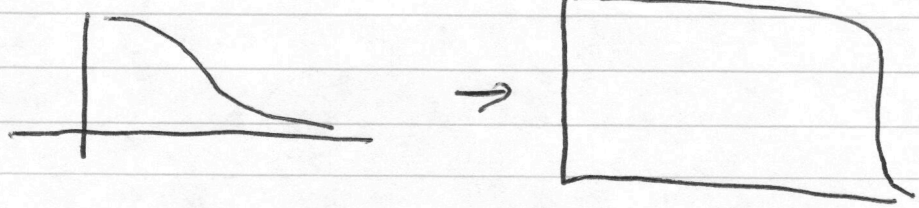
Class 7 → Physics of the L→H Transition

→ N.B.: Recent PR from EAST (Hefei, China) is 100 sec H-mode (400kA).

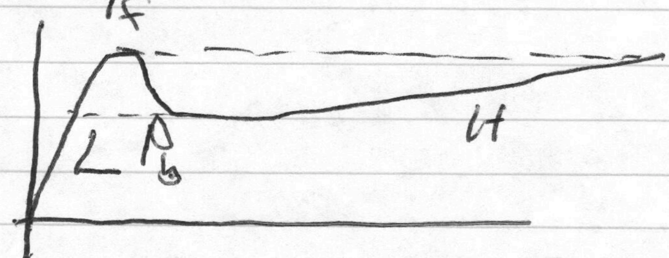
→ H-mode is

- edge barrier formation (spontaneous)

$Q_{edge} > Q_{crit}$



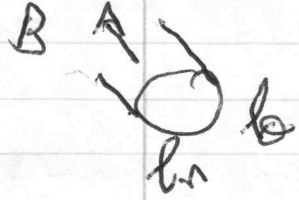
- improved confinement $\tau_E \sim W/P_{in}$
- radical drop in edge turbulence, transport
- bifurcation



– [redacted] How?

— $\underline{E} \times \underline{B}$ Shear Suppression

→ turbulence: — eddys, elongated along $\underline{B}$



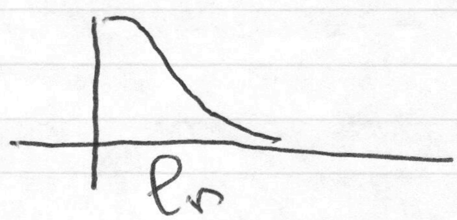
= driven ∇T, ∇n

— akin convection cells (Rayleigh – Benard)

Can characterize (loosely) eddy by

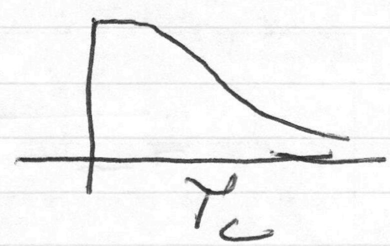
— radial, poloidal coherence lengths

$$\langle \tilde{n}(r,\theta)\, \tilde{n}(r+l_r,\theta) \rangle \quad \text{etc.}$$



— coherence time (lifetime)

$$\langle \tilde{n}(t)\, \tilde{n}(t+\tau_c) \rangle$$



— lifetime ~ turn over

$1/\tau_c \sim l^{-1} \tilde{v}$. rate

– $D \sim l_c^2 / \tau_c$

→ At transition, strong sheared flow develops at boundary

shear → radial variation of θ direction

Flow is $\underline{E} \times \underline{B}$

$$M \frac{dv}{dt} = q\underline{E} + \frac{q}{c} \underline{v} \times \underline{B}$$

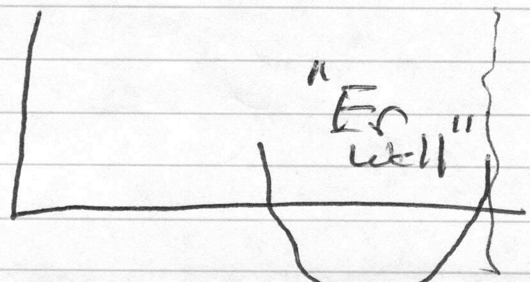
particle (also fluid)

avg $$\overline{M \frac{dv}{dt}} = 0 = q\underline{E} + \frac{q}{c} \underline{v} \times \underline{B}$$

$$\underline{V} = \frac{c}{B^2} \underline{E} \times \underline{B}$$ → $\underline{E} \times \underline{B}$ drift

Point is edge radial electric field.

i.e. typical



last few cm.

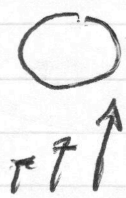
→ typical H-mode structure.

⇒ Begs 2 questions:

ⓐ — what does shear flow do to eddy?
(easy)

ⓑ — how does shear flow form?
(harder)

ⓐ



compare:

$1/\tau_c$ vs. V_E'
$\left(\frac{\partial}{\partial r} V_E\right)$

$V_E' < 1/\tau_c$ → shear irrelevant

$V_E' > 1/\tau_c$ → eddy torn apart before it can transport.

shear → $\langle \tilde{v}_r \tilde{T} \rangle$ — phase / amplitude

cross-over $\tau_c V_E' \sim 1$

⇒ shear suppression criterion

$\Rightarrow$ well satisfied at L$\to$H transition.

(b) ~~Hard~~ How does edge shear layer form ?

- momentum transport

i.e. so far $\langle \tilde{V}_r \tilde{n} \rangle = -D \nabla n$

$\langle \tilde{V}_r \tilde{T} \rangle = -\chi \nabla T$

i.e. fluxes with Fick's Law

but also

$\rho_0 \langle \tilde{V}_r \tilde{V}_\theta \rangle \Rightarrow$ Flux of poloidal momentum

$\to$ stress (Reynolds)

and

$$\partial_t \langle V_\theta \rangle = -\frac{\partial}{\partial r} \langle \tilde{V}_r \tilde{V}_\theta \rangle$$

$\Downarrow$

gradient in momentum stress

$\Rightarrow$ drives flow.

n.b. - re-distribution

- no source except bndry.

— so, rising transport ($Q \uparrow$) $\Rightarrow$ rising stress $\Rightarrow$ rising shear

— shear hits $\tau_c V_E' \sim 1$ threshold
$\Rightarrow$ transport quenched.

— ∇P steepens, locking in $\langle E_r \rangle$

$$\cancel{m\frac{dv}{dt}} = \frac{q}{m}\underline{E} - \frac{\nabla P}{n} + \frac{q}{c}\underline{V}\times\underline{B}$$

$\Rightarrow$ H-mode.

Note: 2 step

① $\rightarrow$ rising heat flux $\Rightarrow$ rising turbulence
$\Rightarrow$ rising momentum flux/stress.

② $\rightarrow$ $V_E' \sim V_{E\,crit}'$ $\Rightarrow$ transport drops
(turning off stress) but

∇P steepens $\langle E \rangle \sim \frac{\nabla \langle P \rangle}{n}$

and strong mean shear.

Critical issues

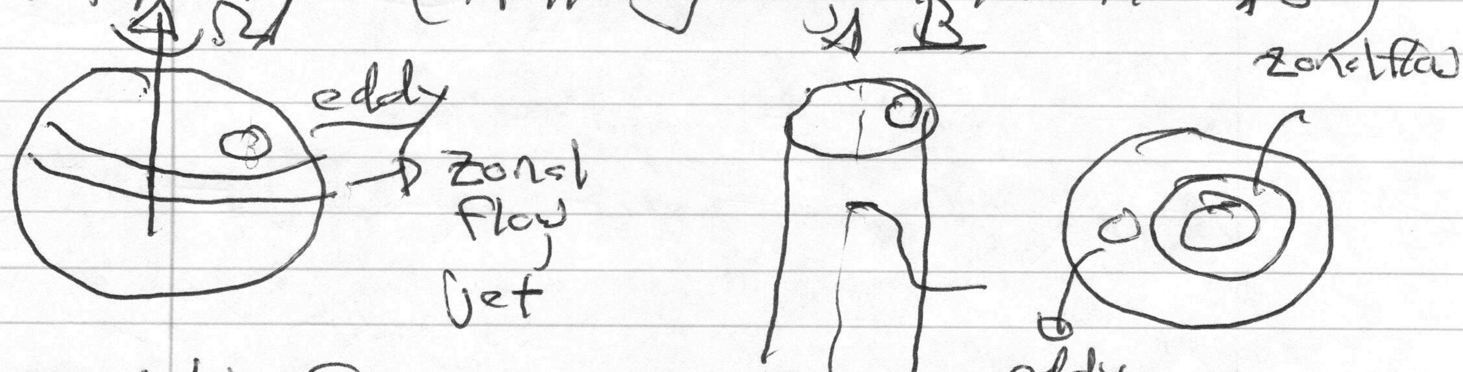
$$\partial_t \langle V_\theta \rangle = -\frac{\partial}{\partial r} \langle \tilde{V}_r \tilde{V}_\theta \rangle + \text{"} \nu \nabla^2 \langle V_\theta \rangle \text{"}$$

stresses / momentum transport

flow damping

→ A Bit on Physics of Flows in Magnetized Plasma

Similarity (A. Hasegawa, K. Mima '78)



coriolis force

$\underline{F}_c = +2m\, \underline{\Omega} \times \underline{V}$

Lorentz force

$\underline{F}_L = m\, \underline{V} \times \underline{\Omega}_c$

$$\underline{\omega} = \underline{\nabla} \times \underline{v}$$

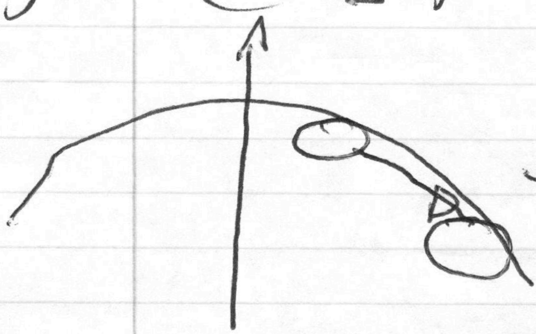
$$\partial_t (\underline{\omega} + 2\underline{\Omega}) = \underline{\nabla} \times \underline{v} \times (\underline{\omega} + 2\underline{\Omega})$$

$+$

$\Rightarrow$

$$\int d\underline{a} \, (\underline{\omega} + 2\underline{\Omega}) = \text{const}$$

$\Rightarrow$ Kelvin's Theorem.



$\Omega \cdot da$ changes

$\therefore$ ω must change

$\Rightarrow$ local increase in vorticity.

so

$$\underline{\omega} = \nabla^2 \phi$$

y x

grad (f) coriolis

Planet

$$\partial_t \nabla^2\phi + \underline{v} \cdot \underline{\nabla}\, \nabla^2 \phi = -\beta \frac{\partial \phi}{\partial x}$$

QG Charney

Plasma $(e\phi/T)$

HM

$$\partial_t (\phi - \rho_s^2 \nabla^2 \phi) - \underline{v} \cdot \underline{\nabla}\, \rho_s^2 \nabla^2 \phi = v_* \frac{\partial \phi}{\partial y}$$

electrons (2 species)

density grad.

Planet: $\omega = -k_x \beta / k^2$ Rossby Waves.

$k_x = 0$ Z.F.

Plasma: $\omega = k_\theta V_* / 1 + k_\perp^2 \rho_s^2$ Drift Waves.

$k_\theta = 0$, Z.F.

Both: $\langle \tilde{\underline{V}} \nabla^2 \tilde{\phi} \rangle$ → vorticity flux

intrinsic to dynamics.

but: – vorticity flux
– 1 degree symmetry

$\langle \tilde{V}_y \nabla^2 \tilde{\phi} \rangle = -\partial_y \langle \tilde{V}_y \tilde{V}_x \rangle$

Reynolds Force planet

$\langle \tilde{V}_x \nabla^2 \tilde{\phi} \rangle = \partial_x \langle \tilde{V}_x \tilde{V}_y \rangle$ plasma

$\Rightarrow$ Zonal shear layers are intrinsic to magnetized plasma.