Local Turbulence Suppression and Shear Flow Dynamics at Low-Order Rational q Surfaces

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Overview

- **Low-order rational q surfaces previously observed to trigger ITBs**

- **What happens to turbulence and flow shear at low-order rational *q* surfaces at low magnetic shear?**
  - ...Zonal Flows (Waltz, et. al.),
    ...Convective Cells (Diamond & McDevitt)

- **Expanded 8x8 Beam Emission Spectroscopy (BES) used to measure turbulence and turbulence flow**
  - ECH used to increase ρ_{qmin} and thus BES sensitivity

- **Local & simultaneous measurements of ExB shear suppression at low-order rational q_{min}**
  - Reduced in fluctuations
  - Local poloidal velocity shear in advection of turbulent eddies
  - Increased decorrelation rate, τ_c^{-1}
  - Reduced radial correlation length

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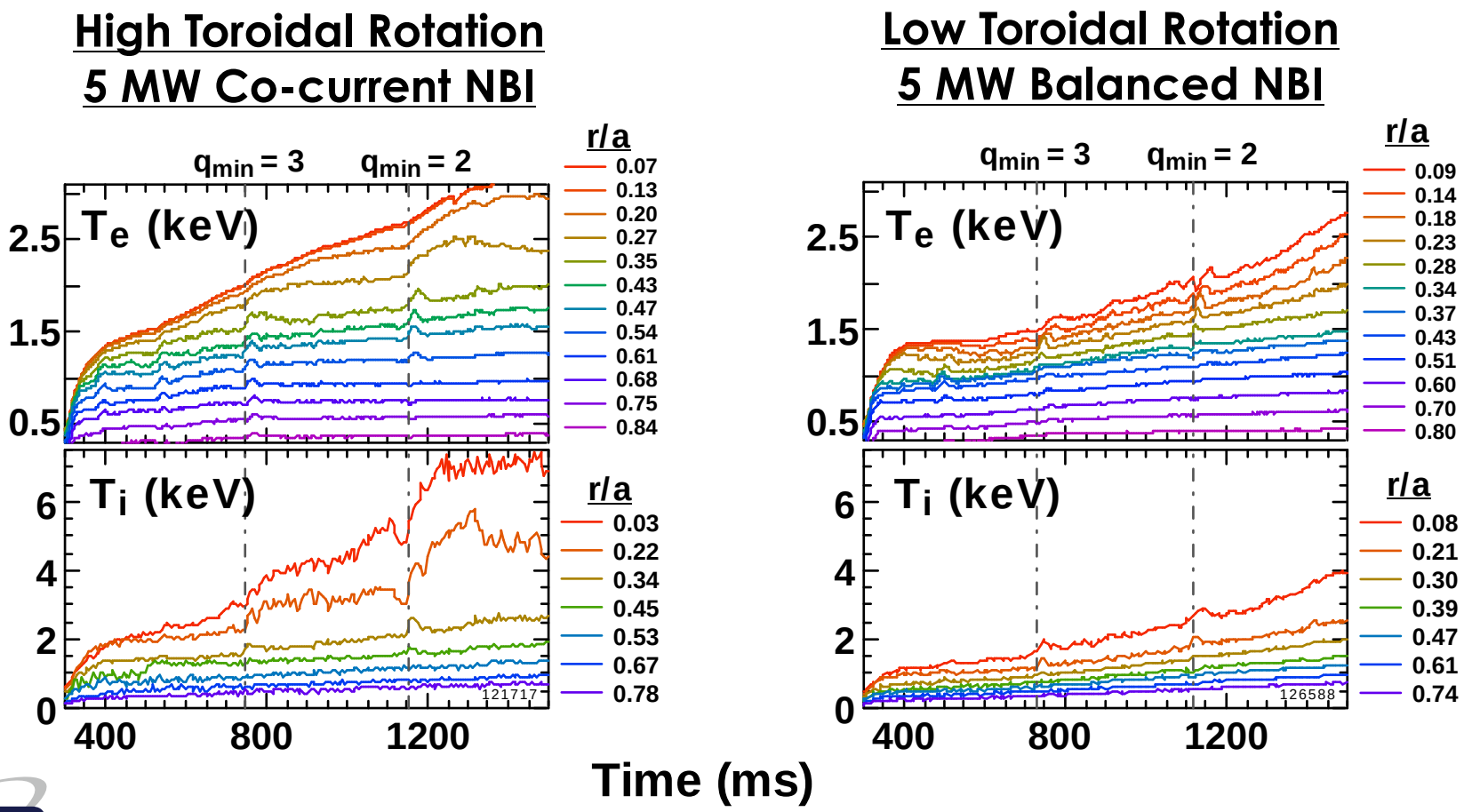
q_{min}=2 Triggers Internal Transport Barrier with Sufficient ExB Shear

- **Sufficient ExB shear obtained via high rotation in Negative Central Shear (NCS)**
  - No ITB at low rotation

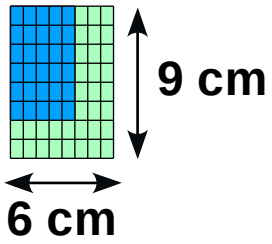
- **Transport transiently improves independent of subsequent ITB formation**
  - Sudden changes in confinement at low-order rational q_{min} surfaces



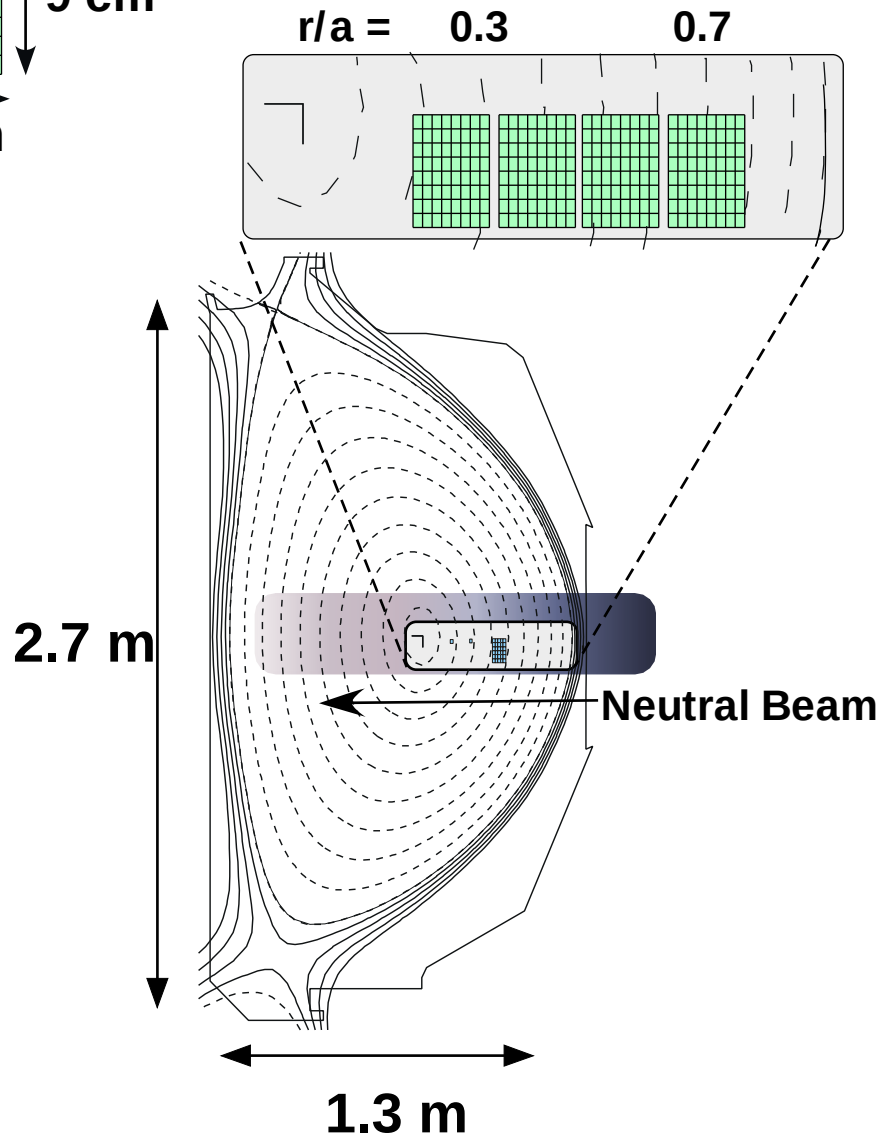
M.E. Austin, et. al., Phys. Plasmas **13** 082502 (2006)

Expanded 2D BES Array Measures Local Turbulence and Flow

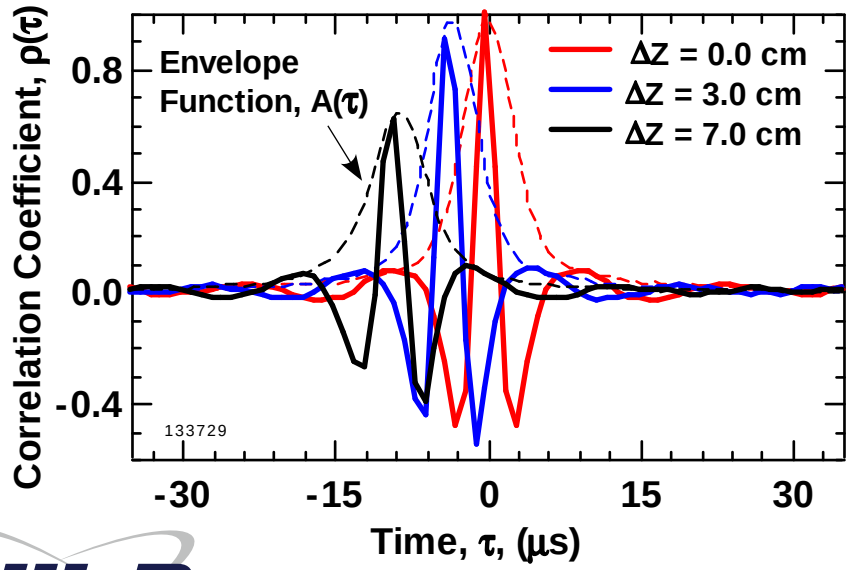
- **Expanded BES array: 5x6 to 8x8**
  - Measures 2D correlation function



- **Simultaneous Turbulence Measurements:**
  - Density Fluctuations, $\tilde{n}_e/n_e$
  - Turbulence Flow, $v_\theta \sim v_{ExB}$
  - Correlation Length, L_{cr}, $L_{c\theta}$
  - Correlation Time, τ_c



Poloidally Separated Cross-Correlations



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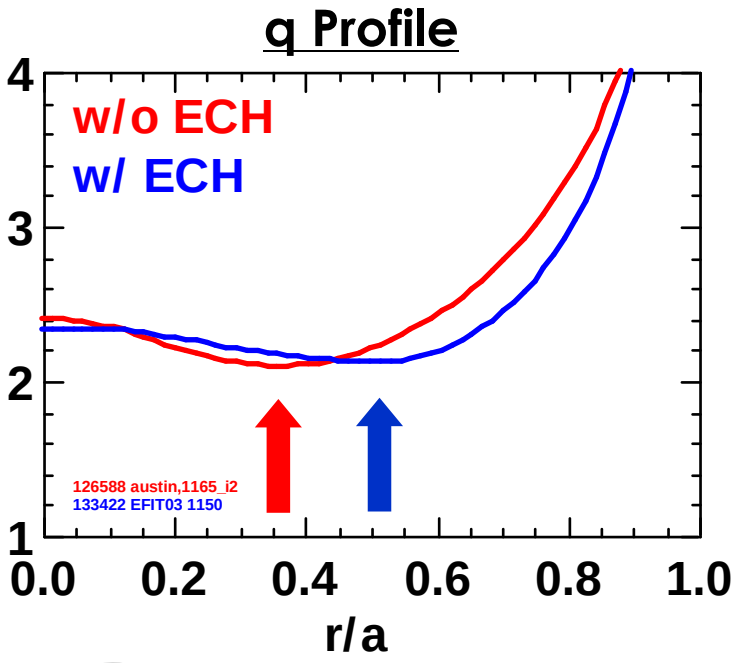
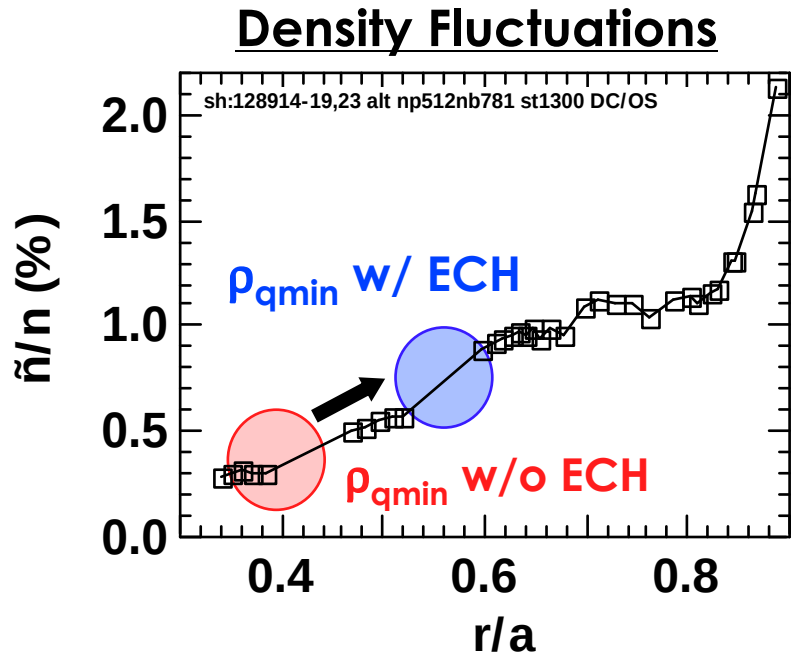
ECH Increases ρ_{qmin} ➞ Higher BES Sensitivity

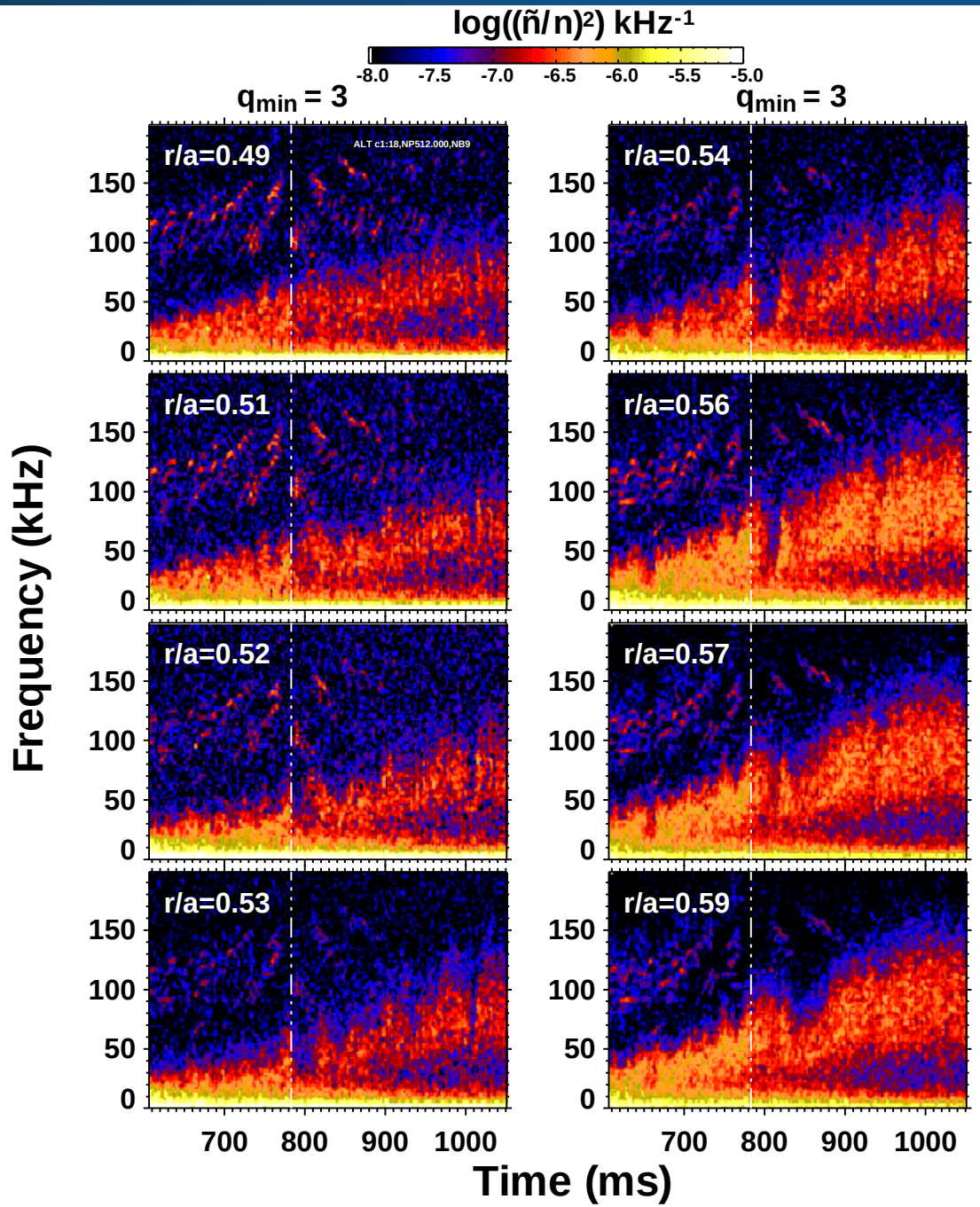
- **Previous BES measurements limited by low signal levels**
  - Access inside q_{min} difficult
- **ECH increases ρ_{qmin} from r/a ~ 0.35 to 0.5 where ñ/n levels are 2x higher**
  - Provides increased signal-to-noise ratio for turbulence analysis
- **Slower current evolution to provide better statistics**





Spectra Show Structure of Minimum in Fluctuations

- **Focus: Low v_ϕ at q_{min}=3**
  - ρ_{qmin} ~ 0.45 - 0.55



Fluctuation Levels Show Localized Minimum and Propagation

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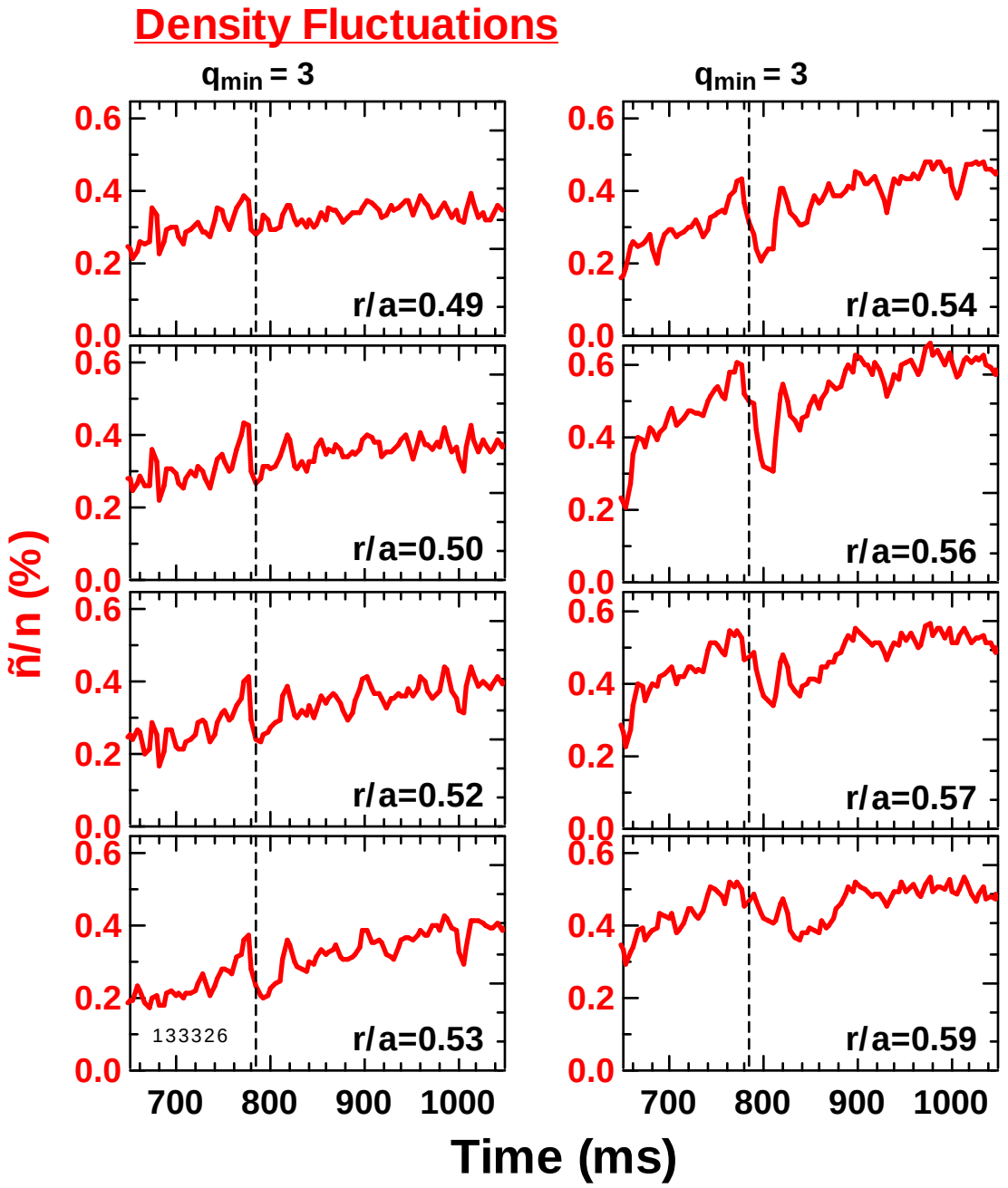

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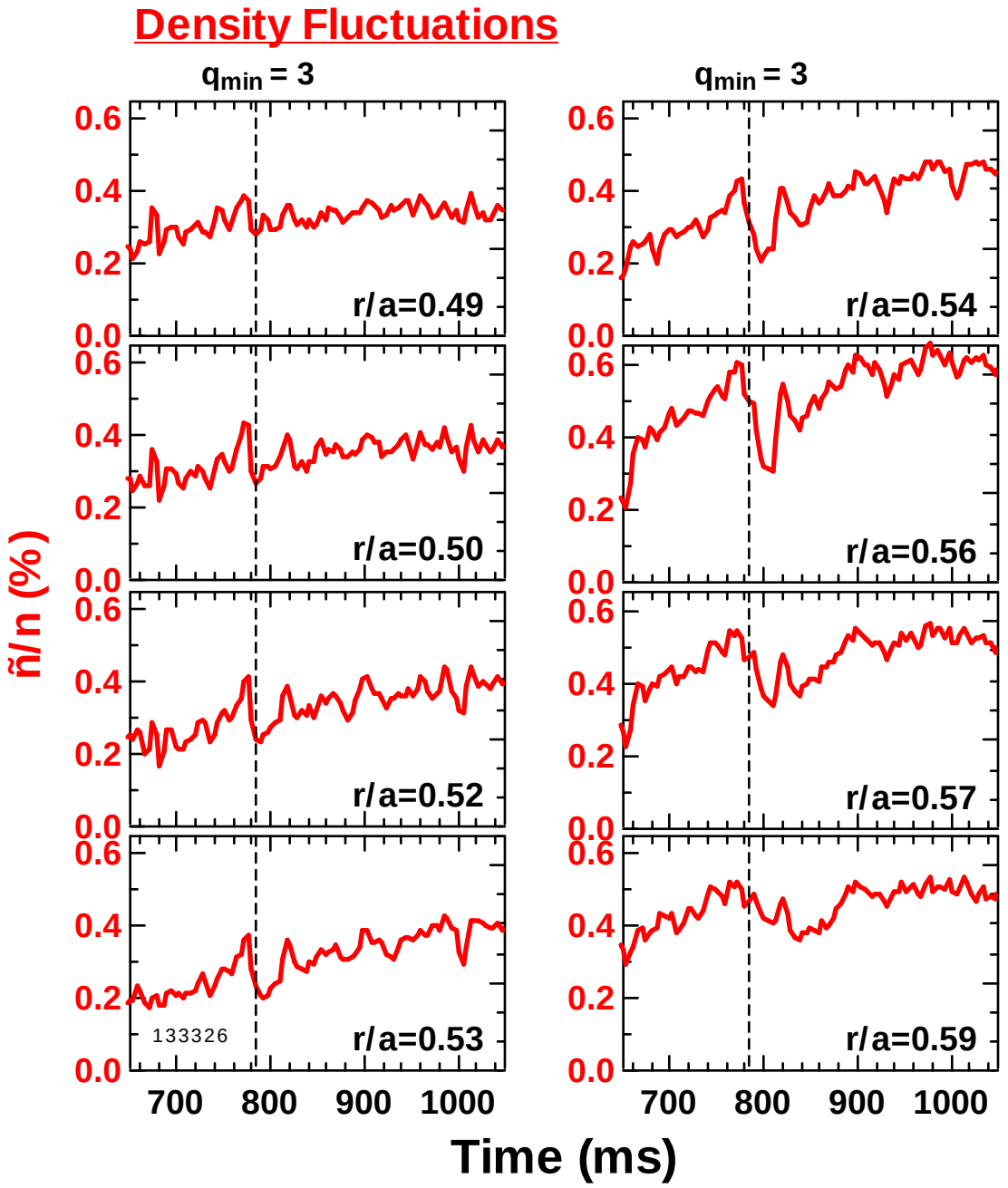
- **Focus: Low v_ϕ at q_{min}=3**
  - ρ_{qmin} ~ 0.45 - 0.55
- **Largest reduction at r/a ~ 0.53 - 0.56**
  - Localized near q_{min}



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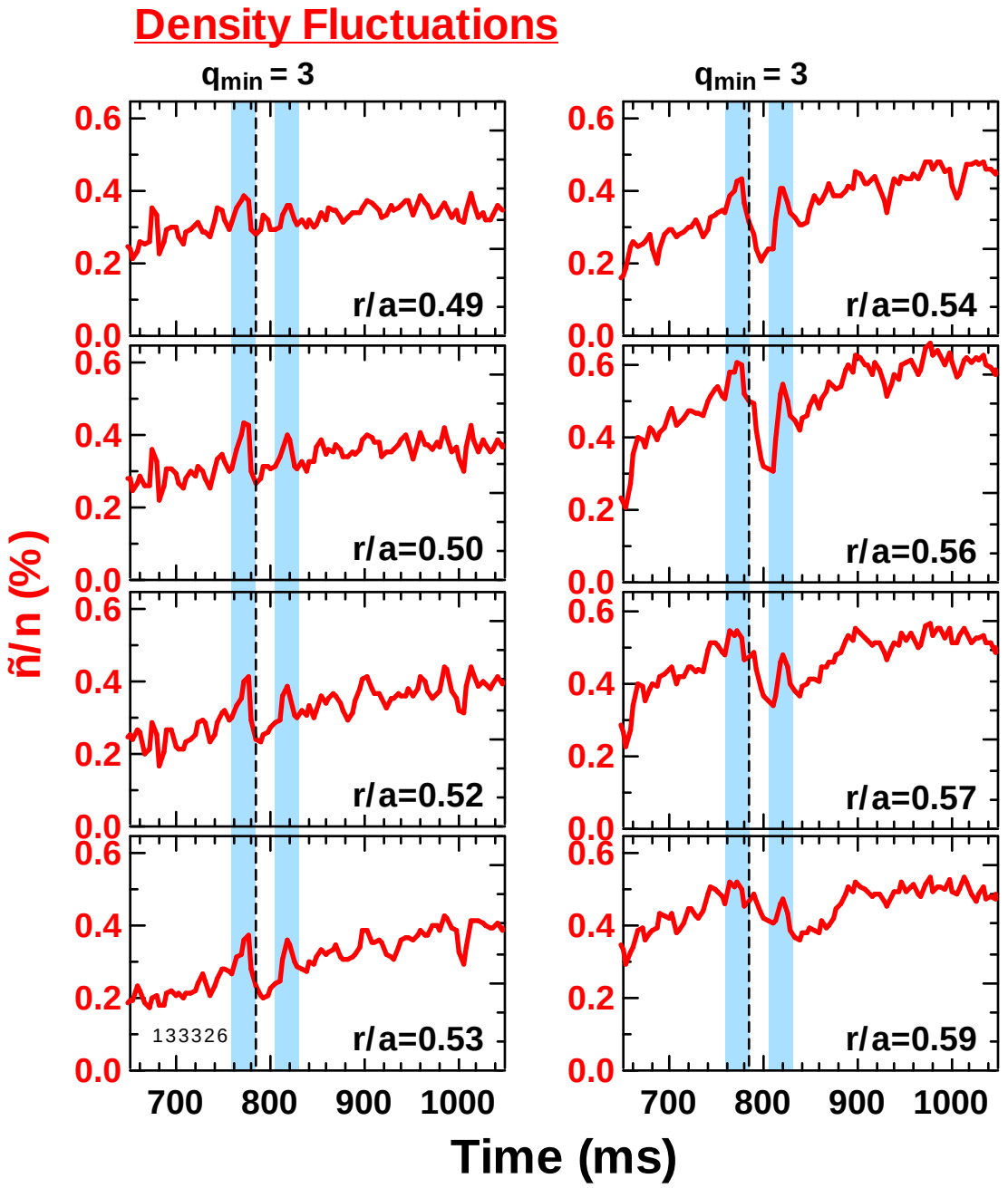
- **Peak in fluctuations just before and after q_{min} crosses 3**
  - Possible mode resonance



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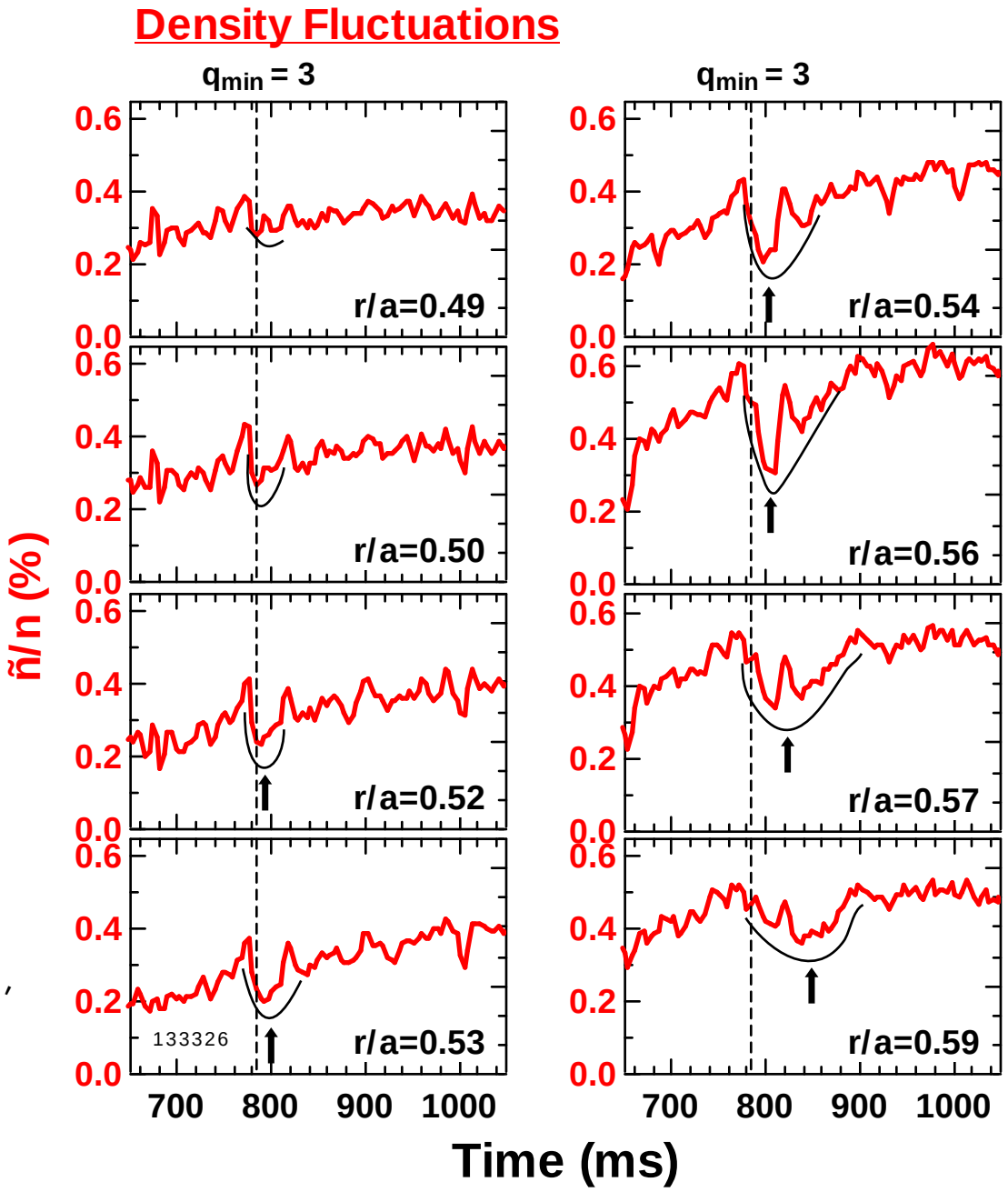
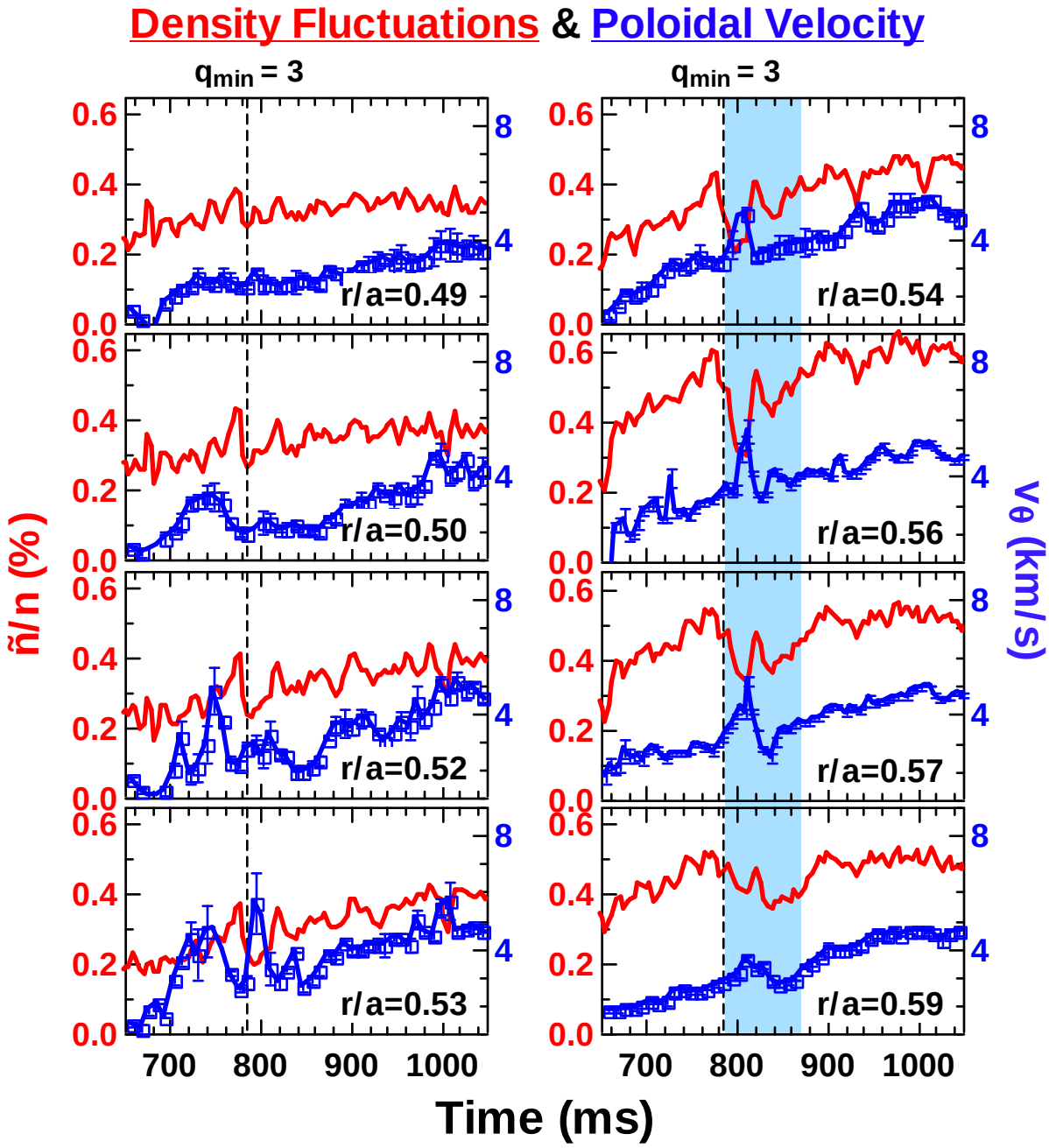
  - Possible mode resonance
- **Minimum "spreads" radially**
  - Wider, shallow minimum propagates radially outward, close to q=3 surface



Poloidal Velocity Perturbations Observed at q_{min}=3

- **Perturbations in poloidal velocity observed at time q_{min}=3**
- **Reduced fluctuations during v_θ perturbation**
- **v_θ perturbation propagates radially outward with q=3 surface**
  - decays from q_{min} surface



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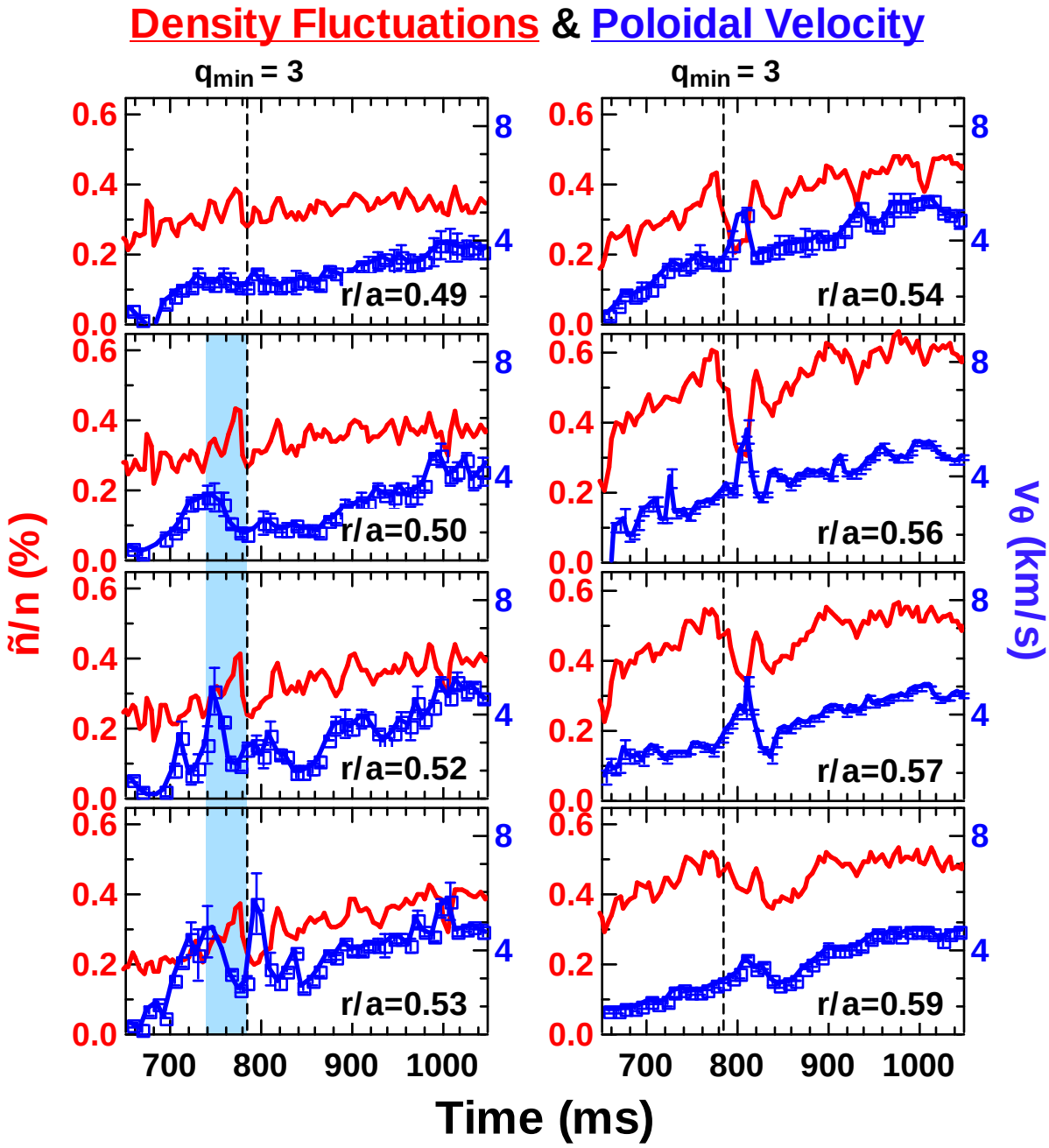

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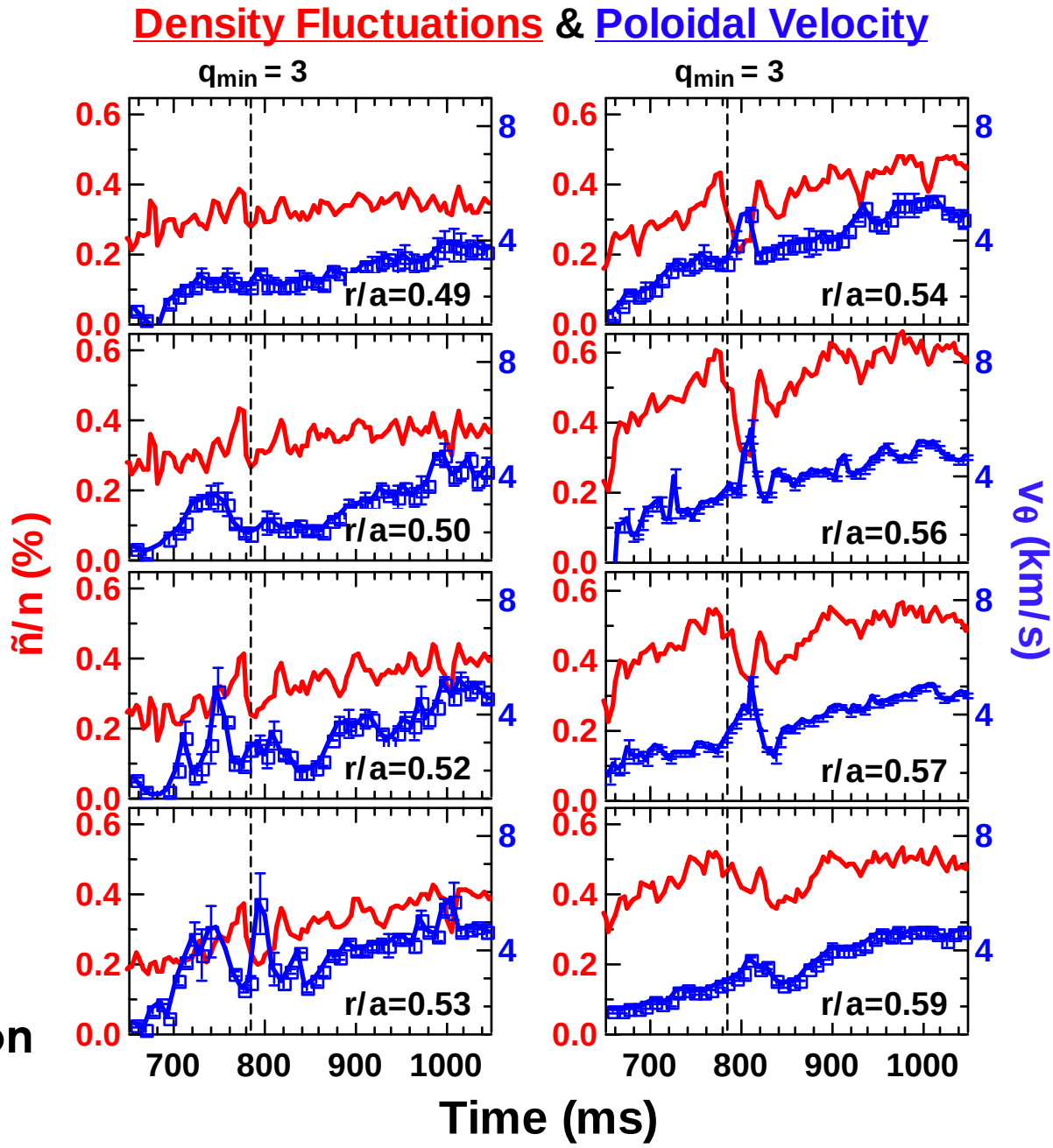
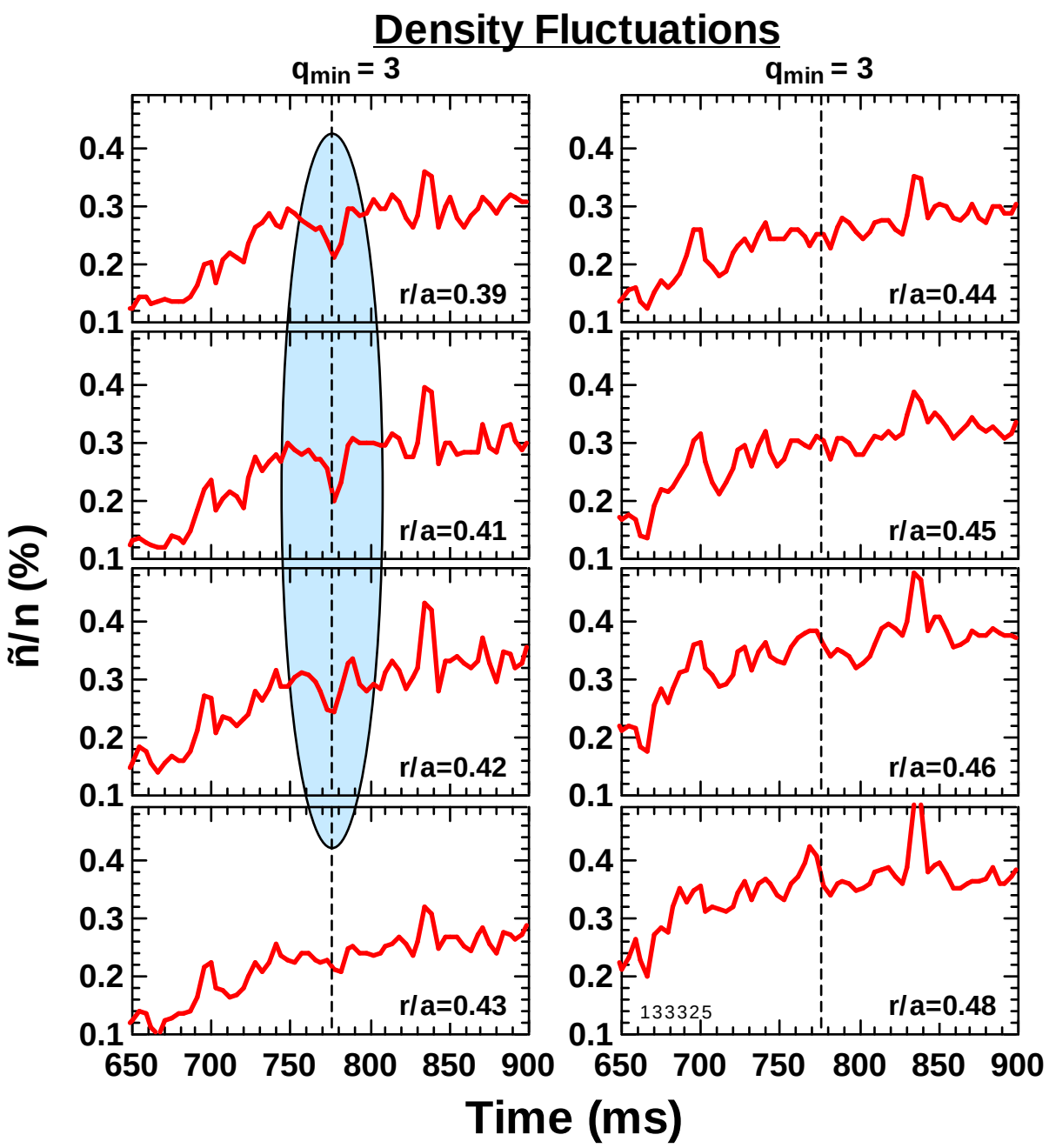
- Precursor flow perturbations observed
- Consistent with GYRO sim. showing zonal flow generation



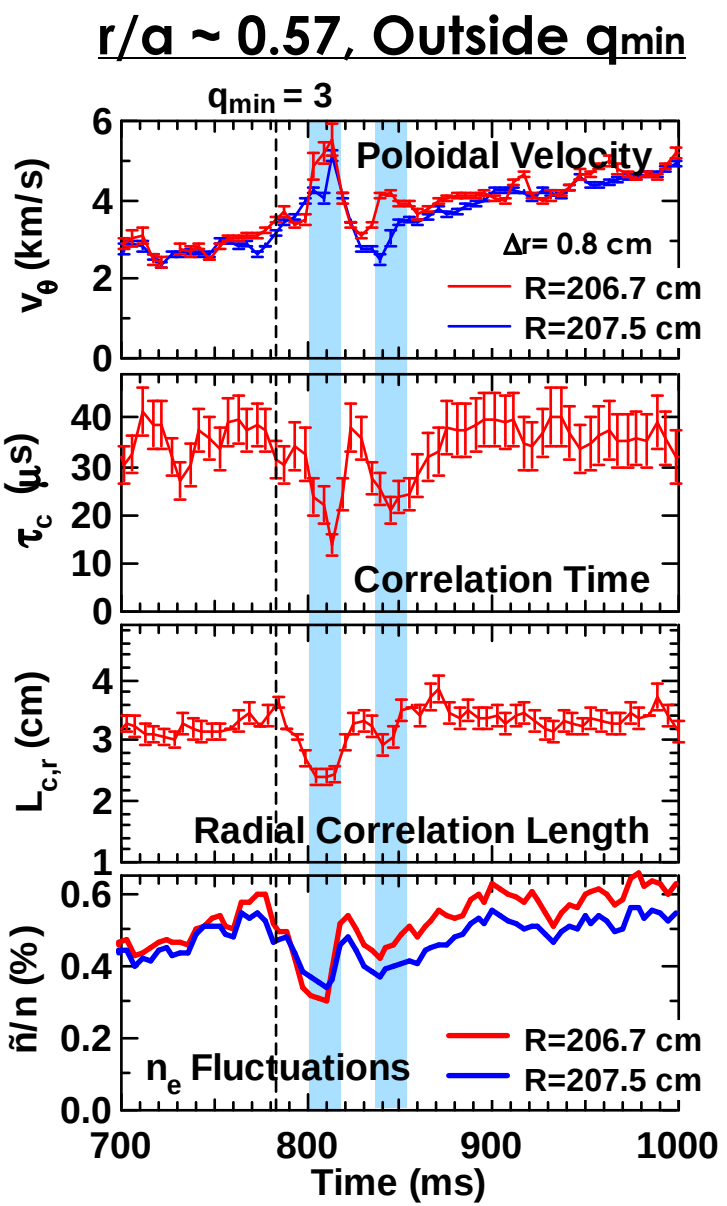
Reduction in Fluctuations Observed Inside q_{min} Surface

- **Fluctuations drop 50% inside q_{min}=3 surface**
  - ρ_{qmin} ~ 0.45 - 0.55
- **Suggests double suppression layer inside and outside of q_{min} surface**
  - consistent with GYRO results and convective cell theory



Increased Local Shear Suppresses and Decorrelates Turbulence

- **Local poloidal velocity shear rate calculated via $\Delta v_\theta/\Delta r$**
  - Shear rate increases following $q_{min}=3$
- **Correlation time shortens during increased velocity shear**
  - Increased decorrelation rate
- **Reduction in radial correlation length and density fluctuation simultaneously observed**
- **Fits shear suppression model***
  - Eddy lifetime and size decreases as shear rate rises



* P.W. Terry, Rev. Mod. Phys. **72** 109 (2000)

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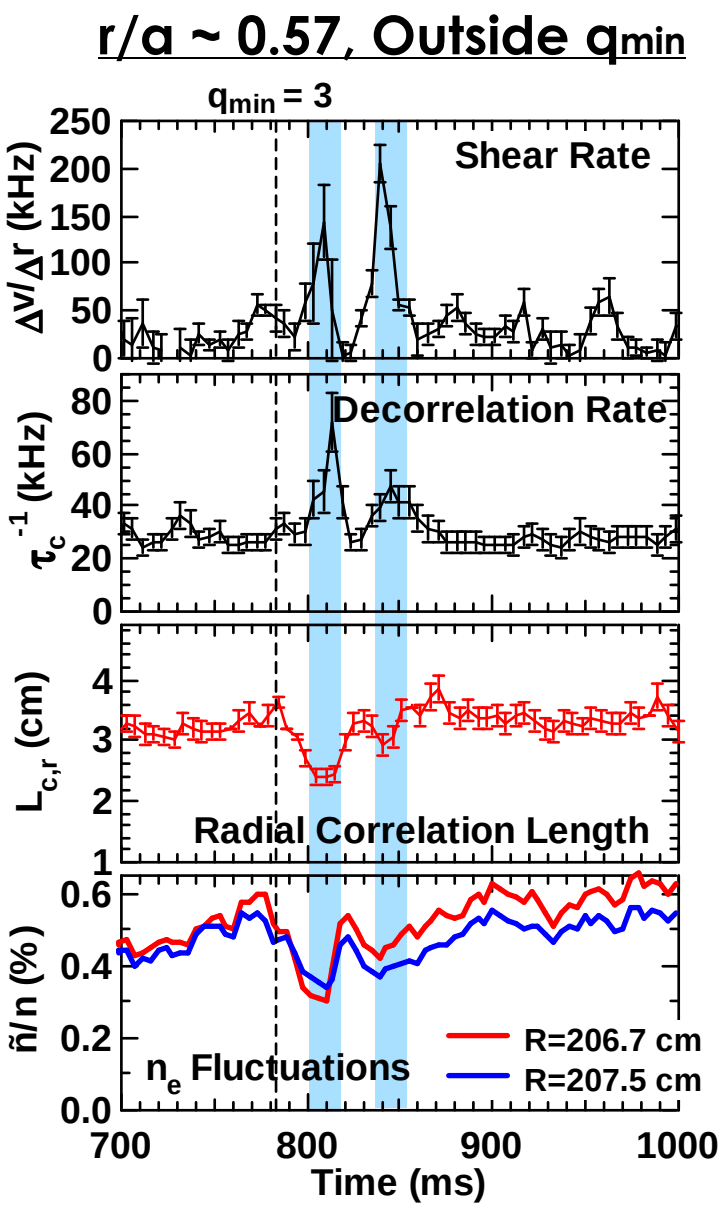


* P.W. Terry, Rev. Mod. Phys. **72** 109 (2000)

Summary and Conclusions

- **Spatio-temporal turbulence dynamics examined during NCS q_{min} events via localized BES fluctuation measurements.**

- **Transient turbulence suppression correlates with low-order rational q minima.**
  - Possible double shearing layer inside and outside of q_{min}

- **Velocity perturbation develops immediately after -- and possibly *before* q_{min} reaches integer**
  - Consistent with zonal flow/convective cell generation

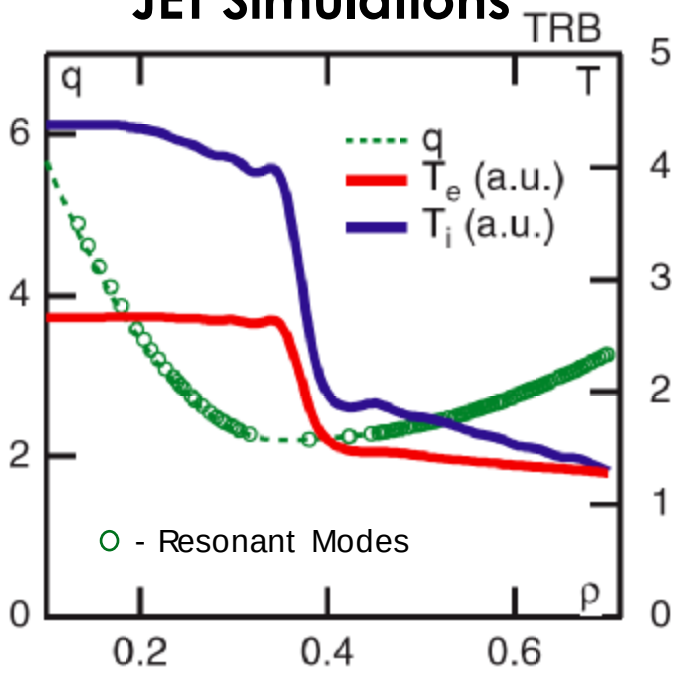
- **Simultaneous localized measurements of suppression:**
  - Increased shear rate
  - Increased decorrelation rate
  - Reduced radial correlation length
  - Reduced fluctuations

Theories Part 1: Rarefaction and MHD

- **Rarefaction of resonant surfaces**
  - Layer with no resonant surface near low-order $q_{min}=m_0/n_0$
  - gap of resonant modes larger than correlation length
  - Only for low-k ITG-like modes ($k\rho_\theta < 1$)
  - *X. Garbet, et al. Nucl. Fusion* ***43****, 975 (2003)**

$$d_{gap} = 2\left[\frac{q_{\min}\rho_s}{q''_{\min} r_{q_{\min}} n_0}\right]^{1/2}$$

JET Simulations*



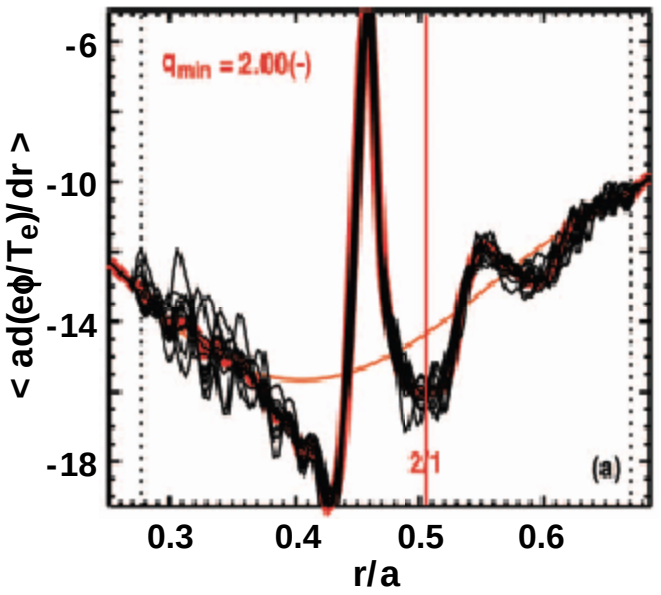
- **Redistribution of Fast Ions**
  - fishbones on ASDEX-U at $q_{min}=2$
  - *A. Gunter, et. al., Nucl. Fusion* ***41****, 1283 (2001)*

- **MHD Flow layer**
  - Driven by double tearing modes
  - *J.Q. Dong, et al., Phys. Plasmas* ***14****, 114501 (2007)*

Part 2: Sheared Flows Predicted Near Low-Order Rational *q* Minima

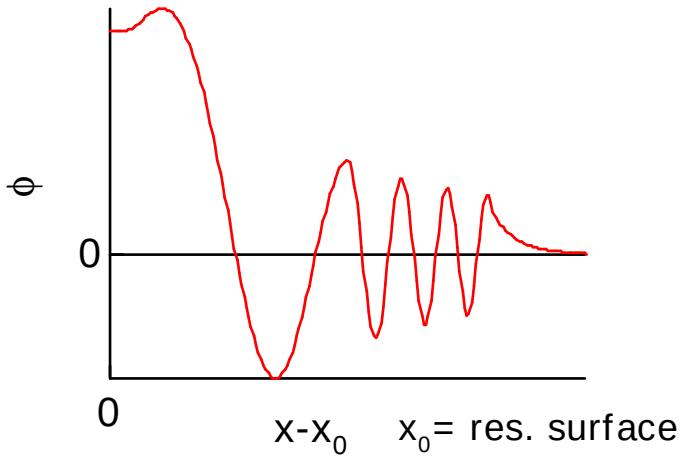
- **GYRO simulations suggest zonal flows (*m*=0, *n*=0)**
  - GYRO: 3-D nonlinear gyrokinetic code
  - Explained by a resonance of turbulence modes at low-order rational surface.
  - Enhanced turbulence at lowest-order surface.
  - Radial divergence drives zonal flows.
  - *R.E. Waltz, et. al., Phys. Plasmas, **13** 052301 (2006)**

GYRO E_r simulations*



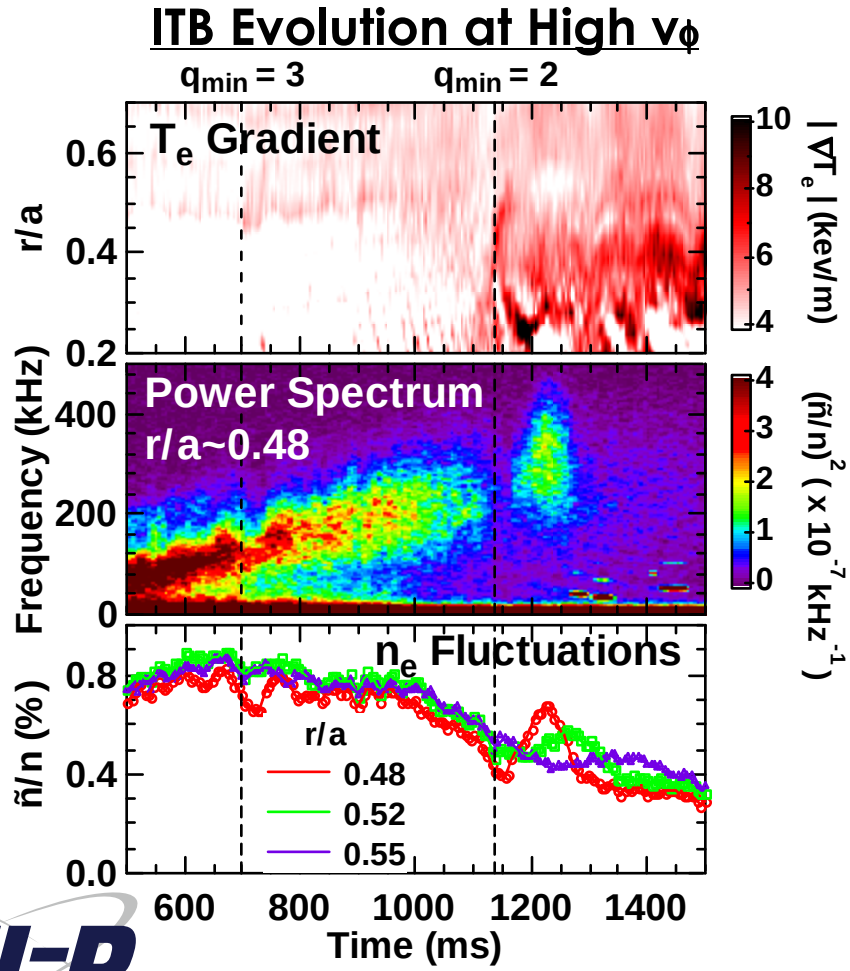
- **Secondary Convective Cells theorized**
  - Energy transfer from drift waves to low-*m*,*n* convective cell, resonant at *q*=*m*/*n*.
  - Can drive radial transport.
  - Damped by magnetic shear.
  - *P. Diamond, et. al. IAEA 2006*
    *C.J. McDevitt, et. al., Phys. Plasmas **14** 112306 (2007)**

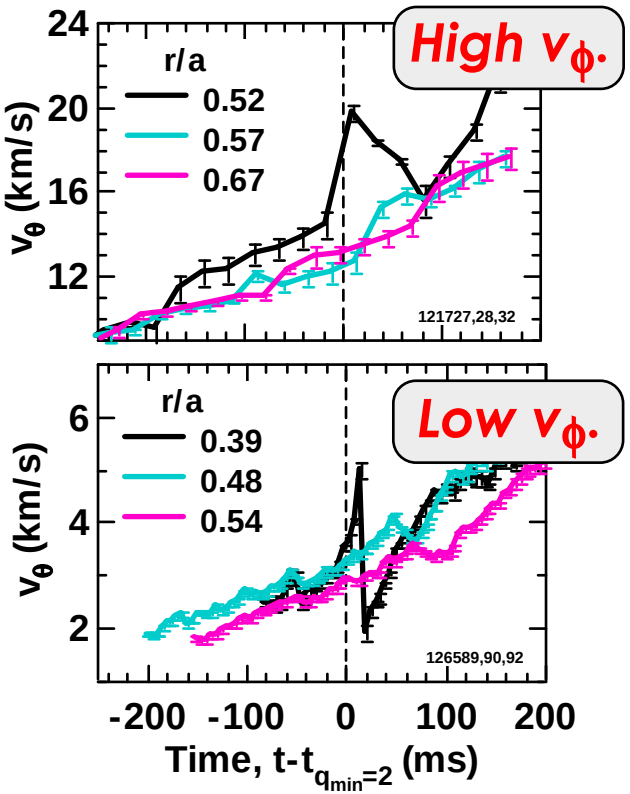
Cell Spatial Variation*



Reduced Fluctuations and Increased Flow Previously Observed

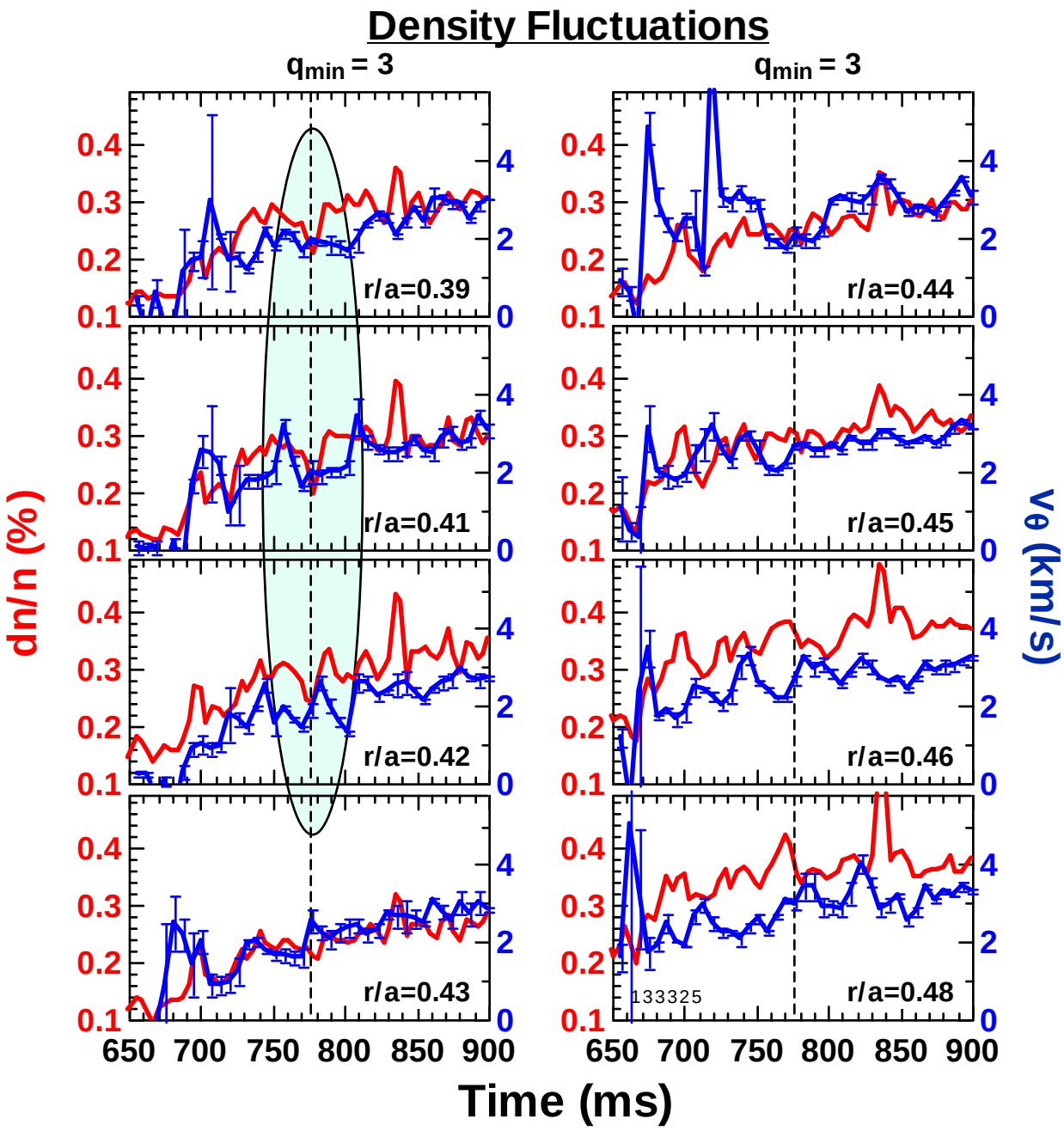
- Transient turbulence suppression correlates with low-order rational q minima.
- Low-frequency velocity shear develops immediately after q_{min} reaches 2.
- Outward propagation of shear and suppression layer, following q=2 surface.





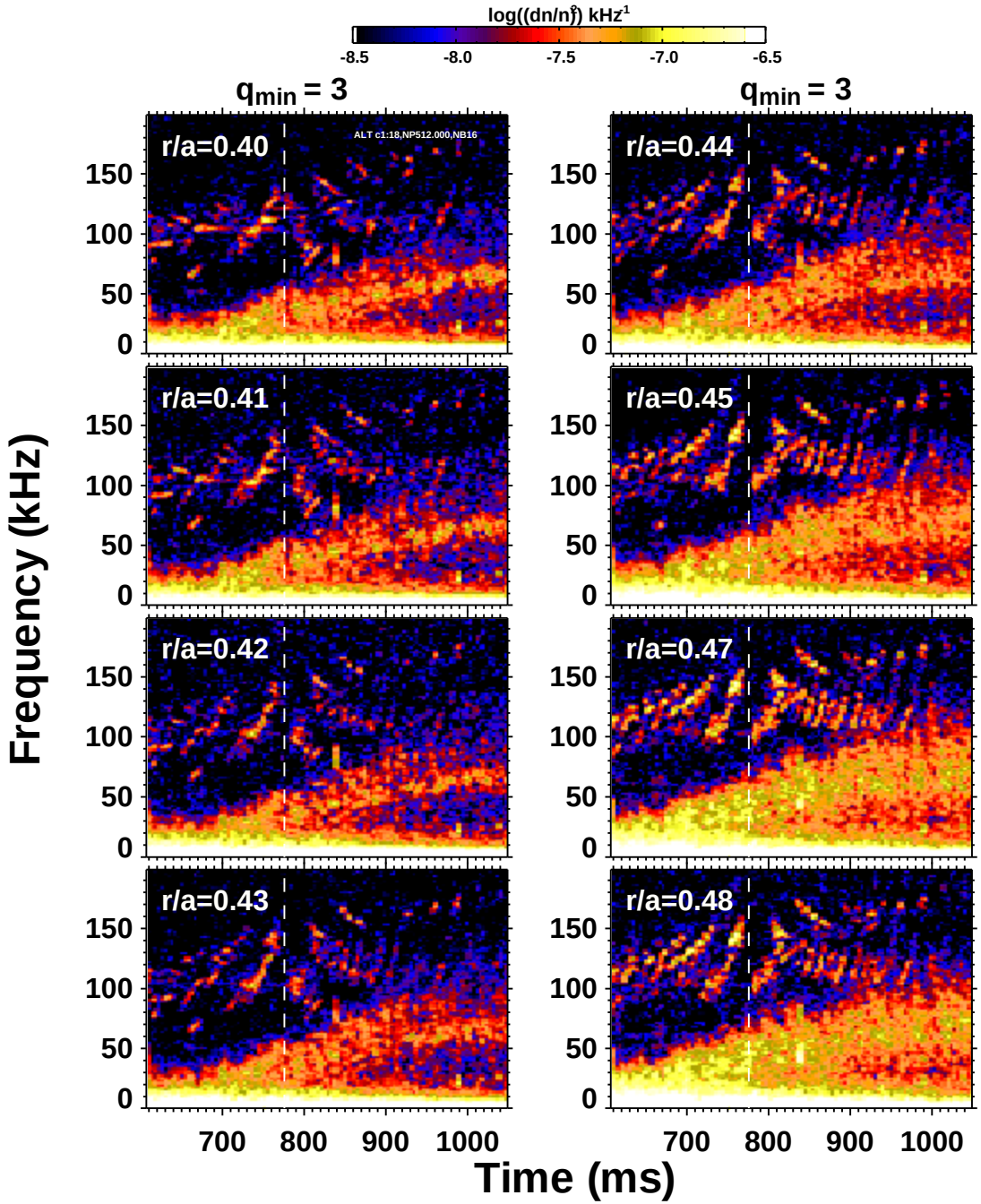
Flow Perturbation Inside q_{min} Surface Shows Possible Shear

- **Fluctuations drop 50% inside q_{min}=3 surface.**
- **Indicates possible double suppression layer inside and outside of q_{min} surface.**
  - consistent with GYRO results and convective cell theory.
- **Corresponding flow measurements show little change.**



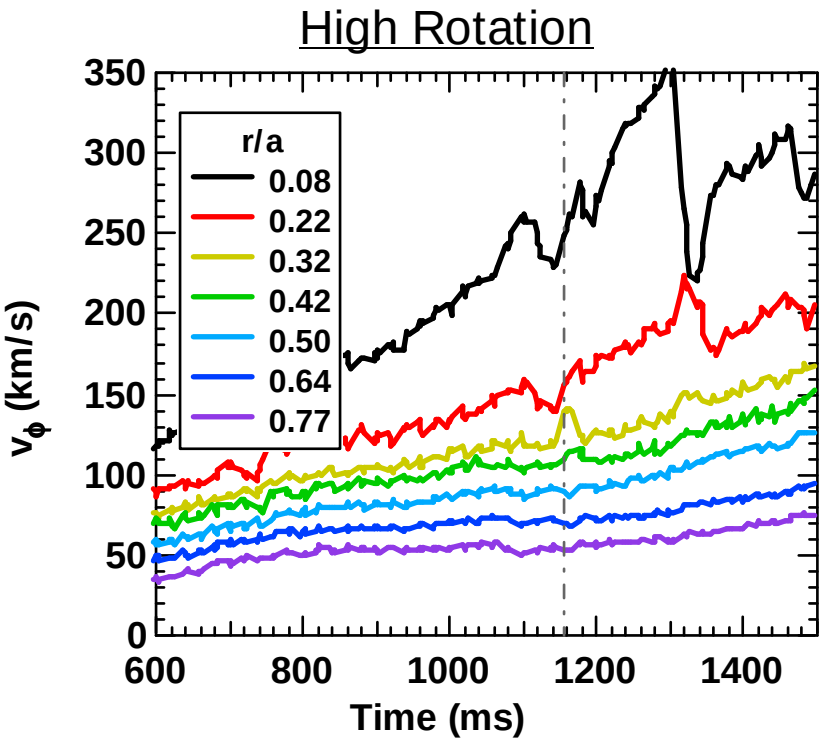
Spectra Inside q_{min} Surface Show Transient Reduction

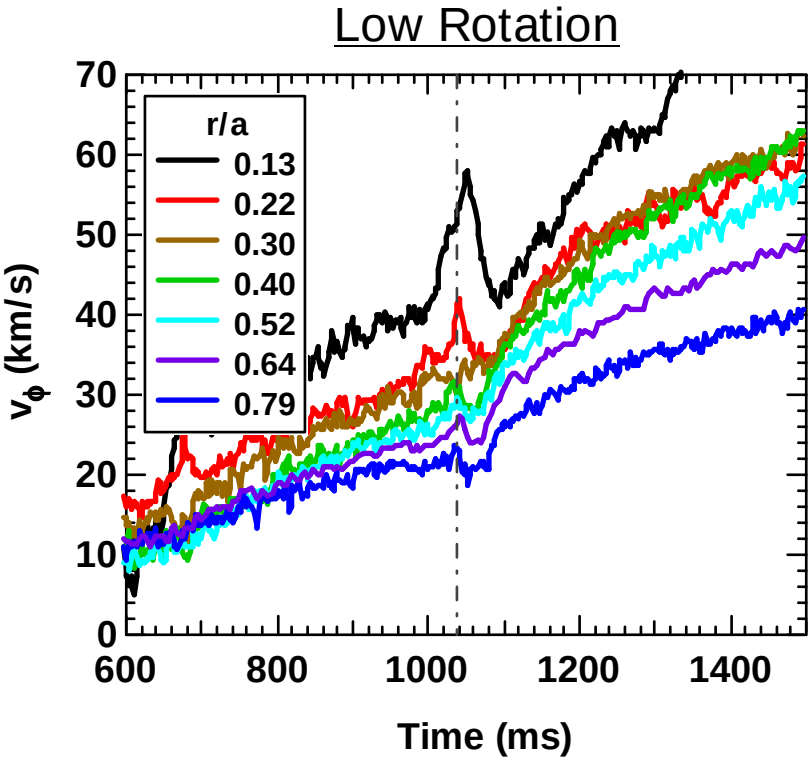
- **Focus: Low v_ϕ at q_{min}=3**
  - ρ_{qmin} ~ 0.45 - 0.55
- **Largest reduction observed radially inboard of qmin surface**
- **Possible double shearing layer in and outside of q_{min} surface.**



Sudden Change in Toroidal Rotation at $q_{min} = 2$

- **E_r strongly affected by v_ϕ**
  - Capable of creating temporary ExB shear.



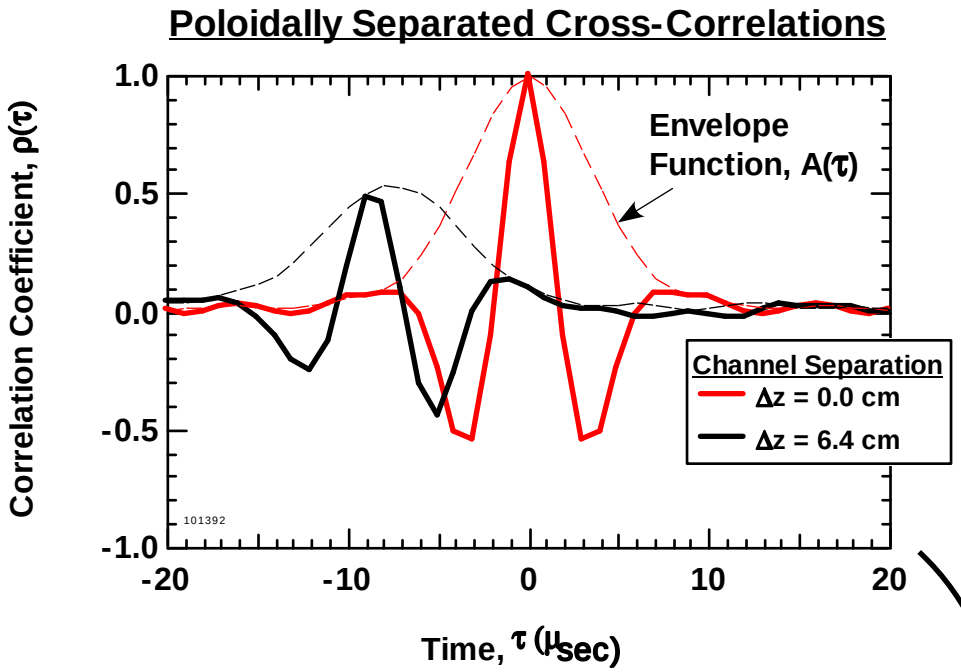


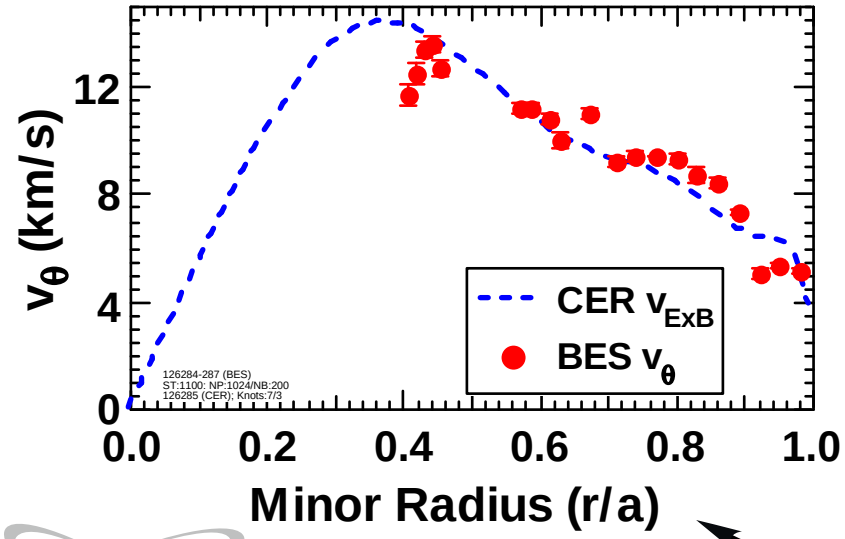
2D BES Array Measures Local Turbulence and Poloidal Flow

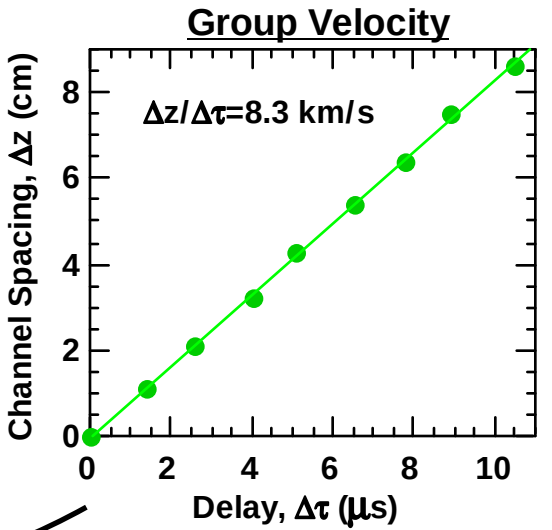
- **5x6 BES array scanned radially shot-to-shot**
- **Turbulence advection measured via Cross Correlation Time Lag ⇒**

$$v_{\theta,turbulence} = v_{ExB} + v_D$$

  - Typically, $v_D << v_{ExB}$
  - Compares well to CER-measured E_r.

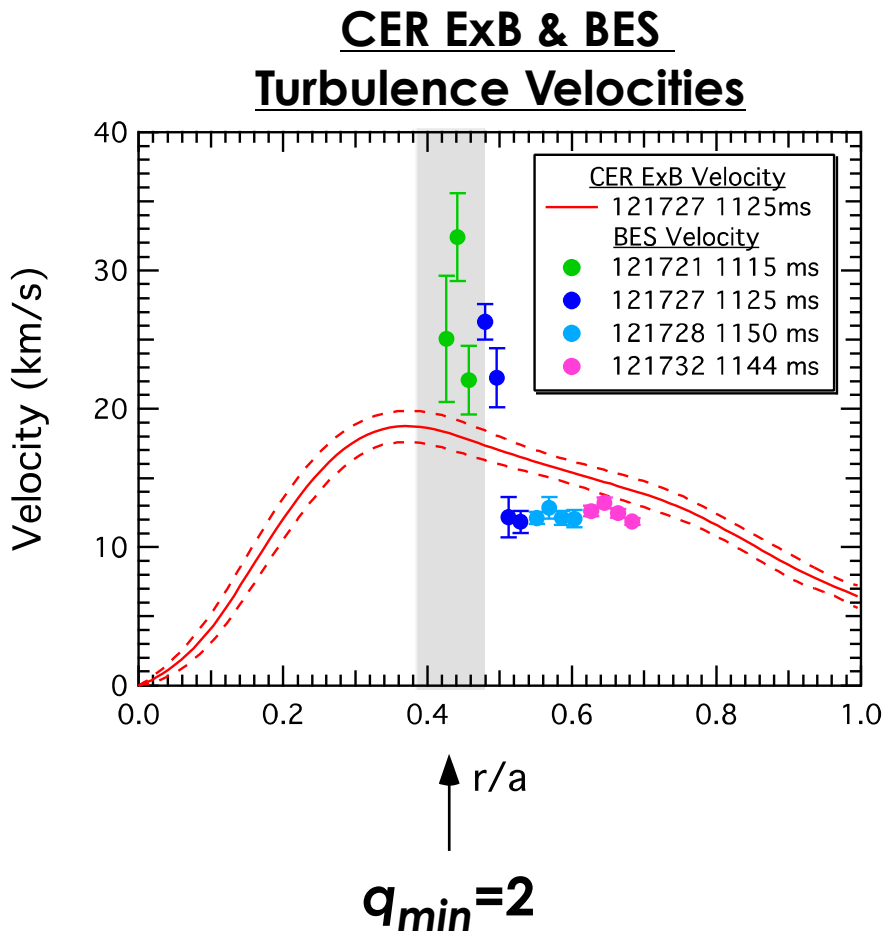






Max Velocity Shear Near q_{min}=2

- **Spatial profile acquired over multiple repeat shots**
  - Time of q_{min}=2 used as fiducial.
- **Compared CER ExB profile doesn't detect transient v_θ**
  - Time averaged profile calculations.
- **Transient Velocity Excursion near q_{min}=2.**



**BES Velocities are plotted during T_e jump.*