DIAGNOSTICS FOR ADVANCED TOKAMAK RESEARCH

by
K.H. Burrell

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ROLE OF DIAGNOSTICS IN ADVANCED TOKAMAK RESEARCH

- Advanced tokamak research seeks to find the ultimate potential of the tokamak as a magnetic confinement system

- This requires innovative improvement of the tokamak concept towards
  - Higher power density
    - ★ Requires improved MHD stability
  - Smaller size
    - ★ Requires improved energy confinement
  - Steady-state operation
    - ★ Requires large fraction of self-generated (bootstrap) current to minimize current drive power

- Improved diagnostic measurements are a key aspect of this improvement
  - Essential for developing predictive understanding
  - Required as part of active feedback control of the state of the plasma

ADVANCED TOKAMAK BASICS

- In the range of densities and temperatures for planned magnetic fusion devices, increasing fusion power density requires increasing plasma pressure
  - Power density $\propto \langle p^2 \rangle \propto \beta_T^2 \; B_T^4$
  - $\beta_T = \langle p \rangle / (B_T^2 / 2\, \mu_0)$

- To achieve the plasma pressure needed for fusion, energy confinement time τ_E must be big enough that the total power P_T (fusion plus auxiliary) flowing through the plasma can produce that pressure
  - $\langle p \rangle = (2/3)\, \tau_E \, P_T$
  - τ_E depends on many plasma parameters; generally increases with size
  - Decreasing plasma energy loss allows us to achieve the needed $\langle p \rangle$ at a smaller size

- Tokamak plasmas require a toroidal current I to maintain the configuration; a portion of this is self-generated (bootstrap) provided by the plasma itself. Since current drive costs power, we want to maximize bootstrap current for steady-state operation
  - $f_{BS} = C_{BS}\, \varepsilon^{1/2}\, \beta_p$
  - $\beta_p = \langle p \rangle / (\mu_0\, I^2 / 2\, \Gamma^2)$
  - Γ is plasma poloidal circumference, $\varepsilon = a/R$ is inverse aspect ratio

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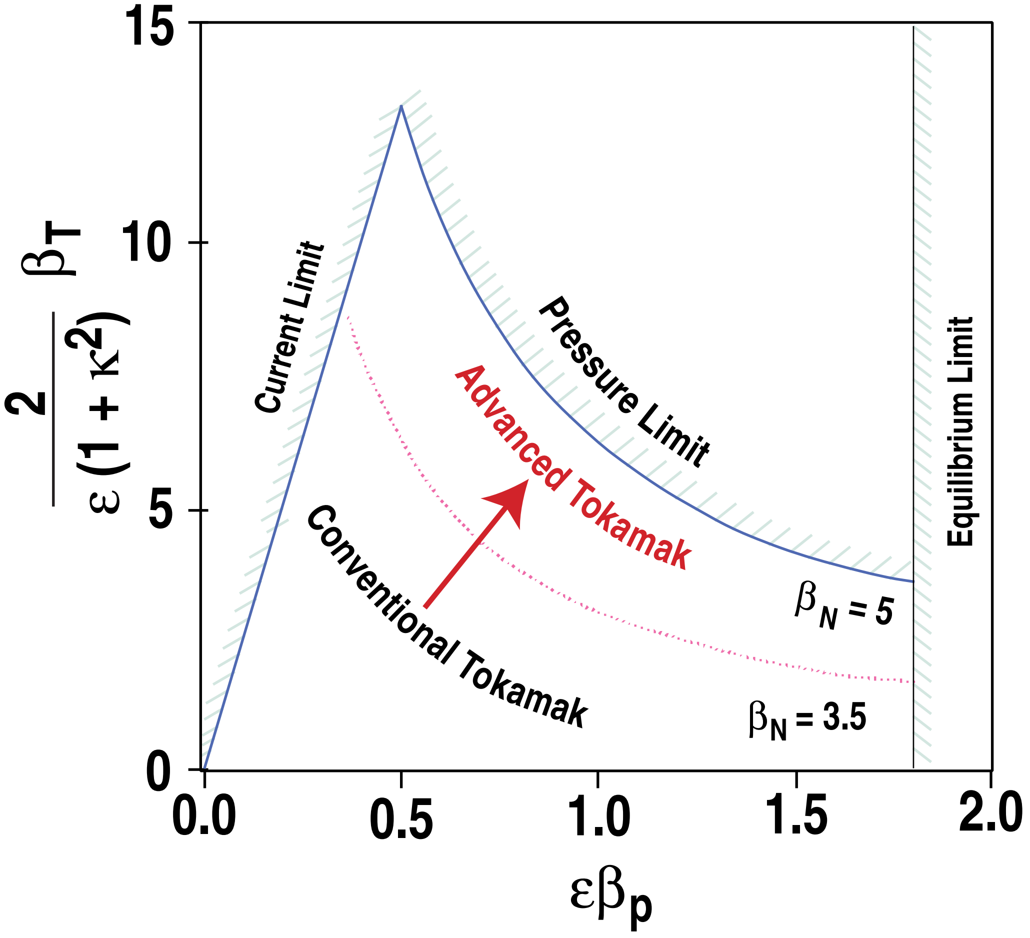
A COMPACT STEADY-STATE TOKAMAK REQUIRES OPERATION AT HIGH β_N



$$\beta_T\,\beta_p = 25\left(\frac{1+\kappa^2}{2}\right)\left(\frac{\beta_N}{100}\right)^2$$

$$\beta_N \equiv \beta_T/(\mathbf{I}/aB_T)$$

κ = vertical plasma elongation

a = plasma half-width

ε = inverse aspect ratio

TECHNIQUES FOR IMPROVING β_N

- Plasma shaping
  - Vertically elongated, somewhat triangular cross sections are much better than circles

- Current and pressure profile control
  - Broad pressure profiles give higher β_N
  - Broad or hollow current profiles required for alignment with bootstrap current and provide access to second stable regime for ballooning modes in plasma core

- Wall stabilization
  - Feedback control required to compensate for finite resistivity of wall material

Advanced tokamak optimization is profile optimization

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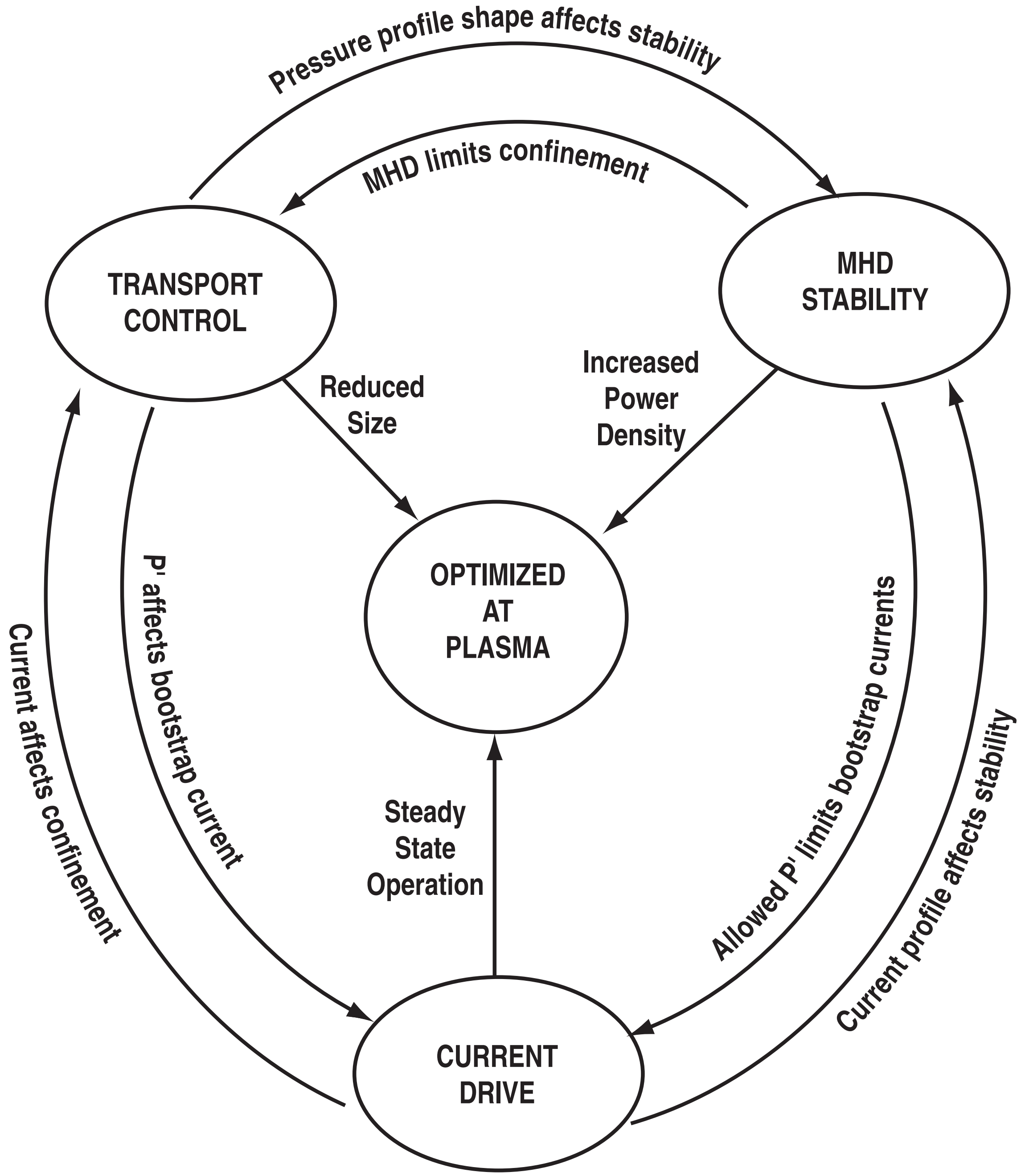
MULTIPLE INTERACTIONS MAKE ADVANCED TOKAMAK OPTIMIZATION A GRAND CHALLENGE



Pressure profile shape affects stability

MHD limits confinement

TRANSPORT CONTROL

MHD STABILITY

Reduced Size

Increased Power Density

OPTIMIZED AT PLASMA

P' affects bootstrap current

Current affects confinement

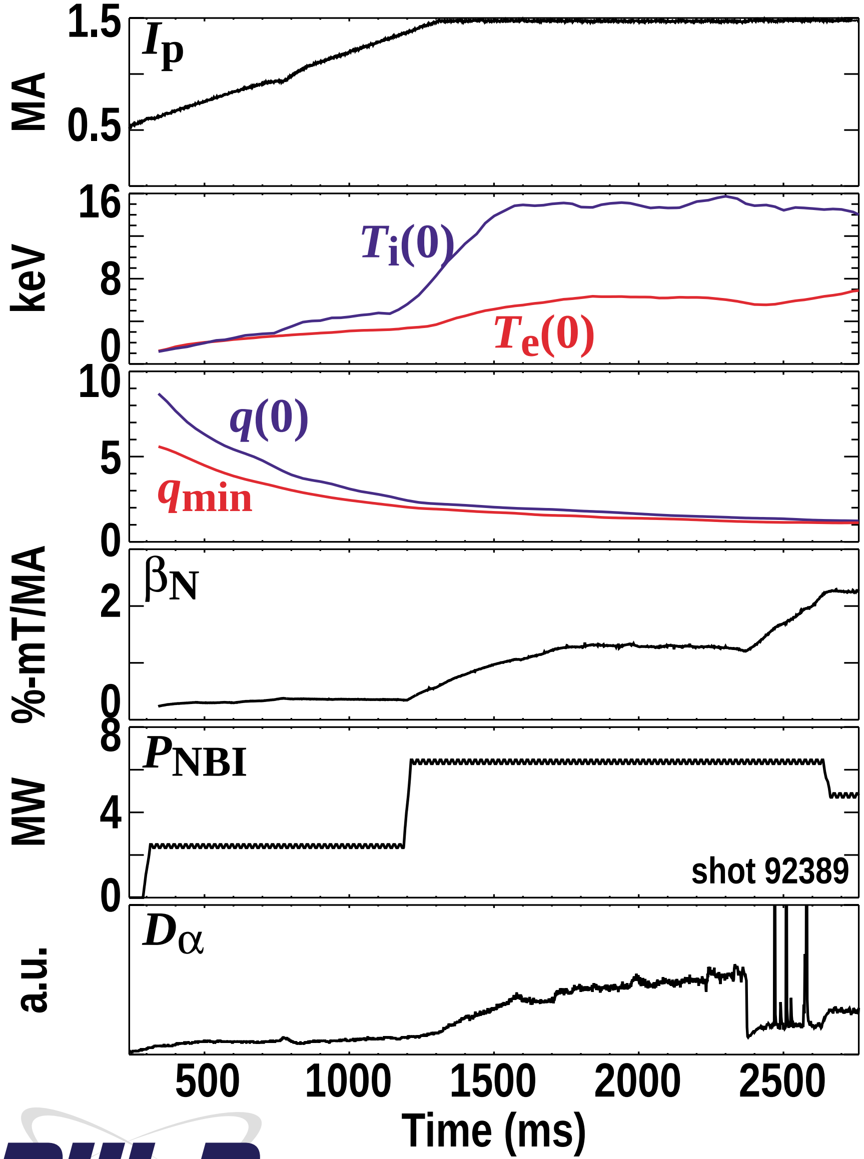
Steady State Operation

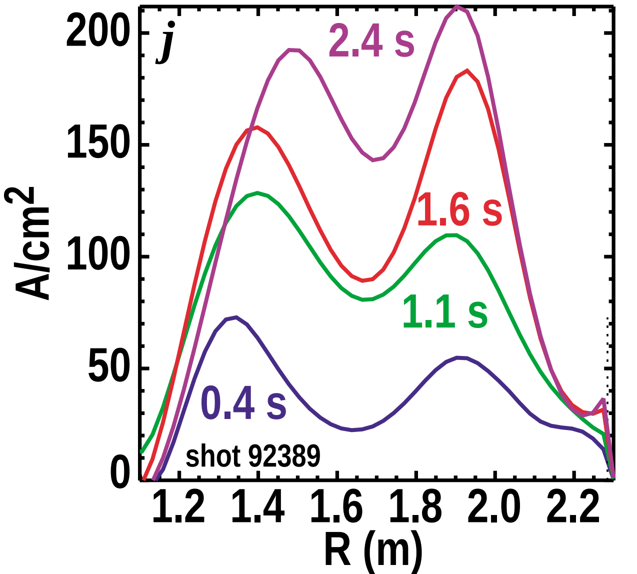
Allowed P' limits bootstrap currents

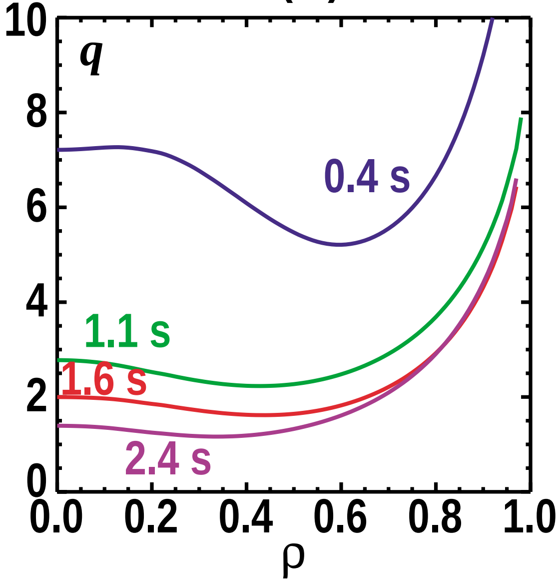
Current profile affects stability

CURRENT DRIVE

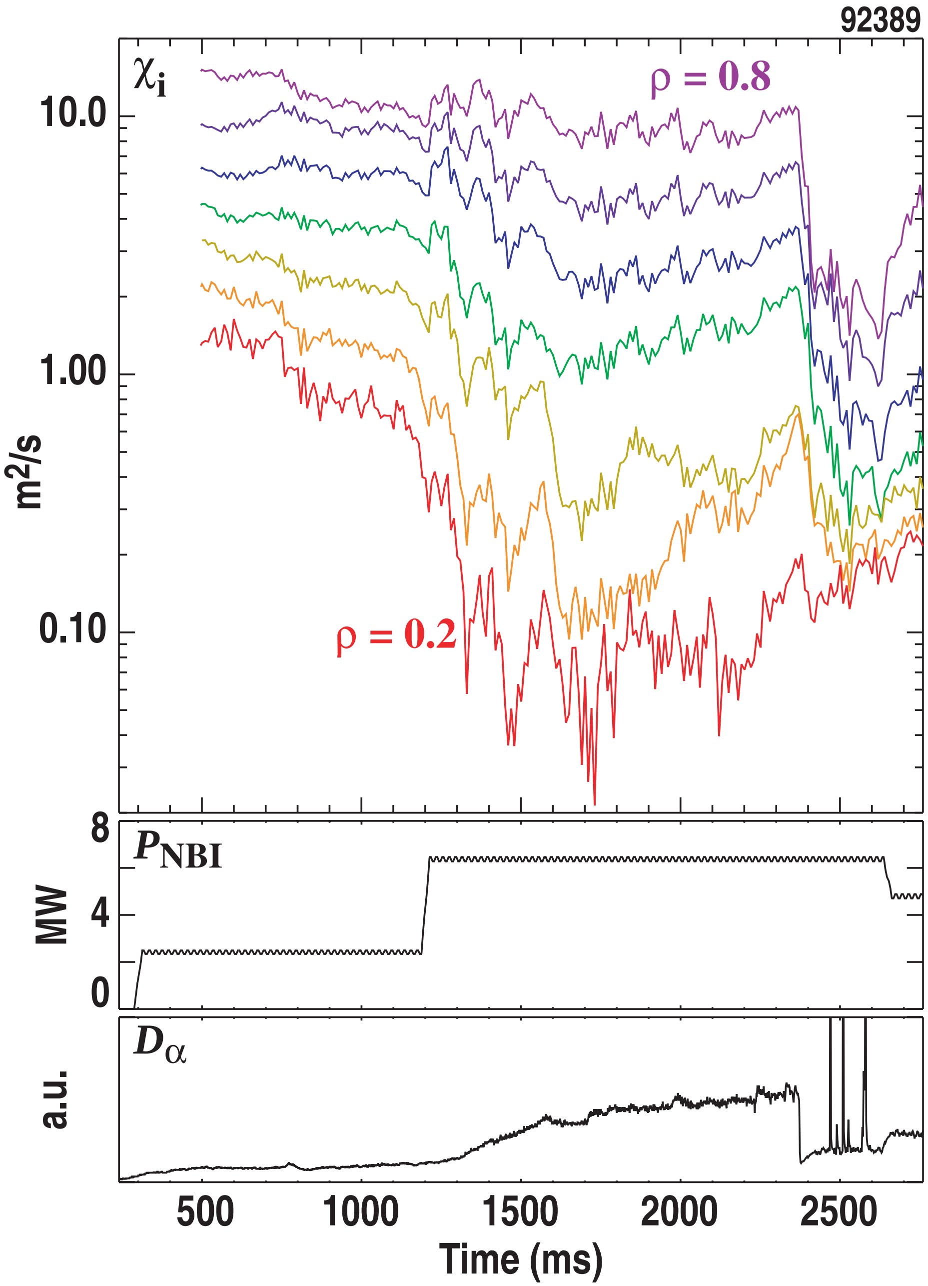
MSE MEASUREMENTS ALLOW DETERMINATION OF CURRENT DENSITY AND q PROFILES IN I_p RAMP EXPERIMENTS







COMPLETE SET OF TIME DEPENDENT PROFILES NEEDED TO STUDY TRANSPORT REDUCTION



- **Profile diagnostics**

n_e: Thomson scattering, interferometry, reflectometry

T_e: Thomson scattering, ECE

T_i, v_ϕ, n_I: Charge exchange spectroscopy

- **Ion transport reduced to neoclassical level in best cases**

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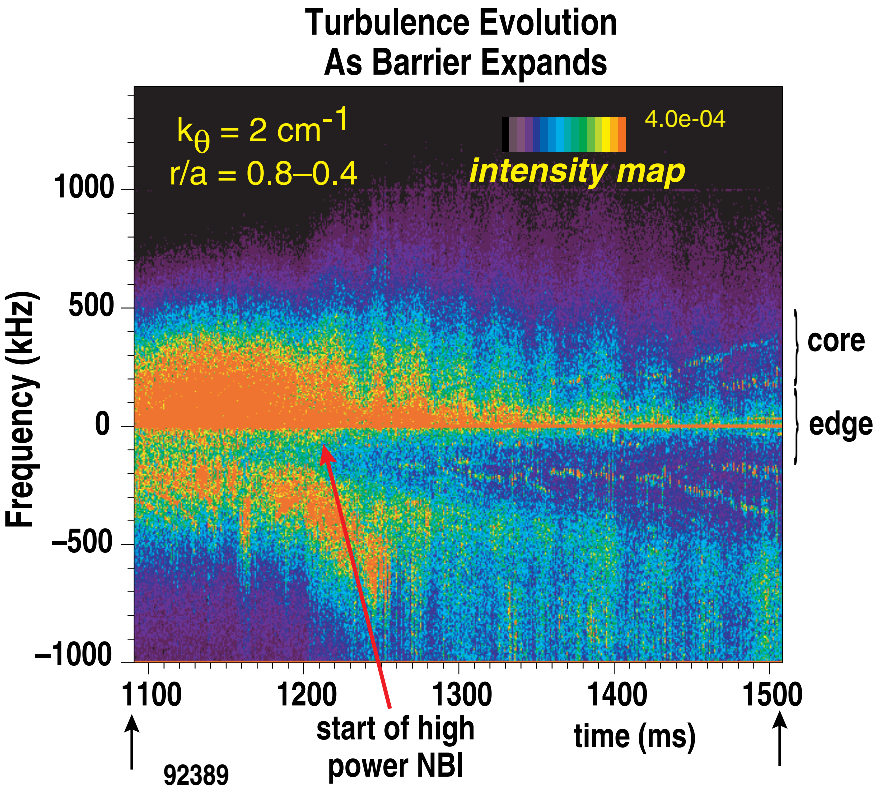
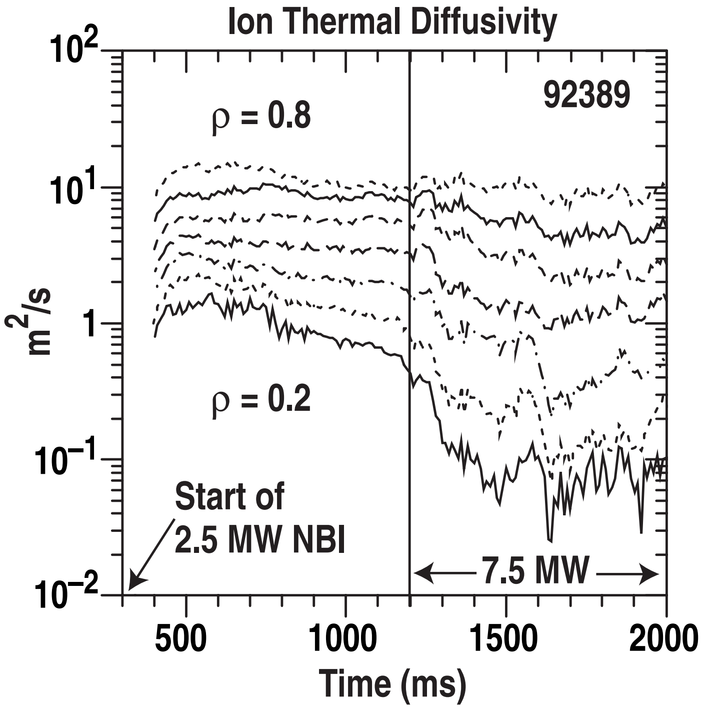
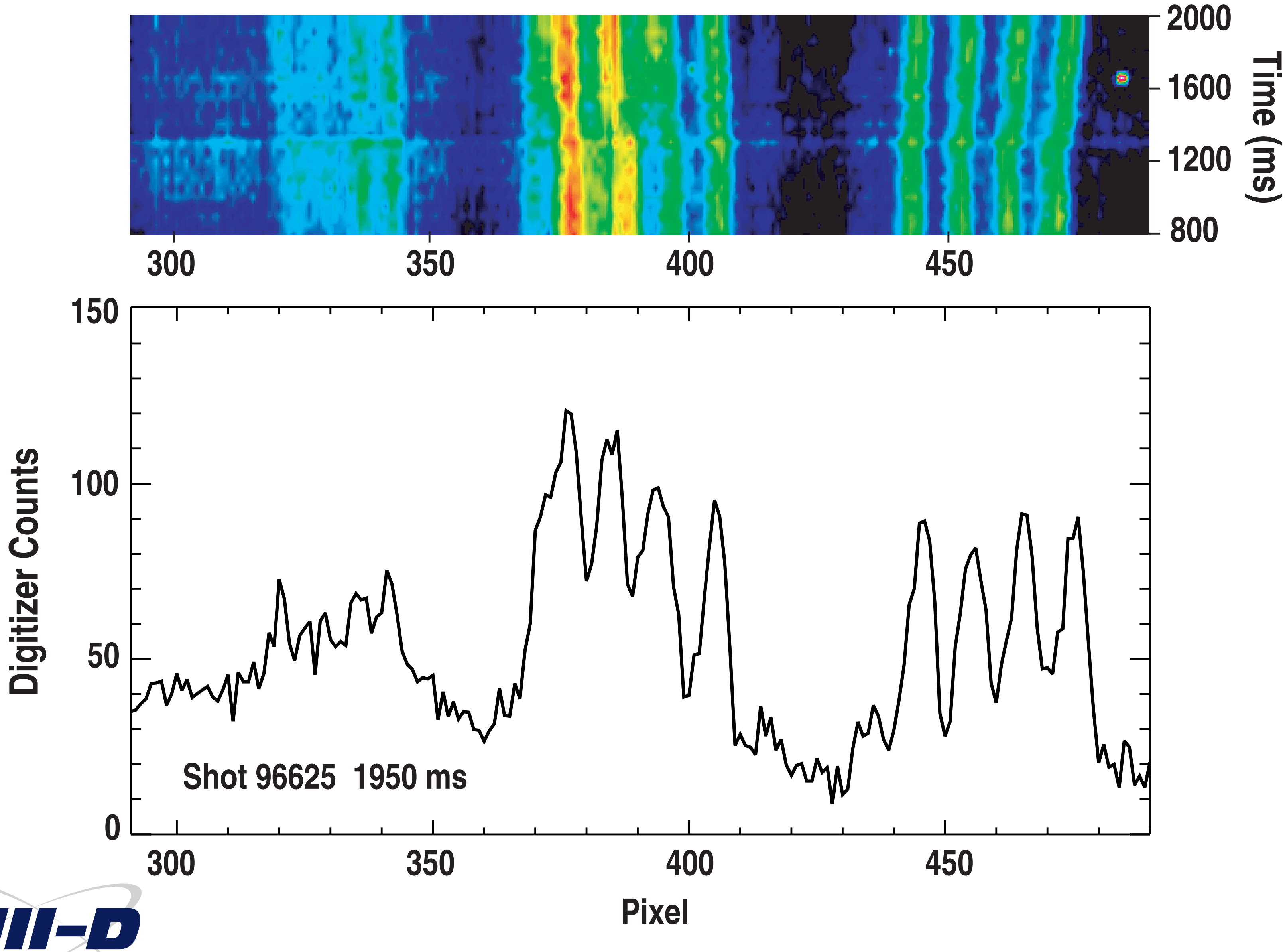
CORE TURBULENCE DROPS AS TRANSPORT DECREASES AFTER INPUT POWER INCREASE


Turbulence Evolution As Barrier Expands


Ion Thermal Diffusivity

- Fluctuation diagnostics used at present in tokamaks: BES, FIR scattering, Langmuir probes, PCI, reflectometry

STARK SPLITTING OF D_β FROM BEAM COMPONENTS VARIES IN TIME SHOWING SENSITIVITY TO $|B|$ CHANGES



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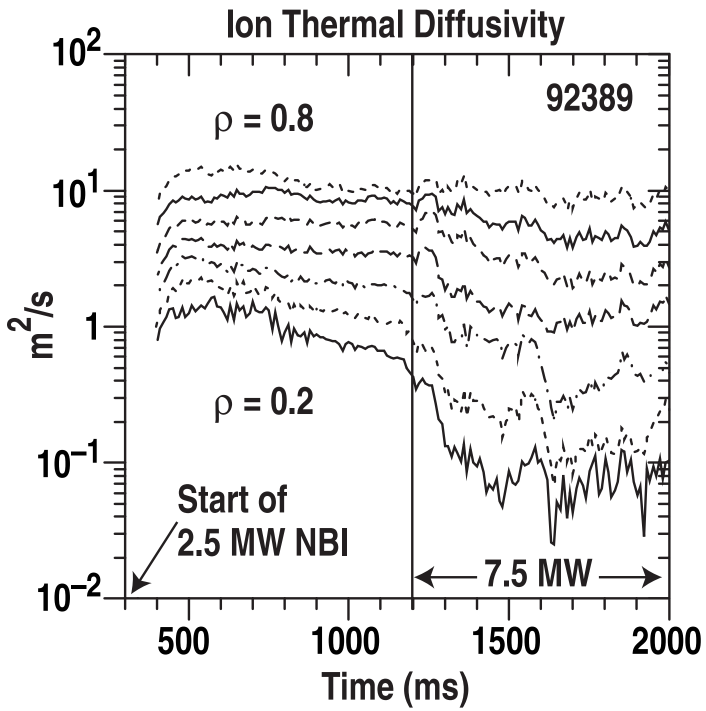
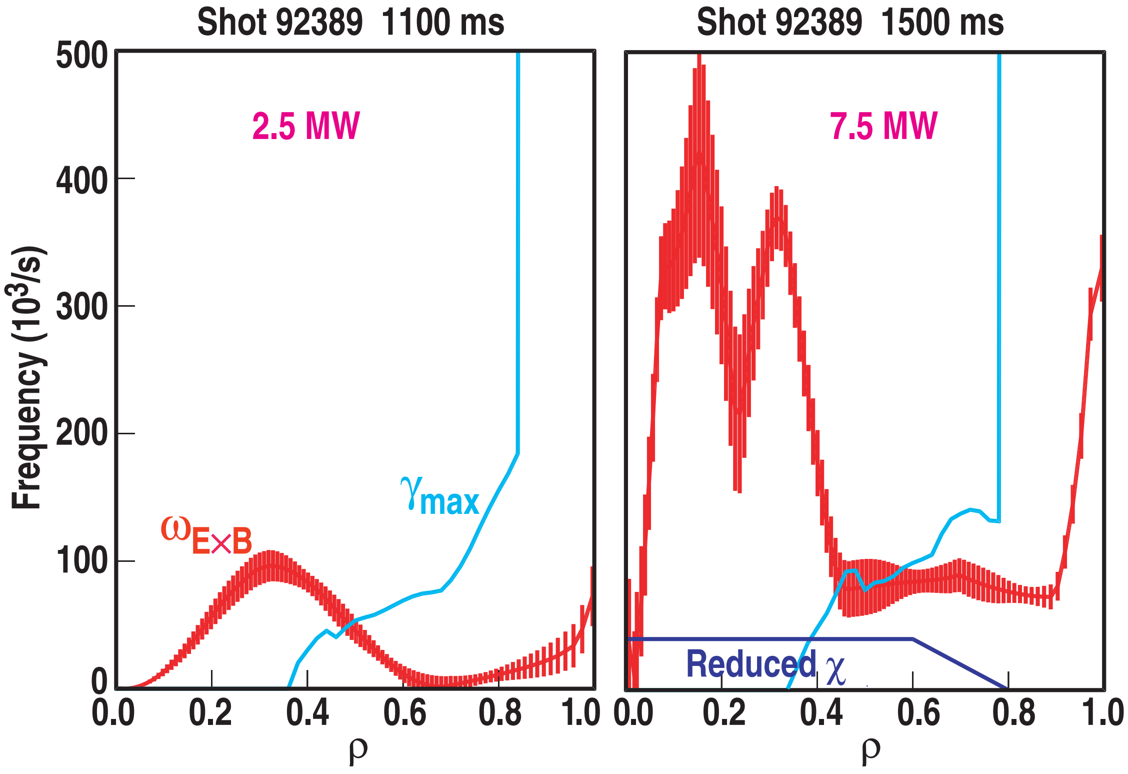
E × B SHEARING RATE INCREASES FASTER THAN TURBULENCE GROWTH RATE WHEN POWER INCREASES AND TRANSPORT DROPS

- E_r from change exchange spectroscopy





$$\omega_{E\times B} = \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial\psi} \left(\frac{E_r}{RB_\theta} \right)$$

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GENERAL ATOMICS

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PREDICTIVE UNDERSTANDING OF MHD STABILITY

- MHD stability limits are the most fundamental
  - If they are violated, plasma disrupts or has significantly reduced confinement

- Ideal MHD equilibrium and stability calculations are very accurate
  - Accurate, measured profiles needed for input to calculation
  - Theory is one of the success stories of plasma physics

- Active research now focuses on non-ideal effects
  - Effect of neoclassically-driven currents on stability (neoclassical tearing modes)
  - Resistive effects on wall-stabilization of kinks (resistive wall modes)
  - Multiple coupled modes near the plasma boundary participating in edge localized modes

- Diagnostic needs concentrate on testing stability models

EXAMPLES OF TECHNIQUES FOR MHD STABILITY DIAGNOSTICS

- Measure internal structure of rotating and non-rotating low toroidal mode number (1–5) MHD modes
  - Radial profiles of temperature at several toroidal locations (ECE)
  - 2-D imaging at several toroidal locations (tangential SXR cameras, BES)

- Edge poloidal field measurement
  - MSE measurement with counter plus co injected diagnostic neutral beams
    - ★ Two views needed to take care of sensitivity to E_r and B_θ
  - Zeeman polarimetry using lithium beam (Thomas, EP34)

- ff′ diagnostic through |B| measurement
  - Spectroscopic measurement of wavelength shift of motional Stark components of D_α or D_β from fast beam neutrals
  - Simultaneous X–mode and O–mode correlation reflectometry (Gilmore, AI2)

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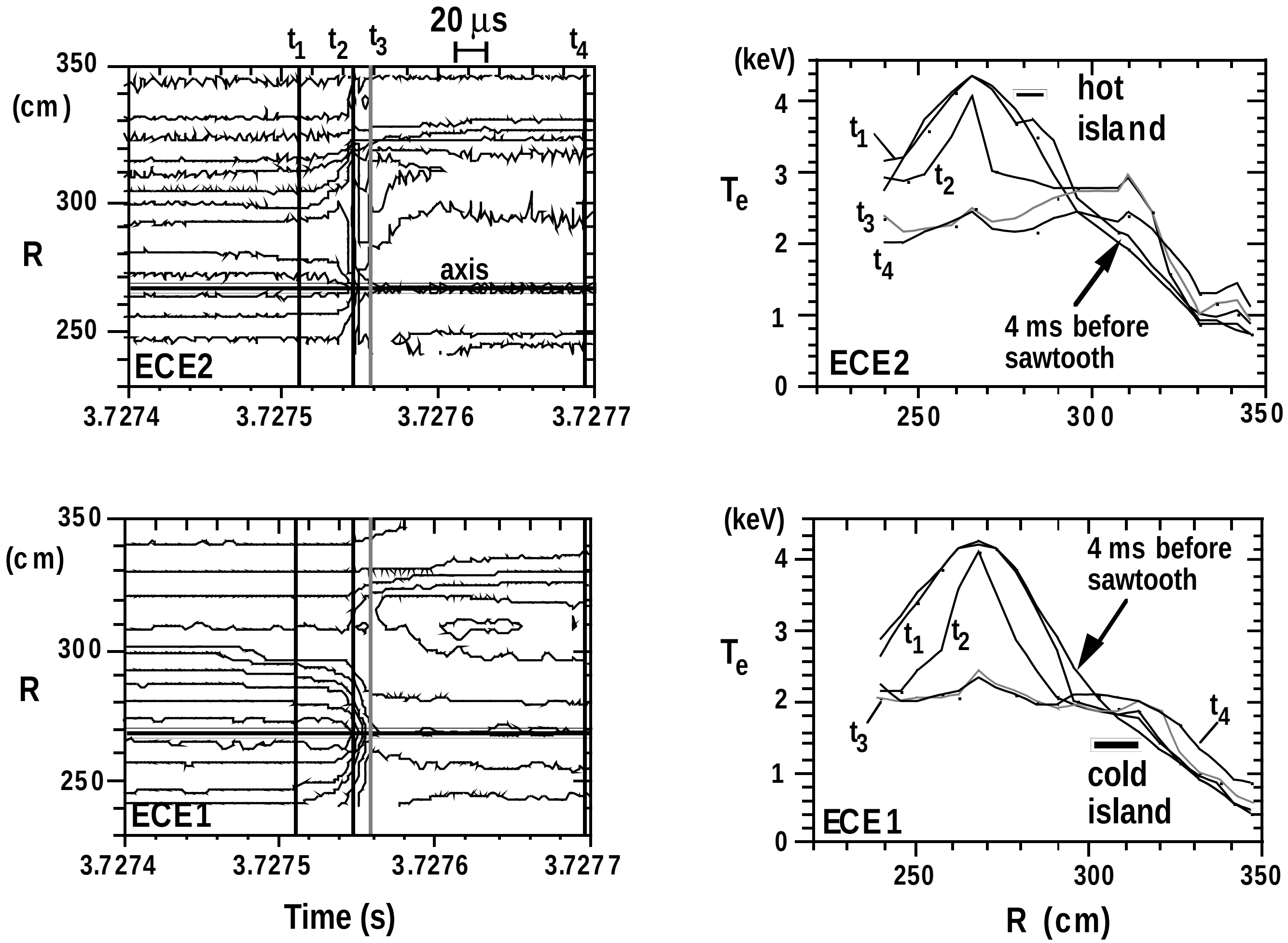
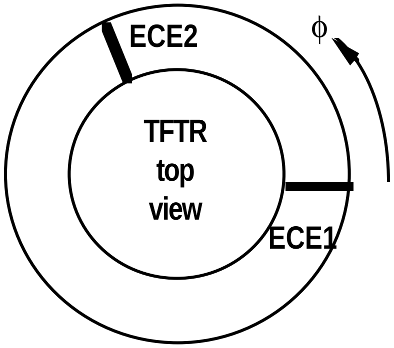
MULTIPLE ECE SYSTEMS USED TO DEDUCE SAWTOOTH STRUCTURE IN TFTR REVERSE SHEAR PLASMAS





Z. Chang et al. Phys. Rev. Lett. 77, 3553 (1996)

PREDICTIVE UNDERSTANDING OF TRANSPORT

- A fundamental assumption is that turbulence-driven transport can explain the difference between measured fluxes and the neoclassical predictions
  - So far, this assumption has only been shown to be consistent with measurements of edge particle flux and edge electron heat flux
  - Turbulence-driven transport has not been measured in plasma core
- Theory of turbulent-driven transport in tokamaks is not nearly as well developed and well tested as ideal MHD
  - Significant progress recently with the gyrofluid and gyrokinetic approaches

EXAMPLES OF DIAGNOSTIC TECHNIQUES FOR TRANSPORT DIAGNOSTICS

- **2-D turbulence visualization**
  - BES (Fenzi, EP25)
  - Laser fluorescence (Levinton, EI3)
  - Gas puff imaging (Magueda, EP5)
  - Thomson scattering (Zweben, FP31)

- **Test basic modes included in theories**
  - Ion temperature gradient mode tests using high frequency charge exchange spectroscopy (HFCHERS on TFTR)

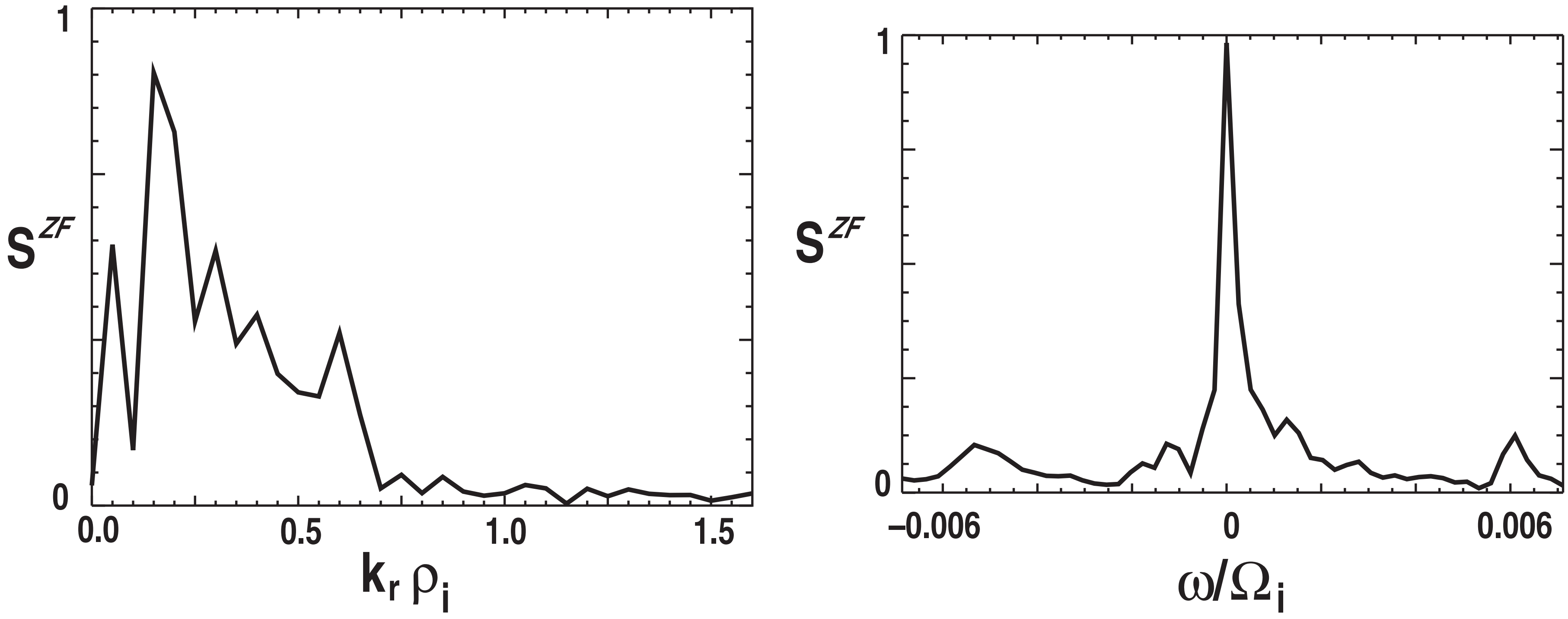
- **Electron transport and electron temperature gradient modes**
  - High k ($\sim 10\ \mathrm{cm}^{-1}$) measurements with FIR scattering

- **Zonal flow measurements**
  - Seek long correlation lengths in poloidal flow measured by BES, high frequency charge exchange spectroscopy or reflectometry

- **Determine quantitatively whether fluctuation driven transport is big enough to be significant in the plasma core**
  - Requires measurements of cross correlation between $\tilde{n}$, $\tilde{v}_r$, and $\tilde{T}$ in plasma core
  - Major innovation required to do this

ZONAL FLOW CHARACTERISTICS

- Low frequency (~5 kHz), axisymmetric ($k_\phi = 0$) and poloidally symmetric ($k_\theta = 0$) oscillations in electrostatic potential
- $0.1 \lesssim k_r\rho_i \lesssim 0.5$, comparable to standard turbulence scales



T.S. Hahm et al., Plasma Phys. and Contr. Fusion 42, A205 (2000)

REAL TIME MEASUREMENTS FOR FEEDBACK CONTROL

- Holding an advanced tokamak plasma reliably at peak performance will almost certainly require various types of feedback control
  - For example, real time q profile measurement is crucial since current profile is so important for MHD stability
- Feedback loops require sensors and effectors that can work in real time
  - Time scale is probably milliseconds to 100s of milliseconds
- Diagnostic challenge is to acquire the data, produce analyzed values and get these to the plasma control system in time for it to act
- Examples of real time sensors needed
  - MSE polarimetry for q profile
  - Radial and/or poloidal magnetic field at vessel wall for resistive wall mode (RWM) control
  - Plasma rotation profile for RWM control
  - β_T value for stability limit feedback
  - Electron density and temperature profiles for current drive control

CONCLUSION

- Advanced tokamak research seeks to find the ultimate potential of the tokamak as a magnetic confinement system
- This requires innovative improvement of the tokamak concept
  - Increase power density, reduce size, achieve steady-state operation
  - These require improvements in MHD stability, reduction in transport, and efficient current drive techniques
- This simultaneous, nonlinear optimization of current, pressure, and E_r profiles to meet multiple goals is a grand challenge to plasma physics
- Innovation in diagnostic measurements is a key aspect of meeting this challenge
  - Essential for developing predictive understanding
  - Required as part of active feedback control of the state of the plasma