Main-ion Thermal Transport in High Performance DIII-D Edge Transport Barriers

S. R. Haskey[1]

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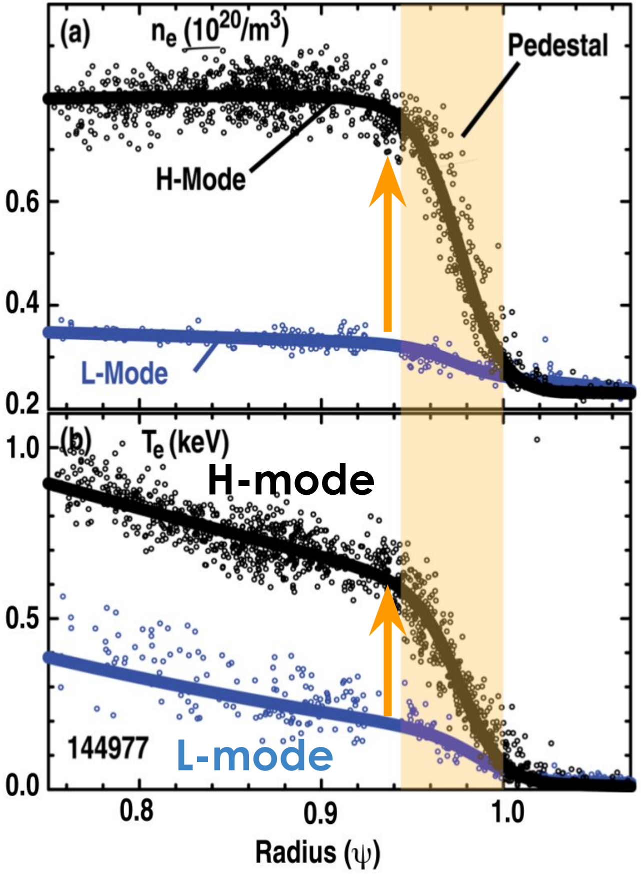
Tokamaks can Achieve High Performance Through an Edge Transport Barrier (H-mode Pedestal)

- H-mode is the typical planned operational mode of tokamaks due to the superior energy confinement
- What mechanisms are responsible for transport in the pedestal, how do they project to larger devices (i.e ITER)?
- Poster is focused on a piece of this puzzle, ion heat transport, using new direct meas of D+ properties



A. W. Leonard, *PoP*, 2014

Overview of Results

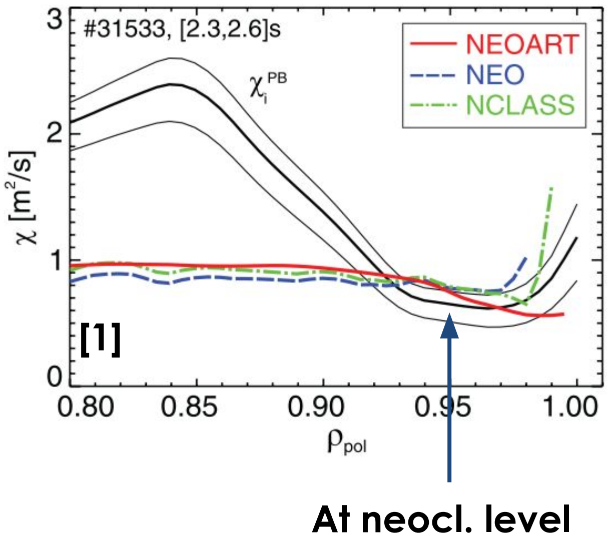
- **Direct main-ion temperature measurements resolve historical issues calculating ion heat flux (Qi) in the pedestal region on DIII-D**

- **DIII-D collisionality scan to study ion thermal transport vs ν^***
  - Scan by varying heating power and fueling
  - Doubling of Qi and increased density fluctuations in pedestal →low ν^*

- **Details of the power flow in steep gradient region captured using neoclassical (NEO) and nonlinear gyrokinetic simulations (CGYRO)**
  - Qi is carried by both collisions and electrostatic ion scale turbulence
  - Ion scale turbulence increasingly important at lower ν^*
  - Nature of turbulence changes moving to low ν^*, broader wavenumber spectrum, weaker sensitivity to ExB shear, and strong dependence on a/Ln

Previous Work Has Shown Mixed Importance of Neoclassical and Ion-Scale Driven Ion Heat Flux in the Pedestal

- **AUG: pedestal χ_i mostly neoclassical[1]**
  - Qi, Qe based on impurity ion temperatures
- **JET-ILW: Role of ion-scale turbulent transport in constraining pedestal temperature[2]**
- **DIII-D: Limited analysis due to challenges and anomalies when setting T_i=T_{C6+}**
  - χ_i<~ neocl.[3]
- **Direct meas of the D+ properties using main-ion CER (MICER)[4,5,6,7] used in this work**
  - Improved Qi, Qe from power balance



[1] E. Viezzer, *NF*, 2017
[2] D. Hatch, *NF*, 2017, 2019
[3] *J. Callen, PoP, 2010*
[4]B. A. Grierson, *RSI*, 2012
[5] B. A. Grierson, *RSI*, 2016
[6]S. R. Haskey, *RSI*, 2016
[7] S. R. Haskey, *RSI*, 2018
B. Grierson DOE ECA (https://sites.google.com/pppl.gov/briangrierson/work/eca)

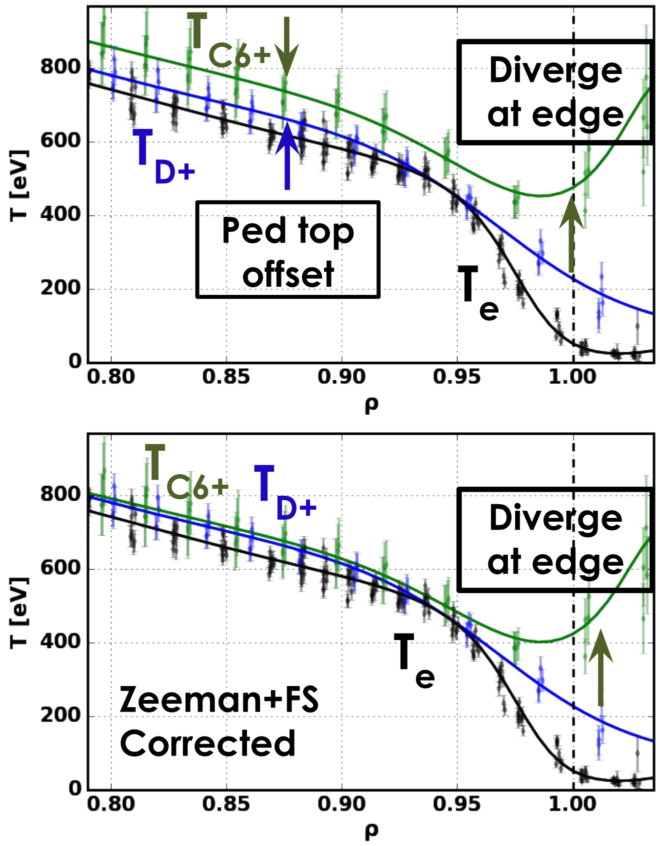
Main-Ion CER (MICER) Has Revealed Differences Between D+ and Impurity Edge Temperatures

- **Ped top offset, and divergence near separatrix[1]**
  - Unexpected, rapid species therm eq time
  - Large effects on ∇T_i and power balance Qi, Qe

- **Ped top offset largely explained by Zeeman+fine structure broadening[2] affecting T_{C6+}**

- **Divergence at edge not completely understood**
  - C^{6+} dominated by higher energy particles with wide orbits from pedestal top[3], D+ cooled by charge exchange with edge neutrals, etc…

- **Work shown in this poster, uses direct T_{D+} measurement**

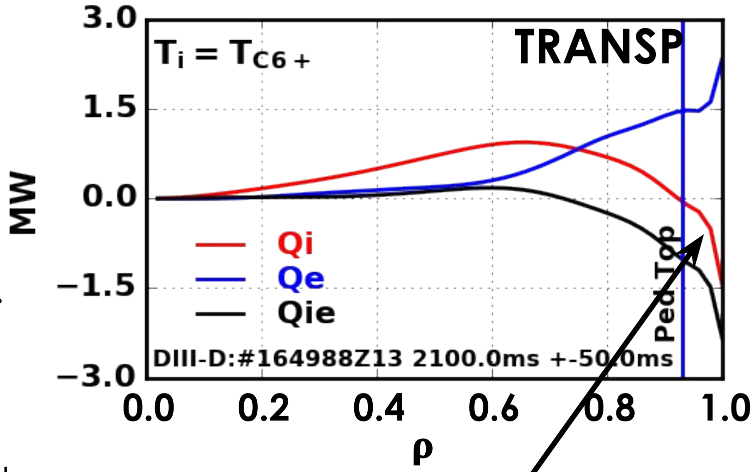


[1] S. R. Haskey, *PPCF*, 2018
[2] A. Blom, *PPCF*, 2002
[3] D. Battaglia, *PoP*, 2014

Accurate Ion Temperature Profiles Required to Infer Qi, Qe From Interpretive Power Balance Using TRANSP[1]

Calculating Qi, Qe more challenging than Q

- **Species dependent sources and sinks**
  - NBI heating (e, i), ECH (e), Ohmic (e), etc...
  - Radiation (e), charge exchange losses (i), etc...
- **Ion-electron collisional energy exchange Qie**
  - $\sim n_e n_i (\Delta T)/T_e^{3/2}$ affects both Qi and Qe
  - Term can become dominant in the pedestal, need accurate Ti, Te profiles



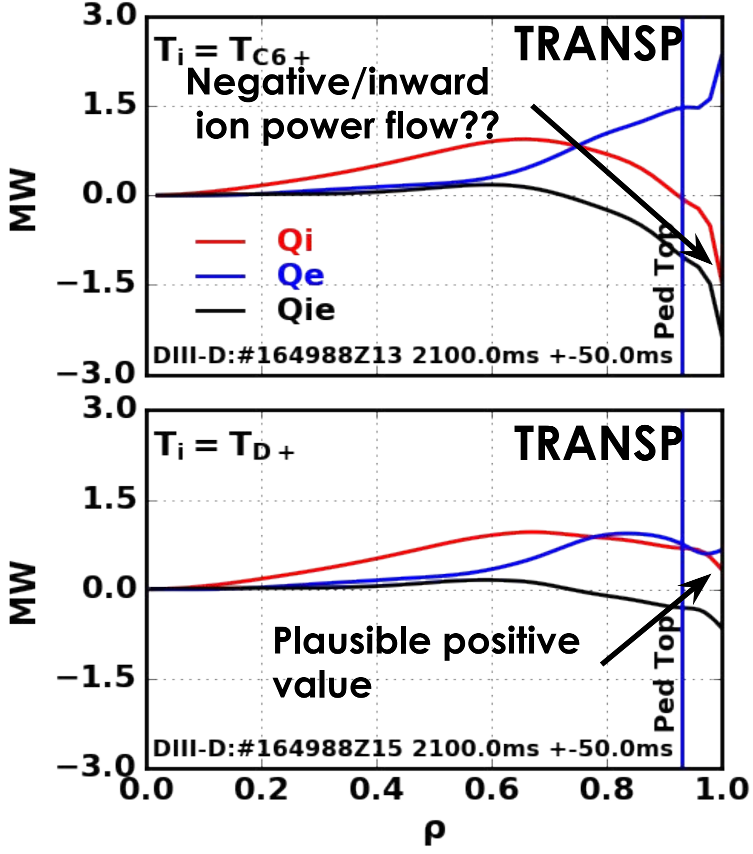
Using Ti=T_{C6+} for power balance often led to physically suspicious negative Qi in pedestal

[1] J. Breslau, *et al*, 2018

Historical Issue of Negative Ion Heat Fluxes Resolved Using MICER T_{D+} Measurements

- **Using main-ion measurements resolves negative Qi**
  - Most important for higher density, low temperature plasmas - amplifies effect of ΔT errors on Qie
- **Qi, Qe are essential in several research areas**
  - Comparison with theories of different transport mechanisms[1], Qi role in L-H[2], power flow into the SOL

S. R. Haskey, *EPS proceedings*, 2019



[1] M. Kotschenreuther, *NF*, 2019
[2] F. Ryter, *NF*, 2014

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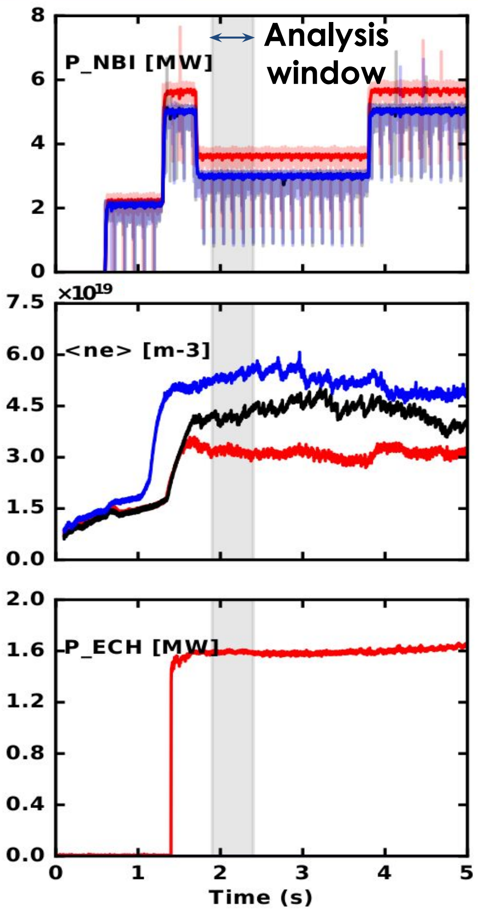
Pedestal Ion Thermal Transport vs ν^* (Approaching ITER) Assessed Using MICER Measurements on DIII-D 'Collisionality Scan' Experiment

- **ITER similar shape, Ip=1MA, Bt=-2T**

- **ν^* scan by varying input power and fueling**
  - Trade off between n and T at similar P
  - Not a dimensionless scan

- **An order of magnitude variation in ped top ν_i^*, 1.2 to 0.1 (approaching ITER)**
  - P:2.7→5MW, ν^*:1.2→ 0.1, ρ*:0.007→0.012, q95: 5.8→6, τ_e:230→150ms, H_{98y2}~1.4, Z_{eff}:1.9 → 2.4, P_e^{ped}:2.5→3.5kPa

- **Higher ν_i^* (~1.2), Medium ν_i^* (~0.4), Low ν_i^* (~0.1)**



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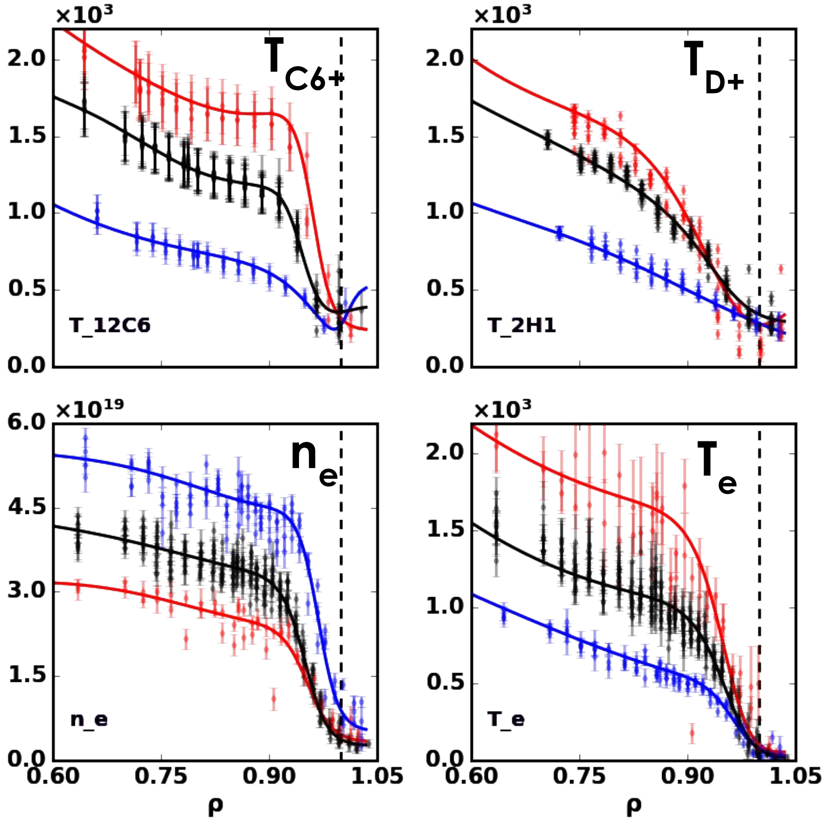
- **ELM synchronized profiles (80-95%) from 300ms time window used for power balance analysis**
  - Quasi-stationary saturated profiles just before the ELM

- **Higher ν_i^* (~1.2), Medium ν_i^* (~0.4), Low ν_i^* (~0.1)**
  - Ped top ne: 4.5→2.3e19m^{-3}
  - Ped top T: 550→1500eV

- **Analysis performed using OMFIT[1]**



[1] O. Meneghini, *NF*, 2015
https://omfit.io

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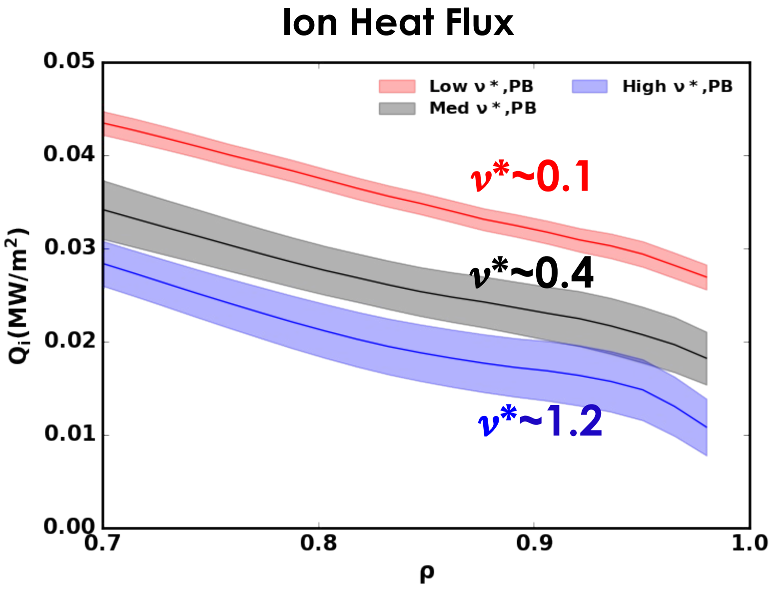
Moving to Low ν^* Pedestals Required Increased Power, Results in Doubling of Qi

- **ELM synchronized profiles (80-95%) from 300ms time window used for power balance analysis**
  - Quasi-stationary saturated profiles just before an ELM

- **Profiles used as inputs to TRANSP[1] for power balance calculations**

- **Higher input power required to get to low ν^***
  - Ion heat flux is larger for low collisionality



See K. Barada Ex/2-951, and S. Banerjee P1-939 for more details on inter-ELM behaviour

[1] J. Breslau, *et al*, 2018

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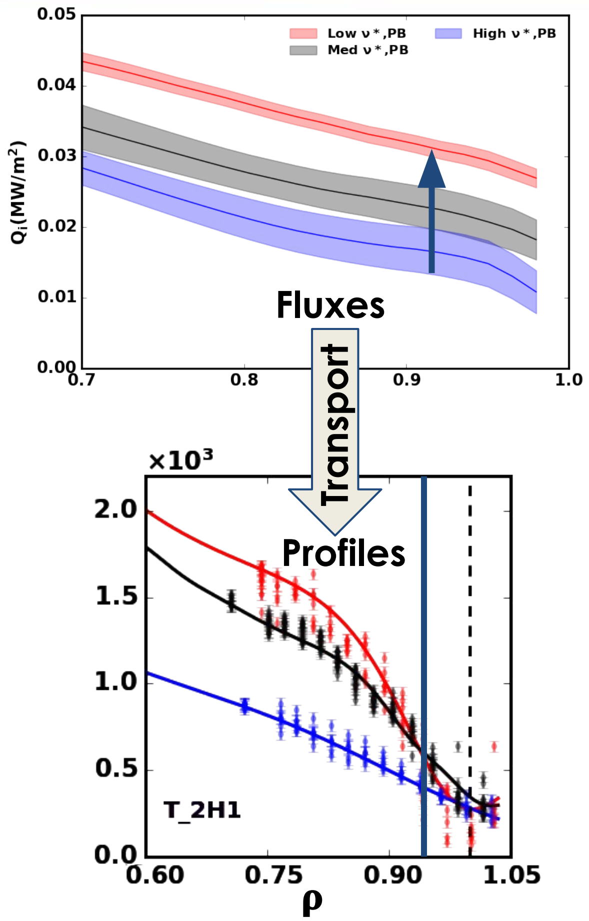
What are the Dominant Inter-ELM Transport Mechanisms, Do They Change Moving to Lower ν^*?

Interplay between fluxes (sources and sinks) and transport (NC+Turb) sets the gradients (→profiles)

1. **Neoclassical (NEO[1]): collisional transport, mainly Γ & Qi, 'irreducible' base level of transport**

2. **MHD-like turbulent transport**
   - KBM driven by and clamps ∇p, transport in all channels
   - Identified with CGYRO[2]
   - Part of EPED[3] model used to predict pressure pedestal height & width

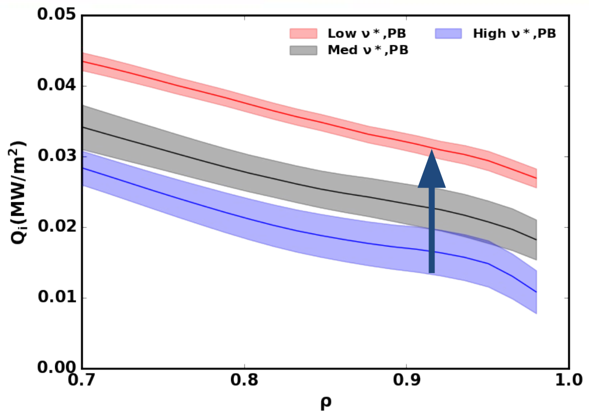
3. **Drift-wave turbulent transport (nonlinear CGYRO[2])**
   - ITG/TEM: ion scale ES, transport all channels
   - ETG: electron scale ES, mainly Qe
   - MTM: ion scale EM, mainly Qe

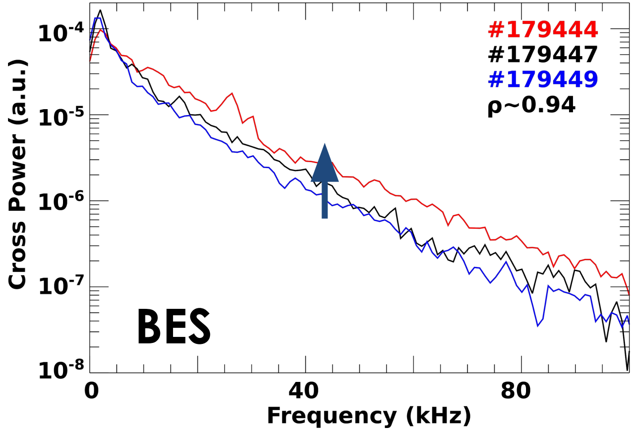


[1] E. A. Belli, *PPCF*, 2008
[2] J. Candy, *J Comp Phys*, 2016
[3] P. Snyder, PoP, 2012

BES Fluctuations Suggest Increased Importance of Transport by Ion Scale Fluctuations at low ν^*

- **Beam emission spectroscopy[1] shows increased ion scale broadband fluctuations for low ν^* case[2]**
  - Role ion scale fluctuations in the pedestal?





See K. Barada Ex/2-951 for more details on inter-ELM fluctuations

[1] Z. Yan, PoP, 2011

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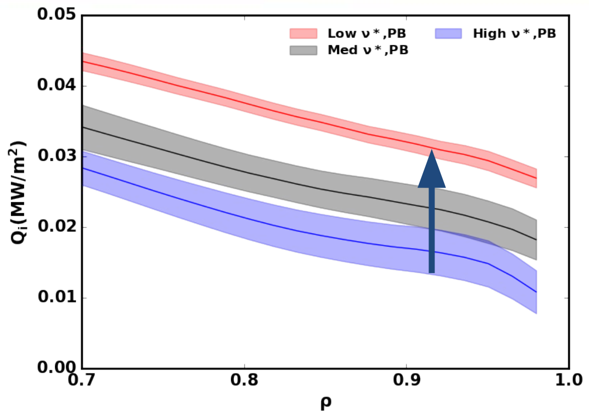
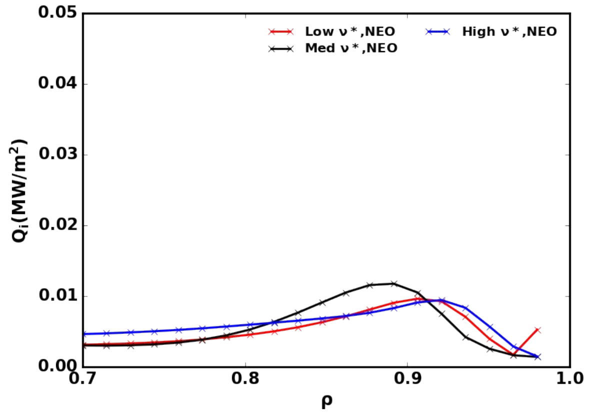
NEO[2] Simulations Show Significant Neoclassical (NC) Qi, but Similar Level Across Shots - Qi Increasingly Anomalous at Low ν^*

- **Beam emission spectroscopy[1] shows increased ion scale broadband fluctuations for low ν^* case**
  - Role ion scale fluctuations in the pedestal?
- **NC Qi similar going from high ν^* (~plateau regime) to low ν^* (banana regime)**
  - Reduction in χ_i^{NC} (plateau ⟶ banana) offset by increase in ∇Ti
- **Does not match increase seen in Expt Qi at low ν^* (banana regime)**
  - Qi transport not at the 'irreducible base level' - additional transport mechanisms at play
  - This is different from the results seen on AUG where Qi was at the neoclassical level across a range of ν^*

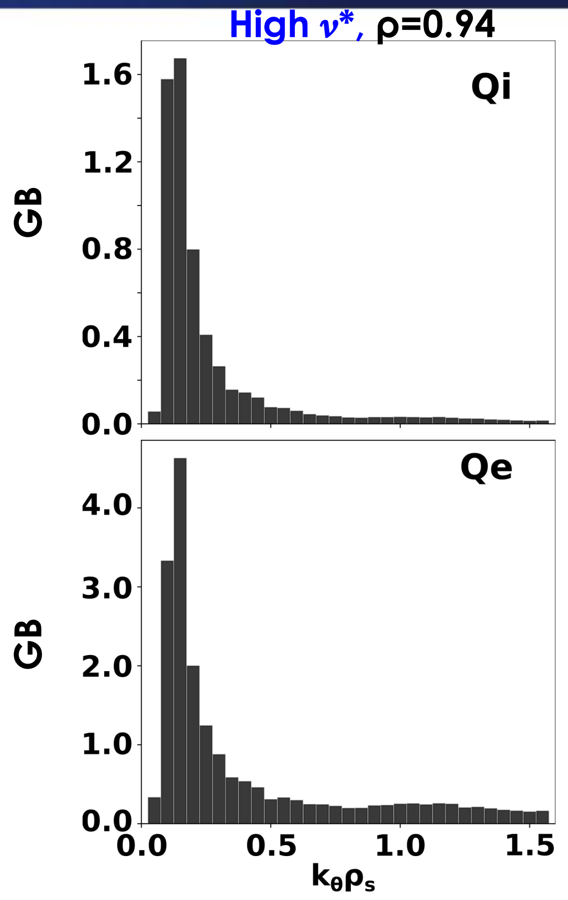




[1] Z. Yan, PoP, 2011
[2] E. A. Belli, *PPCF*, 2008

High ν^*: CGYRO[1] Simulations Show KBM Close to Threshold, Low-k Electrostatic Turbulence Fluxes Significant

- **Pedestal within βe+15 % of KBM threshold (linear CGYRO[1] scans)**
- **Nonlinear ion scale CGYRO, low k wavenumber distribution, $k_\theta \rho_s$~0.15**



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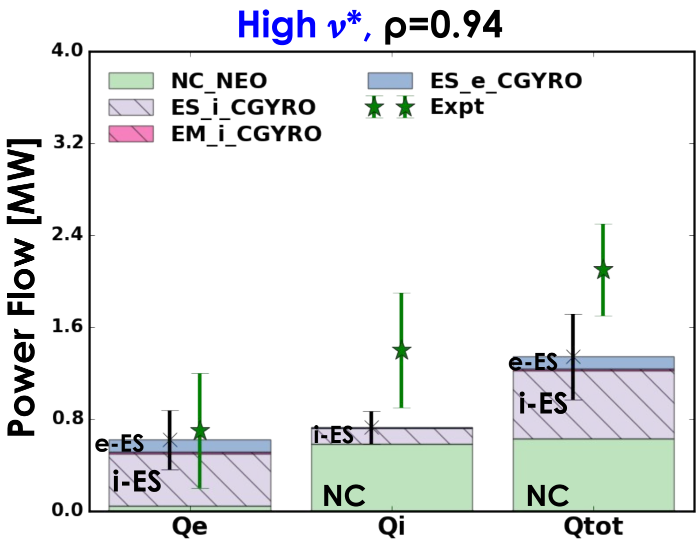
- **Qi: ~80/20 neoclassical/ion scale ES**
  - Qe is dominated by i-scale electrostatic (ES) turbulence, some e-scale
  - Minimal EM contributions
  - Additional fluxes possibly due to KBM



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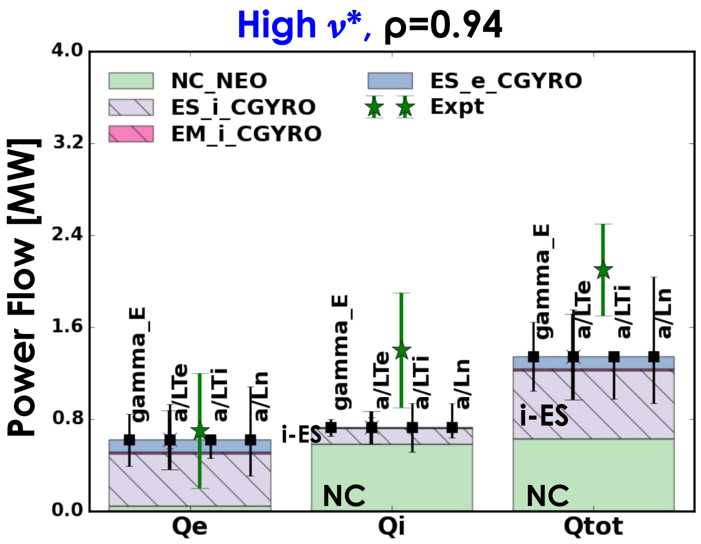
- **Dominantly sensitive to ExB shear and a/Ln**
  - ±20% sensitivity scan for NEO+i-scale CGYRO



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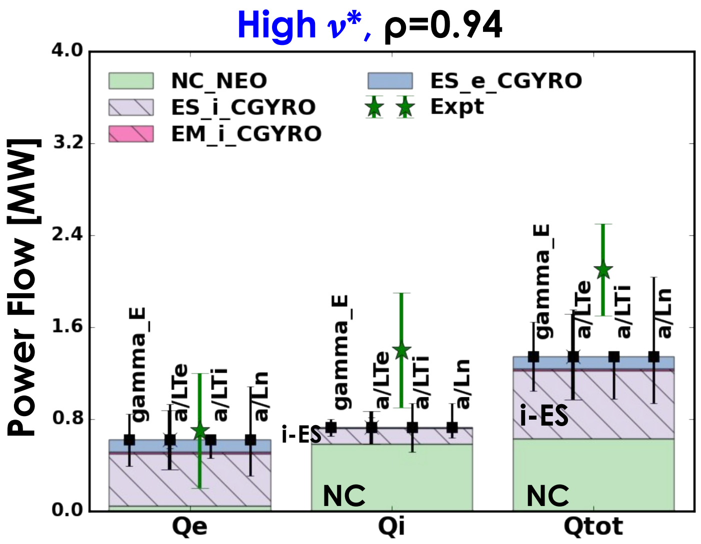
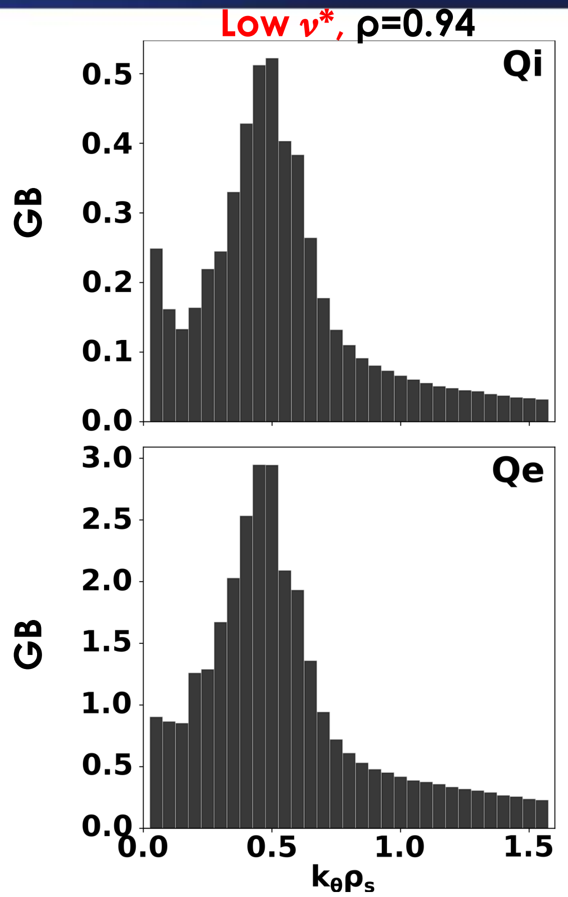


High ν^* case: Simulations suggest Qi dominated by NC with some ion scale ES contribution, and possibly KBM

[1] J. Candy, *J Comp Phys*, 2016

Low ν*: CGYRO Simulations, Broad Low-k Electrostatic Turbulence Fluxes Significant, KBM far from Threshold

- Pedestal far from KBM threshold βe+35 %, except at foot of pedestal (linear CGYRO scans)
- Nonlinear ion scale CGYRO, broad wavenumber distribution, $k_\theta \rho_s$~0.5

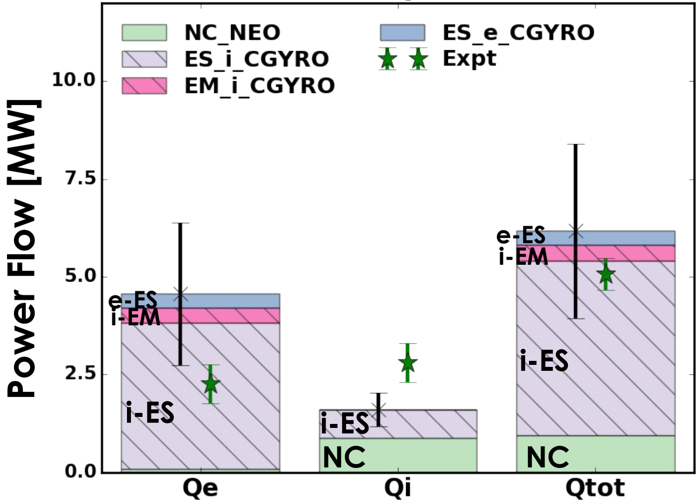


S. R. Haskey/IAEA FEC/May 2021

Low ν^*: Total Heat Flux Close to Experimental Value, Simulated Ion Heat Flux 50/50 Neoclassical, Ion Scale Electrostatic

- **Pedestal far from KBM threshold βe+35 %, except at foot of pedestal (linear CGYRO scans)**
- **Nonlinear ion scale CGYRO, broad wavenumber distribution, $k_\theta \rho_s$~0.5**
- **Total NC+turb heat flux (Qtot) close to expt Q**
  - Qe dominated by i-scale electrostatic (ES) turbulence, some EM and e-scale
  - Qi: ~50/50 neoclassical/ion scale ES

Low ν^*, ρ=0.94



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- **Dominantly sensitive to a/Ln, and weakly sensitive to ExB shear**
  - ±20% sensitivity scan for NEO+i-scale CGYRO

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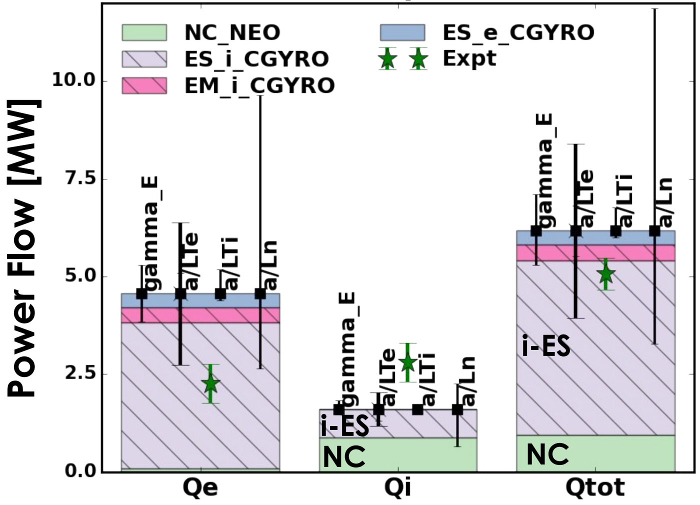

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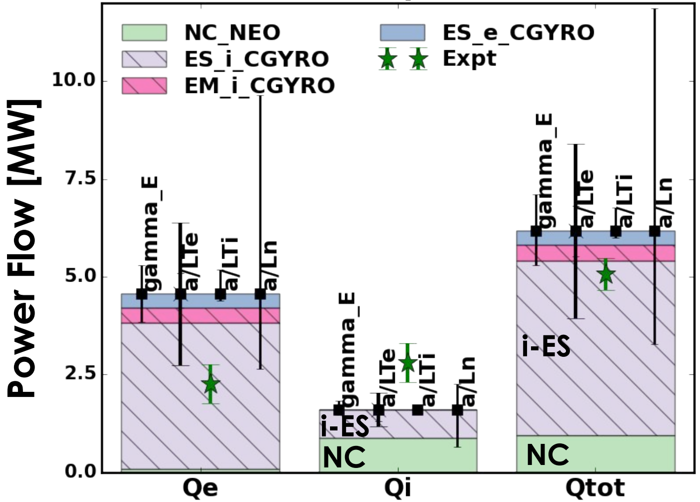

Low ν^* case: Simulations suggest Qi dominated by combination of NC and ion scale ES turb

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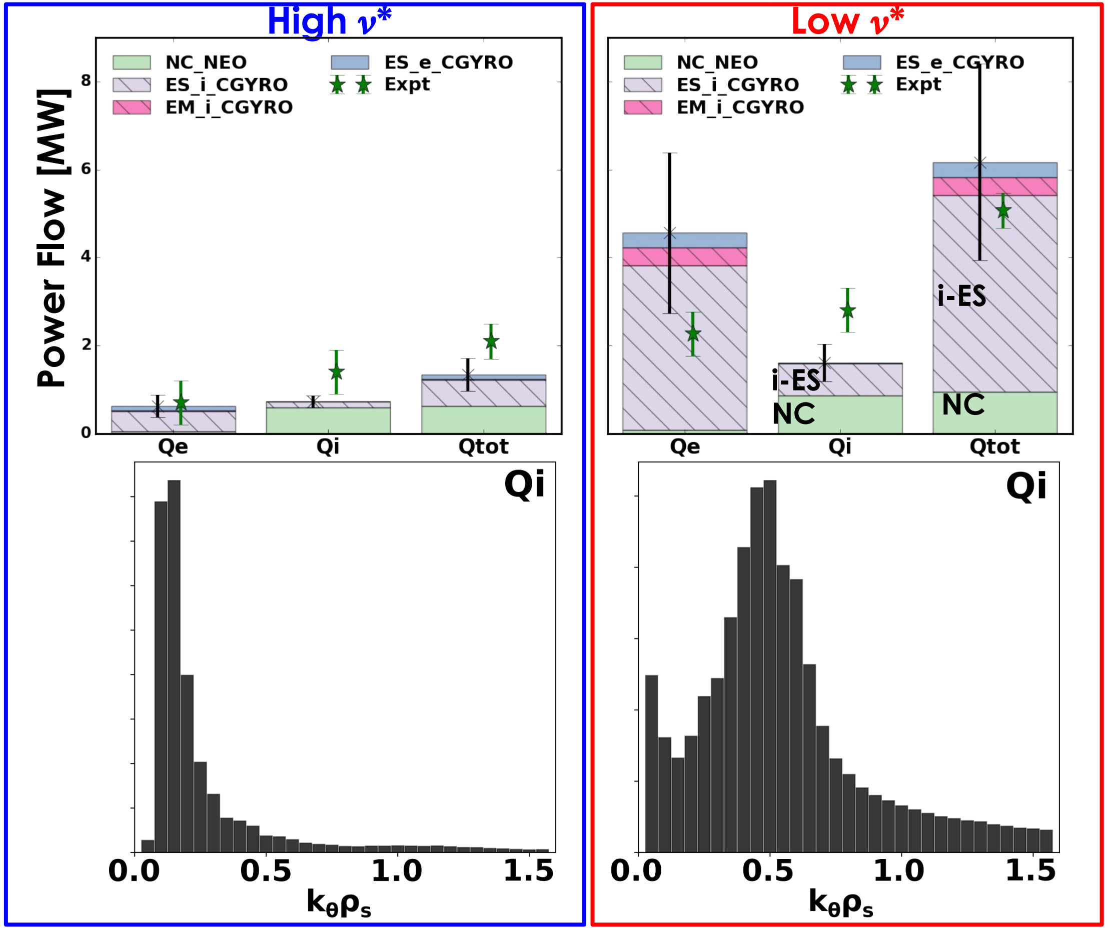
Ion Scale Electrostatic Turbulence Increasingly Important for Pedestal Ion Thermal Transport at Lower ν^*

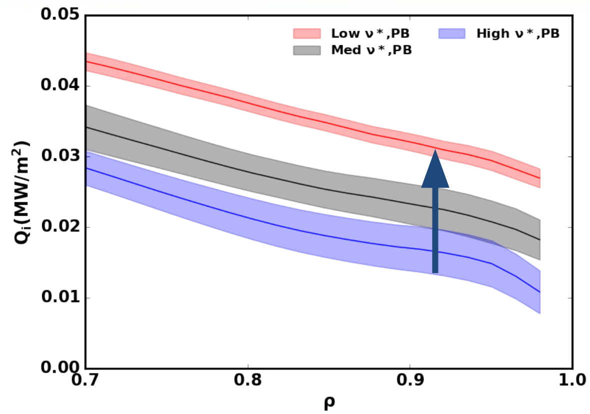
<u>ρ=0.94: steep gradient region</u>

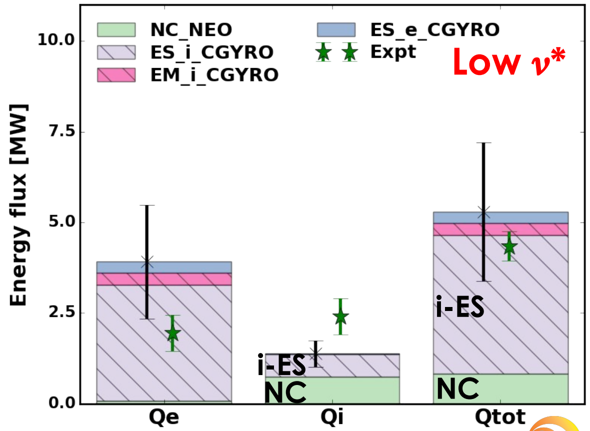
- Both neoclassical and ion scale ES transport important for Qi
- Ion scale ES turbulence increasingly important at low ν^* (Qi NC/ES 80/20 → 50/50)
- Moving to low ν^*: KBM further from instability, broader k distribution with strong sensitivity to a/Ln and weaker sensitivity to ExB shear



Summary

- **Historical issues calculating ion heat flux (Qi) in the pedestal region on DIII-D resolved using direct main-ion temperature measurements**
  - ∇T_i , Qi, Qe: stronger test of transport models
- **Higher input power required to get low ν^* on DIII-D, doubling of Qi in the pedestal, increased ion scale fluctuations (BES)**
- **Details of total power flow and importance of both neoclassical and ion scale ES turbulence captured with NEO+nonlinear CGYRO**
  - Differences in the Qi, Qe split
- **Ion scale electrostatic turbulence increasingly important at low ν^***





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