31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.082 (2004)

Investigation of Jet Plasma Stream Formation as a Result of Flutter Mode Growth in Large-Scale and Laboratory Plasma Experiments

N.E. Lavrinenko, E.L. Stupitsky

Central Institute of Physics and Technology, Sergiev Posad, Russia

Many diverse plasma rocket experiments, in which a plasma cloud, at first small, having considerable energy density, was brought into Earth's superstandard layers, have been made in the last few decades. These are the well-known experiments "Argus", "Starfish", "Dogwood", "Spoloh", AMPTE, "Flux", "North Star". The explosive plasma interacts with background medium and the terrestrial magnetic field, is decelerated, sets in motion the medium and results in disturbances of the geomagnetic field.

According to the extent to which the rarefied air affects the plasma dynamics, we can conditionally subdivide explosions in the near-Earth space into two ranges. The explosions at heights of h~120÷400 km can be classified as explosions in the upper atmosphere (where the air affects the plasma dynamics). The explosions at heights of more than 400 km can be classified as magnetospheric ones (where the geomagnetic field mainly affects the plasma behaviour).

At present, the physical model and the basis of the complex MHD-algorithm, which allows one to calculate the whole evolution of the plasma stream from 10^{-6} up to hundreds of seconds (200÷300), are developed as applied to explosions in the upper atmosphere. There is no sufficiently complete physical model of the development of a powerful explosion for magnetospheric explosions yet. There exist both the computational difficulties associated with the large difference of parameters and the difficulties associated with an insufficient development of the physical model itself.

In this paper, using the simplified models we theoretically and experimentally investigate the plasma expansion and deceleration in the magnetic field. We analyze the possibility of the growth of the flutter mode on the plasma front and the formation of the jet stream. If the initial energy density of the plasma is small, we can neglect the inhomogeneity of the geomagnetic field and estimate the plasma deceleration from the equation

$$\frac{d(MU)}{dt} = -\left(\frac{B^2}{8\pi} + p\right)\cdot 4\pi R^2$$

$$M = M_0 + \frac{4}{3}\pi R^3 \cdot \rho \cdot f(\beta),$$

where M_0 – the initial plasma mass, ρ , p – the density and pressure of the background gas. The function $f(\beta)$ takes account of the mass of the added air

$$f(\beta) = \frac{6}{\beta^3}\cdot\left[1-\left(1+\beta+\frac{\beta^2}{2}\right)\cdot e^{-\beta}\right],\ \beta = \frac{R}{\Delta}\cdot\cos\Theta,$$

where Δ – the height of the homogeneous atmosphere; Θ – an angle of the vertical line with the direction R. After some not fundamental simplifications (assuming, e.g.,

$\sqrt{p(R)/\rho(R)} = c = 1{,}2\cdot 10^5$ cm/s) we derive the simple expression for the plasma deceleration radius

$$R_T = \sqrt[3]{\frac{6E}{B^2\left(1+\frac{\rho_0 c^2}{B^2/8\pi}\right)\cdot\left(1+\frac{2}{3}\cdot\frac{\pi\rho_0 R_T^3}{M_0}\cdot f(\beta)\right)}} \tag{1}$$

where $E = M_0 U_0^2/2$; ρ_0 – the air density at the height of an explosion.

Fig. 1 shows radii R_T depending on h for the angle of 30^0 of the field $\vec{B}$ with the vertical. In calculations we take into account the angular variation of the tangential component of the field on the exterior boundary of the plasma.

If the energy of an explosion is large, the plasma break across the inhomogeneous geomagnetic field to great heights becomes possible. In considering the equatorial area of great heights, where the decelerating effect of air can be completely neglected, and assuming for the field $B = B_0 (R_E/R)^3$, where B_0 =0,5 Gs, R_E =6370 km, $R = h + R_E$, can derive the approximate expression for the plasma energy, when its break across the field is possible

$$E \ge B_0^2 R_E^3/100 \cdot (1 + h/R_E)^6. \tag{2}$$

That is, for $h = R_E$ the break takes place for $E \ge 0{,}8\cdot 10^{22}$ erg. Actually, because of the possible growth of the flutter mode on the plasma front, its break in the form of a jet can exist at a considerably lesser value of energy E.

Let us consider the growth of the flutter mode on the basis of the approximate model. The equation for the radial velocity of the plasma expanding in the magnetic field has the form in the spherical coordinates:

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{v}{r\sin\Theta}\frac{\partial u}{\partial \varphi} - \frac{v^2}{r}\right) = -\frac{\partial p}{\partial r} + \eta\left[\frac{1}{r}\frac{\partial^2 (ru)}{\partial r^2} + \frac{1}{r^2\sin^2\Theta}\frac{\partial^2 u}{\partial \varphi^2} - \frac{2}{r^2\sin\Theta}\frac{\partial v}{\partial \varphi} - \frac{2u}{r^2}\right] \tag{3}$$

Here we neglect the motion in Θ ($w = 0, \partial/\partial\Theta = 0$). The sector model of channels is shown in Fig. 2. In multiplying (3) by $r\cdot\sin\Theta d\Theta d\varphi dr$ and integrating over the volume of each sector we obtain the approximate system of equations, which describes the change of the plasma velocity in each sector

$$\begin{cases} \frac{m_1}{R_1}\frac{dU_1}{dt} = -2R_1\varphi_1(p_1 - p) + \frac{\dot m_1(U_2 - U_1)}{R_1}\chi(\dot m_1) - \eta\frac{\pi}{2R_1}\left(\frac{R_1+R_2}{2}\right)^2\frac{U_1 - U_2}{\Delta} \\ \frac{m_2}{R_2}\frac{dU_2}{dt} = -2R\varphi_{21}(p_2 - p) + \frac{\dot m_1(U_2 - U_1)}{R_2}\chi(-\dot m_1) - \eta\frac{\pi}{2R_2}\left(\frac{R_1+R_2}{2}\right)^2\frac{U_2 - U_1}{\Delta} \end{cases},$$

where $\Delta = 0{,}5\cdot(\varphi_1 R_1 + \varphi_2 R_2)$, the term with $\dot m_1$ takes account of the mass flow among sectors, $\chi(\dot m_1)$ – is the Heaviside function. We calculate the pressure and temperature inside the plasma in adiabatic approximation. The coefficient of viscosity is $\eta \sim T^{5/2}$. The form of initial disturbances is varied. For the nonlinear stage we suppose $\delta B = \varepsilon B/2$, where

$\varepsilon = (R_2 - R_1)/(R_1 + R_2)$. The frequency of the initial disturbances is given by the wave number $k = 2\pi R_0 / \lambda$. The calculations show that in the absence of viscosity the instability grows rapidly with the characteristic time $\tau \sim 1/\sqrt{k}$. However, the viscosity decelerates the growth of low-frequency disturbances (Fig. 3) and limits high-frequency ones. The calculations show that the disturbances with $k \geq 10$ essentially do not grow or grow very slowly, the velocity changing nonmonotonically. Thus, on the basis of the proposed simplified model we thoroughly analyzed the process of the formation and growth of the jet stream.

The analysis shows that for an explosion of the "Starfish" type the viscosity limits the initial number of channels by the value $k \cong 6$. However, after the transition of the instability to the nonlinear stage ($R_2 - R_1 > \lambda$) the only jet apparently becomes stable. As the analysis of the photographs shows, this jet extends with a small deflection to the west from the vertical (~11^0) and the main part of the plasma mass flows into it. The estimates showed that in time 100 sec the Coriolis force $2m[\vec{\omega} \times \vec{v}]$ can deflect a jet less than by 1^0. Therefore we made the special experiments with the laser plasma spread in the magnetic field. The scheme and main experimental results are presented in Fig. 4. For B=30 Gs ($\beta = mnu^2/(B^2/8\pi) << 1$) the distribution of plasma mass is close to the uniform in the angle φ. As *B* increases up to 1000 Gs ($\beta \approx 1$), the distribution over φ becomes wavy, which is typical for the growth of the flutter mode, the disturbance with $\varphi \approx 10^0$ having the greatest amplitude. As the field increases to 5300 Gs ($\beta >> 1$), all the disturbances except the main one are extinguished and the flat plasma jet, which extends at an angle of $\varphi_m \approx 11 \pm 2^0$ with the normal, is formed. The value φ_m does not depend on a material of the target, an angle of laser beam fall on the target and the value of the magnetic field (for sufficiently large fields). Since the count of the angle of deflection is essentially given by the target plane, it is the interaction with it that defines the jet deflection, whose main parameter is the wave number *k*. The dissipative processes of viscosity and conductivity limit the maximum value of *k*. The estimates show that k_m=6 for the laser experiment. The plasma is polarized on crests of a disturbance under the action of the magnetic field and the forming electric field $\vec{E}$ along with the perpendicular magnetic field $\vec{B}$ cause the plasma to drift in the direction $[\vec{E} \times \vec{B}]$. Charges of the disturbance arising on a crest form a dipole, which interacts with the conducting underlying surface, i.e. with the target – in the case with the laser plasma and with the ionized layer of air – in the case of the magnetospheric explosion, where charges of the opposite sign are induced. Since electrons are low-inertia, it is they that will turn the axis of a dipole so that the potential energy of their interaction with the charges of the underlying surface is minimum, i.e. the force is equal to zero. This condition is fulfilled only at the certain angle of inclination of a jet with the vertical (or of the axis of a dipole with the target plane)

$$tg\varphi_m = \frac{(1+a^2)^{3/4} - 1}{a},$$

where $a = d/2R = \pi/2k$, where *d* is an arm of a dipole. For *k*=6 we get φ_m=11^0. Thus, the disturbances extending at angle ~11^0 experience the least destructive effect of the induced electric field and, consequently, are the most stable. The other disturbances arising in the beginning are gradually destroyed and their mass flows into the main jet. The complete statement of the problem of the jet stream formation at an explosion must take into account electric fields everywhere over the disturbed area. The analysis carried out allowed us to understand the basis of the physical model of the formation of the large-scale jet plasma stream in the magnetic field.

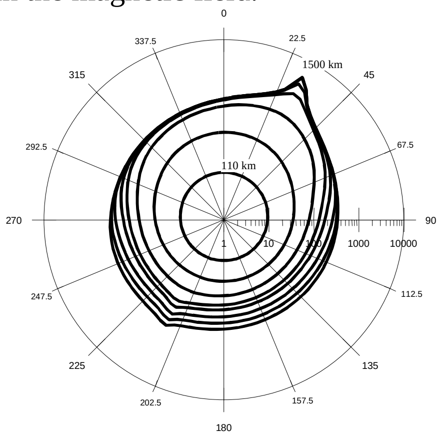

Fig. 1 The angular distribution of the radii of the plasma deceleration for various heights h.

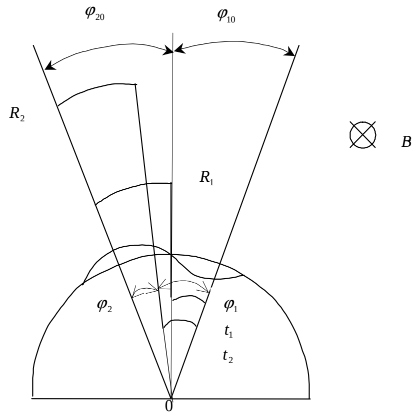

Fig. 2 The sector model of channels.

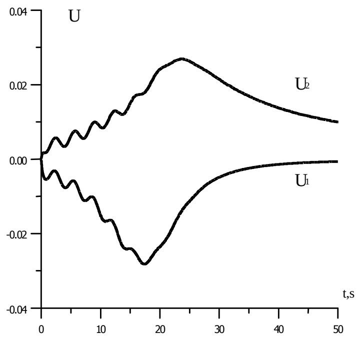

Fig.3 The growth of a disturbance if the viscosity is taken into account, k=6.

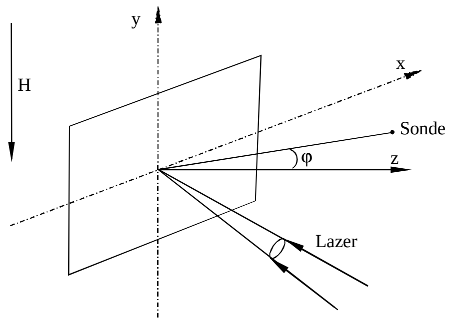

Fig. 4a The scheme of the experiment.

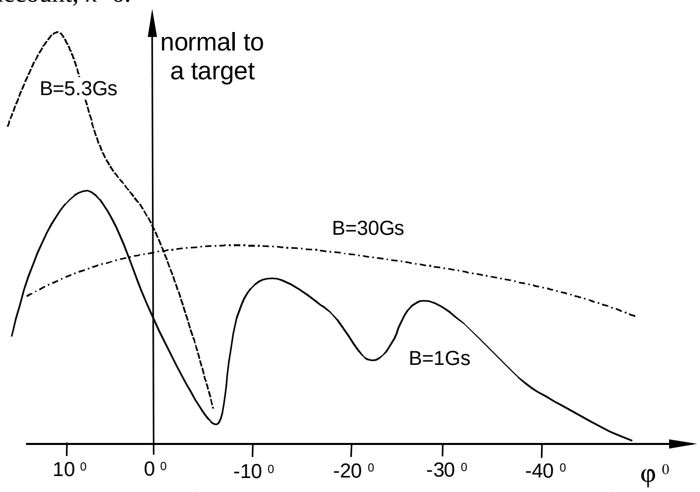

Fig. 4b The angular distribution of the spreading laser plasma at a range of R=6 cm from the target.