Perturbative Thermal Transport Studies on Alcator C-Mod

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Heat pulses generated by partial sawteeth used for first time to measure perturbative, or heat pulse, thermal diffusivity on extensive set of Alcator C-Mod plasmas.

Avoids issues with non-diffusive “ballistic” transport associated with heat pulses generated by full sawteeth.

New physics results [Creely NF Submitted]:

- Perturbative thermal diffusivity is correlated to stiffness differences between L-mode and I-mode regimes, as well as to density and temperature.

- Experimental perturbative thermal diffusivity agrees quantitatively with nonlinear GYRO multi-scale simulations [Howard NI3.00001].
Perturbative Thermal Diffusivity Governs the Propagation of Heat Pulses

- Standard power balance electron thermal diffusivity governs steady state diffusion.
- Perturbative, or heat pulse, thermal diffusivity, governs the diffusion of perturbations [Tubbing NF 1987].
- Should not be directly compared with one another.
- Same only if heat flux and temperature gradient are linearly related with no offset [Cardozo PPCF 1995].

\[
\chi_e^{PB} = \frac{1}{n_e} \frac{Q_e}{\nabla T_e} \quad \chi_e^{HP} = \frac{1}{n_e} \frac{\partial Q_e}{\partial (\nabla T_e)}
\]
Heat Pulse Thermal Diffusivity is Related to Gyrokinetic Temperature Profile Stiffness

- In gyrokinetic simulations, define electron temperature profile stiffness as slope of electron heat flux against \(a/L_{Te}\) above the critical gradient [Citrin NF 2014, Smith NF 2015].

\[
Stiffness = \frac{\partial Q_e}{\partial (a / L_{Te})} = \chi_e^{HP} \cdot \frac{n_e T_e}{a}
\]

- High confinement regimes tend to have higher temperature stiffness [White PoP 2015], so expect to find higher heat pulse thermal diffusivity.

\[Q_e (\text{MW/m}^2)\]

\[a/L_{Te}\]

Higher Stiffness

Lower Stiffness

High and low stiffness plasmas, with same critical gradient.

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Heat Pulse Propagation Tracked with ECE Profile Diagnostics

- Grating Polychromometer (GPC) uses diffraction grating to split ECE, 9 channels [O’Shea PhD 1995].

- Fusion Research Center ECE (FRCECE) uses a heterodyne radiometer to collect ECE, 32 channels [Chatterjee FED 2001, Houshmandyar CP12.00007].

- Both standard electron temperature profile diagnostics on C-Mod. Both used to track heat pulses.

Illustration of a heat pulse propagating radially outward in the plasma. $r_1 < r_2 < r_3 < r_4$
Alcator C Mod Exhibits Heat Pulses Generated by Full and Partial Sawtooth Crashes

- Full sawtooth crashes utilized to study heat pulse thermal diffusivity [Callen PRL 1977, Cardozo PPCF 1995, etc.].

- Modeling reveals full sawtooth heat pulses often inconsistent with diffusive transport [Fredrickson PoP 2000].

- Full sawtooth crash “ballistic” effect is observed on C-Mod.

Full Sawtooth

Non-Diffusive Temperature Spike

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Partial Sawteeth Generated Heat Pulses Used to Calculate Perturbative Diffusivity

- Modeling showed partial sawtooth heat pulses consistent with diffusive transport [Fredrickson 2000].
- C-Mod Partial sawteeth exhibit diffusive characteristics.
- Can be measured with Extended-Time-to-Peak Method [Tubbing NF 1987].

\[ \chi_e^{HP} = 4.2 \frac{a_c V_{HP}}{\alpha} \]

Velocity of Peak: \( V_{HP} \)
Pulse Damping: \( \alpha \)
Minor Radius: \( a_c \)

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L-Mode Experiments Show Perturbative Diffusivity Decreases as Density Increases

5.4 T on Axis

0.8 MA

0.0 – 1.2 MW $P_{RF}$

$\chi^H_P$ shows strong trend with density (L/I data set shows same trend)

Weaker trend with $T_e$ and $\nabla T_e$

![Graph showing perturbative diffusivity and density relationship](image-url)
Heat Pulse Diffusivity is Generally Higher in I-Mode than in L-Mode Within the Same Shot

I-Mode is High Confinement with temperature but no density pedestal [Hubbard KI2.00003]

\[ I_p = 0.9-1.3 \, \text{MA} \quad B_t = 5.4 \, \text{T} \]
\[ n_e = 0.4-1.3 \, 10^{20}/\text{m}^3 \]
All Unfavorable Grad B Drift
0.6 < r/a < 0.9

L- and I-mode diffusivities from same shot

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\[ 0.6 < r/a < 0.9 \]

L- and I-mode diffusivities from same shot

Consistent with trend seen in Gyrokinetic simulations [White PoP 2015]

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Stiffness from Multi-Scale Gyrokinetic Simulations Can Match L-Mode Experiment

- Ion-scale simulations (ITG/TEM) under-predict stiffness for L-mode plasma [White PoP 2015]

- New multi-scale simulations (ITG/TEM/ETG) match experimental values [Howard PoP 2014, Howard NI3.00001]

- Perturbative diffusivities extracted from partial sawtooth heat pulses provide a validation constraint for gyrokinetic simulations.

\[ \chi_{exp}^{HP} = 1.6 \pm 0.4 \, \frac{m^2}{s} \]
\[ \chi_{Multi}^{HP} = 1.4 \, \frac{m^2}{s} \]
\[ \chi_{Ion}^{HP} = 0.2 \, \frac{m^2}{s} \]
Conclusions and Future Work

- Perturbative thermal diffusivity in tokamak plasmas has been measured via partial sawtooth heat pulses on large data set for the first time.

- Heat pulse thermal diffusivity appears to be correlated with L-mode and I-mode stiffness differences, as well as local density, temperature and temperature gradient.

- Quantitative agreement found between experimental $\chi_e^{HP}$ and multi-scale GYRO results, leading to new validation constraint.

- Future Work
  - Further study of density trend (collisionality, etc.)
  - Expansion of data set to include H-mode
  - Application of method to additional machines (ASDEX-Upgrade)
  - Further comparison to GYRO gyrokinetic simulations [White PoP 2015] and [Howard PoP 2014]
References

 Backup:
Standard ion-scale simulations (ITG/TEM turbulence) underpredict the perturbative thermal diffusivity [White PoP 2015], but new multi-scale (ITG/TEM coupled with ETG) simulations can match the experimental perturbative diffusivity within error bars [Howard PoP 2014].

Perturbative diffusivities extracted from heat pulses due to partial sawteeth provide a new constraint that can be used to validate gyrokinetic simulations.
First Table showing Partial/Full comparisons?

<table>
<thead>
<tr>
<th>Shot</th>
<th>Confinement</th>
<th>$\chi_{\text{Partial}}^{HP}$ ($m^2/s$)</th>
<th>$\chi_{\text{Full}}^{HP}$ ($m^2/s$)</th>
<th>$\chi_{\text{ePB}}^{PB}$ ($m^2/s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1120221011</td>
<td>L-Mode</td>
<td>1.13 ± 0.26</td>
<td>3.30 ± 0.53</td>
<td>1.84</td>
</tr>
<tr>
<td>1120626023</td>
<td>Ohmic (LOC)</td>
<td>2.67 ± 0.52</td>
<td>3.79 ± 0.65</td>
<td>1.26</td>
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<tr>
<td>1120626028</td>
<td>Ohmic (SOC)</td>
<td>1.70 ± 0.38</td>
<td>2.81 ± 0.46</td>
<td>1.02</td>
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<tr>
<td>1101209029</td>
<td>L-Mode</td>
<td>1.74 ± 0.27</td>
<td>4.67 ± 1.09</td>
<td>1.39</td>
</tr>
<tr>
<td>1101209029</td>
<td>I-Mode</td>
<td>2.03 ± 0.39</td>
<td>3.03 ± 0.87</td>
<td>0.73</td>
</tr>
<tr>
<td>1120221012</td>
<td>L-Mode</td>
<td>1.61 ± 0.36</td>
<td>3.59 ± 0.56</td>
<td>1.83</td>
</tr>
</tbody>
</table>
Radial Dependence of Perturbative Diffusivity Appears to Vary with Density

High/low density RF L-mode plasmas

5.4 T, 0.8 MA, 1.2 MW $P_{RF}$

High = $1.4 \times 10^{20}$/m$^3$
Low = $0.7 \times 10^{20}$/m$^3$

$\chi_e^{HP}$ Radially Averaged

$\sim$10% Correction Due to Radial Dependence of ETTP Calculation
Heat Pulse Diffusivity Shows Correlation with Pulse Location Temperature

Thermal Diffusivity versus Radially Averaged Temperature

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Temperature Gradient Shows Correlation Similar to that of Temperature
\( a/L_{Te} \) Shows Separation Between L-mode and I-mode, Possible Cutoff

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Heat Pulse Diffusivity Shows Correlation with Radially Averaged Density

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Density Gradient Exhibits Possible Correlation, Possible Critical Density

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$a/Ln$ shows slightly clearer cutoff, above which diffusivity is limited.
Heat Pulse Diffusivity Uncorrelated With Pulse Amplitude

Perturbative Diffusivity ($m^2/s$) vs. Pulse Amplitude (keV)

L Mode
I Mode

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I-Mode Tends to Have Larger Stored Energy for a Given Current than L-Mode
Density and Stored Energy Have a Weak Positive Correlation

Density versus Stored Energy

- L Mode
- I Mode

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Thermal Diffusivity Shows Little Correlation with Stored Energy

**Thermal Diffusivity versus Stored Energy**

- **Perturbative Diffusivity (m²/s)**
  - L Mode
  - I Mode

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Current and Density are Highly Correlated

Current versus Density

Density (1/m$^3$)

Plasma Current (MA)

- L Mode
- I Mode

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Thermal Diffusivity and Plasma Current are Weakly Correlated

Thermal Diffusivity versus Plasma Current

Perturbative Diffusivity (m²/s)

Plasma Current (MA)

L Mode
I Mode

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Thermal Diffusivity and RF Power are Generally Uncorrelated

Thermal Diffusivity versus RF Power

Perturbative Diffusivity (m²/s)

L Mode
I Mode

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The MHD Nature of Full Sawtooth Causes the Non-Diffusive “Ballistic” Transport

- Sawteeth involve the n=1, m=1 MHD kink instability, and a macroscopic redistribution of plasma after reconnection [Udintsev PPCF 2005], [Park PRL 2006].

- Magnetic stochastization leads to non-diffusive “ballistic” transport [Fredrickson PoP 2000].

- Partial sawteeth caused by partial reconnection, so are qualitatively different from full sawteeth [Fredrickson PoP 2000].
The Extended-Time-to-Peak method of calculating the perturbative thermal diffusivity uses the following equation (see [Tubbing NF 1987] for the full derivation):

Heat Pulse Thermal Diffusivity:

\[ \chi_{e}^{HP} = 4.2 \frac{a_{c} V_{HP}}{\alpha} \]

Where:

- \(a_{c}\) is the minor radius corrected for elongation (m)
- \(V_{HP}\) is the velocity of the peak of the heat pulse (m/s)
- \(\alpha\) is a measure of heat pulse amplitude spread with increasing radius (unitless)

Has been compared to Fourier analysis with good agreement [Mantica NF 1992]
Derivation of formula for Heat Pulse Thermal Diffusivity

From [Tubbing 1987]:

Has been compared to Fourier analysis with good agreement [Mantica NF 1992]

For:

\[ \chi_e^{HP} = 4.2 \frac{a_c v_{HP}}{\alpha} \]

\[ v_{HP} = \sqrt{\kappa} \frac{a}{a-s} \left( \frac{dt_{peak}}{dr} \right)^{-1} \]

\[ a_c = a \sqrt{\kappa} \]

\[ \alpha = 10(a-s) \frac{d}{dr} \log A \]

Where:  
- \( A \) = Pulse Amplitude  
- \( a \) = Minor Radius  
- \( s \) = Shafranov Shift  
- \( \kappa \) = Elongation  
- \( t_{peak} \) = Time at which pulse peak passes radius \( r \)

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Heat Pulse Thermal Diffusivity Model is Applicable to C-Mod

Assumptions included in [Tubbing 1987] model:

- Assume heat transport is dominated by conduction (convection is ignored)
- Includes Shafranov and elongation corrections to cylindrical plasma
- Assume thermal diffusivity is a function only of the electron temperature gradient
- Model includes decay of heat pulse amplitude in addition to velocity
- Radially averages over region of pulse propagation
- Has been compared to Fourier analysis with good agreement [Jacchia 91]
Alcator C Mod is a high-field, compact, divertor tokamak

- $R = 0.67 \, \text{m}$
- $a = 0.22 \, \text{m}$
- $B_T = 2.5 \text{ – } 8 \, \text{T}$
- $I_p < 1.3 \, \text{MA}$
- $P_{ICRF} < 6 \, \text{MW}$
- Moly/W PFCs with Boron coating
- Cryopump density control
  [Greenwald 2014]
ECE Diagnostics (GPC and FRCECE)

- Uses diffraction grating to split ECE spectrum [O’Shea PhD 1995].
- 9 channels corresponding to different frequencies and thus different radial locations
- 100 kHz sampling
- Radial channel spacing of approximately 2 cm
- Heat Pulse Thermal Diffusivity averaged in $0.6 < \frac{r}{a} < 0.9$
Partial Sawtooth Heat Pulse Results Agree More Closely with Gyrokinetic Simulation

Using:

\[ \chi_{e}^{HP} = \frac{1}{n_e} \frac{\partial Q}{\partial (\nabla r T_e)} \]

GYRO scans a/L_{te} and then calculates the heat pulse thermal diffusivity.

[White 2015]

\[ \chi_{GYRO}^{HP} = 0.3 \, m^2/s \]

\[ \chi_{full}^{HP} = 4.7 \, m^2/s \]

\[ \chi_{partial}^{HP} = 1.7 \, m^2/s \]

L-mode:

I-mode:

\[ \chi_{GYRO}^{HP} = 0.8 \, m^2/s \]

\[ \chi_{full}^{HP} = 3.0 \, m^2/s \]

\[ \chi_{partial}^{HP} = 2.0 \, m^2/s \]

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Stiffness from GYRO Simulations Can Be Compared to Experimental Diffusivity

- Set of non-linear GYRO simulations (input a/L_{Te} scan) is used to extract incremental diffusivity as slope of; Q_{e}/n_{e} versus Grad T_{e} [Smith NF 2015]
- Have used ion-scale simulations (ITG/TEM only) to model L-mode and I-mode plasmas [White PoP 2015]
- Have also used multi-scale simulations (ITG/TEM/ETG) to model an L-mode plasma [Howard PoP 2014]

Ion-scale only GYRO Stiffness

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GYRO is a Nonlinear Gyrokinetic Simulation Environment

GYRO used as follows:

- Local simulations conducted at $r/a = 0.6$
- Flux tube with non-periodic boundary conditions
- Experimental $n_e$, $T_e$, $T_i$, $Z_{\text{eff}}$, $v_{\text{rot}}$ etc. used as input to code
- ExB shear, collisions included, impurities included, electrostatic only
- Long wavelength ITG/TEM only ($k_\Theta \rho_s < 1.4$)
- High-k ETG not included

[White 2015]
Sawtooth Crash

[Udintsev PPCF 2006]

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Heat Pulse Thermal Diffusivity in L-Mode and I-Mode Confinement Will be Compared

- I-Mode is a high confinement regime
- Steep $T_e$ pedestal, no $n_e$ pedestal
  - $T_i$ pedestals are similar
  - High $T_e$, $T_i$ and rotation across profile
- Energy confinement comparable to or exceed H-mode [Whyte 2010]
- L-mode density profile
  - Impurity confinement like L-mode
- I-mode observed on C-Mod, ASDEX Upgrade and DIII-D. [Hubbard 2012]
I-mode transition features reduction in edge turbulence, appearance of WCM

- As the Temperature pedestal forms across the L-I transition
  - Broadband edge turbulence decreases in the range $f = 100$-$200$ kHz

- Turbulence increases at higher $f$
  - Known as the Weakly Coherent Mode
  - $F = 200$-$300$ kHz

- Sawtooth heat pulses modulate WCM amplitude

[White 2013]