Update: Multichannel Transport Studies on Alcator C-Mod

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Multichannel transport studies look for correlations among heat, particle and momentum channels

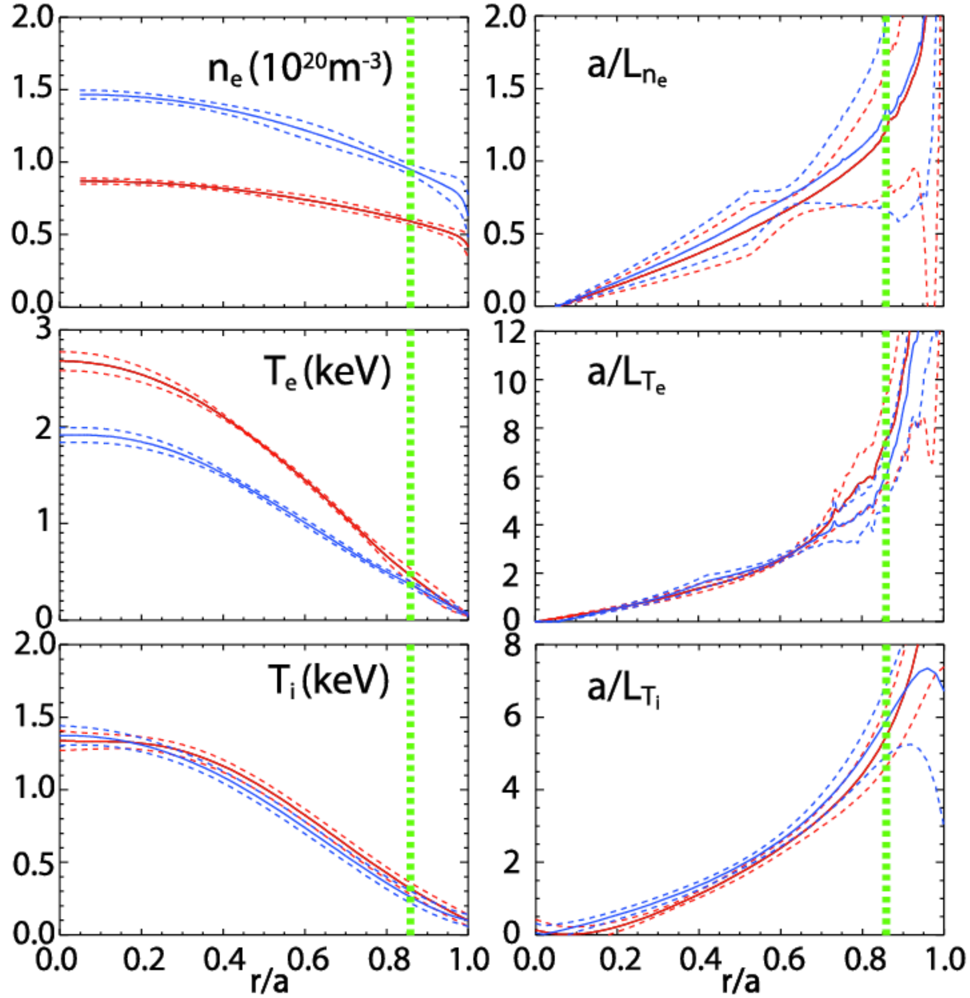
- Plasmas with peaked & hollow rotation profiles
  - Change of rotation not tracked by a linear ITG/TEM transition
    - Low power RF heated L-modes (White POP 2013)
    - SOC/LOC Ohmic plasmas (Sung PPCF 2013)
  - No DIII-D type transport shortfall
    - Ohmic plasmas (Sung, POP, in progress)
    - L-mode plasmas (Howard POP 2013)
  - Q_i and impurity D&V can be matched by GYRO, but Q_e is underpredicted in these low power L-mode plasmas (Howard POP 2013)

- Fixing the electron heat flux underprediction at C-Mod
  - Realistic mass ($\mu = 60$), multiscale ($k_\theta \rho_s < 48$) sims needed to match experimental Q_e in the low power L-mode plasmas (Howard PRL submitted)
  - In contrast, Q_e can be matched in high power L-modes using standard Realistic mass ($\mu = 60$), ion-scale ($k_\theta \rho_s < 1.0$) low-k GYRO simulations (Howard POP 2013)

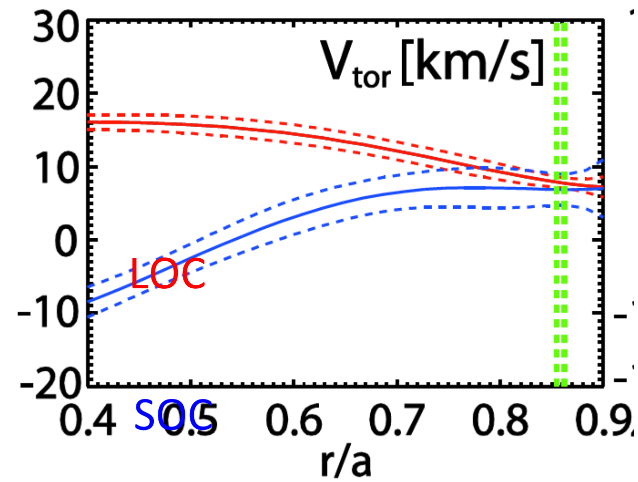
Ohmic plasmas with peaked & hollow rotation profiles

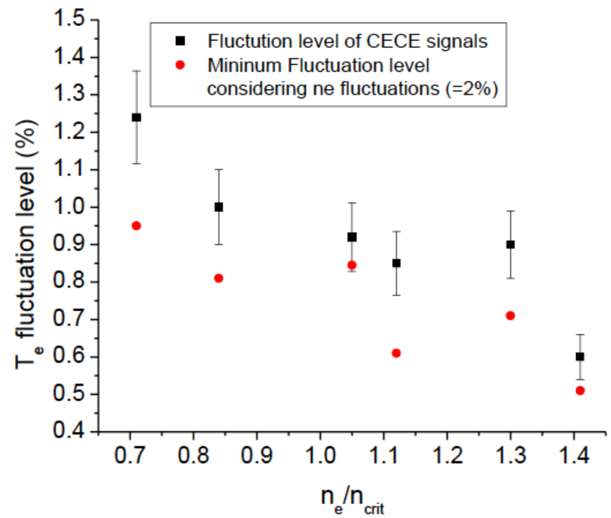
LOC / SOC Ohmic plasmas exhibit rotation reversals; Temperature fluctuations lower in SOC than in LOC

(LOC plasma, SOC plasma, CECE position)



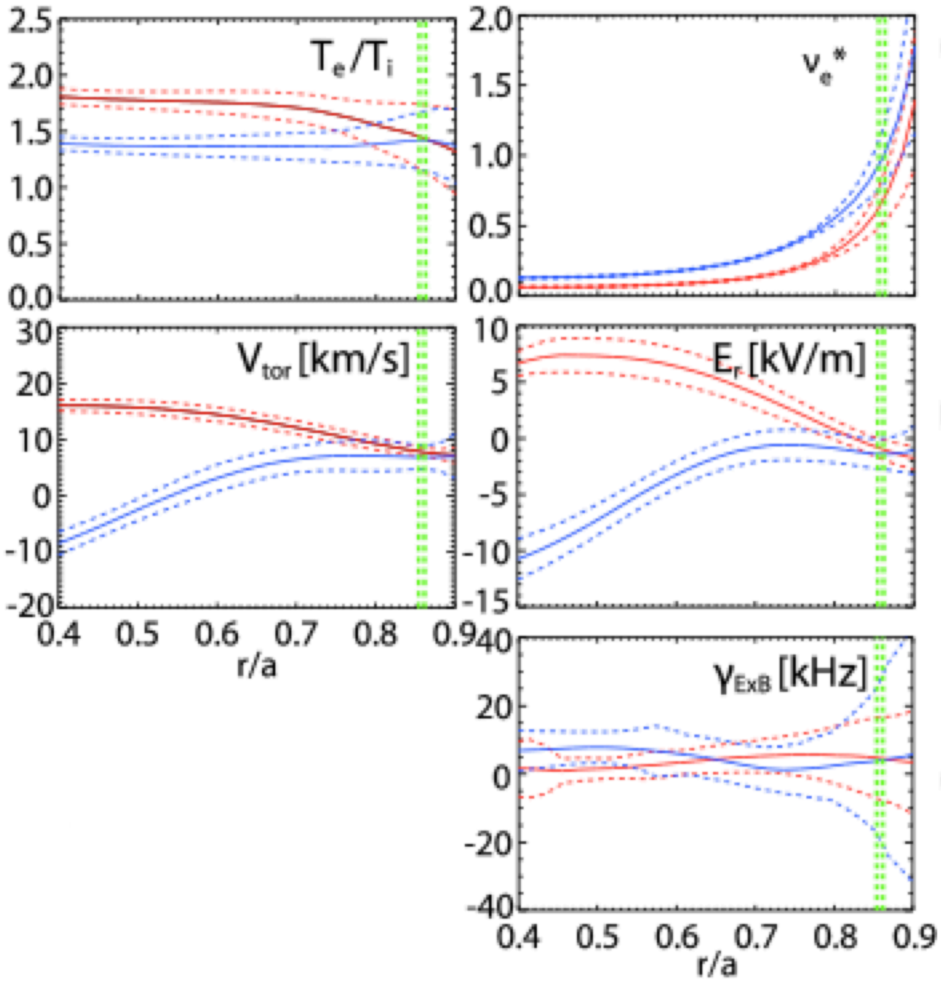
(Sung, PPCF 2013; Sung POP, in progress)



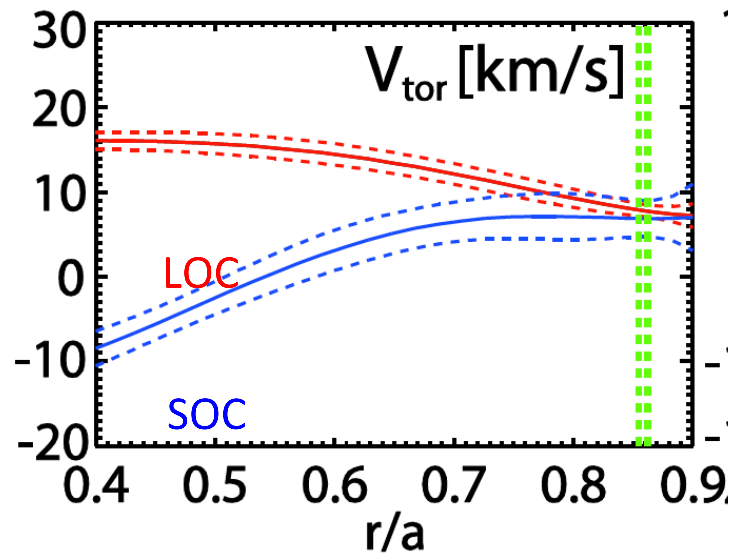


LOC / SOC Ohmic plasmas exhibit rotation reversals; T_e/T_i and collisionality are different

(LOC plasma, SOC plasma, CECE position)

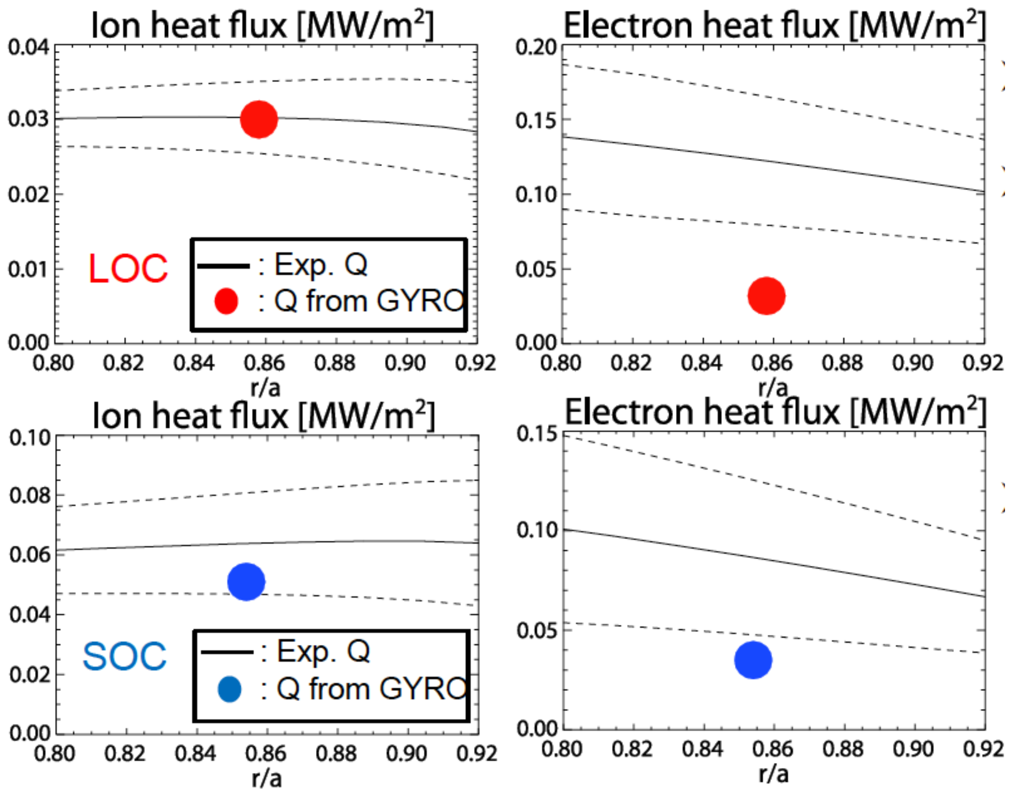


(Sung, PPCF 2013; Sung POP, in progress)

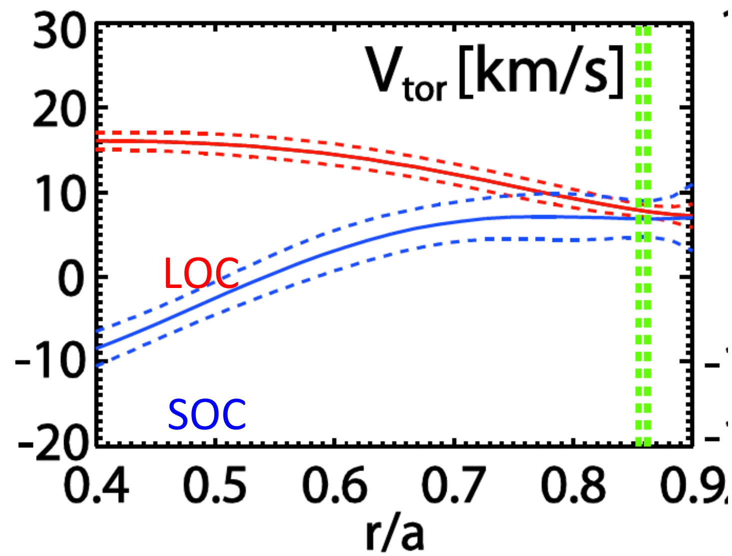


- Collisionality is different outside its uncertainty at r/a~0.85
- ν_e*=0.67 (LOC), 0.93 (SOC)

LOC / SOC Ohmic plasmas exhibit rotation reversals; GYRO can match Q_i in both plasmas; under in Q_e



(Sung, PPCF 2013; Sung POP, in progress)



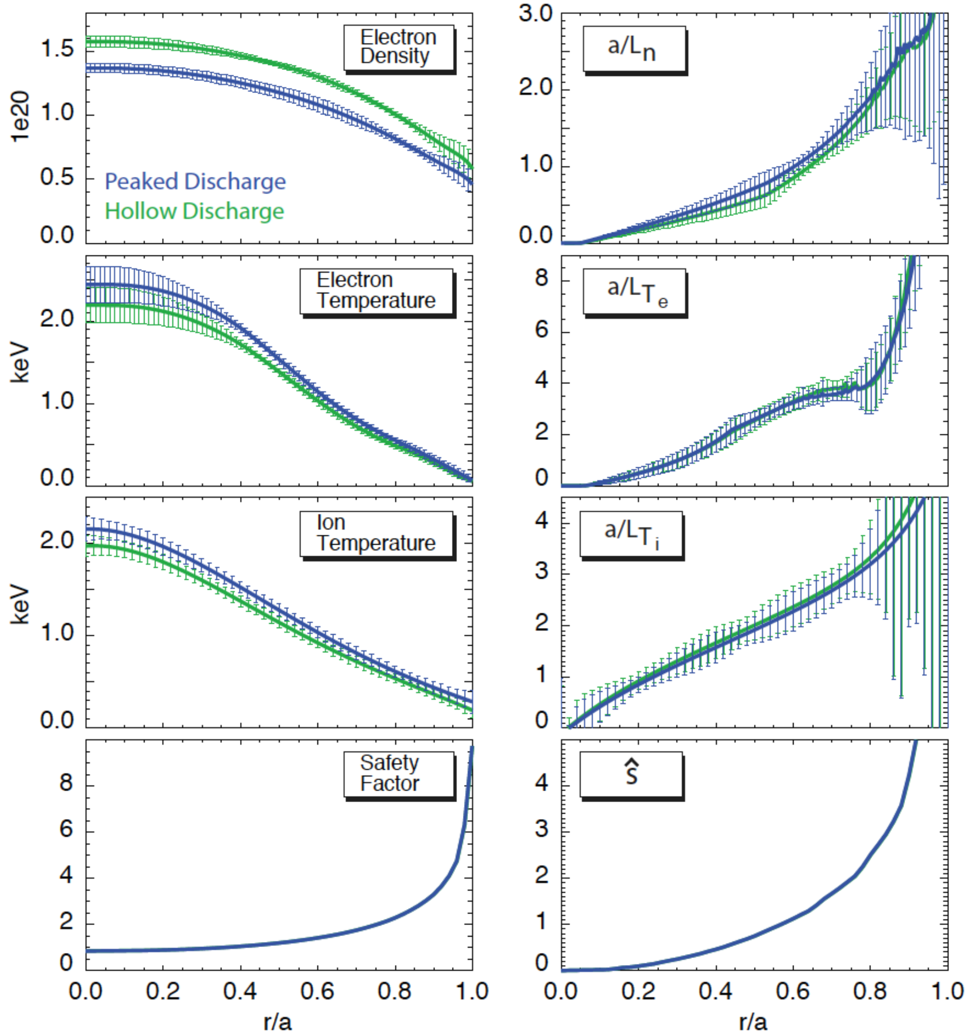
GYRO Results

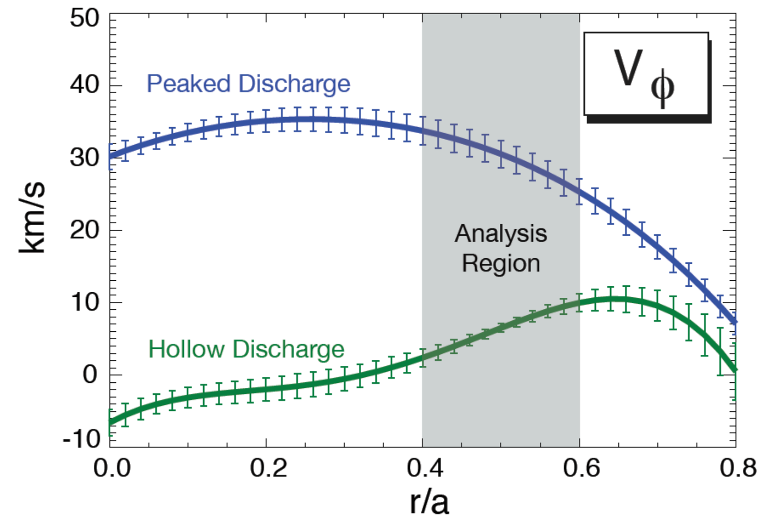
- **No linear TEM/ITG transition between LOC/SOC plasmas**
- **Simulated heat fluxes in nonlinear simulations respond to ITG drive not TEM drives in both LOC and SOC**

Alcator C-Mod

L-mode plasmas with peaked & hollow rotation profiles

Low power L-modes (1 MW ICRF) differ in $\langle n_e \rangle$ by 20%, But one has peaked (blue), one has hollow (green) rotation

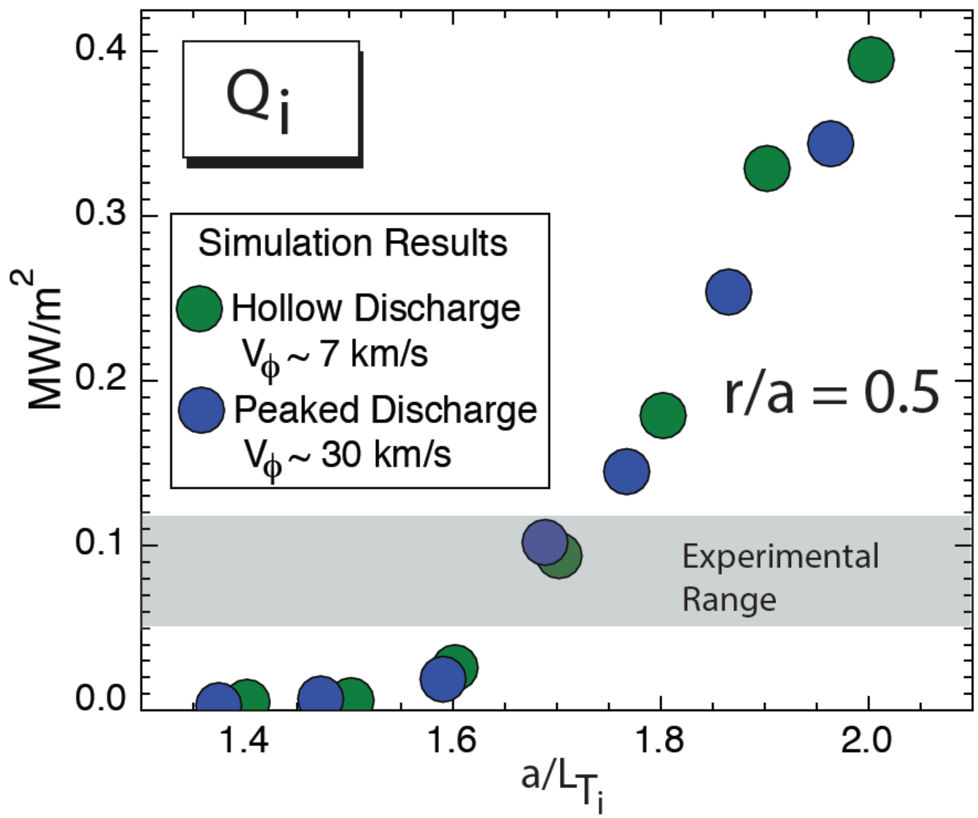


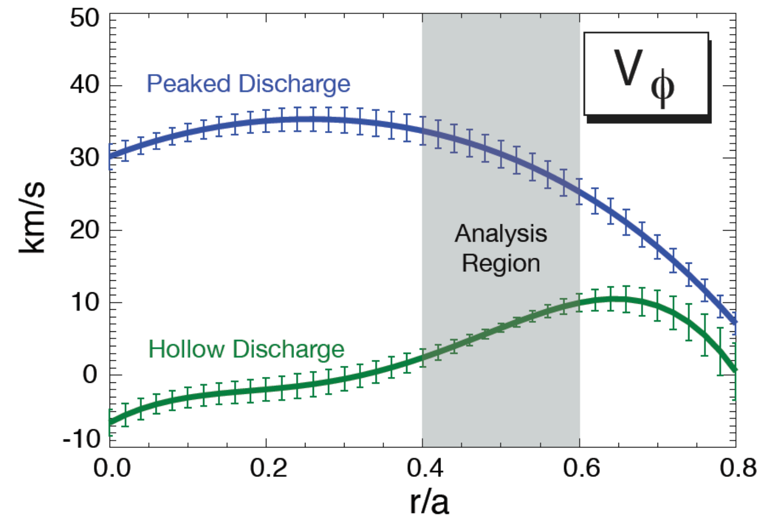


GYRO Results

- **No linear TEM/ITG transition between peaked/hollow shots**

Nonlinear scans of a/L_{Ti} show no change in the ITG critical gradient between the two shots





GYRO Results

- No linear TEM/ITG transition between peaked/hollow shots
- Simulated heat fluxes in nonlinear simulations respond to ITG drive not TEM drives in both shots
- No change in ITG Nonlinear critical gradient between the shots

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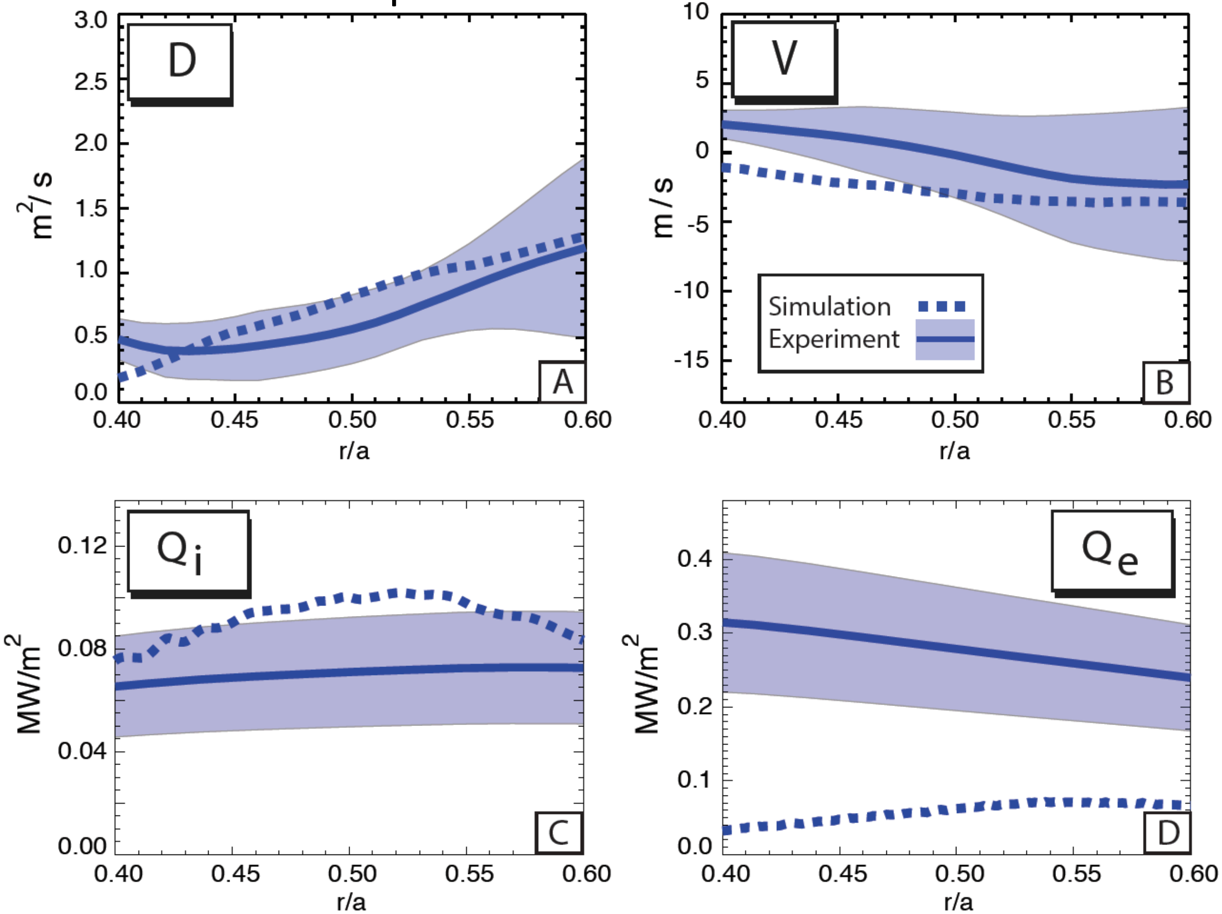
In low power L-modes, "standard" low-k GYRO simulations can match Q_i and impurity particle flux regardless of rotation profile

Peaked rotation profile shot



- **Low-k, $k_\theta \rho_s$ <1.3, nonlinear GYRO simulations match Ca impurity particle transport (D&V) and Q_i, but miss Q_e**

A. White POP 2013, Howard PPCF submitted

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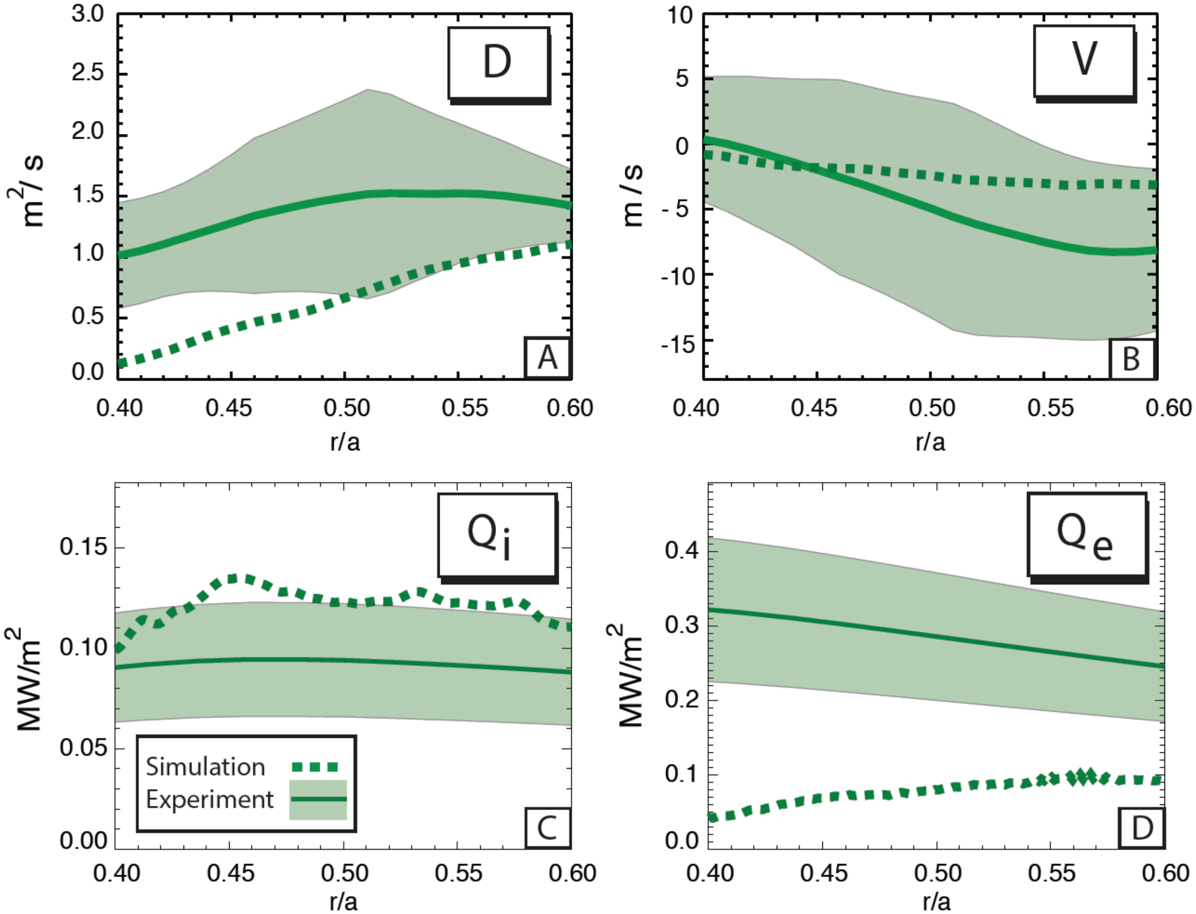
In low power L-modes, "standard" low-k GYRO simulations can match Q_i and impurity particle flux. Q_e is underpredicted

Hollow rotation profile shot



- **Low-k, $k_\theta\rho_s$ <1.3, nonlinear GYRO simulations underpredict electron heat transport**
- **Problem with Q_e under-prediction happens in both the peaked and hollow rotation shots**
- **But Q_e underprediction is not universal in C-Mod L-mode plasmas**

A. White POP 2013, Howard PPCF submitted

In contrast to the low power L-mode (blue), standard low-k GYRO simulations match Q_e in high power shot (red)

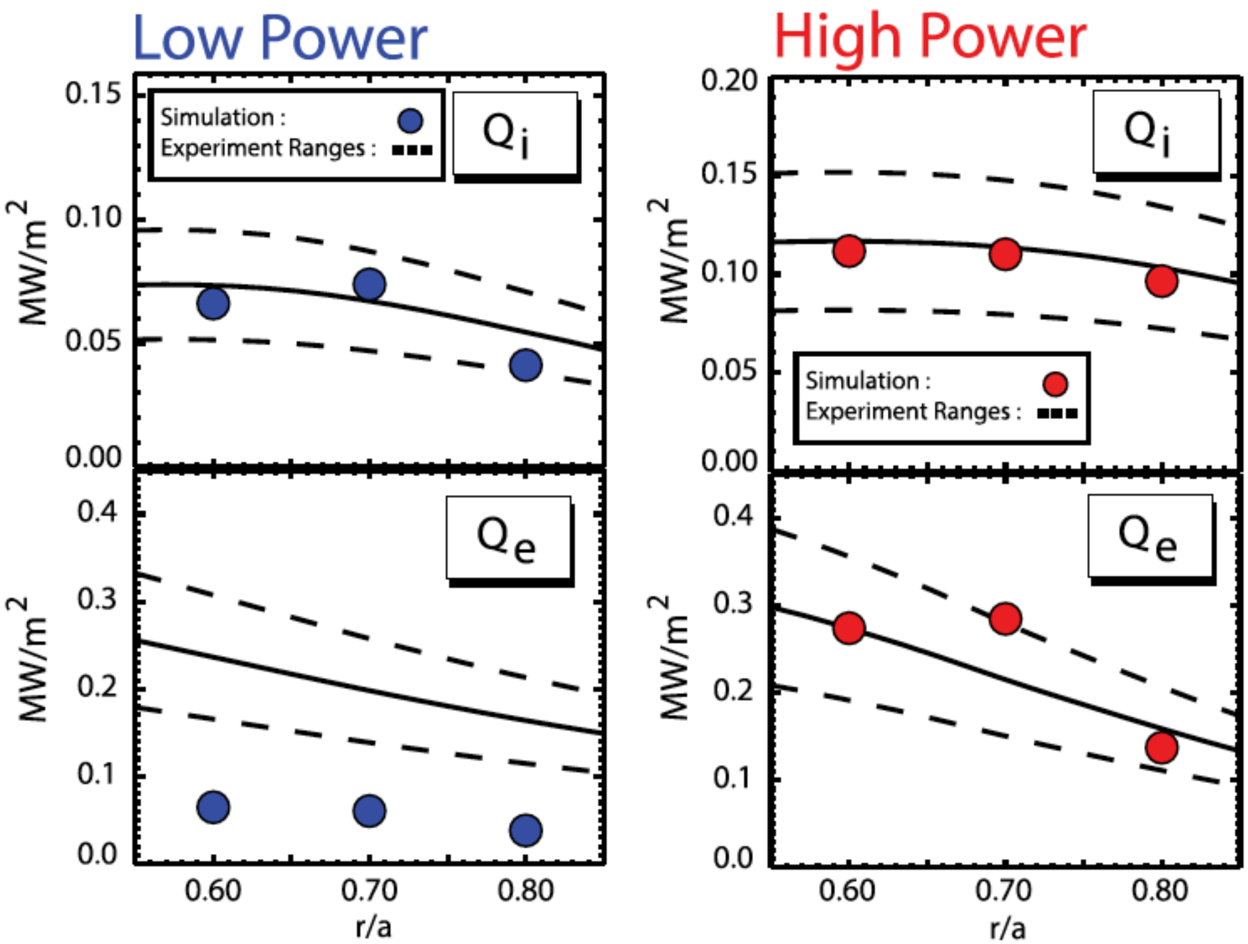


Figure from Nathan Howard, POP, 2013

- Low-k, ES nonlinear simulations used for both shots
- In low-power shot Q_e is underpredicted
- In high power shot the "standard" GYRO simulations recover Q_i *and* Q_e
- No DIII-D type shortfall

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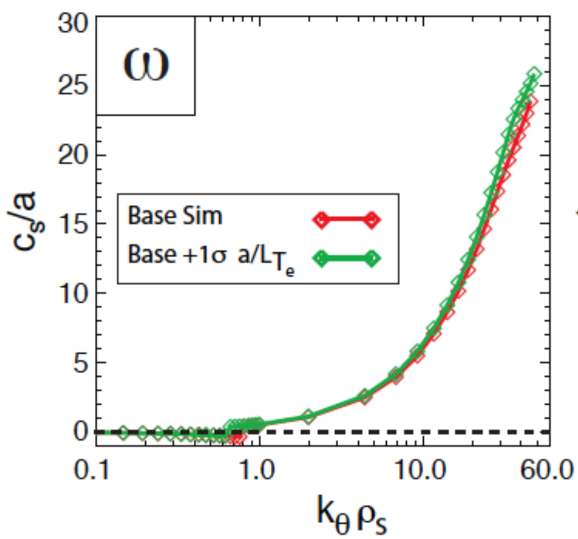
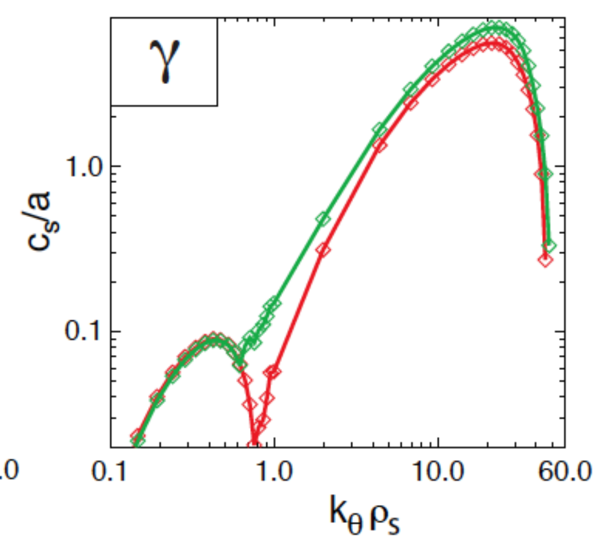
Linear stability analysis suggests that ETG is unstable at high-k in L-mode plasma where Q_e is underpredicted

Nathan Howard, submitted to PRL

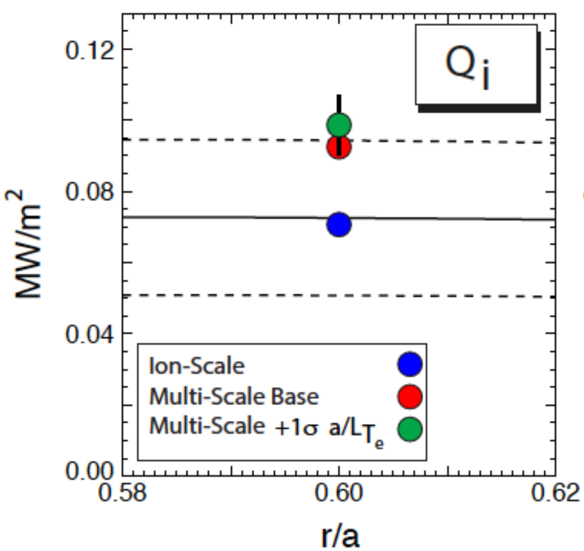


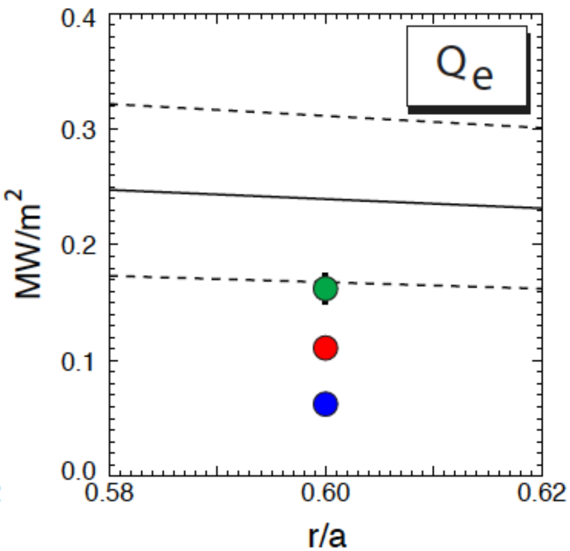


- Real frequency and growth rate for the base case L-mode simulation at r/a = 0.6
- Increase of one sigma in a/L_{Te} shown in green
- Above $k_\theta\rho_s > 0.48$ ETG growth rate reduced; mode is stable

New multi-scale simulations ($k_\theta \rho_s$< 48) using realistic mass ratio $(m_i/m_e)^{1/2}$ = 60 can recover the experimental Q_e

Nathan Howard, submitted to PRL





Heat Flux (MW/m²)	Ion-Scale	Multi-Scale	Change
Q_i (all $k_\theta \rho_s$)	0.071	0.093	+31%
Q_i ($k_\theta \rho_s < 1.0$)	0.071	0.093	+31%
Q_i ($k_\theta \rho_s > 1.0$)	n/a	0.000	n/a
Q_e (all $k_\theta \rho_s$)	0.062	0.111	+79%
Q_e ($k_\theta \rho_s < 1.0$)	0.058	0.079	+36%
Q_e ($k_\theta \rho_s > 1.0$)	n/a	0.032	n/a

- **New results from Nathan Howard (ORISE post-doc) and Chris Holland (UCSD)**
- **Realistic mass, multiscale GYRO simulations can recover the experimental levels of Q_e in C-Mod L-mode plasmas**

ORISE UCSD Alcator C-Mod

Multichannel transport studies look for correlations among heat, particle and momentum

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    - RF heated L-modes (White POP 2013)
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  - No DIII-D type transport shortfall
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- Fixing the electron heat flux underprediction at C-Mod
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  - In contrast, Q_e can be matched in high power L-modes using standard Realistic mass ($\mu = 60$), ion-scale ($k_\theta \rho_s < 1.0$) low-k GYRO simulations (Howard POP 2013)

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Future / Ongoing Work

- Provide data sets to theory and computational groups; compare peaked/hollow rotation cases to models of momentum transport
- Generate database of linear stability results for many C-Mod plasmas to better examine correlation between ITG/TEM stability and rotation reversals (Daniel Kwak, MS degree in progress)
- Compare high-Z (Ar) mid-Z (Ca) and low-Z (B) impurity transport in plasmas with peaked and hollow rotation profiles (In collab. with Matt Reinke, York)
- Use GYRO to model H-mode plasmas with rotation reversals – look for unifying explanation for Ohmic, L-mode and H-mode plasmas (and why I-mode has always peaked rotation…)
- Study non-diffusive transport observed in LOC plasmas using reduced models and gyrokinetic codes (C. Gao, J. Rice *et al*. submitted to Nucl. Fusion)

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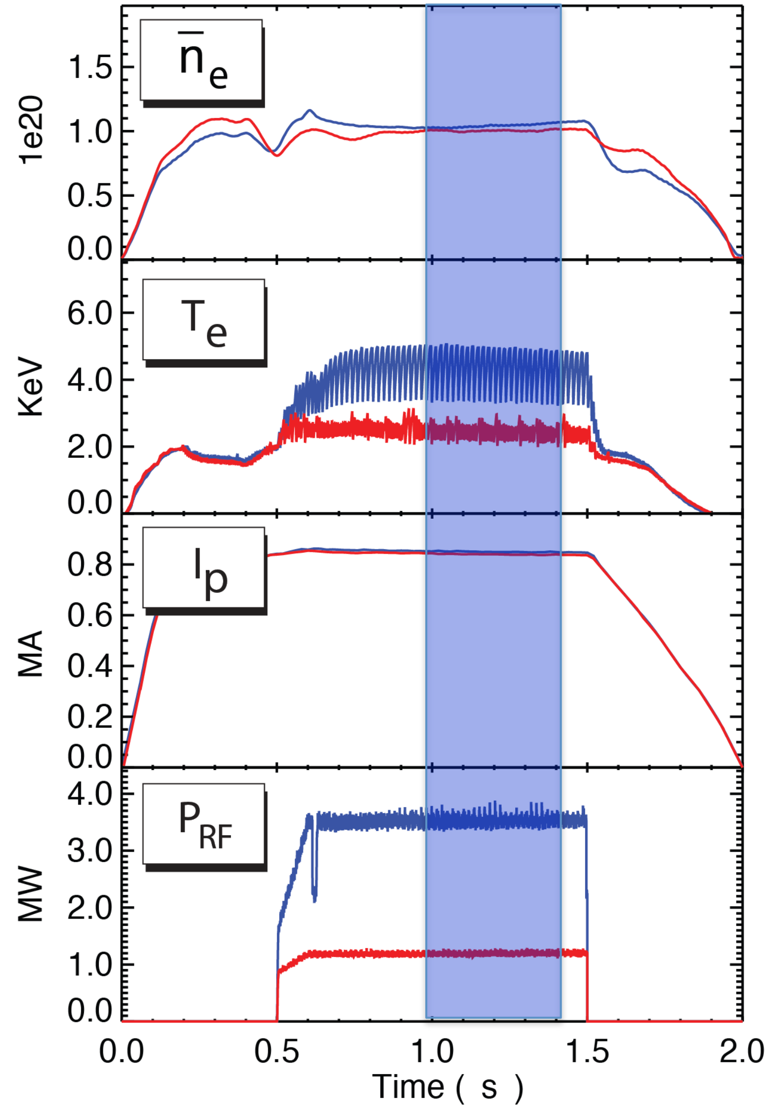
Extra Slides

Comparison of high power (P_{RF} = 3.5 MW) and low power (P_{RF} = 1 MW) L-modes with peaked rotation profiles

Two Steady L-mode Discharges Were Performed With Different Levels of Ion Cyclotron Heating

- **Probe boundary between ITG and TEM dominated plasmas with RF power scan.**
- **The discharges feature:**
  - Unfavorable ∇B drift direction
  - $n_e(0) \sim 1.5$ e20 m^{-3}
  - $T_e(0) \sim 2.5$ and 4.2 keV
  - I_p = 0.8 MA
  - P_{icrf} = 1.0 and 3.5 MW
  - B_T = 5.4 T
  - Both plasmas sawtoothing
- **Stationary plasma conditions were obtained from 1.0 to 1.4 seconds**
  - Blue shaded period was used for profile / transport analysis



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Gyrokinetic Simulations Were Performed to Understand the Turbulence and Investigate the Shortfall

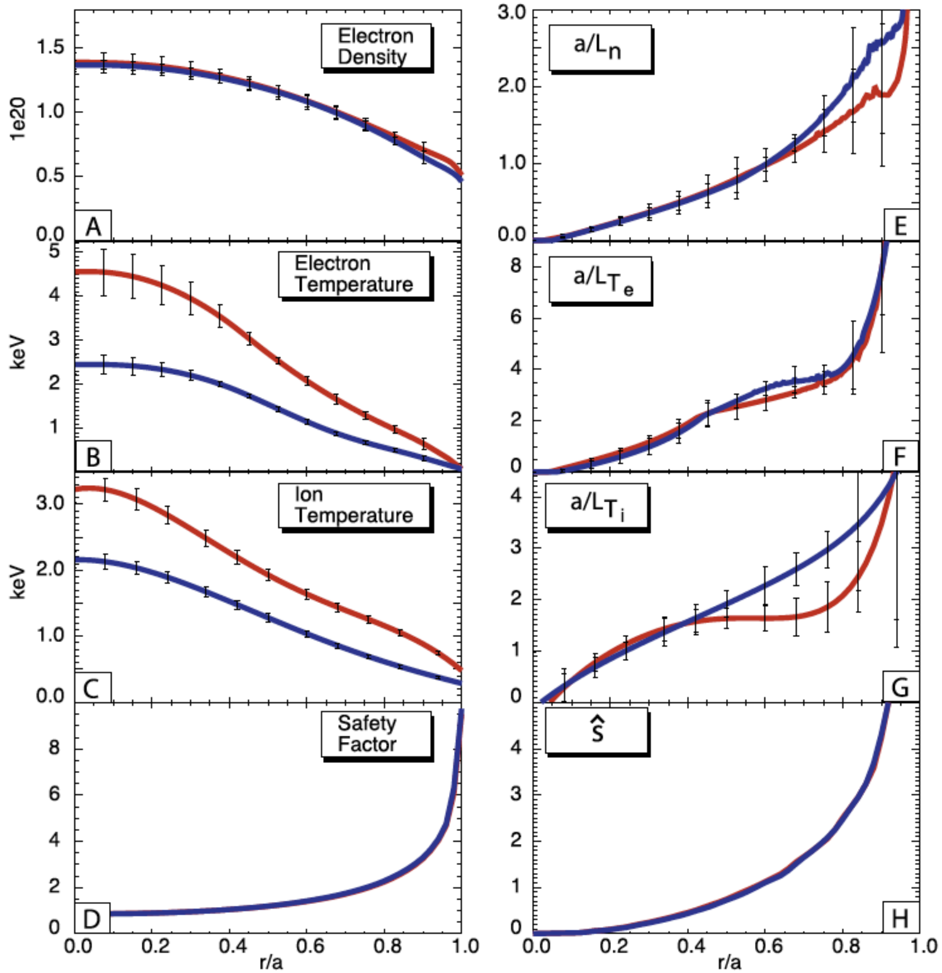

Figure from Nathan Howard, POP, 2013

- **A significant reduction in the ITG drive term, a/L_{Ti} is observed**
  - **All other drive terms ~ fixed**
- **The gyrokinetic code, GYRO was used:**
  - **Linear stability analysis**
- **Local, nonlinear gyrokinetic simulations:**
  - **Experimental profiles (n_e, T_e, T_i, V_{rot}, etc.) used as input**
  - **Electrostatic**
  - ***$k_\theta\rho_s$ up to 1.3 , ion scale***
  - ***No ETG or high-k TEM included***
  - **Kinetic electrons, with impurities, and collisions**

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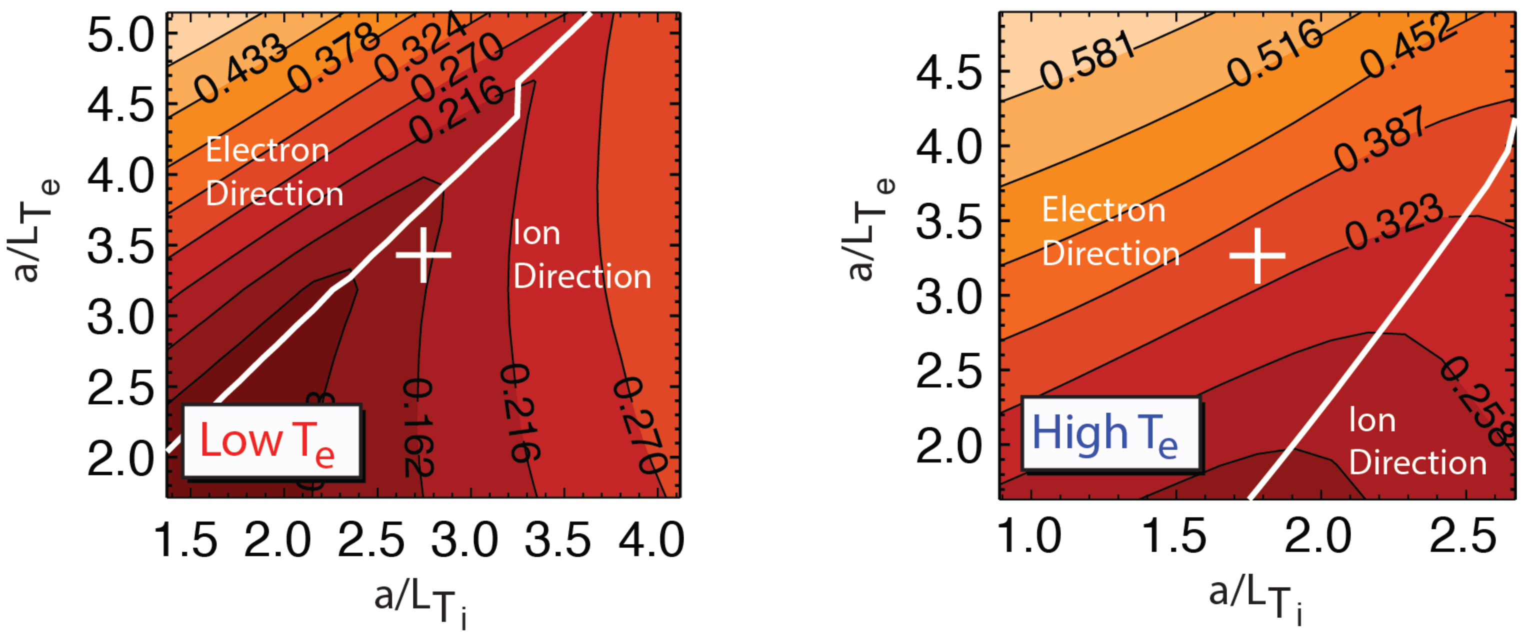
Linear Stability Analysis Suggests a Transition from ITG to TEM Turbulence Occurs Between the Low and High T_e Discharges

Most Unstable Mode (a/c_s) in $k_\theta \rho_s$ =[.25, .75] @ r/a = 0.75

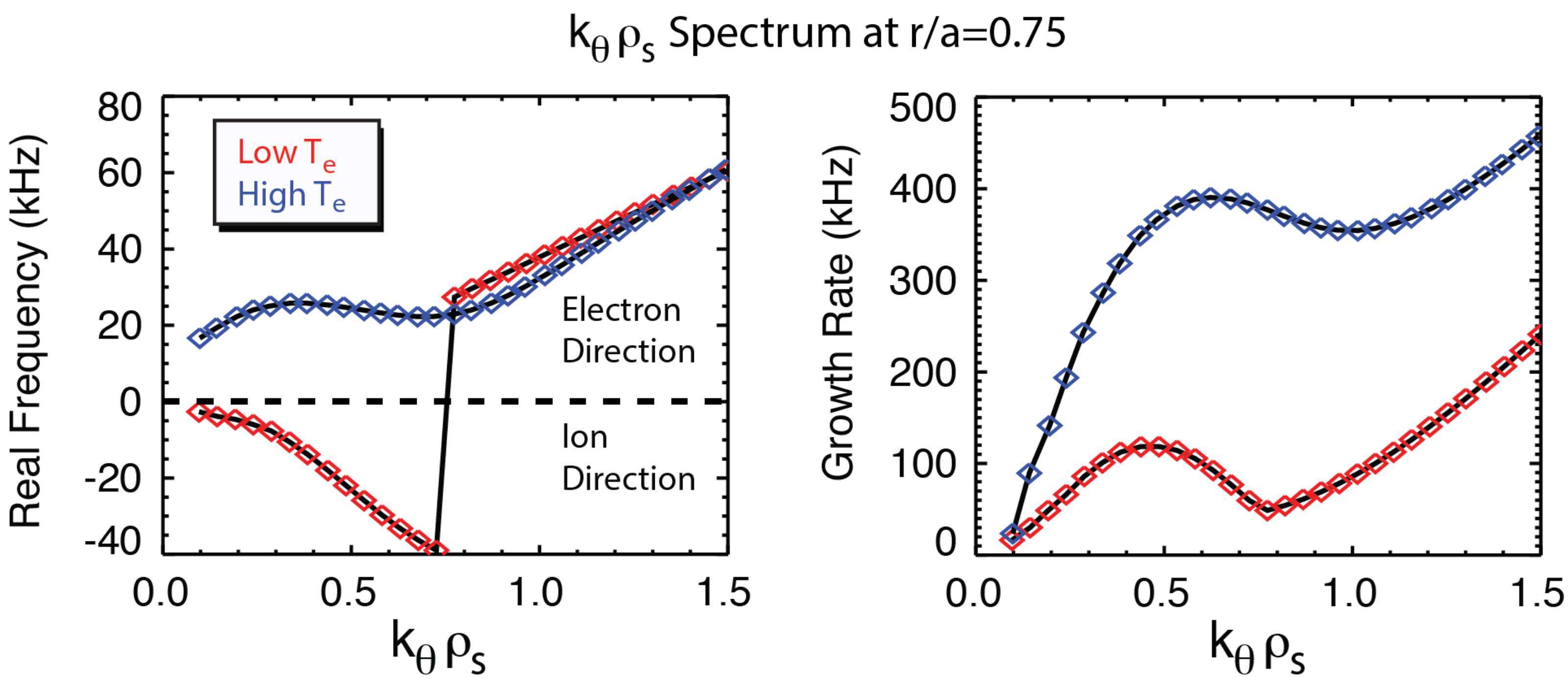


- **Linear Stability analysis indicates that:**

- **The low T_e discharge is dominated by ITG low-k turbulence.**
- **The high T_e discharge is dominated by TEM low-k turbulence.**

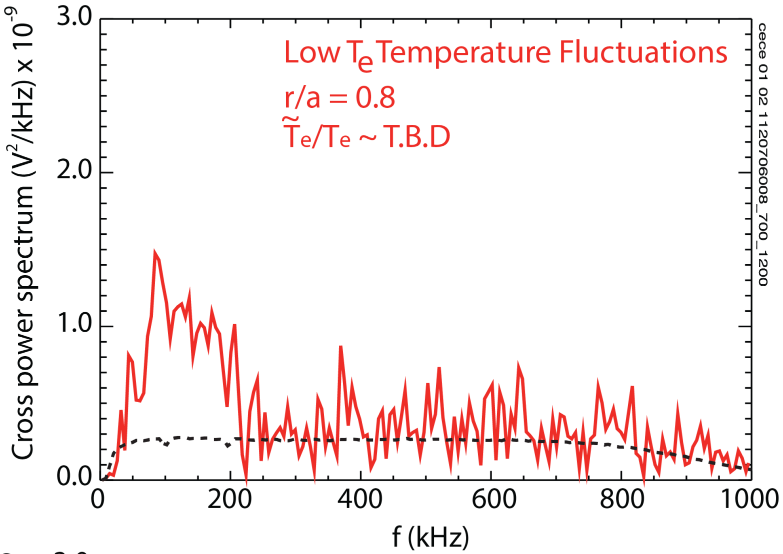
Alcator C-Mod

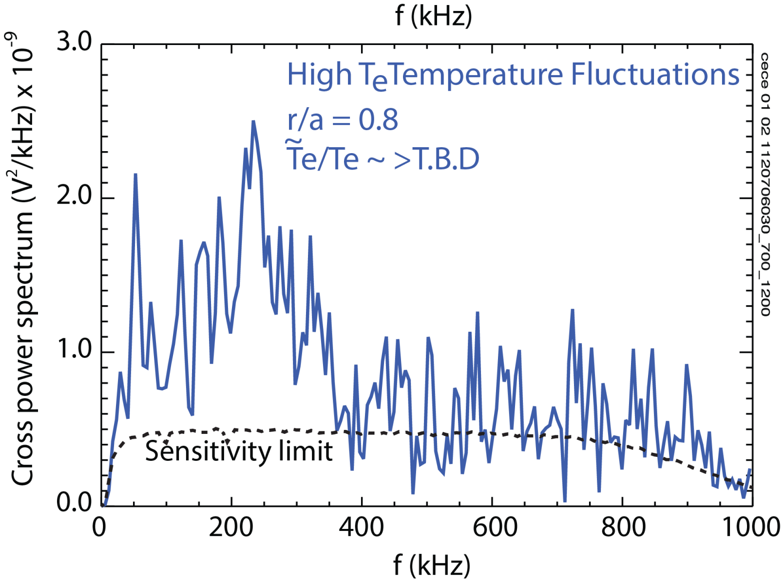
Linear Stability Analysis Suggests a Transition from ITG to TEM Turbulence Between the Low and High power Discharges



- **Linear Stability analysis indicates that:**
  - **low T_e (low power) discharge is dominated by ITG low-k turbulence.**
  - **high T_e (high power) discharge is dominated by TEM low-k turbulence.**
- **These results have been confirmed by a more rigorous linear analysis.**

Increased Electron Temperature Fluctuations at High T_e Support an ITG to TEM Transition





- **Local $\tilde{T}_e/T_e$ measurements were made using the new Correlation Electron Cyclotron Emission (CECE) system.** [See C.Sung, PPCF 2013]
  - **r/a = 0.8**
  - **$k_\theta \rho_s < 0.3$**
  - **Measured in repeat discharges of the original low and high T_e plasmas**
- **The high T_e discharge displays an increase in the T_e level at r/a= 0.8**
  - **CECE is sensitive to trapped electron mode dynamics.**
  - **Consistent with a transition from ITG to TEM turbulence.**

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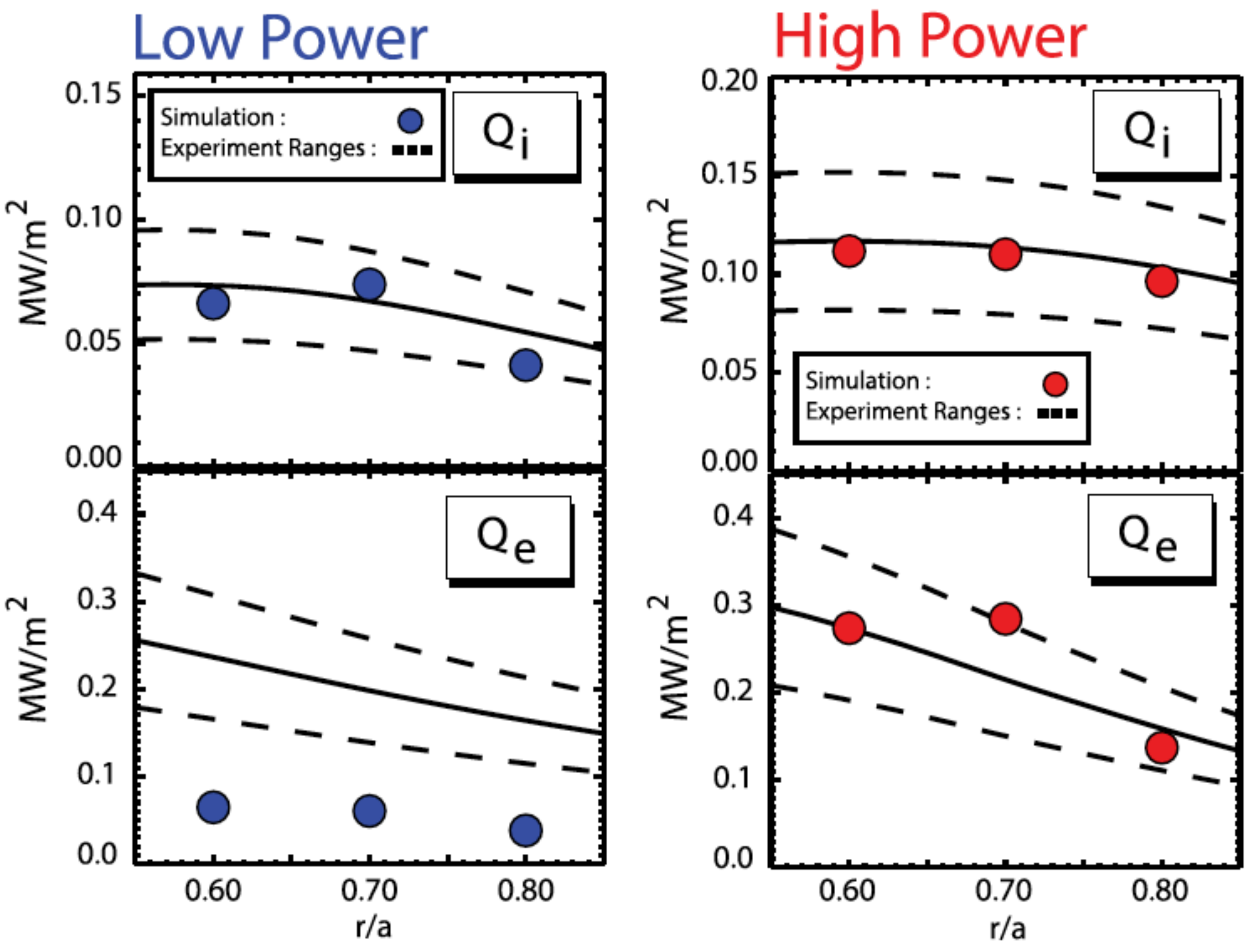
C-Mod L-mode plasmas *do not exhibit* the same transport shortfall seen at DIII-D

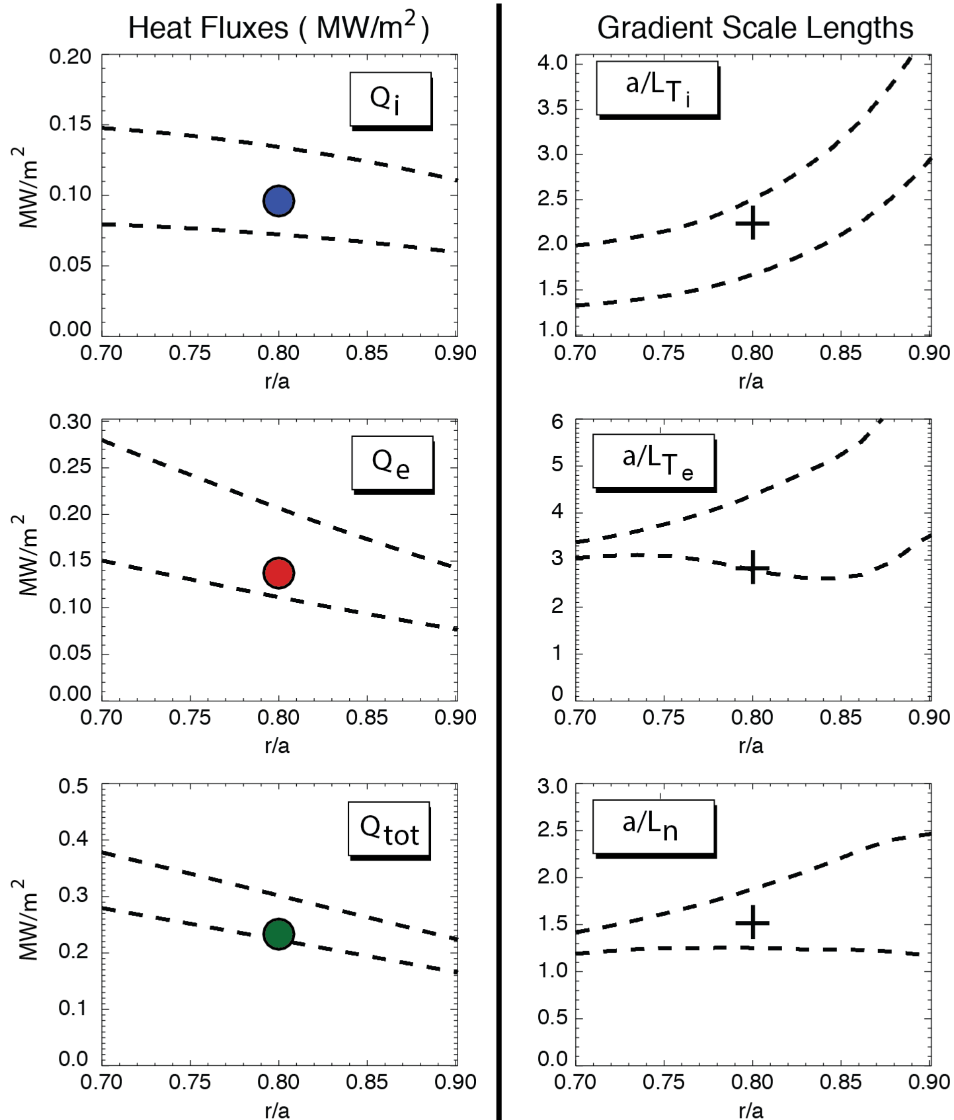


- **Low Power L-mode**
- **No shortfall in the ion channel**
- **<u>Clear shortfall</u> in the electron channel.**

- **High Power L-mode**
- **No shortfall in the ion channel**
- **<u>No shortfall</u> in the electron channel.**

Figure from Nathan Howard, POP, 2013

Nonlinear Simulations Included Modifications of Turbulence Drive and Suppression Terms Within Experimental Error



- **Local, nonlinear simulations were performed at r/a > 0.6, anticipated shortfall region**

- **Experimental uncertainty (dashed lines) was derived for: Q_i, Q_e, a/L_{Ti}, a/L_{Te}, a/L_n, and ExB shear**

- **Modification of these turbulence drive/ suppression terms (+ symbols) was allowed only within these ranges.**

- **Attempted to match experiment heat fluxes with simulations output (circles)**

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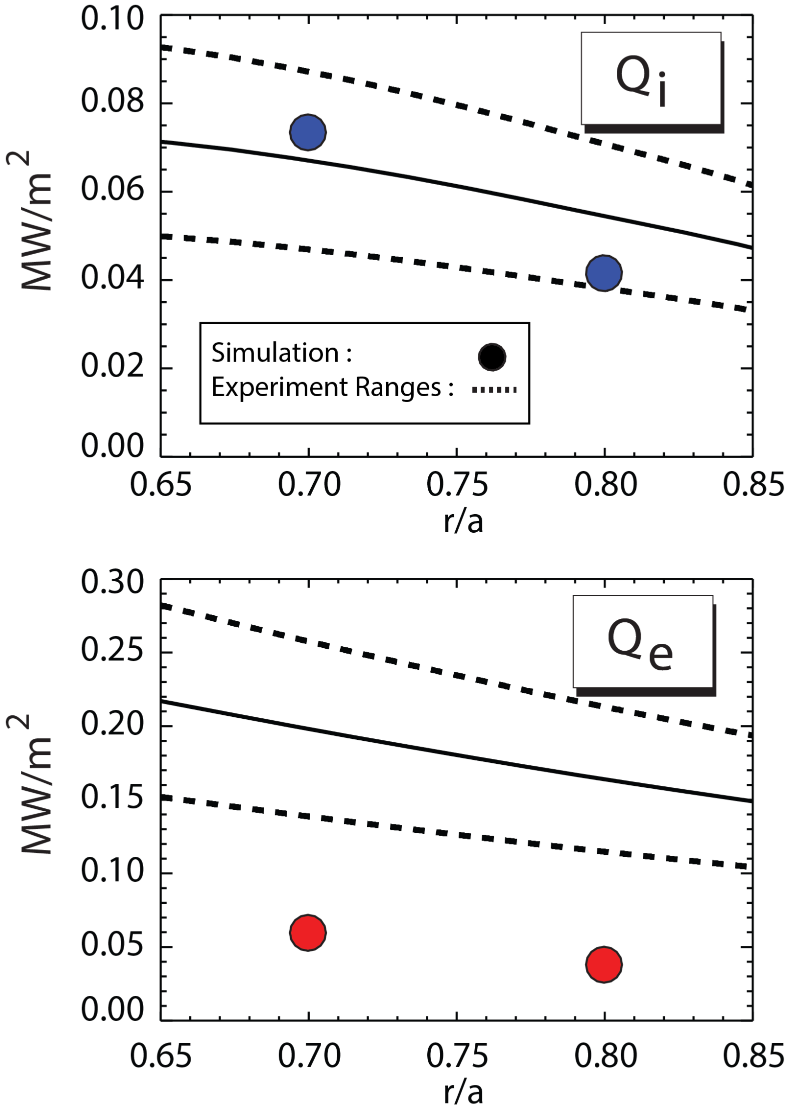
GYRO Exhibits Low Electron Heat Flux for the Low T_e Discharge

- The low T_e discharge exhibits behavior similar DIII-D in the electron channel.
  - No shortfall in the ion channel
  - Clear shortfall in the electron channel.
  - ~ 70% under prediction relative to mean Q_e
- Modifications of drive/suppression terms within experimental uncertainties are unable to resolve the electron discrepancy.



LOC/SOC plasmas

Linear and Nonlinear simulations of LOC/SOC plasmas show no evidence of TEM/ITG transition

Local Nonlinear GYRO simulations

- Electrostatic
- Ion scale ($k_\theta \rho_s$ < ~1.7)
- Kinetic electrons with e-i collisions
- Rotation / ExB effects were included
- Boron (Z=5) was used as impurity with estimated dilution (LOC : 18(±9)%, SOC : 5(±3)%)

Results

- No linear TEM/ITG transition between LOC/SOC plasmas
- Simulated heat flux (Q_i and Q_e) in Nonlinear simulations for both LOC and SOC plasmas respond to ITG drive not TEM drives
- Ion heat flux matched robustly in LOC and SOC
- Electron heat flux is robustly under-predicted in the LOC, but marginal match in SOC

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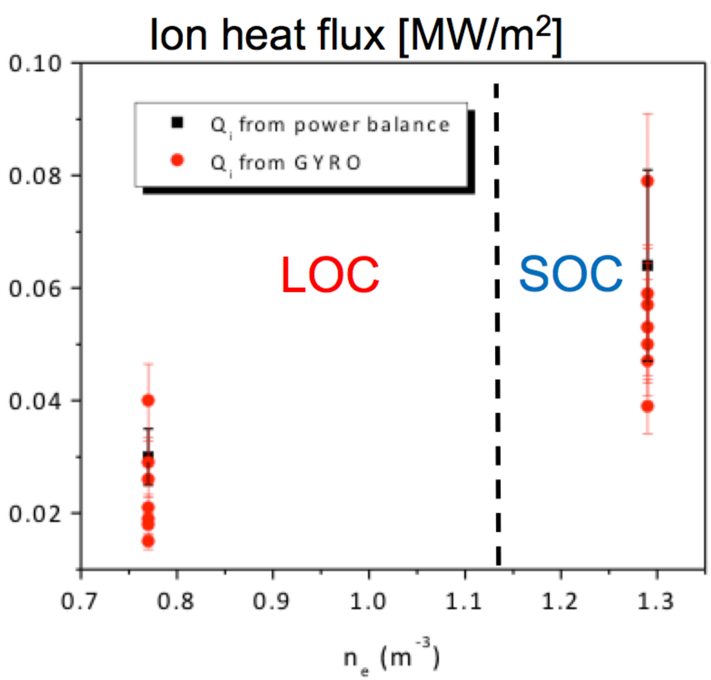
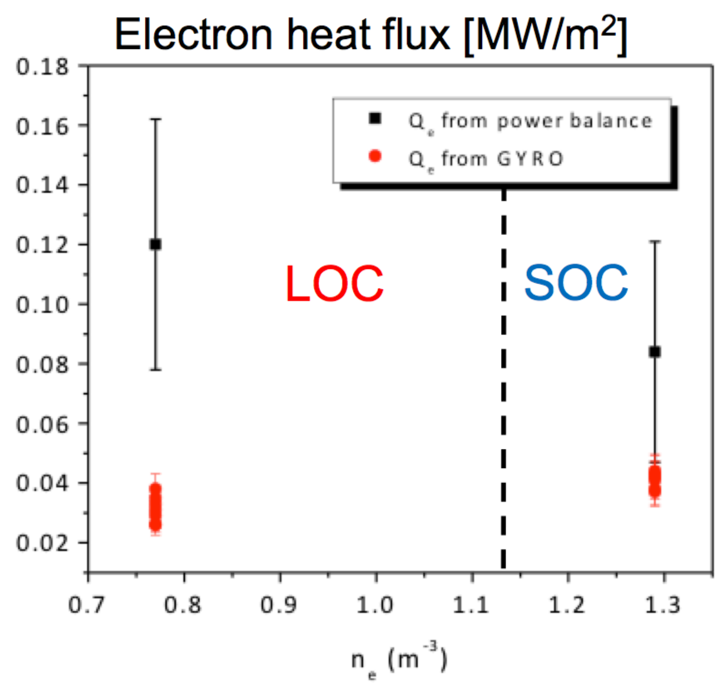
Scans in nonlinear runs of input parameters (a/Ln, a/Lti, a/Ln, dilution) show that Qi can be matched, but QE remains underpredicted



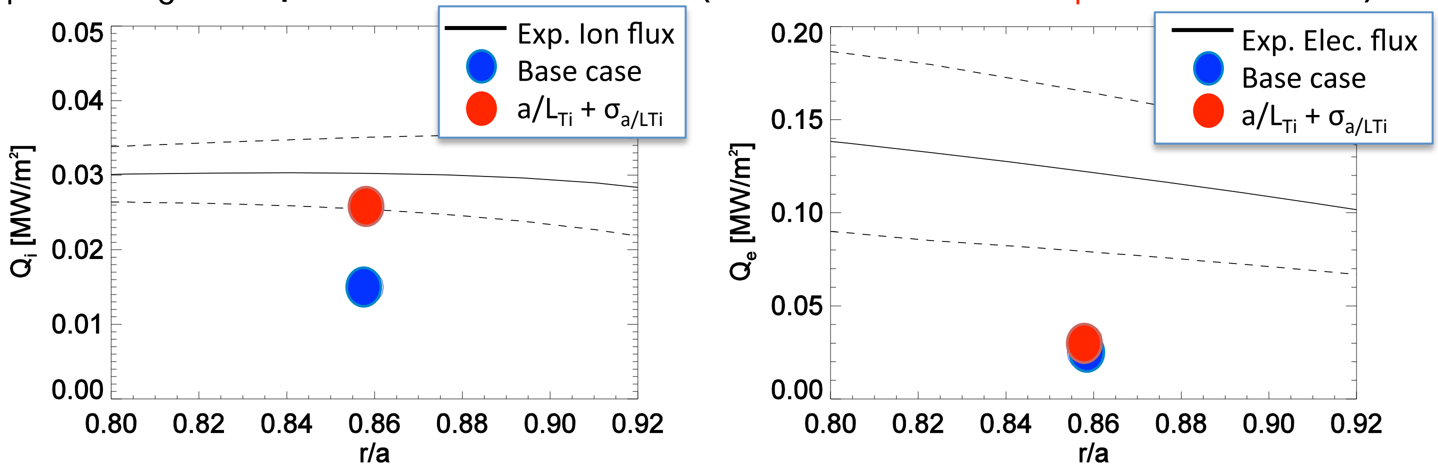


- Red points are results of GYRO runs with input parameters scanned
- ***Electron heat flux is under-predicted in the LOC, marginal match in SOC***
- Electron heat flux was **insensitive** to a/L_n and a/L_{Te} TEM drives, but Q_e did increase slightly with a/L_{Ti} ITG drive increase

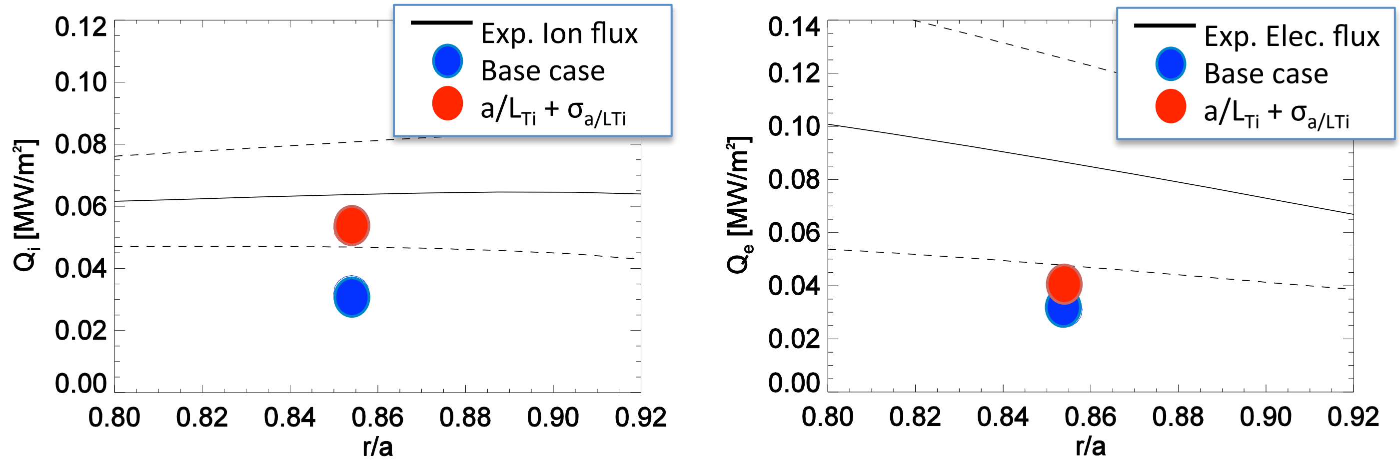
Alcator C-Mod

There is no evidence of the DIII-D type shortfall in GYRO runs for LOC/SOC plasmas (r/a ~ 0.86)

Q_i and Q_e comparison in LOC run (base case and Q_i matched run)



Q_i and Q_e comparison in SOC run (base case and Qi matched run)



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