# Confinement and Transport Topical Area

by
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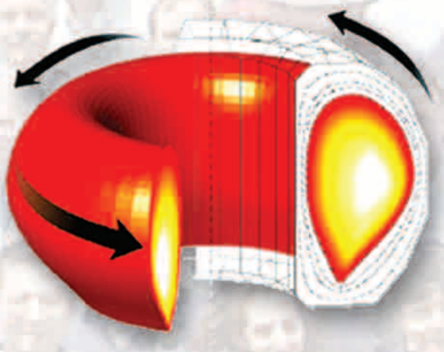
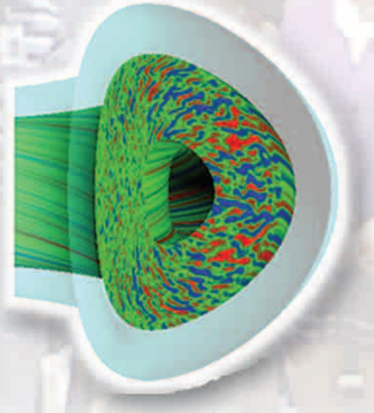


Presented to
DIII–D Program
Advisory Committee



January 31– February 2, 2006

# Long-term Goals for Confinement and Transport Topical Science Area

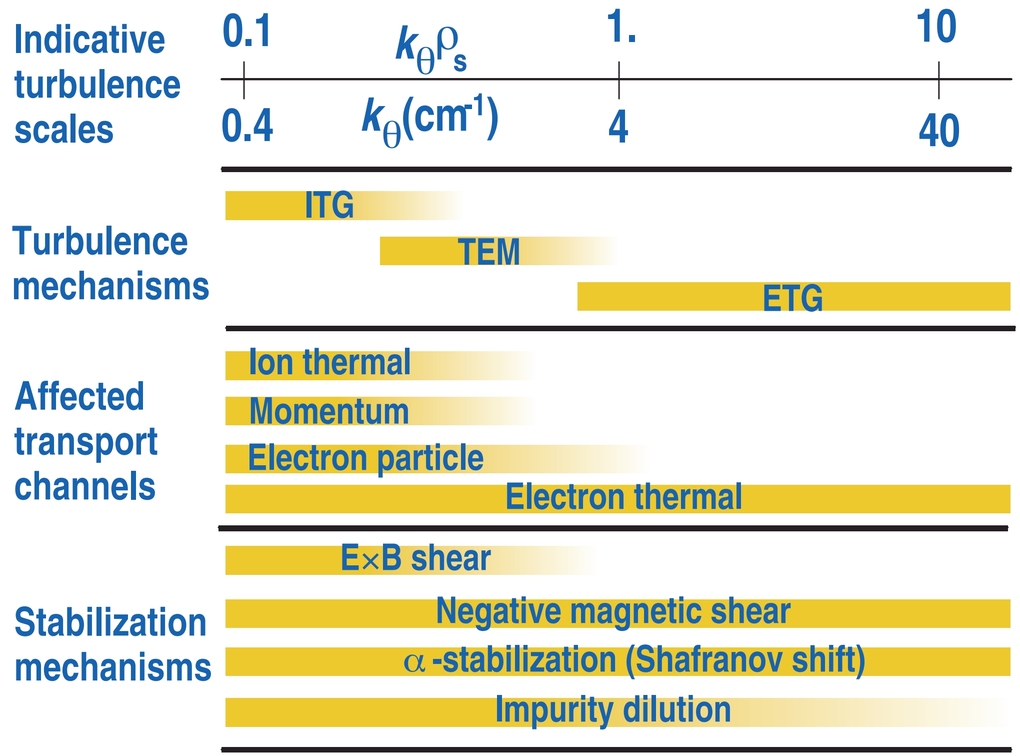
- Over-arching goal for the confinement and transport topical science area is to develop a predictive understanding of transport
- Investigate the fundamental transport physics issues that are raised by DIII–D advanced tokamak research
- Foster investigations of novel transport ideas and develop new discoveries

# Confinement and Transport Summary

- **In the DIII-D five year plan, Confinement and Transport is one of the three main foci for DIII–D research**
- **Confinement and Transport plan for 2006–2007 relies heavily on the new tools developed during the last few years**
  - Balanced beam injection
  - New fluctuation diagnostics
  - Upgraded computer cluster for GYRO runs
- **ITER-relevant experiments from ITPA list are an important part of the plan**
- **In the longer term, research leading to a predictive understanding of transport will allow the US to contribute significantly to ITER and to benefit from ITER**
  - DIII-D is playing a major role in this research

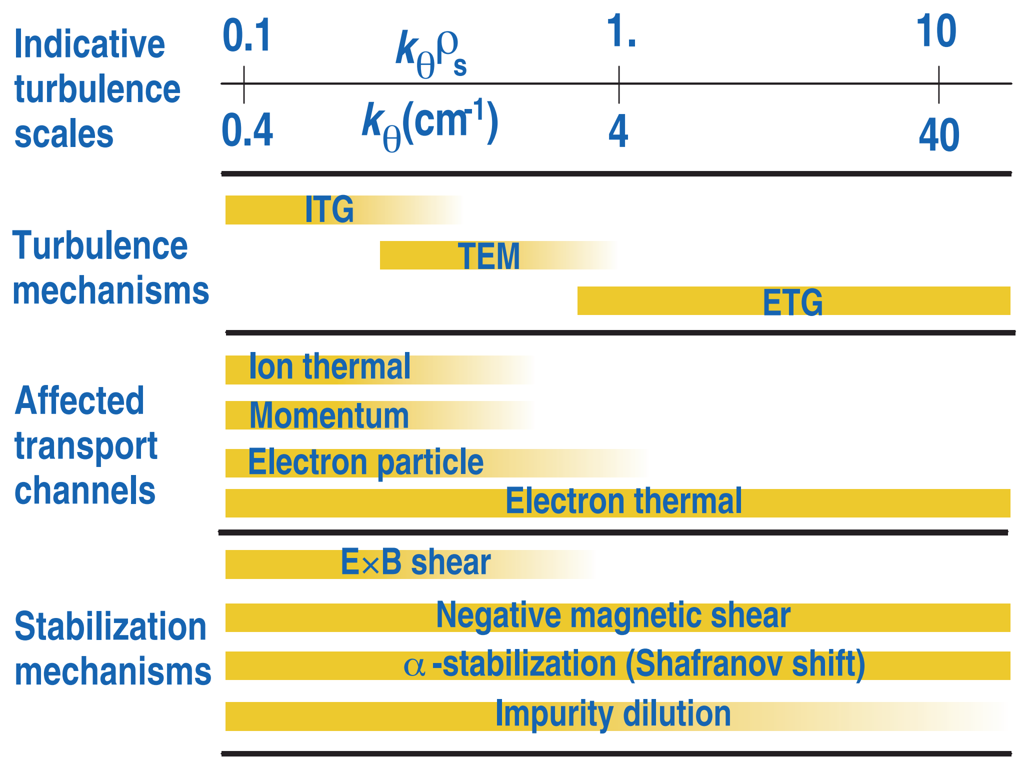
# Transport is Driven by Several Turbulence Modes with a Range of Spatial Scales

- **Ion thermal transport is affected primarily by the longer spatial scale ITG modes**
  - Frontier here is effect of zonal flows
  - New results on zonal flows and core barriers forming at integer $q_{min}$
- **Present models suggest angular momentum transport is also dominated by longer scale modes**
  - Role of torque due to radial current leads to speculation that short scale, electron processes might also be important
- **Electron thermal and particle transport can be affected by turbulence modes at all spatial scales**



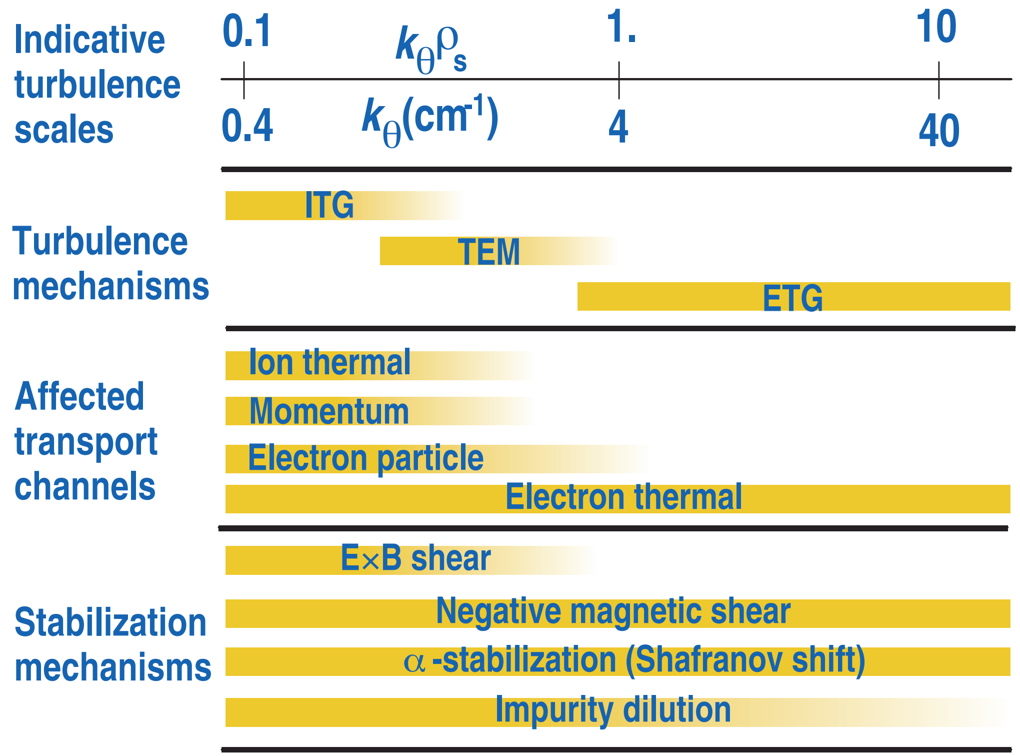
# Transport is Driven by Several Turbulence Modes with a Range of Spatial Scales

- **We have the best understanding of the ITG modes; according, the frontier for turbulence research is the shorter wavelength ETG and TEM**
- **There are several general turbulence stabilization mechanisms**
  - ExB shear affects primarily the longer wavelength modes
  - Shape effects ($\hat{s}$, $\alpha$) can affect turbulence over a broad range of spatial scales
- **This year, we finally have the tools to separately control E×B shear and shape effects**



# Transport is Driven by Several Turbulence Modes with a Range of Spatial Scales

- **Although we have a reasonable understanding of E×B shear stabilization, to apply this understanding in future devices we need a better understanding of plasma rotation**
  - A special issue here is rotation in plasmas with little or no external torque
- **E×B shear stabilization is also the key to the L to H transition**
  - We need to determine what triggers the change in E×B shear before we have a predictive understanding of the transition



# Hardware and Software Upgrades Provide New Transport Tools On DIII–D

- **Simultaneous co plus counter neutral beam injection at powers up to 10 MW**
  - Separate control on heat and torque input
  - Enables improved MSE and CER measurements

- **Improved turbulence diagnostics**
  - Turbulent density field ($0.1 \lesssim k_\perp \rho_s \lesssim 10$)
  - Turbulent velocity field ($0.1 \lesssim k_\perp \rho_s \lesssim 0.3$)

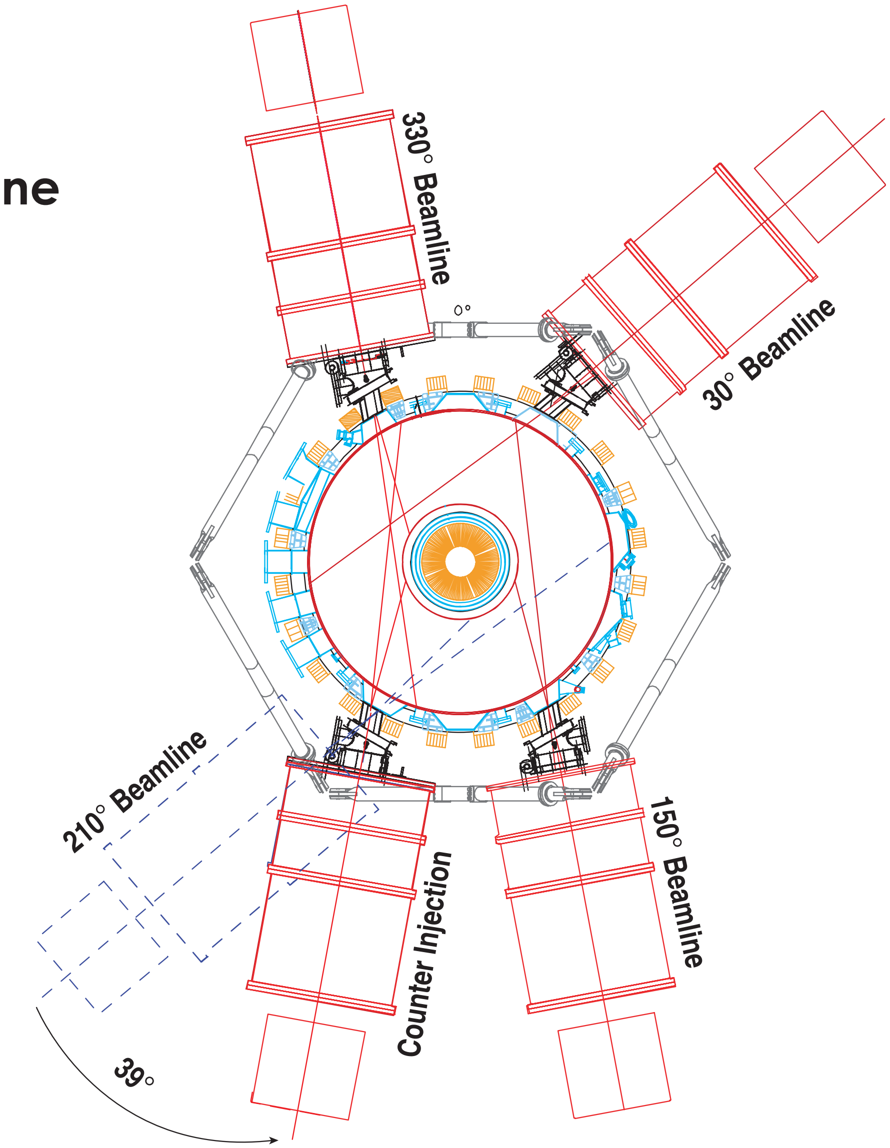
- **New high availability computer cluster**
  - Gives greatly improved throughput with GYRO

- **Additional ECH power and pulse length (6 long pulse gyrotrons)**
  - Improved modulated transport studies

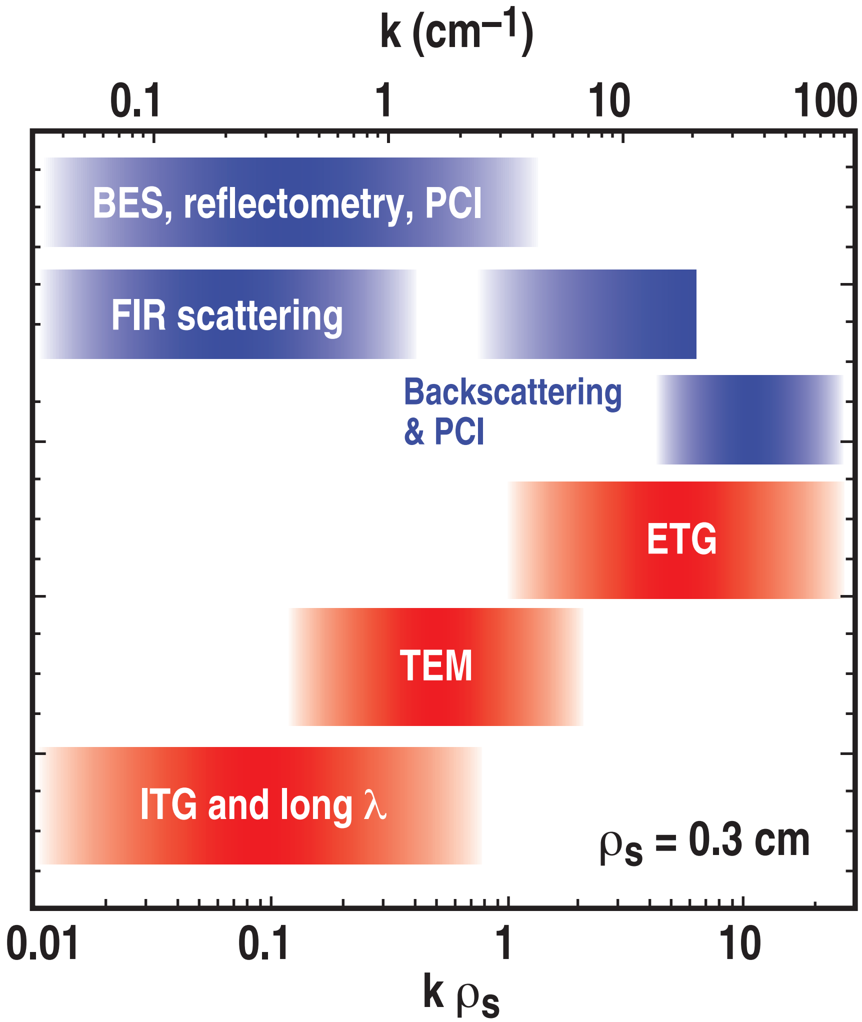
- **Divertor upgrade**
  - Density control in high triangularity discharges ($\delta \leq 1$)

# CO Plus Counter NBI on DIII–D

- Changed direction of 210° beamline so it became mirror image of 150° beamline
- Five ion sources injecting in co-direction, two ion sources counter for standard $I_p$ direction
- Balanced injection possible up to 10 MW input power

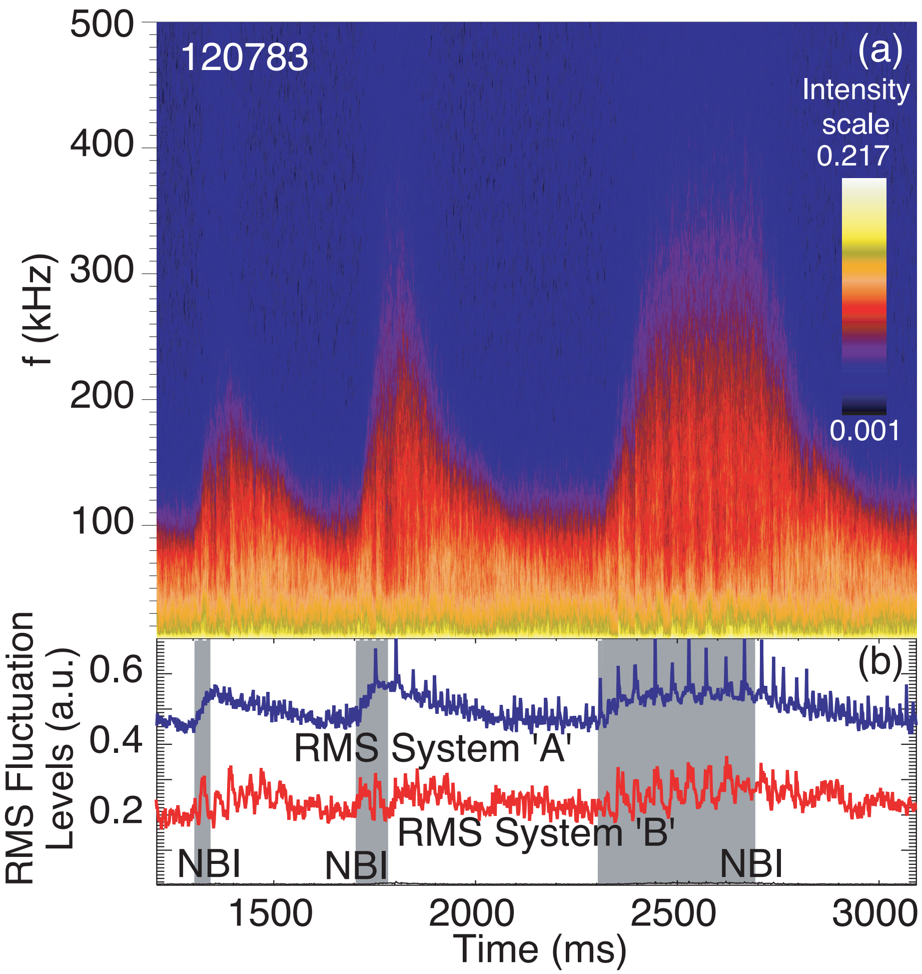


# Broad Wavenumber Diagnostic Set Being Developed at DIII–D



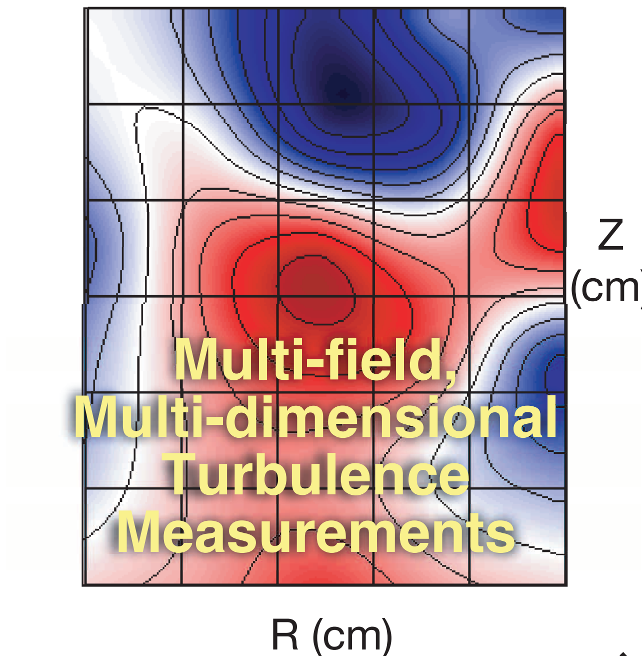

- **Wavenumber region potentially occupied by ITG, TEM and ETG type instabilities**
- **Large k-space probed by fluctuation diagnostics on DII–D**
  - — U. Wisc. beam emission spectroscopy (BES), upgraded for improved sensitivity, probes 0 - 3.5 $cm^{-1}$
  - — UCLA FIR scattering system upgraded to probe low (0-2 $cm^{-1}$) and intermediate wavenumbers (6-15 $cm^{-1}$)
  - — New concept high-k backscattering system added (~40 $cm^{-1}$) (UCLA)
  - — MIT phase contrast imaging (PCI) upgraded to probe core plasma, 0-30 $cm^{-1}$
  - — Fluctuation and correlation reflectometry probe 0-5 $cm^{-1}$

# Existence of High-k Turbulence Demonstrated in DIII–D




- **Existence of high k density fluctuations ($k \sim 35\ cm^{-1}$, $k_{\perp}\rho_i \sim 2\text{-}10$) demonstrated through direct measurements**
  - Broadband turbulent activity out to ~400 kHz, increases due to NBI (changes in $T_e$, $T_i$, $\nabla T_e$, $\nabla T_i$)
  - Coexists with lower k, higher fluctuation level turbulence

# DIII–D BES Capabilities: High-Sensitivity, 2D Density Fluctuations




Upgraded BES will provide:

$\tilde{n}(r,Z,t)$, $\tilde{v}(r,Z,t)$

at high sensitivity

**Physics Topics**

**Zonal Flows:**
- Core Zonal Flow Identification
- Geodesic Acoustic Mode
- Generation & Interaction

**Nonlinear Physics:**
- Energy cascade
- Growth rate
- Reynolds Stress

**Turbulence Imaging**
- Eddy visualization
- Velocity field turbulence

**Turbulent Particle Flux**

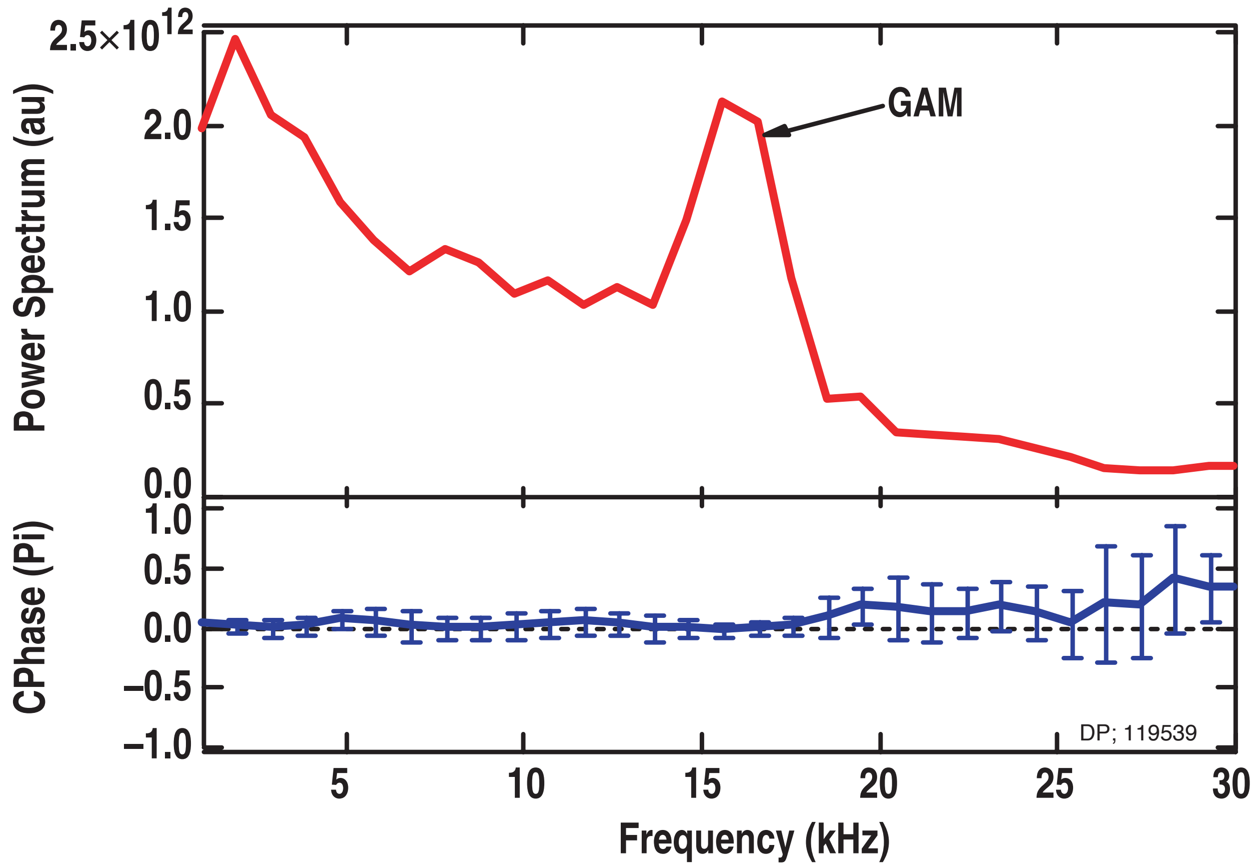
$\Gamma = \langle \tilde{n}\tilde{v}_r \rangle$

**Driving Mode Identification (TEM vs. ITG)**

# Broad Feature at Low Frequency in Poloidal Turbulence Flow is Suggestive of Zonal Flow

- Broad feature seen in power spectrum below GAM frequency
- Cross phase between distant (~4 cm) channels is zero
- Consistent with zonal flow

Poloidal velocity fluctuation spectrum at r/a = 0.80, $q_{95}$ = 8.2



# Confinement and Transport Focus Areas for 2006–2007

- **Primary foci**
  - Angular momentum transport
    - ★ Develop control of rotation with co plus counter NBI
  - Transport barrier physics and control (core and edge)
    - ★ Exploit direct control of E×B shear
  - Electron thermal transport (high k turbulence)
  - Turbulence characterization (zonal flows)
- **Secondary foci**
  - Ion thermal transport
  - Particle transport

# Developing Predictive Understanding Requires Theory-Experiment Comparison

- **Theory-experiment comparison is the sine qua non of developing predictive understanding**

- **Within the national DIII–D team, this is promoted by**
  - Including theorists, modelers and experimentalists in Confinement and Transport group meetings
  - Series of seminars in 2005 on new diagnostics and new simulation and modelling capabilities
  - Remote participation routinely available for those off-site

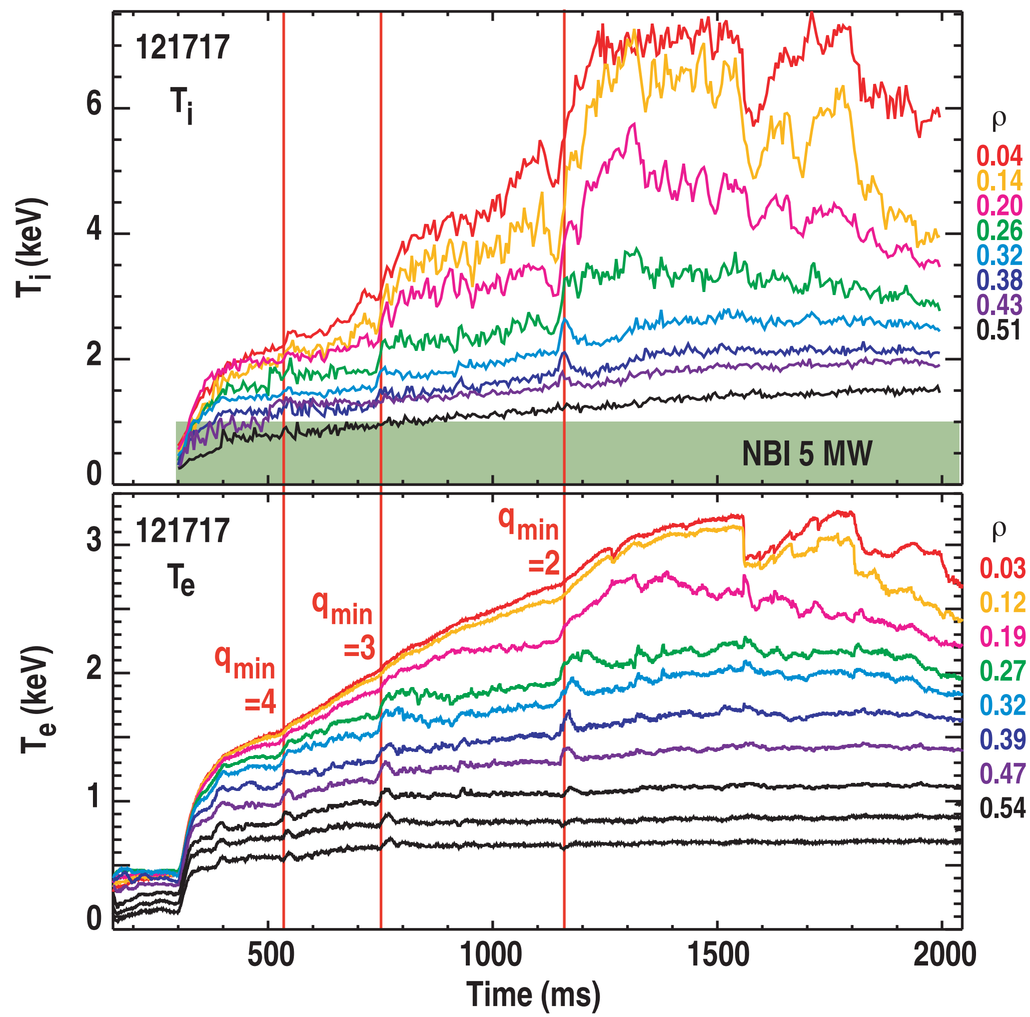
- **Nationally and internationally, members of the DIII–D team are deeply involved in the US/EU Transport Task Force and in the ITPA activities**
  - TTF has a major emphasis on code validation

# Integrated Modeling Meetings on Transport During 2005

| | | |
|---|---|---|
| 08/03/2005 | McKee | BES Capabilities |
| 08/17/2005 | Burrell | CER System Capabilities |
| 08/24/2005 | Waltz/Candy | GYRO Turbulence Predictions |
| 08/31/2005 | Holland | BES Analysis Techniques |
| 09/07/2005 | Rhodes | High k Turbulence Measurements |
| 09/14/2005 | Staebler/Kinsey | Latest GLF23 Capabilities |
| 09/21/2005 | Rost | PCI Capabilities |
| 11/09/2005 | Hinton | Zonal Flows and GAMs |

# DIII–D Experiment Investigated ITB Triggering at Low-order Rational $q_{min}$

- **Typical L-mode NCS discharge with step-wise changes in transport near integer $q_{min}$**
- **Sustained core barrier formation when $q_{min}$ is near integer requires correct input power**
  - Too little input power (e.g. 2.5 MW) produces only transient $T_e$ and $T_i$ excursions when $q_{min}$ passes through integer values
  - Too much input power (e.g. 10 MW)allows core barrier formation at a time when $q_{min}$ is well away from integer value

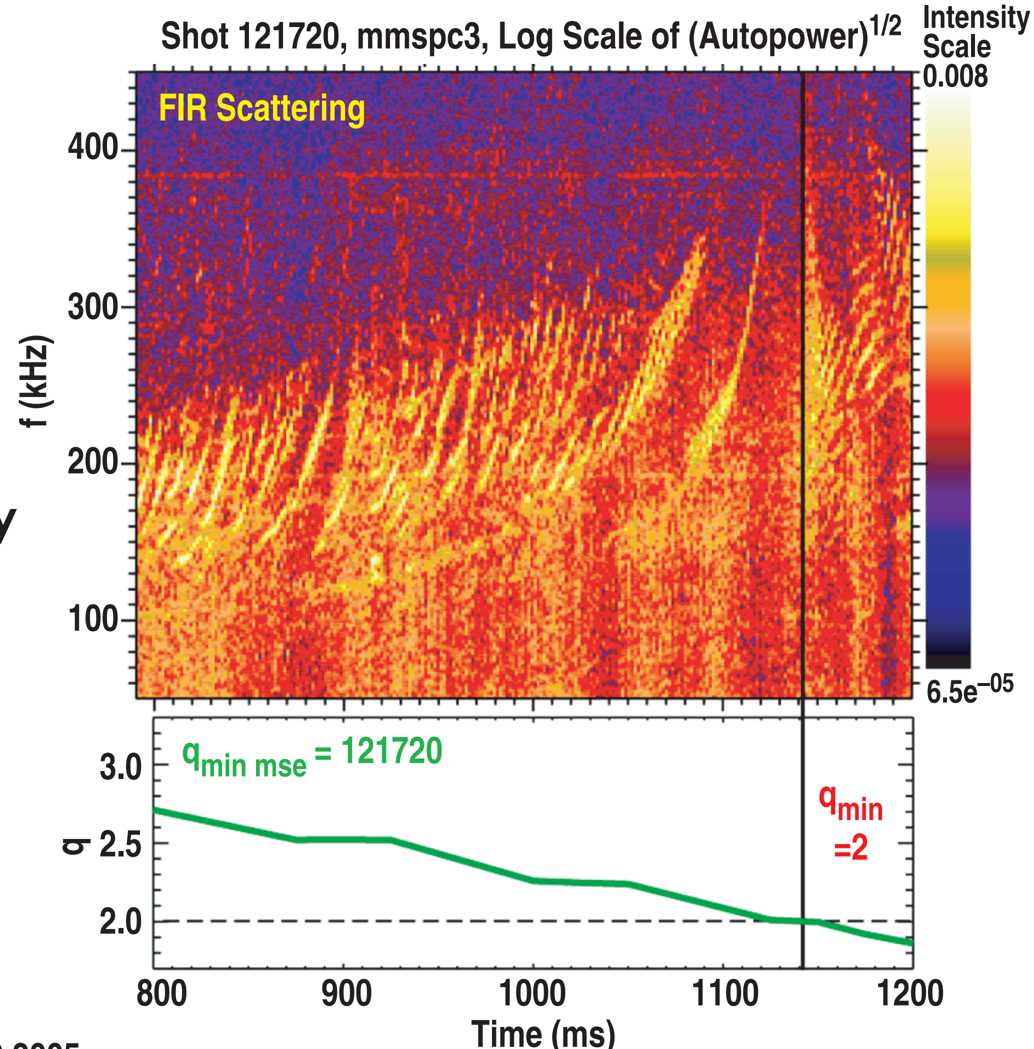



M. Austin APS 2005

# Alfvén Cascade Marks Exact Time When $q_{min}$ Reaches 2

- **FIR scattering measurements used to greatly improve accuracy of $q_{min}$ timing**

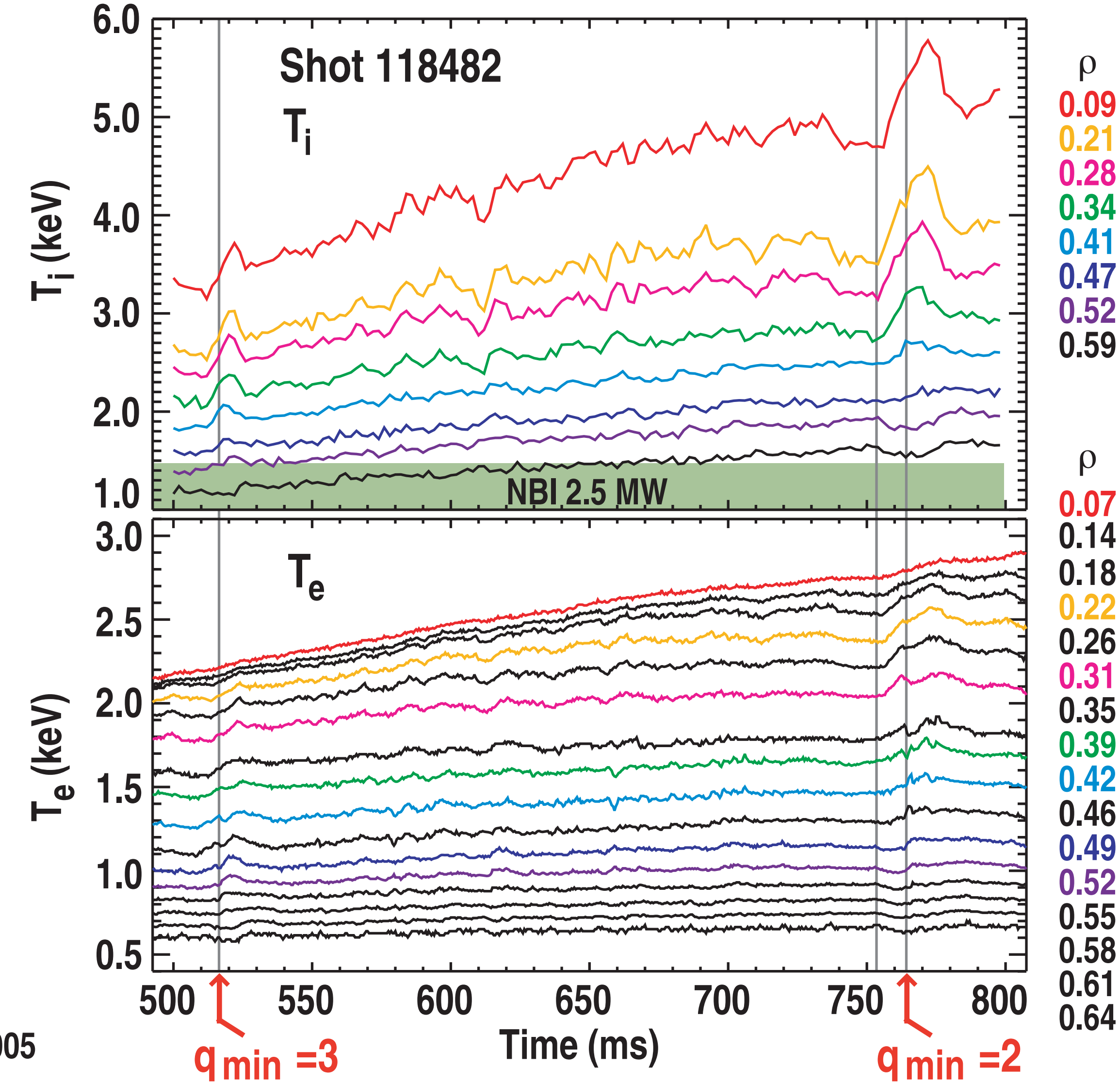
- **Alfvén mode coupled with density fluctuation diagnostic provides important suplement to MSE diagnostic**




M. Austin APS 2005

# Transport Improvement Precedes Appearance of Rational Surface

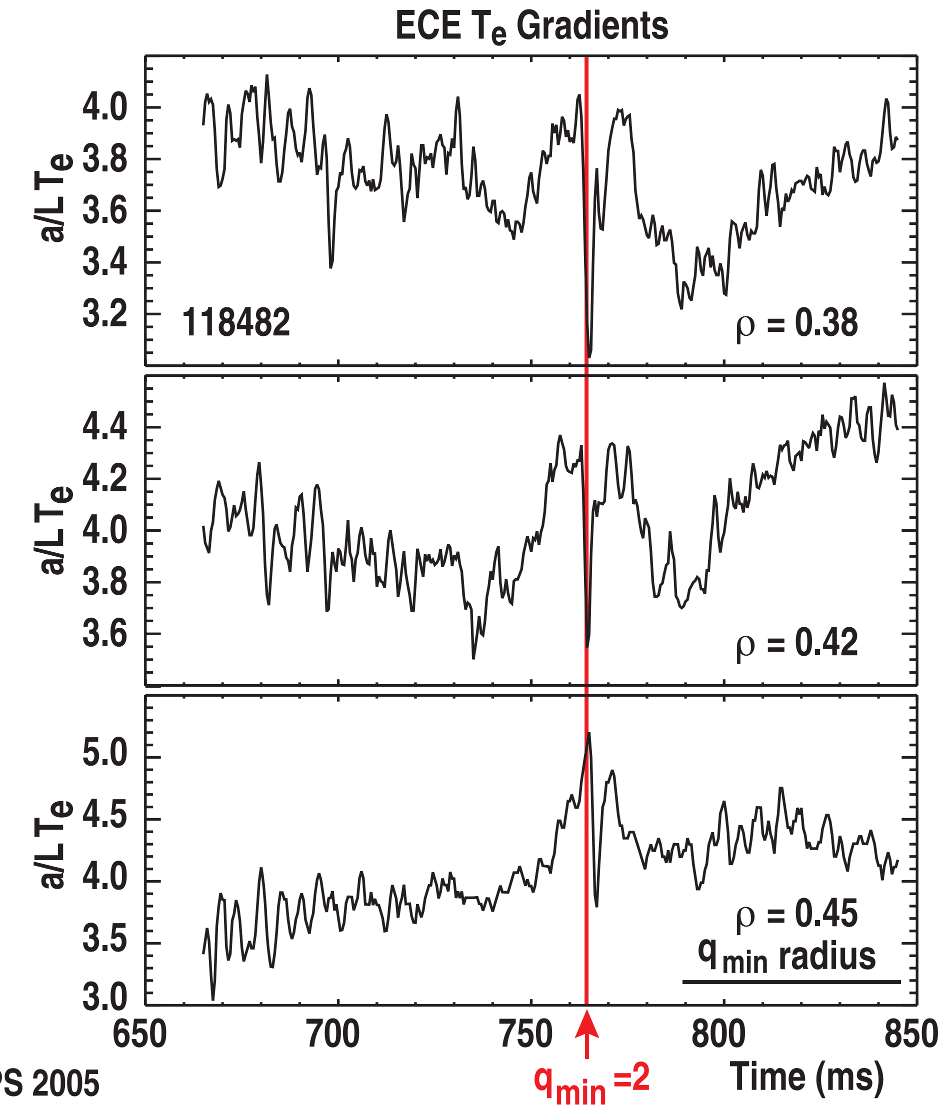
- **Lower NB power (2.5 MW) produces transient confinement improvement**
- **Temperature rise starts 10–12 ms before $q_{min}=2$**
- **$T_i$ ,$T_e$ rise continues for a similar interval afterwards**




M. Austin APS 2005

# $T_e$ Gradient Steepens Before and After $q_{min}$ = 2, Dips at $q_{min}$ = 2

- $T_e$ gradients derived from adjacent ECE channels
- Changes shown are near and just inside radius of $q_{min}$, ρ ~ 0.45
- Further evidence of transport changes preceding $q_{min}$ = 2

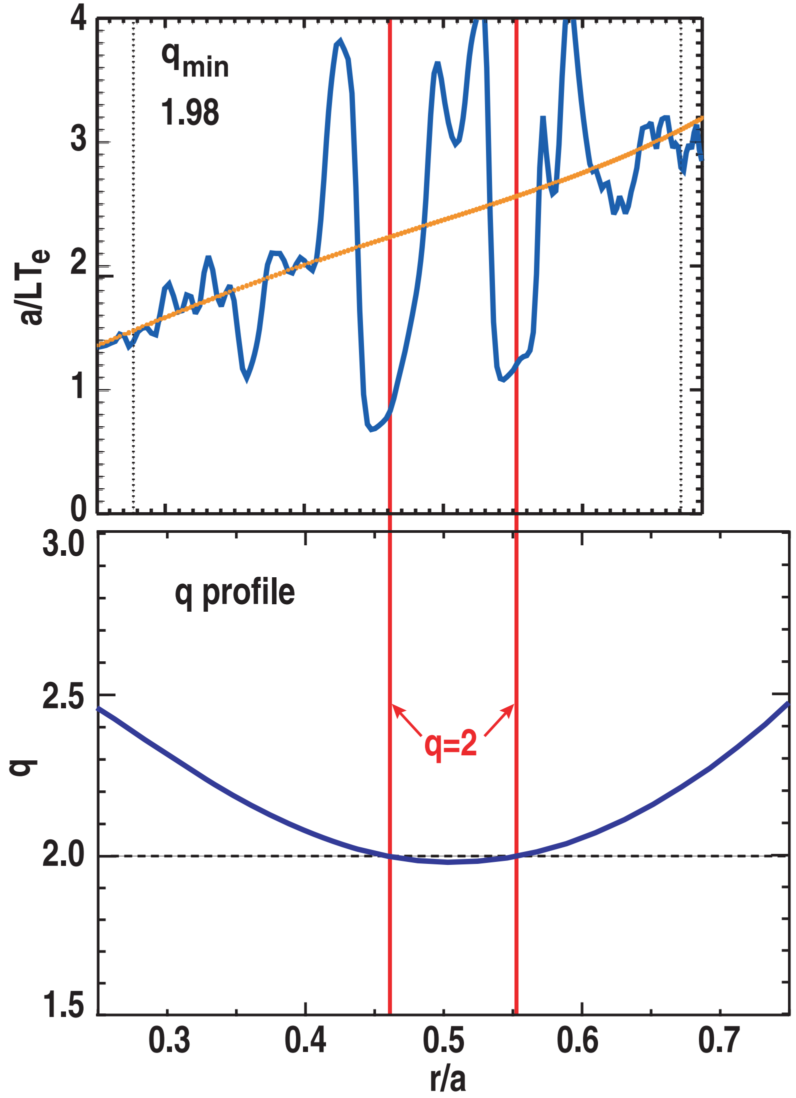



M. Austin APS 2005

# GYRO Runs Show Corrugations in $\nabla T_e/T_e$ at Low Order Rational q Values Near a $q_{min}$

- **Profiles produced in GYRO simulations have large profile corrugations tied to low order rational surfaces**

- **These corrugations correspond to the various components of the time and flux surfaces averaged n=0 zonal flows on top of to the given smooth equilibrium**

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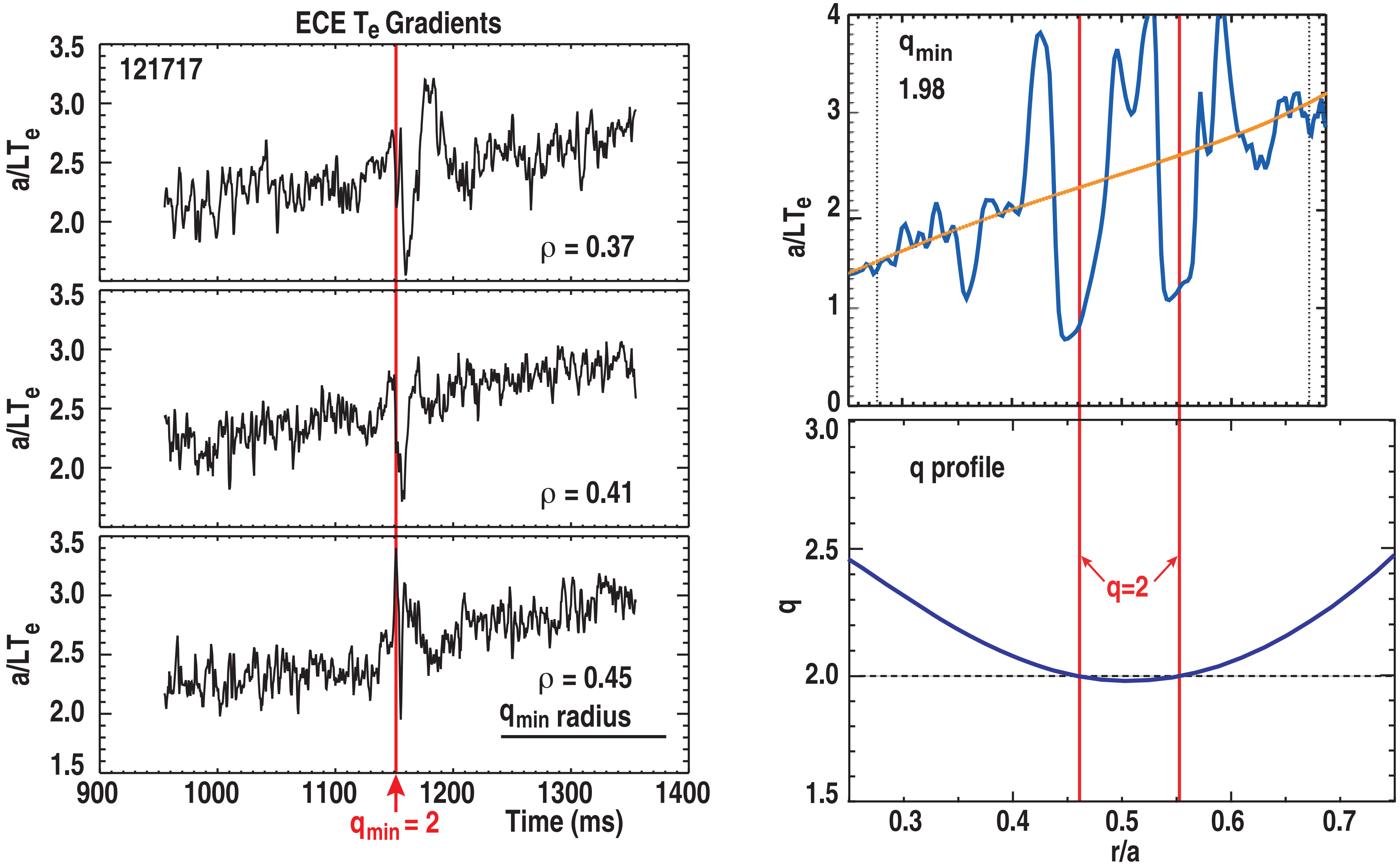
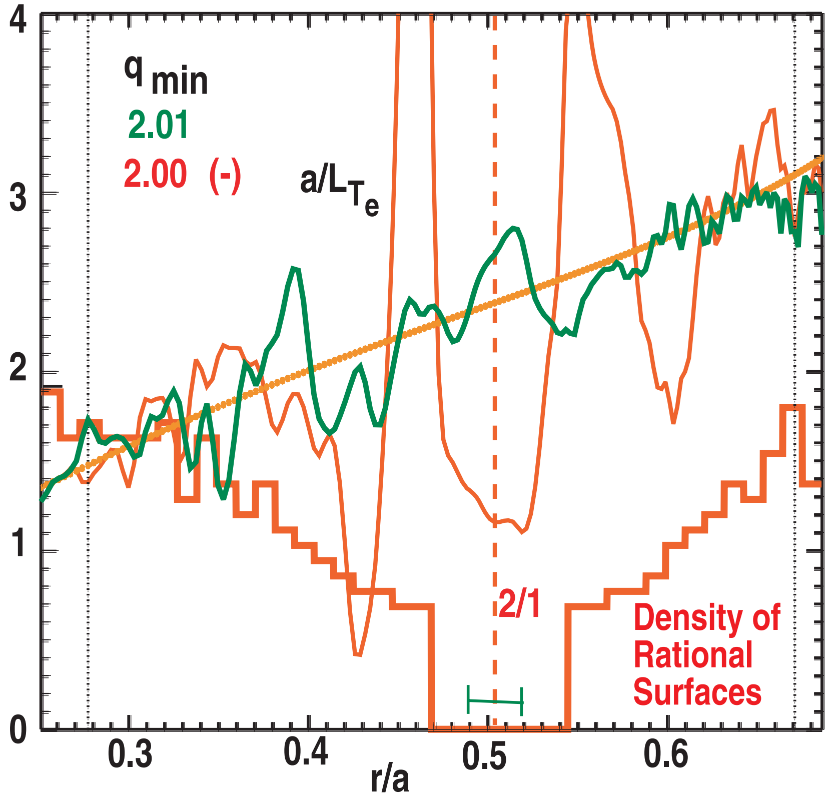
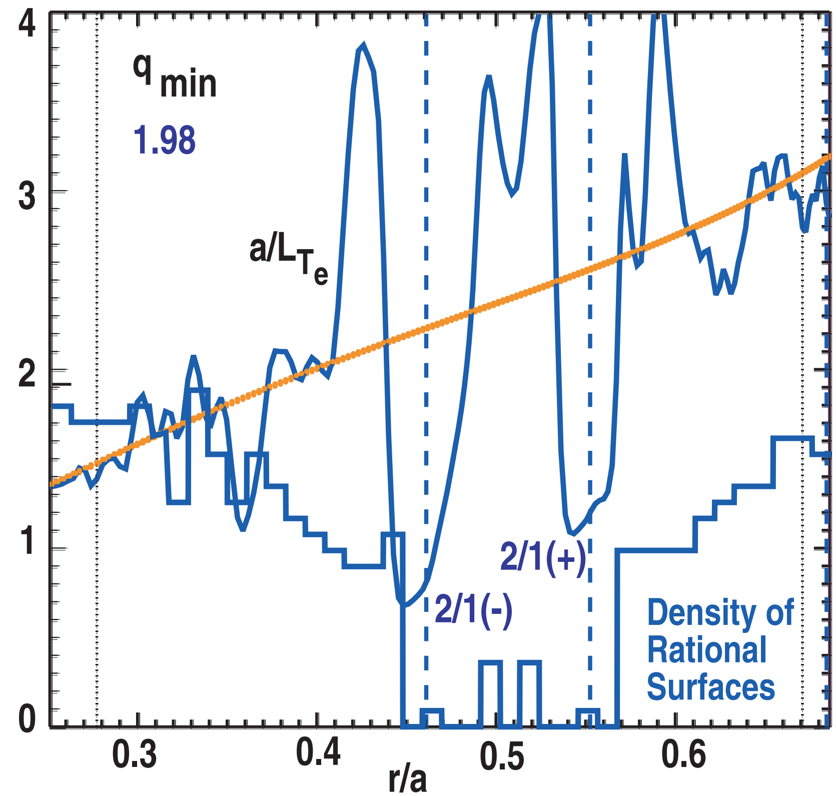
# Gyro Corrugations in Radius Should Track the Experimental Time Traces



# GYRO Results Show Profile Corrugations Are Locked to Integer q Surface

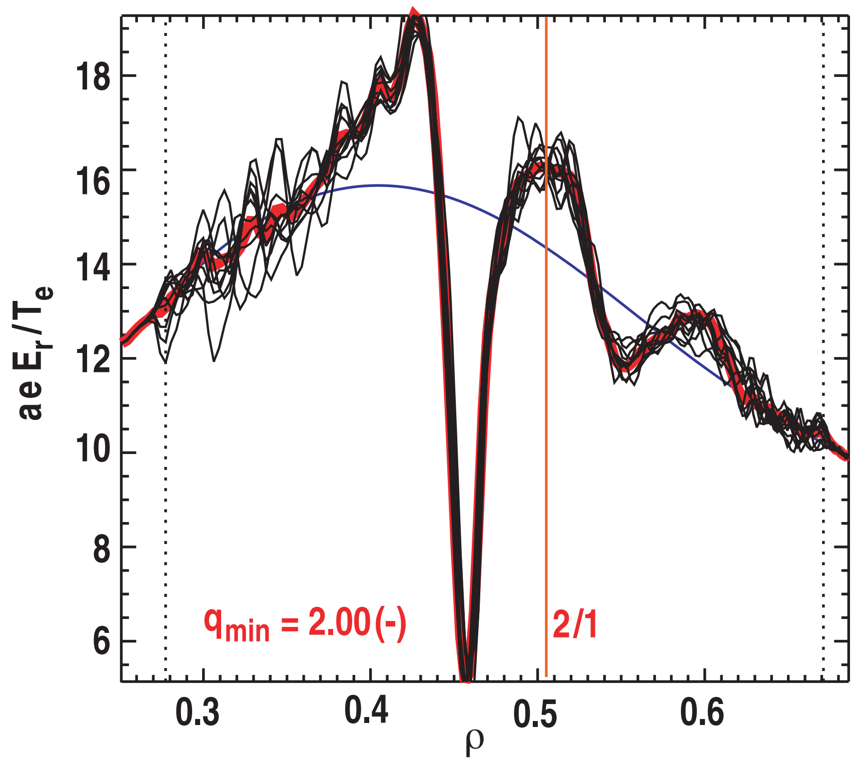
- Density of rational magnetic surfaces influences computed $T_e$ gradients
- Increased $\nabla T_e$ starts when $q_{min}$ is slightly above 2



# Zonal flow Produces Substantial Modification in $E_r$ profile

- **Equilibrium $E_r$ profile (blue) is modified by time-averaged zonal flow**
  – Black curves are snapshots every $\Delta t = 50\ a/c_s$
- **Increased E×B shear may be trigger for core ion transport barrier**



# Core Barrier Formation Involves Magnetic Field Structure, Zonal Flows and E×B shear from Slowly Evolving Radial Profiles

- **As $q_{min}$ approaches integer value, zonal flow structure grows up to significant amplitude because of low density of rational magnetic surfaces**
- **Because of low magnetic shear near $q_{min}$ in NCS discharges, this zonal flow structure has significant radial extent**
- **Oscillating E×B shear associated with zonal flows produces changes in local turbulent transport**
  - Increase in $a/L_{T_e}$ away from q = 2 location
  - Decrease in $a/L_{T_e}$ at q = 2 location
- **As $q_{min}$ continues to drop, these zonal-flow-induced changes are transient unless equilibrium E×B shear associated with background profiles is large enough**
- **Sustained core barrier is triggered by zonal flow if equilibrium E×B shear is close to that needed to stabilize turbulence**
  - Requires sufficient input power and torque
- **Key synthesis here is the realization that zonal flows are sensitive to magnetic field structure near low order rational q surfaces**
  - Provides a connection between magnetic structure and transport

# 2006–2007 Research Plan in Confinement and Transport Topical Science Area

| Working Group | Leader | Experiments |
|---|---|---|
| Shear and Rotation Control | K. Burrell | 5 |
| Fundamental Turbulence Studies | T. Rhodes | 4 |
| Core Transport Physics | J. DeBoo | 5 |
| H-mode Physics | G. Wang | 2 |
| | Total | 15 |

- Chosen from 93 proposed experiments (83 distinct proposals)

# Scientific Topics and Questions Considered in Experiments in 2006–2007: Shear and Rotation Control

- **Develop control of rotation using co plus counter NBI**
  – How does rotation change with varying momentum input at constant input power?

- **Test Waltz's GYRO-based model of core transport barrier triggering at integer $q_{min}$**
  – Does zonal flow trigger sustained core barrier only when equilibrium E×B shear is big enough?

- **Separate rotational shear and $\rho_*$ scaling effects on transport**
  – ITPA TP-6.2 and CDB-8

- **Investigate rotation in torque-free plasmas**
  – ITPA TP-6.1

- **Separate roles of E×B shear and Shafranov shift in ITB formation**

# Scientific Topics and Questions Considered in Fundamental Turbulence Experiments in 2006–2007

- **Can we experimentally separate the effects of ITG and TEM?**
  – Frequency shift discrimination in plasmas with controlled, small toroidal rotation
  – Use ECH modulation to turn TEM on and off
  – ITPA TP-7

- **Do predictions of E×B shear stabilization theory agree quantitatively with BES measurements turbulence growth rates, decorrelation rates and shearing rates?**
  – Compare GYRO results with Mach number scan with all other parameters held fixed

- **Does the magnetic shear dependence of low, intermediate and high k turbulence agree with theory?**

- **How does the damping of zonal flows measured with BES compare with the various theoretical predictions?**

# Scientific Topics and Questions Considered in Experiments In 2006–2007: Core Transport Physics

- **Does $\rho_*$ scaling to ITER give the same result at low toroidal rotation speed?**
  - ITPA CDB-8
- **How does particle transport vary with $T_e/T_i$ ratio?**
  - Test Angioni's GS-2 based prediction that ITG and TEM give different particle pinch
  - ITPA CDB-9
- **Investigate modulated ion thermal and angular momentum transport using ECH-induced modulations**
  - Investigate cross-couplings between transport channels
- **How does local transport depend on flux surface elongation?**
  - Test various elongation dependences predicted by different transport models

# Scientific Topics and Questions Considered in Experiments in 2006–2007: H–Mode Physics

- **Utilize detailed edge BES measurements across the L to H transition to determine whether zonal flows trigger the transition**
  - Manipulate edge rotation with co plus counter beams

- **Investigate effects of I-coil induced resonant edge magnetic perturbations on the L to H transition**
  - Does lack of screening of RMPs in low rotation L-mode affect power threshold?

# Fusion Physics and Long-Term ITER Needs Drive Transport Research to Same Goal

- **Transport reseach will allow the US to contribute significantly to and to benefit from ITER**
- **Developing proposals for experiments on ITER will require extensive integrated modelling**
  - Discharge development will have to be done on the computer, not on the tokamak
  - Novel operating scenarios will have to be demonstrated computationally before they are run on ITER
- **Validated predictive transport models will be an essential part of the integrated modeling codes**
  - US can contribute substantially to ITER by developing these models
- **One of the major ways the US can benefit from ITER is to come out of the project with a full suite of modelling codes suitable for fusion reactor design**
  - Transport models validated under burning plasma conditions are a key part of this

# What Can the U.S. Do to Address Burning Plasma Related Transport Issues?

- **U.S. is the world leader in all areas of transport research:**
  - Most flexible, best diagnosed facilities
  - Superior theory, modeling and simulation capabilities
  - Unmatched turbulence diagnostics
  - Opportunity for U.S. to lead ITER research in this area, but this requires focus and commitment
- **Transport provides a good mix of short and long term research possibilities**
  - Theory/simulation, modeling, turbulence and transport measurements

# While ITER Extends Operational Space, It is Not an Ideal Vehicle for Transport Studies

- **Answering BP transport questions prior to and during ITER operation will require solid base program with viable experiments**
  - Virtual non-existence of fluctuation diagnostics on ITER
  - Next step questions not addressable due to ITER's design realities
- **U.S. will need ancillary facilities to ITER for transport studies and to serve as test beds of ideas**
- **DIII–D team intends to play a major role in the U.S. effort to develop the predictive transport understanding required for ITER**

# Confinement and Transport Summary

- **In the DIII-D five year plan, Confinement and Transport is one of the three main foci for DIII–D research**
- **Confinement and Transport plan for 2006–2007 relies heavily on the new tools developed during the last few years**
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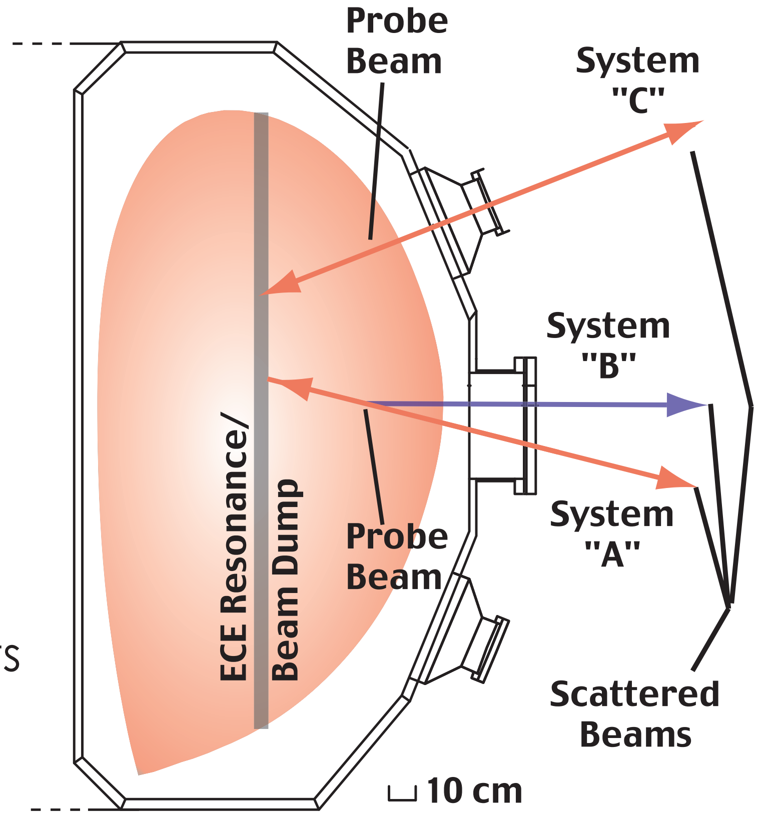
- **ITER-relevant experiments from ITPA list are an important part of the plan**
- **In the longer term, research leading to a predictive understanding of transport will allow the US to contribute significantly to ITER and to benefit from ITER**
  - DIII-D is playing a major role in this research

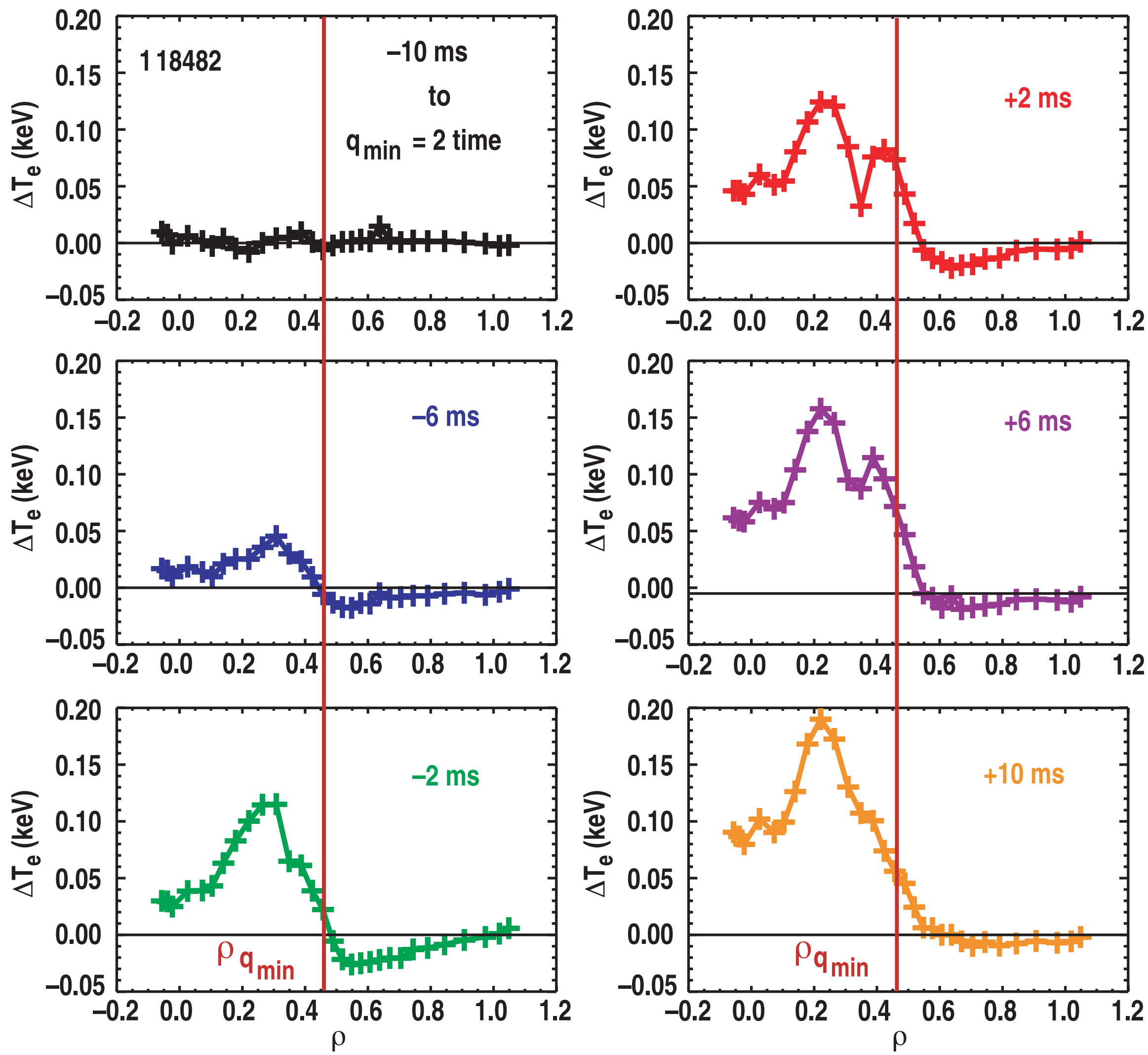
# DIII–D Experiment on High k Turbulence and Test of Models

- **Experimental goals: search for existence and behavior of high-k (ETG range) turbulence**
  - Use **new mm-wave backscatter systems** ($k \sim 35\ cm^{-1}$)
    - 3 backscatter systems: 2 at 195˚ (systems A, B) and one at 240˚ (systems C)
      - System B has better spatial resolution, ~±10 cm
- **Three experiments performed**
  - Existence of high-k turbulence and validity tests
  - Test high-k turbulence models
  - Spatial distribution of high-k turbulence



# $\Delta T_e$ Change Shows Definite Barrier Signature

- $\Delta T_e$ profiles referenced to 14 ms before $q_{min}$ = 2 time
- Dipole change in $T_e$ oberved about $q_{min}$ radius



# Localized Jump in Poloidal Velocity Occurs at $q_{min}$= 2 Trigger Event

- Observed radial variation of velocity represents very large shear
- BES measurement near Rqmin