Why Magnetically Confined Plasmas Rotate, and Why it is Important

Stanley M. Kaye
Princeton Plasma Physics Laboratory
Princeton University, Princeton NJ 08543

American Physical Society Meeting
Atlanta, GA
31 March-2 April 2012

PPPL
PRINCETON
PLASMA PHYSICS
LABORATORY

Office of Science
U.S. DEPARTMENT OF ENERGY

I would like to acknowledge the direct and indirect contributions of:

C. Angioni[1], P. Diamond[2], S.-H. Ku[3], R. McDermott[1], J.-K. Park[3], J. Rice[4], F. Ryter[1] **W. Solomon[3]**, T. Tala[5], W. Wang[3], M. Yoshida[6]

[1] Max-Planck Institut fur Plasmaphsik, Garching, Germany

[2] UCSD, San Diego CA, USA

[3] PPPL, Princeton University, Princeton NJ, USA

[4] PSFC, MIT, Cambridge MA, USA

[5] Association Euratom-Tekes, VTT, Finland

[6] JAEA, Japan

This work was supported in part by U.S. DOE Contract # DE-AC02-09CH11466

In this talk, I will explore aspects of rotation and momentum confinement in magnetically-confined plasmas

I. Background

- Magnetically confined plasmas in tokamaks/spherical tokamaks
- Rotation observed in other configurations (stellarator, RFP, linear devices), but will focus on tokamak/ST

II. Why is rotation important

- Stabilization of micro-, macro-turbulence leads to higher performance

III. How do rotation profiles develop and evolve – how can we understand rotation?

- Rotation generation (driven, self-generated)
- Transport of momentum

  Find tokamak/ST results similar → gives glimpse into underlying common physics

- Predictions for fusion power devices (ITER)

III. Future work and summary

- What else do we need to understand

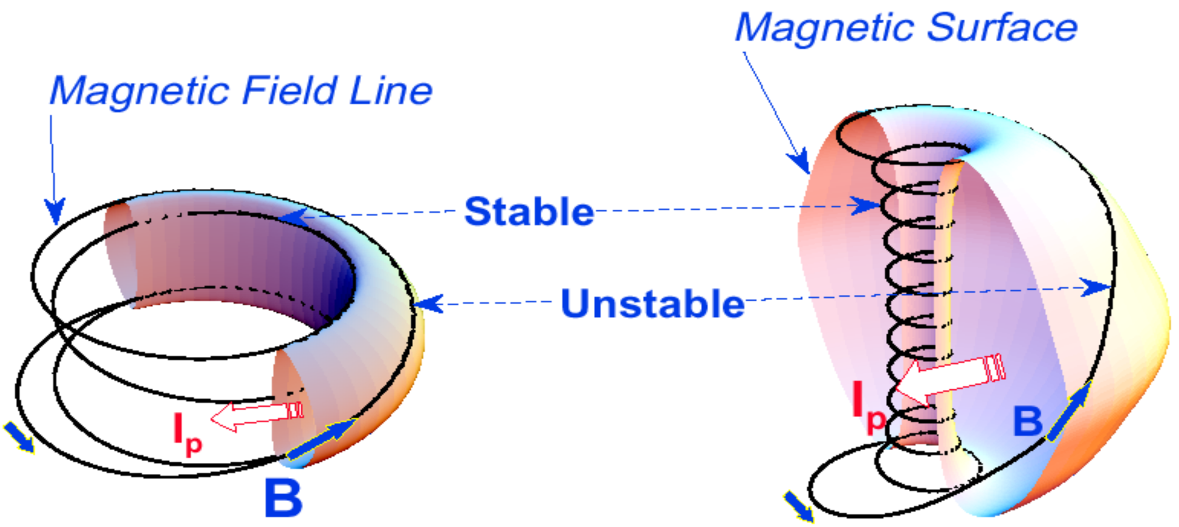
Rotation/momentum transport strongly coupled primarily to ion-gyroradius scale turbulence

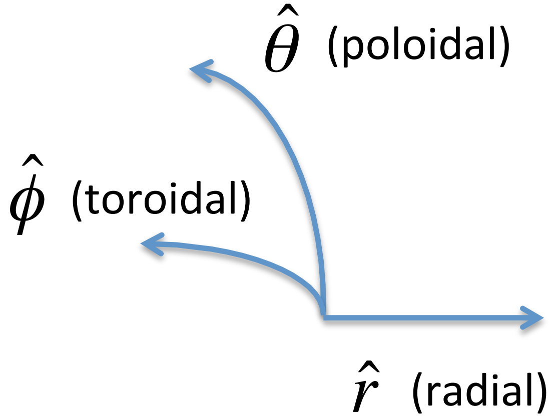
Fusion-grade plasmas are magnetically confined in toroidal devices

Most of tokamak research historically and presently conducted at conventional aspect ratio

Only a decade of research on Spherical Tokamaks (STs)

Strong toroidicity at low aspect ratio benefits both stability and confinement



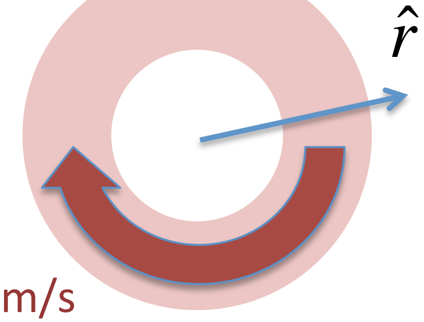


a~ 0.65 m, R~1.7 m

I_p ~ 1 MA, B_T~ few T

a~ 0.65 m, R~0.85 m

I_p ~ 1 MA, B_T~ 0.5 T



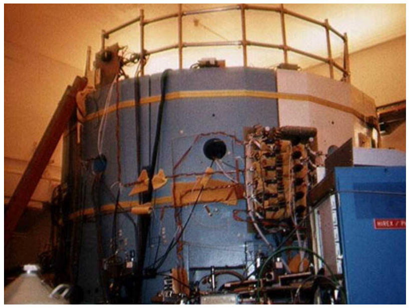
V_ϕ(center) up to 300 km/s

Rotation profiles measured by Doppler shift of spectroscopic lines

Results from tokamaks/STs from around the world contribute to this talk

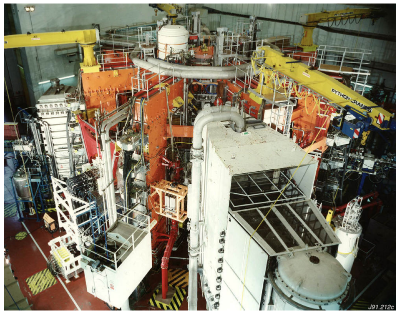
ASDEX-Upgrade (EU)

Alcator C-Mod (US)



DIII-D (US)

JET (UK/EU)



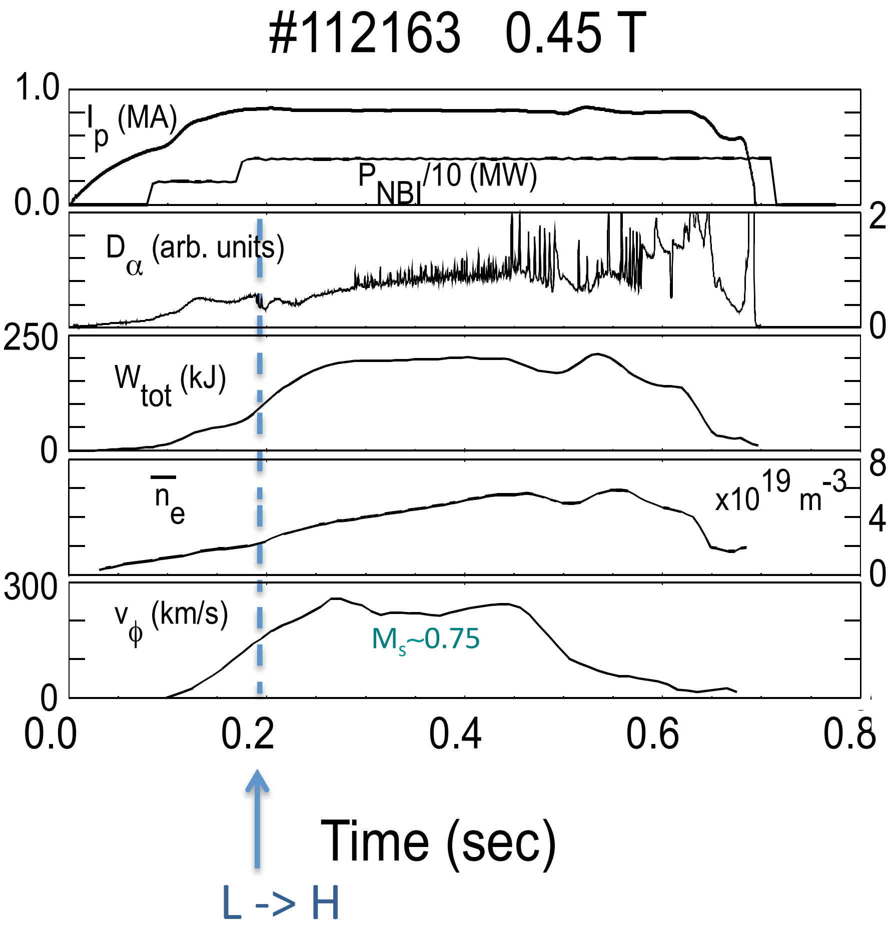
NSTX (US, ST)

MAST (UK, ST)

JT-60U (Japan)

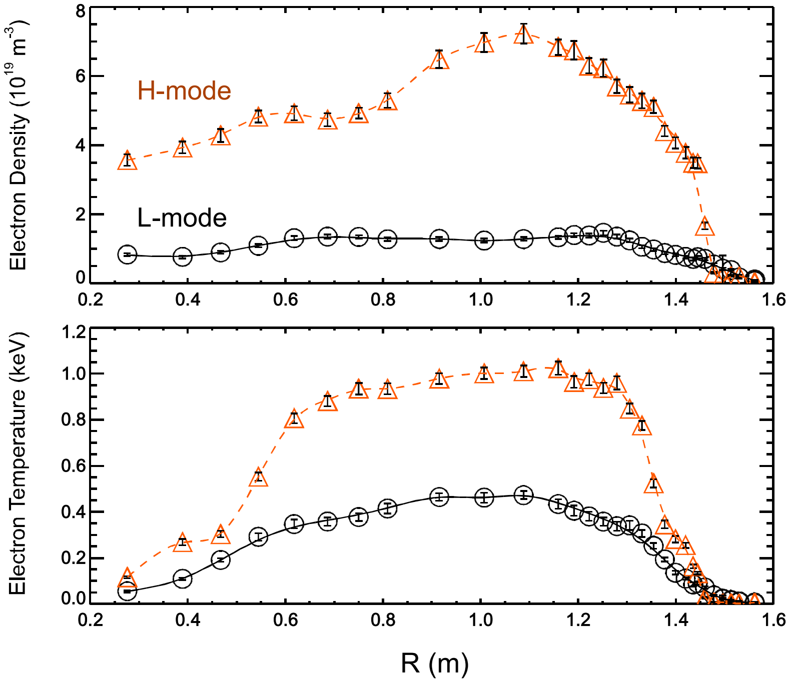
Evolution of key parameters during a plasma discharge

NSTX



Plasma undergoes abrupt transition from a lower to a higher energy state at ~ 0.2 s

Low (L-) ➔ High (H-) confinement mode (observed on all devices)



In this talk, I will explore aspects of rotation and momentum confinement in magnetically-confined plasmas

I. Background
- Magnetically confined plasmas in tokamaks/spherical tokamaks
- Rotation observed in other configurations (stellarator, RFP, linear devices), but will focus on tokamak/ST

II. Why is rotation important
- Stabilization of micro-, macro-turbulence leads to higher performance

III. How do rotation profiles develop and evolve – how can we understand rotation?
- Rotation generation (driven, self-generated)
- Transport of momentum

  Find tokamak/ST results similar ⇒ gives glimpse into underlying common physics
- Predictions for fusion power devices (ITER)

III. Future work and summary
- What else do we need to understand

There are two main sources of radial transport in tokamaks/STs

1. Neoclassical – collisional processes in toroidal systems

   ➔ sets minimum transport level
2. Anomalous– turbulent microinstabilities: scale lengths from the ion to the electron gyroradius

Most of the transport in tokamaks/STs is anomalous

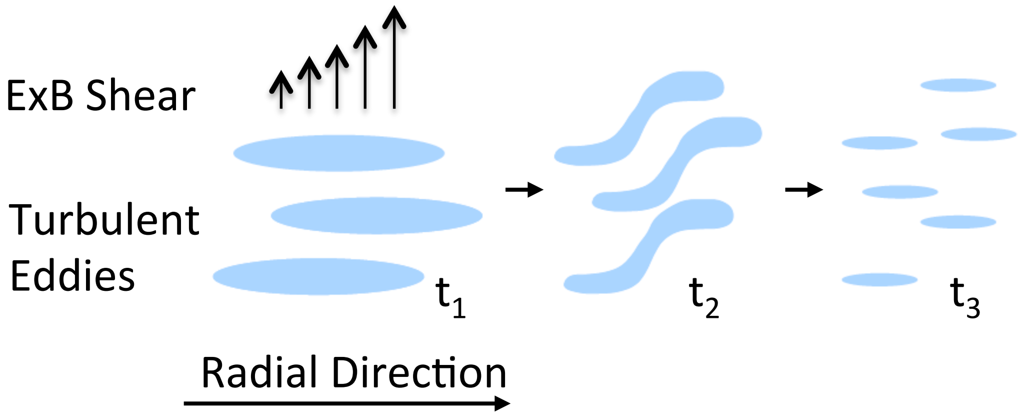
Rotation plays an important role in the suppression of microturbulence

E_{radial} determined by $\nabla p, v$

$$E_{radial} = \frac{\nabla p}{n_i Z e} + v_\phi B_\theta - v_\theta B_\phi$$

Usually dominant

E_rxB shear can stretch and break up turbulent eddies

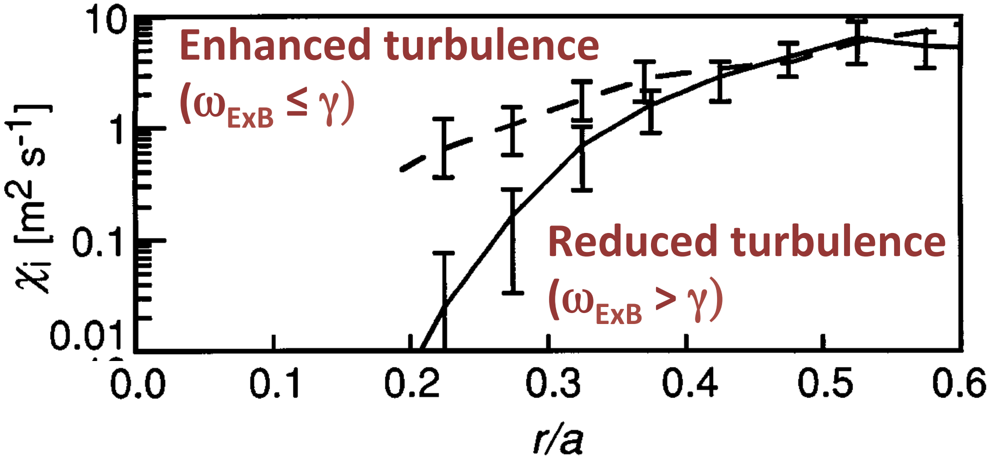


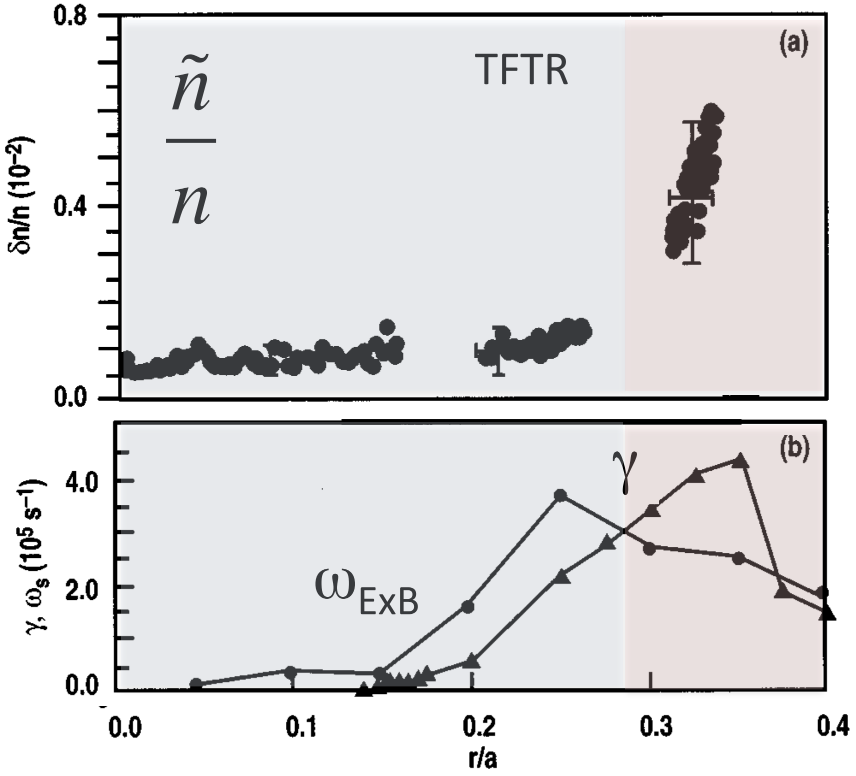
Rule of thumb: turbulence suppression when $\omega_{ExB} > \gamma_{mode}$

Larger ExB shear is correlated with reduced turbulence and reduced transport

Reduced ion-scale turbulence when $\omega_{ExB} > \gamma$

Ion thermal diffusivity (a measure of radial transport of heat) is lower when turbulence is lower

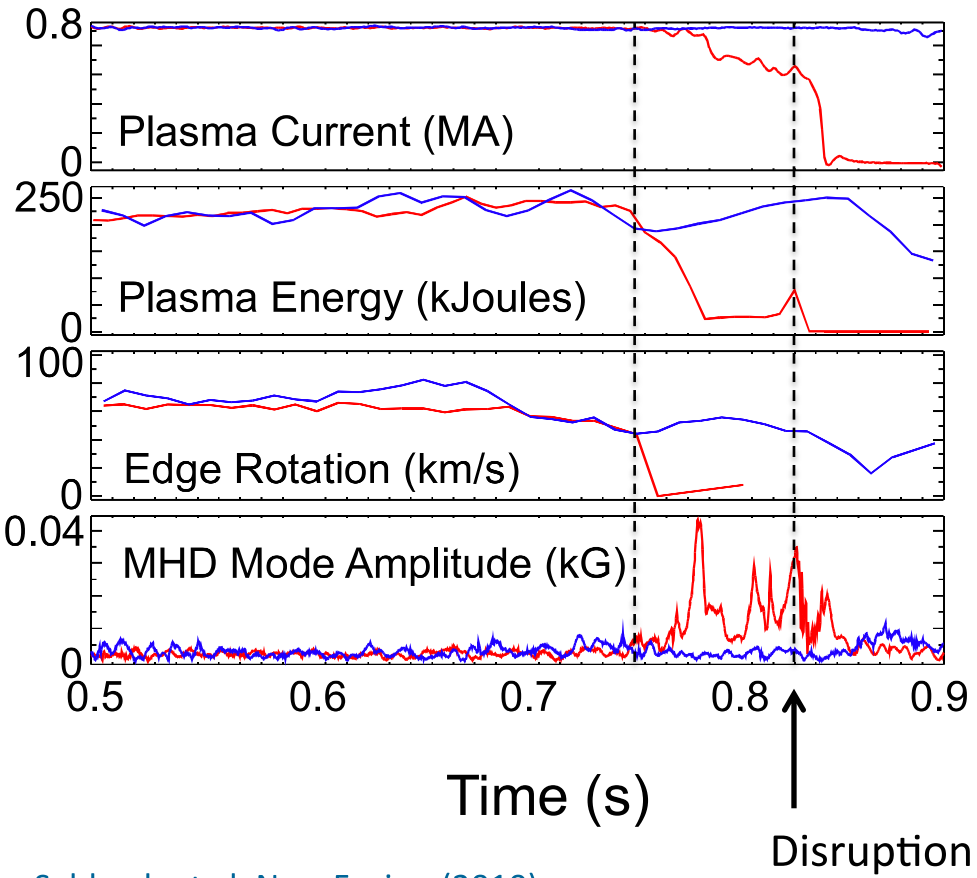




Mazzucato et al., PRL (1996)

Rotation important for the suppression of macro-scale MHD modes that can lead to sudden plasma termination

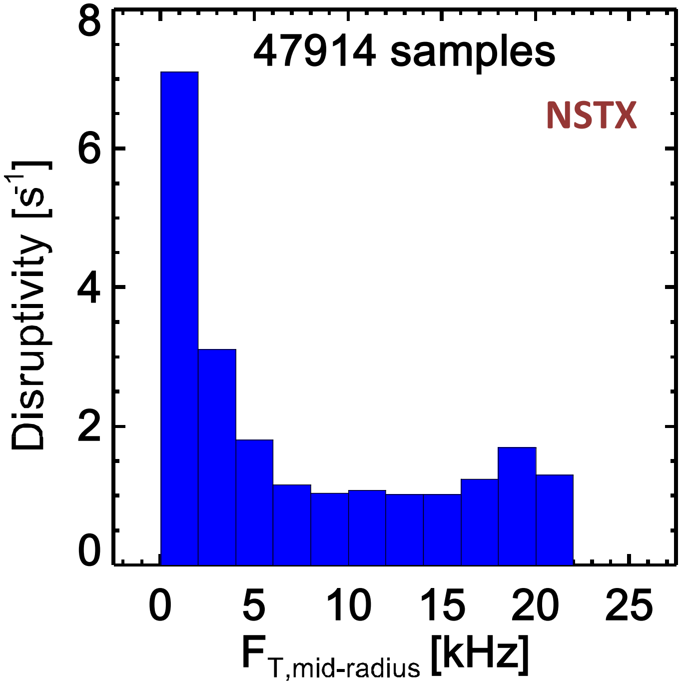
MHD mode growth follows damping of rotation – **disruption** follows



Sabbagh et al, Nuc. Fusion (2010)

also on DIII-D: Garafalo et al, Nuc. Fusion (2001)

Higher rate of disruptivity with lower rotation



S. Gerhardt (2012)

In this talk, I will explore aspects of rotation and momentum confinement in magnetically-confined plasmas

I. Background
  - Magnetically confined plasmas in tokamaks/spherical tokamaks
  - Rotation observed in other configurations (stellarator, RFP, linear devices), but will focus on tokamak/ST

II. Why is rotation important
  - Stabilization of micro-, macro-turbulence leads to higher performance

III. How do rotation profiles develop and evolve – how can we understand rotation?
  - Rotation generation (driven, self-generated)
  - Transport of momentum

    Find tokamak/ST results similar ➡ gives glimpse into underlying common physics

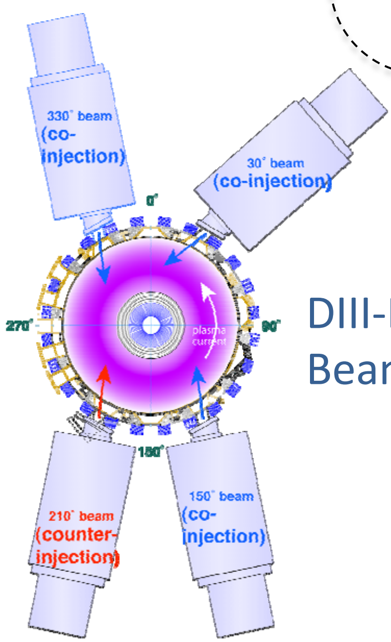
  - Predictions for fusion power devices (ITER)

III. Future work and summary
  - What else do we need to understand

Momentum balance *is the basis for addressing the* ***sources*** *and* ***transport*** *of rotation and momentum*

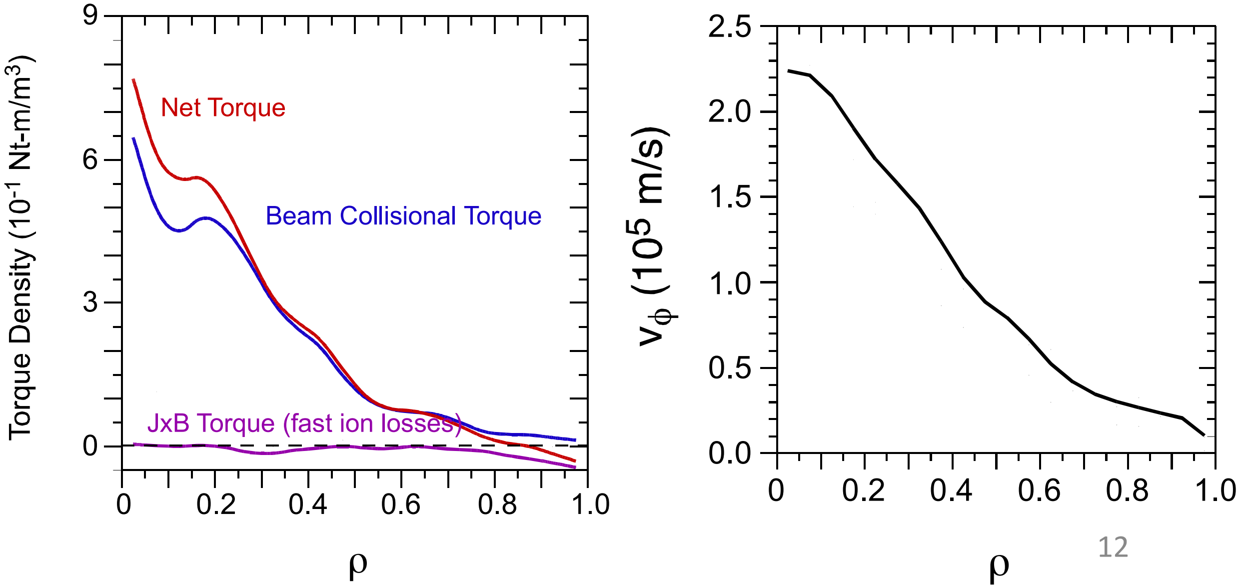
$$\underbrace{mnR\frac{\partial v_\phi}{\partial t}}_{\text{Time rate of change of angular momentum}} = \underbrace{\sum T_{input}}_{\text{Input torques}} - \underbrace{\nabla\cdot\Pi_\phi}_{\text{Momentum transport}} - \underbrace{\frac{mnR(v_\phi - v_\phi^*)}{\tau_{damp}}}_{\text{Viscous torque (c-x, i-i, etc)}}$$

$$= T_{driven} + T_{intrinsic}$$



DIII-D Neutral Beam Injectors

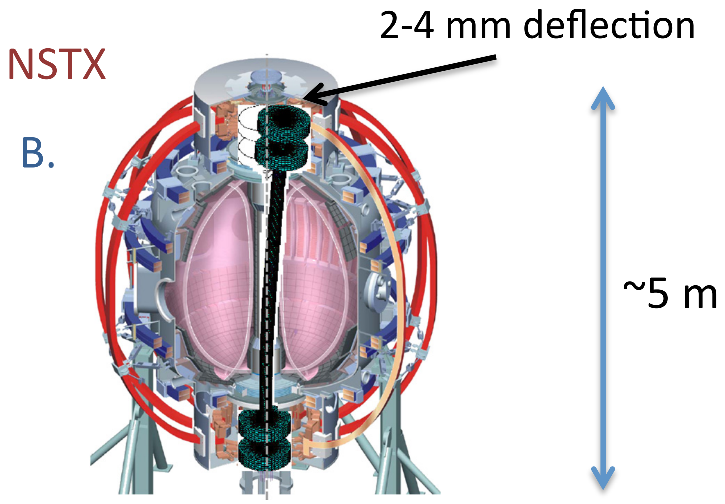
Neutral beam injection provides torque through classical collisions to drive rotation

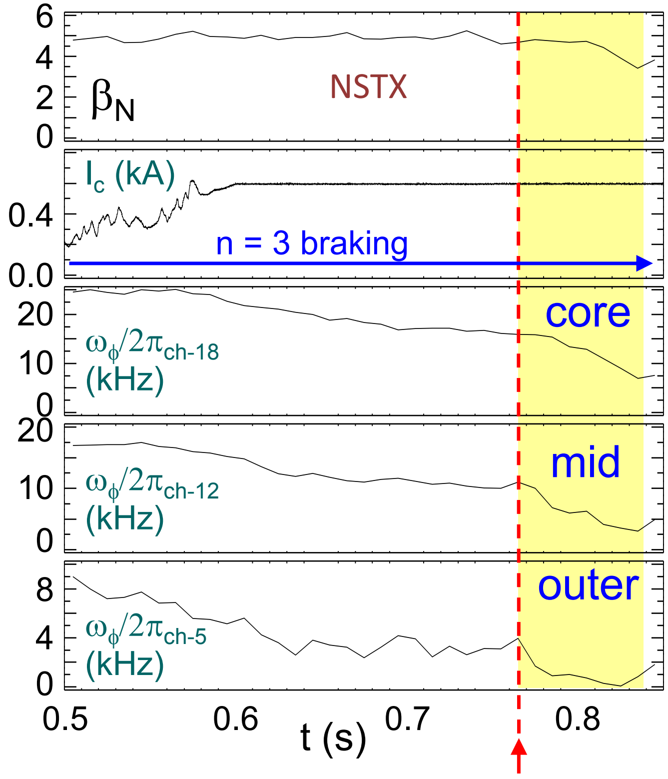


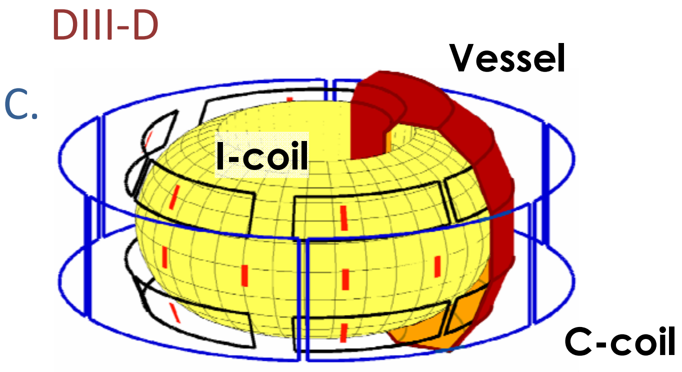
Magnetic field asymmetries are a source of viscous torque

- 3D toroidal magnetic field asymmetries can result from
  A. Magnetic field ripple (finite # TF coils) – studied in JET
  B. Intrinsic error fields (coil misalignments or motion during discharge due to JxB forces)
  C. Applied non-axisymmetric B-field perturbations at edge

Sabbagh et al. (2010)







$T_{NBI} \sim T_{\Delta B}$

Magnetic field (ctr) torque increases at low rotation; consistent with theory:
Park et al. PRL (2009), Cole et al. PRL (2011)

There is evidence that some "intrinsic drive" exists in tokamak/ST plasmas

Momentum evolution given by

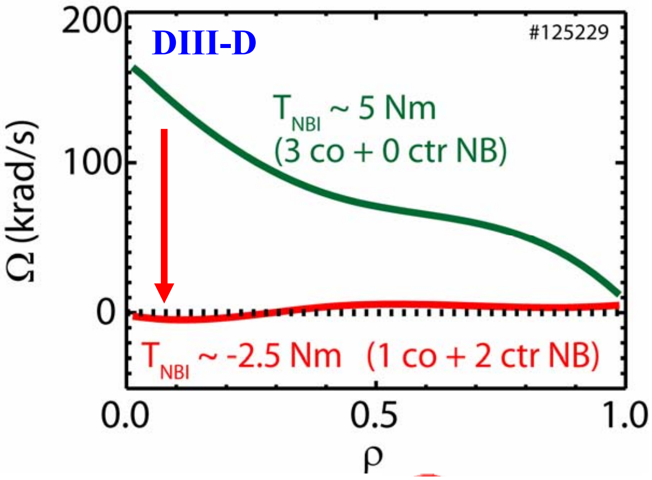
$$\frac{dL(\rho)}{dt} = T_{NBI} + T_{intrinsic} - \frac{L}{\tau_{\phi}}$$

Solve for two unknowns from time evolution of angular momentum, L

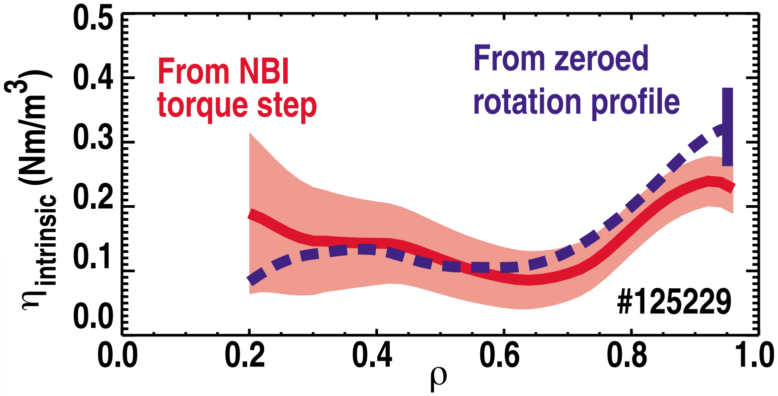
Co-, ctr-NBI on DIII-D allows for flexibility to produce <u>non-rotating</u> plasmas across profile

For steady-state, can produce non-rotating plasmas when:

$$T_{NBI} = -T_{intrinsic}$$



Can also measure intrinsic torque via evolution of angular momentum



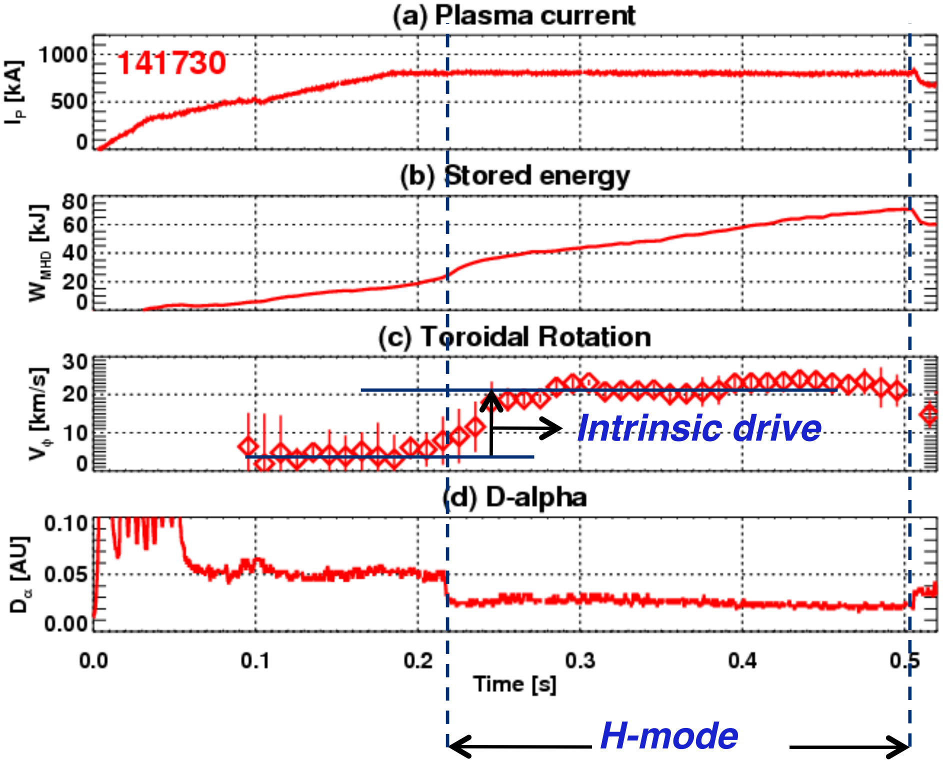
Solomon et al. PoP (2010)

Edge intrinsic torques lead to edge intrinsic rotation

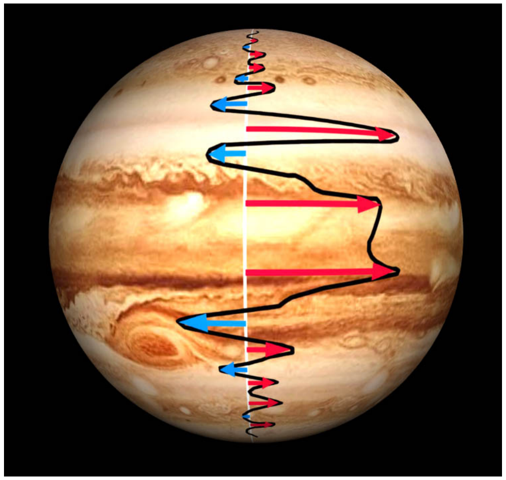
Typically use L-H transitions in OH or RF-heated (torque-free) plasmas to study change in intrinsic rotation

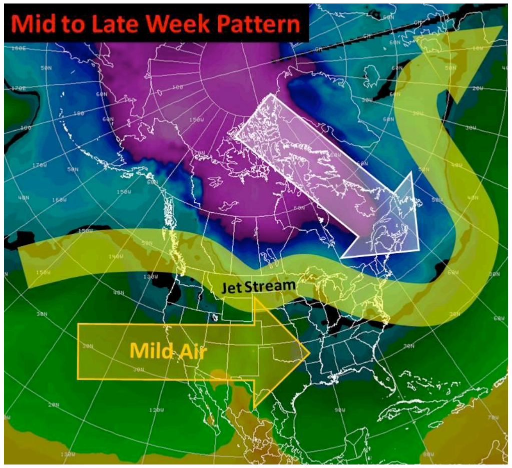
Self-generated flow is seen in a number of physical systems

NSTX



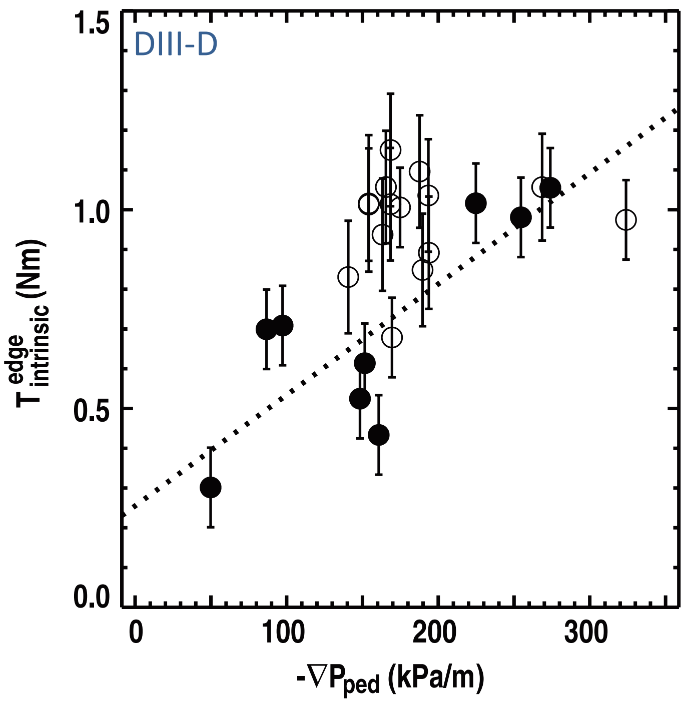
Park (2011)





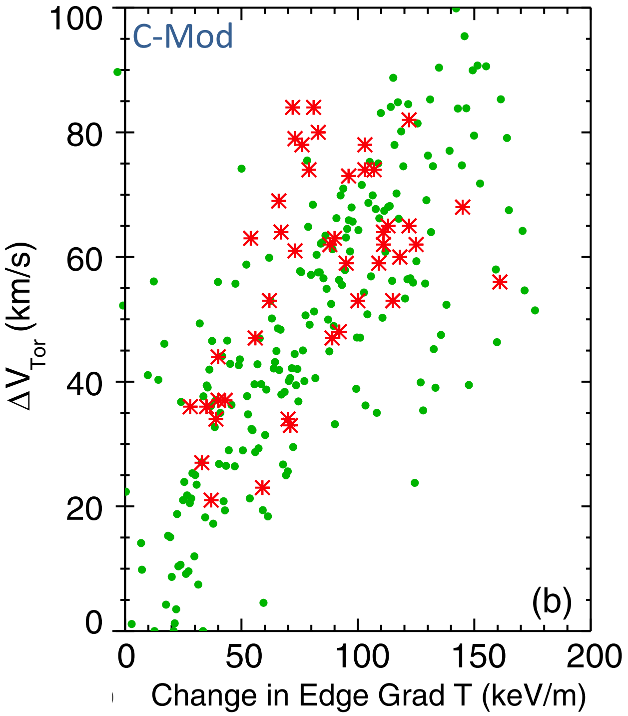
Intrinsic drive and rotation appears to be controlled strongly by $\nabla p, \nabla T_i$ respectively

Intrinsic torque scales with ∇p



Solomon et al. NF (2011)

Intrinsic rotation scales with ∇T



Rice et al. PRL (2011)

Dependences consistent with ion-scale turbulence theory:

Gurcan et al. PoP (2007), Wang et al. PoP (2010),
Kosuga et al. PoP (2010), Gurcan et al. PoP (2010)

In this talk, I will explore aspects of rotation and momentum confinement in magnetically-confined plasmas

I. Background
  - Magnetically confined plasmas in tokamaks/spherical tokamaks
  - Rotation observed in other configurations (stellarator, RFP, linear devices), but will focus on tokamak/ST

II. Why is rotation important
  - Stabilization of micro-, macro-turbulence leads to higher performance

III. How do rotation profiles develop and evolve – how can we understand rotation?
  - Rotation generation (driven, self-generated)
  - Transport of momentum

    Find tokamak/ST results similar ➡ gives glimpse into underlying common physics

  - Predictions for fusion power devices (ITER)

III. Future work and summary
  - What else do we need to understand

Now that sources of rotation are established, need to understand what controls momentum transport & development of rotation profile

$$mnR\frac{\partial v_\phi}{\partial t} = \sum T_{input} - \underbrace{\nabla\cdot\Pi_\phi}_{\text{Momentum transport}} - \frac{mnR(v_\phi - v_\phi^*)}{\tau_{damp}}$$

$$-\nabla\bullet\left(-mR\left[\langle n\rangle\underbrace{\langle\tilde{v}_r\tilde{v}_\phi\rangle}_{\text{Reynold's stress}} + v_\phi\underbrace{\langle\tilde{v}_r\tilde{n}\rangle}_{\text{Particle flux}}\right]\right)$$

A theorist's approach

Langmuir probes can measure Reynold's stress and particle flux near the edge in lower temperature devices (Prager, PPCF 1999); these measurements are challenging on high temperature tokamaks/STs

Momentum transport characteristics can be inferred from experimental data

$$mnR\frac{\partial v_\phi}{\partial t} = \sum T_{input} - \underbrace{\nabla\cdot\Pi_\phi}_{\text{Momentum transport}} - \frac{mnR(v_\phi - v_\phi^*)}{\tau_{damp}}$$

$$-\nabla\bullet\left(-mnR\left[\chi_\phi^{eff}\frac{\partial v_\phi}{\partial r}\right]\right)$$

Steady-state momentum balance with known torques (diffusion paradigm)

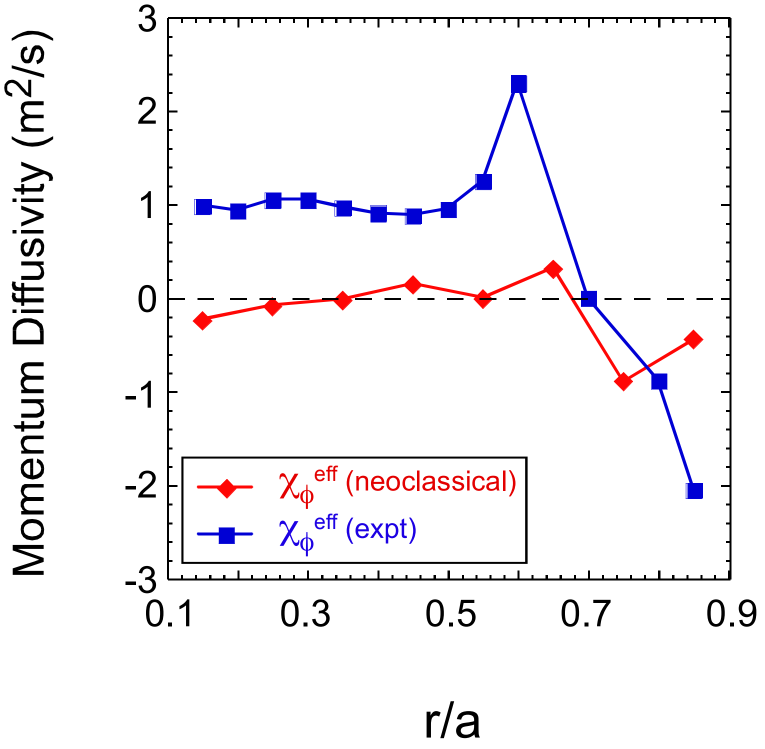
$$-\nabla\bullet\left(-mnR\left[\underbrace{\chi_\phi}_{\text{Conduction}}\frac{\partial v_\phi}{\partial r} - \underbrace{v_r}_{\text{Convection}} v_\phi\right]\right)$$

Perturbation analysis allows separation of diffusive and pinch terms

Steady-state analysis shows that momentum transport is always anomalous

χ_ϕ neoclassical ≈ 0

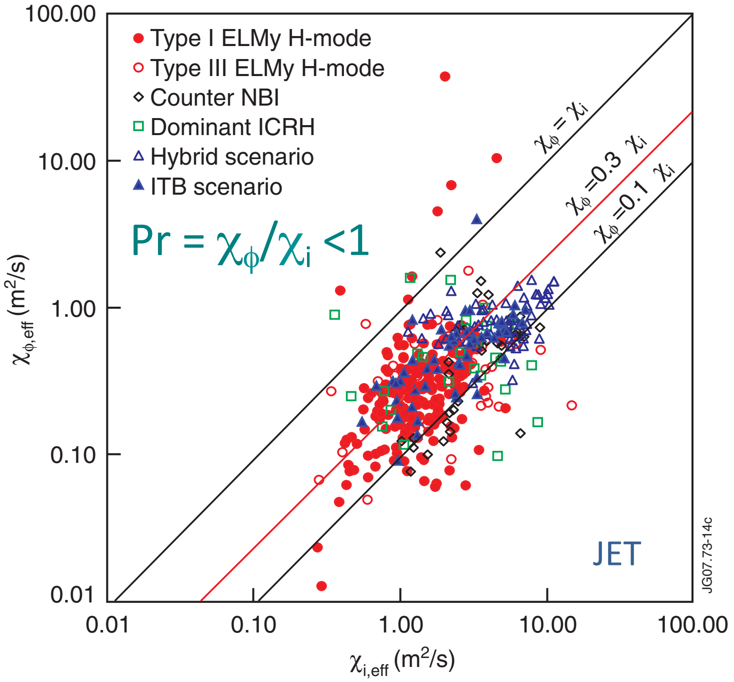
$\chi_\phi >> \chi_{\phi,neo}$(turbulence impt!)



Kaye et al. Nuc. Fusion (2009)

Ion-scale turbulence theory predicts χ_ϕ~χ_i

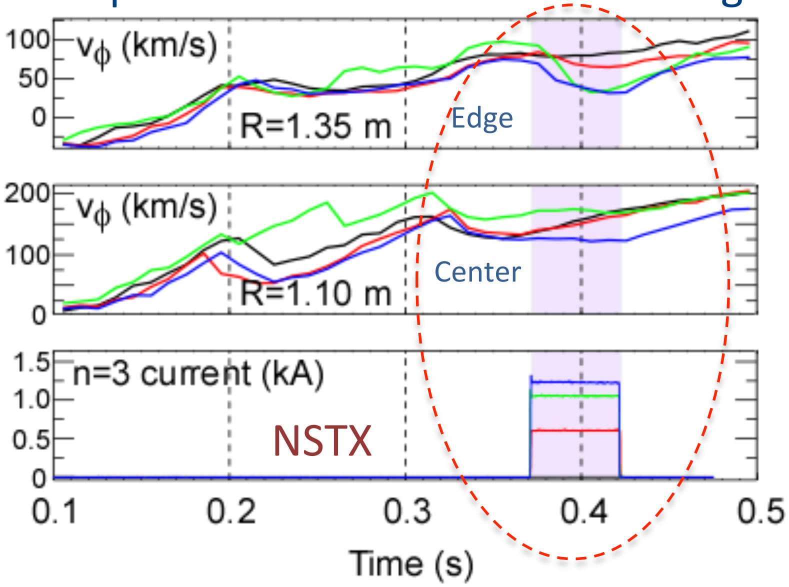
χ_ϕ~ 0.1-0.4 χ_i from experiment



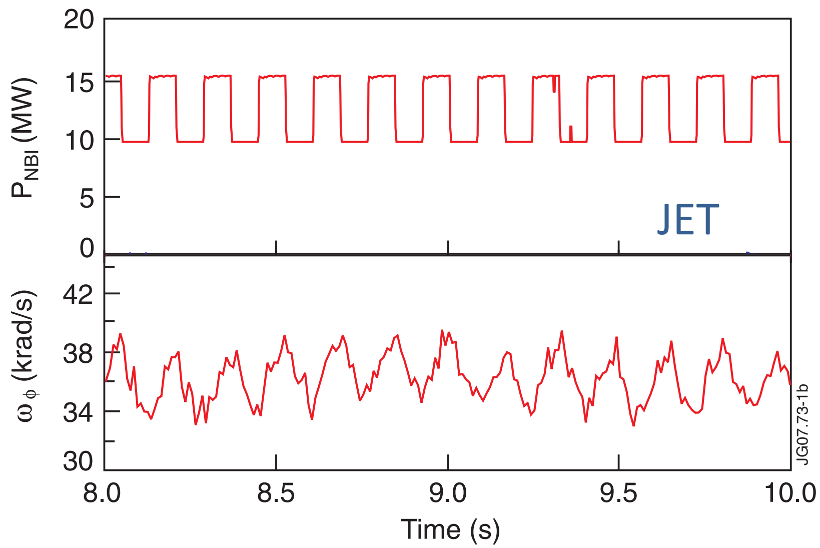
Tala et al. PPCF (2009)

Perturbation techniques used to isolate χ_ϕ, v_{pinch}

ΔB pulse modifies rotation near edge

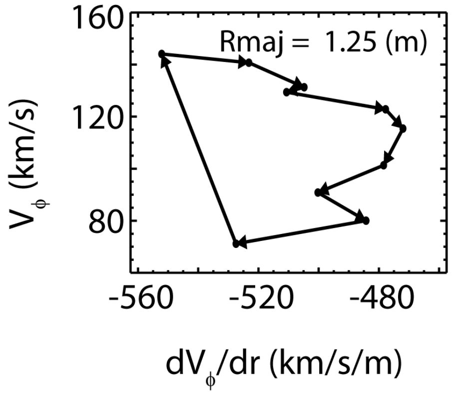


NB modulation



NB pulse preferentially modifies rotation near core

Separation of v_ϕ, ∇v_ϕ essential to determining χ_ϕ, v_{pinch}

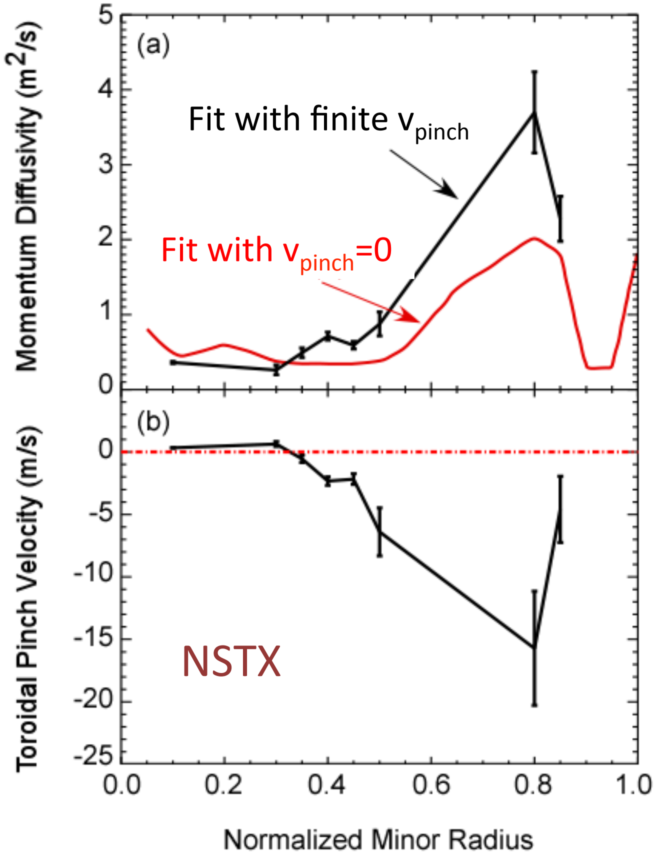


Use forward modeling to determine χ_ϕ, V_{pinch} by matching phase, amplitude of response

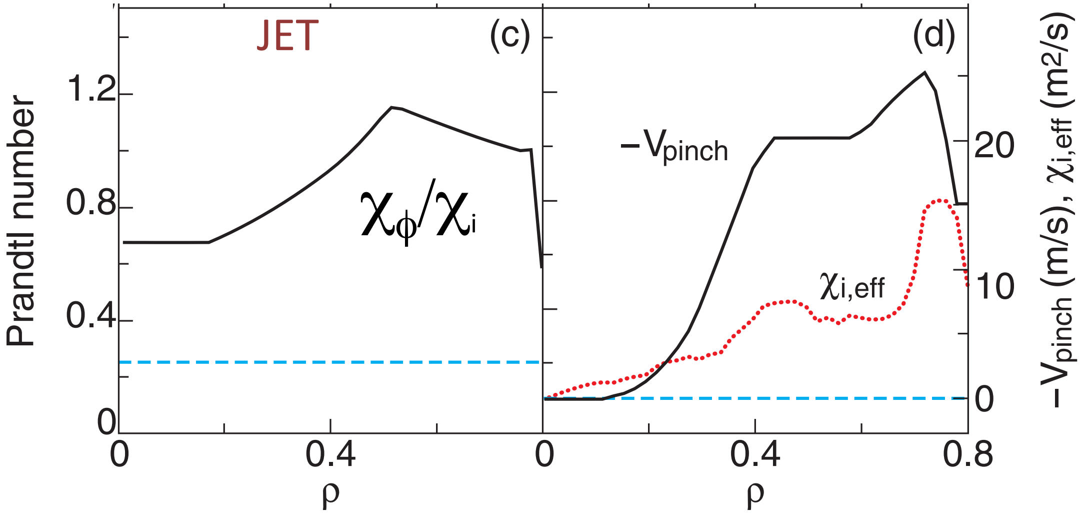
Tala et al. PRL (2009)

Perturbative momentum transport analysis reveals significant inward pinch in outer region of plasma

ΔB pulse



NB modulation



Tala et al. PRL (2009)

χ_ϕ (finite v_{pinch})~ $2\chi_\phi^{eff}$ (v_{pinch}=0)

Including v_{pinch} brings Pr closer to ion-scale turbulence theory prediction (~1)

Developing a comprehensive theoretical model of momentum transport is challenging

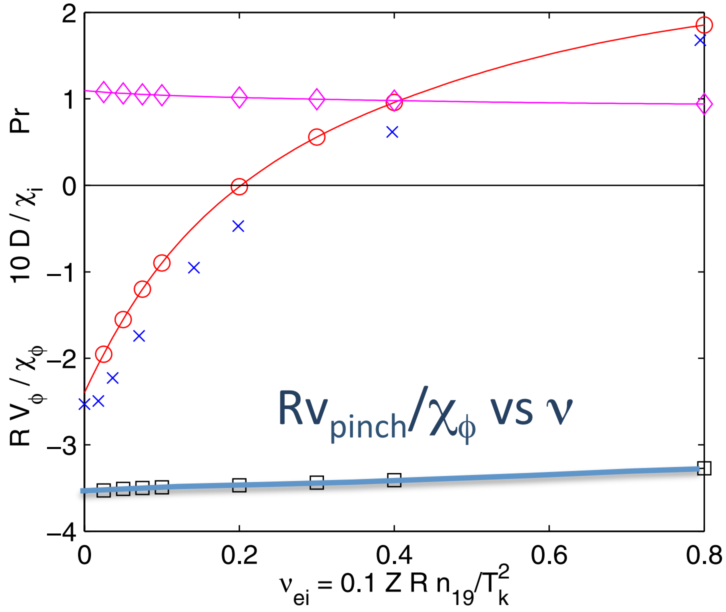
- Need to know
  - Realistic boundary conditions
  - Importance of off-diagonal terms in turbulence generation
  - Nature of turbulence (strongly turbulent or near marginality)
- Fluid treatment of plasma can capture much physics, but almost always need to include kinetic effects

- ⇨ Validation of theoretical model through comparisons with experimental data

> Are there any dominant parametric dependence (or lack thereof) predicted by theory that can be tested?
>
> → Some insight, but questions remain

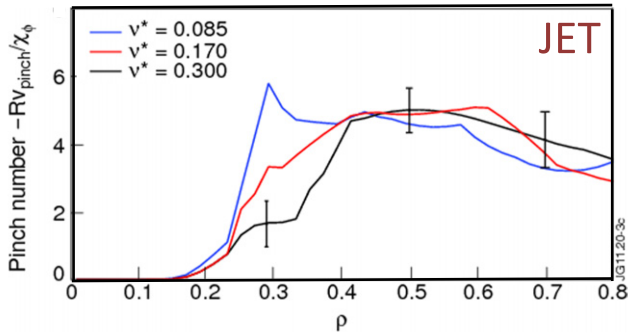
Ion-scale turbulence theory predicts virtually NO dependence of pinch number (Rv_{pinch}/χ_ϕ) on collisionality (ν)

Theory

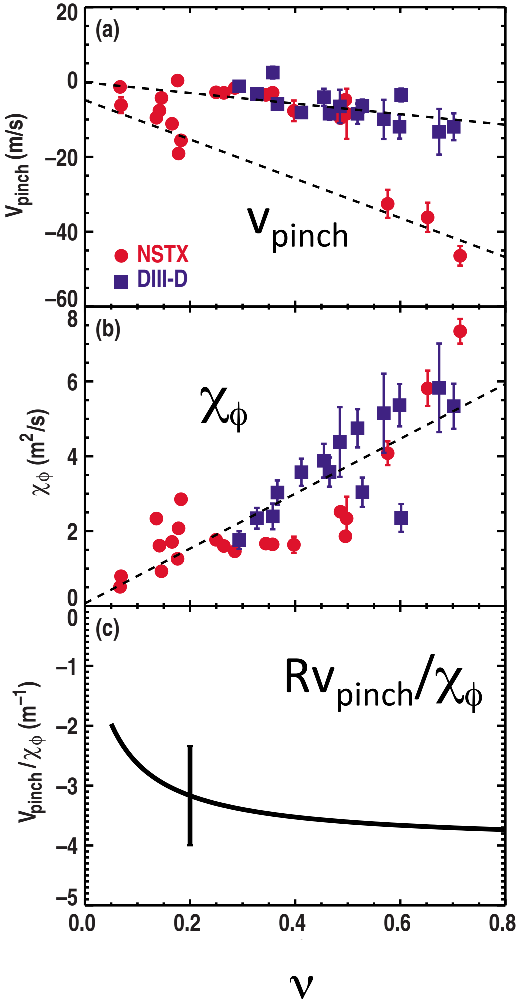


Peeters et al. PoP (2009)

Experiment



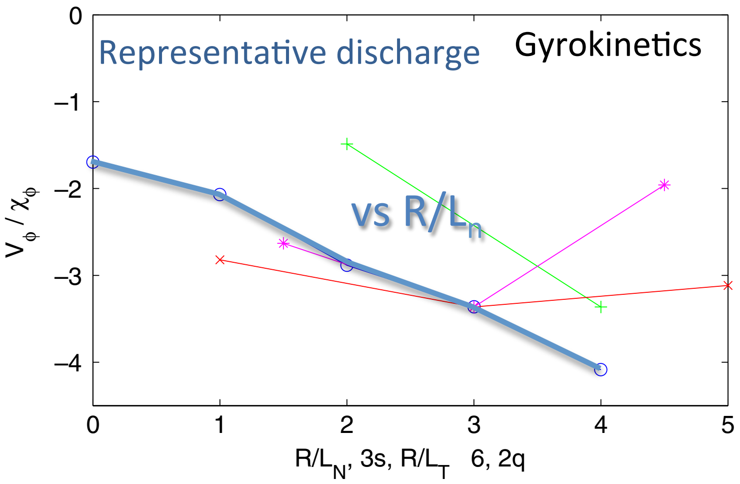
Tala et al. Nucl. Fusion (2011)



Solomon et al. PoP (2011)

Ion-scale turbulence theory predicts dependence of pinch number (Rv_{pinch}/χ_ϕ) on density gradient (R/L_n)

Theory



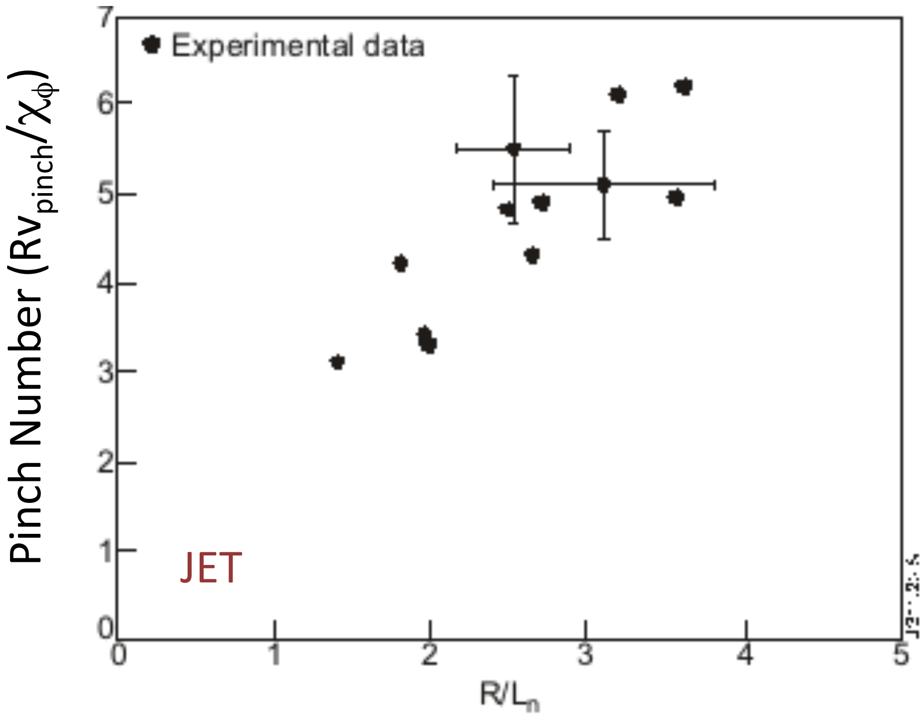
Peeters et al. Nucl. Fusion (2011)

Reduced fluid models also indicate linear dependence on R/L_n

Peeters et al. PoP (2009)

Yoon and Hahm (2011)

Experiment

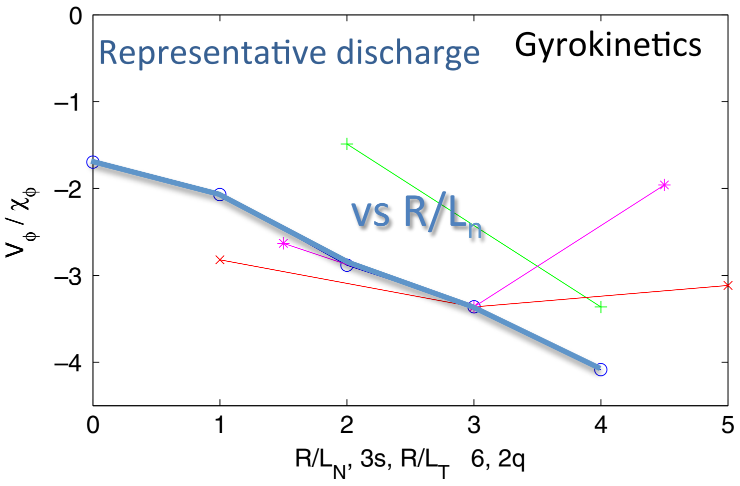


Tala et al. Nucl. Fusion (2011)

Also, ASDEX-Upgrade, DIII-D, JT-60U, NSTX

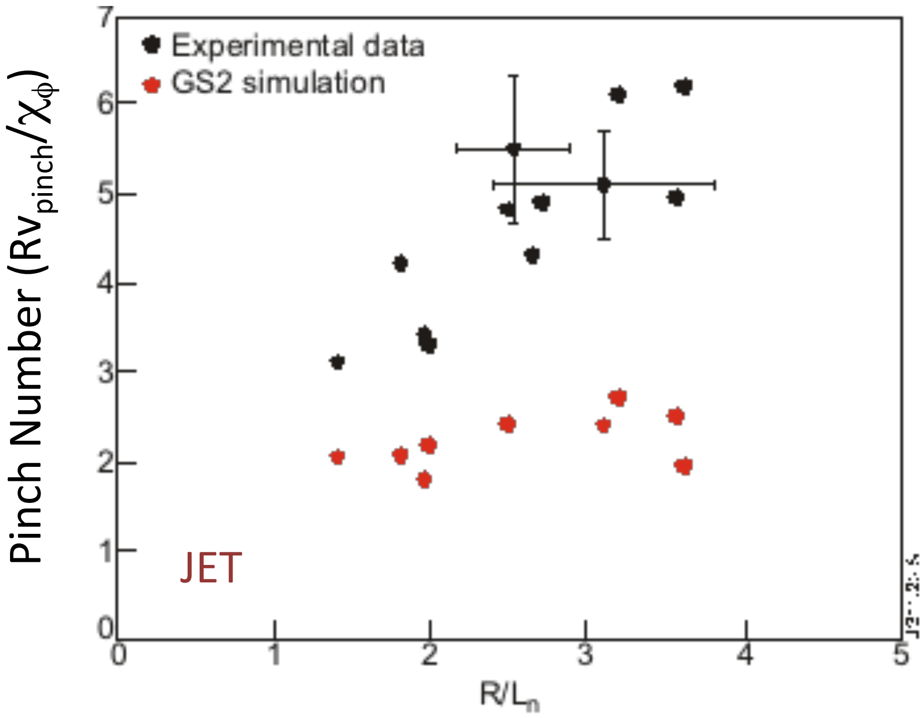
ITG theory predicts dependence of pinch number (Rv_{pinch}/χ_{ϕ}) on density gradient (R/L_n)

Theory



Peeters et al. Nucl. Fusion (2011)

Experiment



Tala et al. Nucl. Fusion (2011)

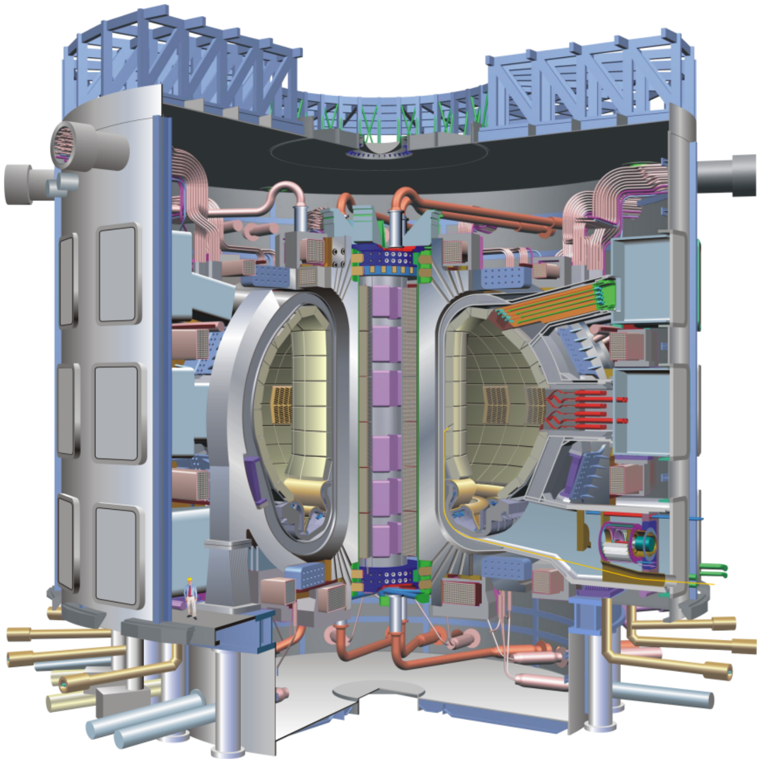
Reduced fluid models also indicate linear dependence on R/L_n

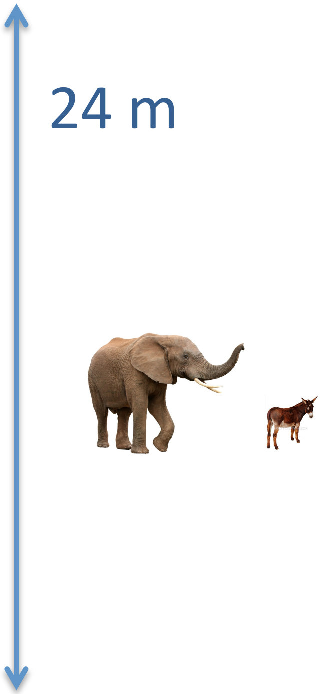
Peeters et al. PoP (2009)

Yoon and Hahm (2011)

Theory calculations predicts **weaker** dependence than is observed in experiment

A fusion power production device is presently under construction (ITER)





Operating Parameters

$a = 2.0$ m

$R = 6.2$ m (R/a= 3.1)

$I_p = 15$ MA

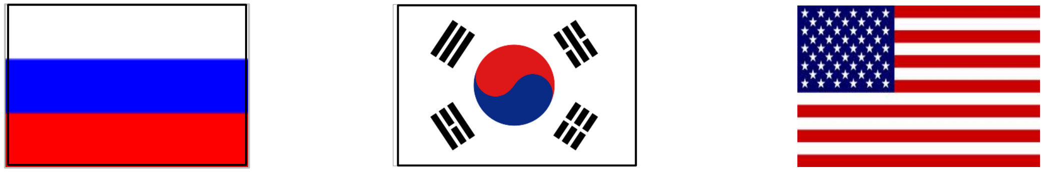
$B_T = 5.3$ T

Performance Parameters

Fusion Power ~ 0.5 GW

Power Amplification ~ 10

Burn Flattop > 400 s



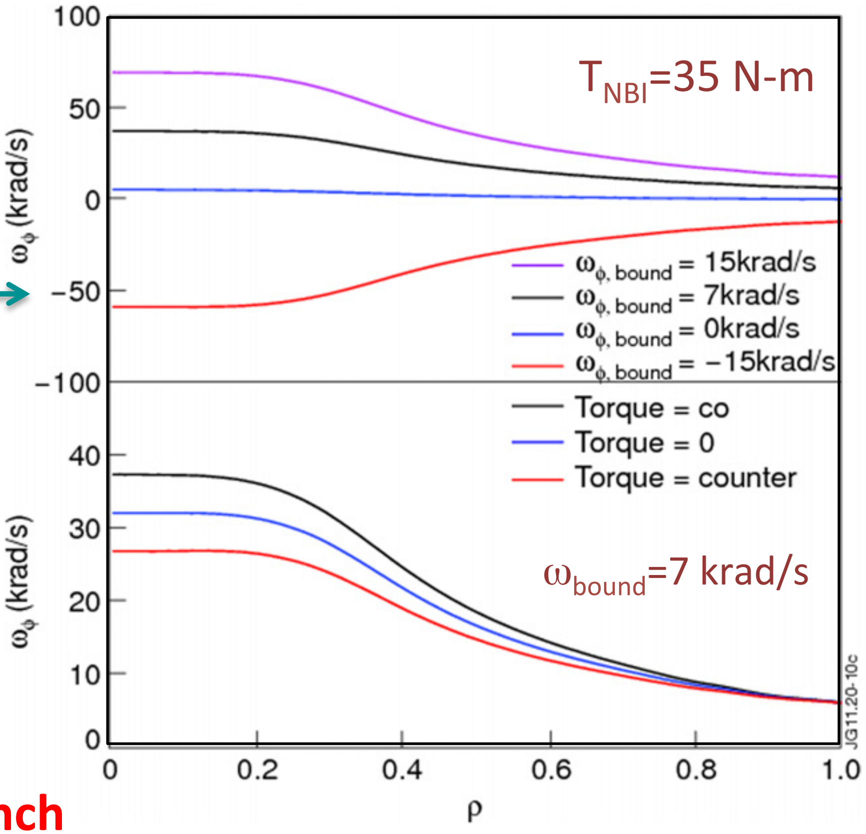
Do we know enough to extrapolate to ITER?

- Making progress in developing a theory-based predictive capability, but not there yet

Predictive simulations based JET values of Pr, Rv_{pinch}/χ_ϕ

Fixed NB torque simulations indicate importance of boundary conditions

Little change of v_ϕ profile with different torque profiles with fixed boundary condition

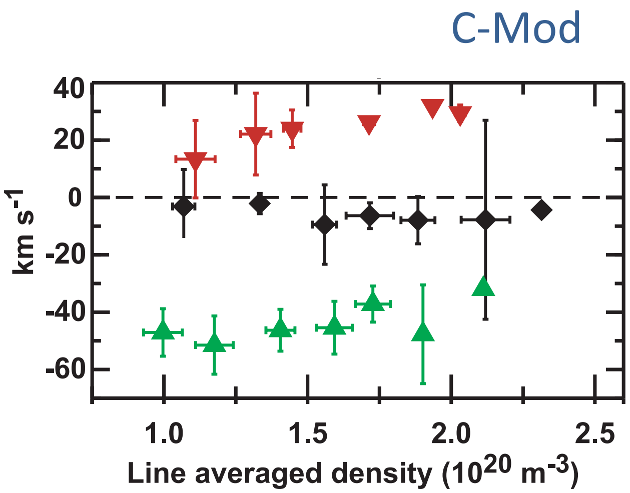


Rotation boundary condition, inward pinch most critical in determining core rotation

Tala et al. Nucl. Fusion (2011)

Many open questions for "comprehensive" understanding

- A strong coupling between turbulence/transport and ExB shear exists
  - Can we establish causality (is it possible)?
- Boundary conditions: typically no slip has been assumed by theory (BC critical)
  - Edge flows observed, however
- Effect of core MHD, energetic particle modes on rotation
- Understand and quantify RF "torques"
- Influence of high-k (electron mode) turbulence on rotation generation/momentum transport



LaBombard et al. Nucl. Fusion (2004)

Summary

- Rotation in tokamaks and STs can be large and can have a profound effect on discharge performance (transport and stability)

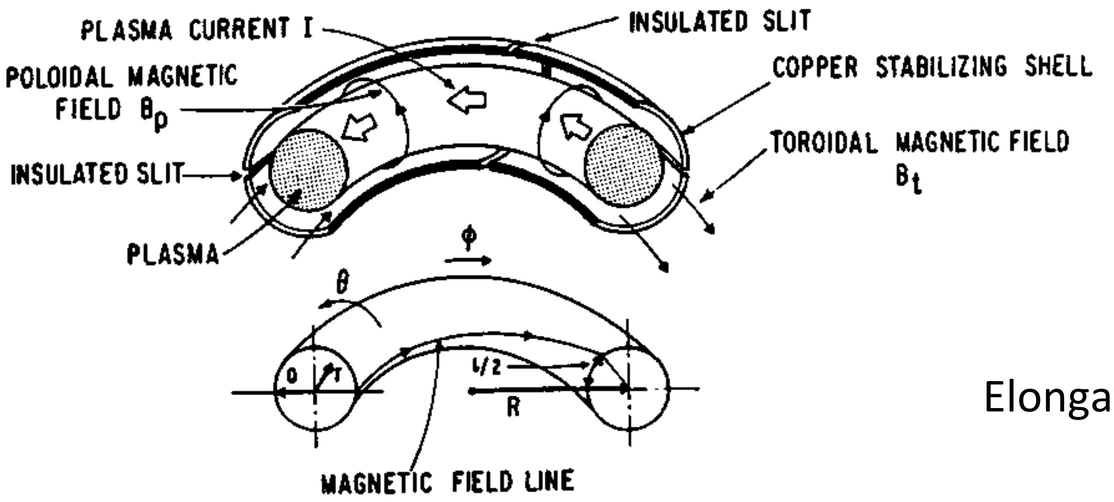
- Intrinsic rotation generation and momentum transport strongly coupled to ion-scale microturbulence

- A comprehensive theoretical understanding is at its early stages
  - Boundary conditions critical – theory must apply across full plasma
  - Requires detailed validation with existing data

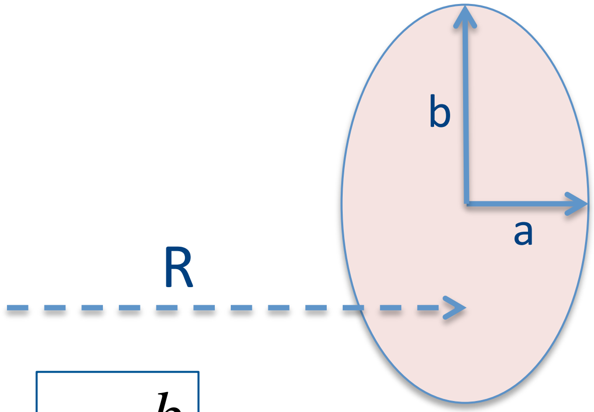
Backup

Fusion-grade plasmas are magnetically confined in toroidal devices

Tokamak (also, stellarators, RFPs)



Present day tokamaks have elongated cross-sections



Elongation $\boxed{\kappa = \frac{b}{a}}$

Aspect Ratio $\boxed{A = \frac{R}{a}}$

Helical magnetic field line topology described by **safety factor**

(Helicity critical for confining plasmas)

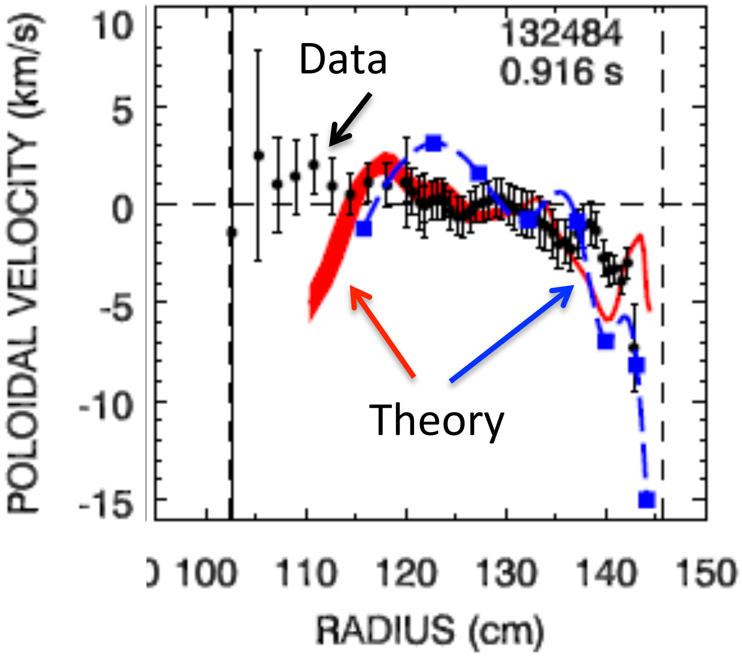
Describes magnetic field "pitch"

$$\boxed{q \cong f(\kappa)\frac{a^2}{R}\frac{B_\varphi}{B_\theta}}$$

Poloidal rotation << toroidal rotation in tokamak/STs

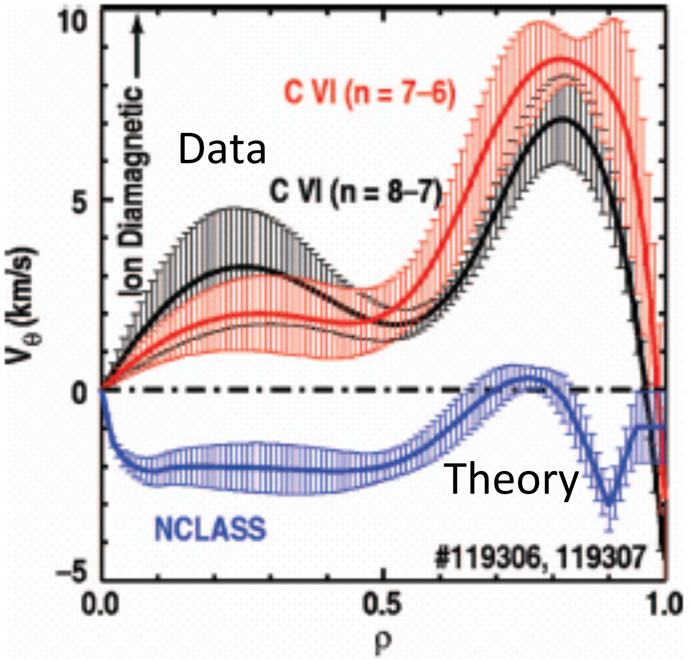
Discrepancy between STs and higher aspect ratio tokamaks seen

V_θ in STs consistent with predictions from neoclassical theory[*]



NSTX (from Bell et al., PoP 2010)

Difference of V_θ with neoclassical predictions can be large in tokamaks



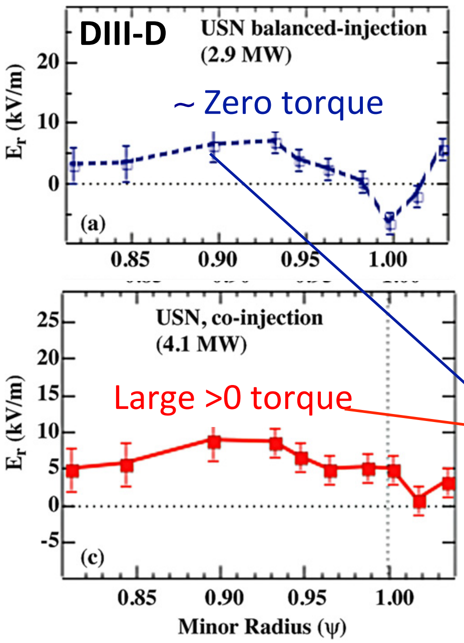
DIII-D (from Solomon et al., PoP 2005)

[*] **Neoclassical transport** ~ Enhanced collisional transport due to connection length, particle trapping effects in toroidal geometries

ExB shear facilitates transitions to enhanced confinement regimes

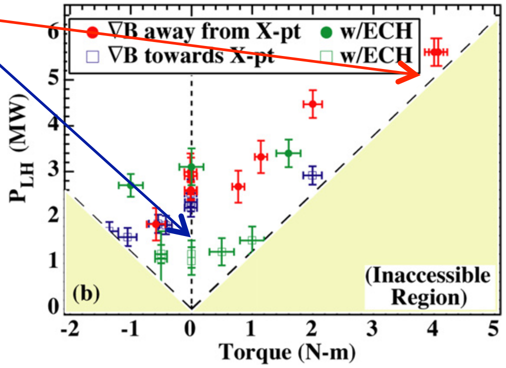
Large E_r shear leads to lower power needed for L- to H-mode transition

McKee et al, Nuc. Fusion (2009)



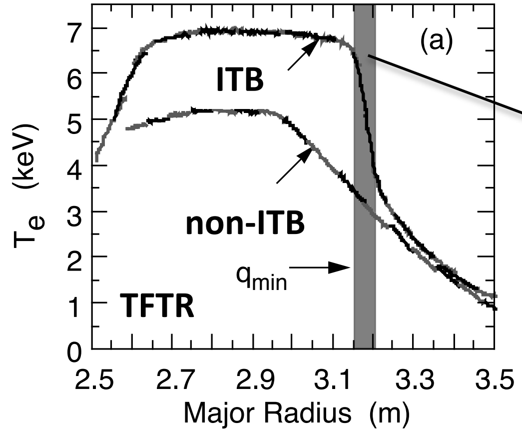
~ Zero torque

Large >0 torque



Strong ExB shear leads to “Internal Transport Barriers”

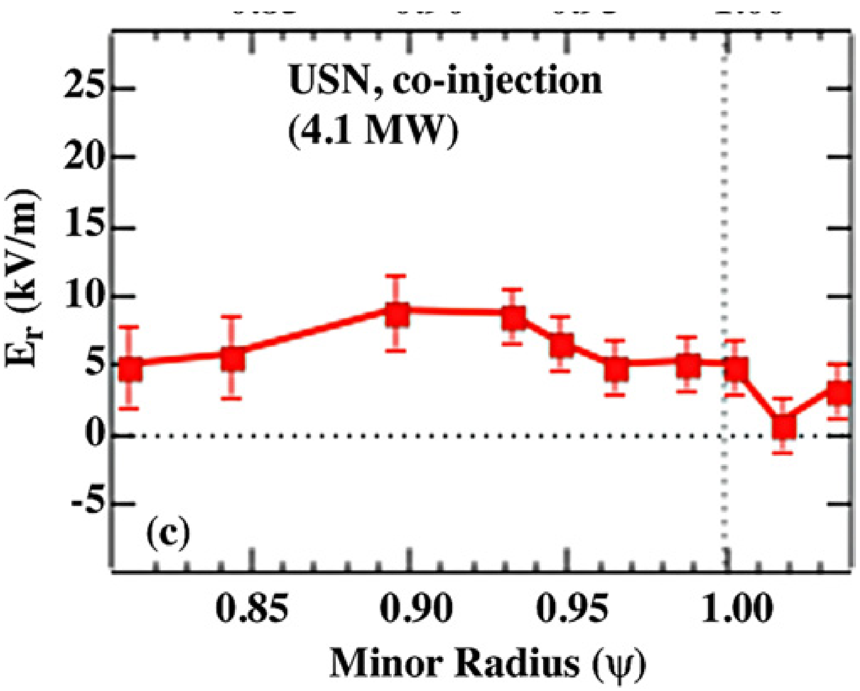
Bell et al, PPCF (1999)



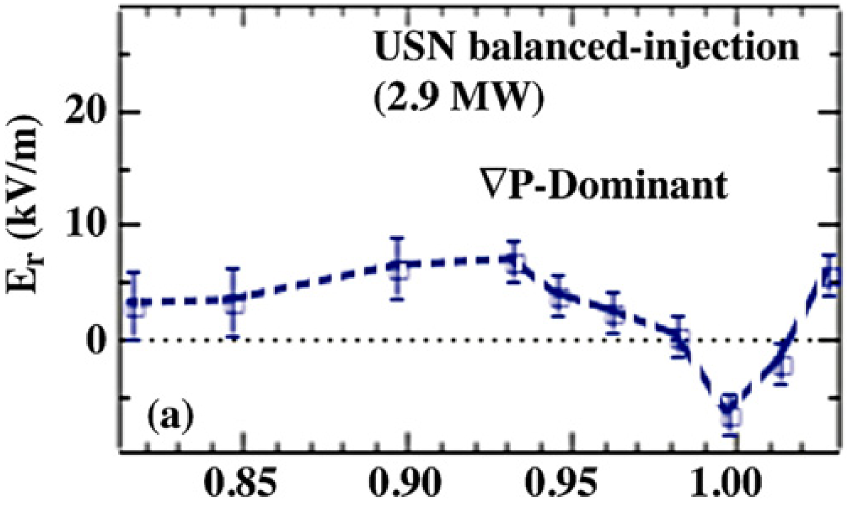
ITB

Synakowski et al, Nuc. Fusion (1999)

Large E_r shear leads to lower power needed for L- to H-mode transition

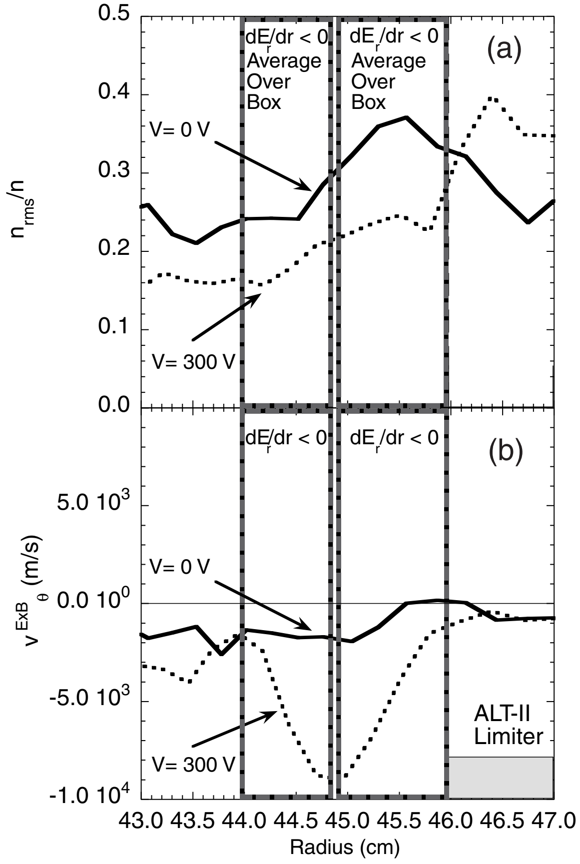


DIII-D



McKee et al, Nuc. Fusion (2009)

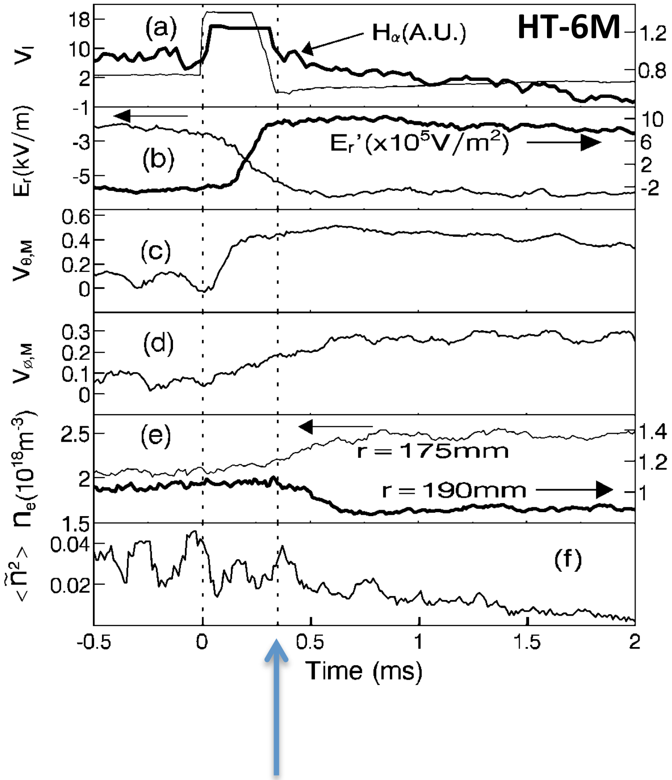
- Electrode biasing in TEXTOR drives ExB shear and associated reduction in turbulence levels



Boedo et al, PPCF(2002)

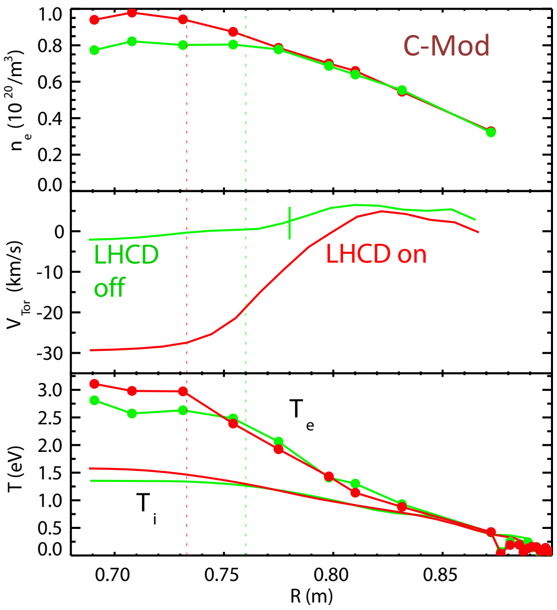
Higher E_r shear facilitates the transition from L- to H-mode

Xu et al, Phys. Rev. Lett. (2000)

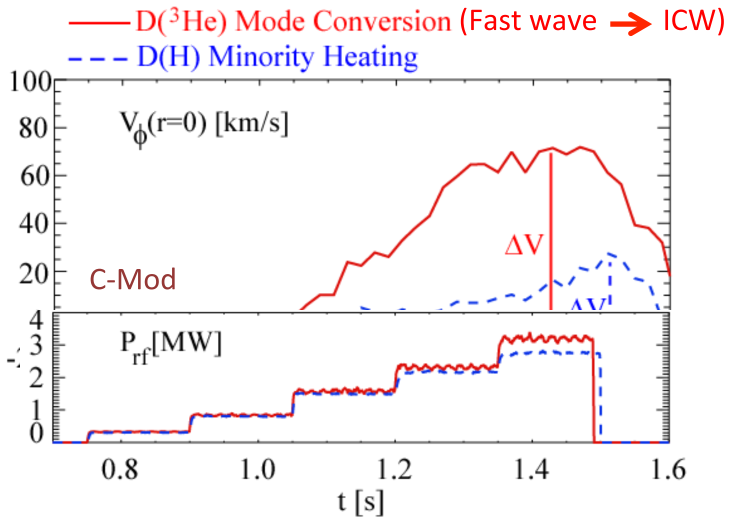


L->H

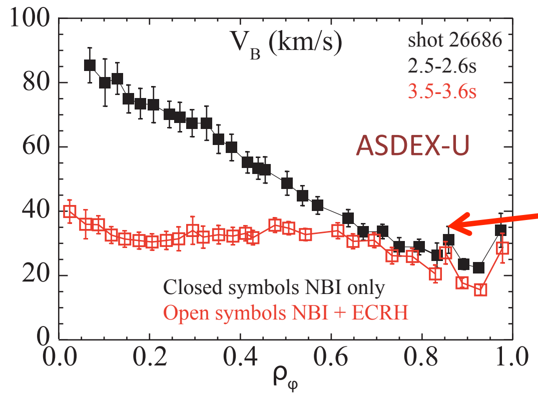
Radio-frequency heating of plasma also provides torque - Ubiquitous, but not well understood -



Ince-Cushman et al, PRL (2011)

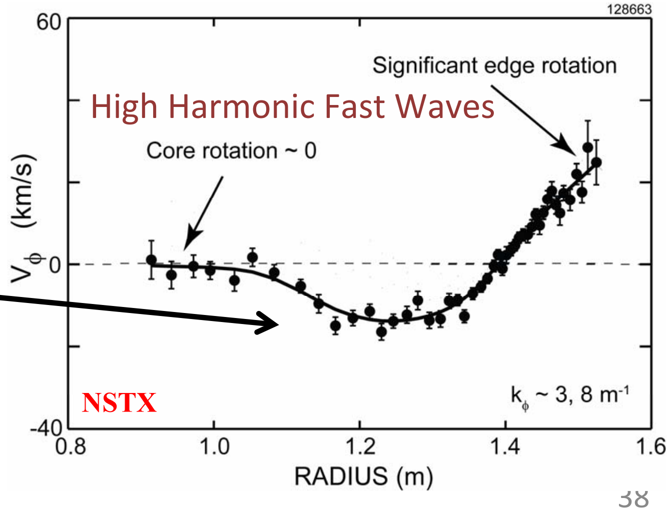


Lin et al, Nuc. Fusion (2011)



McDermott et al, PPCF (2011)

RF can reduce co-rotation and/or lead to counter-rotation



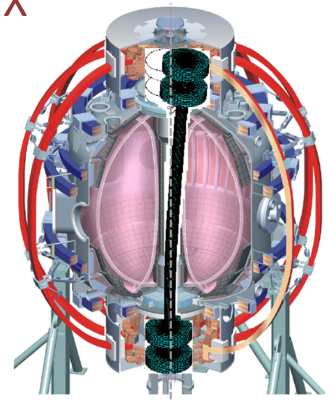
Taylor et al, PoP (2010)

Magnetic field asymmetries are a source of viscous torque

- 3D toroidal magnetic field asymmetries can result from
  - A. Magnetic field ripple (finite # TF coils)
  - B. Intrinsic error fields (coil misalignments or motion during discharge due to JxB forces)
  - C. Applied non-axisymmetric B-field perturbations at edge

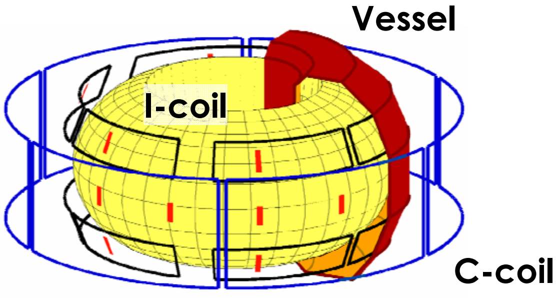
NSTX

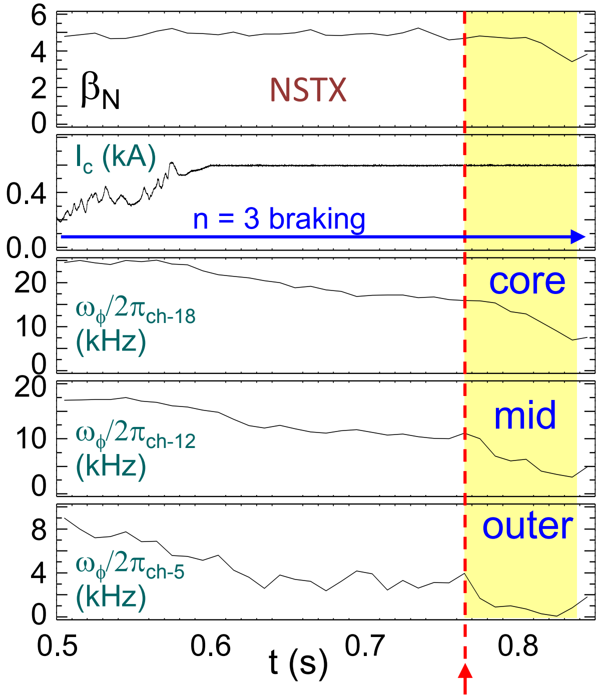
B.



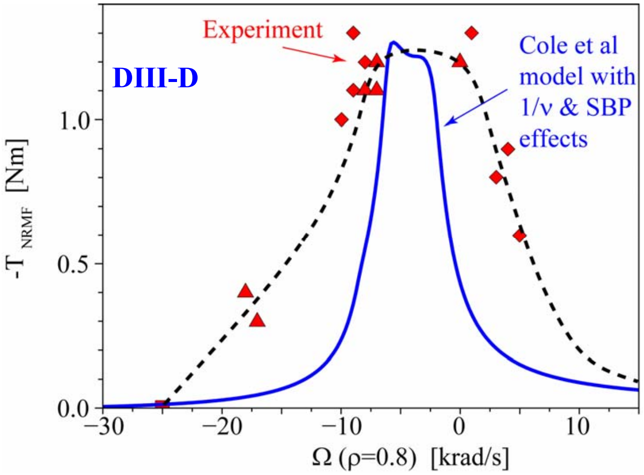
DIII-D

C.





Non-resonant magnetic field (ctr) torque increases at low rotation; consistent with theory:
Cole et al. PRL (2011)
Park et al. PRL (2009)

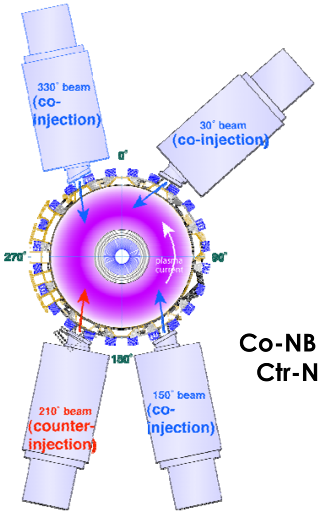


Solomon et al. PoP (2010)

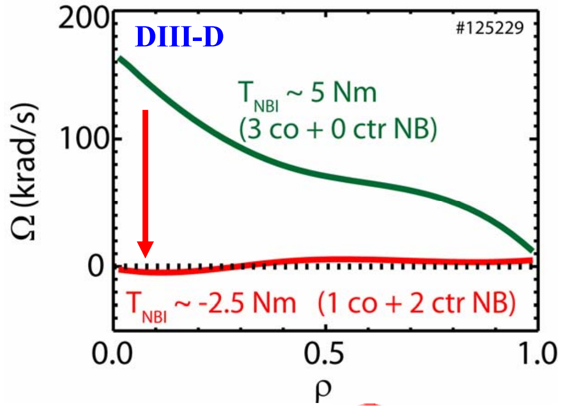
There is evidence that some "intrinsic drive" exists in tokamak/ST plasmas ($T_{self\text{-}driven}$)

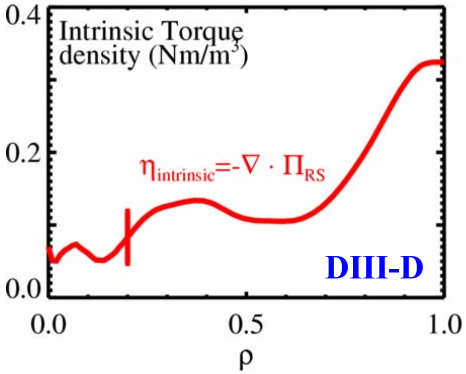
Co-, ctr-NBI on DIII-D allows for flexibility to produce non-rotating plasmas across profile

- Counter torque required to offset intrinsic drive



Co-NBI 12.5 MW
Ctr-NBI 5 MW

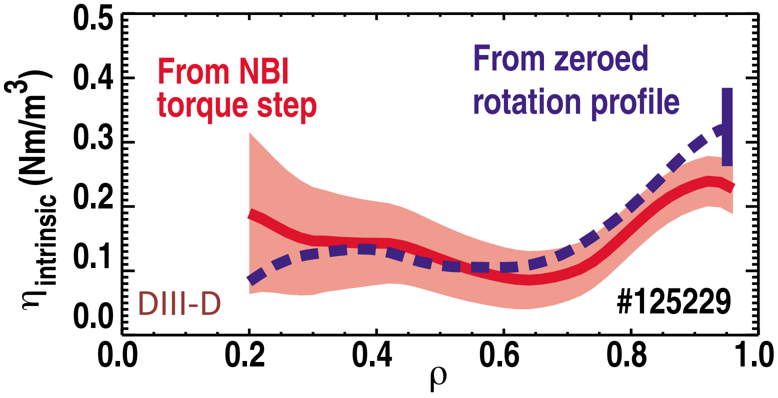




Can also measure intrinsic torque via evolution of angular momentum

$$\frac{dL(\rho)}{dt}=T_{NBI}+T_{intrinsic}-\frac{L}{\tau_{\phi}}$$

Solve for two unknowns from time evolution of angular momentum, L

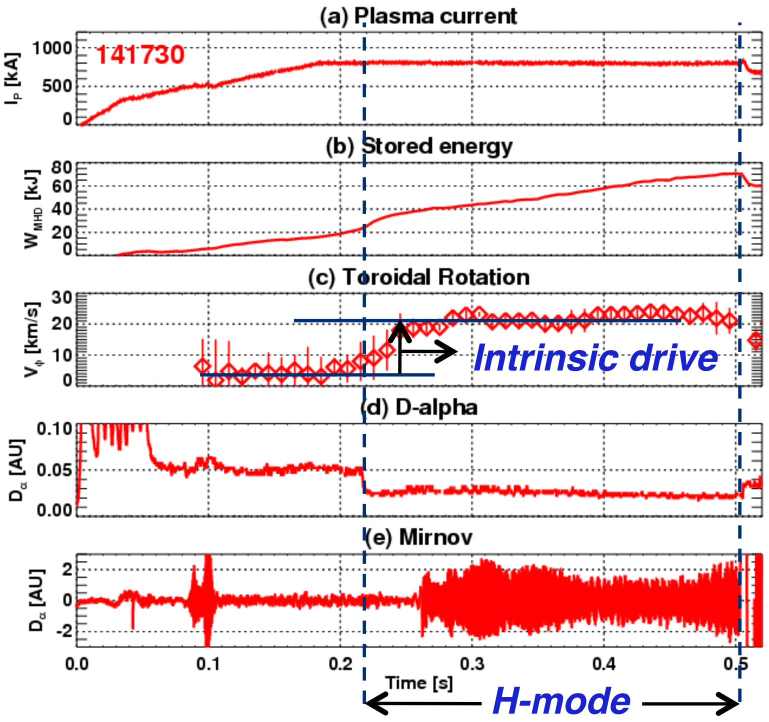


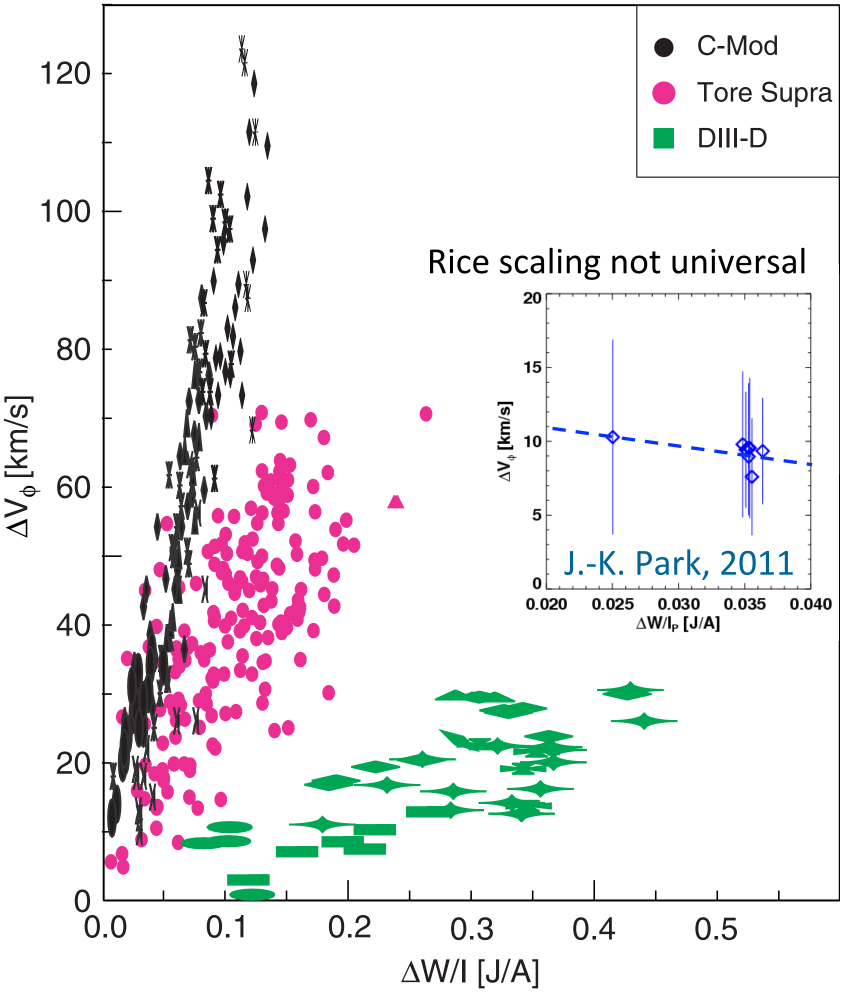
Solomon et al. PoP (2010)

Edge intrinsic torques lead to edge intrinsic rotation

Typically use L-H transitions in OH or RF-heated plasmas to study change in intrinsic rotation

NSTX OH L-H-mode





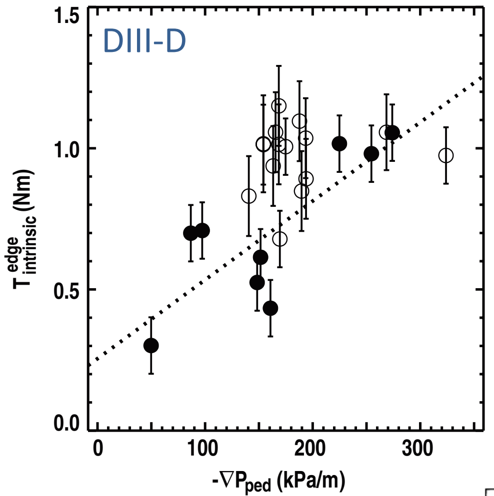
Rice scaling not universal

J.-K. Park, 2011

Rice et al. Nucl. Fusion (2007)

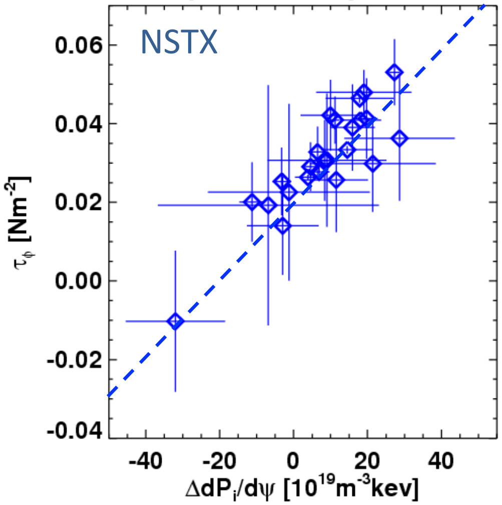
Intrinsic drive and rotation appears to be controlled strongly by $\nabla p, \nabla T_i$ respectively

Intrinsic torque scales strongly with ∇p, consistent with low-k turbulence theory, Gurcan et al. PoP (2007)



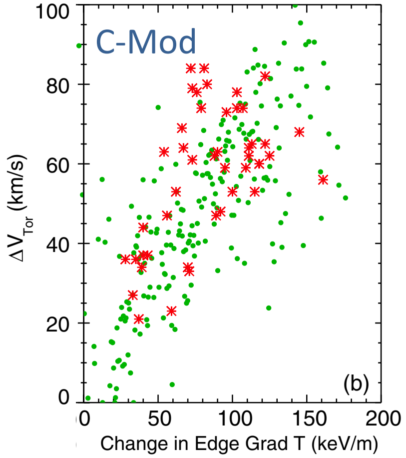
Solomon et al. NF (2011)

Torque vs. Ion pressure



J.K. Park (PPPL)

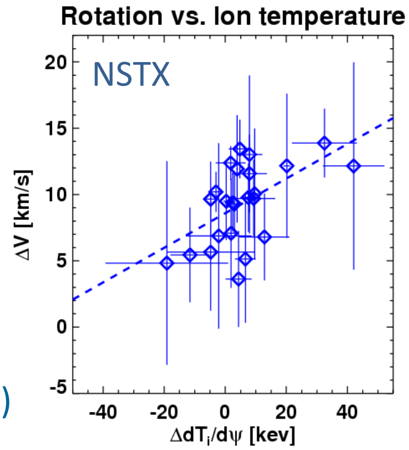
Correlation found between intrinsic rotation and ∇T_i in C-Mod and NSTX (also JT-60U)



Rice et al. PRL (2011)

Wang et al. PoP (2010)
Kosuga et al. PoP (2010)
Gurcan et al. PoP (2010)
theory ---

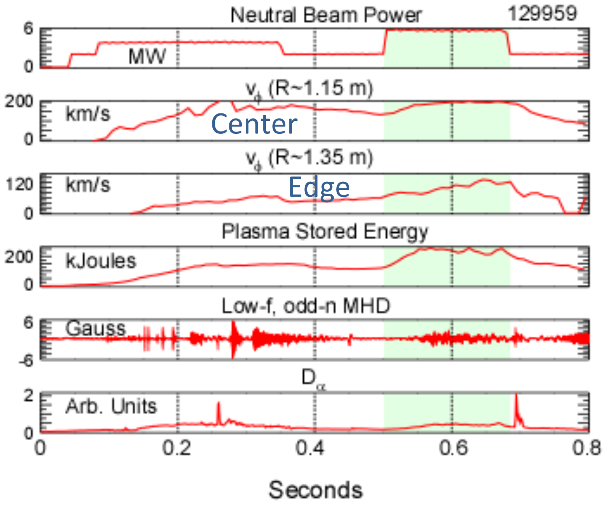
$$v_{IR} \propto \nabla T_i$$



J.K. Park (PPPL)

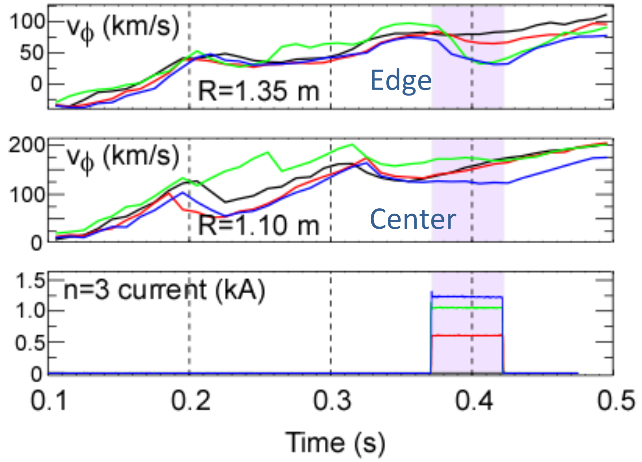
Perturbation techniques used to isolate χ_ϕ, v_{pinch}

NB step

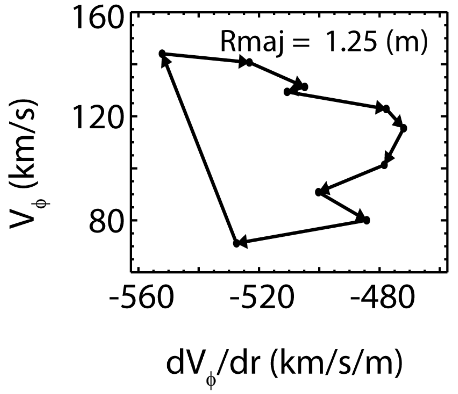


NSTX

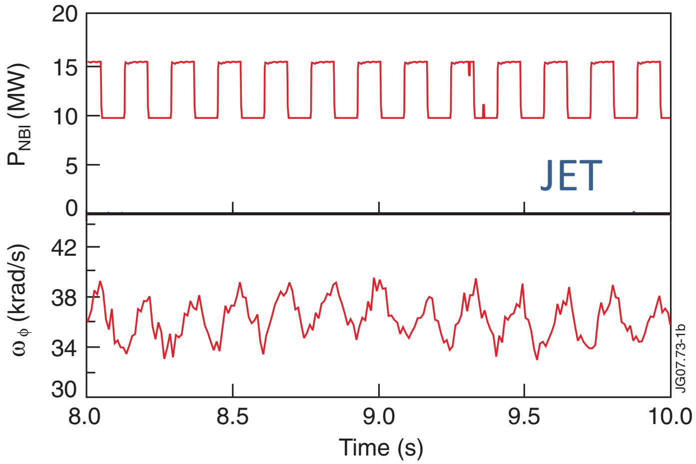
Applied ΔB step



Separation of v_ϕ, ∇v_ϕ essential to determining χ_ϕ, v_{pinch}



NB modulation



Tala et al. PRL (2009)

Can solve for χ_ϕ, V_{pinch} in source-free region from amplitude & phase of response

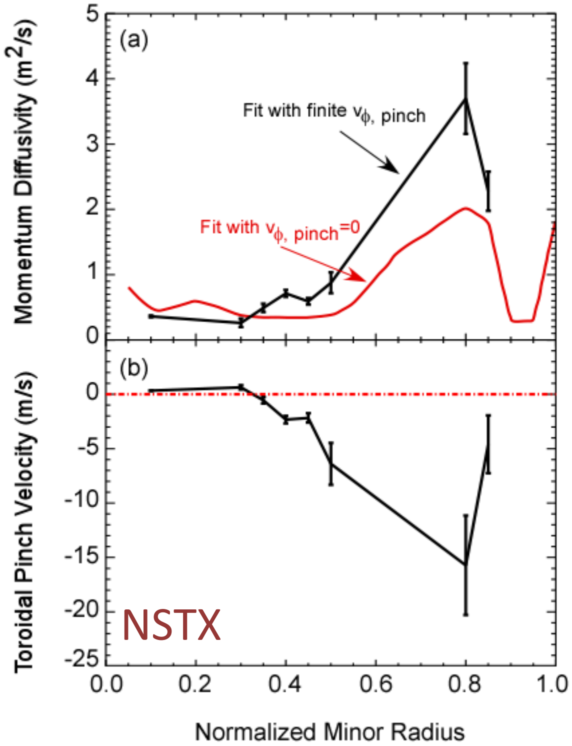
- Usually find source region broad – technique not valid
- Use forward modeling to determine χ_ϕ, V_{pinch}

Perturbative momentum transport analysis reveals significant inward pinch in outer region of plasma

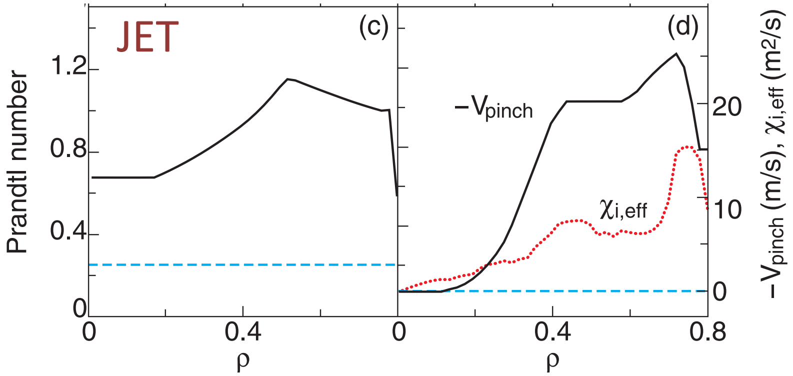
Including v_{pinch} brings Pr closer to 1 (0.5 – 0.8)

$\chi_\phi \sim 2\chi_\phi^{eff}$

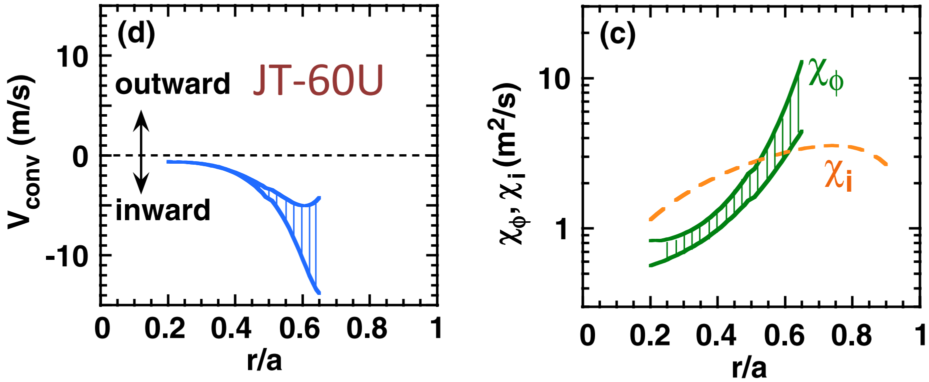
MP step



NB modulation



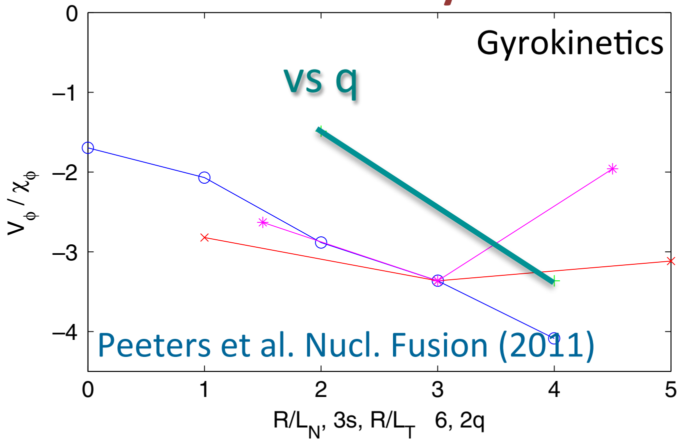
Tala et al. PRL (2009)



Yoshida et al. Nucl. Fusion (2007)

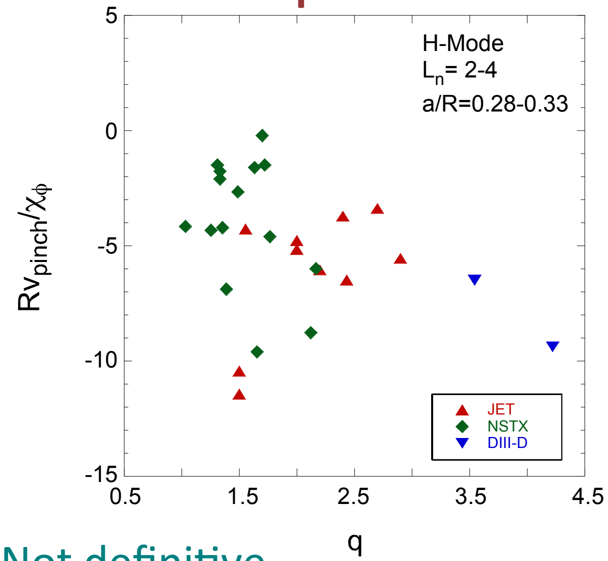
Not all theory predictions are seen in the data

Theory



Peeters et al. Nucl. Fusion (2011)

Experiment

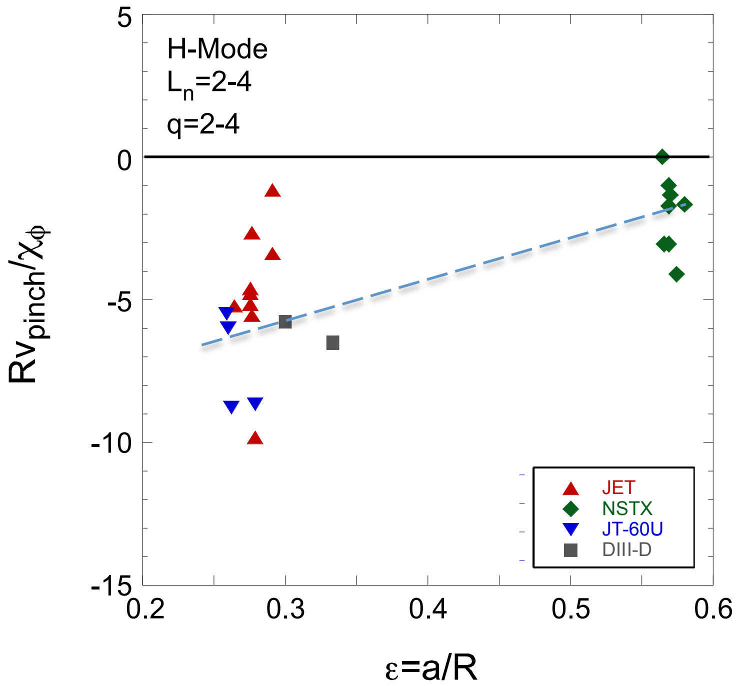


Not definitive

Theory indicates inward pinch should increase with increasing inverse aspect ratio (ε)

Peeters et al, PoP (2009)

Experiments do not show this from device-to-device



Drift wave turbulence is basis for understanding dependences of intrinsic rotation/torque (stress)

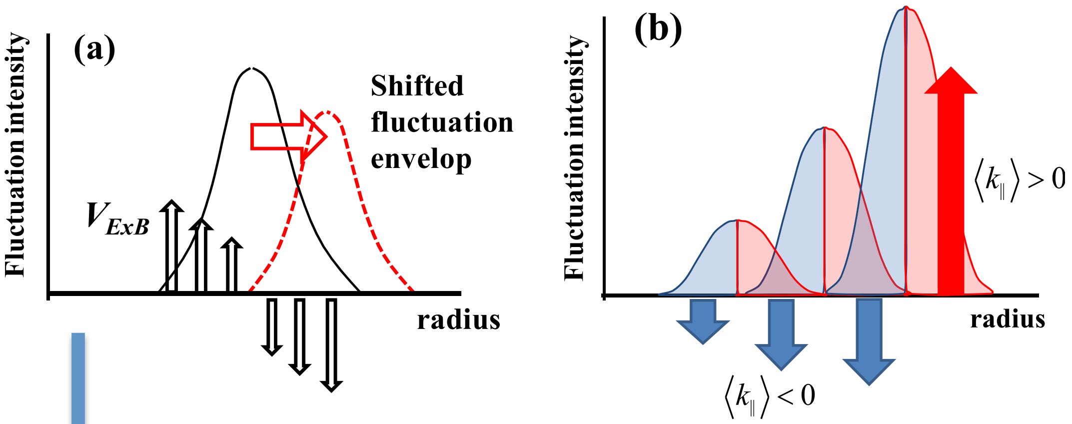
- Conversion of turbulent energy to directed flow (leading theory)
- Driven by gradients in T, p, n; requires "symmetry breaking" (rotation imbalance in Φ)

Gurcan et al. PoP (2007)

Symmetry breaking accomplished in several ways

ExB shear

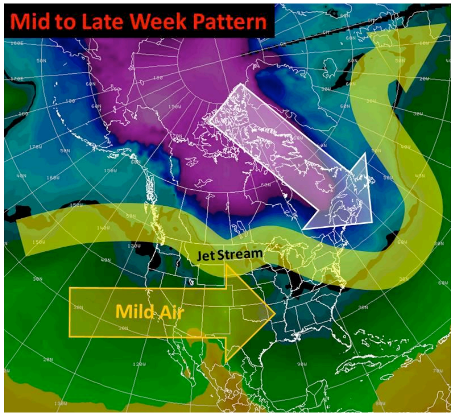
Fluctuation intensity gradient

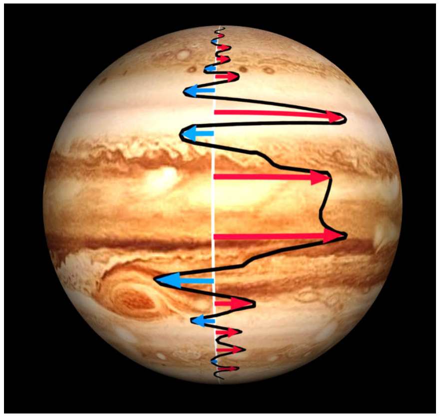


Ku et al. submitted to PoP (2011)

ExB shearing can come from generation of Zonal Flows/GAMS (Geodesic Acoustic Modes)

- Flow in poloidal direction with m=0/n=0
- Associated with radial zones of varying E_r
- ω~0 (ZFs) or few kHz (GAMs)

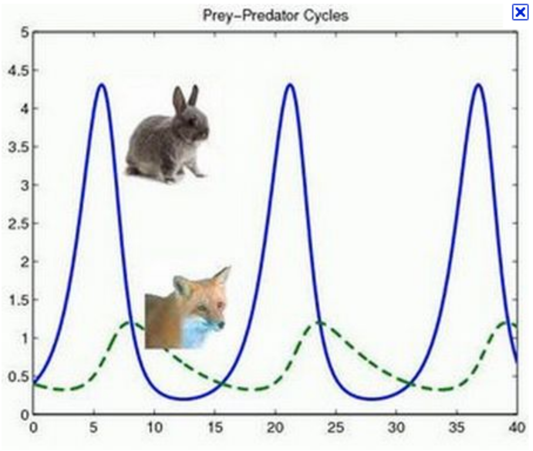




Turbulence/flow energy coupled strongly through energy conservation (and predator-prey paradigm)

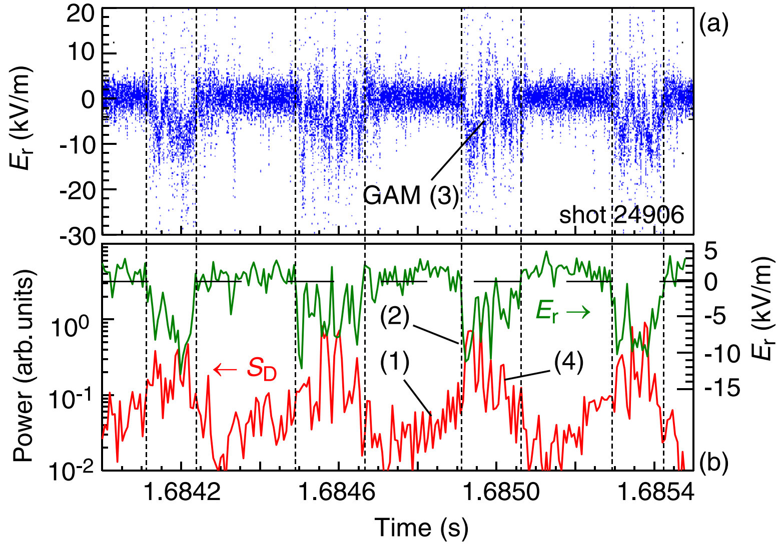
- ZF is like predator (eats turbulence)
- Turbulence is like prey (eats gradients)
- Transport and turbulence reduced by ZFs

Gurcan et al. PoP (2007)

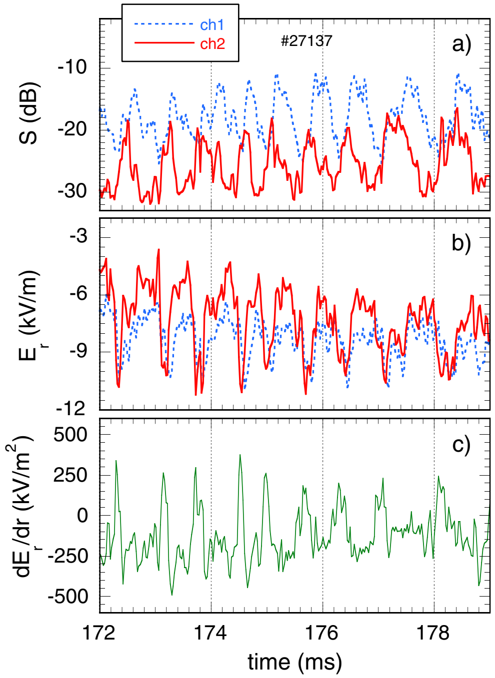


Predator-Prey relation observed in toroidal devices

ASDEX-U



Conway et al. PRL (2011)

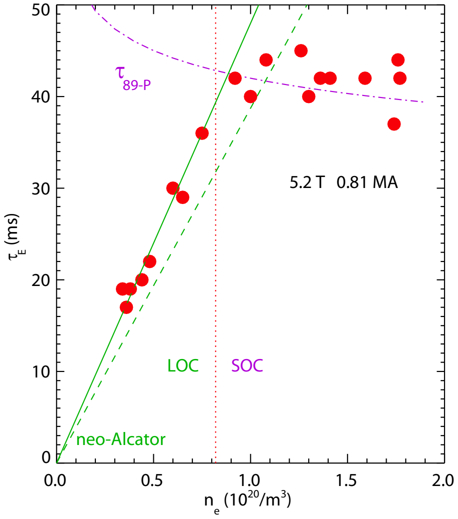


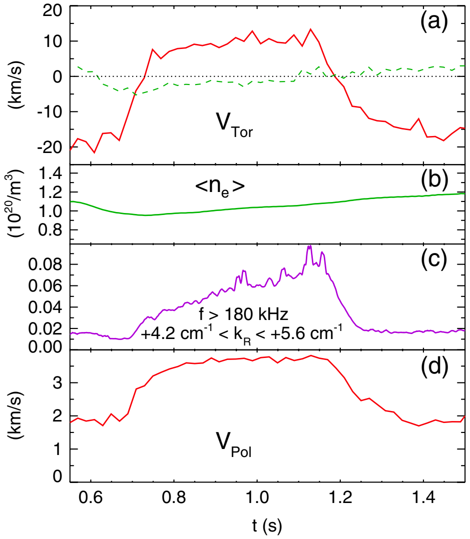
TJ-II stellarator

Estrada et al. PRL (2011)

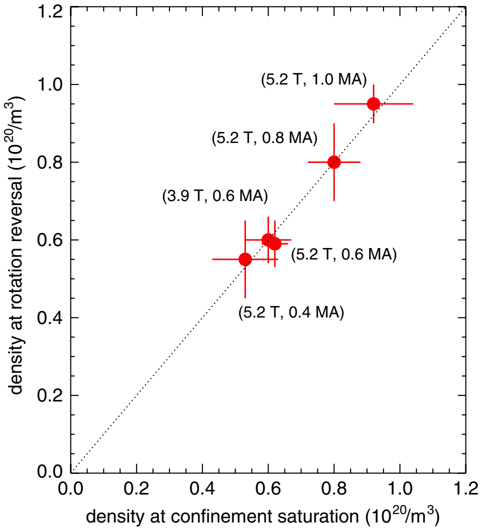
Intrinsic rotation reversals may give insight into which specific drift wave modes are dominant

Alcator C-Mod finds confinement regimes/rotation directions depend strongly on density



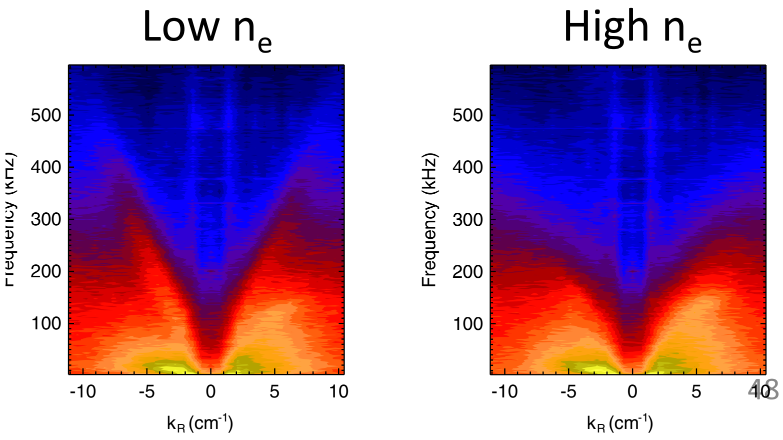


Rice et al. to appear in Phys. Plasmas (2012)



Rice et al. PRL (2011)

Turbulence measurements indicate likely transition from TEM (low n_e, T_e>T_i) to ITG (high n_e, T_e~T_i) –dominated regime



High-k scattering shows drop in turbulence across k-spectrum with increasing ExB shear