Impact of the Pedestal on Global Performance and Confinement Scalings in I-Mode

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The problem...

Fusion reactor characterized by three overarching requirements:

- high energy confinement – sufficient self-heating for economical power production
- low particle confinement – low enough, at least, to avoid high-Z radiative issues
- avoid, suppress, or mitigate large ELMs

A number of solutions exist:

- engineering solutions – RMP, pellet pacing
- physics solutions – QH mode, EDA H-mode, high-recycling H-modes, small-ELM regimes

but each of these still has problems – other options?
I-mode: a new solution?

![Graph showing L-mode and I-mode parameters](image)

- **P\text{ICRF} (MW)**
- **n\text{e} \left(10^{20} \text{ m}^{-3}\right)**
- **T\text{e}(0) (keV)**
- **T\text{e,ped} (keV)**
- **\langle P\rangle (atm)**
- **D\alpha**

**Pedestal Structure in I-mode**

- **EDA H-mode**
- **ELMy H-mode**
- **I-mode**
- **L-mode**

**Graphs showing**

- **Electron density (n\text{e})**
- **Electron temperature (T\text{e})**
- **normalized poloidal flux**

**Legend**

- **EDA H-mode**
- **ELMy H-mode**
- **I-mode**
- **L-mode**

**Core T\text{e} 4 -> 8 keV**

**High pressure**

**ELM-free**

**Normalized poloidal flux**
Good progress has been made in understanding pedestal structure, stability against ELMs in I-mode\textsuperscript{1,2}. Next step: extrapolation to other devices in access\textsuperscript{3} and performance.

\textsuperscript{1}JR Walk \textit{et al.}, \textit{Physics of Plasmas} 21 (2014)
\textsuperscript{2}JR Walk, ScD thesis, Massachusetts Institute of Technology (2014)
\textsuperscript{3}AE Hubbard, plenary talk
Temperature pedestal H-mode-like, set by plasma current, heating power

- pedestal $T_e$ trends positively $T_e \sim I_p$, spread at given current due to heating power
- input power strongly affects pedestal temperature (as with EDA H-mode) – more properly, power per particle sets pedestal temperature at fixed current
Pedestal density separately controlled from temperature, independent of MHD limits

- with sufficient power to maintain $P_{\text{net}}/n_e$, temperature pedestal matched across range of fueling
- Contrasts to MHD-limited pedestals (fixed $\beta_{p,\text{ped}} \rightarrow$ limit on $n_e T_e$) – path to strongly increase pedestal beta
What does this get us?

- Independent determination of density profile (via fueling), temperature profile (via heating power) – operator control, rather than physics limits, sets pedestal

- Path to strongly improved performance in I-mode – matched increases in fueling, heating power strongly increase pedestal pressure at same size, current, field

- Good for ITER access as well: sidestep high power threshold by accessing at low density, step up to $Q = 10$ scenario with matched density, power increase

- L-mode density profile $\rightarrow$ no impurity pinch in edge

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$^4$DG Whyte et al., APS-DPP Nov. 2011
Strong temperature pedestal supports high core temperature, pressure

- stiff \((R/L_{T_e} \sim \text{fixed})\) temperature profiles → higher \(T_{\text{ped}}\) supports greatly increased core temperatures

- provided moderate density peaking \((n_{e,0}/\langle n_e \rangle \sim 1.1 - 1.3 \text{ in I-mode})\), reaches comparable core, vol-average pressure despite relaxed \(p_{ped}\)

- fusion-reactive plasma where \(T_e > 4 \text{ keV}\), high \(T_{ped}\) maximizes fusing volume
Strong temperature pedestal supports high core temperature, pressure

\[ \psi_{\text{norm}} \]

\[ n_e \left[10^{20} \text{ m}^{-3}\right] \]

\[ T_e \left[ \text{keV} \right] \]

\[ p_e \left[ \text{kPa} \right] \]

\[ \beta_N \]

→ same \( \langle \beta_N \rangle \), normalized confinement to ELMy H-mode
First pass at an I-mode confinement scaling

Following practice in ITER89, ITER98 scalings, express I-mode energy confinement as a power law of the form

\[ \tau_E = C I_p^{\alpha_I} B_T^{\alpha_B} n_e^{\alpha_n} R^{\alpha_R} \varepsilon^{\alpha_\varepsilon} K^{\alpha_K} P_{\text{loss}}^{\alpha_P} \]

Using high-res pedestal database plus older forward- and reversed-field datasets for expanded parameter range
**Reduced fitting parameter set captures I-mode physics**

<table>
<thead>
<tr>
<th>( \alpha \chi )</th>
<th>(a)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C )</td>
<td>0.040 ± 0.066</td>
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<td>( \bar{n}_e )</td>
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<tr>
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<tr>
<td>( \varepsilon )</td>
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Reduced fitting parameter set captures I-mode physics

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Both fits capture weak degradation of $\tau_E$ with heating power, strong response to current, field
Distinct physics phenomena from L-, H-mode scalings

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need other machine input
Distinct physics phenomena from L-, H-mode scalings

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Strong B-field dependence, weak power degradation consistent with experimental observation

\[ q_{95} = 3-4 \]

\[ P_{\text{loss}}/\bar{n}_e S \times 10^{-20} \text{MW m} \]

\[ B_T \ (T) \]

A. Hubbard et al., IAEA 2014

\[ \text{stored energy, } W \sim P_{\text{net}} \tau_E \]

\[ W \sim P_{\text{net}} I_p \]

little degradation of \( \tau_E \) with power
Thought experiment: apply ITER89, ITER98-like size dependence to I-mode, extrapolate to larger devices

\[
\tau_{I-mode, y_1} = 0.036 \times R^{1.5} \varepsilon^{0.3} \times I_p^{0.68} B_T^{0.77} n_e^{-0.01} P_{loss}^{-0.27}
\]

\[
\tau_{I-mode, y_2} = 0.055 \times R^2 \sqrt{\varepsilon} \times I_p^{0.68} B_T^{0.77} n_e^{-0.01} P_{loss}^{-0.27}
\]
Either extrapolates to highly favorable energy confinement on large, high-power devices.

\[ \tau_E \sim 0.5 - 1.0 \text{ s for JET, } 2.5 - 8 \text{ s for ITER(!)} \]
Behavior desirable for reactor regime

- Strong response of pedestal to fueling, heating power → desirable operator control – not limited by MHD stability, transport constraints, reflected in global response of confinement with power, density
- consistent with access, $Q = 10$ operation on ITER
- temperature pedestal without density pedestal desirable for reactor operation – high core pressure, fusion reactivity with good fueling behavior, impurity handling

Confinement scaling laws consistent with observed behaviors

- captures weak degradation with heating power, strong dependence on magnetic field (suppression of H-mode transition?)
- Extrapolate highly favorably to larger, higher-power devices, consistent with benefits of higher-field operation as well
Questions remain

Access on other devices

- experiments on ASDEX-Upgrade, DIII-D – some possible observations on JET?
- access thresholds not well-understood, necessary for extrapolation – input from other devices essential to lock down scaling as well

Understanding of pedestal, global limits

- higher densities desirable for burning plasmas, $P_\alpha \sim n_i^2$ – I-mode limited to lower densities, how hard can we push while maintaining temperature pedestal?
- pedestal regulation by WCM, but physics not well-understood – upper bound ultimately set by H-mode transition, or is there other limit?
Supplemental Slides
Pedestal impacts core, global performance

\[ W_{MHD} \text{ [kJ]} \]

\[ p_{95} \text{ [kPa]} \]

JR Walk (MIT PSFC)

Pedestal Structure in I-mode

30 Apr. 2015
I-mode temperature, pressure pedestal widths uncorrelated with physics parameters

\[ \rho_{i,\text{pol}}? \quad \nu_{95}^*? \quad q_{95}? \quad P_{\text{net}}/n_e? \]

\[ \Delta_T \text{[norm. pol. flux]} \quad \Delta_p \text{[norm. pol. flux]} \]

\[ \rho_{i,\text{pol}} \rightarrow \text{ion-orbit-loss models for } E_r \text{ well width} \]
I-mode temperature, pressure pedestal widths uncorrelated with physics parameters

\[ \rho_{i, \text{pol}} \quad \nu^*_9 ? \quad q_9 ? \quad P_{\text{net}/n_e} ? \]

edge collisionality $\rightarrow$ bootstrap current instability drive
I-mode temperature, pressure pedestal widths uncorrelated with physics parameters

\[ \rho_{i,\text{pol}} \quad \nu_{95}^* \quad q_{95} \quad P_{\text{net}}/n_e \]

edge safety factor \( \rightarrow \) magnetic shear, ballooning stabilization
I-mode temperature, pressure pedestal widths uncorrelated with physics parameters

\[ \rho_{i,pol} \quad \nu_{95}^* \quad q_{95} \quad P_{\text{net}}/n_e? \]

heating power per particle → heat flux through temperature pedestal

\[ \Delta_T \quad \Delta_p \]

\[ P_{\text{net}}/n_e [\text{MW}/10^{20} \text{ m}^{-3}] \]
Pedestal width uncorrelated with $\beta_{p,\text{ped}}$, contrary to KBM limit

- I-mode pedestal width shows no trend with $\beta_{p,\text{ped}}$, consistently broader than predicted by EPED1-like KBM limit $\Delta_\psi = 0.076\beta^{1/2}_{p,\text{ped}}$

- Intuitively, pedestal $\nabla p$ insufficient to drive ballooning-like instabilities
I-mode pedestal scalings consistent with stability against peeling-ballooning MHD

- Ballooning stability, to lowest order, limits pedestal $\beta_p$ in ELMy H-mode; I-mode $n_e$, $T_e$ independent, rather than fixed $n_e T_e$

- Pedestal $\beta_p$ scaling with density consistent with constant $T_{e,95}/B_p \rightarrow T_e \sim I_p$, rather than $T_e \sim 1/n_e$
I-mode pedestal scalings consistent with stability against peeling-ballooning MHD

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- Pedestal $\beta_p$ scaling with density consistent with constant $T_{e,95}/B_p \rightarrow T_e \sim I_p$, rather than $T_e \sim 1/n_e$
I-mode pedestal strongly stable against peeling-ballooning MHD, KBM turbulence

- $P_{net} = 2.9 \text{ MW}$
- $W = 177 \text{ kJ}$
- high-current, high stored energy
- $\beta_{p,ped} = 0.077$
- $\psi = 2.14\%$
- $\Delta_{EPED} = 2.10\%$

---

**Graph:**

- Normalized Pedestal Current vs Normalized Pressure Gradient ($\alpha$)
- $\beta_{p,ped} = 0.077$
- $\psi = 2.14\%$
- $\Delta_{EPED} = 2.10\%$

---

**Graph Details:**

- $P_{net} = 2.9 \text{ MW}$
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---

**Legend:**

- $\pi_e [10^{20} \text{ m}^{-3}]$
- core $T_e [\text{keV}]$
- edge $T_e [\text{keV}]$
- $\langle p \rangle [\text{atm}]$
- $H_\alpha$

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**Time:**

- $t [\text{s}]$

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**Modelled Phase:**

- 1120824019
- 1.3MA
- 5.3T

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**Note:**

- JR Walk (MIT PSFC)
- Pedestal Structure in I-mode
- 30 Apr. 2015