Physics 218C

Lecture 49 — Phenomenology & Basic Physics of ITG/η_i Modes

→ Some Phenomenology:

- drift waves understood since 60's, 70's

  c.f. Sagdeev et. al., Kadomtsev, et. al., Rosenbluth et. al

- to mid '70s:

  → "real men do MHD" →

  "microturbulence not regarded as important topic".

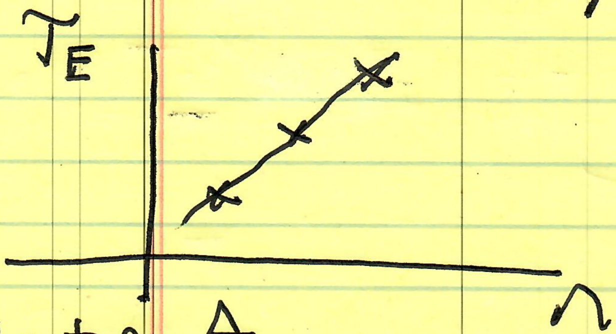
- Mid - late 70's :

  - Neo-Alcator + OH saturation
  - scattering experiments → direct measured turbulence in tokamaks

Ideas for LOC
~ DTEM, CTEM
$\sim (v_{the}/R)\, c^2/\omega_{pe}^2$
vs

Alcator scaling " / (LOC) — Linear Ohmic Confinement

$\boxed{n \sim I_p \text{ both tokamaks}}$ RFP



Alcator A

$\boxed{\tau_E \sim n}$

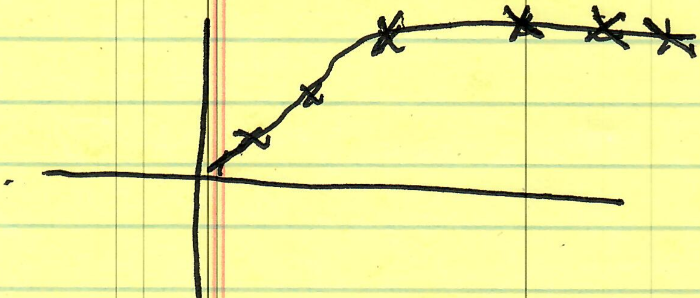
later:

neo

$\tau_E \sim n a^3 \rightarrow n R^2 a$

→ explain ?

→ favorable
but then:



Alcator C

SOC { Favorable Linear scaling ends }

Linear Ohmic Confinement
→ Saturated Ohmic Confinement

(see John Rice, et al recent NF)

What's happening ? ⇒ collisional coupling to ions !

$\sim \nu_{ei}\, n\, (T_e - T_i)$ ~n²

~> and then

Multiple confinement regimes challenged simplistic views !

LOC-SOC ⇒ Ohmic intrinsic rotation reversals.

but then : Alcator-C Pellet Injection

{yuge} (1984)

- recall :- edge fueling

  - density pinch

$$\frac{\partial \langle n\rangle}{\partial t} = -\nabla\cdot\Gamma + \underset{\text{edge}}{S_n}$$

Physics of $V<0$?

$$\Gamma = -D\nabla n + Vn$$

$V<0$.

⇒ - difficulty in fueling

- flat-ish n (also n-limit)

Fueling remains major issue for ITER

⇒ peak n via pellet ?

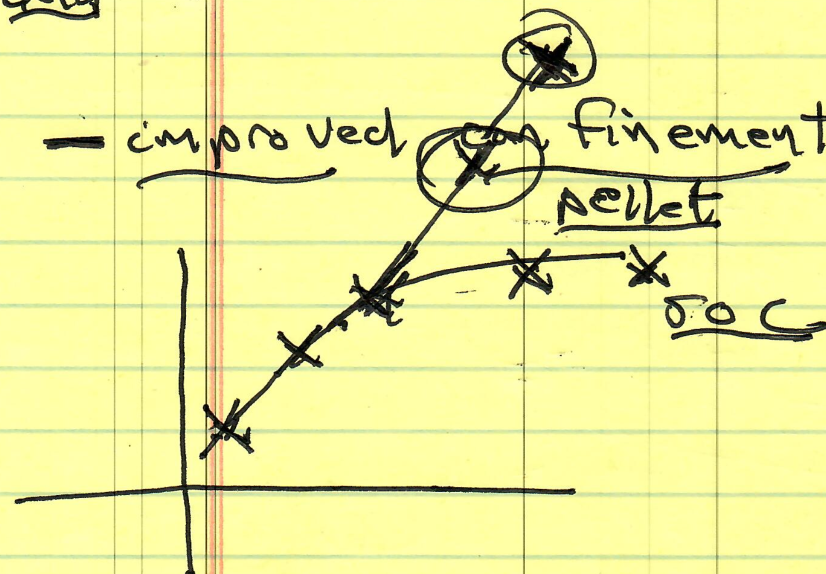
Surprise?

— peaked n

and

— improved confinement of energy

(an "ITB")



N.B.: Electron HPP ~ 1/n in post pellet

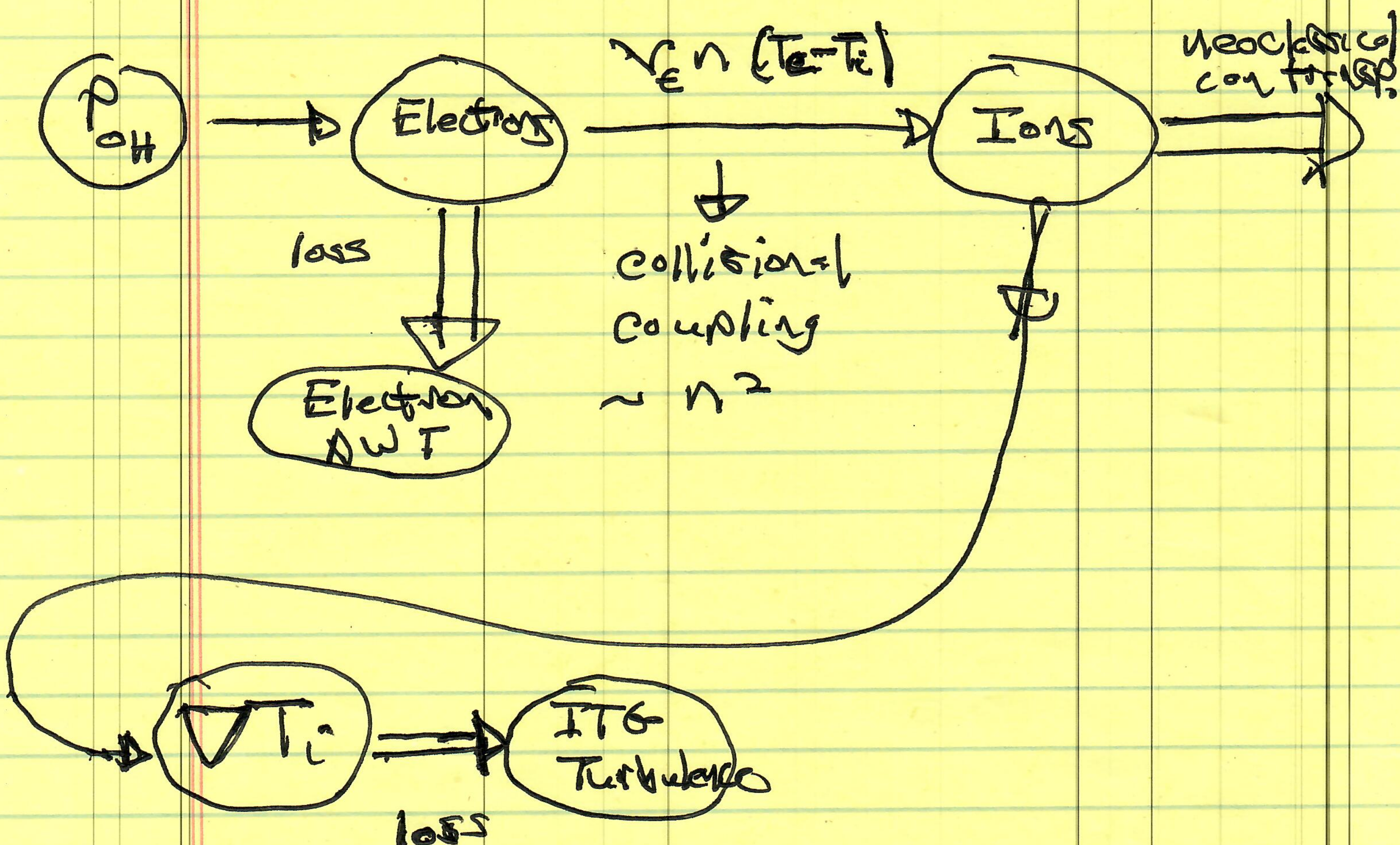
i.e. pellet + peaked n ⇒

~ restored LOC trend.

see also: IOC (Saturated → Improved Ohmic Confinement)

⇒ Confinement experiments indicated that peaked profiles are good → Can improve confinement.

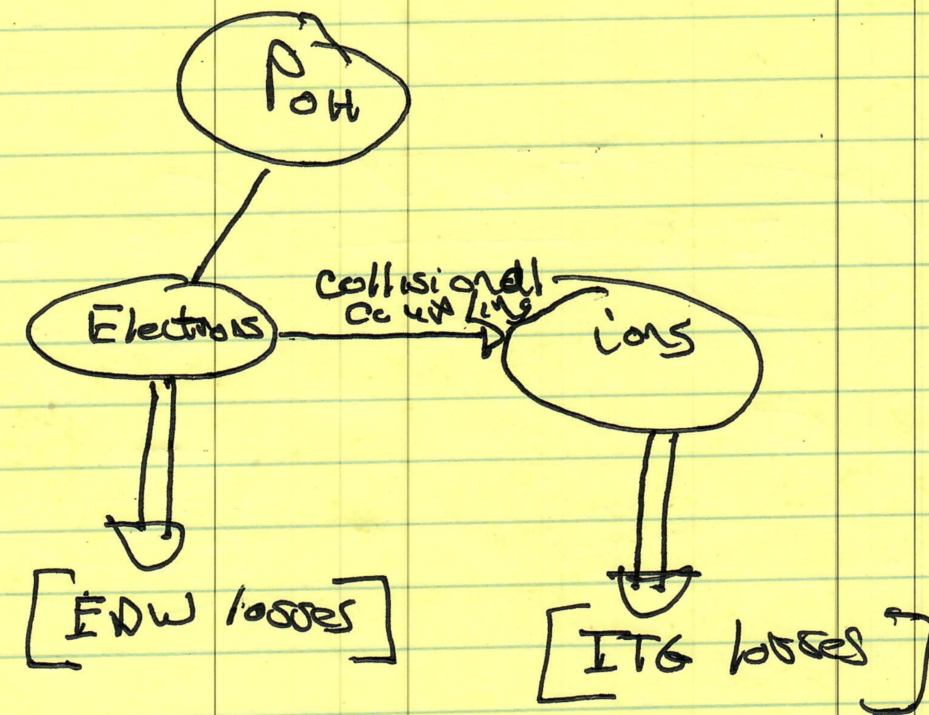
Note energetics :



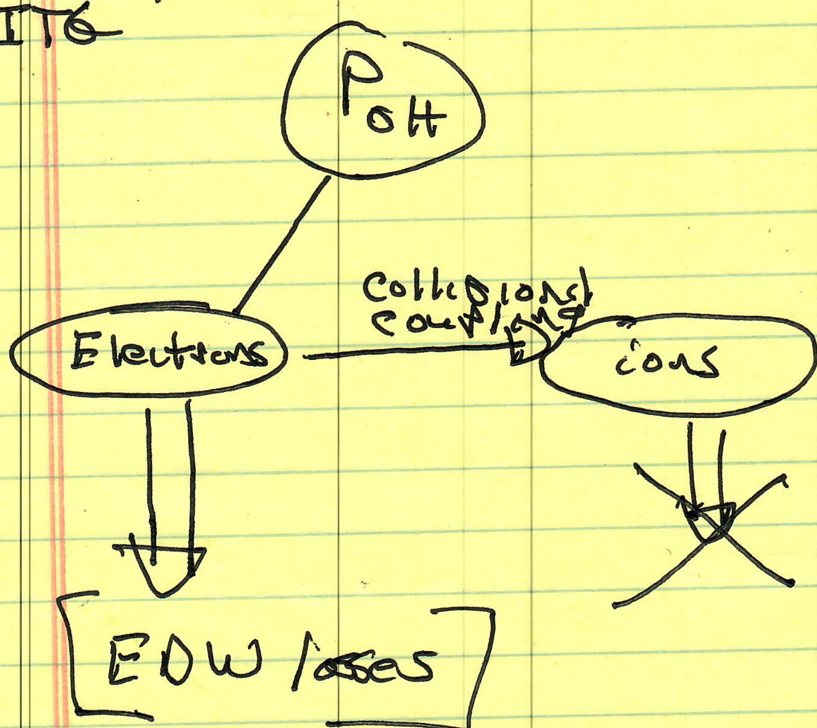
Note: Collisional coupling converts electron heating to ion ∇T_i free energy, and can trigger ITG loss channel.

i.e. ECH + high n $\Rightarrow$ ITG.

Now



with peaked n-profile → eliminate ITG



c.f. $\chi_{HPP} \sim 1/n$ in peaked density plasmas

Previous: Q-machine

→ In the meantime:

- Mazzucato
- Surko & Slusher

} scattering experiments

- microturbulence happens!

- $\langle \tilde{n}^2 \rangle_{k,\omega}$
- $\omega \sim \omega_{*e}$
- $\Delta\omega_k \sim \omega_k$, fixed $\underline{k}$ ⇒ strong turbulence
- crudely consistent with drift waves

⇒ drift waves not a phantom of theorists' collective imagination.

but ⇒ connection to confinement not made.

→ While all this going on....

Since '60's:

→ Ion drift waves / η_i / ITG studied

– Sagdeev, Rudakov early '60's

– Coppi, Rosenbluth, Sagdeev, Trieste '67

(magnetic shear)

but, since T3:

"Party Line" $\left\{ \begin{array}{l} \text{CCCP} \\ \text{and} \\ \text{PPPL} \end{array} \right.$ ⇒

→ electrons anomalous

$\chi_e \gg \chi_{neoclassical}$

→ Ions neoclassical (collisional)

→ Theory of ITG was ignored
until :

→ Alcator - C Pellet Injection

→ Dn steepening lowers η_i

→ τ_E improved

and

→ Good T_i measurements via
Charge Exchange Recombination
Spectroscopy (ancestor of BES)

CHRS → Fonck, Goldston (PPPL)
(PDX, TFTR)
CHS → Groebner, Burrell (GA)
DIII → DIII-D

⇒ good T_i measurements

⇒ Transport analysis ⇒ χ_i anomalous
(especially NBI)

so

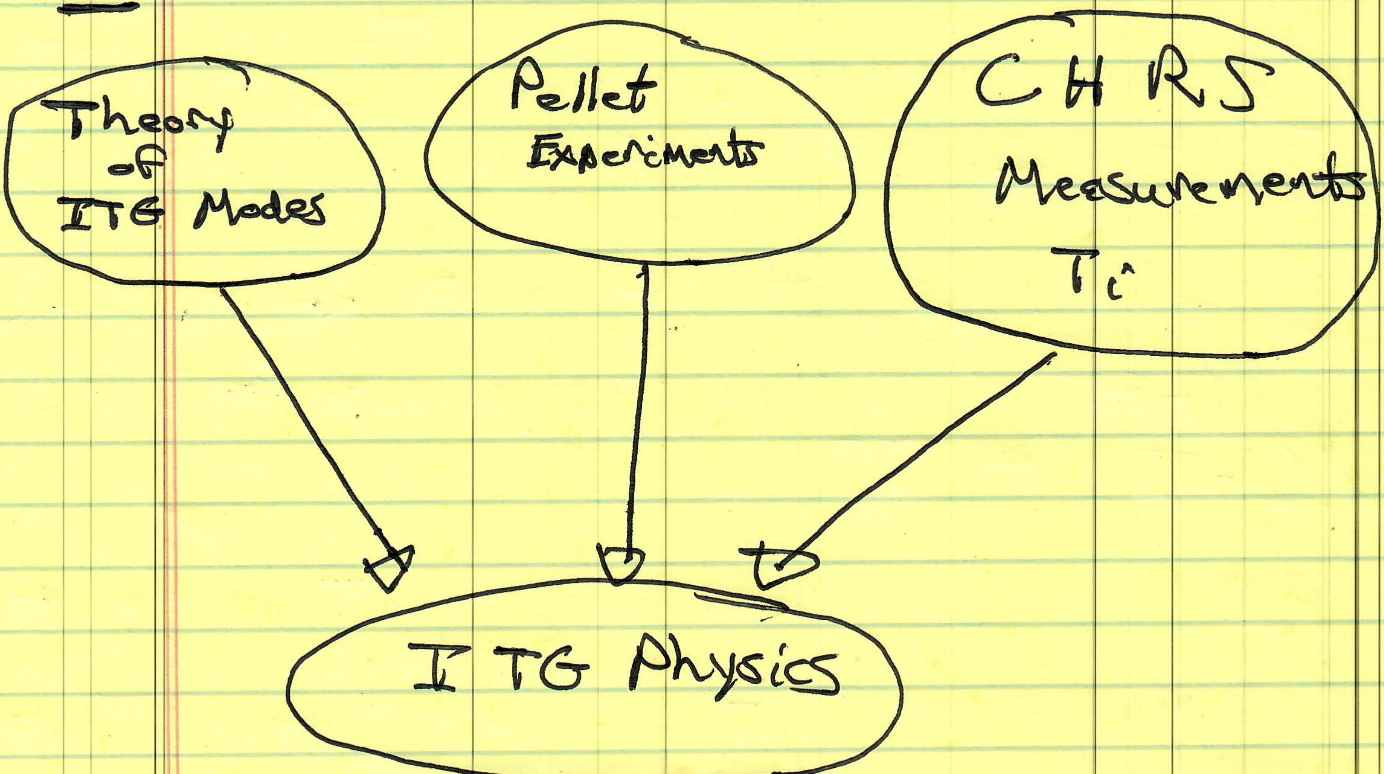
⇒ Theorists vindicated

and

ITG taken seriously

⇒ ITG Physics !

N.B.



→ Fluid Theory / ITG / η_i " "

[Slab
sound wave

What is simplest theory of ITG?

have

$\nabla \cdot \underline{V} = \nabla \cdot \underline{V}_\perp + \nabla_\parallel V_\parallel$

$$\frac{\partial n}{\partial t} + \underline{V}_\perp \cdot \nabla n + n \nabla \cdot \underline{V} = 0$$

→ continuity

[(c.f. standard H-M derivation)

$$m_i n \left(\frac{\partial V_\parallel}{\partial t} + \underbrace{\underline{V}_\perp \cdot \nabla V_\parallel}_{\text{acoustic scattering}} \right) = -\nabla_\parallel \tilde{P}_i - n|e|\nabla_\parallel \tilde{\phi}$$

ion pressure — electron pressure

→ parallel flow.

⇓

$$\frac{\partial T_i}{\partial t} + \underbrace{\underline{V}_\perp \cdot \nabla T_i}_{\text{temperature mixing}} = -\tilde{V}_{E r} \frac{\partial \langle T_i \rangle}{\partial r} - \frac{2}{3} T_i \cancel{\nabla \cdot \underline{V}}$$

$\nabla_\parallel \tilde{V}_\parallel$

grad. T_i → $\boxed{\text{free energy source.}}$

Γ → compression factor.

→ ion temperature Eqn.

Now

$$\frac{\tilde{n}}{n_0} \approx \frac{|e|\tilde{\phi}}{T_e}$$

→ Boltzmann electrons

(Eqn. of state)

$\boxed{\text{non-dissipative!}}$

$\boxed{\text{Non-dissipative character of ITG is fundamental}}$

then $\quad \tilde{\underline{V}}\cdot\underline{\nabla}_\perp = \langle V_E\rangle \dfrac{\partial}{\partial y} + \tilde{\underline{V}}_E\cdot\underline{\nabla}_\perp$

shear (zonal flow) ↳ driven by Reynolds stresses

E×B NL.

$\tilde{\underline{V}}\cdot\underline{\nabla}\tilde{n} \Rightarrow 0.$

Ignoring shear flow here: (Linear Eqn.)

$$\partial_t \frac{|e|\tilde{\phi}}{T} + \frac{\tilde{V}_{Er}}{n_0}\partial_r n_0 + \underline{\nabla}\cdot\underline{\tilde{V}}_{pol} + \boxed{\nabla_\parallel \tilde{V}_\parallel} = 0$$

new, rel. H-M. (acoustics)

$$\partial_t \tilde{V}_\parallel + \tilde{V}_{Er}\partial_r\langle V_\parallel\rangle = -\frac{(T_e+T_i)}{M_i}\nabla_\parallel \frac{|e|\tilde{\phi}}{T} - \frac{T_i}{M_i}\nabla_\parallel\left(\tilde{T}_i/T\right)$$

PSFI/PVG (related process)

acoustic resp. of

$\tilde{T}_0/T$ (phase)

$$\partial_t \frac{\tilde{T}_i}{T} = -\frac{\tilde{V}_{Er}}{T_i}\frac{\partial\langle T_i\rangle}{\partial r} - \frac{2}{3}T_i\nabla_\parallel\tilde{V}_\parallel$$

free energy source

coupling to acoustics

$$\frac{\tilde{T}_i}{T} = \underbrace{-\frac{\tilde{V}_{Er}}{\boxed{L_{T_i}}(-i\omega)} + \frac{2}{3}\frac{k_\parallel \tilde{v}_\parallel}{\omega}}_{\hookrightarrow \text{ drive}}$$

For $\tilde{v}_\parallel$:

$$\frac{\tilde{T}_i}{T} = -\tilde{V}_{Er}/L_{T_i}(-i\omega) + \frac{2}{3}\cancel{T_i}\frac{\cancel{i}k_\parallel \tilde{v}_\parallel}{-\cancel{i}\omega}$$

then plug into $\tilde{v}_\parallel$ eqn:

$$-\cancel{i}\omega(\tilde{v}_\parallel) = +v_{Ti}^2\,\cancel{i}k_\parallel\left(\frac{-V_{Er}}{L_{T_i}(-i\omega)} + \frac{2}{3}\frac{k_\parallel \tilde{v}_\parallel}{\omega}\right)$$

+ acoustics

$$\tilde{v}_\parallel\left(1 - \frac{2}{3}\frac{k_\parallel^2 v_{Ti}^2}{\omega^2}\right) = -v_{Ti}^2\left(\frac{k_\parallel \tilde{V}_{Er}}{L_{T_i}(-i\omega)\,\omega}\right)$$

$$\boxed{\tilde{v}_\parallel = -\frac{v_{Ti}^2 k_\parallel \tilde{V}_{Er}}{L_{T_i}(-i\omega)\left(1 - \frac{2}{3}\frac{k_\parallel^2 v_{Ti}^2}{\omega^2}\right)\omega}}$$

acoustic response perturbed by $\tilde{V}_{Er}$ and ∇T_i

Then plugging into continuity:

$k_\parallel^2 v_{Ti}^2 < 1$ → drop polarization.

$$\tilde{v}_\parallel = -i\frac{v_{Ti}^2 k_\parallel \tilde{V}_{Er}}{L_{T_i}(\omega^2)\left(1 - \frac{2}{3}\frac{k_\parallel^2 v_{Thi}^2}{\omega^2}\right)}$$

Thus:

① ② ② ~ ③ (retain polarization in ①)

$$\left(-i\omega + i\omega_{*n}\right)\frac{|e|\tilde{\phi}}{T}$$

③

$$+ \cancel{i} k_{\parallel}\left(\frac{+ v_{Ti}^2 k_{\parallel} \tilde{V}_{E_r}}{+\cancel{i}\omega^2 L_{Ti}\left(1 - \frac{2}{3}\frac{k_{\parallel}^2 v_{thi}^2}{\omega^2}\right)}\right) \simeq 0$$

$\omega_{*n} > \omega \Rightarrow$ drop 1

diamagnetic with L_{Ti}.

$$\omega_{*n} + \frac{k_{\parallel}^2 v_{thi}^2}{\omega^2}\frac{\omega_{*T_i}}{\left[1 - \frac{2}{3}\frac{k_{\parallel}^2 v_{Ti}^2}{\omega^2}\right]} \simeq 0$$

$$\eta_i = \frac{L_n}{L_{Ti}}$$

$$1 - \frac{2}{3}\frac{k_{\parallel}^2 v_{Ti}^2}{\omega^2} = -\frac{k_{\parallel}^2 v_{Ti}^2}{\omega^2}\eta_i$$

$$\boxed{\eta_i = \frac{L_n}{L_{Ti}} = \frac{d\ln T_i}{d\ln n}}$$

$\rightarrow$ hence "eta-i" mode

and thus:

$$1 = \frac{k_{\parallel}^2 v_{ti}^2}{\omega^2}\left(\frac{2}{3} - \eta_i\right)$$

$$\boxed{\omega^2 = k_{\parallel}^2 v_{thi}^2 \left(\frac{2}{3} - \eta_i\right)}$$ → dispersion relation and threshold

$\omega^2 \to -\gamma^2$ for $\eta_i > \frac{2}{3}$

ITG has critical value of ∇T_i → here set by ∇n

→ defines "critical value" of η_i

→ onset instability

Kadomtsev & Pogutse '70
Tang '78 reviews

Comments:

① → η_i / ITG mode is fundamentally different from Electron Drift Wave / TEM family.

Recall: contrast

$$\text{EDW} \to \frac{\tilde{n}}{n} = \frac{|e|\tilde{\phi}}{T} + \tilde{h}$$

wave $\alpha \to \infty$

↳ dissipative

$$\tilde{h}$$

$$\oplus$$

and : $\omega - \omega_* < 0$ + dissipation. $\Rightarrow$ $\left\{\begin{array}{l} \text{inverse} \\ \text{negative} \\ \text{dissipation} \\ \text{instability} \end{array}\right.$

ITG/η_i → Boltzmann electrons suffice

Instability is $\boxed{\text{reactive}}$

Caution: $\boxed{\text{Non-adiabatic electrons can enter ITG - couple branches}}$

⊙

⇒ What's the Physics?

Recall drift wave:

now add acoustic

Drift-Acoustic

$$1 + k_\perp^2 \rho_s^2 = \frac{\omega_{*e}}{\omega} + \frac{k_\parallel^2 c_s^2}{\omega^2}$$

$\omega = \frac{\omega_*}{1+k_\perp^2\rho_s^2}$

$\boxed{\text{Show this}}$

acoustic wave

$\omega_* > k_\parallel c_s$

→ drift-acoustic wave.

i.e. $\nabla n \to 0$;

$$\omega^2 = k_\parallel^2 c_s^2 / [1 + k_\perp^2 \rho_s^2]$$

usually heavily damped → L.D.

parallel sound.

enhanced inertia

(destabilize by current ?) → like CDIA

analogous: $\omega^2 = k^2 c_s^2 / 1 + k_\perp^2 \lambda_D^2$

work out.

Acoustic wave: positive compressibility

$$\omega^2 = k_\parallel^2 \underbrace{\left(\frac{dP}{d\rho}\right)}_{c_s^2 > 0}$$

i.e. $\delta\uparrow \Rightarrow \tilde{P} \Rightarrow$ div. flow $\Rightarrow$ reduces $\tilde{P}, \delta$

i.e. [pressure P with density $\Downarrow$ compressibility]

ITG/η_i: Negative compressibility $\Downarrow$ instability

$$\omega^2 = k_\parallel^2 V_{Ti}^2 \underbrace{\left(\frac{2}{3} - \eta_i\right)}$$

$\tilde{\rho} \Rightarrow \tilde{P}_\delta \Rightarrow$ conv flow $\Rightarrow$ increase $\tilde{\rho}, \tilde{P}$.

$$\frac{\partial^2}{\partial t^2}\rho = V_{Th_i}^2 \left(\frac{2}{3} - \eta\right) \frac{\partial^2 \rho}{\partial z^2}$$

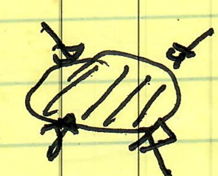
$\sim p < 0$ for $\eta_i > \eta_{i\,crit} = 2/3$.

$\delta \nabla n_0$

Familiar Example of Negative Compressibility ??

$\boxed{\text{Jeans Instability !}}$

self-gravitating



Matter

$$\partial_t \rho + \nabla \cdot (\rho \underline{v}) = 0$$

$$\rho \frac{d\underline{v}}{dt} = -\nabla P - \rho \nabla \phi$$

Gravitational force.

$$\boxed{\nabla^2 \phi = 4\pi G \rho}$$

Poisson's Eqn: for Gravity ($1/r^2$ force)

$\Rightarrow$

$$\partial_t^2 \tilde{\rho} + \rho_0 \partial_t \underline{\nabla \cdot \tilde{v}} = 0$$

$$\partial_t \underline{\nabla \cdot \tilde{v}} = -\frac{\nabla^2 \tilde{p}}{\rho} - \nabla^2 \phi$$

$$\partial_t^2 \frac{\tilde{\rho}}{\rho_0} - \nabla^2 c_s^2 \left(\frac{\tilde{\rho}}{\rho_0}\right) - G \frac{\tilde{\rho}}{\rho_0}(4\pi\rho_0) = 0$$

$$\boxed{\omega^2 = k^2 c_s^2 - 4\pi G \rho_0}$$

classic Jeans dispersion

$$\omega^2 = k^2 c_s^2 \left(1 - \frac{4\pi G \rho_0}{c_s^2 k^2}\right)$$

$$\left[\text{"Compr"}\right] \simeq 1 - \frac{4\pi G \rho_0}{c_s^2 k^2}$$

Can have negative compression

< 0 for $k < k_J$

> 0, $k > k_J$

$$k_J = \left(4\pi G \rho_0 / c_s^2\right)^{1/2}$$

$\ell_{Jeans} \rightarrow$ Jeans Length $= \left(\dfrac{c_s^2}{4\pi G \rho_0}\right)^{1/2}$

i.e. $\left\{\begin{array}{l}\text{negative compression for} \\ l > l_J \Rightarrow \text{gravity} \\ \text{overcomes pressure}\end{array}\right\}$ ⇒ collapse

Why negative compression? ⇒ [Very Physical Question]

acoustics

$$\frac{\partial \tilde{v}_{\parallel}}{\partial t} = -\frac{c_s^2}{m_i} \nabla_{\parallel} \frac{|e|\tilde{\phi}}{T} - v_{Th_i}^2 \nabla_{\parallel}\left(\frac{\tilde{T}}{T}\right)$$

phase ⇒ $\delta P_i = n_0 \tilde{T}_0 + T_i \tilde{n}$

$\sim \frac{|e|\tilde{\phi}}{T}$

Point: $\tilde{T}/T$ not in phase with $\frac{|e|\tilde{\phi}}{T}$;

$$\frac{\tilde{T}}{T} \neq \frac{|e|\tilde{\phi}}{T}$$

What induces neg compression ? ⇒ $\nabla\langle T_i \rangle$; → via coupling to acoustic wave.

i.e. crudely:

$$\frac{\tilde{T}}{T_0} \simeq \frac{-V_r}{-i\omega} \frac{\partial \langle T \rangle}{T \partial r} = -\frac{i\omega_{*Ti}}{\gamma} \frac{|e|\tilde{\phi}}{T}$$

↳ phase $\qquad$ δ phase.

$\frac{\tilde{T}_i}{T}$ $\searrow$ $\curvearrowright$ $\langle \tilde{v}_r \tilde{T} \rangle \rightarrow -\chi_i \nabla \langle T_i \rangle$

$\chi_i \sim \langle \tilde{v}_r^2 \rangle \tau_c \sim \langle \tilde{v}_r^2 \rangle \gamma^{-1}$

→ What is the full dispersion relation

crank from n, T, $V_{\parallel}$ eqns. + Boltzmann

$$\underbrace{1 - \frac{\omega_{*n}}{\omega}}_{DW} - \underbrace{\frac{k_{\parallel}^2 c_s^2}{\omega^2}\left(1 - \frac{\omega_{*pi}}{\omega}\right)}_{\text{acoustics}} \underbrace{- \frac{5}{3}\frac{k_{\parallel}^2 T_i}{M_i \omega^2}\left(1 - \frac{\omega_{*n}}{\omega}\right)}_{\nabla T_i \text{ coupling}} = 0$$

$$\boxed{1 - \frac{\omega_{*n}}{\omega} - \frac{k_{\parallel}^2 c_s^2}{\omega^2}\left(1 - \frac{\omega_{*pi}}{\omega}\right) - \frac{5}{3}\frac{k_{\parallel}^2 v_{thi}^2}{\omega^2}\left(1 - \frac{\omega_{*n}}{\omega}\right) = 0}$$

→ Is there a "quickie"?

$\nabla \cdot (\rho \underline{V}) = 0$ [incompressible mass flow!

$$\tilde{v}_r \frac{d\langle n \rangle}{dr} + n_0 \cancel{\nabla \cdot V_{pol}} + n_0 \nabla_{\parallel} \tilde{V}_{\parallel} = 0$$

$+ \frac{V_{\parallel}}{T}$ > eqns, follows

→ What of "Flat Density" Regime?

→ η_i large?

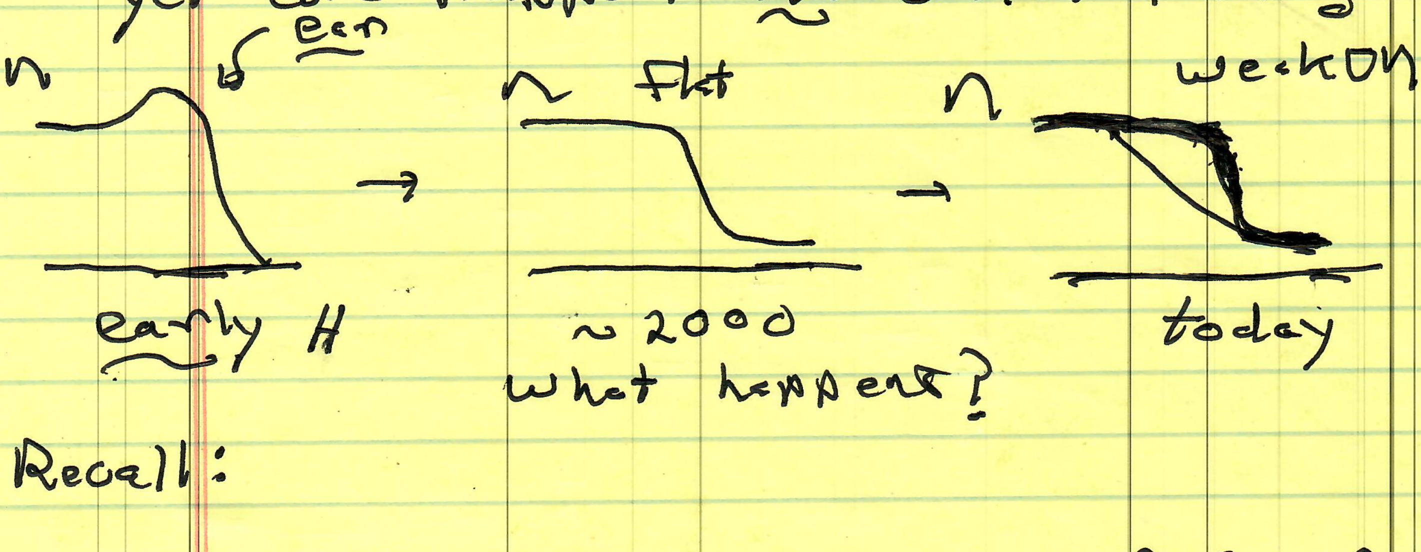
→ Gist of η_i mode:

- Peaked density profiles are good!

Alcator-C Pellet, et. seq. ⇒ steepen ∇n, reduce η_i s/t $\eta_i < \eta_{i\,crit}$

- but H-mode density profiles ~ flat ⇒ $\eta_i \to \infty$!!

yet core transport not catastrophic!



early H → ~2000 → today

what happens?

Recall:

$$1 - \frac{\omega_{*n}}{\omega} - \frac{k_\parallel^2 c_s^2}{\omega^2}\left(1 - \frac{\omega_{*pi}}{\omega}\right) - k_\parallel^2 \frac{\frac{5}{3} v_{Ti}^2}{\omega^2}\left(1 - \frac{\omega_{*n}}{\omega}\right) = 0$$

take $\omega_{*n} \to 0 \leftrightarrow \nabla n \to 0$

$$1 - \frac{k_{\parallel}^2 c_s^2}{\omega^2}\left(1 - \frac{\omega_{*Ti}}{\omega}\right) - \frac{5}{3}\frac{k_{\parallel}^2 v_{Ti}^2}{\omega^2} = 0$$

$\omega_{*Ti} > \omega \Rightarrow \left\{ \nabla T_i \text{ strong, for simplicity} \right.$

$$1 + \frac{k_{\parallel}^2 c_s^2 \omega_{*Ti}}{\omega^3} = 0$$

$$\Rightarrow \boxed{\omega = (-1)^{1/3} \left(k_{\parallel}^2 c_s^2 \omega_{*Ti}\right)^{1/3}}$$

instability!
(Threshold not addressed)

- "flat density" ITG (not η_i)
- ω_r, γ set by ∇T_i
- no odd behavior, $\nabla n \to 0$.
- balance $\nabla_{\parallel} \tilde{v}_{\parallel}$ with $\frac{\partial n_i}{\partial t}$
- will be a cross-over value of ∇n.

⇒ 'Flat density' ITG "η_i" is.

one reason why [redacted] became "ITG".

(Can also have "flat density" drift/TEM → ∇T_i ⇒ wave
$\boxed{\nabla T_e \Rightarrow \text{drives}}$)

→ Accuracy ?

- Fluid theory not accurate for threshold, useful for physical understanding

- $\omega^2 = k_\parallel^2 v_{Ti}^2 \left(\frac{2}{3} - \eta_i\right)$

$\omega^2 \lesssim 0$ ⇒ $\omega - k_\parallel v_\parallel$ easily resonant

∴ ion Landau damping enters...

⇒ $\boxed{\text{Kinetics}}$

→ PV ? shear flow can modify significantly → Dimits shift!

- $\underbrace{\nabla_\parallel \tilde{v}_\parallel}$ breaks PV conservation of H-M.

⇒ can formulate PV budget, Potential enstrophy budget. Useful.

$\Rightarrow$ Related ? — $\left\{ \begin{array}{l} \text{PSFI} \\ \text{PVG} \\ \vdots \end{array} \right.$ $\left\{ \begin{array}{l} \text{Parallel shear} \\ \text{flow instability} \end{array} \right.$

$\underline{\nabla\langle V_{\parallel}\rangle}$ driven instability ! (S)

So what? — shear flow ! .... (R)

Negative compression, not KH ! (S)
↓ Inf. R_t
acoustic coupling !

$\Rightarrow$ $\boxed{\text{'relative' of ITG}/\eta_i \Rightarrow \text{PSFI}}$

$\Rightarrow$ couples linearly to ITG/η_i.

$\Rightarrow$ rather delicate, but $\underline{\text{active}}$.

To clarify, $\underline{\text{put}}$ $\left\{ \begin{array}{l} \nabla T \to 0 \\ \nabla n \to 0 \end{array} \right.$, $\underline{T_i \to 0}$

$$\partial_t \frac{|e|\hat{\phi}}{T} + \nabla_{\parallel} \underset{\substack{\text{PVG} \\ \downarrow}}{\tilde{V}_{\parallel}} = 0$$

$$\partial_t \tilde{V}_{\parallel} = -V_{Er}\,\partial_r \langle V_{\parallel}\rangle - C_s^2 \nabla_{\parallel} \frac{|e|\phi}{T}$$

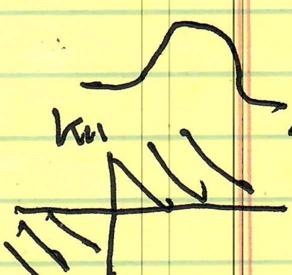
$$\partial_t^2 \frac{|e|\hat{\phi}}{T} + \nabla_\parallel\left(-V_{Er}\,\partial_r\langle V_\parallel\rangle - c_s^2 \nabla_\parallel \frac{|e|\hat{\phi}}{T}\right) = 0$$

$$-\omega^2 - k_\parallel k_\theta \rho_s c_s\, \partial_r\langle V_\parallel\rangle + k_\parallel^2 c_s^2 = 0$$

$$\boxed{\begin{aligned}\omega^2 &= -k_\parallel k_\theta \rho_s c_s\, \partial_r\langle V_\parallel\rangle + k_\parallel^2 c_s^2 \\ &= -k_\parallel c_s\left(k_\theta \rho_s\, \partial_r\langle V_\parallel\rangle - k_\parallel c_s\right)\end{aligned}}$$

Need $-k_\theta \rho_s\, \partial_r\langle V_\parallel\rangle > k_\parallel c_s$ $\Big\{$ for instability
$\rightarrow$ criterion on $\nabla_r\langle V_\parallel\rangle$

- $\boxed{k_\parallel k_\theta} > 0$ for $\partial_r\langle V_\parallel\rangle < 0$



$\Leftrightarrow$ spectral asymmetry $\Big\{$ required, develops.

- clearly negative compression;
$\Rightarrow$ $\nabla\langle V_\parallel\rangle$ induces needed phase.
- $\nabla V_\parallel$ stabilizing, (as M_i)

- couples to ITG. cf. N Mattor, PD.
  and ultimately $\chi_\phi \sim \chi_i$

PSFI **most** important in strong rotation, flat n regimes $\Rightarrow$ Core H-mode, with NBI, strong.

$\rightarrow$ **Also**: <u>Toroidal</u> ITG

$\rightarrow$ curvature driven

$\rightarrow$ commonality with FLR stabilized interchange
$\omega_D \omega_{*p_i}$ vs ω_{*n}^2

$\rightarrow$ R/L_{Ti}, L_n/L_{Ti} are critical parameters.

$\rightarrow$ <u>Fluid</u>, but Mechanism different than negative compression.

→ (Zonal) Flows and Saturation

→ clearly $\underline{\nabla}\cdot\underline{V}_{pol} \rightarrow \frac{d}{dt}\nabla_\perp^2\phi$

$\rightarrow \partial_r \langle \tilde{v}_r \nabla^2 \tilde{\phi} \rangle$

⇒ ITG generates zonal flows !

⇒ additional coupling from diamagnetic contribution

⇒ shear feedback, as usual.

also Zonal eqns:

→ $\underbrace{\partial_r \langle \tilde{v}_r \tilde{T} \rangle + \partial_t \langle T \rangle}_{\text{Zonal}} + \ldots\ldots = 0$

⇒ Ion temperature profile corrugations formed.

$\left\{ \begin{array}{l} \phi_Z \\ \delta T_Z \end{array} \right.$

also

→ $\underbrace{\partial_t \langle v_\parallel \rangle + \partial_r \langle \tilde{v}_r \tilde{v}_\parallel \rangle}\, + \cdots = 0$

⇒ (Zonal) acoustic flows generated.

Note:

$$\tilde{v}_\parallel = - \frac{i\, v_{Ti}^2 k_\parallel \tilde{V}_{Er}}{L_{Ti}\, \omega^2 (1 - \ )}$$

small

$$\omega_r^2 + 2i\gamma\omega_r - \gamma^2$$

so

$$\langle \tilde{v}_r \tilde{v}_\parallel \rangle = + \Pi_r \frac{\partial \langle T_i \rangle}{\partial r}$$

symmetry ?

$$\Pi_r = \mathrm{re}\left\{ \sum_n |V_{r_n}|^2 (-i)\, \frac{v_{Ti}^2 k_\parallel}{T_i (\omega_r + 2i\gamma\omega_r - \gamma^2)} \right\}$$

i.e. then:

$$\partial_t \langle \delta V_\parallel \rangle = -\partial_r \left(\Pi_r \frac{\partial \langle T_i \rangle}{\partial r} \right)$$

$\nabla \langle T_i \rangle$ drives parallel flow

$\Rightarrow$ welcome to intrinsic rotation !

→ Flows driven by :

$Q_i \rightarrow \nabla T_i \rightarrow \langle \tilde{V}_r \tilde{V}_\parallel \rangle \rightarrow \langle V_\parallel \rangle$

Plasma can rotate without torque.

→ symmetry breaking required.

What sets $\langle k_\parallel \rangle$?

ala' α effect in dynamo.

TBC.

also : Impurity Modes