured one by the order of magnitude

$$\tau_{\text{viscosity}} \sim 1.5 \cdot 10^{-6} s\ .$$

Both, the ions mean free path and Larmor radius have the same order of magnitude. Also, characteristic distance $2\Delta y$ of plasma parameters change has this order of value.

$$l_{free\ path} = \tau_i v_{Ti} \sim 0.15 cm\ ,$$

$$\rho_{Li} = v_{Ti}/\omega_{ci} \sim 1\ \ cm\ ,$$

$$v_{Ti} = \sqrt{T_i/m_i} \approx 1.4 \cdot 10^6\ \ cm/s\ .$$

CONCLUSIONS

The research of ion viscosity influence on the formation and heating of current sheet in a X-line magnetic configuration in terms of equations of multicomponent magnetic hydrodynamics was carried out. An analysis of the magnetic fields data which is received on CS-2D device, allows to reveal that besides Ampere force, which takes part in the current sheet formation and plasma acceleration, essential role can take force of plasma pressure and viscid stress force. These two forces become equal to Ampere force by order of magnitude after a lapse of time.

Such estimations show that viscid friction force is responsible for the heating of plasma ion component (Ar+ ions) and heating time of these ions has order of magnitude of measured heating time.

The calculated time of ion-to-ion collisions coincides by order of magnitude with typical time of the sheet macroscopic parameters changing. Mean free path, Larmor radius of the ions and typical distance have the same order, when such macroscopic sheet parameters like density, temperature, magnetic field component and current density across the magnetic field change their values. In this case the magnetohydrodynamic description of current sheet dynamics can not be used and carried out estimations is valid only by order of magnitude and point on considerable role of the dissipative processes of the viscosity upon the formation of a current sheet.

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ВЛИЯНИЕ ИОННОЙ ВЯЗКОСТИ НА ФОРМИРОВАНИЕ И НАГРЕВ ТОКОВОГО СЛОЯ

А.А. Куров, К.Н. Степанов

Сделаны оценки влияния ионной вязкости на нагрев и формирование токового слоя в экспериментах, проведённых на установке “Токовый слой” (Институт общей физики им. Прохорова РАН). На основе магнитогидродинамической теории показано, что сила давления и сила вязких напряжений могут играть существенную роль в формировании и нагреве токового слоя. Полученные оценки показывают, что эффект ионной вязкости сравним с другими эффектами, которые учитывались ранее.

ВПЛИВ ІОННОЇ В’ЯЗКОСТІ НА ФОРМУВАННЯ ТА НАГРІВ СТРУМОВОГО ШАРУ

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Зроблено оцінки впливу іонної в’язкості на нагрів та формування струмового шару в експериментах, проведених на установці “Струмовий шар” (Інститут загальної фізики ім. Прохорова РАН). На основі магнітогідродинамічної теорії показано, що сила тиску та сила в’язких напружень можуть відігравати істотне значення у формуванні та нагріві струмового шару. Отримані оцінки показують, що ефект іонної в’язкості порівняний з іншими ефектами, які враховувалися раніше.