NSTX

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Momentum Transport in Electron-Dominated Spherical Torus Plasmas

S.M. Kaye, W. Solomon and the NSTX Group

PPPL

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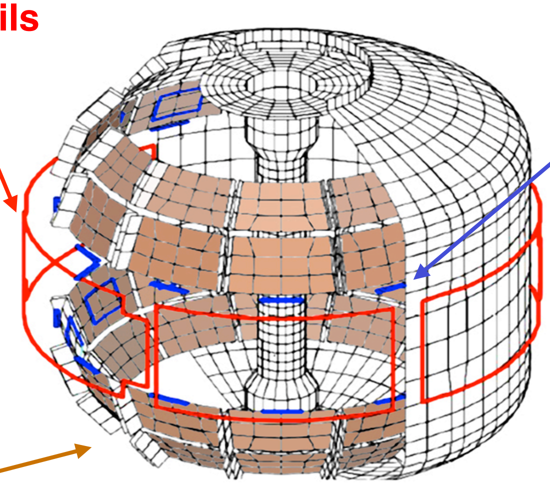
Outline

- 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

Sabbagh et al. EX5-1
Canik et al., PD

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

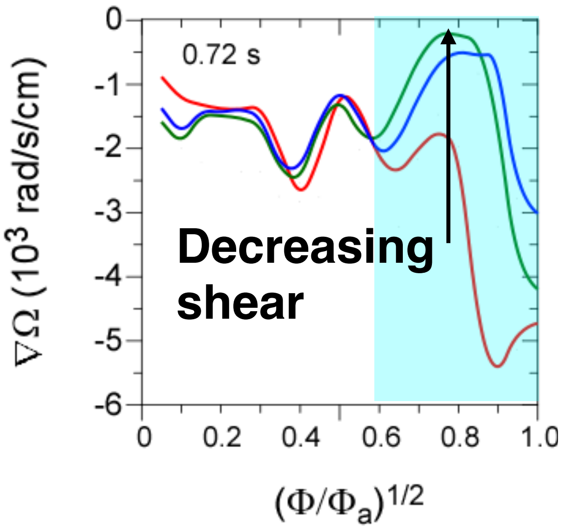


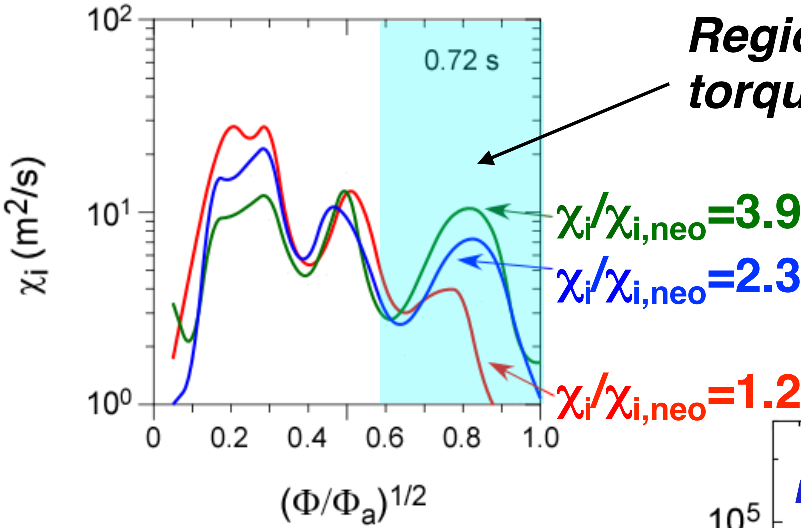
NSTX Typically Operates in an Electron-Dominated Regime

- 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

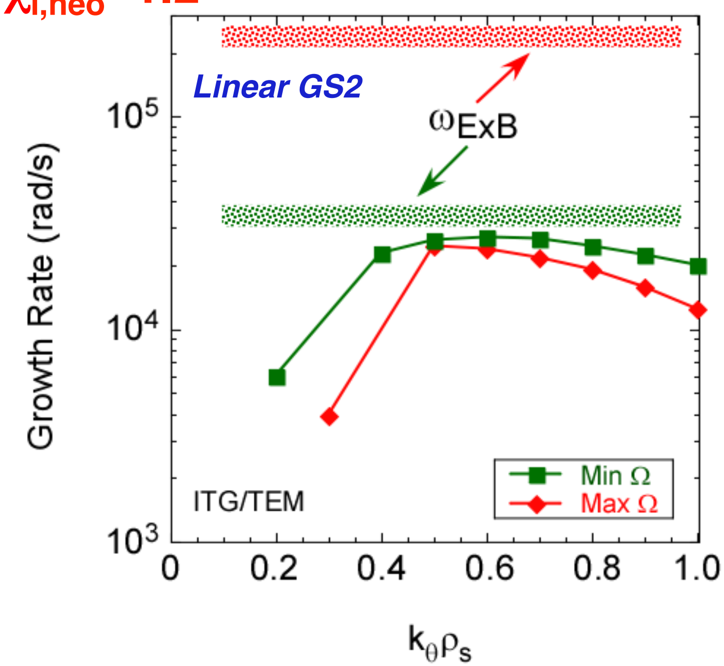
Ion Transport Tightly Coupled to Rotation, Rotation Shear

Ion thermal diffusivity decreases with increasing rotation shear





Region of maximum torque from applied n=3

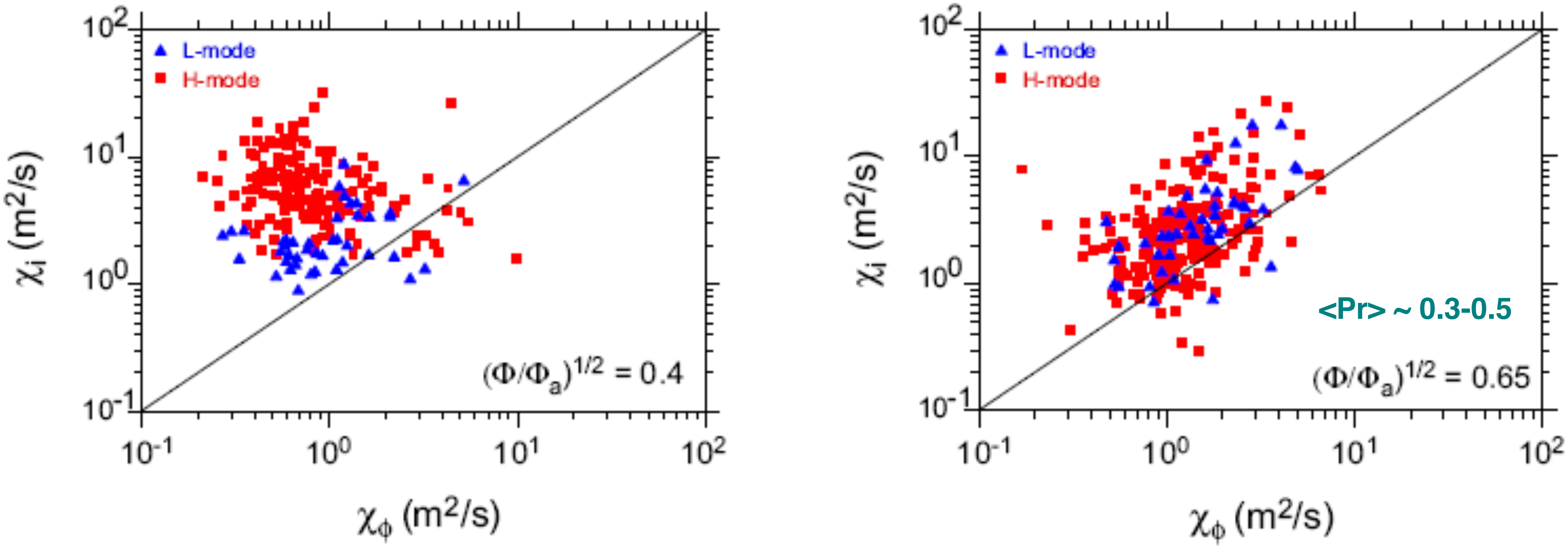


Non-linear calculations needed to determine magnitude of turbulence reduction and resulting heat flux levels

ExB shear may also be important for reducing high-k turbulence (Yuh, EX/P3-1)

Effective Momentum Diffusivity Usually Greater than Ion Thermal Diffusivity in All Operating Regimes

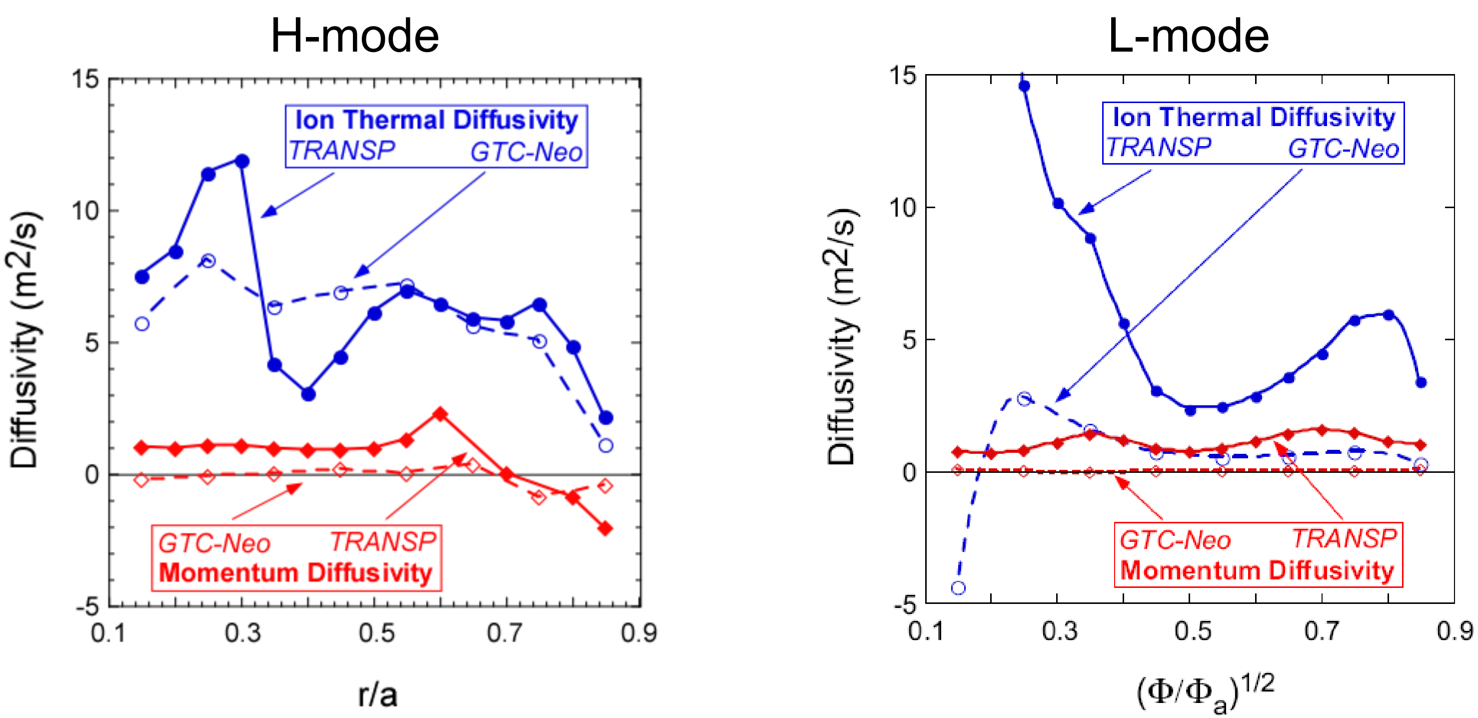
- χ_ϕ^{eff} inferred from steady-state momentum balance: implicit assumption that v_{pinch}=0
  - Find $\chi_\phi^{eff} < \chi_i$ for both L- and H-modes



- ***Statistical coupling between χ_i and χ_ϕ^{eff} observed only in outer region***
  - ***Consistent with results from higher aspect ratio tokamaks***
- ***No statistical coupling of χ_e and χ_ϕ^{eff} at any radius (χ_e>>χ_ϕ^{eff})***

(What Controls χ_ϕ?)
Momentum Transport is Always Anomalous

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

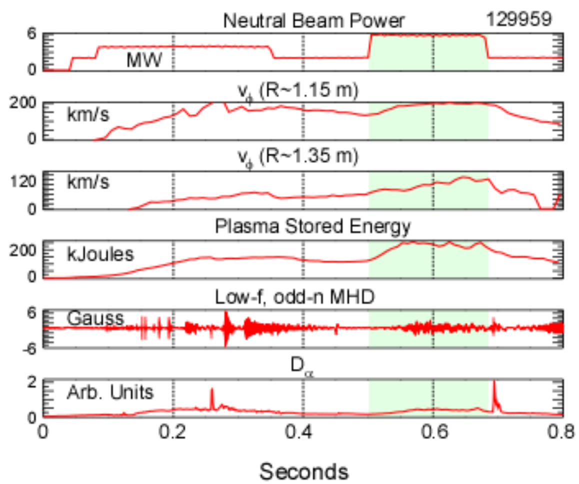


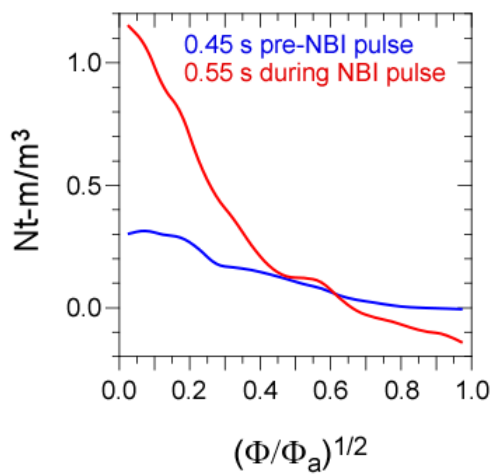
Is χ_ϕ controlled by low-k turbulence?

Perturbative experiments can help determine this

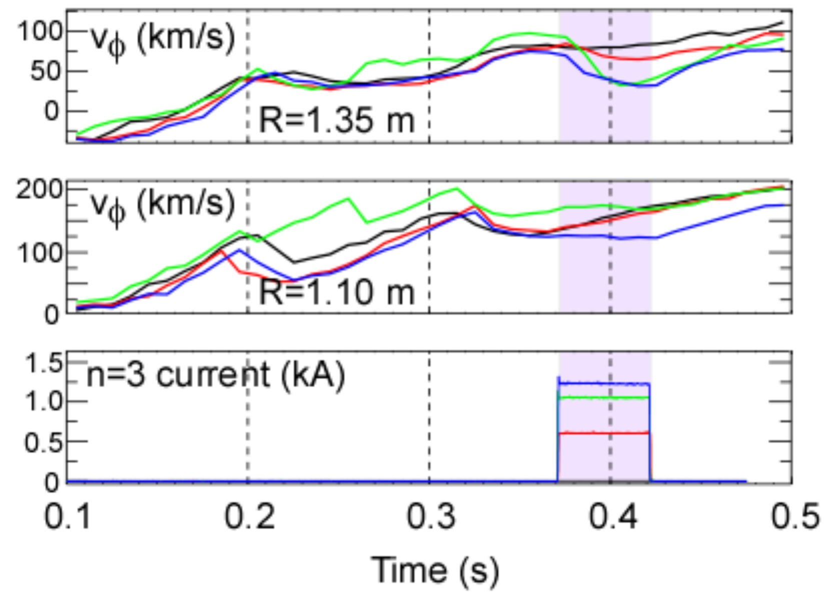
Application of NBI and n=3 Braking Pulses Lead to Perturbative Change in Rotation

- 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 χ_ϕ, v_{pinch} at n=3 pulse turn-off: NBI only known torque (determined from TRANSP)

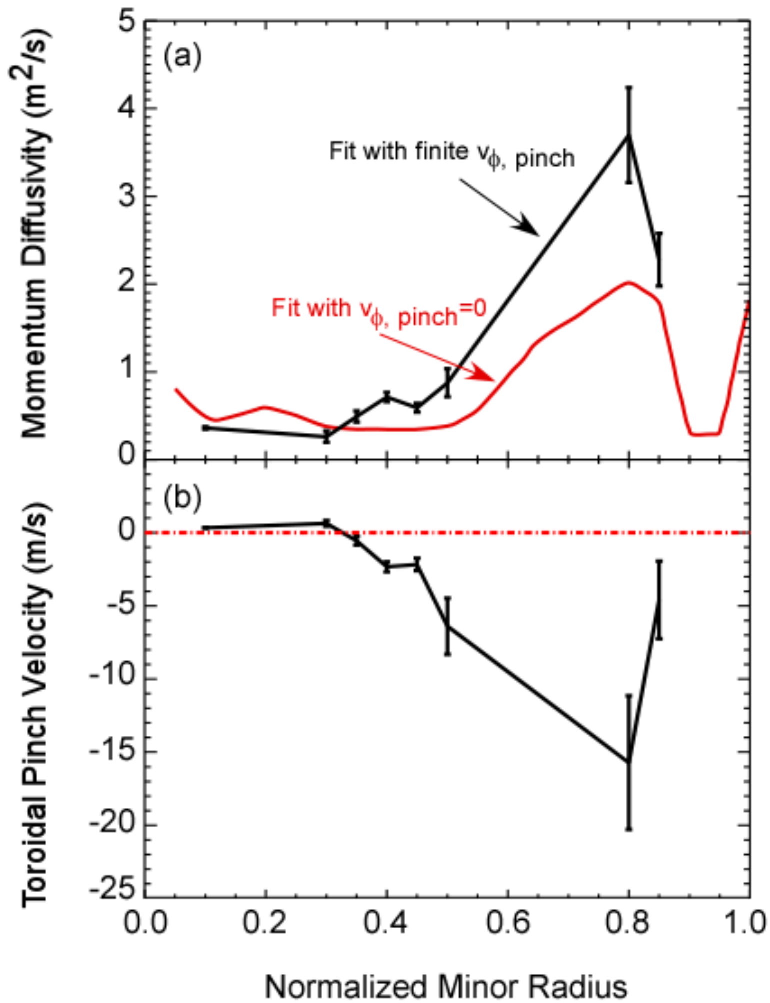
Perturbative Momentum Transport Analysis Reveals Significant Inward Pinch in Outer Region of Plasma

- 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 χ_ϕ 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)

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

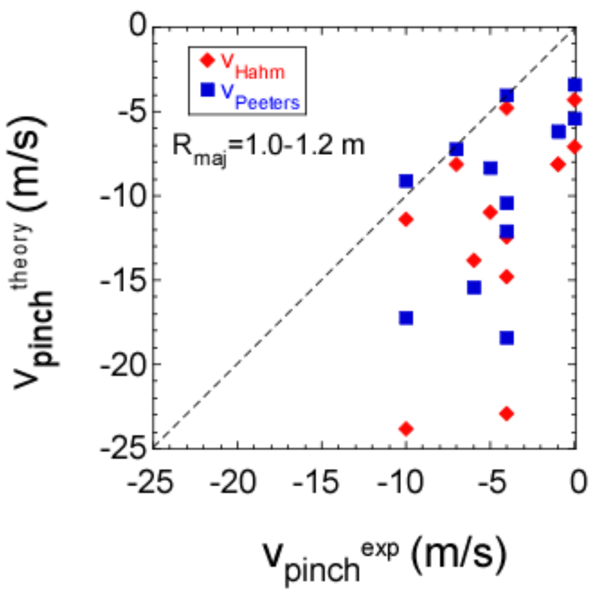
- Both based on low-k, but have different approaches
  - End up with similar expressions

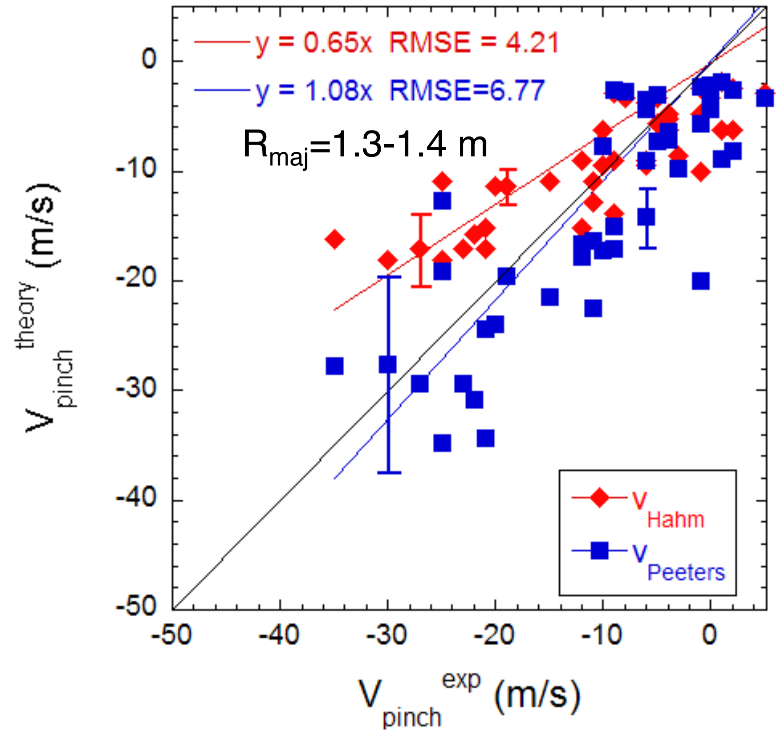
Peeters et al. (PRL, 2007)

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

Hahm et al. (PoP, 2007)

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



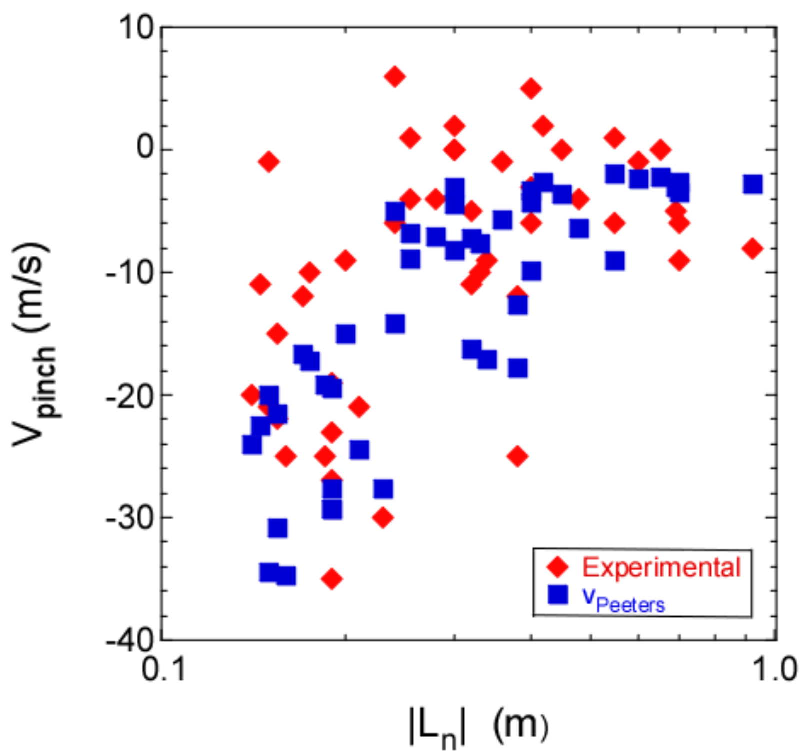


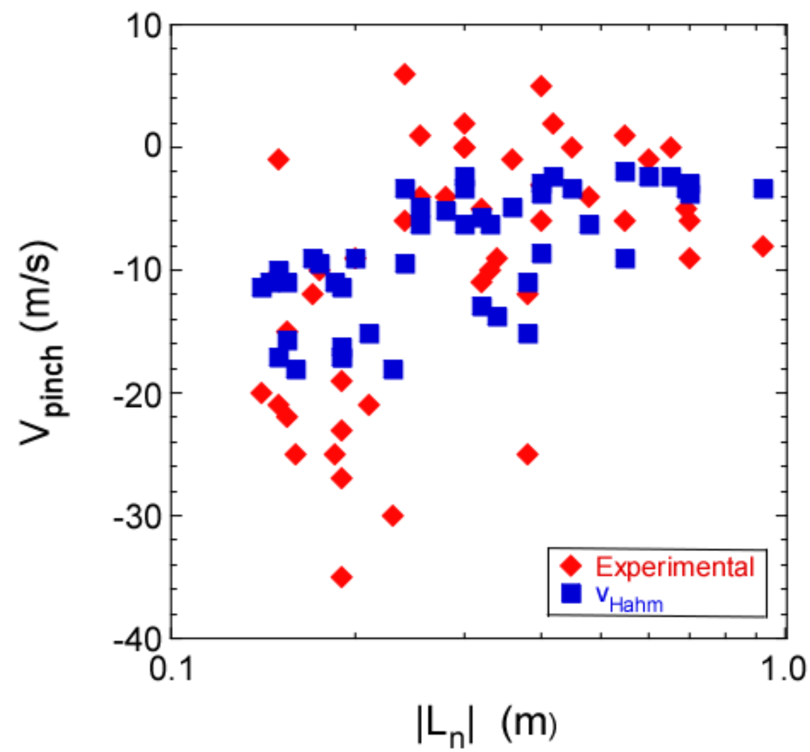
Why is there a difference between theories at high v_{pinch}? ***L_n dependence***

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

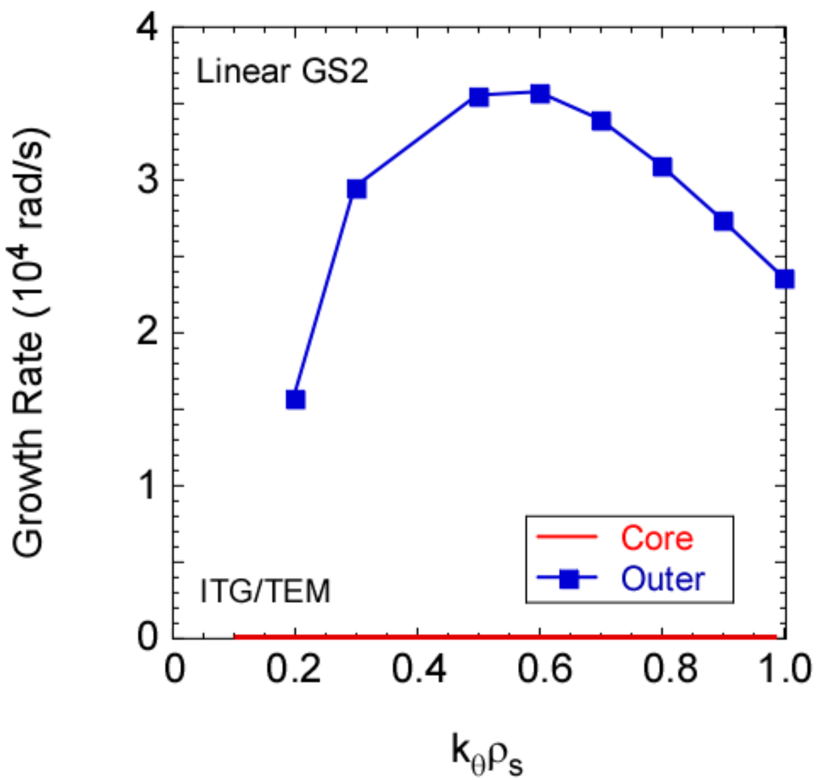
v_{Hahm} underpredicts v_{pinch}^{exp} for $L_n <$ ~0.2 m





(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 v_{pinch} than 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 χ_ϕ closer to χ_i: $\langle Pr \rangle = 0.5 - 0.8$
  - 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)

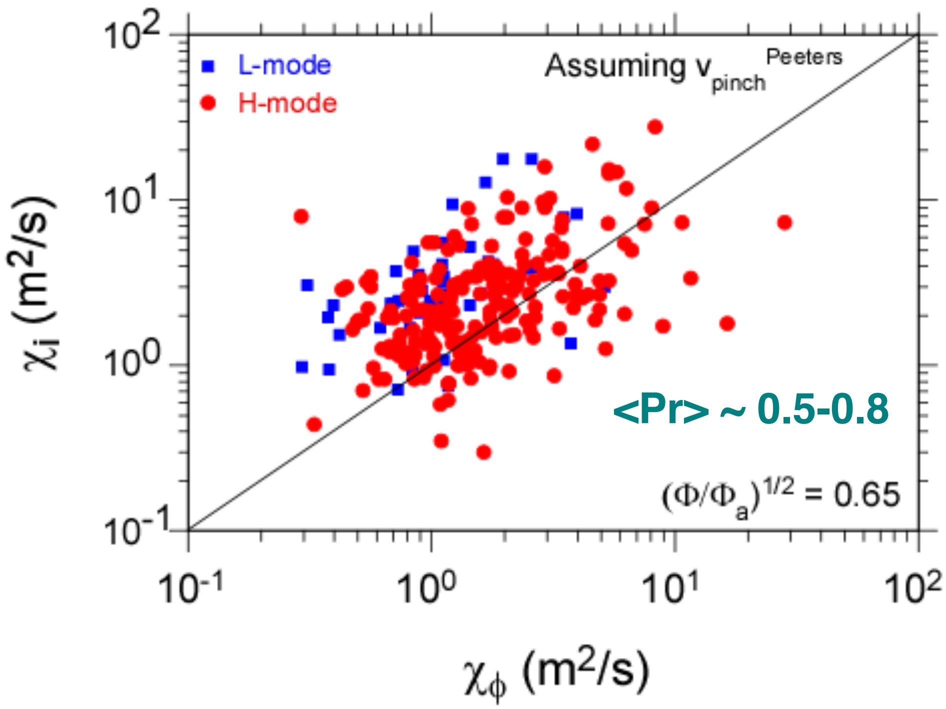
- Comparisons to theory are just beginning
  - Residual stress [Gurcan et al., PoP, 2007] not taken into account
  - Gyrokinetic calculations needed to determine v_{pinch} more accurately
  - What drives momentum transport in core?

- 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

Simple Inclusion v_{pinch} Brings χ_ϕ Closer to χ_i

- Assume v_{pinch} governed by low-k turbulence for all discharges, and is given by simple theory expressions
- Include this term in momentum balance to re-solve for a "corrected" χ_ϕ



χ_ϕ closer to χ_i than is χ_ϕ^{eff} by a factor of ~2

Scatter still large

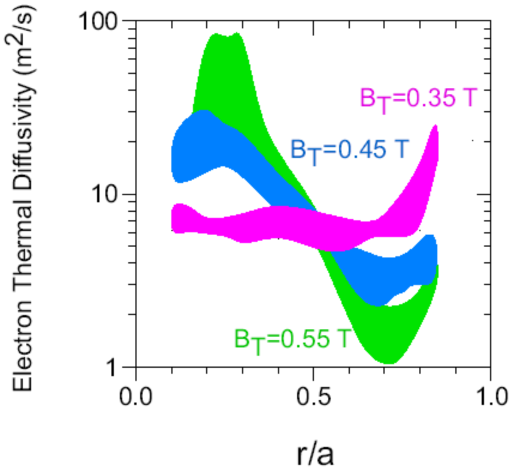
Physics governing momentum transport/pinch appears to be similar between low A, electron-dominated and high-A, ion-dominated regimes

Introduction

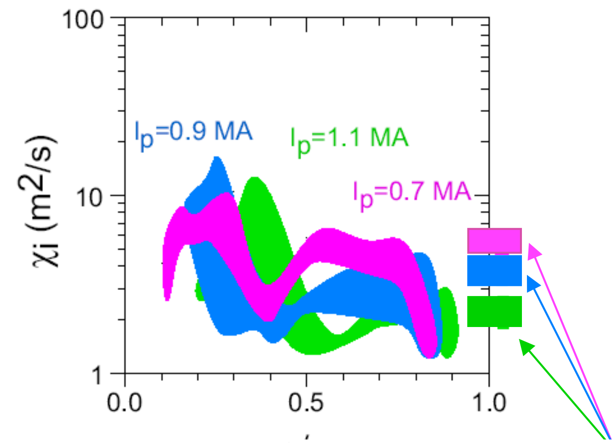
- Rotation plays an important role in fusion plasmas
  - Suppression of low-k microturbulence
  - Internal/External MHD mode suppression
- Predictive understanding of momentum transport desirable
  - ITER, CTF,….
- Studies performed in NSTX to investigate momentum transport
  - In electron-dominated plasmas at low aspect ratio
    - Large ExB shear (low-k turbulence suppression/reduction?)
  - ***What is the relation of rotation and momentum flux to energy flux?***
  - ***What is the source of the momentum diffusivity & pinch?***

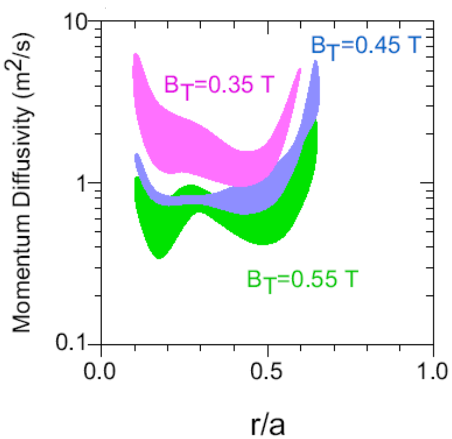
Local Transport Studies Reveal Sources of Energy Confinement Trends

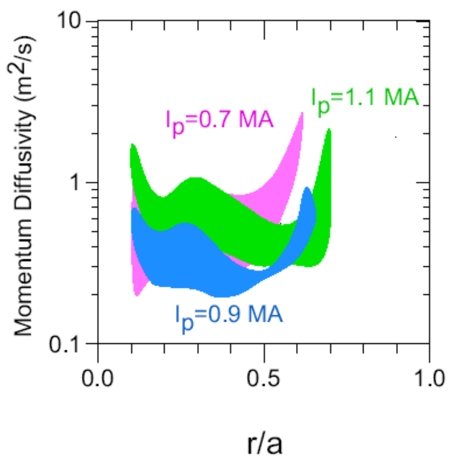
Electrons primarily responsible for strong B_T scaling in NSTX ($\tau_E \sim B_T^{0.9}$)



Variation in near-neoclassical ion transport primarily responsible for I_p scaling ($\tau_E \sim I_p^{0.4}$)





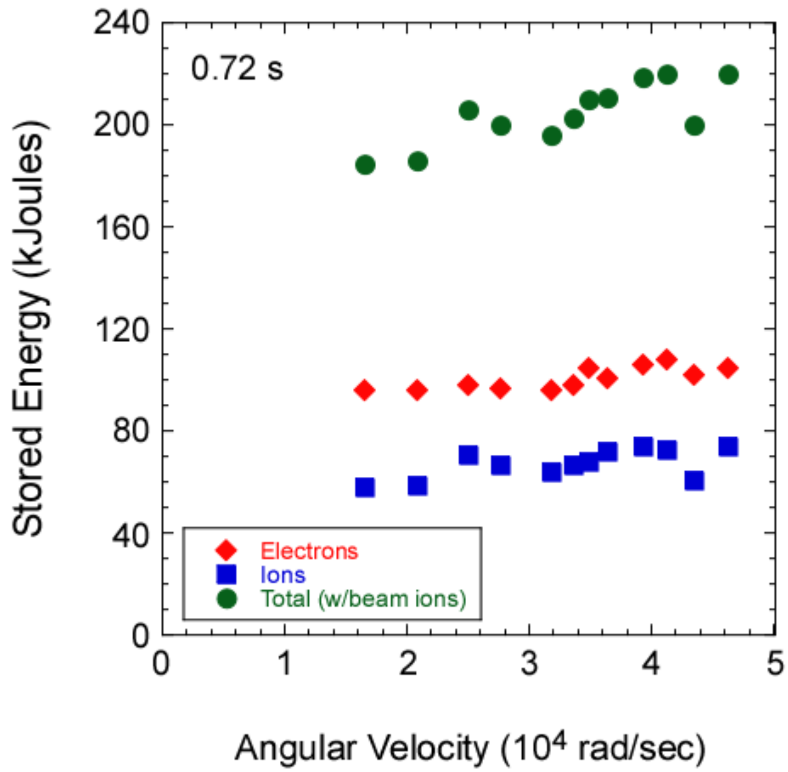


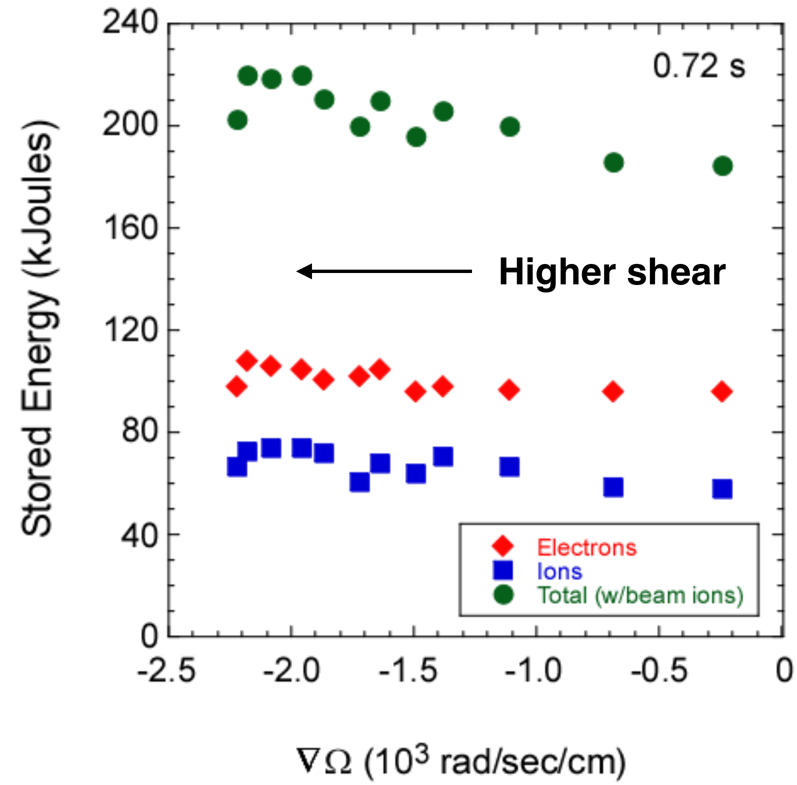
Neoclassical levels determined from GTC-Neo: includes finite banana width effects (non-local)

Is momentum diffusivity tied more to electron diffusivity when ions are neoclassical?

Slight Effect of Rotation/Rotation Shear on Stored Energy

Possibly some small effect on fast ions

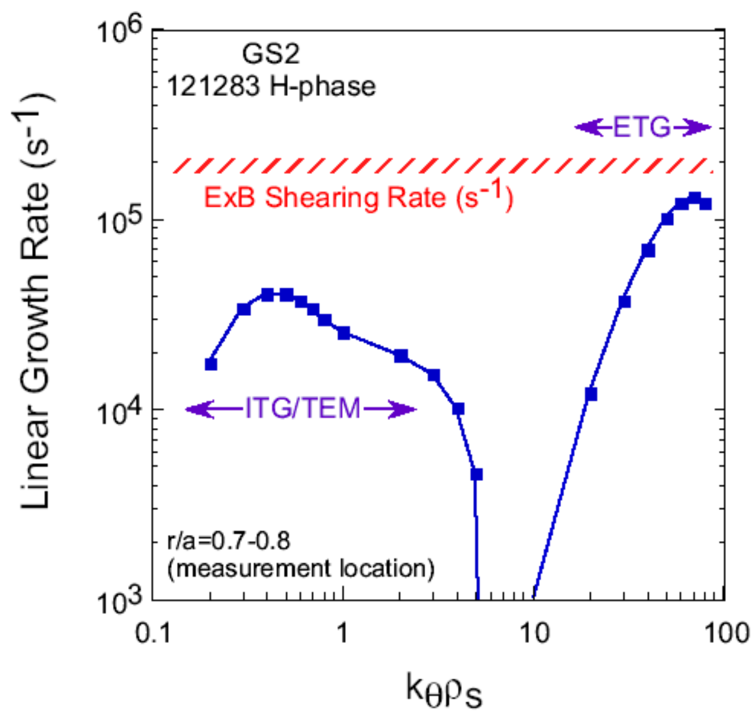


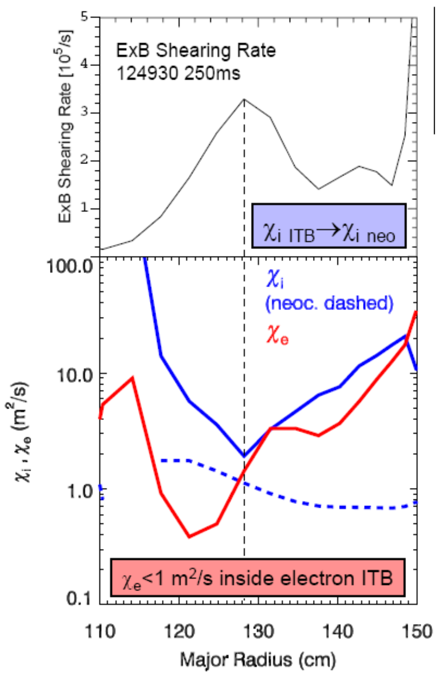


Rotation shear is acting on a small part of plasma
– improvement may be limited to that region

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
  - Suppression or reduction of low-k turbulence
- Transport losses dominated by electrons
  - Ion energy transport in H-modes typically neoclassical
- Confinement dependences differ from those at higher aspect ratio
  - $\tau_E \sim B_T^{0.9} I_p^{0.4}$





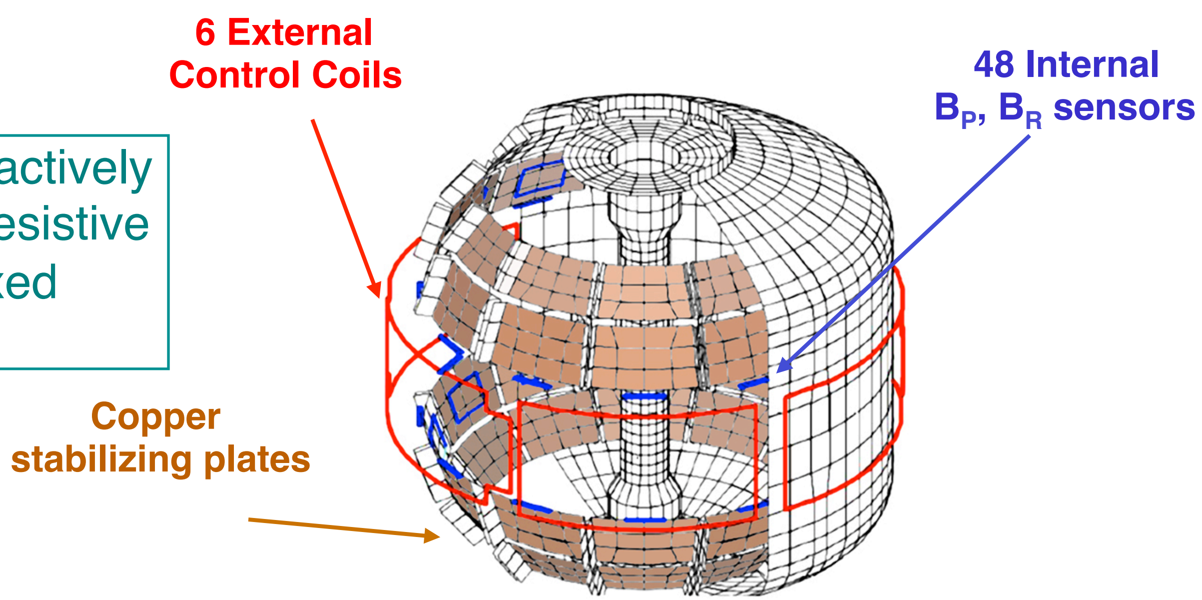
L-Mode

- Location of maximum ExB shear correlated with that of ion ITB

Effect of Rotation and Rotation Shear on Global Confinement/ Local Transport

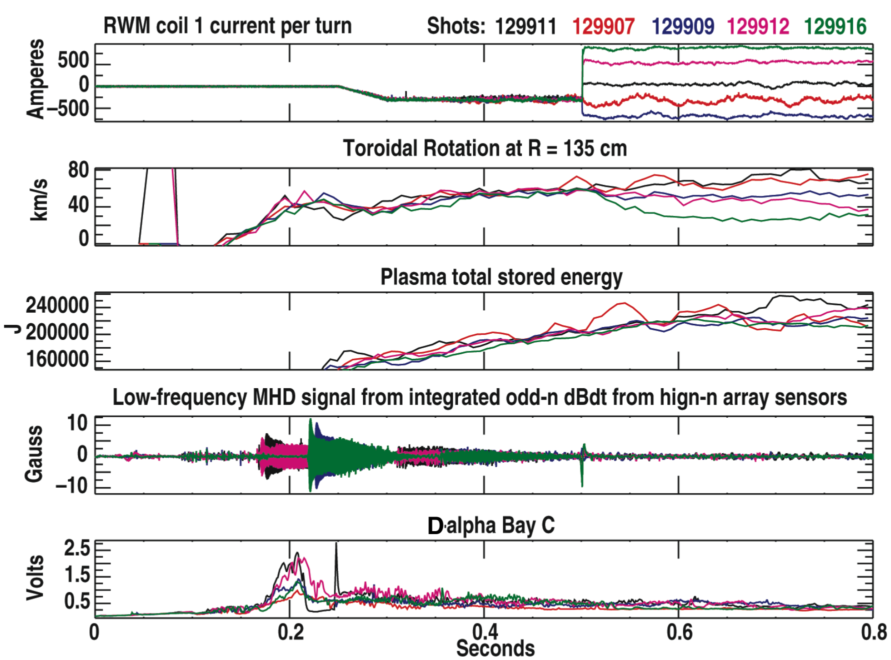
- Motivation
  - Study whether rotation or rotation shear has an effect on global confinement and/or local transport
- Approach
  - Use n=3 applied fields to slow plasma down and establish new rotational equilibrium

External control coils used to actively compensate error fields and resistive wall modes (n=1 to 3, and mixed mode)



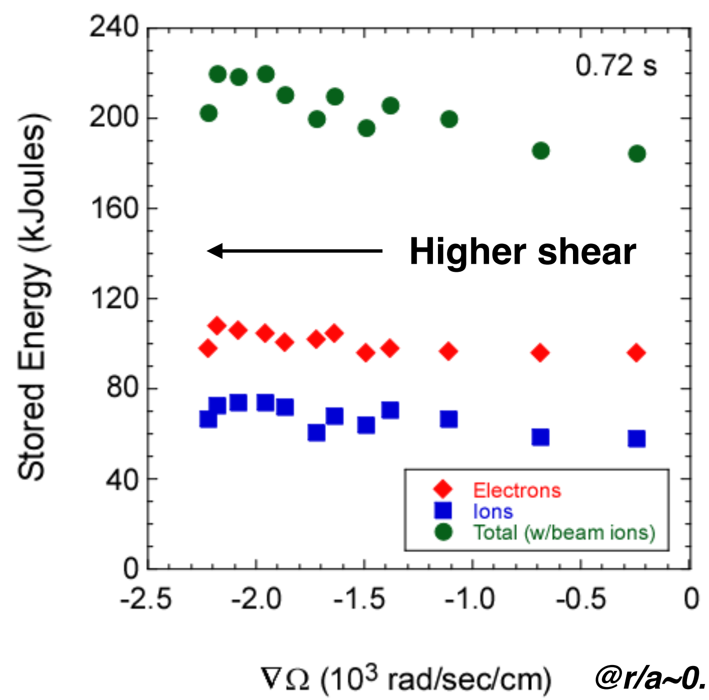
Rotational Equilibria Were Established at Various Levels of n=3 Braking Fields

- 15 mg/min Li, n=1 active mode control
- Low-levels of low-n MHD activity



Max NTV torque from braking near R=135 cm (Zhu et al, '06)

Note suppressed zero



@r/a~0.7

Little effect of rotation/rotation shear on global confinement

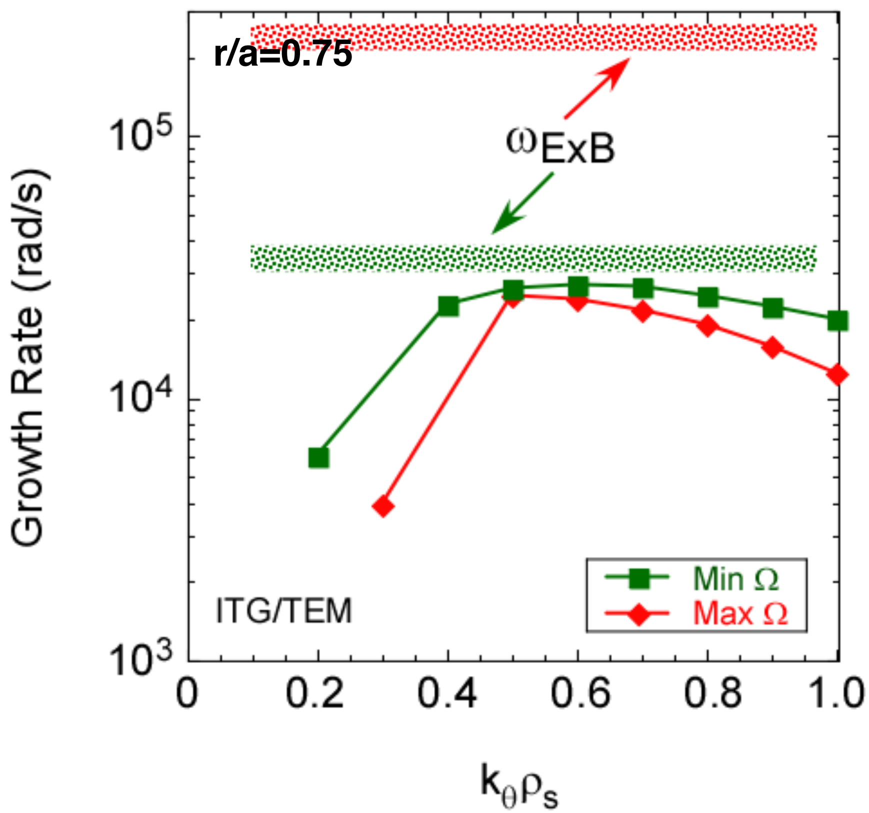
Rotation shear is acting on a small part of plasma

– Improvement may be spatially limited

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

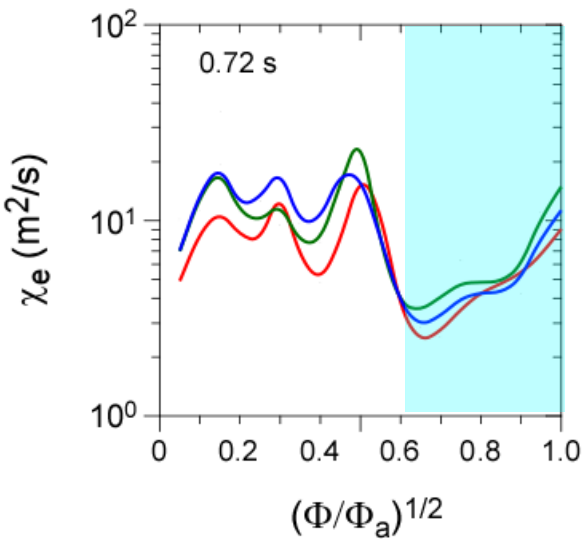
ω_{ExB} >> γ_{lin} for high Ω, $\nabla\Omega$ case

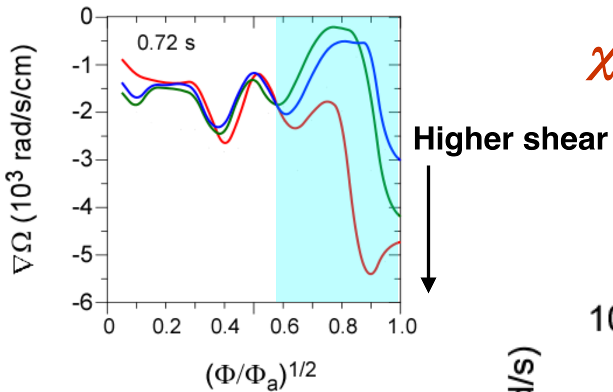
~ γ_{lin} for low Ω, $\nabla\Omega$ case



- 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

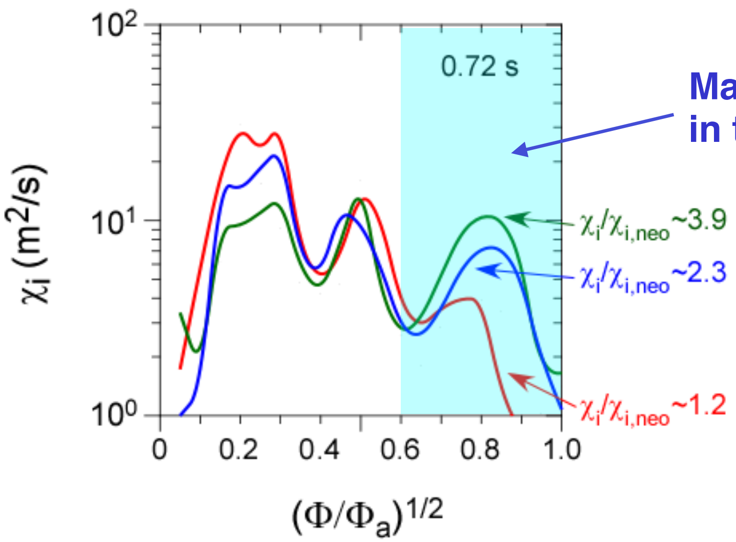
Thermal Diffusivities Decrease with Increasing Rotation Shear (Most Notably χ_i)





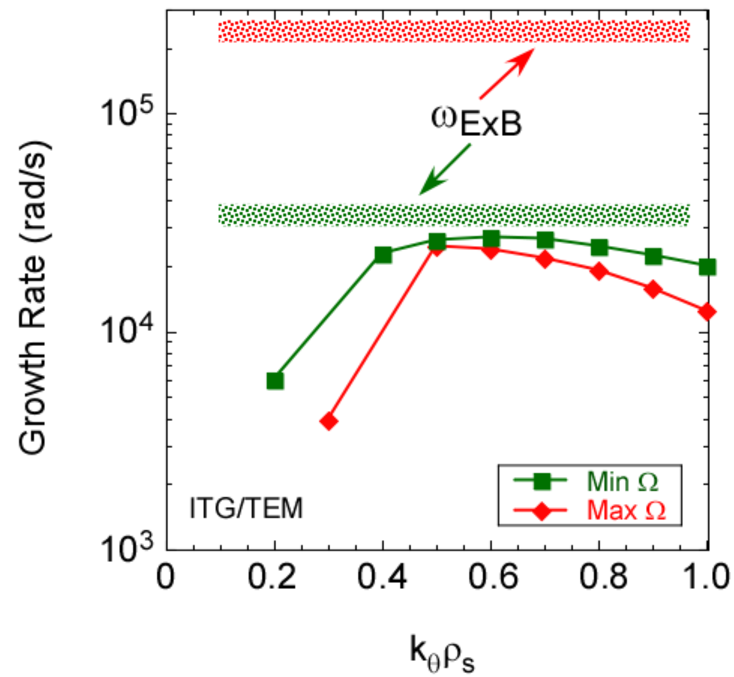
Min rotation, shear

Max rotation, shear



$\chi_i/\chi_{i,neo}$ ~ 1 when $\omega_{ExB} >> \gamma_{lin}$

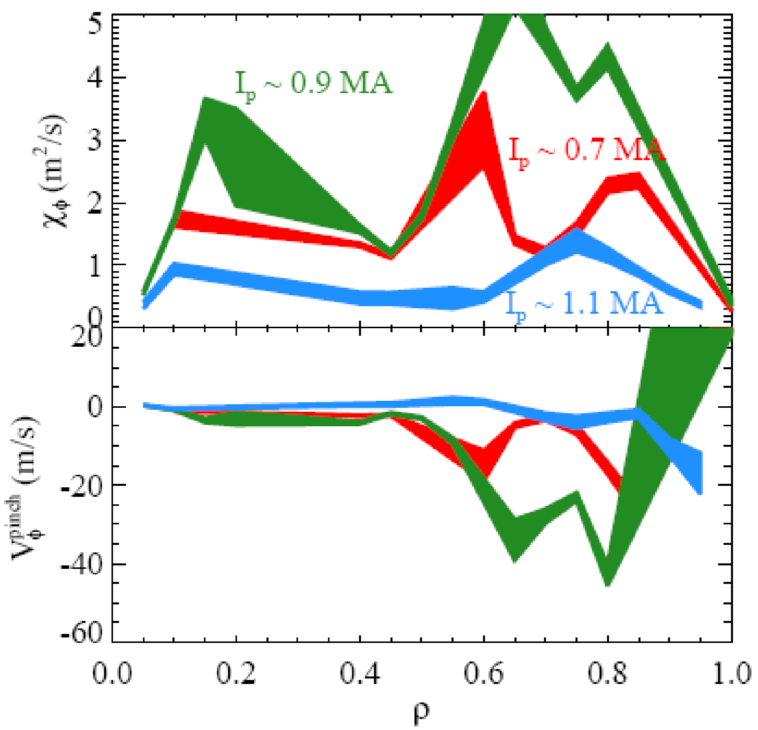
> 1 when $\omega_{ExB} \sim \gamma_{lin}$



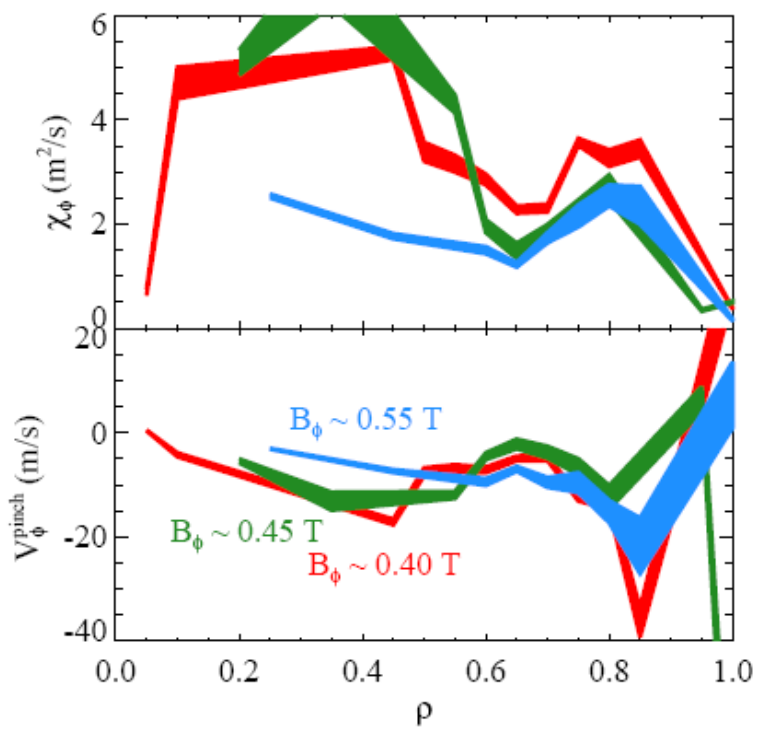
Non-linear calculations needed to determine magnitude of low-k turbulence reduction and resulting heat flux levels

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

I_p scan



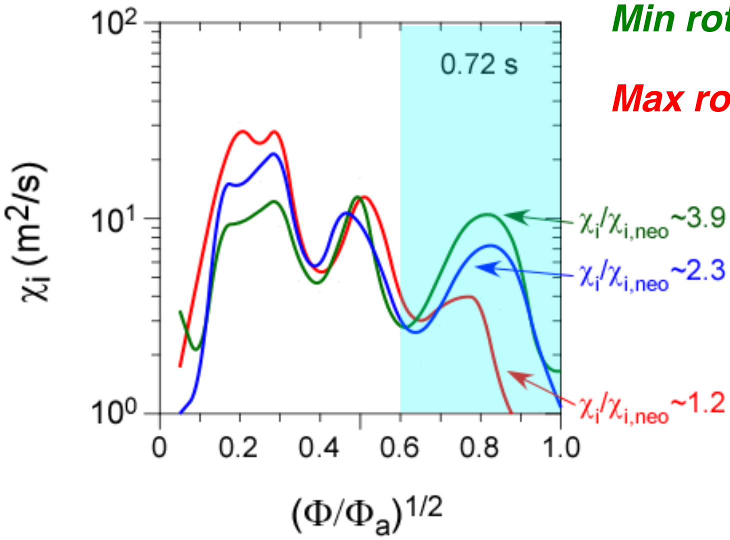
B_T scan



χ_ϕ, v_{pinch} at each position not all equally valid (depends on v_ϕ, ∇v_ϕ decoupling)

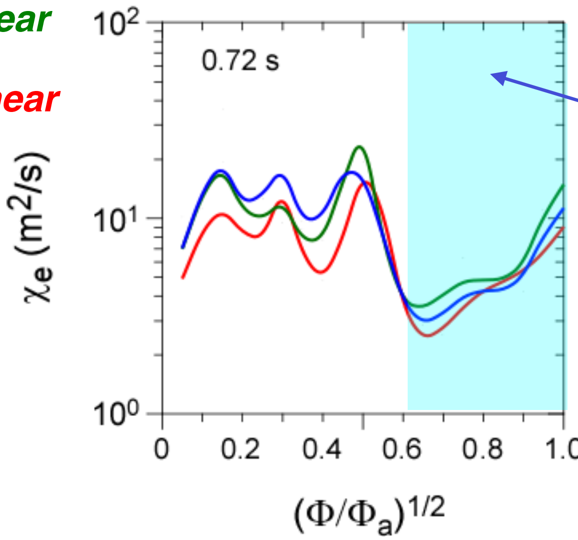
Not clear if there is a controlling current and/or field dependence to χ_ϕ, v_{pinch} variation

Thermal Diffusivities Correlate with Rotation and Rotation Shear

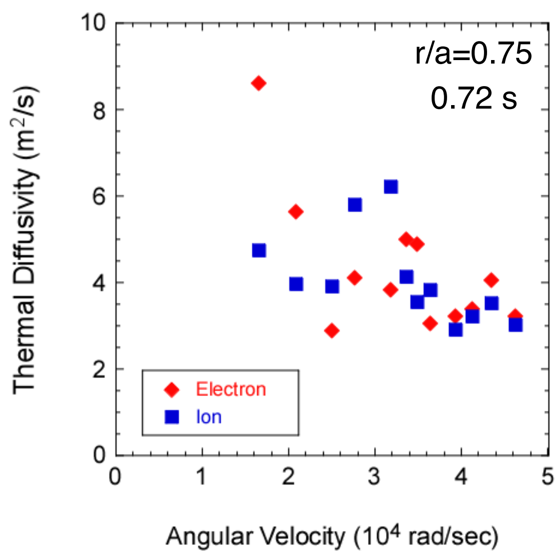


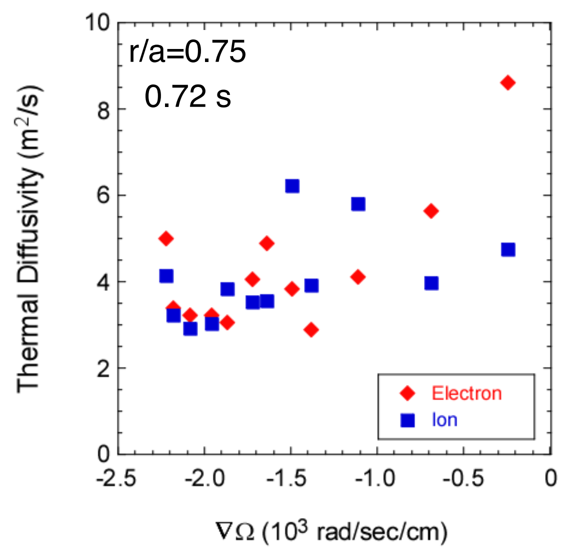
Min rotation, shear

Max rotation, shear

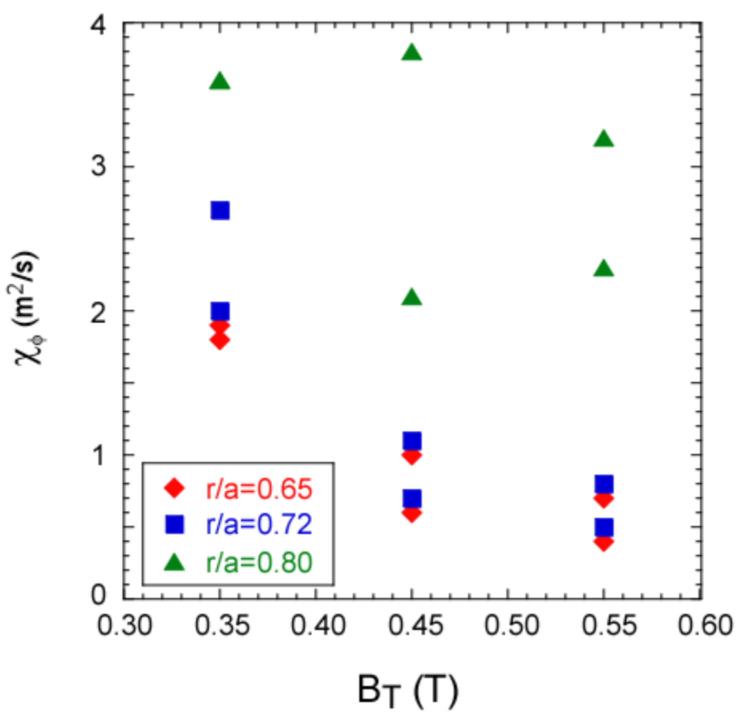


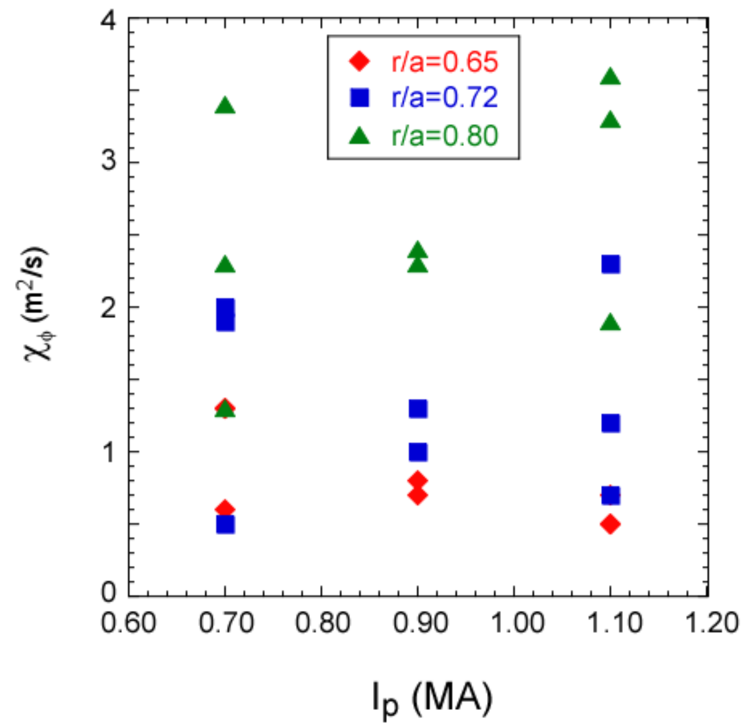
Max variation of ∇Ω in this region





χ_ϕ Decreases With Increasing B_T at Some Outer Locations



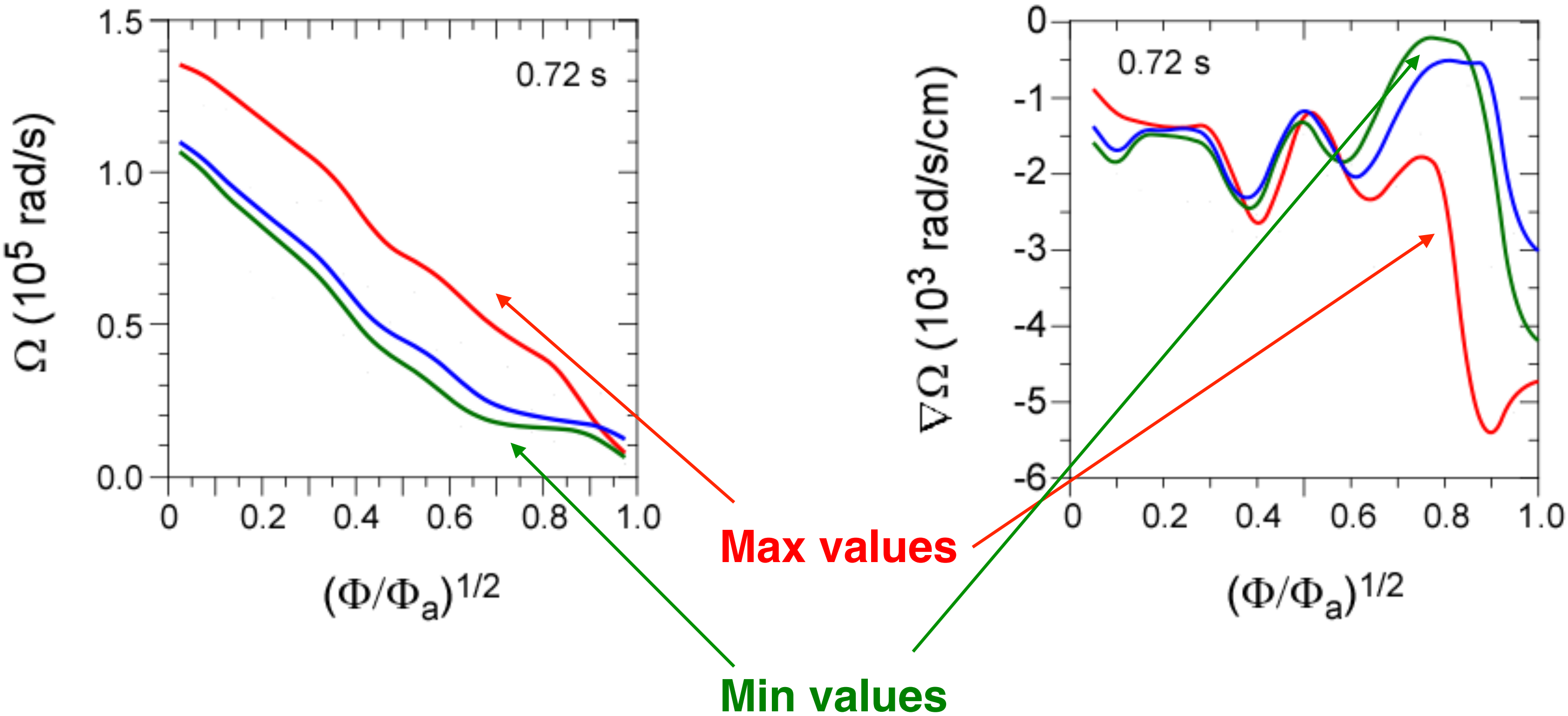


- No dependence on I_p
- No dependence on B_T or I_p in core region
- V_{pinch} shows no dependence on I_p or B_T in core or gradient regions

Effects of Magnetic Braking Seen Across Profile in Equilibrium

Decrease in rotation across profile

Variation in rotation shear seen mainly in outer portion of plasma



Inclusion of Momentum Pinch Leads to Better χ_ϕ, χ_i Correlation in the Outer (Gradient) Region

- Assume either Peeters and Hahm pinch using measured ∇v and L_n
- Compute "corrected" χ_ϕ
- Large scatter remains; still no χ_e, χ_ϕ correlation