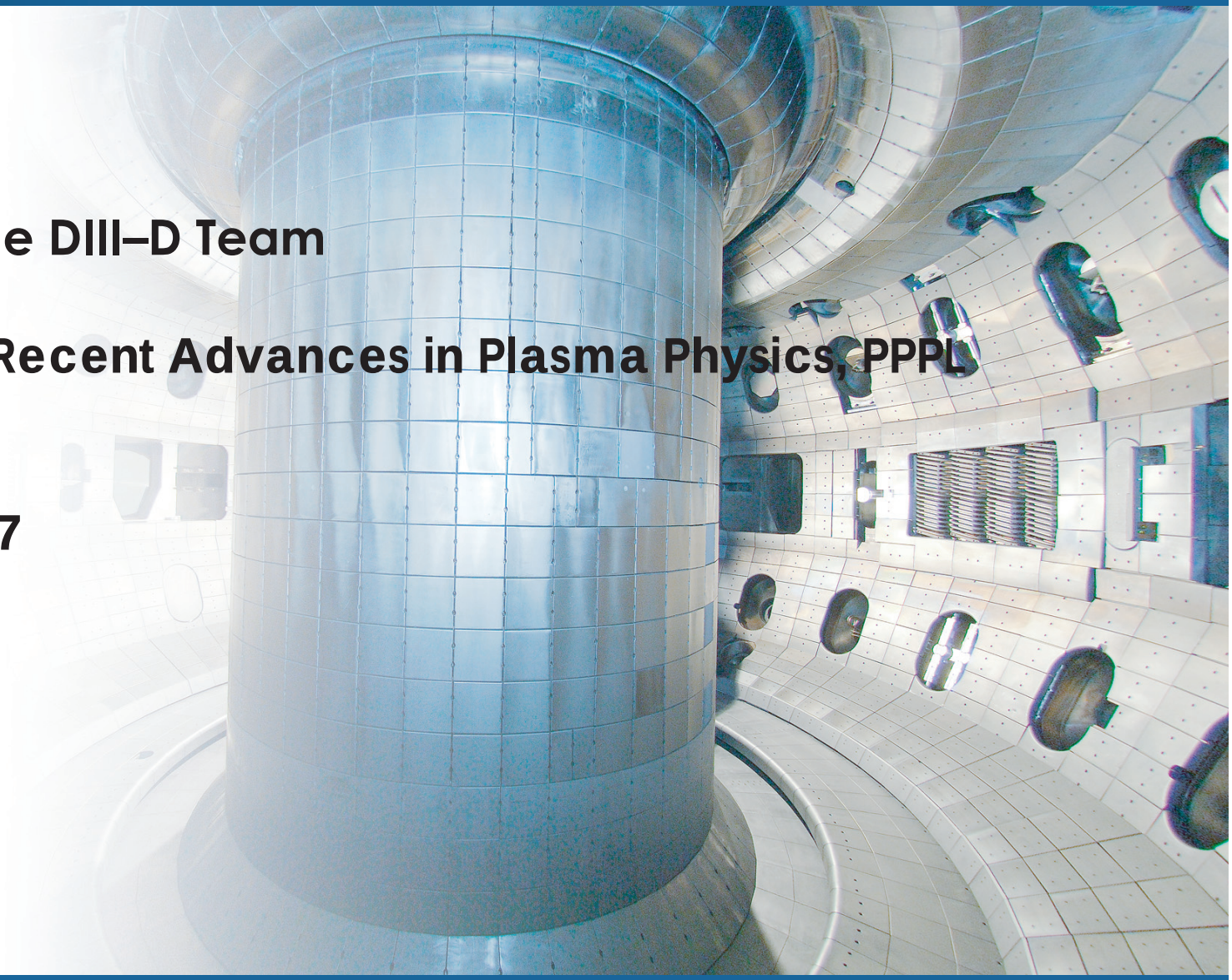
Results from DIII-D and Future Directions



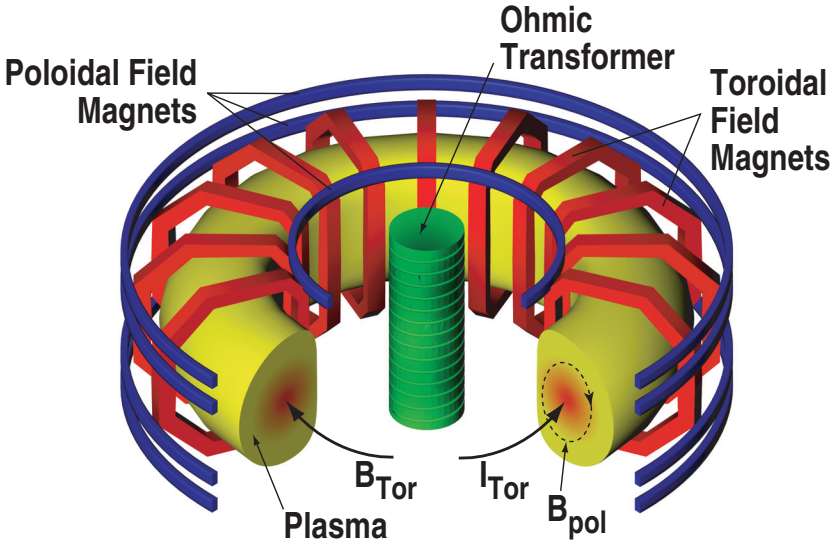
by
V. S. Chan for the DIII–D Team

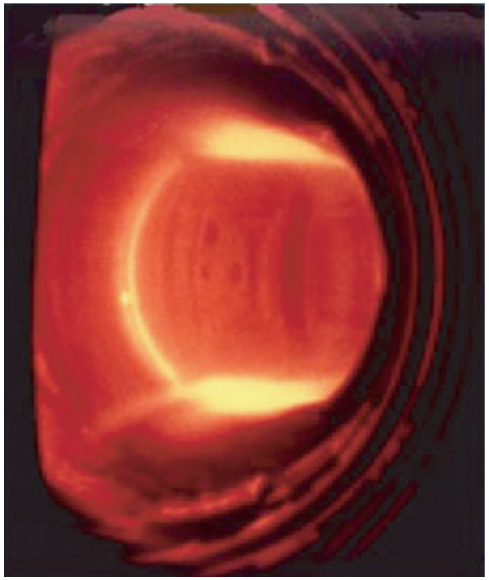
Symposium on Recent Advances in Plasma Physics, PPPL

June 11-12, 2007

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 MW of fusion power**

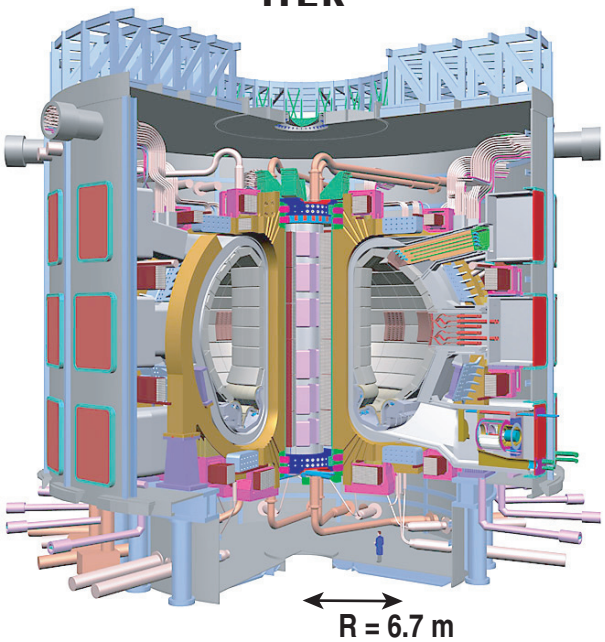
ITER: The Next Frontier in Fusion Energy Research and a Grand Scientific Challenge for the World Community

- 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



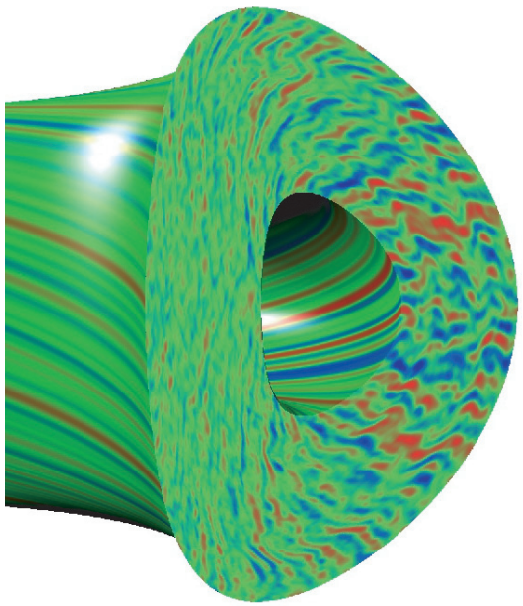
- Designed for 500 MW fusion power production for pulse of 300 s

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**

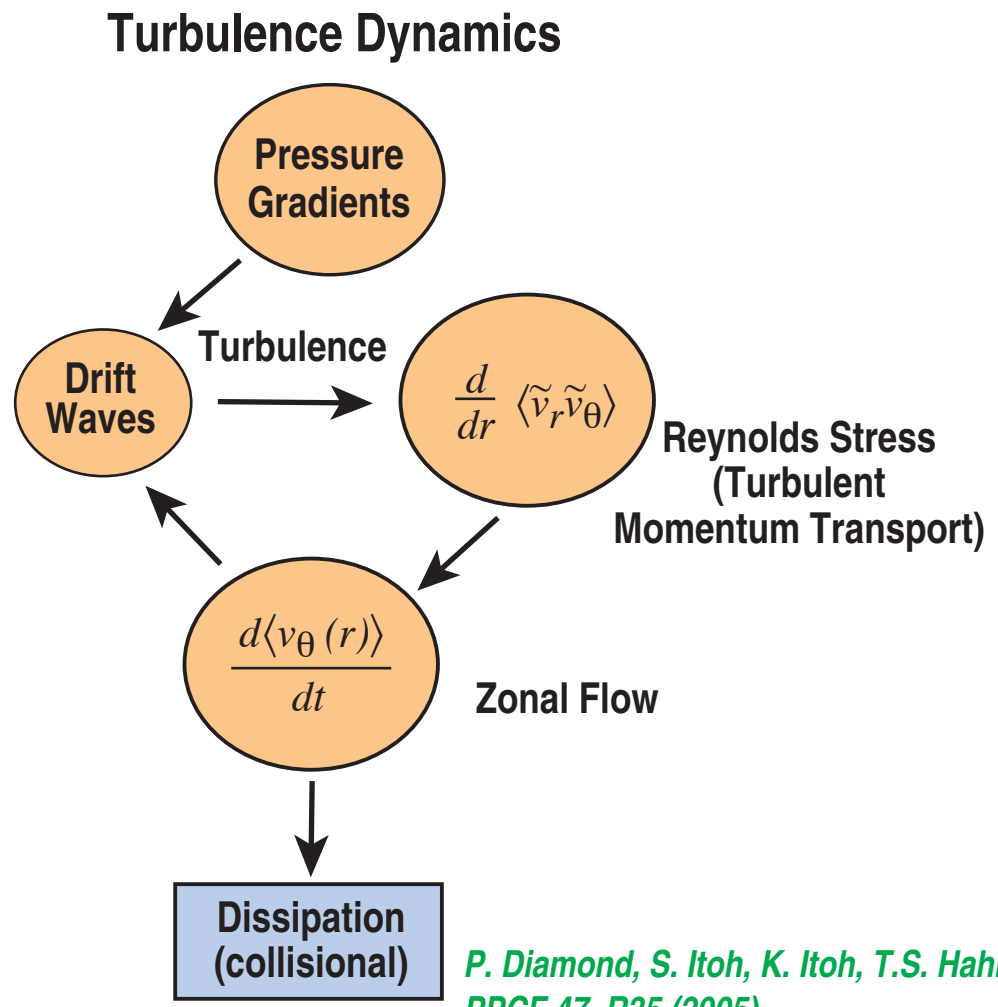
DIII–D Experiments are Confirming Theoretical Picture of Turbulence-Driven Transport

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



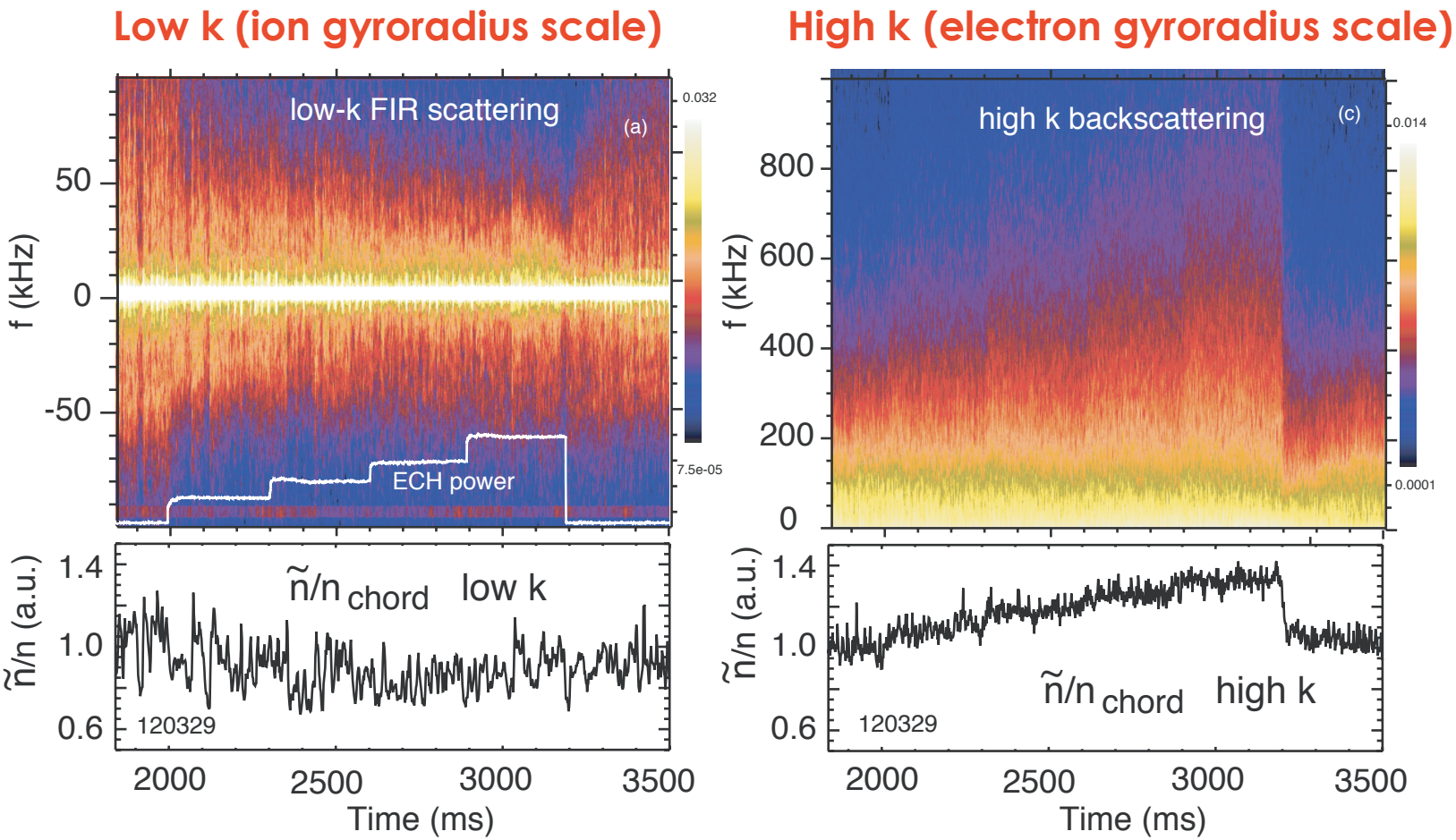
Includes:

- Kinetic electrons
- Finite pressure (β)

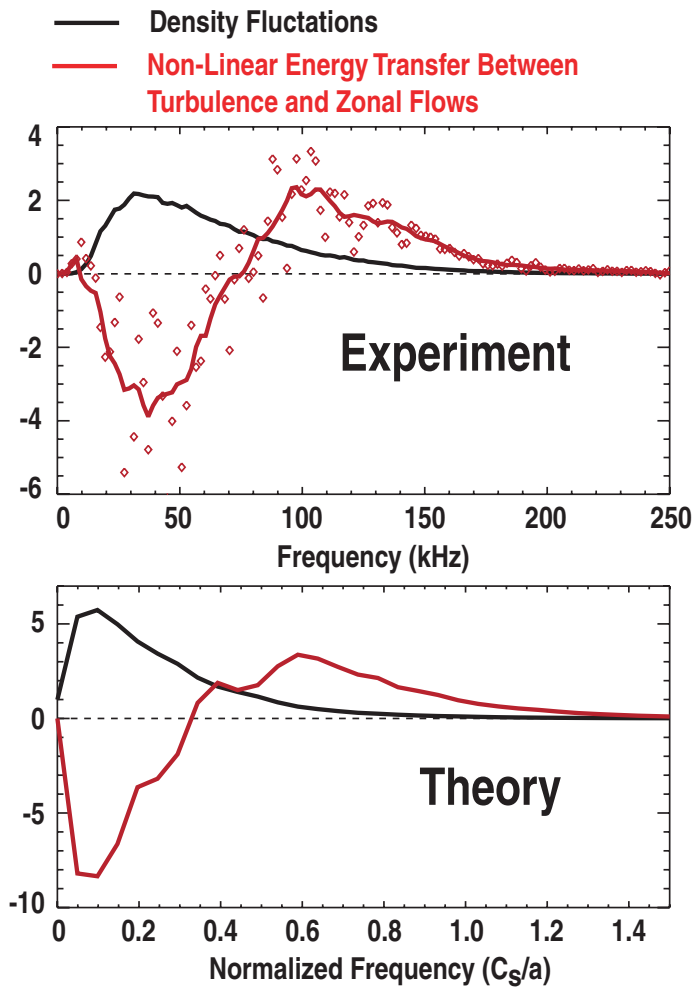


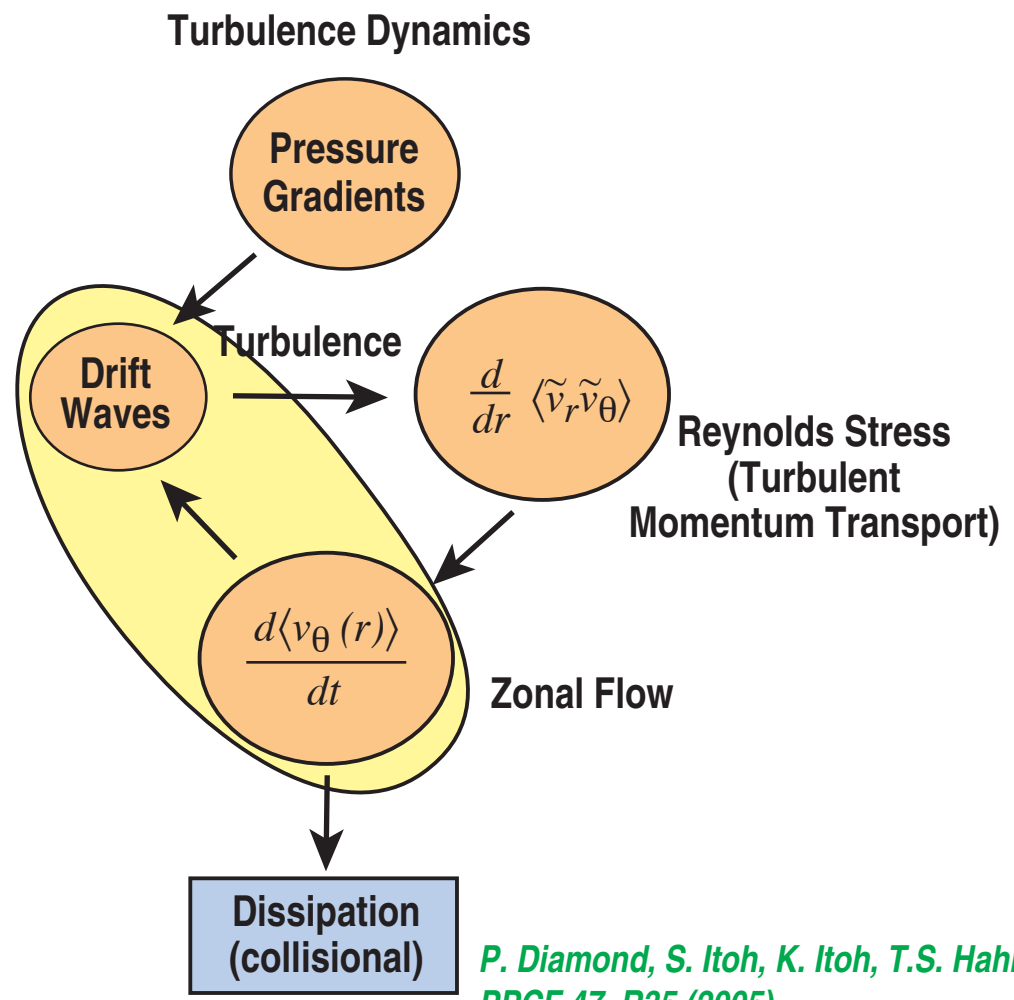
P. Diamond, S. Itoh, K. Itoh, T.S. Hahm, PPCF 47, R35 (2005)

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



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

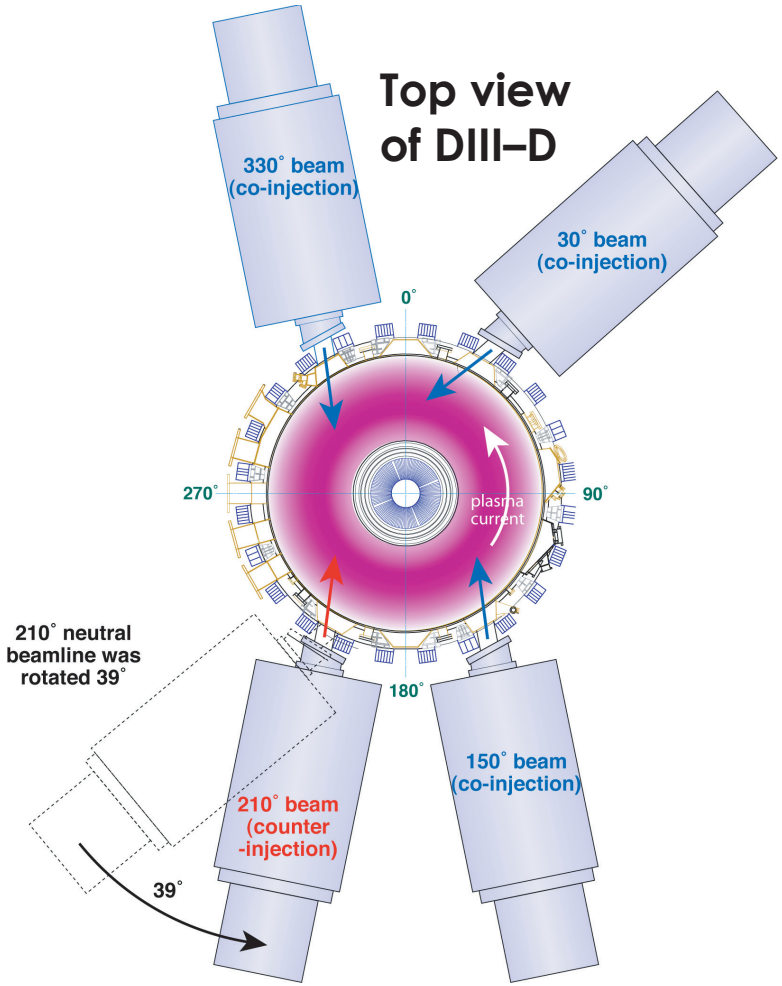




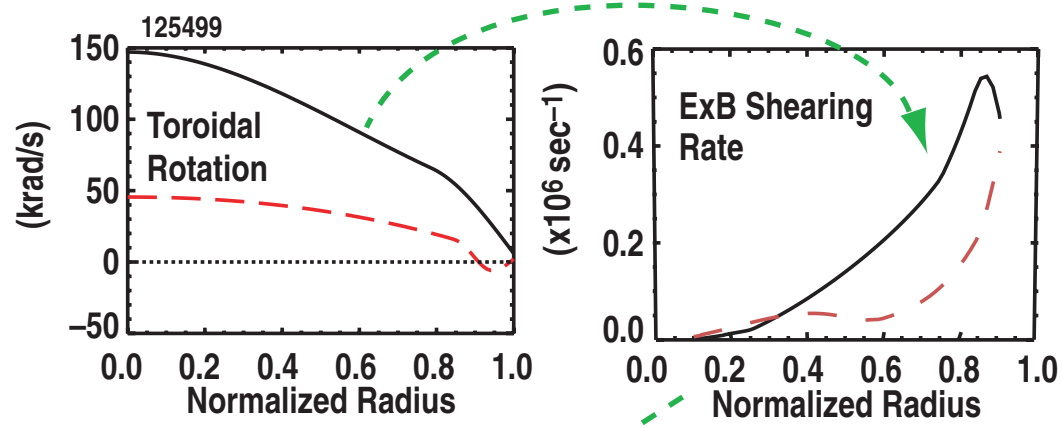
P. Diamond, S. Itoh, K. Itoh, T.S. Hahm, PPCF 47, R35 (2005)

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

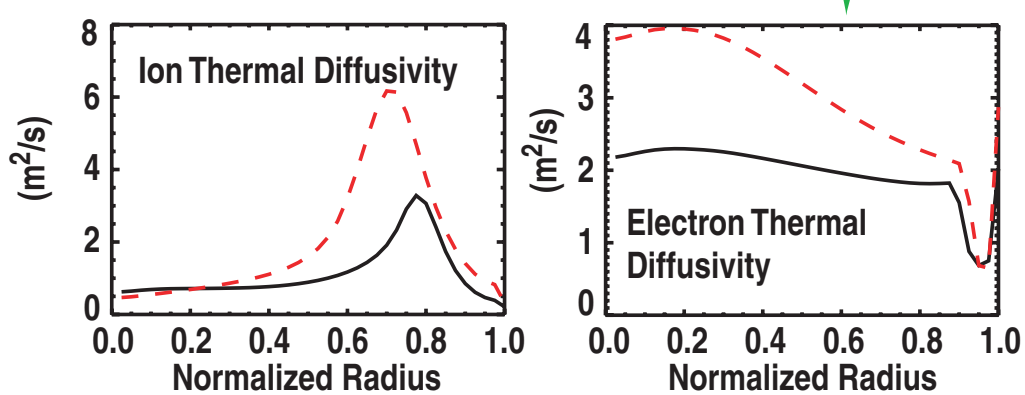
Theoretically Predicted Improvement in Transport as Rotational Shear is Increased Confirmed by Experiments



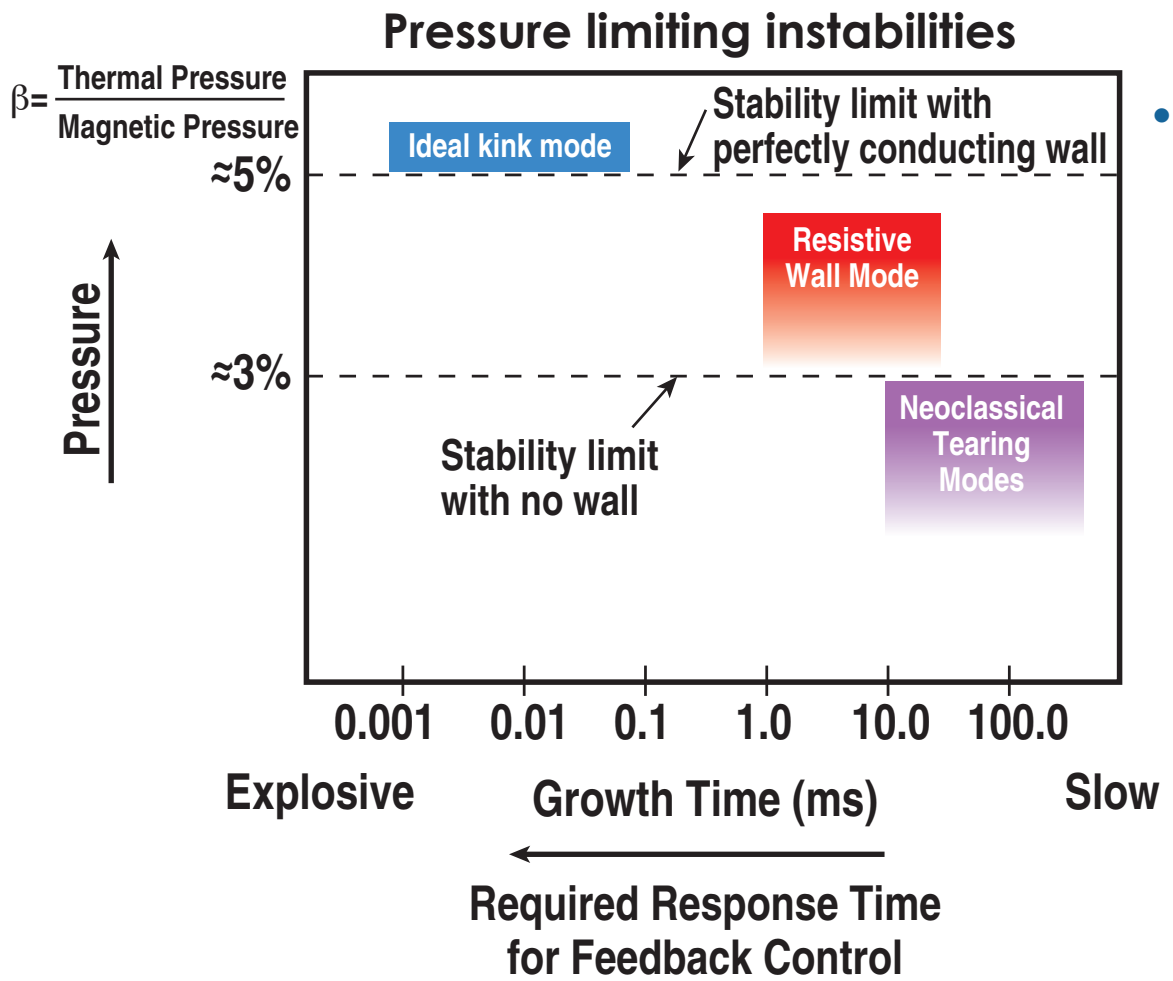
Higher Plasma Rotation Leads to Increased Shear in ExB Flows



Reduced Transport

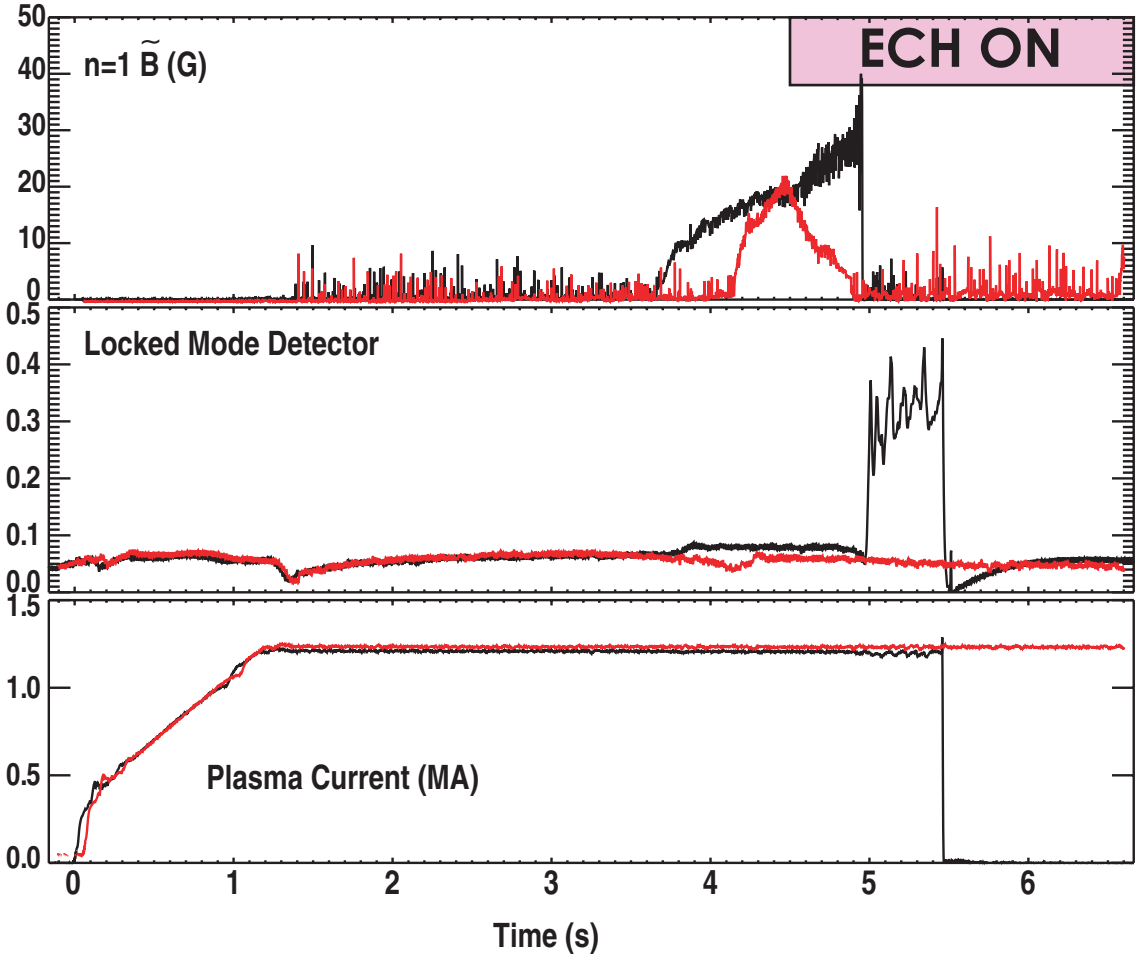


Avoiding or Controlling Large-Scale Instabilities is Essential to Operate at High Pressure

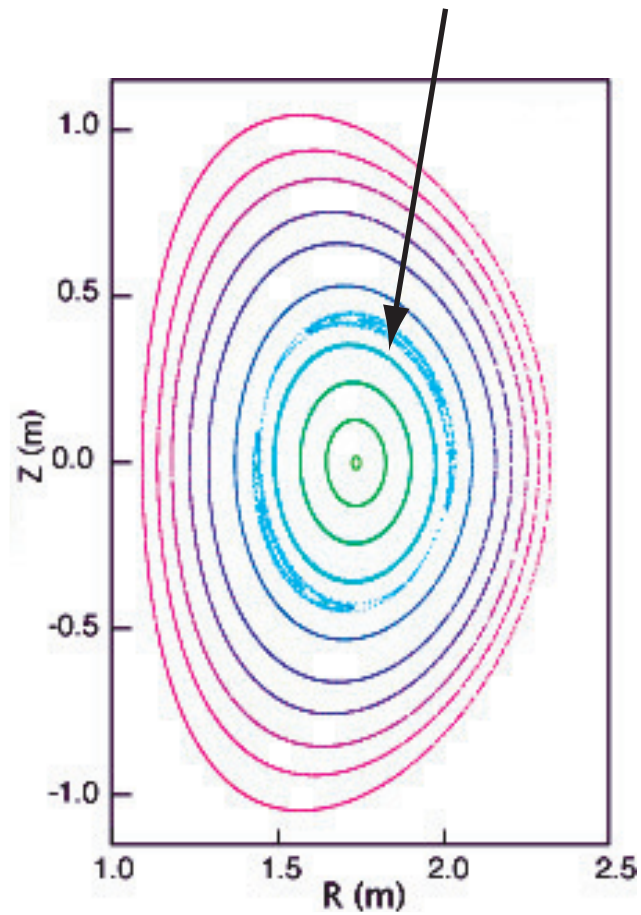


- **Other Instabilities of Importance:**
  - Edge localized modes (ELMs)
  - Fast-Ion Driven Instabilities

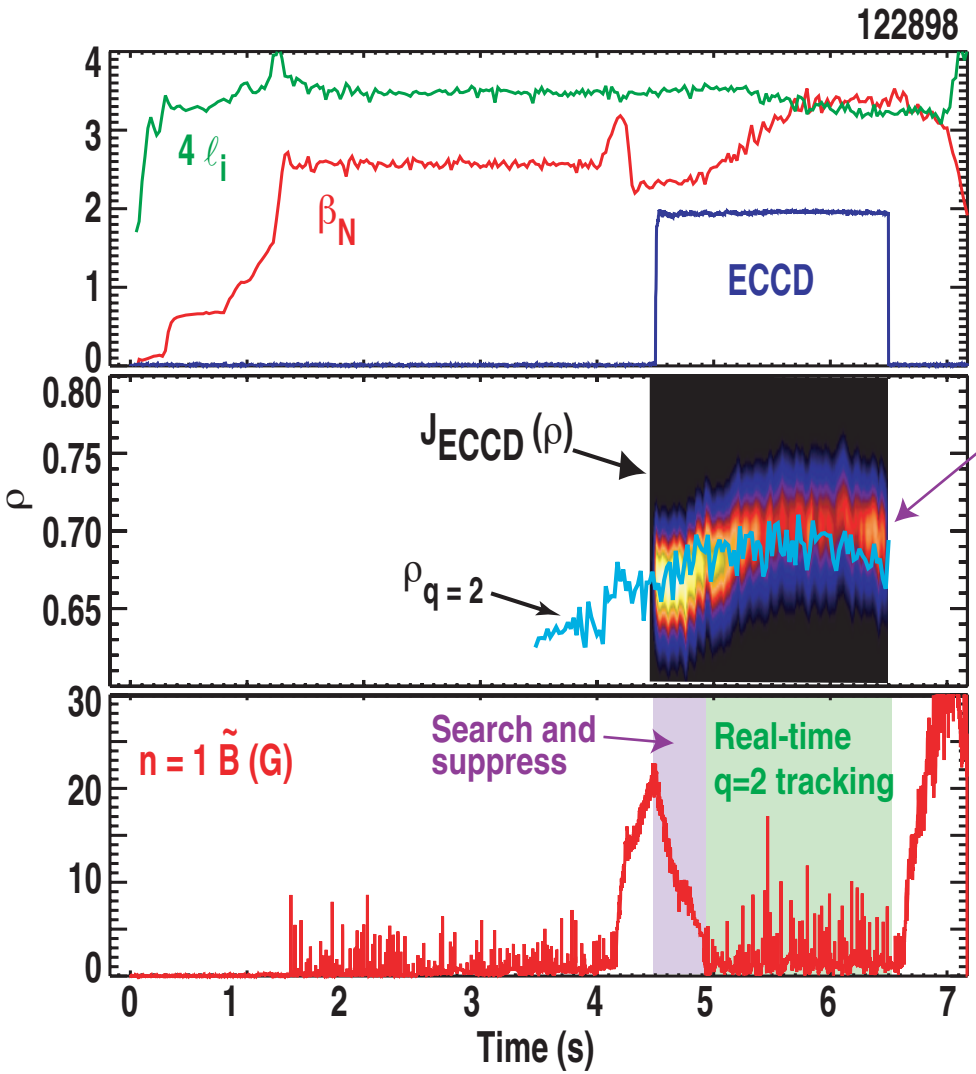
Experiments Have Proven Theoretical Expectation that Driving Current At Island Location Will Stabilize NTM



- Localized current drive at island location

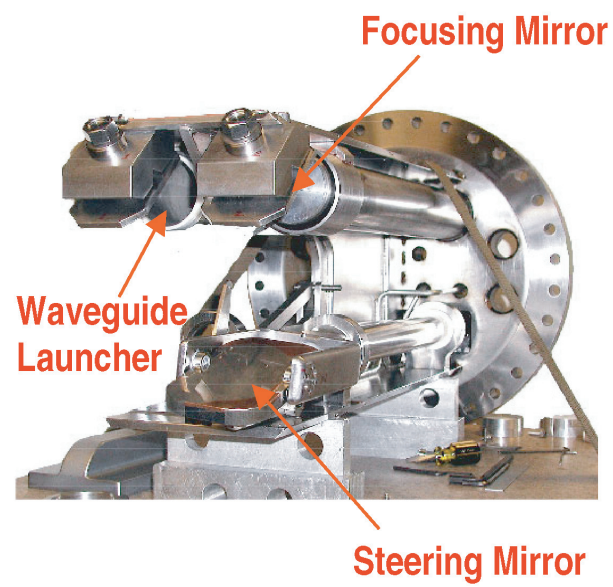


Real-time Tracking of Island Location Required for NTM Suppression



- 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)

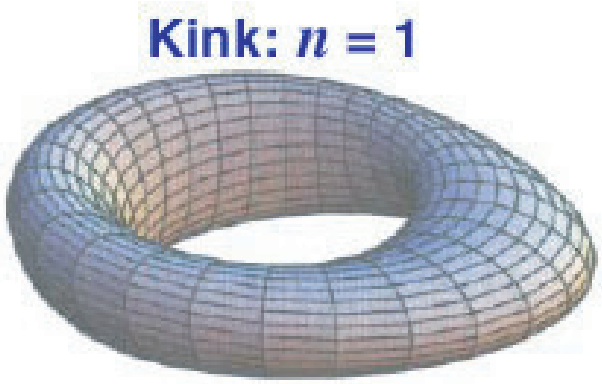
Microwave deposition location controlled by moving 2nd harmonic resonance



PPPL PRINCETON PLASMA PHYSICS LABORATORY

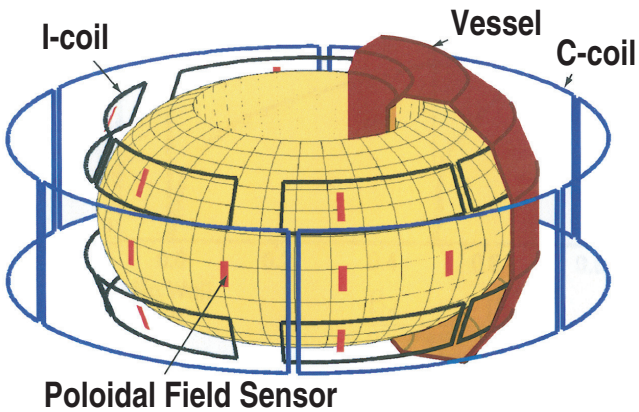
Resistive Wall Mode Stabilization Relies on Dynamic Control Via Non-Asymmetric Coils

- **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)

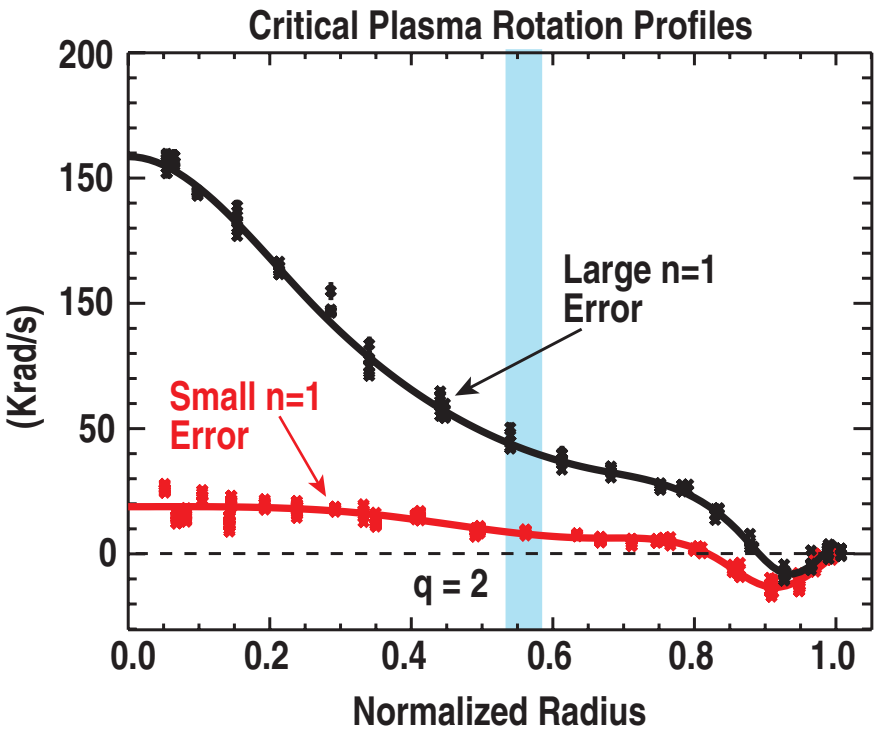
- **DIII–D experiments have identified two methods for RWM stabilization:**
  - Plasma rotation (magnitude dependent on n=1 error field)
  - Feedback control using non-axisymmetric coils

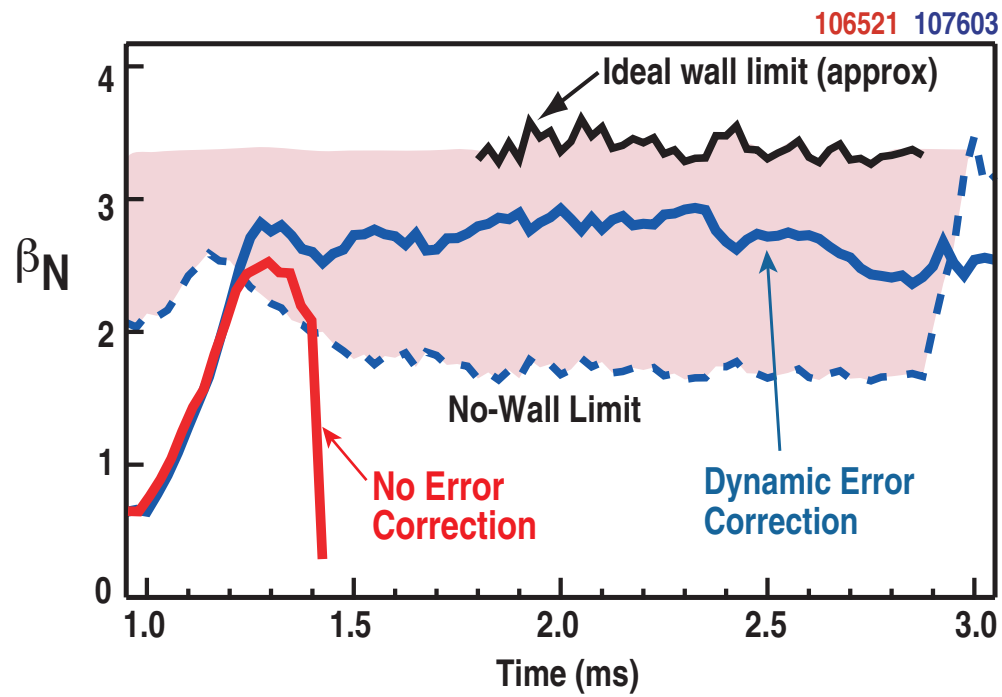


- **Using internal coils (I-coils), high bandwidth feedback system stabilizes RWM (NMA code, Chu and Chance)**

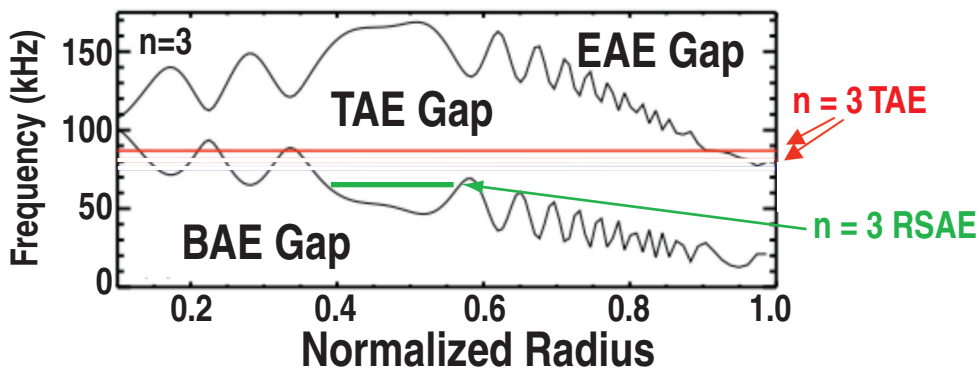
Real-time Error Field Correction Enables Sustained Operation Near Absolute Pressure

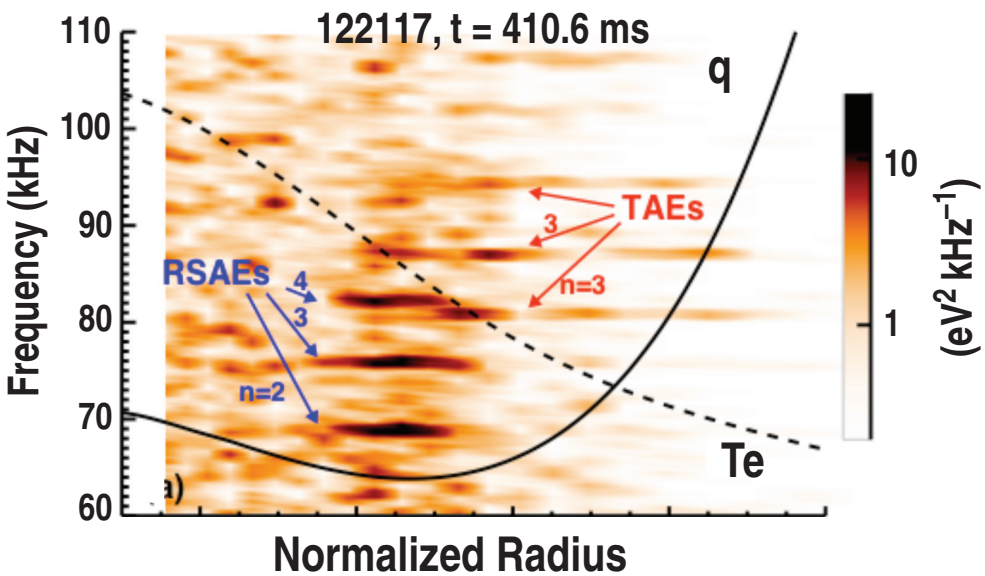
- Critical Rotation for RWM Stabilization Sensitive to n=1 Error Field
- With n=1 error dynamically controlled, high pressure can be maintained





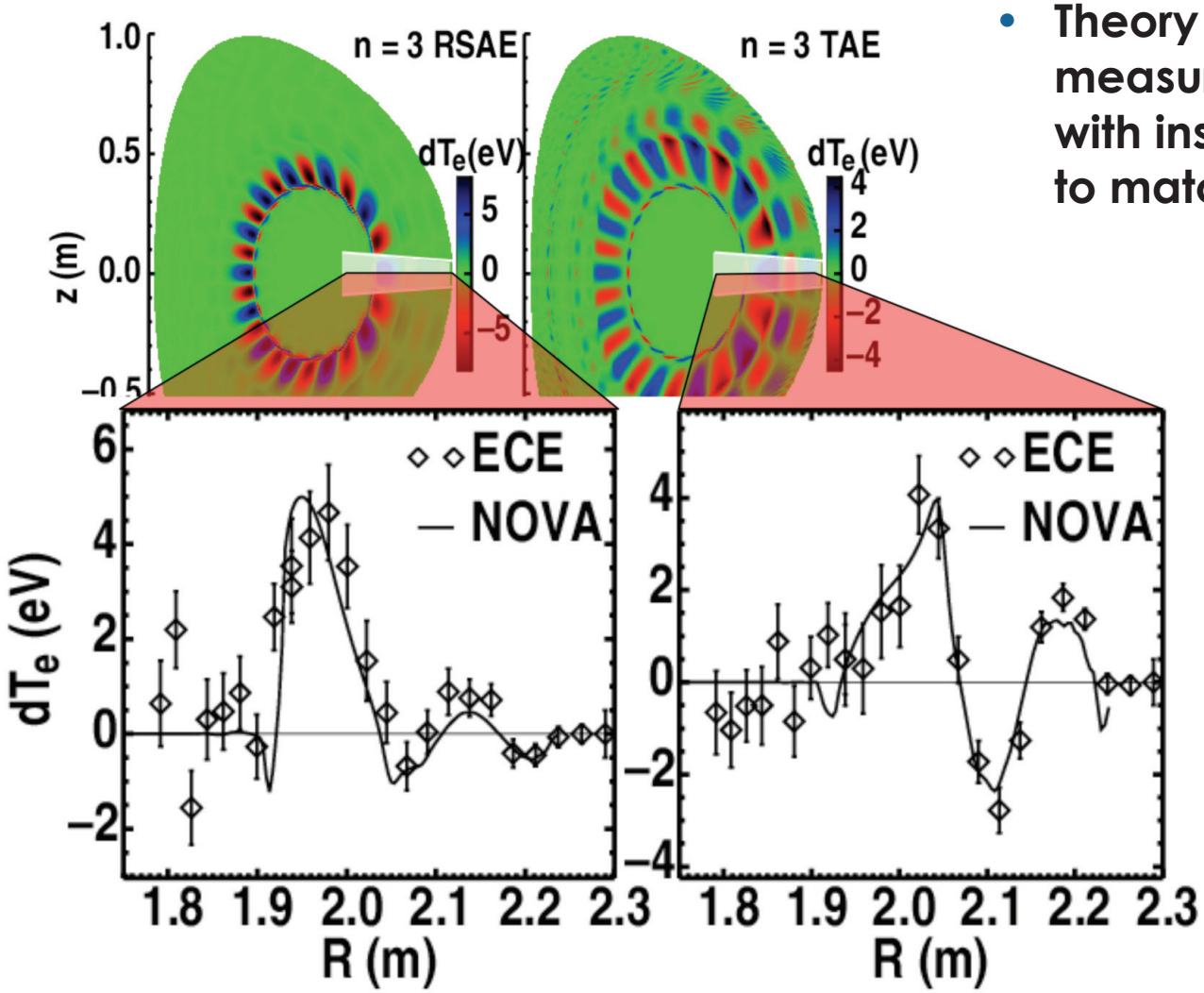
Improved Diagnostics Now Allow Detailed Investigation of Fast Particle Driven Instabilities





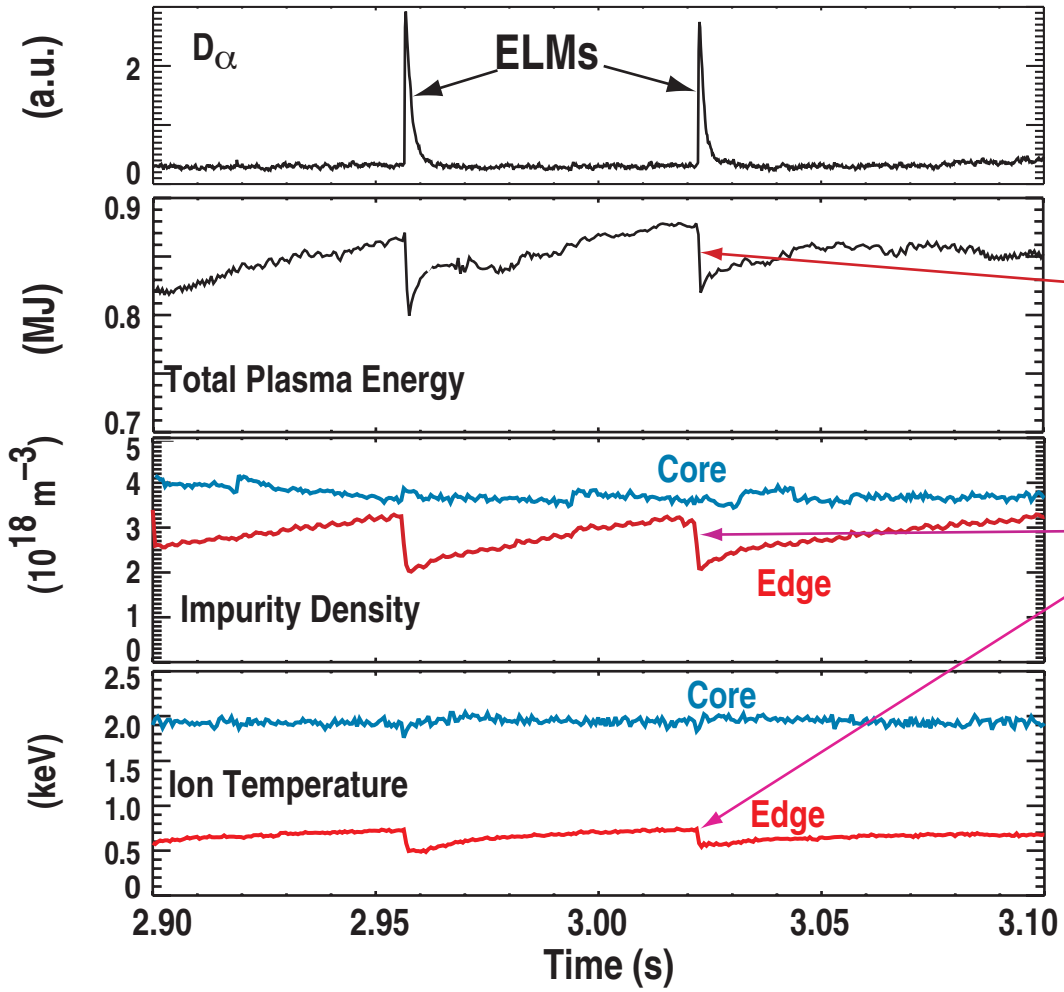
- **Small-scale instabilities driven by fast particle population exist in "gaps" of Alfvén continuum**
- **Radial extent of instabilities determined by interaction with continuum**
  - Not easy to measure with external diagnostics
- **New fluctuation diagnostics with high spatial resolution allow precise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

Measured Radial Structure Agrees Extremely Well with Theory Predictions



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

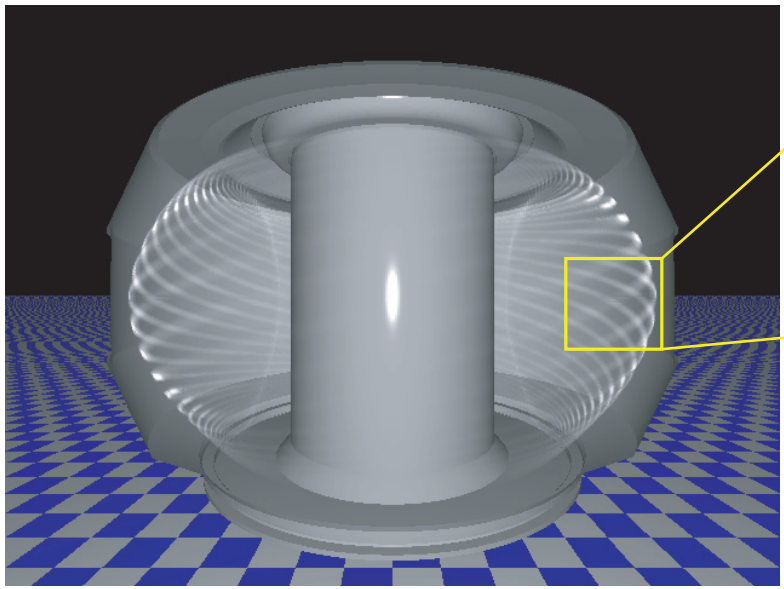
High Confinement Regimes (known as H-mode) Are Generally Accompanied by Edge Instabilities (ELMs)



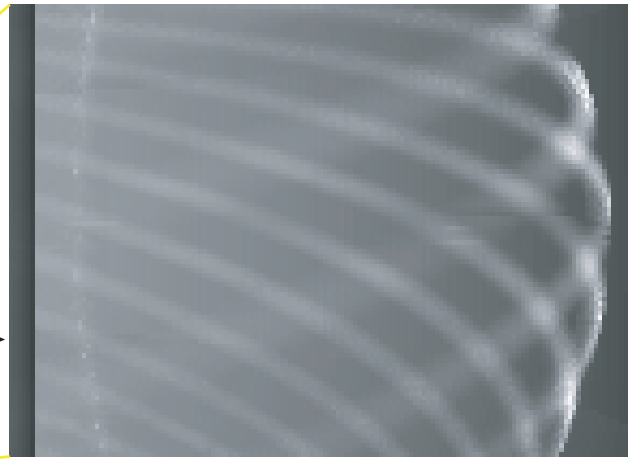
- **Plasma Energy Builds Up Until an Instability Causes a Rapid Loss of Energy**
  - **In this case, 10% of plasma energy is lost in 100 μs**
- **High time resolution measurements indicate that the instability only impacts the edge plasma**
  - Known as an Edge Localized Mode (or ELM)

High Speed Camera Images Confirm Predicted Filamentary Structure of Peeling-Ballooning Modes

In 3-D, Filamentary Structure is Evident



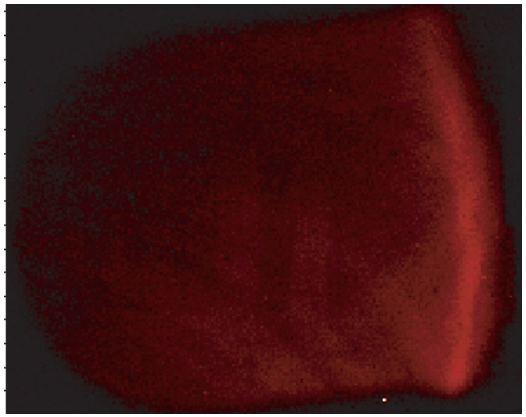
← Simulation →



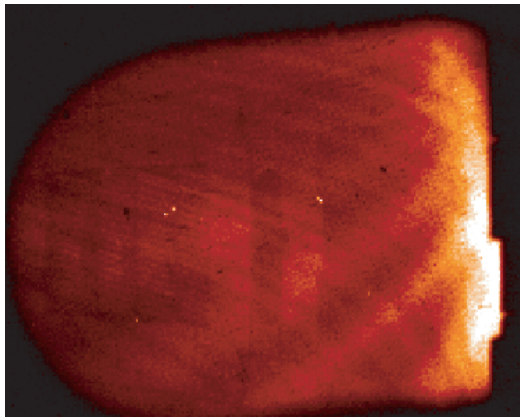
Camera Images of CIII Emission During ELM Event

Experiment

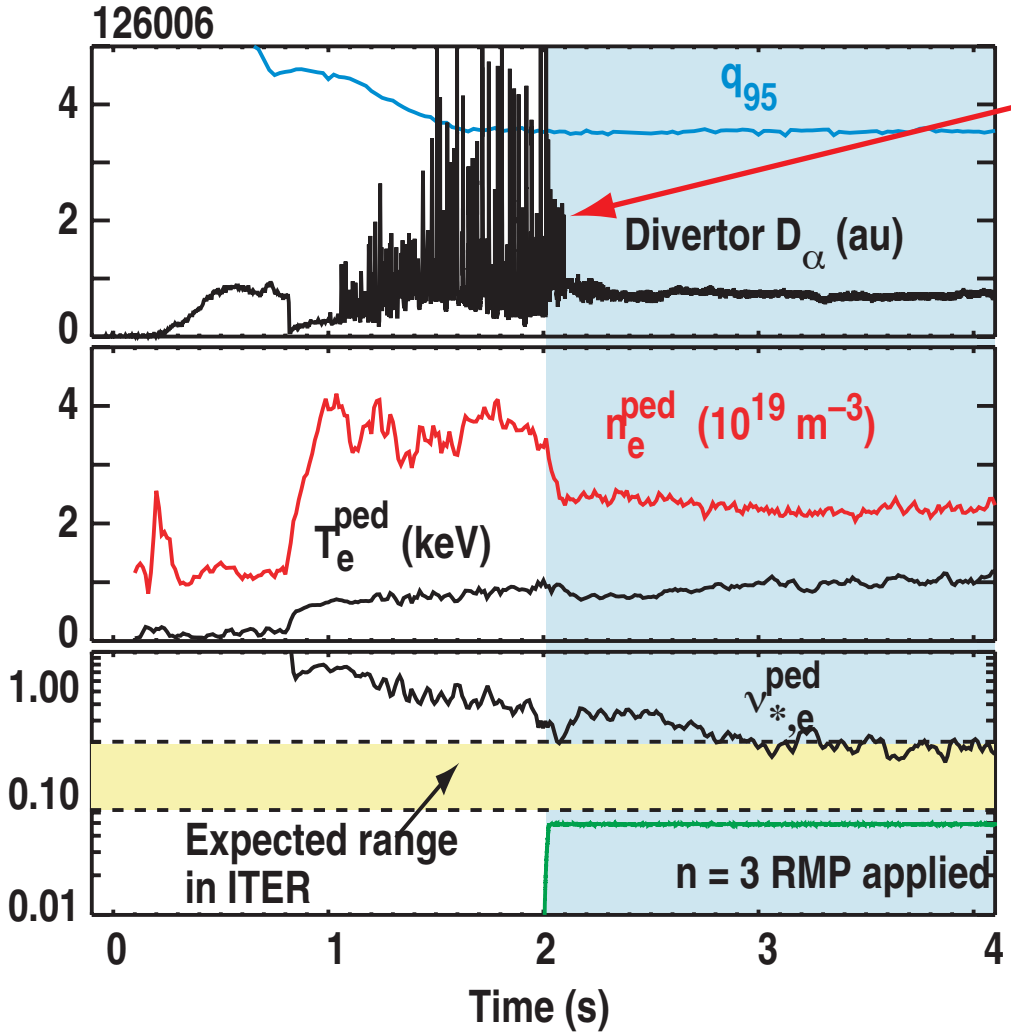
1 ms Before ELM



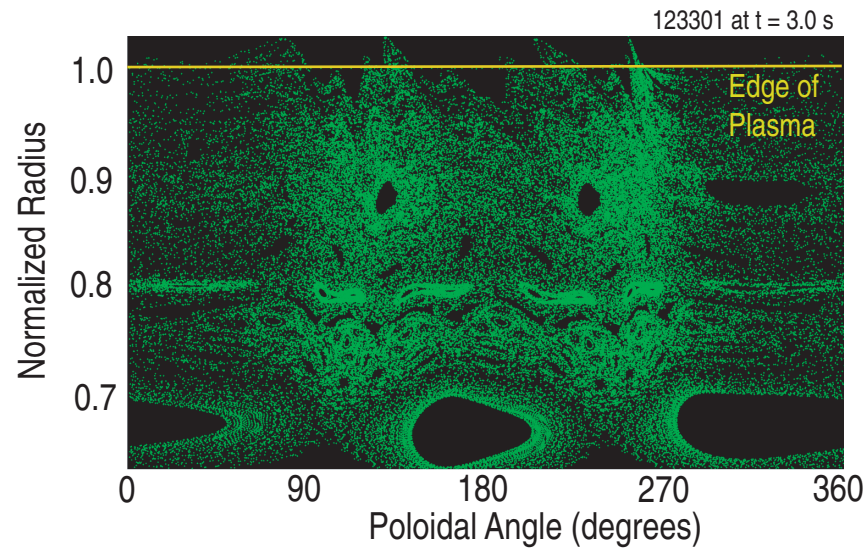
During ELM



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



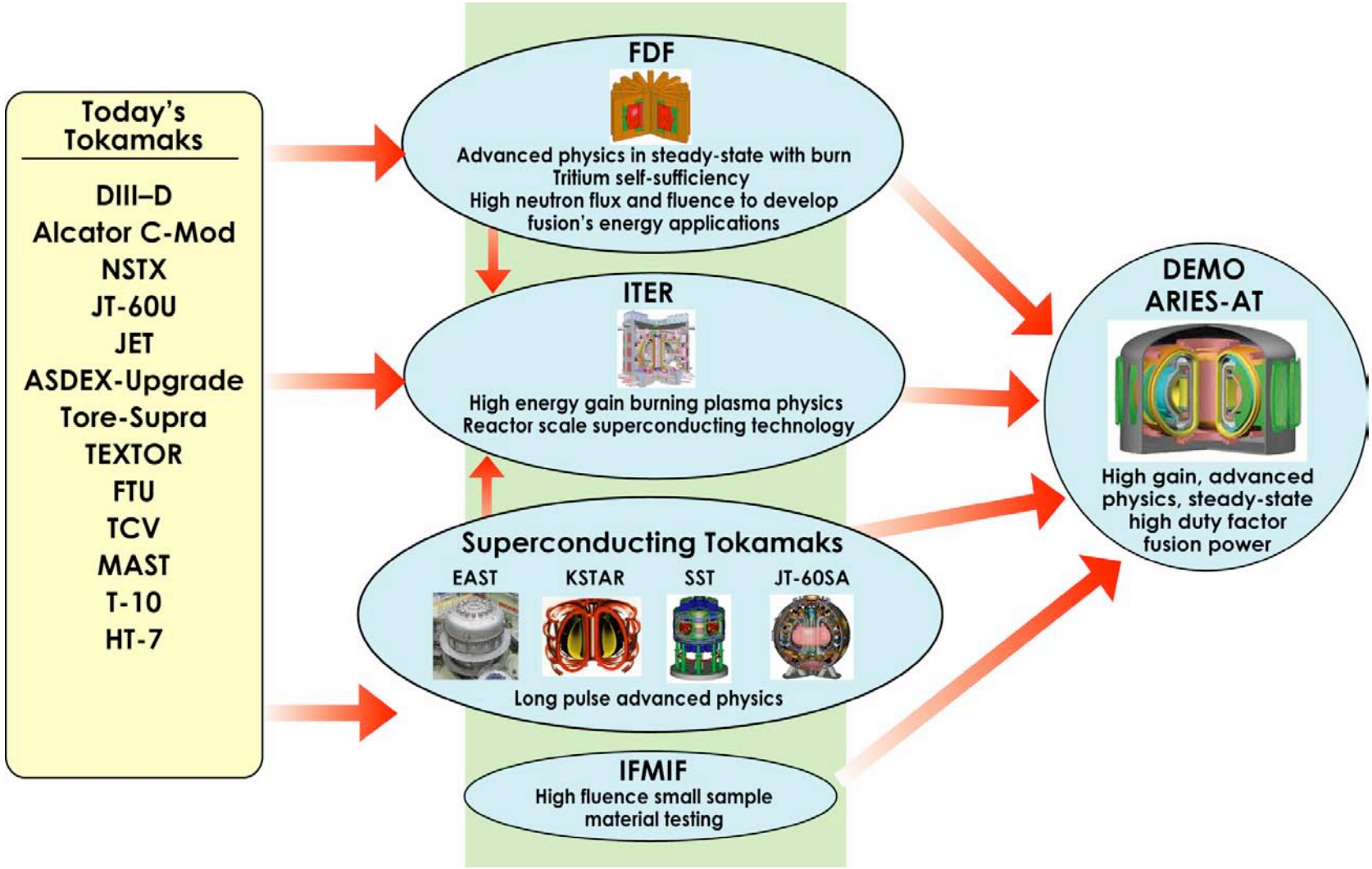
- **ELMs suppressed immediately when 3-D fields are applied**



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**

The World is Ready to Move Forward with Fusion Energy Development



GENERAL ATOMICS