Experimental Techniques at ASDEX Upgrade for Validation of Gyrokinetic Simulations

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Validation of Gyrokinetic Codes Requires Detailed Comparison to Experiment

- Gyrokinetic simulations must be validated with experimental results before they can be used predictively.

- Ion-scale simulations contain reduced physics, but run much faster than multi-scale simulations ($\sim 10^7$ CPU hours) [Howard PoP 2016].

- Would like to use ion-scale simulations, but recent results on Alcator C-Mod suggest that ion-scale GYRO simulations are insufficient for some L- and I-mode plasmas [Creely PoP 2017].

- New techniques on ASDEX Upgrade enable further investigation of these discrepancies, as well as cross-machine and cross-code comparisons:
  - Long Wavelength Electron Temperature fluctuations (CECE)
  - Perturbative Thermal Diffusivity (Partial Sawtooth Heat Pulses)
Ion-Scale Simulations of Alcator C-Mod
L-mode Plasmas Motivate Further Work

- Ion Heat Flux (Matched)

![Graph of L-Mode Ion Heat Flux]

[Creely PoP 2017]
Ion-Scale Simulations of Alcator C-Mod
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- Ion Heat Flux (Matched)
- Electron Heat Flux (Under)

[Creely PoP 2017]
Ion-Scale Simulations of Alcator C-Mod

L-mode Plasmas Motivate Further Work

- Ion Heat Flux (Matched)
- Electron Heat Flux (Under)
- Perturbative Diffusivity (Under)

\[ \chi_{Exp}^{pert} = 4.0 \, m^2/s \]
\[ \chi_{GYRO}^{pert} = 0.4 \, m^2/s \]

[Creely PoP 2017]
Ion-Scale Simulations of Alcator C-Mod
L-mode Plasmas Motivate Further Work

- Ion Heat Flux (Matched)
- Electron Heat Flux (Under)
- Perturbative Diffusivity (Under)
- Temperature Fluctuations (Under)

[Creely PoP 2017]
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- Ion Heat Flux (Matched)
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- Temperature Fluctuations (Under)

[Told PoP 2013]

Ion Heat Flux (Matched)

Electron Heat Flux

Perturbative Diffusivity

Temperature Fluctuations

[Told PoP 2013]

### Graphs

**L-Mode Ion Heat Flux**
- \( \chi_{\text{GYRO}} = 0.4 \, m^2/s \)
- \( \chi_{\text{TRANSP Qi}} \)
- \( \chi_{\text{TRANSP Qi}} \)

**L-Mode Electron Heat Flux**
- \( \chi_{\text{GYRO}} = 4.0 \, m^2/s \)
- \( \chi_{\text{TRANSP Qe}} \)
- \( \chi_{\text{TRANSP Qe}} \)

**Ion Heat Flux**
- Matched Simulation

**Temperature Fluctuations**
- ASDEX Upgrade

**Sensitivity Limit**
- ASDEX Upgrade

[Creely PoP 2017]
Perturbative Thermal Diffusivity Governs the Propagation of Heat Pulses

- Standard power balance electron thermal diffusivity, governs steady state diffusion.

- Perturbative, or incremental, thermal diffusivity governs the diffusion of perturbations and is related to stiffness [Tubbing NF 1987].

- Should not be directly compared with one another [Cardozo PPCF 1995].
Perturbative Diffusivity is Measured Experimentally through Heat Pulses

- Heat pulses generated with partial sawteeth [Creely NF 2016], modulated ECH [Ryter PPCF 2010], etc.

- Partial sawteeth avoid non-diffusive ‘ballistic’ transport associated with full sawteeth [Fredrickson PoP 2000].

- Perturbative diffusivity calculated here with Extended-Time-to-Peak Method for partial sawteeth [Tubbing NF 1987, Creely NF 2016].

- Can then compare to gyrokinetics [Smith NF 2015].

\[ \chi_e^{pert} \sim \frac{V_{\text{HP}}}{\alpha} \]

Velocity of Peak: \( V_{\text{HP}} \)

Pulse Damping: \( \alpha \)

Alcator C-Mod Partial Sawtooth Heat Pulse

\( r/a = 0.64 \)
\( r/a = 0.74 \)
\( r/a = 0.84 \)
Perturbative Thermal Diffusivity Found to Correlate with Various Plasma Parameters

- Previous work investigated the correlation between perturbative diffusivity and various plasma parameters ($n_e$, $T_e$, $a/L_T$, etc.)

C-Mod data from [Creely NF 2016]
Perturbative Thermal Diffusivity Found to Correlate with Various Plasma Parameters

- Previous work investigated the correlation between perturbative diffusivity and various plasma parameters ($n_e$, $T_e$, $a/L_{Te}$, etc.)

- Initial work on ASDEX Upgrade shows trends consistent with those found on Alcator C-Mod

C-Mod data from [Creely NF 2016]
Future Work Will Compare to Perturbative Diffusivity Measured with Modulated ECH

- All previous work with partial sawteeth has been on Alcator C-Mod, which doesn’t have ECH.
- ASDEX Upgrade can also measure perturbative diffusivity with modulated ECH [Ryter PPCF 2001].
- Allows for cross-machine gyrokinetic validation (GENE and GYRO), and multi-scale simulations

[Adapted from Ryter PPCF 2001]
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ADAPTED FROM RYTER PPCF 2001

Preliminary Data Falls in this Range

-\( \chi_e^{\text{HP}} \) vs. \( \nabla T_e / T_e \) [m\(^{-1}\)]

-\( \chi_e \) vs. \( \chi_e^{\text{HP}} / T^{3/2} \) [m\(^2\)s, keV]
Correlation Electron Cyclotron Emission (CECE) Measures Temperature Fluctuations

- CECE measures low-k \( (k_\theta \rho_s < 0.4) \) electron temperature fluctuations, key to understanding ITG/TEM turbulence [Freethy RSI 2016, This Conference]

- Correlating two closely spaced ECE radiometer channels allows detection of fluctuations below thermal noise of single channel

- Statistical noise floor depends on length of the measurement time period.
New Hardware on ASDEX can Measure Radial Profiles and Correlation Length

- Recent upgrade from 10 channels on two systems to 30 channels on one system
- Allows for fine radial profile measurements
- Preliminary analysis of L-modes shows that temperature fluctuation levels increase with radius
- Future work will look at radial correlation lengths
Conclusions and Future Work

- Would like to use ion-scale gyrokinetic simulations, but recent results on Alcator C-Mod suggest that ion-scale GYRO simulations are insufficient for some L- and I-mode plasmas [Creely PoP 2017].

- New techniques on ASDEX Upgrade enable further investigation of these discrepancies, as well as cross-machine and cross-code comparisons:
  - New CECE enables fine radial profile and correlation length measurements
  - Partial Sawtooth Heat Pulses enable passive measurement of perturbative thermal diffusivity

- Currently in the process of comparing GYRO and GENE on Alcator C-Mod and utilizing new techniques on ASDEX Upgrade for GENE comparisons.
References


Backup Slides
Radial Profile Resolution Greatly Expanded

- In 2017 – Greater flexibility and increased number of channels to allow finer $\delta T_e/T_e$ radial profiles (below) and radial correlation lengths.

![AUG #32766 fluctuation profile]

2015/16 radial profile

![AUG #33995 fluctuation profile]

2017 radial profile
Perturbative Thermal Diffusivity is Related to Gyrokinetic Temperature Profile Stiffness

- In gyrokinetic simulations, can measure slope of heat flux against $a/L_{Te}$ above the critical gradient [Citrin NF 2014].

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

- Run gyrokinetics with different $a/L_{Te}$ to map out slope.

- Can compare to experimentally measured perturbative diffusivity [Smith NF 2015]

\[ L_{Te} = \frac{T_e}{\nabla T_e} \]

High and low stiffness plasmas, with same critical gradient.
Before Sawtooth

\[ T_e \]
The diagram illustrates the change in $T_e$ (electron temperature) as a function of radius $r$. The graph shows two distinct phases:

1. **Before Sawtooth**: The curve for $T_e$ is relatively flat, indicating a stable phase before the sawtooth event.
2. **After Full Sawtooth**: The curve drops sharply, indicating a significant change in $T_e$ after the sawtooth event.

Key points:
- **Inversion Radius**: The point where the curve begins to drop sharply.
- **Ballistic Effect**: The rapid decrease in $T_e$ post-sawtooth.
- **Mixing Radius**: The radius at which the change in $T_e$ is most pronounced.

The diagram highlights the impact of sawtooth events on plasma parameters in tokamaks.
Partial Sawtooth

Before Sawtooth

After Partial Sawtooth

Inversion Radius

Mixing Radius

$T_e$
Perturbative Diffusivity is Measured Experimentally through Heat Pulses

- Propagation of diffusive heat pulses in plasma can be used to measure perturbative diffusivity.

- Heat pulses generated with partial sawteeth crashes, modulated ECH, etc. [Creely NF 2016, Cardozo PPCF 1995, Ryter PPCF 2010]

- Perturbative diffusivity calculated here with Extended-Time-to-Peak Method for partial sawteeth [Tubbing NF 1987, Creely NF 2016].
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New Hardware on ASDEX can Measure Radial Profiles and Correlation Length

24 Fixed Frequency Channels
6 Tunable Frequency Channels
New Hardware on ASDEX can Measure Radial Profiles and Correlation Length

- Recent upgrade from 10 channels on two systems to 30 channels on one system
- Preliminary analysis of L-modes shows that temperature fluctuation levels increase with radius:
  \[ \frac{\tilde{T}}{T} = 0.48\% \]
  \[ \frac{\tilde{T}}{T} = 0.63\% \]
  \[ \frac{\tilde{T}}{T} = 0.80\% \]
Alcator C-Mod GYRO parameters

- Will compare experimental $Q_i$, $Q_e$, fluctuations and perturbative diffusivity to global ($r/a = 0.65 - 0.9$) nonlinear GYRO simulations.

- Simulations exhibit high physics fidelity:
  - All inputs were obtained from experiment
  - 3 kinetic species (deuterium, electrons, impurities)
  - Realistic geometry (Miller parameterization)
  - Electrostatic turbulence (E&M effects neglected due to low beta)
  - Rotation effects (ExB shear, etc.)
  - $e$-$i$, and $i$-$i$ collisions are included

- Simulation box size of approximately $105 \times 120 \rho_s$
- 28 toroidal modes; $\sim 500$ radial grid points
- Captures long wavelength (ITG/TEM) up to $k_{\theta}\rho_s$ up to $\sim 1.35$
  [Candy PRL 2003]