Dynamo and Reverse Dynamo –

Acceleration / Generation of Flows

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Stellar Atmospheres – fields and flows

Stellar atmospheres are hot and charged – Much of the observed phenomena are caused by the motion of these charged hot particles (electrons and protons mostly) in Magnetic fields.

Magnetic fields play a key role in the formation of stars (planetary systems) – Control the atmospheres dynamics – the stellar coronae and the stellar winds, the space weather etc.

Stellar magnetic field is generated in the interior of a star like the Sun by a "dynamo mechanism" – still a mystery – rotation and convection are the most important ingredients.

The atmospheric magnetic field continually adjusts to the large-scale flows on the surface, to flux emergence and subduction, and to forces opening up the field into space.

Corona – Observations – Inferences

- **The solar corona – a highly dynamic arena replete with multi-species multiple–scale spatiotemporal structures**.
- Magnetic field was always known to be a controlling player.
- Enters a major new element – discovery that **strong flows are found everywhere in the low atmosphere — in the sub-coronal (chromosphere) as well as in coronal regions**.
- Directed kinetic energy has to find its rightful place in dynamics: **the plasma flows may, in fact, do complement the abilities of the magnetic field in the creation of the amazing richness observed in the coronal structures**.

Challenge – to develop a theory of energy transformations for understanding the **acceleration/flow generation** events.

Dynamo Action – a short review-1:

The Dynamo mechanism is the generic process of generating macroscopic magnetic fields from an initially turbulent system. It is biggest industry in plasma astrophysics; is highly investigated in a variety of fusion devices.

Standard Dynamo – generation of macroscopic fields from (primarily microscopic) velocity fields.

The relaxations observed in the reverse field pinches is a vivid illustration of the Dynamo in action.

The Myriad phenomena in stellar atmospheres (heating, field opening, wind) impossible to explain without knowing the origin/nature of magnetic field structures.

Search for interactions that may result in efficient dynamo action is one of the most flourishing fields in plasma astrophysics.

Dynamo Action – a short review-2:

- **In the so called kinematic dynamo, the velocity field is externally specified and is not a dynamical variable.**

- **In "higher" theories – MHD, Hall MHD, two fluid etc, the velocity field evolves just as the mag. field does – the fields are in mutual interaction.**

A question – A possible inference:

If short–scale turbulence can generate long–scale magnetic fields, then short-scale turbulence should also be able to generate macroscopic velocity fields.

After all, in the equations of motion the magnetic field and the vorticity appear almost on equal footing.

Reverse Dynamo – Flow generation

If the process of conversion of short–scale kinetic energy to long–scale magnetic energy is termed "dynamo" (D) then the mirror image process of the conversion of short–scale magnetic energy to long–scale kinetic energy could be called "Reverse dynamo" (RD).

Extending the definitions:

- **Dynamo(D) process** - Generation of macroscopic magnetic field from any mix of short–scale energy (magnetic and kinetic).

- **Reverse Dynamo(RD) process** - Generation of macroscopic flow from any mix of short–scale energy (magnetic and kinetic).

Theory and simulation show

(1) D and RD processes operate simultaneously — whenever a large scale magnetic field is generated there is a concomitant generation of a long scale plasma flow.

(2) The composition of the turbulent energy determines the ratio of the macroscopic flow/macroscopic magnetic field.

Reverse Dynamo Relationship – Theory

Minimal two fluid model – incompressible, constant density Hall MHD – gravity is ignored.

Dimensionless system in standard Alfvenic units. Velocities are normalized to the Alfven speed with some appropriate normalizer of the magnetic field. Times are measured in terms of the inverse cyclotron time, and Lengths are normalized to the collisionless skin depth λ_{i0}.

Defining equations are:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \Big[[\boldsymbol{V} - \boldsymbol{\nabla} \times \boldsymbol{B}] \times \boldsymbol{B} \Big], \qquad \boldsymbol{V}_e = \boldsymbol{V} - \boldsymbol{\nabla} \times \boldsymbol{B} \quad (1)$$

$$\frac{\partial \boldsymbol{V}}{\partial t} = \boldsymbol{V} \times (\boldsymbol{\nabla} \times \boldsymbol{V}) + (\boldsymbol{\nabla} \times \boldsymbol{B}) \times \boldsymbol{B} - \boldsymbol{\nabla} \left(P + \frac{V^2}{2} \right) \quad (2)$$

The red terms are due to Hall current and the blue terms are vorticity forces.

Micro and Macro Fields

Similar to stability theory, the total fields are broken into ambient and generated fields. But the generated fields, now, are further split into **micro** and **macro** fields:

$$\begin{aligned} \boldsymbol{B} &= \boldsymbol{b}_0 + \boldsymbol{H} + \boldsymbol{b} \\ \boldsymbol{V} &= \boldsymbol{v}_0 + \boldsymbol{U} + \boldsymbol{v} \end{aligned}$$

$\boldsymbol{b}_0,\ \boldsymbol{v}_0$ - equilibrium; $\boldsymbol{H},\ \boldsymbol{U}$ - macroscopic; $\boldsymbol{b},\ \boldsymbol{v}$ - microscopic fields.

In the traditional dynamo theories, $\boldsymbol{v}_0$, the short scale velocity field is dominant.

We shall not introduce any initial hierarchy between $\boldsymbol{v}_0$ and $\boldsymbol{b}_0$.

We shall simply develop the natural unified Flow–Field theory.

Equilibrium – Initial State

Real departure from the standard dynamo approach is in our choice of the initial plasma state. Equilibrium fields are taken to be the Double Beltrami(DB) pair
(obeying Bernoulli condition $\boldsymbol{\nabla}(p_0 + \boldsymbol{v_0}^2/2) = const$)

$$\frac{\boldsymbol{b}_0}{a} + \boldsymbol{\nabla} \times \boldsymbol{b}_0 = \boldsymbol{v}_0, \quad \boldsymbol{b}_0 + \boldsymbol{\nabla} \times \boldsymbol{v}_0 = d\boldsymbol{v}_0, \tag{3}$$

which may be solved in terms of the Single Beltrami (SB) states $(\boldsymbol{\nabla} \times \boldsymbol{G}(\mu) = \mu \boldsymbol{G}(\mu))$

$$\boldsymbol{b}_0 = C_\lambda \boldsymbol{G}(\lambda) + C_\mu \boldsymbol{G}(\mu), \tag{4}$$

$$\boldsymbol{v}_0 = \left(a^{-1} + \lambda\right) C_\lambda \boldsymbol{G}(\lambda) + C_\mu \left(a^{-1} + \mu\right) \boldsymbol{G}(\mu). \tag{5}$$

$C_{\lambda/\mu}$ - arbitrary constants; a, d - set by invariants of the equilibrium system.

See: Mahajan & Yoshida, *Phys. Rev. Lett.*, **81**, 4863 (1998); Mahajan et al. *Phys. Plasmas*, **8**, 1340 (2001); Yoshida et al., *Phys. Plasmas*, **8**, 2125 (2001)

Equilibrium – Initial State – Cont.

Inverse scale lengths λ, μ are fully determined in terms of a, d (hence, initial helicities). As a, d vary, λ, μ can range from real to complex values of arbitrary magnitude.
Below: λ - micro-scale; μ - macro-scale structures;
$|b| \ll b_0, |v| < v_0$ **at the same scale**; $\boldsymbol{v}_{e0} \equiv \boldsymbol{v}_0 - \boldsymbol{\nabla} \times \boldsymbol{b}_0$

Ideal invariants: **The Magnetic and the Generalized helicities** (Mahajan & Yoshida 1998; Mahajan et al. 2001)

$$h_1 = \int (\mathbf{A} \cdot \mathbf{b})\, d^3x, \tag{6}$$

$$h_2 = \int (\mathbf{A} + \mathbf{V}) \cdot (\mathbf{b} + \nabla \times \mathbf{V}) d^3x. \tag{7}$$

Details of closure model of Hall MHD can be found in Mininni, Gomez & Mahajan, ApJ (2003), (2005).

Evolution Equations of the macrofields

Primary interest – to create macro fields from the ambient microfields. Later we will assume that the ambient fields are purely microscopic.

The simplifying assumptions: $|b| \ll b_0, |v| < v_0$ at the same scale. After some direct algebra, using the properties of the DB fields, we find the evolution equation of the macrofields:

$$\partial_t \boldsymbol{U} = \boldsymbol{U} \times (\boldsymbol{\nabla} \times \boldsymbol{U}) + \boldsymbol{\nabla} \times \boldsymbol{H} \times \boldsymbol{H} + \langle \boldsymbol{v}_0 \times (\boldsymbol{\nabla} \times \boldsymbol{v}) \rangle$$
$$+ \langle \boldsymbol{v} \times (\boldsymbol{\nabla} \times \boldsymbol{v}_0) + (\boldsymbol{\nabla} \times \boldsymbol{b}_0) \times \boldsymbol{b} + (\boldsymbol{\nabla} \times \boldsymbol{b}) \times \boldsymbol{b}_0 \rangle$$
$$- \langle \boldsymbol{\nabla}(\boldsymbol{v}_0 \cdot \boldsymbol{v}) \rangle - \boldsymbol{\nabla} \left(p + \frac{\boldsymbol{U}^2}{2} \right) \tag{8}$$

$$\frac{\partial \boldsymbol{H}}{\partial t} = \boldsymbol{\nabla} \times \langle [\boldsymbol{v}_e \times \boldsymbol{b}_0] + \boldsymbol{v}_{e0} \times \boldsymbol{b} \rangle + \boldsymbol{\nabla} \times [(\boldsymbol{U} - \boldsymbol{\nabla} \times \boldsymbol{H}) \times \boldsymbol{H}] \tag{9}$$

where the blue terms are nonlinear – and the ensemble averages of the black terms have to be found after solving for $\boldsymbol{v}$ and $\boldsymbol{b}$.

Equations for the microfields

The evolution of the short scale fields $\boldsymbol{v}$ and $\boldsymbol{b}$ follows:

$$\frac{\partial \boldsymbol{v}}{\partial t} = -(\boldsymbol{U} \cdot \boldsymbol{\nabla})\boldsymbol{v}_0 + (\boldsymbol{H} \cdot \boldsymbol{\nabla})\boldsymbol{b}_0 \tag{10}$$

$$\frac{\partial \boldsymbol{b}}{\partial t} = (\boldsymbol{H} \cdot \boldsymbol{\nabla})\boldsymbol{v}_{e0} - (\boldsymbol{U} \cdot \boldsymbol{\nabla})\boldsymbol{b}_0 \tag{11}$$

Since one can, in principle, solve the above set for $\boldsymbol{v}$ and $\boldsymbol{b}$ in terms of $\boldsymbol{U}$ and $\boldsymbol{H}$, one can go back to (8-9) and have a closed set of equations for the macroscopic fields.

This closure model of the Hall MHD equations is rather general – two essential features :
1) a closure of full set of equations – feedback of the micro-scale is consistently included in the evolution of $\boldsymbol{H}$, $\boldsymbol{U}$.
2) role of the Hall current (especially in the dynamics of the micro–scale) is properly accounted.

Short Scale Initial Fields

The model calculation is best done by assuming that the original equilibrium is predominantly short-scale. Thus from the ***D*B** fields we keep only the λ part. Following relations, then, follow:

$$\boldsymbol{v}_0 = \boldsymbol{b}_0 \left(\lambda + a^{-1}\right) \tag{12}$$

leading to

$$\boldsymbol{v}_{e0} = \boldsymbol{v}_0 - \boldsymbol{\nabla} \times \boldsymbol{b}_0 = \boldsymbol{b}_0 \; a^{-1} \tag{13}$$

yielding the system:

$$\dot{\boldsymbol{b}} = \left(a^{-1}\boldsymbol{H} - \boldsymbol{U}\right) \cdot \boldsymbol{\nabla} \boldsymbol{b}_0 \tag{14}$$

and

$$\dot{\boldsymbol{v}} = \left(\boldsymbol{H} - \left(\lambda + a^{-1}\right) \boldsymbol{U}\right) \cdot \boldsymbol{\nabla} \boldsymbol{b}_0. \tag{15}$$

Substituting (12-15) in (8-9) and carrying out appropriate averages over the short scale ambient fields (all expressed in terms $\boldsymbol{b}_0$) will give us the time behavior of the macro fields $\boldsymbol{U}$ and $\boldsymbol{H}$.

Macro-field Evolution

Before averaging over the short scale, the macro-field equations are:

$$\ddot{\boldsymbol{H}} = \boldsymbol{N}_1 + \boldsymbol{\nabla} \times \left[\left(1 - \frac{\lambda}{a} - \frac{1}{a^2} \right) (H \cdot \boldsymbol{\nabla} \boldsymbol{b}_0) \times \boldsymbol{b}_0 \right], \tag{16}$$

$$\begin{aligned} \ddot{\boldsymbol{U}} &= \boldsymbol{N}_2 + \left(\lambda + \frac{1}{a} \right) \boldsymbol{\lambda} \dot{\boldsymbol{v}} - (\boldsymbol{\nabla} \times \dot{\boldsymbol{v}}) \times \boldsymbol{b}_0 \\ &\quad + (\boldsymbol{\nabla} \times \dot{\boldsymbol{b}} - \lambda \dot{\boldsymbol{b}}) \times \boldsymbol{b}_0 - \left(\lambda + \frac{1}{a} \right) \boldsymbol{\nabla} (\boldsymbol{b}_0 \cdot \dot{\boldsymbol{v}}). \end{aligned} \tag{17}$$

where $\boldsymbol{N}_1$ and $\boldsymbol{N}_2$ are the time derivatives of the nonlinear terms displayed earlier – they will not change on short-scale averaging.

Micro-averaged Evolution

Spatial averages with isotropic ABC flow

$$
\begin{aligned}
b_{0x} &= \frac{b_0}{\sqrt{3}}\left[\sin\lambda y + \cos\lambda z\right] \\
b_{0y} &= \frac{b_0}{\sqrt{3}}\left[\sin\lambda z + \cos\lambda x\right] \\
b_{0z} &= \frac{b_0}{\sqrt{3}}\left[\sin\lambda x + \cos\lambda y\right].
\end{aligned}
$$

yield:

$$
\ddot{U} = bN_1 + \frac{\lambda}{2}\frac{b_0^2}{3}\boldsymbol{\nabla}\times\left[\left(\left(\lambda + \frac{1}{a}\right)^2\right)\boldsymbol{U} - \lambda\boldsymbol{H}\right] \tag{18}
$$

$$
\ddot{H} = bN_2 - \lambda\frac{b_0^2}{3}\left(1 - \frac{\lambda}{a} - \frac{1}{a^2}\right)\boldsymbol{\nabla}\times\boldsymbol{H}. \tag{19}
$$

b_0^2 – **the ambient micro scale energy**. ***H*** **evolves independently of *U* but evolution of *U* does require knowledge of *H*.**

A Nonlinear Solution in Linear Clothing

We now work out a solution obtained by neglecting the nonlinear terms. Writing (18) and (19) formally as

$$\ddot{\boldsymbol{H}} = -r(\lambda)(\boldsymbol{\nabla} \times \boldsymbol{H}), \qquad \ddot{\boldsymbol{U}} = \boldsymbol{\nabla} \times [s(\lambda)\boldsymbol{U} + q(\lambda)\boldsymbol{H}], \tag{20}$$

and Fourier analyzing

$$-\omega^2 \boldsymbol{H} = -i\, r\, (\boldsymbol{k} \times \boldsymbol{H}), \qquad -\omega^2 \boldsymbol{U} = -i\, k\, \times (s\boldsymbol{U} + q\boldsymbol{H}), \tag{21}$$

we find the **growth rate** at which $\boldsymbol{H}$ and $\boldsymbol{U}$ increase,

$$\omega^4 = r^2 k^2 \qquad \omega^2 = -|r|(k). \tag{22}$$

The growing Macro-fields are related as

$$\boldsymbol{U} = \frac{q}{(s+r)} \boldsymbol{H}. \tag{23}$$

A Nonlinear Solution in Linear Clothing

The linear solution has a few remarkable features:

Since a choice of a, d (and hence of λ) fixes relative amounts of microscopic energy in ambient fields, it also fixes the relative amount of energy in **the nascent macroscopic fields *U* and *H*.**

The linear solution makes nonlinear terms strictly zero – it is an exact (a special class) solution of the nonlinear system and thus remains valid even as *U* and *H* grow to larger amplitudes

(This behavior appears again and again in Alfvenic systems: MHD - nonlinear Alfvén wave: Walen 1944,1945; in HMHD - Mahajan & Krishan, MNRAS 2005).

Analytical Results — An Almost straight dynamo

Explicit connections for mix in the ambient turbulence to the mix in the macro fields.:
(i) $a \sim d \gg 1$, inverse micro scale $\lambda \sim a \gg 1 \Longrightarrow \boldsymbol{v}_0 \sim a\, \boldsymbol{b}_0 \gg \boldsymbol{b}_0$ i.e, the ambient micro-scales fields are primarily kinetic. The Generated macro-fields have opposite ordering, $\boldsymbol{U} \sim a^{-1}\boldsymbol{H} \ll \boldsymbol{H}$.

An example of the straight **dynamo mechanism** – super-Alfvénic "turbulent flows" generate magnetic energy far in excess of kinetic energy – super-Alfvénic "turbulent flows" lead to steady flows that are equally sub–Alfvénic.

Important: the dynamo effect must always be accompanied by the generation of macro-scale plasma flows.

This realization can have serious consequences for defining the initial setup for the later dynamics in the stellar atmosphere. The presence of an initial macro-scale velocity field during the flux emergence processes is, for instance, always guaranteed by the mechanism exposed above.

Analytical Results — An Almost Reverse dynamo

(ii) $a \sim d \ll 1$ the inverse micro scale $\lambda \sim a - a^{-1} \gg 1 \Longrightarrow$ $\boldsymbol{v}_0 \sim a\,\boldsymbol{b}_0 \ll \boldsymbol{b}_0$. **The ambient energy is mostly magnetic.** (Photospheres/chromospheres)

Micro-scale magnetically dominant initial system creates macro-scale fields $\boldsymbol{U} \sim a^{-1}\boldsymbol{H} \gg \boldsymbol{H}$ that are kinetically abundant.

From a strongly sub-Alfvénic turbulent flow, the system generates a strongly super-Alfvénic macro–scale flow [**reverse dynamo**]

Initial Dominance of fluctuating/turbulent magnetic field + magneto-fluid coupling = efficient/significant acceleration. Part of the magnetic energy will be transferred to steady plasma flows – a steady super–Alfvénic flow; a macro flow accompanied by a weak magnetic field.

RD → observations: fast flows are found in weak field regions.

(Woo et al, ApJ, 2004).

D, RD Summary:

- Dynamo and "Reverse Dynamo" mechanisms have the same origin – are manifestation of the magneto-fluid coupling;

- $\boldsymbol{U}$ and $\boldsymbol{H}$ are generated simultaneously and proportionately.

  Greater the macro-scale magnetic field (generated locally), greater the macro-scale velocity field (generated locally);

- **Growth rate of macro-fields** is defined by DB parameters (by the ambient magnetic and generalized helicities) and **scales directly with ambient turbulent energy** $\sim b_0^2\ (v_0^2)$.

  Larger the initial turbulent magnetic energy, the stronger the acceleration of the flow.

  Impacts: on the evolution of large-scale magnetic fields and their opening up with respect to fast particle escape from stellar coronae; on the dynamical and continuous kinetic energy supply of plasma flows observed in astrophysical systems.

  Initial and final states have finite heliciies (magnetic and kinetic). The helicity densities are dynamical parameters that evolve self-consistently during the flow acceleration.

A simulation Example for Dynamical Acceleration

2.5D numerical simulation of the general two-fluid equations in Cartesian Geometry.

Code: Mahajan et al. PoP 2001, Mahajan et al, ApJ 2005, Mahajan et al, PoP 2006

Simulation system contains:

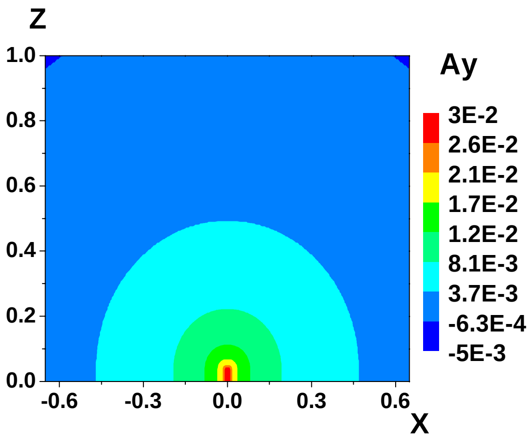
- an ambient macroscopic field
- effects not included in the analysis:
    1. dissipation and heat flux; radiative cooling;
    2. plasma is compressible embedded in a gravitational field $\rightarrow$ extra possibility for micro-scale structure creation (see Mahajan et al, PoP 2006).

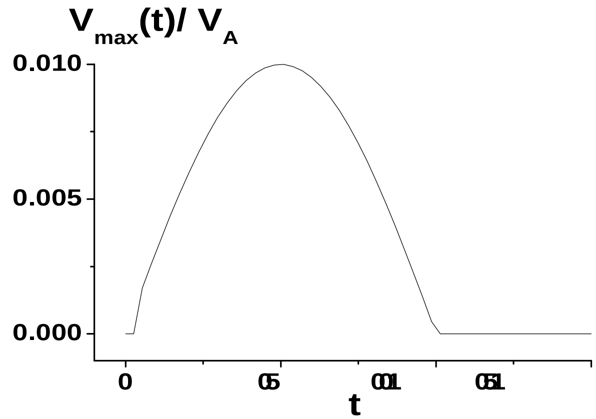
Transport coefficients are taken from Braginskii and are local.

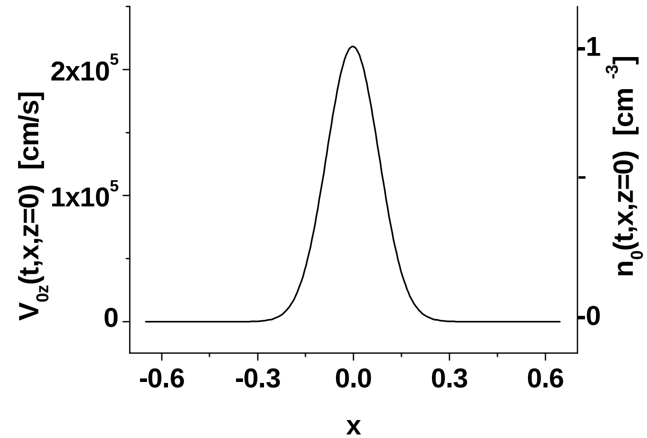
Diffusion time of magnetic field > duration of interaction process (would require $T \leq$ a few eV-s).

Trapping and amplification of a weak flow impinging on a single closed-line structure.

Initial characteristics of magnetic field and flow







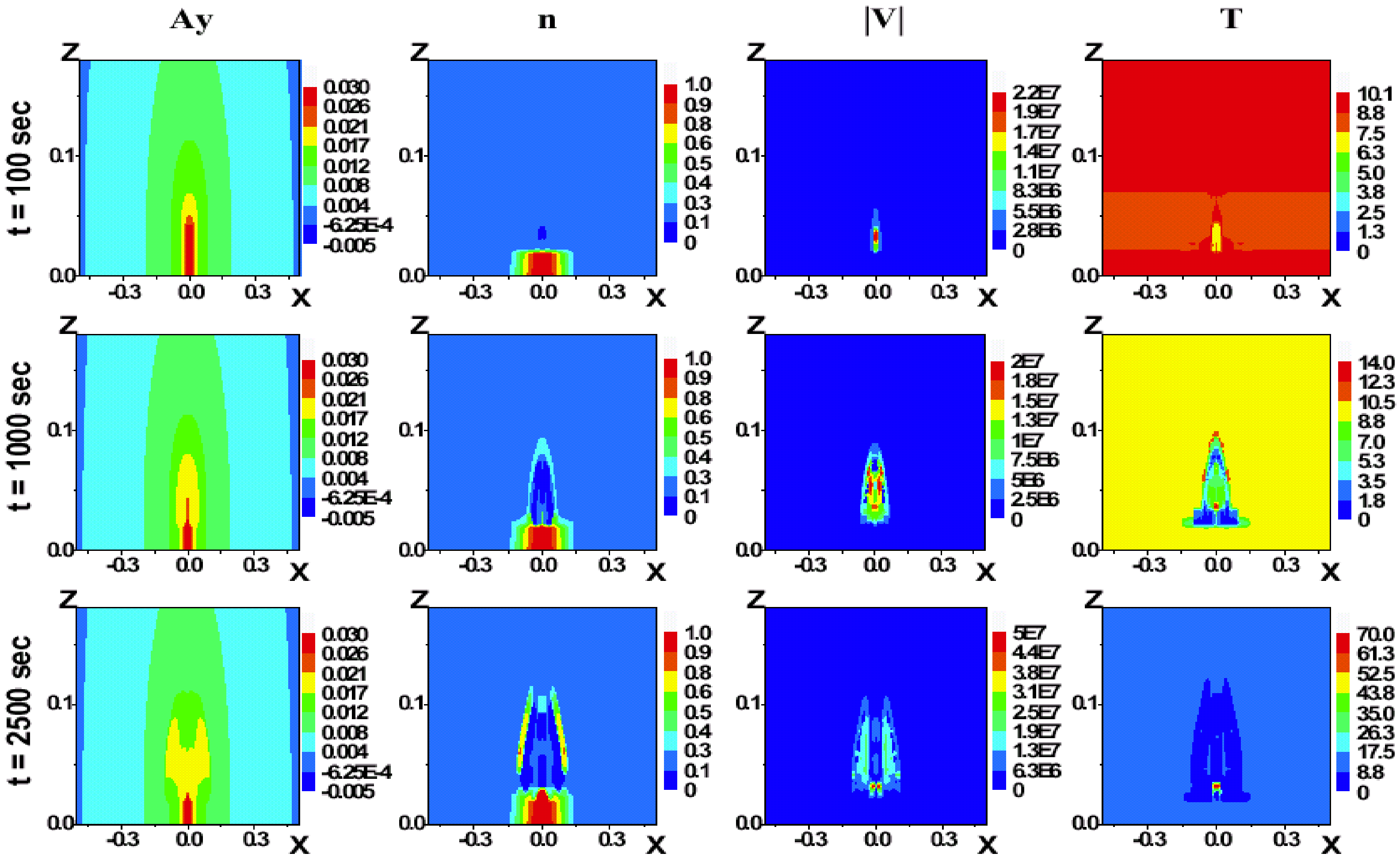
$\mathbf{B} = \nabla \times \mathbf{A} + B_z \hat{\mathbf{z}}$ $\mathbf{A}(0; A_y; 0)$; $\mathbf{b}=\mathbf{B}/B_{0z}$; $b_x(t, x, z \neq 0) \neq 0$ B_{0z}=100G - uniform it time.

Weak symmetric up-flow (pulse-like): **$|V|_{0max} << C_{s0}$**   **C_{s0} - initial sound speed; time duration - t_0=100s**

Initially Gaussian; peak is located in the central region of a single closed magnetic field structure.

Initial flow parameters: **$V_{0max}(x_o, z=0)=V_{0z}=2.18 \bullet 10^5$cm/s;**   **$n_{0max}=10^{12}$cm^{-3}; $T(x,z=0)$=const=T_0 =10eV**

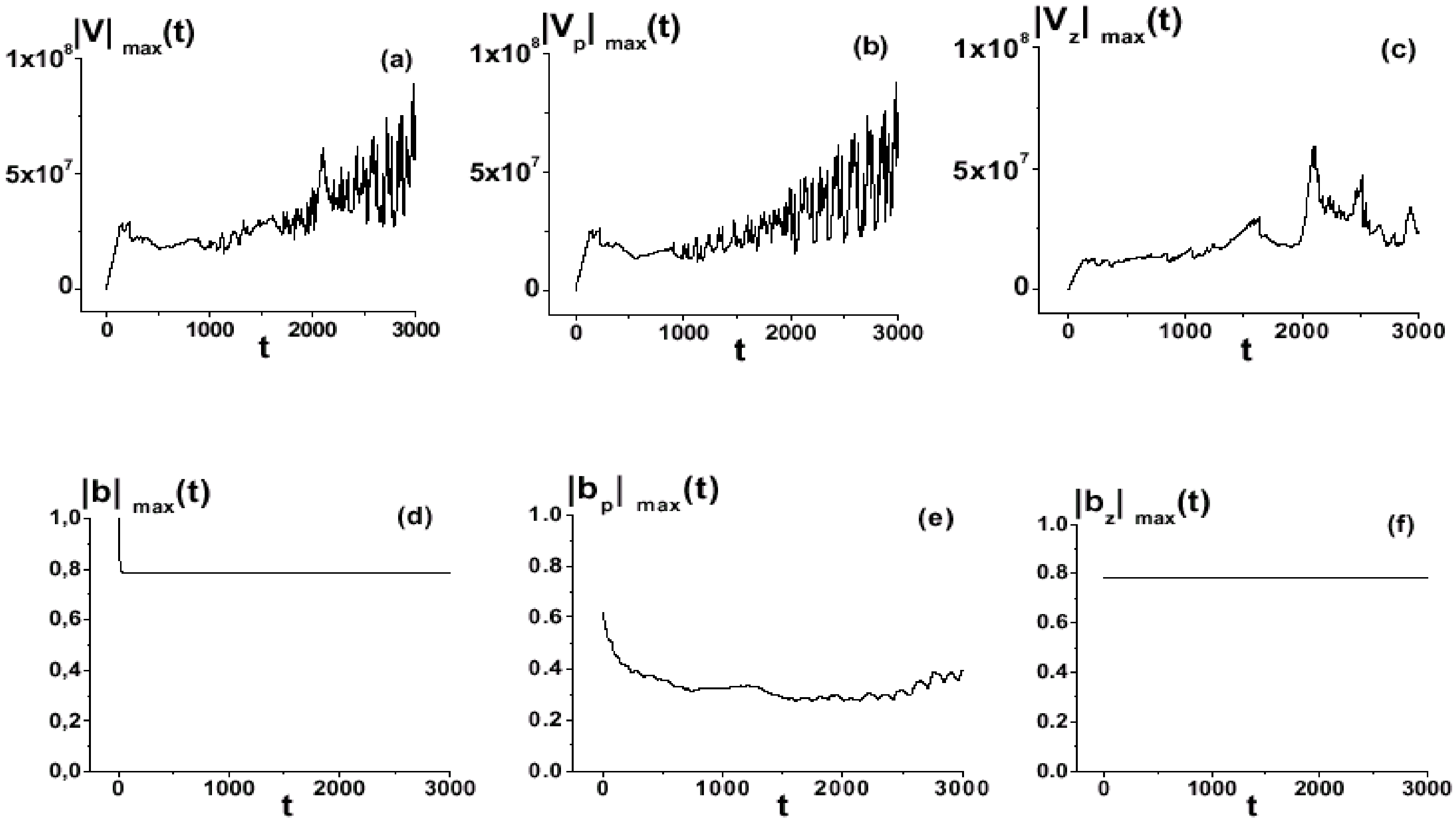
Acceleration of plasma flow due to Magneto-fluid coupling - RD



- Acceleration is significant in the vicinity of magnetic field-maximum with strong deformation of field lines + energy re-distribution due to MFC+dissipation
- A part of flow is trapped in the maximum field localization area, accumulated, cooled and accelerated. The accelerated flow reaches speeds greater than 100km/s in less than 100s
- Accelerated flow follows to the maximum magnetic field localization areas - RD

Then the flow passes through a series of quasi-equilibria. In this relatively extended era ~1000s of stochastic/oscillating acceleration, the intermittent flows continuously acquire energy $\rightarrow$ bifurcation

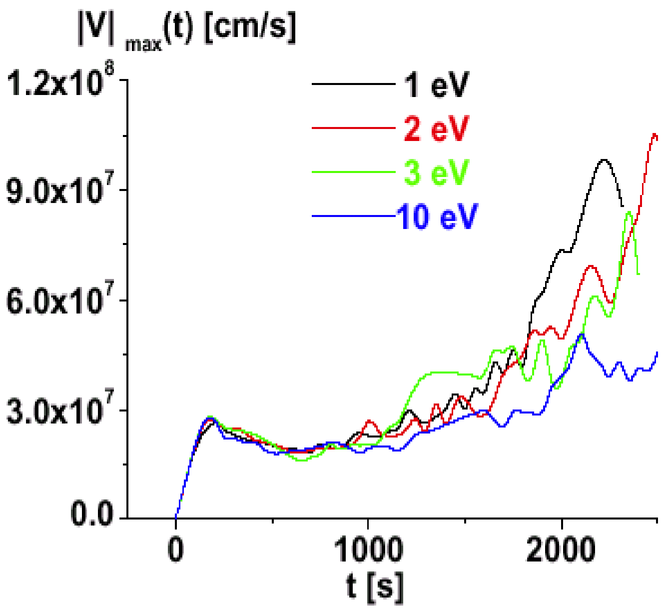
Flow starts to accelerate again - acceleration highest in strong field regions (newly generated!)

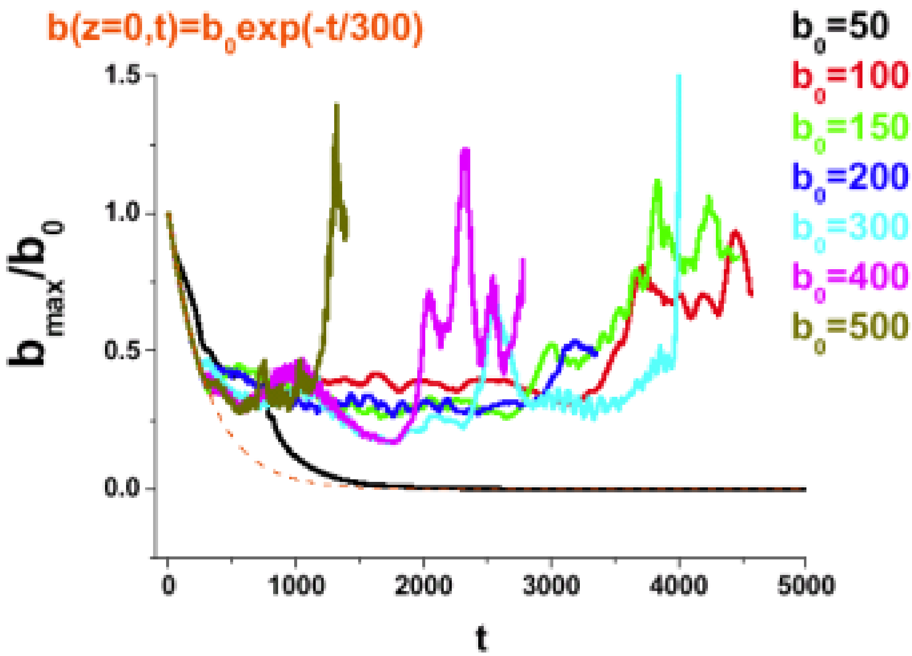


Initial stage of acceleration: macroscopic magnetic energy $\rightarrow$ macroscopic flow energy

Second stage of acceleration after the quasi-equilibrium: microscopic magnetic energy is converted to macroscopic flow energy

Acceleration of flows for different initial parameters
Robustness of the results





Acceleration of flow for different initial temperatures for a given B_0 magnetic field closed structure – Controlling effect of T_0 and B_0

Several distinct phases of acceleration process are observed

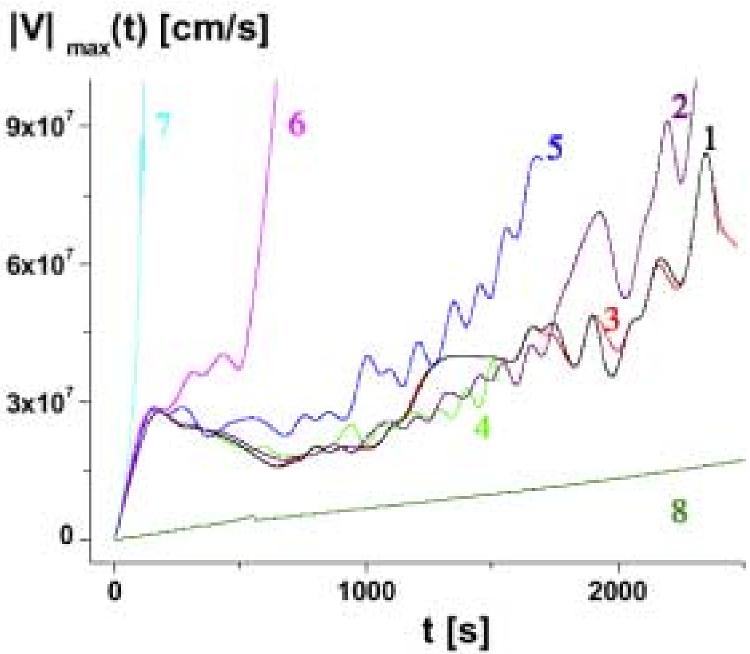
Acceleration of flow for different initial magnetic field structures for a given T_0 initial flow – Controlling effect of T_0 and B_0

Dynamo and Reverse Dynamo effects are clearly distinguished

Larger the b_0 earlier the blow-up starts

Larger the b_0 faster the initial acceleration

Importance of Hall-Effect



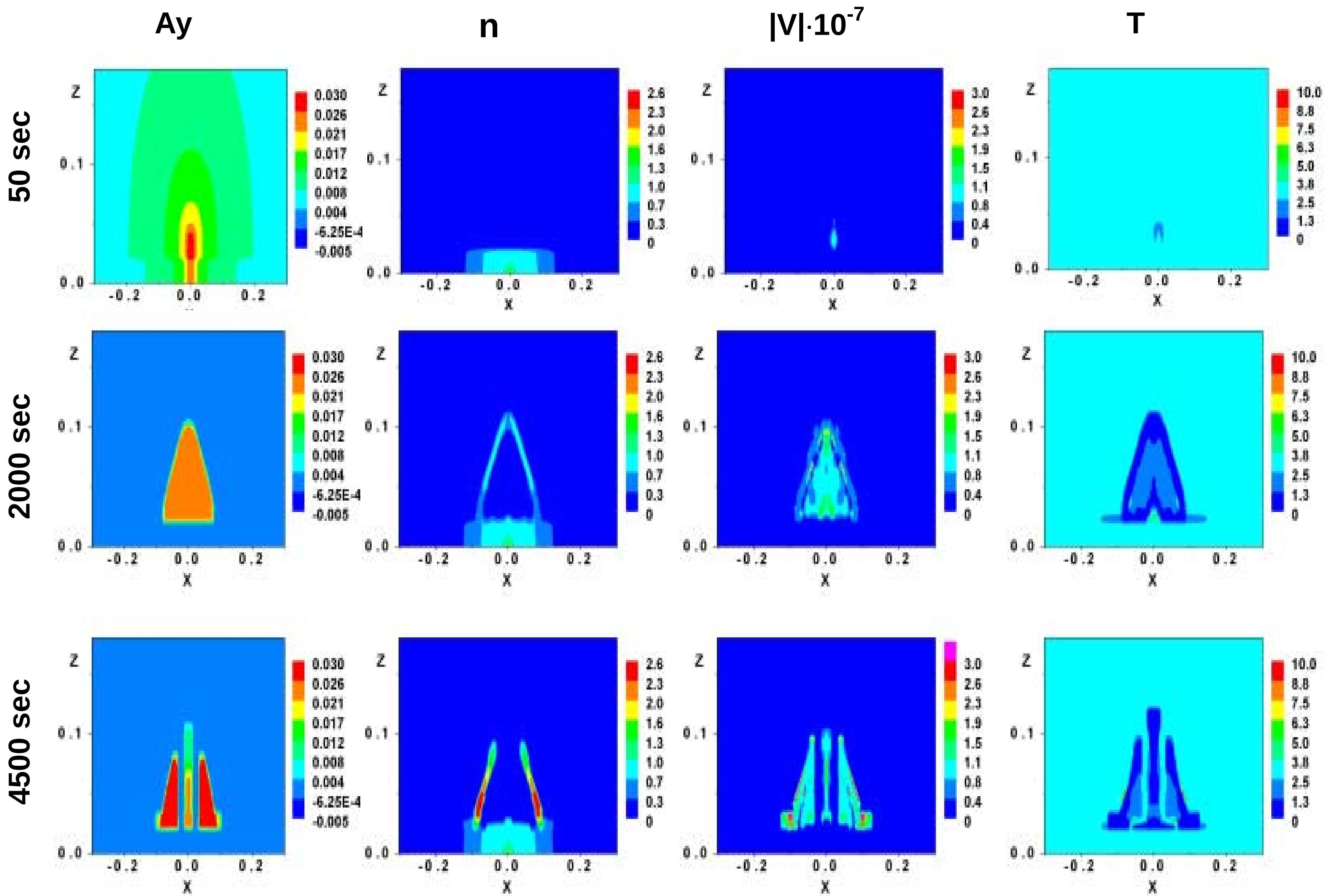
Time evolution of $V_{max}(t)$ for different α_0 values

Curves: 1, 2, 3, 4, 5, 6, 7 -
[α_0 = $3.27 \cdot 10^{-10}$ (realistic); 0 (dissipation is ignored); 10^{-5}; 10^{-4}; 10^{-3}; $2 \cdot 10^{-3}$; $5 \cdot 10^{-3}$; Respectively] – two-fluid effects are ignored in all equations except the equation of motion where the contribution of Hall term is taken into account

Curve 8 - the Hall term is ignored along with other two-fluid effects

- **Ignoring the Hall term contributions makes the quasi-equilibrium stage disappear**
- **Larger the Hall parameter, the shorter the duration of quasi-equilibrium stage; the faster the second acceleration phase ending up with higher velocities**
- **for large Hall parameter the blow-up starts very soon, already in the initial stage of acceleration**
- **The value of α_0 is specifically important for the second acceleration phase (Reverse Dynamo)**

Acceleration of plasma flow interacting with the dynamical closed field structure – R & RD



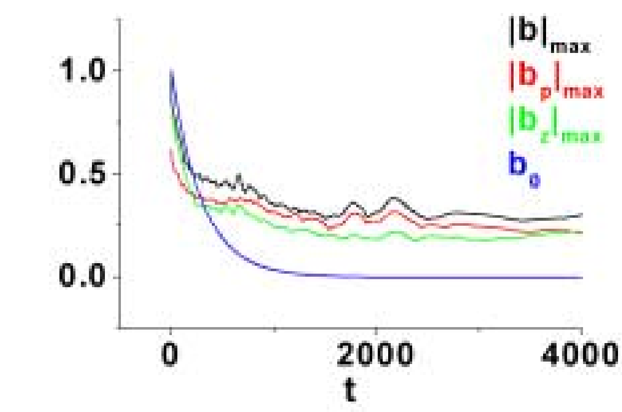
R & RD phenomena are observed first in the newly generated magnetic field localization areas

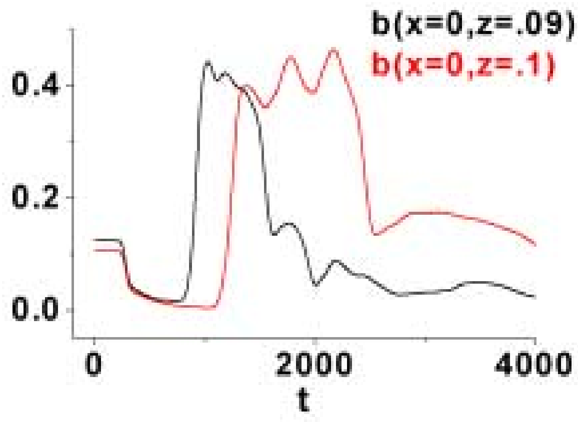
The similar process later starts in the center of the original arcade where the accelerated flow is pushed up significantly

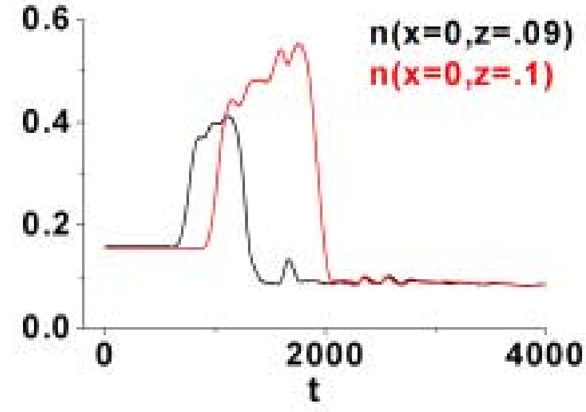
Dynamo and Reverse Dynamo – Acceleration of plasma flows

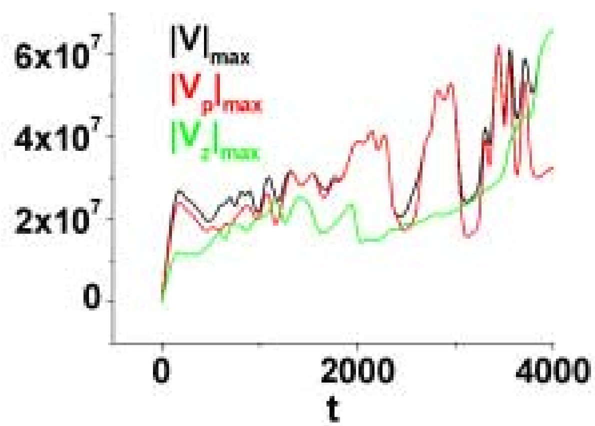
$b_0(t,z=0)=b_0\exp(-t/300)$ (b_0=100G) $V_z(z=0)=V_0\sin(\pi t/100+\pi/36)$ ($V_0=2{,}18\times10^5$cm/s)

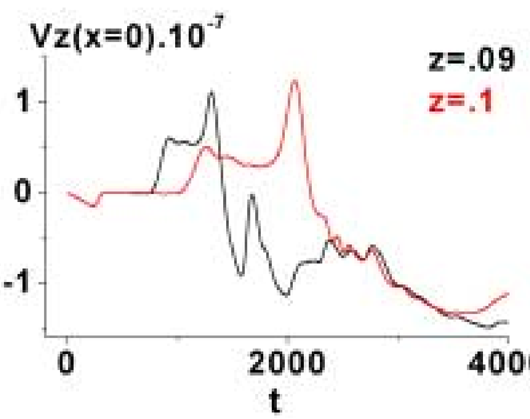
T_0=3eV ; $n_0=10^{12}\text{cm}^{-3}$; $n_{bg}=0.1n_0$

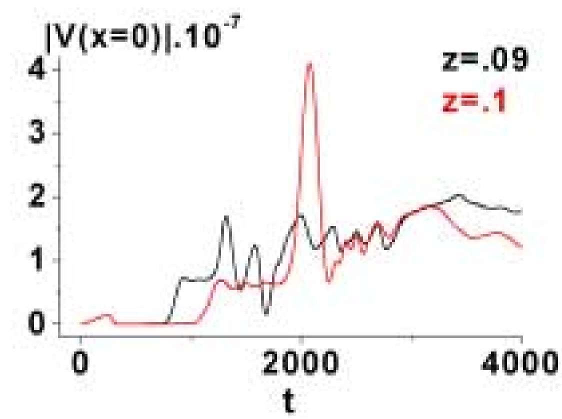










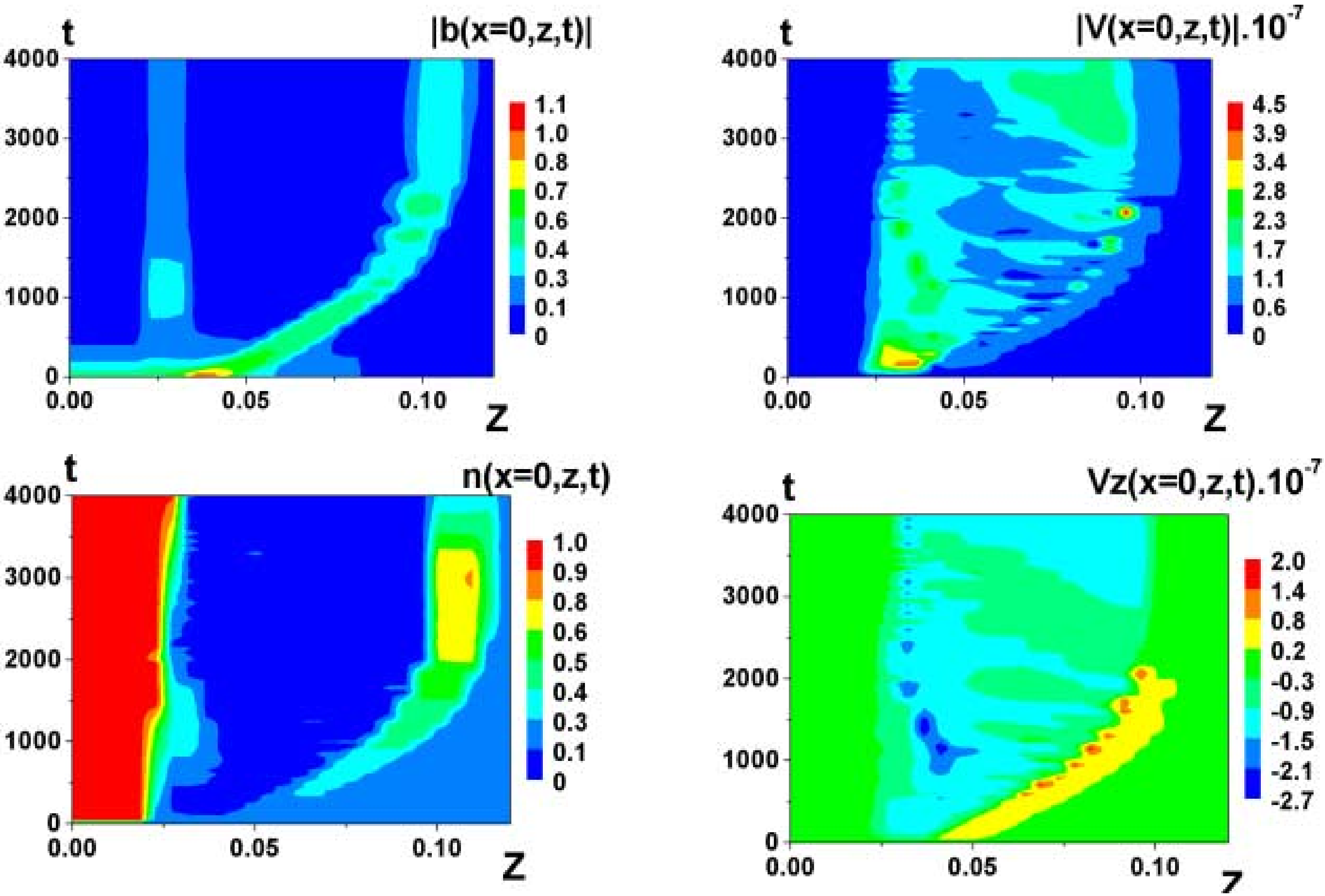


Combined effects of D and RD Phenomena
Quasi-equilibrium is reached for accelerated flow trapped in newly generated magnetic field structure

D and RD phenomena in the center of the original closed field structure
Flow is pushed up. The accelerated flow moves to upper heights with time with practically the same radial speed ~100km/s

Effects of incompressibility on the D and RD phenomena in the center of the original closed field structure
Location of significant flow generation coincides with the location of sharp drop in density

Dynamo and Reverce Dynamo Phenomena
In the center of the original closed magnetic field structure



Dynamical Emergence of the new magnetic field in region different from original; flux moves to the upper heights with time!

Accelerated flow follows the maximum field localization area – RD!   D & RD phenomena have oscillating/pulsating character.

Generated field maximum ~0.5b_0 ; accelerated flow max. radial speed ~200km/s ; at ~2000sec time flow converts to down-flow!

Non–uniform density case

Closed HMHD system of equilibrium equations ($g(r) = r_{c0}/r$) $\Longrightarrow$

$$\frac{\alpha_0^2}{n}\nabla \times \nabla \times \mathbf{V} + \alpha_0\, \nabla \times \left[\left(\frac{1}{a\, n} - d\right) n\,\mathbf{V}\right] + \left(1 - \frac{d}{a}\right)\mathbf{V} = 0, \quad (24)$$

$$n = \exp\left(-\left[2g_0 - \frac{V_0^2}{2\beta_0} - 2g + \frac{V^2}{2\beta_0}\right]\right), \quad (25)$$

1D simulation - a variety of boundary conditions: Mahajan et al. ApJL 2002
for small α_0 there exists some height where **the density begins to drop precipitously with a corresponding sharp rise in the flow speed**.

Velocity blow-up distance depends mainly on β_0

Flow with $3.3\,\mathrm{km/s}$ ends up with $\sim 100\,\mathrm{km/s}$ at $(Z - Z_0) \sim 0.09\, R_0$.

If density fall is at a much slower rate than the slow scale and $n \gg (a\,d)^{-1}$ the straightforward algebra for 1D problem gives:

$$|V_{max}| = \frac{1}{d\,n_{min}} \tag{26}$$

Principal results:

- the transverse components of the magnetic field vary keeping $b_x^2 + b_y^2 = b_{0\perp}^2 = const.$
- The density and the velocity fields are related approximately by $|V|^2 = 1/d^2 n^2$ so that the magnetic energy does not change much, $|\mathbf{b}|^2 = const$ to leading order.
- The Bernoulli condition transforms to the defining differential equation for density which has to be larger than $n_{min} = (2\beta_0)^{-1/2} d^{-1}$.

Note: Similar results are obtained for $a \sim d \ll 1$ when the inverse micro scale $\sim a - a^{-1} \gg 1$ with $dn - a \ll 1$; and also when we assume an equation of state and temperature is allowed to vary.

Summing up:

- Dissipation present: Hall term ($\sim \alpha_0$) (through the mediation of micro-scale physics) plays a crucial role in acceleration/heating processes

- Initial fast acceleration in the region of maximum original magnetic field + the creation of new areas of macro-scale magnetic field localization with simultaneous transfer of the micro-scale magnetic energy to flow kinetic energy = manifestations of the **combined effects of the D and RD phenomena**

- Continuous energy supply from fluctuations (dissipative, Hall, vorticity) → maintenance of quasi-steady flows for significant period

- Simulation: **actual h_1, h_2 are dynamical**. Even if they are not in the required range initially, their evolution could bring them in the range where they could satisfy conditions needed to efficiently generate flows → **several phases of acceleration**