FORCED AND FORCELESS CONFIGURATIONS IN THE IMPEDANCE CHARACTERISTICS OF THE 3D ASYMMETRIC ELECTRON DIFFUSION MAGNETIC RECONNECTION REGION

Snezhinsk, March 21, 2017

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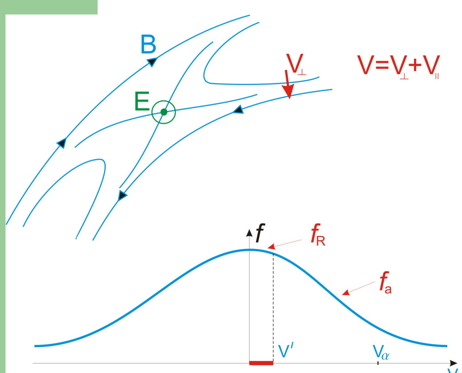
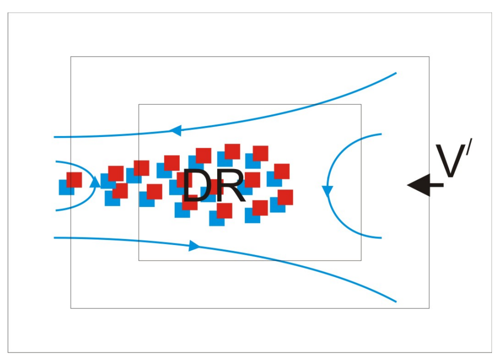
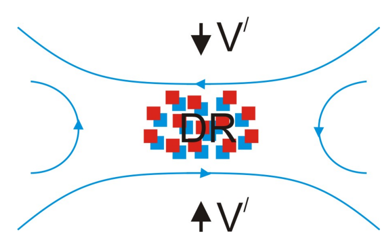
Study of the HED/Space pasma e.m. dynamics: hot, collisionless, flowing/expanding. Electron kinetics/electron MHD appears when flow velocity is less then thermal velocity of plasma electrons.

- V. M. Gubchenko, Kinetic Description of the 3D Electromagnetic Structures Formation in Flows of Expanding Plasma Coronas. I: **General**. ISSN 0016-7932, Geomagnetism and Aeronomy, 2015. Vol. 55, No. 7, PP. 831-845. Pleiades Publishing, Ltd., 2015. DOI: 10.1134/S0016793215070099
- V. M. Gubchenko, Kinetic Approach to the Formation of the 3D Electromagnetic Structures in Flows of Expanding Plasma Coronas. II. **Flow Anisotropy Parameters**. ISSN 0016-7932, Geomagnetism and Aeronomy, 2015. Vol. 55, No. 8, PP.1009-1025. Pleiades Publishing, Ltd., 2015. DOI: 10.1134/S0016793215080101

- Proc./Thes. ZNCH 12, ZNCH-14:







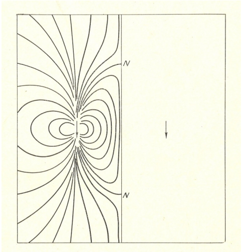
Three regimes on value of the magnetic field (plasma beta, anomalous resistive and diamagnetic scales and giroradius)

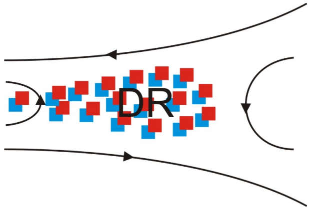
- Nonmagnetized electrons and ions (Chapman "micro magnetosphere") – high beta
- Magnetized electrons and nonmagnetized ions (Hall «minimagnetosphere»)
- Magnetized electrons and ions (Dungy "macromagnetosphere") - low beta

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

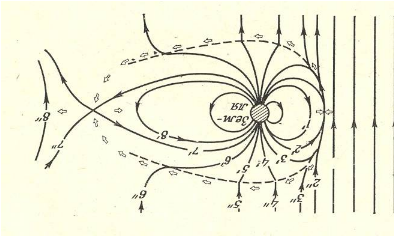
$$\kappa_D \beta >> 1 \qquad \kappa_D \beta \approx M_A^{-2}$$

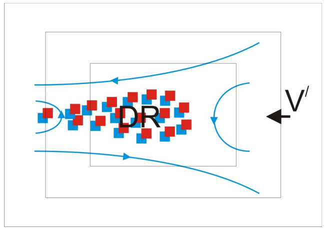
$r_{c\alpha} >> r_G, r_{DM}$ $\quad (k_\perp r_{c\alpha} >> 1)$



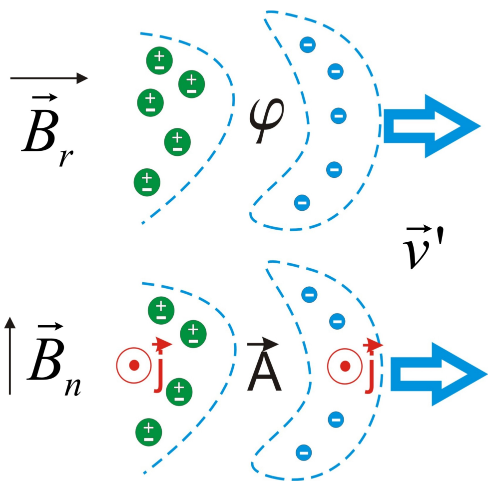


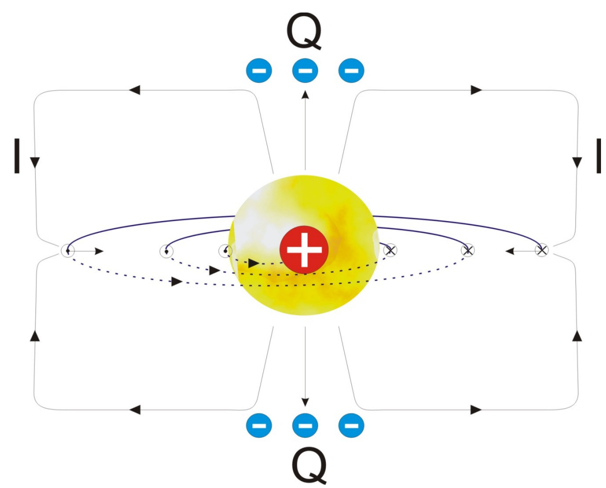
$r_{c\alpha} << r_G, r_{DM}$ $\quad (k_\perp r_{c\alpha} << 1)$

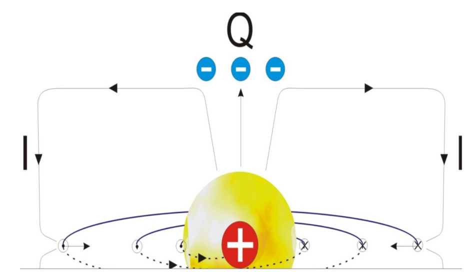


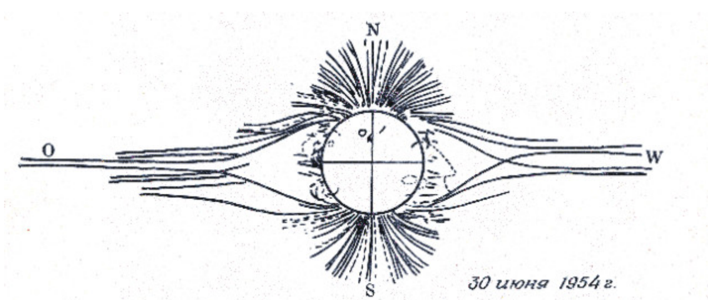


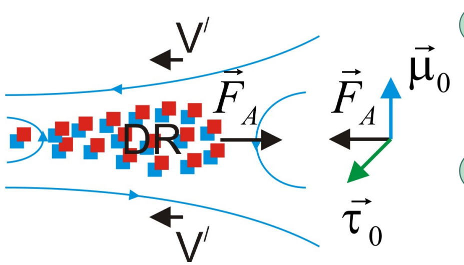
Magnetic Reconnection Diffusion region formation.
Plasma flow expansion along and perependicular to magnetic field. Stationary (Space plasma) and nonstationary (Laser/HED plasma).
There two problems: plasma flow expansion along and perpendicular to magnetic field. Stationary (Space plasma) and nonstationary (Laser/HED plasma) flows

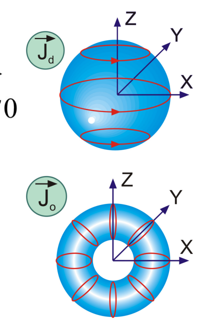




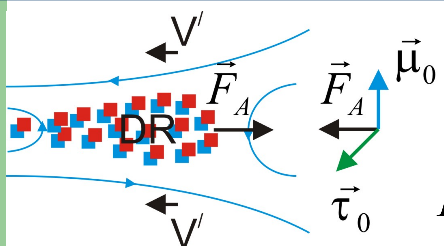






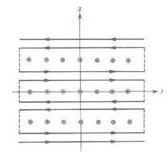


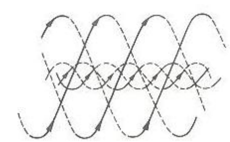
Forced and Forceless 3D components (boundaries) in fields and currents: from 1D (plane, cylindrical, spherical) to 3D. Linear, circular, elliptic polarization. From 1D to 3D.

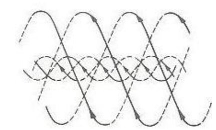


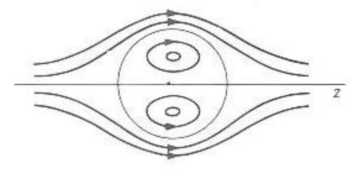
$$f_x = \frac{1}{c}[\vec{j} \times \vec{B}]_x \neq 0$$

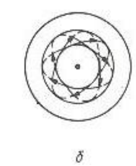
$$P = I^2 \operatorname{Re} Z = \int d^3x f_{Ax} v' \neq 0$$

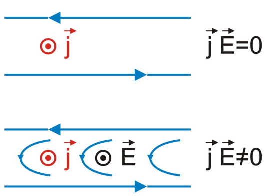


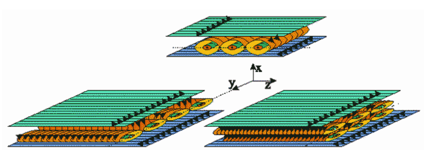






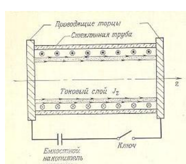


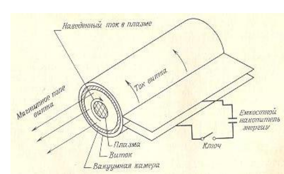


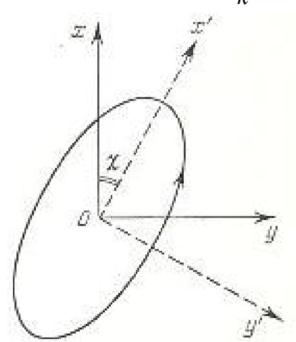


$$\vec{B}_{\vec{k}}(\vec{v},\vec{k},t) = \int_{-\infty}^{\infty} d\vec{x} \frac{1}{(2\pi)^3} \vec{B}(\vec{x},\vec{v},t)\exp(-i\vec{k}\vec{x})$$

$$\vec{B}_{\vec{k}} = i[\vec{k} \times \vec{A}_{\vec{k}}] \qquad \vec{j}_{\vec{k}} = \frac{c}{4\pi} i[\vec{k} \times \vec{B}_{\vec{k}}]$$



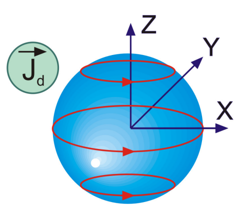


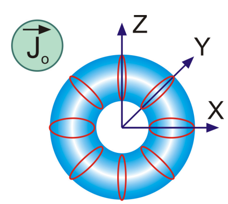


$\exp - i\omega t$ $\qquad$ $\exp i\vec{k}\vec{z}$

$$\vec{B}_{\vec{k}}(\vec{v},\vec{k},t) = B_{\vec{k}x}(\vec{v},\vec{k},t)\vec{x}_0 + B_{\vec{k}y}(\vec{v},\vec{k},t)\vec{y}_0$$

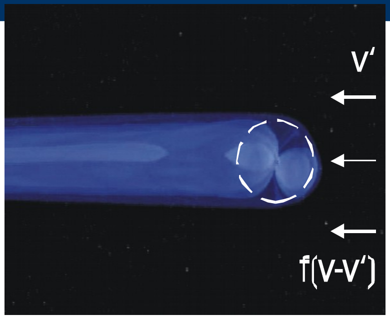
$$\vec{B}_{\vec{k}}(\vec{v},\vec{k},t) = B_{\vec{k}x}(\vec{v},\vec{k},t)\vec{x}_0 + iB_{\vec{k}y}(\vec{v},\vec{k},t)\vec{y}_0$$

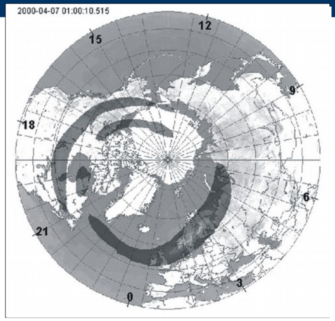


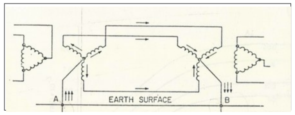


Stationary Space plasma.

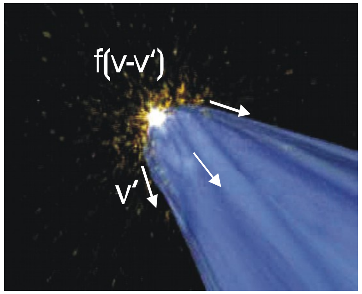
Sun-Earth Physics: Earth magnetosphere, separate solar streamer, streamer belt in solar wind flow. Internal (quasiparticle) and external magnetosphere (hot flow initiated structure). Nonrelativistic magnetic diffusion regions.

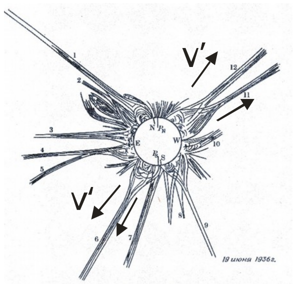


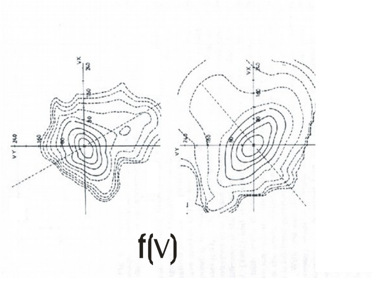




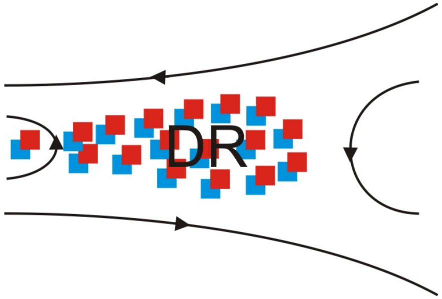
$v_i << V' << v_e$

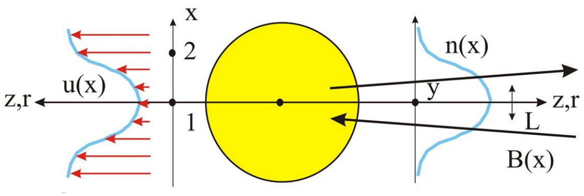


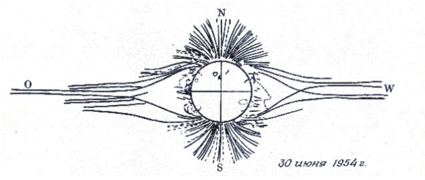




$kT << mc^2$

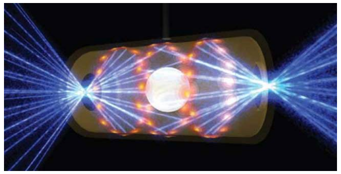


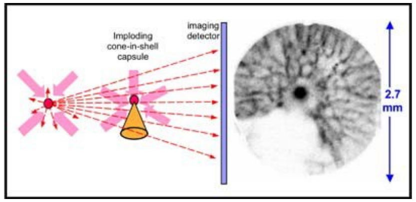


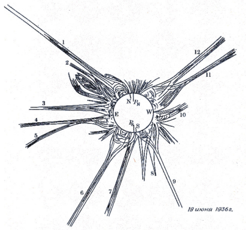


Nonstationary HED plasma
without external magnetic field $\mathbf{B}_n$
Magnetic reconnection near vertical toroid (two vertical toroids) expansion.
Magnetic reconnection noise in laser plasma coronas.

- NIF, Rochester -MIT, LULI







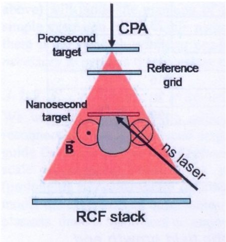
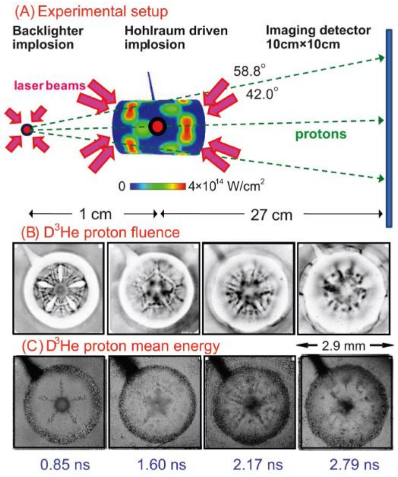
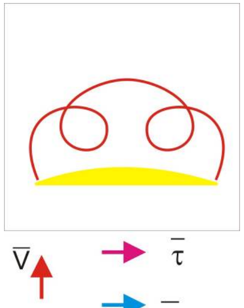
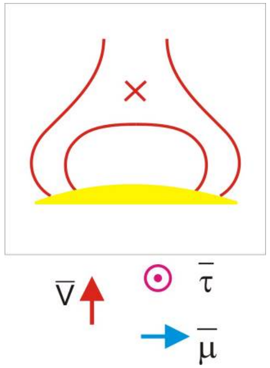


Figure 9: *Principle of magnetic field probing by laser accelerated proton beam.*

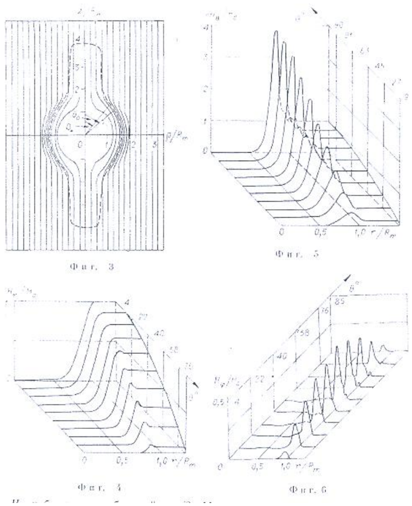


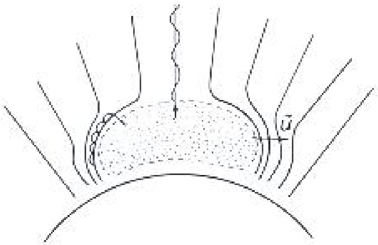


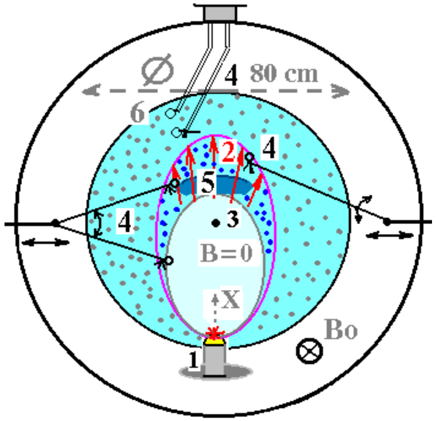


Nonstationary source of space and laser plasma in magnetized plasma with B_n .

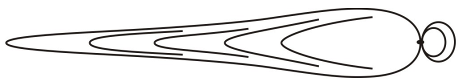
- Formation of magnetic diffusion (diamagnetic) region and radiation of sonic and Alfven waves ("Argus" experiment, solar flare magnetic cloud «CME») ILF RAN.

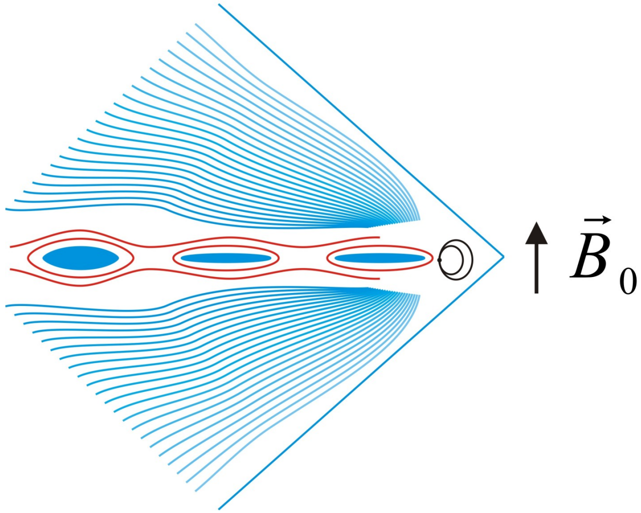


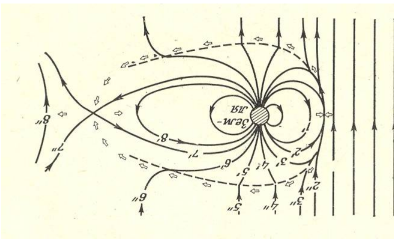


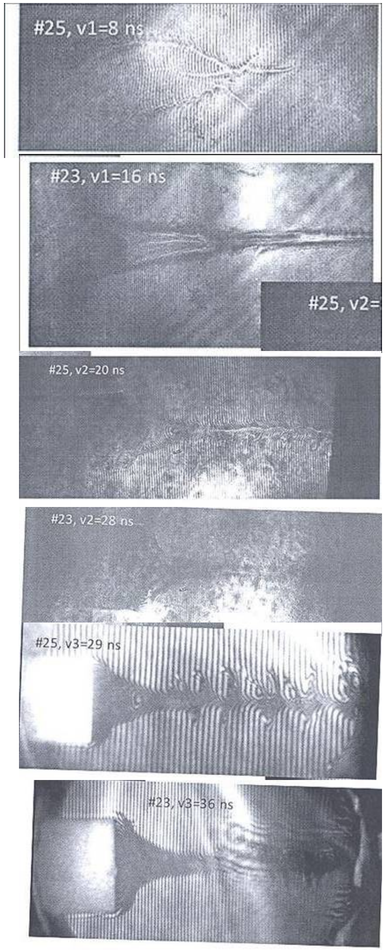


Nonstationary laser HED plasma experiments (LULI, France and IAP RAS, Nizhny Novgorod) with external magnetic field B_{nand}



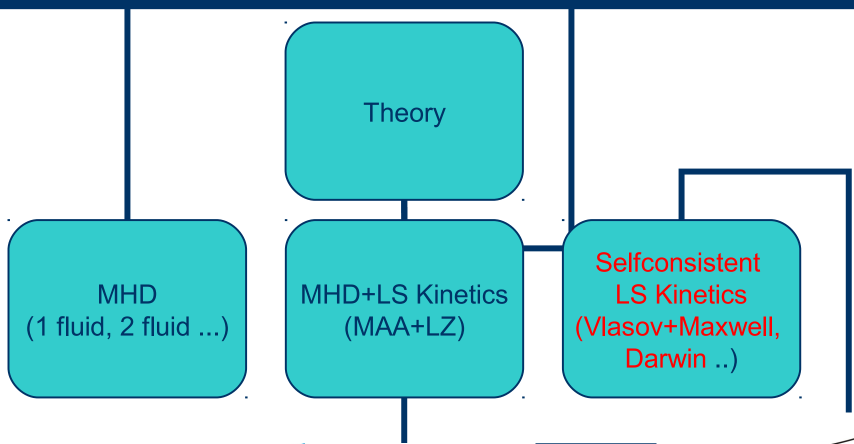






MHD to Vlasov/Maxwell? Hot regime.

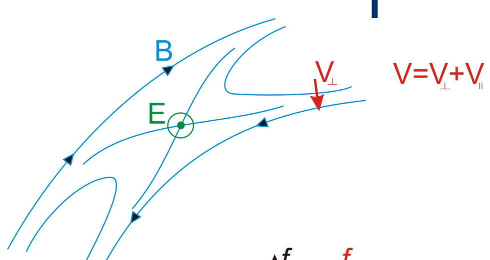
Is a high beta special LSK – Large scale kinetic plasma description Magnetosphere –the effect of Cherenkov "radiation" by quasiparticle in the absorption and nontransparency of the e.m. fields – anomalous skin effect.

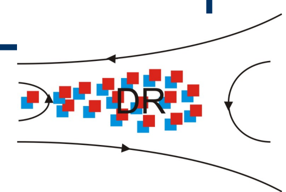


$$r / v_\alpha << t' \quad (\omega / k v_\alpha << 1)$$

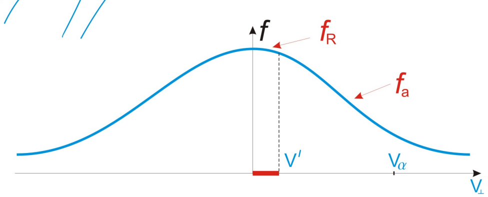
$$v' << v_\alpha \qquad c_s << v' << v_e$$

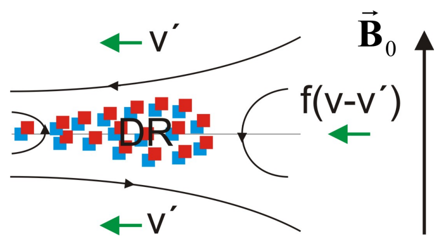
$$\mathbf{j}_{flyby} = \mathbf{j}_r + \mathbf{j}_d$$





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

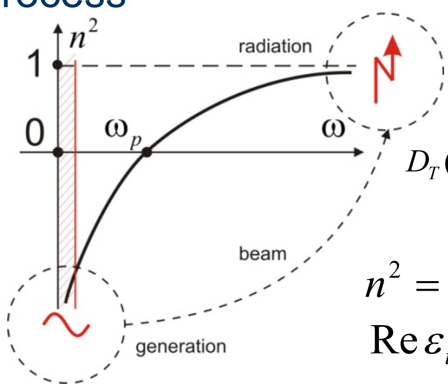




$$r_{c\alpha} << r_G, r_{DM}$$

On the plasma resonance line with „zero resonance frequency“ . **Outside line – MHD, inside line – Vlasov/MHD electron kinetics. Magnetic Structures and electronic diffusion region (DR) formation process is fully inside of the resonance line. What is a power P of the process?**
Here $t=\omega^{-1}$ **characteristic time,** $r=k^{-1}$ **characteristic scale,** $\omega/k=v' << v_e$ **characreistic velocity. MHD limit** $\omega/kv_e=v'/v_e>>1$ **. Kinetic limit** $\omega/kv_e=v'/v_e<<1$

- Light (overcritical) and Dark (subcritical) e.m. process



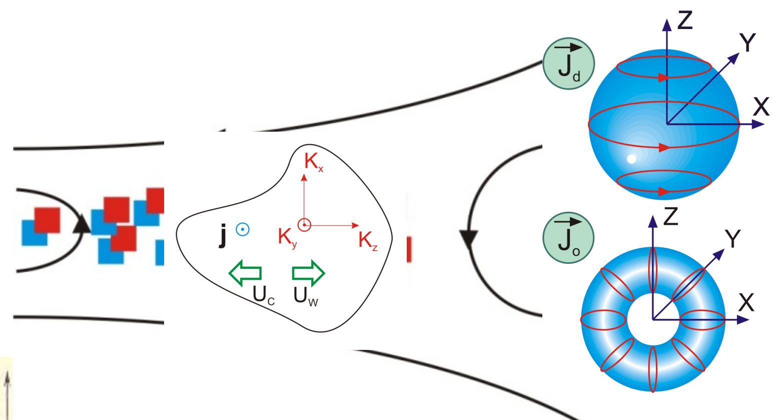
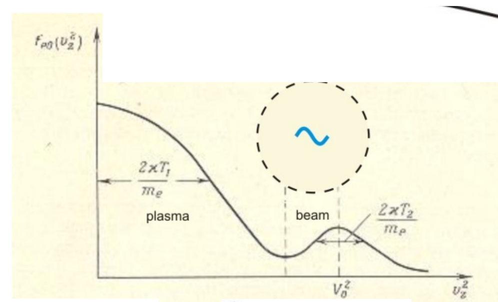
$$D_T(\mathbf{k},\omega)=1-\frac{\omega^2}{(ck)^2}\varepsilon_t(\omega,\mathbf{k})=0.$$

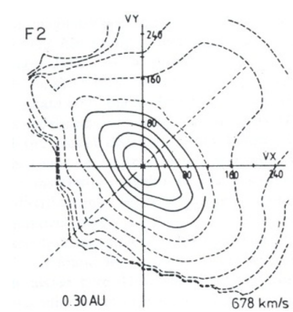
$$n^2=c^2k^2/\omega^2$$

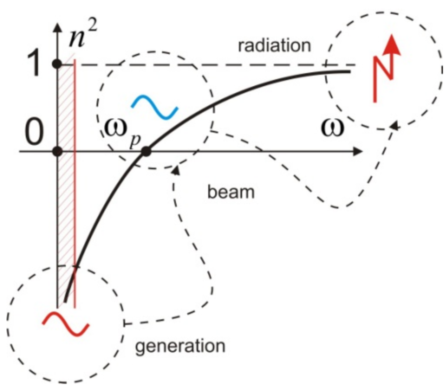
$$\mathrm{Re}\,\varepsilon_t(\omega,k)\neq 1$$

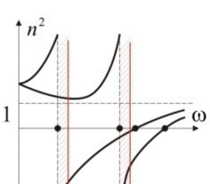
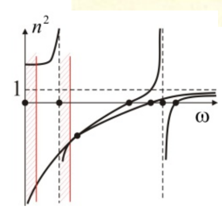
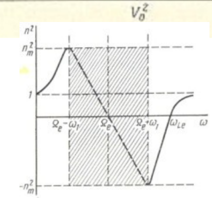
$$\mathrm{Im}\,\varepsilon_t(\omega,k)\neq 0$$

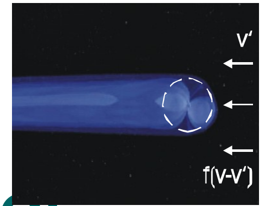
$$\mathrm{Im}\,\varepsilon_t(\omega,k)=0$$

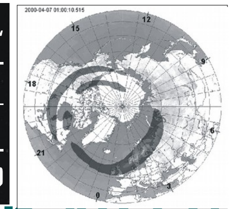



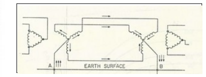




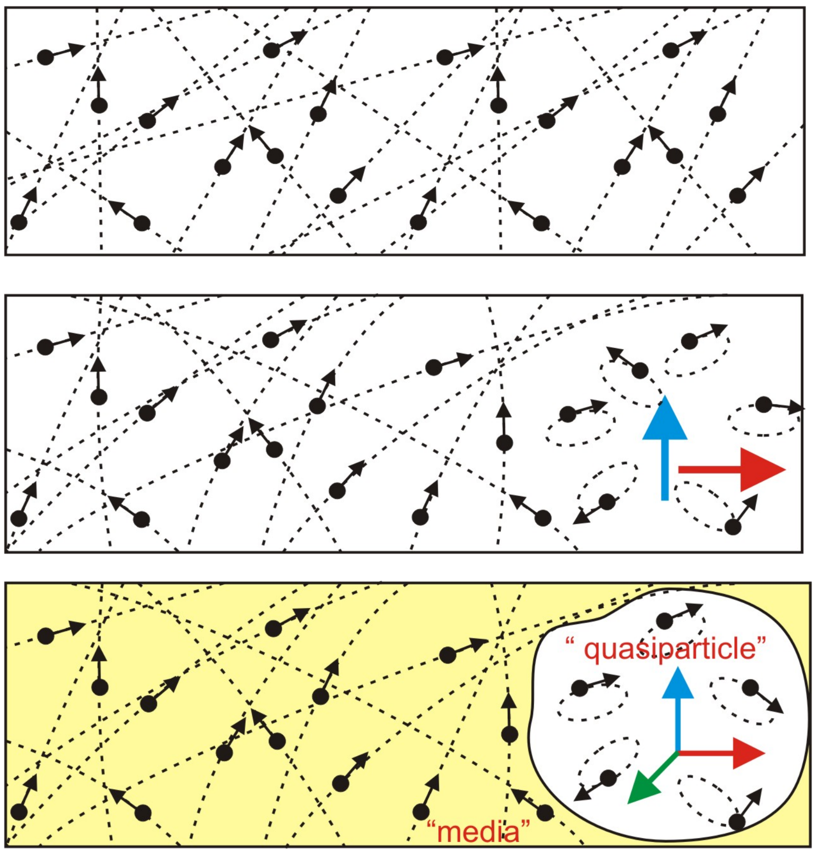










Nonmagnetized flow (Chapman-1933) . Classical plasma electrodynamics. Micromagnetosphere



- Free particles in hot collisionless plasma with VDF f(v).
- "Trapped" and "flyby" particles in presence of the moving dipole with velocity **v**'.
- The "Internal magnetosphere" is a "Quasi particle" as moving magnetization in the "media" having Magnetic Dipole and Magnetic Toroid moments. The "Outer Magnetosphere" is inductive mode Cherenkov excitation in media.

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

$$\mathbf{j}_{flyby} = \mathbf{j}_r + \mathbf{j}_d$$

$$r_{c\alpha} >> r_G, r_{DM} \qquad (k_\perp r_{c\alpha} >> 1)$$

"Thin" (anomalous skin) and "thick" (magnetic Debye) scales for Large Scale Kinetic modeling

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

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

Diamagnetic Debye scale

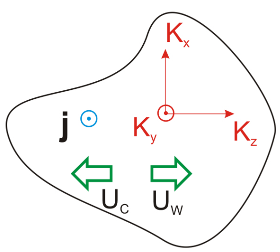
$$r_{DM}^{-2} = \boldsymbol{\Sigma}_\alpha \frac{\omega_{p\alpha}^2}{c^2} v'^2 2 \int_{-\infty}^{\infty} du \frac{\partial F_{\alpha 0}}{\partial u^2} = \boldsymbol{\Sigma}_\alpha \frac{\omega_{p\alpha}^2}{c^2} \kappa_{D\alpha}$$

"Energy" anisotropy

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

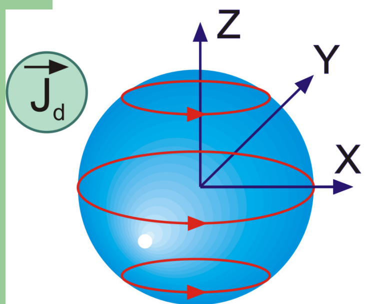
The LSK limit appeared when: $\kappa_D, \kappa_G << 1$

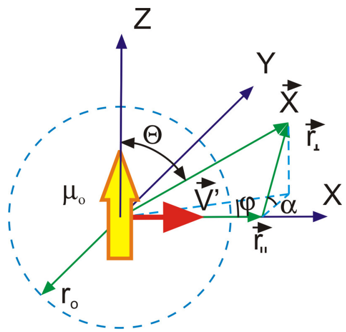
Maxwellian flow: $\kappa_{D\alpha} = v'^2 / v_\alpha^2 << 1 \qquad \kappa_{G\alpha} = v' / v_\alpha << 1$



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

Two families of elementary prescribed magnetization sources, forming «quasiparticle» in plasma flow: magnetic dipole and magnetic toroid

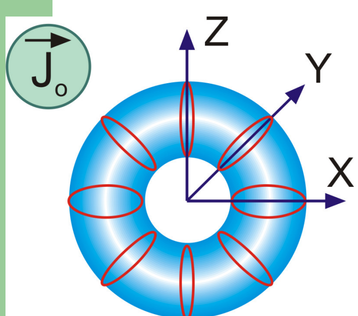


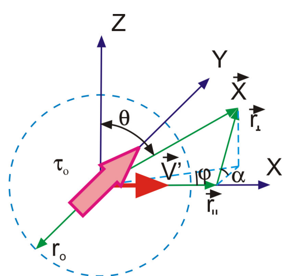


$$\mu(\mathbf{X}) = \mathbf{z}_0 \mu_0 \frac{1}{(2\pi r_0^2)^{3/2}} \exp\left(-\frac{\mathbf{X}^2}{2r_0^2}\right)$$

$$\boldsymbol{\mu}_0 = I_\mu \boldsymbol{\pi} r_0^2 \qquad \mathbf{X} = \mathbf{x} - v`\mathbf{x}_0 t$$

$$\omega = k_\perp v'$$

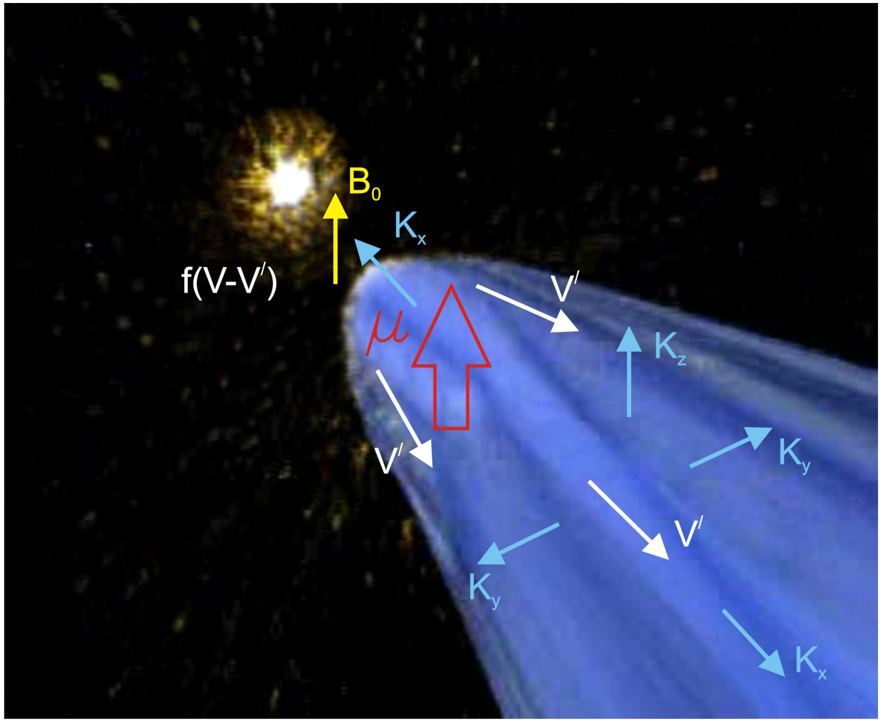




$$\tau(\mathbf{X}) = \mathbf{y}_0 \tau_0 \frac{1}{(2\pi r_0^2)^{3/2}} \exp\left(-\frac{\mathbf{X}^2}{2r_0^2}\right)$$

$$\tau_0 = I_\tau (4/3)\pi r_0^3 \qquad \Gamma_{\tau\mu} = I_\tau / I_\mu$$

Magnetosphere- «wave» package constructed from excited quasiparalle;l and quasiperpendicular EM perturbations. Dissipative «magnetotail and magnetopause», as effects of spatial dispersion in hot flows of collissionless solar wind flow



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

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

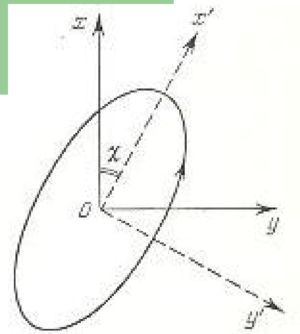
$$\varepsilon_{ij}(\omega,\vec{k}) = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ \varepsilon_{yx} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

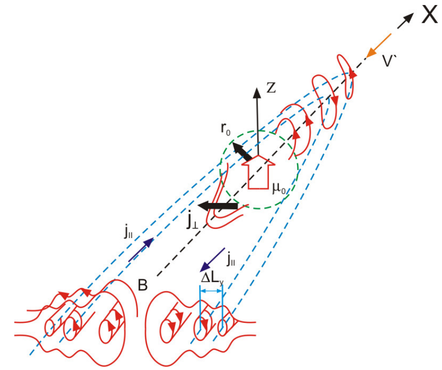
$$\varepsilon_{ij}(\omega,\vec{k}) = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & \varepsilon_{yz} \\ 0 & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix}$$

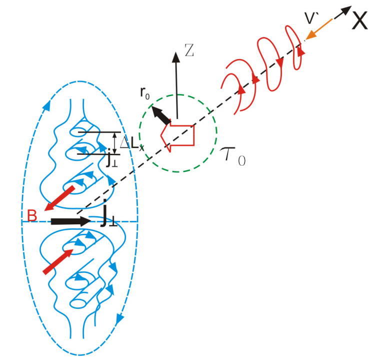
$$D_{ij} = \delta_{ij} - \frac{k_i k_j}{k^2} - \frac{\omega^2}{k^2 c^2}\varepsilon_{ij}(\omega,\vec{k})$$

$$k^2 D_{ij} E_{\vec{k}j} = 4\pi \frac{i\omega}{c^2} j_{i\vec{k}} \qquad E_{\vec{k}i}(\omega,\vec{k}) = \frac{\Delta_i(\omega,\vec{k})}{Det(\omega,\vec{k})} \qquad \Delta_i(\omega,\vec{k}) \qquad Det(\omega,\vec{k}) = \Lambda(\omega,\vec{k}) = |D_{ik}(\omega,\vec{k})| = |\Lambda_{ij} / k^2|$$

Fields







- Furie images

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

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

$$M_{Gk}(\mathbf{X},\mathrm{Re}_m,G_V) = \frac{4\pi}{(2\pi)^3}\frac{\exp(-\frac{k^2r_0^2}{2})}{k^2D_T(\mathbf{k},\mathbf{kv'})}$$

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

$$\tan\theta'^* = \frac{2}{3}k_\tau\Gamma_{\tau\mu}kr_0$$

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

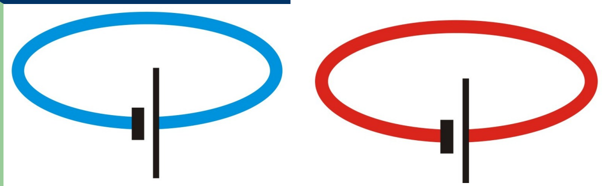
$$\mathbf{A}_\mu = \mu_0(\frac{\partial M_G}{\partial Y}\mathbf{x}_0 - \frac{\partial M_G}{\partial X}\mathbf{y}_0)$$

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

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

$$D_T(\mathbf{k},\omega) = 1 - \frac{\omega^2}{(ck)^2}\varepsilon_t(\omega,\mathbf{k})$$

First magnetic loop (dipole+ toroid) as transformer and generator of the constant current (Vlasov analog of MHD generator). Second loop as a load- plasma low. Measuring the impedance Z with R and L we can measure dimensionless parameters.



$$R_{\Sigma}(\mathrm{Re}_m, G_V) = ??? \neq R_{vac} = 0$$

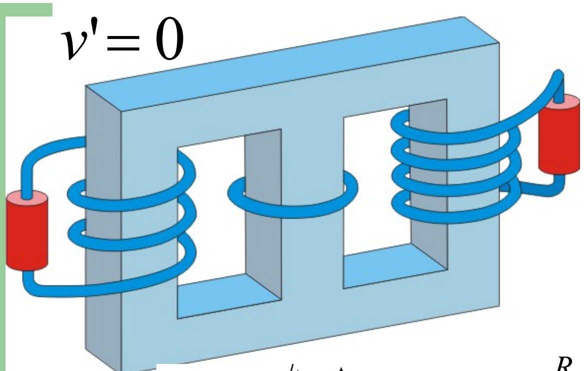
$$P(G_V, \mathrm{Re}_m) = \int d^3x (\vec{j}_0 \vec{E}) =$$

$$P_{\mu} + P_{\tau} + 2P_{\tau\mu} = I_{\mu}^2 \,\mathrm{Re}\, Z$$

$$L_{vac} \neq L(\mathrm{Re}_m, G) = ?$$

$$I_{\mu}^2 (R_{\mu} + \Gamma_{\tau\mu}^2 R_{\tau} + 2\Gamma_{\tau\mu} R_{\mu\tau})$$

$v' = 0$



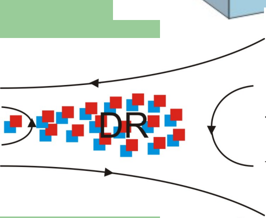
ω

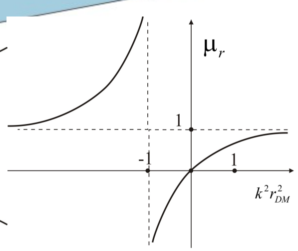
$$\omega = \vec{k}\vec{v}'$$

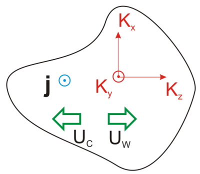
$$R_{\mu} = \frac{v'}{c^2}\frac{4\pi}{(2\pi)^4} i r_G^{-4} r_0^4 \int_0^{\infty} d\xi \xi^3 \exp(-\xi^2 \mathrm{Re}_m^2) \int_0^{\pi} d\theta (\sin\theta)^4 \int_0^{2\pi} d\varphi' \frac{\cos\varphi'}{D_T(G_V)}$$

$$R_{\tau} = i \frac{v'}{c^2}\frac{k_{\tau}^2}{9}\frac{2}{(2\pi)^3} r_0^6 r_G^{-6} \int_0^{\infty} d\xi \xi^5 \exp(-\xi^2 \mathrm{Re}_m^2) \int_0^{\pi} d\theta' \sin^2\theta' \int_0^{2\pi} d\varphi' \frac{\cos\varphi'(1-\sin^2\theta' \sin^2\varphi')}{D_T(\vec{k}\vec{v}', \vec{k})}$$

$$R_{\mu\tau} = \frac{P_{cross}}{I_{\mu}^2} = \frac{v'}{c^2}\frac{1}{(2\pi)^3}\frac{4}{3} 2k_{\tau} r_0^5 r_G^{-5} \Gamma_{\tau\mu}^2 \int_0^{\infty} d\xi \xi^4 \exp[(-\xi^2 \mathrm{Re}_m^2)] \int_0^{\pi} d\theta' \sin^3\theta' \int_0^{2\pi} d\varphi' \cos^2\varphi' \frac{1}{k^2 D_T(\vec{k}\vec{v}', \vec{k})}$$

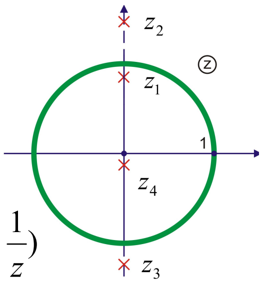




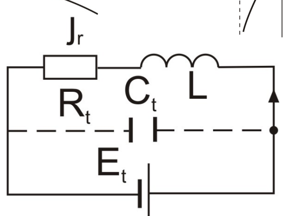


$$D_T(\mathbf{k}, \omega) = 1 - \frac{\omega^2}{(ck)^2} \varepsilon_t(\omega, \mathbf{k})$$

$$D_T = 1 - i \frac{\sin\theta\cos\varphi'}{\xi^2} + G_V \frac{\sin^2\theta\cos^2\varphi'}{\xi^2}$$

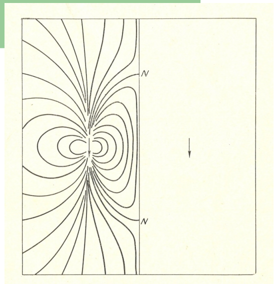


$$\cos\varphi = \frac{1}{2}\left(z + \frac{1}{z}\right)$$

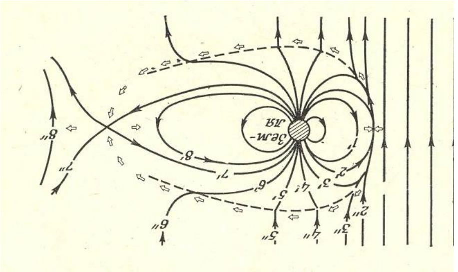


$$1 - \frac{1}{\mu(\omega)} = \frac{\omega^2}{c^2} \lim_{k \to 0} \frac{\varepsilon_t(\omega, k) - \varepsilon_l(\omega, k)}{k^2}$$

Conclusion:



$B_0 = 0$



B

- 3D electron magnetic diffusion region (DR) - result of inductive interaction of the external flow, with the source with dipole and toroid components.
- Flow itself can be diamagnetic and resistive.
- 3D magnetic field in he DR has force and forceless components.
- Forceless component appears with circular polarization, force component appears with linear polarization.
- Forceless components are due to mixing of the fields from dipole and toroid components.
- Power of the source interaction with flow is expressed via real part of the impedance - resistance.
- Resistance includes a negative component due to the forceless component in magnetic field distribution.

Спасибо!

- Вопросы?