Decoupling transport channels in tokamaks: I-mode phenomenology and physics

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With thanks for input from

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I-mode phenomenology and physics

• What is “I-mode”? Why of interest for fusion? How to access?

• Evidence for separation of thermal and particle transport

• Phenomenology: Measurements of profiles, turbulence and flows on C-Mod and ASDEX Upgrade tokamaks

• Physics: Possible contributions to separation of transport channels (for workshop discussion, still no definitive explanation)

• Conclusions, questions, prospects
I-mode is a stationary, high energy confinement regime, without a particle barrier

- Temperature pedestal and high energy confinement.
- L-mode density pedestal and low particle confinement.
  - Stationary, controlled densities.
  - Avoids accumulation of high or low Z impurities.
- ELM-free, avoiding damaging heat pulses. — Pedestals are MHD stable.
- Highly attractive combination of features for fusion energy.

* Clarification: This is NOT the same regime as the transient Limit Cycle Oscillation phase between L and H-mode, sometimes known as “I-phase”.

A. Hubbard, ISHW2017, Kyoto
I-mode is accessed robustly on tokamaks with ion $B_x \nabla B$ drift *away* from X-pt.

- This configuration has long (since Wagner 1982) been known to have higher L-H power threshold, hence called ‘unfavourable’.
- I-mode is accessed by slowly increasing input power, to below this higher L-H threshold (all results in this talk).
  - Some cases with “favourable” drift towards X-pt, with atypical shaping, but these are limited to low power.
- Further increases in power can sometimes lead to I-H transitions. Power range varies with device parameters.
I-mode has been accessed in several tokamaks, over wide ranges of parameters: **Robust**

- Most widely studied on **Alcator C-Mod**, **ASDEX Upgrade (AUG)** (hence focus in this talk).

- Also observed on DIII-D ~2013 (Marinoni NF15), and very recently on EAST (Z. Liu H-mode workshop 2017). ITPA comparison study in Hubbard NF 2016)

- Together, I-mode discharges have used
  - Heating with ICRH, NBI, ECH and/or LH.
  - Mo, W and C PFCs.
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At L-I transition, pedestal develops in $T_e$, $T_i$. Density remains nearly unchanged.

- Increasing $T_e$, $T_i$, $\nabla T$, at similar input power implies lower thermal transport than L-mode.
- Constant $n_e$, $D_\alpha$ imply ~same main species particle transport as L-mode.
- More quantitative estimates (to follow) support this.
I-mode also has high global energy confinement, low global impurity confinement

- Range of $H_{98,y2} \sim 0.6-1.2$, correlating well with pedestal (ie stiff core profiles)
- Weaker power degradation in I-mode: $\tau_{E, I-mode} \sim P_L^{-0.3}$ vs $\tau_{ITER98p} \sim P_L^{-0.7}$

C-Mod

see Rice NF 2015

($\tau_1$ for Ca, Mo are similar)

Ca and Molybdenum injections

AUG Ryter NF 2017

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Several characteristic changes in edge fluctuations, flows at L-I, I-H transitions

At **L-I transition**, as T pedestal forms, see

1. A DECREASE in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz)
2. Usually a PEAK in turbulence at higher f “Weakly Coherent Mode” (~200-400 kHz on C-Mod).
3. Fluctuating flow at **GAM frequency**. (10’s of kHz)

At the **I-H-mode** (particle barrier) transition, remaining turbulence drops suddenly, density and impurities rise.

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A. Hubbard, ISHW2017, Kyoto
Weakly Coherent Mode seen in density, magnetics, ECE, localized to barrier region

- In most I-modes, a higher frequency turbulence feature appears, simultaneous with mid-freq reduction. On C-Mod: \( f_0 \sim 200-400 \text{ kHz}, \Delta f/ f \sim 0.3-1 \)

- Fluctuations seen in \( B \) (magnetics), \textbf{Density} and \textbf{Electron Temperature} (ECE). \( \delta T_e/ T_e \ 1-1.6\% \ < \delta n_e/ n_e \ 6-13\% \).

- All diagnostics localize WCM to the region of T pedestal. \( (0.9 < r/a < 1.0) \)

- \textbf{2-D Gas Puff Imaging} reveals WCM details:
  - \( k_{pol} \sim 1.5 \text{ cm}^{-1} \ (k_{\perp} \rho_s \sim 0.1) \)
  - Propagation in \textbf{electron diamagnetic direction}

Cziegler PoP 2013, White, NF 2011
Now clear that GAM is also important, and interacts with WCM in complex ways

- Fluctuating flow $v_0$ at GAM frequency appears only in I-mode on C-Mod, also in L-mode on AUG. A density, $\tilde{B}$ fluctuation at similar frequency (10’s of kHz) is sometimes measured.

- In both tokamaks, bispectral analysis shows GAM exchanges energy with the WCM, leading to its broad $\delta f/f$.

AUG
Manz, NF 2015

C-Mod
Cziegler
PoP
2013

A. Hubbard, ISHW2017, Kyoto
Density fluctuations are strongly intermittent during I-mode

- Recent AUG measurements show I-mode has lower base-level of fluctuations than L-mode, but exhibits strong irregularly spaced ‘solitary’ bursts (intermittency).
- At all measured structure sizes ($k_\perp = 5-12 \text{ cm}^{-1}$): **Low fluctuation amplitudes decrease, while large fluctuation amplitudes increase (PDF broadens).** Note bursts extend to larger $k$ than WCM ($k_\perp \sim 15 \text{ cm}^{-1}$).
- Intermittency increases with $\nabla T$.

T. Happel *et al*, NF **56** 064004 (2016)
T. Happel *et al*, PPCF **59** 014004 (2017)
P. Manz *et al*, NF **57** 086022 (2017)
Density ‘bursts’ are connected to WCM, and to radiation at divertor.

- Intermittent events are preceded by smaller density perturbations.
- $\Delta t$ of precursor events corresponds to $1/f_{\text{WCM}}$.

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Density ‘bursts’ are connected to WCM, and to radiation at divertor.

- Intermittent events are preceded by smaller density perturbations.
- $\Delta t$ of precursor events corresponds to $1/f_{WCM}$
- Bolometry signal in divertor is correlated with fluctuation amplitude, with a time delay.
  - Suggests a particle flux from inside separatrix.

A. Hubbard, ISHW2017, Kyoto

T. Happel et al, PPCF 59 014004 (2017)
E_r well develops during I-modes

- Builds up gradually along with T_ped
- ExB shear greatest in outer region.
- Steeper, deeper well than L-mode.
$E_r$ well develops during I-modes

- ExB shear greatest in outer region.
- Steeper, deeper well than L-mode.
- But, $E_{r\text{min}}$ less than most H-modes.
WCM and low freq GAM fluctuations are localized in the $E_r$ well, extend to near separatrix

- WCM and GAM have similar radial extent.
- In $E_r$ well, peaked in outer shear layer.
- Still detected near separatrix.

C-Mod
Cziegler
PoP 2013,
Theiler
PPCF 2017
Wilks
HMW17
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- Mode location is important since $T_{e,sep}$ is always low ($\sim 100$ eV, SOL physics), while $n_{e,sep}$ can be relatively high.
- Any mode near LCFS would be expected to drive more particle than heat flux. (This has been measured with probes for EDA H-mode. LaBombard PoP 2014)
- Further studies of radial location and extent of turbulent features in I-mode would be valuable - and are a diagnostic challenge!
Decrease in edge thermal conductivity correlates with reduction in mid-f turbulence

- At transition from L to I-mode edge $\nabla T$ steepens, at near-constant $P_{\text{net}}$ and edge $n_e \Rightarrow$ Edge $\chi_{\text{eff}}$ is decreasing. Edge power balance: $\chi_{\text{eff}}$ 0.6-0.2 $m^2/s$.
- Edge $\chi_{\text{eff}}$ correlates well to the drop in mid-f turbulence. (~60-150 kHz) from reflectometry
- Further, fast, drops are seen in both turbulence and $\chi_{\text{eff}}$ at I-H transitions.
- Consistent with (but does not prove) this mid-freq turbulence playing a key role in thermal transport.
Edge particle flux correlates with amplitude of Weakly Coherent Mode

- Relative amplitude of WCM from edge reflectometer.
- Edge particle flux $\Gamma_{\text{LCFS}}$ derived from calibrated $D_\alpha$ imaging near the outboard midplane.

- Correlation with $\Gamma_{\text{LCFS}}$ is consistent with (does not prove) the WCM playing a role in driving particle transport, perhaps helping avoid transition to H-mode.

**Caveats:** $\Gamma_{\text{LCFS}}$ analysis was only done for a few discharges. Have not tried similar correlations for recently observed turbulence features (eg GAM, bursts)

C-Mod A. Dominguez, MIT Ph.D 2012.
I-mode phenomenology and physics

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• **Physics:** Possible contributions to separation of transport channels
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Physics picture(s) of I-mode

Need to explain many puzzling observations, eg.:

- Several complex, closely related changes in turbulence and flows (WCM, GAM and low frequency density fluctuation, intermittent $n_e$ bursts with precursors ($\delta t \sim 1/f_{WCM}$), mid-frequency decrease.)

- Relatively gradual decrease in thermal transport, and development of $E_r$ well.

- Particle transport (electrons, impurities, likely main species) all remaining close to L-mode levels; no barrier ever develops.

- I-mode depends on $B_x \nabla B$ direction, which should be away from X-point; Configuration towards X-pt usually gives direct L-H transition, at lower P.

- Weak $B_T$ dependence of $P(L-I)$, vs strong for $P(L-H)$.

Not yet an explanation for all this. Will discuss ideas, and ongoing modeling, from several colleagues. Perspectives are my own.
Role of $E_r \times B$ shear in decreasing turbulence, thermal transport.

- $E_r$ well is developing in I-mode, together with temperature gradient, and correlated reduction in mid-frequency turbulence.
- Qualitatively consistent with reduction in pedestal $\chi$ due to ExB shear, as is thought to be happening in L-H transition.
Role of $E_r \times B$ shear in decreasing turbulence, thermal transport.

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Open questions, and differences to L-H transition:
- Why does L-I transition happen so slowly, evolving over $\sim$10-100 ms? (vs $\mu$s)
- Why not a strong positive feedback loop and sharp bifurcation as in L-H transition? Does that require a particle barrier? *Why would $E_r$ shear not affect the particle channel in this case?*
- How do critical $E_r$ quantities (eg $\omega_{\text{ExB}}$, $\gamma_E$, $E_{r,\text{min}}$, $V_{\perp}=E_r/B$) in I-mode compare to values at L-H transition? How does magnetic configuration influence them?

*Answers could help understand L-H as well as L-I, I-H physics!*
Turbulence nonlinearities could explain intermittent density ‘bursts’, linked to WCM

• Recall intermittent ‘solitary’ bursts are seen at all scales, extend to higher k than WCM. And, WCM is modulated.

Possible explanation, by Happel, Manz (IPP):

• Apparently highly nonlinear turbulent interactions involving WCM, GAM, ‘bursts’; we could qualitatively consider I-mode as being at the boundary between laminar and turbulent (L-mode) flow, which is known to produce intermittency.

• 2-D drift wave equations contain nonlinearities which could give intermittent behavior:

\[ \frac{\partial}{\partial t} \tilde{p} = \{ \tilde{\mathcal{G}} \tilde{p} \} = \{ \tilde{\mathcal{G}} \tilde{p} \} + \{ \tilde{\mathcal{G}} \tilde{p} \} \rightarrow \text{Nonlinear interaction.} \]

Turbulence drive

Turbulence nonlinearities could explain intermittent density ‘bursts’, linked to WCM

• Several sub-terms in this nonlinear interaction (of KdV or Burgers’ type).
• A term of particular interest for I-mode is amplified by radial temperature gradient. Note the intermittency measured on AUG increased with pedestal $\nabla T$.
• This gives particle and heat transport in different directions.
  $\Gamma$ is outward and larger

$$\Gamma = \vec{v}_{E \times B} \times \vec{n} = + (k_y 1.71^2 \tilde{T}_e^2) / (\delta B)$$

Heat flux $q$ is inward and small

$$q = \vec{v}_{E \times B} \times \vec{n} \tilde{T}_e = - \frac{1.71 k_y^2 \tilde{T}_e^3}{\delta B}$$


A. Hubbard, ISHW2017, Kyoto
Turbulence nonlinearity could explain intermittent density ‘bursts’, linked to WCM

- Several sub-terms in this nonlinear interaction (of KdV or Burgers’ type).
- A term of particular interest for I-mode is amplified by radial temperature gradient. Note the intermittency measured on AUG increased with pedestal $\nabla T$.

\[
\frac{\partial \tilde{T}_e}{\partial t} \sim \tilde{n} \frac{\partial \phi}{\partial y} \frac{\partial \tilde{T}_e}{\partial x}
\]

- Model qualitatively fits with several observed features of I-mode. Remains to assess fluxes quantitatively. There should also be bursts in T, which are hard to measure.

- How would this model relate to $E_r$, and to I-mode threshold conditions?
- Why does particle transport end up just at L-mode levels?
- Why does $B_x \nabla B$ drift direction matter?
Transfer from turbulence to zonal flows is 2x lower with $B \times \nabla B$ away from X-pt, opening an I-mode power window

- Prior work has shown L-H transition occurs when energy transfer rate into ZF exceeds turbulent drive. [Manz PoP12, Yan PRL14, Cziegler PoP 14,NF15]
- **Measured 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 power threshold!

Opens a power window for I-mode. In the I-mode, energy is transferred to GAMs as well as ZFs

Somehow, even in L-mode, nonlinear turbulence-flow interactions depend on magnetic configuration. **Why? Related to mean flows, SOL?**

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**C-Mod** I. Cziegler, York, PRL 118, 105003 2017

A. Hubbard, ISHW2017, Kyoto
Simulations of I-mode pedestals

• BOUT++ (6-field 2-fluid) model used to simulate a high \( n_e \), 5.8 T C-Mod I-mode.
• Linear simulations show Drive Alfven, Resistive ballooning mode dominate.
• Nonlinear simulations find a mode with many features of WCM (\( n=20 \), 350 kHz, electron diamagnetic direction). Predicts larger particle diffusivity than thermal, consistent with the key feature of I-mode. Predicted \( \chi_{\text{eff}}, \Gamma \) are close to expt.

C-Mod
Z. Liu (ASIPP)
PoP 2016.
Simulations of I-mode pedestals

- **BOUT++** (6-field 2-fluid) model used to simulate a high $n_e$, 5.8 T C-Mod I-mode.
- Linear simulations show Drive Alfven, Resistive ballooning mode dominate.
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- These initial runs set equilibrium $ZF$ to zero, cannot capture interaction with GAM which seems important in experiment.
  - Extensions to include flows are in progress.

- Other groups are working on gyrokinetic simulations of I-mode pedestal (U. Texas), and of L-I transitions (C.S. Chang et al, PPPL).
- More such simulation work, over the evolution from L to I-mode and for a range of plasma parameters, is needed.
Neoclassical impurity transport: Predicted to be outward in I-mode pedestal.

- Recent theoretical analysis of typical C-Mod I-mode, based on experimental profiles, finds **all terms in radial impurity flux are OUTWARD**.
  - First term is outward if $\eta_e > 2$
    - i.e. $L_T < 2 L_n$, which is typical for I-modes due to steep $\nabla T/T$, low $\nabla n/n$. (also most L-modes; H-mode have lower $\eta_e \sim 1$).
  - Other terms, depending on poloidal asymmetries and flows, are also outward.

\[
\text{Radial impurity flux } \propto -2e^2 g + \frac{n_{dH} - n_{dL}}{n_{dH} + n_{dL}} (g + U)
\]

\[
\text{Thomson scattering: } \propto \left( \frac{1}{2} \frac{\partial \ln T_e}{\partial \psi} - \frac{\partial \ln n_e}{\partial \psi} \right)
\]

\[
\text{Imp.dens: } \propto \frac{n_{dH} - n_{dL}}{n_{dH} + n_{dL}} \quad \text{Pol.flow: } \propto \frac{n_z V_z \cdot \nabla \theta}{B \cdot \nabla \theta}
\]
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- Recent theoretical analysis of typical C-Mod I-mode, based on experimental profiles, finds all terms in radial impurity flux are OUTWARD.
  First term is outward if $\eta_e > 2$

- Total transport is sum of turbulent, neoclassical fluxes.
- Quantitative analysis of impurity, main species, and thermal neoclassical transport, and comparison to estimated turbulent fluxes, are needed.
- Outward neoclassical transport would certainly help avoid accumulation in I-mode.
- Would not explain sudden increase in density, impurities at I-H transitions, when turbulence is suppressed.
- Why is particle transport the same in L and I-mode?
I-mode phenomenology and physics

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Summary: I-mode phenomenology and physics

- I-mode is a distinct confinement regime in which energy confinement is improved, but all measures of particle confinement remain at L-mode levels. Also ELM-free. This has many attractions as a fusion regime.
- Observed on multiple tokamaks, now over wide ranges of parameters.
- **Detailed measurements of pedestal profiles, turbulence, flows on C-Mod and AUG reveal complex physics** (GAM, Weakly coherent mode, intermittent bursts are all linked).
- Poses a very interesting challenge to our understanding of transport and transport barriers. Linked to longstanding differences in L-H threshold with magnetic configuration.
- Several physics ideas are emerging which might explain separation of particle and energy transport, but more work is needed to develop and test them.
  - New ideas from the stellarator community are welcomed!
Future prospects

• Prospects for extrapolation of I-mode to tokamak burning plasmas (presented IAEA16, EPS17 but not much in this talk) are promising, especially for high \(B_T\) devices. An ELM risk mitigation strategy for ITER, DEMO.
  — More experiments are planned on AUG, EAST, KSTAR, WEST, ST’s.
  — Need larger scale experiments for confident extrapolation. JT-60SA, with its flexible configuration, will be highly valuable.

For discussion:
• *Has a similar regime, with high thermal confinement but low particle confinement, been observed in stellarators?*
• In tokamaks, up-down magnetic configuration (X-point wrt \(B \times \nabla B\) drift) clearly plays a major role in obtaining I-mode. *How would this condition relate to non-axisymmetric configurations?*

Thank you for this invitation.
I look forward to discussing during the workshop!