NSTX

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# Momentum Transport in Electron-Dominated Spherical Torus Plasmas


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PPPL


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# *Abstract*

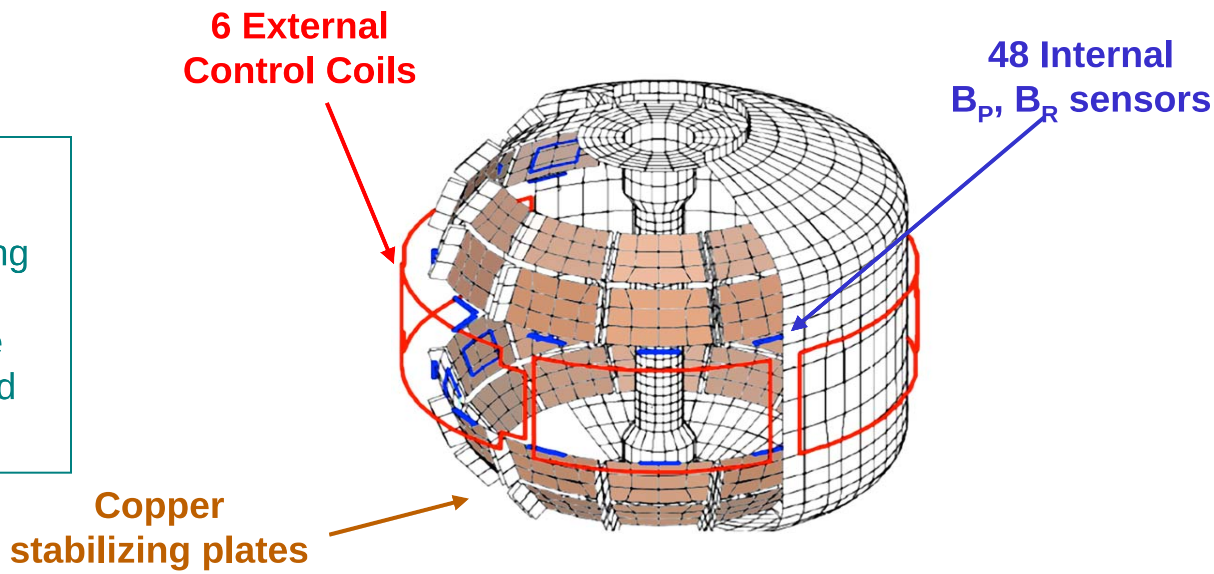

NSTX plasmas operate in an electron-dominated transport regime due to suppression of ion-scale modes by large ExB shearing rates. In this regime, the ion thermal diffusivity is neoclassical, and can be up to a factor of 30 greater than the momentum diffusivity. The momentum diffusivity, however, is much larger than the neoclassical value. Analysis of perturbative experiments that used applied n=3 magnetic fields to brake the plasma rotation indicate inward pinch velocities up to 40 m/s and perturbative momentum diffusivities larger by a factor of several than those values inferred from steady-state analysis with a zero pinch velocity assumed. The inferred pinch velocity values are consistent with values based on theories in which low-k turbulence drives the inward momentum pinch. Thus, in NSTX, the momentum transport can be a better probe of low-k turbulence, since unlike the ion energy transport, the neoclassical driven momentum transport is near zero. Understanding the source of the momentum transport, and how it scales to larger devices operating at lower collisionality, is critical to the performance of future devices

# *Outline*

- Motivation and special features of NSTX plasmas that test theory
  - Is there any difference in momentum transport between electron- and ion-dominated regimes?
- Steady-state momentum transport studies ($v_{pinch}$ assumed to be 0)
  - Momentum transport anomalous even when ion heat transport      neoclassical
- Perturbative momentum transport studies
  - $v_{pinch}$ significant and consistent with predictions from theories based on low-k turbulence

External control coils used to actively compensate error fields, resistive wall modes (RWM) and for ELM pacing

Applied n=3 fields used to change the plasma rotation (both steady-state and transiently)

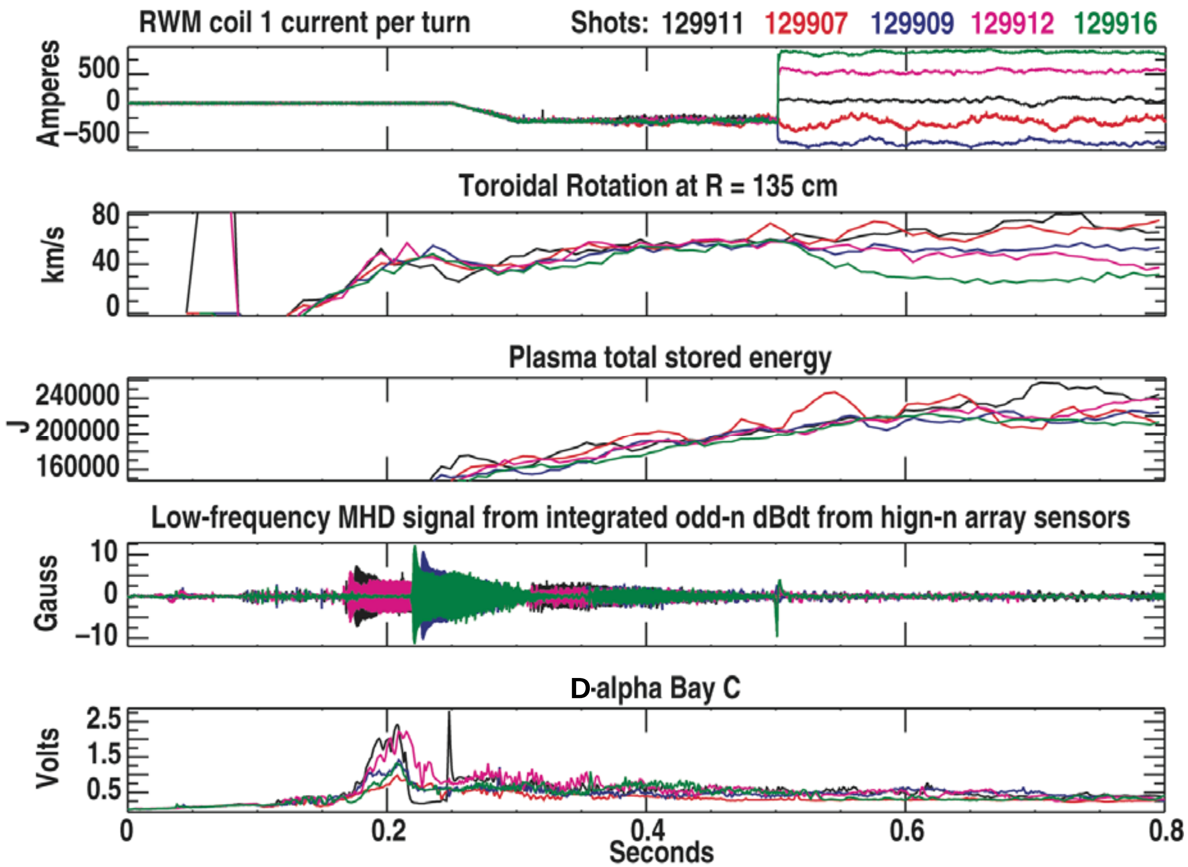


# ***NSTX Typically Operates in an Electron-Dominated Regime***

- High rotation (M ~ 0.5) and rotational shear observed in NSTX
  - ExB shear values of up to 1 MHz can exceed ITG/TEM growth rates by a factor of 5 to 10
    - Reduction of low-k turbulence
  - **Ion energy transport in H-modes typically neoclassical**
    - ***Transport losses dominated by electrons***
- External control coils (ECC) provide a tool to study the effect of rotation and rotation shear on transport

# *Rotational Equilibria Were Established at Various Levels of n=3 Braking Fields*

- 15 mg/min Li, n=1 active mode control
- Low-levels of low-n MHD activity
- Little effect of rotation seen on global confinement

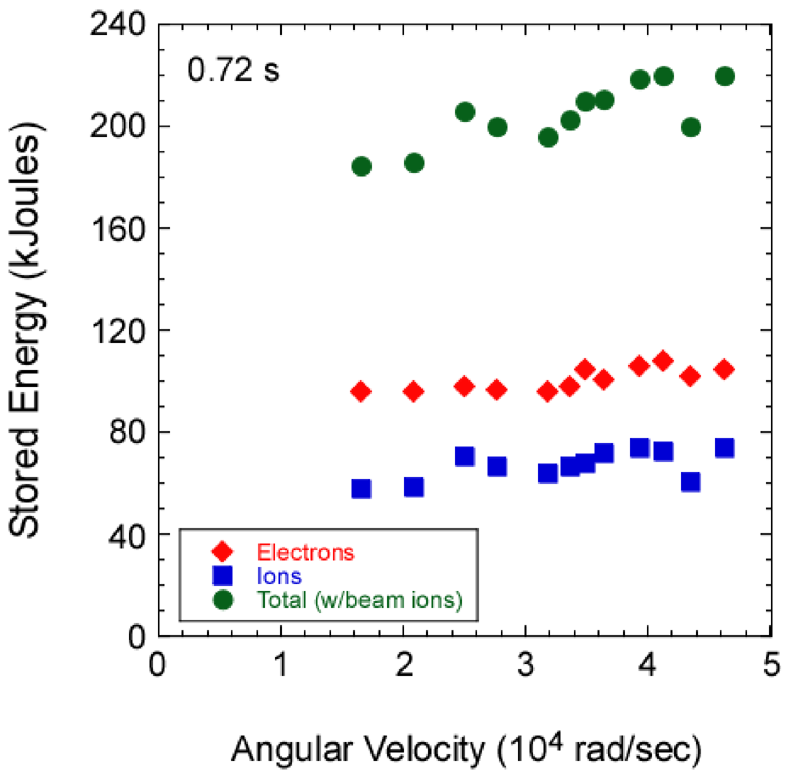


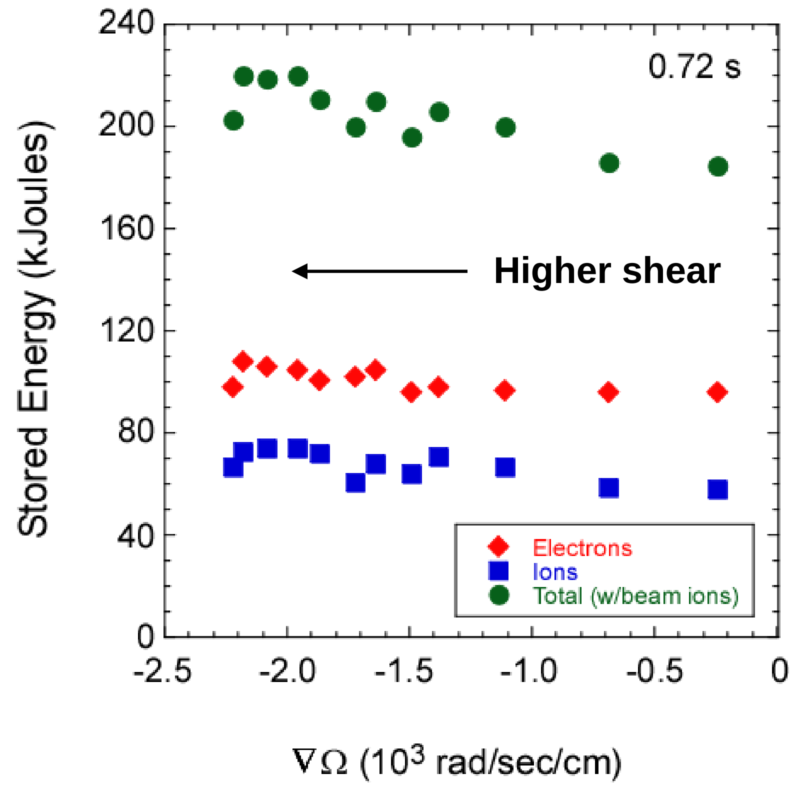

***Max torque from braking near R=135 cm***

***Note suppressed zero***

# *Slight Effect of Rotation/Rotation Shear on Stored Energy*

Possibly some small effect on fast ions

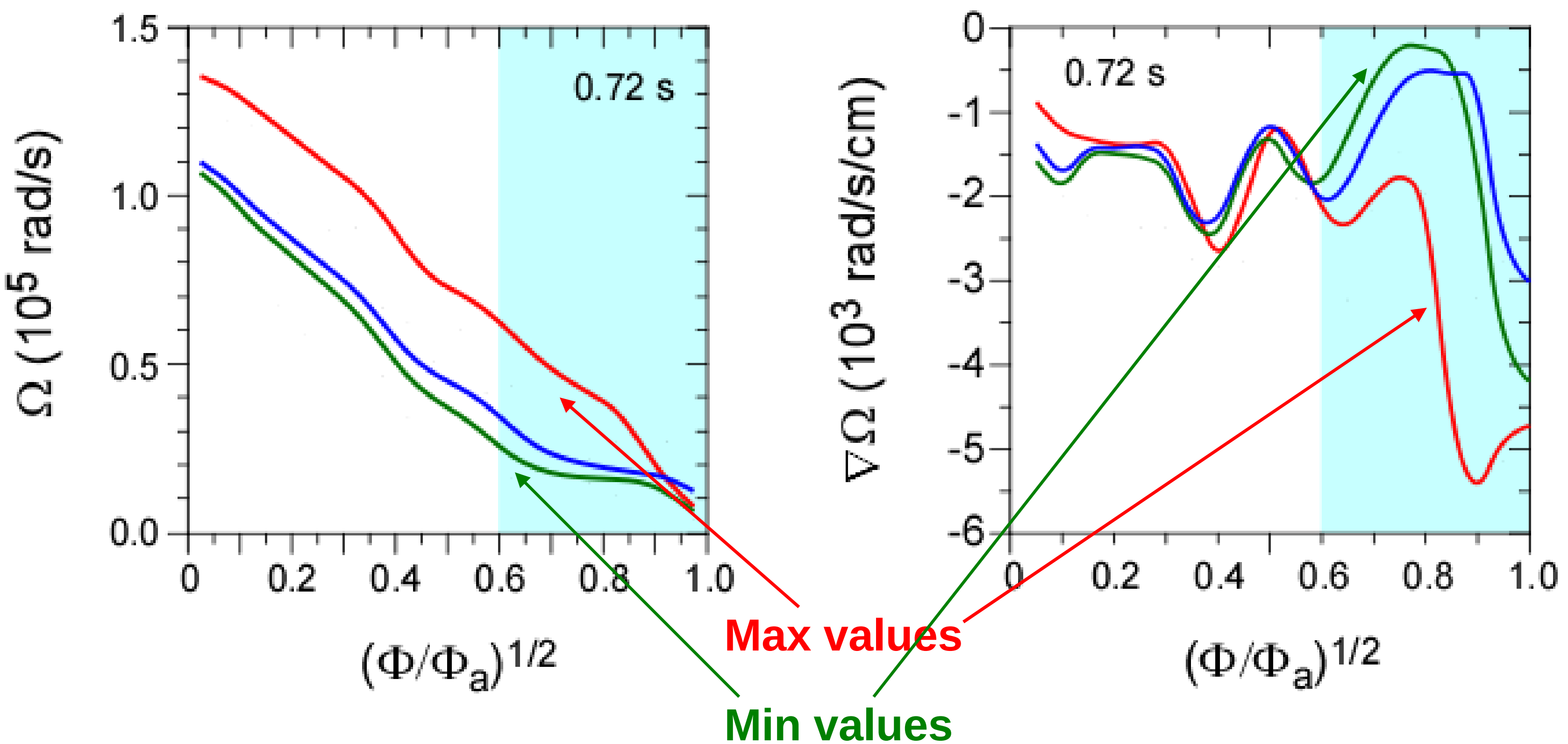



***Rotation shear is acting on a small part of plasma***
***– improvement may be limited to that region***

Decrease in rotation across profile

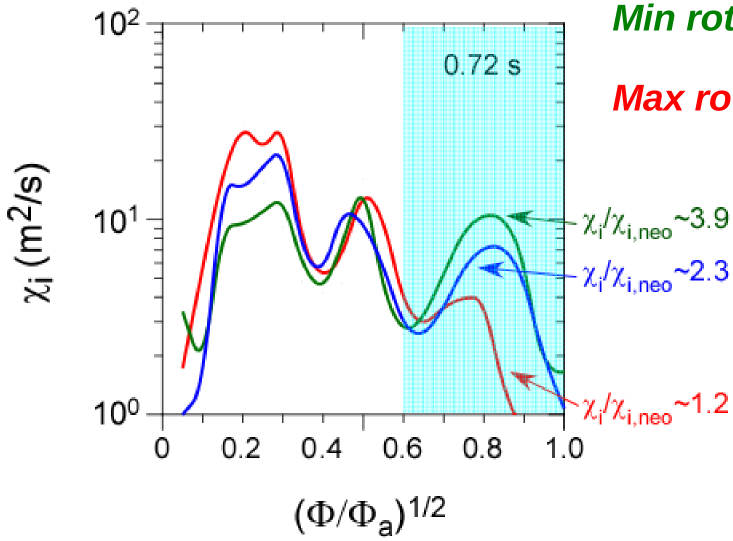
Variation in rotation shear seen mainly in outer portion of plasma

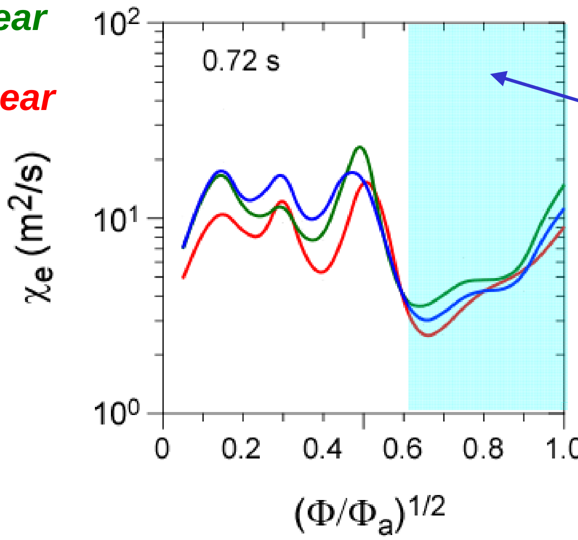


# *Thermal Diffusivities Correlate with Rotation and Rotation Shear*

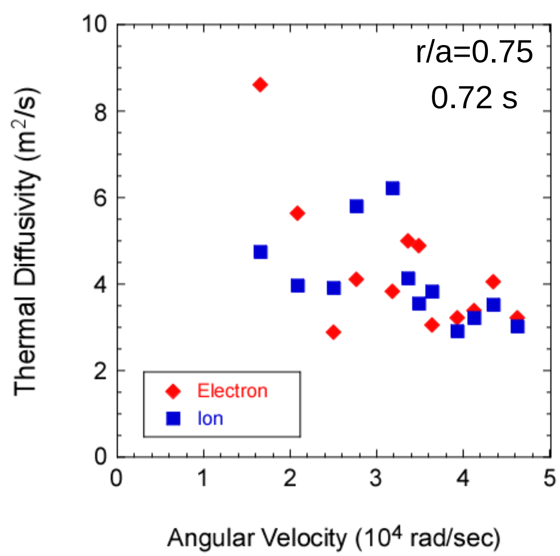
***Min rotation, shear***

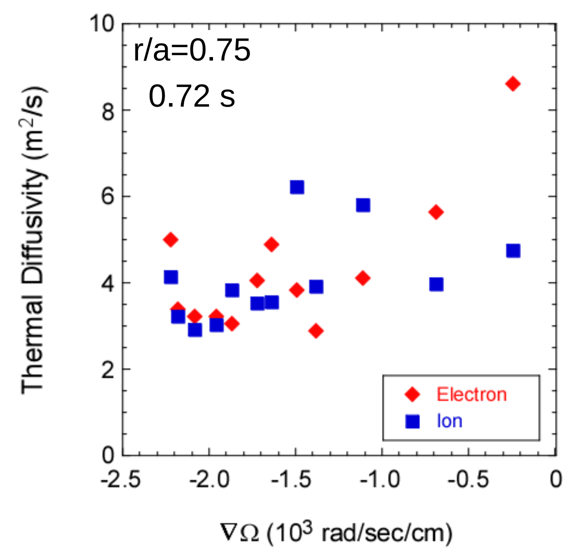
***Max rotation, shear***




**Max variation of $\nabla\Omega$ in this region**

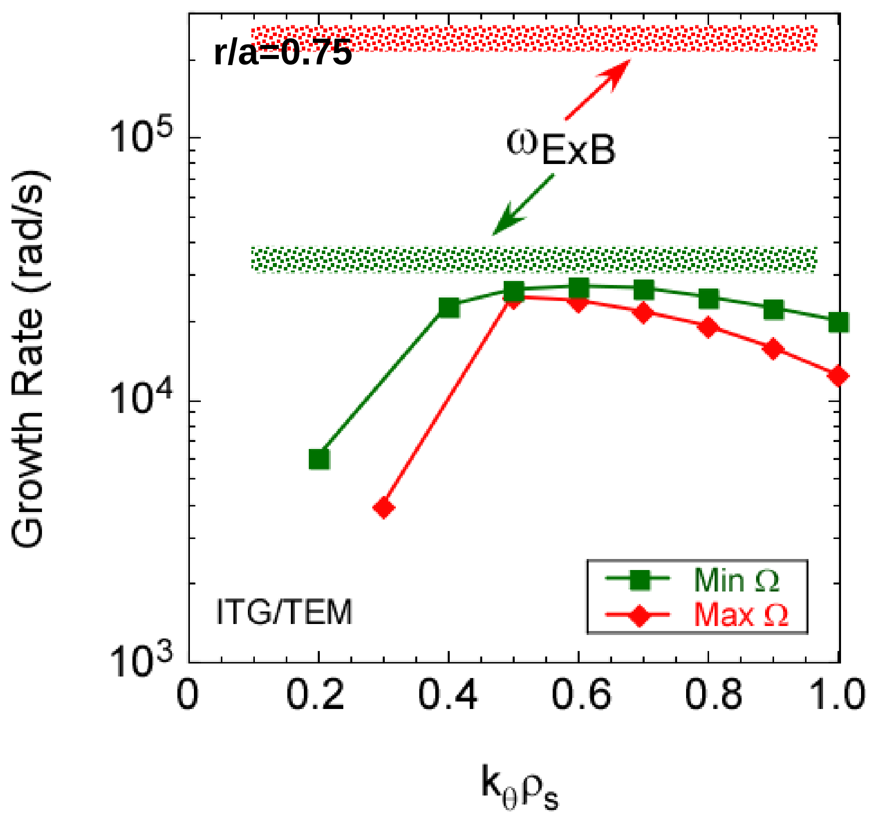


# *Linear Gyrokinetic (GS2) Calculations Indicate Increasing Suppression of Low-k Turbulence by ExB Shear*

***$\omega_{ExB}$ >> $\gamma_{lin}$ for high $\Omega$, $\nabla\Omega$ case***

***~ $\gamma_{lin}$ for low $\Omega$, $\nabla\Omega$ case***



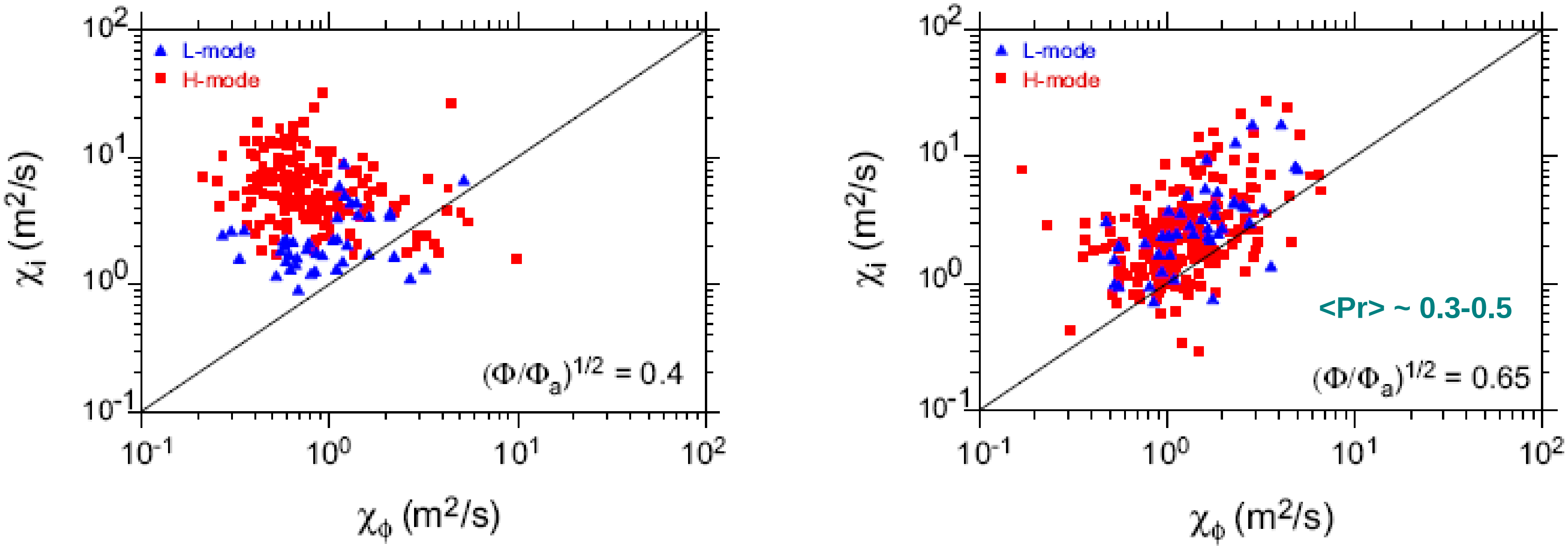

- Consistent with result that $\chi_i/\chi_{i,neo}$ decreases with increasing rotation shear
  - $\chi_i/\chi_{i,neo}$~ 1.2 for max shear
  - $\chi_i/\chi_{i,neo}$~ 3.9 for min shear

- Non-linear calculations needed to infer heat flux levels

- Consistent with ExB shear as a necessary condition for formation of ion ITB

# *Momentum Transport and Pinch*

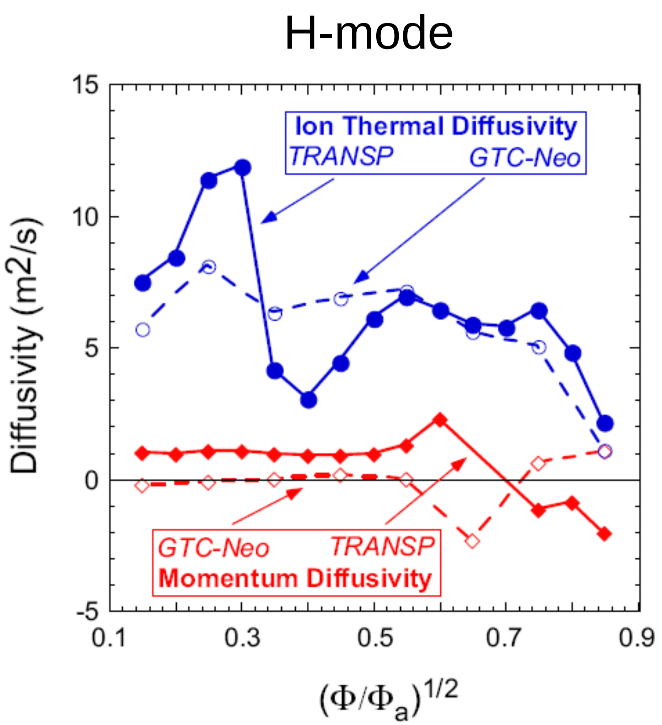
- $\chi_\phi^{eff}$ inferred from steady-state momentum balance: implicit assumption that $v_{pinch}$=0
  - Find $\chi_\phi^{eff} < \chi_i$ for both L- and H-modes

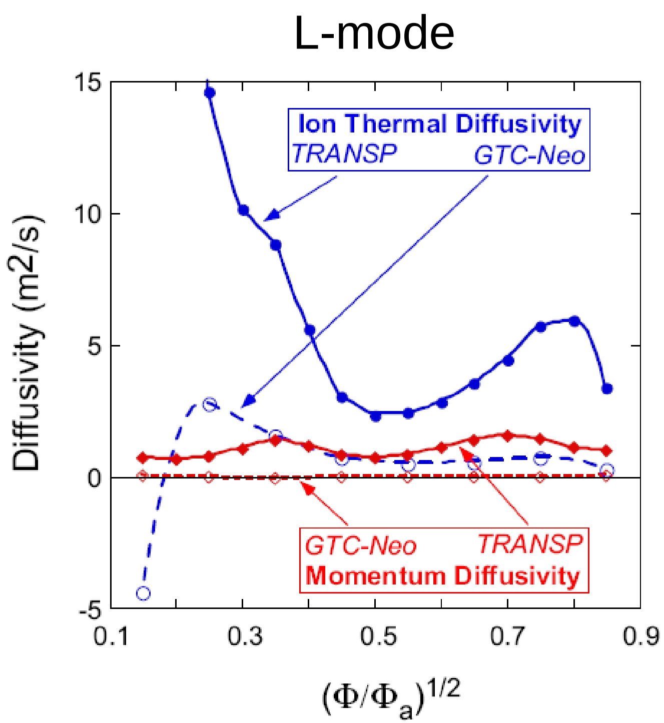



- ***Statistical coupling between $\chi_i$ and $\chi_\phi^{eff}$ observed only in outer region***
  - ***Consistent with results from higher aspect ratio tokamaks***
- ***No statistical coupling of $\chi_e$ and $\chi_\phi^{eff}$ at any radius ($\chi_e >> \chi_\phi^{eff}$)***

# *(What Controls $\chi_\phi$?)*
# *Momentum Transport is Always Anomalous*

- $\chi_\phi >> \chi_{\phi,neo}$ in both H- and L-mode plasmas, irrespective of $\chi_i/\chi_{i,neo}$



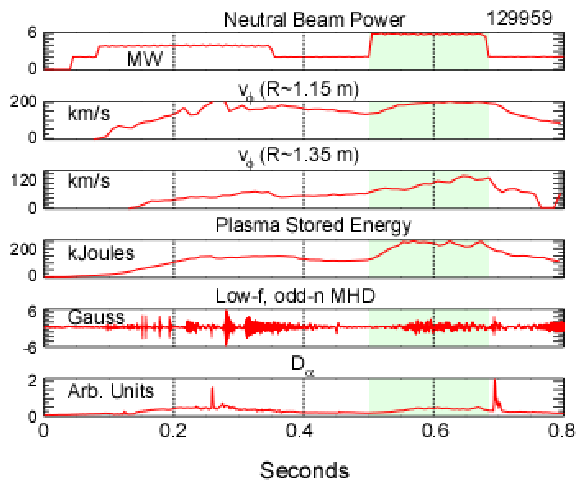



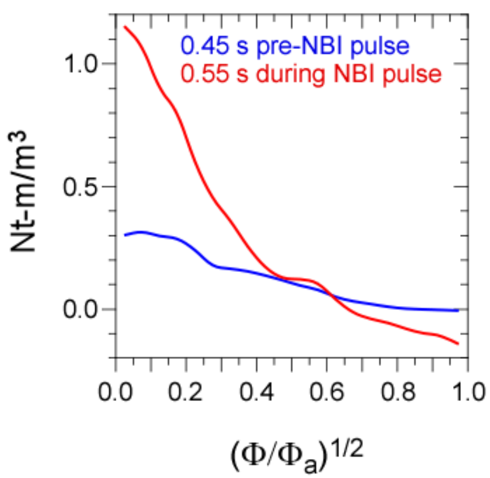

*Is $\chi_\phi$ controlled by low-k turbulence?*

*Perturbative experiments can help determine this*

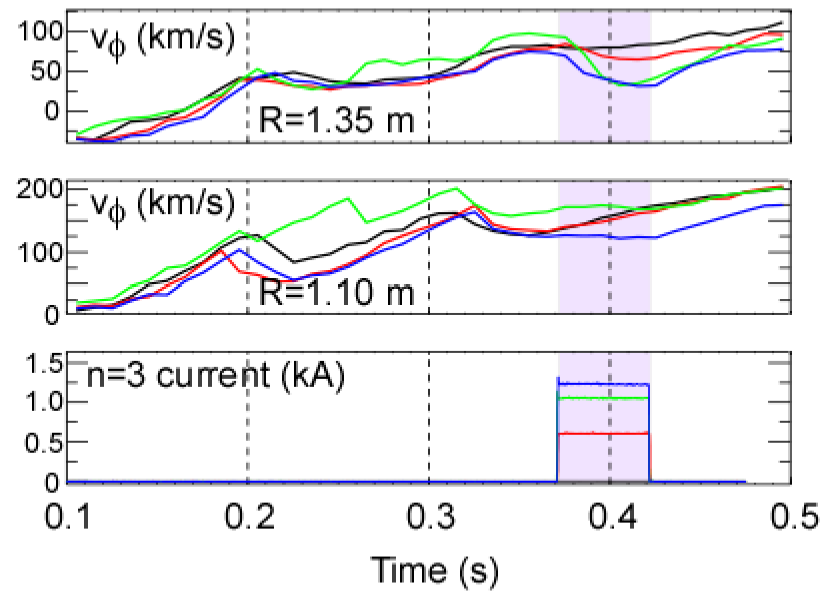
# *Application of NBI and n=3 Braking Pulses Lead to Perturbative Change in Rotation*

- Core most affected by **NBI pulses**
  - Change in torque localized to r/a < 0.3




- Outer region immediately affected by **n=3 braking pulses**




- Determine $\chi_\phi$, $v_{pinch}$ at n=3 pulse turn-off: NBI only known torque (determined from TRANSP)

# Perturbative Momentum Transport Analysis Reveals Significant Inward Pinch in Outer Region of Plasma

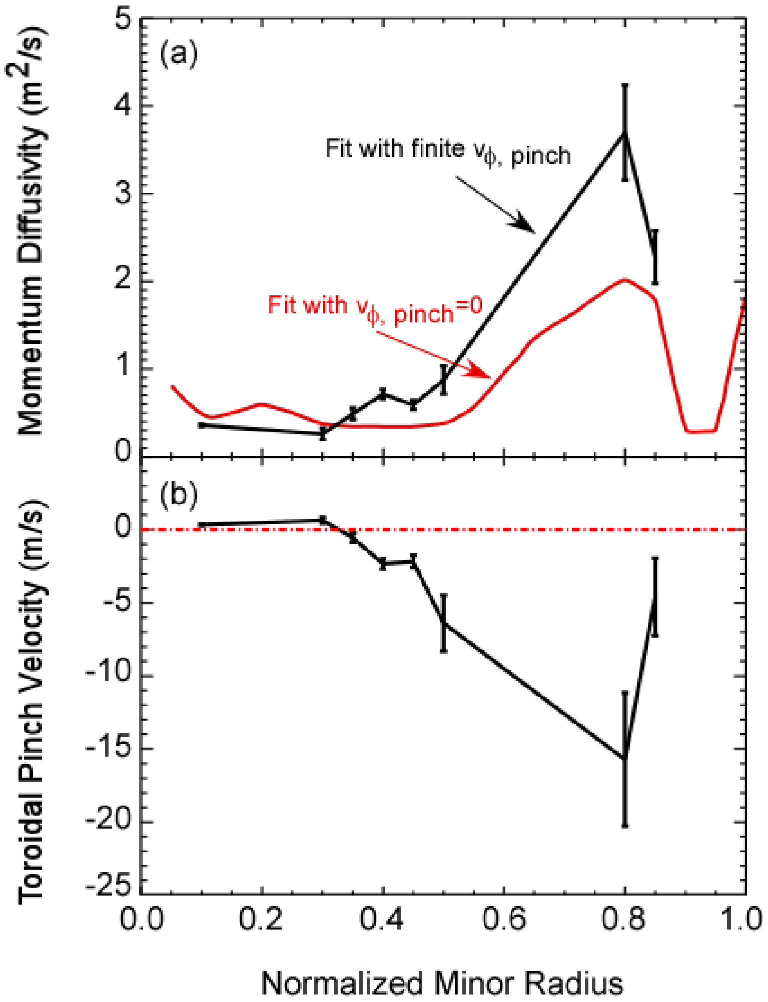
- Toroidal rotation evolves according to momentum balance
  - Rotation measured by CHERS
  - NBI torque only one considered
- Momentum flux governed by

$$\Gamma_\phi = mnR\left(\underbrace{\chi_\phi \frac{\partial V_\phi}{\partial r}}_{diffusion} - \underbrace{V_\phi V^{pinch}}_{convection}\right)$$

(Residual stress assumed to be 0)

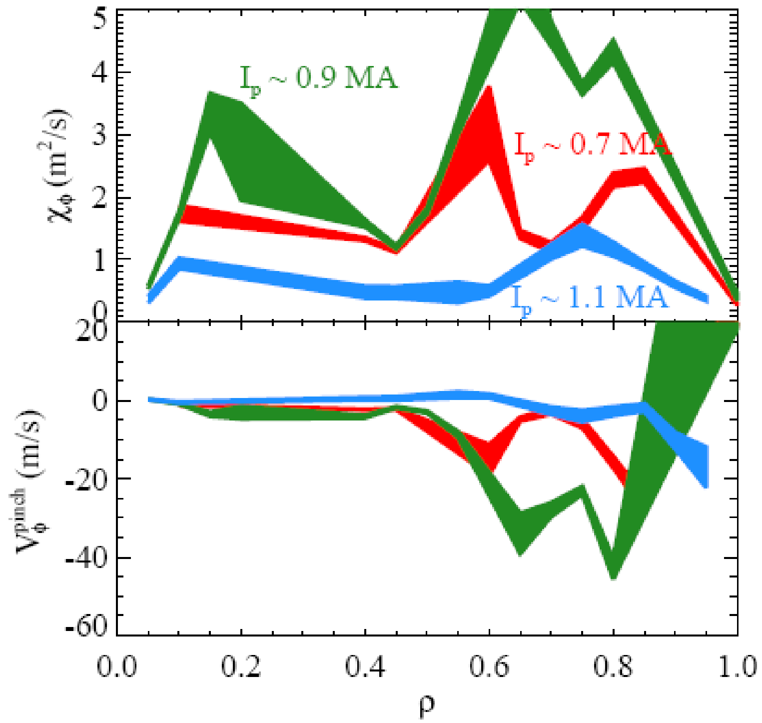
- v and ∇v have to be decoupled to determine $\chi_\phi$ and $v_{pinch}$ independently
  - This requirement is satisfied in outer portion and in a limited spatial region in the core

*(Solomon et al., PRL '08)*

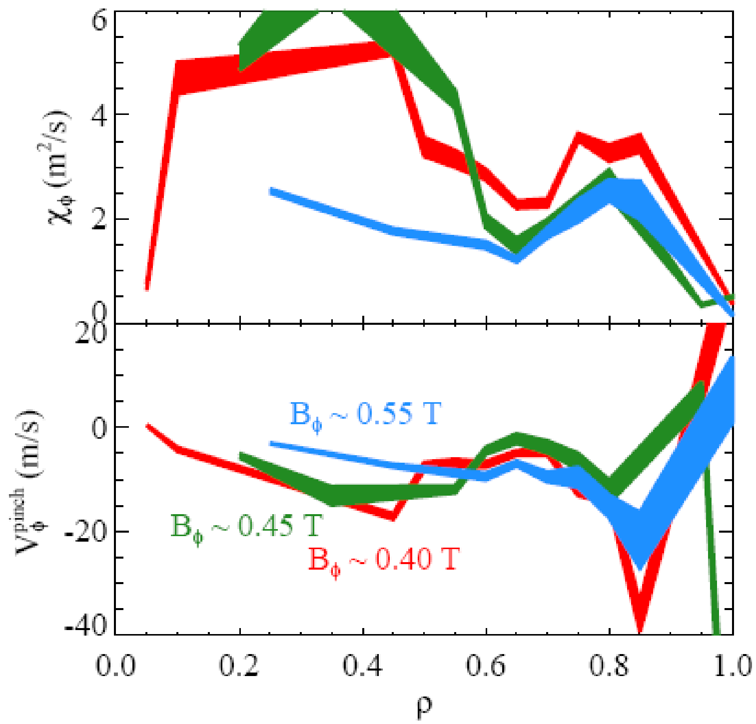


# *Pinch velocities in core generally much less than those near the plasma edge*

$I_p$ scan



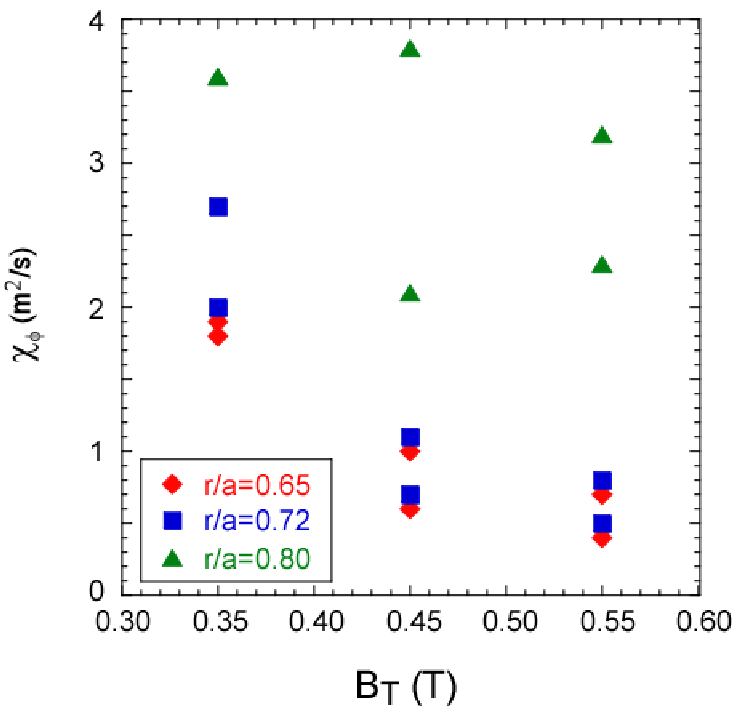

$B_T$ scan

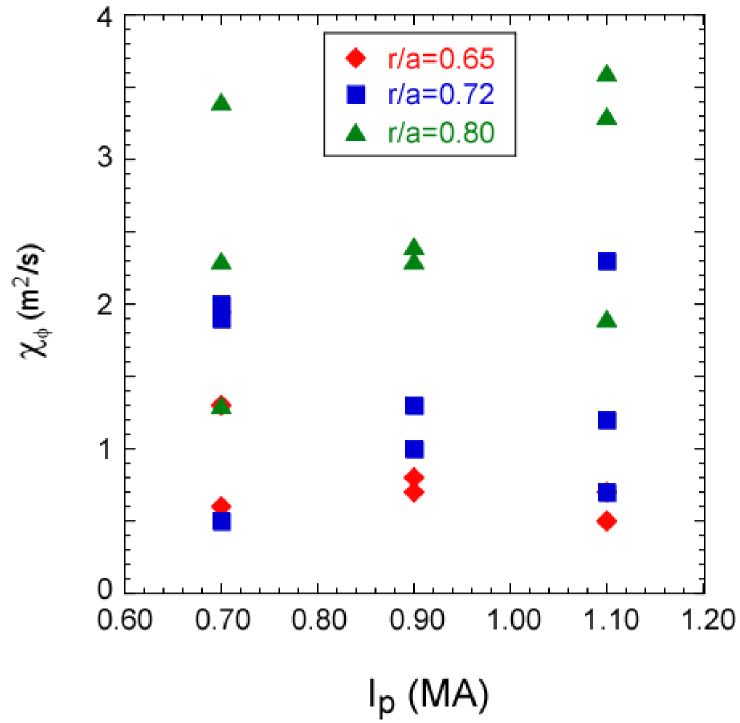



***$\chi_\phi$, $v_{pinch}$ at each position not all equally valid (depends on $v_\phi$, $\nabla v_\phi$ decoupling)***

***Not clear if there is a controlling current and/or field dependence to $\chi_\phi$, $v_{pinch}$ variation***

# $\chi_\phi$ Decreases With Increasing $B_T$ at Some Outer Locations




- No dependence on $I_p$
- No dependence on $B_T$ or $I_p$ in core region
- $V_{pinch}$ shows no dependence on $I_p$ or $B_T$ in core or gradient regions

# *Calculated Pinch Velocities Agree Reasonably Well With Theories Based on Low-k Turbulence in Outer Region*

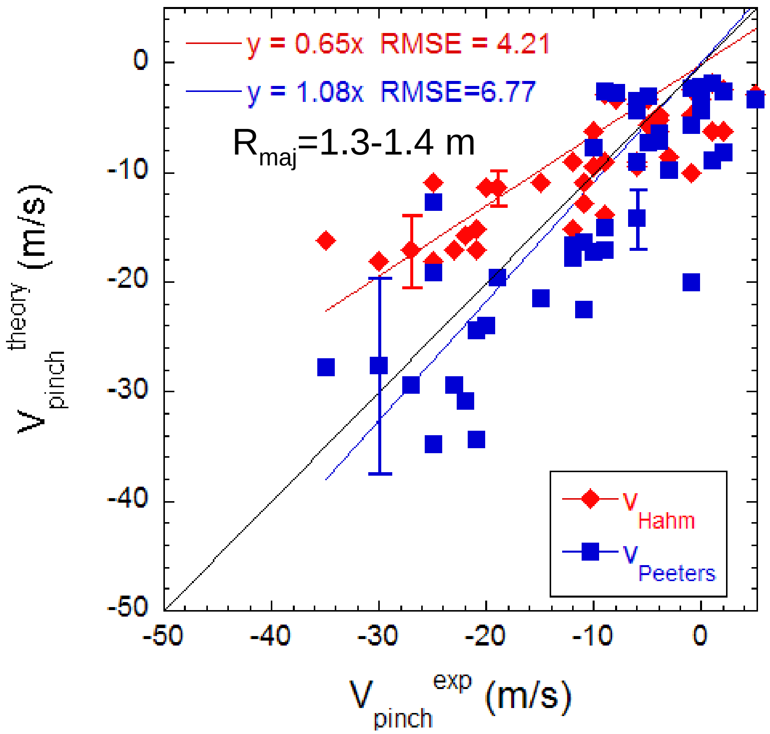
- Both based on low-k, but have different approaches
  - End up with similar expressions

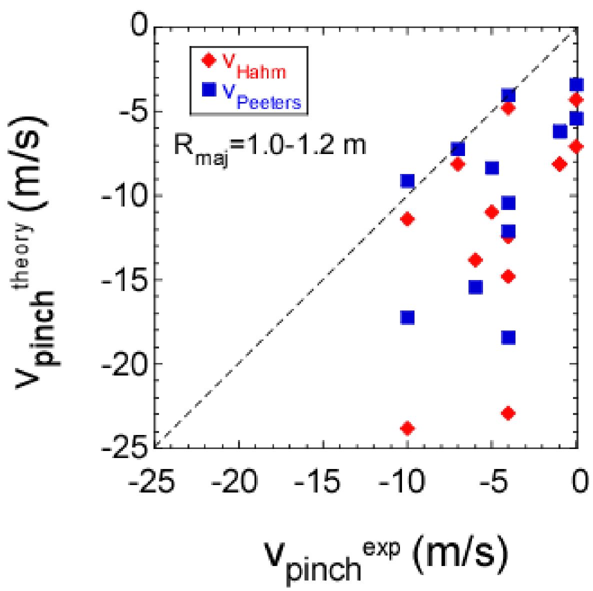
    Peeters et al. (PRL, 2007)

    $v_{Peeters}/\chi_\phi = [-4-R/\boldsymbol{L_n}]/R$

    Hahm et al. (PoP, 2007)

    $v_{Hahm}/\chi_\phi = [-4]/R$



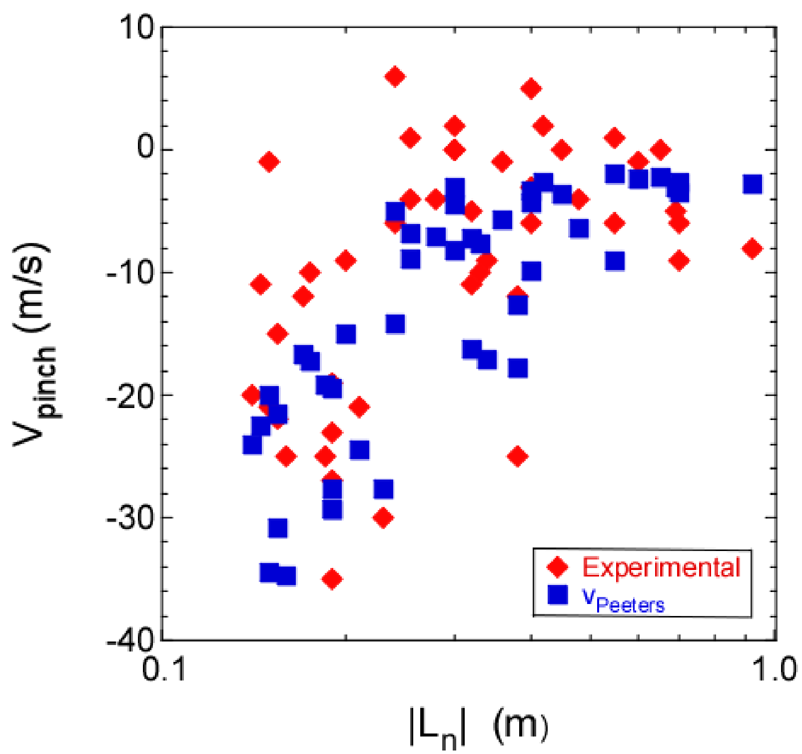



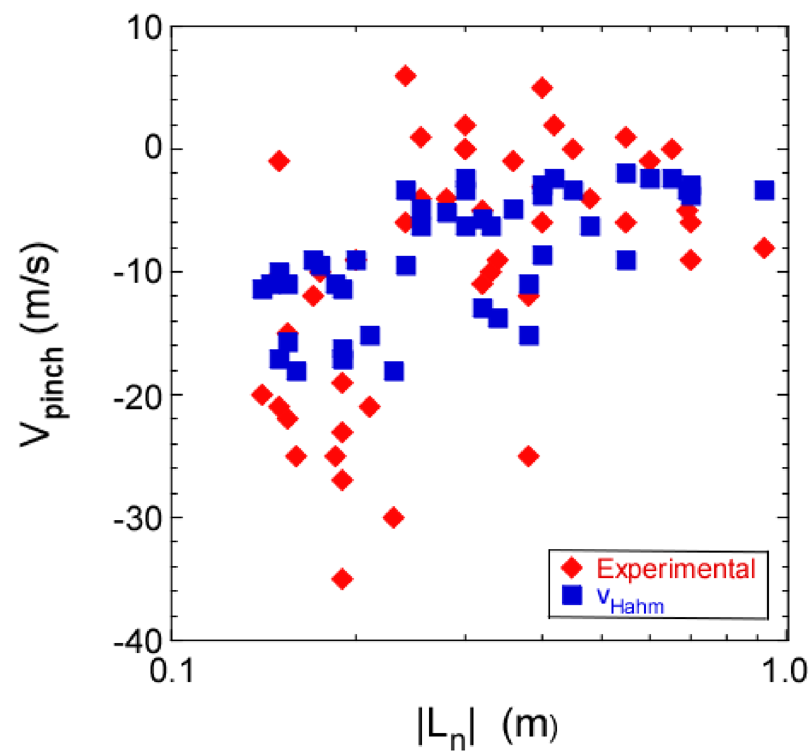

***Why is there a difference between theories at high $v_{pinch}$?*** ***$L_n$ dependence***

***Why does theory match in outer region better than in core?*** ***ITG/TEM stable in core***

# *(Why do theories differ at high $v_{pinch}$?)*
# *The Density Gradient Scale Length Term Matters*

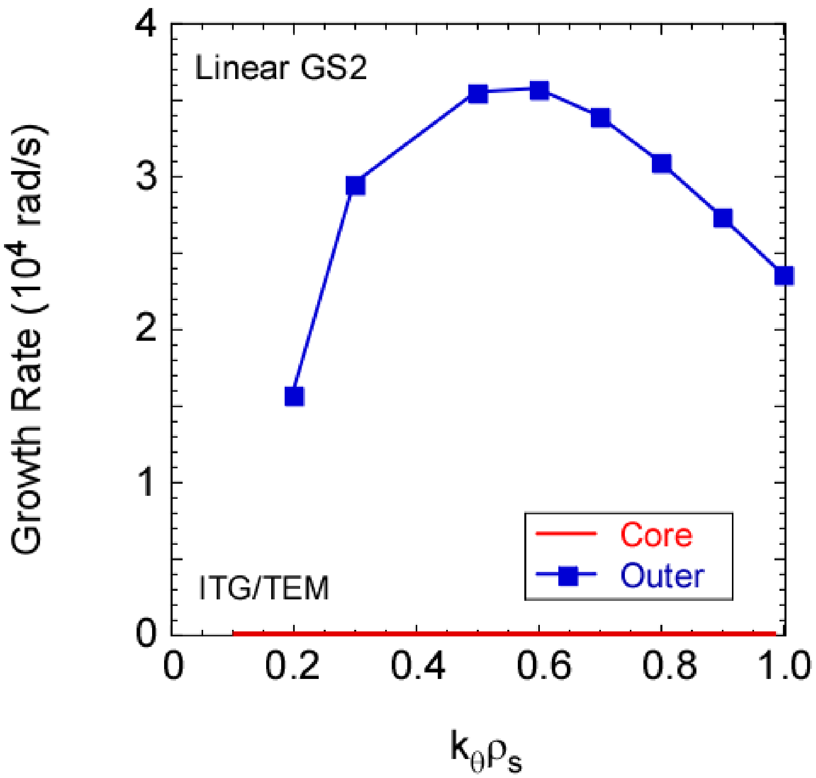
$v_{Hahm}$ underpredicts $v_{pinch}^{exp}$ for $L_n <$ ~0.2 m



# *(Why does theory match in outer region better than in core?)* *ITG/TEM Modes Unstable in Outer Region, Stable in Core*

- $V_{pinch}$ consistent with low-k turbulence theory predictions (Peeters, Hahm) in outer region but not in core
  - In core, much smaller vpinchthan predicted by low-k turbulence theories




***BES to measure low-k turbulence will be implemented in 2009***

***Physics governing momentum transport/pinch appears to be similar between low A, electron-dominated and high-A, ion-dominated regimes (in outer region)***

# *Conclusions (I)*

- Momentum transport anomalous even when ion thermal transport is near neoclassical
  - Something other than collisions must be driving momentum transport

- Perturbative experiments indicate that the inward pinch can be significant and consistent with predictions from theories based on low-k turbulence
  - Agreement using simple formulae surprisingly good!
  - Inclusion of pinch brings ensemble of $\chi_\phi$ closer to $\chi_i$: <Pr> = 0.5 – 0.8
  - Results suggest similar physics is driving momentum transport across a range of transport regimes

  - ***Points to the importance of performing experiments in different operating regimes to "stress test" theories***

# *Conclusions (II)*

- Comparisons to theory are just beginning
  - Residual stress [Gurcan et al., PoP, 2007] not taken into account
  - Gyrokinetic calculations needed to determine $v_{pinch}$ more accurately
  - What drives momentum transport in core?
- Theories are still in early stages of development
  - Validity in low-R/a, electron-dominated regimes
  - Role of kinetic electrons, electron-scale turbulence
- Momentum transport can be a better indicator of low-k turbulence than energy transport in these electron-dominated regimes
  - Neoclassical energy flux is high and dominates turbulence-induced fluxes for ions (typical H-modes)
  - Turbulence dominates momentum flux since neoclassical momentum flux is essentially zero