I-mode and H-mode plasmas at high magnetic field and pressure on Alcator C-Mod


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Supported by the U.S. Dept. of Energy, Office of Fusion Energy Sciences

Talk I2:005: 44th EPS conference on Plasma Physics, Belfast, June 27, 2017
Outline

- Overview of Alcator C-Mod and its main confinement regimes. *Why high B and pressure?*

- Extension of regimes to highest field and pressure.
  - EDA H-mode.
  - I-mode.

- Highlights of pedestal and transition physics.

- Implications for future fusion devices
  - Extrapolations, open issues, and needed research to resolve them.
Alcator C-Mod Tokamak: Compact, high B, high power density

- $R=0.68 \text{ m}$
- $a=0.21 \text{ m}$
- $B \leq 8.1 \text{ T}$ (LN2 cooled Cu magnets)
- $I_p \leq 2.0 \text{ MA}$

- Shaped, diverted (similar to ITER).
- Divertor, all PFCs high Z metal.
  — Mostly Mo, from day 1, some W tests.

All RF heating (no torque or core fueling)
- ICRH: 50-80 MHz, $\leq 6 \text{ MW}$
- LHCD: 4.6 GHz, $\leq 1.2 \text{ MW}$
Alcator C-Mod Tokamak: Compact, high B, high power density

- R = 0.68 m
- a = 0.21 m
- B ≤ 8.1 T (LN2 cooled Cu magnets)
- I_p ≤ 2.0 MA

Density limit: n_G = I_p / π a^2 ≤ 1.4 x 10^{21} m^{-3} (Max n_e > 5 x 10^{20} m^{-3}, n_e,0 > 10^{21} m^{-3})

**All RF heating** (no torque or core fueling)
- ICRH: 50-80 MHz, ≤ 6 MW
- LHCD: 4.6 GHz, ≤ 1.2 MW

- P/V ≤ 7.4 MW/m^3, P/S ≤ 0.94 MW/m^2, PB/R ≤ 73 MW-T/m

- Divertor q_∥ ≤ 3 GW/m^2 (λ_q < 0.5 mm)

- Shaped, diverted (similar to ITER).
- Divertor, all PFCs high Z metal.
  - Mostly Mo, from day 1, some W tests.

A. Hubbard, EPS 2017
Confinement physics strongly favors high B to produce fusion capable devices at smaller size.

Lawson criterion: \( n \tau_E = p \tau_E \) sets fusion gain \( Q = \frac{P_{\text{fus}}}{P_{\text{ext}}} \).

\[
\frac{P_{\text{fusion}}}{S_{\text{wall}}} \sim \frac{\beta_N^2 \epsilon^2}{q_*} RB^4
\]

Power density

At fixed power density, aspect ratio \( \epsilon \)

\[
p \tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3
\]

Options for fusion devices:
1. Increase \( H, \beta_N, \) decrease \( q_{95} \). Optimize confinement, at stability limits.
2. Increase \( R \). Increases cost. \( V \propto R^3 \)
3. Increase \( B \). Allows smaller \( R \), away from operational limits.

Alcator program has emphasized the high field approach, especially as new High T Superconductor magnets make higher B steady state reactors feasible.

- How high can field \( B \), pressure be increased in practice?
- Do physics, trends from lower B tokamaks hold, or are there surprises?
Physical models indicate pedestal, core pressure should increase with $B_T$, $I_p$.

If pedestal gradient is limited by high-n ballooning modes:

$$\nabla p(\text{max}) \propto I_p^2$$

(or $\sim B_T^2$ at fixed safety factor $q_{95}$)
Physical models indicate pedestal, core pressure should increase with $B_T, I_p$.

Core transport ‘stiffness’
$L_T = T / \nabla T \approx \text{const}$

$\nabla p(\text{max}) \propto I_p^2$

- Stiffness of core $T$ profiles is widely observed in tokamaks, including all C-Mod regimes. Greenwald NF’97.
  - Now well understood, and predicted by GK models eg N. Howard I1:10

- Implies a minimum **Pedestal pressure**, $p_{ped}$ is needed for fusion.

A. Hubbard, EPS 2017
Physical models indicate pedestal pressure should increase with $B_T, I_p$.

- **Pedestal limit is not quite that simple.** 
  *Set by coupled peeling-ballooning modes.*

- If p-b limit is violated, typically get **Edge Localized Modes (ELMs)** which release bursts of pedestal energy.
- Would be a big problem in a fusion device with high $p_{ped}$.
- Ideally want to operate in a stable region, just below limits.
Physical models indicate pedestal pressure should increase with $B_T$, $I_p$.

- Pedestal limit is not quite that simple. 
  *Set by coupled peeling-ballooning modes.*

- EPED model combines P-B and KBM constraints to predict height and width.

Illustration of EPED1 Model, DIII-D 132010

- P-B Stability Constraint (A)
- KBM Model (B)
- EPED1 Prediction
- Measurement (DIII-D)

Snyder PoP09, NF11
Physical models indicate pedestal pressure should increase with $B_T$, $I_p$.

- Pedestal limit is not quite that simple. Set by coupled peeling-ballooning modes.
- EPED model combines P-B and KBM constraints to predict height and width.
- It typically still predicts that pedestal height scales approximately as $p_{ped} \propto B_T B_{pol} \propto B_T I_p$

- Should operate at highest $B_T$, $I_p$.
- C-Mod can match ITER’s $B_T$, $B_{pol}$.

Can it reach ITER’s predicted pedestal pressure at 15 MA? (90 kPa)

Snyder, PEP ITPA 2012
C-Mod has explored several high energy confinement regimes

<table>
<thead>
<tr>
<th>Regime</th>
<th>ELMs?</th>
<th>Stationary?</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELM-free H-mode</td>
<td>NO</td>
<td>NO ☹️</td>
</tr>
<tr>
<td>ELMy H-mode</td>
<td>YES ☹️</td>
<td>YES</td>
</tr>
<tr>
<td>Enhanced $D_\alpha$ (EDA) H-mode</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>I-mode</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>

Will illustrate each of these regimes with examples at C-Mod’s most typical operating field, $B_T \sim 5.4$ T.

- C-Mod is the only diverted tokamak able to explore these high confinement regimes at full ITER field.
- The most efficient ICRH scenario, $D(H)$, can be used in this B range for $f \sim 80$ MHz.
ELM-free H-mode

- C-Mod tends to access **ELM-free H-mode** in ITER-like shape, at lower $q_{95}$ and density,
  - Note $P/P_{th} \sim 1-2$, at H-mode $n_e$.

- This has **very high energy confinement**, but also high particle confinement.

- **Density and radiation increase**, leading to transient H-mode, radiative collapse.

- **Some edge mechanism is needed to increase particle transport, ‘flush’ impurities!**
ELMy H-mode

- **Type I ELMy H-mode** on C-Mod is *only* accessed in a shape with modified (reduced) pressure limits, at lower $\nu^*$.  
  - Power supply limitations restrict this shape to $I_p < 1$ MA.  
  - Particle transport is provided by ELMs.  
  $\rightarrow$ Stationary density and radiation.

Hughes NF 2013
ELMy H-mode

- **Type I ELMy H-mode** on C-Mod is *only* accessed in a shape with modified (reduced) pressure limits, at lower $\nu^*$.
  - Power supply limitations restrict this shape to $I_p < 1$ MA.
  - Particle transport is provided by ELMs. → Stationary density and radiation.
- C-Mod validates models at unique parameters.
Enhanced D_α H-mode

- In EDA H-mode, particle transport is increased by a **continuous fluctuation**, the Quasicoherent (QC) mode.
- Gives stationary density, impurity radiation, WITHOUT Periodic ELMs.
  - Need boronization.
- Has been routinely achieved over a wide range of C-Mod shapes, plasma parameters
  - until 2016 only up to 6.2 T.
- **Access to EDA regime is favoured by higher ν*, higher q_{95}, ∇p**
Enhanced D$_{\alpha}$ H-mode

- An advantage of the EDA regime is that seeding can readily be used to reduce divertor heat flux, while maintaining needed high confinement.
  - $H_{98} \geq 1$ as long as $P_{\text{net}} \geq P_{\text{thresh}}$ (at H-mode $n_e$)

Loarte, PoP 2011, Hughes, NF 2011
I-mode regime has a thermal barrier, without a particle barrier

- **H-mode-like temperature pedestal and energy confinement.**
- **L-mode density pedestal and low particle confinement.**
  - Avoids impurity accumulation.
  - Unlike C-Mod H-modes, routine boronization is *not* needed.
- **ELM-free.**
- **Accessed when ion $B \times \nabla B$ drift is away from the active X-point (which raises L-H power threshold).**
- **Accessible at low $\nu^*$, low $q_{95}$.**

Whyte NF 2011, Hubbard IAEA 2012
Particle and energy confinement in I-mode vs H-mode

Weaker power degradation in I-mode:

\[ \tau_{E,I-mode} \sim P_l^{-0.3} \quad \text{vs} \quad \tau_{ITER98p} \sim P_l^{-0.7} \]
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EDA H-mode regime extended to 7.8 T

- For 80 MHz ICRH at ~ 8T, need to use D(He$^3$), a lower absorption scenario, hence lower effective power is available. $\eta_{RF} \sim 50$-80%.
- Obtaining EDA H-modes was a challenge
  - L-H power threshold: $P_{th} \sim n_e^{0.7} B^{0.8} S^{0.9}$ (Martin 2008)
  - C-Mod $P_{th}$ at 7.8 T roughly fit ITPA scaling (E. Tolman, TTF17)
  - To get EDA H-mode, we need a minimum L-mode target density ($n/n_G > 0.25$).
- **7.8 T EDA H-modes** accessed for $I_p = 0.7$-1.4 MA ($q_{95} \geq 3.9$)
- **ELM-free H-modes** to 1.8 MA ($q_{95} = 3.1$)
- **ELMy H-modes** at 0.9-1 MA.
EDA H-mode at $7.8\, T$, $I_p = 1.4\, MA$.

- Reached high plasma pressures
  - Pedestal pressure $30\, kPa$
  - Volume average $<p>$ $150\, kPa$
  - Central pressure $p_0$ $350\, kPa$.

- Usual quasicoherent mode in pedestal, at higher freq, $230-150\, kHz$. 

\[ q_{95} = 3.9 \]
Maximum plasma pressure was obtained in EDA at 5.7 T, 1.4 MA

- At this intermediate field we could use more efficient D(H) ICRH, at r/a=0.2-0.35, still with high I_p =1.4 MA.
  - Optimized with strong fueling, N seeding.
- Achieved world record <p> 207 kPa.
- No ELMs, near stationary conditions.
High pressure EDA H-mode pedestals are still below peeling-ballooning stability limit

- Typical of EDA H-modes; tend to be at higher $\nu^*$, far from peeling boundary.

Could peeling limit, and even higher pressures, be reached at low $\nu^*$, more like expected ITER pedestals?
EPED predicted peeling limit, higher $p_{\text{ped}}$ should be possible at low $n_e$, high $T_e$

- Predictions by P. Snyder, well before experiments. How to access such low $\nu^*$ H-mode pedestals?
EPED predicted peeling limit, higher $p_{\text{ped}}$ should be possible at low $n_e$, high $T_e$

- Predictions by P. Snyder, well before experiments.

*How to access such low $\nu^*$ H-mode pedestals?*

1. Start with a **hot** I-mode, instead of a **cold** L-mode!

2. Shift X-point location to trigger H-mode (recall I-mode prefers drift away from X-point).

3. Modify shape to promote instabilities, vs ELM-free.
Experiments confirmed higher pressure pedestal, likely at peeling limit.

- Much higher $T_{\text{ped}}$, $P_{\text{ped}}$ than EDA at same $I_p$ (1 MA).
  - Pressure close to EDA at 1.4 MA.
- Then extended regime to $I_p = 1.4$ MA, record $p_{\text{ped}}$ 80 kPa.
Latest C-Mod H-modes reach 90% of predicted ITER pressure, extend EPED validation

- Major accomplishment, for theory and joint experiments.
- Greatly increases confidence in ITER predictions.
  - Recall that in early 2000’s, $P_{ped}$ was highly uncertain, allowing big range in fusion $Q$.

Hughes, Snyder TTF17
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I-mode has now been extended to a very wide range of parameters

- **Robust I-mode operation on C-Mod:**
  - $B_T$ 2.8-8 T,
  - $I_p$ 0.4-1.7 MA,
  - Density 0.85-2.35 x$10^{20}$ m$^{-3}$

- **Has also been studied on ASDEX Upgrade and DIII-D.**
  Together, I-mode discharges have used
  - Heating with ICRH, NBI and/or ECH.
  - Mo, W and C PFCs.

- **Dimensionless parameters:**
  - $q_{95}$ 2.4-5.4
  - $\nu_{95}$ 0.06-5.4
  - $\rho^*$ 0.0026-0.006
8 T I-modes exhibit typical features

- Example with 7.8 T, 1.35 MA, \(q_{95} = 3.7\), \(P_{RF} = 4.7\) MW:
  - Central \(T_e\) to 7.3 keV,
  - Volume averaged \(<P>\) to 1.4 atm (0.14 MPa).
  - \(H_{98} = 1\), assuming \(\eta_{RF} = 80\%\).
  - No ELMs
  - Weakly Coherent Mode at 350 kHz (again higher than at lower \(I_p\) and \(B_T\)).
    - Up to 450 kHz at 1.7 MA.
Power range for I-mode widens with increasing magnetic field

- In contrast to L-H scalings, L-I power threshold has at most a weak dependence on $B_T$.
  - $P(L-I)/n_e \sim B_T^{0.26}$.
  - Uncertainties in $P_{\text{loss}}$ at 8 T.
- Maximum power for I-mode does increase with $B_T$.
  - NO discharges at 7.8-8 T had I-H transitions, up to 5 MW available ICRF power ($P_{\text{tot}}/S \leq 0.63 \text{ MW/m}^2$)

- More range to stay robustly in I-mode at higher $B$, avoiding H-mode.
- Consistent with experience on lower $B$ tokamaks.
I-mode pedestals have much higher $T$, lower density than EDA H-mode

- Comparison of discharges with 7.8 T, 1.35 MA, $P_{\text{loss}} \sim 4.4$ MW.
- **I-mode** has
  - Steep $T_e$ gradient, $T_{\text{ped}} \sim 1$ keV (also $T_i$)
    Low $\nu^* = 0.15$, $\rho^* = 0.0033$
  - L-mode density profile.
- **EDA** has highest pressure, but is high $\nu^*$.
- Pedestals in both regimes are MHD stable, **Explains lack of ELMs**; regulated by continuous fluctuations.
- Scope to increase further; pressure at 8 T was limited only by input power.
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Pedestal turbulence and flows are key to regimes without ELMs.

**EDA H-mode:**

- Sharp suppression of turbulence at L-H transitions, **rapid formation of both density and temperature pedestals.** Followed by appearance of QC mode.
- **New highly detailed mirror Langmuir probe measurements show that QCM:**
  - spans LCFS region with a mode width of \( \sim 3\text{mm} \)
  - drives transport directly across LCFS
  - is an **electron drift-wave with interchange drive and EM contributions**

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<table>
<thead>
<tr>
<th>Density</th>
<th>Electron Temperature</th>
<th>Plasma Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^20 m^3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>eV</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>volts</td>
<td>80</td>
<td>40</td>
</tr>
</tbody>
</table>

\[
\frac{\Delta n}{\langle n \rangle} \sim 30\% \quad \frac{\Delta T_e}{\langle T_e \rangle} \sim 45\% \quad \frac{\Delta \Phi}{\langle T_e \rangle} \sim 45\%
\]

LaBombard PoP 2014
Pedestal turbulence and flows are key to regimes without ELMs.

**I-mode:**

- **Reduction in mid-freq turbulence**, correlated with $\chi_{\text{eff}}$, **formation of only a temperature pedestal.**
- **Weakly Coherent Mode** – broad fluctuation at few 100 kHz
- Fluctuating flow at **GAM** frequency (10’s of kHz). Important in broadening WCM.
- Both **WCM and GAM likely drive particle transport**
- Consistent results on C-Mod (Cziegler PoP 2013) and AUG (Manz NF 2015).

For details, see Cziegler P5:175 (Friday).
Transfer from turbulence to zonal flows is 2x lower with $B \times \nabla B$ away from X-pt, opening an I-mode power window.

- L-H transition occurs when energy transfer rate into ZF exceeds turbulent drive. [AUG Manz PoP12, DIII-D Yan PRL14, C-Mod Cziegler PoP 14,NF15]
- Transfer rate in the configuration with $B \times \nabla B$ away from X-pt ("unfavourable") is only half the rate towards X-pt ("Favourable") => higher H-mode threshold! Opens up a power window for I-mode.

In I-mode, energy goes into both Zonal Flows and GAMs.

I. Cziegler, York
PRL 118 (2017) 105003
For details see P5:175 (Friday).
In 5.4 T field range, $E_r$ follows same trends as energy confinement:

- **L-mode** has little $E_r$, $\sim 20$ kV/m.
- **EDA H-mode, I-mode** both have significant $E_r$ wells, $\sim 50$-100 kV/m.
In 5.4 T field range, $E_r$ follows same trends as energy confinement:

- **L-mode** has little $E_r$, $\sim 20$ kV/m.
- **EDA H-mode, I-mode** both have significant $E_r$ wells, $\sim 50$-100 kV/m.
- **ELMy H-mode** $\sim 100$-150 kV/m.
- **ELM-Free H-mode** has deepest wells: in some cases 200-300 kV/m.
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C-Mod experience confirms high pressure at high field, current, in a compact tokamak

- Average pressures often exceeded those of larger, lower B, tokamaks ($R_{\text{JET}} > 4 R_{\text{C-Mod}}$).

- Similar $\langle p \rangle$, trends for all confinement regimes (EDA H-mode, I-mode,...)
- Each regime has different advantages, issues.
C-Mod experience confirms high pressure at high field, current, in a compact tokamak

- Average pressures often exceeded those of larger, lower B, tokamaks ($R_{\text{jet}} > 4 R_{\text{C-Mod}}$).
- $\langle p \rangle_{\text{max}} \sim I_p^2$ to $\sim 1 \text{ MA}$, but was limited by heating power at higher currents.
  - With more RF power, at 120 MHz, much higher $\langle p \rangle$ likely possible

- Similar $\langle p \rangle$, trends for all confinement regimes (EDA H-mode, I-mode...)
- Each regime has different advantages, issues.
H-mode: Pedestals, thresholds at 5-8 T closely follow trends from lower B.

- P(L-H) follows ITPA scaling.
- EDA access possible at higher $n_e$, power.
- H-mode pedestal limits follow EPED predictions, to 90% of ITER $P_{ped}$.
- *No surprises!* We can confidently use prior multi-device scalings, and our present models, to project to high field DT tokamaks.

Examples: Assuming $H_{98}=1$, project to

- **R= 1.65 m** (~AUG, DIII-D), $B=12$ T $\rightarrow P_{fus}=50-100$ MW ($Q=2-3.6$)

- **ARC**: **R=3.3 m** (~JET), $B=9.2$ T, $I=12$ MA $\rightarrow P_{fus}=525$ MW ($Q\sim13$)

*B. Sorbom, FED 100 (2015)*
**I-mode:** Pedestals and thresholds trends with field, up to 8 T, are favourable for high B

- **Surprise:** $P(L-I)$ increases weakly with $B_T$.
- Upper range of power increases with $B_T$, making I-mode regime much more robust at 5-8 T than 2-3 T.
- Confinement remains high ($H \sim 1$). No ELMs or impurity accumulation.
- Simple projections indicate I-mode may be accessible in ITER, ARC, and could be maintained to full fusion power.

**BUT:** We do not yet have as much experience with I-mode.

- Multi-device scalings of thresholds, $\tau_E$, density range are needed for confident extrapolation. ITPA activity, including several EU tokamaks. Experiments at larger size (JET, JT60-SA) will be especially valuable.
Some of the remaining issues and questions

Much work remains for understanding, and extrapolation to a fusion reactor. For all regimes.

- How to handle high divertor heat loads? Require advanced divertors
- Sustainment of plasma current, at high density.

**H-mode:**
- Can EDA H-mode still be accessed at needed high temperatures?
- How to fuel plasmas with high SOL density? Will pedestals change?

**I-mode:**
- Confinement scaling. *Why are particle and energy transport separated?*
  At what power, pressure may $p_{\text{ped}}, \tau_E$ saturate?
- Threshold scaling. Dependence on B vs normalized parameters?
- How high in density can the regime be extended?
- Heat footprint? How can it be integrated with a detached divertor solution?
Conclusions

• **C-Mod results have demonstrated the expected strong improvement in plasma pressure at high field and current.**
  - We have developed two stationary, quiescent, high confinement regimes, **EDA H-mode and I-mode** and are making good progress on pedestal physics.
  - Each confinement regime, also ELM-free H-mode and ELMy H-mode, has been extended to $B_T=8$ T. Some to 1.8 MA.
  - Highest pressure of any tokamak, $<p>=207$ kPa, $p_o=450$ kPa, was achieved in EDA H-mode at 5.7 T, 1.4 MA.
  - Highest pedestal pressure, $p_{ped}=80$ kPa, in a low $\nu^*$ H-mode validates the EPED model to 90% of ITER prediction.
  - L-H thresholds agree with ITPA scalings to 8 T.
  - I-mode threshold trends with B are very favourable for high field tokamaks.

• **C-Mod has established a strong design basis for future high field, compact, burning tokamaks for fusion energy.**