FORMATION AND STABILITY OF THE MAGNETOTAIL PLASMA SHEET

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Abstract. A 1-d numerical hybrid simulation shows that a very thin (300-1000 km) steady current sheet is formed in a homoheneous plasma due to a supersonic ExB-drift. The time of current sheet development is about 10^2 s, and the plasma compression rate is 5-10.

Introduction

A single satellite crossing of the magnetotail plasma sheet (PS) can not provide information about the PS thin structure because it is difficult to separate spatial and temporal variations. Hence the greater part of our knowledge on this point is derived from numerical simulation. The first step involved integrating the equations of particle motion in 3-d model fields on the basis of the guiding center approximation [*Voronov and Krinberg*, 1987; *Delcourt et al.*, 1989] or Lorentz force [*Ashour-Abdalla et al.*, 1994; *Delcourt et al.*, 1994; *Voronov and Krinberg*, 1997]. Besides, there were some attempts at a self-consistent MHD-solution for plasma and fields (see, for example, [*Ogino et al*, 1994]). Recently, more correct particle or hybrid numerical codes have been realized in 1-d or 2-d approximations.

One important 1-d solution is related to the forced current sheet equilibrium at a constant B_z and a constant, uniform electric field E_y (see [*Burchart et al.*, 1992; *Delcourt et al.*, 1996], and references therein). It was found that the magnitudes of the current and current sheet thickness are controlled by the motion of individual particles. If the magnetospheric convection velocity $U_0 = c\,E_y/B_z$ exceeds the thermal velocities of the lobe ions v_T, a very thin current sheet is formed. In this case, the ion orbits are of *Speiser's* [1965] type. A few multi-spacecraft observations also suggest that a very thin ($\sim$0.1 R_E) current sheet exists in the near-Earth tail during the growth phase of substorm [*Sergeev et al.*, 1990; *Pulkkinen et al.*, 1991]. *Burchart et al.*, [1993] consider the evolution of the current sheet beyond the steady state conditions through a time-dependent 1-d hybrid simulation taking the forced equilibrium as an initial condition. It should be noted, however, that the consideration of forced sheet decay is valid if only the sheet had already been formed when the cross-tail electric field was enhanced. Since the electric field enhancement can be rather short, it is important to estimate the typical temporal scale of its genesis. In this work we investigate the plasma- and current sheet development from quasi-uniform initial plasma and field conditions.

Equations and initial and boundary conditions

We investigate the formation of PS-like plasma and field configuration by particles of the PS which are supplied from the lobes. We consider the fields as B=(B_x(z), 0, B_z) and E=(0, E_y, E_z(z)), where B_z and E_y are constant components that have external sources, while B_x(z) and E_z(z) are self-consistent fields.

Typical scales of the problem are 10^1-10^4 km for space and 10^1-10^3 s for time, i.e. less than the corresponding scales of gyromotion of protons and greater than those for electrons. So, the hybrid code is applicable [*Winske and Omidi*, 1996]. The ion motion is integrated on the basis of the equation with the Lorentz force

$$m\frac{d\mathbf{v}}{dt} = e\left(\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B}\right),\tag{1}$$

where m is the ion (proton) mass, e is the elementary charge, and c is the velocity of light. The electrons are treated as a massless fluid that provide the quasi-neutrality. Their distribution is considered to be Boltzman $n_e = n_0\exp(e\phi/T_e)$ in a self-consistent field $E_z = -\partial\phi/\partial z$ with the electric potential

$$\phi(z,t) = \frac{T_e}{e}\ln\left(\frac{n(z,t)}{n_0(t)}\right),\tag{2}$$

where n_0 is the plasma density at the center of the sheet, and T_e=const.
The equation for the magnetic field is written in the electrostatic limit:

$$\nabla\times\mathbf{B} = \frac{4\pi}{c}\mathbf{j}.\tag{3}$$

The plasma density n and current density j are calculated from the ion distributions as

$$n(z) = \frac{M_f}{\Delta z}\sum_k\int_{z-\Delta z/2}^{z+\Delta z/2}S(z_k - z')dz',\tag{4}$$

$$\mathbf{j}(z) = \frac{eM_f}{\Delta z} \sum_k \mathbf{V}_k \int_{z-\Delta z/2}^{z+\Delta z/2} S(z_k - z')dz' - nec\frac{\mathbf{E} \times \mathbf{B}}{B^2}. \qquad (5)$$

where M_f is a macro-factor, z is the coordinate of the center of a numerical cell, Δz is the size of the cell, $S(z)$ is the form-factor ($\int_{-\infty}^{\infty} S(z_k - z')dz' = 1$), and the index i runs the particle number. The second term in equation (5) describes the current of electron electric drift.

The initial distribution is taken to be a maxwellian plasma with uniform density n_s and temperatures T_e and T_{is}. For all the ions, the local ExB-drift velocity is added. Another common initial component is a small velocity U_y that simulates the fluctuation and provides the current density j_y and initial magnetic field $B_x(z)$. Plasma with the same density n_s and temperature T_{is} flows from boundaries into the simulation box having a field-aligned velocity v_s. Particles can be ejected from the system; in this case they are treated as being lost.

This initialization, we believe, corresponds to conditions in the far PS where magnetic tubes filled only with thermal plasma start drifting earthward.

Results and discussion

The first stages of the simulation are shown in the figure for the case B_z=1 nT, E_y=0.3 mV/m, n_s=0.1 cm^{-3}, T_{is}=10 eV, T_e=0, and v_s=0. One can see the formation of a thin region of enhanced plasma density near the neutral plane. The electric current of a positive sign is also localized there providing a high gradient of the magnetic B_x component.

In the run presented, the steady state has been attained in 110-120 s, and the last column in the figure just reflects the situation. Certainly, the time depends on the closeness of the initial plasma distribution to steady state. The main factor is the value of the initial current density j_y and the associated magnetic field gradient $\partial B_x / \partial z = 4\pi j_y / c$. Some runs performed with the initial values of $\partial B_x / \partial z$ from 1 nT/R$_E$ to 30 nT/R$_E$ show that the time of steady state development varies from 50-60 s to 150-160 s, with the same final conditions. Hence, the steady state distribution depends only on external fields and plasma source parameters, not on initial conditions.

Drift in the dawn-to-dusk electric field and B_x-inverted magnetic field displaces the warm source plasma toward the neutral plane where centrifugal drift leads to ion acceleration. The accelerated particles are then ejected from the current sheet carrying away the momentum in the x-direction, which provides the pressure balance. For more detail on this balance see *Burchart et al.* [1992] and references therein. Note, that the steady ion distribution function is sufficiently non-maxwellian, hence one should use a tensor of pressure. In the plasma/current sheet the field-transverse pressure exceeds field-aligned pressure, while outside the sheet there are field-aligned counter streams.

Runs with different input parameters lead to the following relations: the maximum B_x value $B_\infty \sim U_0 \sqrt{n_s}$, current sheet half-thickness $L \sim \sqrt{T_{is}}/B_\infty$, total plasma content $N = \int_{-L}^{L} n(z)\,dz \sim \sqrt{n_s}$. It can be shown that the distribution depends on two complex parameters only [*Burchart et al.*, 1992]; let us write them here as $\beta = \left(n_s \frac{mU_0^2}{2} \right) \Big/ \left(\frac{B_z^2}{8\pi} \right)$,

and $M = U_0 / v_T$. The former is the ratio of the ion drift energy density to normal magnetic energy density, while the latter is the Mach number (this is especially obvious in the deHoffman-Teller reference frame). It is the M parameter, on which the sheet thickness and plasma compression rate depend. So, it seems reasonable to interpret the boundary as a collisionless shock wave [*Voronov and Fridman*, 1994].
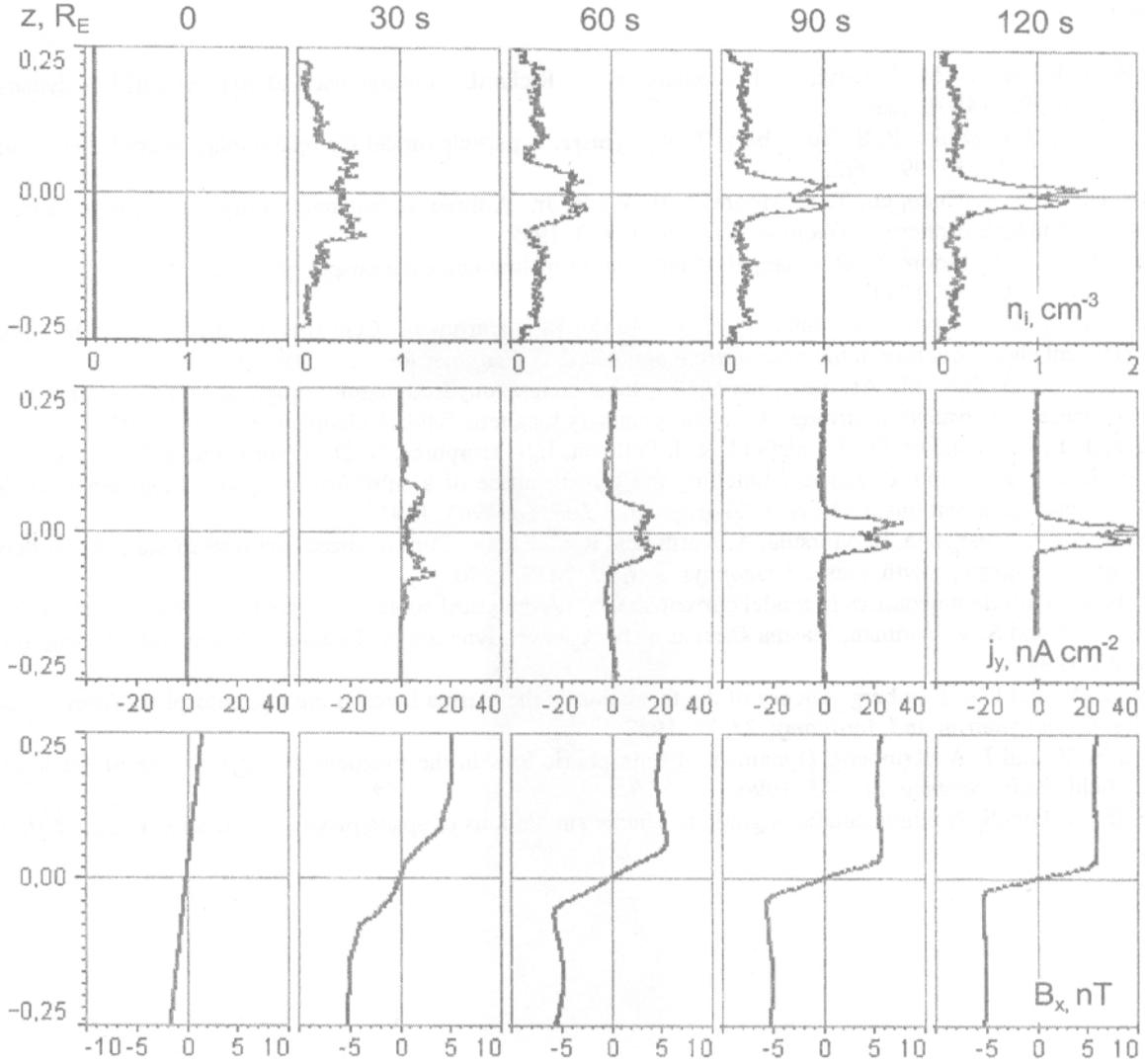
T_e in eV	0	10	40
B_0 in nT	5.9	6.0	5.7
n_m in cm^{-3}	1.2	0.7	0.5
L in R_E	0.022	0.041	0.090
N in 10^7 cm^{-2}	3.3	3.5	3.6

If electrons are considered to be warm, the outward directed E_z electric field arises. This field draws the ions out of the neutral plane and causes the current sheet half-thickness to increase, and plasma compression rate to decrease, as shown in the table. Note that both the total plasma content and the lobe magnetic field do not depend on the electron temperature.

Let us briefly formulate the main results:

1. A hybrid simulation shows that a very thin (300-1000 km) steady current sheet is formed in a uniform plasma under the supersonic ExB-drift. The time of current sheet development is about 10^2 s, *i.e.* small enough compared to the electric field variation time. The plasma compression rate is 5-10.

2. Warm electrons lead to the expansion of this current sheet in the *z*-direction and to a decrease of the plasma compression rate. This can be one more factor of the current sheet instability.

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