Differences in dynamics of enhanced core confinement states in various experimental configurations and the role of driven rotation

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Abstract – Aspects of transport barrier dynamics that can differ between experiments include the heating power required for formation, and rates of formation and collapse. The theory of ExB flow shear effects on turbulence suggests that some differences may be traced to the interplay between terms of the radial force balance equation and changes that result as rotation is modified in magnitude and sign. On DIII-D, studies with counter neutral beam injection complement previous work performed with co-injection, as well as that performed on TFTR with co- and counter-NBI. The role of the interplay between pressure and rotation drive in governing barrier dynamics will be examined using data from these studies. Dynamics are addressed using a 1-dimensional envelope model that self-consistently evolves ExB shear, turbulence, transport, and plasma profiles.

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Examined here:

1. A DIII-D/TFTR similarity experiment
   - by reproducing character of DIII-D NCS E_r evolution, NCS dynamics are recovered
   - a 1-D envelope dynamical model captures aspects of dynamics

2. Counter injection on DIII-D: time scale of barrier formation and expansion varies with applied torque
   - how is slow transition to be understood with counter injection?

3. DIII-D PEP/TFTR ERS: barrier dynamics critically dependent on alignment of pressure and rotation profiles

Different experimental configurations possess different transport barrier dynamics

First: examine the most familiar configurations

DIII-D, Negative Central Shear (NCS) with co-injection

- Slow or fast formation of enhanced confinement region is possible. Rate correlated with applied torque
- No clear power threshold seen (< 5 MW) – is there a true bifurcation? Or is P_{th} below minimum quantum of power?

TFTR Enhanced Reverse Shear (ERS) with balanced NB injection

- Fast development; power threshold – clear bifurcations

Both regimes end up in the same place

- low χ_i, D_e, χ_ϕ; χ_e less consistent

Here: examine if the differences can be explained in the context of E×B flow shear stabilization

1. qualitative expectations

2. TFTR/DIII-D similarity demonstration
   - modify E_r on TFTR: simulate structure and evolution of E_r on DIII-D
   - If DIII-D dynamics reproduced $\Rightarrow$ E_r and its structure are likely causal elements in determining dynamics

3. examine dynamics with 1-D envelope model of turbulence and transport

E×B shear effects on transport create positive feedback loops with background gradients

Force balance:

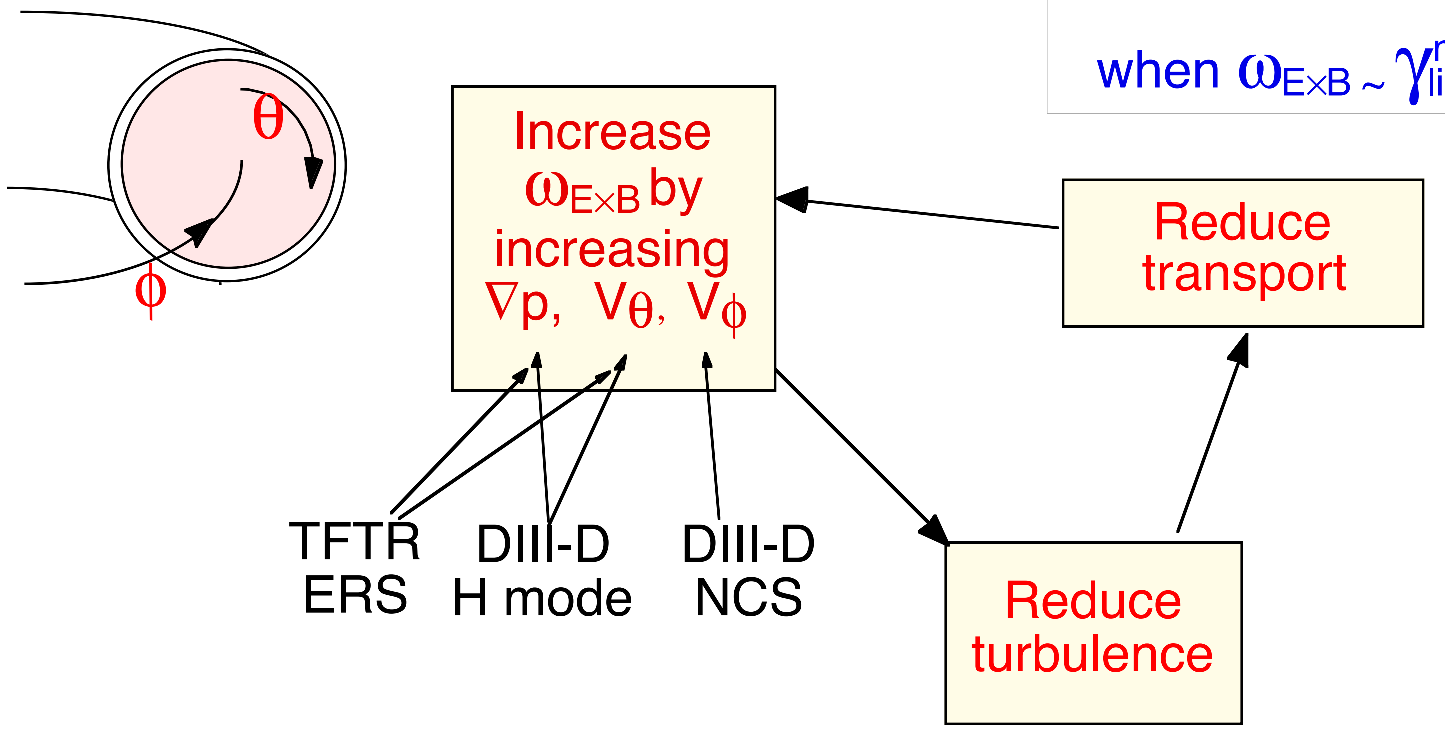
$$E_r = \nabla p / Z n_e + V_\phi B_\theta - V_\theta B_\phi$$

Turbulence “shearing rate” from E×B flow

$$\omega_{E\times B} = \left| \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial \psi} \frac{E_r}{RB_\theta} \right|$$

(Hahm and Burrell, Phys. Plasmas (1995))

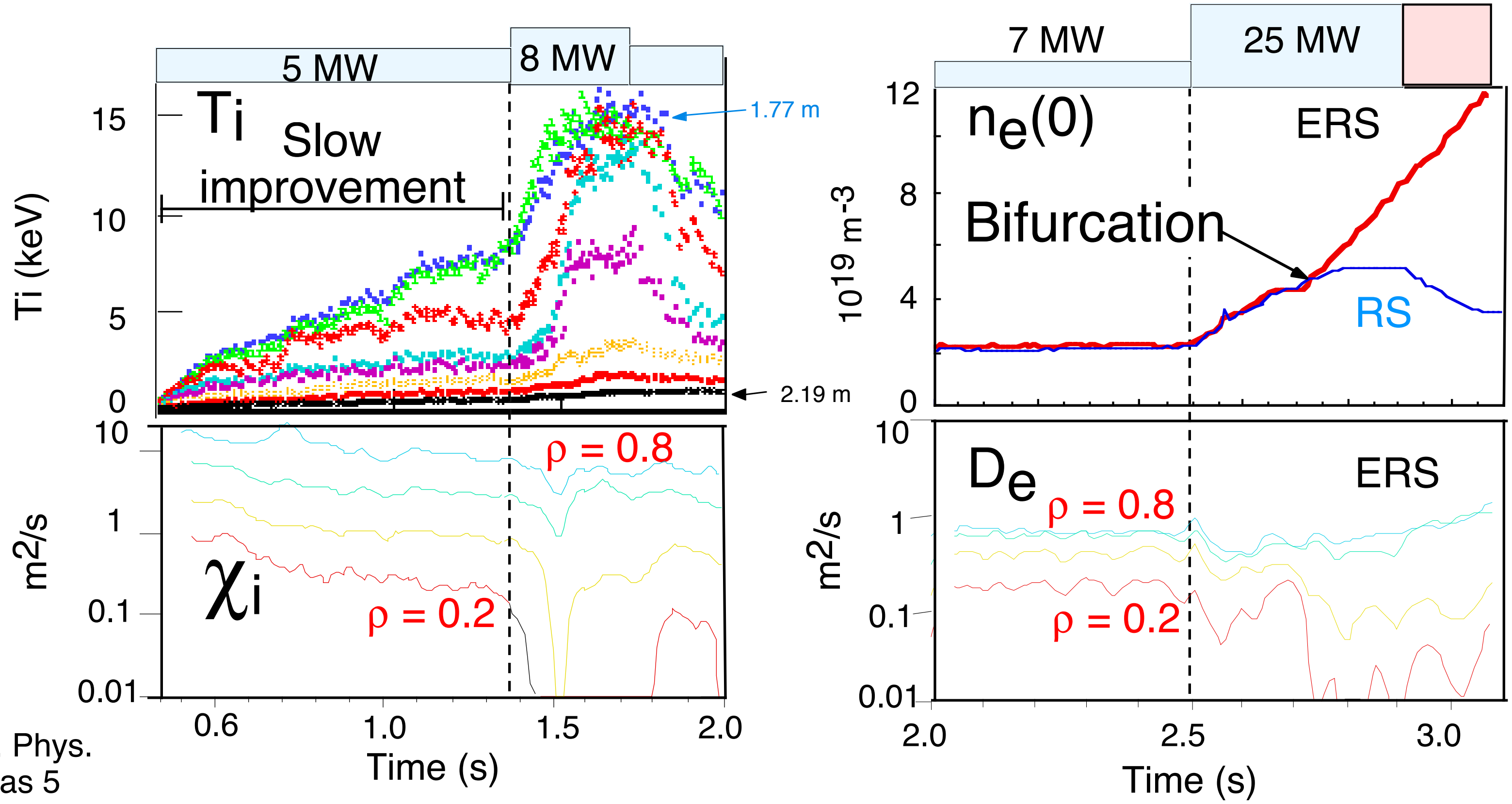
Turbulence affected when $\omega_{E\times B} \sim \gamma_{lin}^{max}$



DIII-D NCS develops more slowly than TFTR ERS plasmas

DIII-D NCS Core

TFTR ERS Core



Rettig, Phys. Plasmas 5 (1998)

ejs101098 NCS, ERS evolution

- DIII-D NCS: Gradual improvement early in time
  Rapid improvement as V_ϕ' increases with power step
- TFTR ERS: Rapid bifurcation at V_θ excursion

The slow development seen in DIII-D NCS plasmas, fast development in TFTR ERS is qualitatively consistent with expectations from the E×B flow shear picture

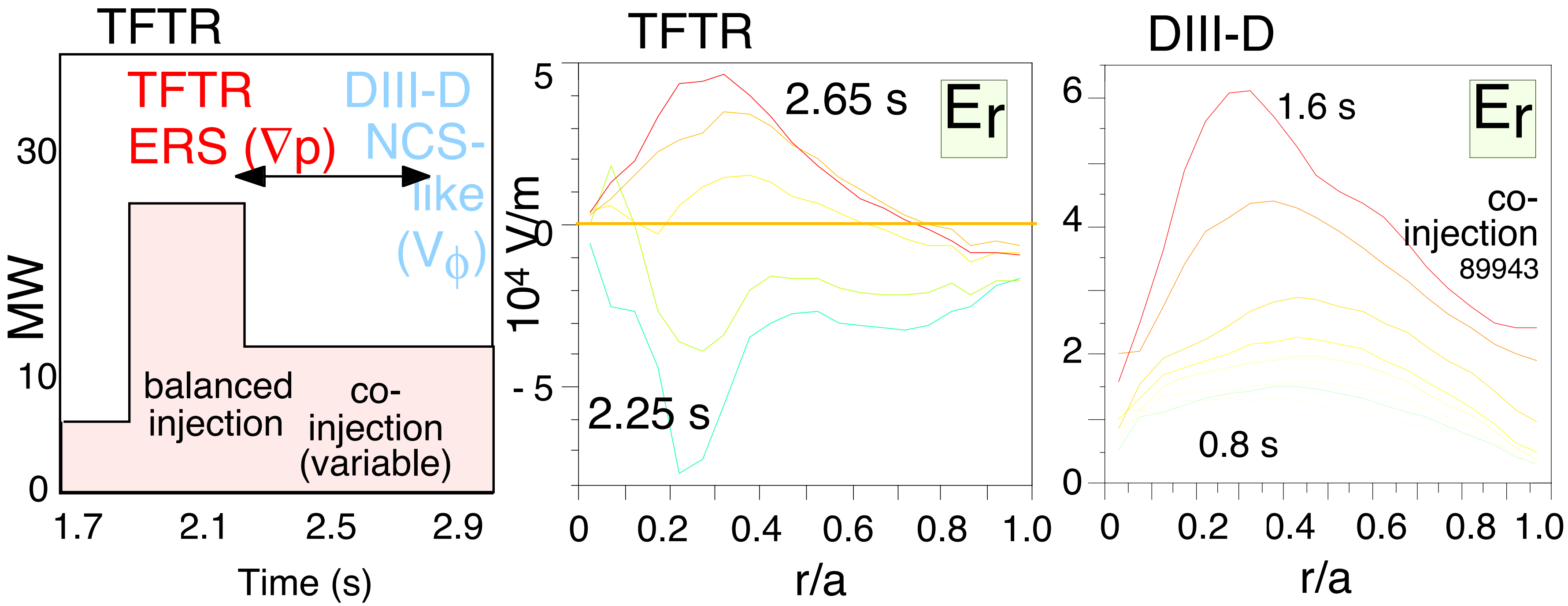
- With co-injection: gradient of V_ϕ opposes gradient of pressure in generating E×B shear

⇒ slow transitions possible. Momentum confinement improvement advances the positive feedback loop, but there can be opposition from increased ∇p from improved thermal confinement

- balanced injection ERS: V_θ trigger, followed by increasing ∇p all contribute in same sense to $\omega_{E\times B}$

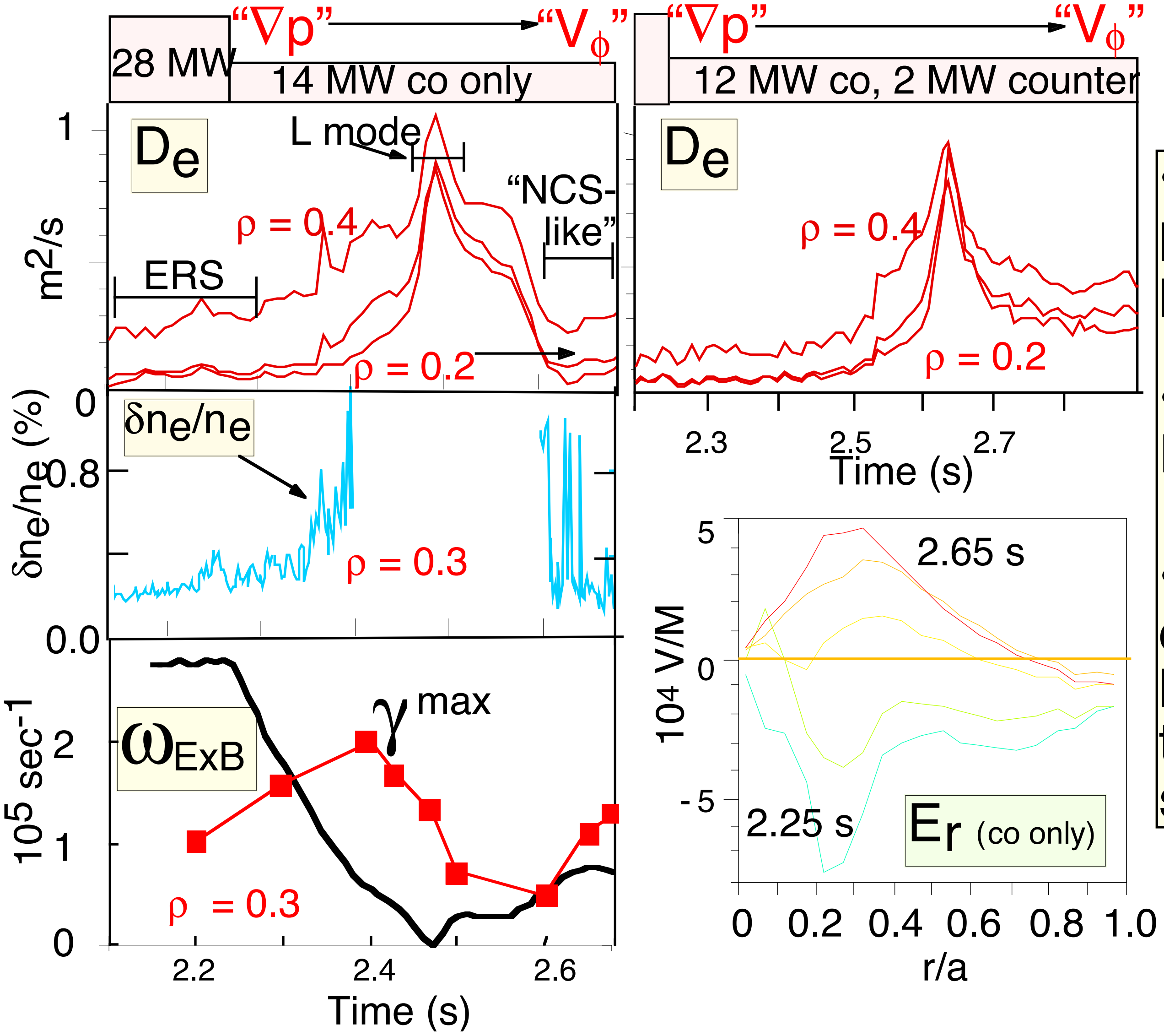
⇒ fast development of enhanced state is possible

Control of V_ϕ shear on TFTR allowed DIII-D NCS-like E_r structure to be generated



- Balanced NBI (typical TFTR) ⇒ co-NBI (DIII-D-like)
- E_r near large ∇p: negative (ERS) ⇒ positive (typical NCS)
- $\omega_{E\times B}$: ∇p, V_θ-driven ⇒ V_ϕ-driven

When co-rotation dominated E_r on TFTR, slow entry into enhanced confinement was observed



- Like early heating phase of DIII-D NCS plasmas

- Low transport with E_r well or hill

- Intermediate levels of improvement can be established if there are opposing sources of flow shear

Calculations evolving RMS value of turbulence have been used to examine dynamics of turbulence and profiles

1-D envelope model, toroidally and poloidally averaged, η_i

E×B shear is explicitly included in the growth and saturation of the fluctuations

phase information is absent

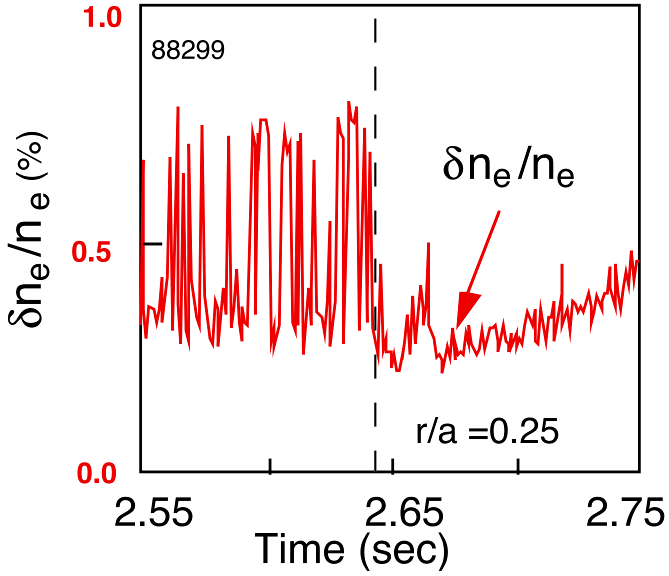
fluctuation levels are input into multimode transport model

profiles are allowed to evolve, fluctuation levels change in response, etc.

aim is to explore the dynamic responses of systems

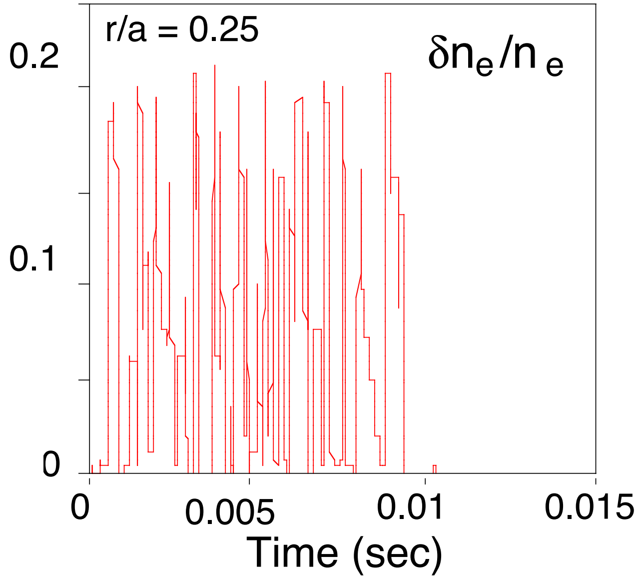
Model reproduces both bursting fluctuation character and fast transport change at transition

Data from reflectometry



Mazzucato, PRL 77, 3145 (‘96)

1-D envelope model

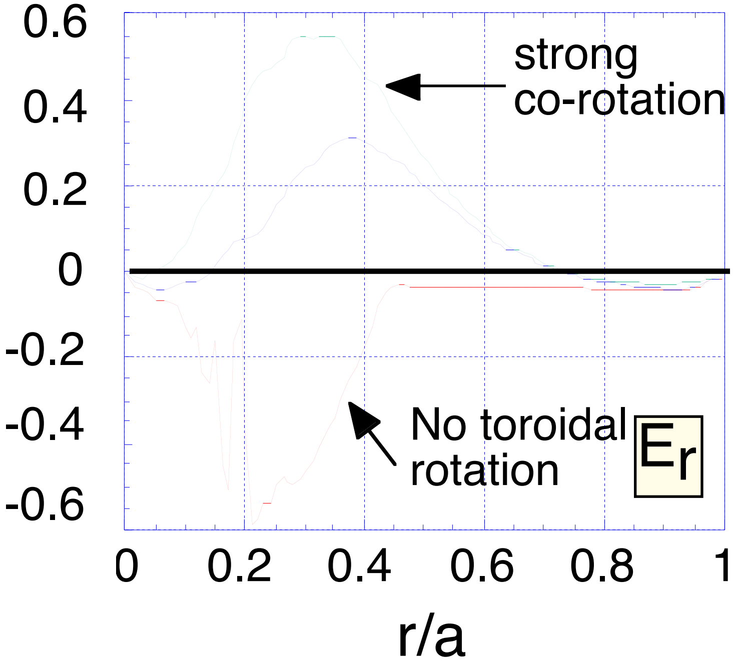


D. Newman

- Fast transition triggered either by ∇p or Reynolds stress-driven V_θ
- Speed of transition determined by positive feedback between $\omega_{E\times B}$ and steepening of pressure gradient

E_r well is lost, E_r hill is built up after application of unidirectional injection in 1-D model

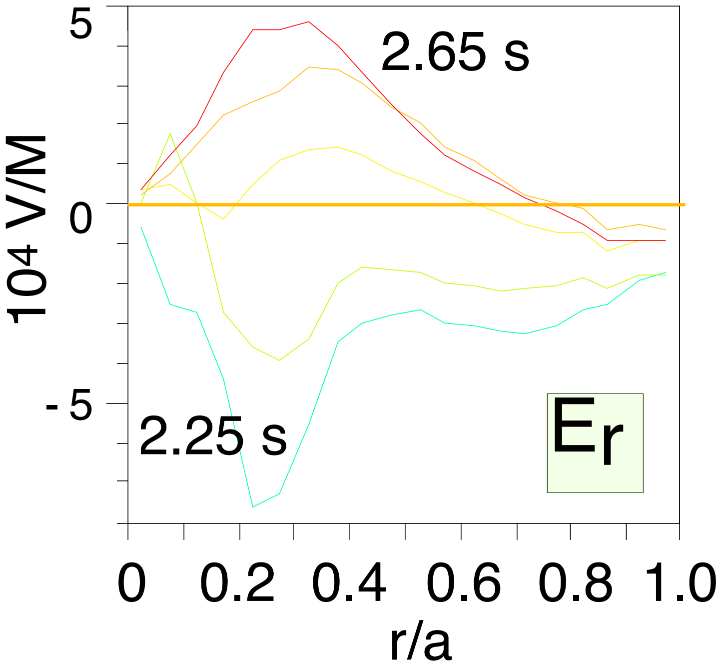
model



strong co-rotation

No toroidal rotation

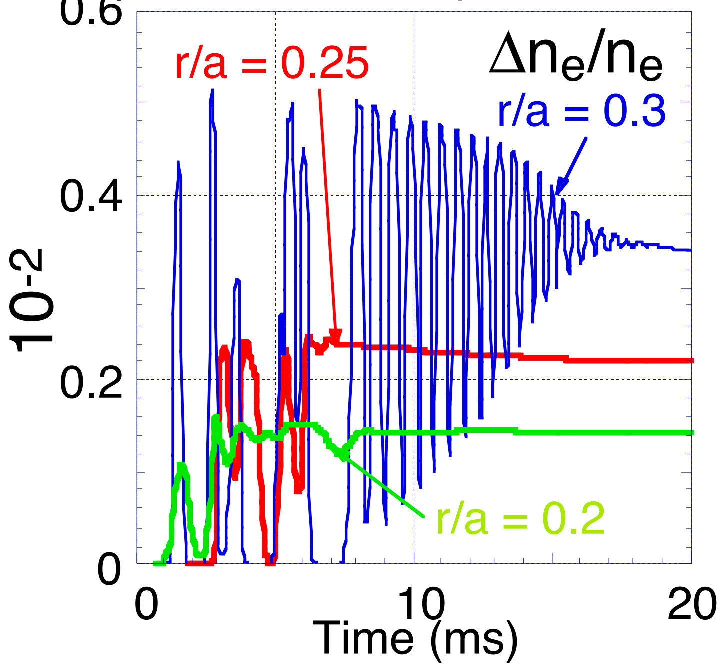
experiment



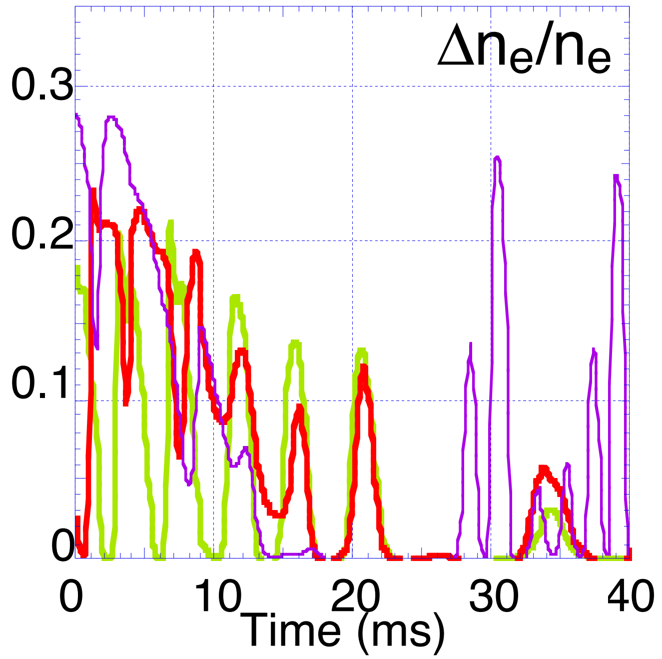
- “Well” is driven by large ∇p in model
- “Hill” generated by strong positive V_ϕ, as in experiment

Slow back transition and re-entry into enhanced confinement are seen in 1-D model

Back transition from loss of E_r well



Forward transition from creation of E_r hill

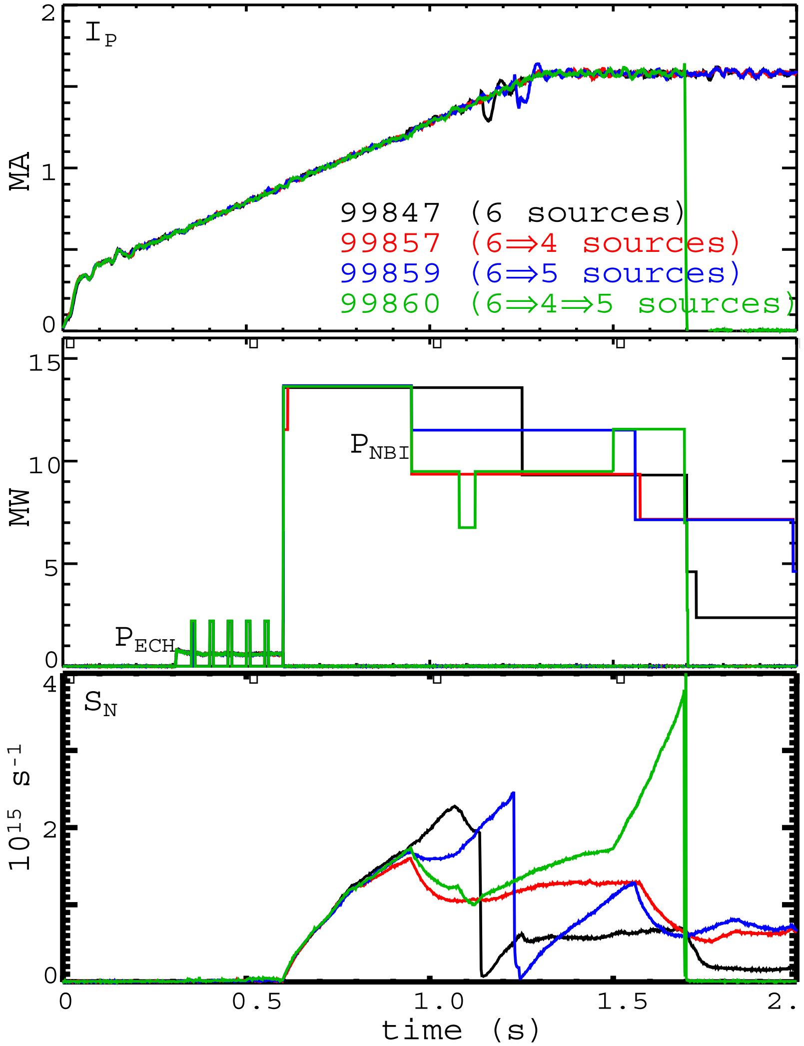


- Contrast with fast ∇p or Reynolds stress-driven forward transition time scale
- Difference between this and fast forward transition is due to competition between ∇p and $V_\phi B_\theta$ terms in ω_{ExB}

A power scan highlights that barrier dynamics can be critically sensitive to small changes in beam timing and power

- At higher powers, rate and degree of improvement is faster than at lower powers
    - but rapidly peaking pressure profile can lead to internal disruption

- Avoiding MHD distress from $q_{min} = 2$ is possible by tailoring beam heating waveform



Transition trigger in ERS appears to be E_r shear layer formation
No such trigger is observed in DIII-D NCS plasmas

TFTR

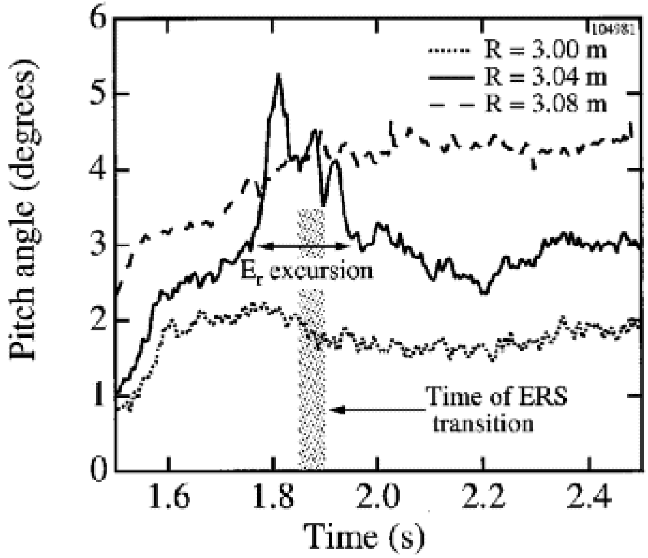
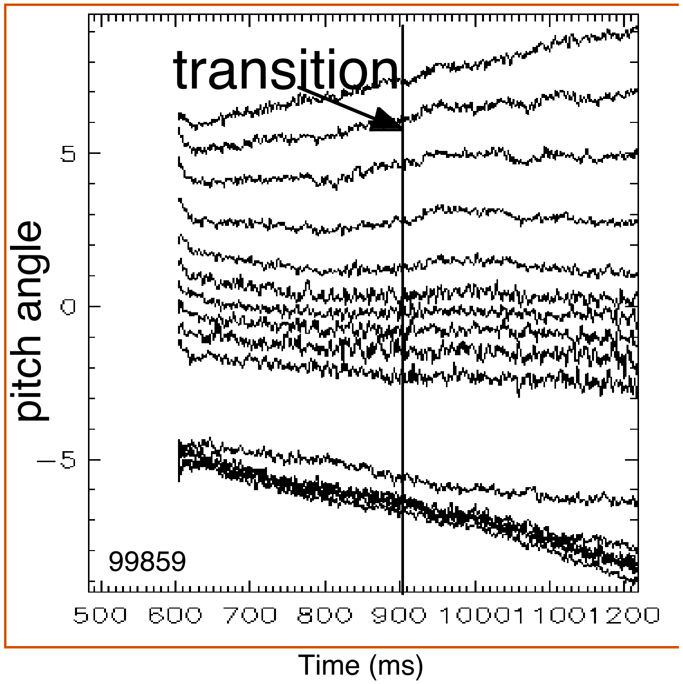


FIG. 3. The magnetic field pitch angle evolution of three sight lines. The time of the ERS transition is at 1.85–1.90 s.

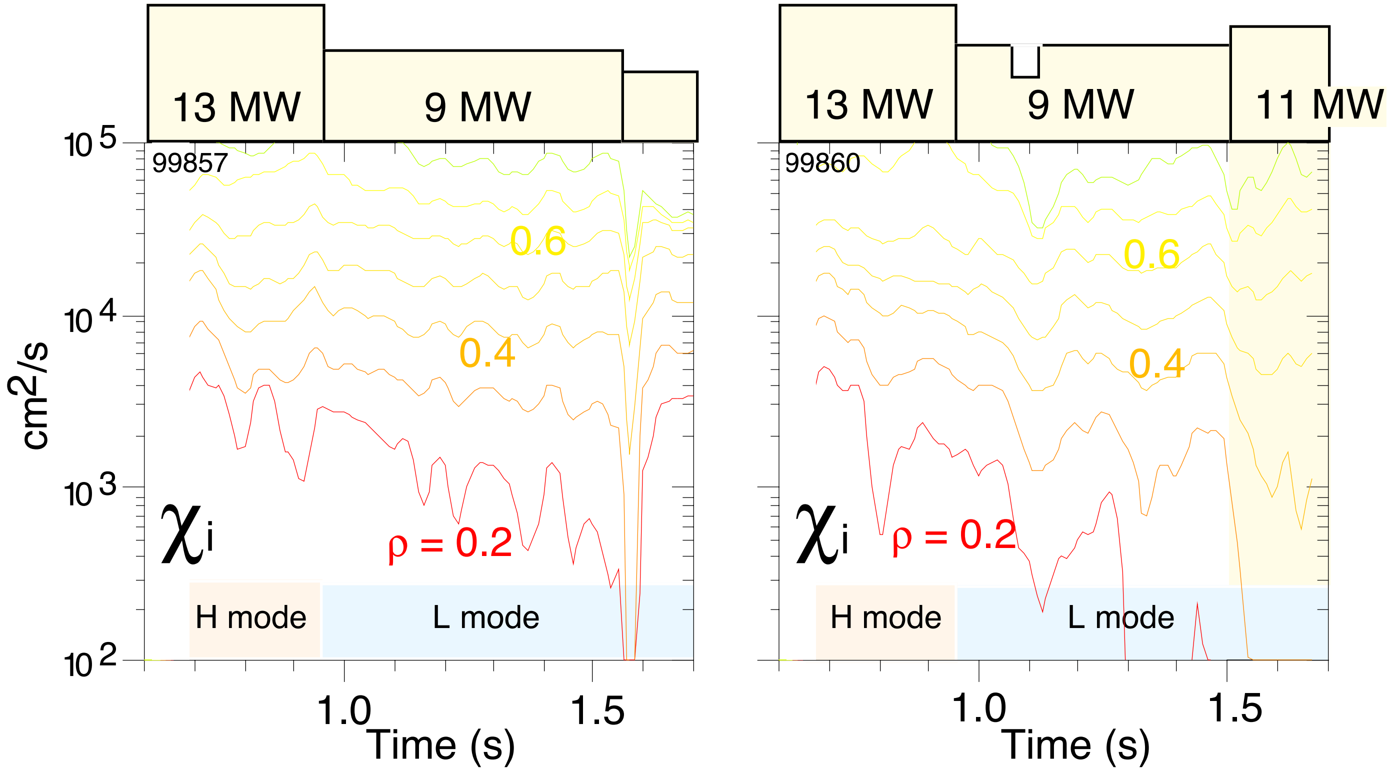
From F. Levinton, PRL 80, 4887 (1998)

DIII-D NCS



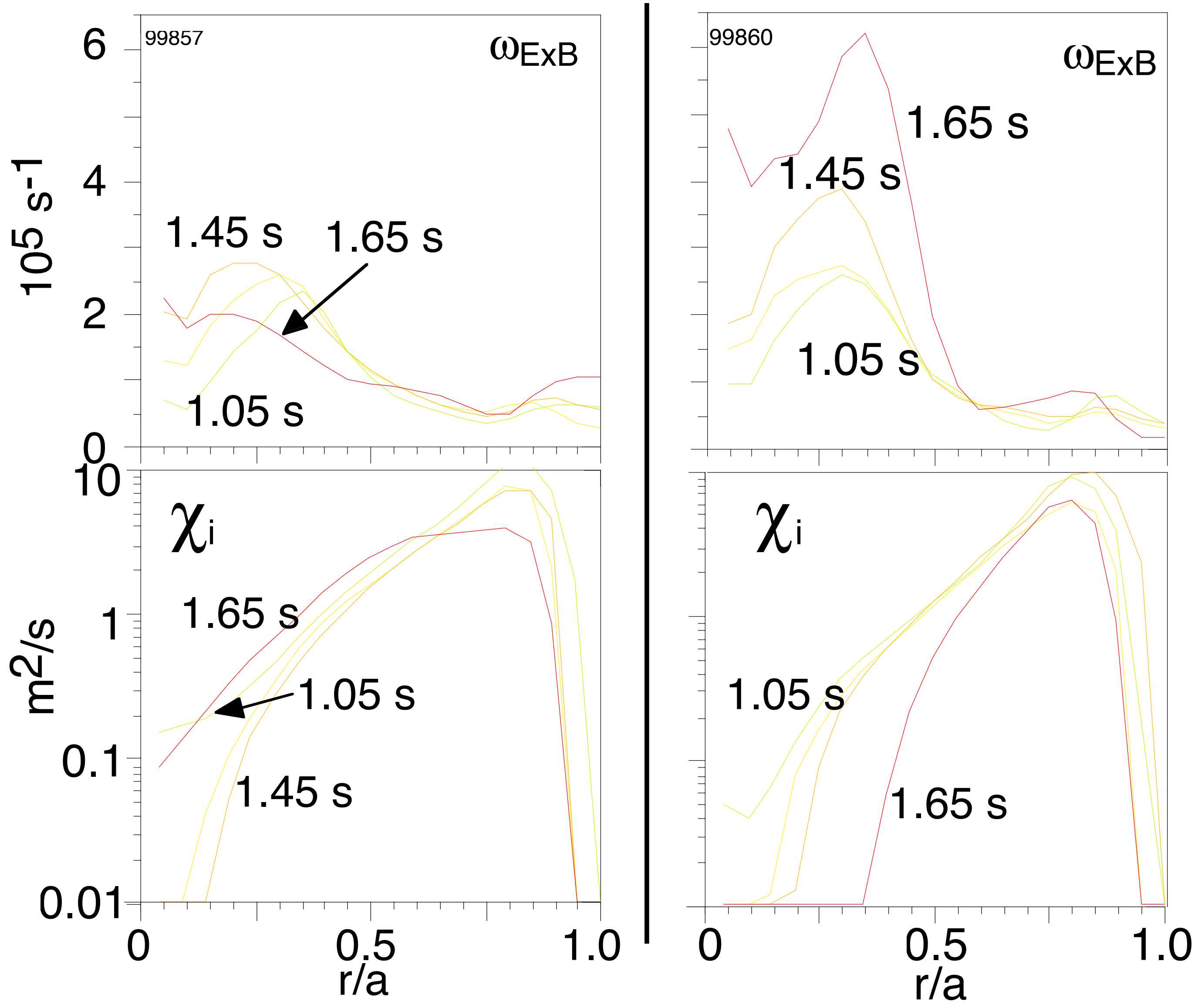
- E_r shear layer formation should appear as an excursion in MSE pitch angle measurement
- Note that theory predicts that $E\times B$ shear from any source (pressure or rotation) can trigger a bifurcation

With counter injection on DIII-D, rate and degree of confinement improvement is also correlated with applied torque



- Slow improvements in 9 MW phase
- Rapid improvements in late power step-up, accompaniec by large ω_{ExB} that is dominated by toroidal rotation
- MHD likely cause of slow response in 13 MW period

Degree of confinement enhancement correlated with ExB shear with counter injection



Although bifurcations are usually fast in simple models, several factors might slow them down

Instability drive increases roughly with ∇p

- ExB shear suppression goes faster than linear with ∇p
  ⇒ fast bifurcation, if amplitude suppression is dominant •

Complicated feedback loops can modify this E×B suppression scenario

- ∇p and rotation terms can oppose each other. Increases in (∇p)’ oppose increases in V_ϕ’

Dephasing with E×B shear before suppression

- if first effect of E×B shear is to dephase fluctuating fields before suppression, E×B effect on transport might be slower than a high power of ∇p

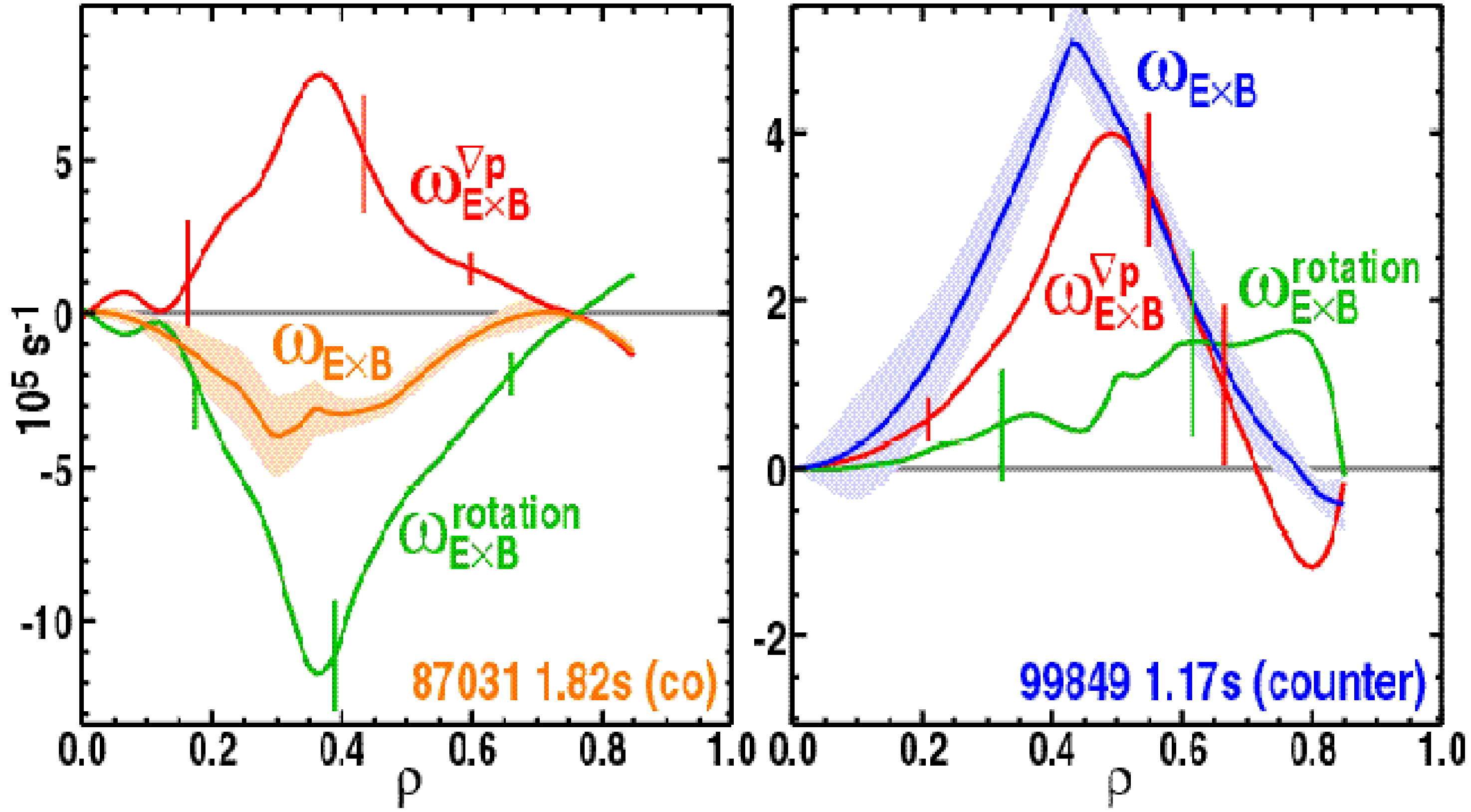
Slow forward transition with counter NBI is hard to understand if only turbulence suppression is considered

The shearing rate $\omega_{E\times B}$ is separated into thermal main ion rotation and pressure gradient terms.

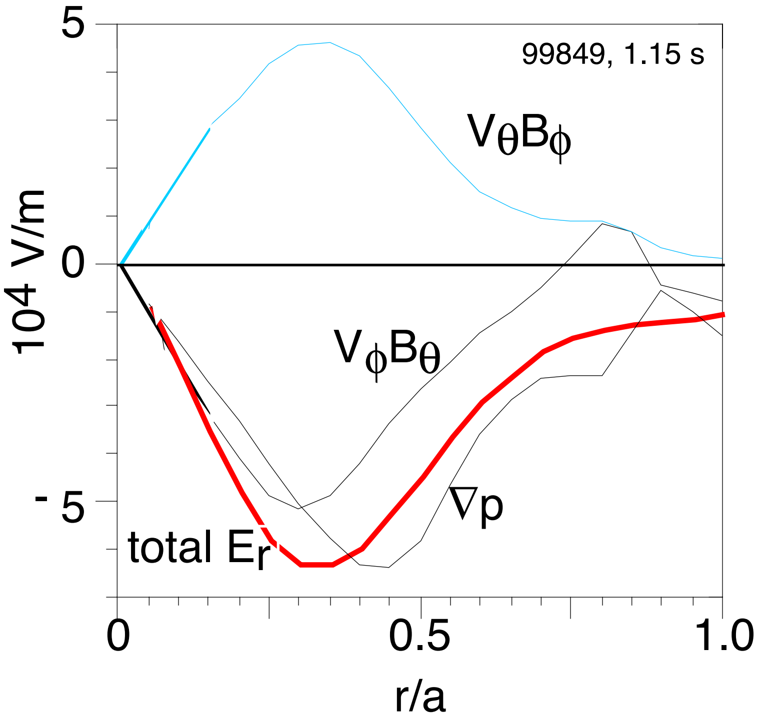
- Total $\omega_{E\times B}$ calculated from CER impurity measurements, main ion pressure term from profile measurements.

Co-NBI: ∇p and rotation terms oppose ⇒ increasing or broadening pressure profile reduces $\omega_{E\times B}$.

Counter-NBI: increasing or broadening the pressure profile *increases* $\omega_{E\times B}$.



From working ion force balance equation, all terms are significant in determining final E_r profile with counter rotation



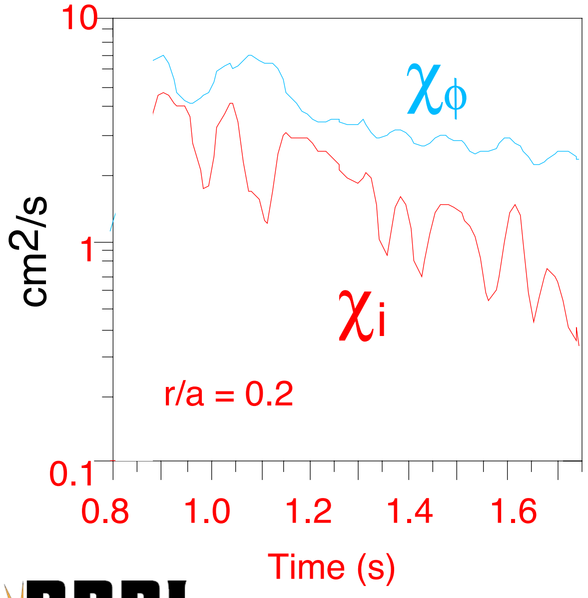
- working ion
- V_θ term from NCLASS

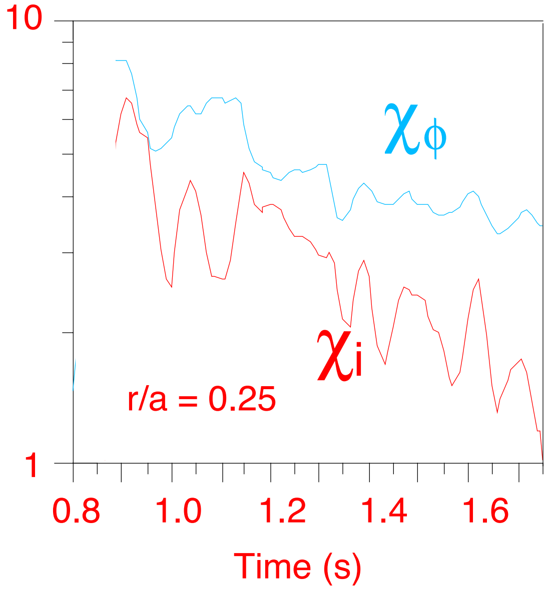
- ∇p, poloidal rotation components large, but residual is negative
- non-neoclassical V_θ contributions might change dynamics considerably

Is the oft-observed correlation between χ_ϕ and χ_I weakened in low power rotating plasmas?

- If only fluctuation amplitude is at work, then $\chi_I \alpha \chi_\phi$
  Important phase relations: for energy transport: $\Delta T_i, \Delta\phi$
  for momentum: $\Delta V_\phi, \Delta\phi$
- $\chi_I \neq \chi_\phi$ late in time: evidence that dephasing may be taking place first? Or just an uncertainty in analysis?
- Working ions: dV_ϕ/dr increase with time ~ 0

Argues for diagnostics of multiple fluctuating fields



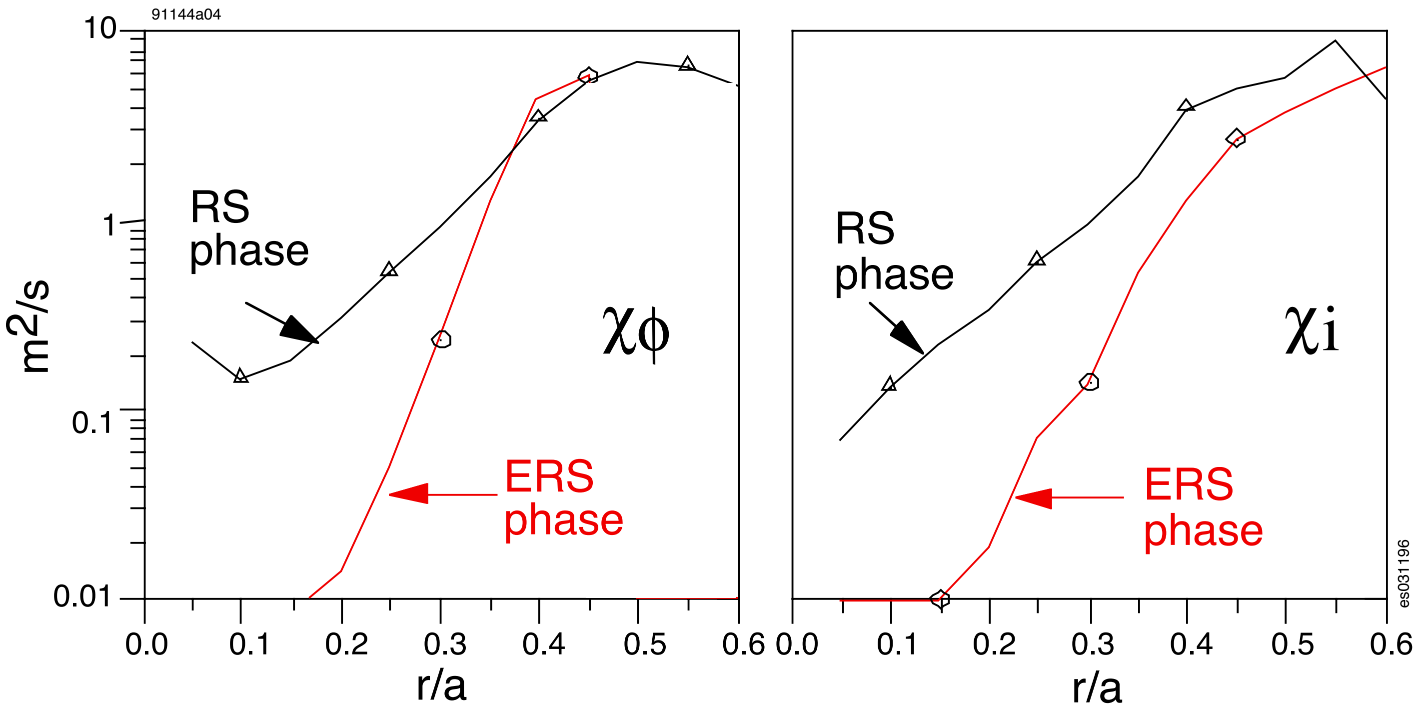


ExB shear and dephasing references:

A. Ware, P.W. Terry, P.H. Diamond, B.A. Carreras, PPCF, 1996

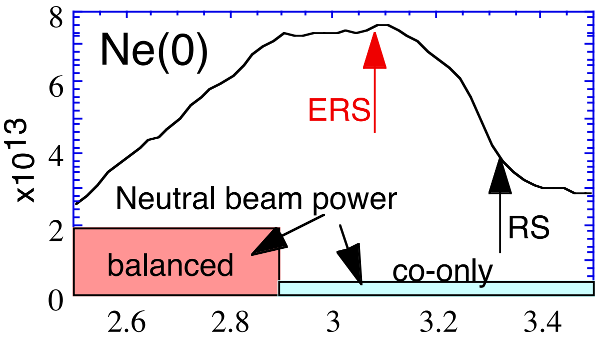
D.E. Newman, B.A. Carreras, P.H. Diamond, T.S. Hahm, Phys. Plasmas 3, May 1996

TFTR ERS plasmas joined a long history of plasmas where χ_i and χ_ϕ are strongly correlated



a plasma integrates torque for r/a < 0.2 during ERS phase

- reports of correlations in L mode-Supershot regime: S. Scott et al., PRL 64, 531 (1990).

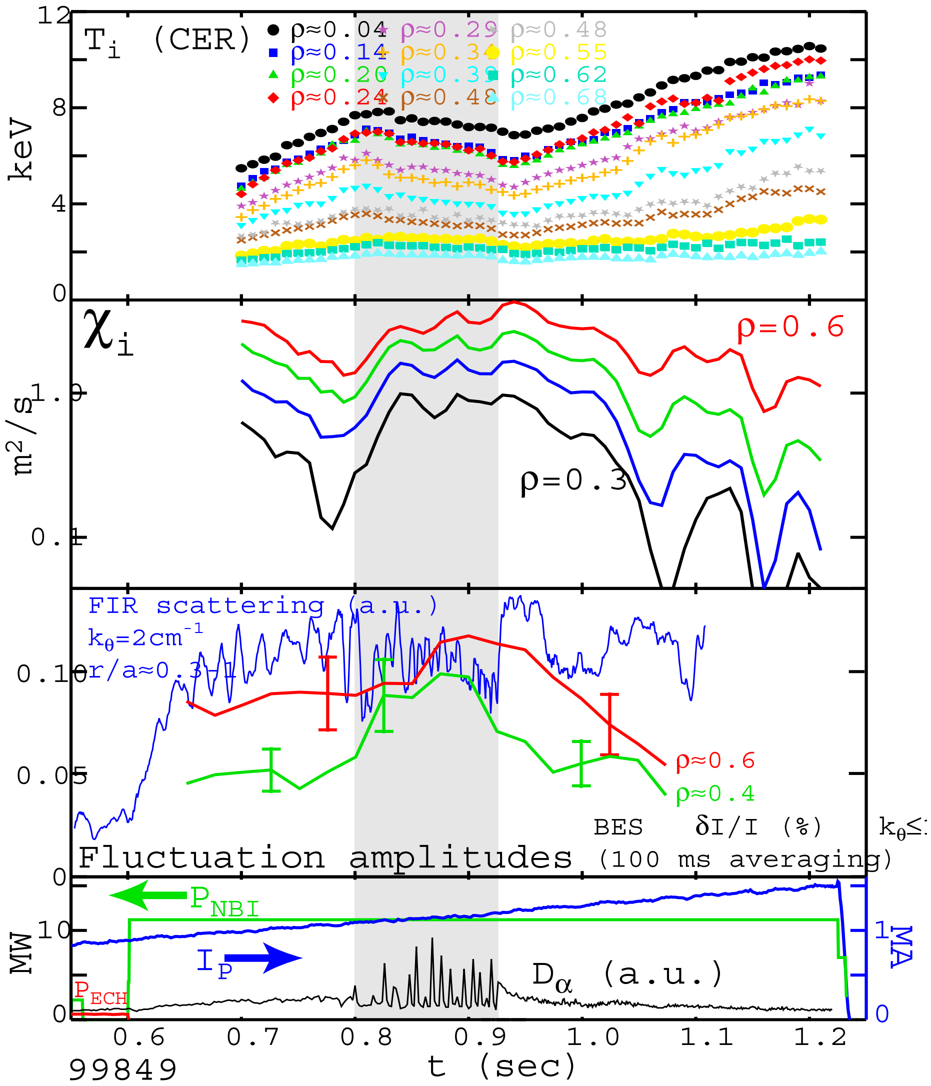


ITB formation is interrupted by a brief ELMing H mode phase

- Barrier begins forming soon after onset of high power neutral beam heating

- Core fluctuations drop following H-L transition, in conjunction with ITB formation

- Barrier expansion is slow, despite favorable alignment of ∇p and V_ϕ terms in force balance



Co- and counter-rotating DIII-D PEP modes permits tests of E×B shear suppression picture

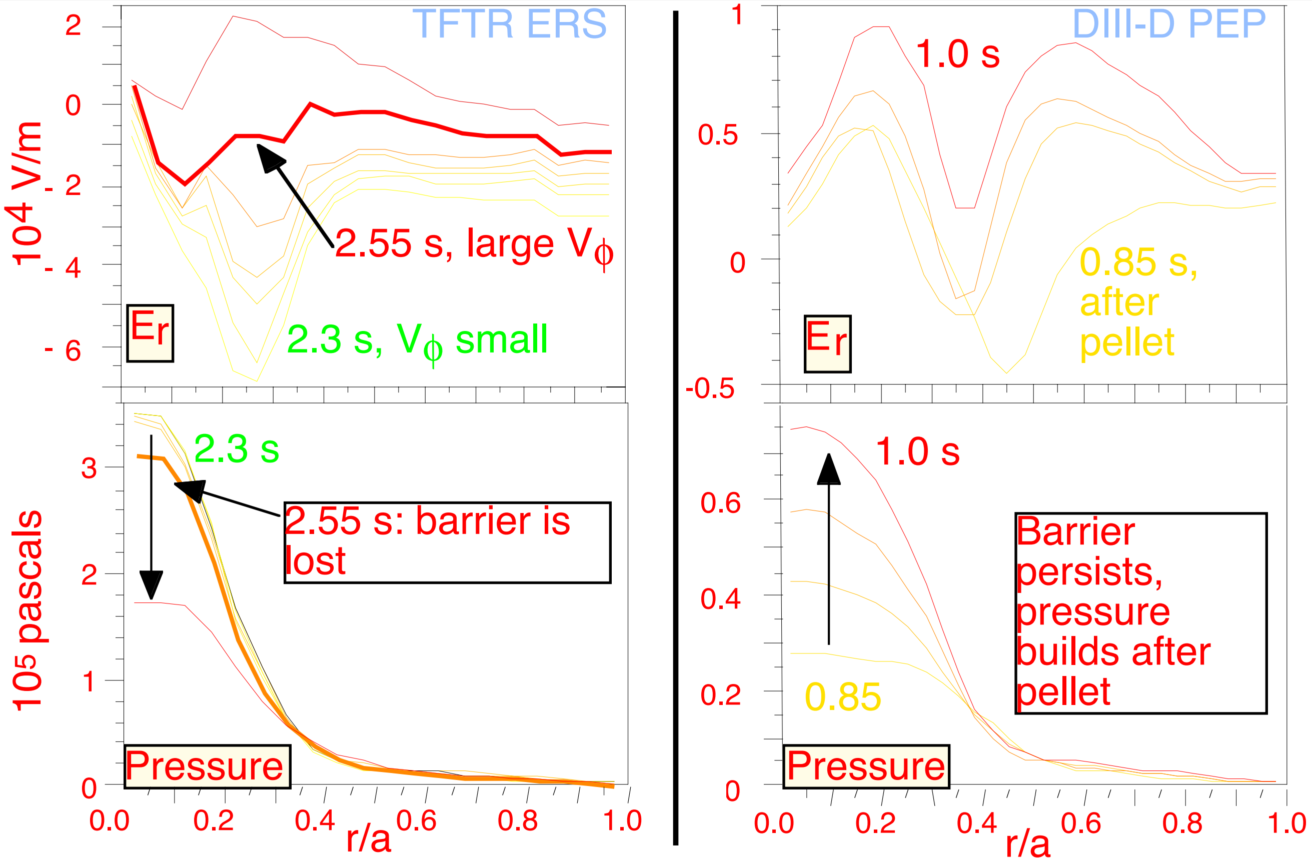
- Recall on TFTR: ERS and PEP were forced to reproducibly collapse with strong co-injection (Synakowski, PRL 78, 2972, 1997).

- Pellet injection on DIII-D allows co-rotation spin-up from $V_\phi \sim 0$ to be created
  - pellet mass initially slows rotation, but rotational shear builds afterward

- Observation: DIII-D co-directed PEPs do not collapse

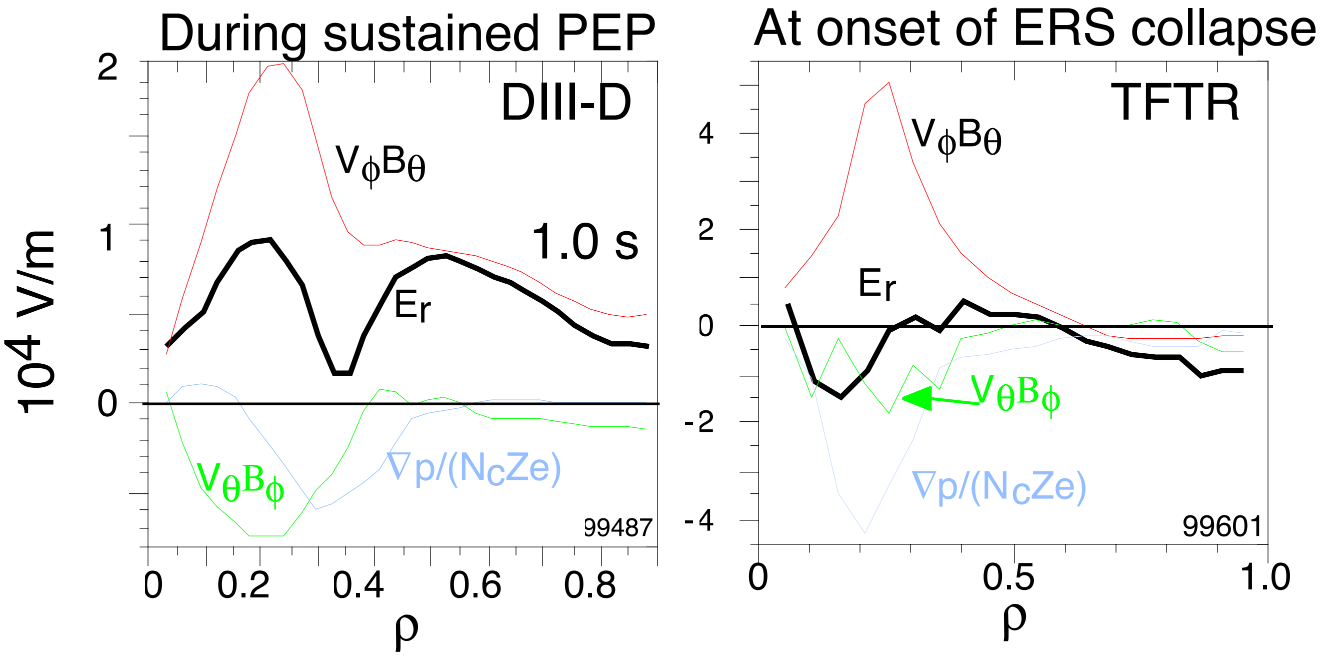
- Interpretation: alignment of gradients in ∇p and V_ϕ differs between DIII-D PEP and TFTR ERS, allowing PEP modes to be sustained due to ExB shear from pressure

Whether or not a barrier even survives is critically dependent on the alignment between different sources of flow shear



- TFTR: $V_\phi B_\theta$ term fills in negative ∇p-driven well as V_ϕ increases
- DIII-D PEP: $V_\phi B_\theta$ term is broad, allowing ∇p well to persist
- Both plasmas have initially small V_ϕ, followed by strong spinup

In DIII-D PEP and TFTR ERS, alignment between rotation and pressure terms in force balance differs, resulting in different dynamics

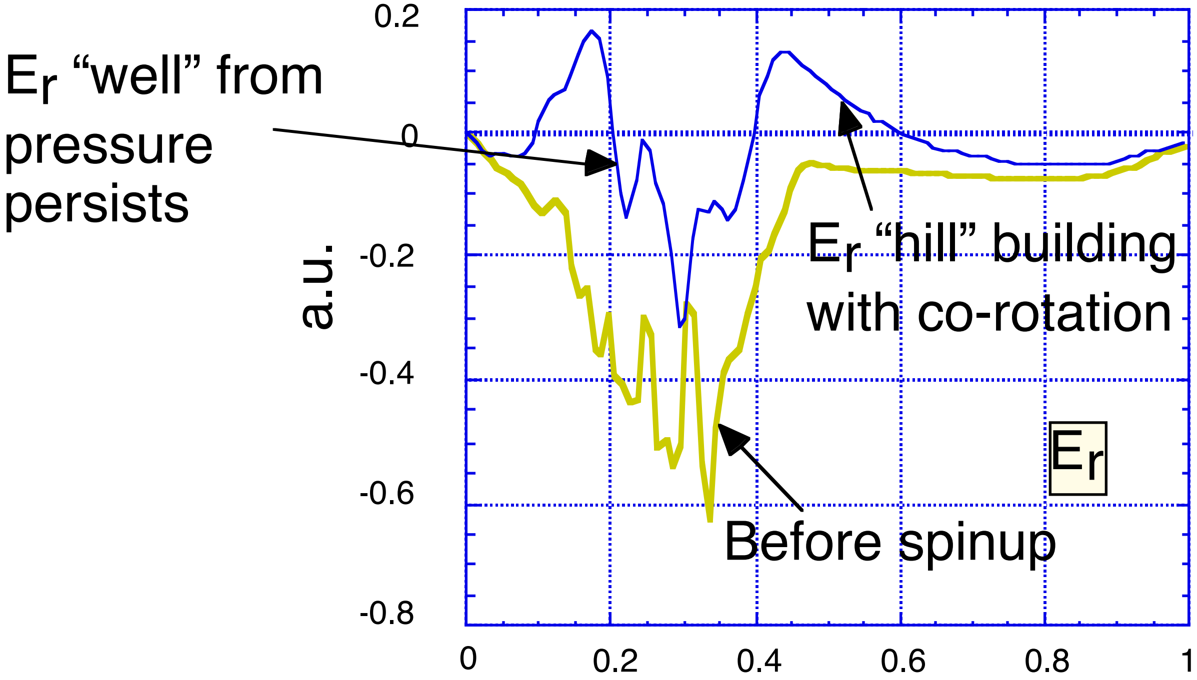


from carbon force balance

- In DIII-D PEP, E_r well persists in large ∇p region with strong toroida rotation due to difference in alignment between toroidal rotation terms and the pressure-related (∇p and V_θ) terms

- In TFTR ERS, alignment results in erosion of E_r shear in region of steep pressure gradient at onset of barrier collapse.

1-D modelling indicates that E_r well can persist in PEP mode in the presence of strong co-rotation



E_r “well” from pressure persists

E_r “hill” building with co-rotation

Before spinup

- Deposition profile key: in modelling, narrower deposition makes it more likely that well will eventually disappear
  - TFTR has relatively narrow deposition compared to DIII-D

A wide variety of barrier dynamics can result if the driven rotation in a system is altered

DIII-D NCS-like dynamics were reproduced on TFTR when E_r structure and evolution were reproduced in reverse shear

Transition time scales and degree of improvement vary with applied torque. 1-D modelling consistent with co-injected experiments

Slow forward transitions with counter NBI harder to understand: evidence for dephasing of turbulent fields?

Core barrier dynamics can be exquisitely sensitive to relation between pressure and rotation profiles

- alignment of pressure and rotation profiles can determine if a barrier survives or collapses

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