Dynamics of the plasma sheet in the magnetotail: interrelation of turbulent flows and thin current sheet structures

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Main topics: both important and still disputable

- Intense nonlinear disturbances in the MAGNETOTAIL PLASMA SHEET.

  Most remarkable features are

  (a) medium scale plasma FLOWS

  and magnetic field variations:

  MHD TURBULENCE

  (b) Sporadic thin CURRENT SHEETS

  embedded in the plasma sheet.

  WHAT IS THE INTER-RELATION?

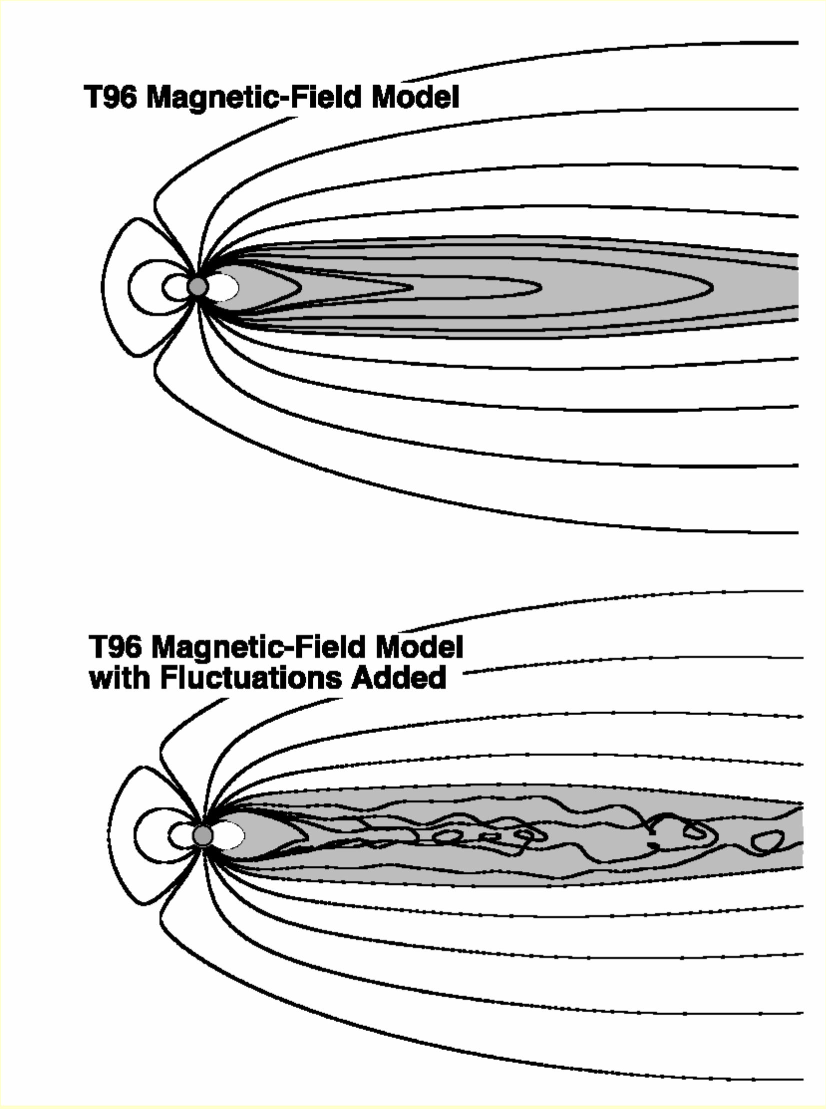
- Dynamical nature of thin current sheets.

  SPONTANEOUS FORMATION OF NONLINEAR KINETIC STRUCTURE

- How do thin current sheets relate to MAGNETIC RECONNECTION?

- Range of temporal and spatial scales.

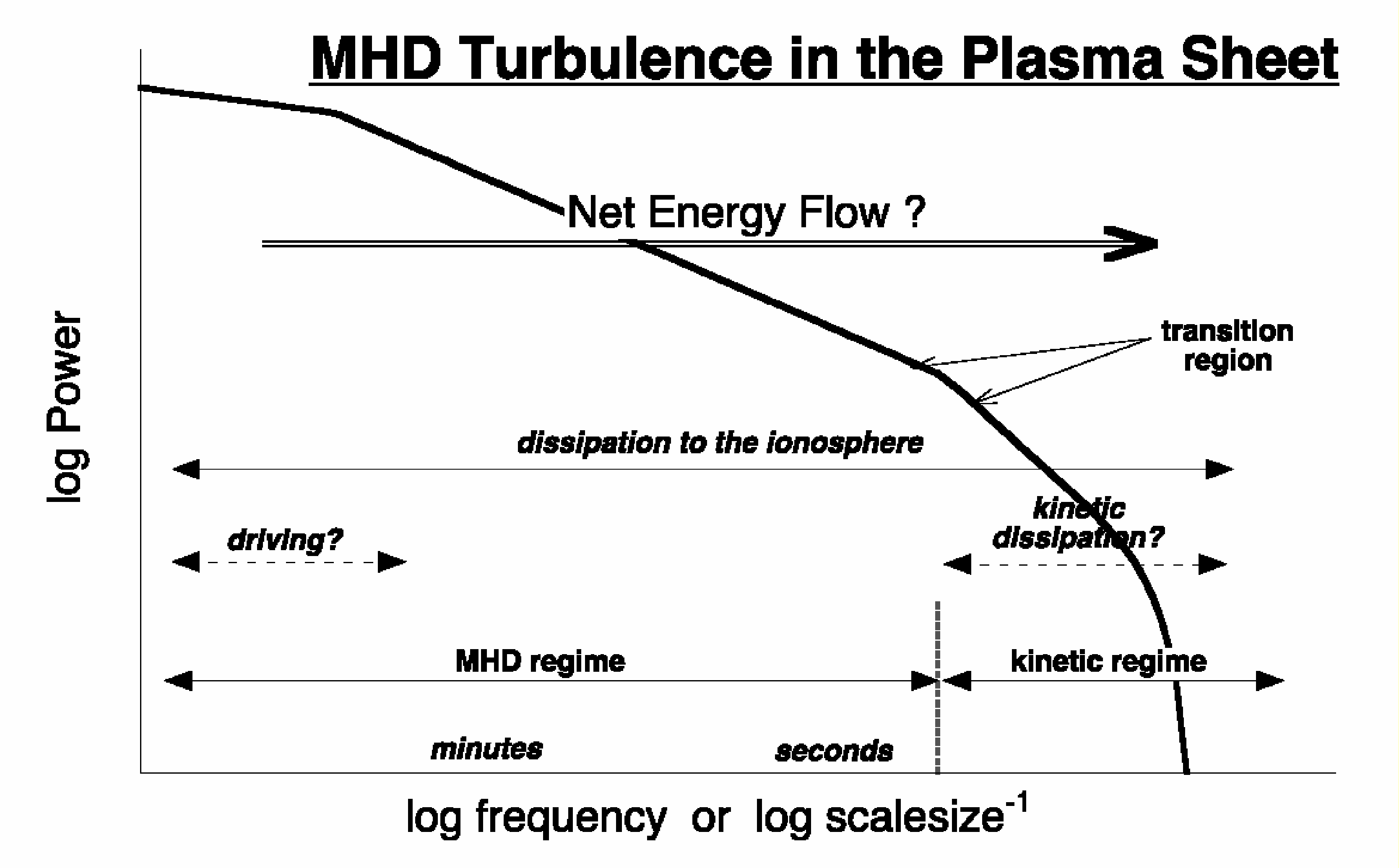
  Why and how is SLOW EVOLUTION of configuration sporadically interrupted by FAST LOSSES OF EQUILIBRIUM?



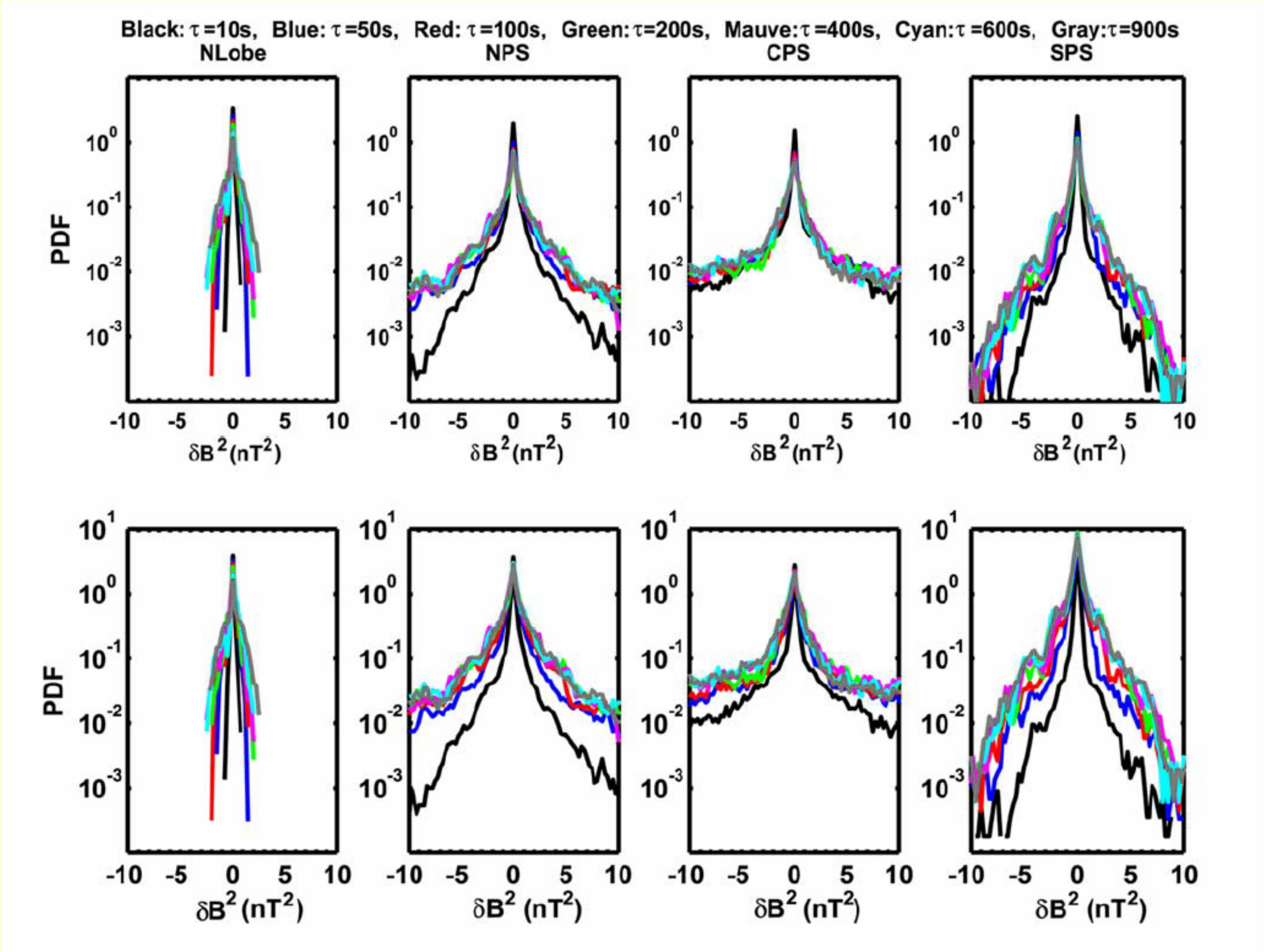
Borovsky et al, 2003

Complicated pattern of convective motions in the plasma sheet of the geomagnetic tail associated with magnetic field variations occurring on MEDIUM SCALES, large as compared to the plasma sheet thickness and small as compared to global dimensions. These motions and magnetic variations are interpreted as manifestations of specific, basically TWO-DIMENSIONAL MHD TURBULENCE.

(*Borovsky et al, Antonova et al*)

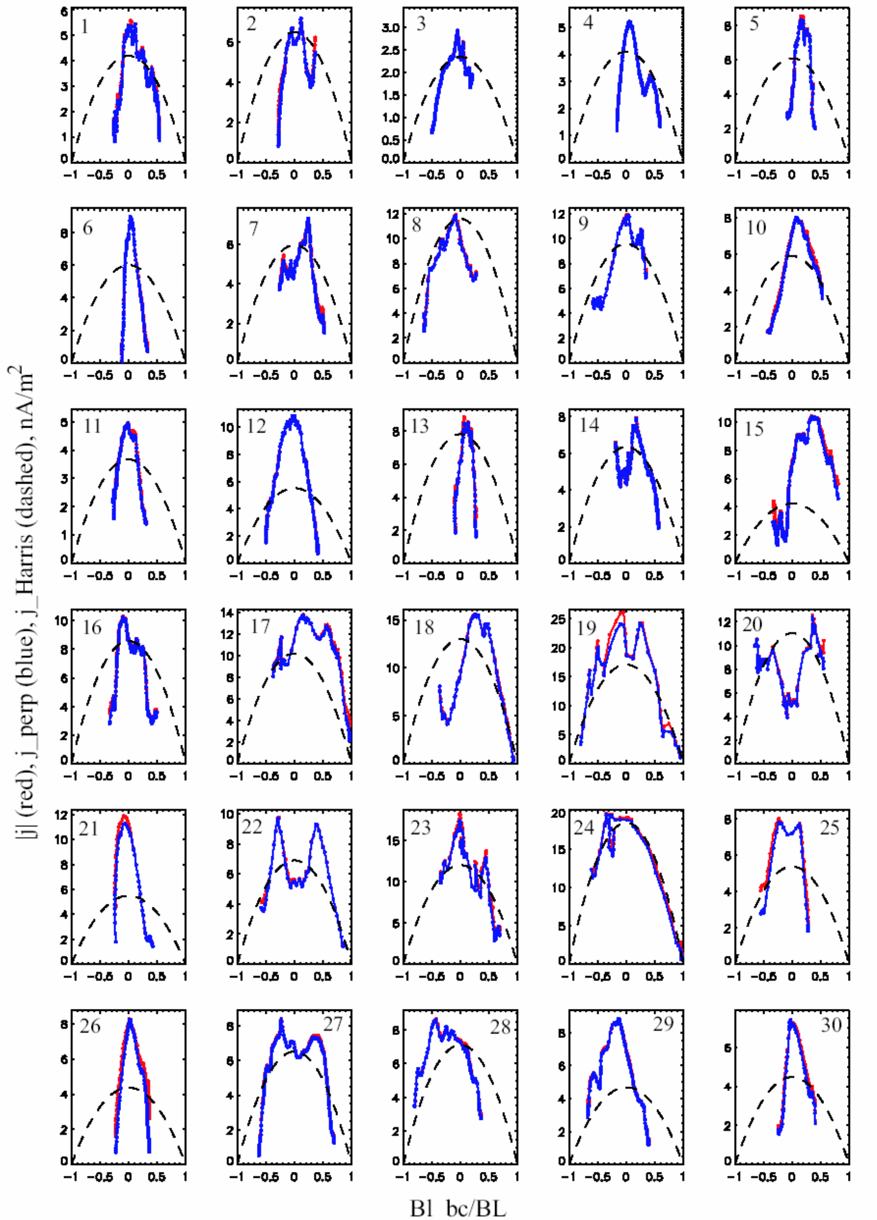


Borovsky et al, 2003



Weigand et al 2005

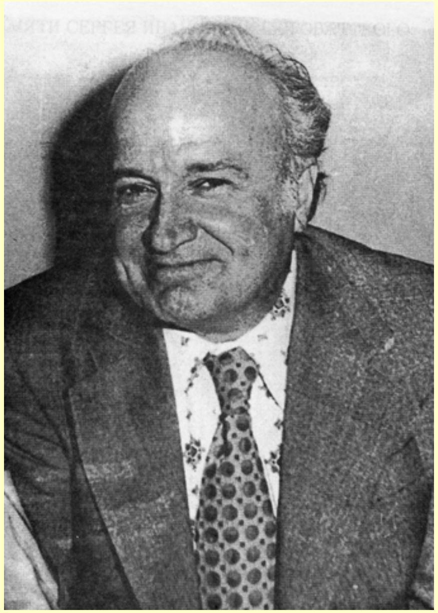
Non-Gaussian probability density functions



Runov et al, 2006

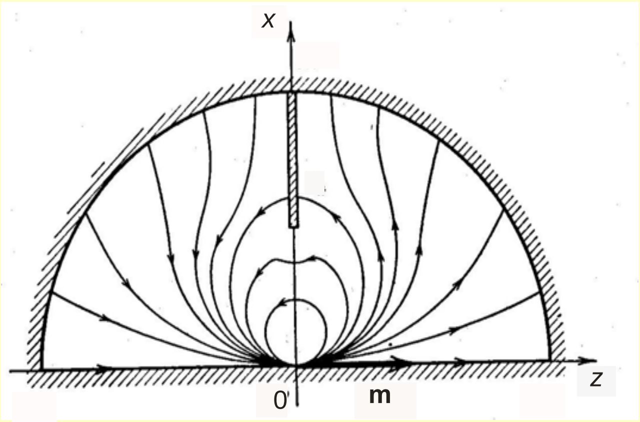
Thin current sheets in the geomagnetic tail

Hodograms of the current density $\mathbf{j} = \mu_0^{-1} \nabla \times \mathbf{B}$ **absolute value (blue) and perpendicular component** $j_\perp = \sqrt{j_m^2 + j_n^2}$ **(red)** ***versus*** **main magnetic field (*B_l*). Dashed lines show the Harris function**



Sergey Ivanovich Syrovatsky

A simple two-dimensional model of the magnetosphere (*Syrovatsky and Somov*, 1974).



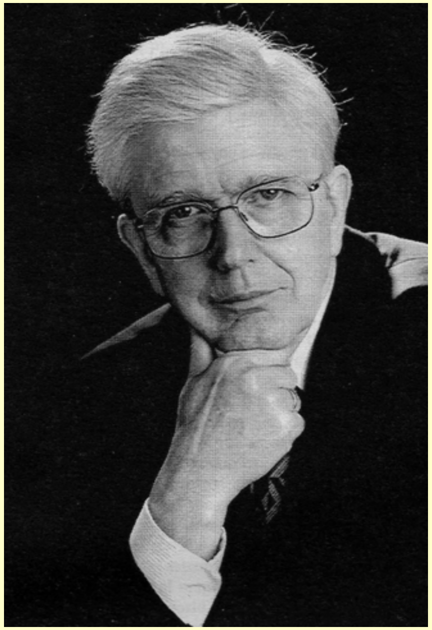
The essence of that modeling was that in a plasma with $\beta \ll 1$ all the CURRENTS ARE CONCENTRATED IN THIN CURRENT SHEETS (CS), and outside them the magnetic field is curl-free. In two dimensions, we thus simply obtain Laplace equation $\Delta A = 0$ for the only nonzero component of the vector-potential, with proper conditions on the boundaries.

OUTSIDE THE CS, the characteristic time scale is the Alfvénic time scale

$$\tau \sim l / V_A \sim l\sqrt{4\pi\rho / B}$$

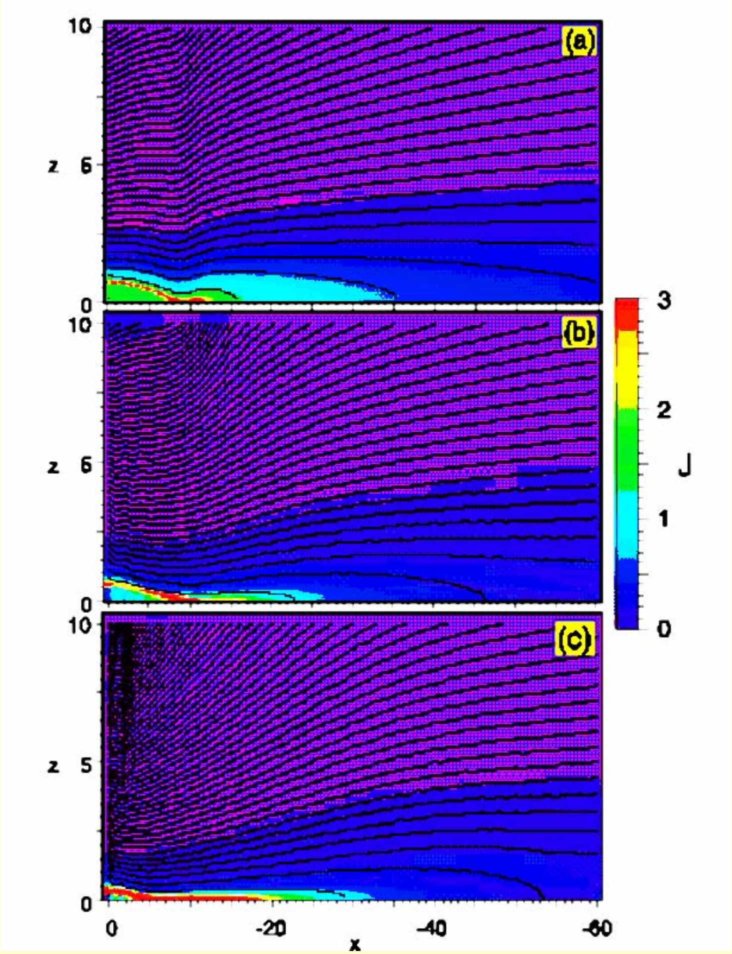
Reconfiguration occurs “instantly”, on a small time scale T_1 , with low density ρ and high B . THE MODEL IS APPLICABLE!

Critical role played by thin CS



Karl Schindler

- Theory and simulation: thin CS inevitably form in reconfiguration occurring in MHD systems.
- At that point, MHD becomes no more valid: a singularity appears in the current density distribution.
- Those singularities are ONE-DIMENSIONAL: CURRENT SHEETS
- This greatly simplifies the problem of KINETIC approach becoming necessary at that stage.
- Role of the CS: energy transformation, $jE > 0$, over a large portion of the CS



Magnetic field lines and color-coded current density for near-critical states

(a) quasi-static theory; (b) MHD simulation with the same boundary deformation as in (a), but with increased amplitude; (c) MHD simulation with tailward propagating perturbation.

(J. Birn, K. Schindler, and M. Hesse, J. Geophys. Res., 108(A9), 2003)

MHD equilibrium equation: $\frac{1}{4\pi}\mathbf{B}\cdot\nabla\mathbf{B} = \nabla\left(p + \frac{B^2}{8\pi}\right)$

Two-dimensional Grad-Shafranov model: $\mathbf{B} = \nabla A \times \nabla y \quad p = p\left(A\right)$

Schindler's asymptotic solution, $l_z / l_x \ll 1$**:**

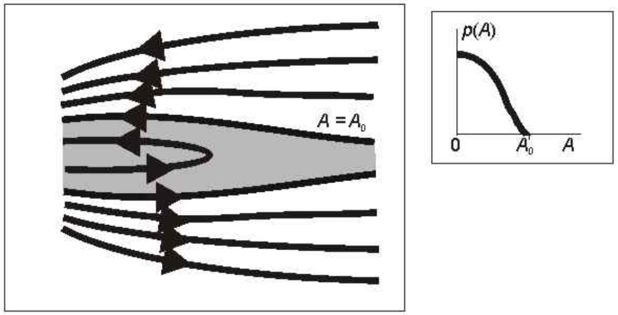
$$\boxed{p + \frac{B^2}{8\pi} = \widehat{p}\left(x\right) \qquad z\left(x, A\right) = \int_{A_0(x)}^{A} \frac{dA}{\sqrt{8\pi\left[\widehat{p}\left(x\right) - p\left(A\right)\right]}}}$$

Tail outer boundary: $a\left(x\right) = \int_{A_0(x)}^{A_b} \frac{dA}{\sqrt{8\pi\left[\widehat{p}\left(x\right) - p\left(A\right)\right]}}$

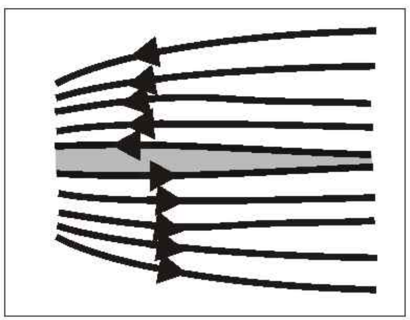
Quasi-static evolution is adiabatic: $\boxed{S = pV^{\gamma}}$ **and entropy are conserved**

DENSITY IS CONCENTRATED IN THE CENTRAL PLASMA SHEET

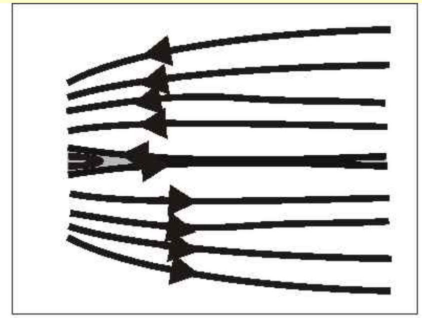
RECONFIGURATION IN THE CENTRAL PLASMA SHEET IS SLOW,
ON A SCALE $T_2, \quad T_2 \gg T_1$
LOSS OF EQUILIBRIUM IS "INSTANTANEOUS"!



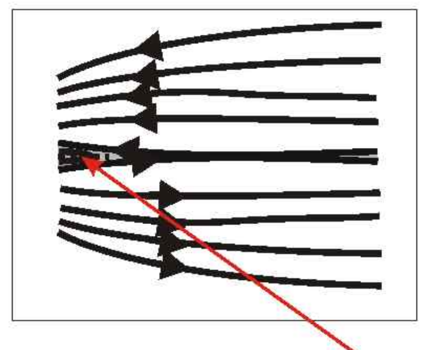
(a) initial configuration with a thick plasma sheet



(b) quasi-static adiabatic evolution leads to equilibrium with a thin current sheet



(c) non-equilibrium configuration with a thin current sheet is formed after a quick reconfiguration initiated by nonlinear tearing mode generation



(d) locally a new equilibrium is formed, with an embedded anisotropic kinetic current sheet

Simulation: basic features

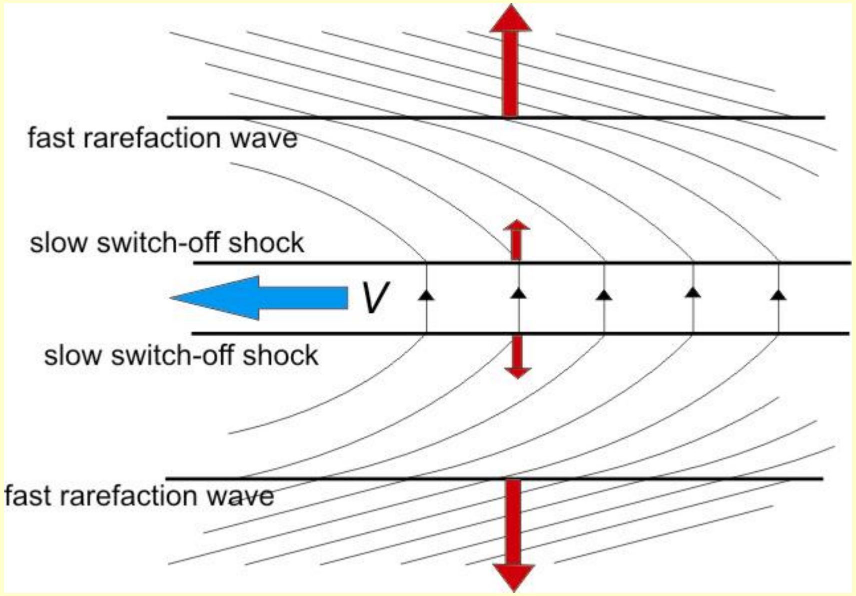
- Initially: hot plasma in a Harris-type CS
- Cold uniform plasma background
- .

$$B_n \neq 0; B_n \ll B_0.$$

- 1D hybrid code: ions treated as macroparticles, electrons as cold massless background; self-consistent electromagnetic fields.
- Simulation domain 6 times larger than the CS thickness.
- Spatial cell size = $0.085\lambda_0$
- Time step = $0.1/\Omega_0$
- About 150000 macroparticles
- Normalization parameters:

$B_0 = B_t\,(z = \infty,\ t = 0)$
$E_0 = B_n V_A / c = B_n B_t / c\,(4\pi m_i N_0)^{1/2}$
$N_0 = N^{(h)}\,(z = 0,\ t = 0)$
$N^{(c)} = N_0$

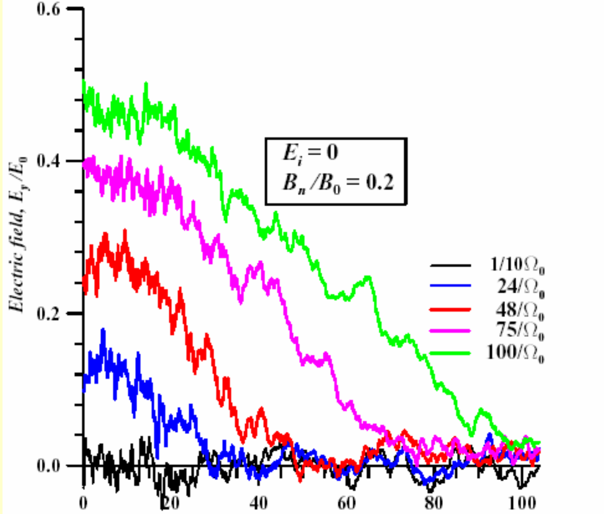
MHD prototype



decay of a non-equilibrium discontinuity with field reversal and $B_n \neq 0$

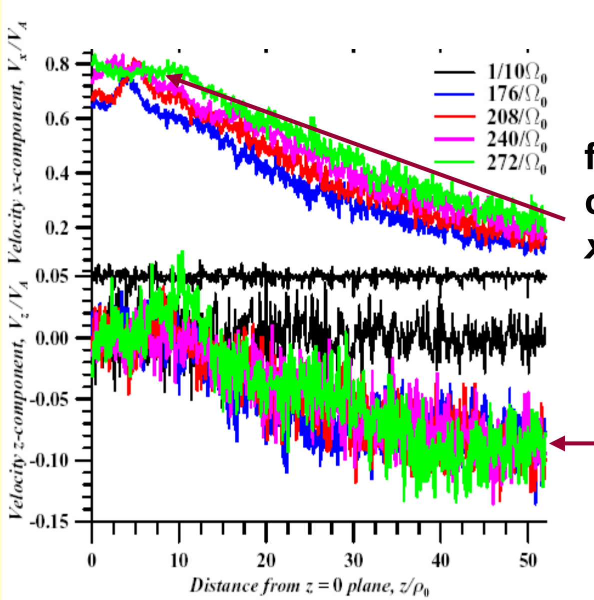
Time evolution of the current sheet: embedded extremely thin shock structure is formed

$$B_n / B_0 = 0.2$$



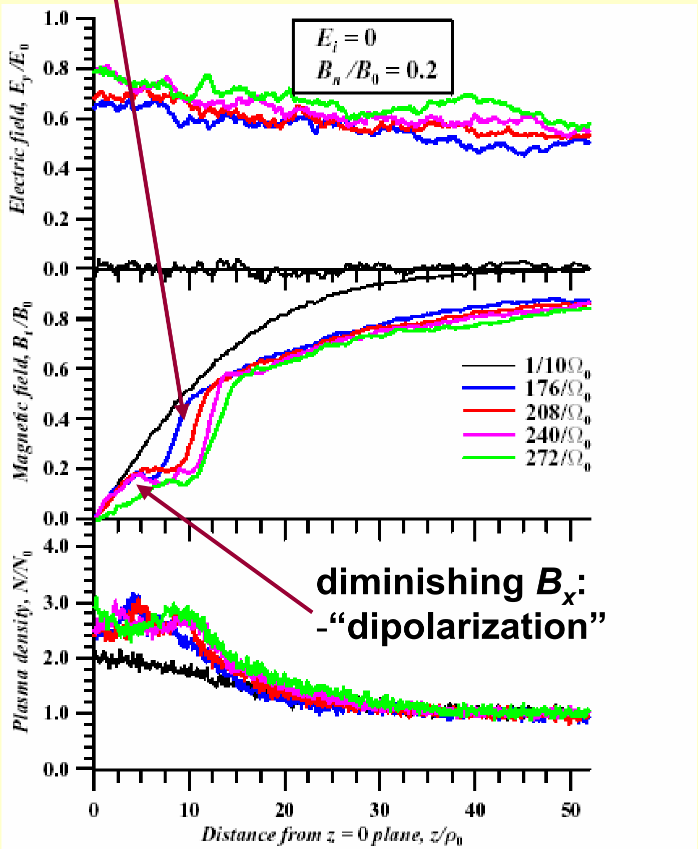
Initial stages: fast MHD wave ahead of slow "switch-off" shock

Later stages



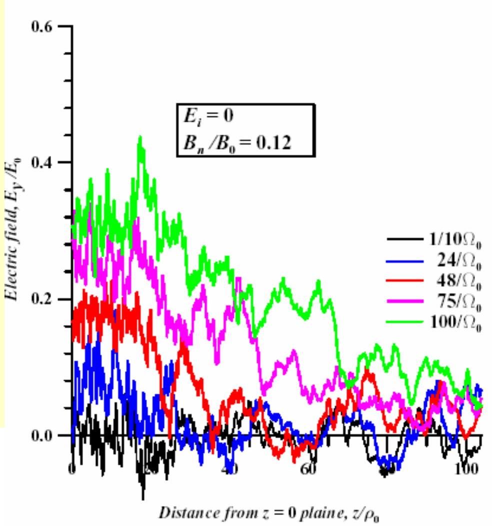
fast ($v \sim V_A$) convection along x at the center

convection towards CS between the fast and slow fronts



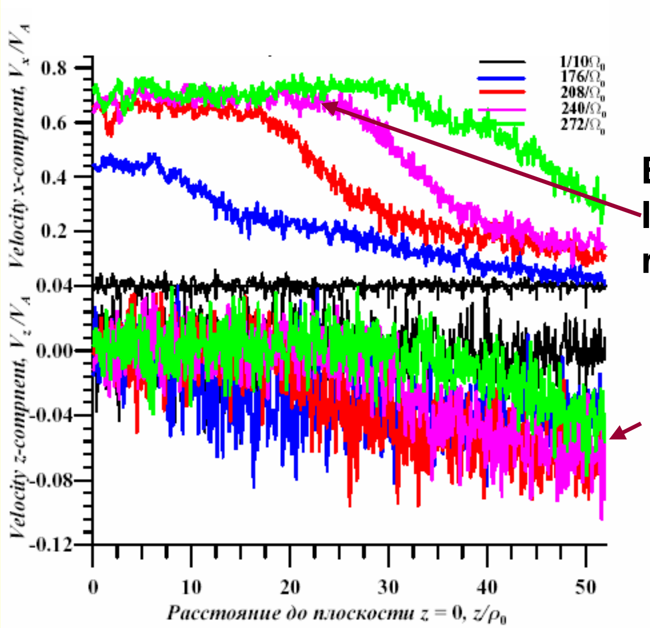
diminishing B_x: -"dipolarization"

Time evolution of the current sheet: embedded extremely thin CS is formed – anisotropic Forced Current Sheet



$$B_n/B_0 = 0.12$$

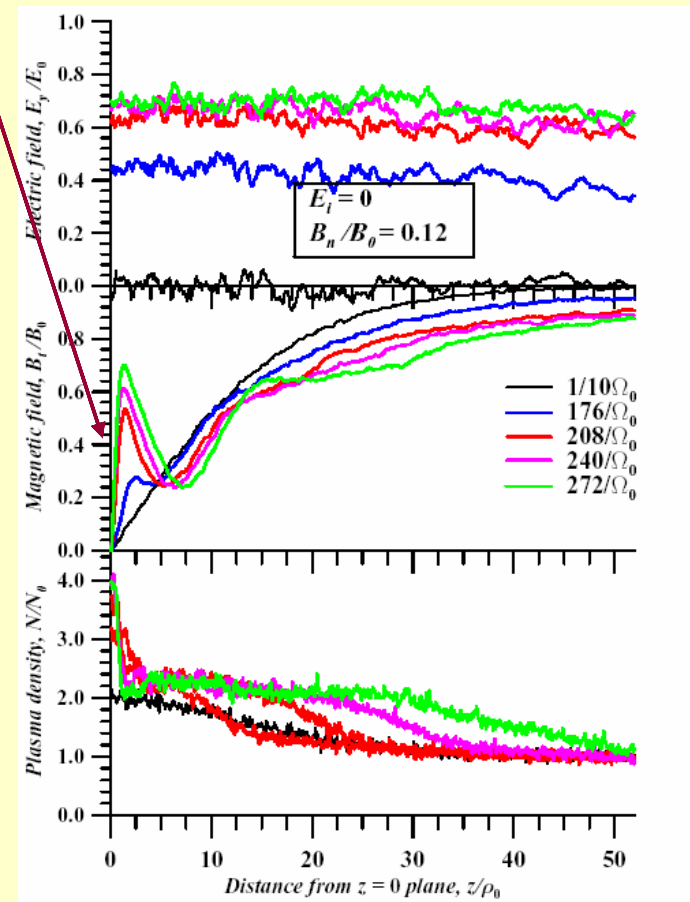
Initial stages: fast MHD wave ahead of slow disturbance



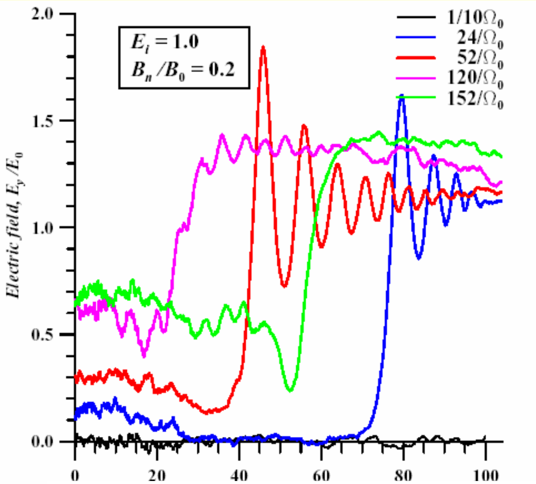
Later stages

Bulk velocity near V_A In the double-flow region

convection towards CS outside the double-flow region

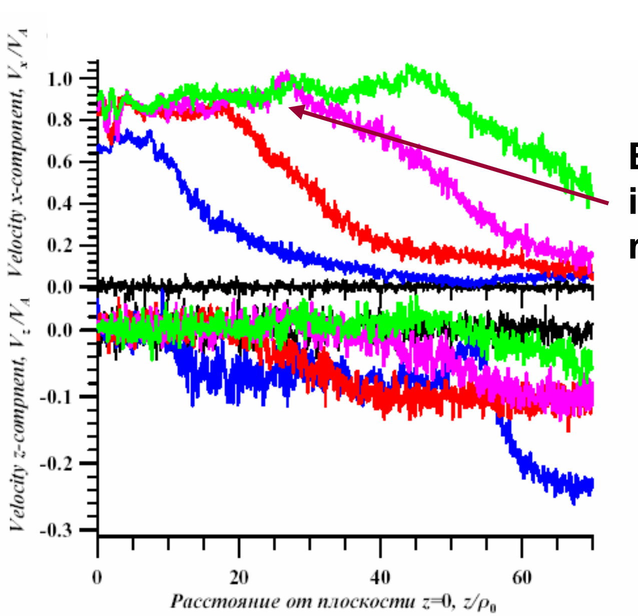


Time evolution of the current sheet, with an external trigger: embedded extremely thin CS is formed – anisotropic Forced Current Sheet



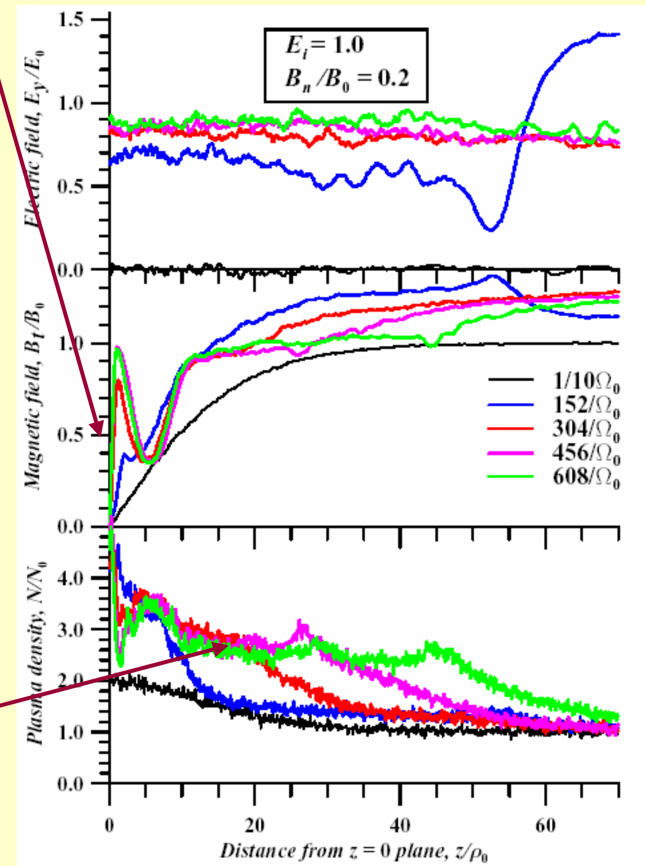
Initial stages: fast collisionless shocks, incident and reflected

Later stages

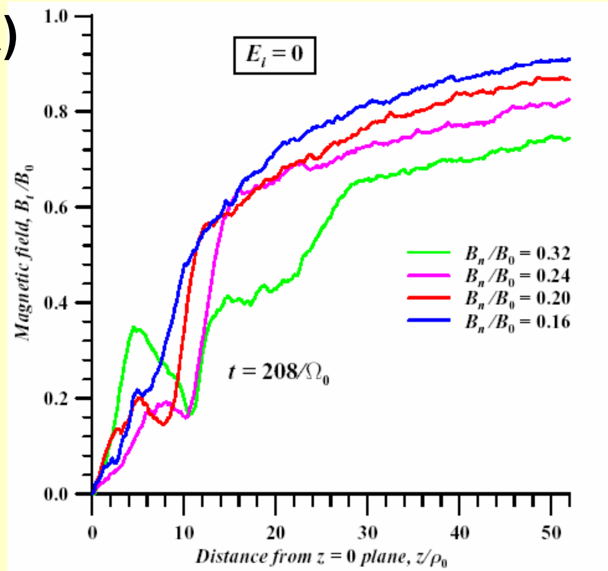


Bulk velocity near V_A in the double-flow region

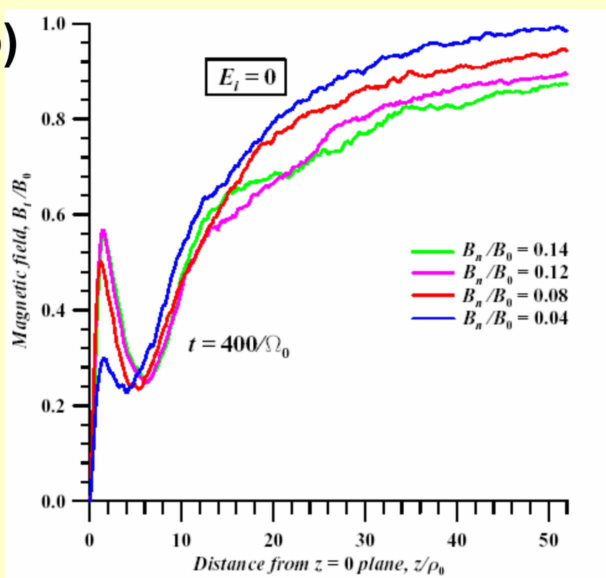
Density is nearly doubled in the double-flow region



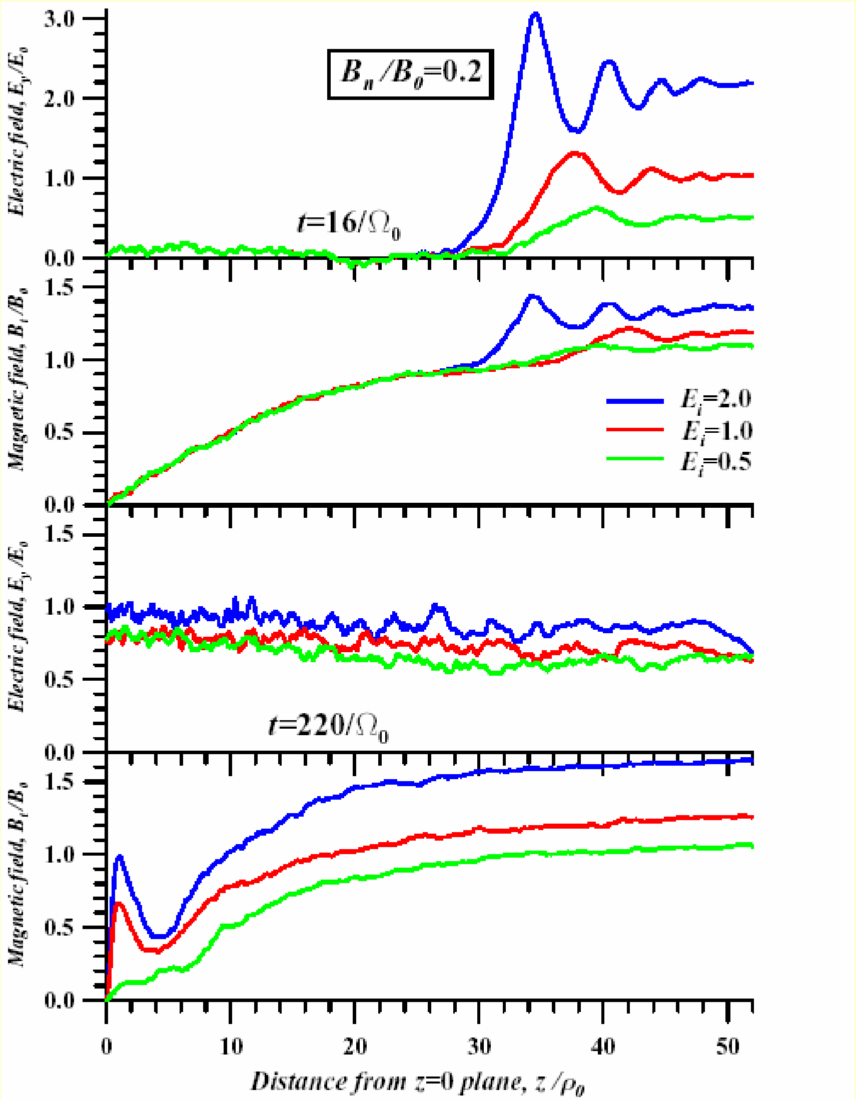
(a)



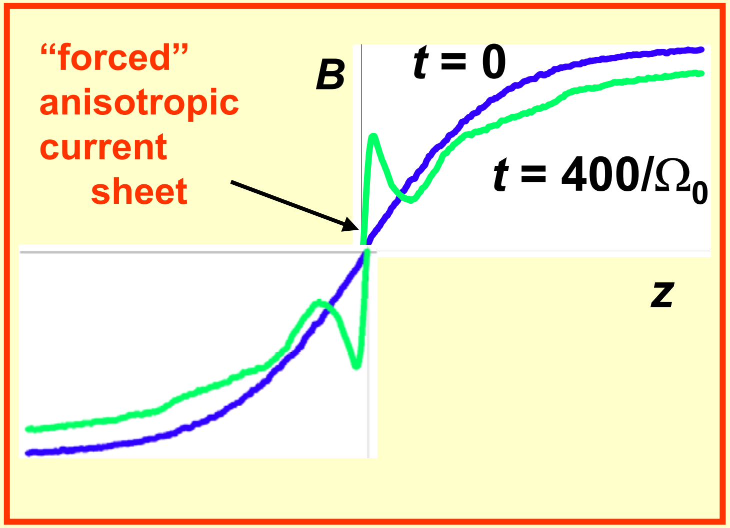
(b)

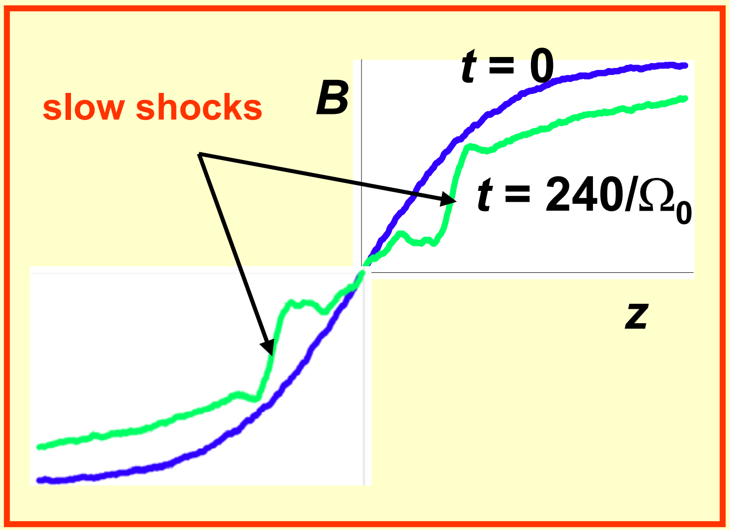


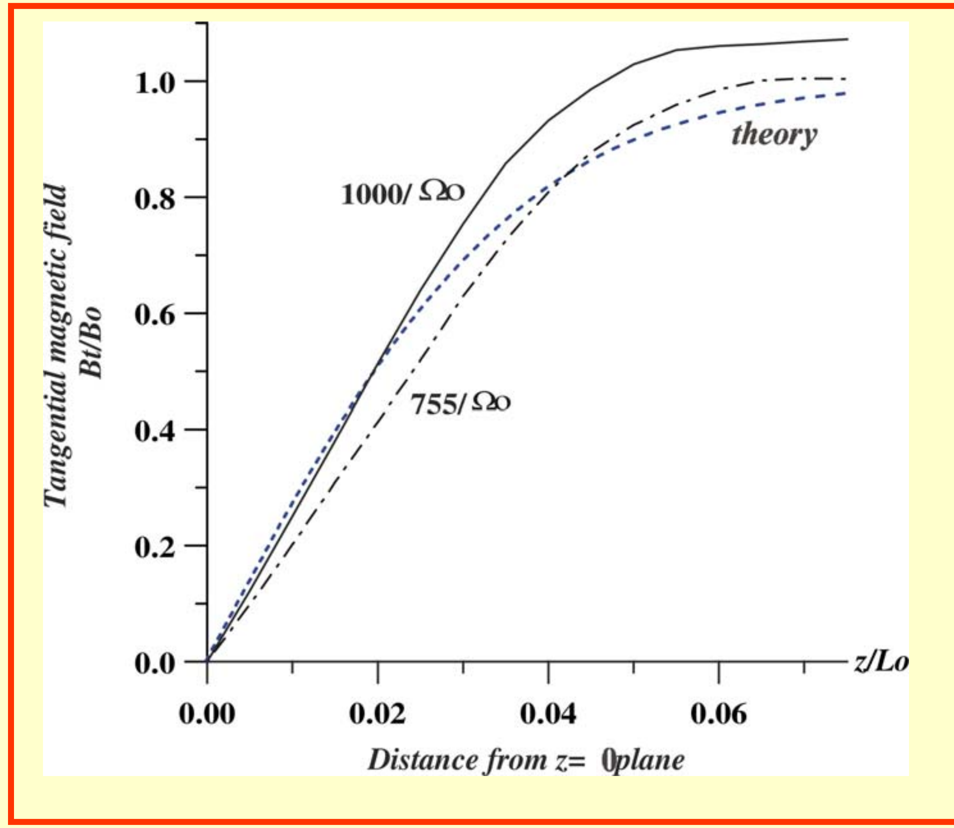
Formation of either a shock (a) or anisotropic FCS (b) depending on B_n/B_0 ratio. Critical B_n/B_0 = 0.14



Formation of anisotropic FCS depending on trigger intensity





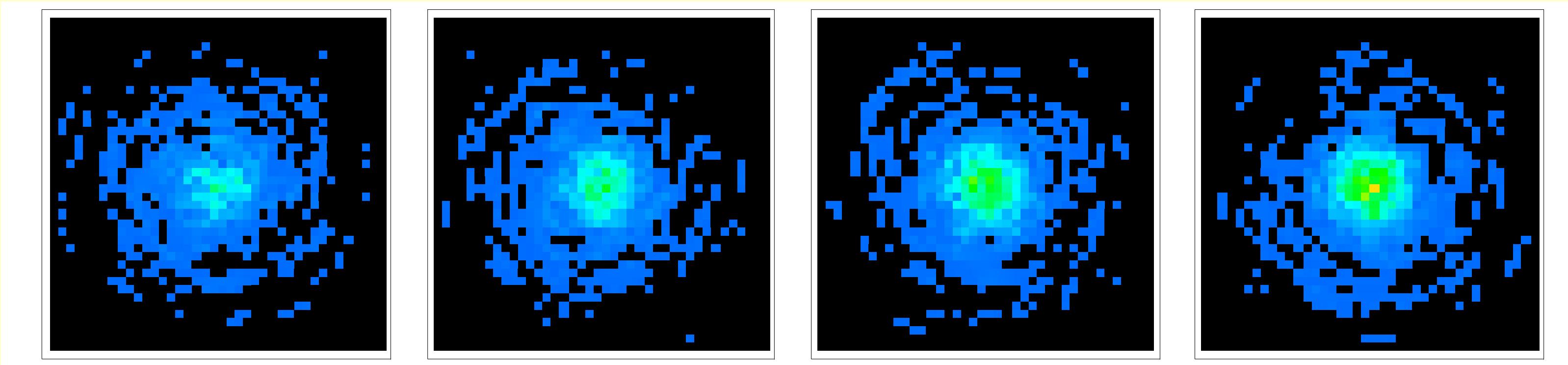


Formation of thin embedded current sheets

Consistency with theory

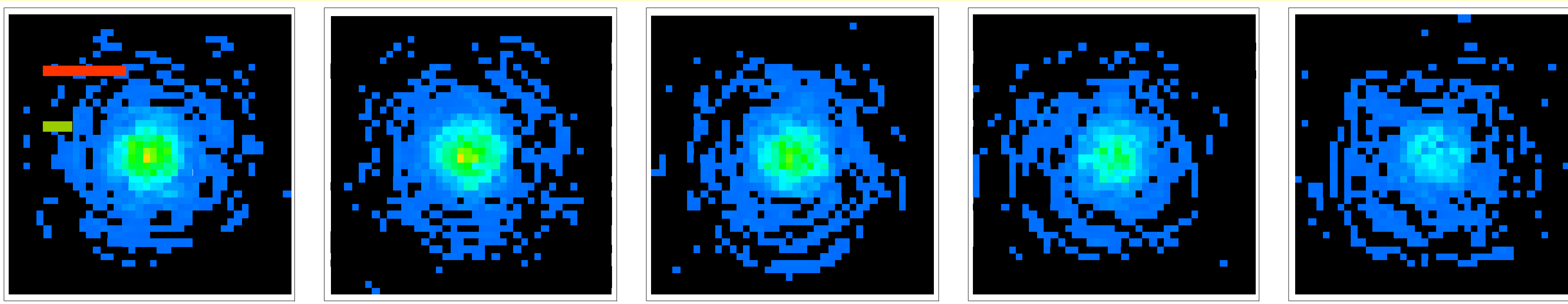
- $B(z)$ profile
- finite energy transformation rate:
- electric field E and the Pointing vector

$$P = c\frac{EB_t}{4\pi} = \frac{B_t^2 B_n}{(4\pi)^{3/2}(N_0 m_i)^{1/2}}$$



$V_z = -2.45 v_T^{(c)}$

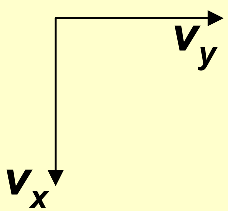
V_z increase



$V_z = 0$

V_z increase

$V_z = 2.45 v_T^{(c)}$



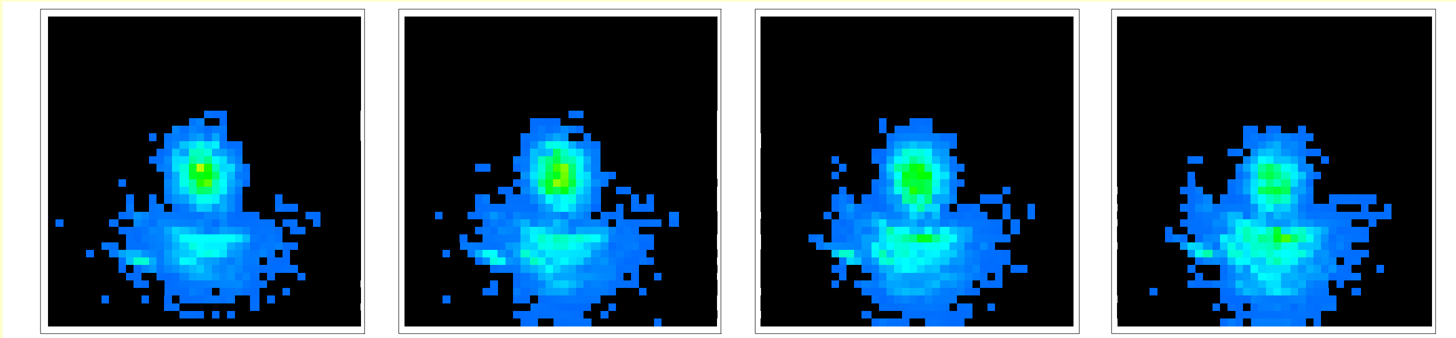
Successive cross-sections of the velocity distribution

No trigger; $B_n/B_0 = 0.2$;

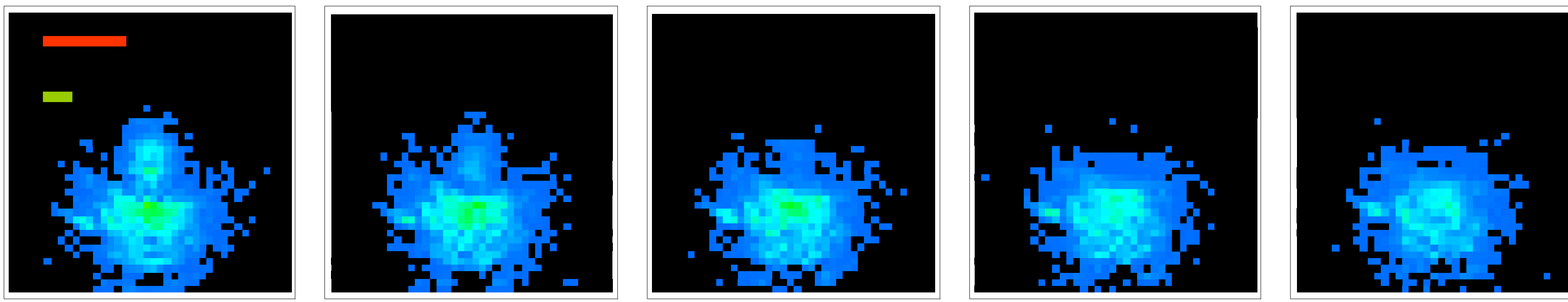
$t = 0$, $Z = 0$

$v_T^{(h)}$

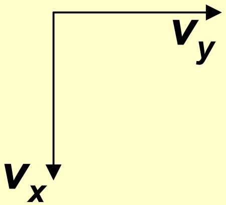
$v_T^{(c)}$



$V_z = -2.45 v_T^{(c)}$ V_z increase



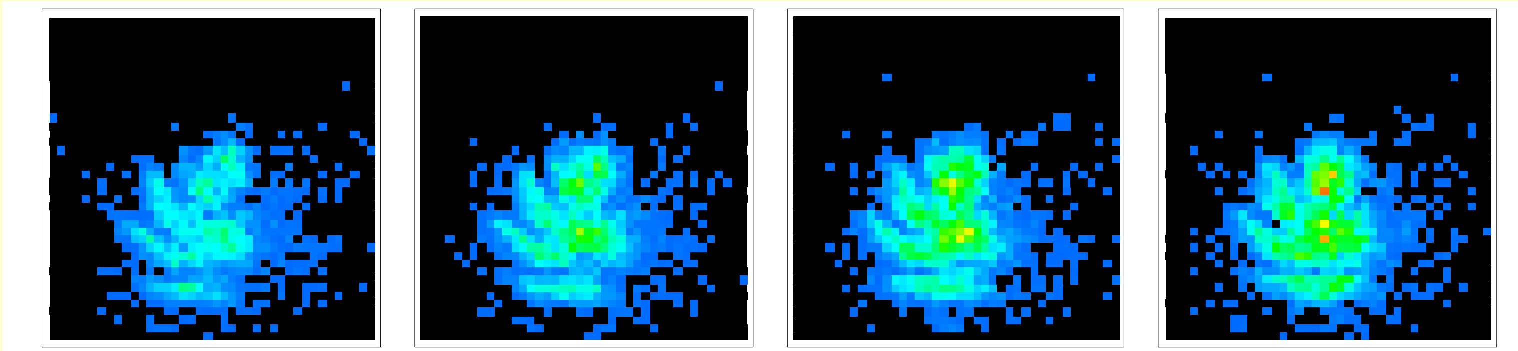
$V_z = 0$ V_z increase $V_z = 2.45 v_T^{(c)}$



Successive cross-sections of the velocity distribution

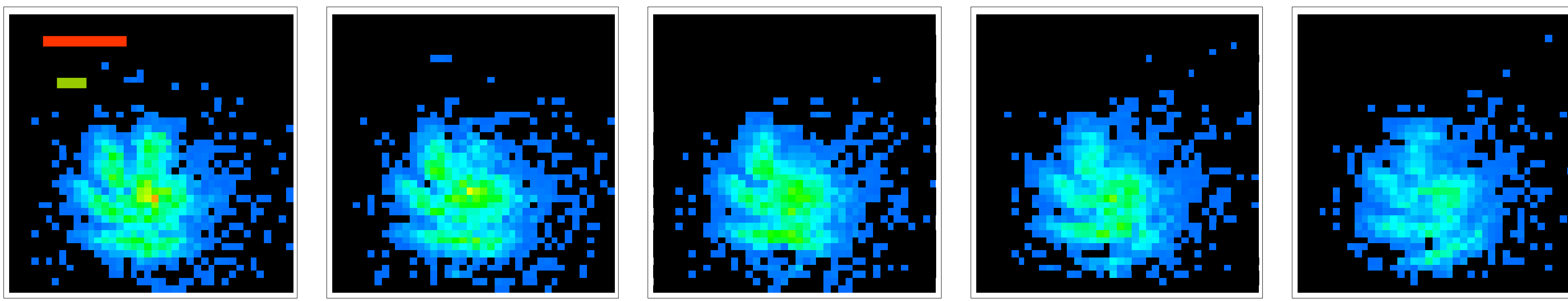
No trigger; $B_n/B_0 = 0.2$; — $v_T^{(h)}$

$t = 4/\Omega_0$, $Z = 12.2\rho_0$ — $v_T^{(c)}$



$V_z = -2.45 v_T^{(c)}$

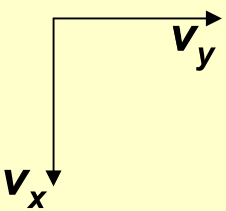
V_z increase



$V_z = 0$

V_z increase

$V_z = 2.45 v_T^{(c)}$



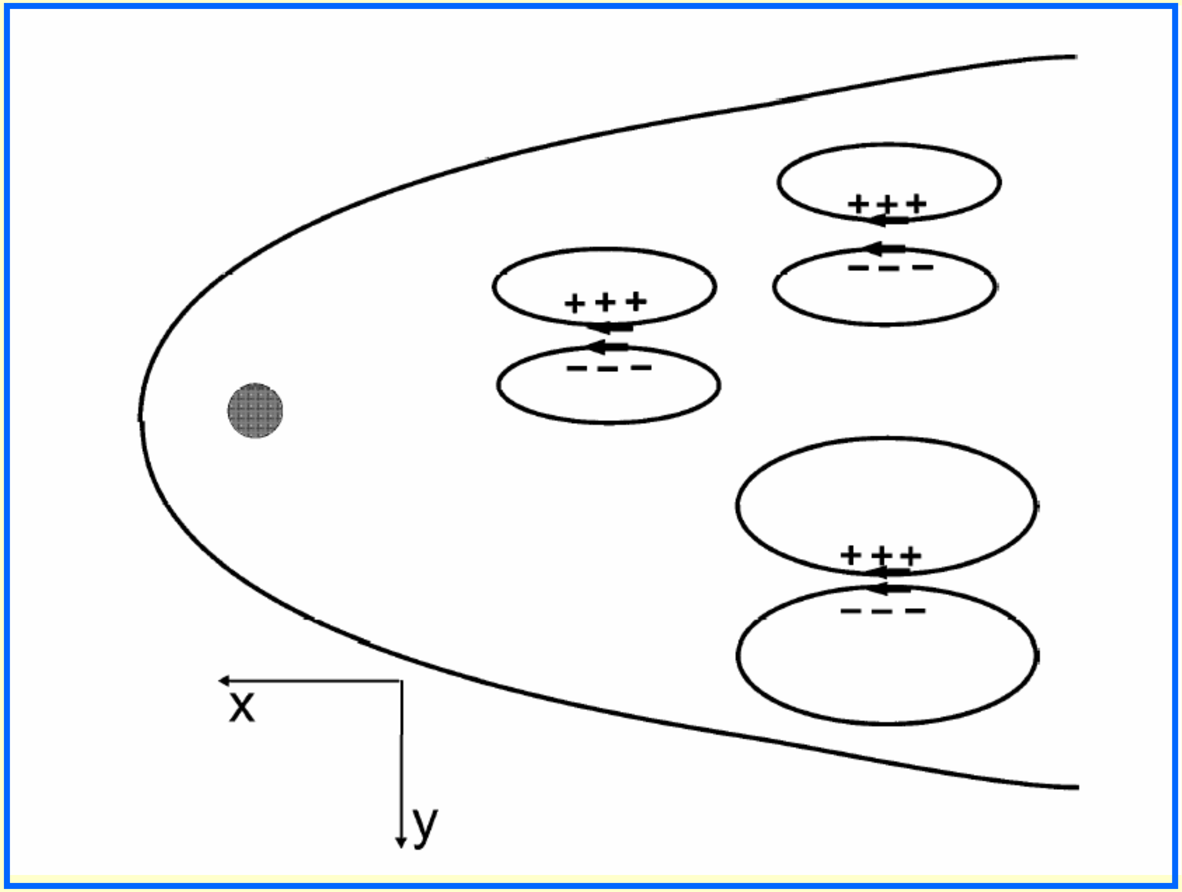
Successive cross-sections of the velocity distribution

No trigger; $B_n/B_0 = 0.12$;

$t = 4/\Omega_0$, $Z = 0$

$v_T^{(h)}$

$v_T^{(c)}$



Patches of magnetic field merging in the geomagnetic tail. Sporadic electric fields and plasma flows

CONCLUSIONS

- **Thin CS initially produced by flux-conserving (MHD) motions, is sporadically affected by LOSS OF EQUILIBRIUM. Via fast MHD disturbance, the loss of equilibrium is remotely INDUCED BY A NONLINEAR (TEARING, BALLOONING) INSTABILITY MECHANISM.**
- **A short time scale T_1 is associated with the MHD disturbance propagating in the tail lobes, with their relatively strong magnetic field and low plasma density.**
- **On those areas of CS where the induced loss of equilibrium occurs, nonlinear quasi-one-dimensional evolution is started. Its crucial feature is SELF-ORGANIZATION expressed in spontaneous formation of EMBEDDED EXTREMELY THIN CURRENT STRUCTURES. A much longer time scale T_2 is associated with that process in the plasma sheet, with its small normal component of the magnetic field and a greater density.**
- **In SIMULATION, both SLOW SHOCKS AND ANISOTROPIC "FORCED" CS are identified as such extremely thin current structures.**

CONCLUSIONS (ctd)

- **KINETIC EFFECTS provide various features of ANISOTROPY: (a) shifted nearly Maxwellian distributions: FAST BULK FLOWS; (b) FIELD-ALIGNED DOUBLE FLOWS, etc.**
- **The thin kinetic structures are responsible for large-scale magnetic MERGING, i.e. transformation of magnetic energy into energy of plasma flows, occurring over the structure. Together with scattering induced by plasma wave turbulence, this provides a mechanism of DISSIPATION IN THE ENTIRE SYSTEM.**
- **In the magnetosphere, this is the basis for INTERMITTENT, sporadic MAGNETOTAIL ACTIVATIONS (fast nonlinear tearing or ballooning instability events initiate the whole process).**
- **The FAST FLOWS may DRIVE TURBULENCE on shorter spatial scales. In their turn, these motions may serve as an origin for neutral line generation, and RECONNECTION. The latter generates signals in MHD modes, propagating in the magnetotail lobes, and thus new fast disturbances on the short time scale T_1 are produced. INTERMITTENCY IS TYPICAL.**