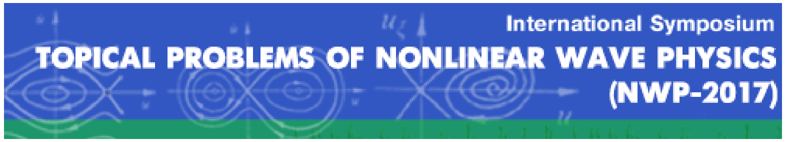
Vladimir M. Gubchenko
Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, RUSSIA (ua3thw@appl.sci-nnov.ru)



ON KINETIC APPROACH TO MAGNETIC RECONNECTION: FROM SPACE TO LASER HED PLASMA

"μicroMEGAS"

The "LaB" workshop series aims at bringing together, in a transdisciplinary forum, scientists interested in the emerging areas of coupling laboratory high-energy-density (HED) plasmas and external and internal intense magnetic fields in varied domains, including plasma astrophysics, inertial fusion, and particle acceleration. Magnetic fields have been widely recognized to haveprofound effects in these areas, but specific progress is hindered by limited theoretical understanding and diagnostics capabilities. The main aim of such a forum is to serve as an exchange of ideas, discussion of theoretical and experimental work that has been done, and to explore potential new collaborations in these critical areas

International Symposium
(NWP-2017)
NONLINEAR WAVE PHYSICS
TOPICAL PROBLEMS OF
Moscow – St.Petersburg, Russia
22-28 July, 2017

Workshop "Magnetic Fields in Laboratory High Energy Density Plasmas (LaB)"

July 27, 2017

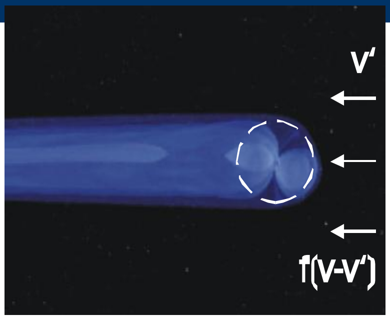
Methods of magnetic fields and eddy currents description in Space and HED plasma. Evolution of methods in time/spatial history with laser power growth and time/spatia resolution by space probes. Evolution from the MHD fluid approach to the Vlasov/Maxwell kinetic approach with separation of the electrons and ions PDFs. Real Kinetics as different respond of the "resonant" and "nonresonant" particles groups in the velocity phase space – consideration of nonmaxwellian (kappa, core, halo, holes in phase space, beams, asymmetry - flows, anisotropy as temperature, currents, interpenetration, etc) shapes of the electrons and ions PDFs.

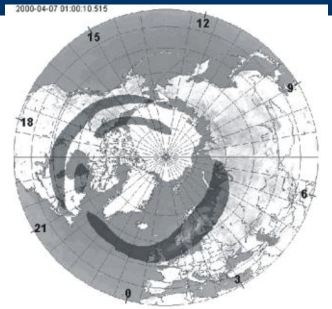
- Ideal cold-warm MHD.
- Nonideal and Quasi MHD (Bierman, Nerst, Ohms, terms … two fluid, etc).
- Hall MHD, "MLM" methods for injection by the VNIIEF.
- Ideal Electron MHD with pressure anisotropy tensor – MHD and ideal Weibel limits by FIAN.
- MHD/EM large scale fields where test electrons and ions particles are moving providing high energy part of the PDF (not selfconsistent with MHD fields) – the LSK for space plasma and overcritical plasma regimes of the particle motions in the EM laser fields.
- 3D EM PIC as selfconsistent method based on Debye, e.m. inertial skin, giroradius as the grid estimations numerical box scalings. No application of the e.m. additional large dispersion scales of the hot dynamical (assymetry, anisotropy of the PDF) hot plasma.
- Vlasov/Maxwell with the PDF (particle distribution function) shape of electrons consideration (PDF anisotropy and asymmetry). Resonant and nonresonant electrons in hot collisionless plasma with the additional e.m. scales in hot flow regimes (flow velocity can be supersonic but less then thermal velocity of electrons). Kinetic Vlasov Weibel limits.

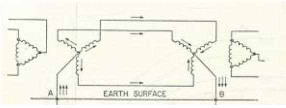
Vlasov/Maxwell hot plasma kinetics. Shape of the electrons PDF - anisotropy and asymmetry. Resonant and nonresonant electrons. From liner 3D to nonliner 1D problems - analytical solutions.

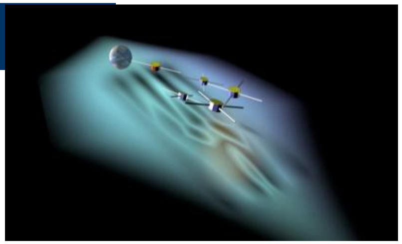
- 0D. Introduction. Homogenous hot collisionless plasma. PDF anisotropy and asymmetry. Eddy modes and dispersion curves. Overcritical and subcritical regimes: out and inside plasma resonance lines – the kinetic regime. Diamagnetism-paramagnetism, “ferromagnetism” of hot dynamical plasma. Nonconductivity and superconductivity. Weibel and e.m. plasma scales of the anisotropic asymmetric hot plasma. Electromagnetic dimensionless parameters of the hot plasma flow related with shape of the PDF. Nonmagnetized and magnetized plasma from Cherenkov to ion/electron cyclotron magnetic reconnection.
- 3D. Liner approach. Interaction of plasma flow with prescribed magnetodipole/toroid magnetization. 3d magnetosphere like structure. Magnetotail-magnetic reconnection and dipolization –no reconnection . Electronic diffusion region (DR) – asymmetric magnetic reconnection du-to plasma flow.. Forced and forceless configurations provided by combination of magnetodipole and toroidal components. RCL parameters, Drag force and power. Plasma ambipolar and e.m. expansion as the active RCL circuit with the e.m.f (electromotive force) and internal quasistationary dynamics og the magnetic configurations (see http://www.vniitf.ru/images/zst/2012/s3/3-13.pdf).
- 2D. Diamagnetic or resistive 1D nonlinear stationary (space) and nonstationary (HED) Current Sheets (CS) with anisotropy or asymmetry of plasma PDF. Additional 1D dynamics is provided by linear e.m. perturbations of the CS. Wiebel type modes providing fine structure. (see in the review)
- 1D. Nonlinear 1D Quasi-Current-Free explosive type dynamics of the Current Sheets, Z cylindrical pinch and theta pinch (see in the review) with opposite current densities from diamagnetic and accelerated particles.
- Review: V. M. Gubchenko, Geomagnetism and Aeronomy, 2015. Vol. 55, No. 7, 831-845, No. 8, 1009-1025. DOI: 10.1134/S0016793215070099, 10.1134/S0016793215080101

Stationary plasma flows of space plasma. **1. Hot collisionless electrons regimes in Sun-Earth Physics: Earth magnetosphere, separate solar streamer and streamer belt in the solar wind flow. Internal (as magnetic quasiparticle) and external magnetosphere (hot flow initiated magnetotail/steramer structure). Magnetosphere dissipative region (DR) – 3D magnetic reconnection region. Multy satellite magnetosphere probes: “Cluster”, “Themis”, “MMS” missions to DR study. Solar probes: “Stereo”, “Parker”. “Helios” ion PDF with anisotropy and asymmetry. Our reference system is moving with flow where for the magnetic field harmonics we get** $\omega = \vec{k}\vec{v}'$

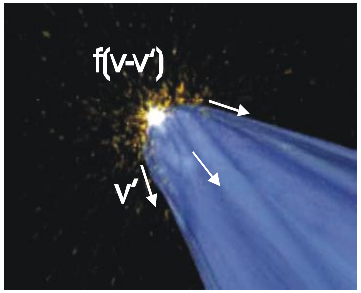


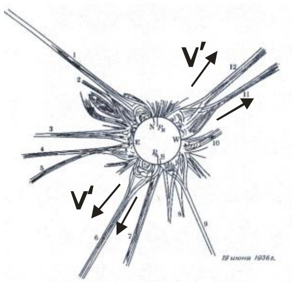


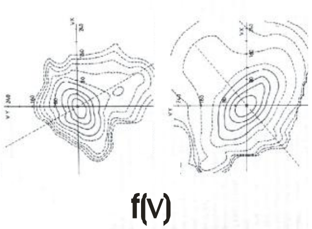




$$\kappa T_e << mc^2$$

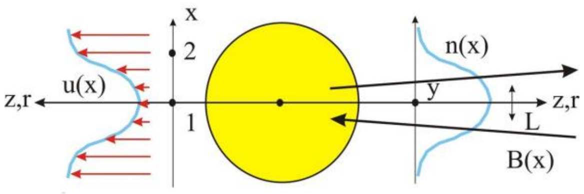


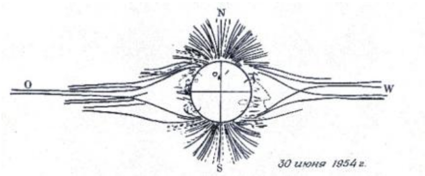


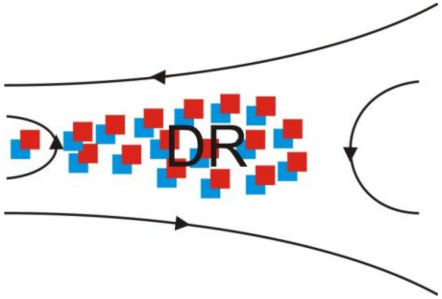


$$v_i << v' << v_e$$

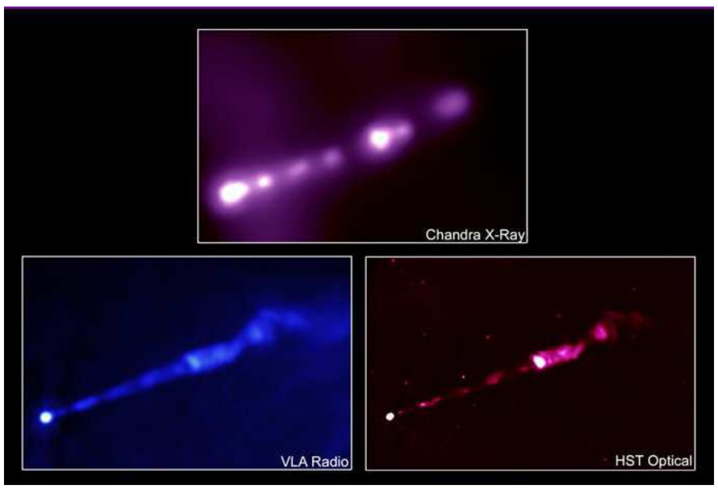
$$v' << v_i << v_e$$

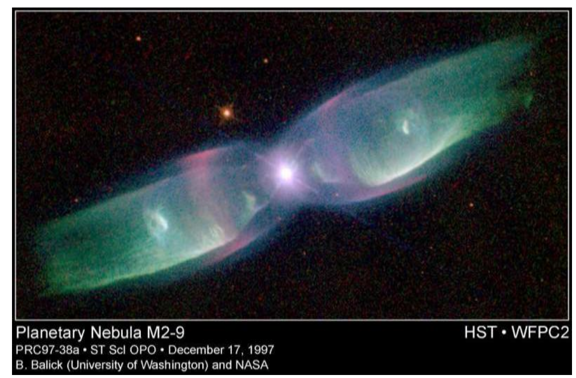






2. Jets & accretion disks as stationary relativistic plasma flows. Reference system is moving with the flow where $\omega = kc'$

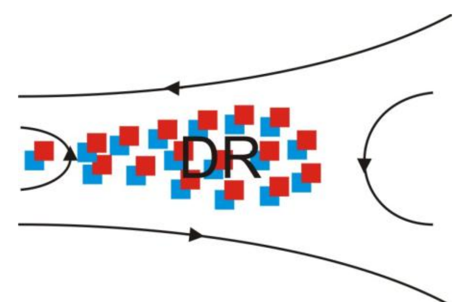




V
,

$$\kappa T_e >> mc^2$$

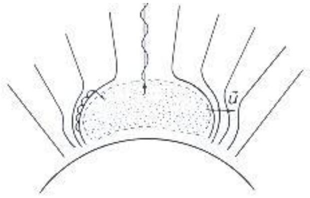
$$v' = c$$

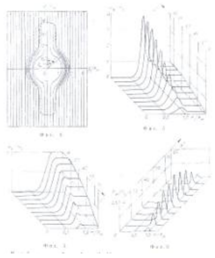


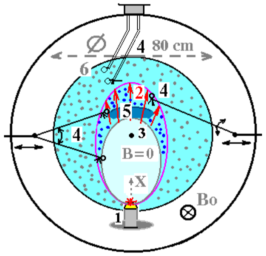
Nonstationary plasma flows. 3. Pulsed regimes (injections and explosions) with hot electrons. Injection is due to thermal (ambipolar) or magnetic pressure (Ampere forces) gradients. Limited energy and limited amount of the injected plasma flowing in the unlimited or limited in space background plasma. Magnetized and unmagnetized background plasma as magnetic trap.

$$\omega \neq \vec{k}\vec{v}'$$

- Formation of “diamagnetic” or “superconducting” hot plasma clouds at the injection point and disruption of magnetic field lines as magnetic reconnection destroying magnetic traps,
- MHD Alfvenic and magnetosonic waves out of the magnetic traps.
- Solar Flare and CME – coronal mass injections.
- Magnetosphere substorms in the electronic diffusion region.
- Current sheet, Z and theta pinch explosions and relaxations.
- Modeling of space events in the Lab plasma units.
- Magnetized and unmagnetized HED plasma (next slide).

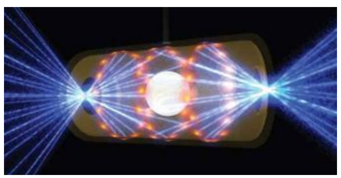


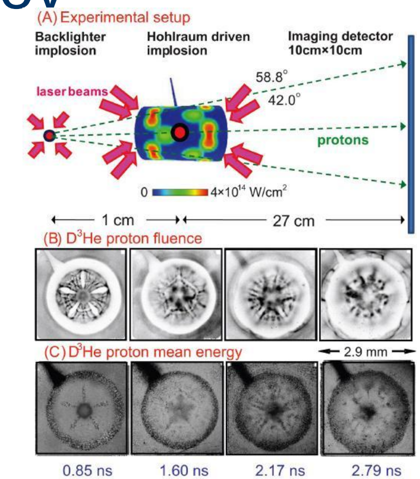


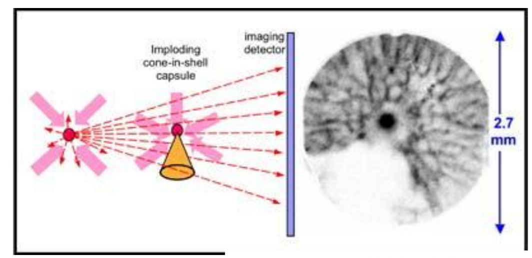


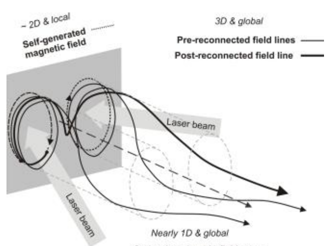
Stationary and nostationary collisionless hot electrons flow regimes. HED plasma in the nonmagnetized and magnetized targets with selfconsistent direct flow and heat flow and magnetic fields. Multy and separated DR magnetic reconnection structures restructuring spatially and in time.
Great similarity of plasma corona magnetic structures in space and HED plasmas. $\omega \neq \vec{k}\vec{v}'$

- NIF, Rochester-MIT, LULI-LMJ, Sarov









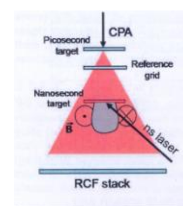
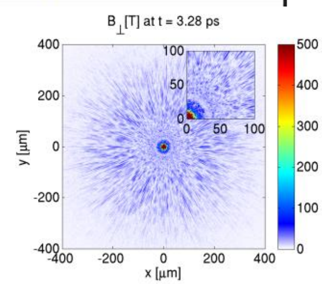
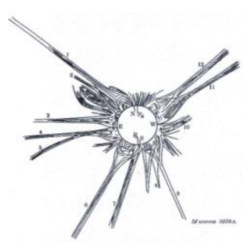
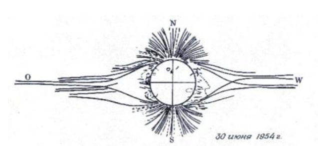
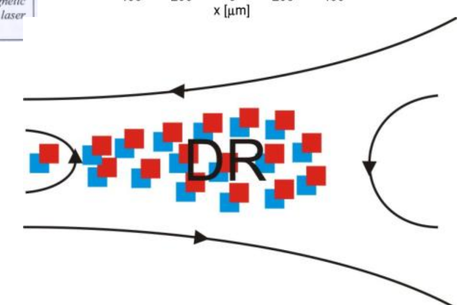


Figure 9: Principle of magnetic field probing by laser accelerated proton beam.

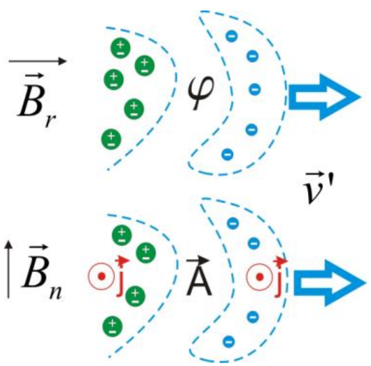


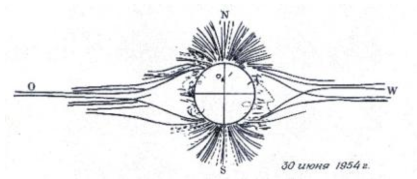


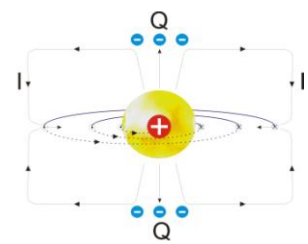


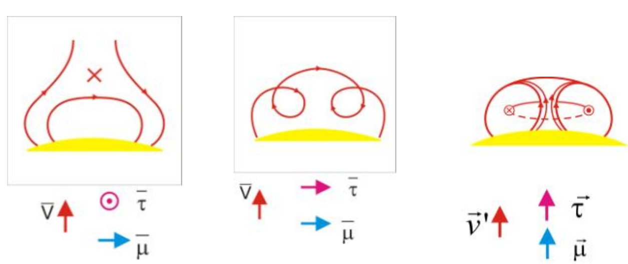


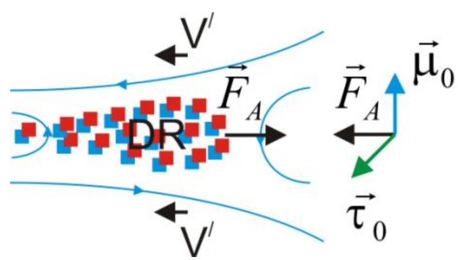
Two types of plasma expansion: plasma flows are directed along magnetic field (polar regions of the solar/laser corona) - electrostatic or directed perpendicular to magnetic field (equatorial regions and nearby polar regions of the solar/laser corona)- electromagnetic. Expansions are illustrated by eclipse corona and by the Alfven corona circuit. Perpendicular magnetic field is provided by magnetic kinematic dynamo or by Biermann battery which are forming three types of magnetoactive regions/targets (helmet and loop – space plasma, toroid – laser plasma) formed by different internal orientation of the magnetic dipole and toroid moments what provides space and laser plasma DR .

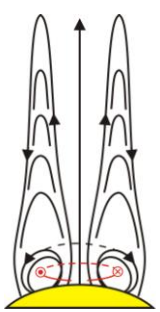




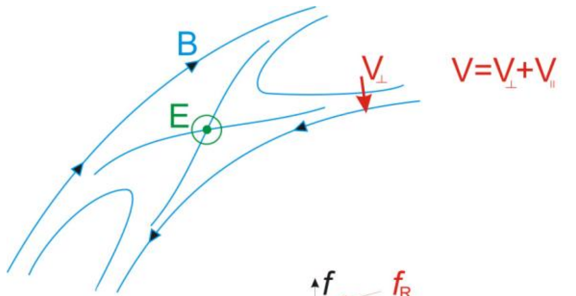


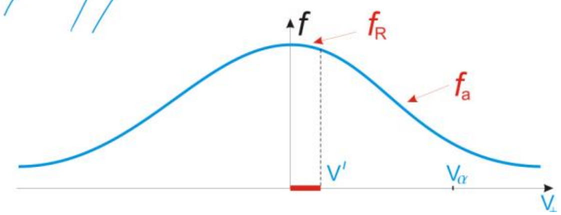


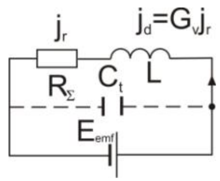




What is magnetic reconnection? **It is dissipative process which provides dissipative change of electromagnetic fields distribution: from the original "vacuum" spatial decrease to the slower - "radiation" type spatial decrease. The electromagnetic dissipation can be due to collisional conductivity, acceleration of the "resonant" particles and the losses due to direct radiation of the e.m. and MHD waves. Shape of the electron PDF is important in the space/HED collisionless plasma in the "hot regime" where we have $M_e = v'/v_e << 1$, $M_i = v'/v_i >> 1$. Here in the moving DR the e.m. dissipation and the resulting resistive currents (red) are provided by the "resonant group of accelerated electrons" under eddy electric field action . Dissipationless diamagnetic (polarization) currents (blue) are provided by the non resonant group particles moving under magnetic field action and provided sharpening original spatial decrease - dipolization. The electromagnetic "Quality parameter $G_{w,k}$ is ratio of density of diamagnetic to resistive currents. The sheme models plasma currents as plane plasma "waves".**



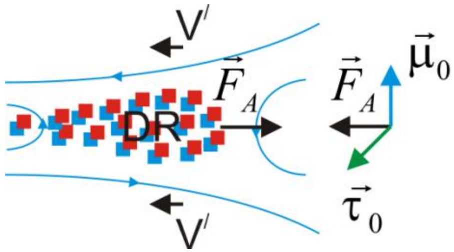




$$\mathbf{j}_{flyby}(\omega,\vec{k}) = \mathbf{j}_r + \mathbf{j}_d$$

- Slow subcritical

$\omega << \omega_{p\alpha}$



- Collisionless

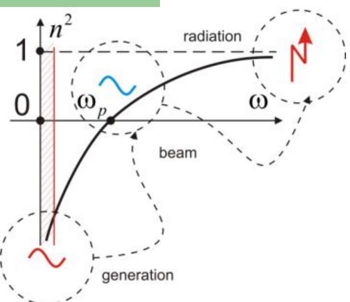
$L_{coll} >> L$

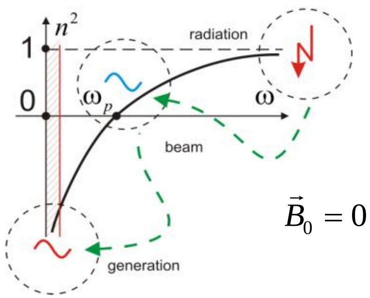
- Hot regime $v'/v_\alpha << 1$

$v' = \omega/k << v_\alpha$

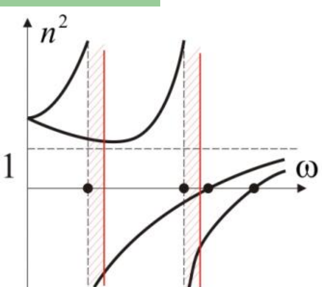
$$G_{\omega,\mathbf{k}} = \frac{j_d}{j_r} = \frac{\mathrm{Re}\,\varepsilon_t(\omega,\mathbf{k})}{\mathrm{Im}\,\varepsilon_t(\omega,\mathbf{k})}$$

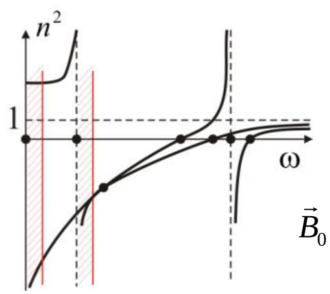
Where magnetic reconnection (electromagnetic dissipation) of the hot collisionless plasma is located on the "cold" ideal (no dissipation) dispersion curves? Plasma resonances are on frequencies where squared refractive index is infinite (with + and -). We get transparent (overcritical with +) and nontransparent (subcritical with – "dark") e.m. processes. Reconnection e.m. fields are in the subcritical regime and are located in the resonances, inside plasma absorption (e.m. dissipation as acceleration of electrons) line which is studied via Vlasov kinetics (hot plasma PDF) . We obtain magnetic reconnection in the zero resonance Cherenkov and cyclotron (or hybrid) lines. We get "new" plasma e.m. dispersion scales and "new" dimensionless parameters. Radiation from and penetration into magnetic reconnection band by e.m. wave provided by energetic electron "beam".





$\vec{B}_0 = 0$





$\vec{B}_0 \neq 0$

$$\varepsilon_{ij}(\omega,\vec{k}) = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix} \qquad \varepsilon_{ij}(\omega,\vec{k}) = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

$$\omega_0 = 0 \qquad \frac{\omega-\omega_0}{|k_z| v_\alpha} >> 1 \qquad \operatorname{Im}\varepsilon(\omega,\vec{k}) = 0 \qquad \frac{\omega-\omega_0}{|k_z| v_\alpha} << 1 \qquad \operatorname{Im}\varepsilon(\omega,\vec{k}) \neq 0$$

$$\omega = \vec{k}\vec{v}' \to v'/v_e << 1 \qquad D_T(\mathbf{k},\omega) = 1 - \frac{\omega^2}{(ck)^2}\varepsilon_t(\omega,\mathbf{k}) = 0. \qquad D_{L1} = \varepsilon_l(\omega,\mathbf{k}) = 0$$

$$D_T(\omega,\vec{k}) = 1 - \frac{1}{k^2\lambda^2} + \frac{1}{k^4\lambda^2 r_{DE}^2} - \frac{1}{k^2 r_{DM}^2} - \frac{i\pi^{1/2}}{2^{1/2}}\Sigma_\alpha \frac{(\kappa_{D\alpha}+1)\omega_{p\alpha}^2\omega}{c^2 v_\alpha |k|^3} \qquad \lambda = c/\omega$$

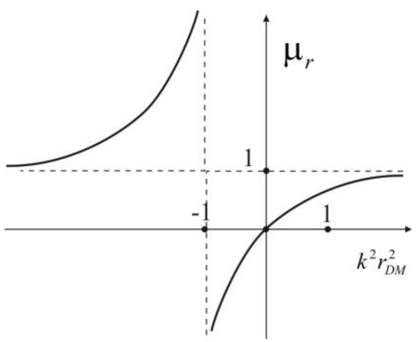
$$D_T(\vec{k}\vec{v}',\vec{k}) = 1 - \frac{v'^2}{c^2} + \frac{1}{k^2 r'^2_{DM}} - i\frac{1}{k^2 r'^2_G} \qquad G_V = G_{\vec{k}\vec{v}',\vec{k}} = r'^2_G / r'^2_{DM}$$

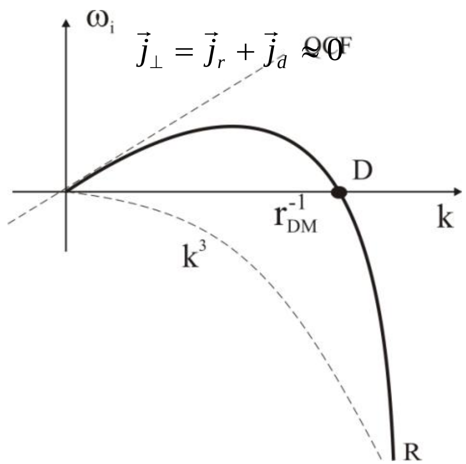
$$\frac{\partial f_{re}}{\partial t} + \left(\vec{V}_\perp \frac{\partial f_{re}}{\partial \vec{r}_\perp}\right) - \frac{e}{m_e}\left(-\frac{\partial\varphi}{\partial r_\perp} - \frac{1}{c}\frac{\partial\vec{A}}{\partial t} + \frac{1}{c}[\vec{V},\nabla\times\vec{A}], \frac{\partial f_{re}}{\partial\vec{V}}\right) = 0$$

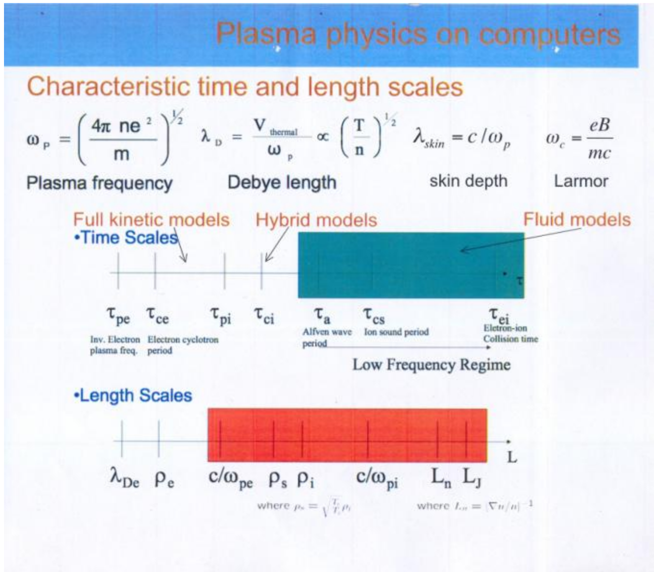
$$\varepsilon_{ij}(\omega,\vec{k}) = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ \varepsilon_{yx} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix} \qquad \varepsilon_{ij}(\omega,\vec{k}) = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & \varepsilon_{yz} \\ 0 & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix}$$

$$\omega = \omega_0 = \omega(\omega_p, \omega_{c\alpha}) \qquad D_{ij} = \delta_{ij} - \frac{k_i k_j}{k^2} - \frac{\omega^2}{k^2c^2}\varepsilon_{ij}(\omega,\vec{k})$$

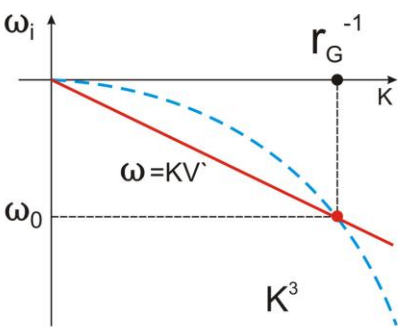
Electrodynamics inside the resonance line. New diamagnetic and resistive plasma e.m. spatial scales as crossing points on the dispersion curves for isotropic and anisotropic plasma (kinetic Weibel). These dispersion scales are not yet included in the EM PIC modelling. Energy anisotropy parameter kappa_D expressed via: temperature anisotropy, relative motions of the electrons and ions - current, relative motion of plasma components. direct plasma flow. Momentum anisotropy kappa_G – see next slide. Magnetic permittivity in the anisotropic plasma: we obtaine plasma diamagnetism and paramagnetism.







$$1-\frac{1}{\mu_t}=\frac{(\vec k\vec v')^2}{c^2}\,\frac{\varepsilon_t(\vec k\vec v',\vec k)-\varepsilon_l(\vec k\vec v',\vec k)}{k^2}$$



$$r_{DM}^{-2}=\sum_\alpha(\omega_{p\alpha}^2/c^2)\kappa_{D\alpha}$$

$$\kappa_{D\alpha}=-\kappa_{V\alpha}+\kappa_{\tau\alpha}-\kappa_{w\alpha}+\kappa_{c\alpha}$$

$$r_G^{-2}=\Sigma_\alpha\frac{\omega_{p\alpha}^2}{c^2}|v'|\pi F_{\alpha 0}\left(\frac{k_x v'}{|\vec k|}\right)=\Sigma_\alpha\frac{\omega_{p\alpha}^2}{c^2}\kappa_{G\alpha}$$

$$\kappa_{c\alpha}=-u_\alpha^2/v_\alpha^2$$

$$\kappa_{\tau\alpha}=1-T_\parallel/T_\perp$$

$$\kappa_{w\alpha}=+u_w^2/v$$

$$\kappa_{V'\alpha}=\frac{v'^2}{v_\alpha^2}$$

The e.m. quality G_V of plasma depends only from the PDF shape and not depends from plasma concentration. The quality can be positive and negative (anisotropic plasma). The e.m. qualty can be expressed via the "loss angle" of plasma or by conjugate "reactivity angle".

- Ratio $G_{w,\mathbf{k}}$ of diamagnetic to resistive current components in the media.
- Ratio $G_{w,\mathbf{k}} = G_{\mathbf{kv}',\mathbf{k}} = G_V$ of diamagnetic to resistive current components for direct stationary motion: Cherenkov process **ω=kv'** .

$$G_{\omega,\mathbf{k}} = \frac{j_d}{j_r} = \frac{\operatorname{Re}\varepsilon_t(\omega,\mathbf{k})}{\operatorname{Im}\varepsilon_t(\omega,\mathbf{k})}$$

$$G_V = ctg\,\gamma_V = \frac{r_G^2}{r_{DM}^2} = \frac{\kappa_D}{\kappa_G}$$

$$G_{\mathbf{kv}',k} = \frac{j_d}{j_r} = \frac{\operatorname{Re}\varepsilon_t}{\operatorname{Im}\varepsilon_t} = \frac{\Sigma_\alpha \omega_{p\alpha}^2 \oint du \dfrac{F_{\alpha 0}(u)}{u - k_x v'/|\mathbf{k}|}}{\Sigma_\alpha \omega_{p\alpha}^2 \pi F_{\alpha 0}(k_x v'/|\mathbf{k}|)} \approx \frac{r_G^2}{r_{DM}^2}\frac{k_x}{|\mathbf{k}|}\frac{v'}{|\mathbf{v}'|} = G_V \frac{k_x}{|\mathbf{k}|}\frac{v'}{|\mathbf{v}'|}$$

“Thin” (anomalous skin) and “thick” (magnetic Debye) dispersion scales “induced” by the SW flow for the Large Scale Kinetic modeling (small kappas are in real nonrelativistic plasmas). The scales of magnetic structures generated by flow are expressed via introduced scales. Condition of nonmagnetization of the scales requires high magnetic beta.

Anomalous skin scale

$$r_G^{-2} = \Sigma_\alpha \frac{\omega_{p\alpha}^2}{c^2} |v'| \pi F_{\alpha 0}\left(\frac{k_x v'}{|\vec{k}|}\right) = \Sigma_\alpha \frac{\omega_{p\alpha}^2}{c^2} \kappa_{G\alpha}$$

“Momentum” anisotropy

$$|v'| \pi F_{\alpha 0}\left(\frac{k_x v'}{|\mathbf{k}|}\right) = \kappa_{G\alpha}$$

Magnetic Debye scale

$$r_{DM}^{-2} = \boldsymbol{\Sigma}_\alpha \frac{\omega_{p\alpha}^2}{c^2} v'^2 2 \int_{-\infty}^{\infty} du \frac{\partial F_{\alpha 0}}{\partial u^2} = \boldsymbol{\Sigma}_\alpha \frac{\omega_{p\alpha}^2}{c^2} \kappa_{D\alpha}$$

“Energy” anisotropy

$$v'^2 2 \int_{-\infty}^{\infty} du \frac{\partial F_{\alpha 0}}{\partial u^2} = \kappa_{D\alpha}$$

The LSK limit appeared when: $\kappa_D, \kappa_G << 1$

High beta plasma $\kappa_D \beta >> 1$ $\kappa_G \beta >> 1$

Calculation of the e.m. plasma parameters for the maxwellian PDF F(V).

$$f_{M\alpha} = \frac{n_{0\alpha}}{(2\pi v_\alpha^2)^{3/2}} \exp\left[-\frac{(v_x - v`)^2}{2v_\alpha^2} - \frac{v_y{}^2}{2v_\alpha^2} - \frac{v_z{}^2}{2v_\alpha^2} \right]$$

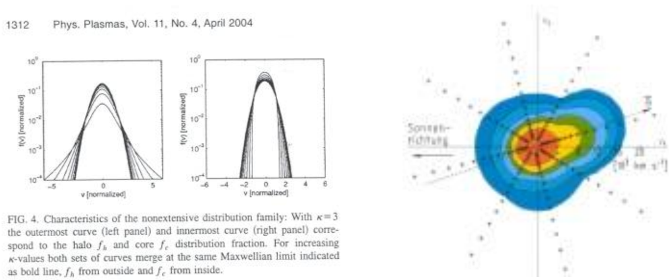
$$D_T(\mathbf{k}, \mathbf{k}\mathbf{v}') = 1 - \frac{(\mathbf{k}\mathbf{v}')^2}{(ck)^2} \varepsilon_t(\mathbf{k}\mathbf{v}'\vec{k}) \approx 1 - \frac{i}{k^2 r_G^2} \frac{k_x}{|\mathbf{k}|} + \frac{1}{k^2 r_{DM}^2} + \ldots$$

$$\varepsilon_t(\omega, \mathbf{k}) = 1 + \mathbf{\Sigma}_\alpha \frac{\omega_{p\alpha}^2}{\omega^2} i\pi^{1/2} w(\xi_\alpha) \qquad \xi_\alpha = \frac{k_x v'}{|\mathbf{k}| v_\alpha} << 1$$

$$r_G^{-2} = \sum_\alpha \frac{\omega_{p\alpha}^2}{c^2} \frac{v`}{v_\alpha} \qquad r_{DM}^{-2} = \sum_\alpha \frac{\omega_{p\alpha}^2}{c^2} \frac{v'^2}{v_\alpha^2} \qquad G_{VM} = ctg\,\gamma_{VM} = \frac{r_G^2}{r_{DM}^2} = \frac{v'}{v_e} << 1$$

The «каппа» PDF as “core” or “halo”: G_V/G_{VM} ratio is function of the parameter “kappa” for the power law PDF.

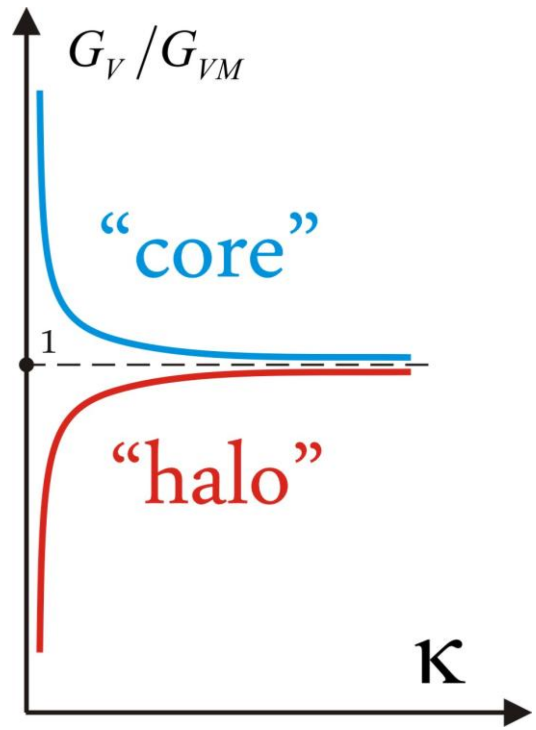
- “Halo” and “Core” kappa distributions of the VDF



$$f_h = \frac{n_0}{\pi^{3/2} v_\alpha^3 \kappa^{3/2}} \frac{\Gamma(\kappa)}{\Gamma(\kappa - 3/2)} \left[1 + \frac{1}{k} \frac{(\vec{V} - \vec{V}')^2}{v_\alpha^2} \right]^{-\kappa}$$

$$f_c = \frac{n_0}{\pi^{3/2} v_\alpha^3 \kappa^{3/2}} \frac{\Gamma(\kappa + 5/2)}{\Gamma(\kappa + 1)} \left[1 - \frac{1}{\kappa} \frac{\vec{v}^2}{v_\alpha^2} \right]^{\kappa}$$

- G_V / G_{VM}



The «ultra relativistic maxwellian plasma» PDF.

- Yuttner (relativistic Maxwell) VDF

$$f_{0e}(\vec{p}) = \frac{N_e}{4\pi(mc)^3} \frac{\exp(-\frac{c\sqrt{m^2c^2 + p^2}}{\kappa T_e})}{(\frac{\kappa T_e}{mc^2})K_2(\frac{mc^2}{\kappa T_e})}$$

$$\kappa T_e >> mc^2$$

$$f_{0e}(\vec{p}) = \frac{N_e}{8\pi} \frac{\exp(-\frac{cp}{\kappa T_e})}{(\frac{\kappa T_e}{c})^3}$$

- V.P. Silin-1961

$$\varepsilon^{tr}(\omega,k) = 1 - \frac{2\pi e^2 N_e c}{\omega k \kappa T_e} K_2^{-1}(\frac{mc^2}{\kappa T_e}) \int_{-kc}^{+kc} \frac{d\omega'}{\omega - \omega'} \times$$

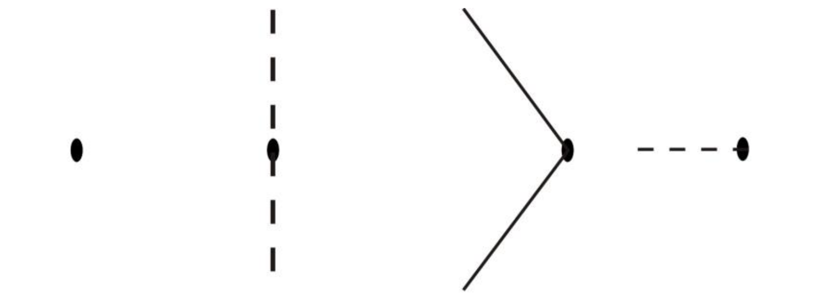
$$\times \exp(-\frac{mc^2}{\kappa T_e} \frac{1}{\sqrt{1 - \frac{\omega'^2}{c^2k^2}}})[(1 - \frac{\omega'^2}{c^2k^2})(\frac{\kappa T_e}{mc^2}) + \sqrt{1 - \frac{\omega'^2}{c^2k^2}}]\frac{\kappa T_e}{mc^2}$$

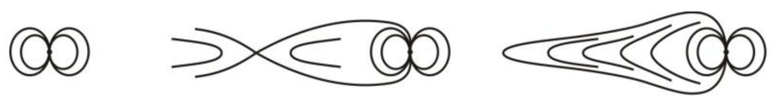
$$\kappa T_e >> mc^2$$

$$r_G^{-2} = \frac{\omega_{pe}^2}{c^2}\kappa_G^R = \frac{\omega_{pe}^2}{c^2}\frac{v'}{v_e}\frac{c}{v_e} \qquad \kappa_G^R = \frac{v'}{v_e}\frac{c}{v_e}$$

$$\kappa_G^R = \frac{v'}{v_e}\frac{c}{v_e} << \kappa_G$$

The acoustic (L) Mach number $M=v'/c_s$ and the e.m. (TEM) quality number G_V for plasma flow and their effects on the acoustic and magnetic fields restructuring.





$$\vec{j}_r, \vec{j}_d \qquad G = j_d / j_r$$

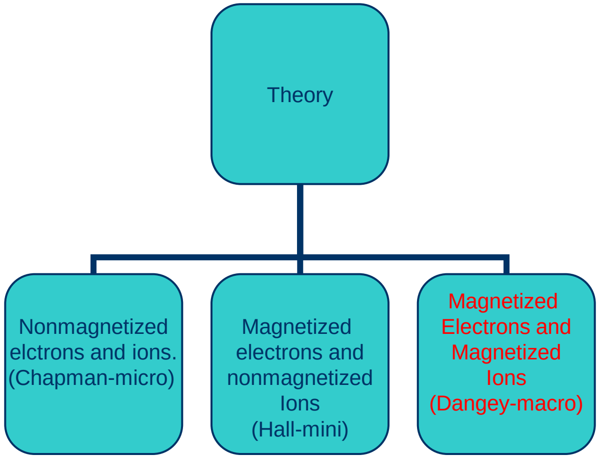
Mach number M governs L fields topology – shape of the Mach cone.

Number G_V governs TEM fields topology --- the “tailization” and “dipolization” effects.

“Resistive” state **G_V** <<1 - plasma flow is as “metallic” conductor and we get magnetic reconnection and slow field decrease in the tail. “Dipolized” state **G_V** >>1 no magnetic reconnection, plasma flow is as diamagnetic and we get screening of the field.

G_V is function of the VDF f(v) shape of hot collisionless plasma flow? How to measure it by probes?

Nonlinear dimensionless electromagnetic parameters of the hot plasma flow: magnetization of the resistive and diamagnetic scales. Three types of magnetospheres due to flow magnetization. Nonmagnetized flow versus magnetized flow: difference in topology of the magnetotails. Scale of the magnetotatil spatial modulations and the ion cyclotron resonances - cyclotron magnetic reconnenction - plasma penetration throw magnetic field in space and laser experiments.



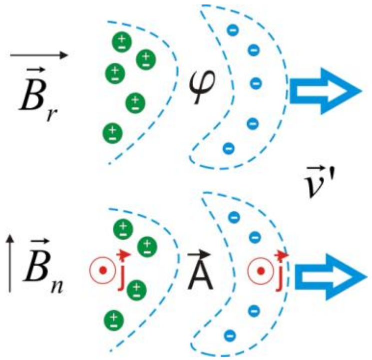
$$r_{c\alpha} >> r_G, r_{DM}$$

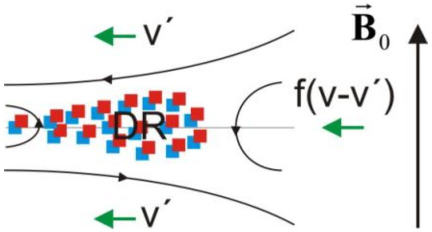
$$\kappa_G \beta >> 1 \qquad \kappa_D \beta >> 1$$

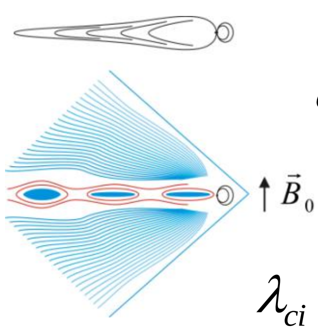
$$\beta_{crD} = 1/\kappa_D > 1 \qquad \beta_{crG} = 1/\kappa_G > 1$$

$$\Gamma_B = G/M_A^2 << 1 \qquad \kappa_D \beta = M_A^2 >> 1$$

$$\kappa_G \beta = \Gamma_B^{-1},$$







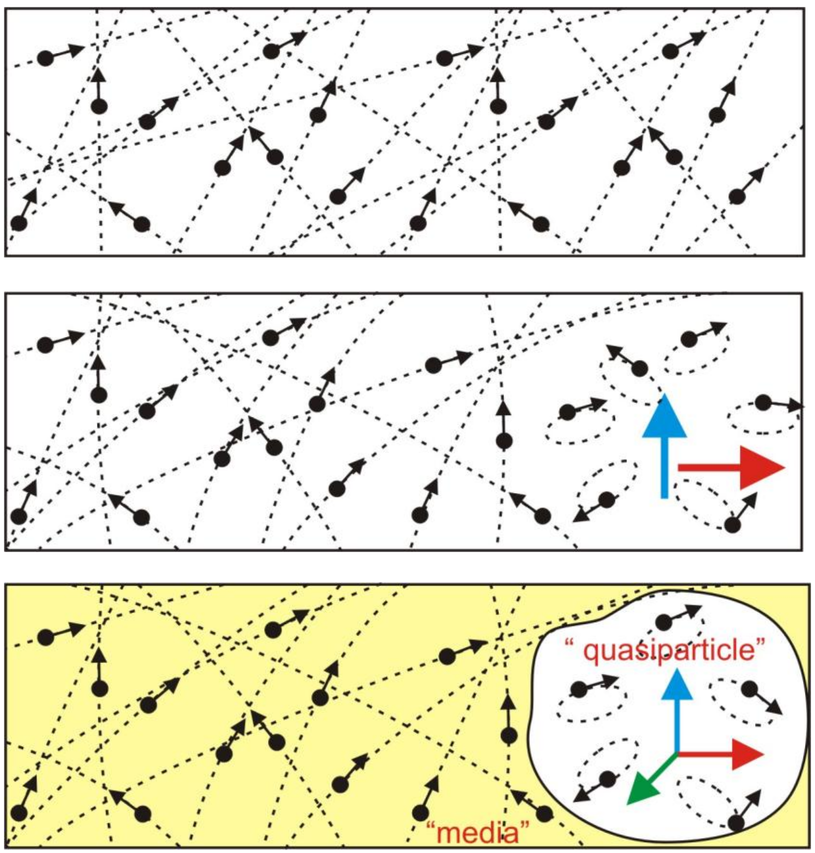
$$\omega_{ci} = k_\perp v'$$

$$\lambda_{ci} = v'/\omega_{ci}$$

Interaction of plasma flow with a source of magnetization - moving magnetic quasiparticle in the media.

Approach: “quaiparticle” (magnetoactive region or laser target) is provided by dynamo and by trapped particles. Quasilinear “media” formed by flyby particles with perturbed trajectries.

3D solution for description of the magnetic reconnection as linear problem, electron diffusion region formed by flyby particles.



- Motion of free particles with VDF f(v).
- “Trapped” and “flyby” particles near magnetic dipole submerged in plasma with velocity **v**’.
- “Magnetization” formed by magnetic dipole and trapped particles providing toroidal moment (space plasma).

$$\mathbf{j}_t = \mathbf{j}_{trapped} + \mathbf{j}_{flyby}$$

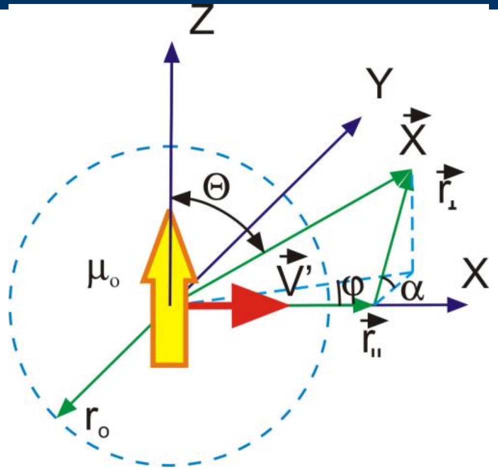
Electric current provided by the «quasiparticle» and directly flowing «media».

$$\mathbf{j}_t = \mathbf{j}_{trapped} + \mathbf{j}_{flyby}$$

“Trapped particles = quasiparticle” form magnetic dipole and toroidal magnetization with postulated moments and spatial distribution (result of independent dynamo type nonlinear solutions). “Flyby particles=media” are perturbed by e.m. fields in their motion and are subject of the selfconsitent Vlasov/Maxwell solution.

$$\mathbf{j}_{trapped} = \mathbf{j}_{\mu} + \mathbf{j}_{\tau} = c[\nabla \times \boldsymbol{\mu}] + c[\nabla \times [\nabla \times \boldsymbol{\tau}]] + \ldots,$$

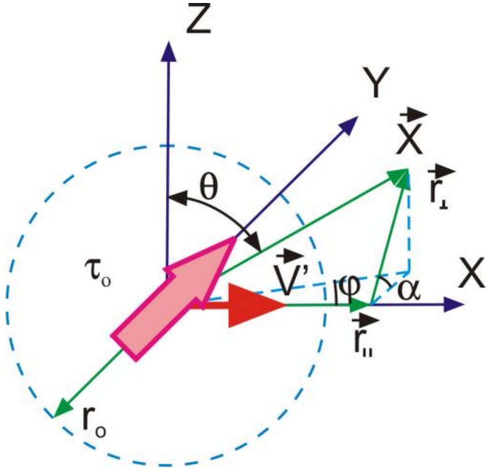
Quasiparticle with gaussian spatial distribution. Toroid is orthogonal to Dipole, both are orthogonal flow (helmet or magnetosphere configuration). Parameter of toroidality \Gamma is ratio of the integral current components forming the toroid and the dipole moments of the quasiparticle.



$$\mu(\mathbf{X}) = \mathbf{z}_0 \mu_0 \frac{1}{(2\pi r_0^2)^{3/2}} \exp\left(-\frac{\mathbf{X}^2}{2r_0^2}\right)$$

$$\boldsymbol{\mu}_0 = I_\mu \pi r_0^2$$

$$\mathbf{X} = \mathbf{x} - v`\mathbf{x}_0 t$$



$$\tau(\mathbf{X}) = \mathbf{y}_0 \tau_0 \frac{1}{(2\pi r_0^2)^{3/2}} \exp\left(-\frac{\mathbf{X}^2}{2r_0^2}\right)$$

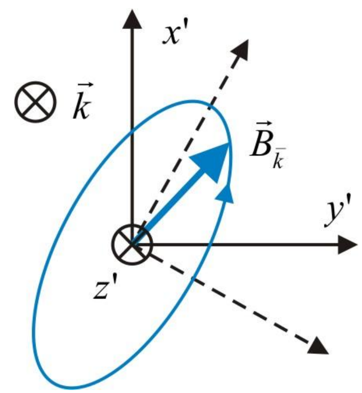
$$\tau_0 = I_\tau (4/3) \pi r_0^3$$

$$\boldsymbol{\Gamma}_{\tau\mu} = I_\tau / I_\mu$$

$$I = \sqrt{I_\mu^2 + I_\tau^2} = I_\mu \sqrt{1 + \Gamma_{\tau\mu}^2}$$

3D e.m. fields of the DR as kombination of derivatives of the 2D characteristic function M_G. Force and forceless components as linear and circular components in the elliptical polarization of the 3D magnetostatic field represented as a „wave“ package. Magnetic dipole and toroid are together providing forceless component in the DR.

$$\mathbf{A}_{\mu} = \mu_0\left(\frac{\partial M_G}{\partial Y}\mathbf{x}_0 - \frac{\partial M_G}{\partial X}\mathbf{y}_0\right)$$



$$\mathbf{A} = \mathbf{A}_{\mu} + \mathbf{A}_{\tau}$$

$$\vec{A}_{\mu,\vec{k}}(\vec{k}) = \mu_0 i(k_y\vec{x}_0 - k_x\vec{y}_0)M_{G\vec{k}}$$

$$\mathbf{A}_{\tau} = \tau_0\left(\frac{\partial^2 M_G}{\partial X\partial Y}\mathbf{x}_0 + \left(\frac{\partial^2 M_G}{\partial X^2} + \frac{\partial^2 M_G}{\partial Z^2}\right)\mathbf{y}_0 - \frac{\partial^2 M_G}{\partial Z\partial Y}\mathbf{z}_0\right)$$

$$\vec{A}_{\tau,\vec{k}} = -\tau_0(\vec{k}k_y - k^2\vec{y}_0)M_{G\vec{k}}$$

$$\mathbf{\Gamma}_{\tau\mu} = I_{\tau} / I_{\mu}$$

2D characteristic function M_G "at hot regimes". Magnetic Reynolds $Re_m = r_0/r_G$ and e.m. quality $G_V = r_G/r_{DM}$ as parametrs!

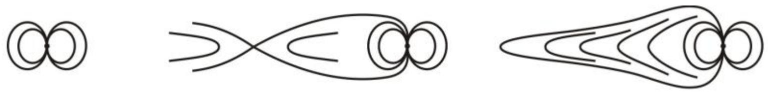
$$M_G(\mathbf{X}, \mathrm{Re}_m, G_V) = \frac{4\pi}{(2\pi)^3}\int d\mathbf{k}\,\frac{\exp\left(-\frac{k^2 r_0^2}{2} + i\mathbf{k}\mathbf{X}\right)}{k^2 D_T(\mathbf{k}, \mathbf{k}\mathbf{v}')}$$

$Re_m = r_0/r_G$

$$M(\chi, \rho_\perp, \mathrm{Re}_m, G_V) = \frac{1}{\pi r_G}\int_0^\infty d\xi_\perp \xi_\perp J_0(\xi_\perp \rho_\perp)\exp\left(-\frac{\xi_\perp^2 \mathrm{Re}_m^2}{2}\right) I_x(\xi_\perp, \chi, \mathrm{Re}_m, G_V)$$

$$I_x(\xi_\perp, \chi, \mathrm{Re}_m, G_V) = 2\,\mathrm{Re}\int_0^\infty d\xi_x \exp\left(i\xi_x\chi - \frac{\xi_x^2 \mathrm{Re}_m^2}{2}\right)\frac{\xi^2}{\xi^4 - i\xi_x|\xi| + G_V \xi_x^2}$$

G_V !!

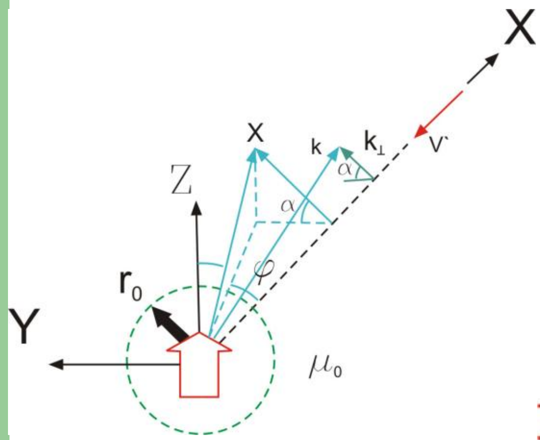


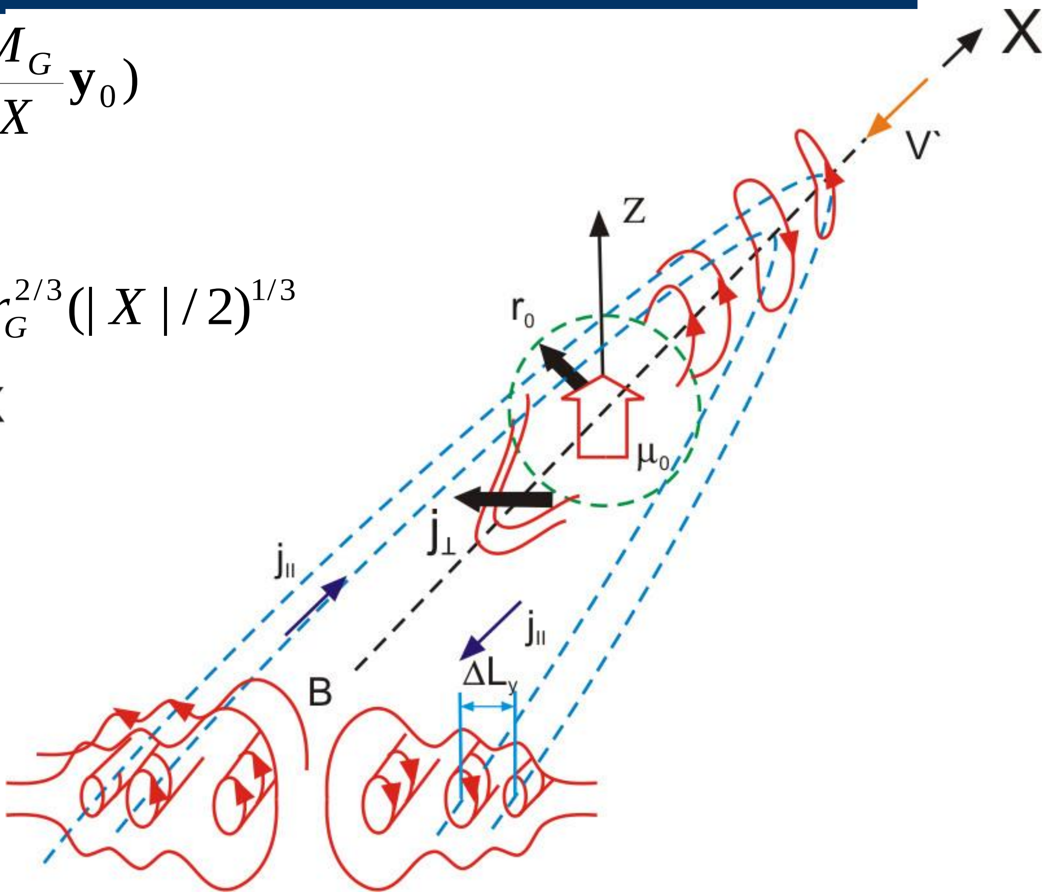
G_V>>1 G_V~1 G_V<<1

3D magnetotail originated from magneto dipole component of the magnetization at far distatnces. $G_V \ll 1$.

$$\mathbf{A}_\mu = \mu_0 \left(\frac{\partial M_G}{\partial Y} \mathbf{x}_0 - \frac{\partial M_G}{\partial X} \mathbf{y}_0 \right)$$

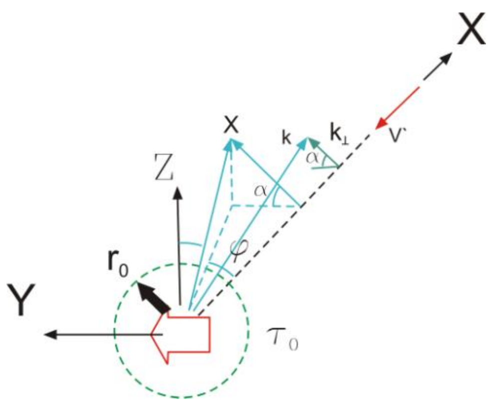
$$L_S = L(r_G, X) = L_y = L_z \approx 3 r_G^{2/3} (|X|/2)^{1/3}$$

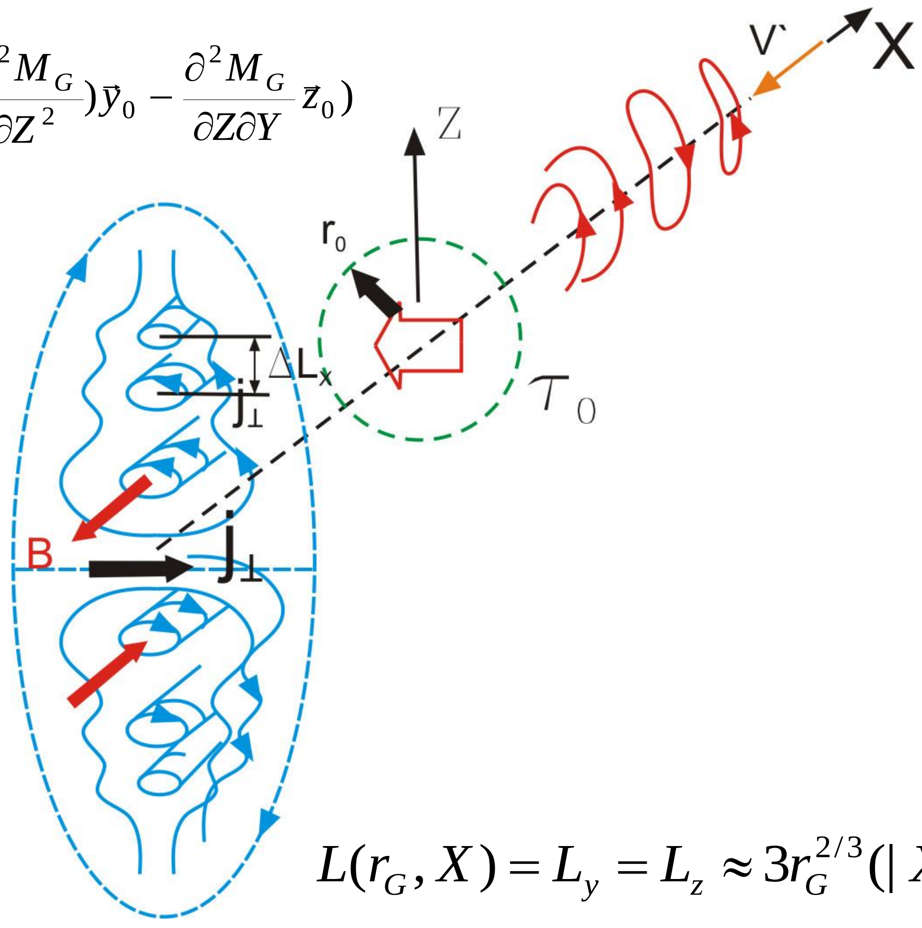




3D magnetotailtail originated from the magnetic toroid component of magnetization at far distances. G_V<<1.

$$\vec{A}_\tau = \tau_0\left(\frac{\partial^2 M_G}{\partial X \partial Y}\vec{x}_0 + \left(\frac{\partial^2 M_G}{\partial X^2} + \frac{\partial^2 M_G}{\partial Z^2}\right)\vec{y}_0 - \frac{\partial^2 M_G}{\partial Z \partial Y}\vec{z}_0\right)$$

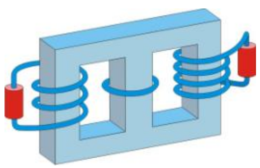


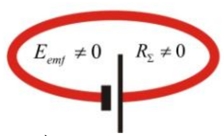


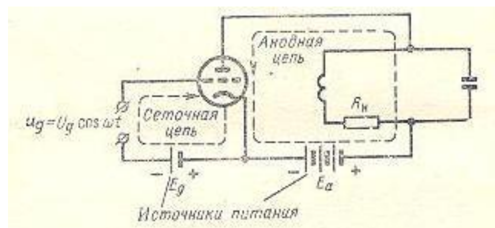
$$L(r_G, X) = L_y = L_z \approx 3r_G^{2/3}(|X|/2)^{1/3}$$

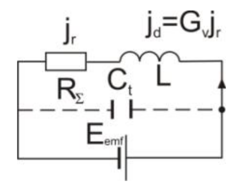
The integral description by the RCL elements (provided by the 3D kinetic solutions for magnetic dipole component here) and by "triode" tube element of the hot plasma dynamic expansion (flow) under action from the ambipolar and quasiatationary electromagnetic fields. There are three governing dimensionless e.m. parameters plus kinetic magnetic Reynolds number. Asymmetric transformer by second loops and by core illustrates plasma flow, the first loop is a coil providing dipole and toroidal magnetizations (laser target or magnetoactive region) . The "grid" circuit models magnetic field action on flow. The "anode" circuit models ambipolar plasma expansion from the "cathode" (laser target) to the virtual "anode". The triode has "magnetron" key type "Volt/Ampere" characteristic where magnetic "grid" provides integral Ampere force drag action. Two types of the circuits reflects two types of the e.m.f. dynamo and the difference in the selfinductance effects in space and HED plasmas.

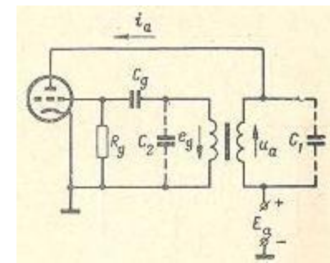
$$G_V, \Gamma_B, \Gamma_{\tau\mu} << 1$$





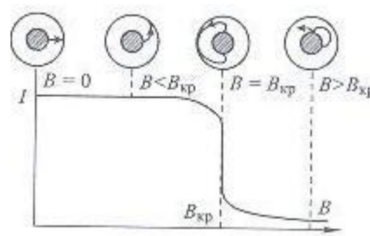


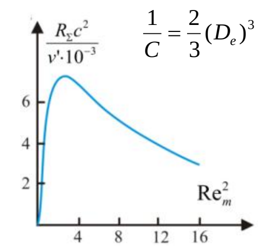




$$\omega = \vec{k}\vec{v}'$$

$$\Delta\varphi = E_{emf} \qquad \varphi = E_a - \Delta\varphi$$





$$\frac{1}{C} = \frac{2}{3}(D_e)^3 \frac{1}{r_0}\int_0^\infty d\xi \frac{\xi^2 \exp(-\xi^2 D_e^2)}{(1+\xi^{-2})^2}$$

$$E_{emf} = R_\Sigma I + \frac{L}{c^2}\frac{dI}{dt} + \frac{I^2}{2c^2}\frac{dL}{dt}$$

$$RI << \left(\frac{L}{c^2}\frac{dI}{dt} + \frac{I^2}{2c^2}\frac{dL}{dt}\right)$$

$$R_\Sigma = R_\mu = \frac{P_\mu}{I_\mu^2} = \frac{v'}{c^2}\frac{2}{(2\pi)^2}\{\frac{4}{3\varepsilon} - \frac{12}{\varepsilon^3} + \frac{5}{\varepsilon} - \frac{3\pi}{2\varepsilon^2} - \frac{48}{\varepsilon^3} + \frac{30\pi}{\varepsilon^4} +$$
$$[ci(\varepsilon)\sin(\varepsilon) - si(\varepsilon)\cos(\varepsilon)](-4 + \frac{33}{\varepsilon^2} - \frac{60}{\varepsilon^4}) + [ci(\varepsilon)\sin(\varepsilon) - si(\varepsilon)\cos(\varepsilon)]\}(\varepsilon - \frac{13}{\varepsilon} + \frac{60}{\varepsilon^3})\}$$

$$L = \frac{4\pi r_0}{c}\varepsilon^{3/2}[15\sqrt{\frac{\pi}{2}}\varepsilon_*^{-7/2} + 4D^{II}(\varepsilon_*) - 16D^{IV}(\varepsilon_*)] \qquad D(\varepsilon_*) = \int_0^\infty d\xi \exp(-\frac{\xi^2\varepsilon_*}{2})\arcsin(\frac{1}{\sqrt{1+\xi^4}}) \qquad \varepsilon_* = 2\varepsilon = 2\,\mathrm{Re}_m^2$$

Resulting linear and nonlinear dimensionless parameters of the kinetic problem for hot plasma flow.

0. The regimes of plasma flow from "hot"electron via supersonic to "cold" electron regimes.

$M_e = v'/v_e << 1$, $M_i = v'/v_i << 1$
$M_e = v'/v_e << 1$, $M_i = v'/v_i >> 1$
$M_e = v'/v_e >> 1$, $M_i = v'/v_i >> 1$

1. E.m. qualty G_V. From magnetic reconnection to diamagnetic polarization

$G_V = r_G/r_{DM} << 1$ resistive-"tail".
$G_V \sim 1$
$G_V >> 1$ diamagnetic-"dipolization"

2. Kinetic magnetic Reynolds number. From nonconductivity to superconductivity

$Re_m = r_0/r_G << 1$
$Re_m \sim 1$
$Re_m >> 1$

3. "Quasiparticle" current loop configuration. From magnetic dipole to toroid.

$$\Gamma_{\tau\mu} = I_\tau / I_\mu << 1$$

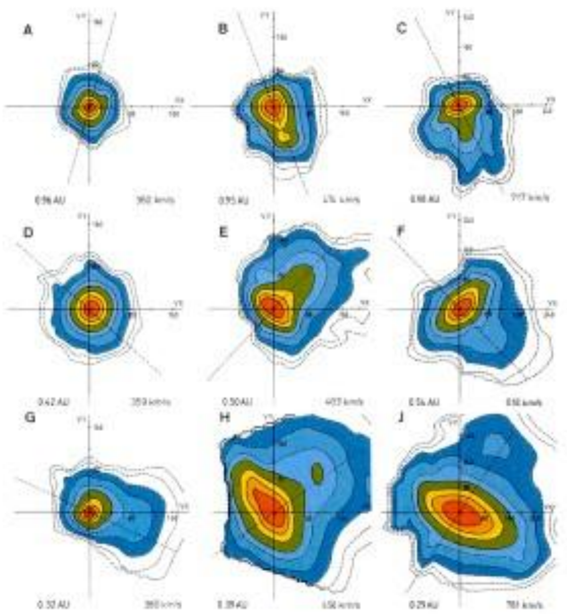
$$\Gamma_{\tau\mu} = I_\tau / I_\mu \sim 1$$

$$\Gamma_{\tau\mu} = I_\tau / I_\mu >> 1$$

4. Nonlinear e.m. magnetization parameters: **resistive \Gamma_B and kinetic Alfvenic Mach number \M_A**

СПАСИБО! **“C’est, repliqua le savant, qu’il faut bien citer ce qu’on ne comprend point du tout danse la lanque qu’on entend le moins”. Voltaire**

PDFs are from “Helios” mission/



Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia