Core Transport Reduction in Tokamak Plasmas with Modified Magnetic Shear

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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
- Stability issues
- Possibilities for exploitation

Plasmas with Modified Magnetic Shear and q(0) > 1 Exhibit Spontaneous Improvements in Confinement

- Theory: stability should improve in regions with reversed magnetic shear, $S = r/q \cdot \partial q/\partial r < 0$

- Experiments: improvements in energy confinement
  - ERS, NCS, Reversed-shear, Optimised-shear modes
  - factors 2 – 4 relative to L-mode scaling

- Formation of prominent internal transport barriers (ITB)
  - obvious in ion temperature and density profiles for NBI heating
  - sometimes exhibit features in electron temperature profile

- Associated with clear transition phenomena in some tokamaks
  - power threshold
  - reminiscent of H-mode transition

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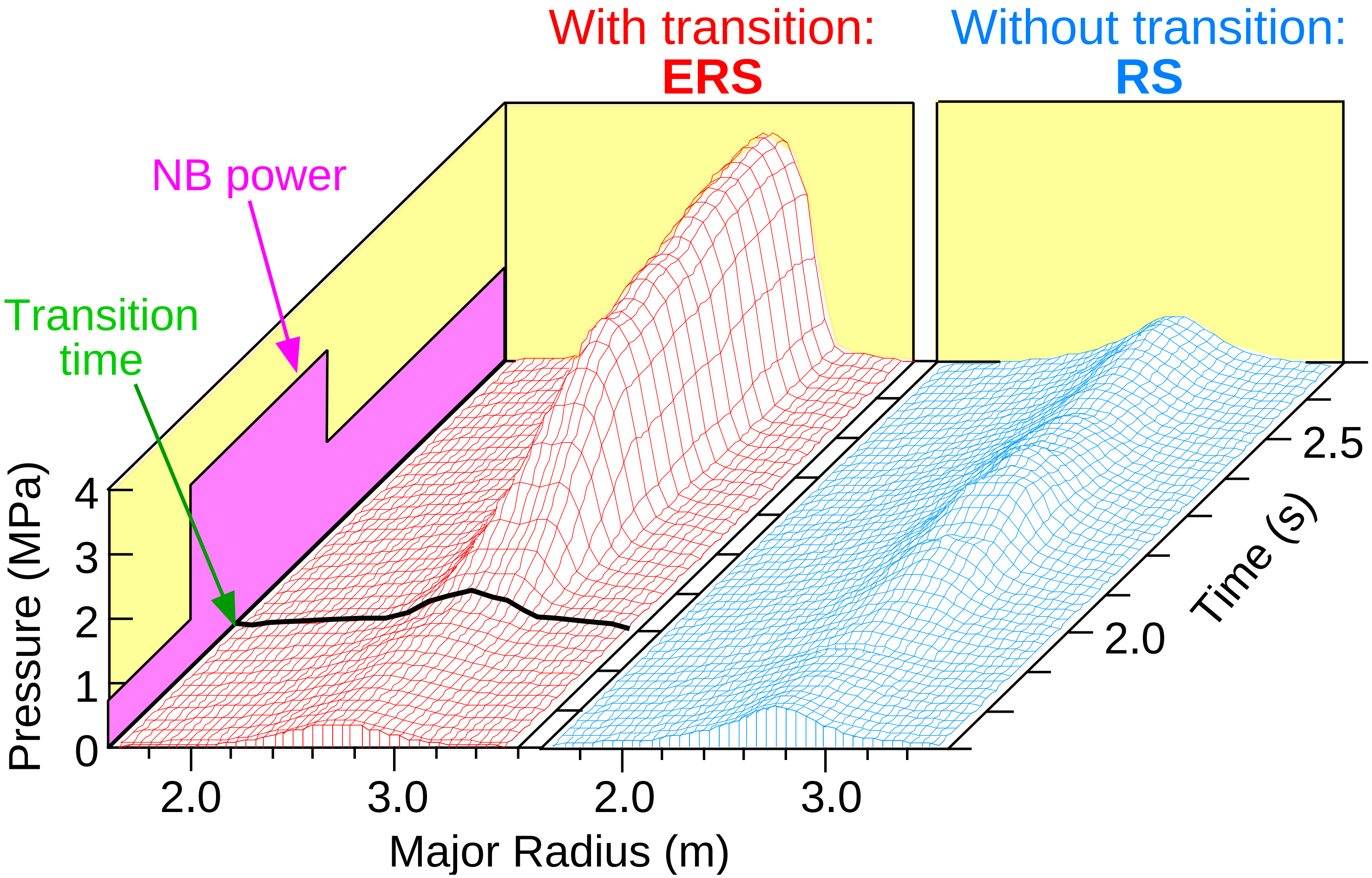
Dramatically Different Pressure Evolution of Reversed-Shear Plasmas with Similar Early States

TFTR



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

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

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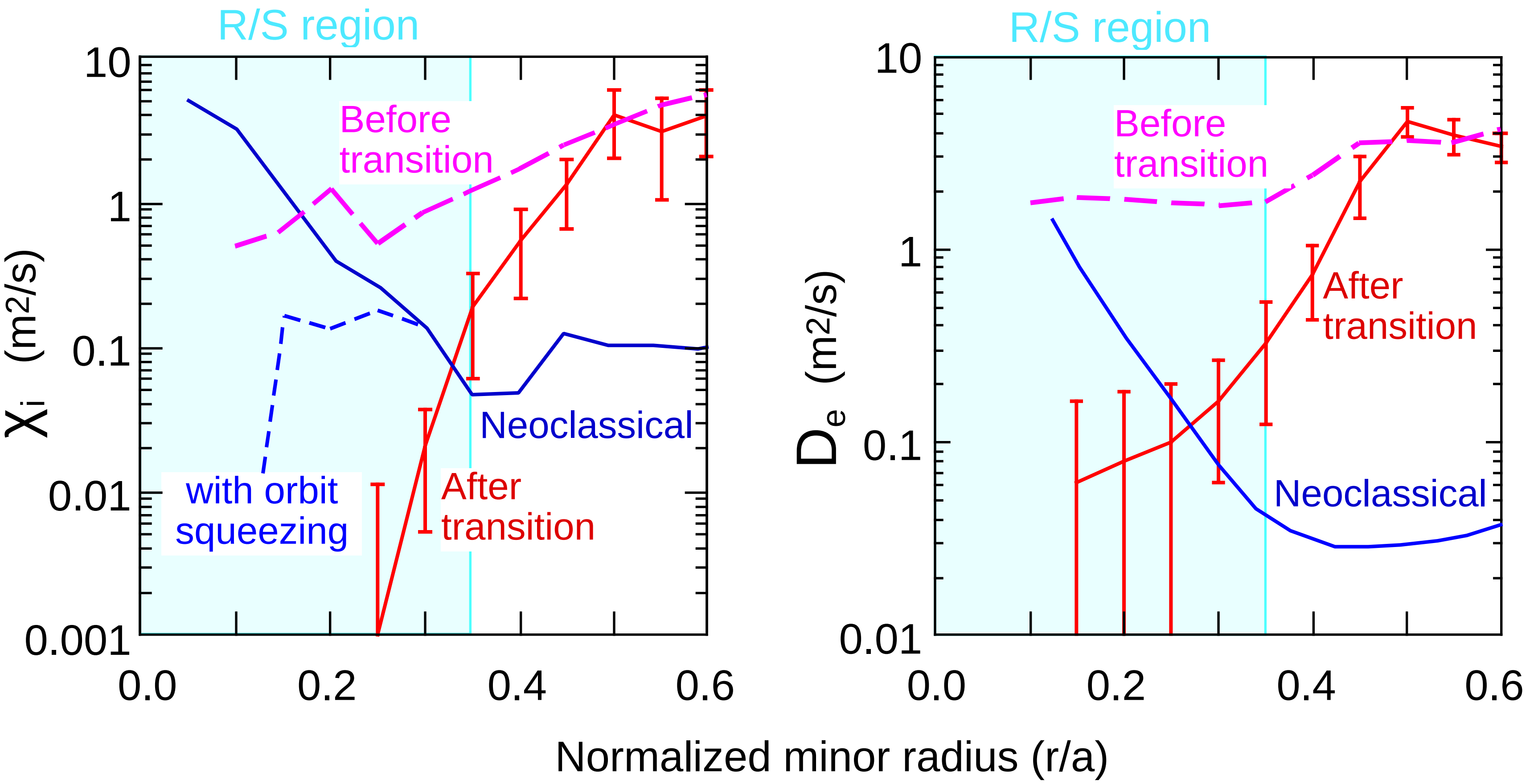

- Flux balance effective χ, D: $q \equiv -n\chi\quad T$ and $\Gamma \equiv -D\quad n$
- Neoclassical calculation includes off-diagonal contributions
- Orbit squeezing effects from Shaing *et al.* [Phys. Plasmas **1**, 3365 (1994)]

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Density Profile Evolution Following Puffs of T and He Show Presence of Particle Transport Barrier in ERS

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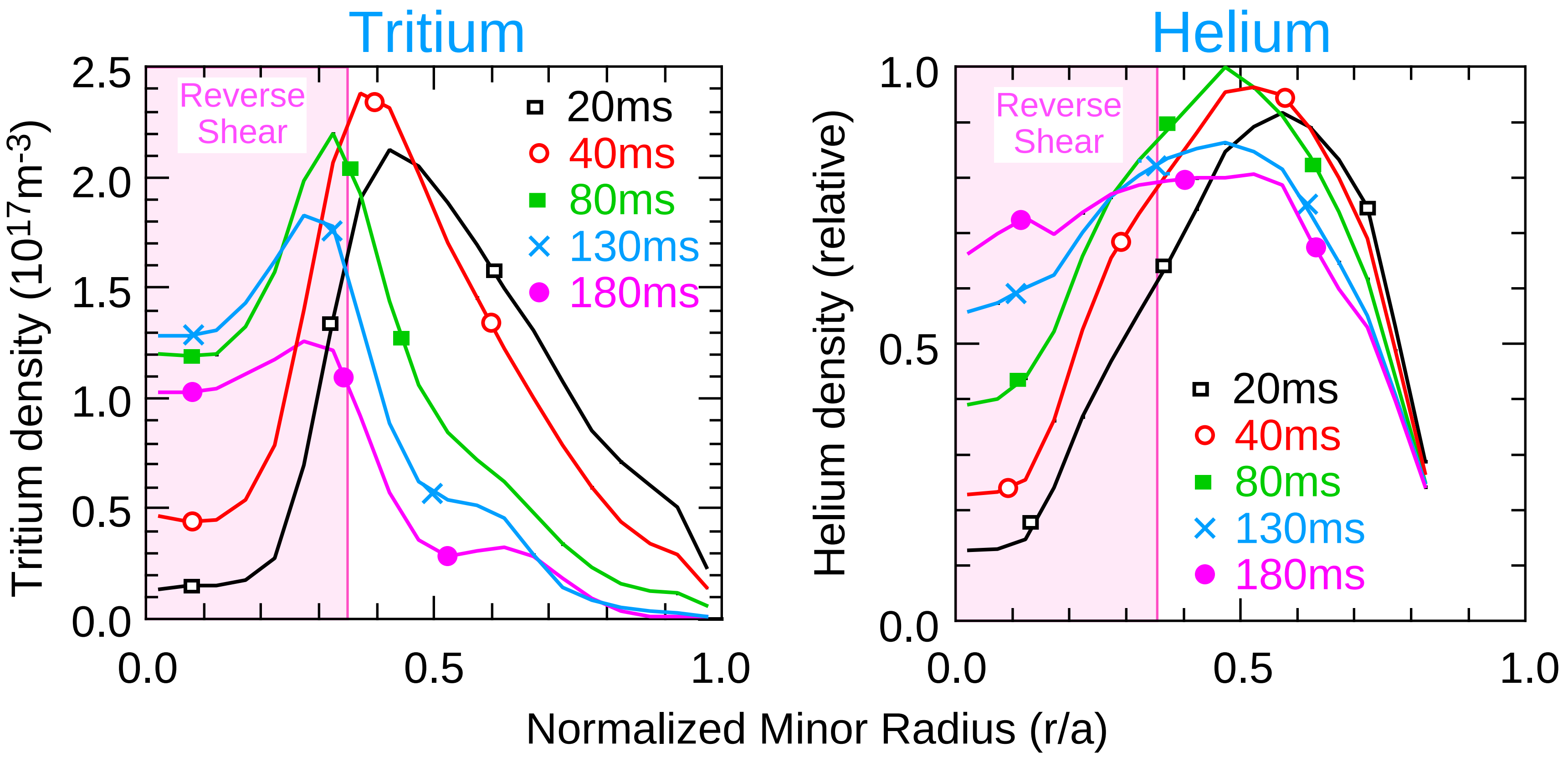

- Times of profiles are from start of 16ms puffs during steady-state ERS phase
- T density inferred from chordal profile of 14MeV DT neutron emission
- He density measured by charge-exchange recombination spectrometry

P. Efthimion ,S. von Goeler, E. Synakowski

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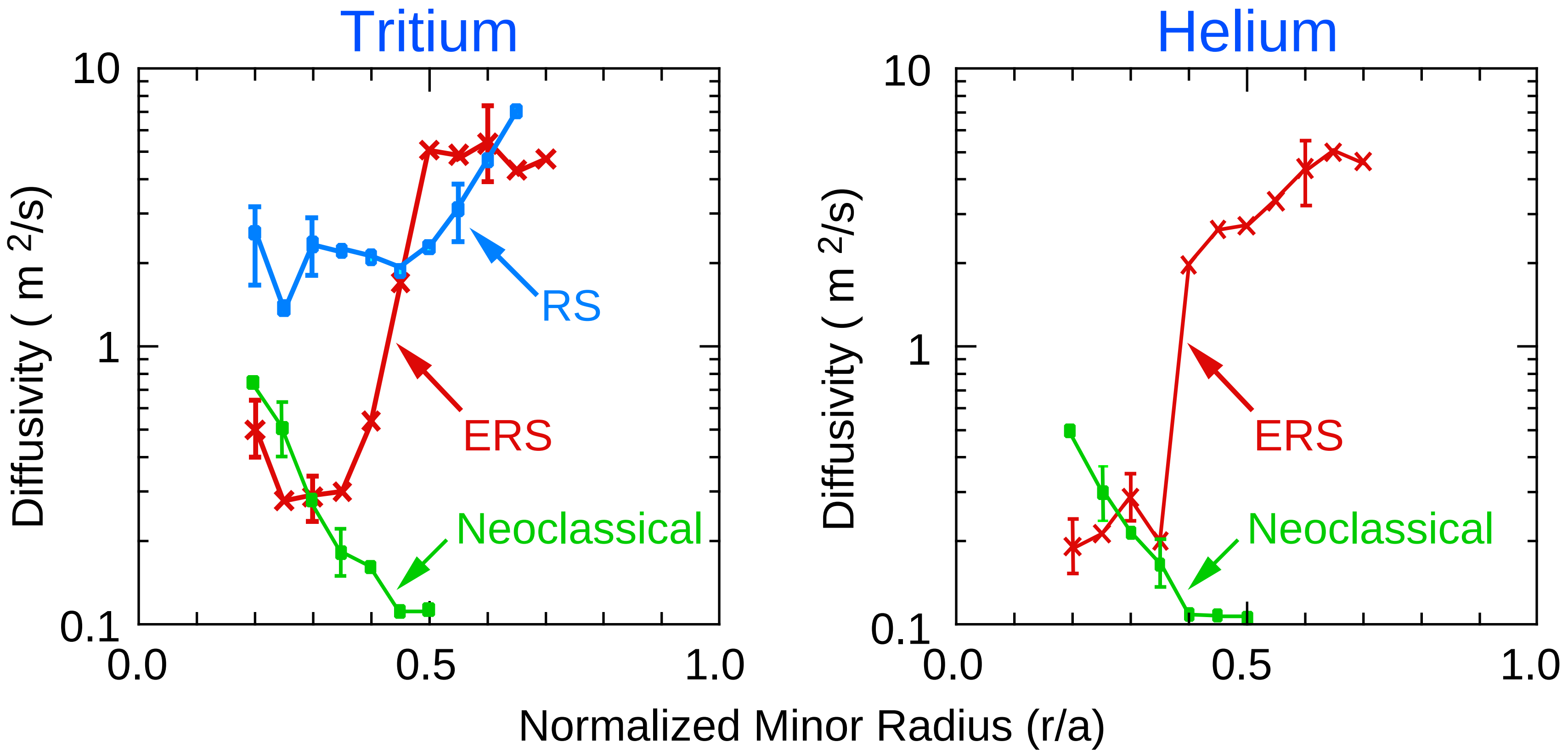
Particle Diffusivities for Trace T and He Approach Neoclassical Levels at ERS Transport Barrier

TFTR



- Analysis of density profile evolution assuming D and v_r functions of space only
- In ERS case, T and He data are best fitted with $|v_r| < 3$m/s for r/a < 0.5
- Tritium diffusivity is ~20 times larger than electron diffusivity from particle balance
- Neoclassical values calculated by NCLASS code

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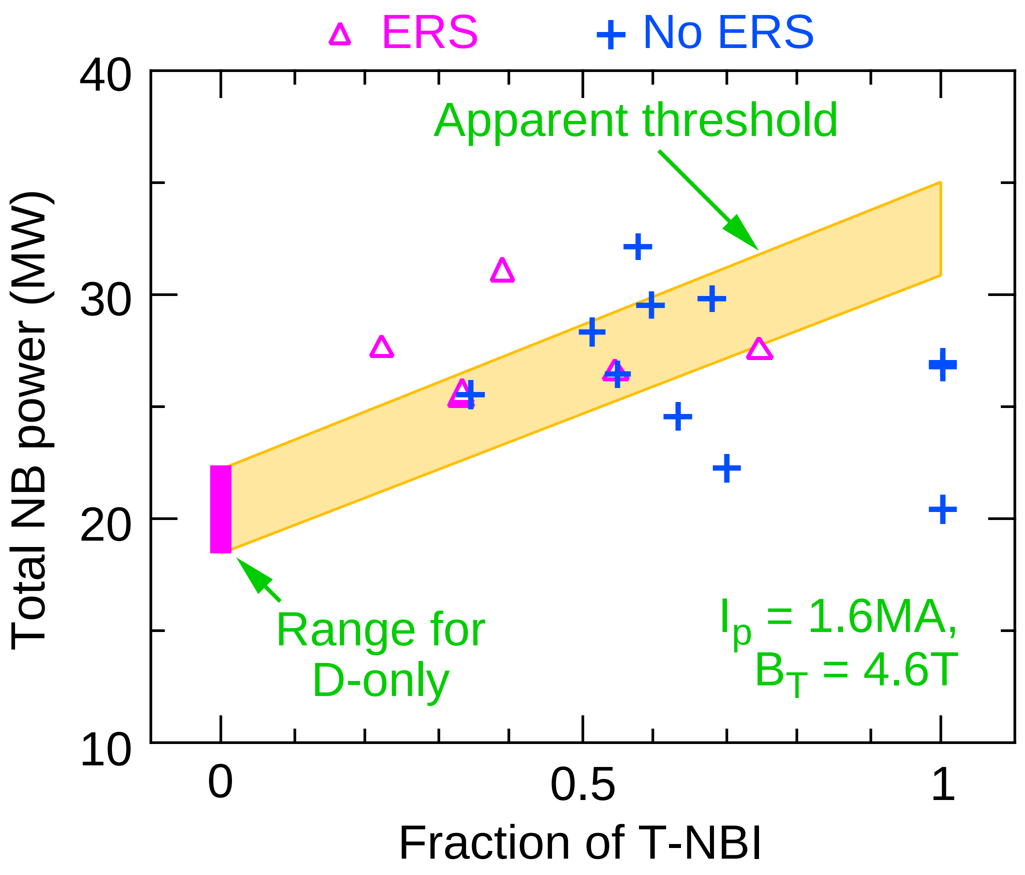
Higher NB Power Required for ERS Transition in D-T

TFTR



- Threshold increases with plasma current and also depends on wall conditions
- Contrary to recent experience in JET where ITBs formed in DT with similar power to D-only

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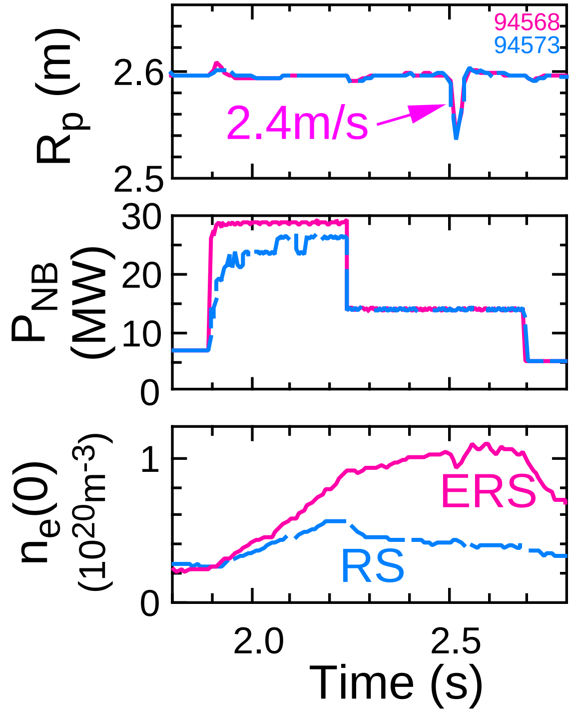
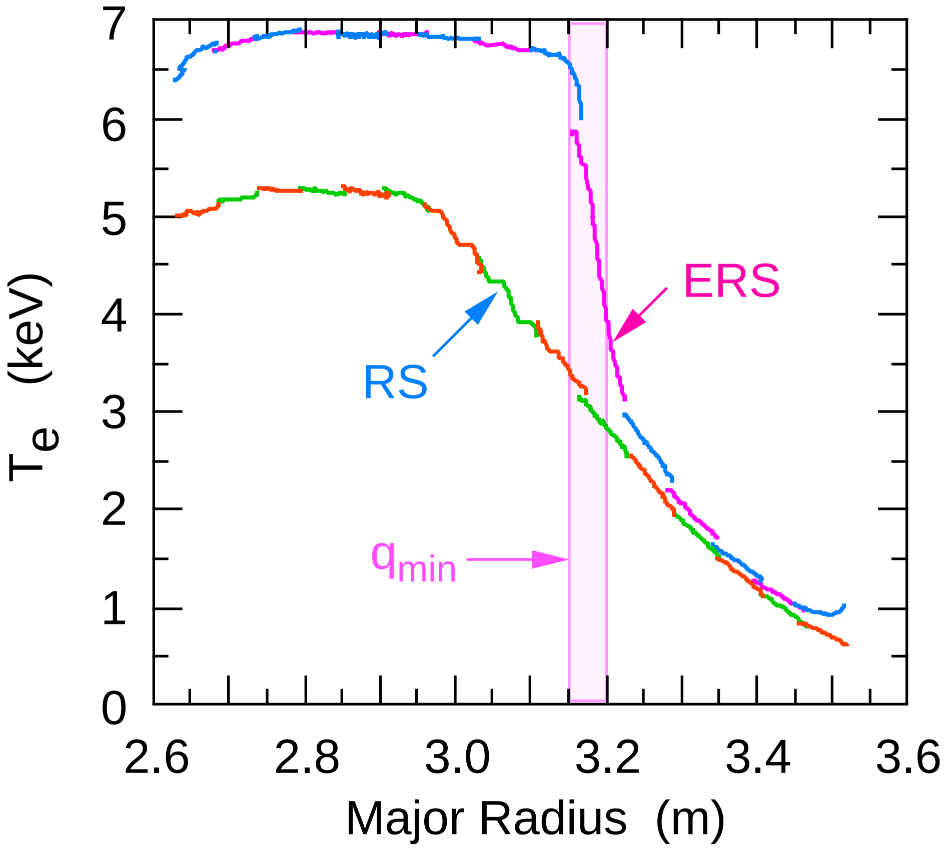
High Resolution Measurement Shows Structure in Electron Temperature Profile during ERS Phase

TFTR





- Motion of plasma during steady-state ERS phase sweeps plasma past detectors
  - gradient measured by single detector
- Sharp transition from flat region to large gradient at resolution of individual detector

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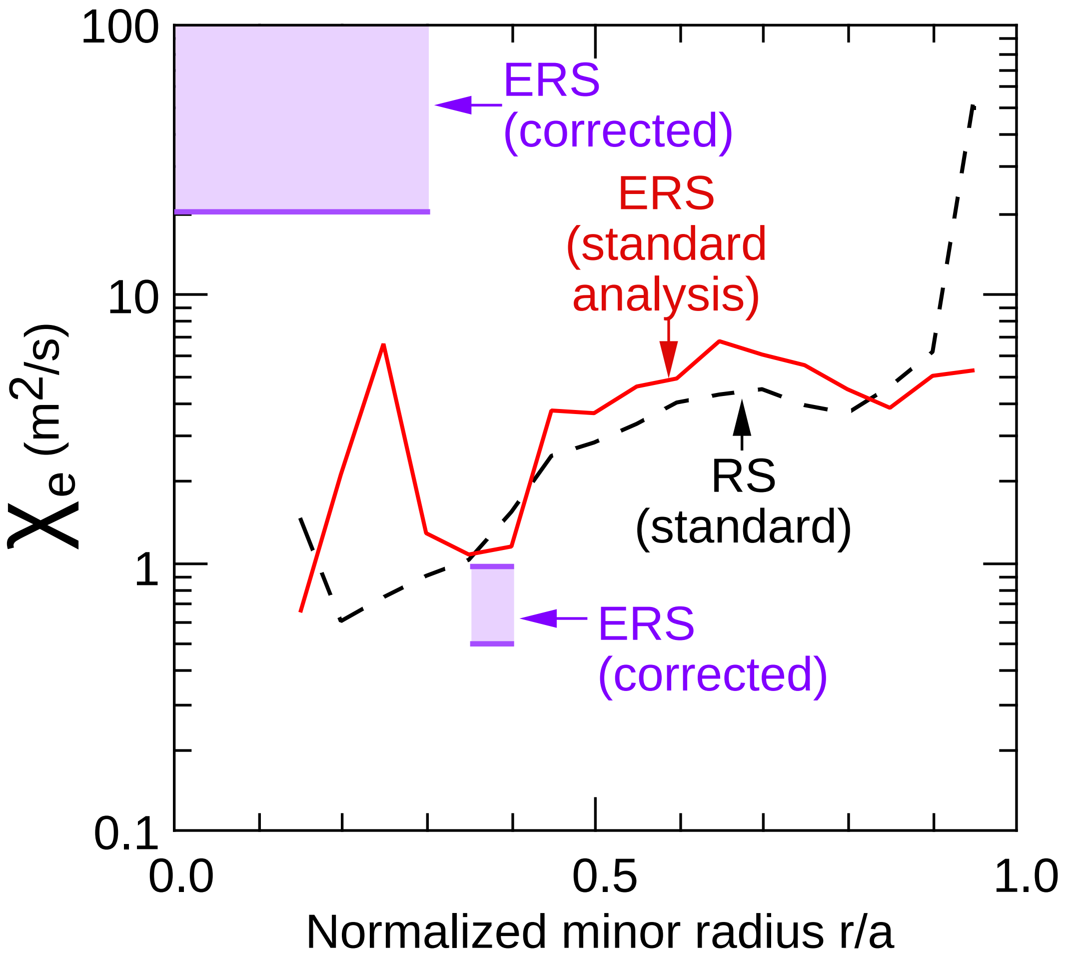
Jog Profiles Reveal Radial Structure in Electron Thermal Transport of ERS Plasmas

TFTR



- Structure in ERS is beyond current resolution of transport analysis code (TRANSP)
- χ_e(ERS) >> χ_e(RS) and χ_e(ERS) >> D_e(ERS) in core
- χ_e(ERS) ~ 10 D_e(ERS) in region of high T_e gradient

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Plasma Turbulence Reduced or Suppressed in Vicinity of Internal Transport Barriers

- Clear association between changes in measured fluctuation levels and transport in the interior of tokamak plasmas
  - already established for reduction of edge turbulence in H-mode

- In TFTR RS, fluctuations have repetitive bursting character

- Bursts disappear rapidly at transition into ERS and plasma becomes quiescent within shear-reversal surface
  - bursts reappear gradually at “back-transition” from ERS

- Behavior consistent with turbulence suppression by sheared plasma flow

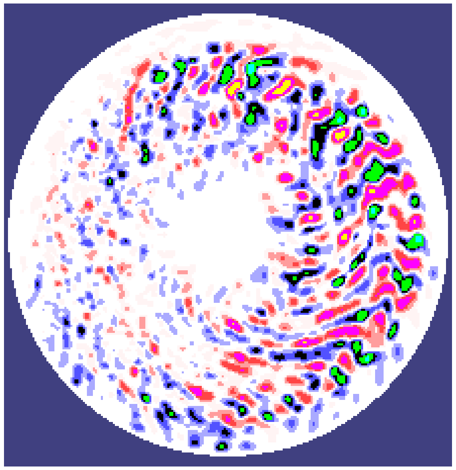
Turbulent Fluctuations Suppressed When E×B Shearing Rate Exceeds Maximum Linear Growth Rate of Instabilities

TFTR

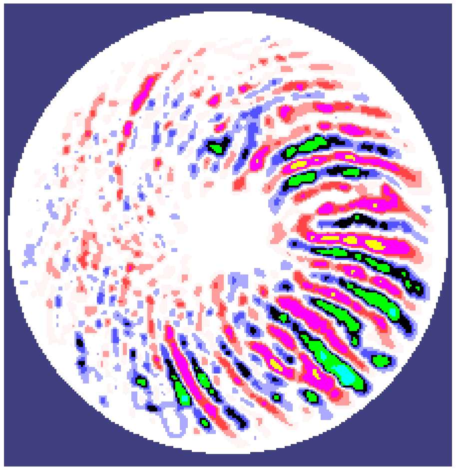
Gyrokinetic Simulations

- Turbulent eddies disrupted by strongly sheared plasma flow

With Flow



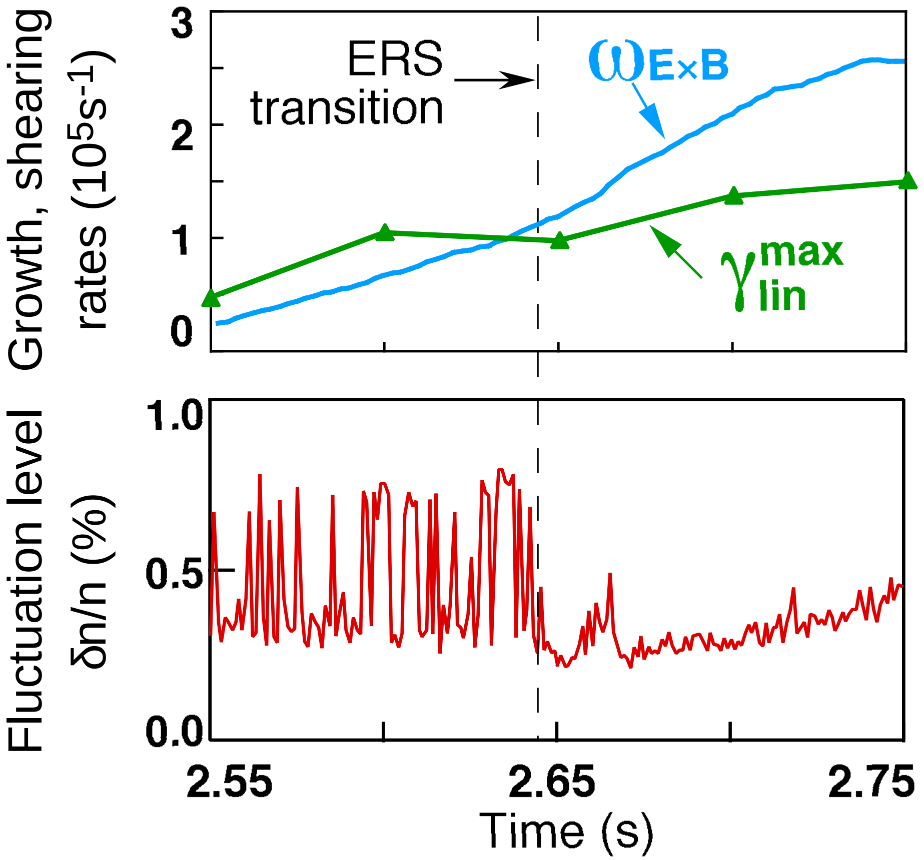
Without Flow



W. Lee, Z. Lin, E. Mazzucato, E. Synakowski, M. Beer

Experiment

- Bursts of fluctuations are suppressed when **E×B** shearing rate exceeds growth rate of most unstable mode



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Core Fluctuation Levels Correlate with Local Transport

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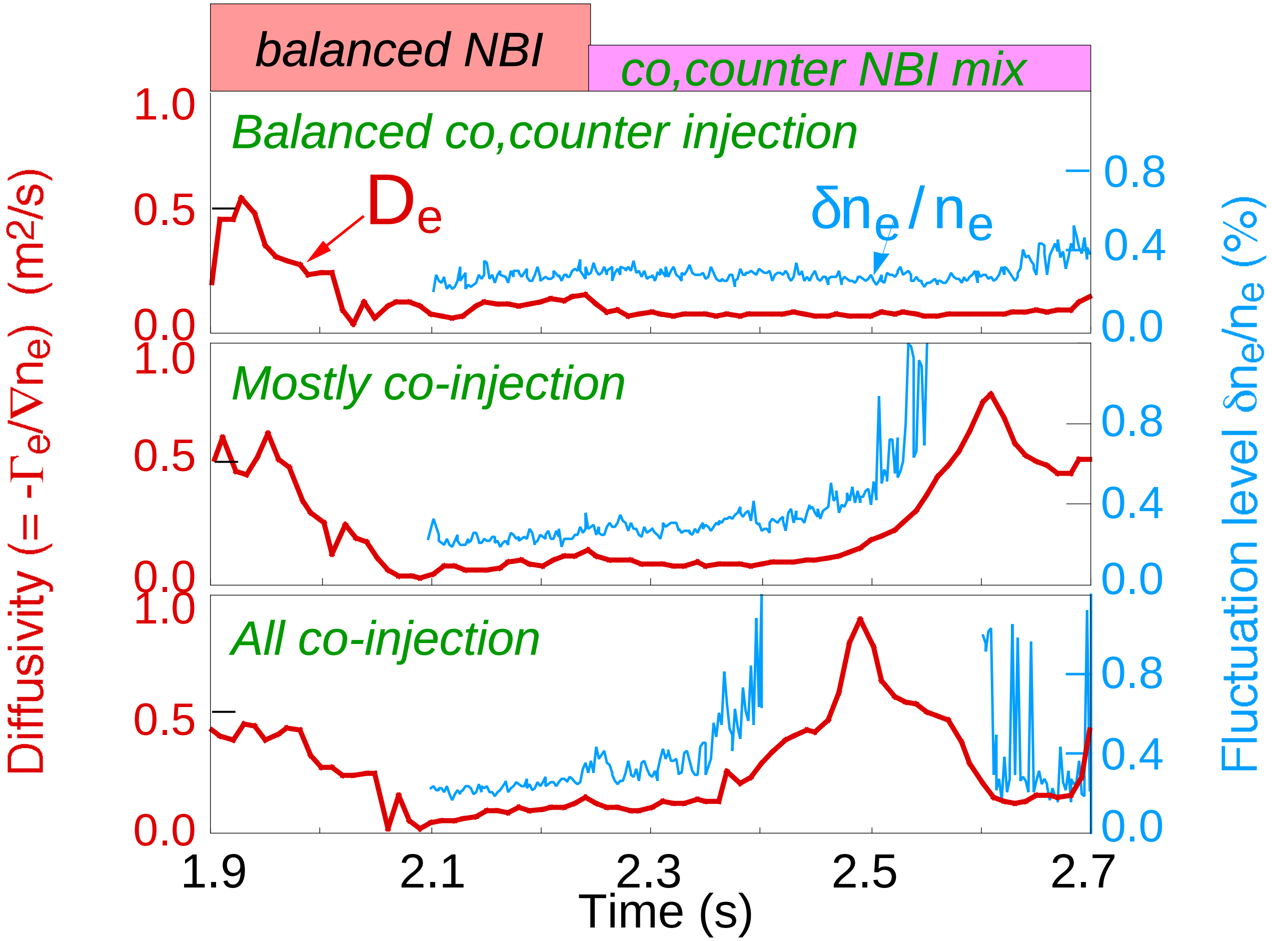

- Fluctuations measured by microwave reflectometer
- $\delta n_e/n_e$, D_e shown in high-gradient region of pressure profile, $r/a \approx 0.3$
- For all co-injection case, fluctuations decrease again when E_r passes through zero and becomes positive

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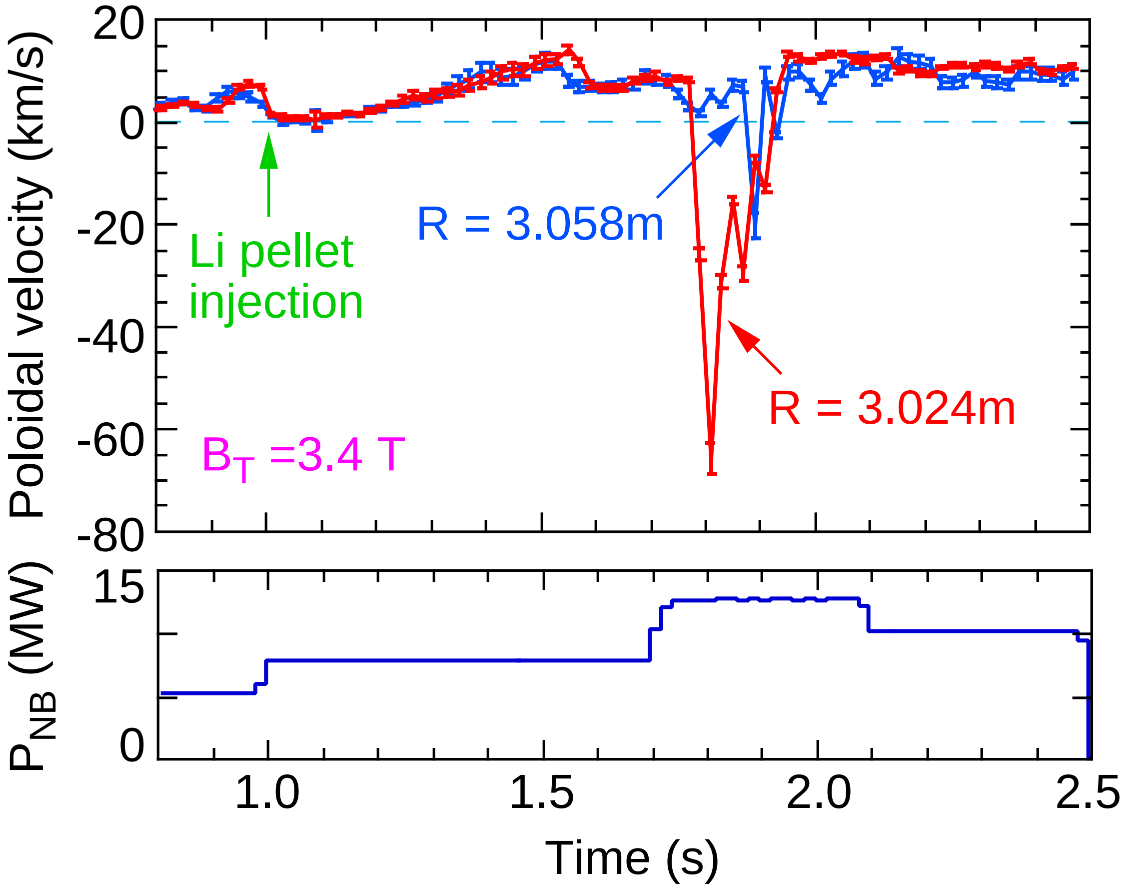
Large Transient Excursion in Poloidal Velocity Measured Prior to ERS Transition

TFTR



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

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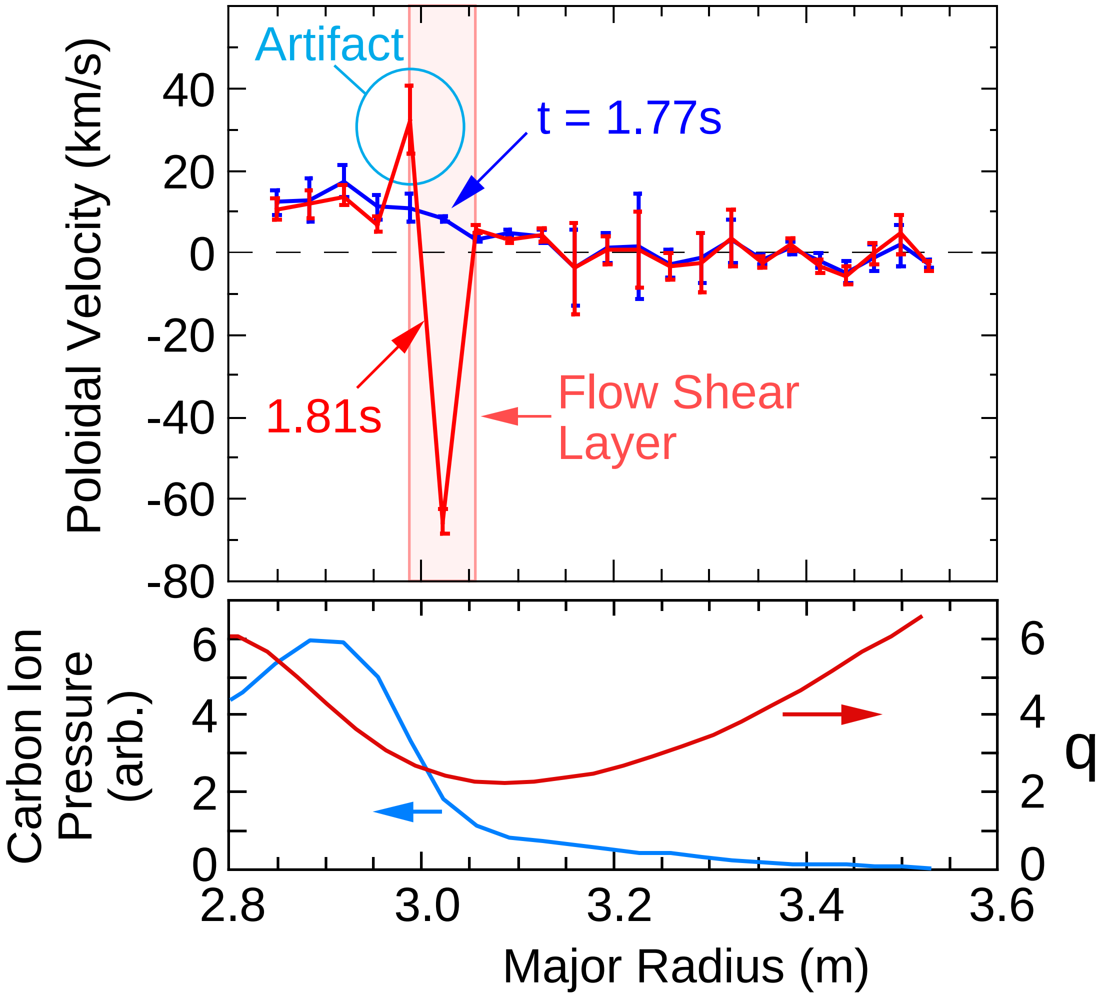
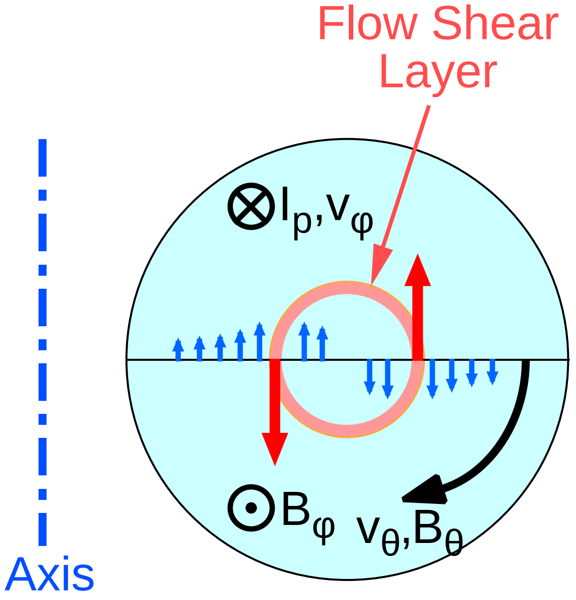
Narrow Poloidal Velocity Shear Layer Develops Inside q_{min} Surface Prior to ERS Transition





- Chordal measurements inverted to produce local poloidal velocity
- Shear layer narrower than sightline separation creates artifact inside
- Located between maximum pressure gradient and shear reversal surface

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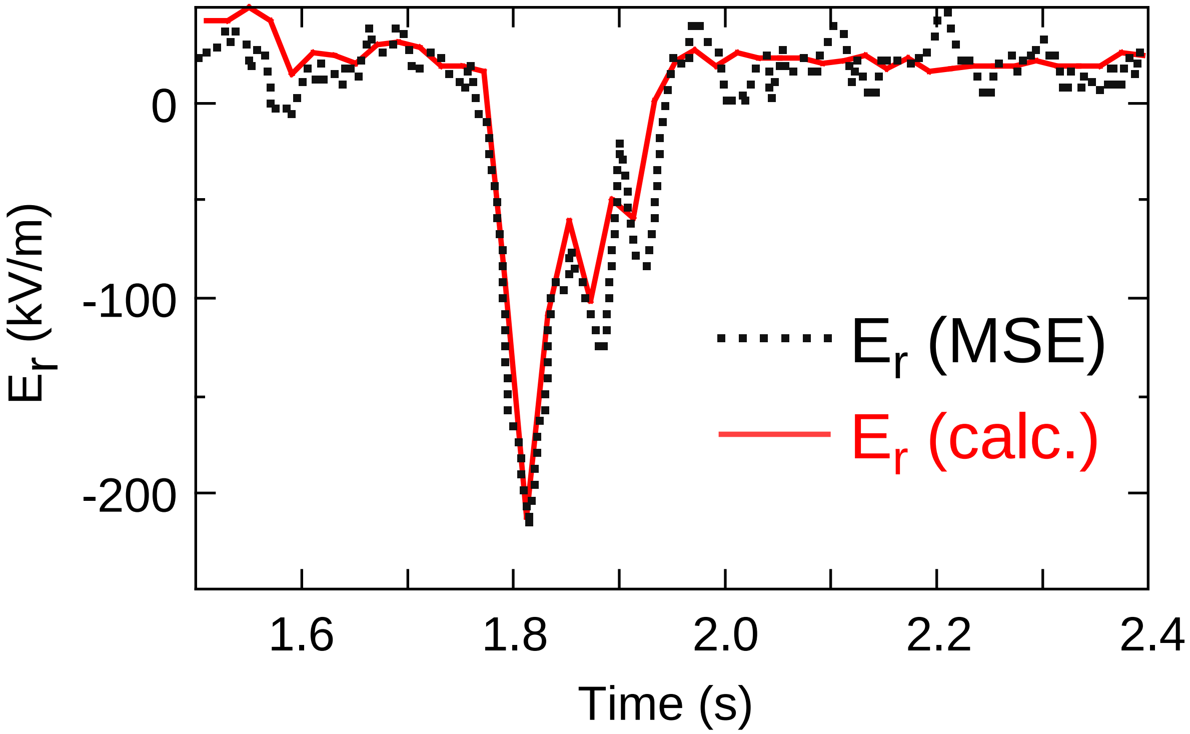
Radial Force Balance Confirmed by Measurement during E_r Transient

TFTR

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



- 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

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Suppression of Turbulence by Sheared Flow Important in Other Confinement Regimes

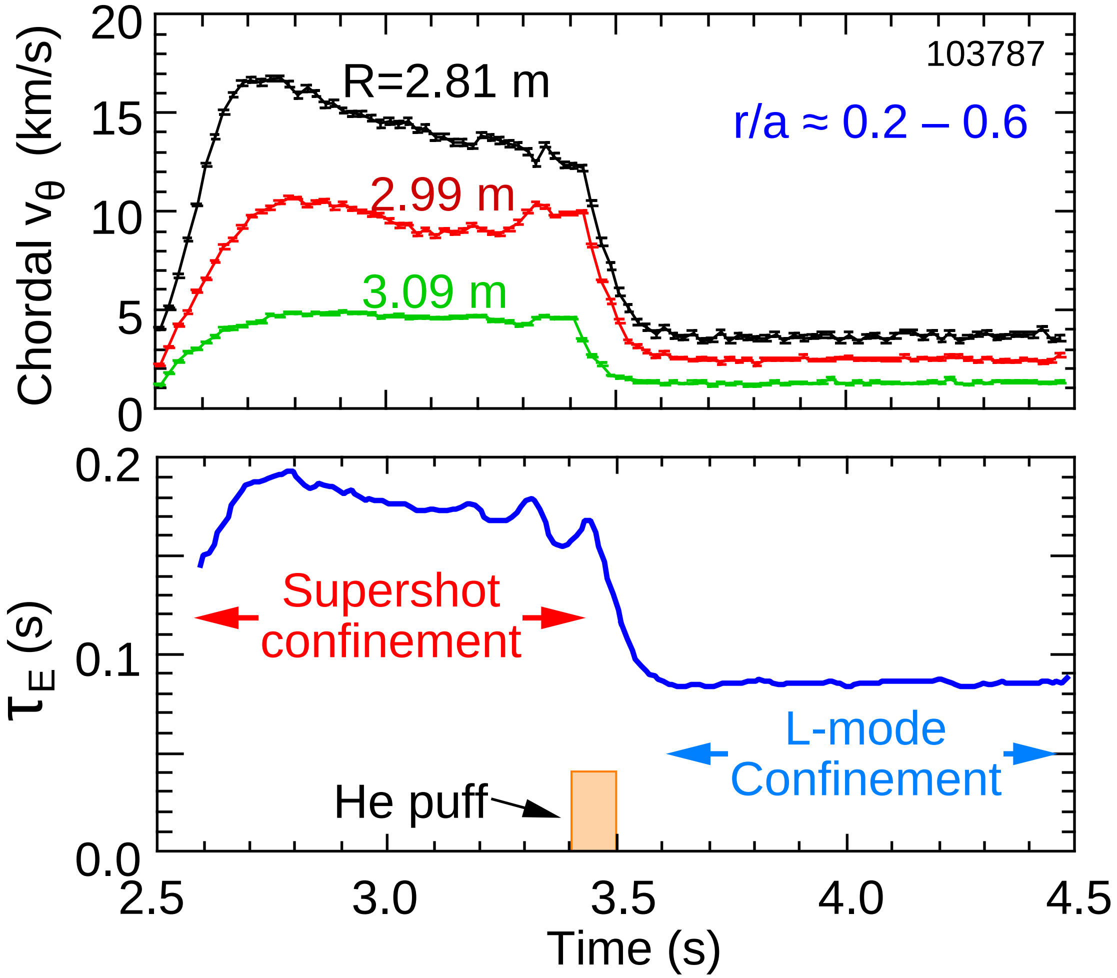
- Majority of TFTR operation in “Supershot” regime with NBI
  - transitionless: develops smoothly from L-mode
  - shear is positive throughout and $q(0) < 1$
  - sawteeth suppressed
  - minimal degradation of confinement with power up to β-limit

- Measured changes in poloidal flow shear as supershots degraded to L-mode

- Model with turbulence suppressed by velocity shear reproduces many features and trends of supershot confinement

Change in Poloidal Velocity Shear Also Accompanies Transition from Supershot to L-mode Confinement

TFTR



- Supershot produced by NBI with edge influx controlled by limiter conditioning
- Helium recycling increases edge influx supershot reverts to L-mode
- Poloidal velocity shear decreases by factor 4 as confinement degrades

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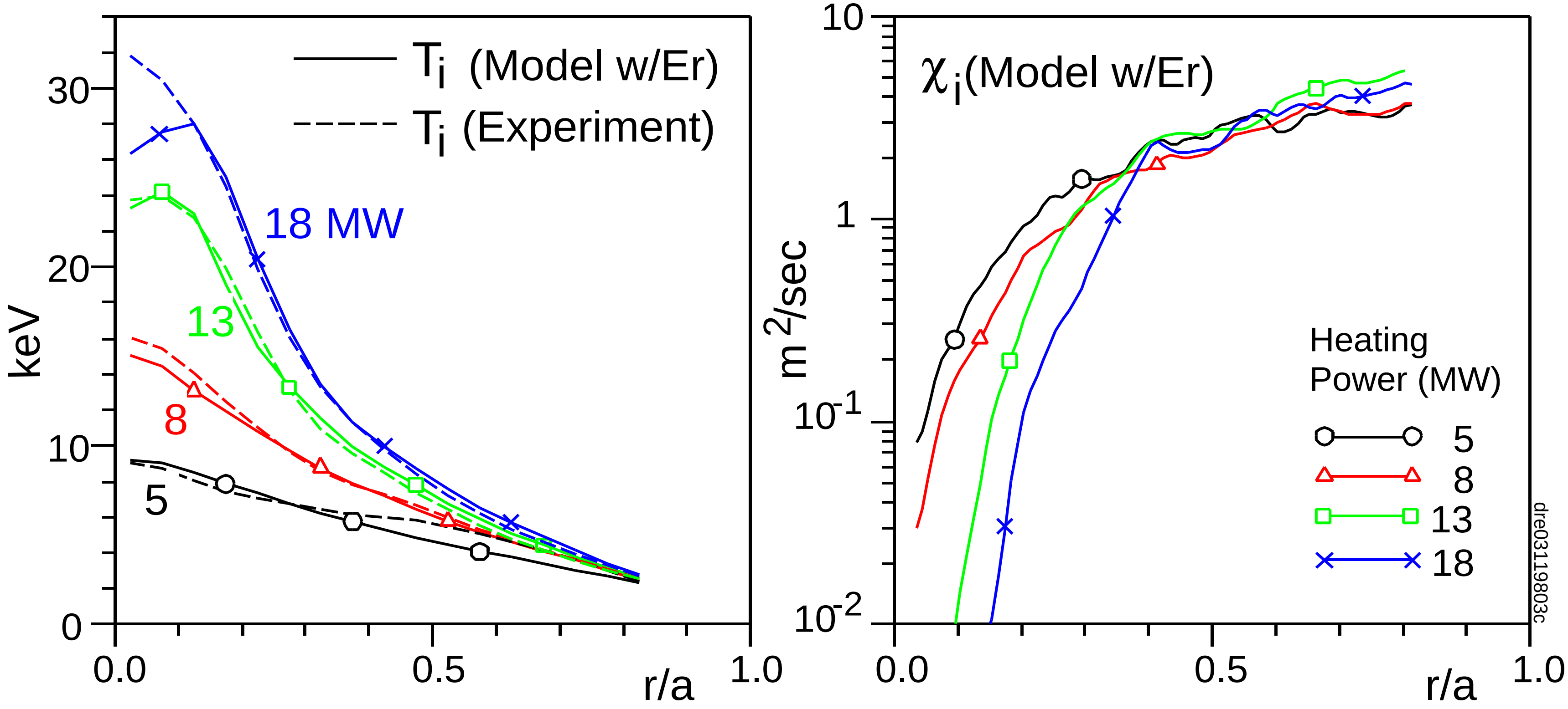
Model with Turbulence Suppressed by Velocity Shear Reproduces Ion Temperature Profiles in Supershots



- 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.

Challenge to Achieve Good MHD Stability in Presence of Internal Transport Barriers

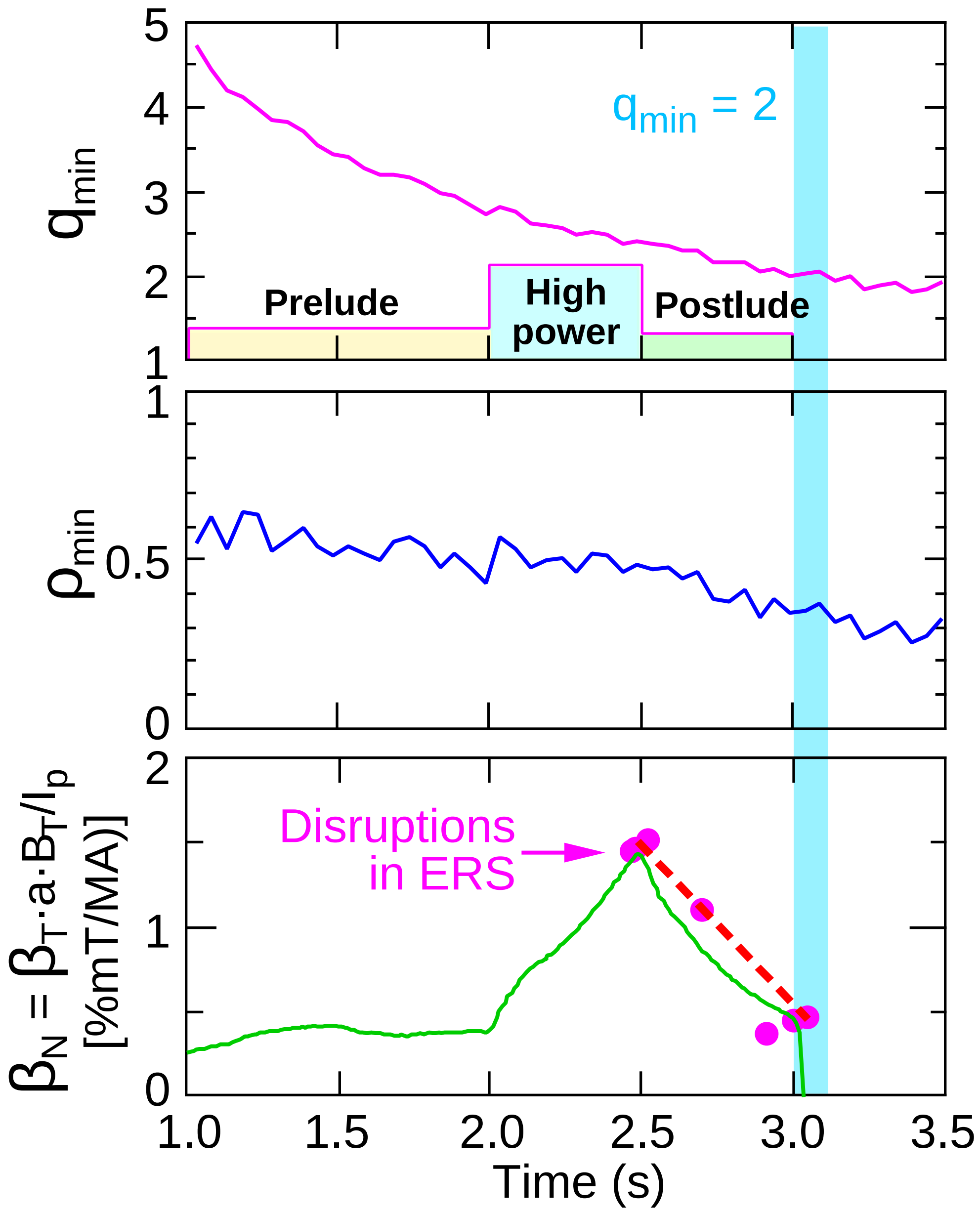
- Most regimes with strong internal transport barriers do not achieve high Troyon-normalized-β, $\beta_N = \beta_T \cdot a \cdot B_T / I_p$

- Maximum $\beta_N < 2$ in reversed (or weak) shear plasmas with *internal* transport barriers only
  - TFTR, DIII-D, JT-60U, JET
  - barriers create extreme local pressure gradients
  - resulting bootstrap current causes q profile to evolve

- $\beta_N \approx 4$ achieved transiently in DIII-D by combining ITB with H-mode edge barrier to reduce local pressure gradient
  - transport barriers “in series”

Natural Evolution of Pressure and q Profiles During ERS Phase Reduces MHD Stability

TFTR



- Large pressure gradient near ρ_{min} persists in ERS plasmas even in "postlude" phase
  - drives large bootstrap current
- q_{min}, ρ_{min} both decrease with time
- β-limit is reduced as $q_{min} \rightarrow 2$
- $\beta_N = 2.0$, $\beta^*_N = 4.1$ achieved with different startup sequence in TFTR
- **Challenge**: control barrier location and shape of q-profile near ρ_{min}

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Summary and Issues

- Modifying the magnetic shear has revealed a wealth of transport phenomena in tokamaks
  - improved confinement and performance
  - correlation of suppression of fluctuations and anomalous transport established in plasma interior
  - suppression of turbulence by sheared flow may underlie many regimes of improved confinement

- Maintaining stability in presence of transport barriers and resulting bootstrap current is a real challenge
  - particularly difficult in self-heated (ignited) plasmas

- Development of tools to control location and “impedance” of transport barriers will be vital
  - flow control by RF waves a possibility