Evolution of Anomalous Transport in Shear Flow of Toroidal Devices

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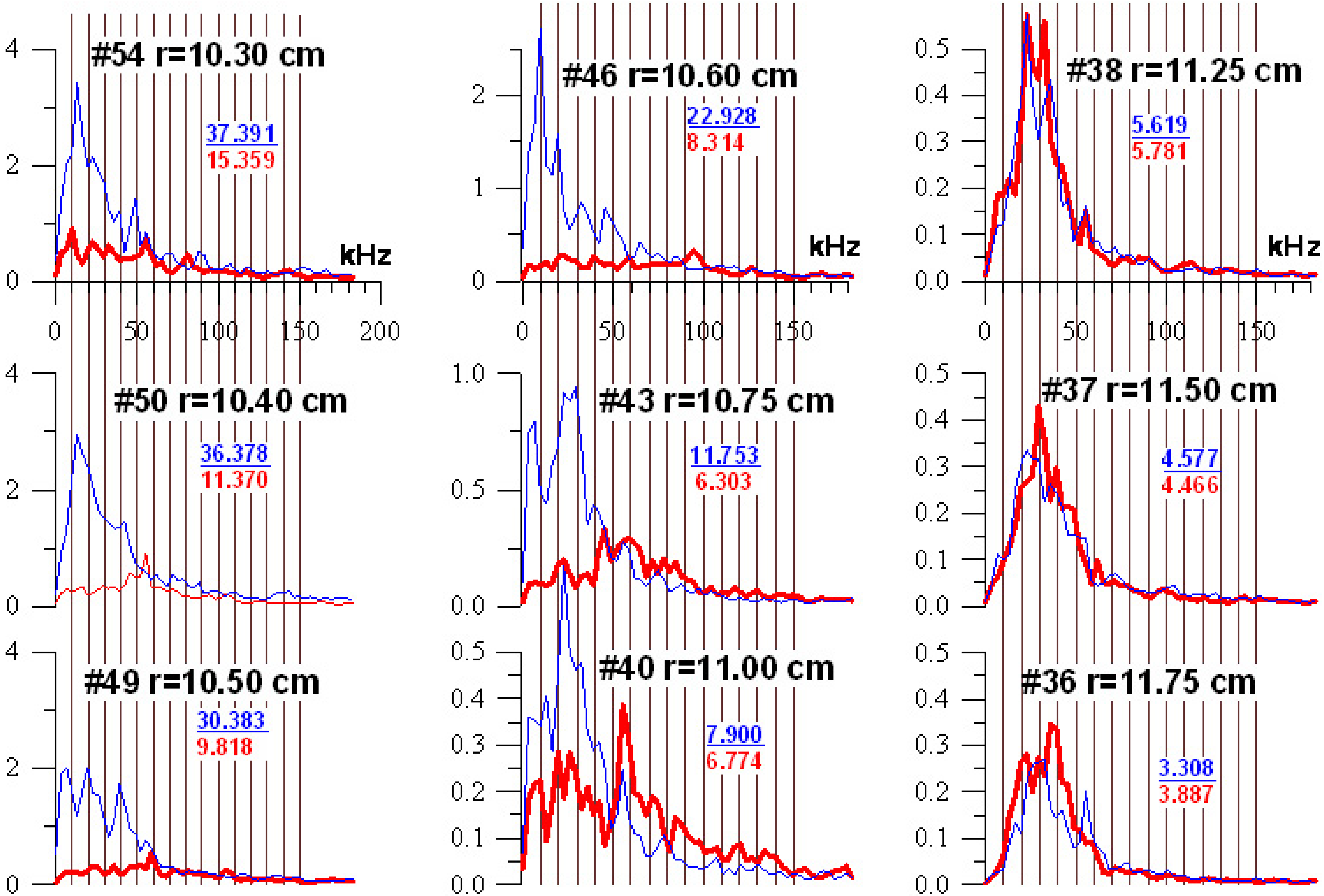
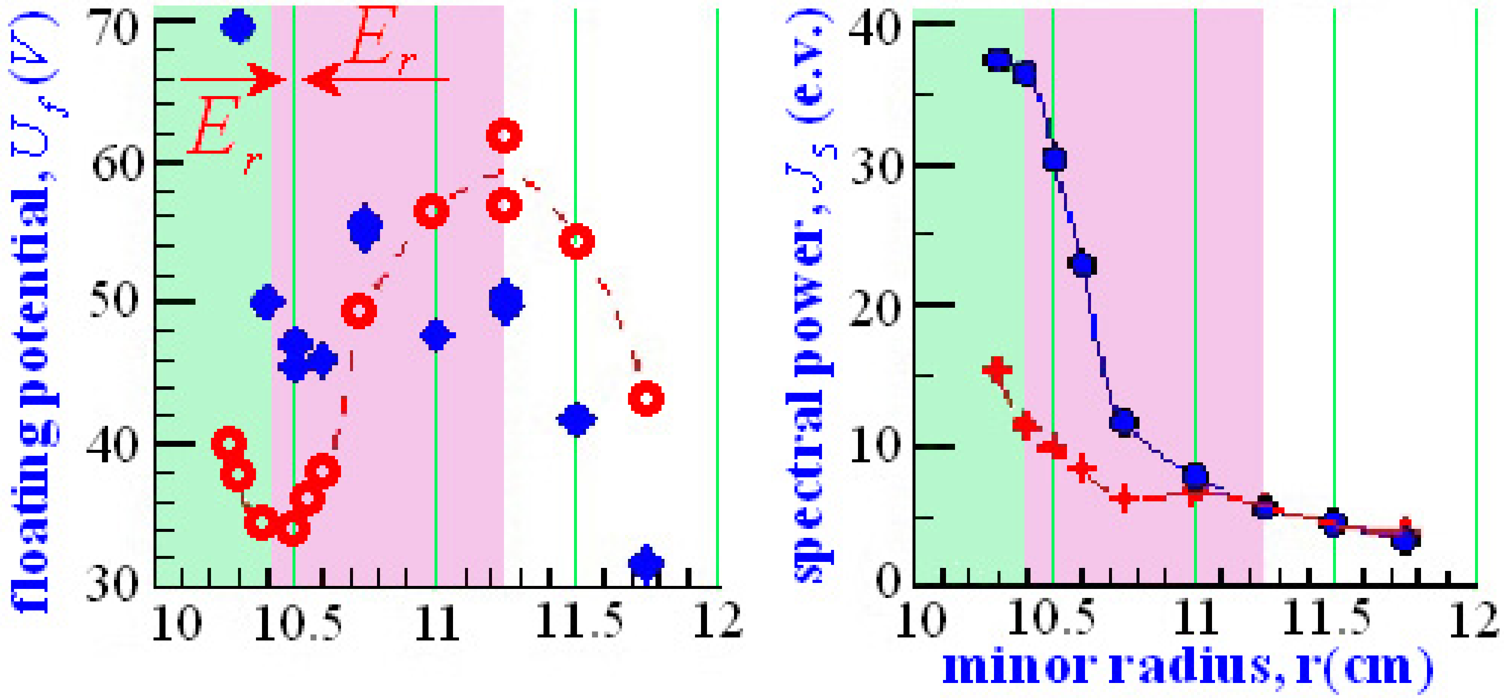
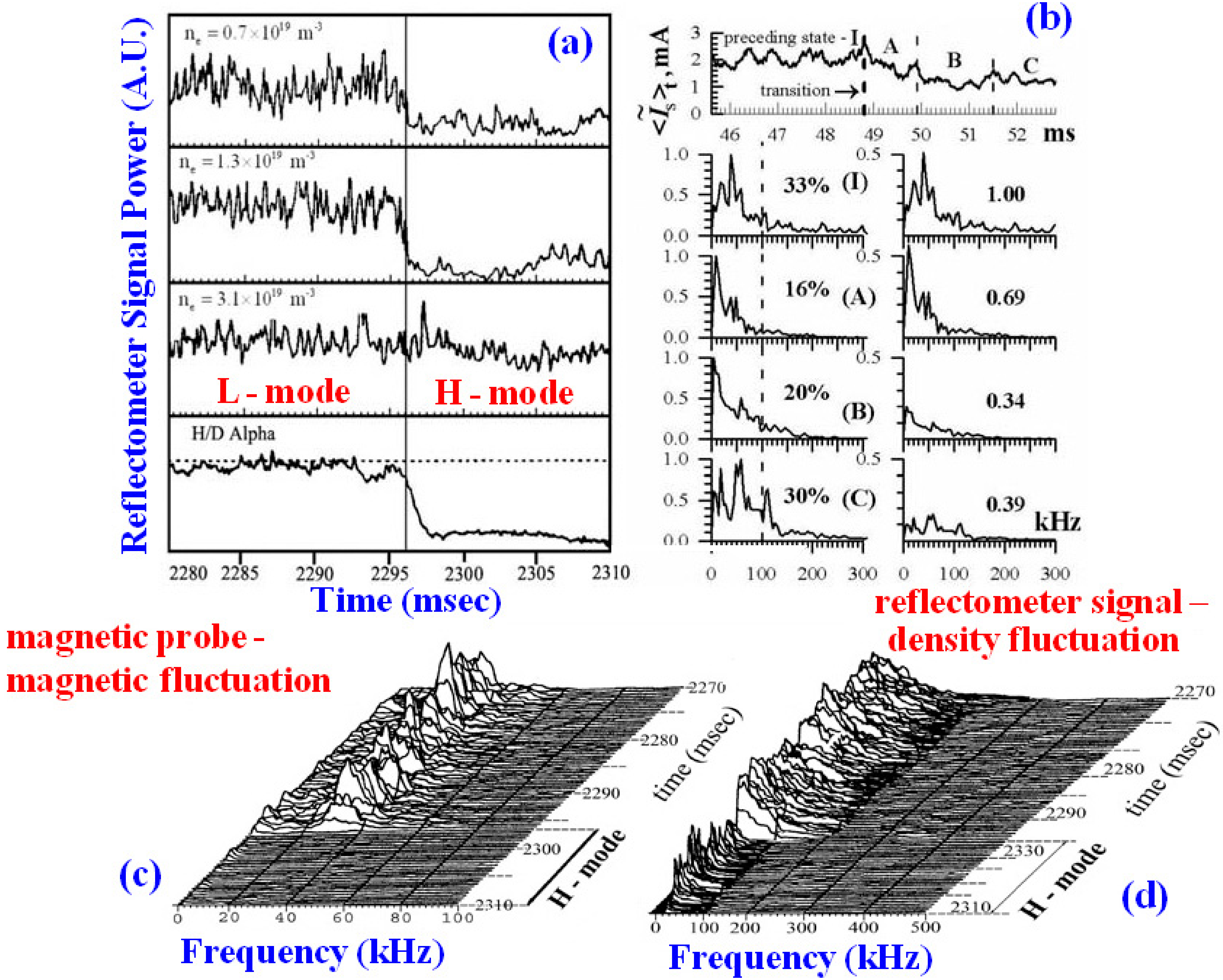


AutoSpectrum I_s (channel 2)



$B = 0.7T$, T_e=50 eV, $k_y = l = 2$ cm^{-1},

$$\omega_{dr} = \frac{lcT_e}{eB_0 L_n} \simeq 0.7 \cdot 10^6 \text{ s}^{-1} \sim \frac{dv_0}{dr}$$



(a)
Reflectometer Signal Power (A.U.)
$n_e = 0.7\times10^{19}$ m^{-3}
$n_e = 1.3\times10^{19}$ m^{-3}
$n_e = 3.1\times10^{19}$ m^{-3}
L - mode
H - mode
H/D Alpha
2280 2285 2290 2295 2300 2305 2310
Time (msec)
(b)
preceding state - I
A
B
C
transition
46 47 48 49 50 51 52 ms
33% (I)
1.00
16% (A)
0.69
20% (B)
0.34
30% (C)
0.39
kHz
0 100 200 300
magnetic probe -
magnetic fluctuation
reflectometer signal –
density fluctuation
(c)
time (msec)
H - mode
Frequency (kHz)
(d)
Frequency (kHz)

Hasegawa–Wakatani system of equations for plasma with shear flow

Mikhailenko V.S., MikhailenkoV.V., and Stepanov K.N., Initial value problem solution for Hasegawa-Wakatani equations for plasma with radial electric field shear. IAEA Technical Committee Meeting on First Principle – based Transport Theory, June 21–23, 1999, Kloster Seeon, Germany, Abstract P15;
Mikhailenko V.S., Mikhailenko V.V., and Stepanov K.N., Temporal evolution of linear drift waves in a collisional plasma with homogeneous shear flow. Physics of Plasmas, 2000, vol.7, N.1, P.94–100.

$$\rho_s^2 \left(\frac{\partial}{\partial t} + v_0' x \vec{e}_y \cdot \nabla \right) \nabla^2 \phi = a \frac{\partial^2}{\partial z^2} (n - \phi) \ ,$$
$$\left(\frac{\partial}{\partial t} + v_0' x \vec{e}_y \cdot \nabla \right) n + v_{de} \frac{\partial \phi}{\partial y} = a \frac{\partial^2}{\partial z^2} (n - \phi) \, ,$$

where $a = v_{Te}^2/\nu_{ei}$, $v_{de} = -cT_e/en_{e0}B_0L_n$.

Transition to convective coordinates

$$\tau = t, \quad \xi = x, \quad \eta = y - v_0(x)\, t = y - v_0' x t, \quad z = z.$$

$$\rho_s^2 \frac{\partial}{\partial \tau} (\Delta_{\perp c}\phi) - \frac{\partial \phi}{\partial \tau} - v_{de}\frac{\partial \phi}{\partial \eta} + \frac{\rho_s^2}{a k_z^2}\frac{\partial^2}{\partial \tau^2} (\Delta_{\perp c}\phi) = 0,$$

where

$$\Delta_{\perp c} = \frac{\partial^2}{\partial \eta^2} + \left(\frac{\partial}{\partial \xi} - v_0' t \frac{\partial}{\partial \eta}\right)^2 .$$

The time dependence in $\Delta_{\perp c}$ is responsible for the shearing of the waves pattern by the basic flow. Equation doesn't contain spatially dependent coefficients. Performing Fourier–transformations over variables ξ and η,

$$\phi\,(\tau, k_\perp, l, k_z) = \iiint d\xi\, d\eta\, dz\, e^{-i(k_\perp \xi + l\eta + k_z z)} \phi\,(\tau, \xi, \eta, z)$$

equation for $\phi\,(\tau, k_\perp, l, k_z)$ is found to be

$$\frac{1}{C}\frac{\partial^2}{\partial T^2}\Big[\left(1 + T^2\right)\phi\Big] + \frac{\partial}{\partial T}\Big\{\left[1 + l^2 \rho_s^2 \left(1 + T^2\right)\right]\phi\Big\} + iSl\rho_s\phi = 0,$$

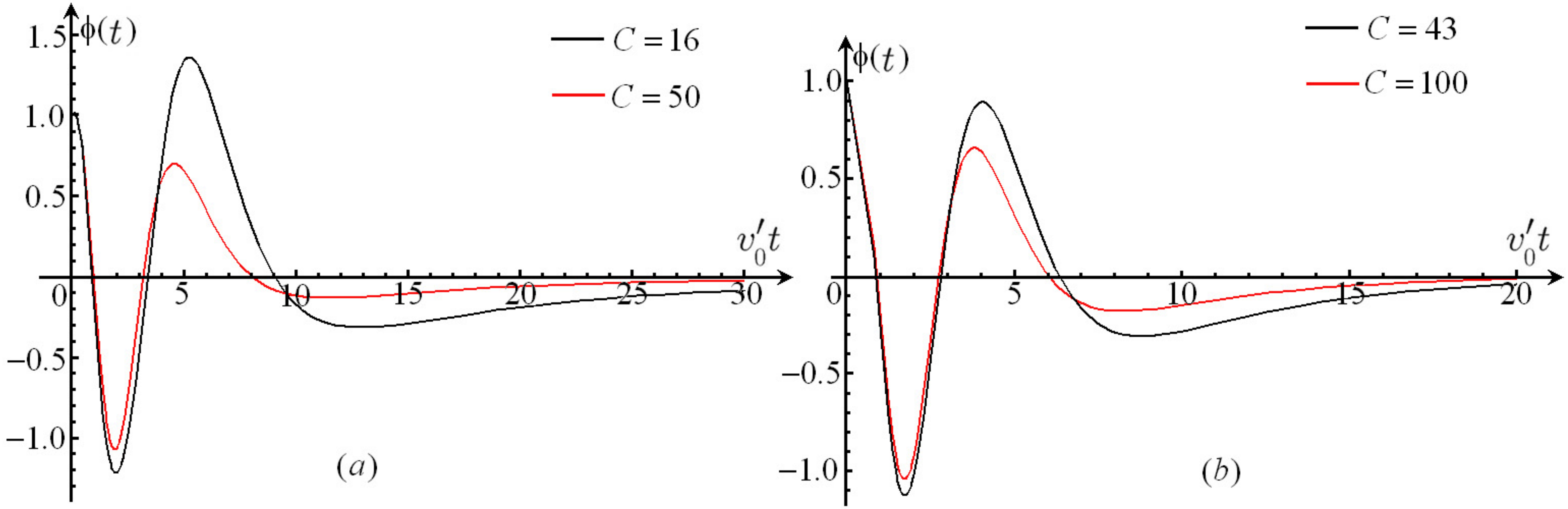
where a dimensionless time variable T is defined by $T = v_0'\tau - (k_\perp / l)$ and parameters C and S are equal respectively to $C = \dfrac{a k_z^2}{\rho_s^2 l^2 v_0'} = \dfrac{T_e k_z^2}{\rho_s^2 l^2\, v_0' n_0 e^2 \eta_\parallel}$, $S = \dfrac{l v_{de}}{v_0' l \rho_s}$. In the laboratory set of reference $k_x = k_\perp - l v_0' t,\ k_y = l$.

The solution for $\phi(\tau, k_\perp, l, k_z)$ for large values of the parameter $C \gg 1$ was obtained and it is equal to

$$
\begin{aligned}
\phi(t, k_\perp, l, k_z) &= \phi(t=0, k_\perp, l, k_z) \frac{1+\rho_s^2\left(l^2+k_\perp^2\right)}{1+\rho_s^2 l^2+\rho_s^2\left(l v_0' t - k_\perp\right)^2} \\
&\times \exp\left\{ -i\frac{S}{\sqrt{1+\rho_s^2 l^2}} \left(\tan^{-1}\frac{\rho_s\left(l v_0' t - k_\perp\right)}{\sqrt{1+\rho_s^2 l^2}} + \tan^{-1}\frac{k_\perp \rho_s}{\sqrt{1+\rho_s^2 l^2}} \right) \right. \\
&+ \frac{1}{C}\left[-2\left(v_0' t - \frac{k_\perp}{l}\right) - \frac{3}{2} i \frac{S}{l\rho_s} - \frac{1}{4}\frac{S^2\left(v_0' t - \frac{k_\perp}{l}\right)}{\left(1+l^2\rho_s^2\right)} \right] \frac{1}{\left(1+l^2\rho_s^2+\rho_s^2\left(l v_0' t - k_\perp\right)^2\right)^2} \\
&+ \frac{1}{C}\left[-2\frac{k_\perp}{l} + \frac{3}{2} i \frac{S}{l\rho_s} - \frac{1}{4}\frac{k_\perp}{l}\frac{S^2}{1+l^2\rho_s^2} \right] \frac{1}{\left(1+\left(l^2+k_\perp^2\right)\rho_s^2\right)^2} \\
&+ \frac{1}{C}\left[i\frac{S}{l\rho_s} + \frac{1}{8}\frac{S^2\left(l v_0' t - k_\perp\right)\left(1+4l^2\rho_s^2\right)}{\left(1+l^2\rho_s^2\right)^2 l} \right] \frac{1}{1+l^2\rho_s^2+\rho_s^2\left(l v_0' t - k_\perp\right)^2} \\
&+ \frac{1}{C}\left[-i\frac{S}{l\rho_s} + \frac{1}{8}\frac{S^2 k_\perp\left(1+4l^2\rho_s^2\right)}{l\left(1+l^2\rho_s^2\right)^2} \right] \frac{1}{1+\rho_s^2\left(k_\perp^2+l^2\right)} \\
&\left. + \frac{1}{8C}\frac{S^2\left(1+4l^2\rho_s^2\right)}{l\rho_s\left(1+l^2\rho_s^2\right)^{5/2}} \left(\tan^{-1}\frac{\rho_s\left(v_0' l t - k_\perp\right)}{\sqrt{1+\rho_s^2 l^2}} + \tan^{-1}\frac{k_\perp\rho_s}{\sqrt{1+\rho_s^2 l^2}} \right) \right\} .
\end{aligned}
$$

For Texas Experimental Tokamak (TEXT) (Ch.P.Ritz,et al., Phys. Fluids., 1984, p.2956) $T_e = 20$ eV, $n_{0e} = 2 \cdot 10^{12}$ cm^{-3}, $B_0 = 0.7 \cdot 10^4$G, $L_{v_0} = 0.5$ cm, $L_n = 1.5$ cm, $\rho_s = 0.06$ cm, $k_\perp \simeq l = 5$cm^{-1}, drift frequency $\omega_{dr} = 7.5 \cdot 10^5$ s^{-1}, $v_0' = 4.5 \cdot 10^5$ s^{-1} we have $S = 6$ and $C = 16$. For these parameters the temporal evolution of the potential $\phi\left(\tau, k_\perp, l, k_z\right)$, is presented on fig.1a.

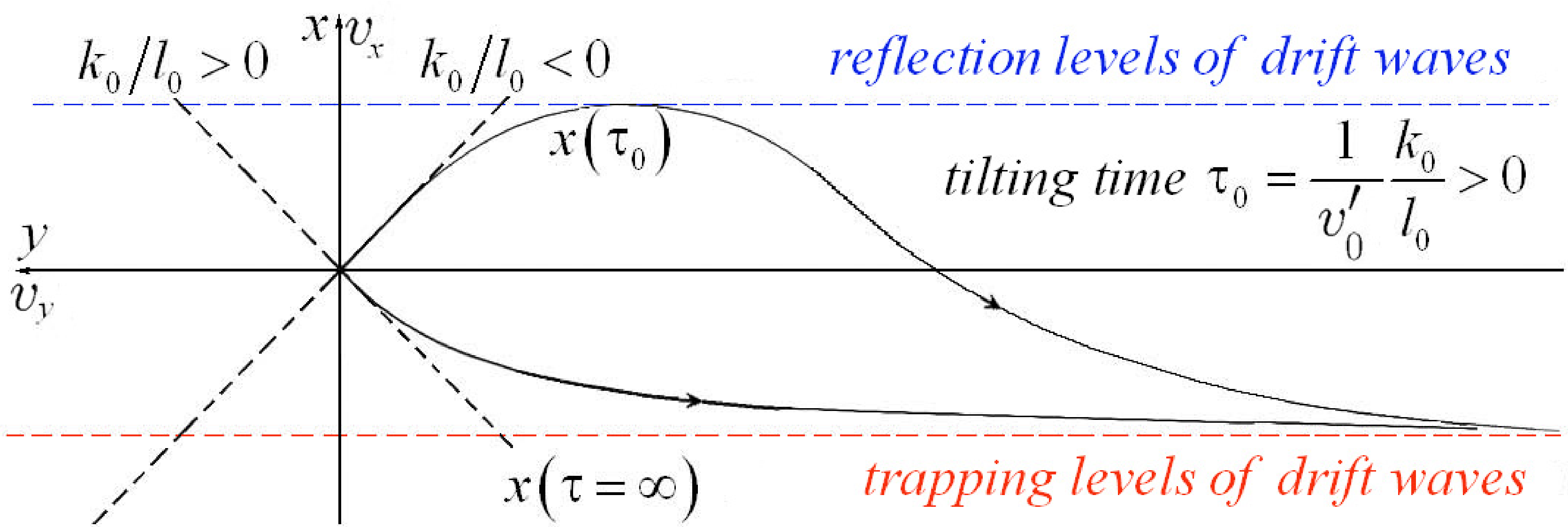
For the Uragan–3M (U–3M) torsatron data ($T_e = 50$ eV, $n_{0e} = 5 \cdot 10^{11}$ cm^{-3}, $B_0 = 0.7 \cdot 10^4$ G, $L_{v_0} = 1$ cm, $L_n = 1.5$ cm, $k_\perp \simeq l = 1$cm^{-1}, $\rho_s = 0.1$ cm, $\omega_{dr} = 10^5 \div 1.4 \cdot 10^6$ s^{-1}, $v_0' = 7 \cdot 10^5$s^{-1}, $S = 6.6$ and $C = 43$) the function $\phi\left(\tau\right)$ is presented on fig.1b. It follows, that the suppression of the drift resistive instability for the above presented data for TEXT and U-3M is a non–modal process.



Temporal evolution of the electrostatic potential of drift waves for the conditions of the tokamak TEXT(a) and torsatron U-3M (b).

$$v_{gx}=-2v_{de}\frac{\rho_s^2 l_0\left(k_{\perp 0}-v_0' l_0\tau\right)}{\left[1+\rho_s^2 l_0^2+\rho_s^2\left(k_{\perp 0}-v_0'\tau l_0\right)^2\right]^2},$$

$$v_{gy}=v_{de}\frac{1-\rho_s^2 l_0^2}{\left(1+\rho_s^2 l_0^2\right)\left(1+\rho_s^2 l_0^2+\rho_s^2\left(k_{\perp 0}-v_0'\tau l_0\right)^2\right)}$$
$$+2v_*\frac{\rho_s^2 l_0\left(k_{\perp 0}-v_0' l_0\tau\right)}{1+\rho_s^2 l_0^2}\frac{\left(k_{\perp 0} l_0\rho_s^2+v_0'\tau\right)}{\left(1+\rho_s^2 l_0^2+\rho_s^2\left(k_{\perp 0}-v_0'\tau l_0\right)^2\right)^2}.$$



Temporal evolution of drift waves energy

$$\frac{\partial E}{\partial t} = \frac{1}{2}\frac{\partial}{\partial t}\int \left[n^2 + \rho_s^2 (\nabla\phi)^2\right] dV = -\int n\left[\widehat{\mathbf{z}} \times \boldsymbol{\kappa}\right] \cdot \nabla\phi \, dV$$

$$\frac{1}{2}\rho_s^2 \frac{\partial}{\partial t}(\nabla\phi)^2 = \iiint dk dl dk_z \; \phi^2 (t, k_\perp, l, k_z)\, v_0'$$
$$\times \left[(v_0' t)\, l^2 \rho_s^2 - \left(l^2 \rho_s^2 \left(1 + (v_0' t)^2\right) + k_z^2 \rho_s^2 \right) \right.$$
$$\left. \times \left(2 (v_0' t)\, l^2 \rho_s^2 + i \frac{S}{(1 + l^2\rho_s^2)\left(1 + l^2 \rho_s^2 (v_0' t)^2\right)} \right) \right] + \mathcal{O}\left(\frac{1}{C}\right) \sim -\frac{1}{v_0' t}$$

$$\frac{1}{2}\frac{\partial n^2}{\partial t} = -\iiint dk dl dk_z \; \phi^2 (t, k_\perp, l, k_z)\, v_0'$$
$$\times \left(2 (v_0' t)\, l^2 \rho_s^2 + i \frac{S}{(1 + l^2\rho_s^2)\left(1 + l^2 \rho_s^2 (v_0' t)^2\right)} \right) + \mathcal{O}\left(\frac{1}{C}\right) \sim -\frac{1}{(v_0' t)^3}$$

Density fluxes

For times $|v_0' t| \gtrsim \left|\frac{k}{l}\right|$ and $|v_0' t| > 1$

$$\Gamma_x = \langle nv \rangle_x \simeq -\frac{c}{B_0} \iint\limits_{-\infty}^{\infty} dkdl \ (\phi_0)^2 \frac{cl}{B_0} \frac{S}{C}$$

$$\times \left[\frac{1 + \rho_s^2 \left(l^2 + k^2\right)}{1 + \rho_s^2 l^2 \left(1 + \left(v_0' t\right)^2\right)} \right]^2 \left(\frac{l \rho_s \left(1 + \left(v_0' t\right)^2\right)}{1 + \rho_s^2 l^2 \left(1 + \left(v_0' t\right)^2\right)} \right) \sim -\frac{1}{\left(v_0' t\right)^4}$$

Rayleigh–Taylor instability

Mikhailenko V.S., Mikhailenko V.V., and Weiland J., Rayleigh–Taylor instability in plasmas with shear flow. Physics of Plasmas, vol. 9, 7, p.2891–2895, 2002;
Mikhailenko V.S., Scime E.E., Mikhailenko V.V., Stability of stratified flow with inhomogeneous shear. Physical Review E, vol.71., 026306, 2005.

$$\frac{d}{dt}\nabla_{\perp}^{2}\phi = -\frac{v_{A}^{2}}{c^{2}}4\pi e\, v_{Re}\frac{\partial n}{\partial y},$$

$$\frac{dn}{dt} + v_{Re}\frac{\partial n}{\partial y} + \frac{en_{0e}}{T_{e}}\left(v_{de} - v_{Re}\right)\frac{\partial \phi}{\partial y} = 0,$$

where

$$v_{de} = -\frac{cT_{e}}{en_{e0}B_{0}}\frac{dn_{e0}}{dx}, \qquad v_{Re} = -\frac{cT_{e}}{eB_{0}R}, \qquad R = \left|\frac{1}{B_{0}}\frac{dB_{0}(x)}{dx}\right|,$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + v_{0}(x)\frac{\partial}{\partial y} + \frac{c}{B_{0}}\left[\vec{e}_{z} \times \nabla\phi\right]\cdot\nabla$$

$$\frac{\partial^{2}}{\partial \tau^{2}}\left[\rho_{s}^{2}\left(l^{2} + \left(k - v_{0}' l\tau\right)^{2}\right)\phi\right] + ilv_{Re}\frac{\partial}{\partial \tau}\left[\rho_{s}^{2}\left(l^{2} + \left(k - v_{0}' l\tau\right)^{2}\right)\phi\right]$$

$$-l^{2}v_{Re}\left(v_{de} - v_{Re}\right)\phi = N\left(k, l, \tau\right) .$$

$$N\left(k, l, \tau\right) = \rho_{s}^{2}\left(\frac{\partial}{\partial \tau}Q\left(k, l, \tau\right) + ilv_{Re}Q\left(k, l, \tau\right)\right) + i\frac{lv_{Re}}{en_{0}}R(k, l, \tau) .$$

Power–like non–modal solutions in the case of the Rayleigh–Taylor instability for the perturbed electrostatic potential and electron density,

$$\phi\left(t\right)\approx C_{1}\left(v_{0}^{\prime}t\right)^{\nu-2},\qquad n\left(t\right)\approx -i\frac{cv_{0}^{\prime}l}{B_{0}\omega_{ci}v_{Re}}\nu C_{1}\left(v_{0}^{\prime}t\right)^{\nu-1},$$

where

$$\nu=\frac{1}{2}+\sqrt{\frac{1}{4}+\left(\frac{\gamma_{0}}{v_{0}^{\prime}}\right)^{2}},\qquad \gamma_{0}=\frac{\sqrt{v_{Re}v_{de}}}{\rho_{s}},$$

is settled in time $tv_{0}^{\prime}\geq 1$. For shear flow with $\frac{1}{\sqrt{2}}\gamma_{0}\leq |v_{0}^{\prime}|$ such non-modal solution is settled in time of the order of the inverse growth rate. In that case the Rayleigh–Taylor instability is suppressed by shear flow in the time less then the inverse growth rate. For this case any nonlinear processes with modal solutions can't develop.

For time $v_{0}^{\prime}t\geqslant\left(k\rho_{s}\right)^{-1}$

$$\phi\left(t\right)\approx\frac{1}{t^{2}}\left(D_{1}\left(k,l\right)e^{ilv_{Re}t}+D_{2}\left(k,l\right)\right),$$

$$n\left(t\right)\approx K_{1}\left(k,l\right)e^{ilv_{Re}t}+K_{2}\left(k,l\right).$$

Energy and Density fluxes

The energy density E and radial flux Γ_x of electron density are reduced with time.

$$\frac{\partial E}{\partial t} = \frac{1}{2}\frac{d}{dt}\int \left[\frac{1}{\rho_s^2}\widetilde{n}^2 + \left(\nabla\widetilde{\phi}\right)^2\right] dV = -\frac{v_{de}}{\rho_s^2}\int \widetilde{n}\frac{\partial\widetilde{\phi}}{\partial y}dV \sim \left(v_0' t\right)^{2\nu-3} C_1^2,$$

For time $1 \leq v_0' t \ll (k\rho_s)^{-1}$

$$\Gamma_x = \langle n v_x \rangle \simeq -\frac{c^2}{B_0^2\omega_{ci}}\frac{v_0'}{v_*}\iint_{-\infty}^{\infty} dkdl\; l^2 \nu C_1^2 \left(v_0' t\right)^{2\nu-3}$$

For time $v_0' t \geqslant (k\rho_s)^{-1}$: $\Gamma_x = \langle n v_x \rangle \sim t^{-2}$.

Drif–Alfven waves and instabilities

Mikhailenko V.S., Mikhailenko V.V., M.F. Heyn, and S.M. Mahajan, Temporal evolution of drift Alfven waves and instabilities in an inhomogeneous plasma with homogeneous shear flow. Phys. Review, E66, p.066409.1 – 066409.12, 2002.;

Basic equations

$$\frac{\partial}{\partial\tau}\left(A_\parallel - \frac{c^2}{\omega_{pe}^2}\nabla_\perp^2 A_\parallel\right) + v_{de}\frac{\partial A_\parallel}{\partial\eta} = -c\frac{\partial\phi}{\partial\zeta} + c\frac{\partial p_e}{\partial\zeta},$$

$$\frac{\partial p_e}{\partial\tau} + v_{de}\frac{\partial\phi}{\partial\eta} + \Gamma\frac{c^2}{\omega_{pe}^2}\frac{v_{Te}^2}{c}\frac{\partial}{\partial\zeta}\nabla_\perp^2 A_\parallel = 0,$$

$$\frac{\partial p_i}{\partial\tau} - v_{di}\frac{\partial\phi}{\partial\eta} = 0,$$

$$\left(\frac{\partial}{\partial\tau} + v_{di}\frac{\partial}{\partial\eta}\right)\nabla_\perp^2\phi = v_0'\frac{\partial}{\partial\eta}\left(\frac{\partial p_i}{\partial\xi} - v_0'\tau\frac{\partial p_i}{\partial\eta}\right) - \frac{v_A^2}{c}\frac{\partial}{\partial\zeta}\nabla_\perp^2 A_\parallel.$$

$$\phi = \left(e\widetilde{\phi}/T_e\right), \quad A_\parallel = \left(e\widetilde{A}_\parallel/T_e\right), \quad p_e = \left(\widetilde{p}_e/n_{0e}T_e\right), \quad p_i = \left(\widetilde{p}_i/n_{0i}T_i\right)$$

$$\frac{\partial}{\partial T}\left[\left(1+\frac{c^2l^2}{\omega_{pe}^2}\left(1+T^2\right)\right)A_\parallel\right]+iC_eA_\parallel=-i\frac{c}{v_A}S\phi+i\frac{c}{v_A}Sp_e,$$

$$\frac{\partial p_e}{\partial T}+iC_e\phi=i\Gamma\frac{c}{v_A}\frac{v_{Te}^2}{\omega_{pe}^2}Sl^2\left(1+T^2\right)A_\parallel,$$

$$\frac{\partial p_i}{\partial T}=iC_i\phi,$$

$$\frac{\partial((1+T^2)\phi)}{\partial T}+iC_i(1+T^2)\phi=-Tp_i-i\frac{v_A}{c}S\left(1+T^2\right)A_\parallel,$$

where

$$T=v_0'\tau-\frac{k_\perp}{l},\qquad S=\frac{k_zv_A}{v_0'},\qquad C_{e,i}=\frac{lv_{de,di}}{v_0'}\,.$$

Inertial Alfven wave ($\beta \ll m_e/m_i$). Cold ions.

$$\frac{\partial}{\partial T}\left(\frac{c^2 l^2}{\omega_{pe}^2}\left(1+T^2\right)A_{\|}\right) = -i\frac{cS}{v_A}\phi,$$
$$\frac{\partial}{\partial T}\left(\left(1+T^2\right)\phi\right) = -i\frac{v_A S}{c}\left(1+T^2\right)A_{\|}.$$

Modal solution for times $|v_0'|t < 1$ with frequency

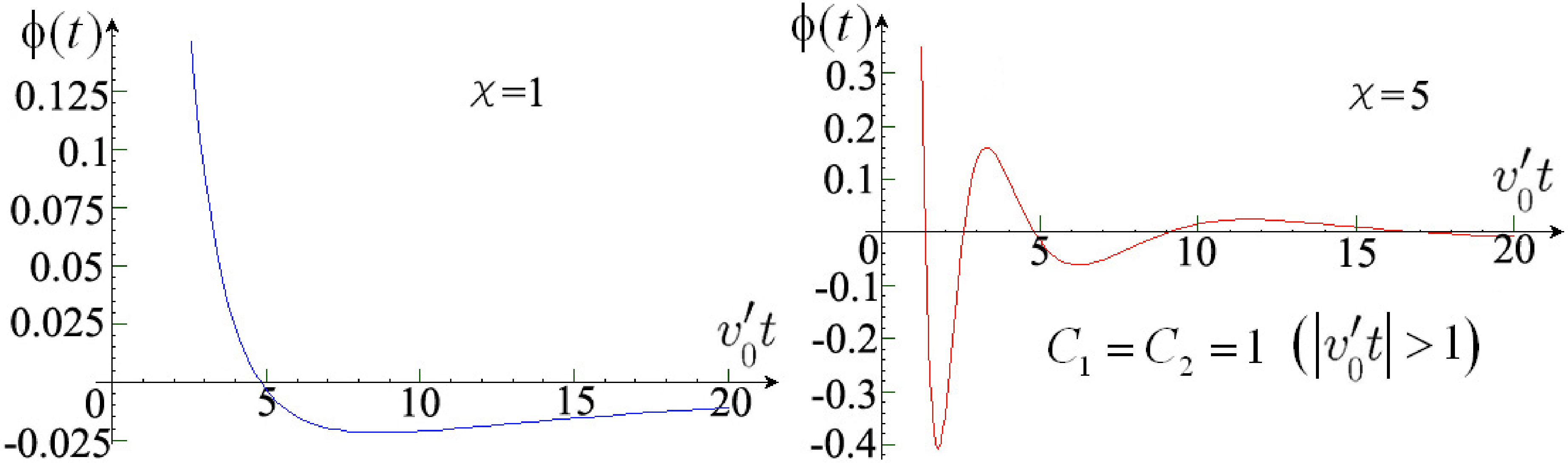
$$\omega^2 = \frac{v_A^2 k_z^2}{1+\dfrac{c^2}{\omega_{pe}^2}\left(l^2+k_\perp^2\right)}.$$

Nonmodal solution for times $|v_0'|t < 1$

$$\phi\left(T, k_\perp, l, k_z\right) \approx \frac{1}{T^{3/2}}\Big(C_1\left(k_\perp, l, k_z\right)T^{i\chi} + C_2\left(k_\perp, l, k_z\right)T^{-i\chi}\Big),$$
$$A_{\|}\left(T, k_\perp, l, k_z\right) \approx \frac{ic}{k_z v_A^2}\frac{1}{T^{5/2}}\left(\frac{C_1\left(k_\perp, l, k_z\right)}{\frac{1}{2}+i\chi}T^{i\chi} + \frac{C_2\left(k_\perp, l, k_z\right)}{\frac{1}{2}-i\chi}T^{-i\chi}\right),$$

where $\chi = \sqrt{\omega^2/(v_0')^2 - 1/4}$.

The different time dependence of different perturbations in a linear system, is a strictly non–modal element introduced by the velocity shear.



φ(t)
0.125
0.1
0.075
0.05
0.025
0
-0.025
5
10
15
20
v′0t
χ=1
φ(t)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
5
10
15
20
v′0t
χ=5
C1 = C2 = 1 (|v′0t| > 1)

Kinetic Alfven wave ($1 \gg \beta \gg m_e/m_i$). Cold ions.

$$\frac{\partial^2}{\partial T^2}\left\{\left(\frac{1}{1+T^2}+\frac{c^2 l^2}{\omega_{pe}^2}\right)\frac{\partial}{\partial T}\left[\left(1+T^2\right)\phi\right]\right\}+S^2\frac{\partial}{\partial T}\left[\left(1+l^2\rho_s^2\left(1+T^2\right)\right)\phi\right]$$
$$+iC_e S^2\phi+iC_e\frac{\partial}{\partial T}\left\{\frac{1}{1+T^2}\frac{\partial}{\partial T}\left[\left(1+T^2\right)\phi\right]\right\}=0.$$

$$\phi_{1,2}(T)\simeq \exp\left(\pm i k_z v_{\scriptscriptstyle A} t\left(1+K_\perp^2\rho_s^2\right)\right)\,, \qquad 0<T<1\,,$$

$$\phi_{1,2}(T)\simeq \frac{1}{T}\exp\left(\pm iST\right)\,, \qquad 1<T<\frac{1}{l\rho_s}\,,$$

$$\phi_{1,2}(T)\simeq \frac{1}{T^{3/2}}\exp\left(\pm i\frac{ST^2}{2}l\rho_s\right)\,, \qquad \frac{1}{l\rho_s}<T<\frac{v_{Te}}{v_{\scriptscriptstyle A}}\frac{1}{l\rho_s},$$

$$\phi_{1,2}(T)\simeq \frac{1}{T^2}\exp\left(\pm i k_z v_{Te} t\right) \qquad \frac{v_{Te}}{v_{\scriptscriptstyle A}}\frac{1}{l\rho_s}<T\,.$$

Kinetic theory of the stability of the inhomogeneous plasmas with transverse inhomogeneous electric field.

Mikhailenko V.S., Mikhailenko V.V. Kinetic theory of the stability of the inhomogeneous plasmas with transverse inhomogeneous electric field. Physics of Plasmas, vol. 13, 012108, 2006

The transformation to the guiding center coordinates, which accounted for the distortion of the gyromotion by the shear flow

$$x = X_g - \frac{v_\perp \sin\phi_1}{\omega_{c\alpha}\sqrt{\eta_\alpha(X_g)}}, \qquad y = Y_g + v_0(X_g)\,t + \frac{v_\perp \cos\phi_1}{\omega_{c\alpha}\eta_\alpha(X_g)},$$

$$v_x = v_\perp \cos\phi_1, \qquad v_y = v_0(X_g) + \frac{v_\perp \sin\phi_1}{\sqrt{\eta_\alpha(X_g)}},$$

where $\eta_\alpha(X_g) = 1 + \left(v_0'(X_g)/\omega_{c\alpha}\right)$, $\phi_1 = \phi - \omega_{c\alpha}\sqrt{\eta(X_g)}t$.

The linearized version of the local dispersion equation is the same as for the plasma without shear flow, but with cyclotron frequency ω_c changed with $\omega_c\sqrt{\eta}$. Therefore the transverse flow with homogeneous shear is not a source of the linear "shear-flow-driven" instabilities. However even the homogeneous flow shear may strongly modify the nonlinear evolution and the saturation of the instabilities.

The inhomogeneity of the flow shear $\left(v_0'' \neq 0\right)$ is a source of the new mechanism of the resonant $\left(\omega - k_y v_0 - n\omega_{ci}\sqrt{\eta_i(X)} - \frac{k_y v_0''(X)\, v_\perp^2}{4\omega_{ci}^2 \eta_i^2(X)} - k_z v_z = 0\right)$ damping of waves across the magnetic field due to their interaction with ions, which is akin to the finite–β resonance in the curved magnetic field. In this case the dispersion equation for long, $k_\perp \rho_i \ll 1$, low frequency, $\omega \ll \omega_{ci}$, waves has a form

$$1 + \frac{1}{k^2\lambda_{Di}^2}\left[1 + \left(1 + \zeta_{i0} - \frac{2\omega_{ci}\eta_i(X)}{L_n v_0''(X)}\right) e^{-\zeta_{i0}} \left(i\frac{\pi}{2}\text{sign}\left(k_y v_0''(X)\right)(1 + \text{sign}\,(\zeta_{i0})) - Ei\,(\zeta_{i0})\right)\right]$$
$$+\frac{1}{k^2\lambda_{De}^2}\left(1 + i\sqrt{\pi} z_{e*} W\,(z_{e0})\right) = 0,$$

where

$$\zeta_{i0} = \frac{2\,(\omega - k_y v_0)\,\eta_i^2(X)}{k_y \rho_i^2 v_0''(X)}.$$

The frequency and the growth rate of the drift instability are

$$\widetilde{\omega}=\frac{1}{2}\frac{k_y\rho_i^2 v_0''(X)}{\eta_i^2(X)\left(\dfrac{T_i}{T_e}+k^2\lambda_{Di}^2\right)}-\frac{\omega_{di}}{\eta_i(X)\left(\dfrac{T_i}{T_e}+k^2\lambda_{Di}^2\right)}$$

$$\gamma=\gamma_i+\gamma_e=-\frac{\widetilde{\omega}^2\eta_i^2(X)\,\pi}{|k_y v_0''(X)|\rho_i^2}\Big(1+\text{sign}(\zeta_{i0})\Big)e^{-\zeta_{i0}}$$
$$\times\frac{1}{\left(1+\dfrac{T_i}{T_e}+k^2\lambda_{Di}^2\right)}-\frac{T_i}{T_e}\frac{\widetilde{\omega}}{\left(\dfrac{T_i}{T_e}+k^2\lambda_{Di}^2\right)}\sqrt{\frac{\pi}{2}}\frac{(\widetilde{\omega}-\omega_{de})}{k_z v_{Te}},$$

where $\zeta_{i0}=2\widetilde{\omega}^2\eta_i^2(X)/k_y\rho_i^2 v_0''(X)$.

It follows that in the case, when $v_0''\neq 0$, the resonant interaction of drift waves with ions in spatially inhomogeneous plasma leads to the damping of these waves.

CONCLUSIONS

- Above presented results proves that the character of fluctuations of the drift and interchange type in plasma flows with sufficiently strong flow shear is dominated by the sheared flow. These mode–specific nonmodal solutions, not the conventional modal solution, have to be used in the development of the theory of plasma turbulence and anomalous transport of the plasma shear flow as well as in the development of the theory of the improved confinement and formation of transport barriers.

- The inhomogeneity of the flow shear forms new kinetic resonant mechanism of the waves damping due to their interaction with ions transverse to magnetic field, which is akin to the finite–β resonance in the curved magnetic field. We find that the interaction of ion cyclotron or drift waves with ions in plasma shear flow impose additional restrictions on the development of the shear flow modified drift–cyclotron and drift instabilities, which are excited due to the inverse electron Landau damping of these waves.

- The development of the nonlocal (nonmodal) kinetic theory of the plasma with inhomogeneous shear flow is actual problem of the plasma theory.