Physics 218c

Lecture Ib - OV of Tokamak Physics, cont'd.

Today:

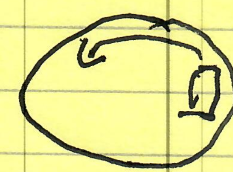
- L→H transition
- shearing feedback loop
- ELMs
- ELM mitigation
- Boundary Physics

- Lawson #
- Lawson, re-visited / re-written
- Fundamental Limits

- Hot Topics
- Roads Forward.

→ Poloidal Rotation

- neoclassical, due asymmetry



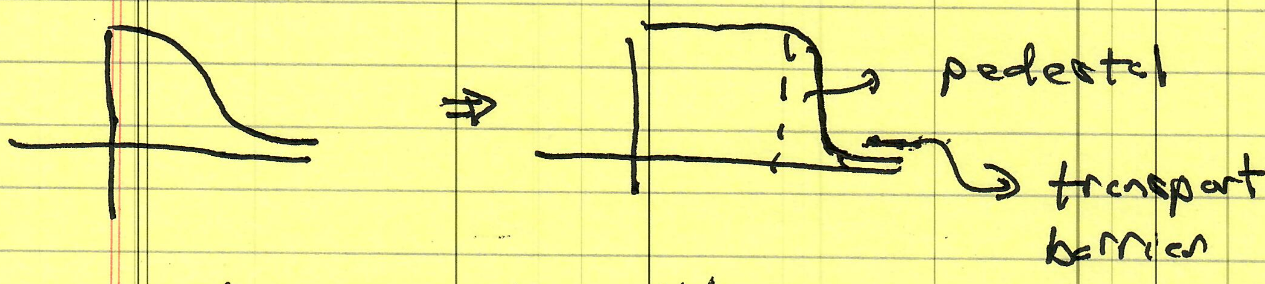
- some shift detected, absent τ_θ.

⇒ Important Aside → $\boxed{\text{H-Mode}}$

→ H-mode L-H Transition
Edge Transport Barrier

→ F. Wagner - ASDEX (1982) (now HL-2A)
(Divertor → boundary control)

$- P > P_{crit} \xrightarrow{local} \left(Q_{i_{edge}} > Q_{i_{crit}} \right)$



spontaneous transition to state of improved confinement with edge transport barrier

n.b. heat pulse trigger!

- Transport Barrier

  - region $w > \Delta x_c$ s/t
    Q_T, Γ_T etc. reduced dramatically
  - turbulence levels drop, not extinguished.

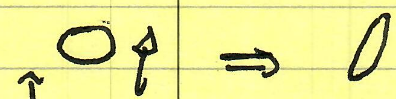
- How? → Shear Flow. (likely)

(BDT 1990 et seq) via radial force balance

$\underline{V}_{E\times B}$ from $0 = \left(+ \frac{Z}{m}\underline{E} + \frac{Z}{mc}\underline{U} \times \underline{B} - \frac{\nabla P_i}{n m_i} \right) \cdot \hat{r}$

⇓

$E \times B$ Flow

Classic cartoon:  etc. $\left\{ \begin{array}{l} \Delta r \\ \text{shrinks} \end{array} \right.$

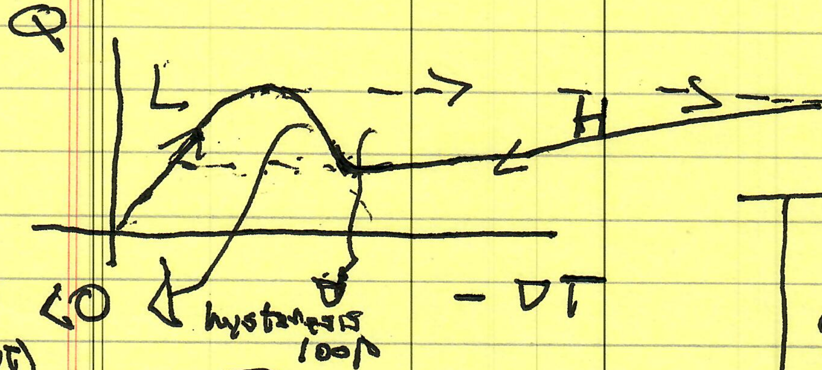
multiple mechanisms

Note: "Feedback loop" → critical concept

$Q \uparrow \;\to\; \nabla P \uparrow \;\to\; V_E \uparrow \;\to\; V_E' \uparrow \;\to\; \chi_i \downarrow$

change in self-consistent state.

— Transport Bifurcation → $P_{crit}(n, B_T, \dots)$

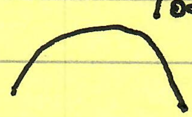


L → low

H – high

$\frac{\delta Q}{\delta(-\nabla T)} < 0$

Transport Barriers are Critical to Self-Organization



+ neo/residual

quenched turbulence

Trigger → flows ⇒ details ongoing
Reynolds stress

⟺ Variant: Internal Transport Barrier (ITB)

[localized by q-profile]

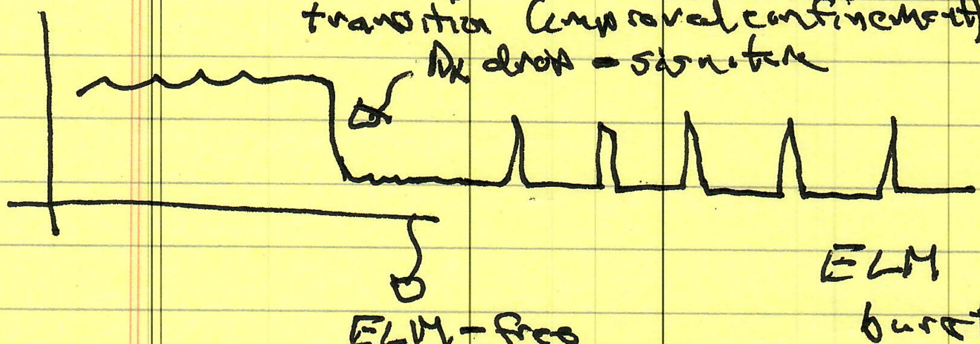
⟺ Variant: Zonal Flow (self-generated)
(E×B Flow)

Not all .....

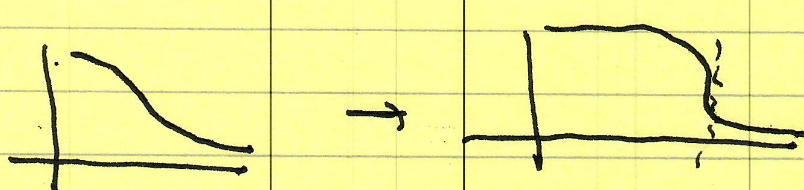
— ELMs — Edge Localized Modes
(a misnomer)
better:
Edge Relaxation Phenomena
(ERP – like hiccup)

ELM = 'small flame' in German.

· L→H sequence H^α, D^α ; [ionization radiation]



What?



"improved confinement needed to test β-limit"

∇P ~ ∇P_{crit} for MHD
∇J ~ ∇J_{crit} instability :

⇒ ELM event relaxes pedestal

δW [→ ballooning, → peeling (surface kink)]

⇒ lots of energy released ⇒ (ITER : 20 MJ)

⇒ Where does it go ? ⇒ PFC's.

~ unacceptable transient heat loads.

→ N.B. ELM event related to proximity to P-B threshold (Chinese)

but ELM ≠ P-B mode.
(n.b. some would disagree)

Nonlinear evolution, interaction etc.
very important

Which brings us to: $\boxed{\text{THE QUESTION}}$

- we want good confinement → H-mode

- we don't want high transient heat loads on PFC

What to do? → a trip to the ZOO .....
all current research

- mitigate/suppress ELMs while maintaining confinement

→ Resonant Magnetic Perturbation (Todd Evans)

coil → relieve ∇T? → relieve ∇n
(stellarTok hybrid) pump out

but P_{LH} ↑

→ QH-mode (Garofalo, Burrell)

strong edge shear quenches/eliminates P-B → EHO (weak saturated kink?).

- Pace ELMs – inject particles
  - → SMBI, pellet pacing (provoke small ELMs) (AUG, HL-2A, DIII-D)
  - → Density Limit ?
- Avoid ELMs
  - → I-mode, crested H-mode (C-Mod, AUG)
    (T ped, not n ped;
    $\tau_E \uparrow$, τ_p const)
  - → Relevance ?

Or, forget H-mode ?! (M. Kikuchi)
which brings us back to....

→ Negative Triangularity ... (again)

- improved L-mode confinement, so far
  No barrier needed   CTEM $\downarrow$ (Cameron)
- ballooning modes at corners

may prevent L→H transition ?!
(Marinoni, DIII-D)

— up-coming DIII-D experiments will be critical for negative T.

<u>Don't</u> <u>want</u> <u>H-mode</u> ...

And ...

→ improve Divertor ⇒ distribute heat Load

(beyond scope of this course)

Message: The self-organization of:

$$\boxed{\begin{array}{l} L \to H \to \text{ELMs} \to \text{ELM mitigation} \to \\ \quad \text{Divertor (includes SOL width)} \end{array}}$$

package is 1 of 2 critical problems in MFE today.

Other is Disruption.

? Is turbulence good or bad ?

→ More

Impurity transport X

EPG and AEs ~~X~~ → UCI ?

Disruption ✓ short

Details of RF heating, CD X

ITB's ✓

Divertor Physics X → others at UCSD ?

⇒ The $\boxed{\text{Magic Number}}$

Lawson Criterion:

$$nT\tau_E > \#_{crit}$$

- n.b. Caveat Emptor re: claims about Lawson #

- interesting to re-write . .

re-writing Lawson:

why high field is attractive (Alcator, SPARC)

$$n T \tau_E = \beta B^2 \tau_E$$

$$= \beta \, \tau_{E,neo} \, \frac{\tau_E}{\tau_{E,neo}} \, B^2$$

DIII-D likes this

MIT ~~likes~~ understands this.

$$= \beta \, \frac{\tau_E}{\tau_{E,neo}} \, \tau_{E,neo} \, B^2$$

Physics (dimensionless)

physics (d-less)

Engineering (Magnet Technology)

limited by understood Physics. → engineering

$$\frac{\tau_E}{\tau_{E,neo}} \lesssim 1 \quad \text{rigorously}$$

i.e. Boltzmann Eqn, H-Thm.
+
Chapman-Enskog
+
Particle Orbits
+
Field structure

So → all the physics issues in:

→ $\tau_E/\tau_{E\,req}$ → confinement

→ β → beta limit (includes density limit)

Rest → Engineering

N.B.: As emphasized by M. Kikuchi, story of fusion has evolved from:

→ quest for good confinement

⇒

→ quest for good confinement + good power handling (boundary control)

My personal opinion:

So claims of victory in Lawson # must establish that good power handling is realizable, for that Lawson solution.

How quantify? → Kikuchi-X number?!

→ What are the Fundamental Physics <u>Limits</u>?

- $\tau_{E_{neo}}$, $\tau_E / \tau_{E_{neo}} \leq 1$

(suggests barriers)

- β limit → stability (macro)

Ballooning, Kinks

(Troyon) → MHD

$$\boxed{\beta_N = \beta \frac{a B_T}{I_p}}$$

beta normal

$\beta_N \sim$ a few, some higher

- Density Limit — Greenwald

$\bar{n}_g \sim I_p$ (enters β)

N.B. - Current (I_p) is clearly <u>good</u>.

(confinement, too)

- but: disruptions, power handling.

→ Hot Topics, Now.

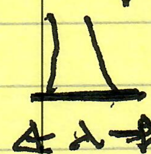
Top 3

— ELM mitigation
{ transport, stoch. field)
phase evolution

{ RMP
QH

— SOL, Divertor → heat loads
(turbulence spreading,
transport ...)

$\lambda \sim 1/B_\theta$ issue



— Disruption
+
runaway
electrons
(MHD)

— Kink/Tearing
interaction
heat, current quench

Others

— LH, ITB ; especially P_{crit}
(Feedback loops) (i.e. RMP on P_{crit} ?)

— Particle transport — fueling
(Physics of Pinch) density limit

— Low torque operation —
(Intrinsic rotation) intrinsic rotation effects

– EP transport, interaction with
(transport, stochasticity) thermal confinement

– NTMs (islands) – ↔ disruption
(islands + transport bifurcations)

– basic transport, turbulence, zonal flows

– impurity transport

– Roads forward

large
→ high β, β_p, high n (DIII-D)

– core ITB, enhancement $nT\tau_E$
– soft disruption

⇝ incrementally-cost ?

→ high n, high B_T, high I_p
$\boxed{\text{compact}}$ (SPARC/Alcator)

– simple, cheap $\beta\, B^2\, \tau_E$

⇝ disruptions ??? vulcan
heat loads

→ Stellarator

$\sim T\tau_E$ → Optimization ↑ τ_{E}, neo (and maybe τ_E T, via ZF) Low disruption hazard

↓

β?

→ cost, complexity ?

→ QSH RFP (= RFP in helical state, good confinement)

$\sim T\tau_E$ → helical state

{

$\sim I_p$ ↑

Unknown.

→ Negative T → discussed.

→ TBD.