Multi-Scale Interactions of $\underline{k} \cdot \underline{B} = 0$ Resonant Surfaces with Drift Wave Turbulence: Progress on a 'Minimalistic Model'

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see also: Talk by McDevitt, Thursday AM

Ackn: D. Escande, S. Cappello, A. Smolyakov, M. Yagi, K. Itoh, S.-I. Itoh

References

→ New material here:

C. J. McDevitt and P.H. Diamond;

PoP 2006 – accepted and in press
also: http://physics.ucsd.edu/plasma theory group

→ Background on {Wave Kinetics, Zonal Flows} etc.:

P.H. Diamond, K. Itoh, S.-I. Itoh, T.S. Hahm;
P.P.C.F. '05
and references therein

→ Background on turbulence effects in Ohms Law:

H. Biglari and P.H. Diamond;
Phys Fluids B 5 3838 (1993).

→ 'Turbulence Spreading' and related:

Recent papers with T.S. Hahm, O. Gurcan
(see web site)

Outline

i.) Motivation and Perspective

ii.) "Radiation Hydrodynamics" for Drift Waves
- a tractable approach.

iii.) Minimalistic (but not so easy) Problem:
- FKR meets Hasegawa-Mima:
Tearing + DWT (Electrostatic) on Cylinder
- thoughts on 'turbulent Rutherford' regime.
(whatever that means)

iv.) Resonant q with $\Delta' \to -\infty$: Resonant ES Vortices
- relation to zonal flows, barriers, cells
- fate of "inverse cascade" in system with $\underline{k} \cdot \underline{B} = 0$ surfaces

[some ideas for transport from MHD]

v.) Thoughts for Computation / F.S.P.

vi.) Discussion and Outlook

i.) Motivation and Perspective

→ "Multi-Scale Problem" : "buzz-word of the year" !?

→ meaning : self-consistent treatment of evolution of :

→ 'low' $\underline{k}$, ω MHD phenomena

→ 'high' $\underline{k}$, ω Drift Wave Phenomena

→ as a coupled system ....

→ MFE Applications (partial listing)

- NTM : turbulent heat + momentum transport ⇒ island evolution

- barriers triggered by resonant q (Cromat, TJ-II, DIII-D, others)

↓

- corrugated / choppy ∇T - a 'question of the ages' for MFE

and more ....

⇒ A Pragmatic View of the "Multi-Scale Problem"

- 'subgrid scale model' of turbulence (drift, ITG, etc.) for MHD/macro codes

[N.B. What this group really wants ....]

- why this is highly non-trivial : **Despite weak turbulence**

→ {small / unresolved} scales must be 'dynamic'
i.e. → strained, advected by large (MHD) scales
→ non-local (in k) coupling

→ "inverse cascade" (i.e. energy transfer to large/resolved scales) generic and fundamental to DWT

- 'eddy viscosity' can be < 0 !

- drift wave + zonal flow evolution is prime example (waves excite flow)

* - Low m MHD should couple to this process. **multiple energy sources!?**

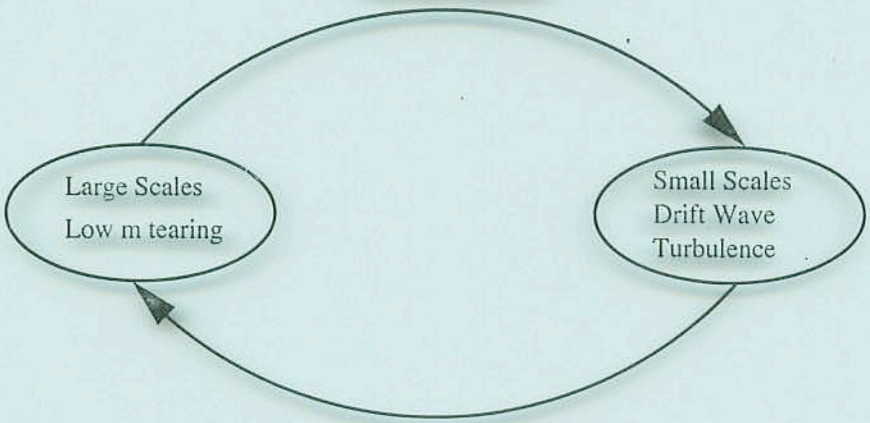


Figure 1: Minimal Multi-scale Model.

Closed loop

Multi-Scale Interaction Processes

small → large : "inverse cascade"

especially via $\underline{k} \triangle \underline{k}'$ type triads
$\underline{q}$

⇒ define stresses "seen" by macroscopics

large → small : adiabatic modulation

i.e. straining, advection of small scales
by large, resolved scales.

→ Despite a "Buzzword of the Year" status, Multi-Scale Problem is hardly new ...

i.e.

i.) Langmuir turbulence – classic

- high frequency plasmon + low frequency ion-acoustic
- described by { wave kinetics + ponderomotive pressure / mean field Zakharov equations

ii.) Zonal Flows + Drift Wave Turbulence (~ past 10 yrs)

- high frequency DW + $\omega = 0$ zonal flow (distinction "slow MHD"?)
- 'closed loop' description by various scale separation expansion techniques

iii.) Long history of (non self-consistent) work on turbulence effects on tearing mode

- Kaw, et. al. 78 — μ = electron viscosity
- Strauss, '86 — MHD hyper-μ
- P.D. et. al. '84 — turbulent μ
- Biglari, P.D. '93 — kinetic formalism
- Itoh, Itoh et. al. '90's, '04 — hyper-μ noise

ii.) A Tractable Approach → Adiabatic Theory
→ "Radiation Hydro" for Drift Waves

(used in more elaborate models, i.e. Camargo-Holm)

→ suggest approach: (a la' zonal flow problem)

① – evolve: $N(\underline{k}, \underline{x}, t)$ → DW population density
→ $\sim |\hat{\phi}_k|^2$, etc.

via wave-kinetic equation, in MHD fields:
i.e. (Boltzmann) (useful framework)

$$\frac{\partial N}{\partial t} + \underbrace{(\underline{V}_{gr} + \underline{V})}_{\text{MHD flow advection}} \cdot \nabla N - \underbrace{\frac{\partial}{\partial \underline{x}}}_{\text{MHD refraction}} (\omega + \underbrace{\underline{k} \cdot \underline{V}}_{\text{MHD strain/shear (Doppler)}}) \cdot \frac{\partial N}{\partial \underline{k}}$$

$$= \underbrace{\gamma_k N}_{\text{growth} \Leftrightarrow \text{ profiles modified}} + \underbrace{C(N, N)}_{\text{DW-DW (non-adiabatic) interactions}}$$

↳ eigenfunction modifications

$\boxed{\text{LHS Hamiltonian}}$

Key: $\tau_{c_{DW}}$ → effective mean free time / DW correlation time (self)

$\tau_{c_{DW}} V' < 1$ → 'Chapman-Enskog' expansion for N about $\langle N \rangle$
→ radiation hydro. approach

③

- use $N(\underline{k}, \underline{x}, t)$ to compute stresses, fluxes of MHD, driven by drift waves

i.e. $\phi^{<} \rightarrow$ resolved - MHD

$\phi^{>} \rightarrow$ unresolved - DW

vorticity equation of RMHD

$$\frac{\partial}{\partial t}\nabla^2\phi + \nabla\phi^{<}\times\hat{z}\cdot\nabla\nabla^2\phi^{<} + \langle\underline{\nabla}\phi^{>}\times z\cdot\underline{\nabla}\nabla^2\phi^{>}\rangle$$

$= \text{......}$

→ subgrid model

$$\langle\underline{\nabla}\phi^{>}\times\hat{z}\cdot\underline{\nabla}\nabla^2\phi^{>}\rangle \Rightarrow \sum_{k>k_M} C_k\, N(\underline{k}, \underline{x}, t)$$

seek : $\boxed{\delta\langle\ \rangle/\delta\phi^{<}} \Rightarrow$ response of stresses to resolved scales

$\Rightarrow \boxed{\sum_{k} C_k\ \delta N(\underline{k}, \underline{x}, t)}$

↳ from wave kinetics

- closed loop - dynamic subgrid scale model

- effectively couple $\left\{\begin{array}{l}\text{Modulational interaction of large, small scales} \\ \text{MHD process.}\end{array}\right.$

→ **Key Points** re: Wave Kinetics

① – no free lunch: – intensity field of small scales, only
i.e. – quadratic NL – no phase info.
– thin triads $\underline{k} \bigtriangleup \underline{k}'$, $\underline{q}$
resolved – ~~cross~~ interaction

② – adiabatic theory: $\Omega_q < \omega_k$
(weaknesses?)

$|\underline{q}| < |\underline{k}|$

for drift-MHD: $\left.\begin{array}{l}\Omega_q \ll \omega_k \\ q_0 \ll k_0\end{array}\right\}$ well satisfied

but . . . ? → $q_r \lesssim k_r$ → ☹ marginal!
(eikonal on radius?)

→ construct N in basis of representation of DW eigen modes (include island ?!)
↓ (see paper for simple example)

→ deals with cross-correlation issue (i.e. $\langle \tilde{v} \tilde{p} \rangle$)
multi-field case

→ also note $\underline{v}_{gr} \cdot \underline{\nabla} N / N \ll \omega_k$

→ time scale separation ☺ most important
(experience especially surface waves)

⇒ often viable to push scale separation . . .

③ Waves Kinetics applicable without "waves" ?

→ ¿ "Turbulence" has $\tau_{c_k} \sim \tau_{wave_k}$?

→ Dubrulle and Nazarenko '97:

- demonstrated can describe nonlocal interactions in 2D Hydro via:

$$\frac{\partial N}{\partial t} + \underline{V} \cdot \underline{\nabla} N - \frac{\partial(\underline{k} \cdot \underline{V})}{\partial \underline{x}} \cdot \frac{\partial N}{\partial \underline{k}} = 0$$

N → unresolved density of excitation

$\underline{V}$ → resolved field (both terms)

Key: Ω = const. along trajectories

where: $N \to \Omega(\underline{k}, \underline{x}, t)$

↳ Wigner dist. for enstrophy field

i.e. $\Omega(\underline{k}, \underline{x}, t) = \int d\underline{q}\, e^{i\underline{q}\cdot\underline{x}} \langle \omega_{\underline{k}+\underline{q}}\, \omega_{-\underline{k}} \rangle$

⇒ [N is density of vortices/rotons/eddies,
$\underline{\text{not}}$ action density (density of waves) ...

- quite relevant to MFE problems ($\underline{B_0}$!)

- $N \to \Omega$ in limit of $n = 0$ strain (Z.F. problem)!

Furthur comments:

→ knowing $\underline{N}$ → wave field $\begin{cases} \text{energy density} \\ \Rightarrow \text{radiation pressure, stresses} \\ \text{momentum density} \end{cases}$

allows calculation

or... evolve as macro moments of N → Rad. Hydro.

→ usually can represent $C(N,N)$ ala' krook,

$$C(N,N) \to -\frac{1}{\tau_c}\left(N - \langle N \rangle\right)$$

↳ derive from model-interaction model

→ approach only sensible if unresolved scales localized, spatially

⇒ ('scattering') / stresses by local radiation field, prevent wave propagation.

but satisfied in MFE, for drift waves

both limit l_{mfp} $\begin{cases} \text{— absorption by ion Landau damping, etc.} \\ \text{— wave-wave scattering} \end{cases}$

restrict individual packet propagation

(contrast: Mattor, P.D. '94).

iii.) A Minimalistic Problem : $\left\{\begin{array}{l}\text{Drift Waves} \\ + \\ \text{Tearing in} \\ \text{cylinder}\end{array}\right.$

i.e. "FKR meets Hasegawa-Mima"

– see $\left\{\begin{array}{l}\text{McDevitt talk} \\ \text{paper}\end{array}\right.$ for extensive calculation
Here emphasize ideas

– Following before : ① $\overset{\text{DW population}}{N} = (1+k_\perp^2\rho_s^2)^2 |\phi_{\underline{k}}^{>}|^2$

$$\frac{\partial N_{\underline{k}}}{\partial t} + \frac{\partial}{\partial \underline{k}}\Big(\omega_{\underline{k}} + \underbrace{\underline{k}\cdot\underline{V}}_{\text{MHD flow advection}}\Big)\cdot\frac{\partial N}{\partial \underline{x}} - \frac{\partial}{\partial \underline{x}}\Big(\omega_{\underline{k}} + \underbrace{\underline{k}\cdot\underline{V}}_{\text{MHD flow shear}}\Big)\cdot\frac{\partial N_{\underline{k}}}{\partial \underline{k}} = S_{\underline{k}}$$

turbulence advection — straining of turbulence

and as turbulence electrostatic :

easily gener. the model....

②
$$0 = \frac{\partial \psi^<}{\partial t} + \nabla\phi^< \times \hat{z}\cdot\nabla\psi^< - V_A \nabla_\parallel \phi^< - \eta_c \nabla^2\psi^<$$

NL polarization

$$0 = \frac{\partial}{\partial t}\nabla^2\phi^< + \nabla\phi^<\times\hat{z}\cdot\nabla\nabla^2\phi^< + \langle\nabla\phi^>\times\hat{z}\cdot\nabla\nabla^2\phi^>\rangle$$
$$- V_A\nabla_\parallel J^< + \nabla\psi^<\times\hat{z}\cdot\nabla J^< + \nu_c\nabla^2\nabla^2\phi^<$$

$\boxed{\langle \underline{v}\cdot\underline{\nabla}\nabla^2\phi\rangle \rightarrow \text{dominant as multi-scale effect}}$

→ $\langle \tilde{\underline{V}} \cdot \underline{\nabla} \nabla^2 \tilde{\phi} \rangle$ is dominant e.s. multi-scale effect, here

→ same multi-scale coupling as in zonal flow problem (n.b. $k_{\parallel} \to 0 \Rightarrow$ 'minimal inertia')

→ usually ignored, in favor of Ohms Law, heat transf in T.M. + turbulence exercises

∴ stress modulation → induced by TM flow.

$$\delta \langle \tilde{\underline{V}} \cdot \underline{\nabla} \nabla^2 \tilde{\phi} \rangle \to -\frac{\partial^2}{\partial x^2} \int d\underline{k} \frac{k_x k_y \, \delta N}{(1+\rho_s^2 k_\perp^2))} + \text{O.T.} \ldots$$

→ modulation of DW field induced by tearing

here:

$$\delta N = \left[\frac{-1}{(\Omega - \underline{q} \cdot \underline{V}_{gr}) + i(\gamma_{\underline{k}})} \right] \left\{ \overset{①}{q_y \frac{\partial N_k^d}{\partial x}} - \overset{②}{i (\underline{k} \times \underline{q})_z \, \underline{q} \cdot \frac{\partial N^0}{\partial \underline{k}}} \right\} \phi_q$$

① → turbulent diamagnetism ($\sim \partial N^0/\partial x$)
$\sim N^0 q_y / L_I$

② → shearing effect ($\sim V'_{TM}$) ⇒ Dominant.
$\sim q_x^2 N^0$

N.B: Diamagnetism phase → relevant island evolution!?

N.B.: Interactions via shearing favored.

$$\langle \underline{\tilde{V}} \cdot \underline{\nabla}\, \nabla^2 \tilde{\phi} \rangle = -\nu_{xx} \frac{\partial^4 \phi^{<}}{\partial x^4} \Rightarrow \left\{ \begin{array}{l} \text{negative viscosity,} \\ \text{for } \partial N^0/\partial k_x < 0 \end{array} \right.$$

$$\nu_{xx} = c_s^2 \int d\underline{k} \frac{\rho_s^2 k_y^2}{(1+\rho_s^2 k_\perp^2)^2} \left(\frac{\gamma_k}{\gamma_k^2 + (\underline{k}\cdot \underline{V}_{gr})^2} \right) k_x \frac{\partial N^0}{\partial k_x}$$

viscosity

< 0, for $\partial N^0/\partial k_x < 0$!

usually true in DWT

interesting question → spectral distortion?

⇒ subgrid scale effect is $\boxed{\text{negative viscosity!}}$

- similar structure to zonal flow problem
- reflects "inverse cascade" of drift wave turbulence → energy inflow → large scale

Key Issue for "Multi-scale" Problem: Representing inverse cascades from un-resolved scales

- closed loop straining/stress coupling
- feedback on $\langle N \rangle$ limits absurd outcome

this group must face this issue

What of <u>Feedback</u> – $\langle N \rangle$ evoln. 16a.

→ "Predator–Prey" Picture

→ alteration $\partial \langle N \rangle / \partial \underline{k}$

⇒ Mean Field / QLT !

$$\frac{\partial \langle N \rangle}{\partial t} = \frac{\partial}{\partial \underline{x}} \cdot \underline{\underline{D}}_x \cdot \frac{\partial \langle N \rangle}{\partial \underline{x}} + \frac{\partial}{\partial \underline{k}} \cdot \underline{\underline{D}}_k \cdot \frac{\partial \langle N \rangle}{\partial \underline{k}}$$

$$+ \langle \gamma N \rangle + \langle C(N, N) \rangle$$

<u>i.e.</u>

$$D_{kx} = \sum_{\underline{q}} q_y^2 k_x^2 |\tilde{V}_{y\underline{q}}|^2 \tilde{\tau}_{c_{\underline{k}, \underline{q}}}$$

– diffusion in $\underline{k}$

– shearing

$$D_x = \sum_{\underline{q}} |\tilde{V}_{y\underline{q}}|^2 \tilde{\tau}_{c_{\underline{k}, \underline{q}}}$$

– diffusion in $\underline{x}$

– spatial mixing

What is $\tilde{\tau}_{c_{\underline{k}, \underline{q}}}$?

wave packet – straining flow resonance

$$\tilde{\tau}_{c_{\underline{k}, \underline{q}}} \cong \gamma_{\underline{k}} \Big/ (\underline{q} \cdot \underline{v}_{gr})^2 + \gamma_{\underline{k}}^2$$

Zonal Flow Shearing — Tearing Mode Shearing

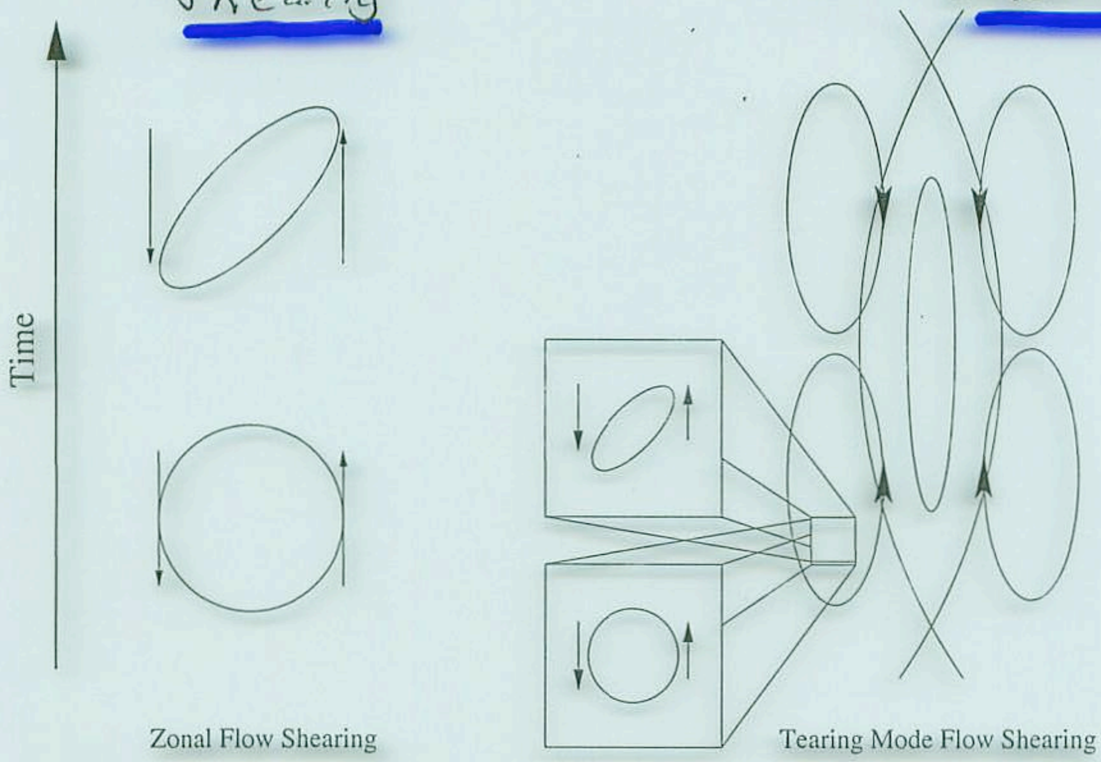


Figure 2: Zonal shear flows are similar to the shear flows of thin, low-m magnetic islands.

Both zonal flow and tearing mode flows produce shears which:

→ modulate drift waves

→ drive energy transfer to large scale.

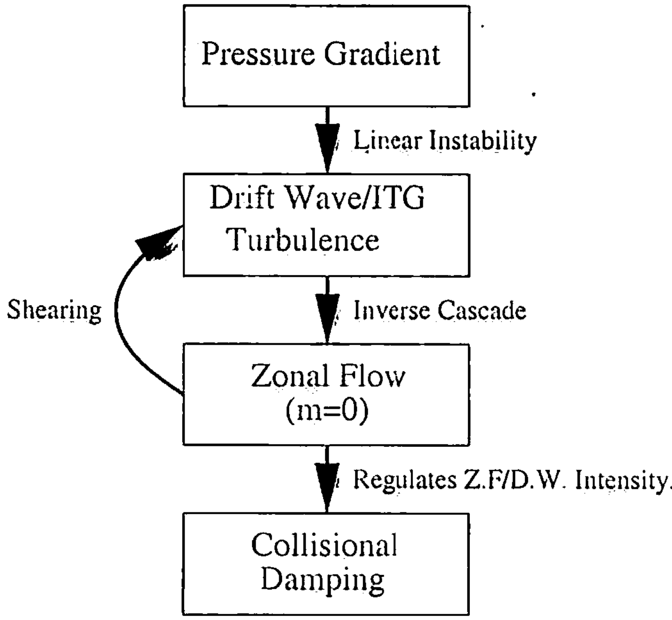


Figure 3: Schematic of drift wave-zonal flow phenomenon.

Interaction Flow Chart:

Drift Wave + Zonal Flow Problem

C. J. McDevitt , P. H. Diamond, Figure 3

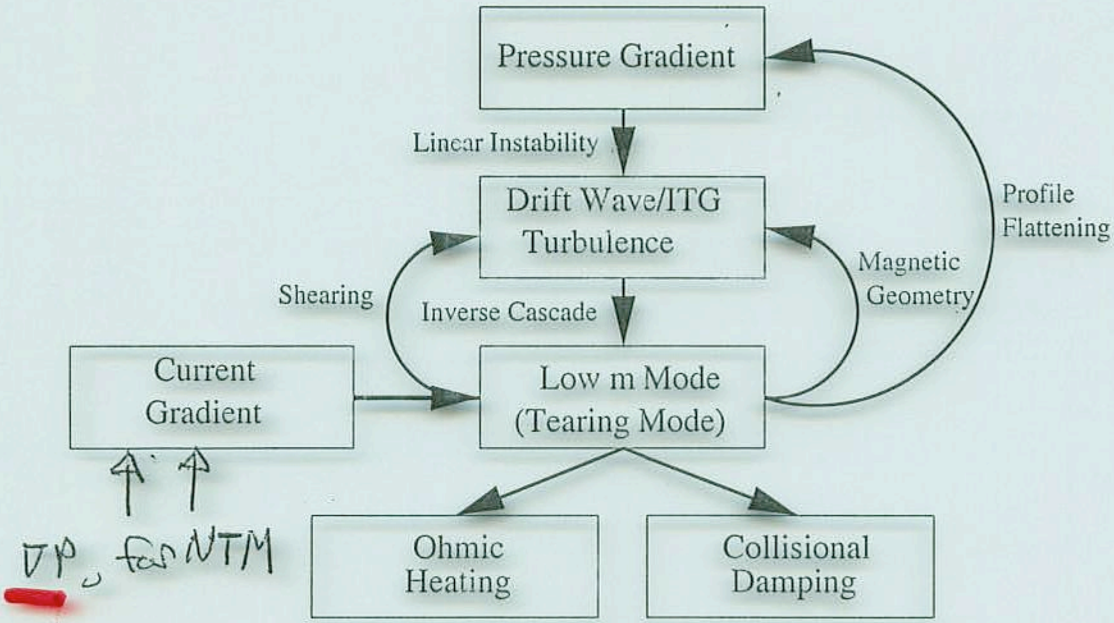


Figure 4: Schematic of Low-m mode interaction with drift wave turbulence.

Interaction Flow Chart for

Tearing + Turbulence

→ much richer, more complicated

→ if NTM, ∇P feeds both high, low m. interesting dilemma ——

Fixed flux BCs strongly advised.

→ How Big is Γ_{xx}?

- recalling Rutherford, key comparison is:

linear inertia vs. negative viscosity
$(\gamma\phi'')$ i.e. measure of 'self' vs. 'turbulent' flow interaction

- using MLT as 'guesstimate'

$$|\nu_{xx}| \sim D_{GB} \sim (\rho V_t)\frac{\rho}{L_\perp}$$

and $|\nu_{xx}| >$ inertia for:

$$D_{GB} > \frac{a^2}{\tau_\eta}(\Delta' a)^{6/5}(1/S)^{3/5}(L_s/aM)^{2/5}$$

⇒ Γ_{xx} dominates, unless fluctuations surpressed!
estimates ⇒ unlikely till finite ω_E

- in reality, "inverse cascade" swamps inertia

⇒ re-defines layer structure!

① → **Tearing Equations — Simplified**

$$\eta_c \nabla^2 \psi^< = \gamma \psi^< - i k_y \frac{V_A}{L_S} x \phi^<$$

$$0 = i k_y V_A \frac{x}{L_S} \nabla^2 \psi^< - |\nu_{xx}| \frac{\partial^4 \phi^<}{\partial x^4}$$

– layer width set by u-turbulence coupling
but
– must match to Δ' ? u-turbulence, Δ' > energy

so

– will have $\gamma_k \sim \frac{\eta \Delta'}{W}$ ⇒ W set by $|\nu_{xx}|$

– clear that: – rapid oscillations result in eigenfctn.
⇒ significant complication ⇒ resolution ?!
– wave propagation, radially

and lots of analysis ⇒ → $\boxed{\text{necessary for propagation direction}}$

key: Imposition of $\boxed{\text{outgoing wave B.C.'s}}$ to effect match to MHD

Results

$\Rightarrow$

$$\gamma_q \sim \frac{\eta_c}{W_q} \Delta' \sim \frac{\eta_c^{5/6}}{|\gamma_{xx}|^{1/6}} \left(\frac{q_y V_A}{L_s}\right)^{1/3} \Delta'$$

$$W_q = (\eta_c |\gamma_{xx}|)^{1/6} \left(L_s / q_y V_A \right)^{1/3} \gg W_q^{FKR}$$

(for $r \sim \rho_{GB}$)

$r_c \omega_q \sim \gamma_q \Rightarrow$ "inverse cascade" sets layer width

- Why? - constant ψ (ab)used $\Rightarrow$ basic form only hope for progress, understanding
  - W_q set by scaling
  - $r_c \omega_q$ as:

$\Rightarrow$ turbulence $\Rightarrow$ shear flow via modulation (initial value amplified)

$\Rightarrow$ well known: shear flow in MHD

$\Rightarrow$ $r_c \omega_q$ results (shear flow $\Rightarrow$ radial propagation)

$\Rightarrow$ mathematically, results from outgoing wave B.C.'s.

Outgoing waves $\Leftrightarrow$ MHD exterior

→ N.B. :

- layer phase persists, as $W_E \gg W_{FKR}$, onset algebraic growth delayed,
  ⇒ need reconsider "island" problem **meaning**

- re ω self-consistently ⇒ wave absorption
  [regulates energy flow]

  n.b. c/a' other cases, outgoing wave b.c.'s

- at crude level : $\gamma_u \sim \frac{D_{k_x} k_r}{k^2}$?
  is shear flow sufficient to quench turbulence ?
  ⇒ $W_T \sim W_Z$ flow levels not
  (prelim) sufficient to quench turbulence via shearing.
  ⇒ complicated parametric dependence ....
  t.b.c.
  → need also consider DT, DN mods.

- "Multiscale" models must consider/accomodate
  ⇒ outgoing wave, etc. b.c.'s
  → re ω and resonances.

② 'Rutherford' – A Look Ahead $(W_I \gtrsim w_2)$
(Preliminary)

- challenging : strong self-interaction
  ⊕ multi-scale interaction ⟩ ~~all~~ simultaneously

- for $w_I \sim w_Z$ ⇒ 3rd order self-nonlinearity
  $\gg w_T$ ⊕ inverse cascade
  ⇒ onset pt.

⇒

$$B \cdot \nabla J = -\frac{\partial^2}{\partial x^2}\left(\int d\underline{k} \, \frac{k_x k_y}{(1+k_\perp^2 \rho_s^2)^2} \, \delta N \right) + \gamma \nabla_\perp^2 \phi$$

self-NL

inverse cascade
(δN with island ?!)

neo-flow damping → critical

$J = J(\psi) + \ldots$

- 'phase' matters in Rutherford $\begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}$

- negative viscosity has 'wrong' phase for reconnection mode

So:

- explore { surface distortion
  Struct. Sim. 2-Fluid → $\nabla \langle N \rangle$ effects → enters with 'right' phase.
  ↳ potentially very important for island problem.

... work ongoing

Is island equilibrium meaningful?

v.) What of Resonant q, with $\Delta' \to -\infty$?

→ all this begs question :

$\boxed{\text{what if} \begin{pmatrix}\text{turn off}\\ \text{ignore}\end{pmatrix} \Delta' \,!}$ (i.e. $\Delta' \to -\infty$) ?

- claim : ⊙ near zonal flow albeit $m \neq 0$ > thin, resonant convective cell

⇒ $\psi_0 = 0$, electrostatics :

$$|\nu_{xx}| \frac{\partial^4 \phi^<}{\partial x^4} + \gamma_q \frac{\partial^2 \phi^<}{\partial x^2} = \frac{q_y^2 V_A^2}{n_0 L_s^2} \phi^<$$

drive via inverse cascade

resistively damped bending ⇒ localization (damping)

→ localized, weakly non-azimuthally symmetric convective cell !

i.e. $\Delta_q = w_q = (\eta_c |\nu|)^{1/6} \left(L_s / q_y V_A\right)^{1/3}$

scale

$$\gamma_q \sim \frac{|\nu_{xx}|^{2/3} (q_y V_A)^{2/3}}{n_0^{1/3} L_s^{2/3}} \sim \rho^{2/3} \tau_\eta^{-1/3} \tau_A^{-2/3}$$

$\xi_{\nu} \sim |\nu_{xx}| / n_0$

Note:

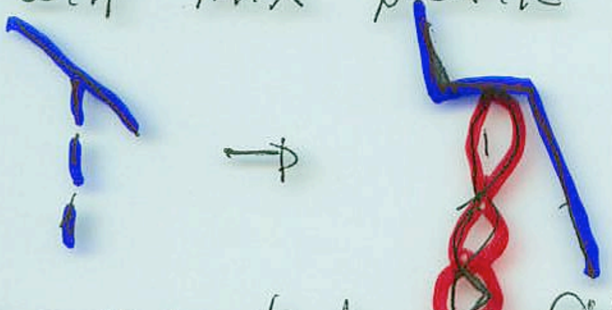
- localized at $k \cdot B$ surfaces: $k_\parallel \sim 0 \Rightarrow$ "minimal inertia".

low-$q(r)$ resonances most prominent ($q_0^{-1/3}$ scaling)

not streamer (high q_y)

akin to Z.F., but $q_y \neq 0 \Rightarrow$ $\left\{ \begin{array}{l} \text{Vortex} \\ \text{Mode} \\ \text{electrostatic} \end{array} \right.$

will mix profile on scale Δ_q



non-axisymmetric cells necessarily mix profiles

$\Rightarrow$ corrugated profiles?!, choppy profiles?!

Implication:

fate of energy in inverse cascade ?? **where does it go!**

usual

$\rightarrow$ μ (scale independent) damping $\Leftrightarrow$ box size

$\Leftrightarrow$ large scale friction $\rightarrow$ **ions**

here

$\rightarrow$ resistive damping at $k \cdot B_0 = 0$ surfaces

$\rightarrow$ electrons **narrow scale**

$\rightarrow$ bending sets natural scale length

(always ambiguous in Z.F. theory)

→ N.B. cont'd

– this offers resolution of long standing puzzle
i.e.

→ experiments indicate k·B surfaces
usually relevant → corrugated profiles, choppy
profiles, etc.

→ theorists (HPF BBK, et. al.) begin
hunt for islands – tearing
– μ-tearing
– RBM, neocl.

usually hard to justify, dynamically speaking

Resolution (possibly):

→ cts on electrostatic cell ! ?
~ independent of islands, magnetics

→ driven by high coupling, a la Z.F.

→ $q_y \neq 0$ → { local mixing
profile distortion

⇒ mesoscale profile fluctuations possible.

→ generic, μ-instability mechanism independent.

1.) Some Thoughts for Computation (FSP, etc.)

- why not implement as dynamic subgrid model?!
- need retain/close $\langle\phi^>\phi^>\rangle$, etc. terms

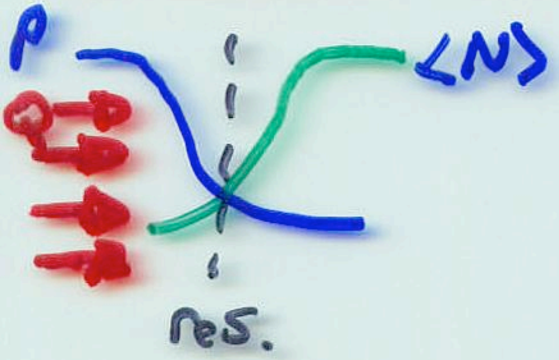
  and solve N equation
- $\underline{\underline{1}}$ additional, Boltzmann-like equation!?

  + additional convolutions, with cut-off

or as moments - DW radiation hydro
- perhaps solve N equation by PIC, for speed, exploiting relation to Boltzmann?!

or take moments in sums $\Rightarrow \int k^n N\, dk$
- track radiation hydro ---- $\Rightarrow$ evolve turbulent pressure, stresses directly!?
- offers tractable, immediately implementable model
- can easily couple to ongoing theoretical analysis ----

Profiles / Turbulence Spreading



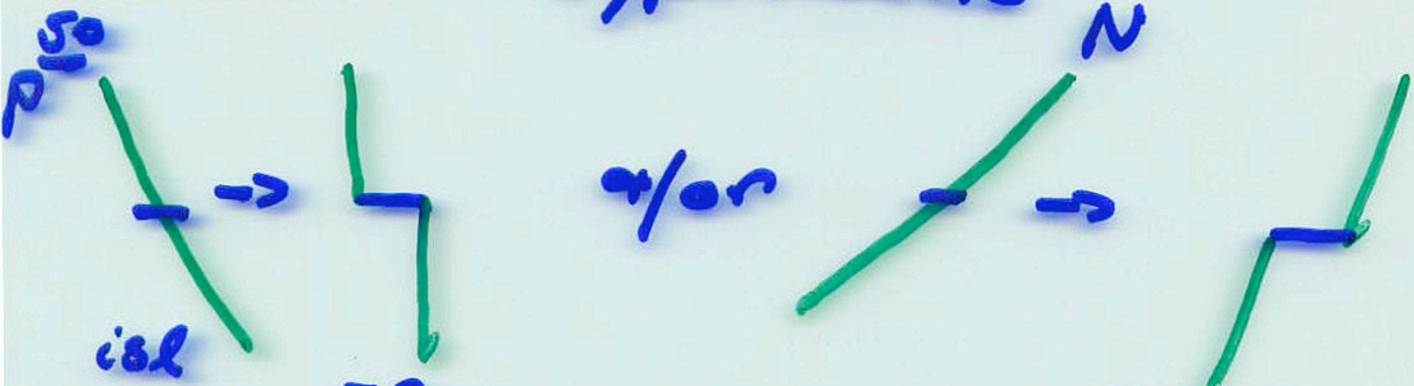
Point: ⟨N⟩ profile **not** set by P, n profiles and γ_L → turbulence spreading

→ entrainment of stable, more weakly excited region

→ diff'n of intensity

- spatial manifestation of NL coupling

isl. growth – universal element in k–ϵ type models



∇P steepens

∇N steepens

neighboring drive up? → influx

∇N up → influx

or

or → E_r, E_r' up

barrier?

or → $\nabla\langle \tilde{v}_x \tilde{v}_y \rangle$ up

?? Bifurcation → possible NTM outcome

Outlook ⇒ Unresolved Issues

→ incoherent noise model
- cf. recent work, by M. Yagi
- can seed right phase

phase in Rutherford calculation

→ spatial evolution of $\langle N \rangle$

- turbulent diamagnetism
- (*) spreading / barrier formation

$d\langle N\rangle/dx \rightarrow$ stresses, etc.

how does turbulent profile respond to flattening

→ EM effects (more detail!)
(→ Zonal field)

- conventional ordering h.o. in β
  $\delta B/B \sim (\delta n/n)\,\beta$
- particularly relevant to Rutherford phase (hyper-resistivity!?)
- conservation $\langle \psi^2 \rangle$ key issue
  ⇒ multiple effects +, - resistivity, hyper-η, etc.

⇒ $\boxed{\text{Only scratching the surface of an interesting problem area ....}}$