Radial Electric Fields and Transport Barrier Formation in TFTR*

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with contributions from

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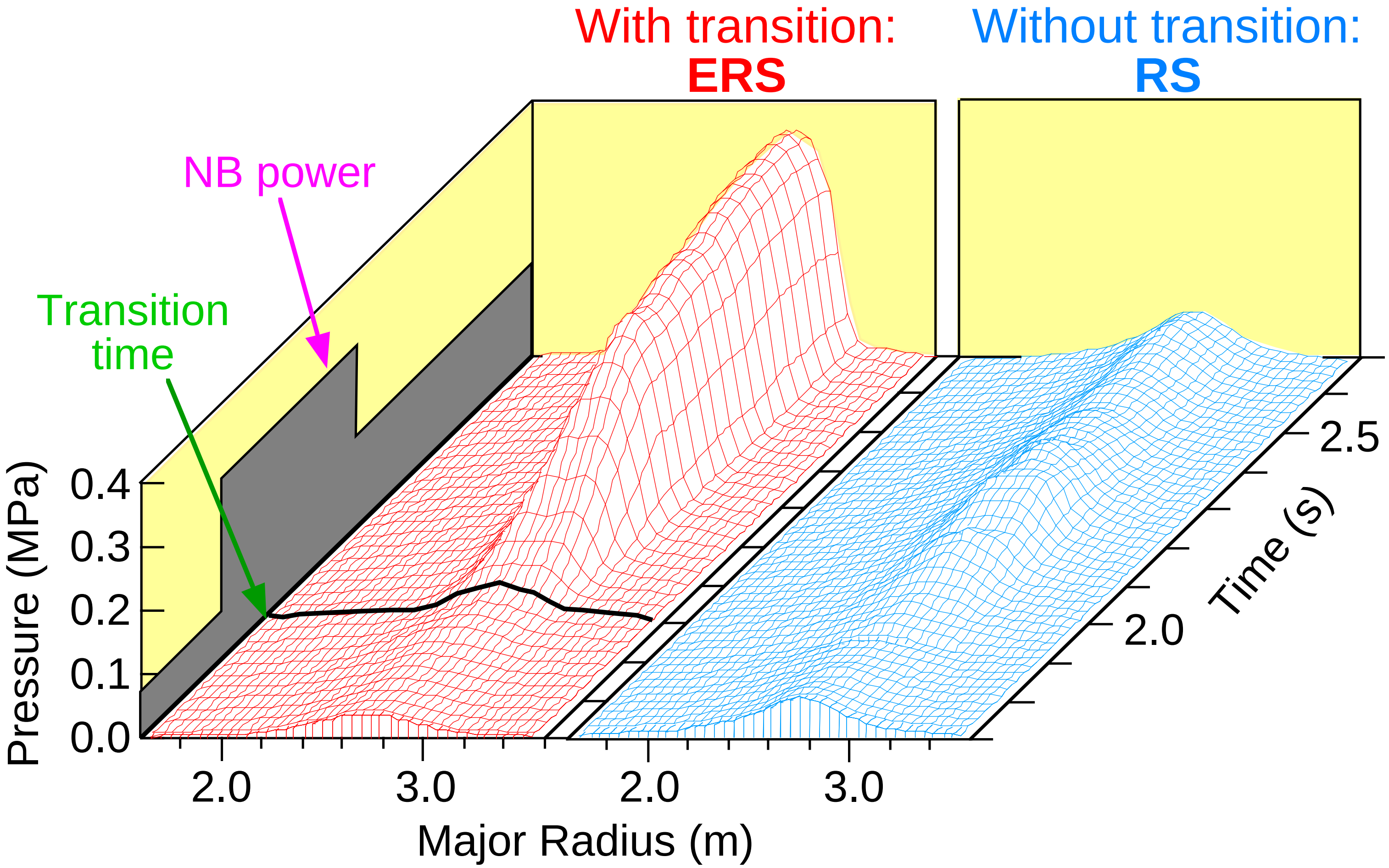
Topics

- Transport effects in TFTR reversed-shear plasmas
- Turbulence suppression mechanisms
- Relationship to other enhanced confinement modes
- Anomalies and counter examples
- Possibilities for control

Reversed-Shear Plasmas Exhibited Bifurcations in Confinement

TFTR



- Rates of neutral beam heating and particle fueling similar
- q profiles similar before transition
- Bifurcation of state: intermediate profiles did not occur

E. Synakowski

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Ion Thermal and Electron Particle Transport Sharply Reduced in Plasma Interior after ERS Transition

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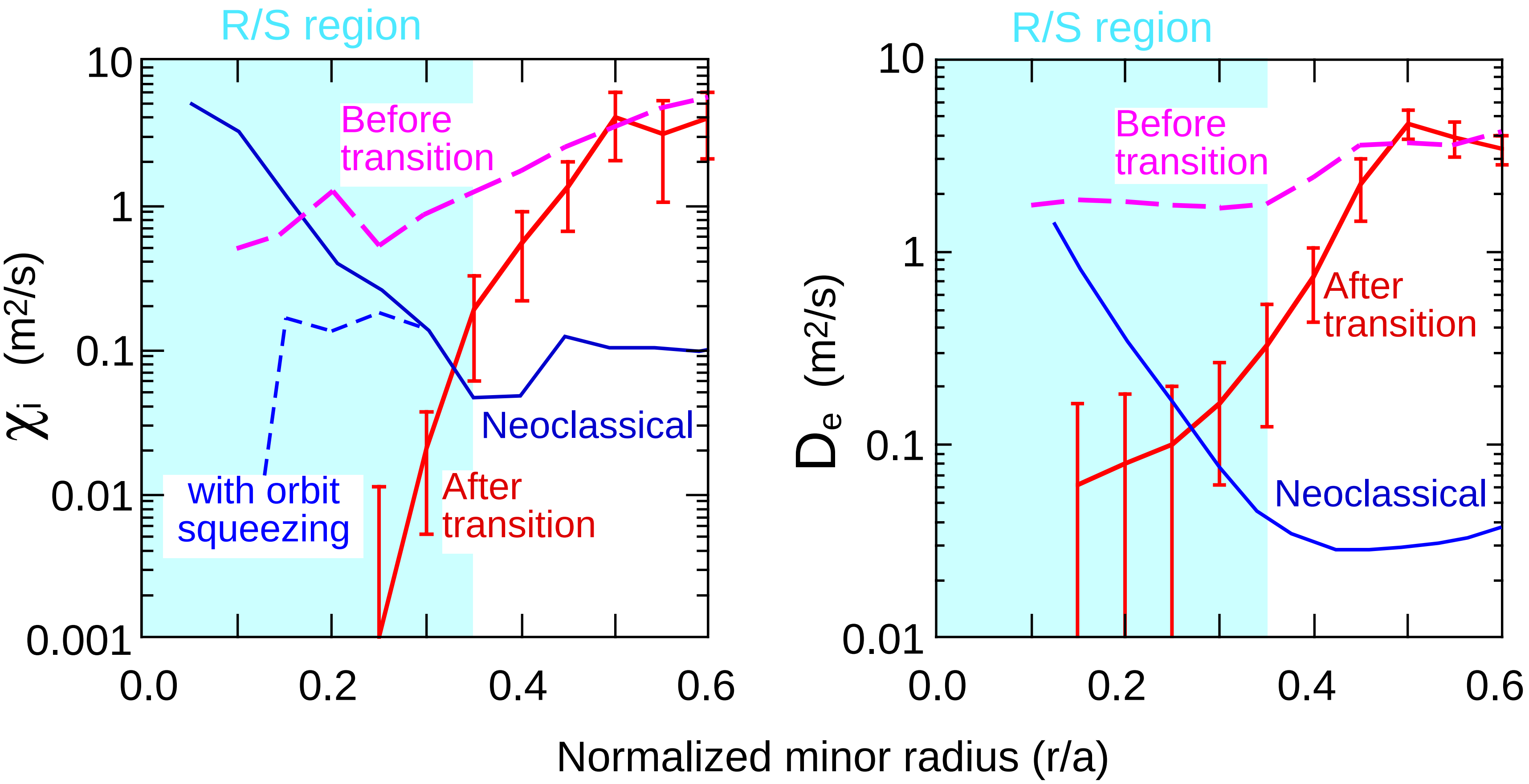

- Flux balance effective χ, D: $q \equiv -n \chi \nabla T$ and $\Gamma \equiv -D \nabla n$
- Neoclassical calculation includes off-diagonal contributions
- Orbit squeezing effects from Shaing *et al.* [Phys. Plasmas **1**, 3365 (1994)]
- Particle transport barrier confirmed for T and He puffed into edge

M. Zarnstorff

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Plasma Turbulence Reduced or Suppressed in Vicinity of Internal Transport Barriers

- In ERS, bursting fluctuations measured by reflectometer disappear within shear-reversal surface
  - fluctuations disappear rapidly at initial transition into ERS
  - reappear gradually at "back-transition" from ERS
- Turbulence suppression by **sheared *E*×*B* flow** when

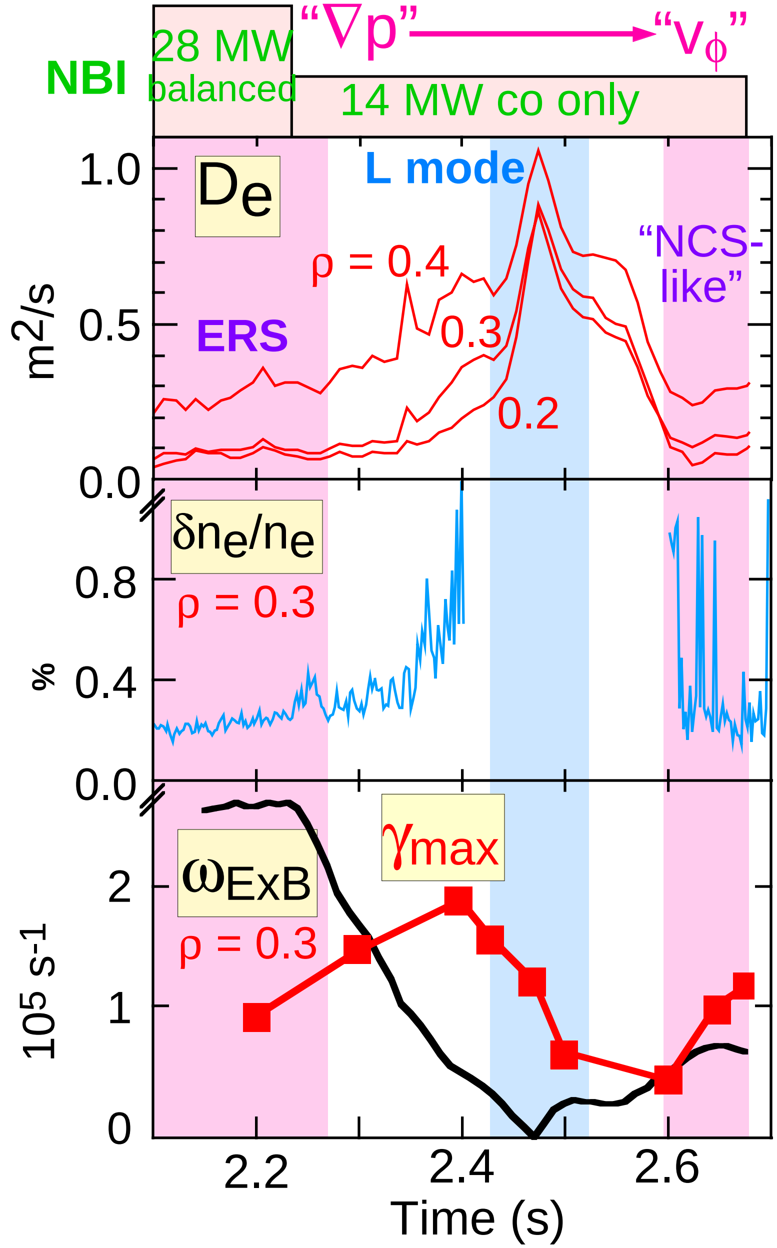
  $\omega_{E\times B} > \gamma_{\max}^{\mathrm{lin}}$ where

  $\omega_{E\times B} = \dfrac{RB_\theta}{B}\dfrac{d}{dr}\left(\dfrac{E_r}{RB_\theta}\right)$ is shearing rate (Hahm and Burrell);

  $\gamma_{\max}^{\mathrm{lin}}$ is linear growth rate of most unstable mode
- Radial force balance: $E_r = \nabla p/(eZn) + v_\phi B_\theta - v_\theta B_\phi$
  - can calculate from measurements for carbon impurities

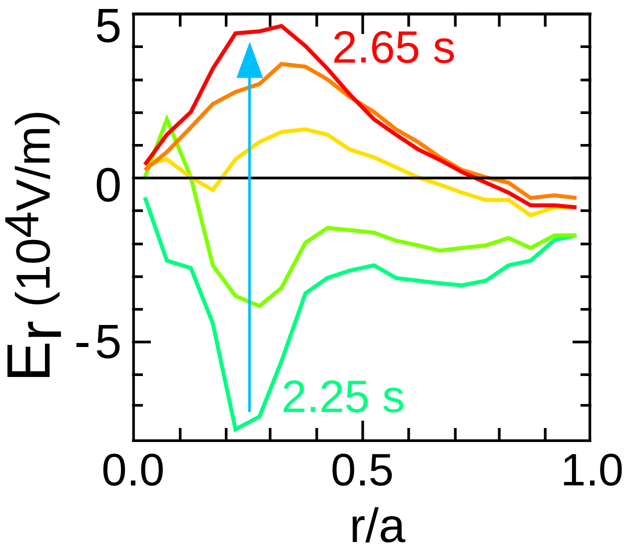
Changing NBI Torque Can Destroy Then Recreate Turbulence Suppression & Enhanced Confinement

TFTR



$$E_r = \nabla p/(eZn) + v_\phi B_\theta - v_\theta B_\phi$$

- Balanced NBI ⇒ E_r dominated by ∇p term
  - positive feedback produces rapid transition
- Co-only NBI ⇒ V_ϕ term opposes ∇p
  - E_r shear drops ⇒ turbulent transport returns
- Eventually, V_ϕ dominates and E_r increases
  - turbulence and transport slowly decrease
  - similar to enhanced NCS plasmas in DIII-D



E. Synakowski, E. Mazzucato, M. Beer

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Suppression of Turbulence by Sheared Flow Important in Other Confinement Regimes

- ♦ Majority of TFTR operation in "Supershot" regime with NBI
  - transitionless: develops smoothly from L-mode
  - shear is positive throughout and $q(0) < 1$
  - sawteeth suppressed
  - minimal degradation of confinement with power up to β-limit
- ♦ Model with turbulence suppressed by flow shear reproduces many features and trends of supershot confinement
  - co-/ctr- NBI effects
  - dependence of central parameters on edge conditions
  - favorable isotope scaling in DT plasmas
  - model developed in parallel with ERS studies *(D.R. Ernst)*

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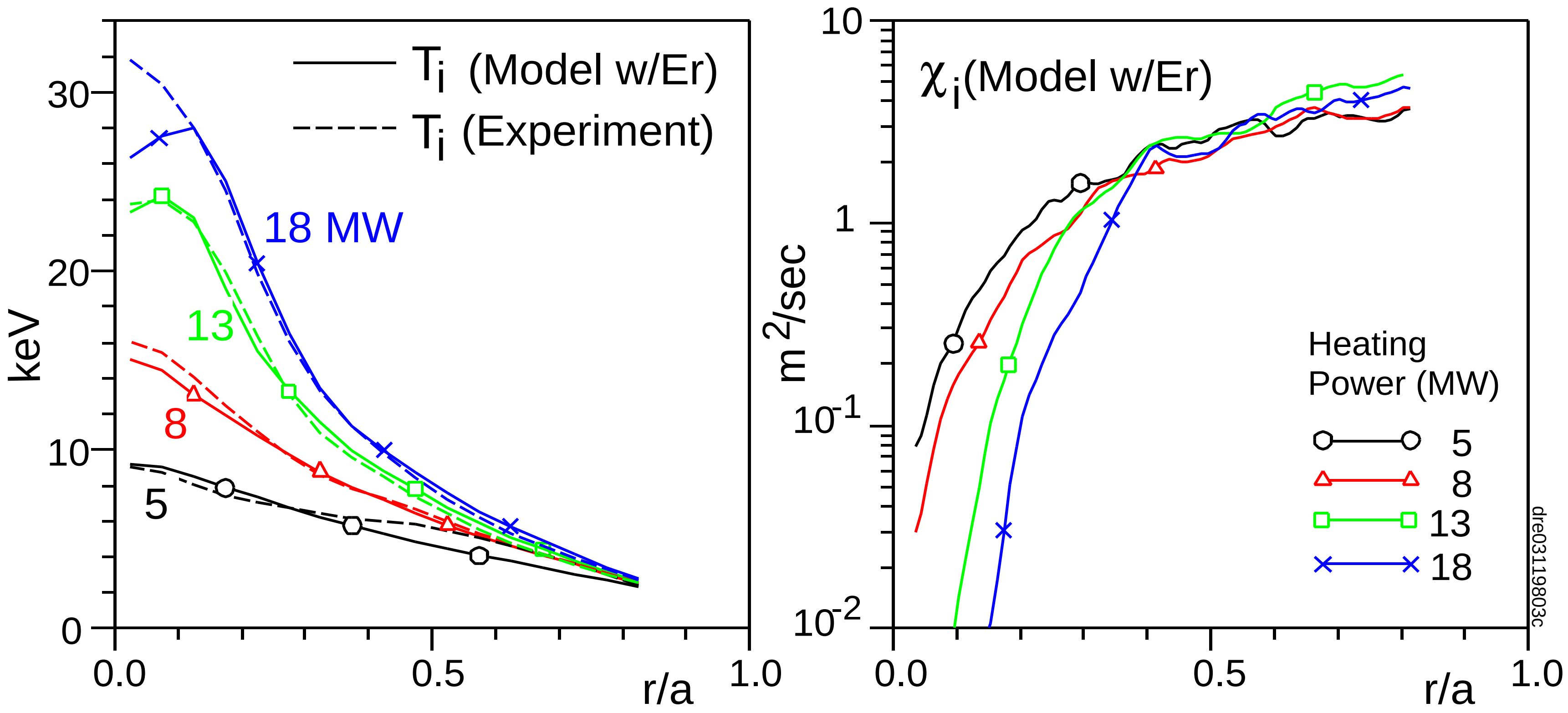
Model with Turbulence Suppressed by Velocity Shear Reproduces Ion Temperature Profiles in Supershots



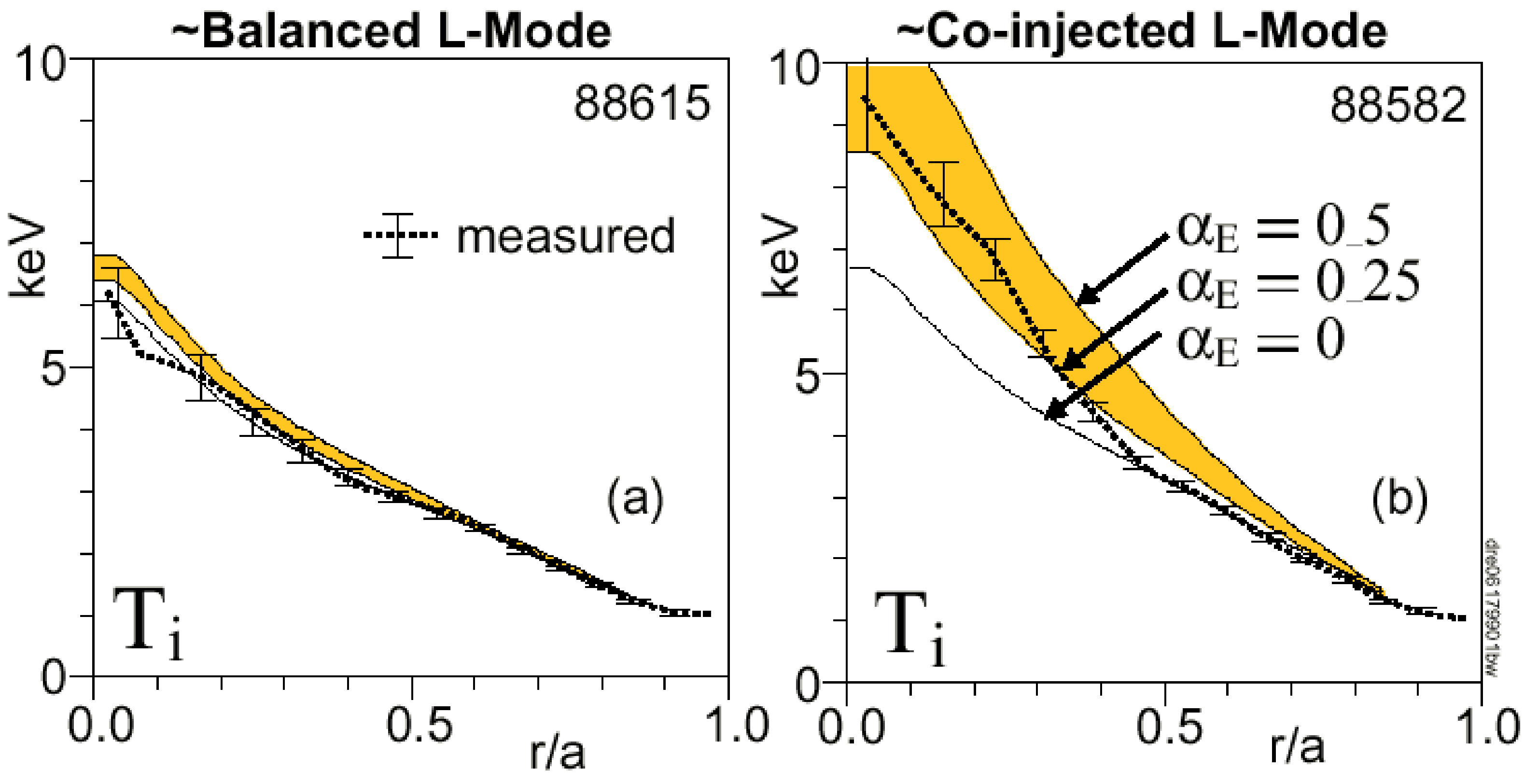
- Based on supppression of ITG turbulent ion thermal diffusivity when $\omega_{\mathrm{E\times B}} \simeq \gamma_{\mathrm{lin}}^{\mathrm{(IFS-PPL)}}$ with self-consistent calculation of neoclassical plasma flow.
- Leads to apparent $\chi_{\mathrm{i}} \propto 1/\mathrm{T_i}$ scaling at fixed radius.
- Enhanced confinement zone expands with heating power.
- Supershot behavior resembles ERS, NCS, JT-60 ITB, etc.

E_r Shear Can Account for T_i Change with Neutral Beam Torque in L-mode Plasmas

- Model power balance with

$$\chi_i = \chi_i^{(\text{IFS-PPPL})} \left(1 - \alpha_E \omega_{E\times B} / \gamma_{lin}^{(max)}\right)$$

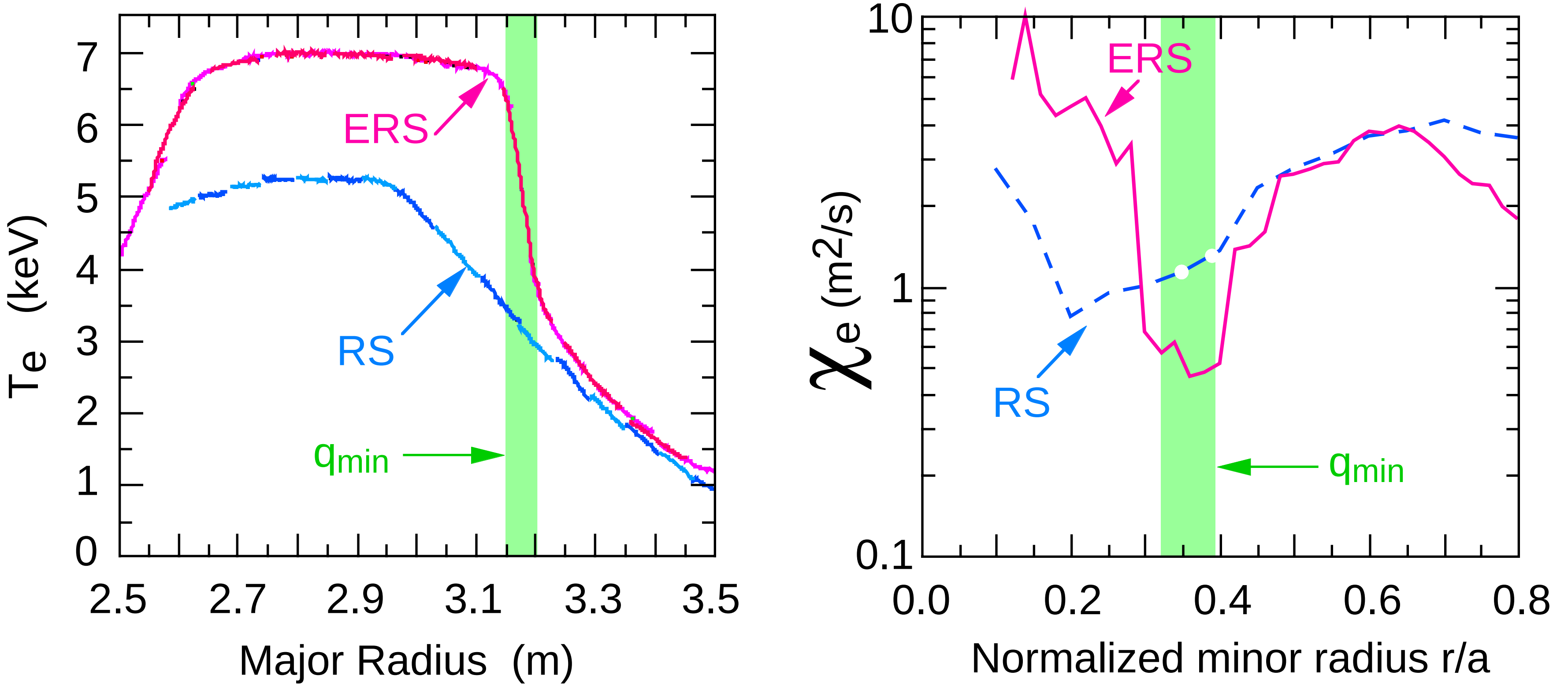
using full neoclassical multi-species treatment of flows



D.R. Ernst

High Resolution Measurement Shows Structure in T_e and χ_e Profiles during ERS Phase

TFTR



- Move plasma during steady-state phase ⇒ gradient from single detector
- Transition from flat core to large gradient at resolution of individual detector
- Transport analysis with 50 radial zones to increase resolution
- In region of high T_e gradient, χ_e reduced by factor ~4 but remains ~ 10 D_e
- In core, χ_e(ERS) >> χ_e(RS) and χ_e(ERS) >> D_e(ERS)

Transient Excursion in Poloidal Velocity Measured Prior to ERS Transition

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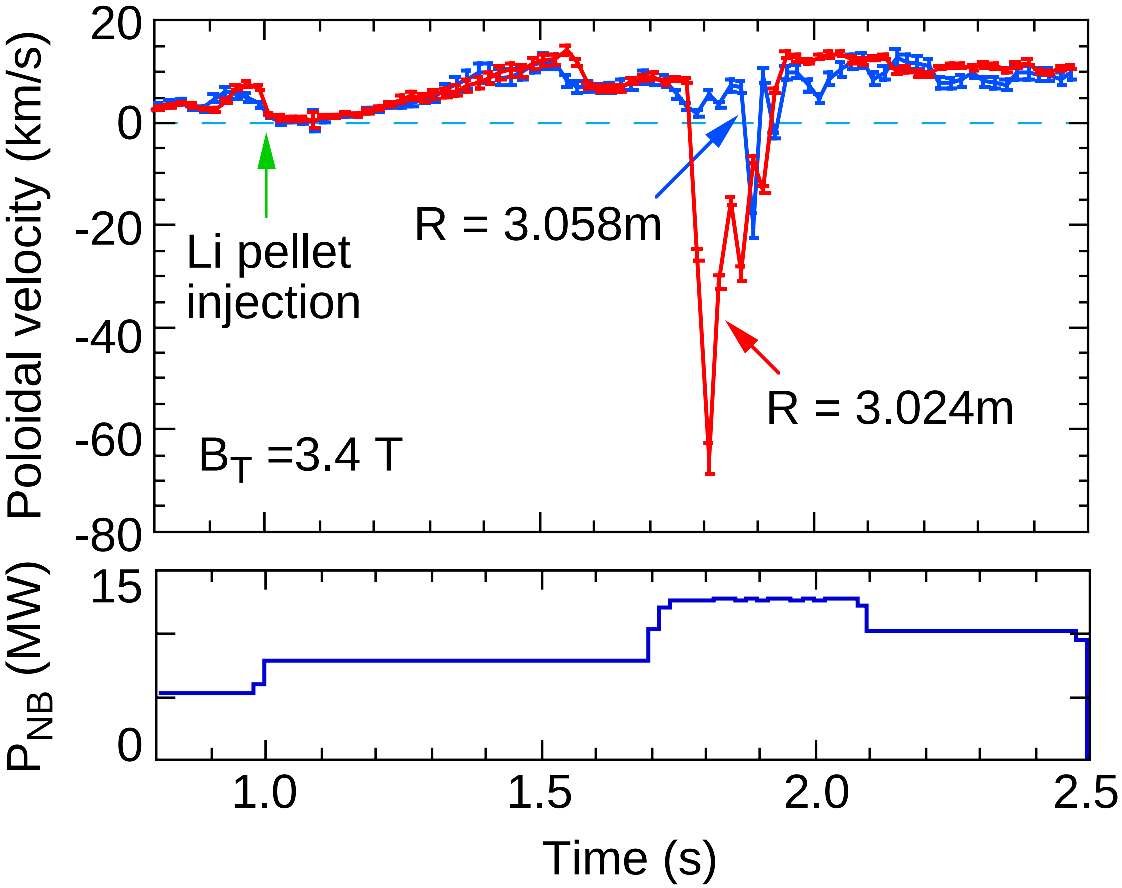

- Occurs in most *but not all* plasmas which transition to ERS
- Precedes signs of ERS in pressure profile by ~50ms

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Narrow Flow Shear Layer Develops Inside q_{min} Prior to ERS Transition

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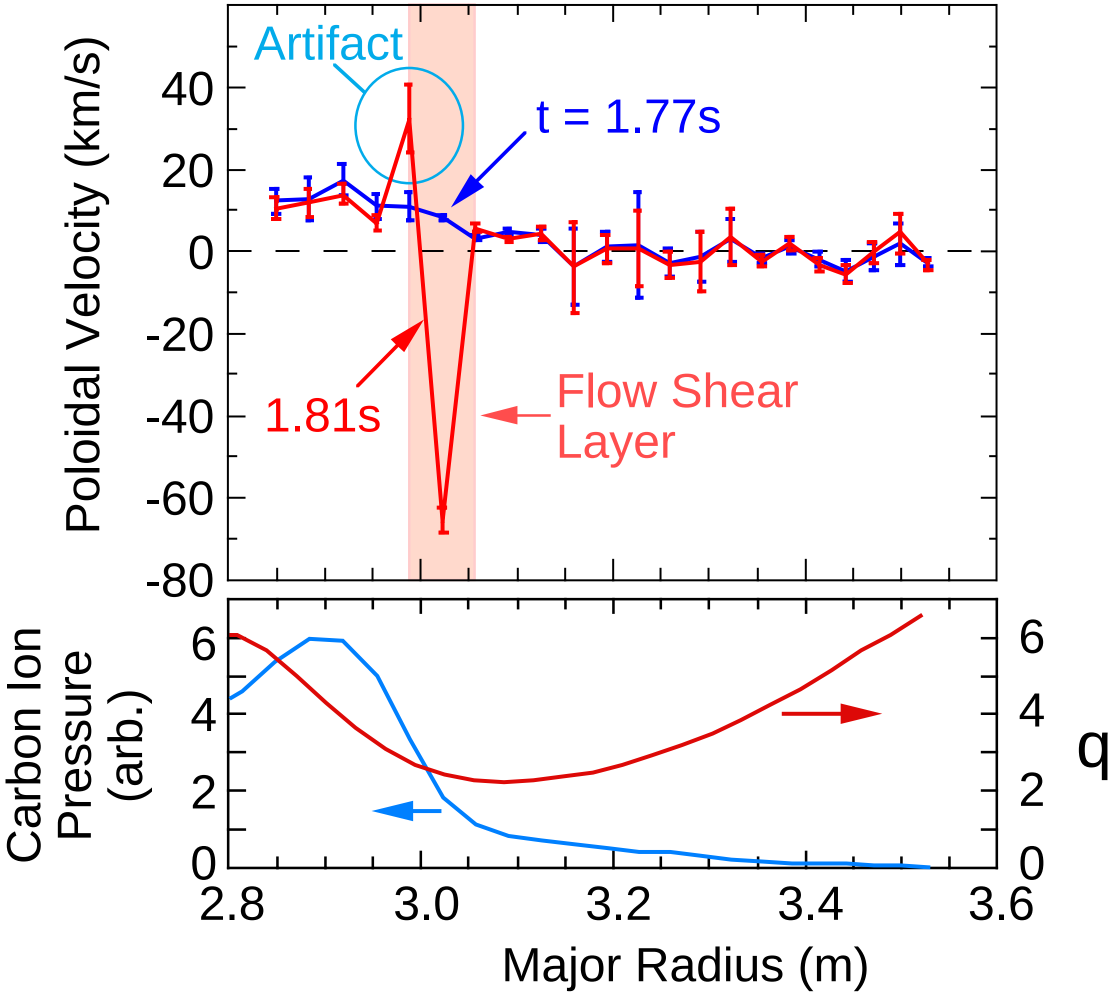

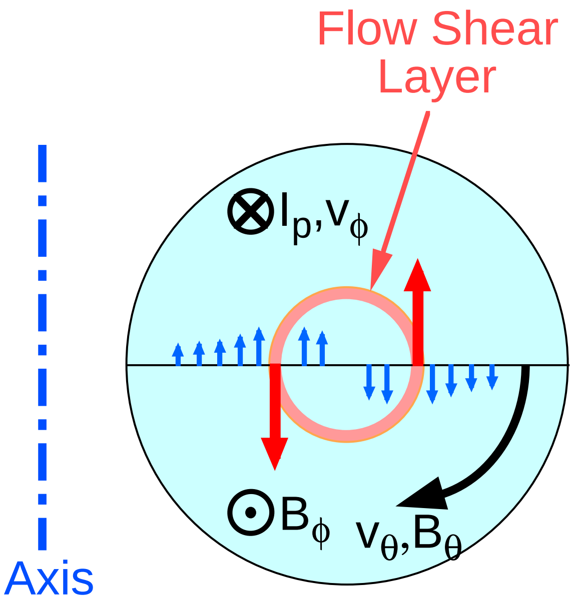

- Chordal data inverted to produce local poloidal velocity
- Layer narrower than sightline separation ⇒ artifact inside
- Located between maximum pressure gradient and q_{min}

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Radial Force Balance Confirmed by Measurement during E_r Transient

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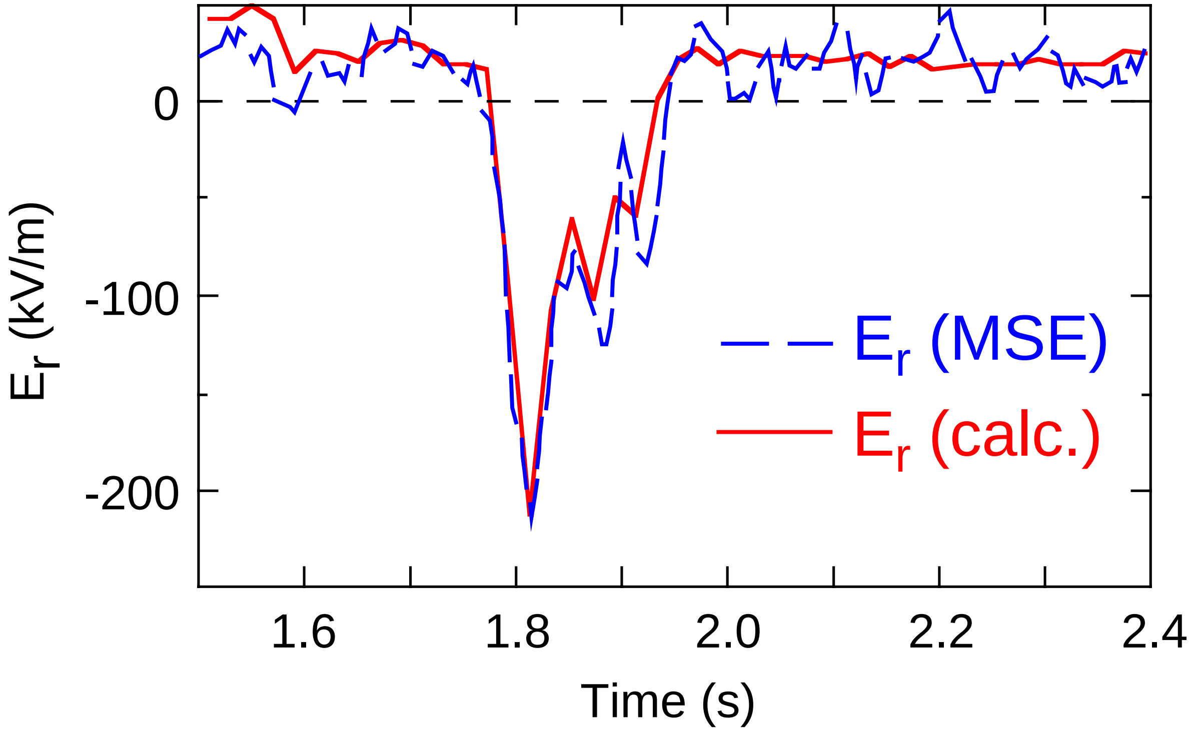
$$E_r \text{ (calc.)} = \nabla p/(eZn) + v_\phi B_\theta - v_\theta B_\phi$$



- All terms measured experimentally
- Motional Stark Effect (MSE) diagnostic modified to measure simultaneously emission from full and half energy injected neutrals ⇒ separation of E_r, B_θ
- Changes in ∇p, v_ϕ terms small compared to change in v_θ term during transient

F. Levinton (FP&T), R. Bell, E. Synakowski

Ion Bernstein Wave Heating Can Drive Localized Poloidal Rotation and Create Velocity Shear

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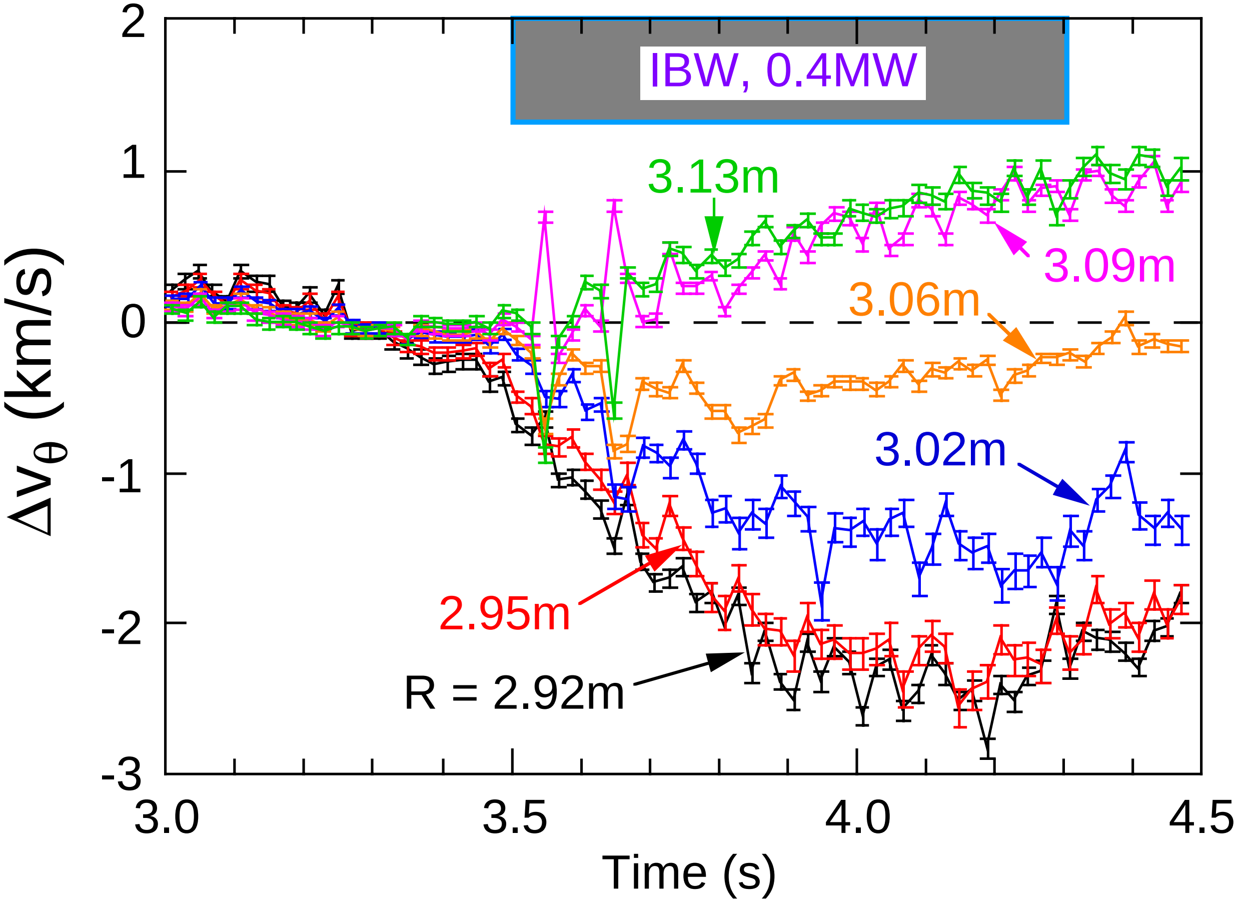

- Chordal data inverted to produce local v_θ
- Shear develops injection in absorption region during Ion Bernstein Wave
- With available power, rotation insufficient to suppress turbulent transport

R. Bell, B. LeBlanc

Second Type of Confinement Transition in RS

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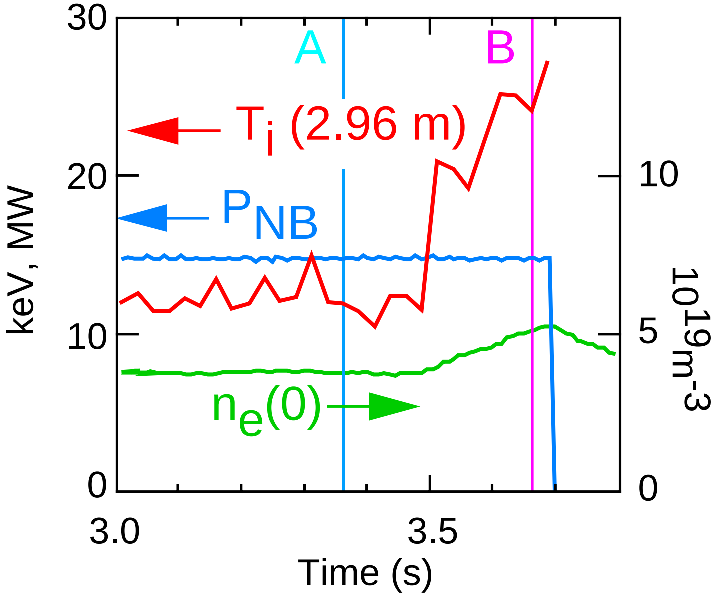

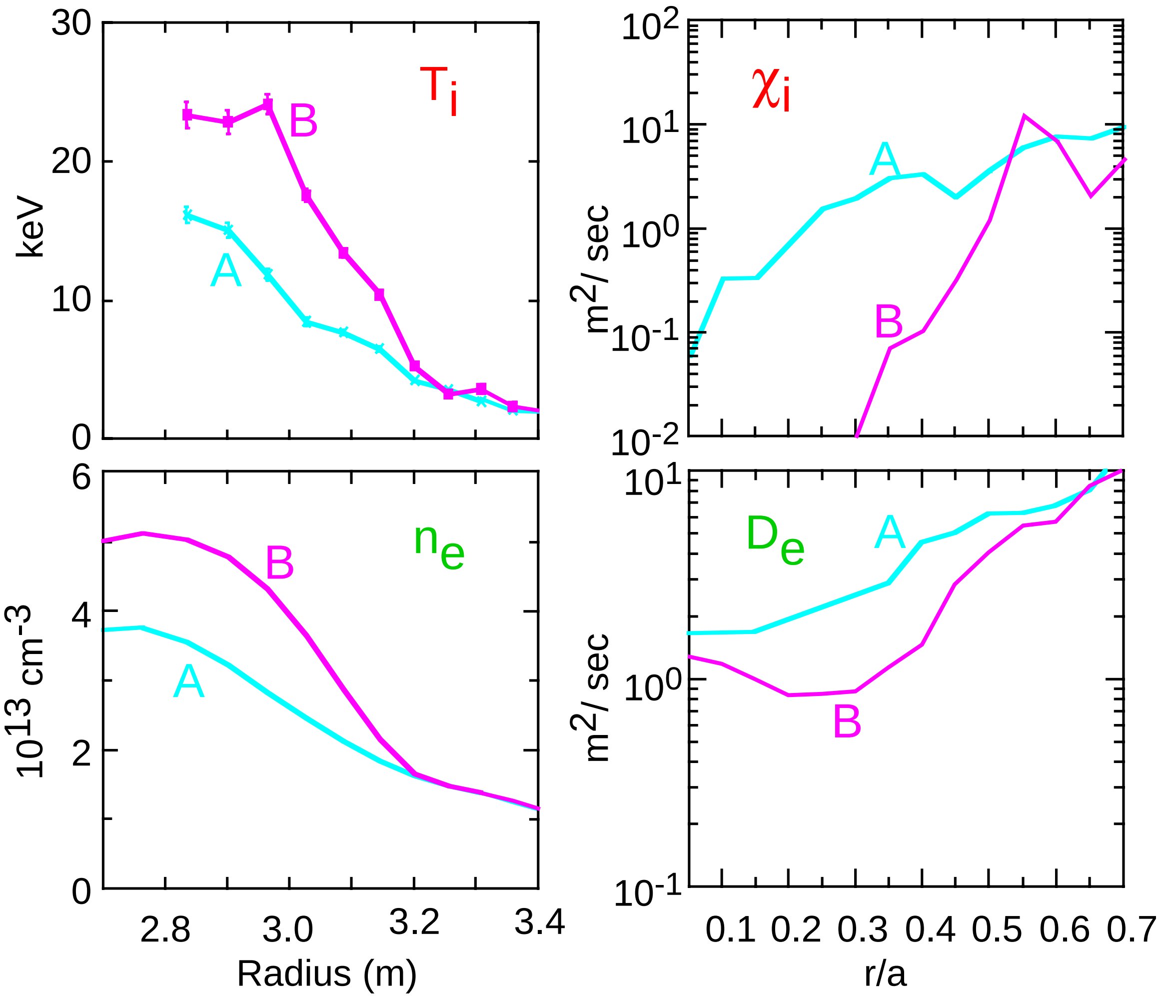

- "Type II" occurs in RS plasmas below threshold power for normal (Type I) ERS
- Reductions in χ_i, χ_ϕ; some reduction in D_e but not as marked as Type I
- Type II occurs as $q_{min} \to 2$; the "foot" of the barrier is just outside q_{min}
  - Similarity to barriers formed in JET OS plasmas

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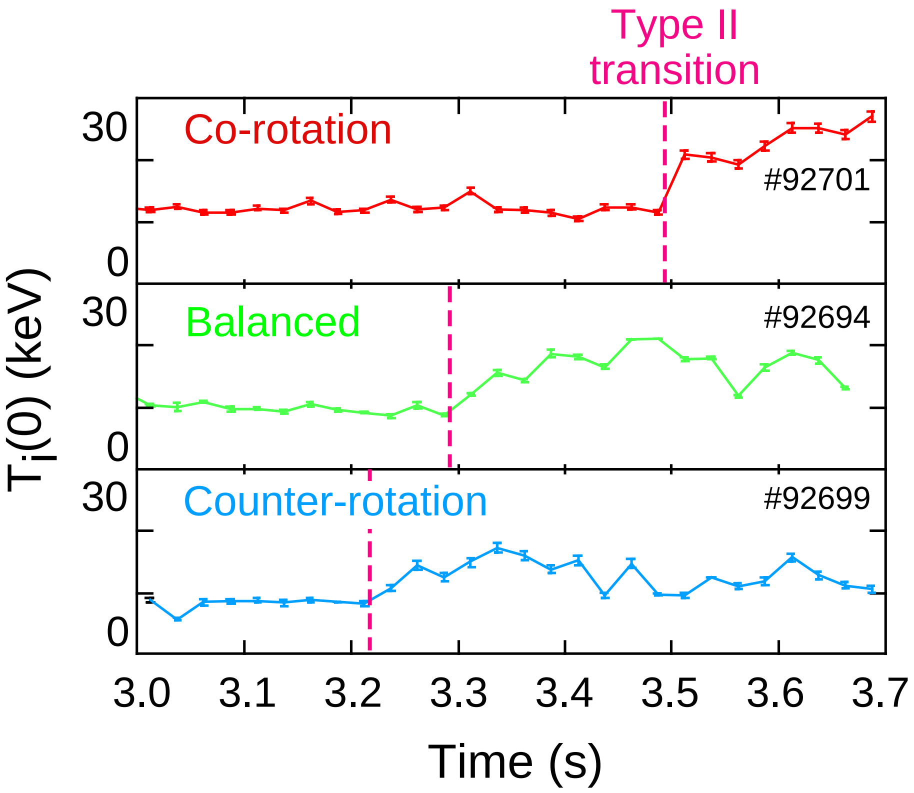
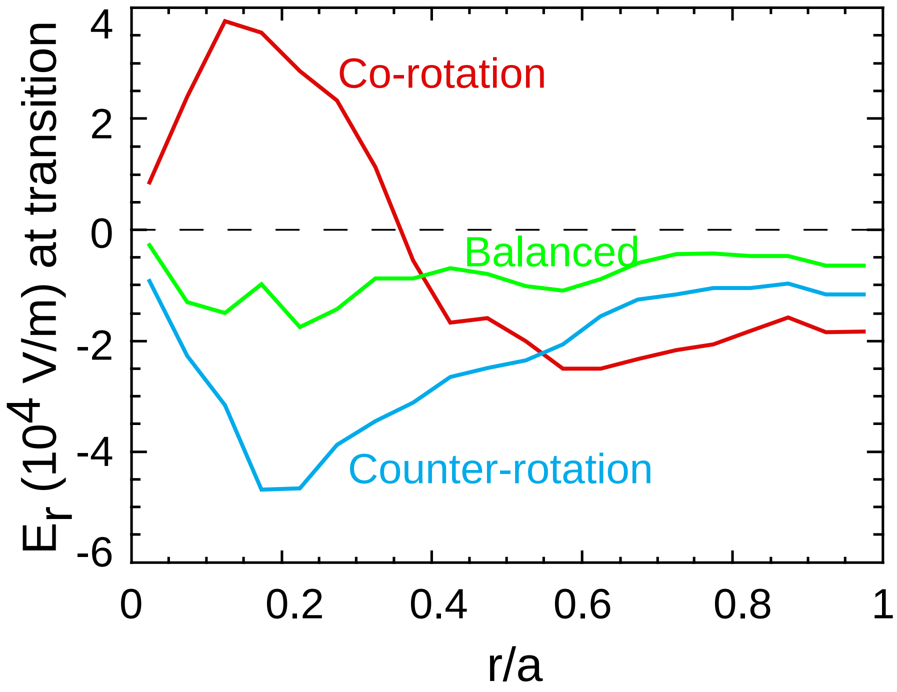
Type II Transitions Occur for Range of E_r Profiles





- Vary co-/ctr- NBI balance at constant power to change rotation
- Transition time does vary as q profile is affected by beam-driven current
- **E** × **B** shear does not appear to be essential for triggering Type II transitions

Summary and Issues

- The radial electric field plays a crucial role in tokamaks
  - possibilities for improved confinement - *the critical issue*
- Suppression of turbulence by sheared **E** × **B** flow may underlie many regimes of improved core confinement
  - correlation between suppression of fluctuations and *some* anomalous transport channels established in plasma interior
  - different loss channels have very different responses
  - anomalous transient flows can accompany ITB formation
- *Caveat:* other mechanisms appear to exist for ITB formation
- Development of tools to control transport barriers will be vital
  - sharp transport barriers create stability problems
  - flow control by RF waves a possibility