Physics 218C

Lecture I b - QV of Tokamak Physics cont'd.

Today:

- L-H transition
- Shearly Feedback loop
- ELMs
- ELM mitigation
- Boundary Physics

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

- Hot Topics
- Road Forward.
- Poloidal Rotation
  - neoclassical, due to asymmetry
  - some shift detected, about \( \theta \)

**Important Aside** \( \rightarrow H\text{-Mode} \)

\( H\text{-mode} \to L-H \text{ Transition} \)
- Edge Transport Barrier

Dr. Wagner - ASDEX (1982) \( \text{(now HL-2A)} \)
- \( P > P_{\text{crit}} \rightarrow (Q_{\text{edge}} > Q_{\text{crit}}) \)

\[ \text{pedestal} \]
\[ \text{transport barrier} \]

Spontaneous transition to state of improved confinement with edge transport barrier.

**n.b.** heat pulse trigger!
- Transport Relation

\[
\begin{align*}
\text{region } \Omega &: W > 4 x_o \Rightarrow \\
\Omega, \Gamma &: reduced \text{ dramatically} \\
\text{etc.} \\
\text{turbulence levels } &\text{drop, not extinguished.}
\end{align*}
\]

- How? \rightarrow \text{Shear Flow, (likely)}

\[
(BOT 1970 \text{ et seq.}) \quad \text{von Kármán force balance}
\]
\[
\frac{V_{\text{ExB Flow}}}{B} \text{ From } 0 = \left( \frac{2E}{m} + \frac{2uxB}{M} - \frac{\partial P}{nM} \right) v_i^2
\]

- Classic cartoon: \( Q \uparrow \Rightarrow 0 \Rightarrow \) etc. \( \sum \)\text{ all\ flows}

\text{multiple mechanisms}

Note: "Feedback loop" \rightarrow \text{critical concept}

\[
Q \uparrow \Rightarrow 0 \quad 0 \Rightarrow V_{E} \uparrow \Rightarrow \frac{1}{V_{E}} \uparrow \Rightarrow \chi_i \downarrow
\]

\text{change on self-consistent state}
- Transport Bifurcation \[ \rightarrow \text{Crit}(\Lambda, B, ...) \]

\[ Q \]

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]

\[ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \rho \mathbf{g} + \nabla \cdot \tau \]

- Transport Rates are Critical to Self-Organization

- Quenched turbulence

Trigger \[ \rightarrow \text{Flow} \]

Reynolds stress

\[ \Delta \rightarrow \text{Variant: Internal Transport Barrier (ITB)} \]

\[ \left[ \text{localized by } Z\text{-profile} \right] \]

\[ \delta \rightarrow \text{Variant: Zonal Flow (self-generated)} \]

Not all \[ \ldots \]

- ELMs

- Edge Localized Modes (ELMs) (in German)

ELM = (small plasma)

IN German:

\[ \frac{\text{Edge Relaxation Phenomena}}{\text{ERP - like hiccup}} \]
- A sequence \( H^x \), \( D^x \) : (confinement, pedestal)

- Transition (improved confinement)

- ELM bursts

- ELM-Free Normal

- What?

- \( D_P \approx D_{P_{crit}} \) for MHD instability:
  - \( D_{J} \approx D_{J_{crit}} \)

- \( \Rightarrow \) ELM event relaxes pedestal

- \( \approx \) lots of energy released

- \( \Rightarrow \) (ITER: 20 MJ)

- \( \Rightarrow \) Where does it go? \( \Rightarrow \) PFC's

- \( \approx \) unacceptable transient heat loads
N.B. ELM event related to proximity to P-B threshold (claim)

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

Nonlinear evolution interaction etc.

which brings us to: \( \text{THE QUESTION} \)

- we want good confinement \( \rightarrow \) H-mode

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

what to do? \( \rightarrow \) a trip to the zoo ....

- mitigate/suppress ELMs

while maintaining confinement

\( \rightarrow \) Resonant Magnetic Perturbation (Todd Evans)

\( \rightarrow \) coil \( \rightarrow \) relieve DT? \( \rightarrow \) relieve DN

but \( P_{\text{HH A}} \) (stellarator\( \rightarrow \) hybrid) \( \rightarrow \) pump out

\( \rightarrow \) oh H-mode (Garofalo, Burrell)

strong edge shear quenches/eliminates P-B \( \rightarrow \) EHC (weak, distorted)
- Pace ELMs - inject particles.
  → SMBI, pellet pacing (provokes small ELMs) (Aug HL-2A, DIII-D)
  → Density limit ?
  - Avoid ELMs.

  → I-mode, instead H-mode. (c-mod) (Aug)
  "T and not n ped."
  "Eρ, Tρ const"

  → Relevance ?

or, Forget H-mode !! (M. Hirshman)
which brings us back to....

→ Negative Triangularity ... (again)
- improved L-mode confinement, so far
  No barrier needed (CERMAA)
- ballooning modes at corners
  Q may prevent L-D H transition ?!
  (Mariotti, DIII-D)
- up-coming Ohm-O experiments will be critical for negative $T$.

Don't want $H$-mode ...

And...

- improve Divertor $\rightarrow$ distribute heat load
  (beyond scope of this course)

Message: The self-organization of:

$\text{L$ \rightarrow H \rightarrow ELMs \rightarrow ELM mitigation \rightarrow Divertor (includes SOL width)$

Package is 1 of 2 critical problems in MFE today.

Other is Disruption.

? Is turbulence good or bad?
More

Impurity transport X

EPL and AES X \rightarrow UCI ?

Disruption \checkmark \text{ short}

Details of RF heating \quad CD X

IT B' \checkmark

Deleterious Physics X \rightarrow others at UCSD ?

\Rightarrow \text{ The Magic Number}

\text{ Lawson criterion :}

nT_{YE} > \# \text{ crit}

\text{- N.B. Coexist Emptor re: claiming about Lawson #}

\text{- interesting to re-write . . .}
Re-writing Lawson:

\[ nT \gamma_E = \frac{B B^2}{\gamma_E} \]

\[ = B \gamma_{E\text{neo}} \gamma_E B^2 \]

\[ = B \gamma_E \gamma_{E\text{neo}} \]

\[ \frac{\gamma_E}{\gamma_{E\text{neo}}} \leq 1 \quad \text{(nigorous)} \]

Physics

Engineering

\[ \text{(Magnet Technology)} \]

\[ \text{Limited by understood physics} \]

\[ \text{e.g., Boltzmann Eq., H-Theo.} + \]

\[ \text{Chapman-Enskog} + \]

\[ \text{Particle Orbits} + \]

\[ \text{Field Structure} \]
So all the issues in:

- $T_E/T_{E \text{ Neo}} \rightarrow \text{confinement}$
- $B \rightarrow \text{beta limit}$ (includes density limit)

Rest $\rightarrow$ Engineering

N.B. As emphasized by M. Hiruchij:
- Story of fusion has evolved from:
  - Quest for good confinement
- Quest for $\{(\text{good confinement} + \text{good power handling}) \text{ (boundary control)}\}$

My personal opinion:

- Claims of victory
- To establish that good power handling is realizable, from Lawson solution, that
- How quantify? $\rightarrow$ Hiruchij-$X$ number?
What are the fundamental physics limits?

- $T_{E_{\text{neo}}}, \frac{T_{E}}{T_{E_{\text{neo}}}} \leq 1$
  (suggests barriers)

- $\beta$ limit $\rightarrow$ stability (macro)
  Ballooning, kinks
  (Troyon) $\rightarrow$ MHD
  $\beta_n \sim$ a few, some higher

- Density limit $\rightarrow$ Greenwald
  $\bar{n}_g \sim I_p$ (enters $\beta$)

N.B. - Current ($I_p$) is clearly good.
  (Confinement, too)

- but: disrupting, power handling
Hot Topics, Now.

- ELMy mitigation
  (transport, edge, field, phase evolution)
  \( R_{\text{M}, \phi} \)
  \( \partial H \)

- SOL, Divertor
  (turbulence, particle, transport, ...)
  \( \lambda \sim 1/8\phi \) issue

- Disruptions
  + Runaway electrons
  (\text{MHD})
  (Other)

- Leak, ITER, i.e., especially Point
  (Feedback loops)
  (Can RAID on Part 3)

- Particle transport
  - Fueling
  (Physics of Puh)
  - Density limit

- Low torque operating
  (Strategic rotation effects)
- EP transport interaction with thermal confinement
  (transport stochastic?)

- NTMs (islands) - CE disruption (islands transport bifurcations)

- Basic transport, turbulence, zonal flows

- Impurity transport

- Roads Forward

  large

  → high $\Theta$, $\rho_p$, high $n$ $(\text{NII-D})$

  - core ITB enhancement
  - soft disruption

  incremental cost?

  → high $n$, high $B_T$, high $\Gamma_p$

  compact

  - simple, cheap

  no disruptions ?? ??

  heat loads
\[ \text{Stellerator} \]
\[ \land \bar{T} \bar{E} \Rightarrow \]
\[ \checkmark \]
\[ \varphi ? \]

\[ \text{No cost complexity?} \]

\[ \Rightarrow \text{QSFH RFP} \]
\[ \land \Gamma \bar{E} \Rightarrow \text{helical state} \]
\[ \sim \Gamma_0 \uparrow \]

Unknown.

\[ \Rightarrow \text{Negative } T \Rightarrow \text{discussed.} \]
\[ \Rightarrow \text{TBD.} \]