EFFECT OF PLASMA FLOWS ON TURBULENT TRANSPORT AND MHD STABILITY*

by

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INTRODUCTION: IMPORTANCE OF PLASMA FLOWS

- Plasma flows have important effects on tokamak stability and transport on spatial scales ranging from the gyro-orbit scale to the machine size
    - In many interesting cases, these flows are self-generated by the plasma
- For example, a key topic of present-day research is the effect of gyro-radius-scale zonal flows on micro-turbulence-driven transport
- Somewhat larger scale flows include the changes in sheared E × B flows observed at the L to H transition, the ERS transition and during the spin-up associated with VH–mode
- Sheared toroidal flows have been predicted to affect MHD ballooning mode stability [R.L. Miller, et al., Phys. Plasmas 2, 3676 (1995)]
- Toroidal flows with scales of the system size have been shown experimentally to stabilize the resistive wall mode

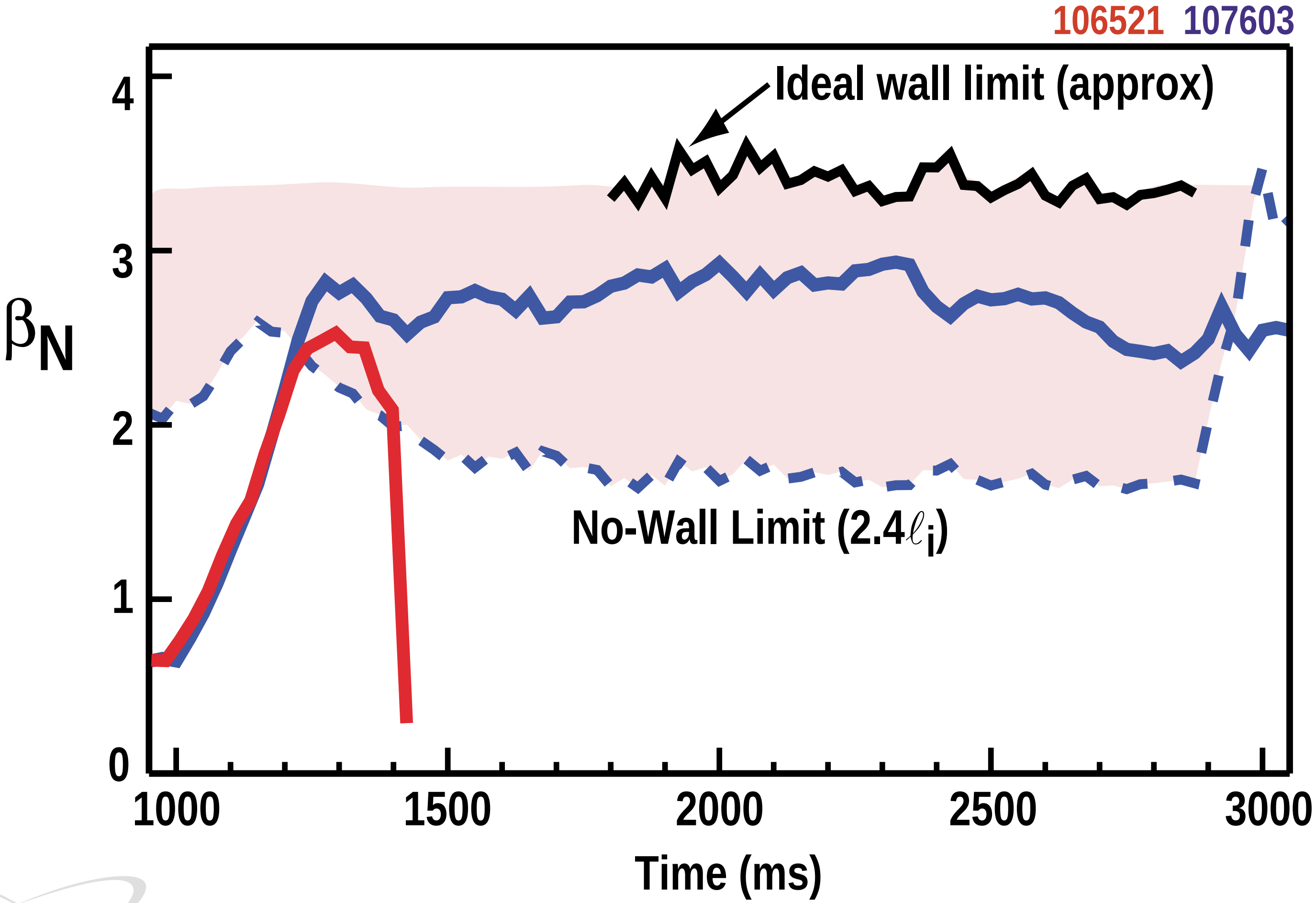
GOALS OF PRESENTATION

- Briefly cover some of the previous results on plasma flows and their effects

- Pose a series of questions to motivate later discussion

STABLE OPERATION WELL ABOVE THE NO-WALL β LIMIT HAS BEEN DEMONSTRATED IN DIII–D

- **Resistive wall mode stabilized by plasma rotation**
  - — Theoretically predicted (Bondeson and Ward, 1994)



A.M. Garofalo et al., APS, 2001

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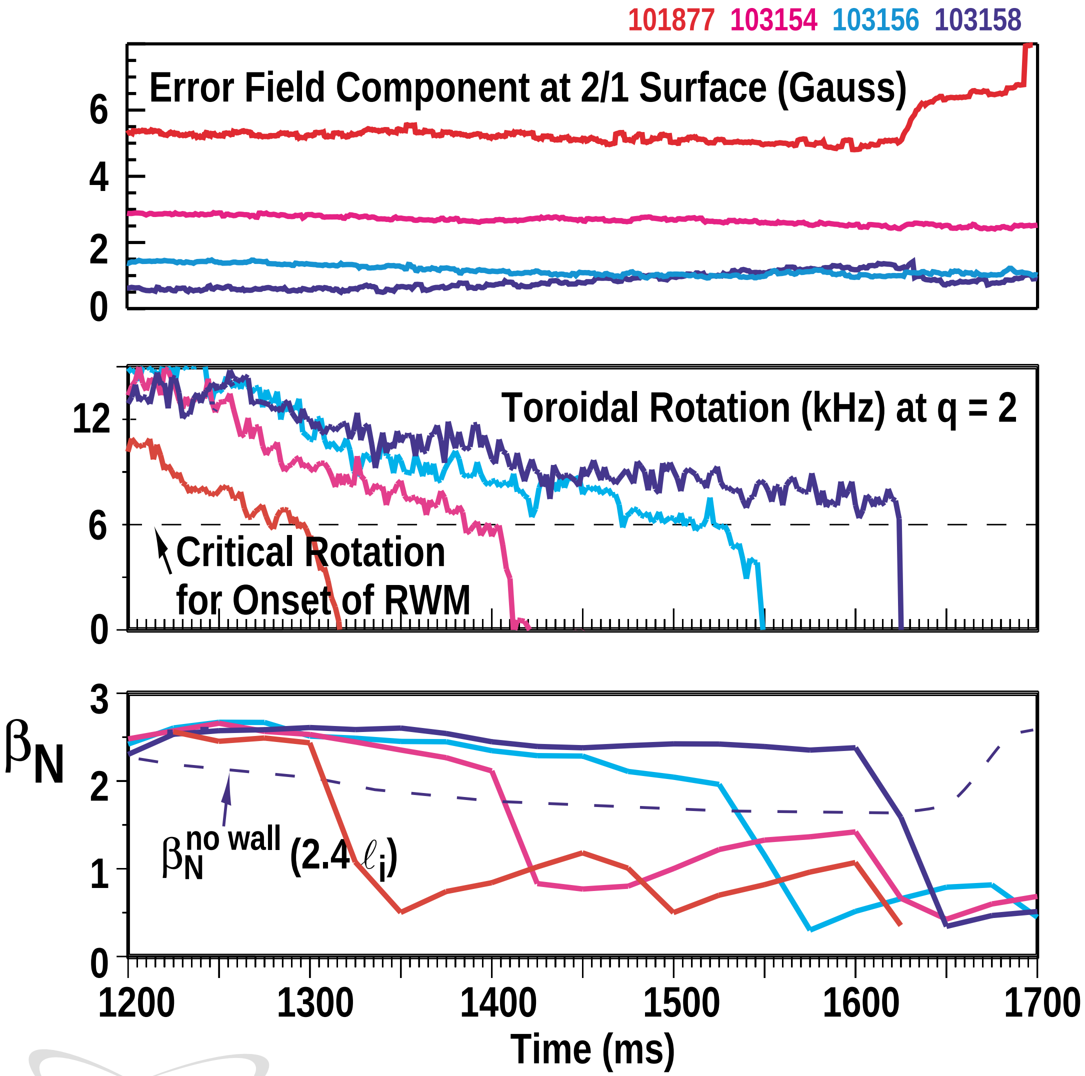
PLASMA ROTATION DECREASES MORE SLOWLY WITH DECREASING ERROR FIELD AMPLITUDE



- Below a critical rotation value, RWM becomes unstable

A.M. Garofalo et al., APS, 2001

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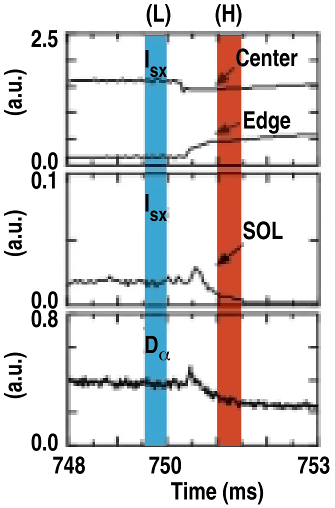
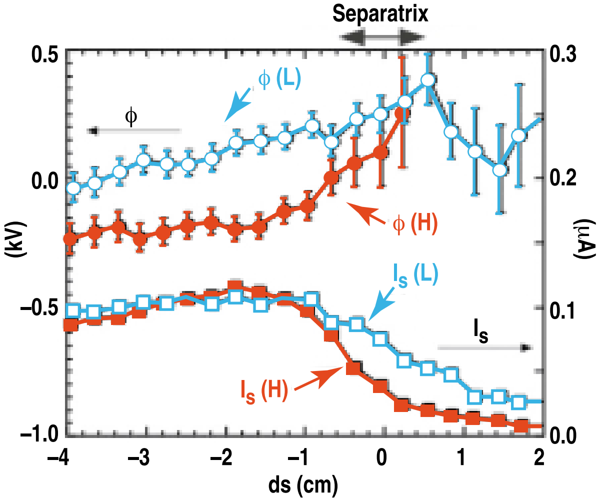
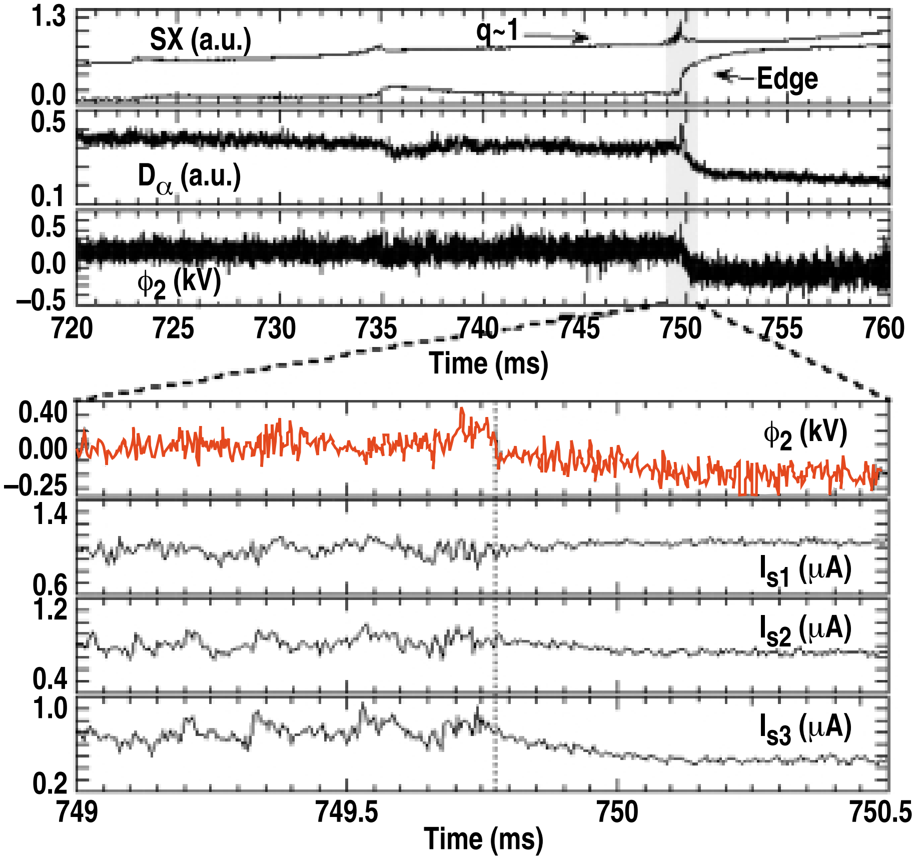
HIBP MEASUREMENTS IN JFT2–M SHOW E×B FLOW CAN CHANGE IN 10 μs AT THE L TO H TRANSITION

- E×B flow changes before profiles change
  - $E = -\nabla\phi$



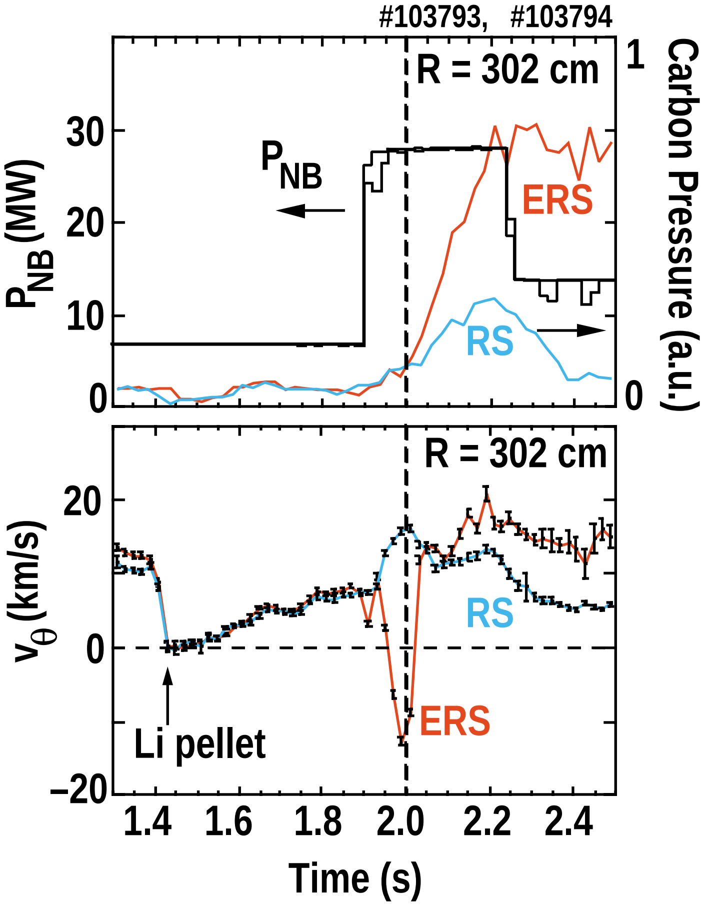


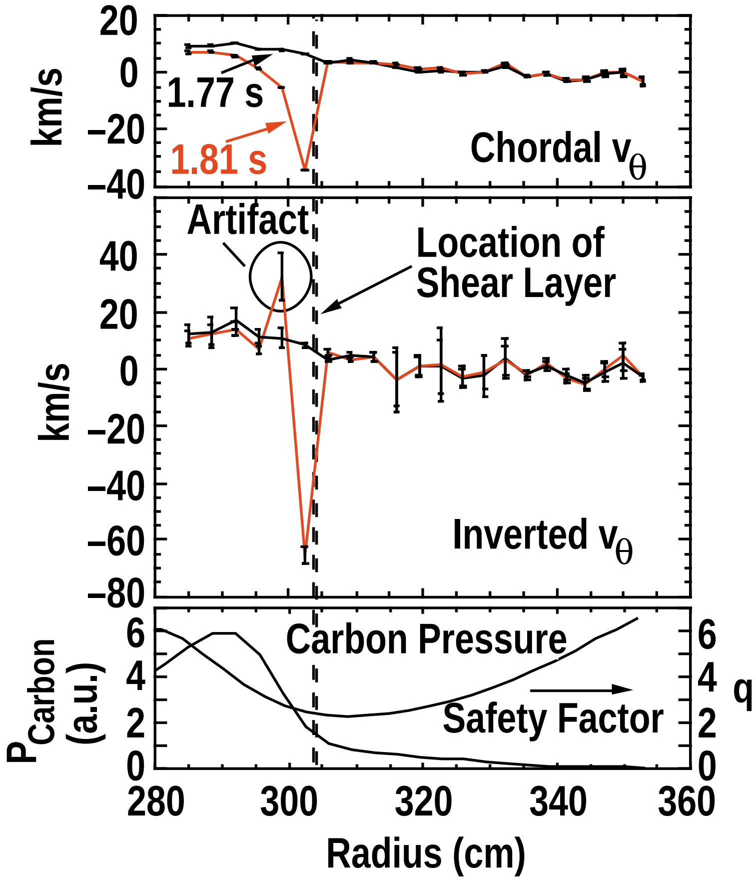


T. Ido et al, Phys. Rev. Lett. 88, 055006-1 (2002)

CARBON POLOIDAL ROTATION CHANGE SHOWS CHANGE IN E×B FLOW PRIOR TO ERS TRANSITION IN TFTR

- “This precursor occurs at a time before there are changes in pressure and temperature associated with enhanced confinement” – R.E. Bell





R.E. Bell et al, Phys. Rev. Lett. 81, 1429 (1998)

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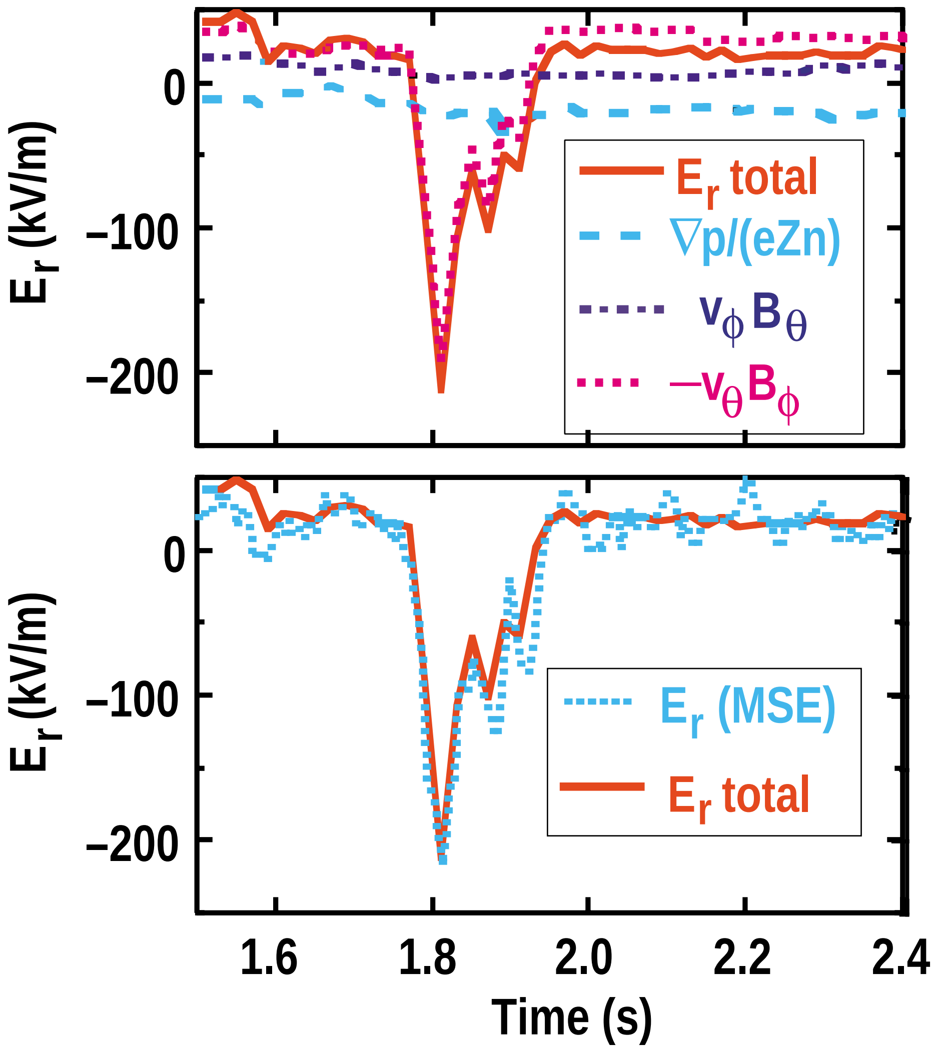
MSE AND SPECTROSCOPY DETERMINE SAME E_r CHANGE AT ERS TRANSITION IN TFTR

- Zero of MSE-determined E_r chosen to match spectroscopic value well after ERS transition

- Rapid change in v_θ relative to ∇p shows neoclassical v_θ is not the whole story



R.E. Bell et al, Phys. Rev. Lett. 81, 1429 (1998)

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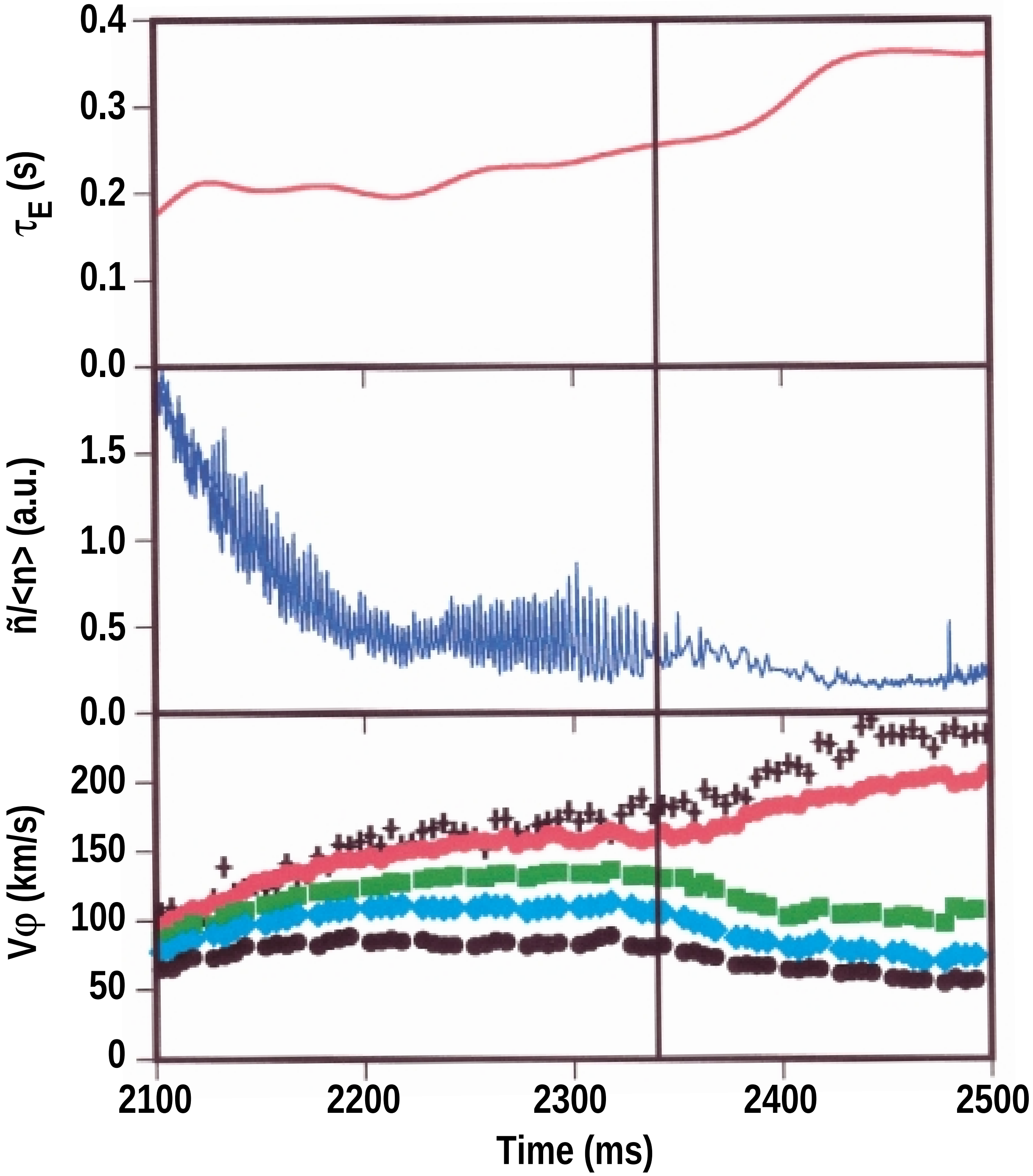
DENSITY FLUCTUATIONS DECREASE AS CONFINMENT AND Er SHEAR INCREASE AS H–MODE GOES TO VH–MODE IN DIII–D



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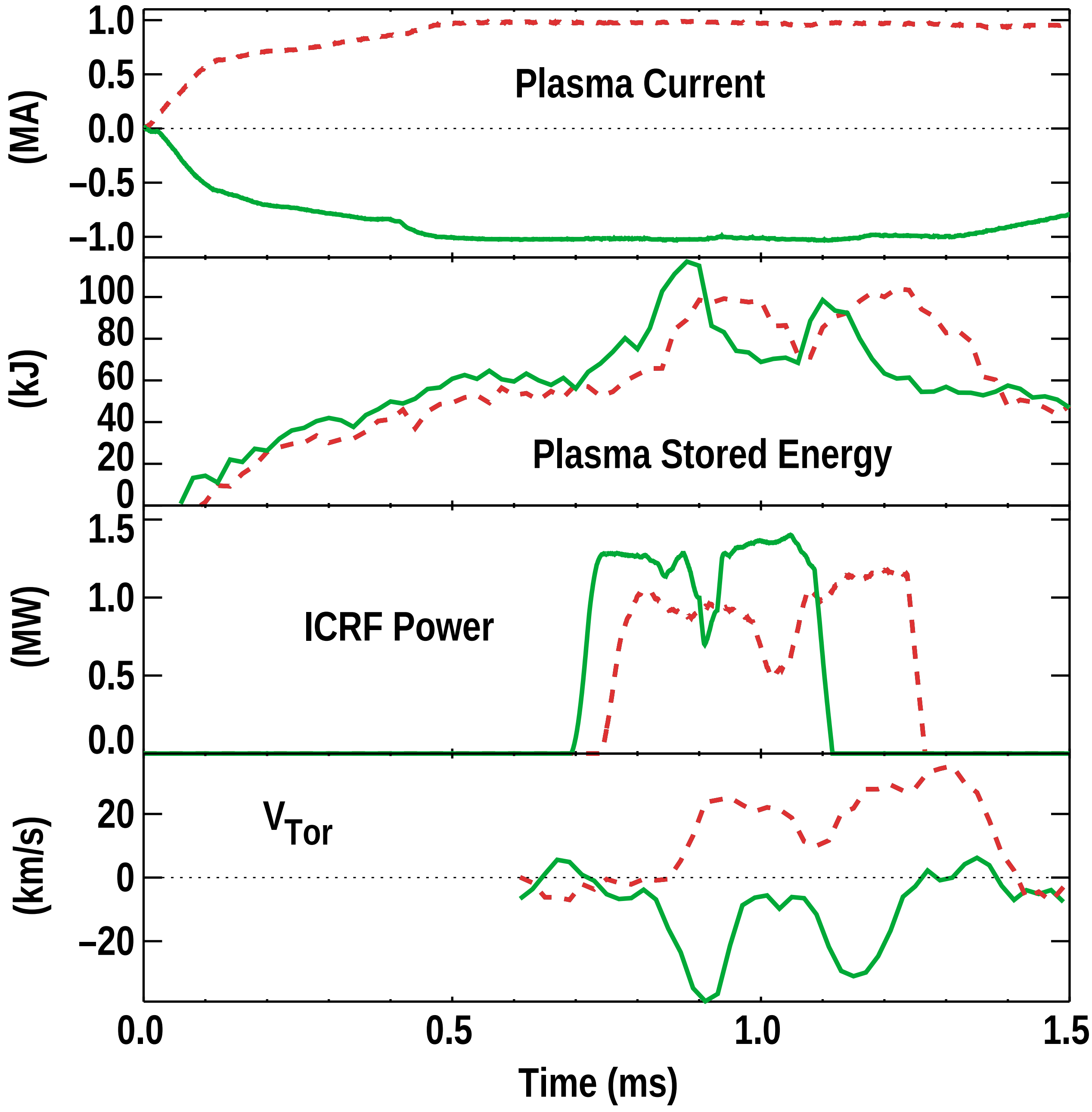
ROTATION REVERSES DIRECTION WITH PLASMA CURRENT IN ALCATOR C–MOD H–MODE PLASMA

- Core $E_r > 0$ in H–mode



J.E. Rice et al., Nucl. Fusion 41, 277 (2001)

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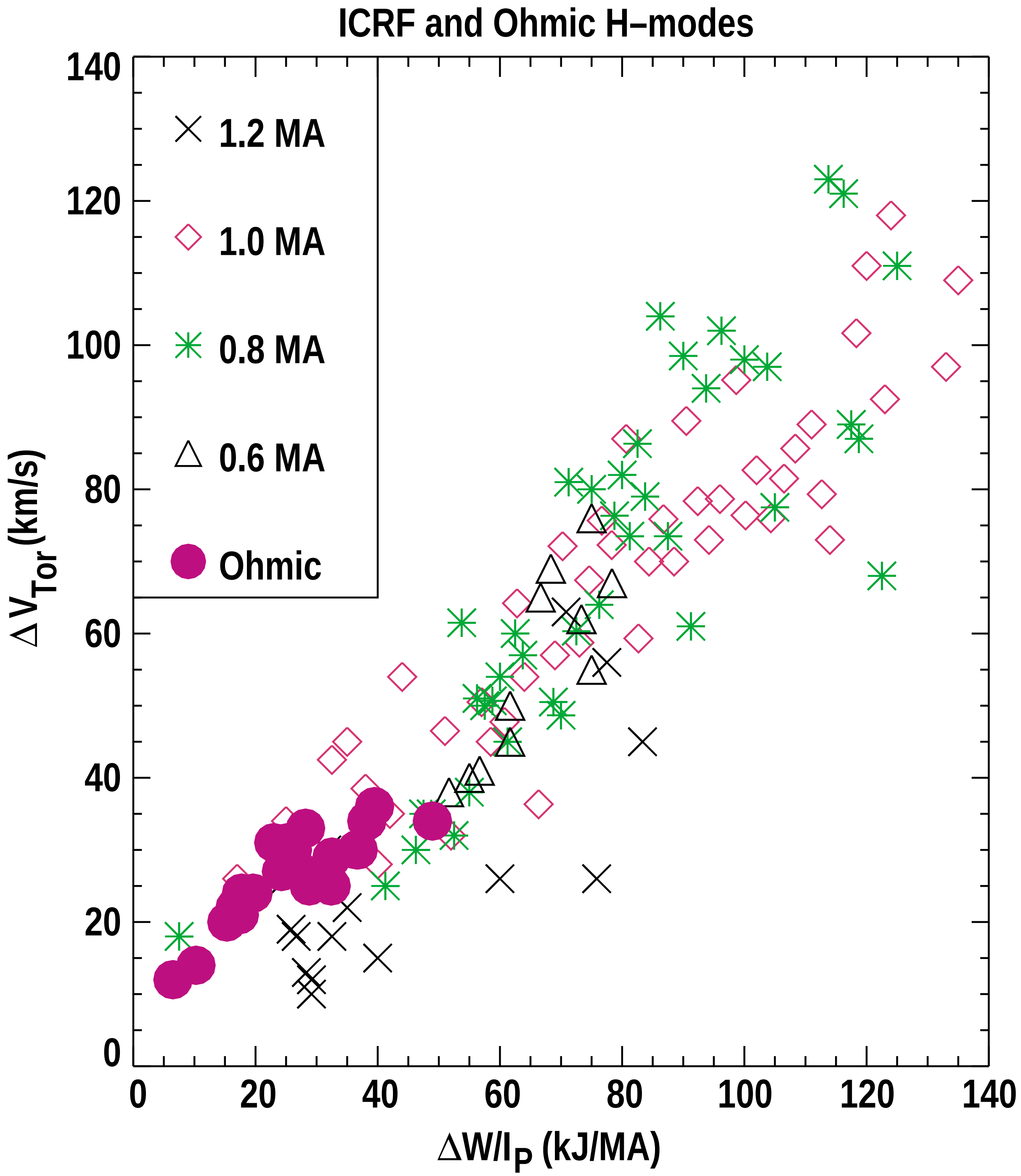
ROTATION AND STORED ENERGY CHANGE TOGETHER IN ICRF AND OHMIC H–MODES IN ALCATOR C–MOD



J.E. Rice et al, Nucl. Fusion 41, 277 (2001)

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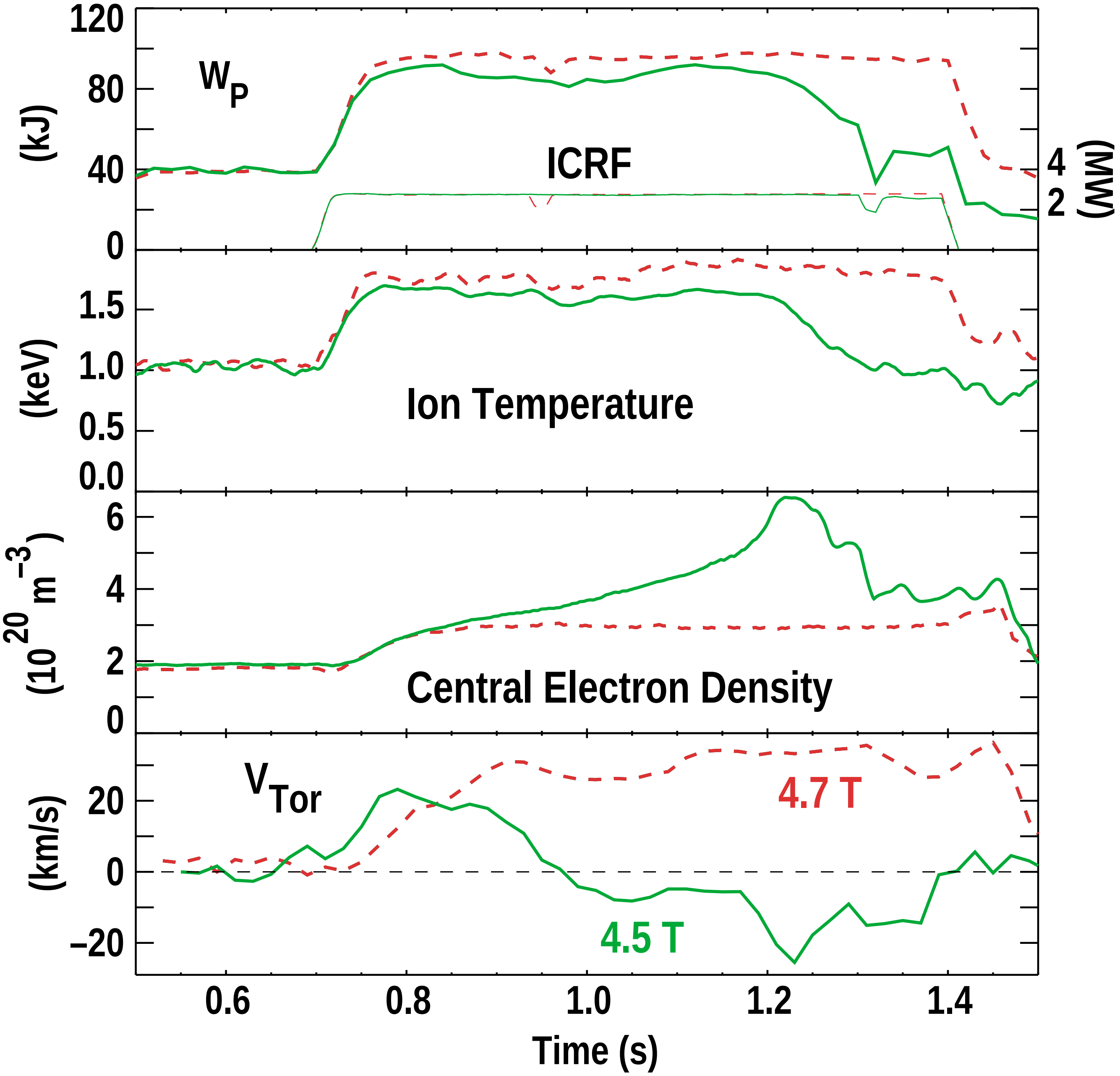
CORE $E_r > 0$ IN H–MODE AND $E_r < 0$ IN H–MODE + ITB IN ALCATOR C-MOD



J.E. Rice et al., Nucl. Fusion 41, 277 (2001)

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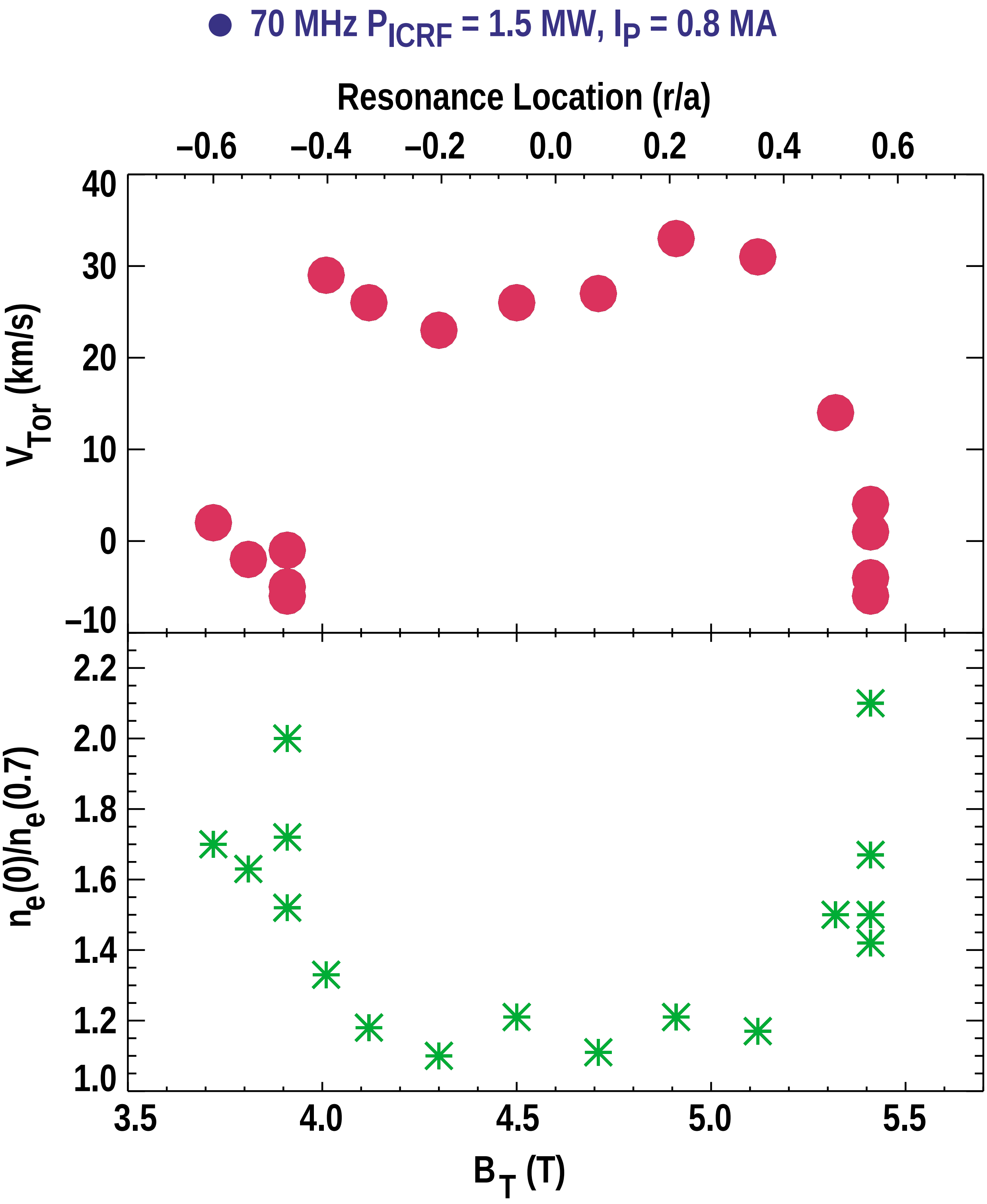
CORE BARRIER FORMS IN ALCATOR C–MOD WITH OFF-AXIS ICRF BOTH INSIDE AND OUTSIDE MAGNETIC AXIS



J.E. Rice et al, Nucl. Fusion 42 (2002) (to be published)

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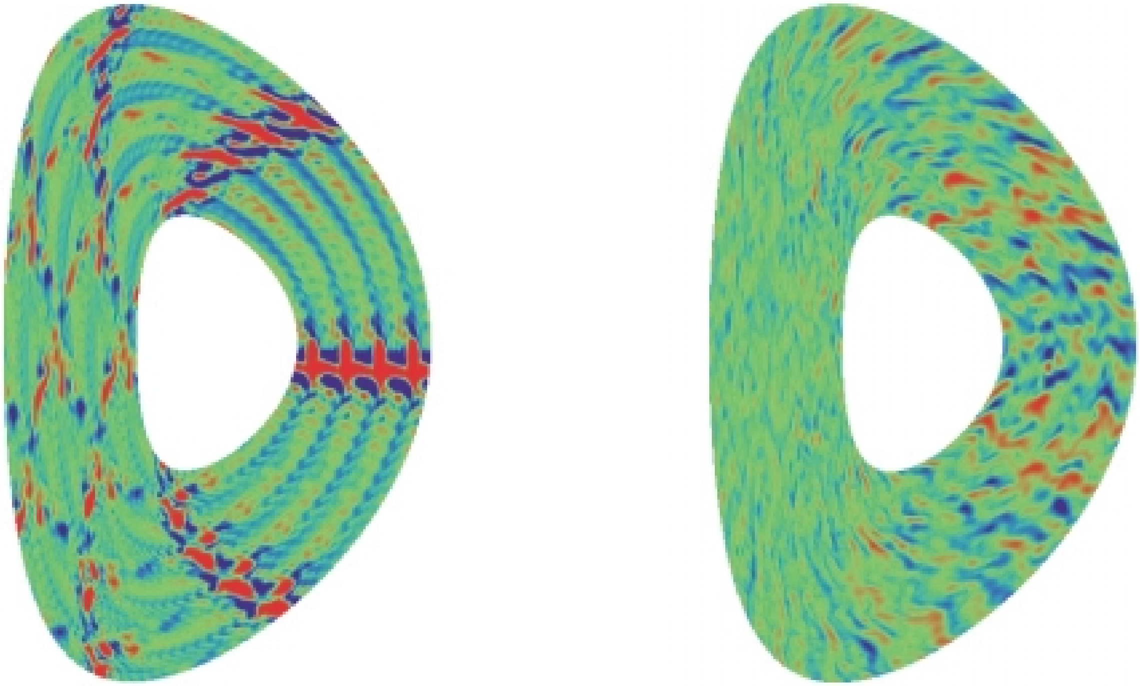
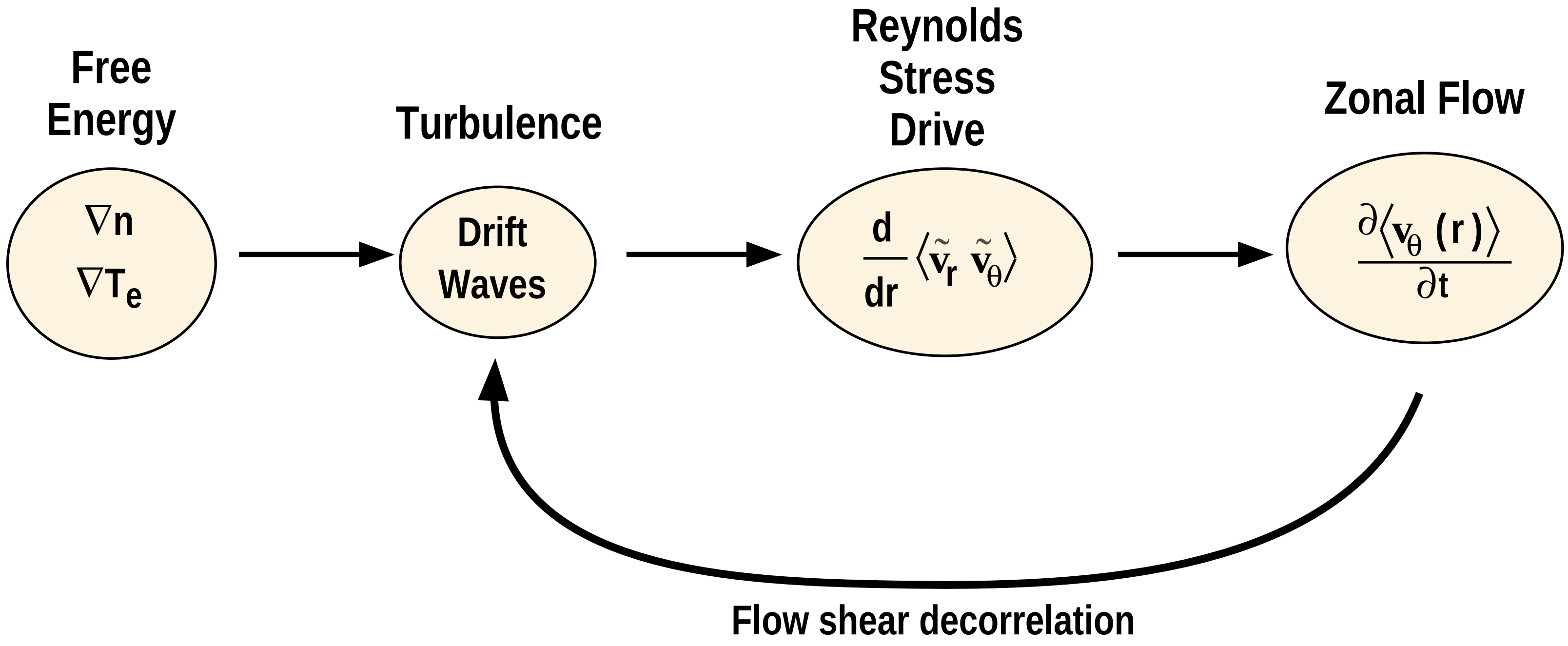
ZONAL FLOWS SHEAR APART RADIAL TURBULENCE STRUCTURES

- Gyro kinetic code (Gyro), toroidal geometry, shaped plasma



J. Candy, R.E. Waltz, J. Comp. Phys. (submitted)

ENERGETICS OF TURBULENCE/ZONAL FLOW INTERACTION



Free Energy

∇n

∇T_e

Turbulence

Drift Waves

Reynolds Stress Drive

$$\frac{d}{dr}\langle \tilde{v}_r \tilde{v}_\theta \rangle$$

Zonal Flow

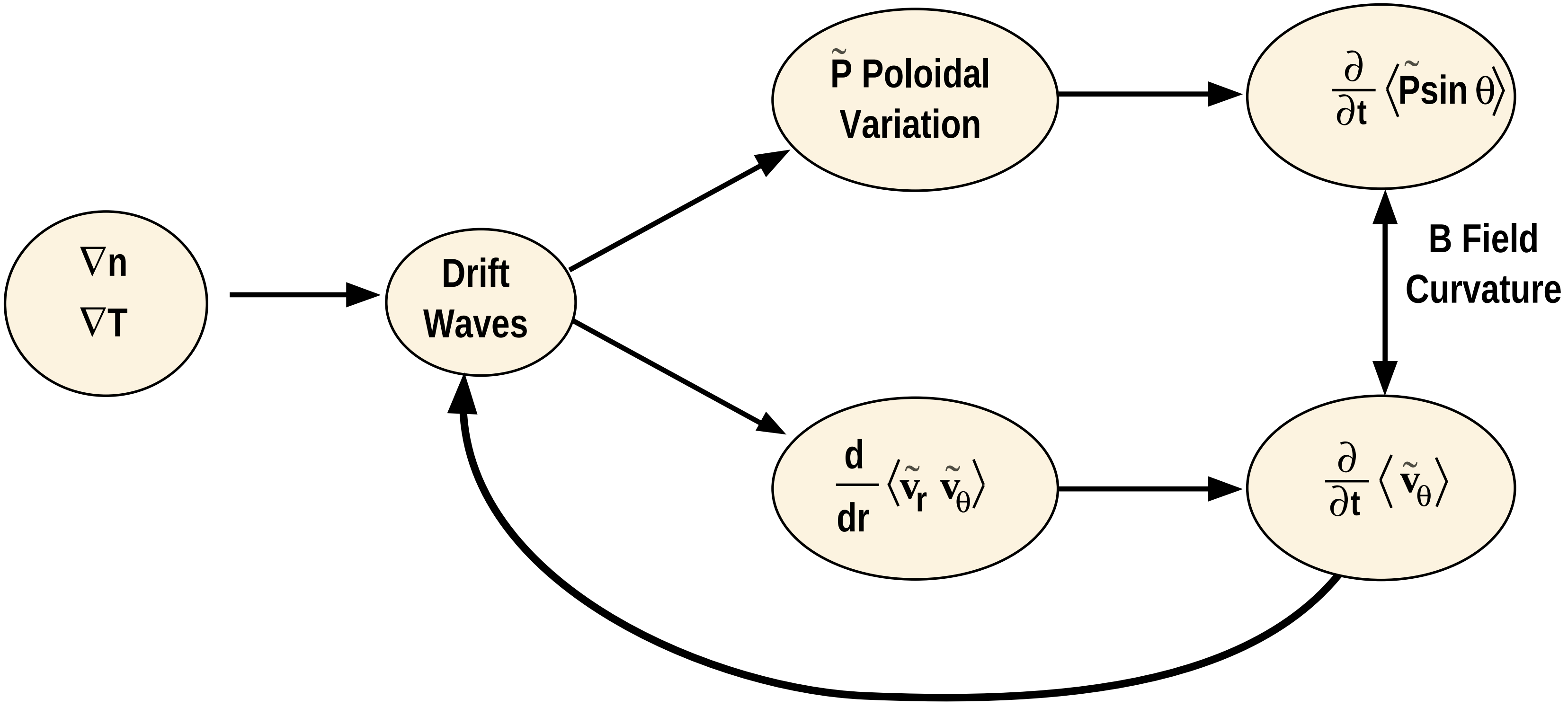
$$\frac{\partial \langle v_\theta (r) \rangle}{\partial t}$$

Flow shear decorrelation

P. Diamond et al., Phys. Fluids B 3, 1626 (1991)

ADDITIONAL ZONAL FLOW DRIVE IN EDGE-CORE TRANSITION REGION

- Stringer-Windsor drive owing to magnetic field curvature plus poloidal asymmetry



∇n
∇T

Drift Waves

$\tilde{P}$ Poloidal Variation

$\frac{\partial}{\partial t}\langle \tilde{P} \sin \theta \rangle$

B Field Curvature

$\frac{d}{dr}\langle \tilde{v}_r \tilde{v}_\theta \rangle$

$\frac{\partial}{\partial t}\langle \tilde{v}_\theta \rangle$

Flow shear decorrelation

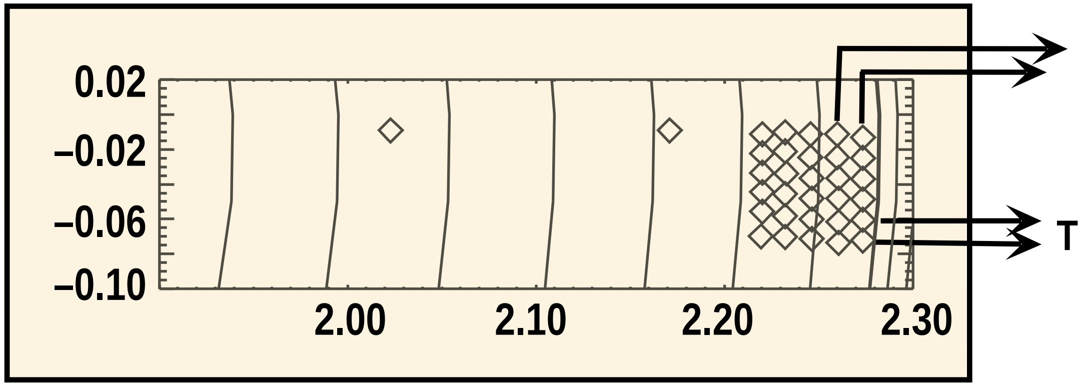
Hallatschek and Biskamp, PRL 86, 1223 (2001)

PHYSICAL CHARACTERISTICS OF ZONAL FLOWS: TESTABLE PREDICTIONS

- Fluctuating poloidal $E_r \times B_T$ flows, $v_\theta(t)$
- Toroidally and poloidally symmetric: n=0, m=0
- Low frequency (<< ambient $\tilde{n}$, 10 kHz)
- Radially localized ($k_\perp \rho_i \sim 0.1$)
- RMS amplitude predicted to be small, $v_{ZF}/v_{th,i} \leq 1\%$ [T.S. Hahm, et al., PPCF 42, A205 (2002)]
- Geodesic acoustic mode (GAM) frequency $f \approx c_s/2\pi R$ [Hallatschek and Biskamp, Phys. Rev. Lett. 86, 1223 (2001)]

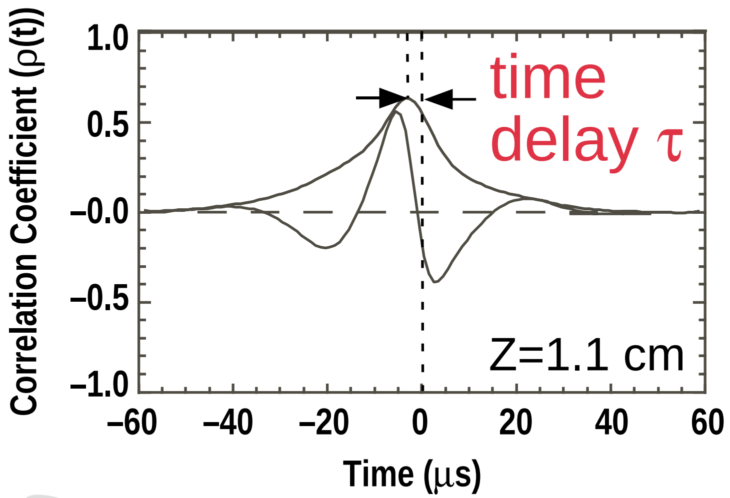
2D TURBULENCE FLOW-FIELD CONSTRUCTED FROM 2D ñ MEASUREMENTS

Poloidal Cross Section of Tokamak



Two radial ñ(t) channels ⇒ v_r

Two poloidal ñ(t) channels ⇒ v_θ



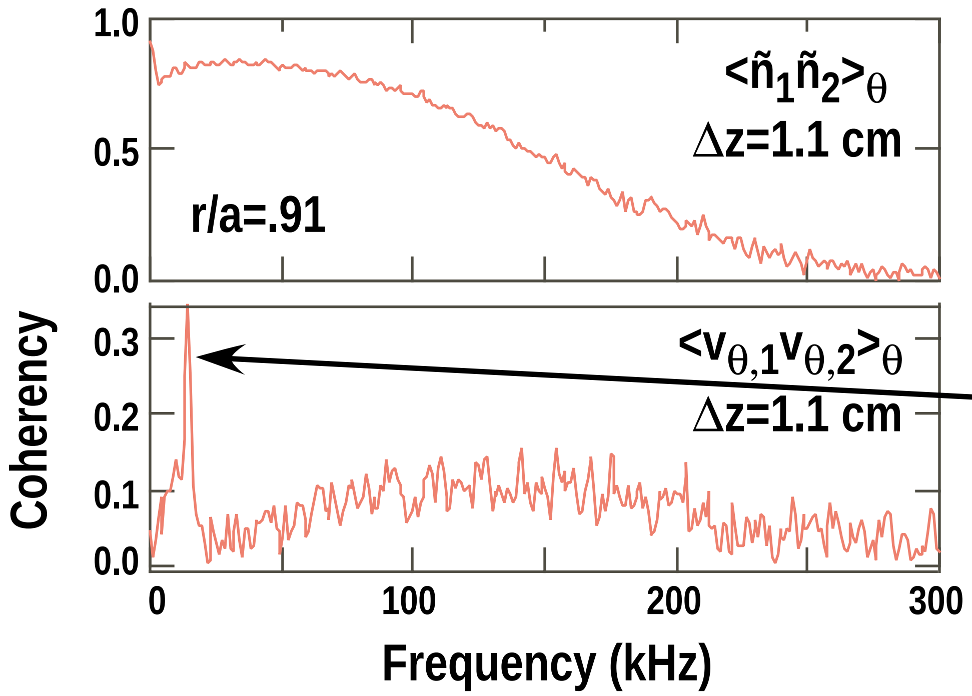
- Eddies convect past spatial channels:

$$v_z(t) = \frac{\Delta z}{\tau(t)}$$ ← delay between two observation points

Jakubowski, McKee, Fonck APS, 2001

$\tilde{n}$, AND v_θ COHERENCY SPECTRA ARE DISTINCTLY DIFFERENT

- Frequency distributions distinct; frequency range similar



- Density

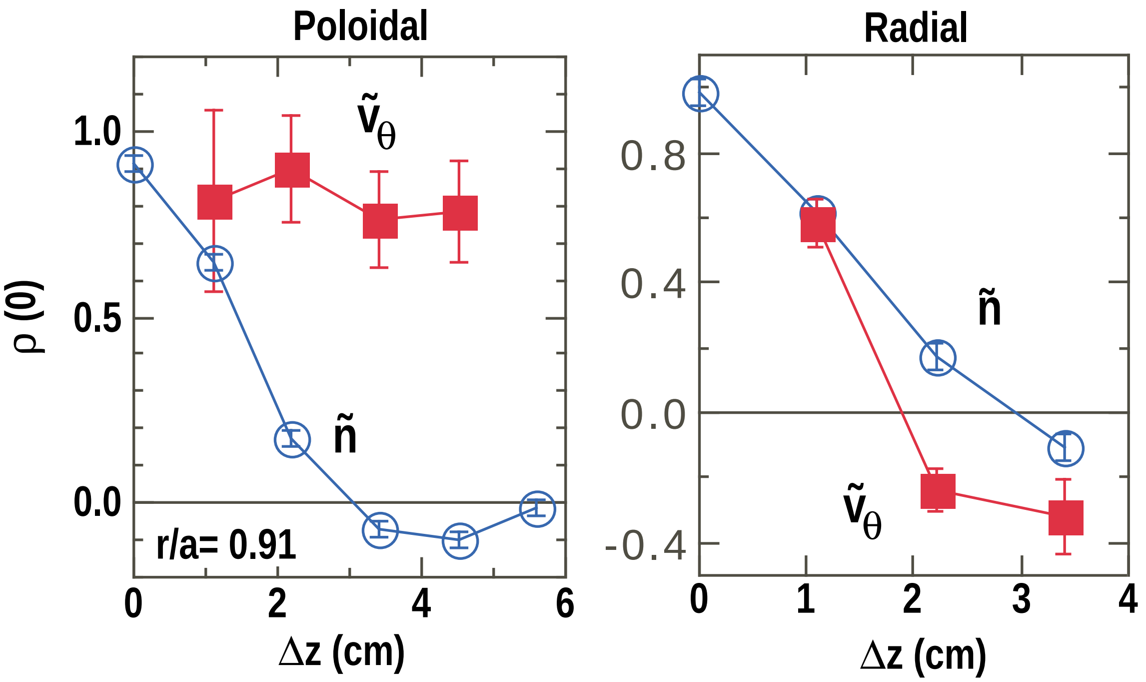
- Poloidal velocity

Strong zonal flow feature in $\tilde{v}_\theta(f)$

Jakubowski, McKee, Fonck APS, 2001

ZONAL FLOW FEATURE EXHIBITS EXPECTED SPATIAL STRUCTURE

$\tilde{v}_{\theta,ZF}$ correlations have long poloidal, short radial length



- Correlation for ñ and $\tilde{v}_\theta$ in zonal flow frequency range (10-20 kHz)

- $\tilde{v}_{\theta,pol} \Rightarrow$ very long wavelength in the poloidal direction
  - Contrasts with $L_{c,\tilde{n}}$~3 cm (poloidal)
- In contrast, $\tilde{v}_{\theta,rad} \Rightarrow L_{c,v} \approx$ 3.3 cm in the radial direction
  - Comparable to the $L_{c,\tilde{n}} \approx$ 2.3 cm (radial)

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Jakubowski, McKee, Fonck APS, 2001

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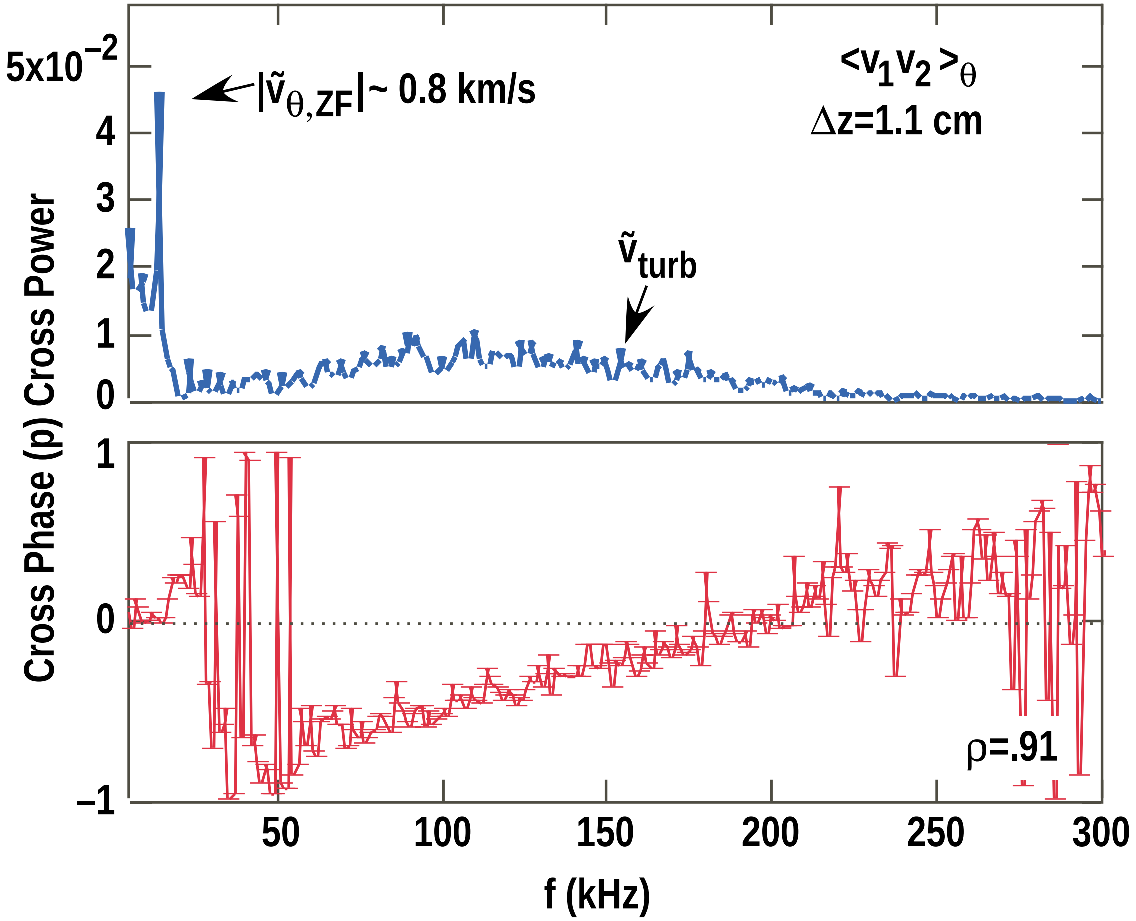
ZONAL FLOW MAGNITUDE CONSISTENT WITH PREDICTIONS
$v_{\theta,ZF}/v_{th,i}$ ~ 1%



- $\tilde{v}_{th,i}$ = 150 km/s
- $\tilde{v}_{\theta,ZF}/v_{th,i}$ ~.005
  - Consistent with Hahm

    ⇒ $\tilde{v}/\tilde{v}_{th,i}$ ~ .01
- Broadband $\tilde{v}_{turb}$ exists in addition to ~15 kHz peak
  - $L_c,\tilde{v}_{turb} \leq$ 2 cm

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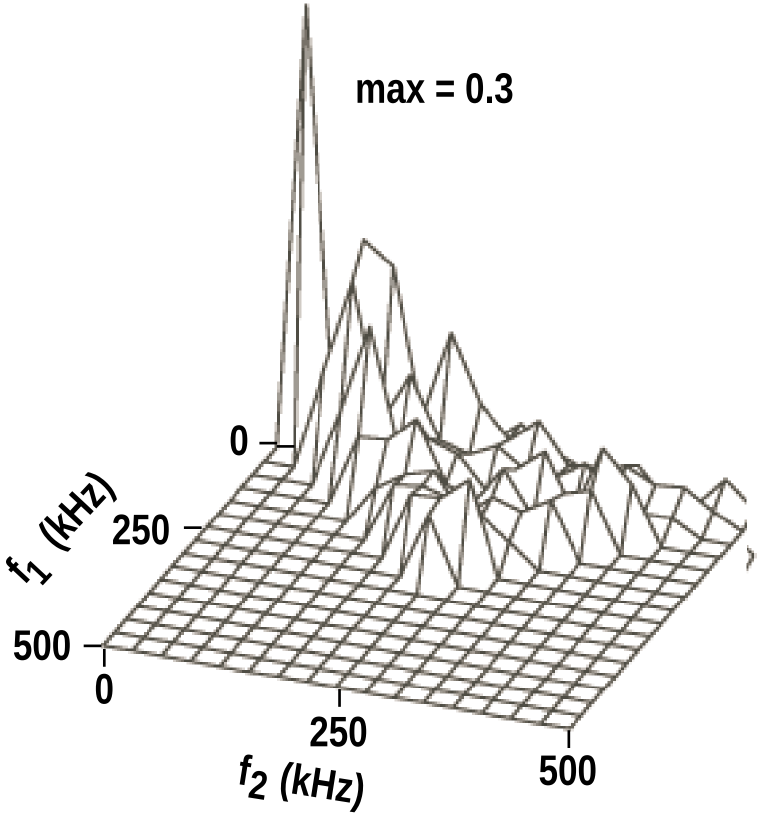
BICOHERENCE SHOWS ñ AND $\tilde{v}_\theta$ PHASE COUPLING



- Three-wave interactions with drift waves zonal flows (Diamond ‘91)
- Zonal flow generation mechanism should be evident in the cross-bispectrum

$$\langle \tilde{v}_\theta^* (k_z)\, \tilde{v}_r (k_1) \tilde{v}_\theta (k_2) \rangle$$

zonal flow scale

turbulent scales

- We observe a nonzero bicoherency at low frequency

$$\langle \tilde{v}_\theta^* (f_1 - f_2)\, \tilde{n} (f_1)\, \tilde{n} (f_2) \rangle$$

– Peak ~ 0.3 at $f_2 - f_1 \approx 15$ kHz = f_{ZF}

⇒ Coupling of ñ to the zonal flow feature

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Jakubowski, McKee, Fonck APS, 2001

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SIMILARITY WITH 3D BRAGINSKII SIMULATION OF EDGE TURBULENCE

- Recent work by Klaus Hallatschek (PRL 86, 1223 (2001)) simulating turbulence in the edge/core transition region:
  - Zonal flows here are Geodesic Acoustic Modes (GAMs)
  - Driven by pressure asymmetry on flux surface, rather than by Reynold’s Stress
  - couple to pressure perturbations (m/n=1/0) by magnetic field inhomogeneity

- Experimental indications
  - Nearly coherent zonal flows (radially and temporally)
  - f ~ 10 kHz for DIII-D edge parameters

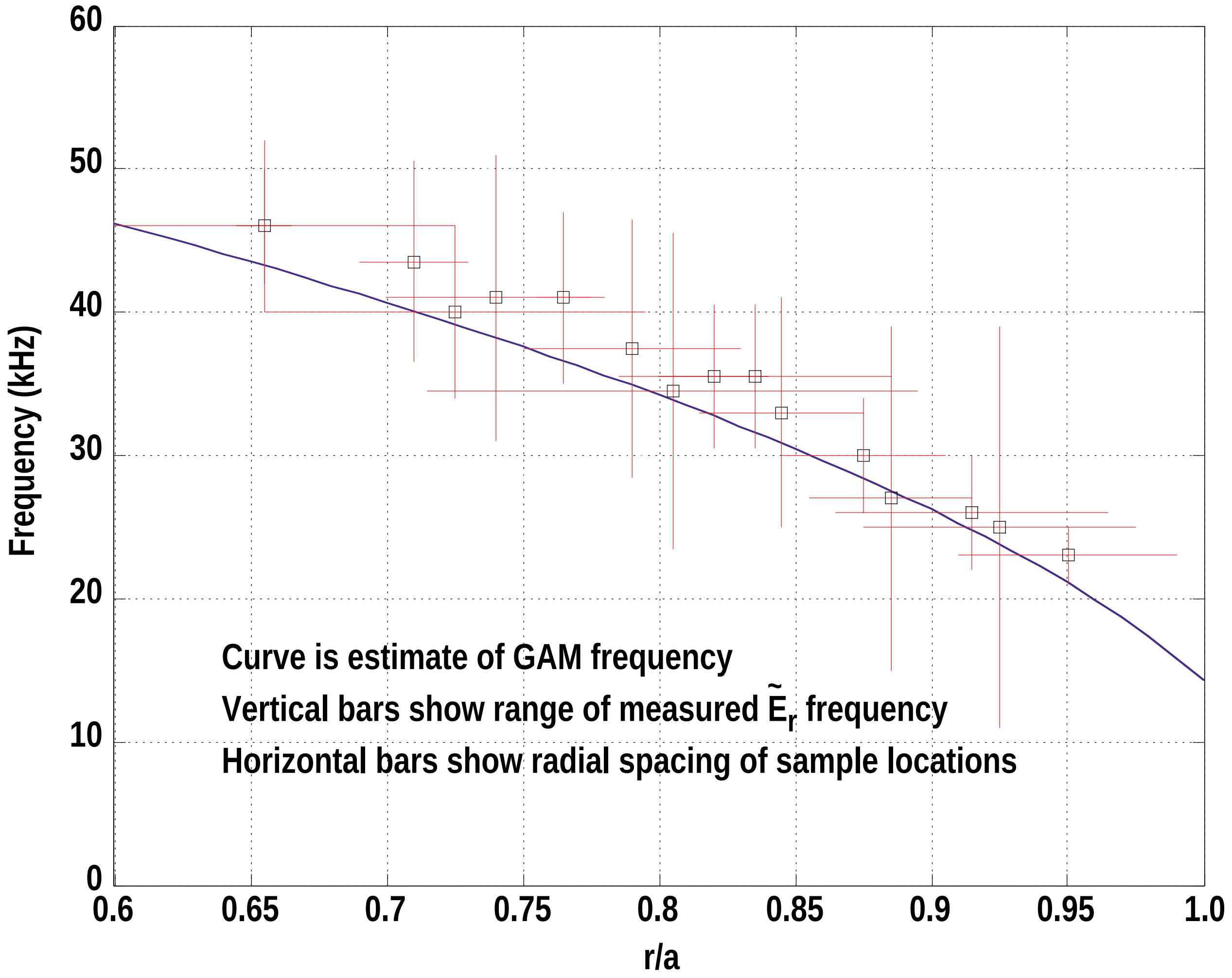
- Suggests experimental tests:
  - Dependence on ion temperature
  - Dependence on plasma shaping/curvature

HEAVY ION BEAM PROBE MEASUREMENTS OF POSSIBLE ZONAL FLOWS

- As was pointed out by P. Schoch (APS, 2001), HIBP systems on many devices (TEXT, JIPP TII-U, ISX-B) have long seen fluctuations in the 20 to 50 kHz range which were not understood
  - TEXT data indicate these may be geodesic acoustic modes

- Retrospective analysis of TEXT results from 1990 show
  - E_r fluctuations are consistent with m=0 poloidal structure
  - Correlation of these E_r fluctuations with density fluctuations is weak
  - Frequency is consistent with GAM frequency over a range of radii
  - E_r fluctuations seen only for $0.6 \le r/a \le = 0.95$ in discharges studied
  - No E_r significant fluctuations at smaller or larger radii
  - Correlation length is short, about the sample volume size

FREQUENCY OF $\tilde{E}_r$ FLUCTUATIONS IN TEXT AGREES WITH GAM FREQUENCY



P. Schoch, APS 2001

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ZONAL FLOW QUESTIONS

- Do the theoretically predicted zonal flows really exist?
  - What criteria do we use to decide that zonal flows have been observed?
- Do detailed zonal flow properties really agree with theory?
  - Why is the geodesic acoustic mode experimentally so obvious compared to the $f \cong 0$ zonal flow?
- How do we best measure the zonal flow’s properties experimentally?
  - Can we distinguish $f \cong 0$ zonal flows from mean flows?
- What are the relative roles of Reynold’s stress and Stringer-Windsor drive in various plasma regions?

POLOIDAL FLOW QUESTIONS

- What physics governs the mean poloidal flows in the plasma?

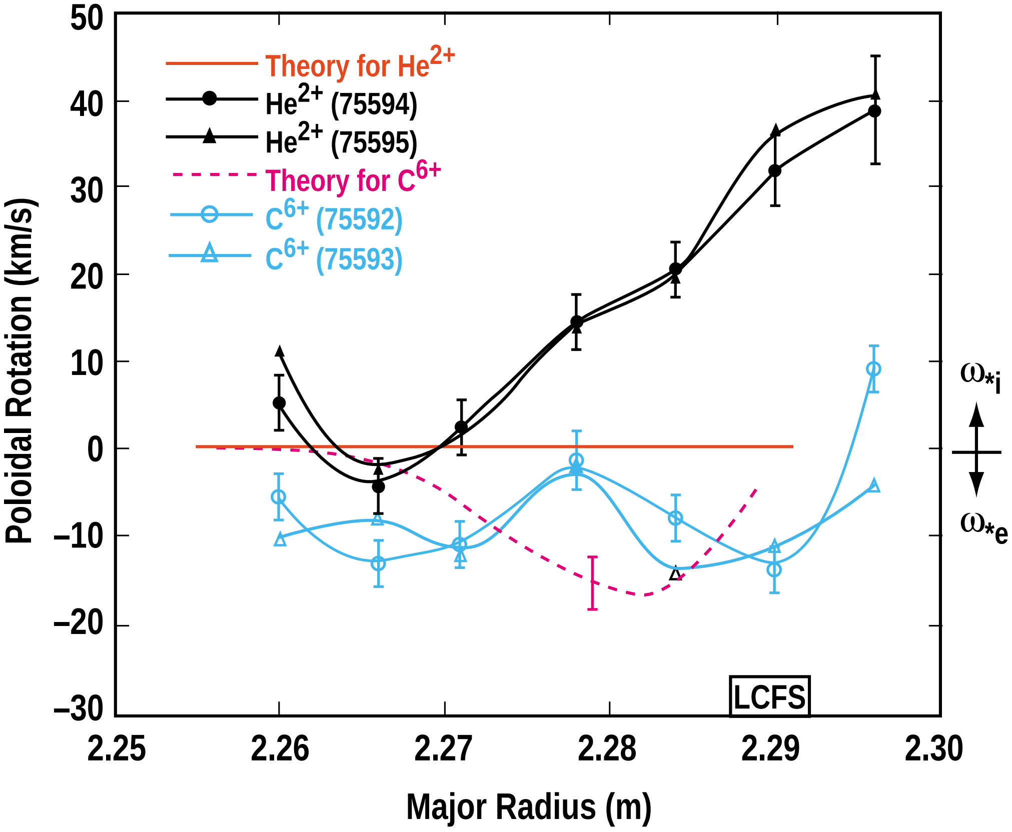
- What is the role of the physics described by neoclassical theory?
  - May need to include collisions with fast ions (W. Houlberg, 2002)

- What additional physics, if any, is needed to understand how the spontaneously generated poloidal rotation arises, for example, at the ERS transition?
  - G.M. Staebler, Phys. Rev. Lett. 84, 3610 (2000)

- How can we best test the neoclassical theory?

IN H–MODE EDGE IN DIII–D, MAIN ION AND CARBON POLOIDAL ROTATION DISAGREE WITH NEOCLASSICAL PREDICTION

- Helium plasma [I_p = 1 MA, B_T = 2T, n_e = (1–4) × 10^{19} m^{-3}]



J. Kim et al, Phys. Rev. Lett. 72, 2199 (1994)

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TOROIDAL ROTATION QUESTIONS

- What physics governs the mean toroidal flow in the plasma?
- Does neoclassical theory play any role here?
  - Even in ITB cases where the ion thermal diffusivity is neoclassical, the toroidal angular momentum diffusivity exceeds neoclassical by about a factor of 50
  - What physics must be added to that in neoclassical theory to understand this?
- How do we understand toroidal flow generation in the core of C-Mod plasmas in the apparent absence of toroidal torque?
- What role do MHD modes play in governing the toroidal plasma rotation?
  - Are MHD modes only important near beta limits?
  - How do we isolate the effects of MHD modes experimentally?

TURBULENCE AND TRANSPORT CONTROL TECHNIQUES

- What new tools can we develop to locally reduce turbulence-driven transport by altering plasma flows?
  - Present control tools (e.g. NBI) are crude and act over broad regions
  - Control is the ultimate demonstration of understanding

DIAGNOSTIC DEVELOPMENT ISSUES AND QUESTIONS

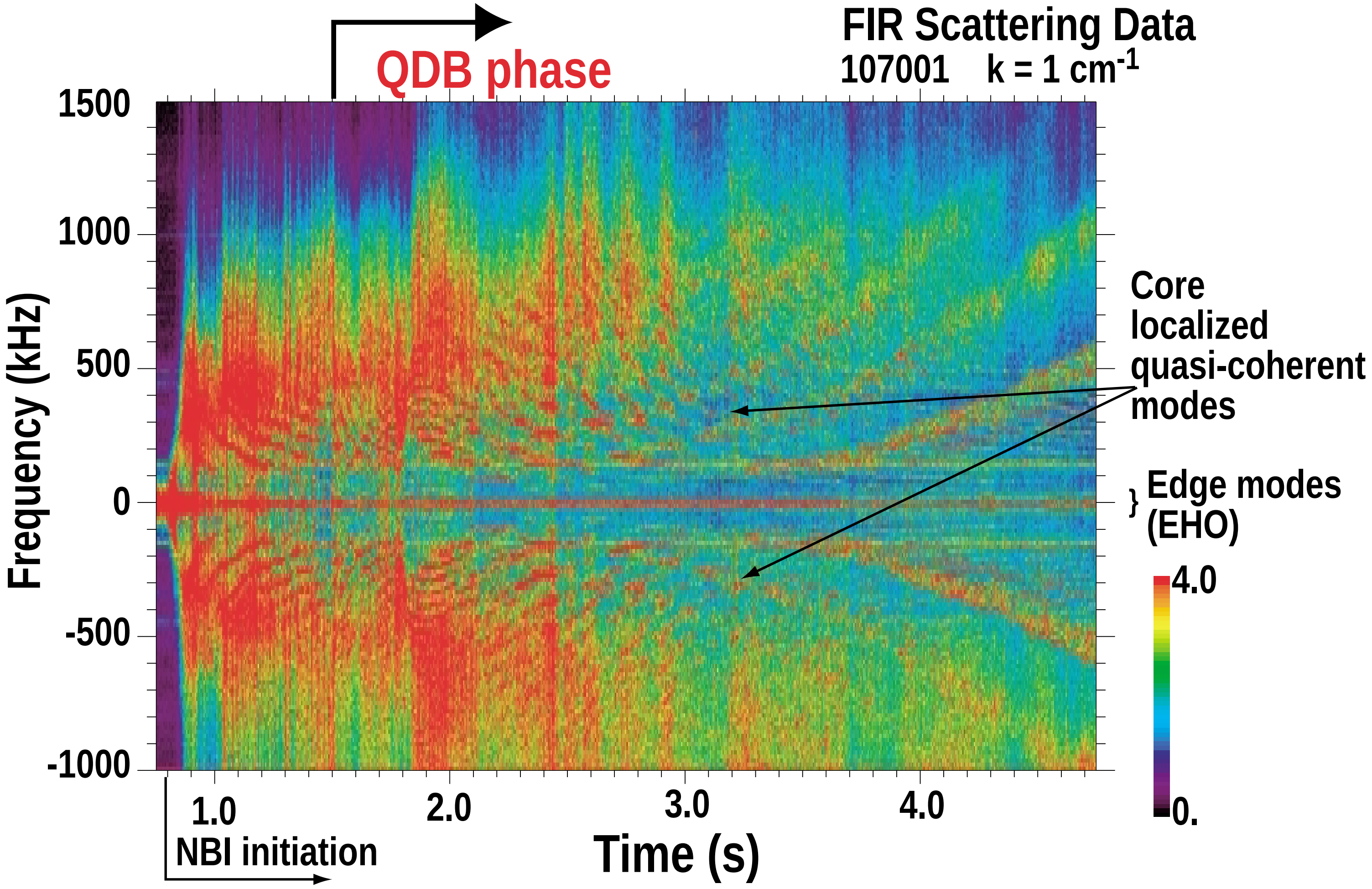
- How can we best use synthetic diagnostics from modeling codes?

- Need to develop improved experimental techniques to measure the zonal flow over wider regions of the plasma
  - Need larger poloidal and radial range
  - Improved signal-to-noise

- Must refine the analysis techniques needed to compute the gyro-orbit cross section effect on poloidal rotation measurements and then verify the calculations experimentally in order to test neoclassical poloidal rotation theory properly

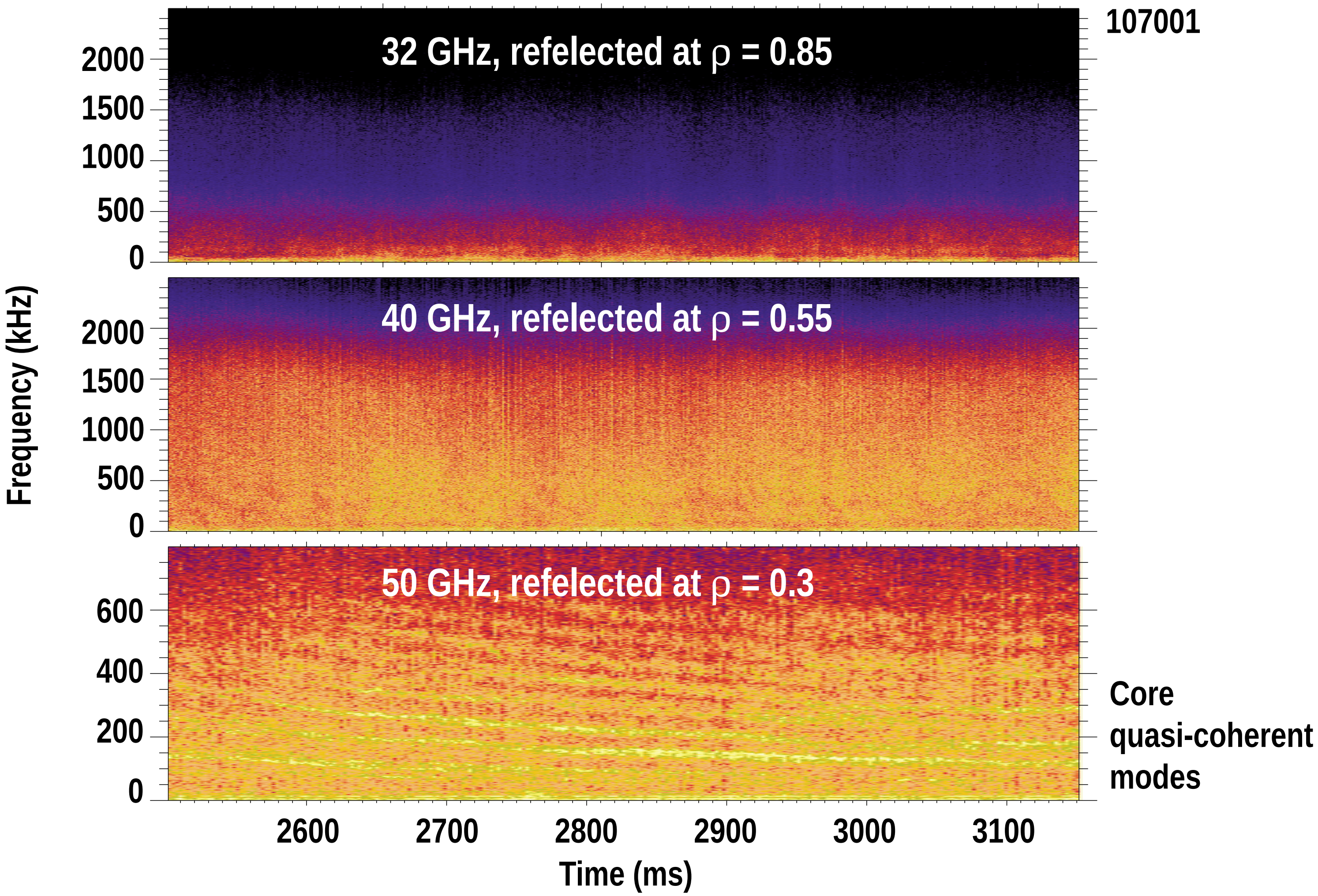
- Improve techniques to measure MHD modes (e.g., resistive wall modes and Alfvén modes) which can affect rotation

FREQUENCY SPECTRUM IN ALFVÉN FREQUENCY RANGE IS EXTREMELY RICH



REFLECTOMETER DATA INDICATE THE CORE QUASI-COHERENT MODES ARE LOCALIZED TO ρ ≈ 0.0–0.4

Frequency spectrum evolution of fixed frequency reflectrometer data



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CONCLUSION

- Plasma flows have important effects on tokamak stability and transport on spatial scales ranging from the gyro-orbit scale to the machine size
  - In many interesting cases, these flows are self-generated by the plasma

- Key open questions include theory and experimental measurements in the areas of
  - Zonal flows
  - Poloidal and toroidal rotation
  - Coupling of rotation and MHD modes