THE INVESTIGATION OF THE FIELD-ALIGNED CURRENT GENERATION DURING THE INJECTION OF PLASMA JET INTO THE MAGNETOSPHERE

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Field-aligned currents (FAC) are generated at plasma jet injection perpendicular to magnetic field lines. The FAC propagate with Alfven velocity and are connected in the ionosphere. The electrons heating produces aurora and ionospheric plasma density enhancement. The value of the Pedersen conductivity determines the current increasing and jet deceleration by the electrodynamical force.

1. Introduction. The physical processes at jet injection of the powerful plasma $nmv^2 \gg B^2/8\pi$ across the magnetic field can be divided into three stages: (a) The jet motion in the cavity from which the magnetic field is expelled. On the borders of the jet the plasma pressure is balanced by magnetic pressure; (b) Magnetic field diffusion in the plasma occurs at time $t \sim R^2/D$, R is plasma jet cross dimension, $D = c^2/4\pi\sigma$. For Coulomb conductivity σ, for the plasma injected out a chemical generator ($T_e \sim 0.1$ eV) at $R \sim 1$ km the time of field penetration is $\tau \sim 30$ s. In real situation the diffusion coefficient is always much bigger. There are several reasons for D increasing: ion diffusion across the field and electron motion along the **B** from background plasma; fast diffusion which is described by Bohm formula $D \sim 1/(B\sqrt{T})$; (c) Motion in perpendicular **E** and **B**, where $\mathbf{E} = -(\mathbf{V}\times\mathbf{B})/c$ is field polarization.

In the present paper the last phase - the plasma jet motion after its penetration in the magnetic field is considered. The main attention is paid to the problem of jet deceleration and ionosphere heating by the induced current. In the model the thermal expansion is not considered as well as MHD instability. The consideration is limited by injections at the altitudes of 300 ÷ 500 km.

2. FAC in space experiments. In the Porcupine experiment [1] the jet behavior was rather unexpected. Diamagnetic effect because of magnetic field expelling was observed at distance ~ 15 m from jet injection. At distances less than 60 m the electric field was detected, which direction and value coincide with $-(\mathbf{V}_0\times\mathbf{B})/c$. At distance ~ 200 m the electric field dropped to $(\mathbf{V}_0\times\mathbf{B})/10c$. For the jet which is moving without deviation in **B** such behavior of **E** can be explained by velocity decreasing due to $j\times B$ force. Such currents should be generated by the electric field $-(\mathbf{V}\times\mathbf{B})/c$ and connected in the ionosphere by Pedersen current.

The appearance of $-(\mathbf{V}\times\mathbf{B})/c$ field produces two layers of FAC. Opposite directed currents propagate along the **B** with Alfven velocity $V_A = B/\sqrt{4\pi\rho} \sim 10^8$ cm/s, if one assumes the oxygen ions density of $n = 3\cdot10^4$ cm^{-3}. In collisionless approximation $\omega\tau \gg 1$ at altitudes 300 ÷ 500 km Alfven wave propagates almost without dumping down to the upper atmosphere. At the altitude about 100 km conductivities along the field lines and across it $\sigma_{\parallel}$ and $\sigma_{\perp}$ become comparable, because of electron collisions with neutral atoms, and Pedersen current connects two oppositely directed layers 'at FAC (Fig.1). The similar wave moves upward in the conjunction region.

Before the FAC layers reach the upper atmosphere the linear current density is $J = \Sigma_A E$ A/cm.

Alfvenic conductivity $\Sigma_A = c^2/4\pi V_A \sim 10^{12}$ cm$\cdot$s^{-1}.

At plasma jet velocity for an active experiment AGRE [2] $V_0 = 2\cdot10^6$ cm/s, $E = 8\cdot10^{-3}$ V/cm and $J = 8\cdot10^{-3}$ A/cm.

FAC generation because of $-\mathbf{V}\times\mathbf{B}$ electric field apparently occurred in Porcupine experiments [1] with xenon plasma jets and in Arcs experiments with argon jets [3]. Fast electrons were observed. The effect was explained by electron acceleration in FAC double electric layers.

However, the influence of FAC on ionosphere state and dynamics of the plasma jet were not considered up till now.

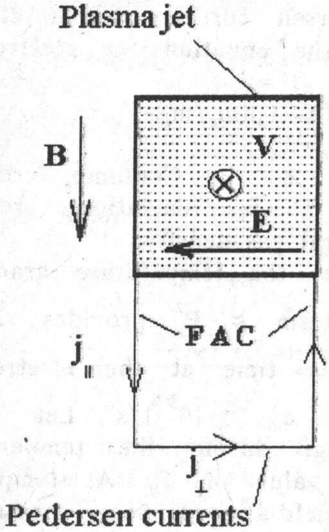

Fig.1.

Electric circuit at plasma jet injection perpendicular to magnetic field lines.

The importance of FAC investigation is determined by decisive role in magnetosphere-ionosphere coupling. Simultaneous measurements of vectors **E** and **B** show that FAC generator is located in the Earth magnetotail and they are connected via Pedersen currents in the ionosphere at altitude of ~ 100 km [4]. The strong magnetic disturbance should produce considerable plasma heating between FAC layers. In the present work an attempt is made to consider the mutual influence the plasma jet, generated FAC and the ionosphere.

3. Electric field and currents generation. Homogeneous plasma jet motion can be determined by two liquids MHD equations without ∇p terms:

$$m_i d\mathbf{V}_i/dt = e\mathbf{E} + e(\mathbf{V}_i\times\mathbf{B})/c + (\mathbf{V}_e-\mathbf{V}_i)m_e/\tau \quad (1)$$

$$m_e d\mathbf{V}_e/dt = -e\mathbf{E} - e(\mathbf{V}_e\times\mathbf{B})/c - (\mathbf{V}_e-\mathbf{V}_i)m_e/\tau \quad (2)$$

In quasi stationary plasma, when Alfven wave reaches the ionosphere, and FAC are closed by Pedersen current, equation(1) can be written:

$$eE_y + eV_xB_z - ej_y/\sigma = 0 \quad (3)$$

We suppose that current is transferred by electrons and jet velocity is the ions velocity. Using the Ohm law for external circuit one can get:

$$\mathbf{E} = -\mathbf{V}\times\mathbf{B}/c(1+\Sigma_P/\sigma b), \quad (4)$$

where Σ_P is integrated along the altitude Pedersen conductivity of the ionosphere. For typical state at mid-latitudes in night time $\Sigma_P = 10^{12}$ cm$\cdot$s^{-1} [5-6] and $\Sigma_P/b\sigma \ll 1$. b - is the jet thickness. For typical jet parameters $V = 2\cdot10^6$ cm/s, $n_j = 10^8$ cm^{-3}, the time of velocity decreasing because of $\mathbf{j}\times\mathbf{B}/c$ force is 10÷20 s, and the deceleration distance is several hundreds km. Such estimation does not take into account the Pedersen conductivity increasing because at Joule losses in the ionosphere.

4. The Joule heating of electrons. For estimation of the Joule losses in the ionosphere associated with Pedersen currents which close the pair of FAC sheets, let us consider the equation for electron temperature:

$$\partial T_e/\partial t + (V\nabla)T_e = (2/3)E^2\sigma_P/n + æ\Delta T_e - \langle\sigma_C V_e\rangle n(T_e - T_i)(m_e/m_i) - -(2/3)\sum(n_0\langle\sigma_{ex}V_e\rangle W_{ex}) - 2/3 n_0\langle\sigma_i V_e\rangle W_i\ , \quad (5)$$

where σ_P is electron Pedersen conductivity, σ_C is Coulomb cross section, σ_{ex} is excitation cross section, σ_i is ionization cross section, æ is electron heat conductivity, n_0 is neutral gas density.

The convective term can be ignored, as the temperature gradient is transverse to the jet velocity. The term $\approx E^2$ provides the temperature increasing $\approx 10^5$ eV/s in the night time at the electron density $n_e = 2\cdot 10^4$ and Pedersen conductivity $\sigma_P \sim 3\cdot 10^5$ 1/s. Let us estimate effects which restrict initial heating, during the temperature increasing in several times from initial value of T_e. At temperature increasing by a factor of five the field-aligned heat conductivity $(\lambda V/3)T/b^2$ provides cooling in $\approx 10^3$ s, so at the beginning it does not limit plasma heating.

Similarly the energy transference from electrons to ions does not limit electron gas heating. For the oxygen the time of electron and ion temperature equalizing is $t \approx 300\ T^{3/2}/n \approx 10^3$ s. At the temperature $T_e \approx 0{,}5$ eV the only energetic level $O(^1D)$ is excited validly. Its excitation cross-section at a maximum is not excess of $3\cdot 10^{-17}$ cm² [7]. The loses to $O(^1D)$ level excitation is an order of magnitude less than the Joule heating. At this temperature the energy loses for ionization can be not taken into account too. So energy loses at the initial stage do not limit the electron temperature increasing.

The actual temperature limitation begins when T_e reaches 3÷5 eV, when the tail of energy distribution provides the ionization and the efficient excitation of $O(^1S)$ level with 5577 Å line emission

Then the energy balance is: $E^2\sigma_P = n_0 n_e\langle\sigma_i V\rangle W_{ef}$, (6)

where W_{ef} - the average energy loses (including excitation) for one ionization act. For $T_p \sim 5$ eV the value of $W_{ef} \approx$ 400-600 eV. After the beginning of valid ionization the electron density increases:

$$dn_e/dt = n_0 n_e\langle\sigma_i V\rangle \quad (7)$$

The recombination time is several orders of magnitude bigger than the experiment duration (1÷10 s), and it can be not regarded. Taken that $\sigma_P \sim n_e$ after combination of (6) and (7) we will obtain the electron density increasing low:

$$n_e = n_{e0}e^{t/\tau},\quad \tau \approx \frac{n_{0e}W_{ef}}{E^2\sigma_{P0}}, \quad (8)$$

At the initial ionosphere density $n_{0e} = 2 \cdot 10^4$ cm^3 we obtain $\tau \approx 10^{-2}$ s. In that consideration we did not take into account the interaction between FAC and plasma jet. So the result is true only for initial stage of process.

5. The inclusion of jet deceleration. The electrodynamic jet deceleration is described by the equation: $n_j m_j \ddot{X} = -jB/c$, (9)
where m_j - ion mass in the jet. If we express j in terms of Pedersen conductivity, the equations (7) and (9) can be brought to form:

$$dn/dt = An_eV^2 \quad (10)$$

$$dV/dt = Dn_eV, \quad (11)$$

which admits the simple analytic solution:

$$V^2 = V_0^2 \cdot (1+\alpha) \cdot \frac{e^{-t/\tau}}{e^{-t/\tau}+\alpha} \quad \text{and} \quad n_e = n_{e0}(1+\alpha)\frac{1}{e^{-t/\tau}+\alpha},$$

where $\alpha = \dfrac{2\Sigma_{pe}W_{ef}n_{e0}}{a\sigma_p n_j m_j V_0^2}$, *a* is jet dimension along the field lines. For a given conditions of the experiment $\alpha \sim 10^{-2}$. The value of τ is differ from one in (8) by the factor $(1+\alpha)^{-1}$.

Fig.2 displays the obtained relationships. As indicated earlier, for the establishment of regarding process, it takes at least a time of Alfven wave pass to the ionosphere ($\approx L/V_A$).

At such consideration we did not take into account the ion Pedersen conductivity. It exceeds σ_{Pe}, but its role in jet deceleration is important only at the beginning of the deceleration, before increasing of the electron density by the order of magnitude.

6. Laboratory simulation. The aims of laboratory experiments are the investigation of the FAC generation in a system with the certain parameters which are determined by the principal of limited simulation [8]. Fig.3 displays the principle scheme of the experiment.

The laboratory tool for getting the plasma jet (1) is an electric discharge generator of the type of "fountain pinch". The quasi stationary magnetic field is created by an impulsive electromagnet (2).

For the simulation of the cross-conductivity in the lower region of the ionosphere current-assemble electrodes (3) near one of magnet poles are used. The velocity of the plasma jet in the model experiment is equal of the one in AGRE - about 20 km/s. The characteristic size (the diameter) of the jet is L = 5÷10 cm. To reproduce the condition $r_{Li}/L < 1$, the Larmor radius $r_{Li} \sim$ 1cm is suitable, and we have B = 5000 G.

To ensure that the plasma should penetrate in the diagnostic region of the magnetic field the electron density in a plasma jet should be

$$n_e = 2 \cdot B^2/8\pi\mu_0 W \approx 1.5 \cdot 10^{15} \text{ cm}^{-3} \quad (12)$$

The background neutral atom density we find from the condition of the space experiment: $n_0 \leqslant 1/(\sigma_{ce} \cdot L)$,where $\sigma_{ce} = 10^{-15}$ cm^2 is the charge-exchange cross-section.

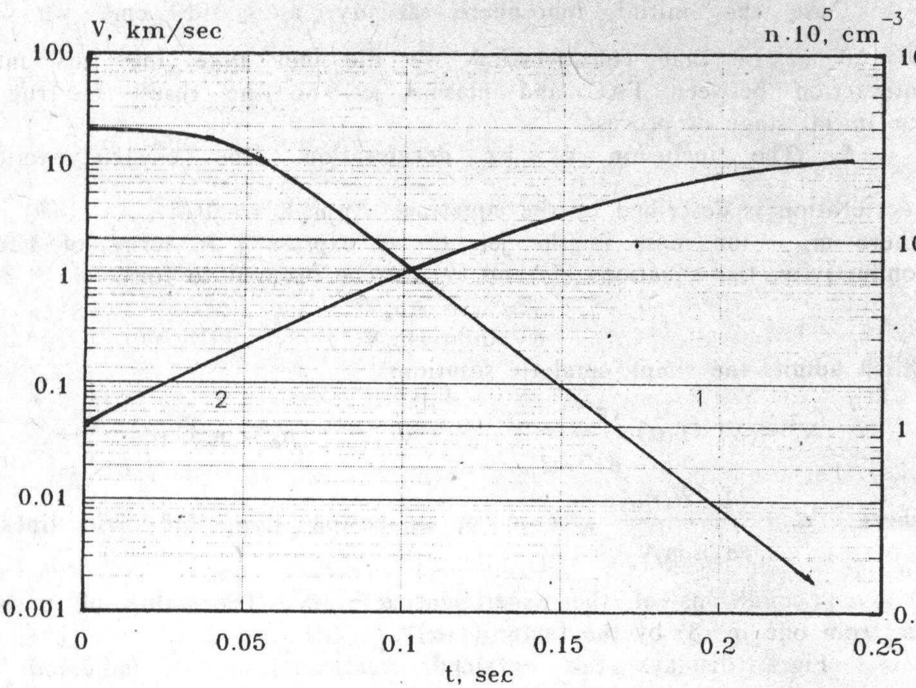

Fig.2. Jet velocity and ionosphere density via time.

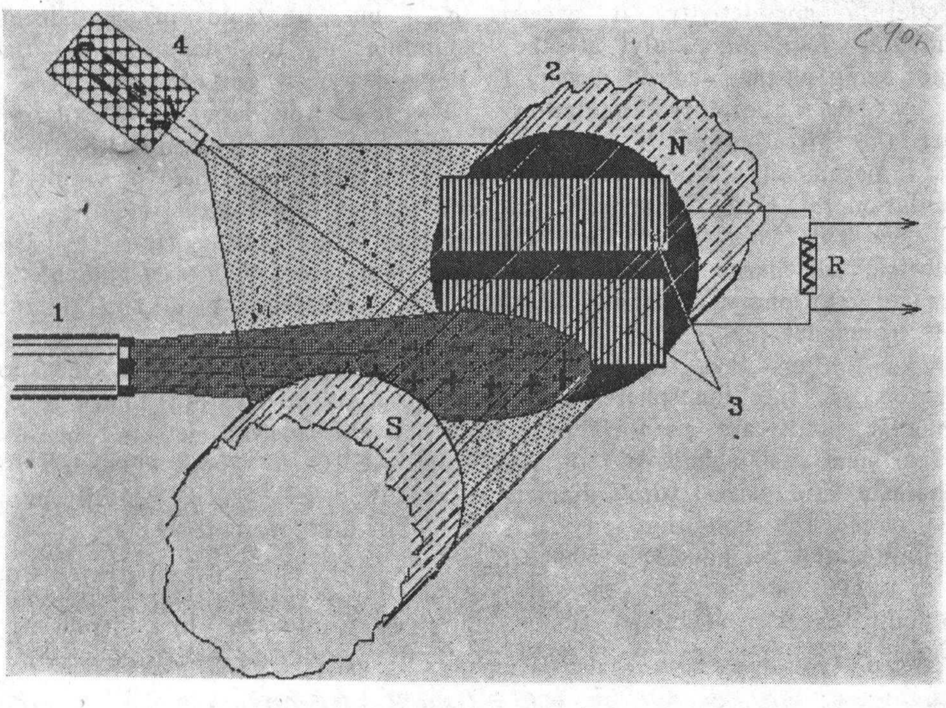

Fig.3. The schematic diagram of the laboratory simulation experiment.

Then $n_0 = 10^{14}$ cm^{-3}. The preliminary ionization can be produced by an electron beam from the gun (4) with energy 150 keV and/or by the UV-radiation of the plasma jet. So it is possible to receive the electron density $n_e \sim 10^8$ cm^{-3} and the background gas parallel conductivity $\sigma_{\parallel} = e^2 n_e \tau_{en}/m_e \cong 30$ $Ohm^{-1} \cdot m^{-1}$. At the pressure in vacuum cumber P = 0.1 Pa and B = 5000 G the electric field of polarization $E = V \cdot B = 8 \cdot 10^3$ V/m.

In the present consideration we did not take into account any possible plasma instability in the jet. We hope that some information about these instabilities can be obtained during this laboratory simulation which is now in progress.

7. **Conclusion**. The consideration of the magnetosphere plasma fluxes influence on the ionosphere state shows the efficient electrons heating by the Pedersen currents. In the region of atomic oxygen predominance the heating would be accompanied by the excitement of $O(^1S)$ - 4,19 eV level with the $\lambda = 5577$ Å emission.

The estimations show that the time of jet deceleration is rather small. This is especially true at the low altitude injection, when the delay determining by the Alfven wave propagation is of no significance. It is in general agreement with the fact that the long time existence of the plasma jet in space experiments was not revealed.

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