Multi-scale/Multi-field Turbulence Measurements to Test Gyrokinetic Simulation Predictions on the DIII-D Tokamak

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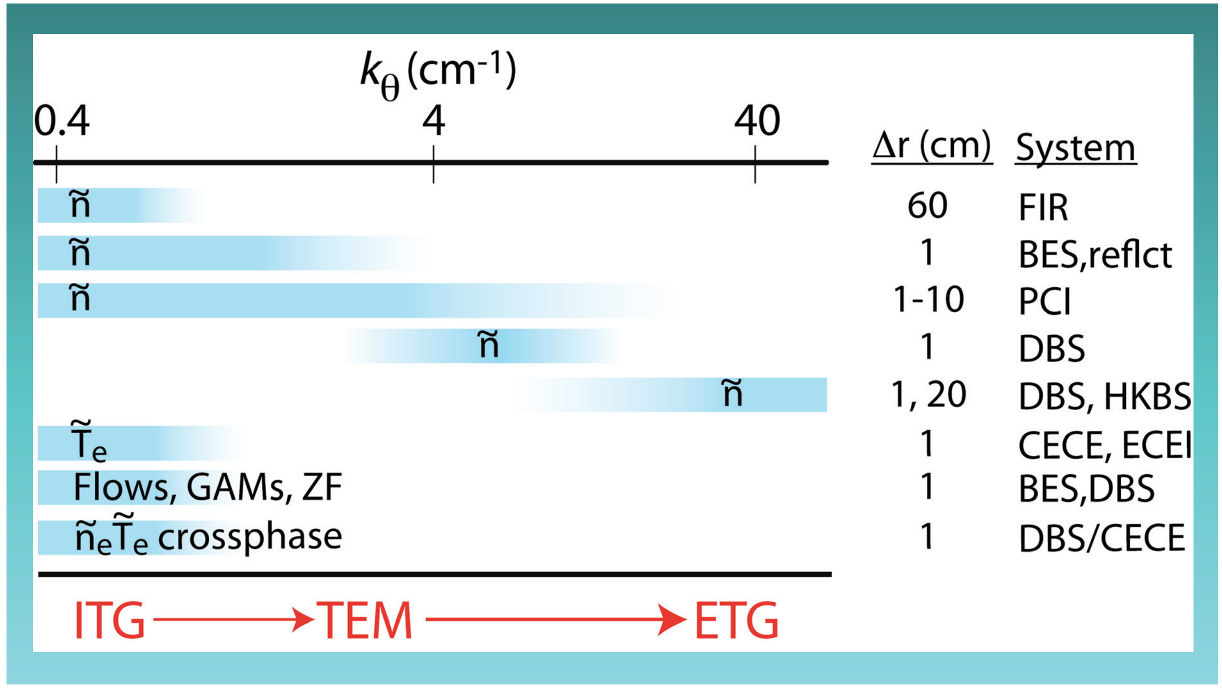


*C. Holland, S.P. Smith, A.E. White, K.H. Burrell, J. Candy, J.C. DeBoo, E.J. Doyle, J.C. Hillesheim, J.E. Kinsey, G.R. McKee, D. Mikkelsen, W.A. Peebles, C.C. Petty, R. Prater, S. Parker, Y. Chen, L. Schmitz, G.M. Staebler, R.E. Waltz, G. Wang, Z. Yan, and L. Zeng

Presented at the
Twenty-third IAEA Fusion Energy Conference
Daejeon, Republic of Korea

October 11-16, 2010

First Principles Predictive Simulation of Plasma Confinement and Performance Is a 'Grand Challenge'* of Fusion Research.

- **A tested and validated first principles based predictive capability is crucial for ITER and other future burning plasmas**
- **A series of carefully designed experiments on DIII-D have taken advantage of an exceptional set of turbulence and profile diagnostics to rigorously test gyrokinetic turbulence simulations.**
  - Will present five different L-mode experiment-simulation comparisons spanning multiple experimental conditions

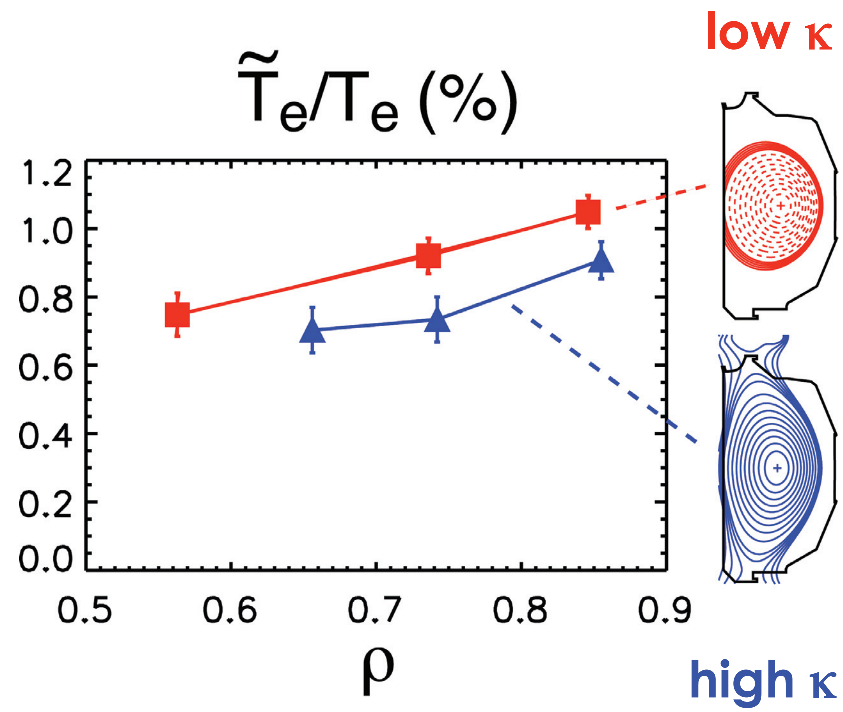
- **Simulation found to be consistent with experiment in many (but not all) fluctuation and transport parameters in the mid-core region ($0.4<\rho<0.6$) of multiple L-modes,**
- **There appears to be a consistent underprediction of transport fluxes as the edge is approached $\rho \geq 0.7$ in L-mode simulations**

*John Dawson, et al., Int. J. High Performance Computing Appl., (1991))

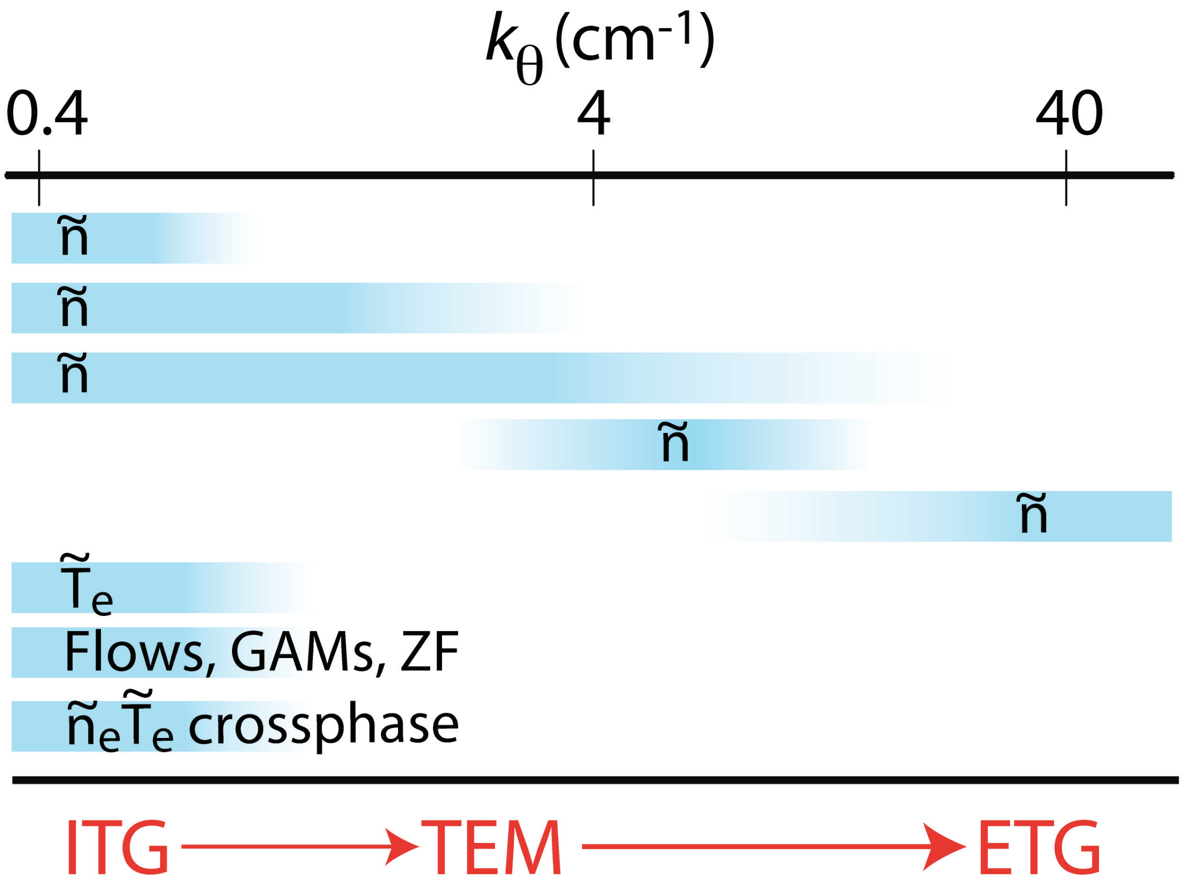
Validation Experiments on DIII-D

Focus Is on Quantitative Comparisons of Multiple Parameters to Predictions

- **Utilize known and/or important plasma dependencies: T_e/T_i, elongation κ, ∇T_e, …**
  - Simulations should reproduce trends as well as quantitative behavior
- **Compare multiple fields, radii, scales, and transport properties**
  - Plus detailed quantities such as $n_e T_e$ crossphase, k–spectra, Δr
- **Multiple simulations being used**
  - GYRO, TGLF most used to date
  - GEM, GENE, GS2, GTC, GYSELA entering mix
- **Synthetic diagnostics are critical to correctly compare predictions to fluctuation measurements**
  - Take into account wavenumber, time, and spatial resolutions, etc.



Validation Studies Utilize DIII-D Fluctuation Diagnostics That Cover Large Range in Scale and Multiple Fields



Δr (cm)	System
60	FIR
1	BES,reflct
1-10	PCI
1	DBS
1, 20	DBS, HKBS
1	CECE, ECEI
1	BES,DBS
1	DBS/CECE

DIII-D NATIONAL FUSION FACILITY

Multiple Parameters and Confinement Regimes Are Being Examined

Parameter	Variation	Plasma
Local ∇T_e	50%	L-mode
$\tilde{n}_e - \tilde{T}_e$ crossphase	50%	L-mode
T_e/T_i	30%	L-mode
Elongation, κ	30%	L-mode
T_e/T_i	25%	Hybrid H-mode
T_e/T_i	50%	QH-mode

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Elongation, κ	30%	L-mode
T_e/T_i	25%	Hybrid H-mode
T_e/T_i	50%	QH-mode

- **Will present results from first three experiments (total of five different L-mode plasma conditions)**

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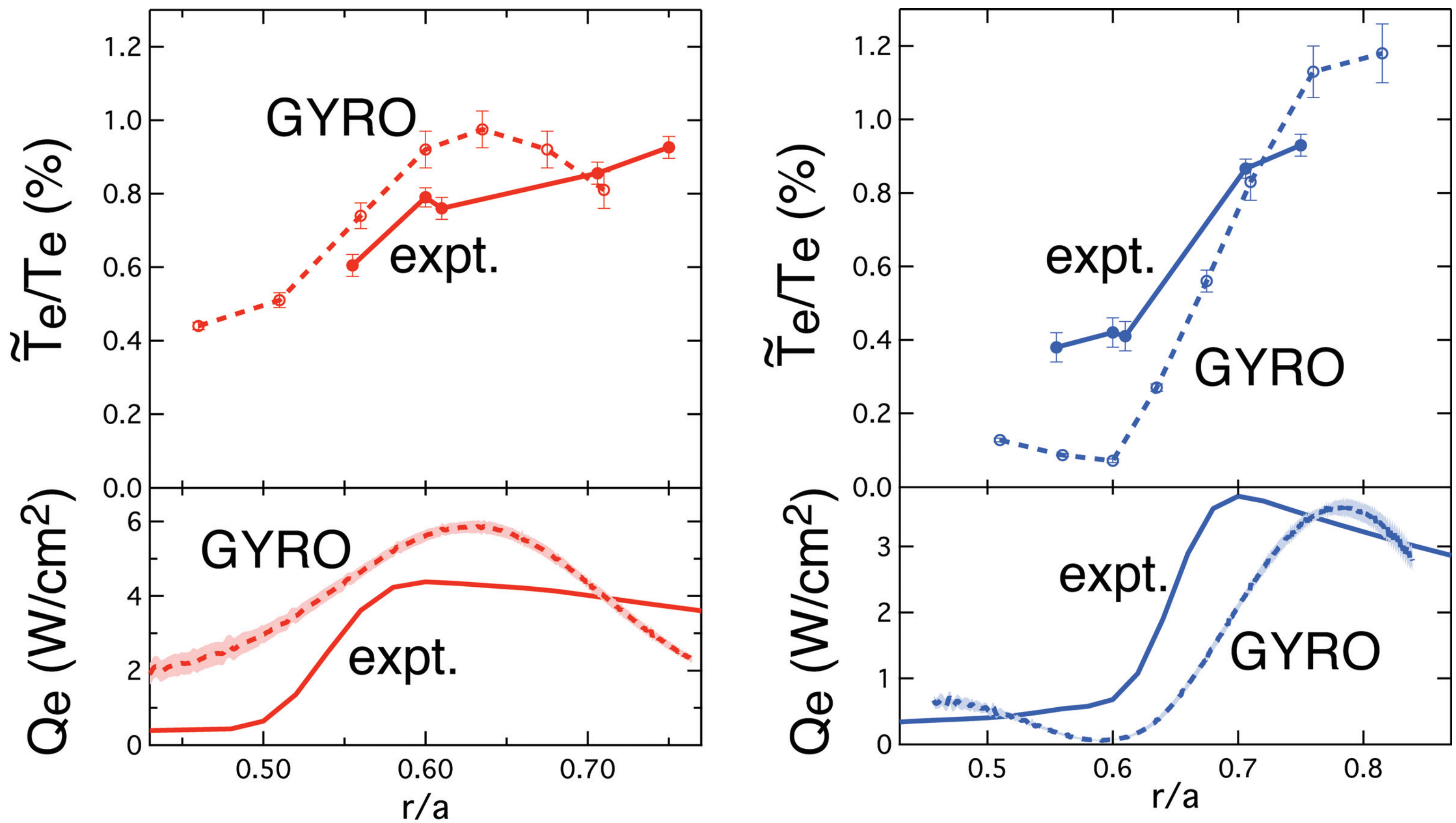
∇T_e Experiment and Simulation Comparison

GYRO Predictions of $\tilde{T}_e/T_e$ and Electron Thermal Transport Consistent With Experiment

High ∇T_e | **Low ∇T_e**

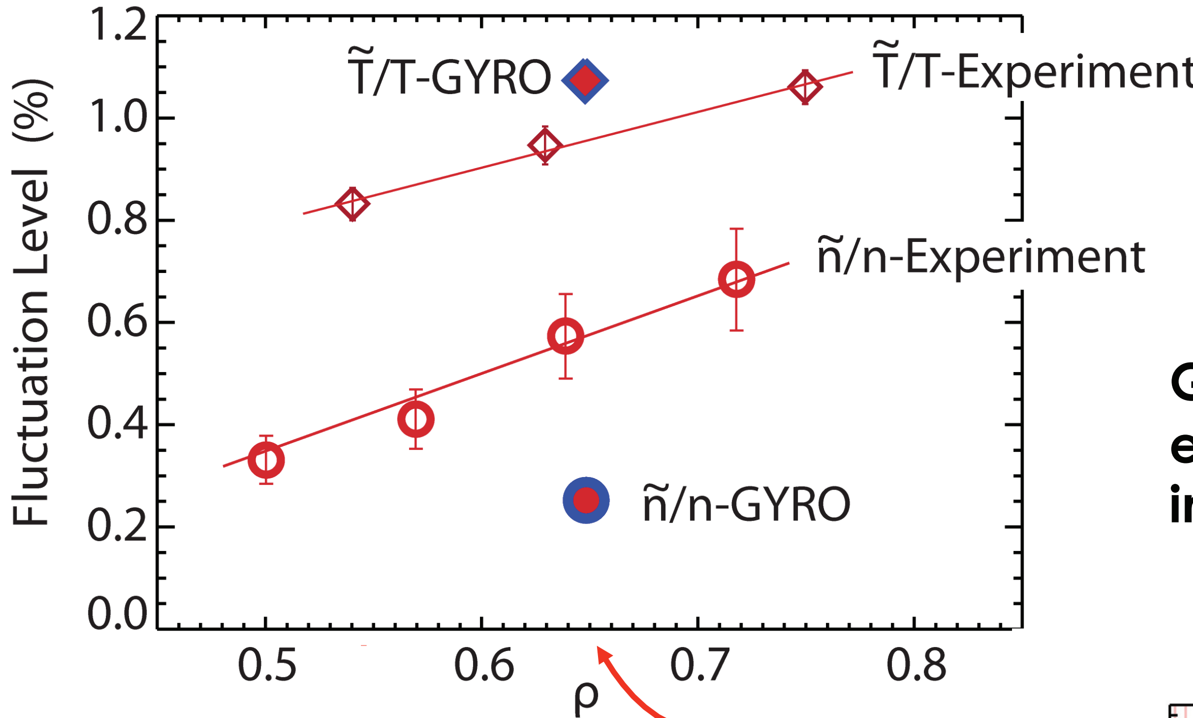


J.C. DeBoo, et al., Phys. Plasmas 2010

- **GYRO simulations - nonlinear, electromagnetic, carbon impurity**
- **Low-k $\tilde{n}/n$ not measured**
- **Ion thermal flux underpredicted by a factor ≥ 2**

$\tilde{n}_e \tilde{T}_e$ Crossphase Experiment and Simulation Comparison

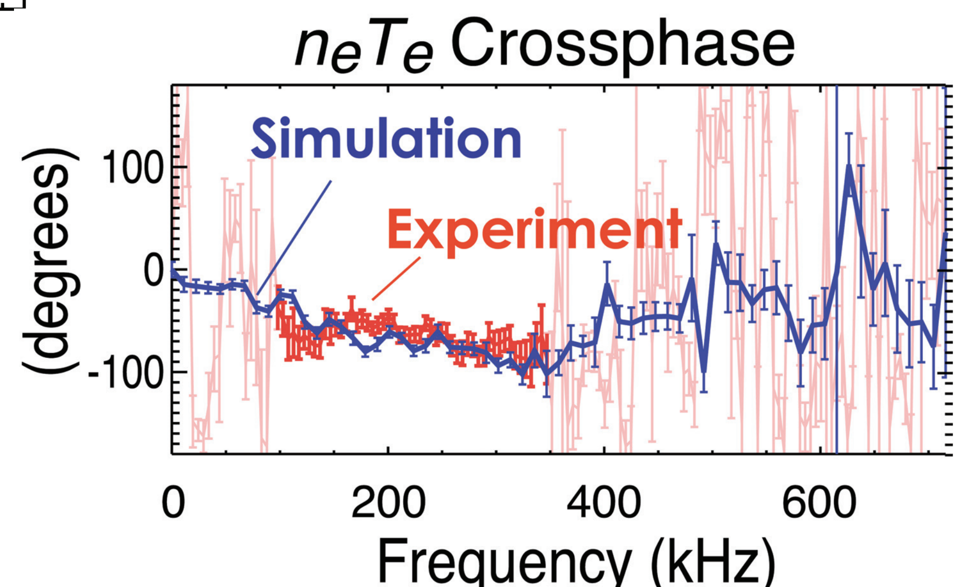
GYRO Simulations Able to Predict $\tilde{n}_e\tilde{T}_e$ Phase and Temperature Fluctuations at Mid-radius



Reported by A. White, et al., Phys. Plasmas 2010

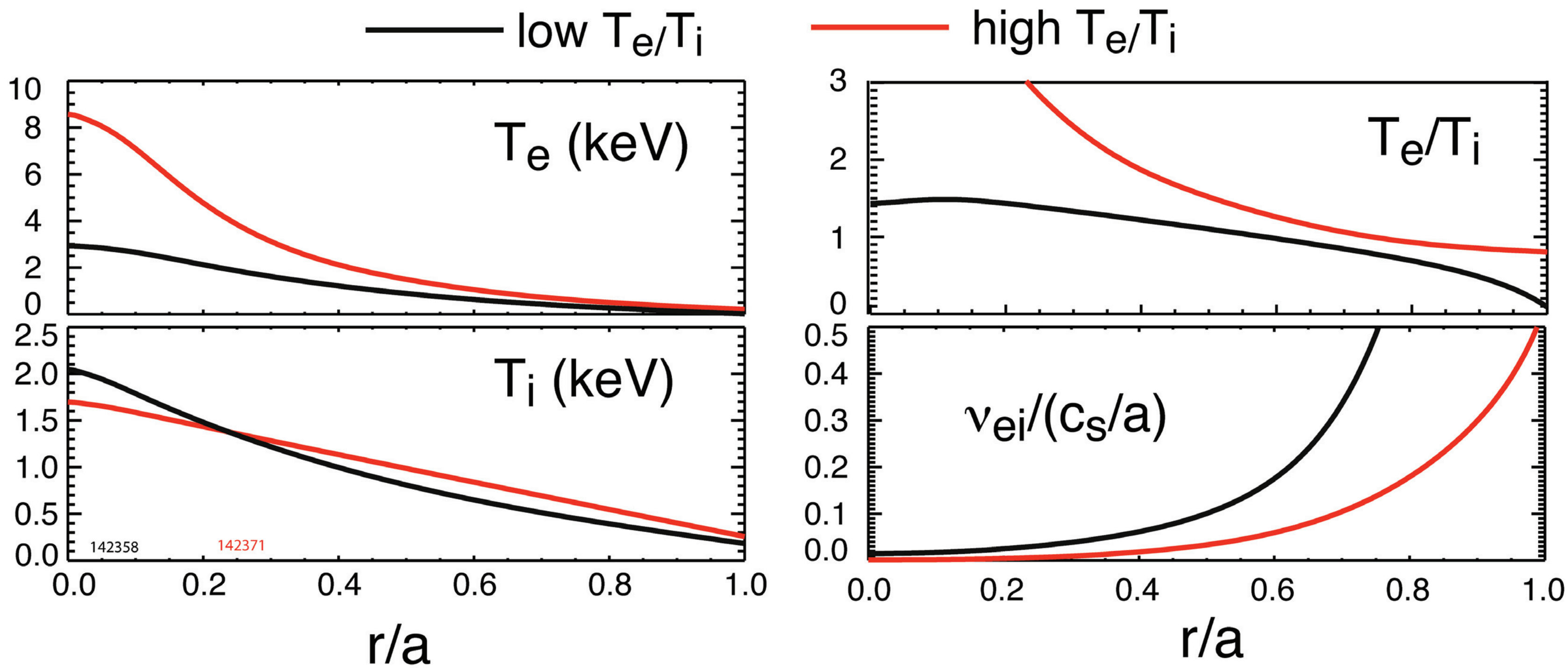
GYRO simulations – nonlinear, electromagnetic, carbon impurity, drift kinetic electrons

- **Thermal flux not well predicted**
- ***ñ/n* underpredicted**
  - Q_e = 3.77±.06 MW (GYRO)
    2.43±.02 MW (EXPT)
  - Q_i = 0.34±.01 MW (GYRO)
    1.32±.02 MW (EXPT)



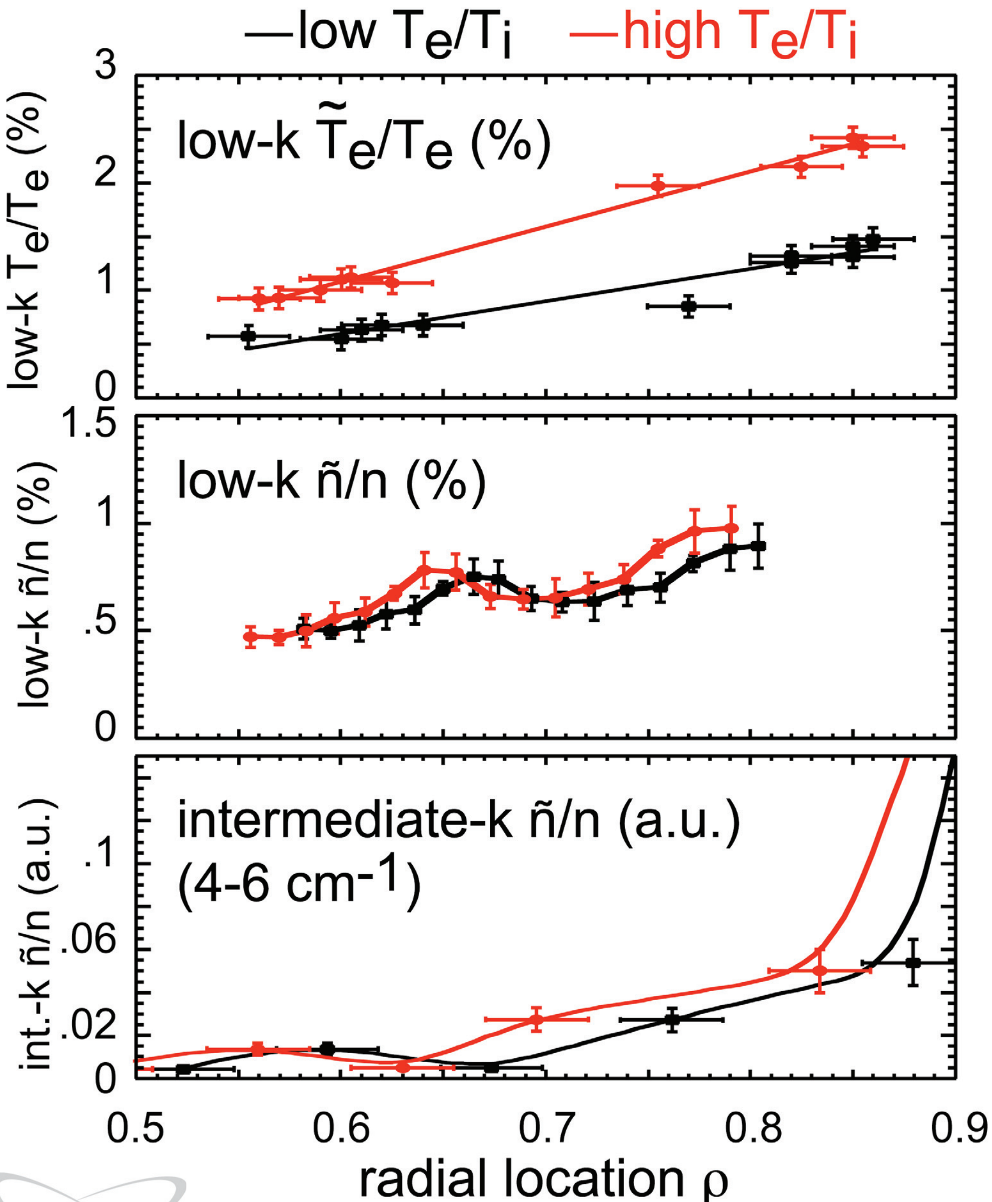
L-mode T_e/T_i Scan Experiment and Simulation Comparison

L-mode T_e/T_i Scan Performed to Compare Measured and Predicted Effect on Transport and Fluctuations



- **Non-sawtoothing, USN, T_e/T_i varied by adding 3.3 MW ECH to 2.5 MW NBI**
- **Difficult to modify only one parameter (in this case T_e/T_i)**
  - Large variation in collisionality $\nu_* \sim n/T^2$, gradient $\nabla T_i \sim T_i / L_{Ti}$
  - Sensitivity analysis shows that linear growth rates are very sensitive to changes in L_{Ti}, much less sensitive to changes in ν_*
  - Expect simulations to self consistently manage all changes

Largest Experimental Response to Increased T_e/T_i was in Electron Temperature Fluctuation Levels

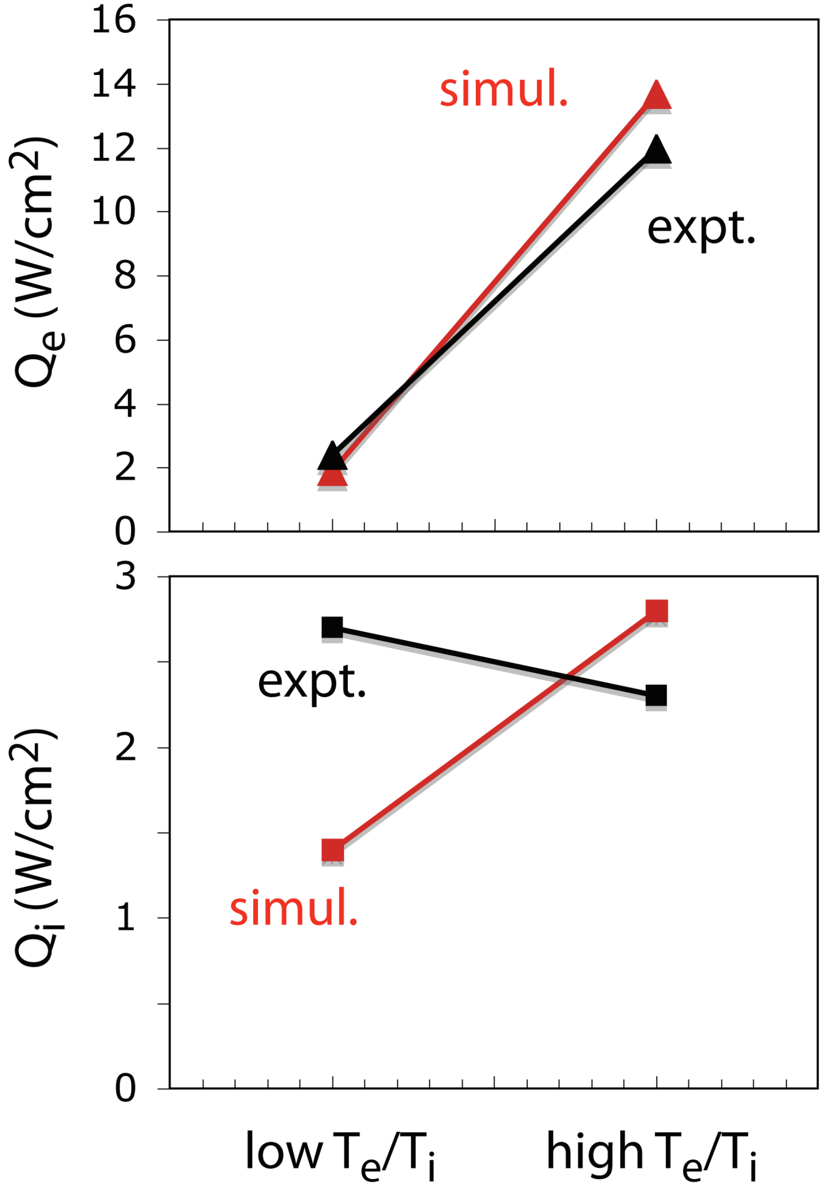


- **>70% change in $\tilde{T}_e/T_e$**
- **Small changes in low-k $\tilde{n}$**
- **No change in either intermediate-k $\tilde{n}$ or high-k $\tilde{n}$ (not shown) within uncertainties**
- **Initial focus was on ρ =0.6 and ρ=0.8 for comparison to simulation**
  - However have not yet obtained converged solutions at ρ =0.8

Nonlinear GYRO Simulations

ρ=0.6

Quantitative Similarities Between Nonlinear GYRO Predictions and Experimental Electron Thermal Fluxes



- **GYRO simulations - non-linear, electromagnetic, carbon impurity, drift kinetic electrons, (mass ratio)$^{1/2}$=$(M_i/m_e)^{1/2}$=40**

- **Simulation does not match trend for ion thermal fluxes**

ρ=0.6

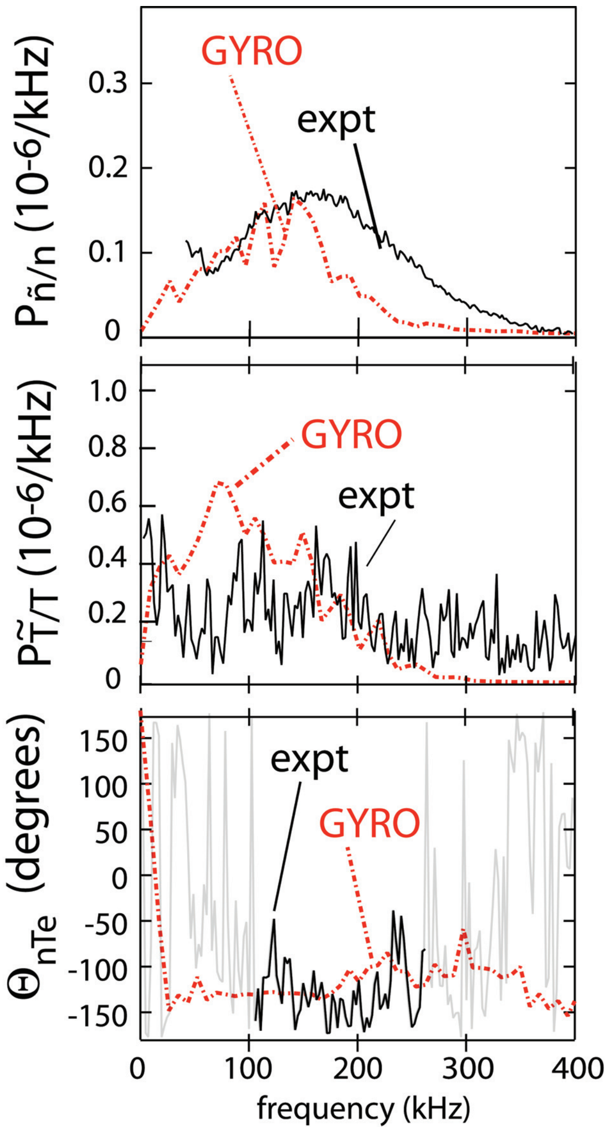
GYRO Predicts Both Changes and Magnitudes of Experimental $\tilde{n}/n$ and $\tilde{n}_e\tilde{T}_e$ Crossphase

Low T_e/T_i **High T_e/T_i**

$\tilde{n}/n$

$\tilde{T}_e/T_e$

Θ_{nT}



ρ=0.6

GYRO Predicts Both Changes and Magnitudes of Experimental $\tilde{n}$ and $\tilde{n}_e\tilde{T}_e$ Crossphase

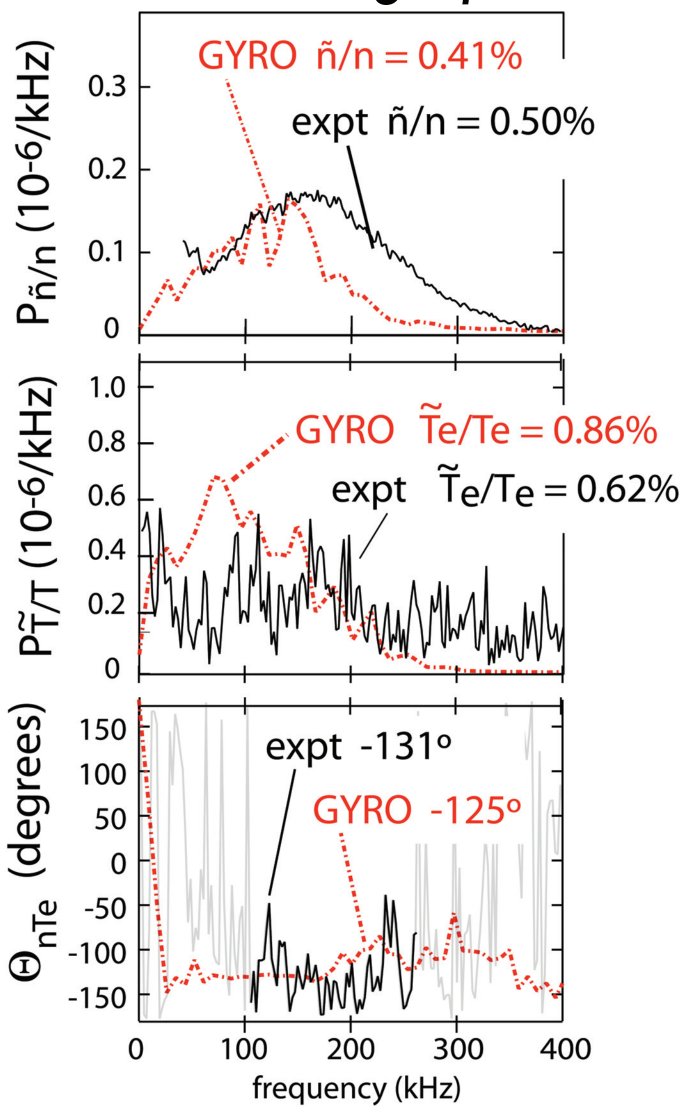
Low T_e/T_i

High T_e/T_i

$\tilde{n}/n$

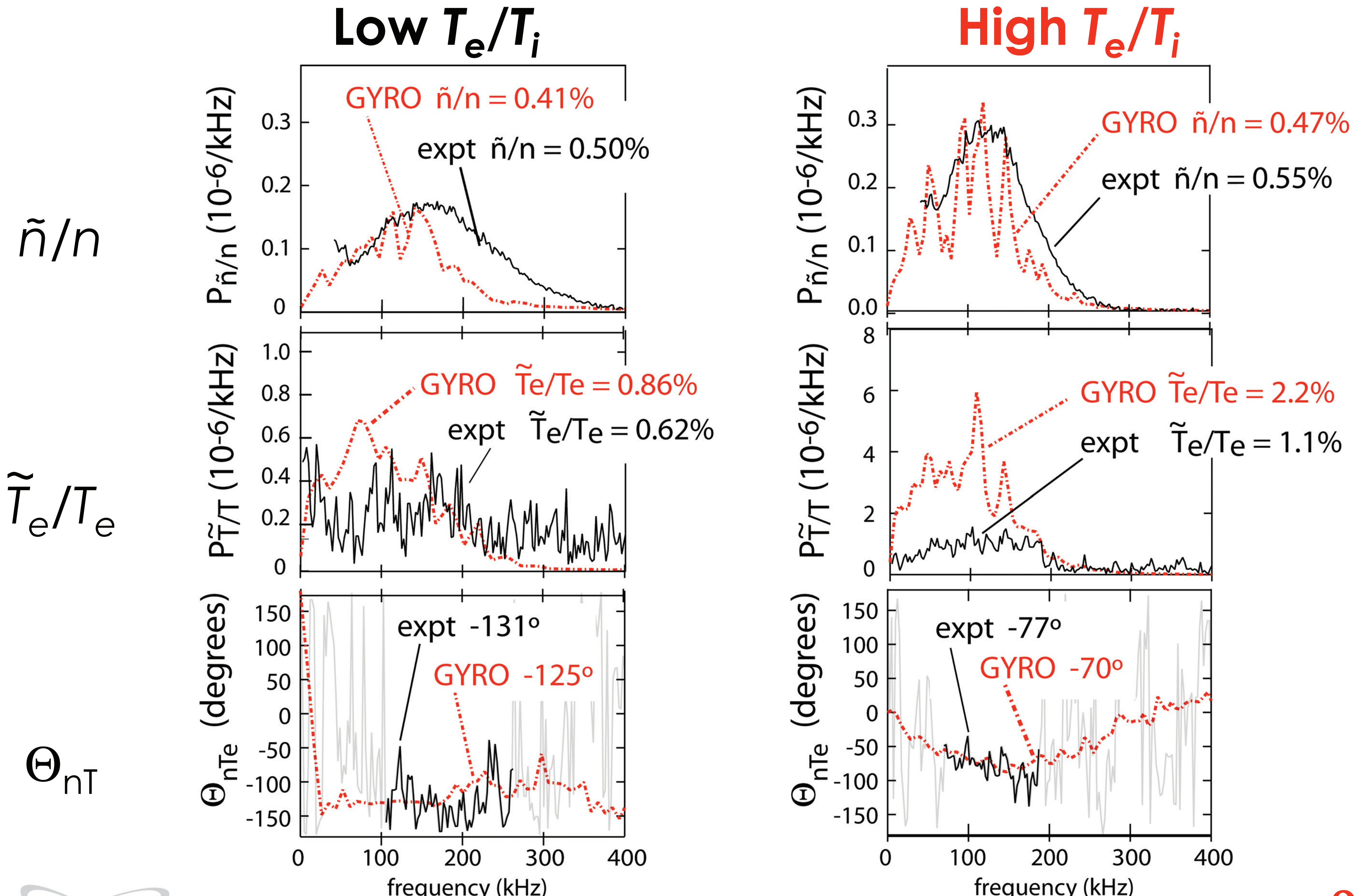
$\tilde{T}_e/T_e$

Θ_{nT}



ρ=0.6

GYRO Predicts Both Changes and Magnitudes of Experimental $\tilde{n}$ and $\tilde{n}_e\tilde{T}_e$ Crossphase

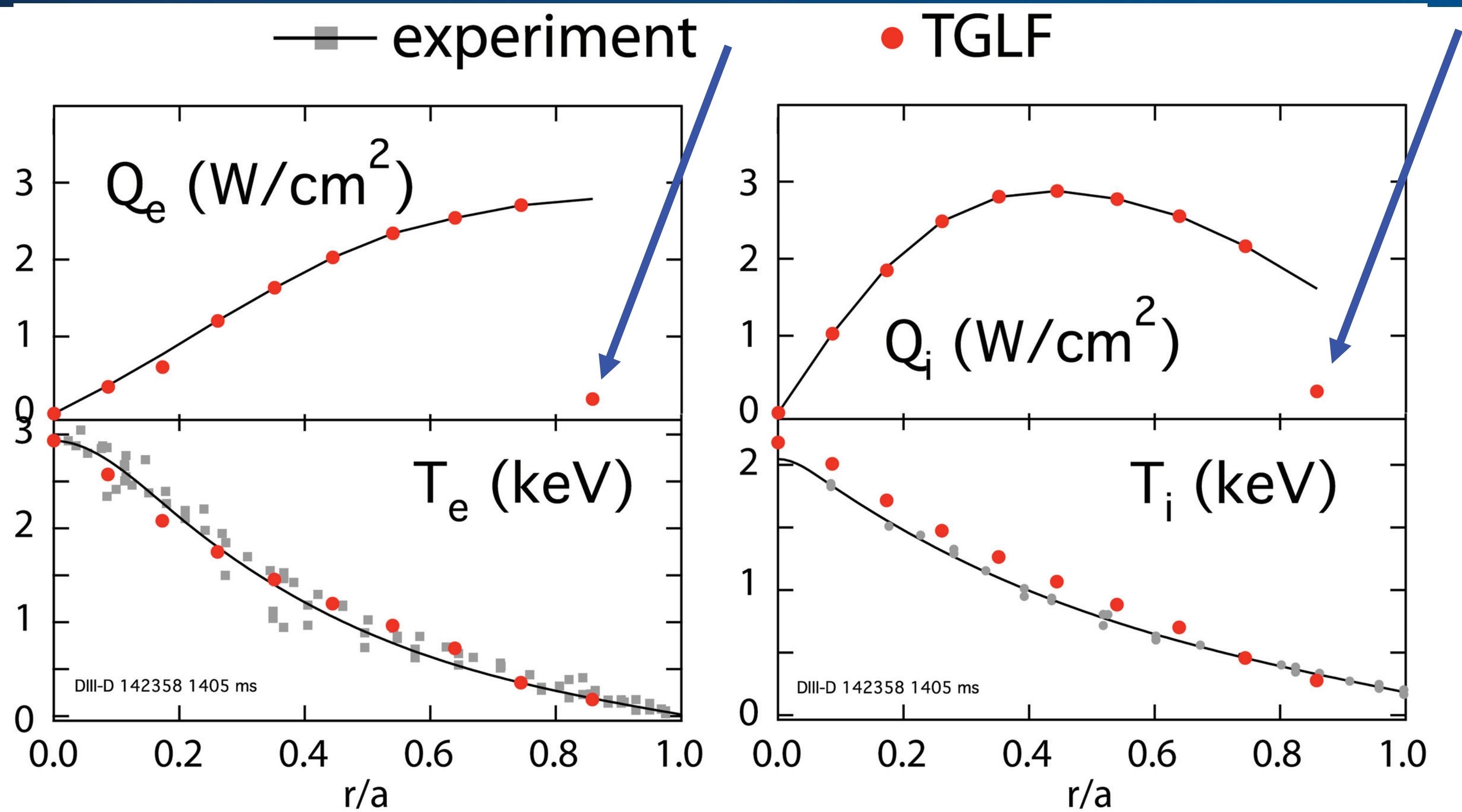


ρ=0.6

IAEA Fusion Energy Conf./2010/T.L. Rhodes

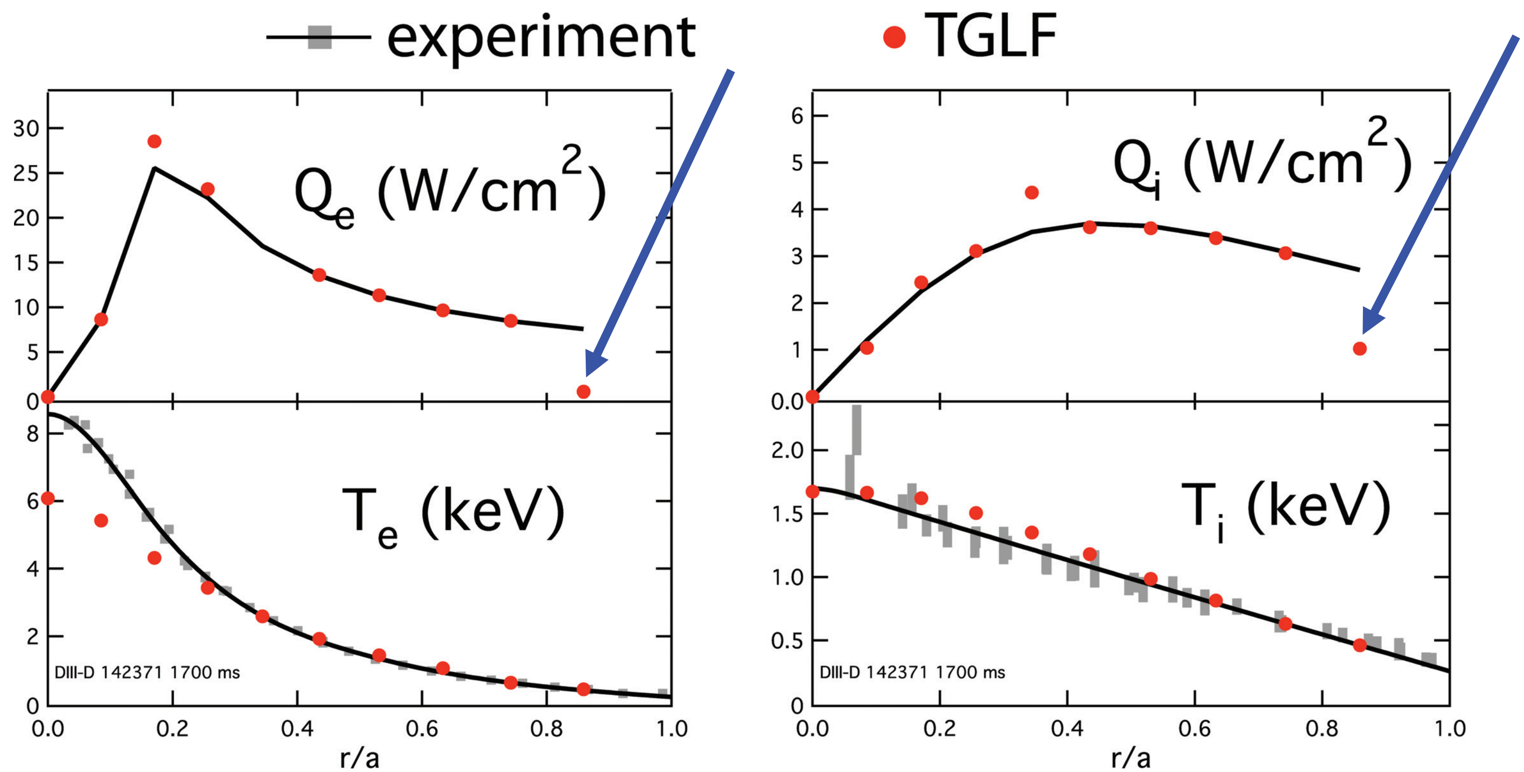
Transport Modeling Using the TGLF Code

TGLF Transport Modeling Shows Underprediction Towards Edge of These Discharges - Low T_e/T_i Case



- **TGLF is a theory based, transport model.**
- **TGLF (and GYRO) extremely sensitive to L_T, L_n which have large uncertainties**
- **Therefore, rather than predict Q_e, Q_i instead predict T_e, T_i based on measured thermal fluxes (= flux matching solution)**

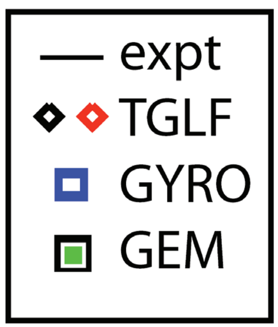
Similar Underprediction Found Towards Edge of High T_e/T_i Case

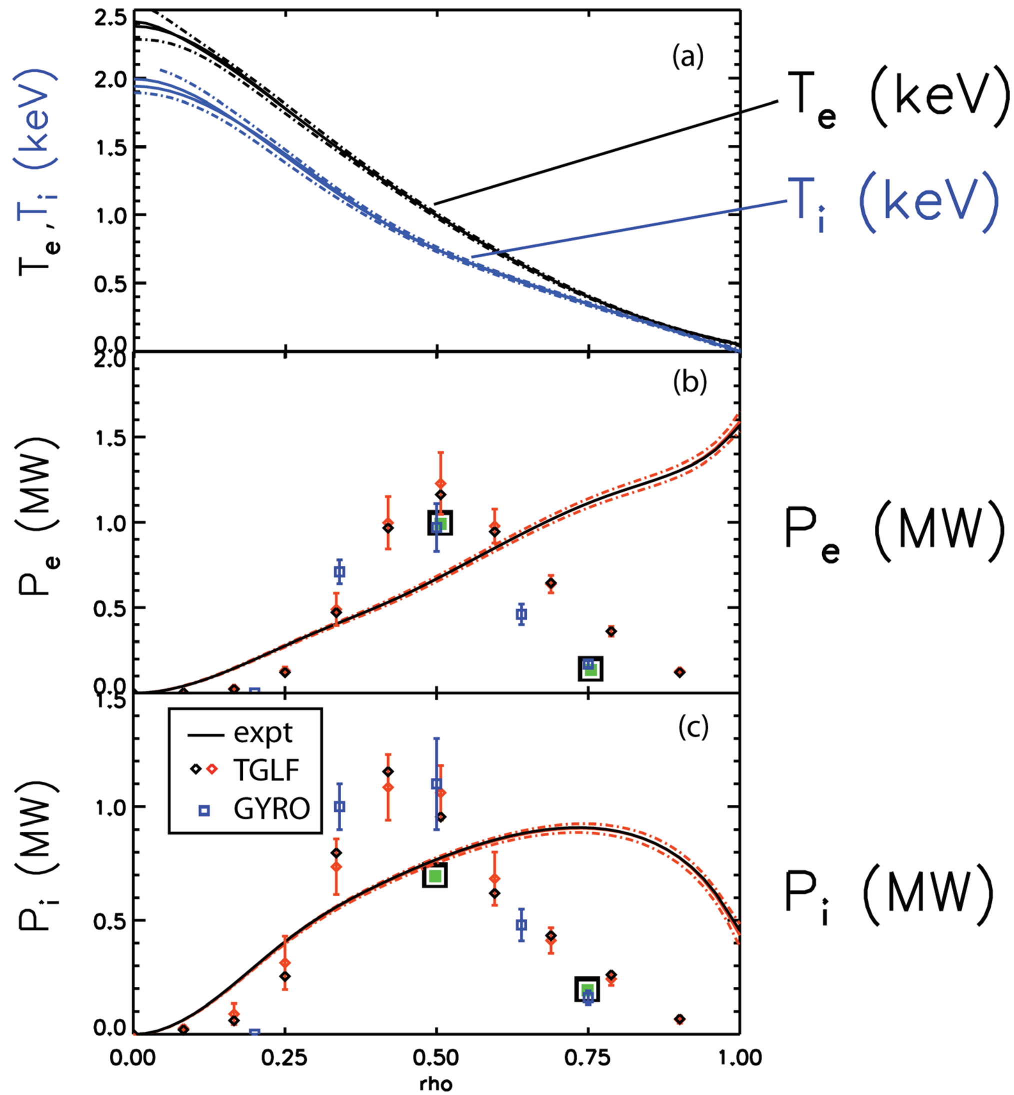


- **Underprediction also found in other L-mode simulation cases, indicate missing physics in GYRO/TGLF as the edge is approached**
  - Possibly due to edge coupling effects and/or necessity of coupled ITG-TEM-ETG simulations.
  - Clearly an important question to pursue in future work/experiments.

Underprediction Towards Edge Seen in Different Codes

- **L-mode discharge, 128913**
- **GYRO and TGLF show underprediction towards edge**
  - GYRO also underpredicted fluctuation levels towards edge (Holland, IAEA 2008)
- **Recent GEM simulation (PIC) results similar to GYRO/TGLF with similar underprediction towards edge (Y. Chen, S. Parker, U Colorado)**





Summary

- **DIII-D is making detailed comparisons between experiment and simulations at multiple levels, from transport fluxes to small scale fluctuation behavior.**
  - Since last IAEA have added five different L-mode experiment–simulation comparisons spanning different conditions.
  - Will add four more comparisons by 2010 APS
- **Encouraging results - simulation is consistent with experiment for many fluctuation and transport parameters in mid-core region ($0.4<\rho<0.6$) of multiple L-modes.**
  - **But not in all parameters, more work to be done**
- **Underprediction of transport towards edge of multiple L-modes ($\rho>0.7$) suggests missing physics in simulations.**
  - Previous work (Holland, IAEA 2008) showed fluctuation intensities also underpredicted by amount similar to transport underprediction.
- **Validation studies underway for ITER relevant H- and QH-mode plasmas**
  - See L. Schmitz, EXC/P7-01, this morning.