Advances in the Control and Understanding of Fusion Plasmas in the DIII–D Tokamak

by
M. Wade for the DIII–D Team

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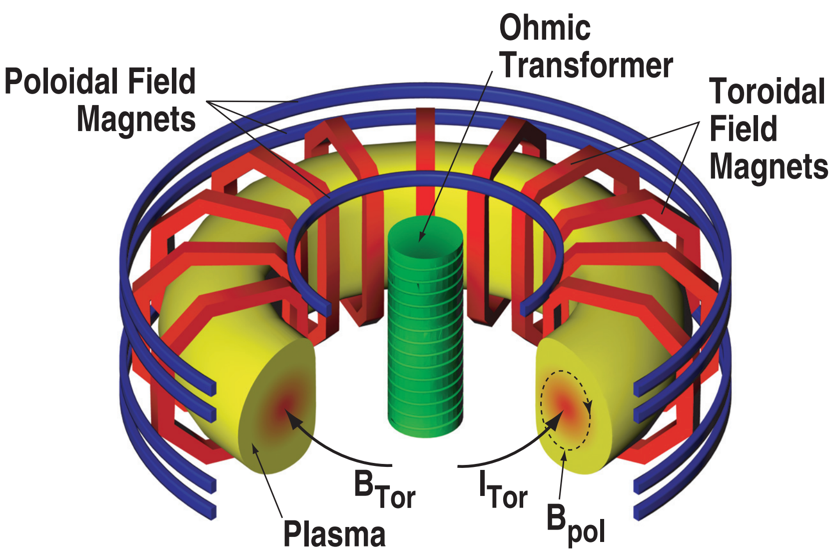
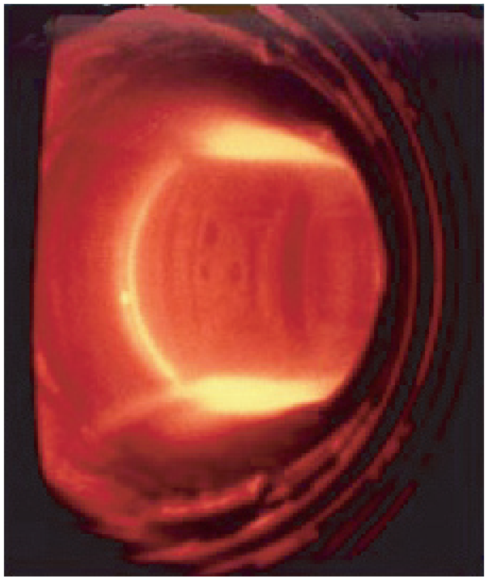
DIII–D
NATIONAL FUSION FACILITY

058-07/MW/jy

The Tokamak is the Most Successful Type of Plasma Confinement Device

Strong magnetic coils confine a ring of plasma





- **Tokamak experiments have produced significant fusion power**
  - 11 MW fusion power in TFTR (1994)
  - 16 MW fusion power in JET (1997)

- **ITER — the big step toward tokamak fusion – will produce up to 500 to 500 MW of fusion power**

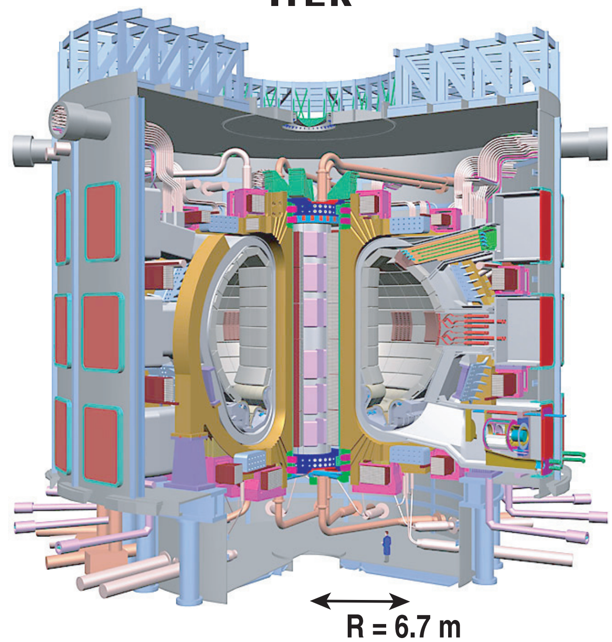
ITER: The Next Frontier in Fusion Energy Research and a Grand Scientific Challenge for the World Community

- Primary mission is to demonstrate viability of "burning" plasma operation (i.e., primary heating source is from fusion by - products)

- Will provide platform for investigation of key physics phenomena in the burning plasma enviroment

- Status
  - ITER Agreement signed by 7 international partners in Nov. 2006 (United States, European Union, Japan, Russia, China, Korea, India)
  - Currently in final design review stage before construction begins in 2008

ITER



- Designed for 500 MW fusion power production for pulse of 300 s

Key Performance Requirements in Achieving Burning Plasma Conditions

- **Good Energy Confinement**
  – Reduce Heat Leakage Rate to a Minimum

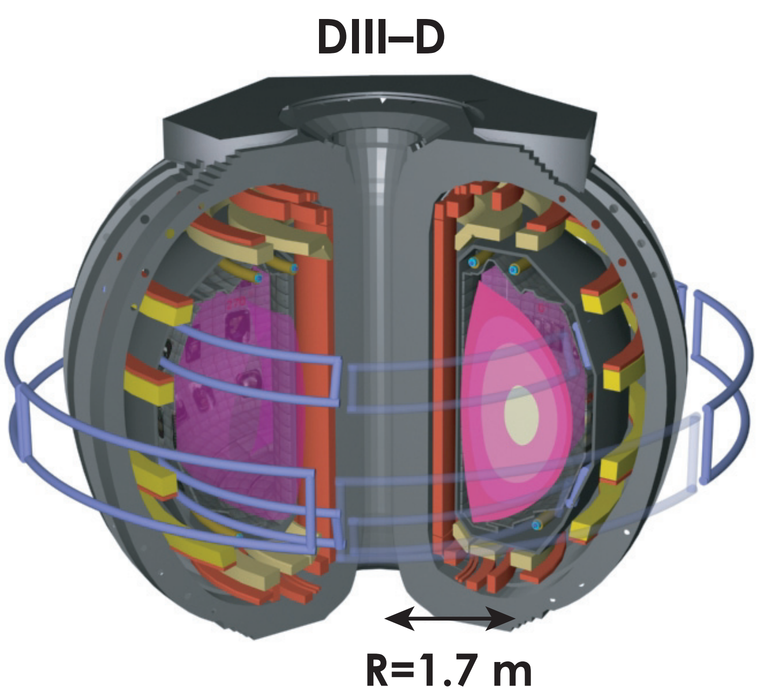
- **High Plasma Pressure**
  – Avoid or Control Large-Scale Instabilities

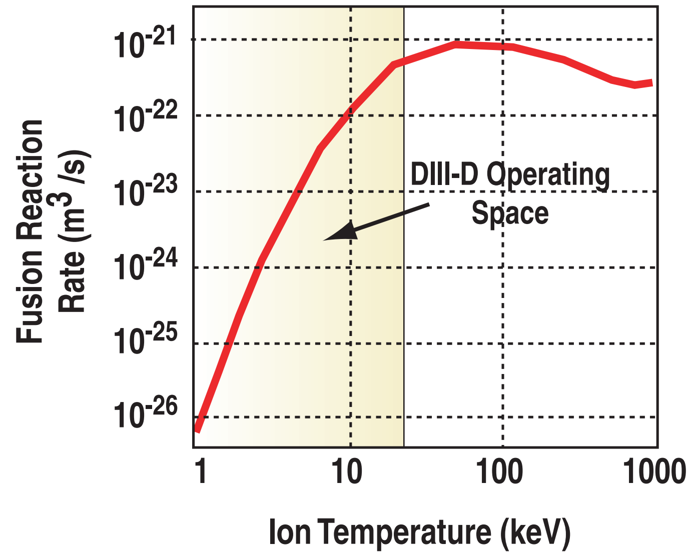
- **Shield Chamber Walls from Hot Core Plasma**
  – Reduce Focusing of Energy on Small Areas

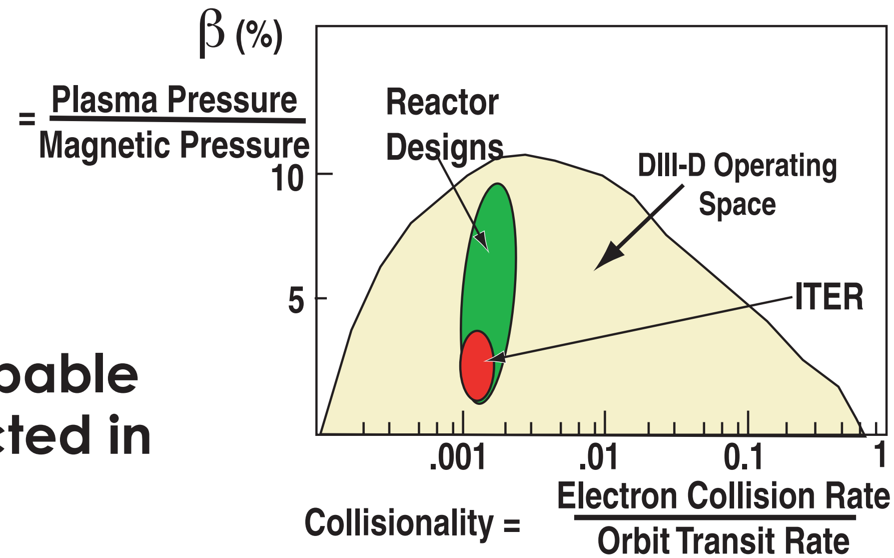
- **DIII–D has demonstrated the ability to achieve all of these requirements simultaneously**

DIII–D is Developing the Scientific Foundation for the Success of ITER

Mission: Develop the scientific basis for the optimization of the tokamak approach to fusion energy production







- DIII–D: is a moderate-size tokamak capable of producing plasma conditions expected in future fusion devices

DIII-D Experiments Have Demonstrated the Capability to Sustain Stability and Confinement Quality Well In Excess of the Requirements of ITER

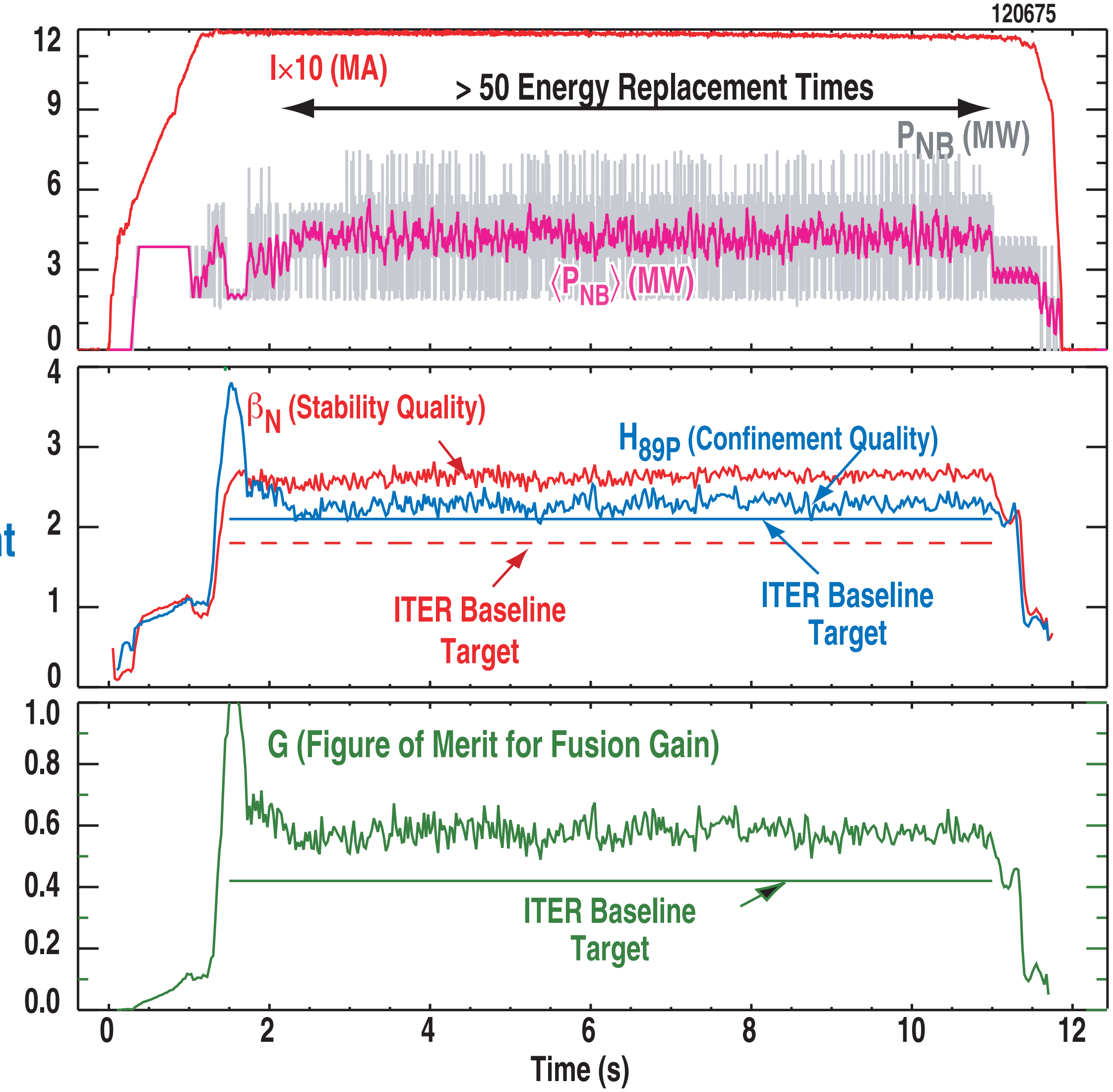
- **Fusion Basics:**

$$\text{Fusion Gain} = \frac{\text{Fusion Power Produced}}{\text{Input Power}}$$

$$\propto \beta \times \tau$$

β → Plasma Pressure

τ → Energy Confinement



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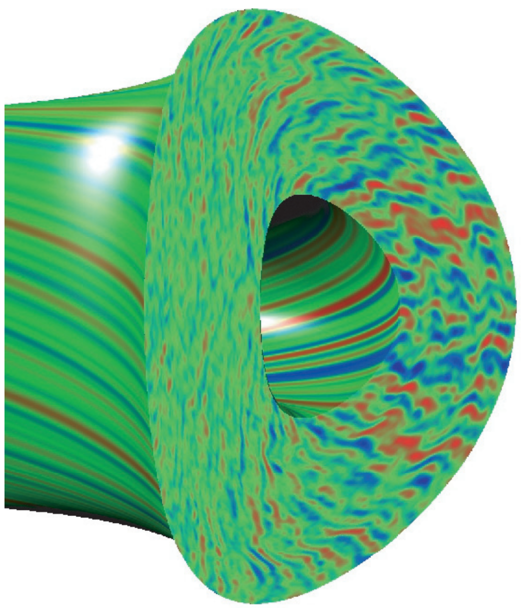
DIII–D Experiments are Confirming Theoretical Picture of Turbulence-Driven Transport

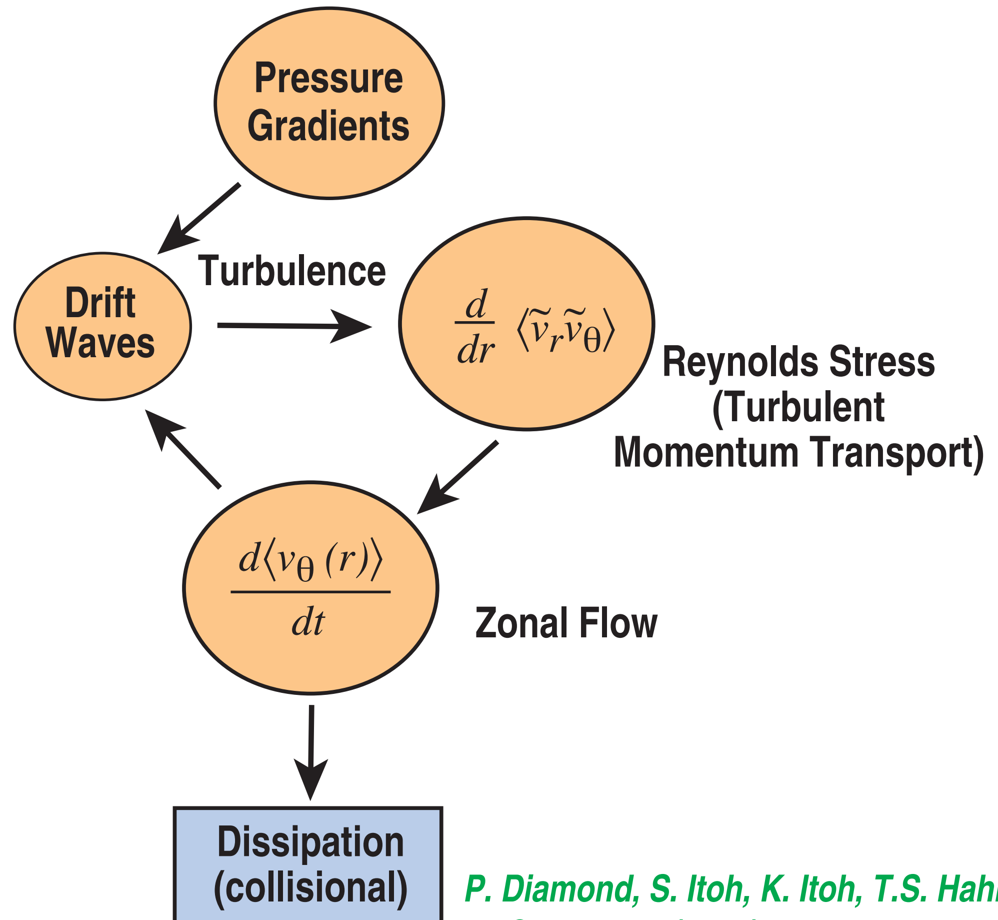
- **GYRO: 5-D Simulation of the gyro-kinetic Maxwell equations in toroidal geometry**



Includes:

- **Kinetic electrons**
- **Finite pressure (β)**

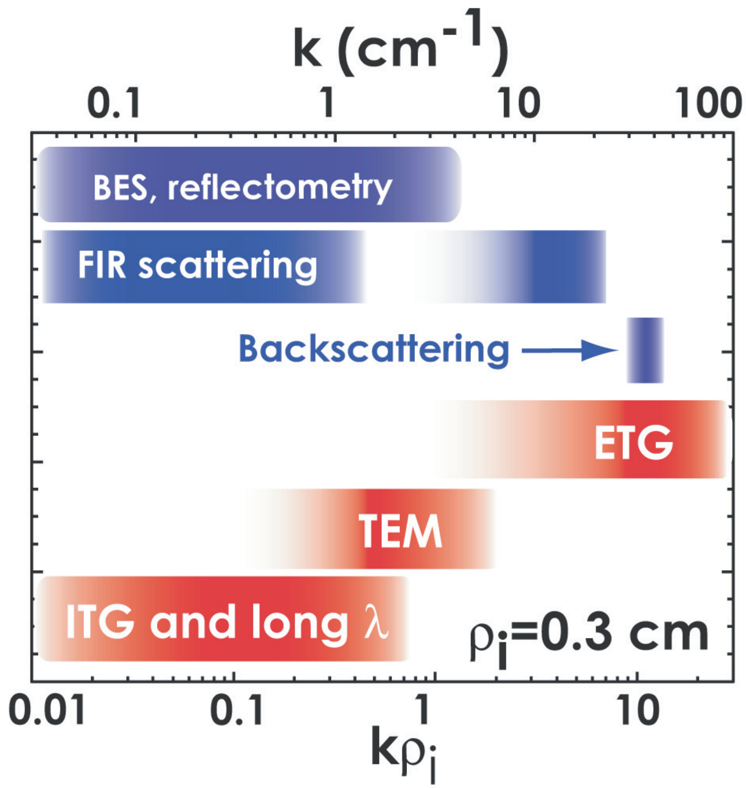
Turbulence Dynamics



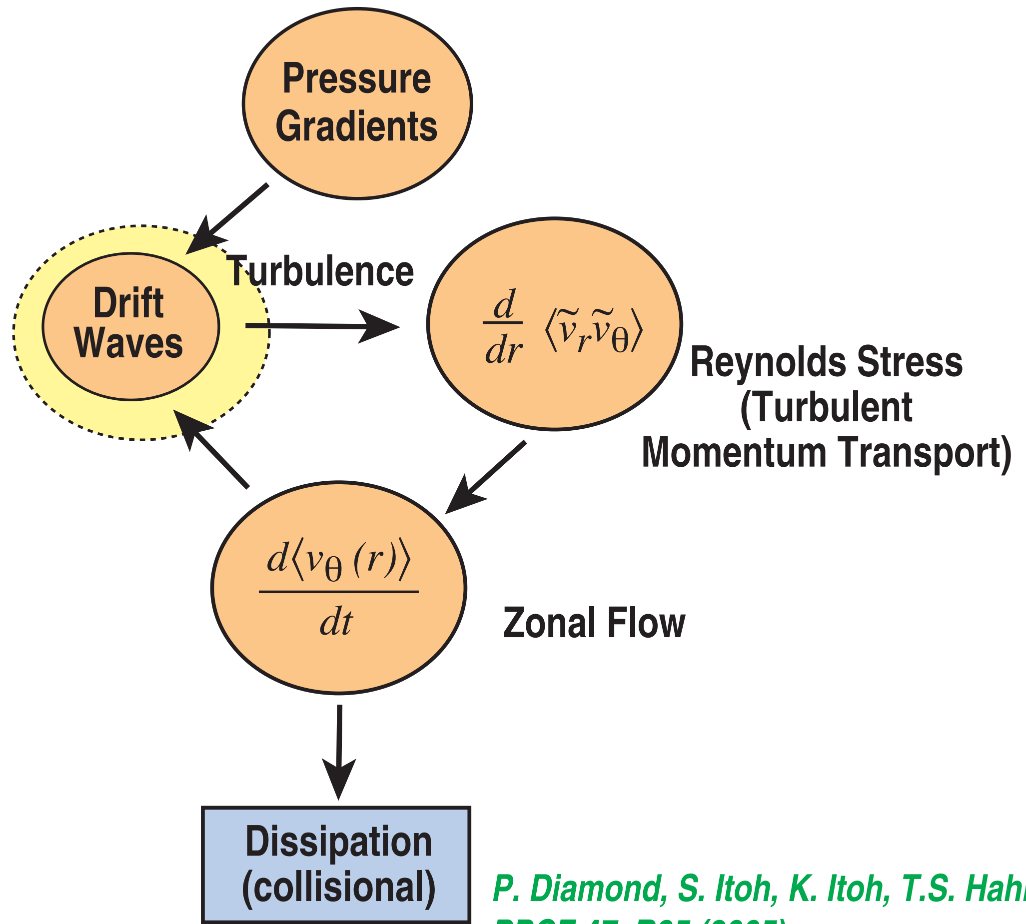
P. Diamond, S. Itoh, K. Itoh, T.S. Hahm, PPCF 47, R35 (2005)

DIII–D Experiments are Confirming Theoretical Picture of Turbulence-Driven Transport

- DIII–D diagnostics can measure turbulence at all relevant spatial scales



Turbulence Dynamics



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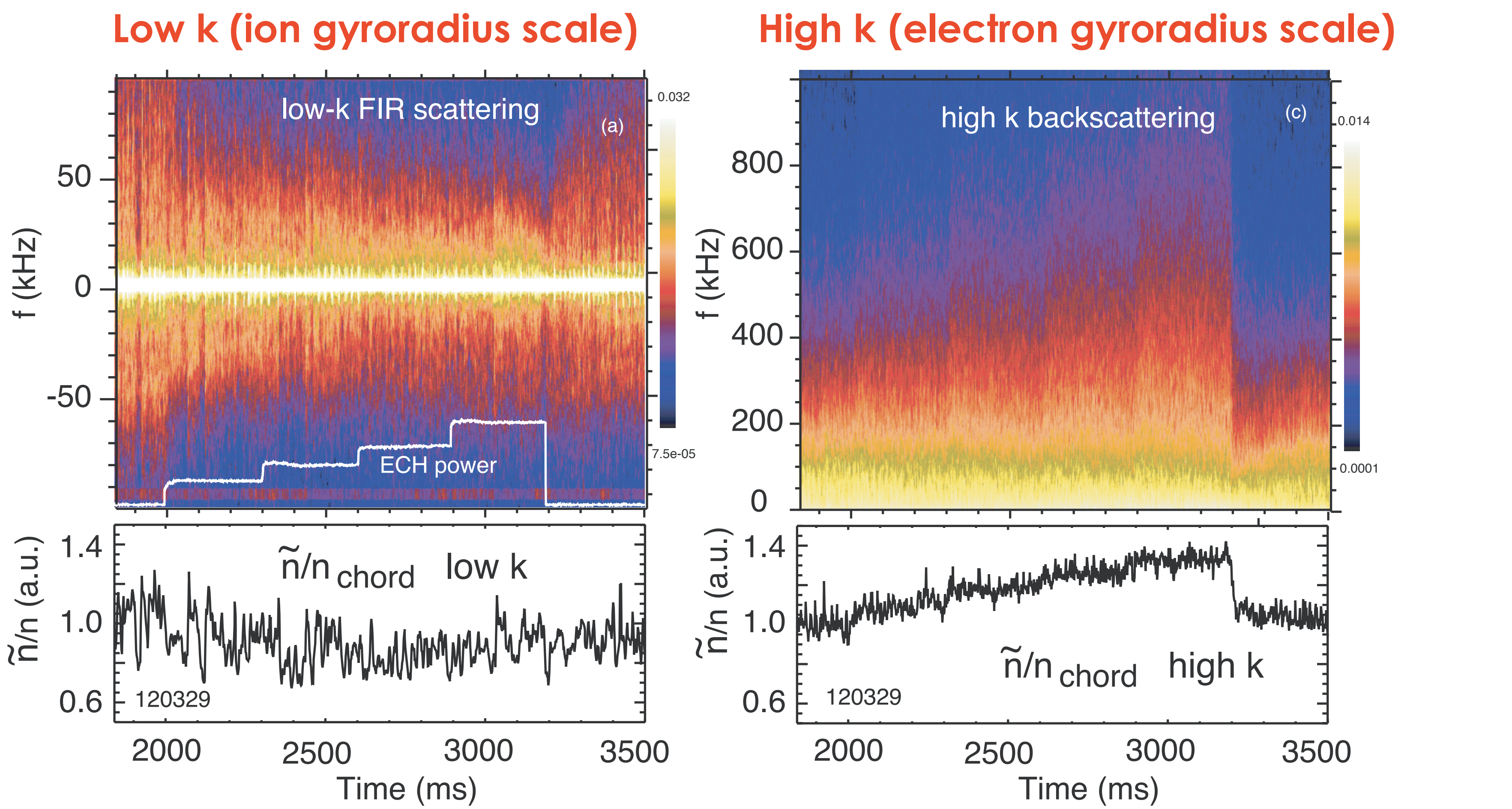
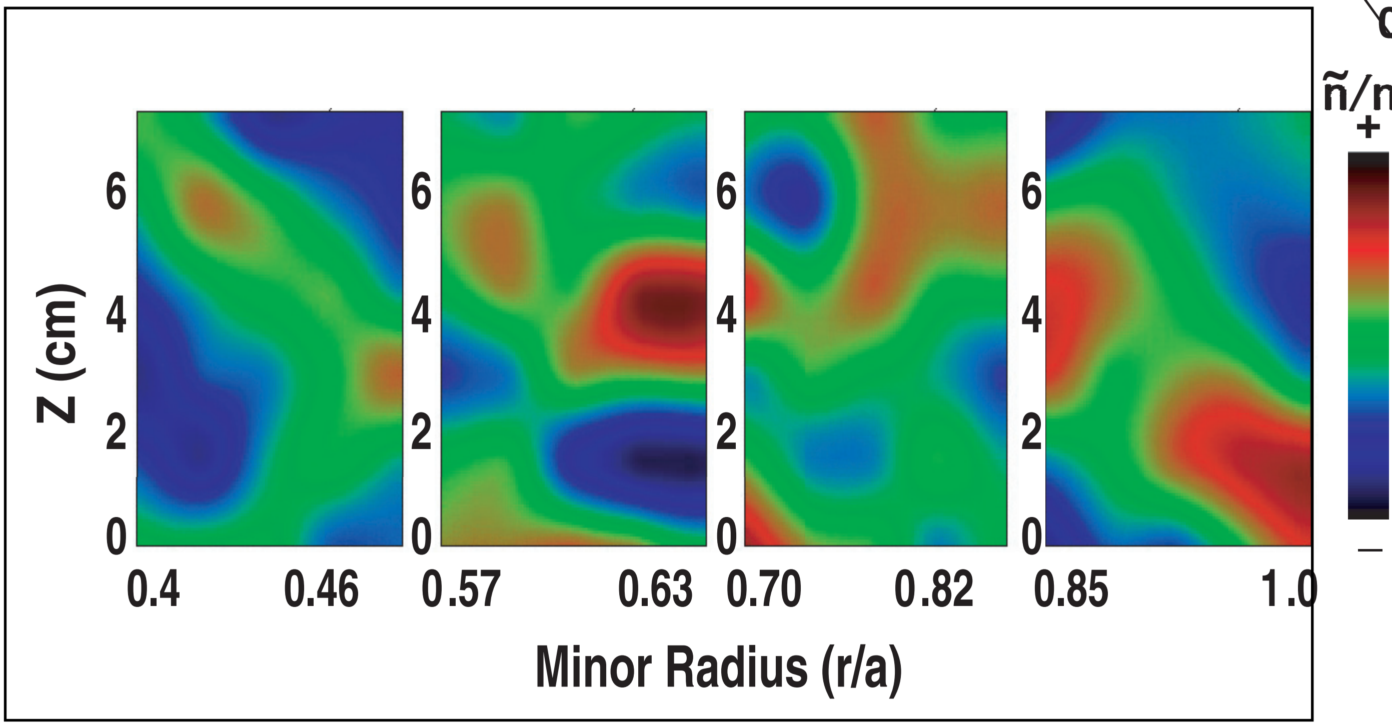
Turbulence Measurements at Different Spatial Scales Show Different Response to Plasma Heating

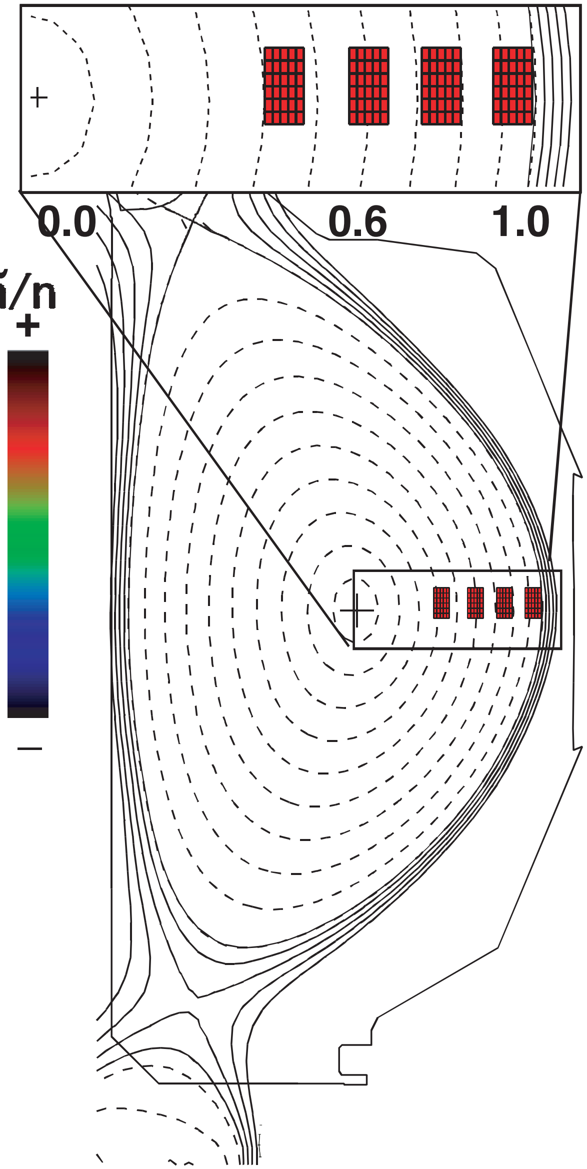


Visualization of Core Plasma Turbulence, Now Possible with High Sensitivity Diagnostics

- **2-D Measurement of Density Fluctuations Enables Imaging of Turbulence Dynamics**

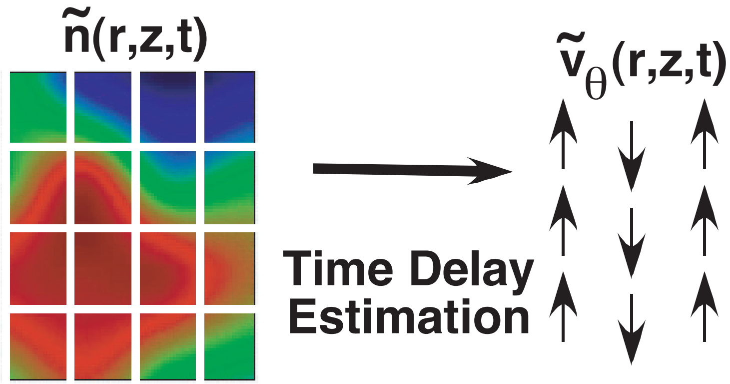


ñ/n	0.4%	0.7 %	0.9%	2-10 %

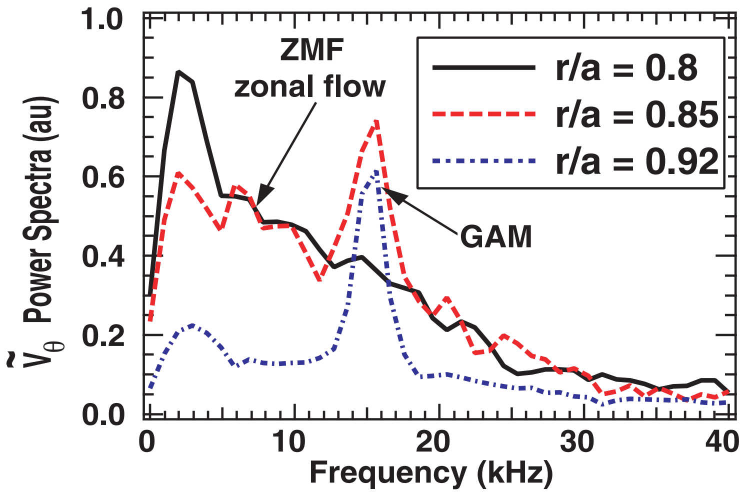


Turbulence Visualization Enables Measurement of Turbulence-Driven Zonal Flows

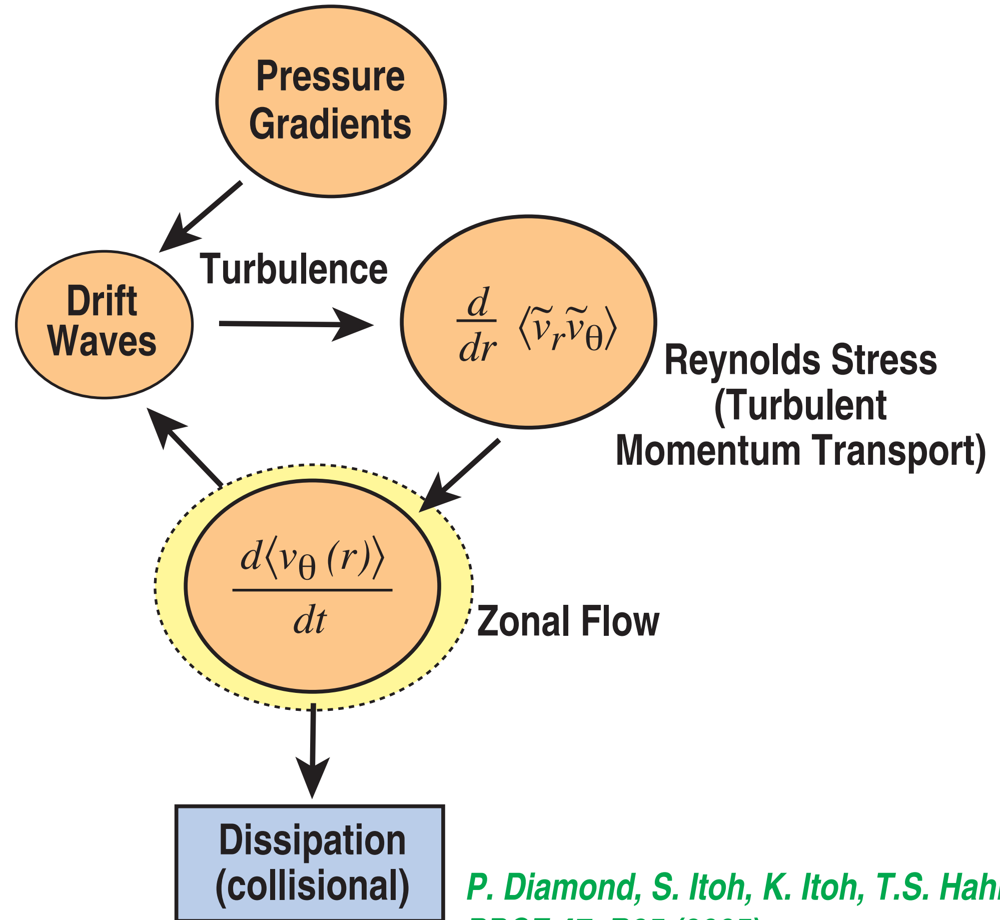
Zonal Flows Measured by Time-resolved Eddy Flows



Two Branches of Zonal Flow Observed at Different Radii



Turbulence Dynamics



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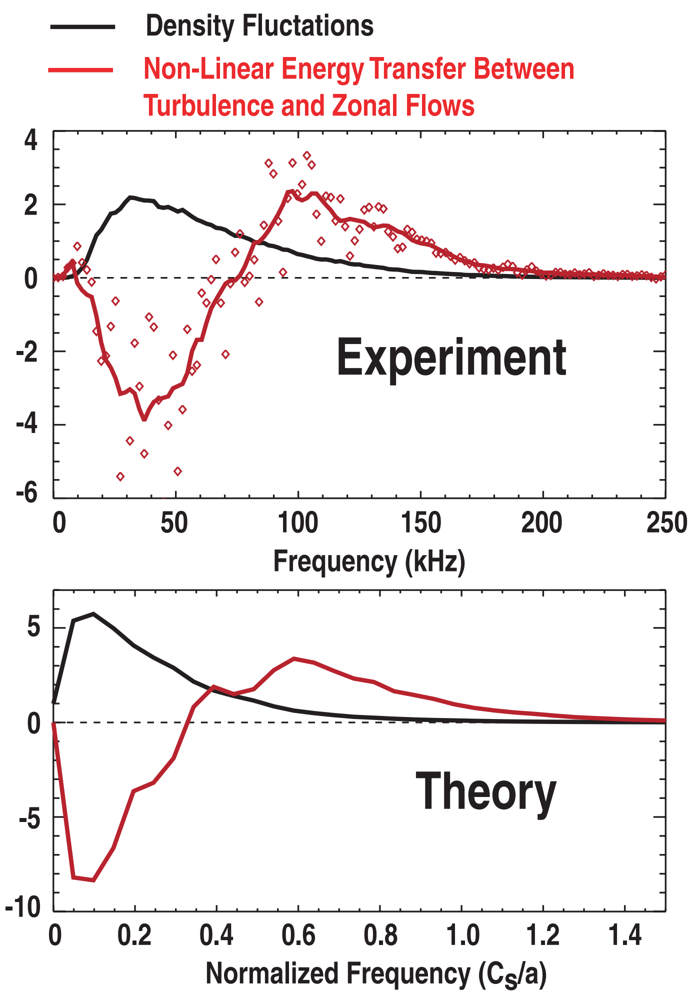
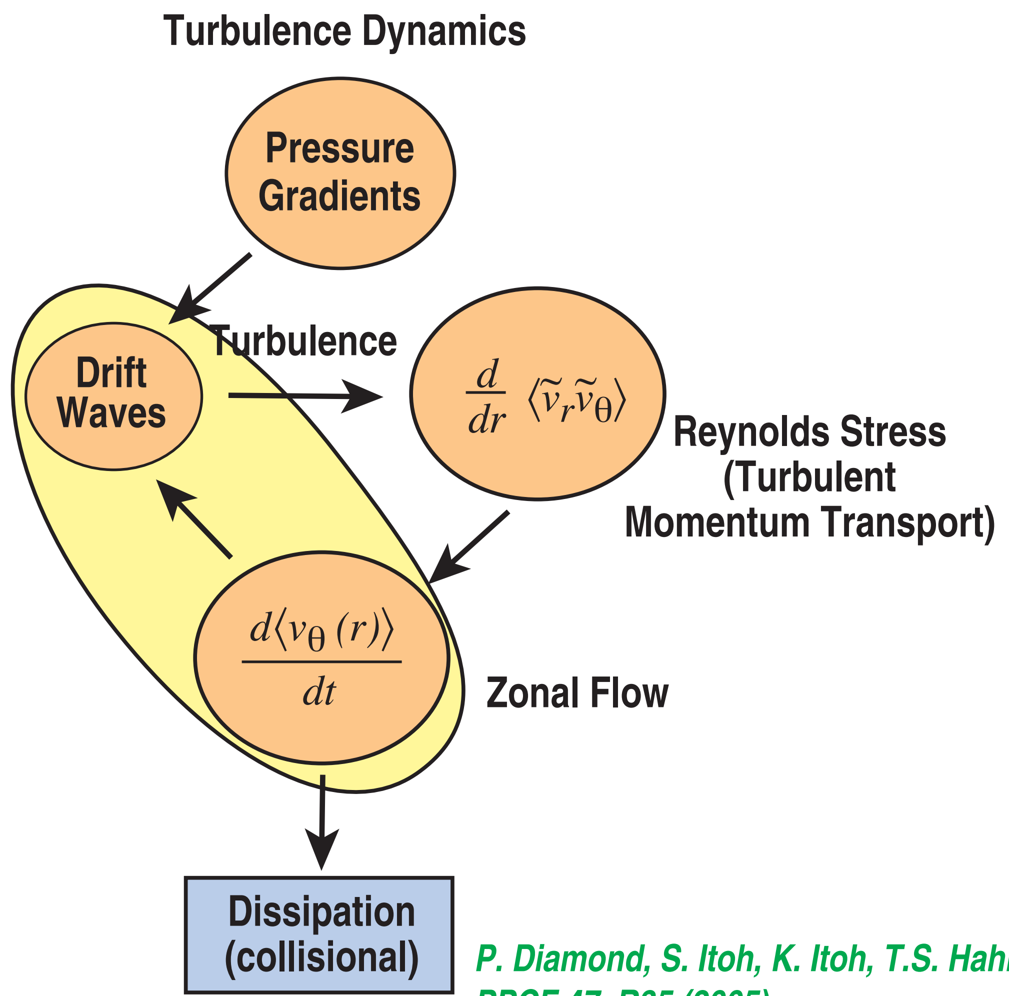
Energy Transfer Between Zonal Flows and Turbulence Has Been Measured - Consistent with Theory Predictions

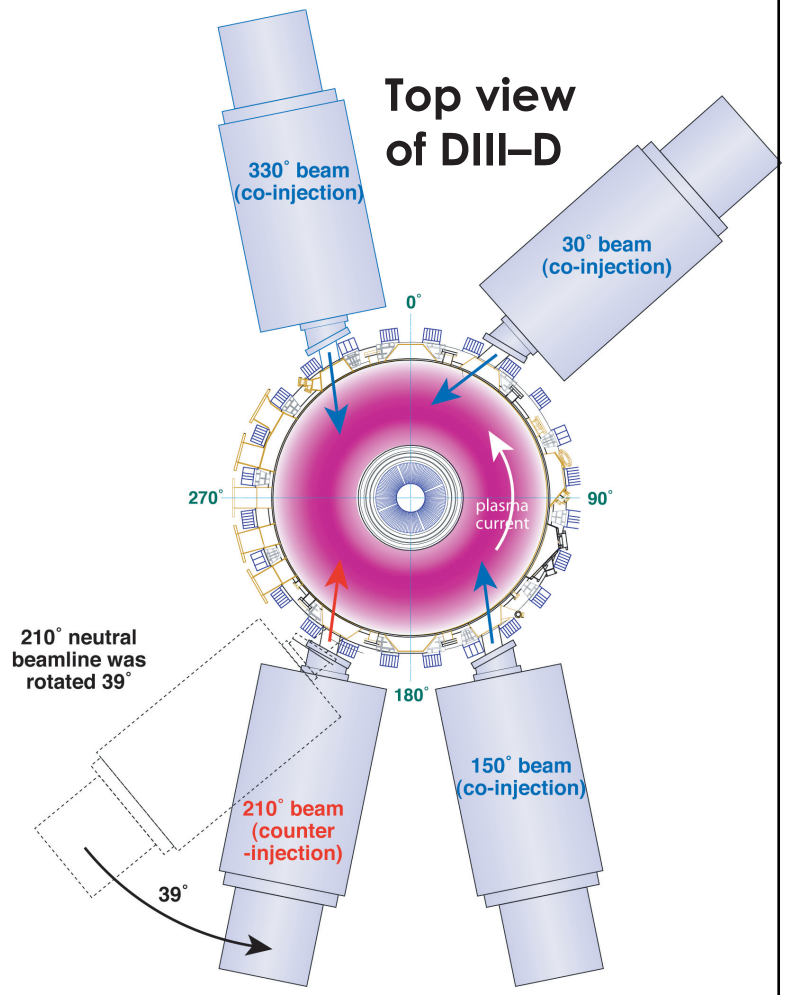


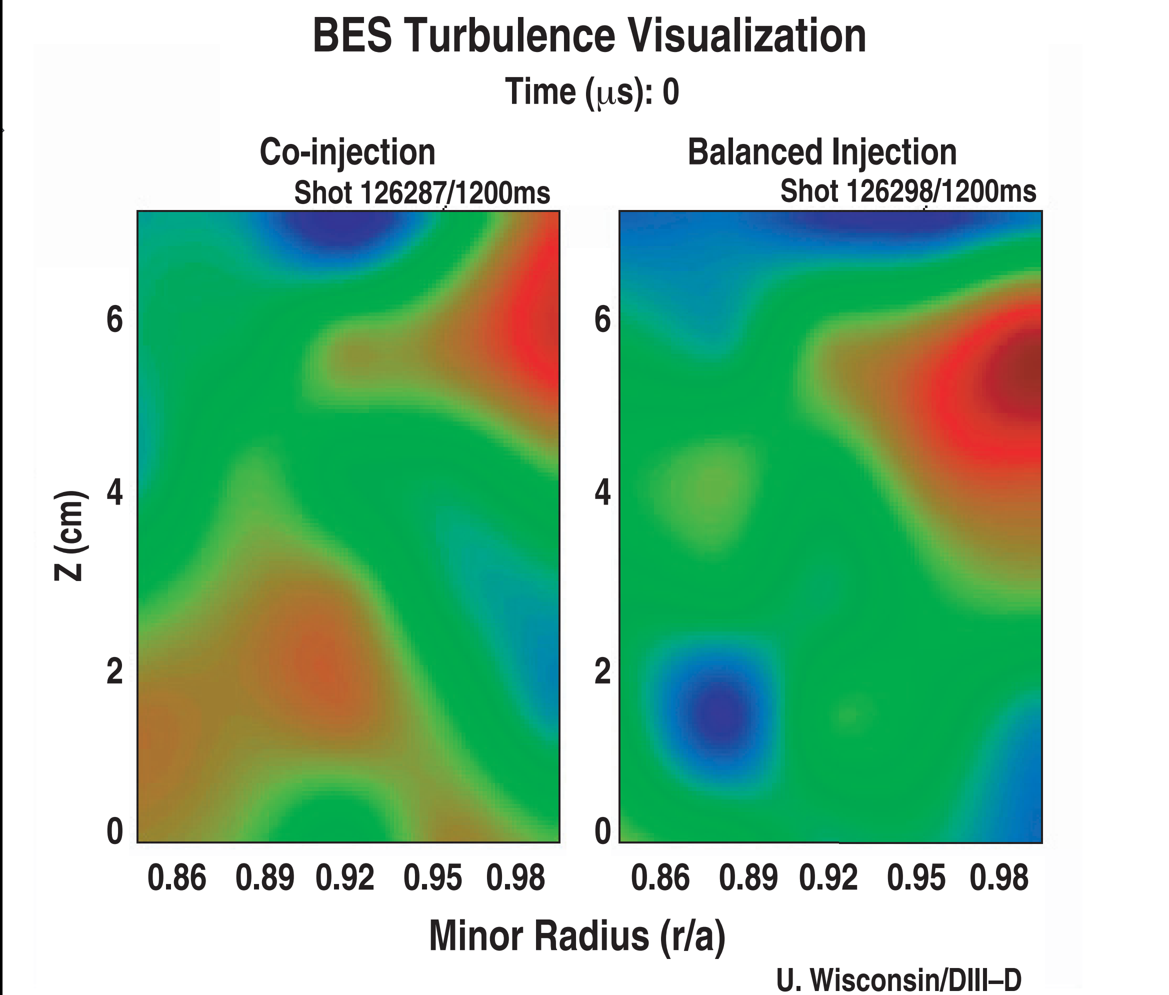


P. Diamond, S. Itoh, K. Itoh, T.S. Hahm, PPCF 47, R35 (2005)

- **First experimental demonstration of interaction of turbulence and zonal flows**

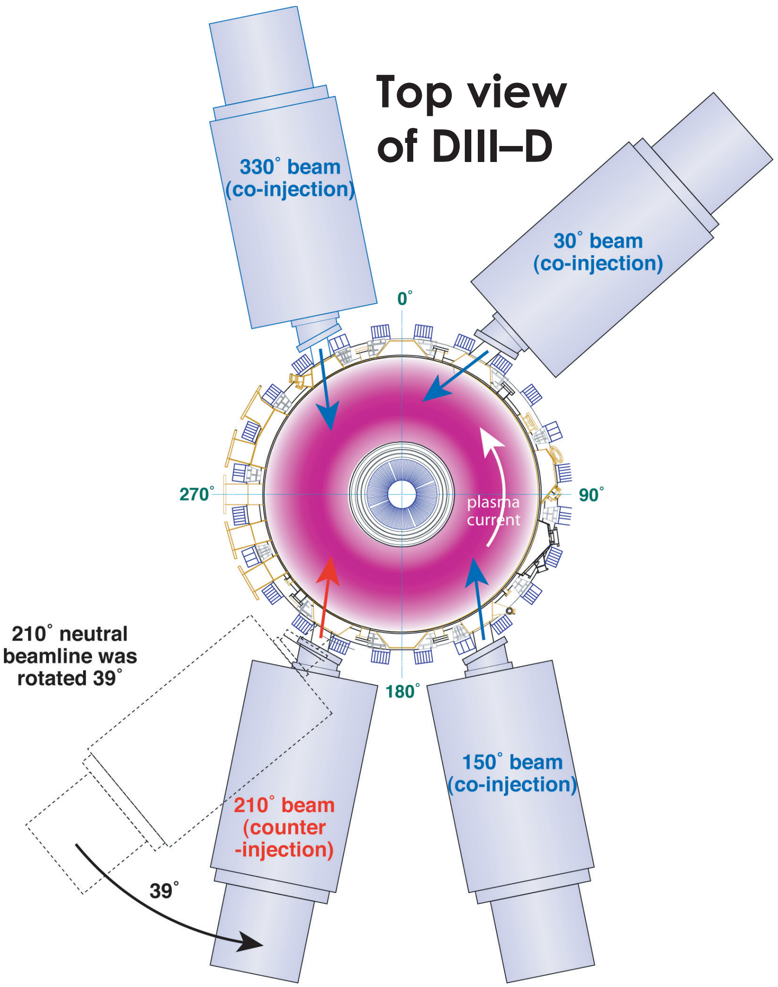
Plasma Rotation Driven By External Torque Input Can Be Used to Control Turbulence

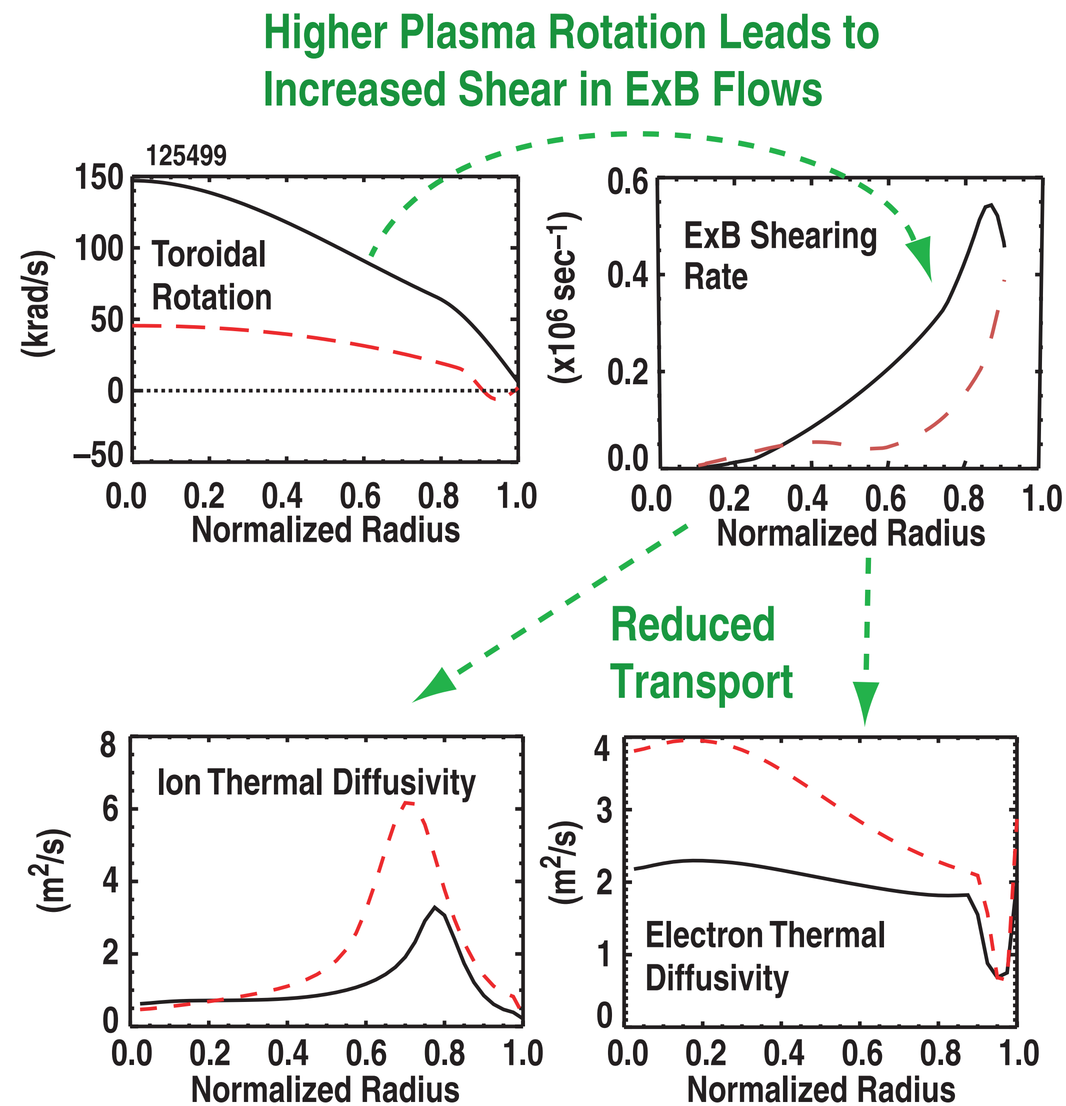




- Example of using plasma control to elucidate key physics issues

Theoretically Predicted Improvement in Transport as Rotational Shear is Increased Confirmed by Experiments





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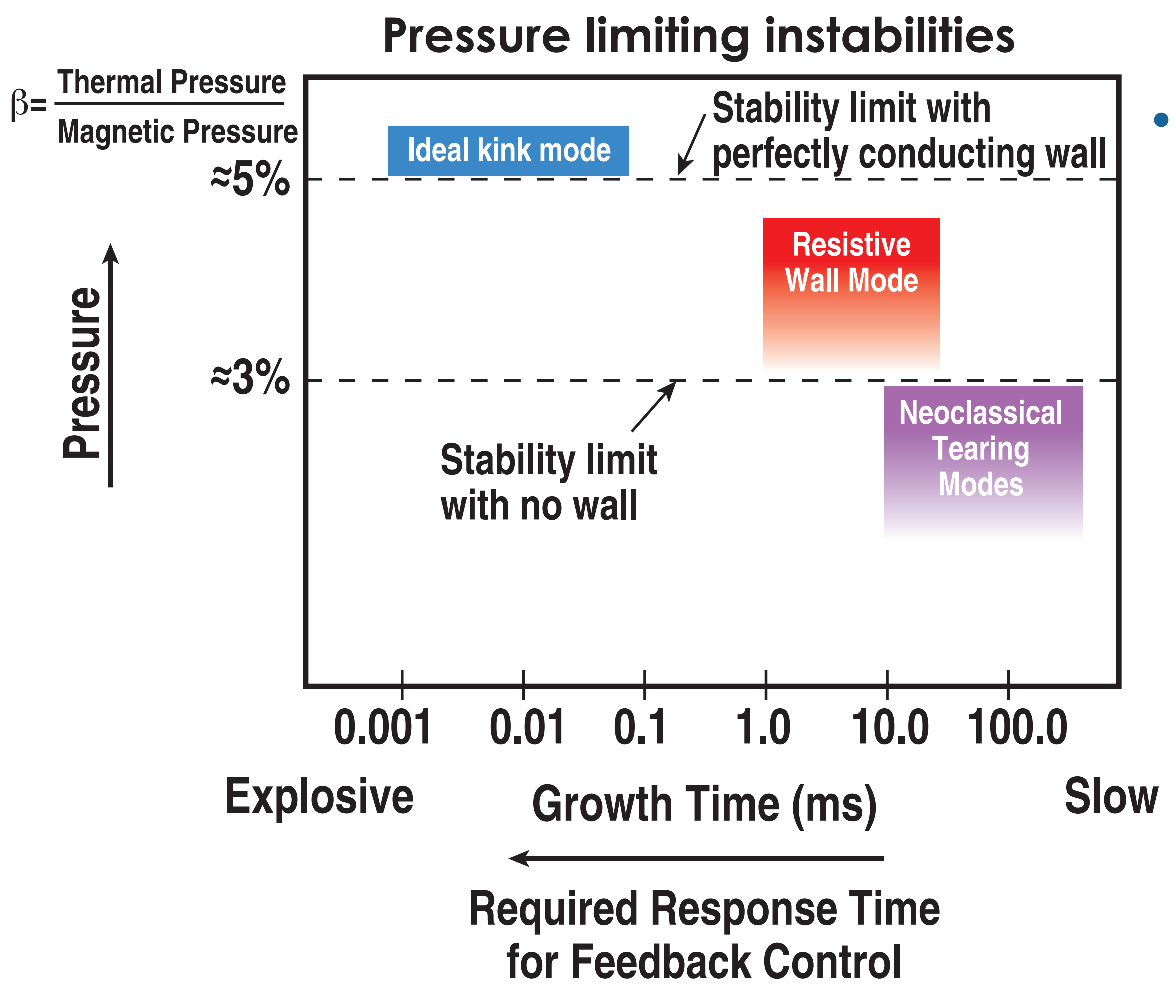
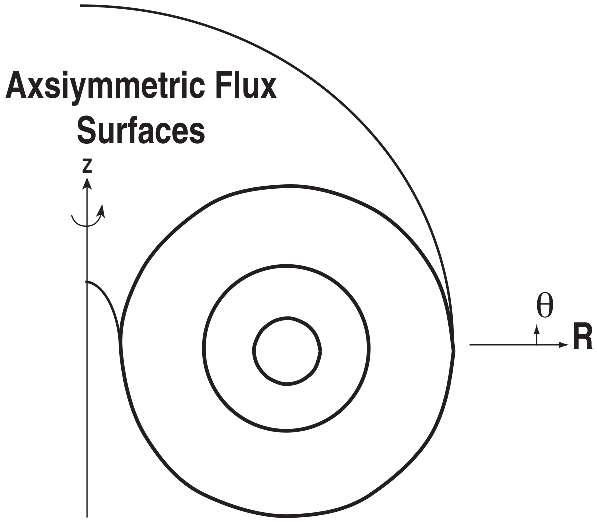
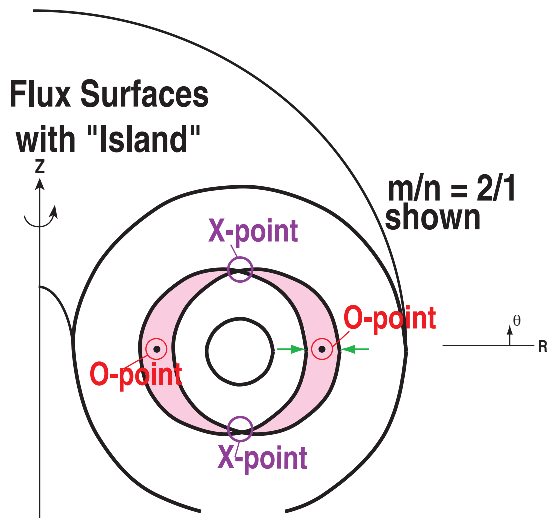
Avoiding or Controlling Large-Scale Instabilities is Essential to Operate at High Pressure



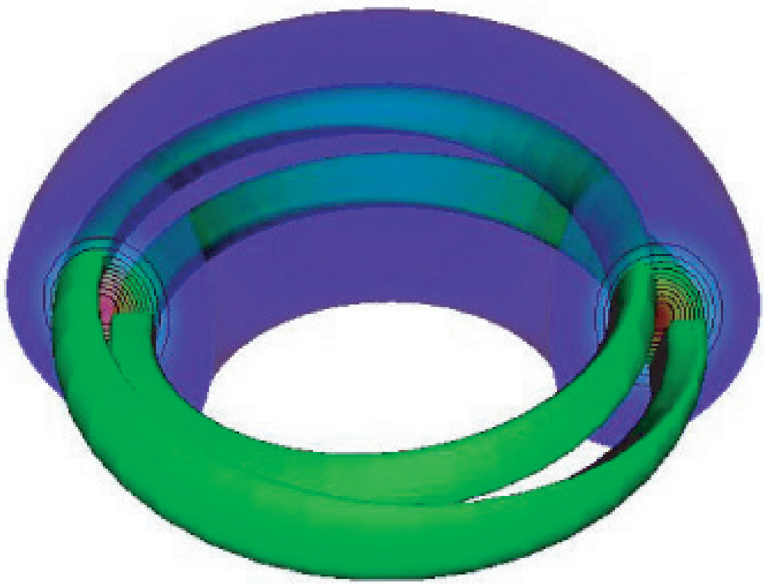
- **Other Instabilities of Importance:**
  - Edge localized modes (ELMs)
  - Fast-Ion Driven Instabilities

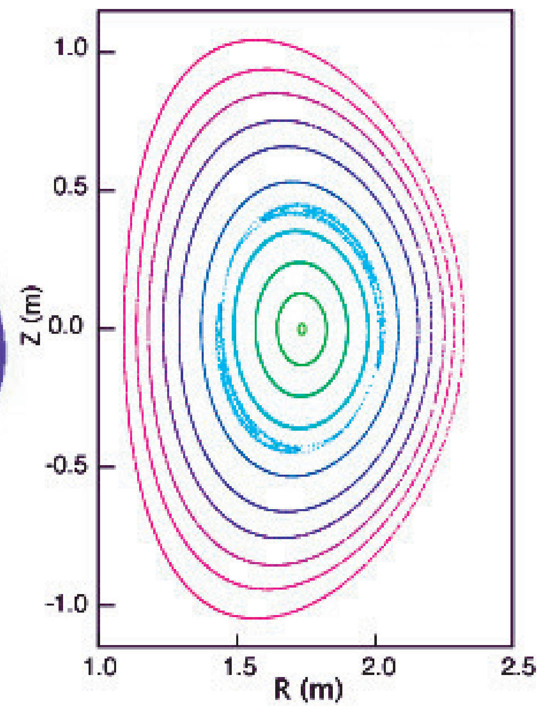
Neoclassical Tearing Modes (NTMs) Are Island Structures That Form on Internal Plasma Surfaces



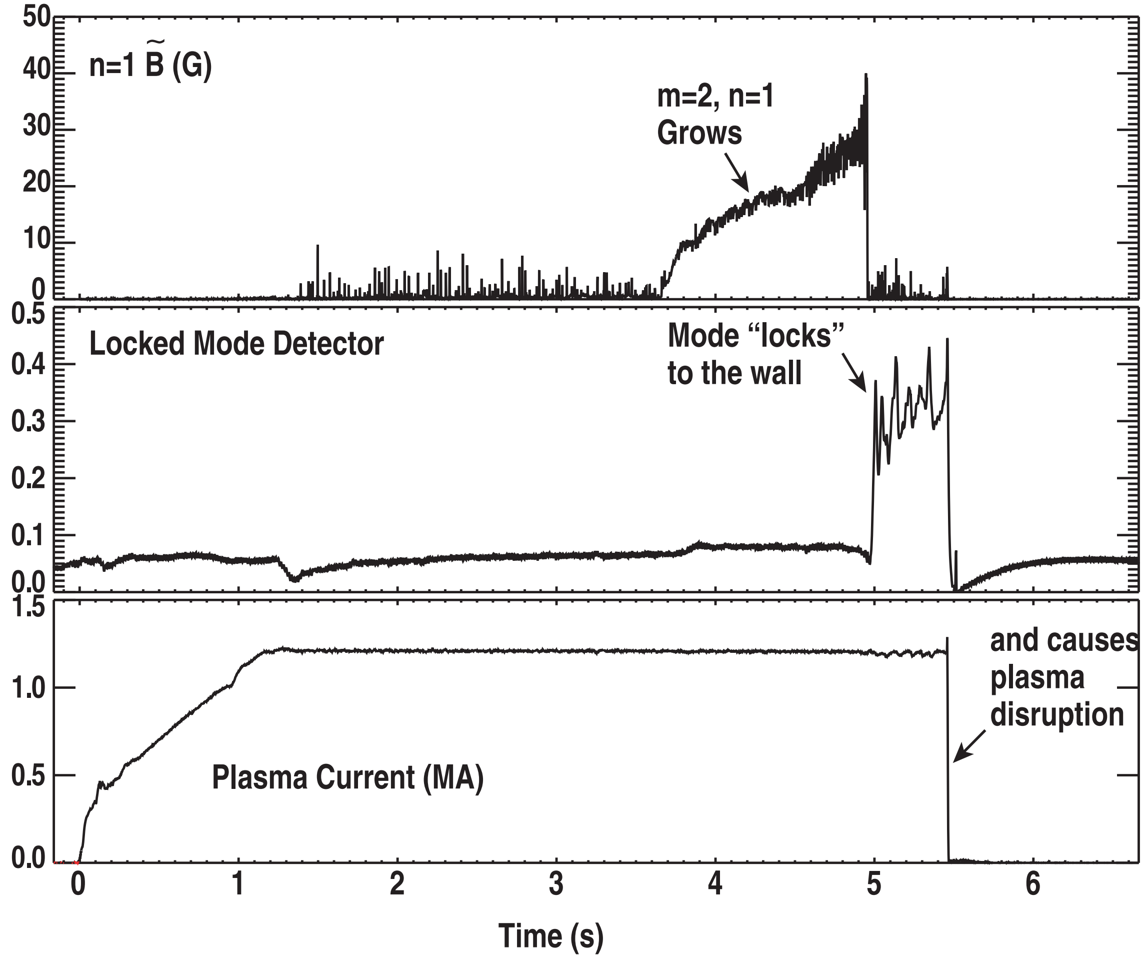


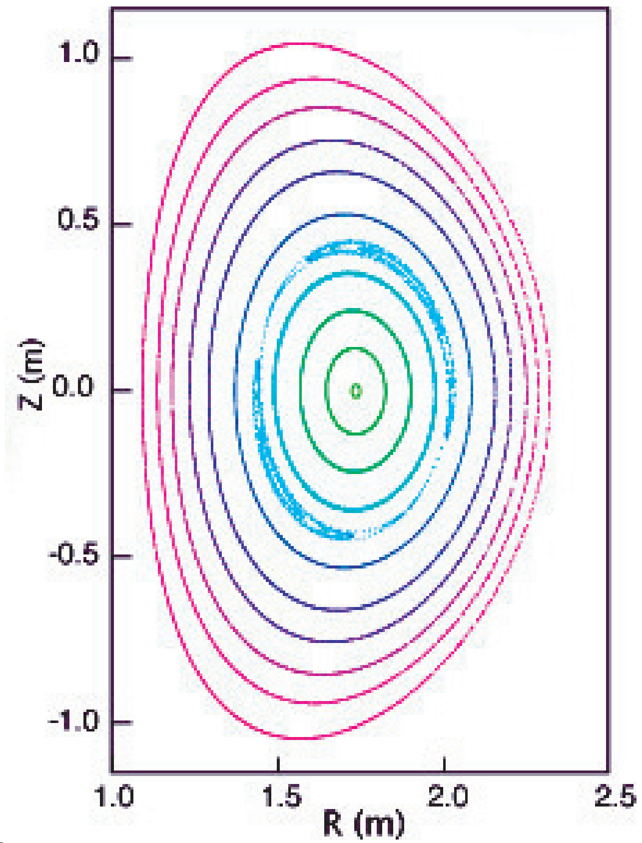
Structure of m=2/n=1 Island in DIII-D Geometry (NIMROD)





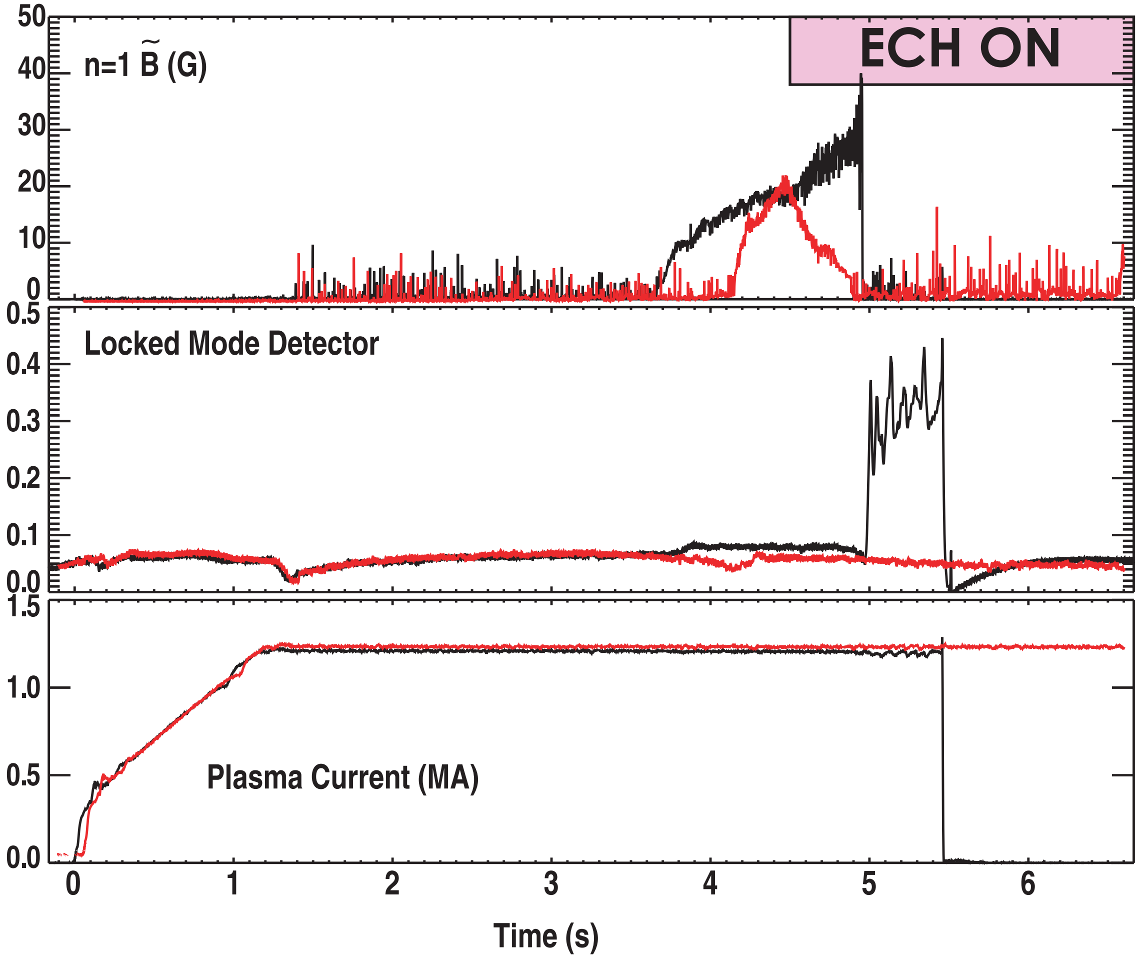
If Uncontrolled, NTM Islands Will Grow and Eventually Cause a Rapid Loss of Plasma Energy ("Disruption")



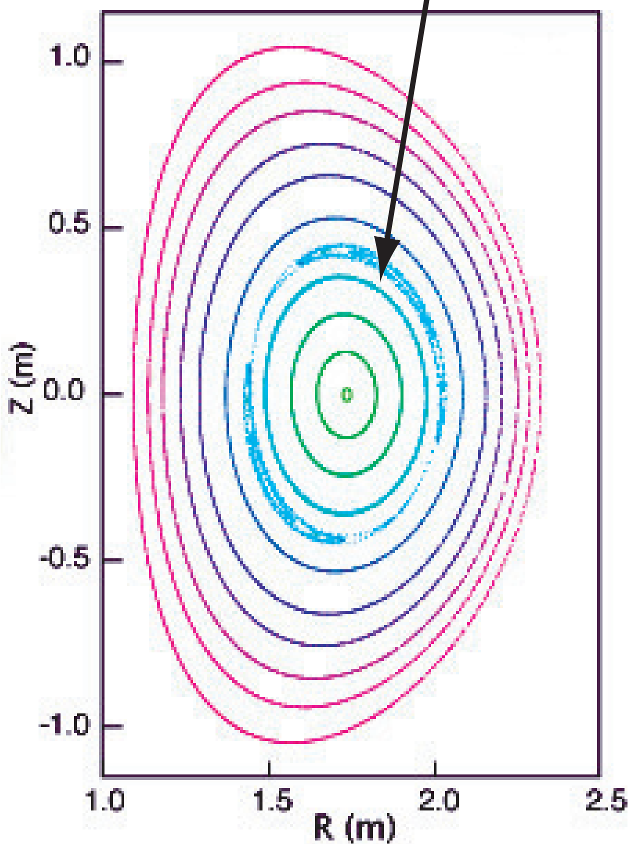


- **Due to need to avoid disruptions, NTMs are a serious risk to ITER achieving optimal performance**

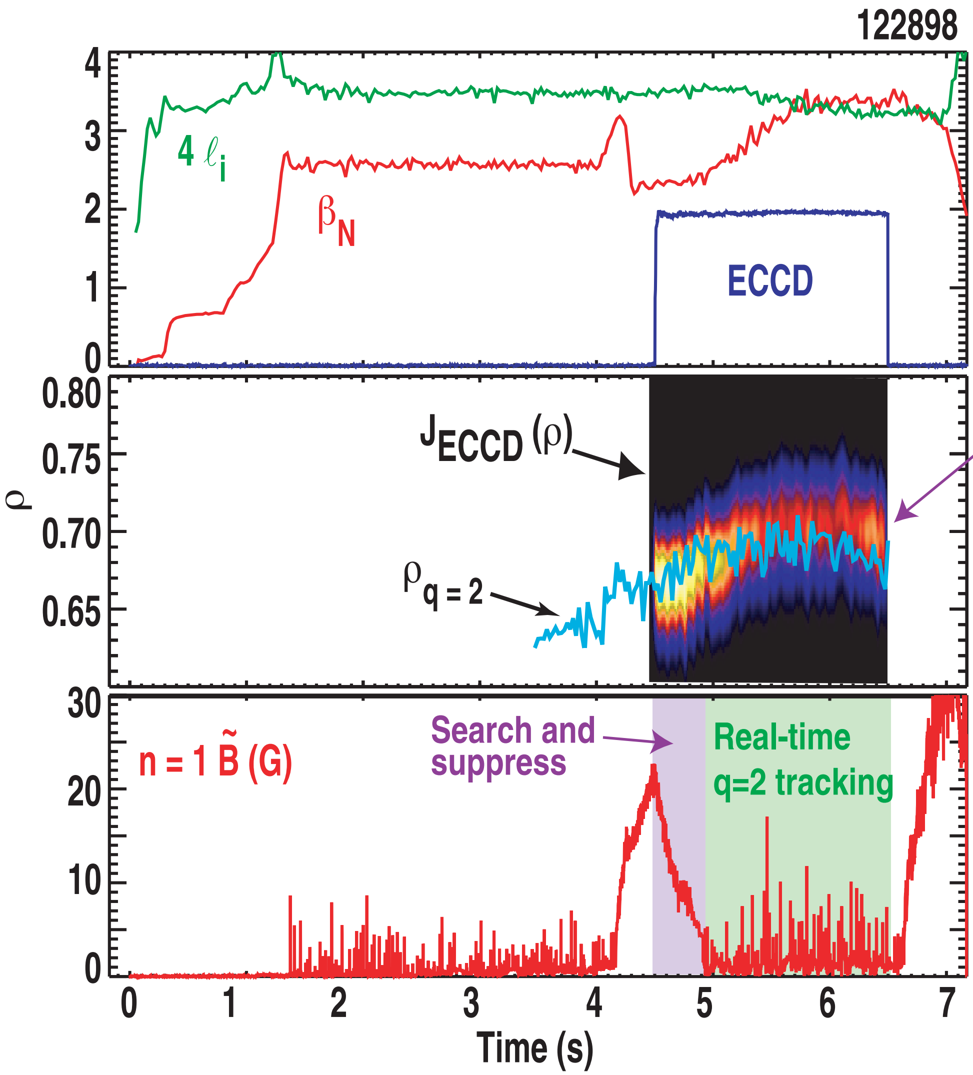
Experiments Have Proven Theoretical Expectation that Driving Current At Island Location Will Stabilize NTM



- Localized current drive at island location

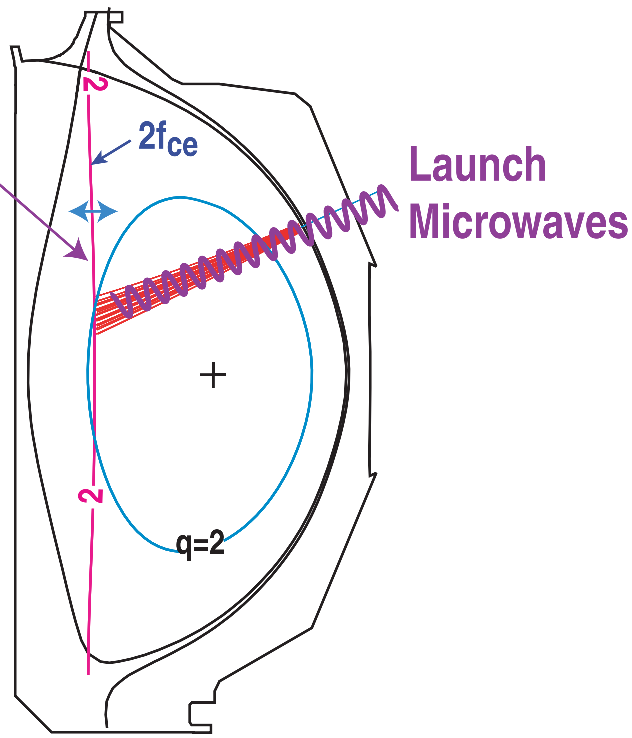


Real-time Tracking of Island Location Required for NTM Suppression

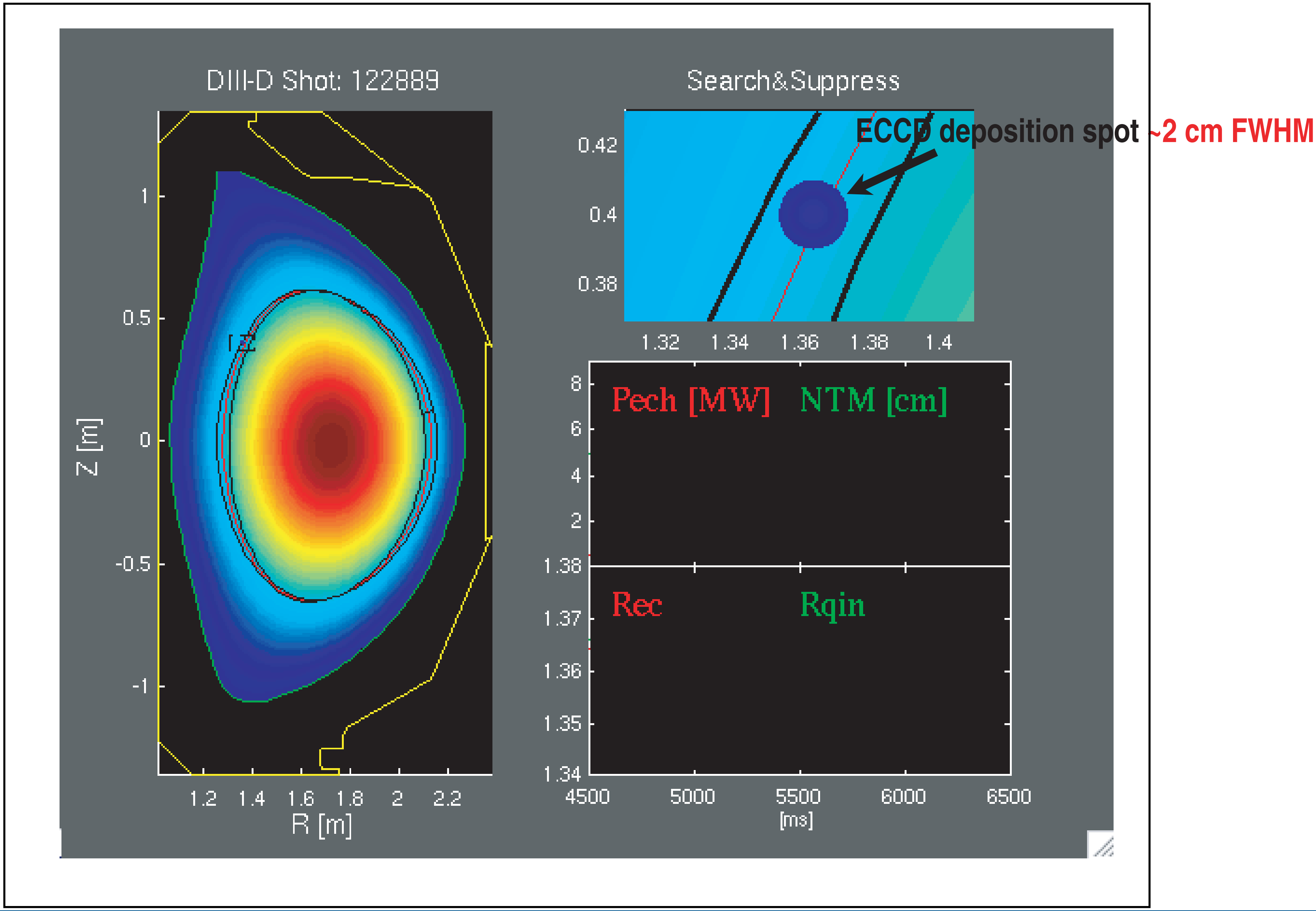


- Optimal location for NTM suppression found by real-time searching and maintained by tracking of q=2 surface using real-time equilibrium reconstructions including MSE (every 6 ms)

Microwave deposition location controlled by moving 2nd harmonic resonance

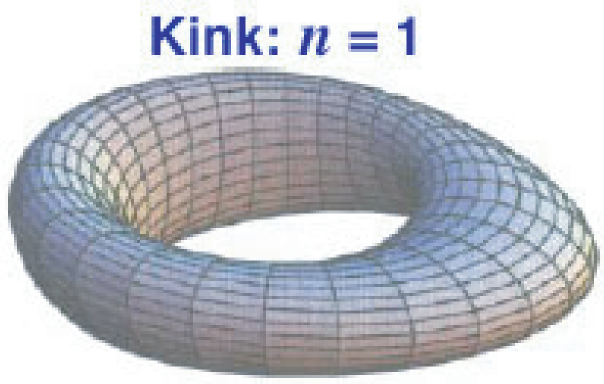


Real-time Dynamic Control Utilized to Maintain Precise Alignment of Current Drive with NTM Location



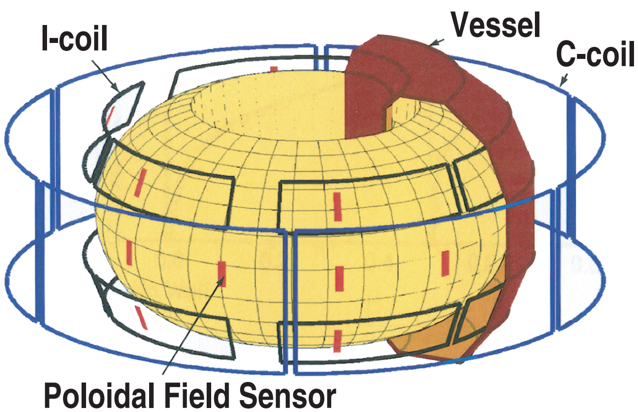
Resistive Wall Mode Stabilization Relies on Dynamic Control Via Non-Axisymmetric Coils

- **Low-n kink instabilities occur at very high plasma pressure**
  - Very fast growth time (~10 μs)
  - Stabilized by perfectly conducting wall



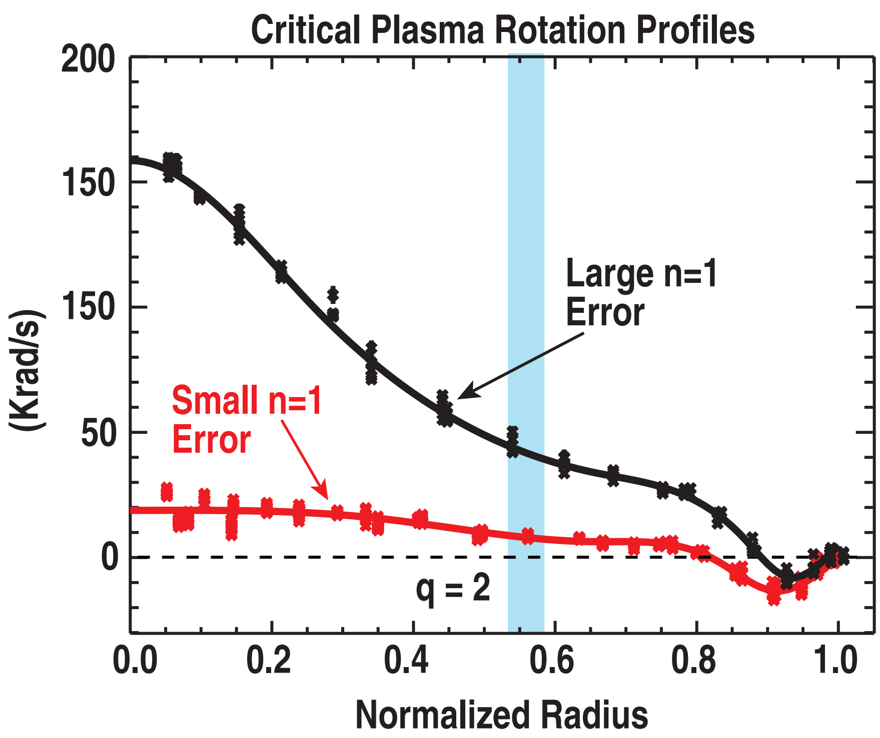
- **With finite conductivity wall, instability is weakly damped leading to resistive wall modes**
  - Moderate growth time (~10 ms)

- **DIII–D experiments have identified two methods for RWM stabilization:**
  - Plasma rotation (magnitude dependent on n=1 error field)
  - Feedback control using non-axisymmetric coils

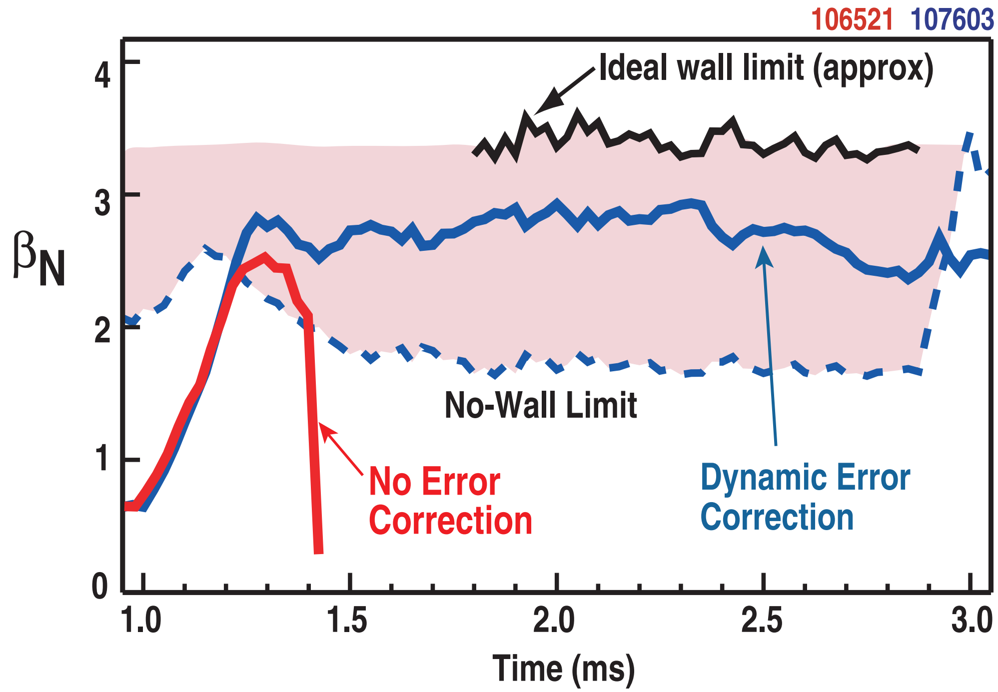


Real-time Error Field Correction Enables Sustained Operation Near Absolute Pressure Limit

- Critical Rotation for RWM Stabilization Sensitive to n=1 Error Field

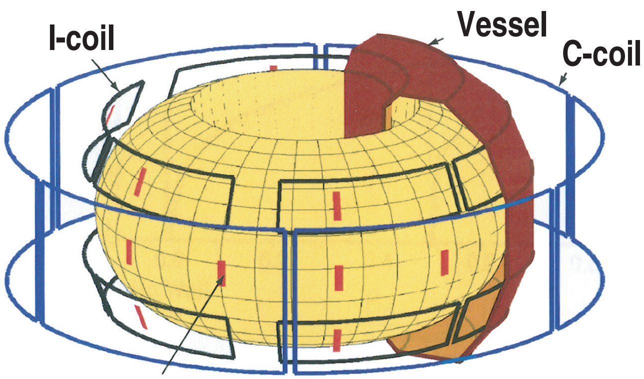


- With n=1 error dynamically controlled, high pressure can be maintained

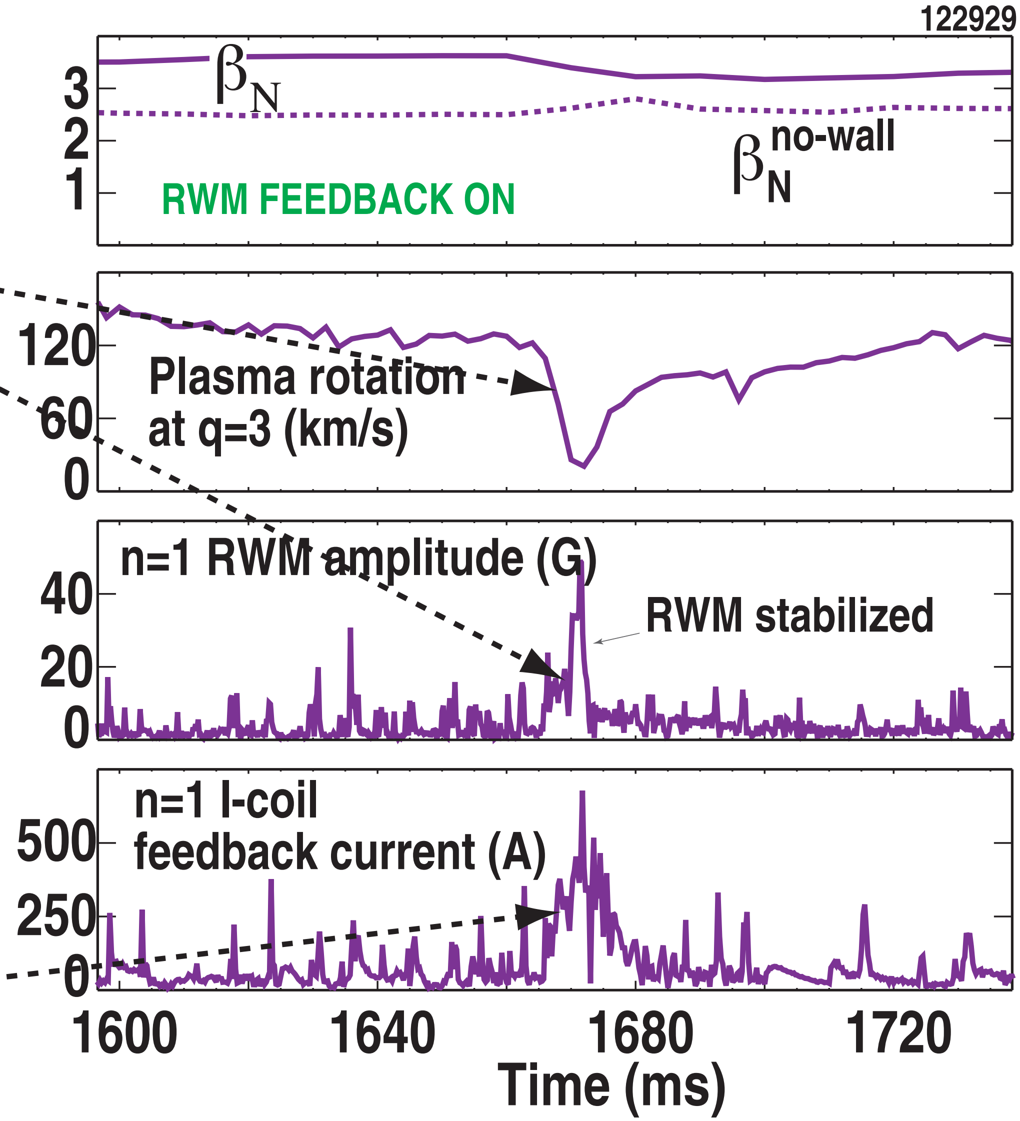


Even in Cases with High Rotation, Rapid Feedback Control System Required to Respond to Transient Events

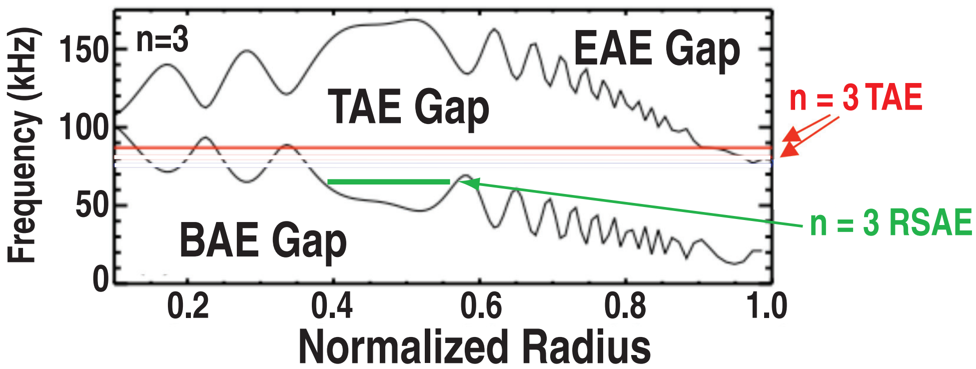
- **Transient event causes loss of rotation and destabilization of RWM**



- **Using internal coils (I-coils), high bandwidth feedback system stabilizes RWM**



Improved Diagnostics Now Allow Detailed Investigation of Fast Particle Driven Instabilities



- **Small-scale instabilities driven by fast particle population exist in "gaps" of Alfvén continuum**
- **Radial extent of instabilities determined by interaction with continuum**
  - Not easy to measure with external diagnostics

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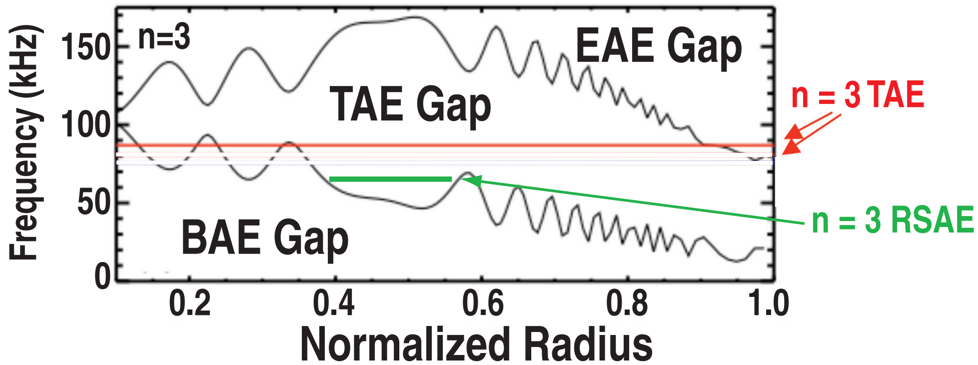
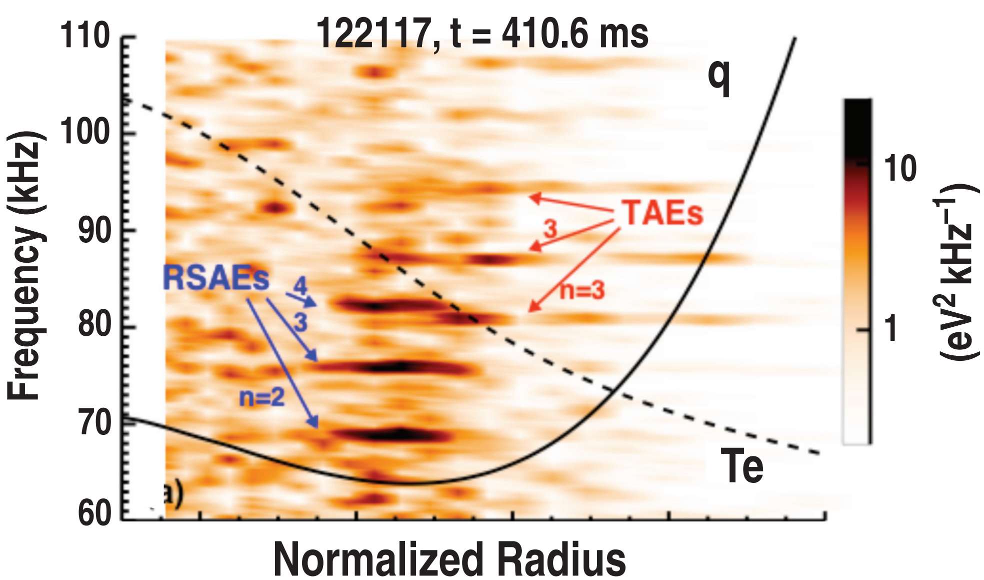
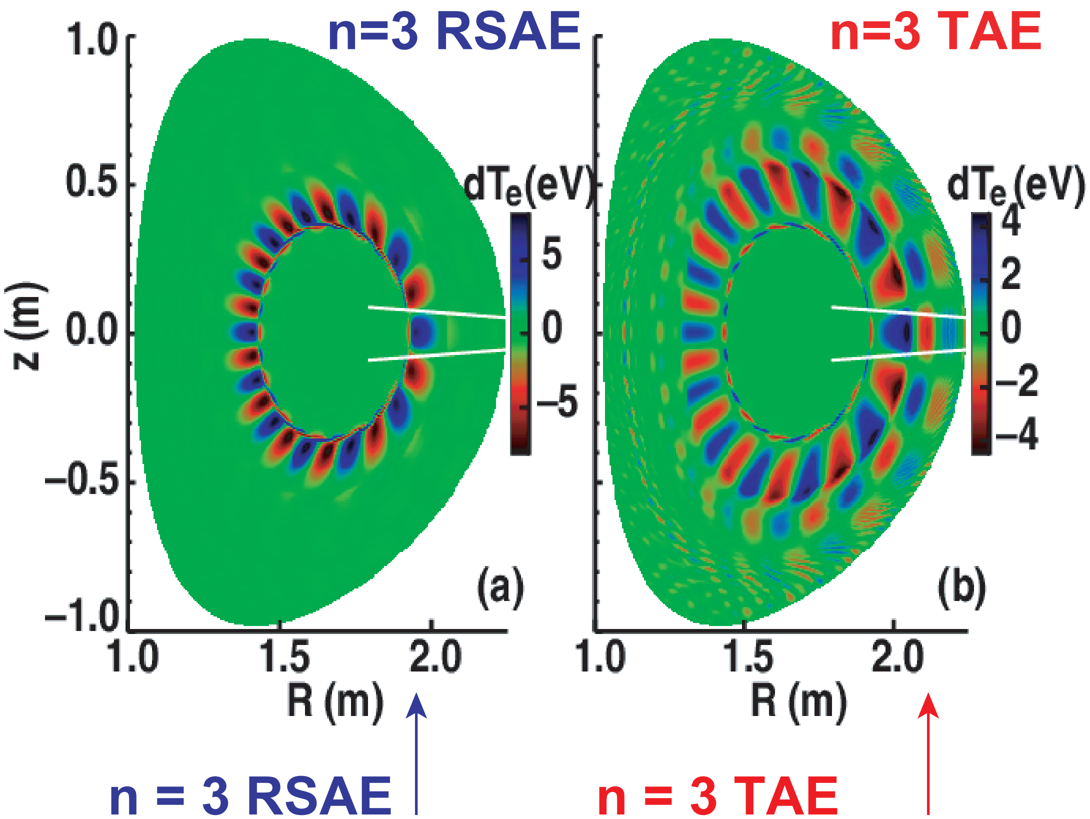




- **Small-scale instabilities driven by fast particle population exist in "gaps" of Alfvén continuum**
- **Radial extent of instabilities determined by interaction with continuum**
  - Not easy to measure with external diagnostics
- **New fluctuation diagnostics with high spatial resolution allow precise measurement of instabilities**

Measured Radial Structure Agrees Extremely Well with Theory Predictions

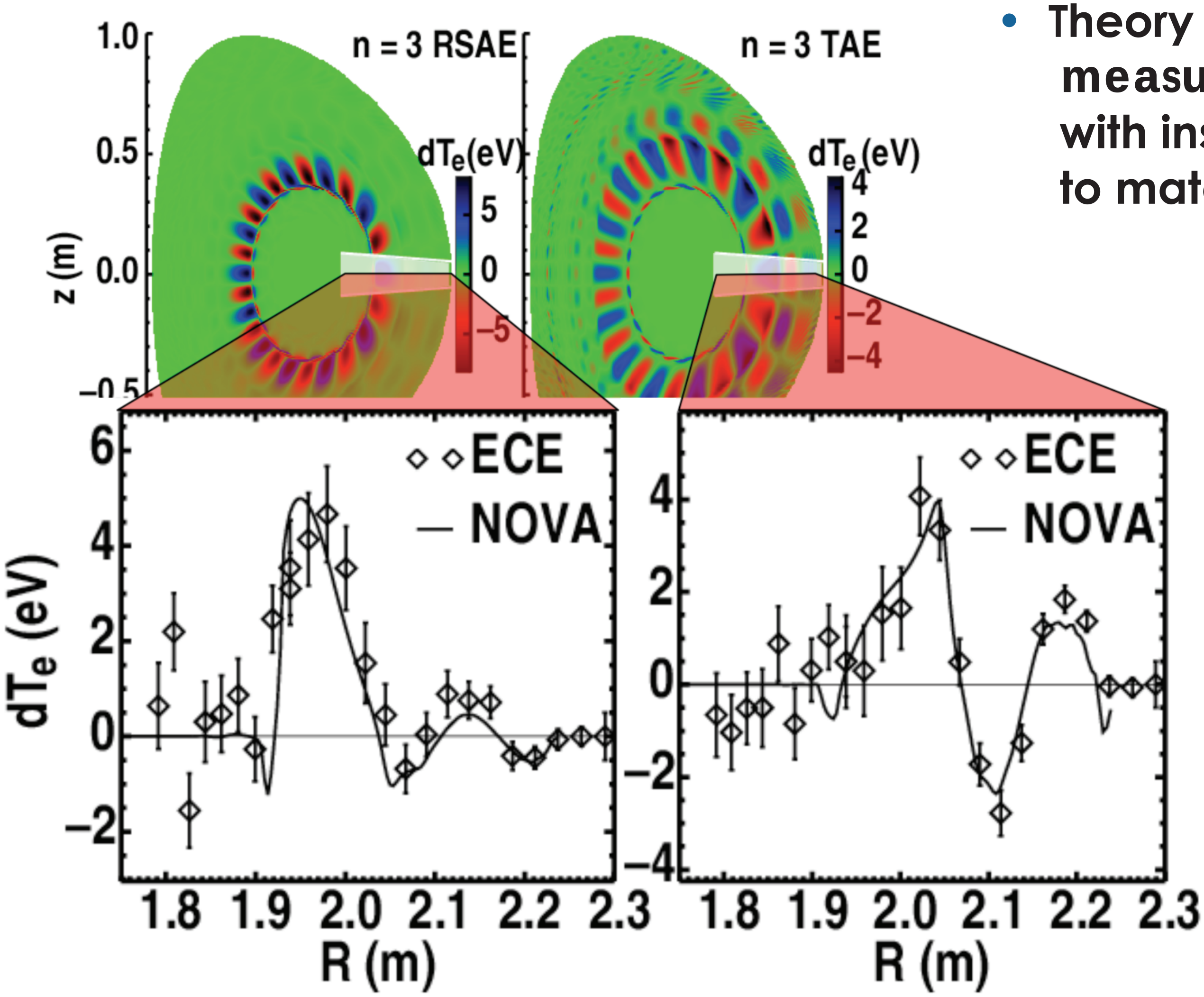


n = 3 RSAE
f_{exp} = 75.8 kHz
f_{NOVA} = 72.3 kHz

n = 3 TAE
f_{exp} = 80.8 kHz
f_{NOVA} = 73.5 kHz

- Theory predictions based on measured plasma properties with instability strength scaled to match measurement

Measured Radial Structure Agrees Extremely Well with Theory Predictions



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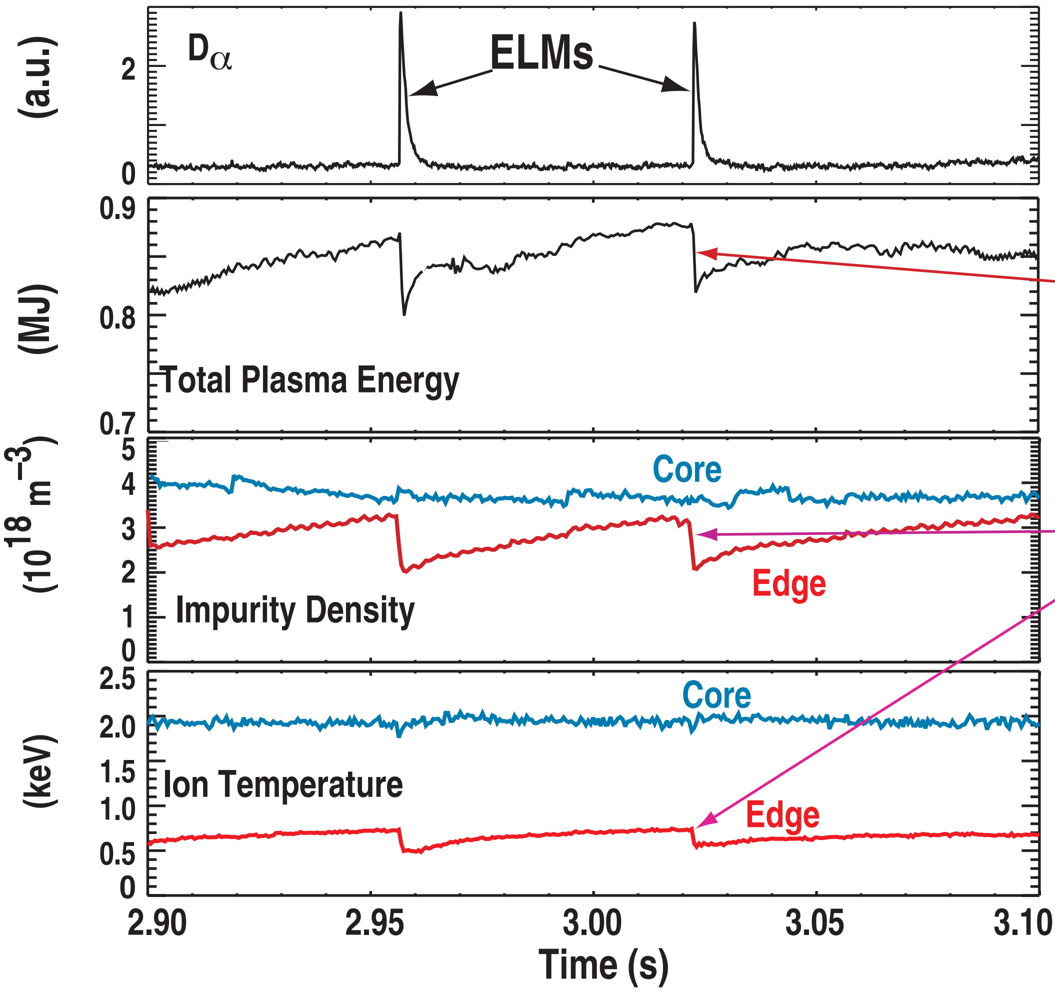
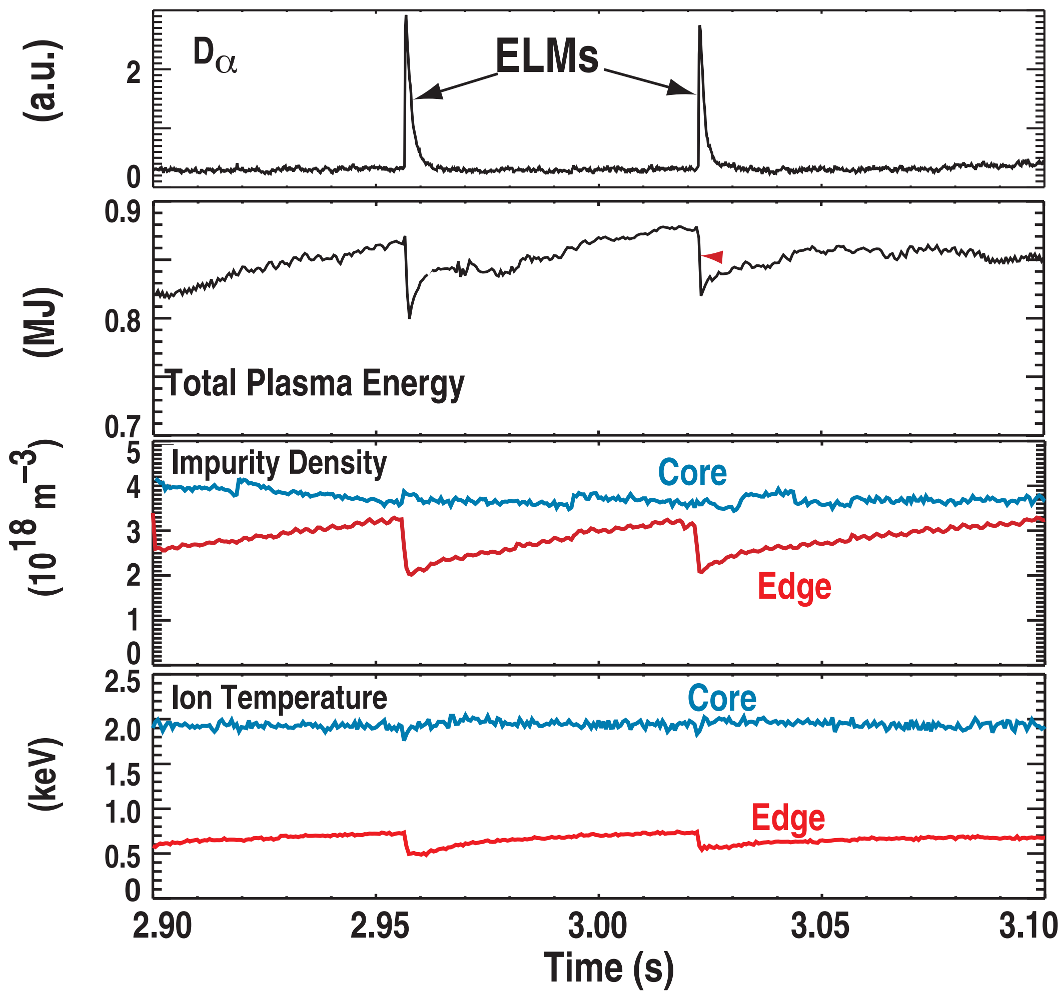
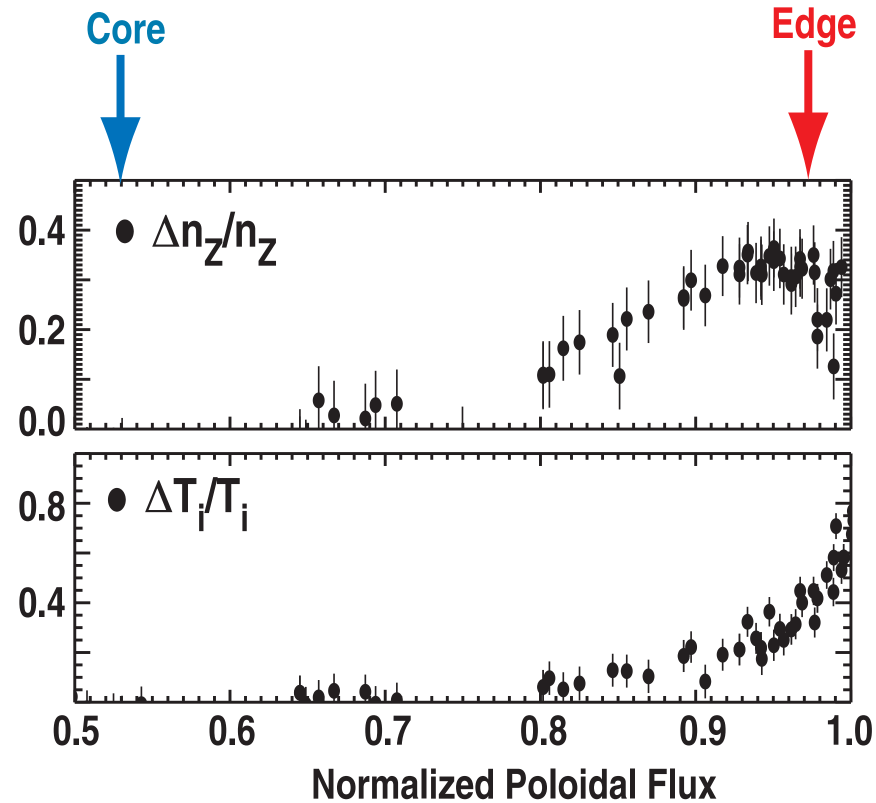
High Confinement Regimes (known as H-mode) Are Generally Accompanied by Edge Instabilities (ELMs)



- **Plasma Energy Builds Up Until an Instability Causes a Rapid Loss of Energy**
  - **In this case, 10% of plasma energy is lost in 100 μs**
- **High time resolution measurements indicate that the instability only impacts the edge plasma**
  - Known as an Edge Localized Mode (or ELM)

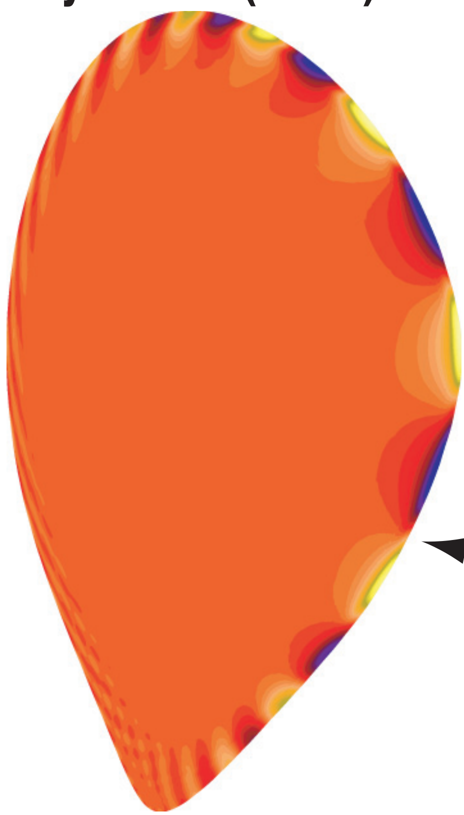
High Spatial Resolution Measurements Show that the ELM-induced Perturbation is Localized Near the Edge



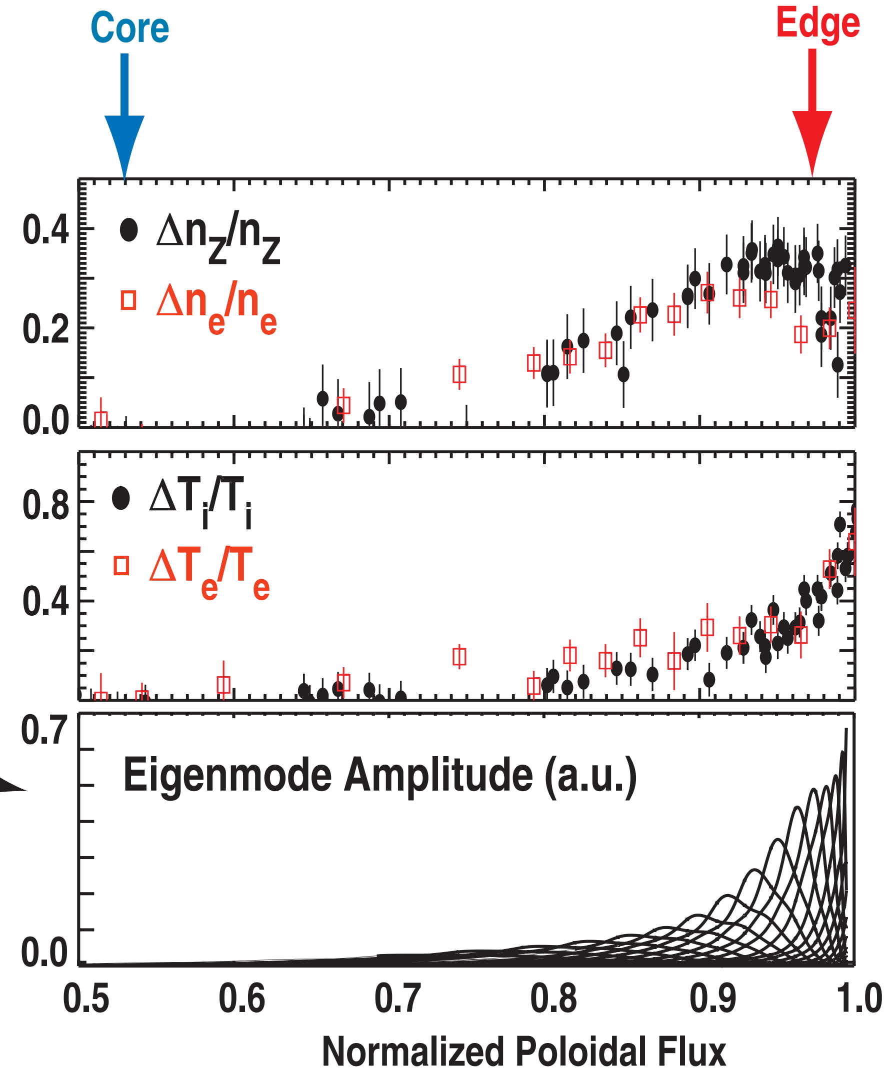


Measured Perturbation is Consistent with Predictions of Expected Radial Structure of Peeling-Ballooning Instability

Eigenmode structure calculated by ELITE (n = 6)

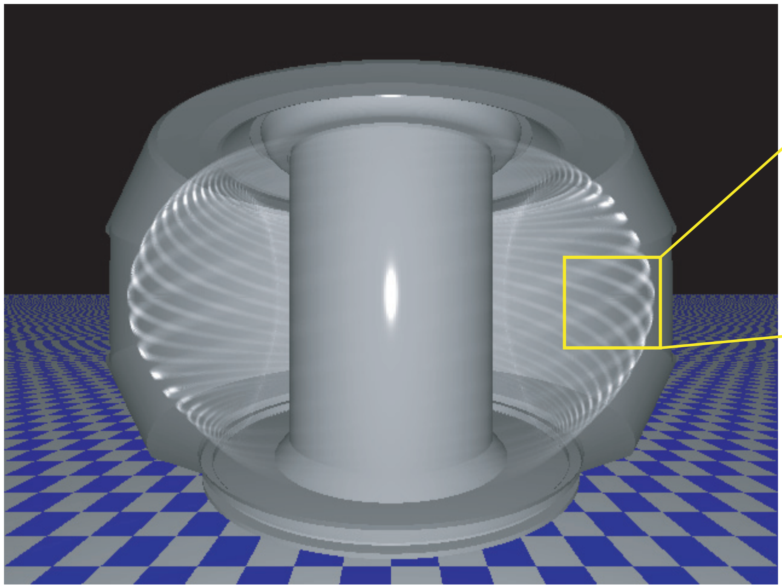


Theory

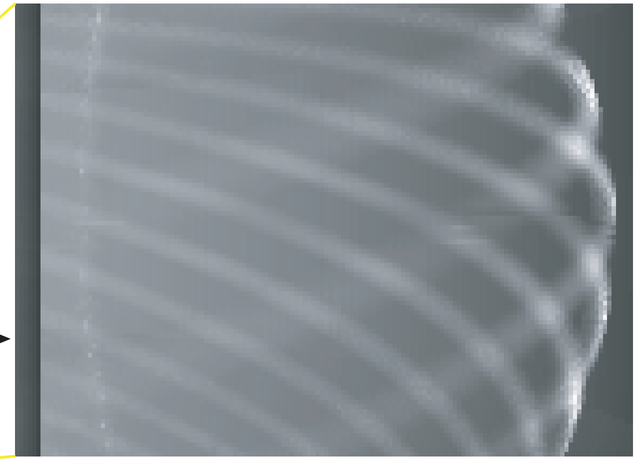


High Speed Camera Images Confirm Predicted Filamentary Structure of ELMs

In 3-D, Filamentary Structure is Evident



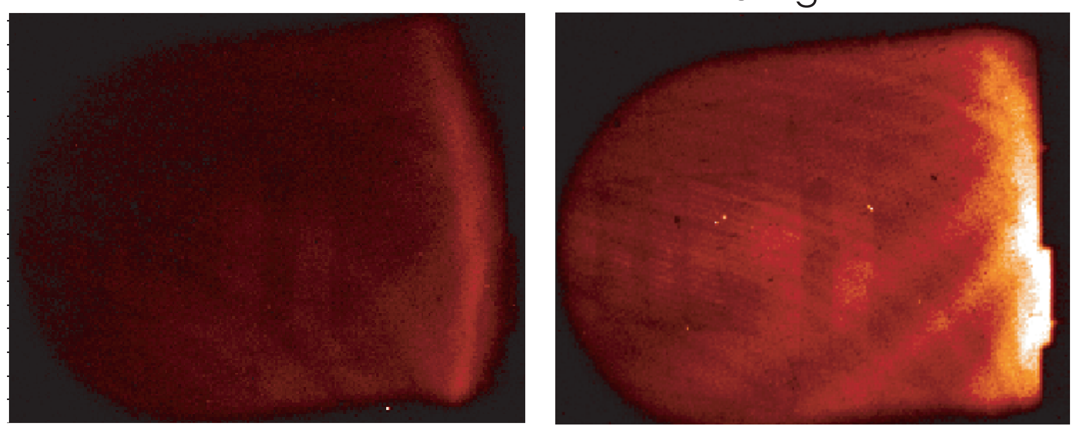
← **Simulation** →



Experiment

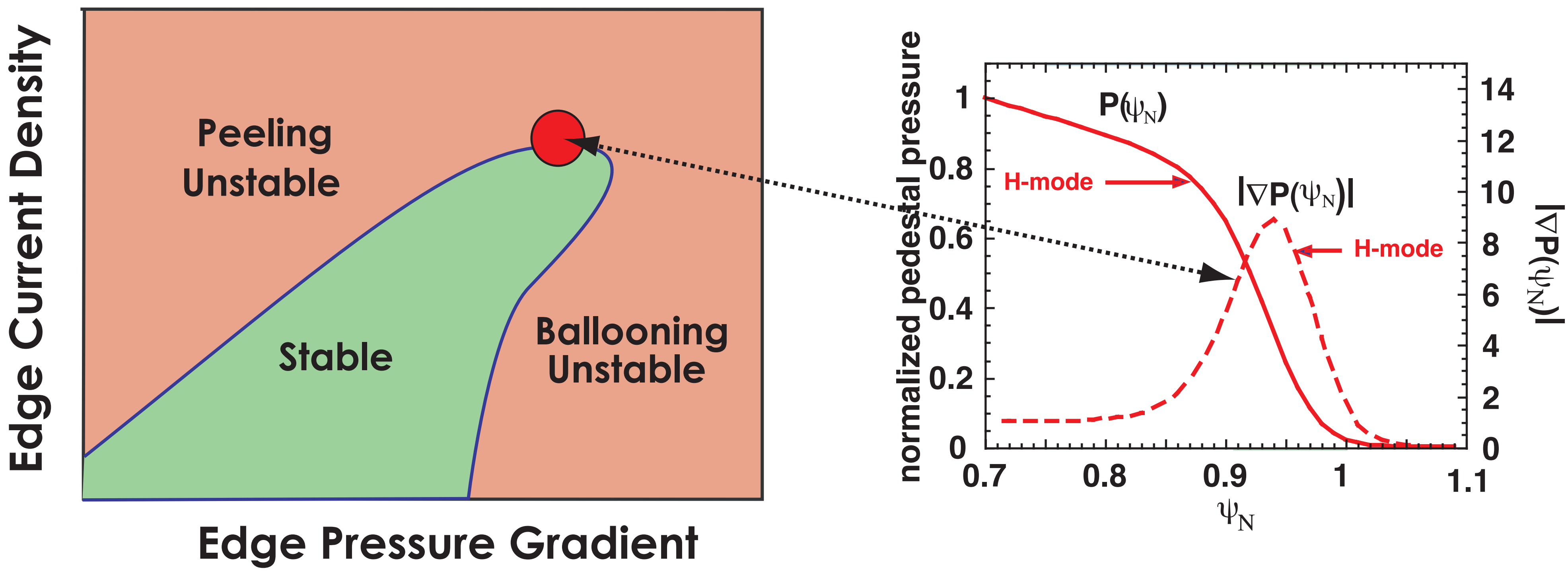
Camera Images of CIII Emission During ELM Event

1 ms Before ELM | During ELM

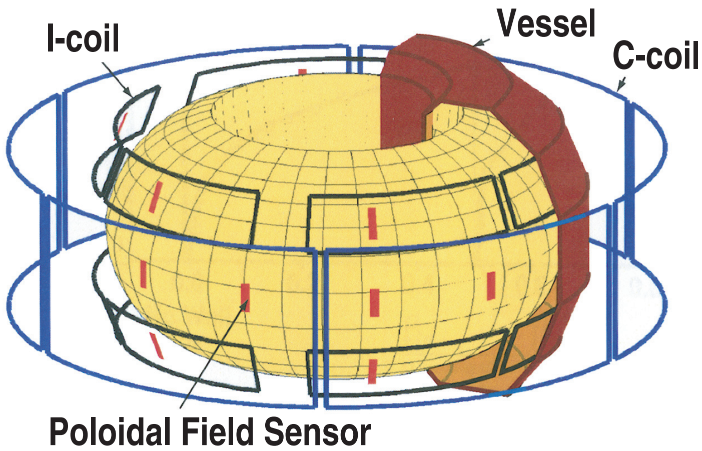


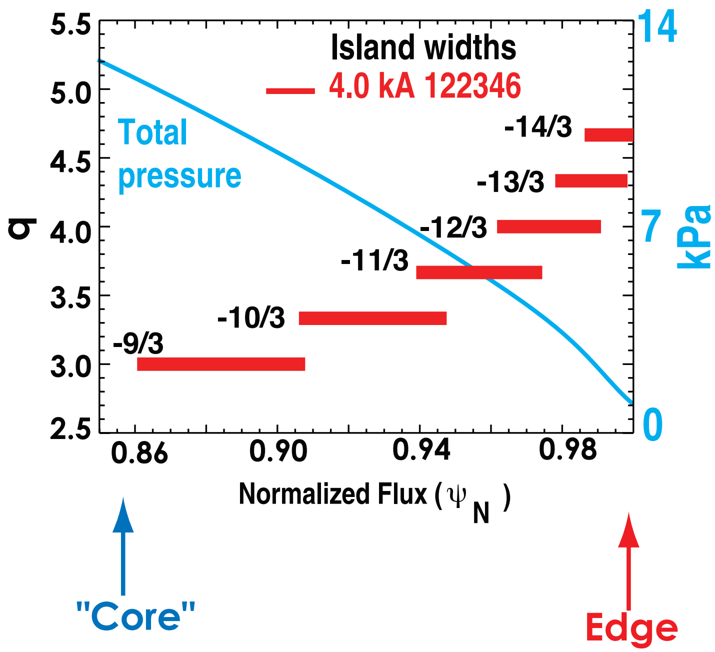
Typical H-mode Plasmas Characterized by Large Pressure Gradient Near the Plasma Edge

- Peeling-Ballooning theory suggests that ELMs are highly sensitive to both the edge pressure gradient and the edge current density

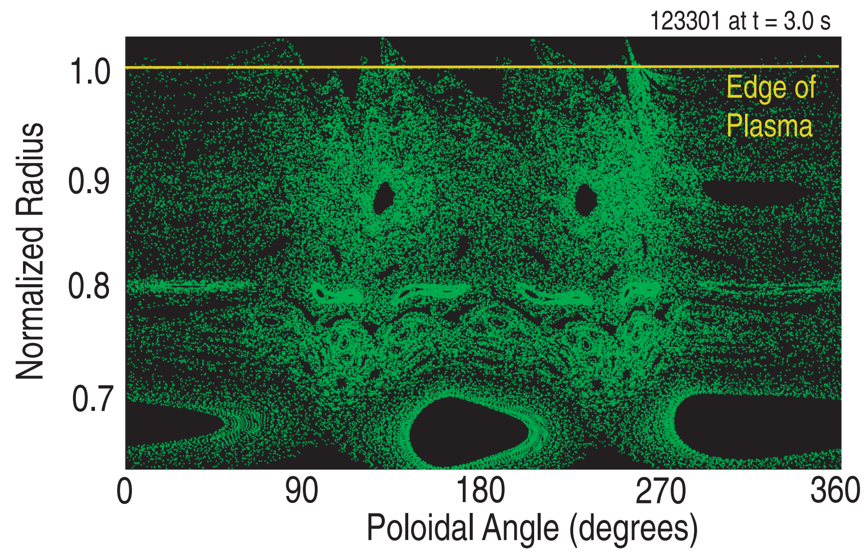


DIII–D Experiments Have Demonstrated That ELMs Can Be Controlled Using 3–D Magnetic Fields

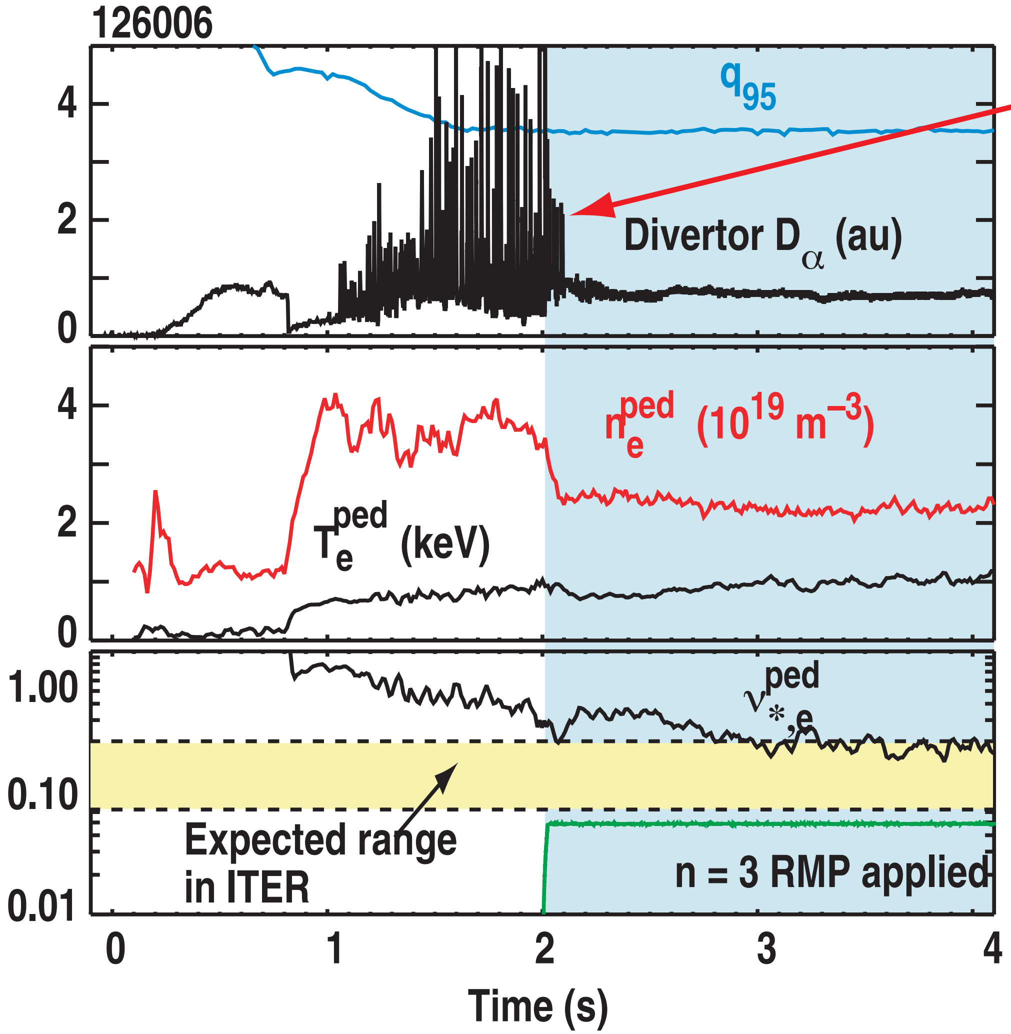




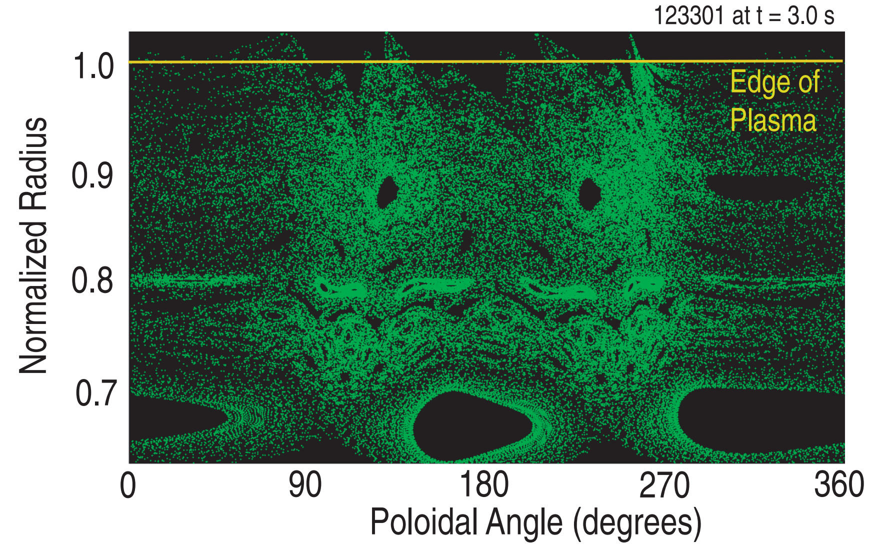
- **3-D fields generate a stochastic region in plasma edge, causing increased transport**



DIII–D Experiments Have Demonstrated That ELMs Can Be Controlled Using 3–D Magnetic Fields

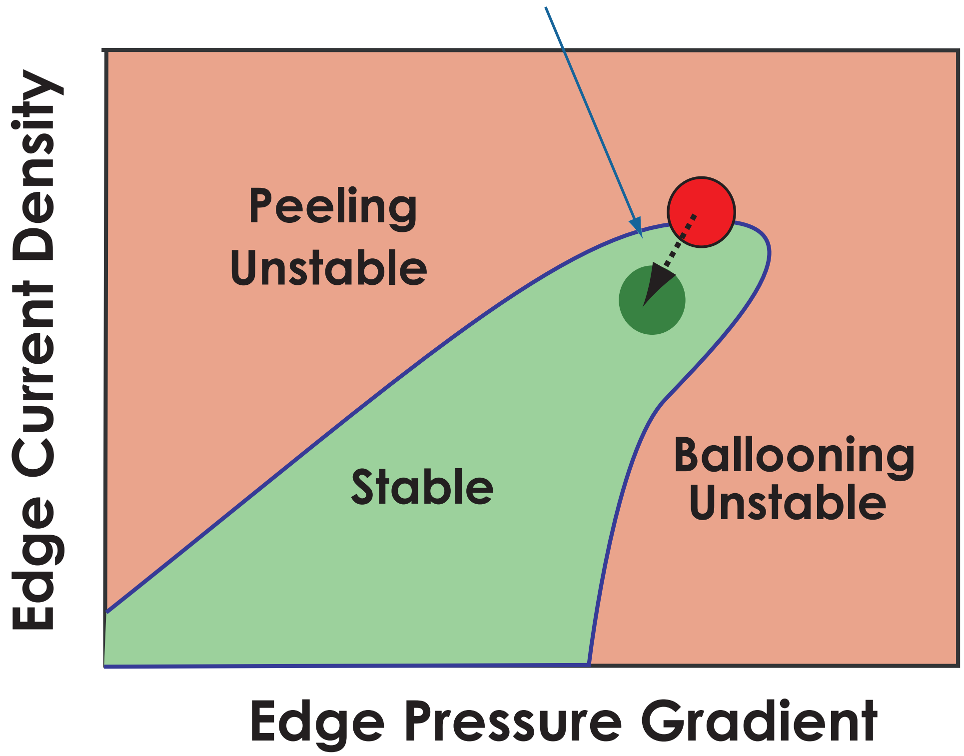


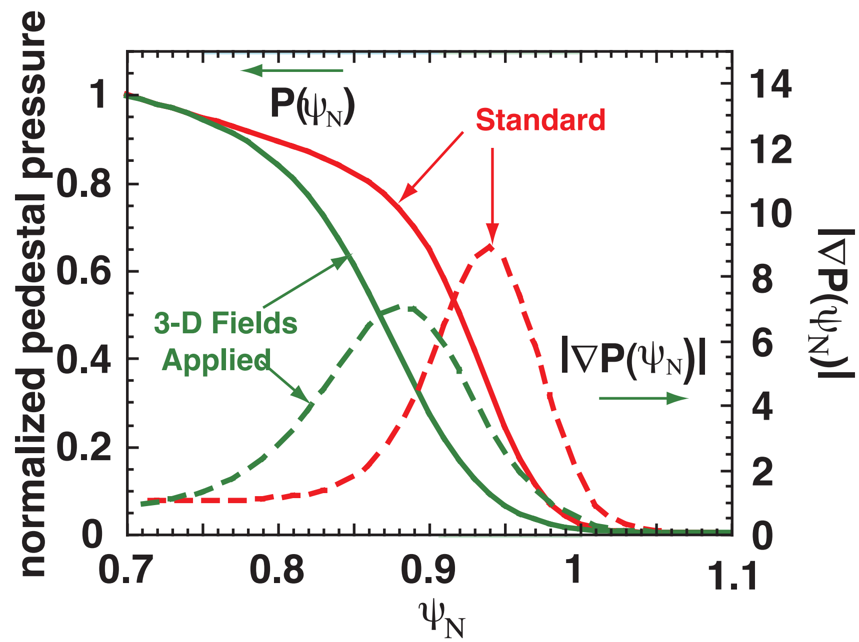
- ELMs suppressed immediately when 3-D fields are applied



Applying 3-D Fields Reduces the Edge Pressure Gradient and Enables ELM-free Operation

- **Increased Transport due to 3-D Fields Moves Pressure Gradient Slightly Away from Stability Boundary, Leading to ELM-free Operation**





- **Required perturbation for ELM suppression is only 10^{-4} of background magnetic field !!!**

Improved Physics Understanding and Control Capabilities Provide Confidence that ITER will Succeed

- **Good Energy Confinement**
  - Reduce Heat Leakage Rate to a Minimum
    - ⇨ **Many Aspects of Turbulent-Driven Transport Now Understood**
      - ➥ **Increased Confidence in Confinement Extroplations to ITER**
- **High Plasma Pressure**
  - Avoid or Control Large-Scale Instabilities
    - ⇨ **Pressure Limits Well Documented; Methods for Controlling Major Instabilities Demonstrated**
      - ➥ **Developed control tools included in ITER baseline design**
- **Shield Chamber Walls from Hot Core Plasma**
  - Reduce Focusing of Energy on Small Areas
    - ⇨ **Methods for Reducing Transient Heat Fluxes Demonstrated**
      - ➥ **3-D magnetic coil set being considered for ITER design**
- **Successful demonstration on DIII-D of "advanced" scenarios provide significant performance margin**