Class 8 — Tokamak Miscellany

A.) Review: the H-Mode { transport bifurcation
importance of shear flow }

B.) How? / Is the H-mode entirely good news?

Class 6: pgs: 5→8, enhanced

C.) A Broader Look at the Physics of Flows.

class 7: pgs: 7-10, et. seq.

→ Transport **Bifurcation**!

→ Some additional signs:

- hysteresis: $P_{H-L} \neq P_{L-H}$
- $P \leq P_{crit}$ + heat-pulse ⇒ transition

→ How get it? → Importance of Boundary Physics

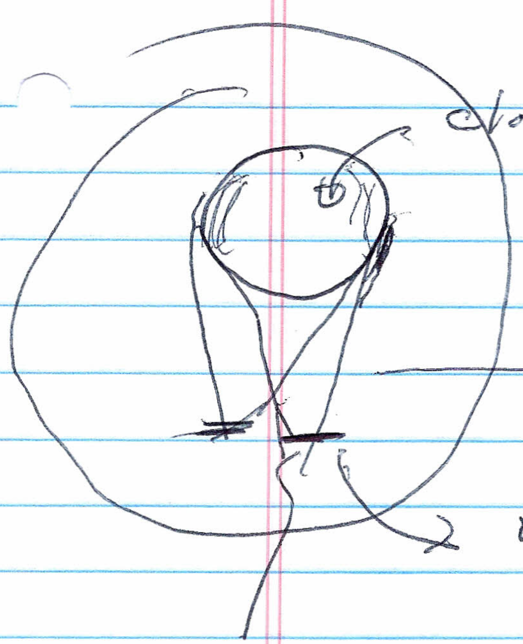
→ Boundary control

limiter ⇒ used to position and control bndry interaction with plasma

⇒ impurities, sputtering ...... no longer used.

vs.

ASDEX
PDX } Divertor



PFC → plasma facing component.

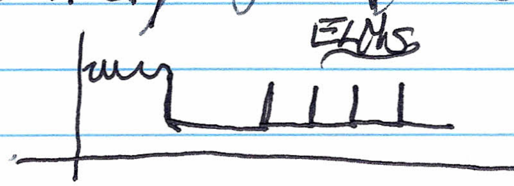
⇒ heat load from main plasma "focused" here.

N.B.: Plasma-wall interaction removed from vicinity of plasma.

→ Boundary control now central to MFE.

→ Was the H-Mode entirely good news?

not entirely → ELM



— ELM = Edge Localized Mode

= Edge Relaxation Phenomenon

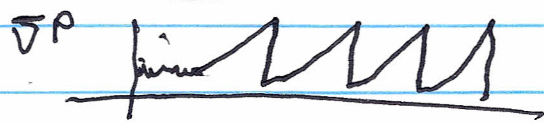
(small fire in German)

— ELM occurs when $\nabla P_{edge} \approx \nabla P$ for MHD instability

$\left\{ \begin{array}{l} \text{surface kink} \rightarrow \bar{J} \text{ driven} \\ \underline{\text{ballooning}} \rightarrow \nabla P + \text{curvature} \end{array} \right.$

— appears due steepening of ∇P as turbulence suppressed. Need enhanced confinement to access stability limit

— relaxation oscillation → build, relax, etc.



physics:
— limit linear, or ?
— fast crash, time scale

— impact:

— good: impurity removal (flushes the edge)

— bad: heat loads ⇒ { enormous on few cm width

on ITER $\boxed{10 \text{ MJ}}$ energy expelled by ELM (i.e. pedestal blown off).

— ELM / Heatload problem has spawned industry of boundary / EM mitigation studies

3D

→ RMP — coil, stoch. fields

→ Pellet pacing

→ Pellet injection } induce small stellarator

→ ergodic divertor ⇒ ⇑ (similar RMP)

and continued search for new regimes in which to operate machine

→ Q H-mode
- exploit strong shear to control MHD
- weak MHD turbulence

→ I-mode :
- induce plasma to make T barrier, not n barrier
- P vs γ asymmetry
- very interesting!

etc.

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

and strong mean shear.

Critical issues:

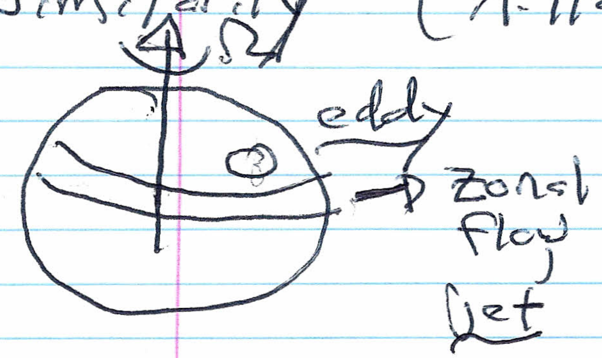
$$\partial_t \langle V_\theta\rangle = -\frac{\partial}{\partial r}\langle \tilde{v}_r \tilde{v}_\theta\rangle + \text{"}\nu \nabla^2 \langle V_\theta\rangle\text{"}$$

$\Downarrow$ stresses momentum transport

$\Uparrow$ Flow damping

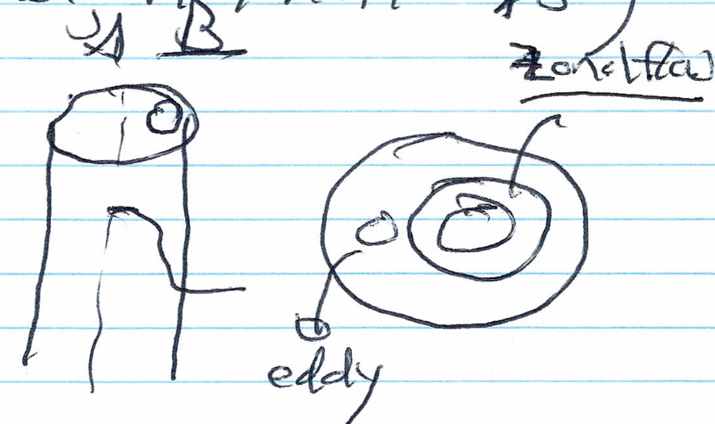
→ A Bit on Physics of Flows in Magnetized Plasma.

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



Coriolis force

$F_c = +2m\,\Omega \times V$



Lorentz force

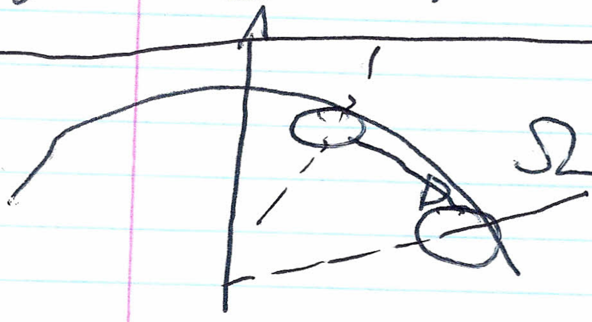
$F_L = m\,V \times \Omega_c$

$\underline{\omega} = \underline{\nabla} \times \underline{V}$ → vorticity (spin) t_0 ↻   8.

$$\partial_t \big(\underset{\text{fluid}}{\underline{\omega}} + \underset{\text{system}}{2\underline{\Omega}} \big) = \underline{\nabla} \times \underline{V} \times \big(\underline{\omega} + 2\underline{\Omega}\big) + \nu \ldots$$

induction eqn

⇒ $\boxed{\int d\underline{a} \cdot \big(\underline{\omega} + 2\underline{\Omega}\big) = \text{const}}$ ⇒ Kelvin's Theorem.



$\underline{\Omega} \cdot d\underline{a}$ changes

∴ ω must change

⇒ {local increase in vorticity, fluid motion evolves}

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

y → x

grad in 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

$$\partial_t \big(\phi - \rho_s^2 \nabla^2 \phi\big) - \underline{V} \cdot \underline{\nabla} \rho_s^2 \nabla^2 \phi = V_* \frac{\partial \phi}{\partial y}$$

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.

(calc' heat particle)

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

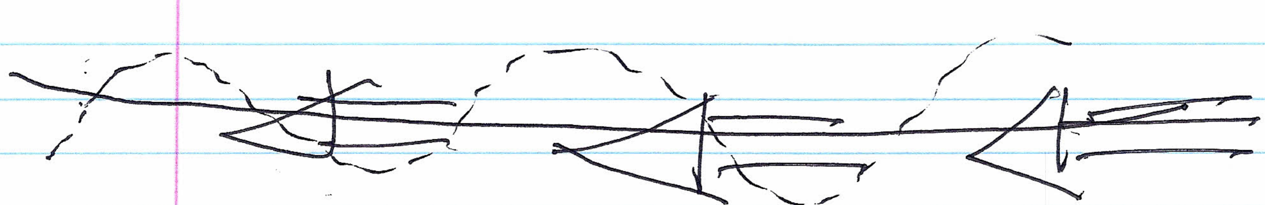
$\int_{\text{within } C} (\underline{\omega} + 2\underline{\Omega}) \cdot d\underline{a}$ must fall

as $\int 2\underline{\Omega} \cdot d\underline{a}$ constant (planetary vorticity unchanged)

$\Rightarrow \int \underline{\omega} \cdot d\underline{a}$ drops $\Rightarrow \int \underline{V} \cdot d\underline{\ell}$ drops

$\Rightarrow$ Westward flow develops

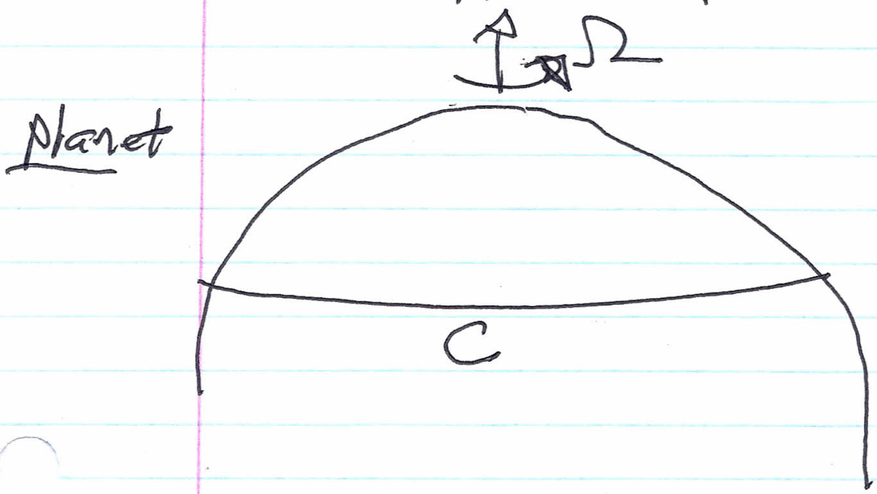
$\Rightarrow$ zonal jet



Can make similar argument for tokamak:

⇒ Zonal shear layers are intrinsic to magnetized plasma.

→ Cartoon Explanation of Z.F. Formation

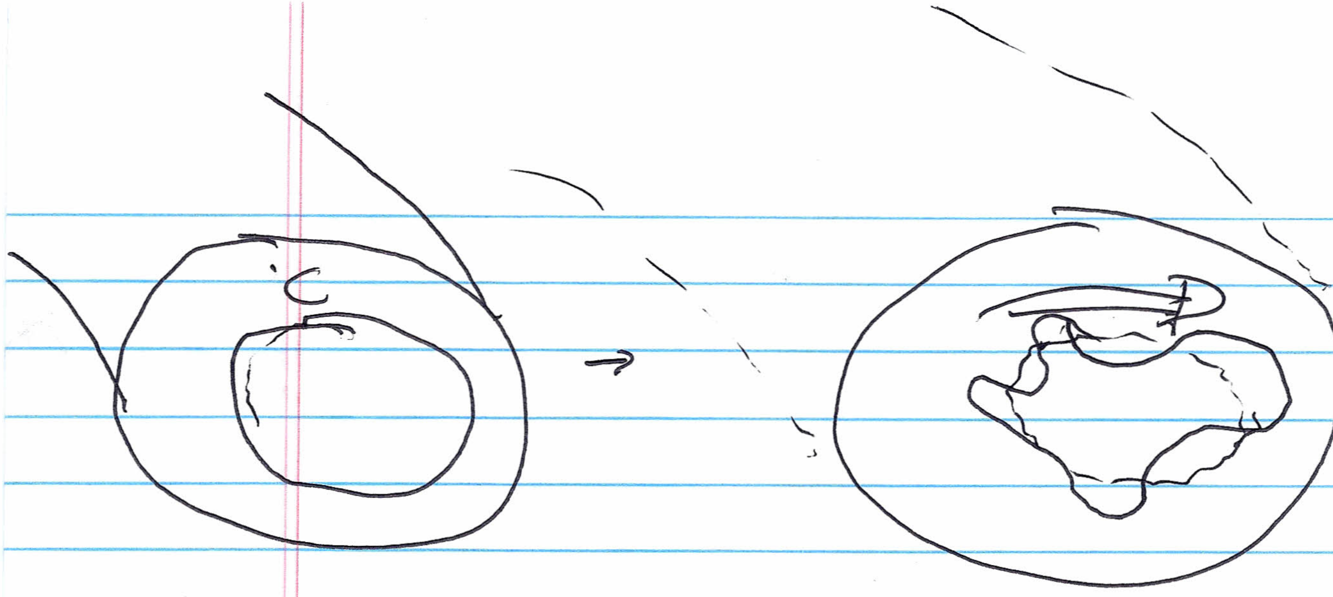


$$\int (\underline{\omega} + 2\underline{\Omega}) \cdot d\underline{a} = \text{const.}$$

$$\int_{\text{within } c} \underline{\Omega} \cdot d\underline{a} = \Omega_0 A$$

now, perturbation ripples contour

perturbation brings low planetary vorticity fluid within C.



The point:

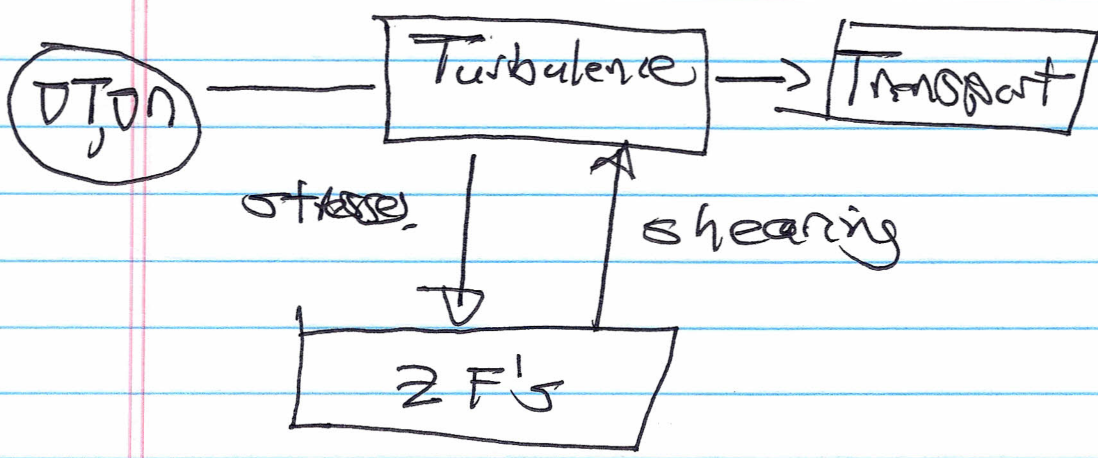
→ (radial transport of vorticity
(latitudinal)
unavoidably generates zonal jets.

→ Follows from:
- conservation / Kelvin argument
- $\underbrace{\langle \tilde{v}\, \nabla^2 \tilde{\phi} \rangle}_{\text{flux}} = \partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle$

→ Key:
⇒ some portion of driving energy converted to azimuthal flow

⇒ azimuthal flow does not contribute to cross-field transport.
Do regulate $\langle \tilde{v}_r \tilde{T} \rangle$, $\langle \tilde{v}_r \tilde{n} \rangle$
cross phase

⇒



⇒ tendency to form ZF's net benefit to confinement.