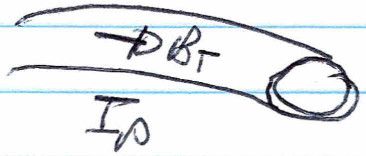
Physics 87

Class 5

⇝ recall **tokamak**



~ toroidal pinch
~ strong field, $q \geq 1$, $q' > 0$
~ MHD stable
~ confinement 'beat Bohm' $\frac{cT}{|e|B} = D_B$

60's

and

~ auxiliary heating raised temperature
~ OH scaling established
$\tau_E \sim n R^2 a$

70's ~ particle pinch raised central n, peaked $n(r)$.

Physics

⇝ 80's, 90's: Decades of Confinement studies, Improvement

– in ohmic tokamak, T, current tightly linked

$$\eta J = E_T = \frac{V_L}{2\pi R} \to \text{const.}$$

$$\eta \sim 1/T^{3/2}$$

→ Aside: 80's → decade of confidence

80's saw the construction of large tokamaks.

TFTR – Princeton (PPPL) → 1998

$T_i \sim$ (40 keV)

JET – Abingdon, still operating

JT-60 – Naka, Japan → 2008

JET: $R \sim 3$ m, $a \sim 1.25$ m

$B \sim 4$ T

$I_p \sim 1$ MA

$P \sim 25$ MW

$T_i \sim 40$ keV

$P_f \sim 16$ MW

$Q \sim .6$

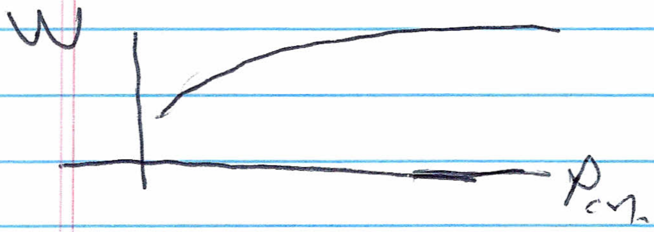
— with P_{aux},

- τ_E degrades with power

$$\tau_E \sim P^{-x}$$

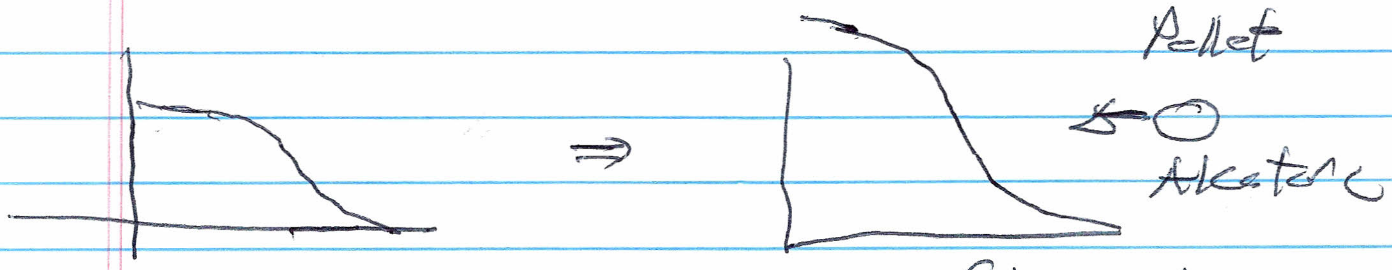
- $\tau_E = \dfrac{W}{P_{in}}$

⇒ energy content saturates/ exhibits diminishing returns to scale with P_{in}



Why? ⇒ transport mechanism?

- good news: peaked density profiles favorable



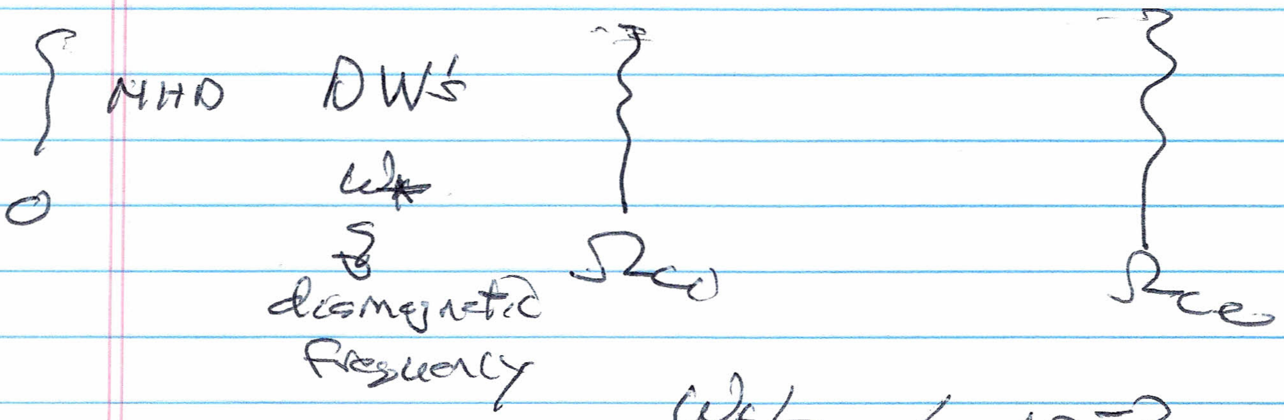
increased confinement.

Why? — Drift Waves

— Drift waves are the "microinstabilities" that drive energy, particle transport

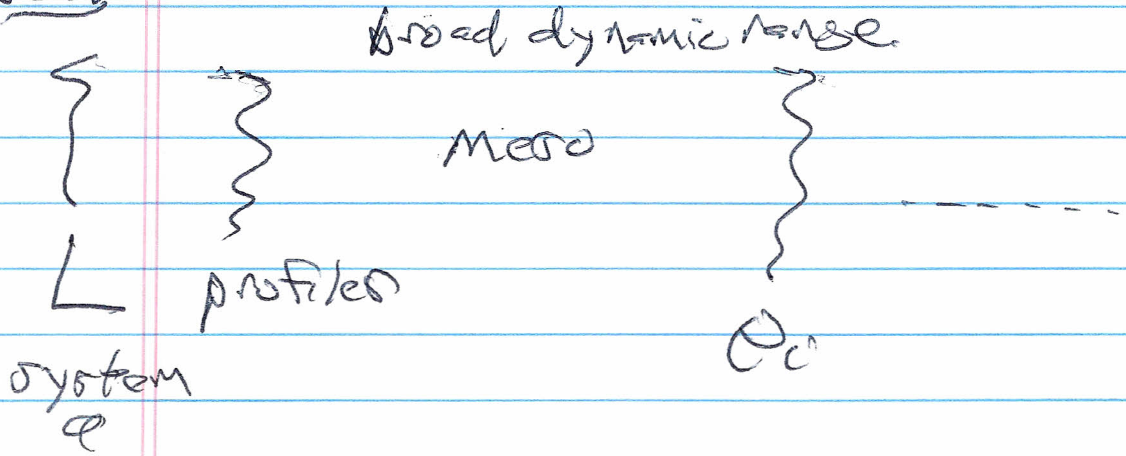
→ Scales

Frequency



$\omega_*/\Omega_c \leq 10^{-2}$

Scale



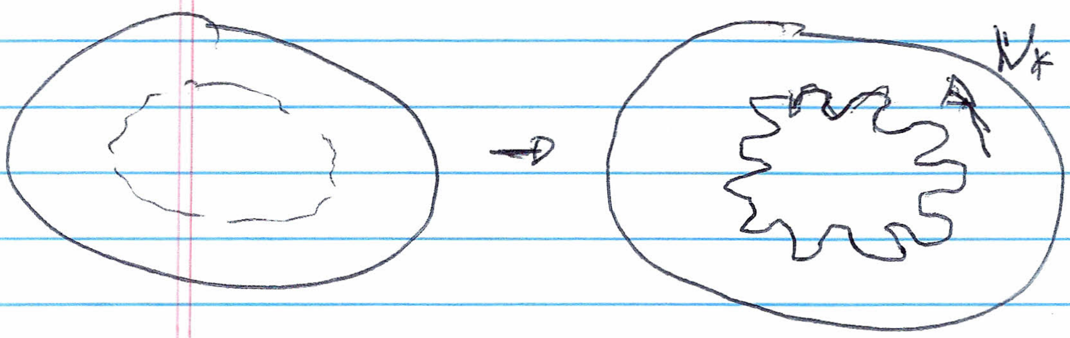
Point $\rho_i/L_p \lesssim 10^{-2}$

Story

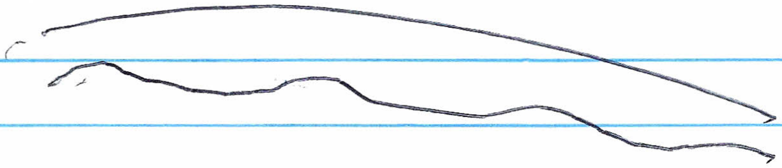
→ predicted in former USSR in late 50's,
⇒ driven by focus on Bohm scaling in linear devices

→ observed in late 70's by { microwave / laser } scattering ⇒ detected density fluctuations
$(\tilde{n}/n)^2_{k,\omega}$ in { relevant scale, ω range / relevant size }

→ small → same ρ_c order



① flute



How fast : V_* → diamagnetic velocity

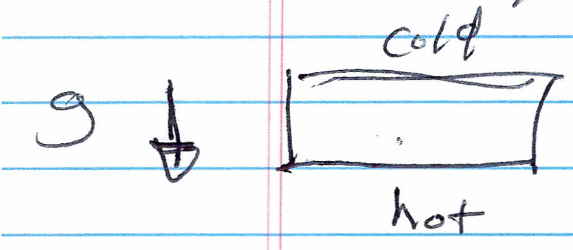
i.e. $\frac{\partial n}{\partial t} + \underline{V}_{E\times B}\cdot\nabla n_0$ $\qquad \frac{n_e}{n_0} = \frac{|e|\phi}{T} = \frac{n_i}{n_0}$

$$-i\omega\frac{\tilde{n}}{n_0} = +\frac{c}{B}k_\theta\phi\frac{\partial}{n_0\partial r}n_0$$

$$\omega = k_\theta V_* \qquad V_* = \rho_s\frac{c_s}{L_n}$$

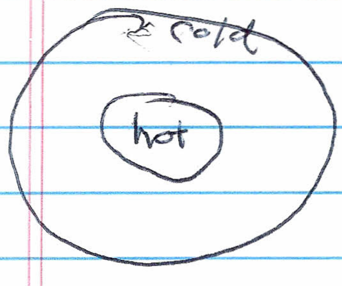
Unstable ?

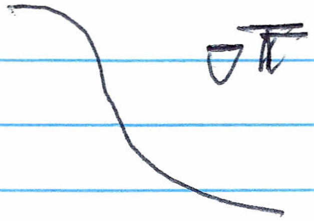
- e-i friction
- à la Rayleigh-Benard



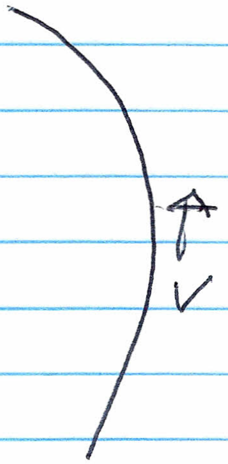
$\Delta T > \Delta T_{crit}$

⇒ heat moved by buoyancy.





analogue of $\underline{g}$ ⇒ magnetic curvature induced centrifugal force



$$F_R = \frac{mV^2}{R_c}$$

↳ radius of curvature of field lines

⇒ R-B micro-convection cells in tokamak.

Now, F-O-M : D → diffusivity

$$D \sim \lambda V \sim \lambda V_*$$

$$\sim \lambda \frac{\rho_s c_s}{L_n}$$

$$\sim \frac{\lambda}{L} D_B$$

what is λ? → few ρ_c

$$\Rightarrow \; D \sim \underbrace{\frac{\rho_c}{L} D_B}_{\text{Gyro-Reduced Bohm.}}$$

$$\sim \frac{T^{3/2}}{B^2}$$

- ρ_c/L smaller than Bohm

but

- $\sim T^{3/2} \rightarrow$ strong degradation

Whole can eliminate some, but not all, via peaked profiles, not a good prognosis...

$\Rightarrow$ Once again, a surprise <u>self-organization</u> intervened!

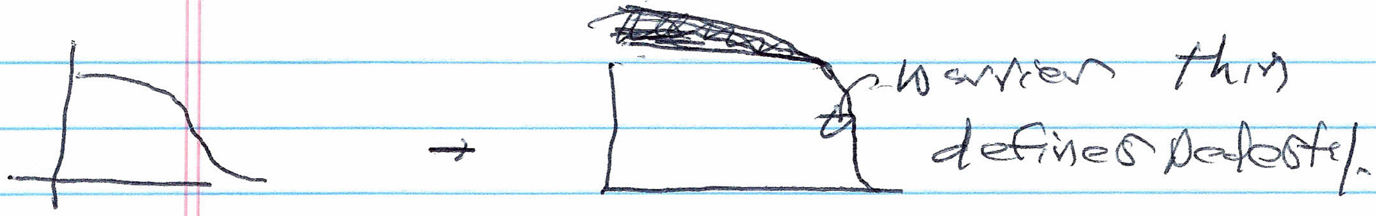
$\boxed{\text{H-Mode}}$

ASDEX Tokamak
Germany 1982
and many other contributors.

L → low
H → high

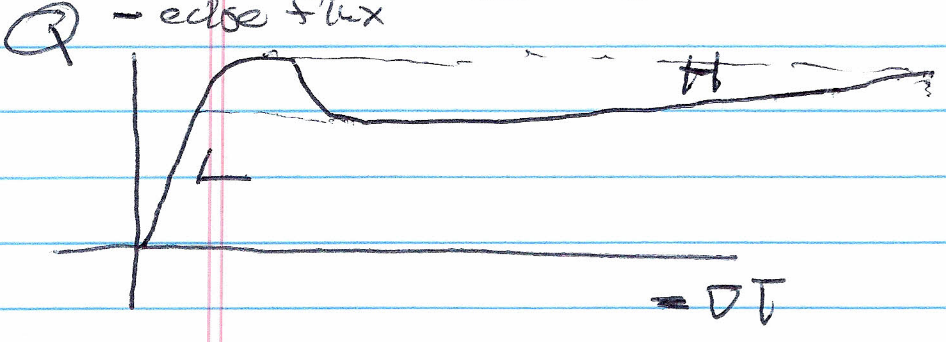
→ W jumps up, for $P > P_{crit}$

→ A transport barrier / thermal insulation layer forms at edge



→ in barriers, fluctuations (~) extinguished.

$\underline{\infty}$ Bifurcation !



$Q = -\kappa \nabla T$

→ mechanism seems to be onset of edge shear flow, ripping up eddies