Multi-device Studies of Pedestal Physics and Confinement in the I-mode Regime

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and the Alcator C-Mod, ASDEX Upgrade and DIII-D Teams

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EX/P6-22, IAEA FEC, Oct 13-18, 2014, St. Petersburg, Russia
KEY NEW RESULTS

- I-mode has now been obtained on **Alcator C-Mod, ASDEX Upgrade and DIII-D**.
  - Regime is ELM-free, can obtain high normalized energy confinement, with low power degradation, and has low particle confinement.
- Wide ranges of device and dimensionless parameters, including low $v^*$ and $q_{95}$.
- Changes in pedestal turbulence, and $E_r$ shear, are observed in all devices.
- L-I threshold increases with $n_e$, but weak $B_T$ dependence.
- Upper range of power for I-mode increases with $B_T$, making regime more steady and robust at higher field.
Features of I-mode regime

I-mode regime is characterized by [Whyte 2010]:
1. Edge thermal barrier, increased energy confinement.
2. L-mode particle confinement (no density barrier).
3. Changes in pedestal turbulence.

Advantages over H-mode:
• Regime is generally **ELM-Free**, while remaining stationary.
• **Avoids accumulation of impurities** (from PFCs, seeding, ‘ash’).
• **More favourable dependence of** $\tau_E$ **on power** than L or H-mode.

This has motivated multi-machine studies of regime properties and access conditions, in both Transport and Pedestal ITPA groups.
**I-mode** is now established on Alcator C-Mod, ASDEX Upgrade and DIII-D, over wide parameter ranges.

<table>
<thead>
<tr>
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<th>C-Mod</th>
<th>AUG</th>
<th>DIII-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p$ (MA)</td>
<td>0.56-1.4</td>
<td>0.8-1.0</td>
<td>0.96-1.4</td>
</tr>
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<td>$B_T$ (T)</td>
<td>2.8-8.0</td>
<td>1.9-2.5</td>
<td>2.04</td>
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<tr>
<td>$q_{95}$</td>
<td>2.4-5.2</td>
<td>3.0-4.1</td>
<td>3.5-5.2</td>
</tr>
<tr>
<td>$ar{n}_e$ ($10^{20}$ m$^{-3}$)</td>
<td>0.9-2.3</td>
<td>0.16-0.3</td>
<td>0.22-0.51</td>
</tr>
<tr>
<td>$P_{\text{loss}}$ (MW)</td>
<td>1.5-5.1</td>
<td>1.6-3.0</td>
<td>2.4-4.1</td>
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</tbody>
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All results in this poster are from **D plasmas**, with ion $B \times \nabla B$ drift away from active divertor (ie ‘unfavourable’ drift for H-mode)
Alcator C-Mod

- 1.1 MA, 5.8 T, \( q_{95} = 3.4 \)
- LSN, upwards \( B \times \nabla B \) drift.
- ICRF heating

ASDEX Upgrade

- 1 MA, 2.45 T, \( q_{95} = 4 \).
- USN, \( B \times \nabla B \) drift downward.
- NBI + ECH heating.
- 0.98 MA, 2.05 T, $q_{95}=5.1$
- LSN, upwards $\mathbf{B} \times \nabla \mathbf{B}$ drift.
- **NBI heating**
- Note $T_i > T_e$ in DIII-D pedestals with NBI.
Global energy confinement in I-mode often reaches or exceeds H-mode scalings, over a wide range of $q_{95}$.

$0.6 < H_{98} < 1.3$

Note that density in I-mode tends to be lower than H-modes, $\tau_{98} \propto n^{0.4}$. 
Stored energy increases strongly with input power

- Much less power degradation of $\tau_E$ than in H-mode (all devices).
- AUG and DIII-D find $H_{98}$ independent of heating method.
- $H_{98}$ tends to increase with density (AUG and C-Mod)
  - Due to transition thresholds, $n_e$ and power ranges are correlated.

Regression fit to C-Mod data gives

$$\tau_E = 0.014 \, I_p^{0.68} \, B_T^{0.77} \, P^{-0.29}$$

[Walk 2014]
Stored energy and \( H_{98} \) are correlated with pedestal pressure

- Consistent with fairly stiff thermal transport in core, most of confinement improvement due to pedestal increase.
- Unlike H-mode, pedestal pressure does not saturate in I-mode at high power, which explains the weak confinement degradation.
Normalized pressure and density so far lower than H-modes

- Achieved $\beta_N$ is modest, $\sim 1.4$.
  - Does not seem to be set by an MHD limit, rather by I-H transitions (AUG, D3D) or available power (C-Mod).
- Density to date up to 60% of Greenwald limit.
  - Also does not seem an intrinsic limit.
  - On C-Mod, density range can be increased by fueling into I-mode, and increases with heating power.

Extending these ranges is a goal of ongoing experiments.
In all devices, a temperature pedestal \((T_e\text{ and } T_i)\) develops in I-mode, while density profiles remain close to L-mode.

Clear separation, not yet well explained, between thermal and particle transport, motivates detailed measurements of profiles and turbulence.

**Alcator C-Mod**

1.1 MA, 5.8 T, \(q_{95}=3.4\)
ASDEX Upgrade

- 1 MA, 2.45 T, $q_{95}=4$
- USN, $B \times \nabla B$ drift downward.
- 2.5 MW NBI heating + 0.7 MW ECH.
- $T_i$ pedestal $\sim T_e$.

DIII-D

- 1.2 MA, 2.05 T, $q_{95}=4.3$
- LSN, $B \times \nabla B$ drift upwards
- 3 MW NBI in I-mode.
- $T_i$ pedestal $> T_e$. 
$E_r$ well develops in T pedestal region, may play role in turbulence reduction

**C-Mod:** CXRS using B$^{5+}$ measures $E_r$ well during I-mode, to -80 kV/m in this case (variable). ExB shear is significant, though weaker than in H-modes.

**AUG:** Doppler reflectometry shows progressively deeper $E_r$ well during I-mode, to -16 kV/m in this case. CXRS measures $E_r$ as low as -30 kV/m in other I-mode discharges.

**DIII-D:** Weaker $E_r$ well, near 0 at minimum, measured by CXRS.
I-mode pedestals span wide parameter ranges, reach low $\nu^*$

- Devices have distinct $T_e$, $n_e$ ranges
- Up to $T_{ped}=1$ keV, $n_{ped}=1.6\times10^{20}$ m$^{-3}$.
- Dimensionless parameters overlap.
- Down to $\nu^*_{ped}=0.17$, $\rho^*_{ped}=2.2\times10^{-3}$
  - no sign of limits in these parameters.
Pedestals are stable to peeling-balloonning MHD and Kinetic Ballooning Mode, explaining lack of ELMs.

- ELITE shows pressure gradient well below limit, room to increase further; Analysis on DIII-D is consistent.
- Pedestal is wider than for ELMy H-modes, exceeds $\beta_p^{0.5}$ scaling in EPED* based on KBM limit (on both DIII-D and C-Mod).

[Graph showing normalized pressure gradient and current with annotations]

* Snyder 2011
Changes in turbulence and fluctuations occur at L-I transitions in each device

**C-Mod**

- **As the T pedestal forms**, see
  - A DECREASE in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz), correlated to decreasing $\chi_{\text{eff}}$.
  - Usually a PEAK in turbulence (n, T and B) at higher f **“Weakly Coherent Mode”**. $f_0 \sim 200-400$ kHz, $\Delta f/f \sim 0.3-1$, r/a 0.9-1.
  - A **fluctuating poloidal flow at GAM frequency** (~20 kHz), which exchanges energy with mid-f turbulence and broadens WCM.
  
- CORE transport and turbulence (both $\delta n_e$ and $\delta T_e$) also promptly decrease.
During formation of $T_e$ and $T_i$ pedestal in I-mode, typically see

- **PCI**: line integrated $n_e$ fluctuations intermediate between L and H-mode spectra, reduced $\sim 150$ kHz, develop peak at $\sim 300$ kHz.

- **Doppler Backscattering**: Decrease in density fluctuations, localized near pedestal top.

- **BES**: Little change in spectra of ion-scale density fluctuations, up to 40 kHz.

Marinoni 2014
In at least some DIII-D I-mode discharges, small discrete events (few kHz) are seen on BES and ECE. These are correlated with increases in $D\alpha$, indicating enhanced particle transport.

- Origin of these ‘ELM-like events is unclear, since as shown above pedestals are far from MHD limits.
Access to I-mode

- In all devices, I-mode is usually accessed by operating with $\mathbf{B} \times \nabla \mathbf{B}$ drift away from X-pt, which raises H-mode threshold. (ie ‘unfavourable’ drift).

- Heating power is gradually increased, while remaining below the H-mode threshold.

- Since I-mode performance ($W$ and $H_{98}$) increase strongly with power, thresholds to enter I-mode (L-I transition) while avoiding H-mode (I-H transition) are key to extrapolating the regime.
L-I threshold increases with density

- Density dependence of $P(\text{L-I})$ at least linear, with a small offset on AUG.
  - C-Mod observes a minimum threshold power at $n_e \sim 10^{20} \text{m}^{-3}$, analogous to ‘low $n_e$ limit’ for L-H transitions.

- Increase in $P(\text{L-I})$ with plasma current has also been observed on C-Mod. [Hubbard NF 2012]
I-H transitions are complex, depend on both power and $n_e$

- I-H transitions do *not* always occur at the maximum power of I-modes.
- On C-Mod, maximum density for sustaining I-mode depends on discharge trajectory and power, can be increased by fueling into hot, high power I-mode.
  - Often an I-H transition occurs when $P_{RF}$ decreases.
L-I threshold increases less than linearly with device surface area $S$

- Linear fit seems too strong, $P(L-I)/n \sim S^{0.5}$ is a better fit.
  - But, there is scatter in data, and parameters are different between devices; need to check covariances.
- We conservatively use $P/n_e S$ to extrapolate thresholds and power range.
  - If $S$ dependence is weaker, threshold power for larger devices will be lower.
Power range while remaining in I-mode increases strongly with field 

Illustrated by C-Mod experiment which compared discharges in same configuration, with $B_T=2.8$ T and 5.4 T.
Both C-Mod and joint datasets show:

- Weak (no?) scaling of L-I threshold $P/nS$ with $B_T$.
- Strong (~linear) scaling of upper range for I-mode with $B_T$.

Results in **expanded power range for I-mode at high field.**

- Consistent with differences seen among devices.
- Result is encouraging for ITER, at 5.3 T, and for application of I-mode to proposed higher $B$ fusion devices*

*eg, LaBombard, Paper FIP/P7-18, Sorbom 2014.
Extrapolation and key issues

One of the aims of this ITPA joint activity has been to assess possible extrapolation of the I-mode regime to larger devices, especially ITER. Many of the results, obtained with ion grad B drift away from the x-pt, are encouraging:

• I-mode is robust over a wide range of global and dimensionless parameters, extending to low \( q_{95}, v^* \) and \( \rho^* \); no indication of a physics limit which would prevent application to burning plasmas.

• High normalized confinement \( (H_{98}>1) \) has been achieved on AUG and C-Mod, though at lower B these discharges often evolve to H-mode.

• L-I threshold power: \( P/n_e S=\text{const} \) would scale to \( P_{\text{thresh}} \approx 70 \text{ MW} \) for ITER at \( n_e=5\times10^{19} \text{ m}^{-3} \). Weaker scaling with S would reduce \( P_{\text{thresh}} \).

• I-H threshold power: Upper power range increases with \( B_T \). C-Mod results at 5.3 T indicate ITER could maintain I-mode to \( P_{\text{loss}}=350 \text{ MW} \) at \( 10^{20} \text{ m}^{-3} \), above the expected heating and alpha power.
Key issues and future work

- **Density and pressure range:** To date I-mode has been achieved at moderate $\beta$ and $n/n_G$.
  - All pedestals seem well below stability limits, with headroom.
    *Is $\beta$ just set by heating or transition power? How can we increase?*
  - C-Mod experiments show density can be increased at higher power.
    *What is the limit in density and can it be robustly maintained?*

- **Confinement and threshold scalings.** I-mode has clear differences to H-mode scalings, including weak power degradation of $\tau_E$, $I_p$ dependence of $P(L-I)$, and $B_T$ dependence of $P(I-H)$. *New multimachine scalings are needed for confident extrapolation.*
  - Experiments are planned soon on EAST and KSTAR.
  - Experiments on JET, with larger size and intermediate $B_T$, would be particularly valuable.

- **Access with favourable vs unfavourable drift.** Reversing $B_T$ (usually along with $I_p$) poses operational issues in devices using NBI, including ITER. *Examples exist with favourable drift, should be explored further.*
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Acknowledgements

• The authors are grateful for the support of the ITPA Pedestal and Edge Physics and Transport and Confinement Topical groups. Some of the experiments reported here were part of Joint Experiments PEP-31, TC-18 and TC-19.

• Work in U.S. was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using Office of Science User Facilities Alcator C-Mod and DIII-D, under Award Numbers DE-FC02-99ER54512-CMOD, DE-FC02-04ER54698, DE-FG02-94ER54235, DE-AC52-07NA27344, DE-AC02-09CH11466, DE-FG02-89ER53296, DE-FG02-08ER54999, and DE-FG02-08ER54984.

• The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.