Access conditions, energy and particle confinement of the I-mode regime on Alcator C-Mod

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Invited talk K12:03, 57th Annual Meeting of the APS Division of Plasma Physics, Savannah, GA, Nov 17, 2015
Features for an ‘optimized’ MFE scenario

• It was once assumed that the ideal plasma regime would have minimal transport, complete turbulence suppression in barriers (eg H-mode, ITB).

• Now clear that this has several disadvantages:
  – Pressure then rises to MHD limits, giving large ELMs (not acceptable in a fusion device) or core collapse.
  – If particle as well as energy transport is reduced, density rises and impurities accumulate (cf JET ILW experience).

• An ideal regime would have:
  – Energy transport *reduced*, not necessarily suppressed.
  – Relatively high *particle* transport, and controllable density.
  – Pressure gradients which remain *below* large-scale instability limits.

• **I-mode is a regime which meets these requirements.**
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• **Main features of the I-mode regime** (pedestal and global).

• **Energy and particle confinement.**

• **Key issues for extrapolation** to fusion devices, and recent research on C-Mod to address them.
  - **Access conditions** (L-I and H-mode thresholds).
  - Density range and control.
  - Integration with boundary solutions.

• **Initial projections to scenarios on fusion devices.**
  - *e.g.* ITER, ARC
I-mode is a stationary, high energy confinement, low $\tau_p$ regime, without ELMs

Defining feature is a temperature pedestal, similar to H-mode, **without** a density pedestal.

- **I-modes** can be maintained at high power for many $\tau_E$, often limited only by plasma and heating pulse duration.

*Not to be confused with Limit Cycle Oscillation “I-phase”*
I-mode pedestals are MHD stable, consistent with the observed lack of ELMs

- Pressure gradients are lower than H-mode, largely due to lower $\nabla n$.
- Pedestal width is greater than for H-modes.
- Resulting pedestal is well away from boundary set by peeling-ballooning (ELITE) and expected KBM thresholds.

- I-mode pedestal height is instead limited by turbulence and heating power - can be controlled, and there is room to increase.
Several characteristic changes in pedestal turbulence at L-I transitions

1. **Decrease in mid-frequency turbulence.** Can be sudden or gradual, correlates with a decrease in pedestal thermal transport.

2. **Increase in higher freq turbulence termed ‘Weakly Coherent Mode’ (WCM).**
   - $f \sim 150-250 \text{ kHz}$, $k_{pol} \sim 1.5 \text{ cm}^{-1}$.
   - $\delta n/n \sim 10\%$, $\delta T/T$, $\delta B/B$ lower.

3. **Fluctuating flow at Geodesic Acoustic Mode (GAM) freq,** exchanges energy with WCM

![Image of graph showing reflectometer data with labels for $\sqrt{T_e,\text{edge}}$, Fluctuations 60-150 kHz (a.u.), and $\chi_{eff}$]
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I-mode is now robustly obtained on several tokamaks over wide ranges of parameters

- In addition to Alcator C-Mod, I-mode has been studied on ASDEX Upgrade and DIII-D.
- Global and pedestal features are mainly consistent across devices. Multi-device: Hubbard, Ryter, Osborne IAEA 2014
  AUG: Ryter EPS 2011, Manz NF 2015, DIII-D: Marinoni NF 2015
- $H_{98}$ often exceeds 1.0, over a wide $q_{95}$ range.
- I-mode in all devices is accessed primarily in the configuration with ion $B_x \nabla B$ drift away from the active X-point, power just below the (increased) H-mode threshold.
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Particle confinement in I-mode is like L-mode, 10-100X lower than H-mode!

- Impurity confinement $\tau_{\text{imp}}$ is measured from injected Ca or Mo (find no species dependence).

- Low $\tau_{\text{imp}}$ is highly beneficial, means high Z impurities do not accumulate.
  - Note most I-modes to date are in metal wall machines (Mo on C-Mod, W on AUG).
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- **Edge electron density gradients in I-mode are also the same as in L-mode** => similar main species particle transport.
Energy confinement in I-mode is in H-mode range, much less power degradation

- $H_{98}$ in C-Mod I-modes ranges from 0.7-1.3, indicating a different scaling.

- Find stored energy increases nearly linearly with power - thus $H_{98}$ increases with power.
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- **Regression on 200 I-mode slices:**
  \[
  \tau_{E,\text{I-mode}} = I_p^{0.68} B_T^{0.77} n_e^{0.02} P_L^{-0.29}
  \]
  - Contrasts with $\tau_{\text{ITER98p}} \sim P_L^{-0.7}$

- A $\tau_E$ scaling with $R^{1.5}$ or $R^2$ (as for $H_{89}$, $H_{98}$ scalings), would be consistent with AUG and very favorable for ITER - $\tau_E$ 2.5-8 s! Assumes full $P_{tot}=150$ MW.

- **How high in power can I-mode extend?** Will pedestal, $\tau_E$, saturate?
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L-I power threshold has similarities and some key differences to the L-H threshold

- L-H threshold, for favorable $B_x \nabla B$ drift, above $n_{\text{min}}$:
  \[ P_{L-H, ITPA08} = 0.049 \, n_{e20}^{0.72} \, B_T^{0.8} \, S^{0.94} \]

- L-I threshold, for unfavorable $B_x \nabla B$ drift has been well characterized and:
  - Increases with density, above $n_{\text{min}}$
  - Increases with $I_p$ (Hubbard NF 2012)
  - Increases with $S$ (at most linear, from multidevice study IAEA 2014)

- Important new result is that $P(L-I)$ has weak or no dependence on $B_T$
  - Indicates different controlling physics to the L-H threshold.
Power window for I-mode increases strongly with field.

Compared discharges in same LSN configuration, same run day, with $B_T = 2.8$ T (second harmonic D(H)) and $5.4$ T (typical D(H) ICRH).
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Narrow window at 2.8 T is qualitatively similar to I-modes on other devices.

AUG: 1.9-2.5 T
DIII-D: 2.04 T
I-modes and L-I threshold scaling were recently extended to $B_T \sim 8T$

- 7.8-8.0 T I-modes display same signatures as lower B; WCM $\sim 300$ kHz.
- L-I threshold again scales with $n_e$.
  - Used D(He$^3$) ICRH, which may have lower core absorption than usual D(H), hence $P_{\text{loss}}$ more uncertain
- No H-modes so I-H threshold is $P_{\text{loss}} > 4$ MW
Power window for I-modes is greater at high $B_T$, making regime more robust

- Normalize loss power by density, as in L-I scalings (and by $S$ to compare with other tokamaks).
- **Weak dependence of $P(L-I)$ ($\sim B^{0.25}$).**
- **Strong dependence of upper limit on $B$** (consistent with $\sim B^{0.8}$ as in L-H scaling) favors higher power I-modes at high $B_T$.
- At 5-6 T, I-mode is robustly maintained over a factor of 2-3 range in $P_{\text{loss}}$ (often to maximum available ICRH, 5.5 MW).
Conditions for the I-H transition are less clear than for L-I threshold

P(I-H) can depend on discharge trajectory. One example is density dependence:

- Above ~1.5x10^{20} m^{-3} target, L-modes typically transition to H-modes, not I-modes.
- BUT: Gas fuelling into a hot I-mode raised \( n_e \) by 30\%, to 2x10^{20} m^{-3}, with constant \( W, H_{98}>1 \).
- Upper density range increases with power.
Conditions for I-H transition are less clear than L-I threshold

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- In some cases, I-H transitions are triggered by a decrease in input power! (or an increase in $n_e$ at lower $P$).

An “I-H power scaling” does not capture all relevant physics.

**We need better understanding of I-H transitions, at the turbulence, flows level.** Good progress was summarized by I. Cziegler BI4:03.

A. Hubbard, APS 2015 KI2:03
Control of pedestal and core density is much easier in I-mode than H-mode

Density control is important to optimize alpha power and current drive (external and bootstrap) in fusion scenarios.

- In high $I_p$ C-Mod H-modes, density is highly constrained by the transport barrier, very hard to fuel or pump. [Hughes IAEA 2006].
- I-modes, without a particle barrier, are more readily controlled.
- With sufficient power, can maintain $T_{ped}$, increase $p_{ped}$, $\beta_{ped}$ – contrasts with ELMy H-modes. [Walk CP12:03].

What is upper limit to pressure?

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A. Hubbard, APS 2015  K12:03
Integration with divertor solutions

- I-mode has the major advantage over ELMy H-mode of eliminating transient heat flux pulses to divertor.
- As for all fusion regimes, the steady heat flux remains a challenge ($\lambda_{q,sol}$ is narrow, $q_{li}$ can exceed 1 GW/m²).
- **Due to BxVB reversal, flux shifts more to inner divertor.**
- Have used Ne, N or Ar seeding to reduce heat flux. Have not yet achieved detachment in I-mode.
  - Other low $\nu^*$ regimes without ELMs have similar challenges.
Integration with divertor solutions

- I-mode has the major advantage over ELMy H-mode of eliminating transient heat flux pulses to divertor.

- As for all fusion regimes, the steady heat flux remains a challenge ($\lambda_{q,\text{sol}}$ is narrow, $q_{\parallel}$ can exceed 1 GW/m²).

- Due to $B_x \nabla B$ reversal, flux shifts more to inner divertor.

- Advanced divertors are needed to handle reactor level $q_{\parallel}$ and reduce the influence of divertor plasma on the pedestal, whether in I-mode or H-mode.
  - Recent simulations of an x-point target divertor concept for ADX showed stable detached state in I-mode-like conditions. M. Umansky G04:03.
I-modes have been maintained in Double Null configuration

- Recent experiments scanning $\delta R_{\text{sep}}$ succeeded in maintaining I-mode in DN (±1 mm).
- SN with unfavorable drift was needed to access I-mode.
  - $\delta R_{\text{sep}}$ can be small, 1-2 mm $\sim \lambda_{q,\text{sol}}$
- DN configuration is expected to share heat flux between upper and lower divertors.
  - Might also affect the balance between inner and outer divertors. Analysis of heat fluxes is in progress.
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I-modes already meet many requirements for burning plasmas

- I-mode has been readily obtained at many relevant conditions which are challenging for some ELM-free regimes, eg:
  - No or low torque, e- heating (all RF).
  - Coupled e- and ions (high density)
  - High Z PFCs (Mo, W on AUG)
  - Low $q_{95}$ (to 2.5)
  - Low collisionality ($\nu^*_95$ to 0.1)

- Has attractive features: Stationary without ELMs, low particle confinement.

How might I-mode project to future fusion devices?
Expanded I-mode power range with $B_T$ is promising for fusion devices including ITER

- For ITER, can extrapolate directly from C-Mod results, scale by $S$ (700 m$^2$).

- Greatest challenge is L-I threshold $\sim 70$ MW at $5 \times 10^{19}$ m$^{-3}$.
  - Technical issues with NBI in reversed $B_T$.

- If accessed, should be able to maintain I-mode to full $Q=10$ power.

- Confinement time scaled from C-Mod ($\tau_E \sim 2-8$ s) appears more than adequate.
  - As for H-mode, would need to raise density to $0.7-1.0 \times 10^{20}$ m$^{-3}$ to increase $P_{\text{fus}}$. 
Projections to compact, high B reactors such as ARC are highly favorable

- ARC design $B_T=9.2$ T, $R=3.3$ m, $S=210$ m$^2$.
- Again should be able to access I-mode, and maintain to full $P_{fus}$ (525 MW) by raising $n_e$, to $\sim 1.3 \times 10^{20}$ m$^{-3}$.
- Scaled $n_e$ and $T_e$ profiles from I-modes were in fact used in scoping studies [Sorbom FED 2015], and found compatible with non-inductive scenarios at $Q \sim 15$, using LHCD+ICRH, $f_{BS}=0.63$.
  - Recent scalings predict even higher $\tau_E$ than was used.

In general, I-mode is likely best suited to high field, moderate $\beta_N$ fusion reactor designs.
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While many issues and uncertainties remain, the attractive features of I-mode, and promising initial projections to fusion devices, justify continued research on tokamaks worldwide.

- Physics of I-mode can and should be studied on devices at a range of B, to improve fundamental understanding. Ongoing comparisons with AUG and DIII-D have proven valuable. Plans on EAST, KSTAR, TCV, NSTX-U.
- More data at larger size (eg JET, JT60-SA) would be extremely valuable to improve size scalings of both thresholds and confinement.
Summary

• The I-mode regime combines high thermal confinement and low particle confinement, both attractive features for MFE scenarios.
  - Now well established on C-Mod, AUG, DIII-D over wide parameter ranges.
• Pedestals are MHD stable, consistent with observed lack of ELMs.
• Impurity confinement and edge density gradients are at L-mode levels.
• Energy confinement has weak degradation with power.
• L-I power threshold scales with $n_e, I_p$, has weak $B_T$ dependence (2-8 T).
• Power window for I-mode increases with field, leading to more robust I-mode operating scenarios at higher $B$ (5-8 T).
• Initial extrapolations to ITER, high B reactors are promising. Motivates further needed I-mode research on multiple tokamaks worldwide.