Experimental Energy Confinement Time Scaling in C-Mod I-modes

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Introduction and previous I-mode scaling calculations

[underlay section label]
I-mode is considered an intrinsically ELM stable candidate regime for future reactors

- **I-mode has energy confinement of H-mode with particle confinement of L-mode without ELMs**
  - Good for impurity expulsion and control
  - Transport barrier present in temperature profile, but not density

- **Enhanced transport associated with unique edge pedestal turbulence**
  - Weakly coherent mode (WCM) fluctuation spanning outer pedestal (~150-300 kHz)
  - Geodesic acoustic mode (GAM) frequency fluctuation spanning outer pedestal (~10-50 kHz)
Local energy transport characteristics can be estimated through gyroradius scalings

- L-mode ion transport found to have Bohm scaling
  - Random walk step sizes scale with plasma dimension (not gyroradius)
  - Random walk on the order of gyroradius happens each gyroperiod

- H-mode ion transport associated with gyroBohm scaling
  - Both radial correlation length and correlation time scale with gyroradius
  - Derived from turbulence arising from plasma waves

- Previous studies highlight the importance of two fluid analysis needed for interpretation of $\rho^*$ scaling

Gyroradius scaling exponents
Interested in projecting I-mode confinement and transport to future reactors

- **C-Mod** is a flexible machine that can operate I-modes over a broad range of magnetic fields
  - Extensive scan in $\rho^*$

- **Dedicated experiments required to compare to previous studies**
  - Multi-dimensional scalings calculated from database studies (Walk, 2014)
  - Engineering parameter scans (Hubbard, NF 2017)
Can estimate I-mode energy confinement time scaling in terms of dimensionless parameters from previous database studies

- Based on Luce et. al. PPCF 2008 review article shows the dimensionless confinement time scaling can be cast in terms of five primary variables
  \[
  \Omega \tau_E \propto \rho^{*\alpha_p} \beta^{\alpha_p} \nu_C^{\alpha_v} q^{\alpha_q} (R^{\alpha_R,D})
  \]

- Previous database studies on C-mod I-modes have determined confinement time scalings based on engineering parameters
  \[
  \tau_E(Walk) = C \ I_p^{\alpha_I} B_T^{\alpha_B} \bar{n}_e^{\alpha_n} P_{loss}^{\alpha_p} R^\alpha \ \kappa^\alpha \epsilon^\alpha
  = (0.014 \pm 0.002) x I_p^{0.685\pm0.076} B_T^{0.768\pm0.072} \bar{n}_e^{-0.017\pm0.048} P_{loss}^{-0.286\pm0.042}
  \]

- Dimensionless exponents can be cast in terms of the dimensional exponents

  \[
  \begin{align*}
  \alpha_p &= \left[-\frac{3}{2} \alpha_I - \frac{3}{2} \alpha_B - 3 \alpha_p - 2 \alpha_n\right] / (1 + \alpha_p) - 3/2 \\
  \alpha_v &= \left[-\frac{1}{4} \alpha_I - \frac{1}{4} \alpha_B - \frac{1}{2} \alpha_p\right] / (1 + \alpha_p) - 1/4 \\
  \alpha_B &= \left[\frac{1}{4} \alpha_I + \frac{1}{4} \alpha_B + \frac{3}{2} \alpha_p + \alpha_n\right] / (1 + \alpha_p) + 1/4 \\
  \alpha_q &= -\alpha_I / (1 + \alpha_p)
  \end{align*}
  \]

- Reformed scaling based on database study then yields
  \[
  \Omega \tau_E(Walk) \propto \rho^{-3.4} \beta^{0.206} \nu_C^{-0.56} q^{-0.96}
  \]

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Previous database analysis has used multiple regression techniques.

Power law fit to a database of C-Mod I-modes includes a few databases (rev-B, for-B, and pedestal):

- Close to gyro-Bohm
- Favorable scaling (opposite from ITER)
- Inverse scaling (ITER has almost no scaling)

\[ \Omega \tau_E (Walk \ Imode) \propto \rho^* \beta^{0.206} \nu_C^{-0.56} q^{-0.96} \]

\[ \Omega \tau_E (ITER \ Hmode) \propto \rho^* \beta^{-0.9} \nu_C^{0.08} q^{-3} \]

- How does this compare to dedicated experiment?
- How do dedicated experiment coefficients change when accounting for parameter correlations?

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Dedicated C-Mod I-mode dimensionless parameter scaling experiments

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**Magnetic field used as primary actuator for dimensionless parameter scans**

- Experiments scanned \( \rho^*, \beta_T, \) and \( v_C \), while holding \( q_{95} \) (~3.5) constant
  - \( 4.6 < B_t < 6.1 \) T (reverse field)
  - \( 0.85 < I_p < 1.3 \) MA
  - \( 2 < P_{\text{loss}} < 5 \) MW
- Used \( W_{\text{MHD}} \) as proxy for temperature using the \( P_{\text{loss}} \) estimate shown for target
  - Assumes \( v_C \) and \( \rho^* \) are functions of volume/density averaged temperature
- Scan maintains fixed size or shape

\[
\rho_i^* = \sqrt{m_i T_{i,0} / a B_\phi}
\]

\[
0.006 < \rho_i^* < 0.008
\]

\[
\begin{align*}
\beta &= \frac{< n T >}{B^2} \\
\beta &= < n T > / B^2 \\
0.69 < \beta_T(\%) < 1.0
\end{align*}
\]

\[
\begin{align*}
\nu_C &= \frac{\bar{n}_e R}{\langle T_e \rangle} \times v_c^2 \\
0.09 < \nu_C < 0.26
\end{align*}
\]

---

<table>
<thead>
<tr>
<th>Scan</th>
<th>I</th>
<th>n</th>
<th>( T(\text{Ploss}) )</th>
<th>( W(\text{Ploss}) )</th>
<th>( B )</th>
<th>( \tau )</th>
<th>( P_{\text{loss}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho^* )</td>
<td>B</td>
<td>( B^{4/3} )</td>
<td>( B^{2/3} )</td>
<td>( B^2 )</td>
<td>( \rho_*^{-2/3} )</td>
<td>( B^{-1} \rho_*^{\alpha \rho} )</td>
<td>( B^3 \rho_*^{-\alpha \rho} )</td>
</tr>
<tr>
<td>( \beta )</td>
<td>B</td>
<td>( B^4 )</td>
<td>( B^2 )</td>
<td>( B^6 )</td>
<td>( \beta^{-4} )</td>
<td>( B^{-1} \beta^{\alpha \beta} )</td>
<td>( B^7 \beta^{-\alpha \beta} )</td>
</tr>
<tr>
<td>( v_C )</td>
<td>B</td>
<td>-</td>
<td>( B^2 )</td>
<td>( B^2 )</td>
<td>( \nu_C^{-4} )</td>
<td>( B^{-1} v_C^{\alpha \nu} )</td>
<td>( B^3 v_C^{-\alpha \nu} )</td>
</tr>
<tr>
<td>( q )</td>
<td>( q^{-1} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>( q^{\alpha q} )</td>
<td>( B q^{-\alpha q} )</td>
</tr>
</tbody>
</table>
C-Mod discharges with reasonably matched dimensionless parameters

- Matched $W_{MHD}$ in the control room
  - Example shows matched $\beta$ and $\rho_i^*$ with varied $\nu_C$

- 13 datapoints well suited for dimensionless parameter scans
  - some in the same discharge with a power step

\[
0.69 < \beta < 1.0 \\
0.0061 < \rho_i^* < 0.0079 \\
0.058 < \nu_C < 0.27
\]
Some assumptions necessary for thermal confinement time calculation

- Additional analysis required to calculate thermal confinement times using integrals of plasma profiles
  - Thomson scattering used for electron quantities
  - HIREX used for ion temperature

- Neoclassical resistivity assumed for estimating \( Z_{eff} \)

- \( T_i/T_e \) fixed from experiment

- Averaged over stationary operation between 75-200ms

- Assumption of fraction of RF power coupling varied from 80-90%
  - Introduces ~3-5% error in confinement time calculation
Confinement time scaling with engineering parameters similar to previous experimental scans, but differ from database regression

- Some power degradation
- Positive scaling with density
- No scaling with $B_\phi$ or $I_p$
- Similar observations to experimental scans in Hubbard NF 2017
- Different scalings calculated than database study using variety of I-modes

$$\tau_E (I_{mode}) = C I_p^{0.685 \pm 0.076} B_T^{0.768 \pm 0.072} n_e^{0.017 \pm 0.048} P_{loss}^{-0.286 \pm 0.042}$$

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Two methods used for calculating experimental energy confinement time scalings

1) **Single parameter**
   Subsets chosen to have two well-matched dimensionless parameters, with variation in the third
   - A: small group of well matched parameters
   - B: extended subset
   - C: full dataset

2) **Multiple regression analysis**
   Considers correlation between all three dimensionless variables
Single parameter: I-mode energy confinement mostly scales negatively with $\beta$

- Variation in $v_C$ and $\rho_*$ range from 0.5-6% in subset A
- Variation in $v_C$ and $\rho_*$ range from 0.5-14% in subset B
- Likely negative scaling with $\beta$ from this dataset, though inconclusive
Single parameter: I-mode energy confinement scales positively with $\nu_C$

- Variation in $\beta$ and $\rho_*$ range from 0.6-3% in subset A
- Variation in $\beta$ and $\rho_*$ range from 0.6-5% in subset B
- Consistently positive scaling

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Single parameter: $\rho_*$ I-mode confinement scaling suggests gyro-Bohm-like transport

- Variation in $\nu_c$ and $\beta$ range from 2-5% in subset A
- Variation in $\nu_c$ and $\beta$ range from 1-14% in subset B
- Consistently strong negative scaling
  - Suggests closer to gyro-Bohm transport scaling than Bohm
Significant correlation in all dimensionless quantities

- Full dataset has significant correlations between all dimensionless quantities
- Highest correlation seen between $\rho_*$ and $\beta$
- Dataset A minimizing variance in dimensionless quantities is most trustworthy
- Additional techniques required to further analyze dependencies

Correlation Matrix

<table>
<thead>
<tr>
<th></th>
<th>$\rho_*$</th>
<th>$\beta$</th>
<th>$\nu_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_*$</td>
<td>1</td>
<td>0.90</td>
<td>-0.65</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.90</td>
<td>1</td>
<td>-0.73</td>
</tr>
<tr>
<td>$\nu_C$</td>
<td>-0.65</td>
<td>-0.73</td>
<td>1</td>
</tr>
</tbody>
</table>

$R^2_{\rho,\beta} = 0.81$
I-mode Confinement Scaling Coefficients
Calculated from Multiple Regression

- Multiple Regression Analysis (MRA) used to compare to experimental single parameter fits for each dataset
  - Confirms $\rho_i^*$ scaling suggests gyro-bohm like transport (though Bohm within error bars)
  - Suggests lower probability of significance of $\beta$ scaling (consistent with large deviations in calculated coefficients)
  - Suggests small but positive scaling with $\nu_C$
  - Confirms $q_{95}$ scaling is negligible in this dataset

\[
\Omega \tau_E \propto \rho^* -3.34 \pm 1.2 \beta 1.33 \pm 1.1 \nu_C^{0.34 \pm 0.15}
\]

Probability of significance:
(0.97, 0.74, 0.95)

F Test = Pass:
10.4 \(\not\approx\) [0.4, 3] (95 % confidence)
10.4 \(\not\approx\) [0.8, 0] (99 % confidence)

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Discussion and projections

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# I-mode Energy Confinement Time Scaling Comparison

<table>
<thead>
<tr>
<th>Confinement Exponents</th>
<th>$\rho^*$</th>
<th>$\beta$</th>
<th>$\nu_C$</th>
<th>$q_{95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER H98</td>
<td>-2.7</td>
<td>-0.9</td>
<td>0.08</td>
<td>-3</td>
</tr>
<tr>
<td>ITER L97</td>
<td>-1.85</td>
<td>-1.41</td>
<td>0.21</td>
<td>-3</td>
</tr>
<tr>
<td>Walk I-mode</td>
<td>-3.4</td>
<td>0.18</td>
<td>-0.56</td>
<td>-0.94</td>
</tr>
<tr>
<td>Experiment 1D</td>
<td>-5.0</td>
<td>-1.1</td>
<td>0.55</td>
<td>x</td>
</tr>
<tr>
<td>Experiment MRA</td>
<td>-3.34</td>
<td>1.33</td>
<td>0.34</td>
<td>x</td>
</tr>
</tbody>
</table>

- $\rho^*$ scaling similar to H-mode
- $\nu_C$ scaling similar to L-mode
- Large uncertainty associated with $\beta$ scaling, though still less degradation than H-mode within error bars of MRA analysis

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Projection to SPARC, ARC, and ITER

- Fairly far extrapolation, but suggests I-mode has confinement projections similar to H-mode

- I-mode ITER projection exceeds IPB98(y,2) estimate for $B\tau_E$

<table>
<thead>
<tr>
<th></th>
<th>$\rho^*$</th>
<th>$\beta_T$</th>
<th>$\nu_C$</th>
<th>$B\tau_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPARC</td>
<td>0.002</td>
<td>1</td>
<td>0.01</td>
<td>2.4</td>
</tr>
<tr>
<td>ARC</td>
<td>0.001</td>
<td>1.9</td>
<td>0.01</td>
<td>21</td>
</tr>
<tr>
<td>ITER</td>
<td>0.001</td>
<td>2.5</td>
<td>0.01</td>
<td>24</td>
</tr>
</tbody>
</table>

Normalized Confinement Time Experimental Scaling
Derived $\beta$ exponent is most sensitive to error in estimated loss power

- Highest uncertainty in engineering exponents is in $P_{\text{loss}}$

- Conversion to dimensionless exponent from engineering exponents yields large uncertainty in $\alpha_{\beta}$

- Derived database formulas have largest uncertainty into $\alpha_{\beta}$ similar to the dedicated experiment
Discussion

- **Updated estimate for the I-mode confinement scaling based on experimental dimensionless parameter scans**
  - $\rho_*$ scaling suggests gyrobohm ion transport (more similar to H-mode than L-mode)
  - $\beta$ scaling suggests less important than $\rho_i^*$ and $\nu_c$, with inconclusive sign on coefficient (albeit consistent with experimental observation of less power degradation than typical H-modes)
  - $\nu_c$ scaling suggests positive coefficient, more similar to L-mode than H-mode

- **Better separation of dimensionless variables in this dataset, though still large uncertainty in $\beta$ and $\nu_c$ scaling**
  - Correlation between dimensionless quantities

- **Suggestive gyro-Bohm scaling of I-mode confinement extrapolates well to compact, high field machines**
  - $\rho^*$ dominates the scaling, making projections of energy confinement times similar to H-mode ITER scaling laws

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