

## PLASMA JET DYNAMICS IN THE MAGNETOSPHERE

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**Abstract.** Injection of a high density jet into the magnetosphere is simulated in 3D MHD compressible and resistive approximation. The PERESVET program is used. At injection across the magnetic field a magnetic cavity is produced during plasma expansion. This cavity prevents the jet from further expansion. Injection along the magnetic field produces a magnetic trap configuration.

### Introduction

Sub Alfvénic plasma flows play a decisive role in many important phenomena in the magnetosphere and solar corona. Apparently, plasma flow from the tail current sheet fills the ring current at a substorm. Several active experiments with jet injection in the magnetosphere were carried out for investigation the mechanism of flow interaction with low beta plasma. All of them met difficulties. Instruments placed in a separated container permit to get information only in a single point. For interpretation such data it is necessary to create models of jet - magnetosphere interaction for different angles between the plasma velocity vector and a magnetic field line. In the previous papers (*Podgorny and Podgorny, 1997a, 1998*) we have presented some results of 3D numerical simulation of a plasma jet interaction with the perpendicular magnetic field and background plasma. Here we consider a high density jet evolution during the first stage of injection and present some other results of numerical simulation of plasma flow interaction with low beta plasma including injection along the magnetic field. The data presented in this work are used to develop a scenario and understand better the results of active experiments in space.

### Numerical method

The 3D compressible resistive MHD equations have been solved with dimensionless parameters corresponding to the conditions in the magnetosphere:  $\beta=4\pi nkT/B^2=10^{-2}-10^{-6}$ , the magnetic Reynolds number  $Re_m=10^3-10^5$ , Reynolds number  $Re=10^3-10^4$ , Peclet number  $\Pi=10-10^6$ . The method of parameters choosing is described in (*Podgorny and Podgorny, 1995*). For solving MHD equations the PERESVET program has been used (*Podgorny, 1995*). This program approximates MHD equations by absolute implicit finite-difference scheme which is solved by a method of iterations. The  $41 \times 41 \times 41$  grid points in the rectangular coordinate system XYZ has been used. All the data are presented in dimensionless units. The dimension of the numerical region  $L$ , the background plasma density  $\rho_0$ , the initial magnetic field  $B_0$ , the initial temperature of background plasma  $T_0$ , the Alfvén velocity  $V_A=B_0/(4\pi\rho_0)^{1/2}$ , and the Alfvénic time  $L/V_A$  are units of length, plasma density, magnetic field, temperature, velocity, and time, respectively. For setting initial conditions the method of characteristics is used (*Podgorny, 1995*).

A plasma jet is ejected from the boundary  $X=0$ . Plasma flows from a circle with the center at  $Y=0.5$  and  $Z=0.5$  and the diameter of 0.2 or 0.4. The plasma density in the source is  $10^4$ , the plasma temperature is 10, the initial velocity is 0.1. In some cases free plasma expansion from the source is set ( $dV_x/dX=0$  at  $X=0$ ).

### Field-aligned currents (FAC)

There are two possibilities of FAC generation during jet propagation across the magnetic field: (a) FAC generation due to the Lorentz electric field  $-\mathbf{V} \times \mathbf{B}/c$ , and (b) generation due to the Hall electric field  $\mathbf{j} \times \mathbf{B}/nec$ . The second case occurs if there is plasma acceleration in the tail current sheet, it produces a FAC system in the magnetosphere (*Podgorny and Podgorny, 1997b*). In the numerical experiment it has been shown that under transverse plasma injection ( $\alpha=90^\circ$ ) the induced electric field  $\mathbf{E}=\mathbf{V} \times \mathbf{B}/c$  generates the Alfvén wave. As a result, the system of upward and downward field-aligned currents appears (*Podgorny and Podgorny, 1997a*), which propagate along field lines with the Alfvén velocity. The corresponding current circuit is shown in Fig. 1. The field-aligned currents initiate involvement of the magnetospheric plasma between the current layers into motion. As a result, the momentum is transferred to magnetospheric plasma, and jet deceleration takes place. This mechanism of jet deceleration permits to estimate the jet path in the magnetosphere:  $l \sim d(\rho_j V_j / \rho_{mf} V_A)$ , where  $d$  is the jet diameter,  $\rho_j$  and  $\rho_{mf}$  are the densities in the jet and magnetosphere, respectively. When the field-aligned currents reach the ionosphere, they are closed by the Pedersen conduction. Apparently, the Alfvén wave which propagates upward can stimulate fast particle precipitation from the magnetosphere.

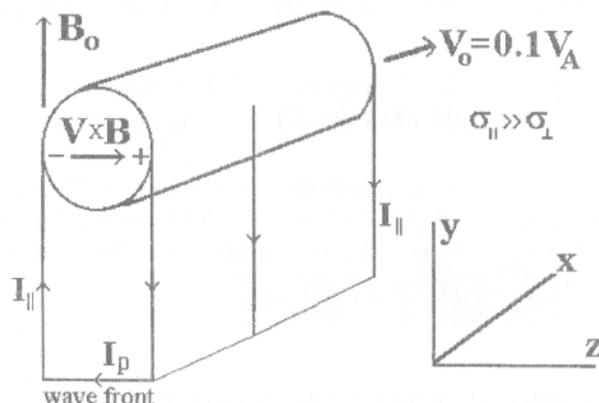


Figure 1. Field-aligned current generation by the plasma sub Alfvénic flow.

### Magnetic cavity formation

The plasma pressure  $p$  in a high beta jet exceeds the magnetic pressure, so jet radial expansion proceeds. Development of jet expansion in the direction perpendicular to  $V_0$  and  $B_0$  for injection across the magnetic field is shown in Fig. 2 *a* and *b*. These data are obtained for the source with the diameter of 0.4. This permits to get better resolution inside the jet. Distributions of the plasma density, magnetic field and velocity ( $V_z$ ) along the  $Z$  axis are shown for the distance of  $X=0.2$  at  $t=4.5$  and at later time  $t=6.7$  for the distance  $X=0.5$  from the source. The plasma expansion begins from the jet borders in the region of  $\text{grad } p$  maximum. The  $\text{grad } p$  force accelerates plasma and expels the magnetic field producing a magnetic barrier, which decelerates plasma expansion owing to the force  $\text{grad} (B^2/8\pi)$  at larger distances from the axis, where  $\text{grad} (B^2/8\pi)$  changes its direction. At the magnetic barrier the expansion velocity drops to zero. Later equilibrium is reached, with the magnetic field minimum and density maximum being located at the jet axis.

Magnetic field lines are stretched by the plasma flow (Fig. 2*c*). In this calculations the source diameter of 0.2 has been chosen, and conditions of plasma free expansion from the source have been used. The  $\mathbf{j} \times \mathbf{B}/c$  force is directed opposite to plasma motion. This force decelerates the plasma jet, but accelerates the background plasma between the downward and upward FAC involving it into motion. At  $X=0.4$  magnetic field compression before the jet front can be seen. Here the magnetosound wave propagates. The magnetic field lines in the plane perpendicular to the velocity vector are shown in Fig. 2*d*. In this plane ( $Y, Z$ ) the  $\mathbf{j} \times \mathbf{B}/c$  force is directed to the jet axis. This prevents plasma from the further radial expansion. Later a balance between the plasma pressure and magnetic pressure is established. After that, plasma expansion takes place only along the field lines (along the  $Y$  axis). During expansion along field lines the plasma pressure in the jet diminishes, and magnetic pressure compresses the jet. The jet diameter decreases.

### Injection along the magnetic field

At high density plasma ejection along the field it expands in radial direction, so that an axially symmetrical magnetic configuration is formed. This configuration is similar to a typical magnetic trap for a charged particle, but here the magnetic field increases in all the directions (including the radial one) toward the periphery. Such type of traps must be stable. Fig. 3*a* shows magnetic field lines in the numerical experiment with a pulsed injection. Injection is stopped at  $t=5.1$ . A charged particle can escape from this trap only by changing its velocity direction due to a particle or wave collision. If plasma injection is accompanied by fast particle appearance, they should be transferred in the trap together with the moving plasma cloud.

Jet deceleration at injection along the field is mostly determined by collisions with background plasma particles. The numerical calculations show that the Alfvénic wave before a jet front is very weak, because the  $\mathbf{j} \times \mathbf{B}/c$  force in this region is directed from the axis producing plasma and magnetic depletion before the jet. It prevents further displacement of magnetic field lines from the axes. As a result, a local depletion of magnetospheric plasma appears before the jet.

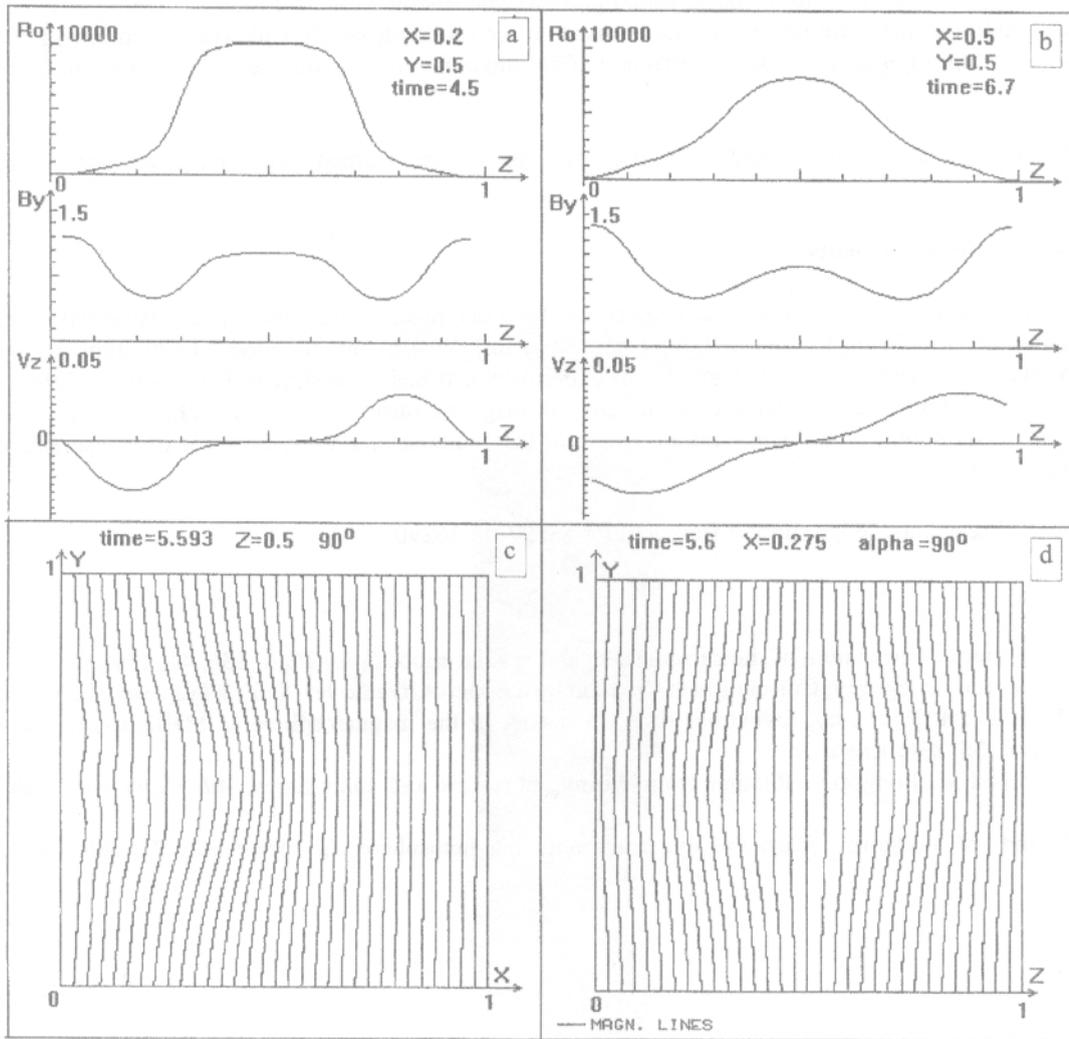


Figure 2. Distributions of the plasma density, magnetic field, and velocity during jet expansion across the magnetic field (a, b), and magnetic field lines in the planes parallel (c) and perpendicular (d) to the jet velocity.

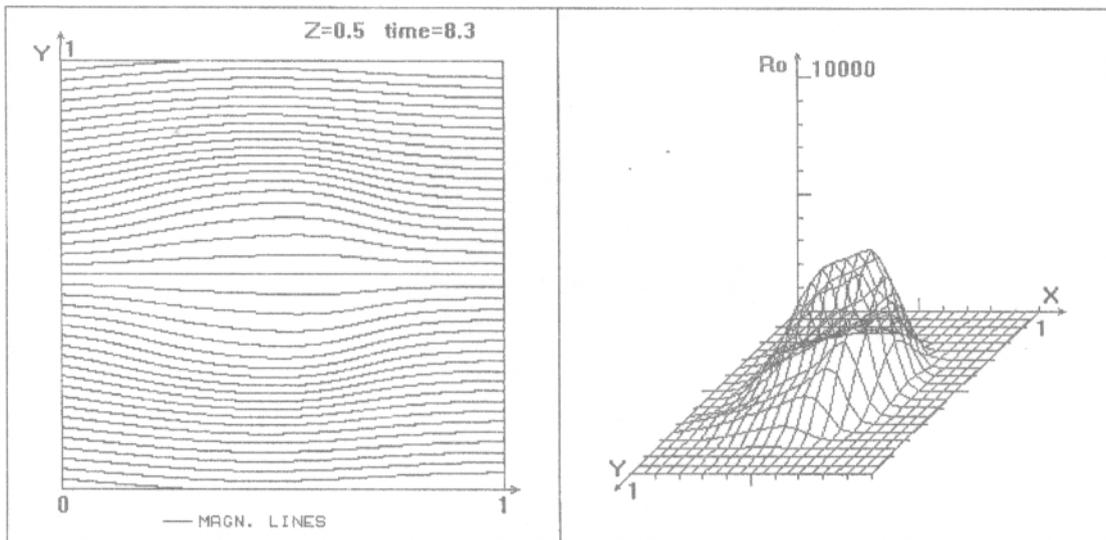


Figure 3. Magnetic field lines (a) and plasma density distribution (b) at injection along the field.

These data are obtained for  $\beta=10^{-4}$  in the background plasma, whereas the initial  $\beta$  inside ejected plasma is equal to 10. Under such conditions the main role in plasma behavior at the initial phase plays plasma pressure, with the shape of plasma flow only slightly depending on the magnetic field direction. The plasma density distribution is shown in Fig. 3b.

During plasma ejection at angles  $0^\circ < \alpha < 90^\circ$  a magnetic trap is also formed, but with asymmetrical magnetic configuration.

#### Facility of magnetic measurements

A magnetic disturbance produced by a jet can be measured by a magnetometer placed on the instrumental container board. Such container should be located in the jet path. The influence of the container conductivity on magnetic measurements has been investigated in our numerical experiments. It has been shown that magnetic field lines are piling up on the conducting container surface, so the error in magnetic measurements can achieve the factor of 5. If the magnetometer is mounting on a boom with the length of the container diameter, the error of measurements does not exceed 10 per cent.

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