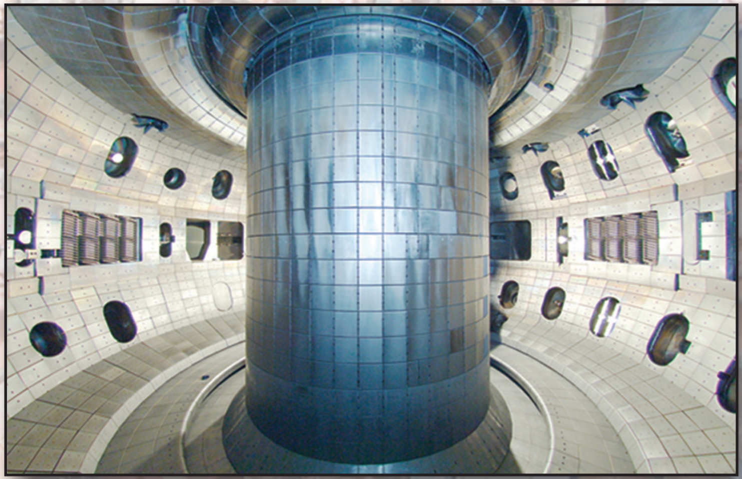
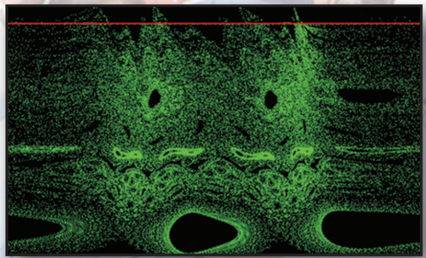
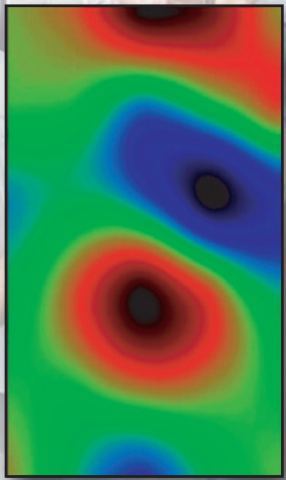
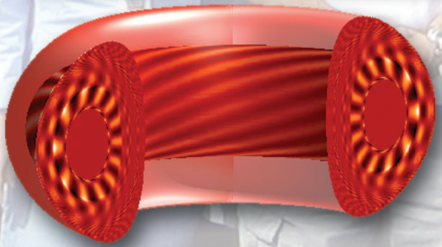
Recent Results, Status, and 5-Year Research Plan for DIII-D









by
M.R. Wade

PPPL Colloquium

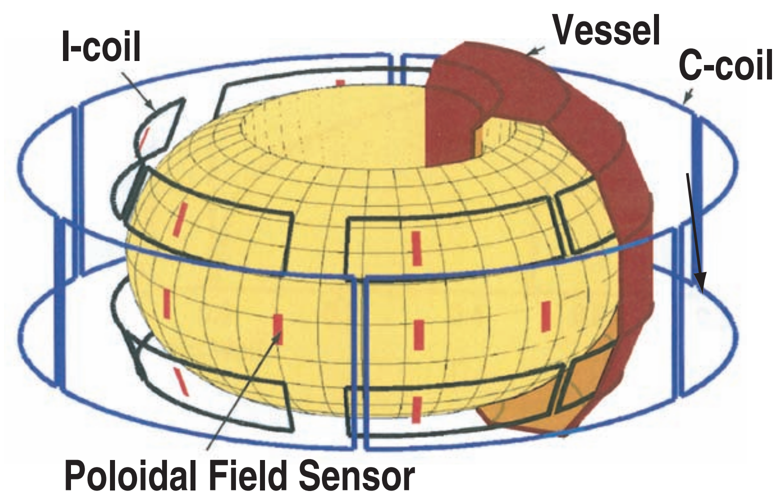
January 21, 2008

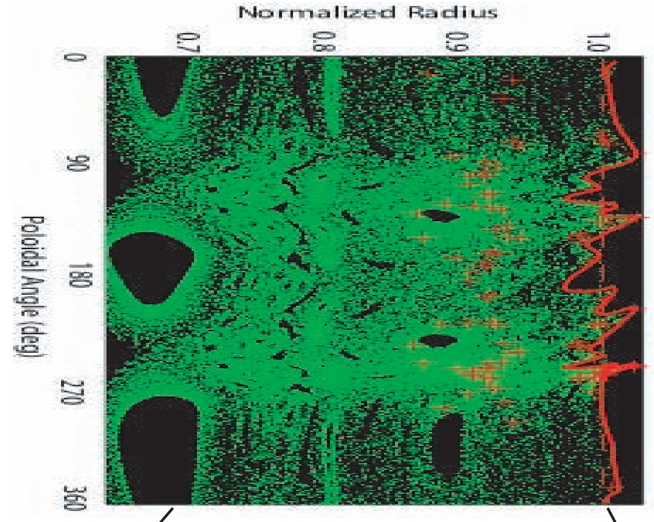
Outline

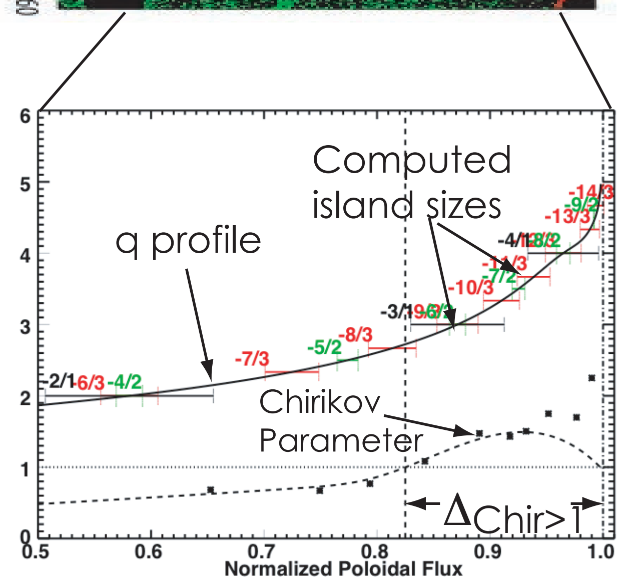
- Recent results aimed at:
  - Addressing urgent ITER design issues
  - Developing long-pulse and steady-state scenarios
  - Advancing the understanding of fusion plasmas
- Present Status
  - 2008 Experimental Emphases
- Brief Overview of DIII-D 5-Year Program Plan

ELM Suppression Studies Have Focused on Testing Ansatz of "Island Overlap" Induced by RMP

- **3-D Islands Produced in Plasma Edge Using External Coils**

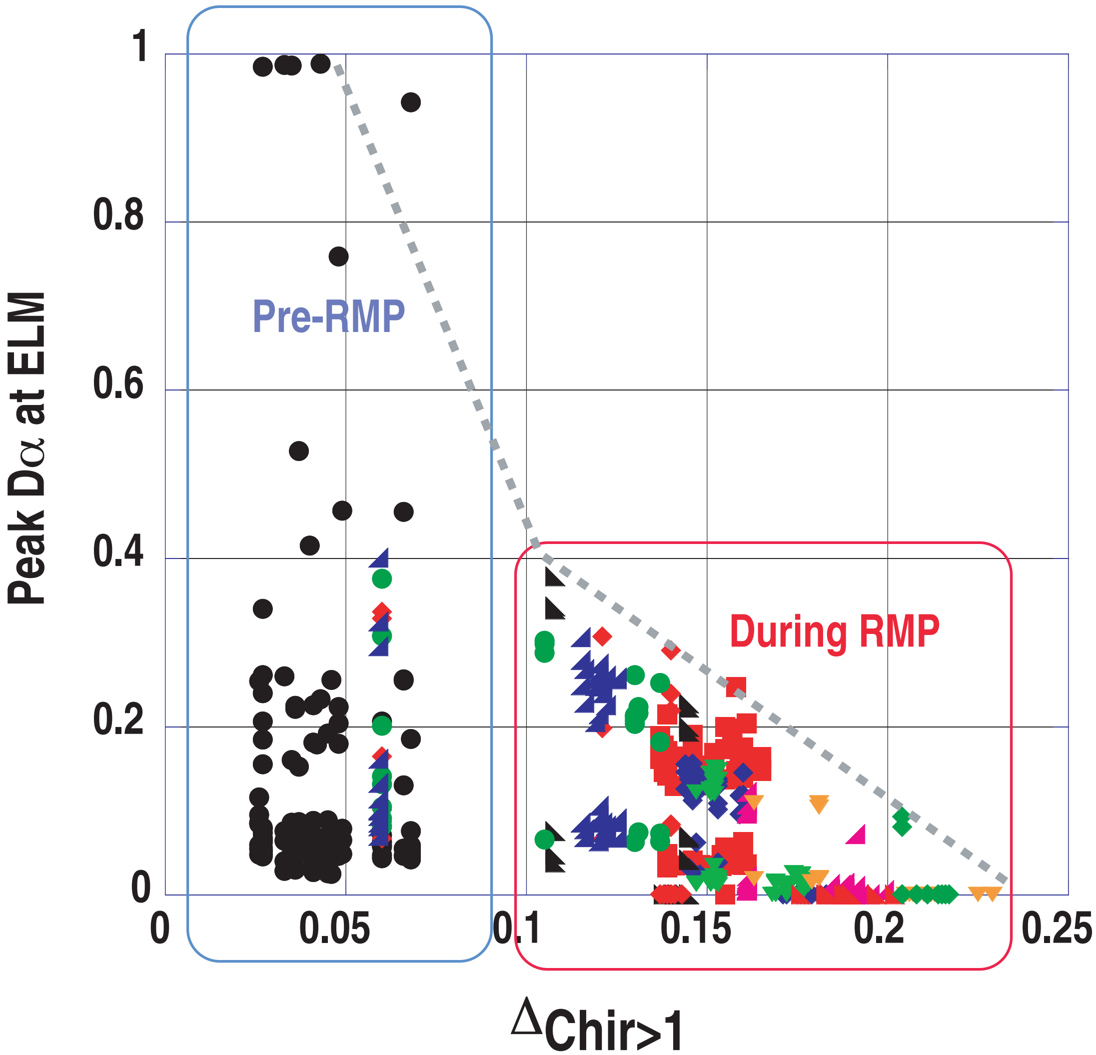






- **"Island overlap" region computed by TRIP3D using magnetic equilibrium and full 3-D coil geometry**
  - **Parameterized by region in which Chirikov parameter is greater than unity ($\Delta_{Chir>1}$)**

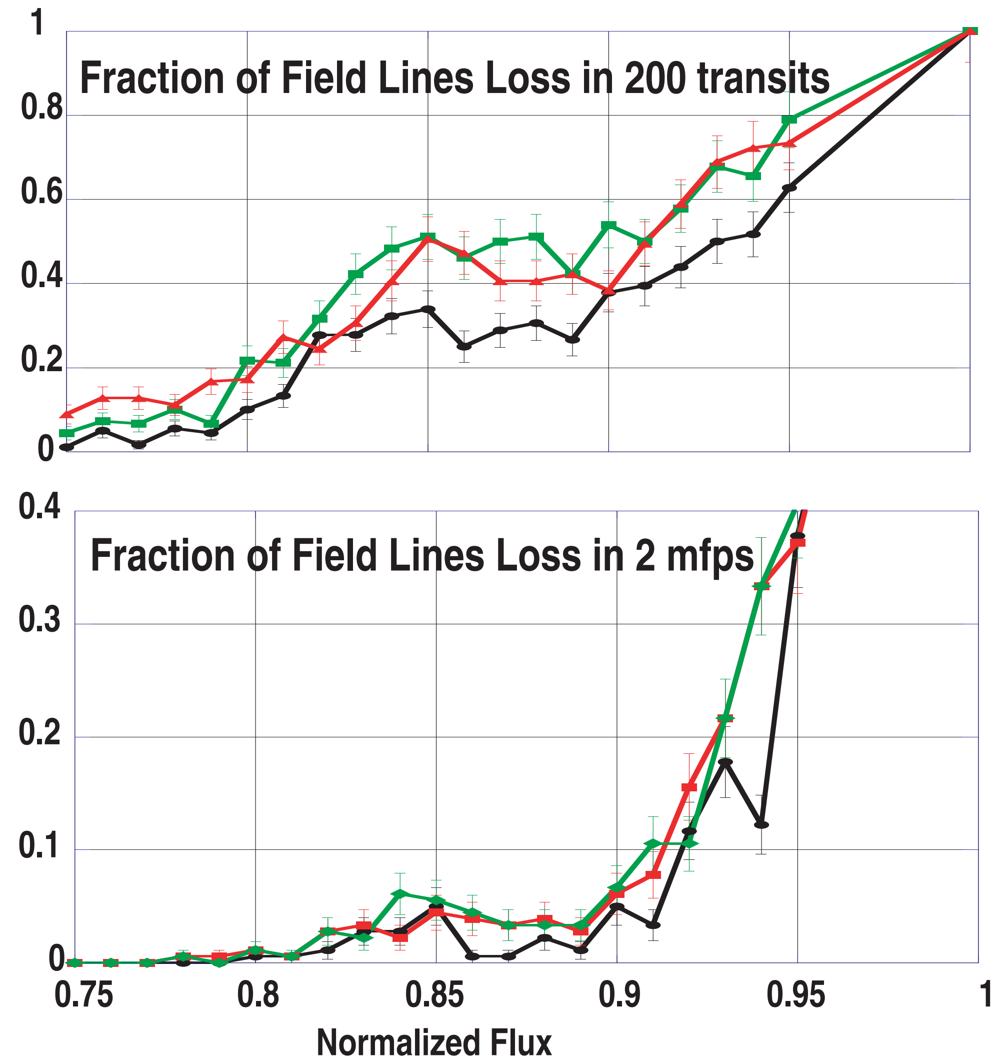
Maximum ELM Size Inversely Correlated with $\Delta_{Chir>1}$



- General trend to smaller ELM size as $\Delta_{Chir>1}$ increases
- Possible indication of threshold for full ELM suppresson at $\Delta_{Chir>1} = 0.17$

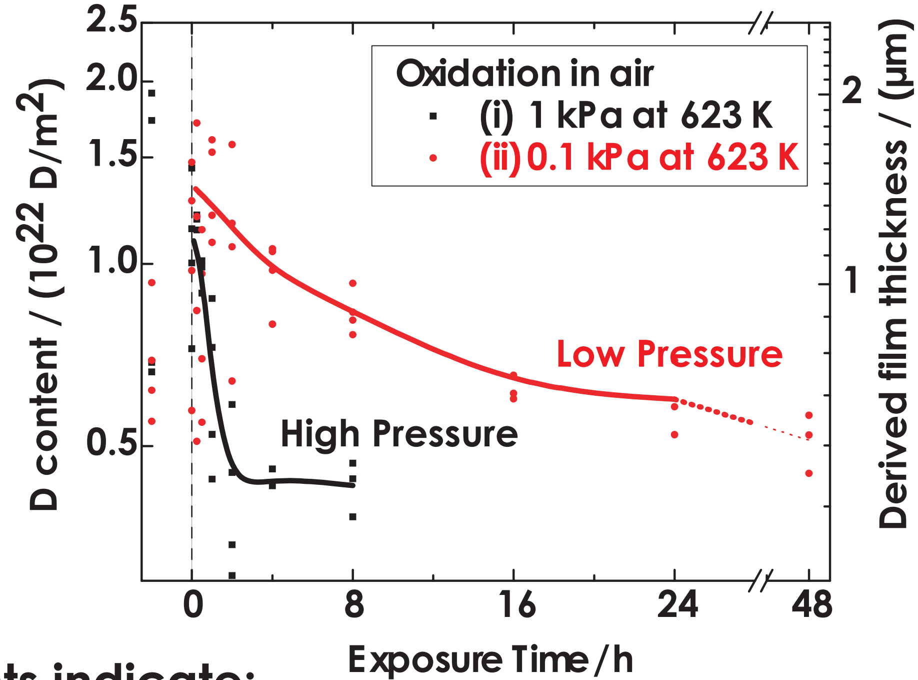
Stochastic Edge Leads to Significant Number of Field Lines that Escape to Divertor Targets

- Field Line Tracing Using TRIP3D follows field lines until a strike on the outer divertor or 200 toroidal transits
- Increased fraction of field lines strike divertor target across the entire region.
- Substantial increases in region near $0.85 < \psi_N < 0.9$
- Potential source of 3-D potentials in edge, leading to ExB convective transport



Laboratory Tests Have Shown Promise and Challenges of Using Thermal Oxidation (O2 Bake) for Tritium Removal in ITER

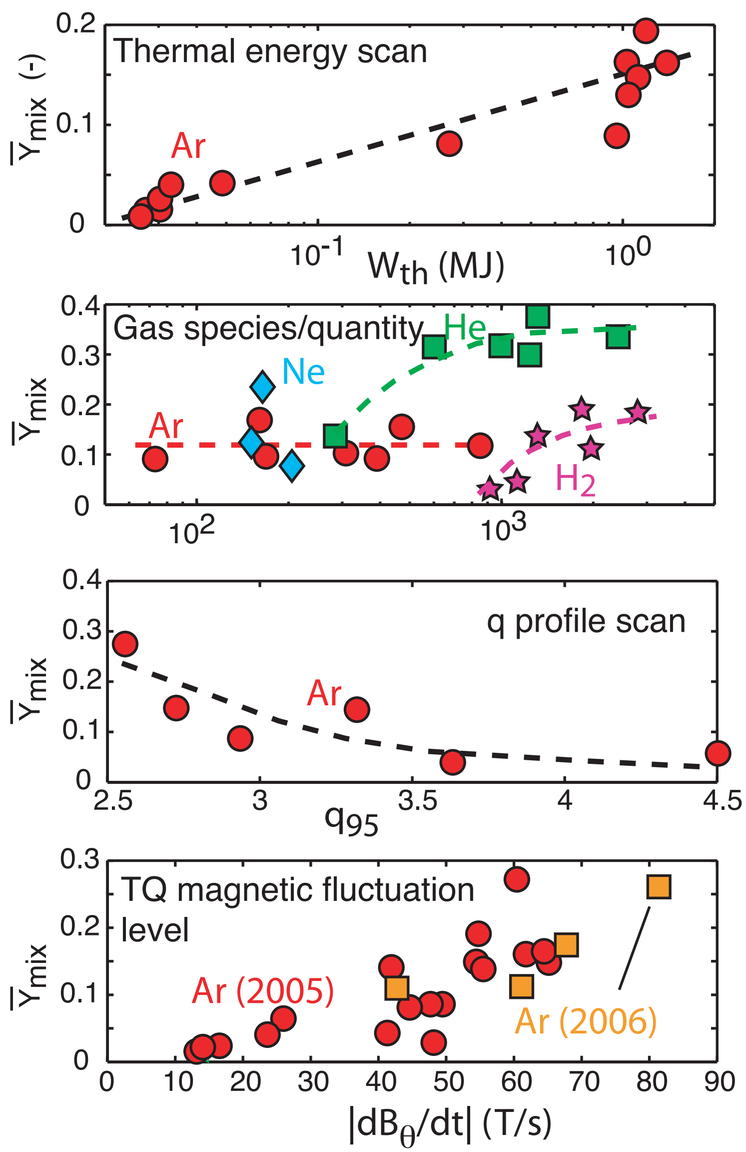
- Tests at Univ. of Toronto have shown that a high temperature (350°K), high pressure (1 kPa) 0_2 bake efficiently removes co-deposited D in films



- Further tests of DIII-D internal components indicate:
  – Most systems/diagnostics are unaffected
  – Mobilization of copper observed when baking components with plasma sprayed copper surfaces (Cu/C/O coating formed)

- Tests are now being conducted to elucidate the processes leading to this coating and means to avoid/mitigation it (if possible)

Disruption Mitigation Studies With Massive Gas Injection Are Identifying Key Dependencies



- **Mixing efficiency:**
  Ymix = Particles assimilated/
  Particles injected before thermal quench

-- **Increases with plasma energy**

-- **Best with helium but Z dependence is compli**

-- **Improves as q95 decreases**

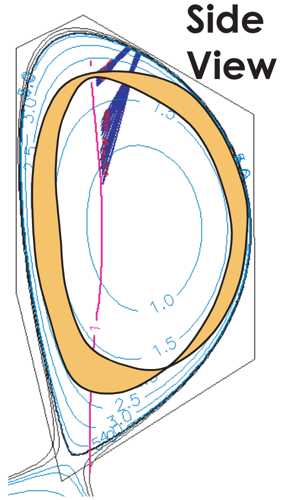
-- **Increases as virulence of magnetic activity increases**

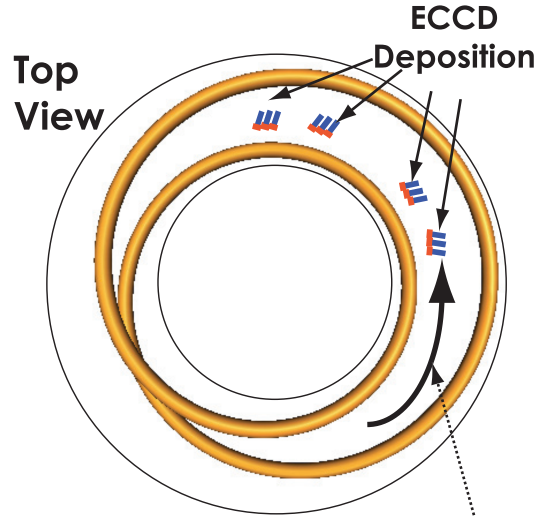
Recent Experiments Have Demonstrated the Ability to Control the Location of Locked Modes

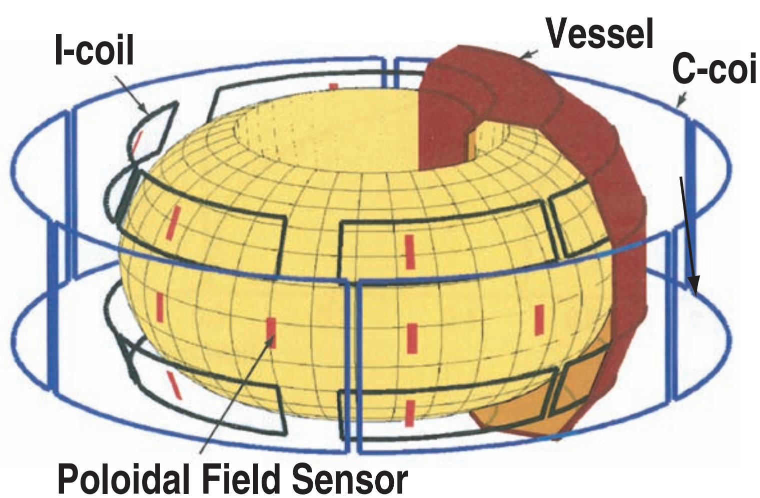
- Large m=2/n=1 NTMs tend to lock to the wall, generally leading to plasma disruptions.

- High probability that NTM will lock in a toroidal position such that its O-point is not accessible by ECCD (shown on right)

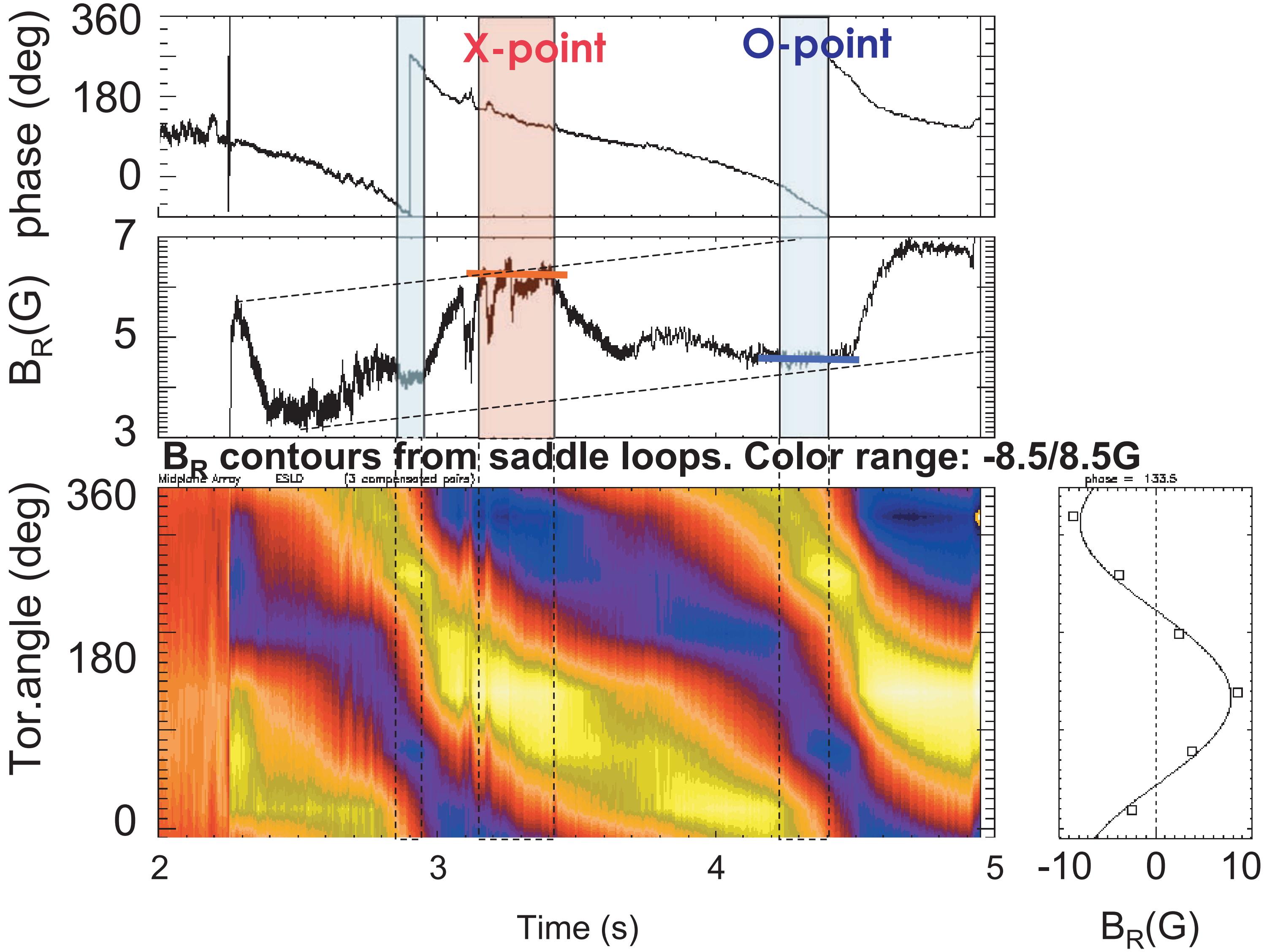
- Taking advantage of island coupling to external fields, external coils can be used to rotate the island in front of the ECCD







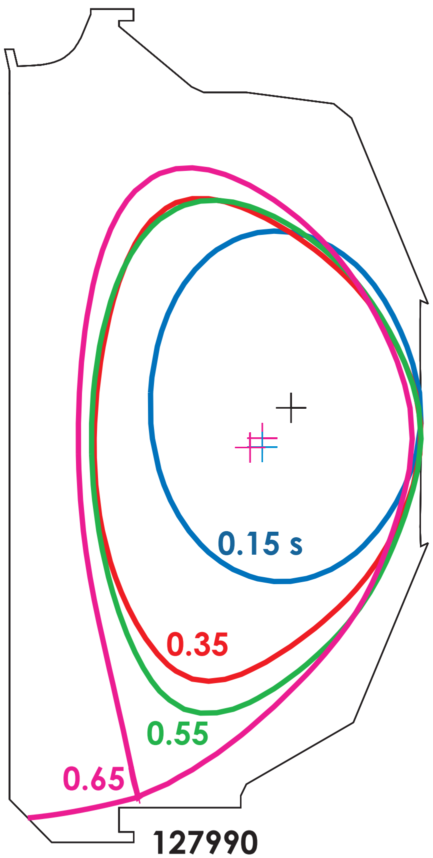
As O-Point of NTM Island is Rotated in Front of ECCD, Mode Amplitude is Observed to Decrease

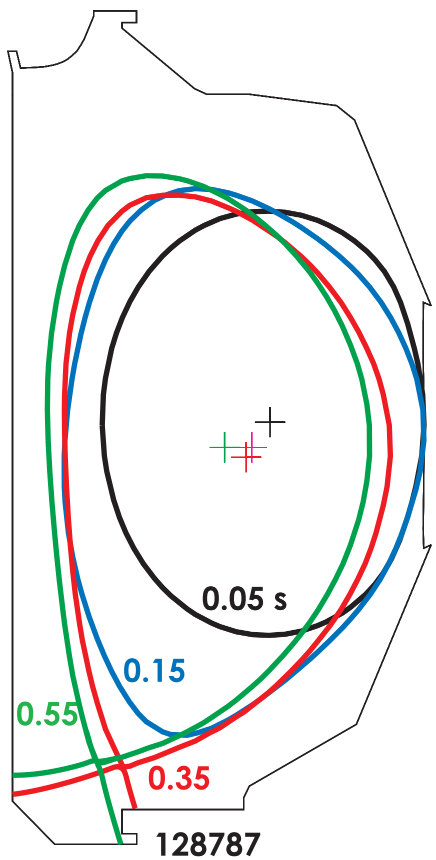


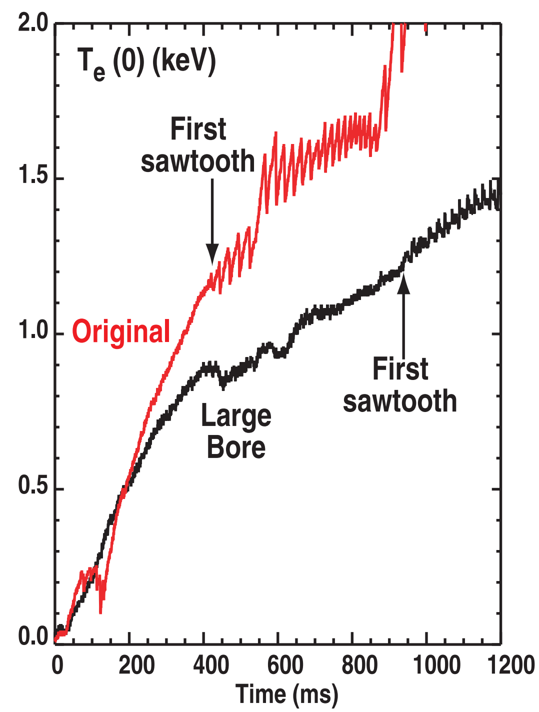
DIII-D NATIONAL FUSION FACILITY

DIII–D Has Responded to Requests for Experimental Input on ITER Startup Scenario

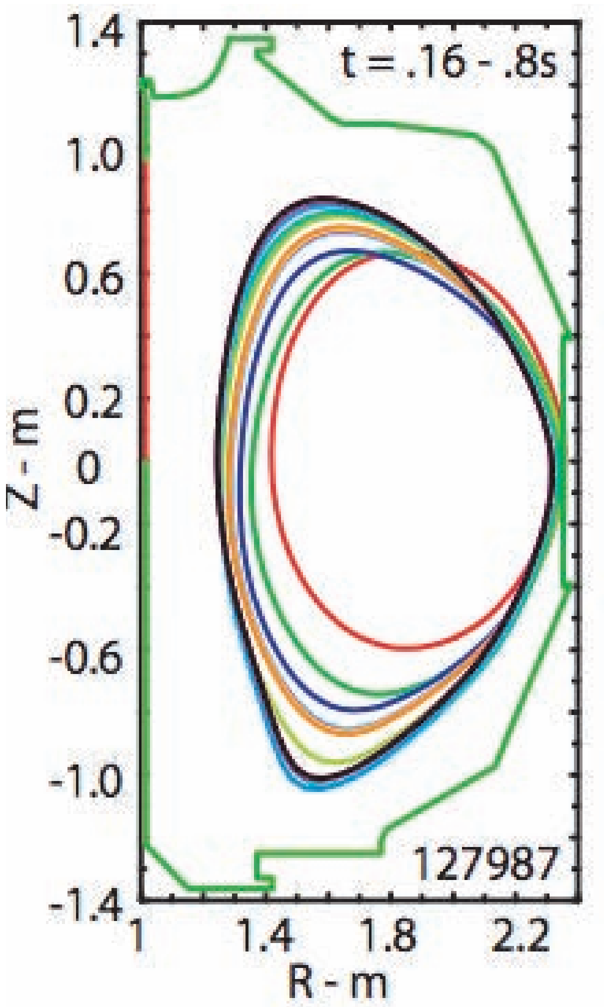
- **Original scenario**
  – Small bore at breakdown
  – Late X-point
- **New scenario**
  – Large bore at breakdown
  – Early X-point
- **New startup results in lower ℓ_i and later sawtooth appearance**



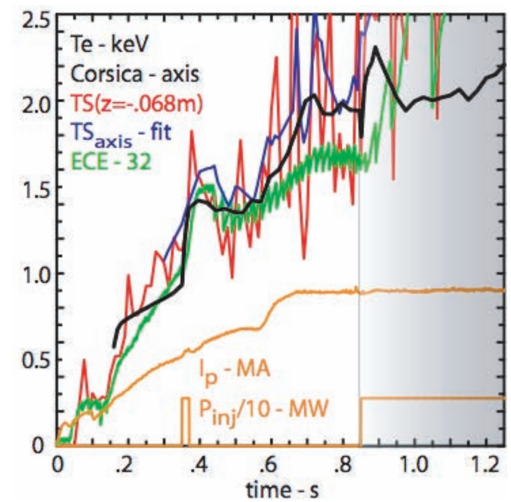


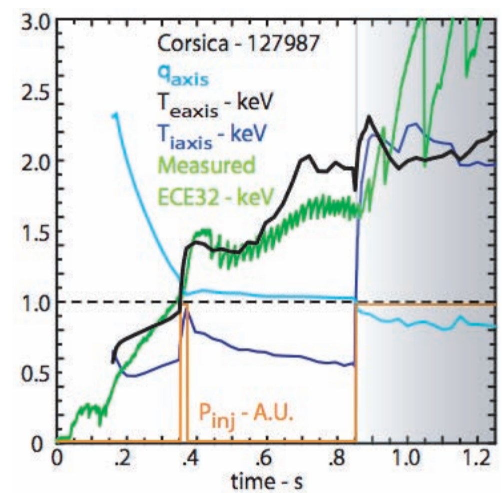


Experiments Simulating ITER Startup are Providing Critical Data for Benchmarking Simulation Codes for ITER



- **CORSICA Simulation Consistent with Profile Evolution**





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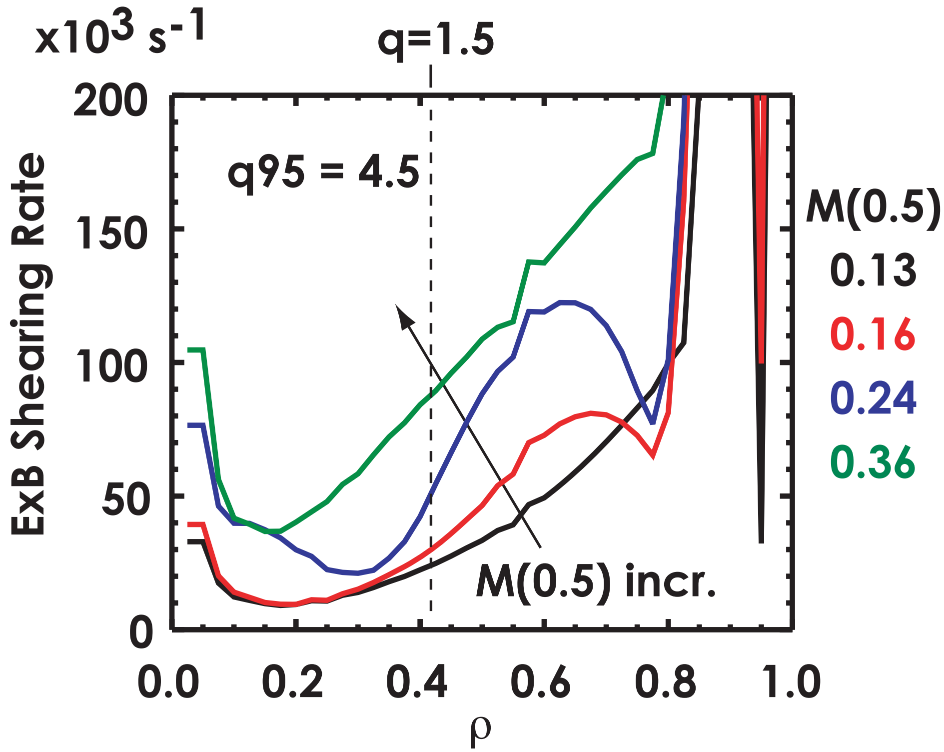
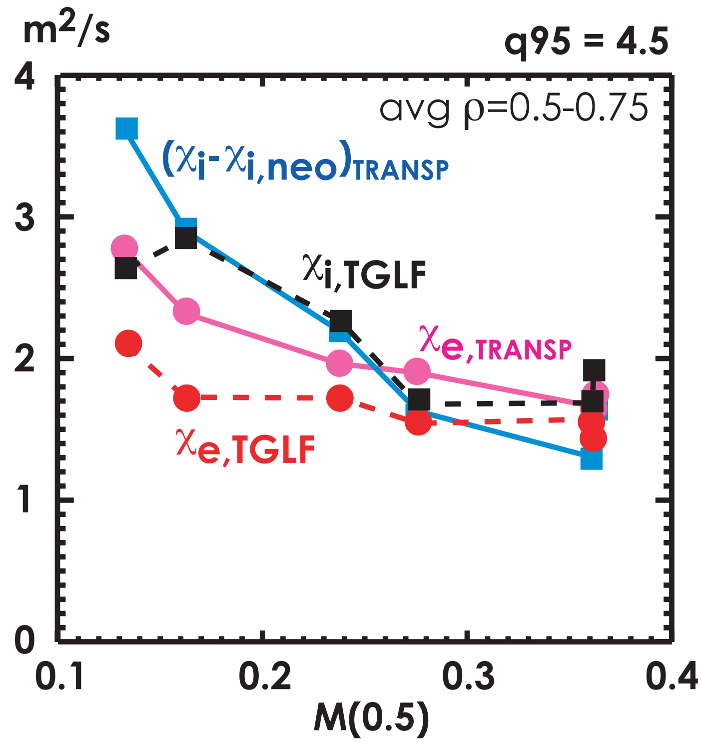
Transport and Confinement in Hybrid Regime is Sensitive to Core Rotation, Consistent with TGLF Predictions

- Co/Counter NBI utilized to assess impact of rotation on core transport



- Both ion and electron transport impacted
- Trend and magnitude consistent with TGLF predictions

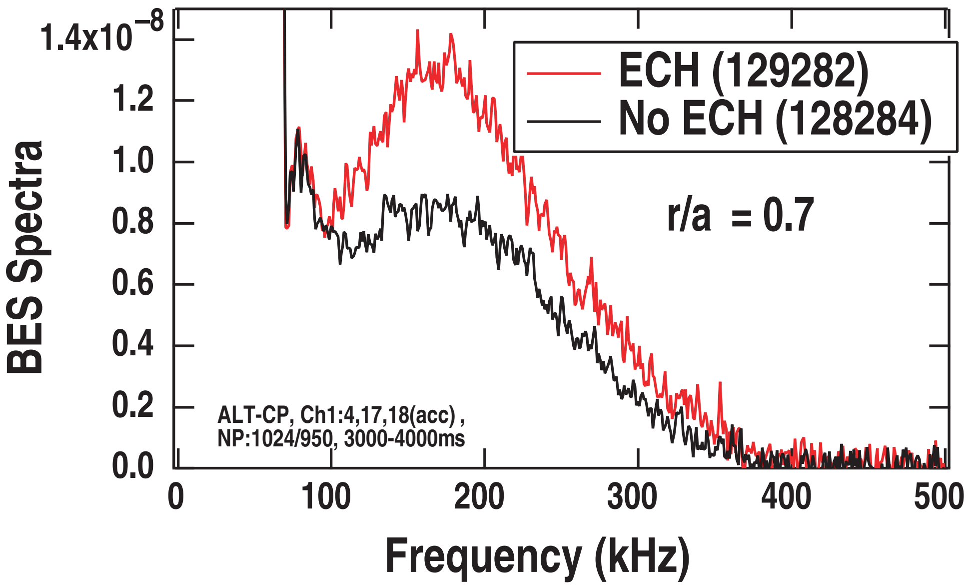


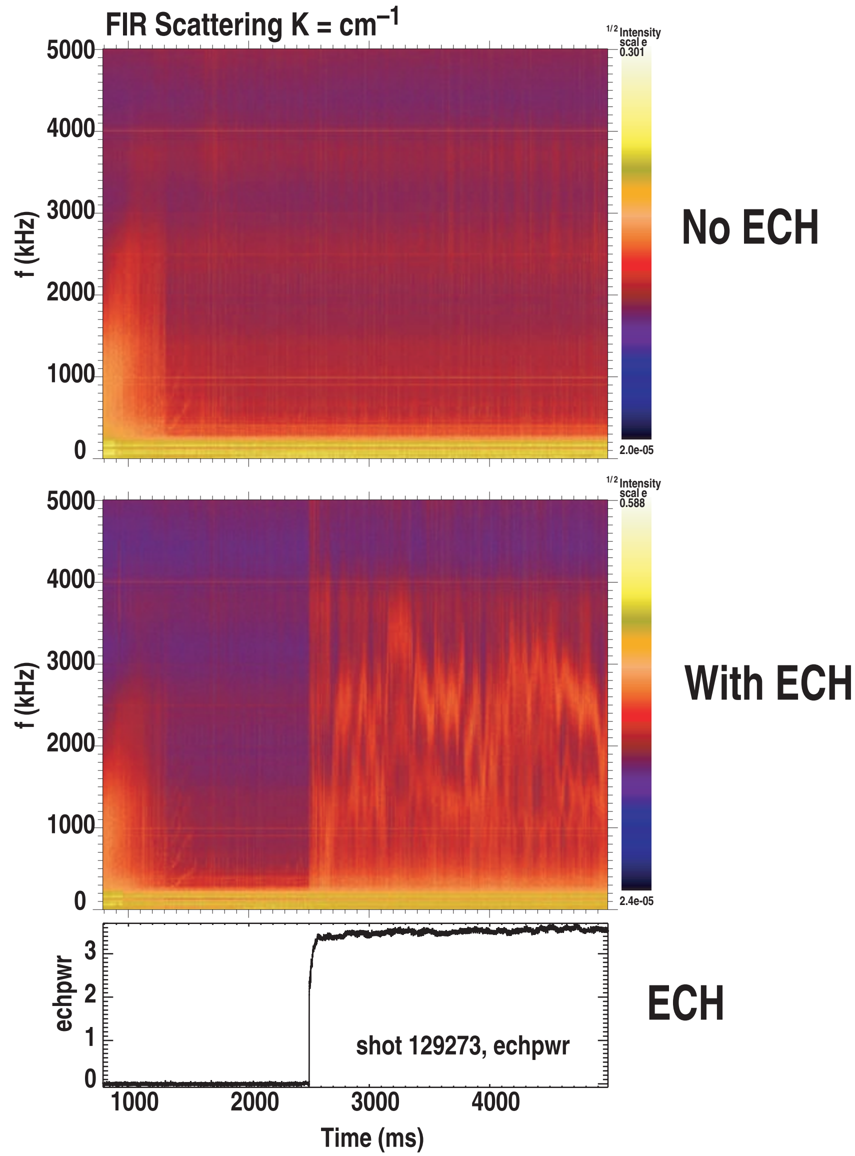
- Approximately 15% reduction in confinement observed across variation in Mach number

DIII-D NATIONAL FUSION FACILITY

Raising T_e/T_i Using ECH in Hybrid Plasmas Reduces Confinement and Increases Low-k Turbulence

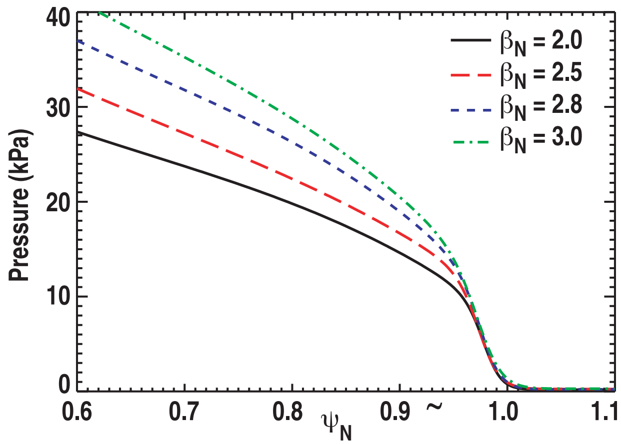
- H_{89P} decreases by 15% with injection of 2.4 MW of ECH at fixed β_N and Mach Number



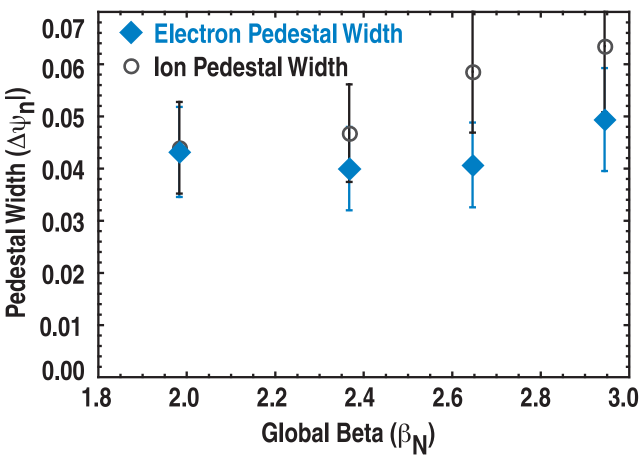


Pedestal Studies Suggests that the Pedestal Width Increases as the Pedestal Pressure Increases

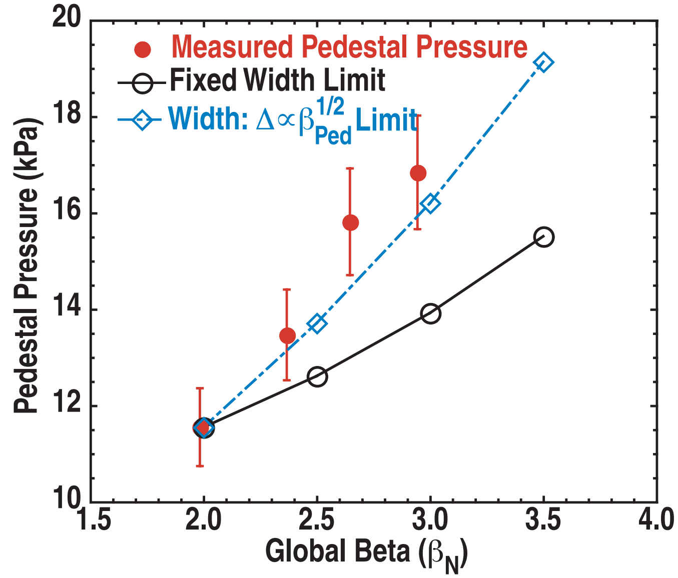
- **Pedestal height observed to be sensitive to β_N in hybrid plasmas**



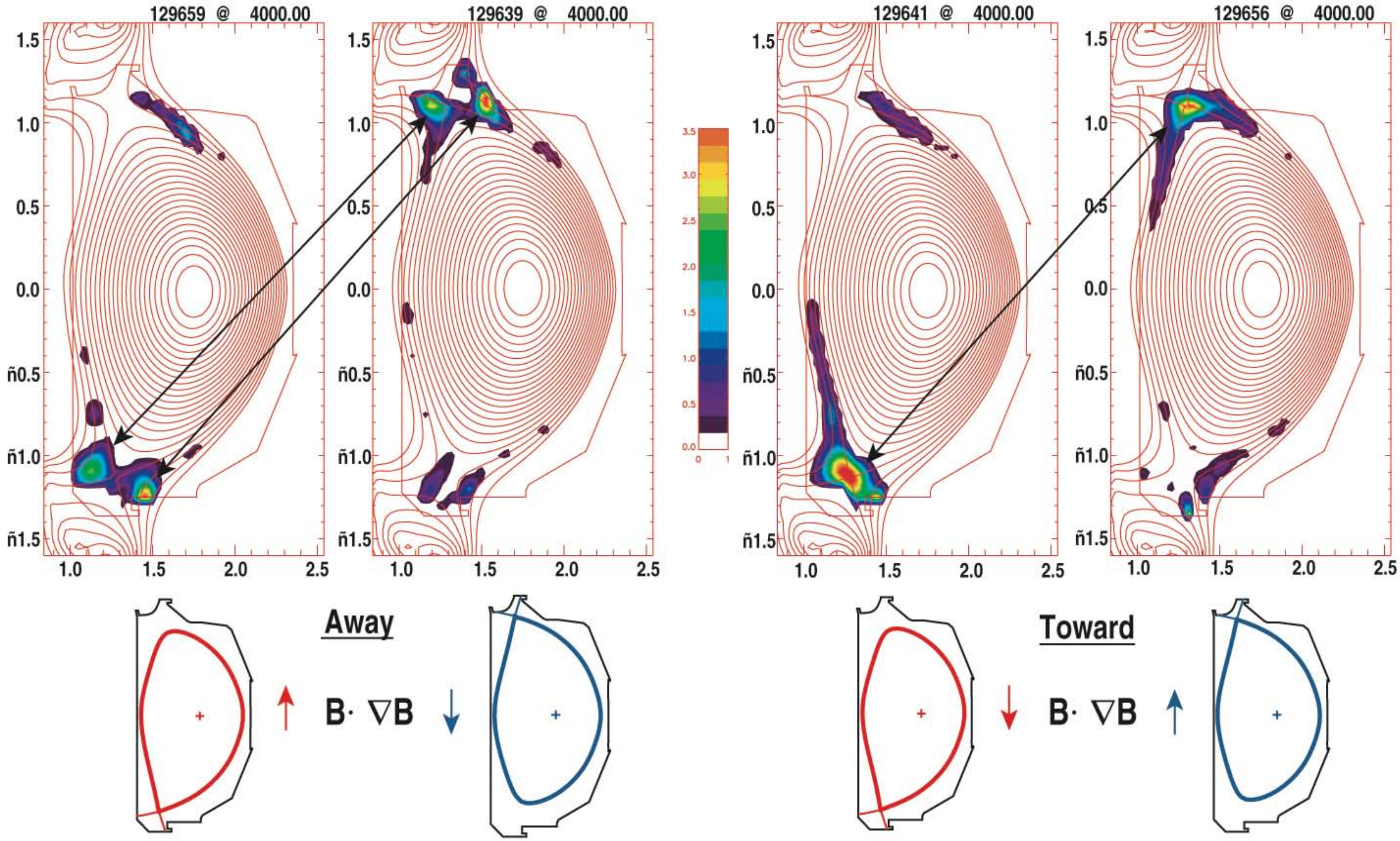
- **Large uncertainties in pedestal width make it difficult to determine width scaling**



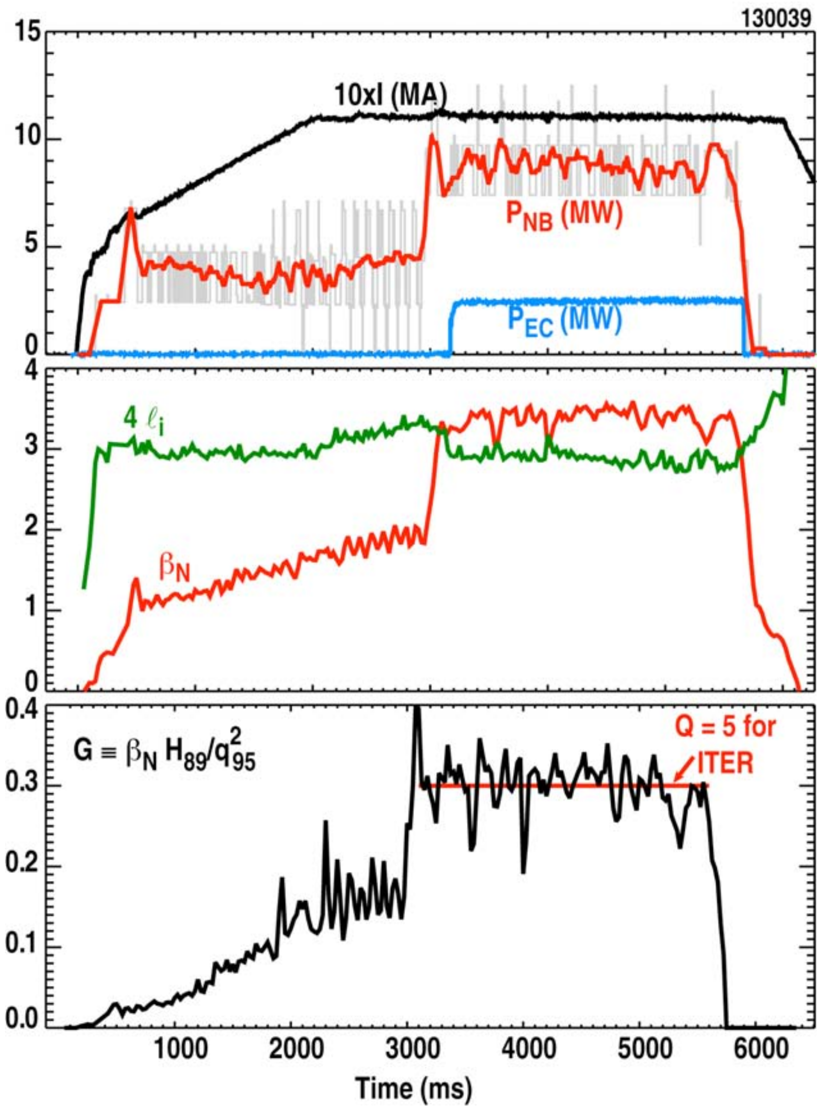
- **Good agreement with data found using pressure gradient limit from ELITE and assuming β dependence of width**

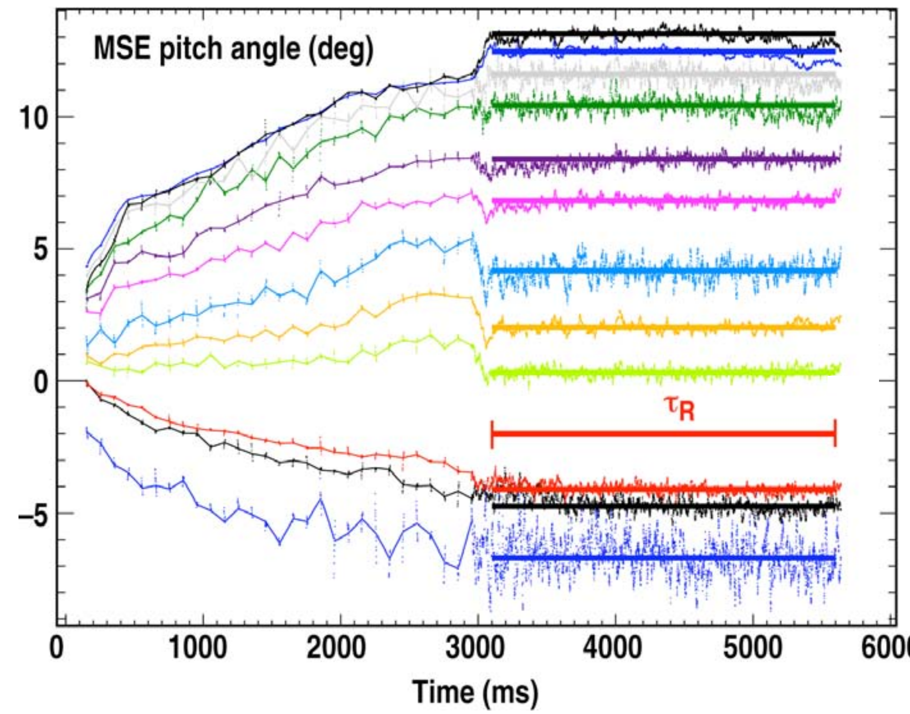


The Direction of the toroidal field appears more important than divertor configuration in radiated power distribution



Steady-State Scenario Reproducibly Maintained for 1τ_R at High β





- Pulse length now limited by co-NB deliverable energy, not EC energy
- Current profile is very stationary, but not fully non-inductive
  - $f_{ni} \approx 90\%$

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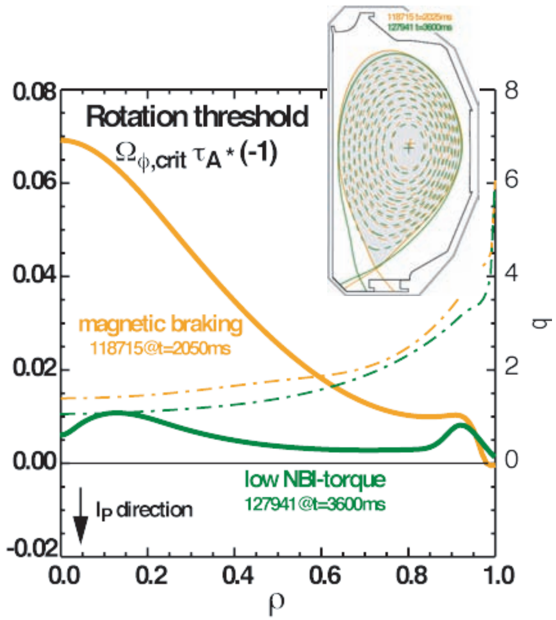
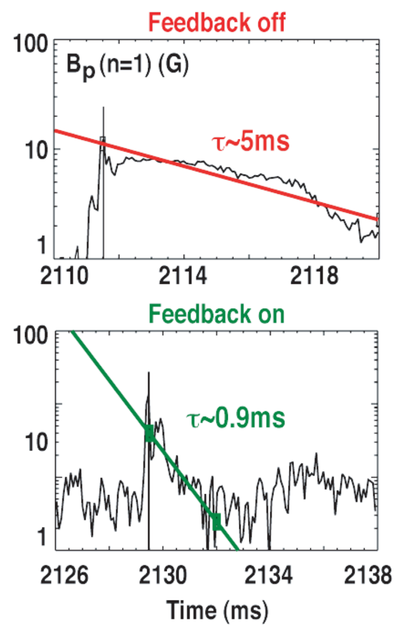
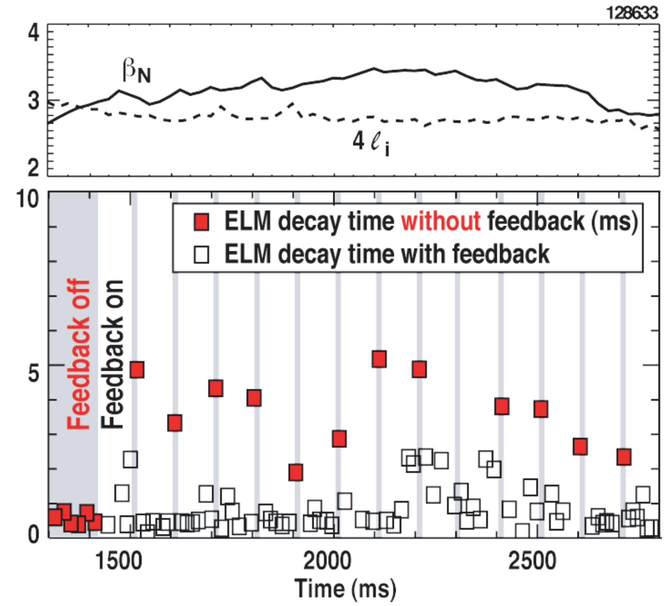
Resistive Wall Mode Rotation Threshold is Small, but Control Still Needed for Transient Events



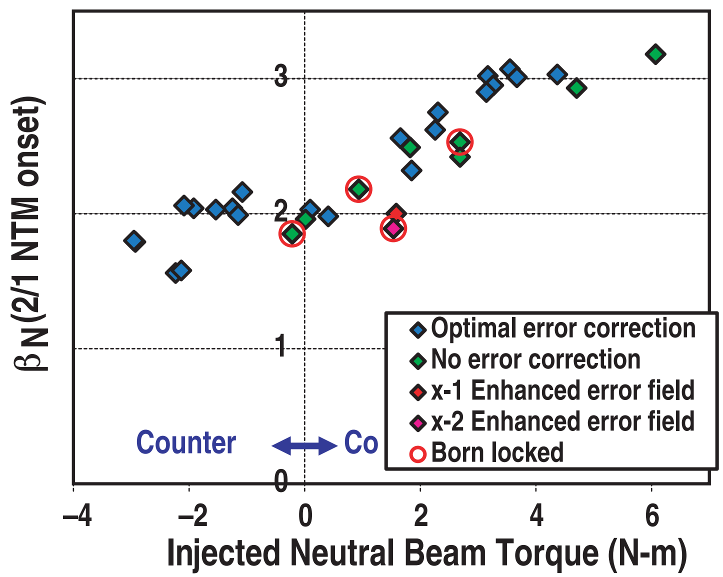


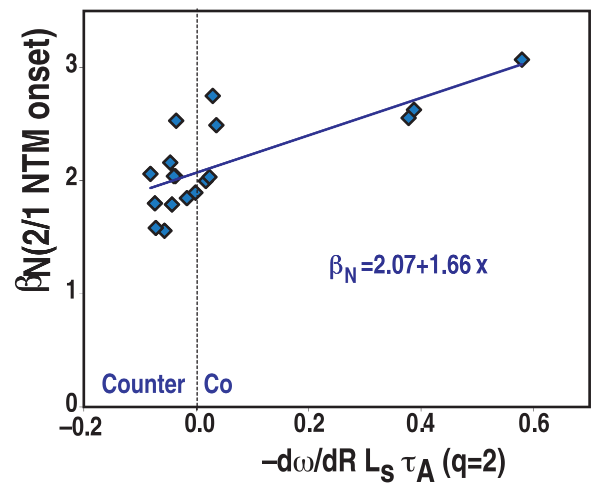


- **Low rotation threshold for RWM stabilization**
  - Low NBI torque yields considerably lower Ω_{crit} than previous results with n=1 magnetic braking
  - Applies to all operating scenarios tested
- **RWM feedback may still be necessary to mitigate the effects of transient events at high β**
  - Accelerates damping of n=1 perturbation following ELMs

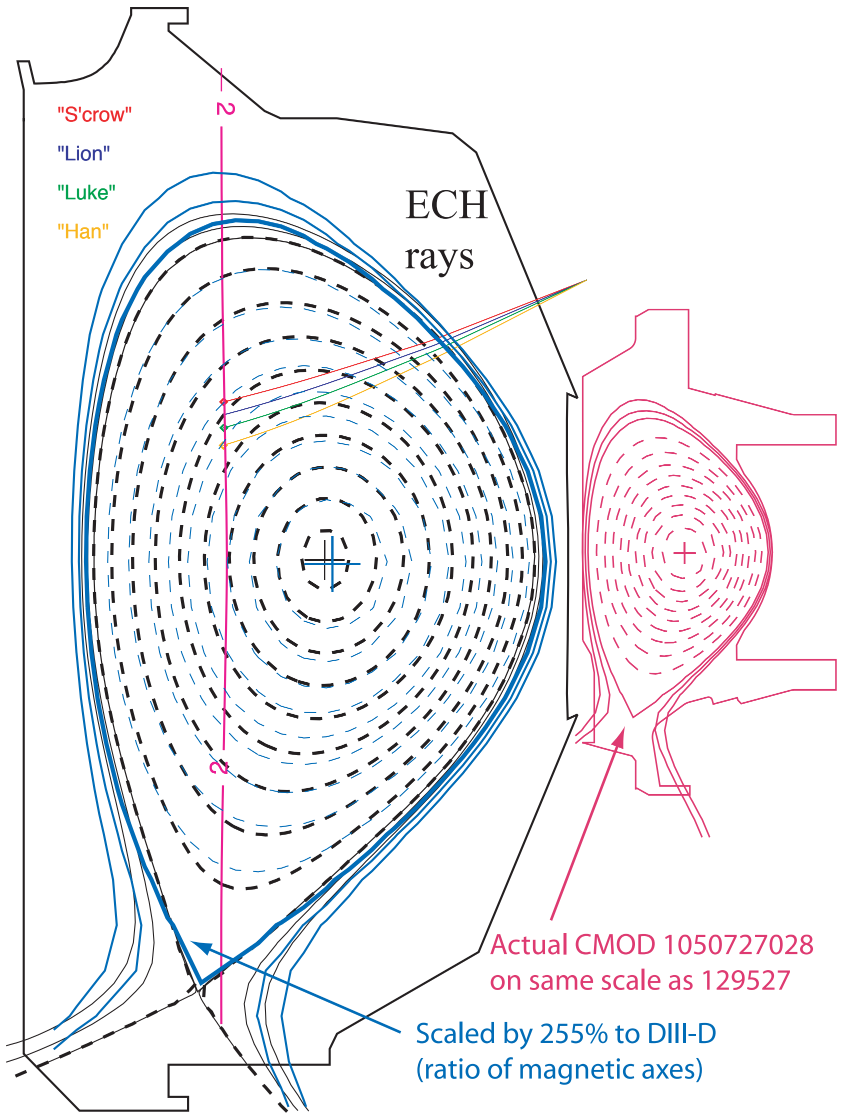
Stability Limit for m=2/n=1 NTM Increases Dramatically as Plasma Rotation Increases

- **50% increase in m=2/n=1 NTM stability when going from balanced NBI to co-NBI only**
- **Stability limit does not appear to be symmetric about zero torque/rotation**
  - more data needed to confirm
- **Influence of error fields on stability limit is less than that of rotation**
- **Analysis indicates that the rotational shear relative to the magnetic shear at the q=2 surface may be important**



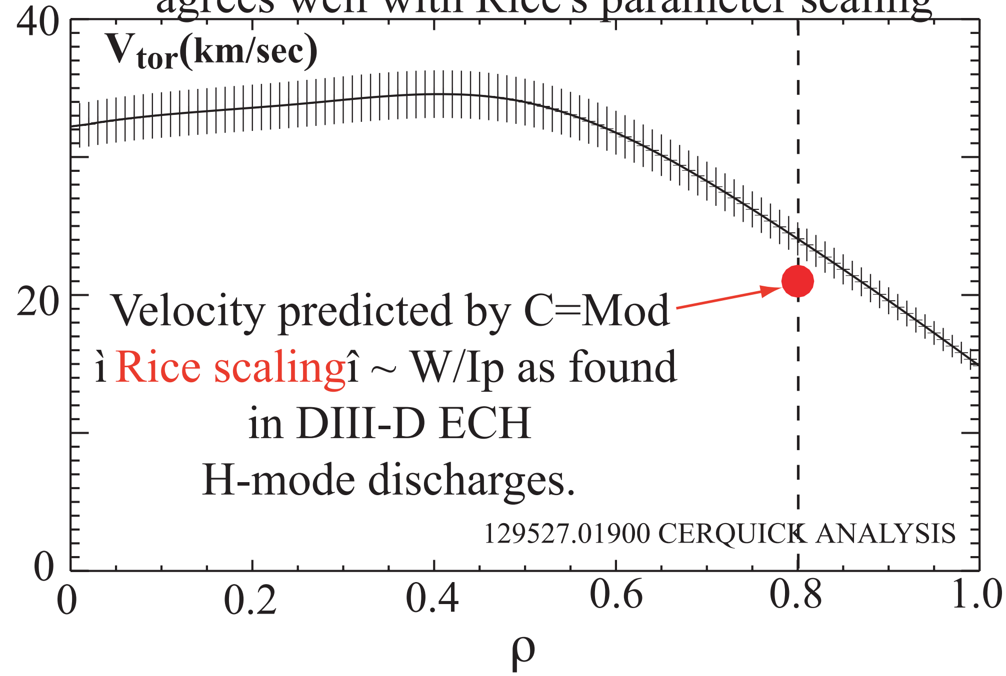


Intrinsic Rotation in DIII-D / C-Mod Similarity Experiment is Consistent with C-Mod engineering paramter scaling



Experiment: Match C-Mod shape and ρ_*, ν_* and β to the extent possible in ECH H-mode

Velocity at C-mod measurement location agrees well with Rice's parameter scaling



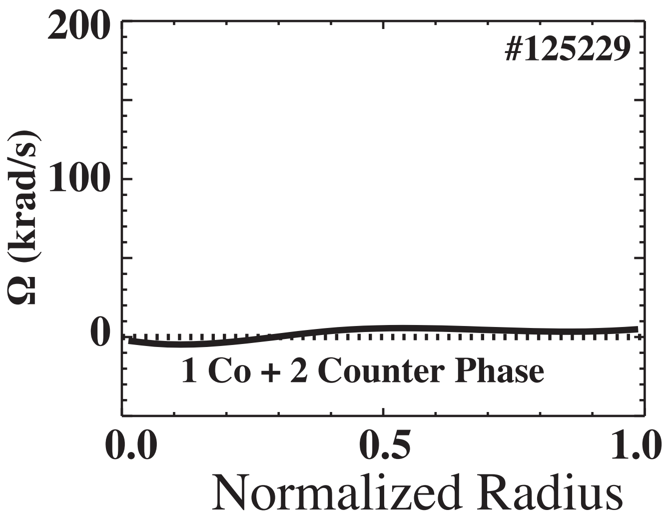
**** Must do full velocity analysis and evaluate results in terms of dimensionless similarity***

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

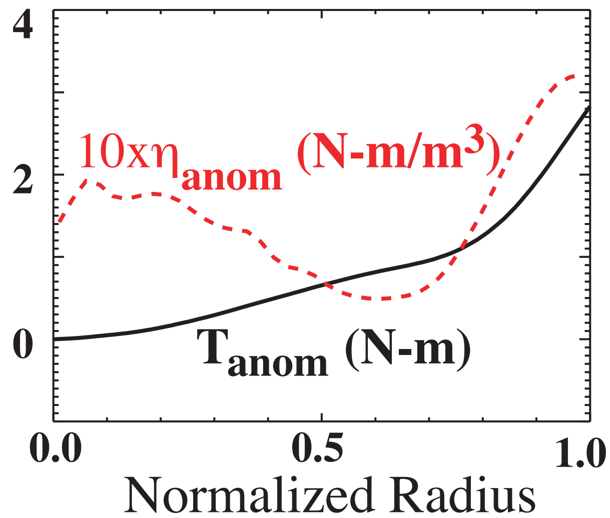
Alcator C-Mod

Co Plus Counter NBI Capability Has Enabled a New Research Path in the Study of Momentum Transport

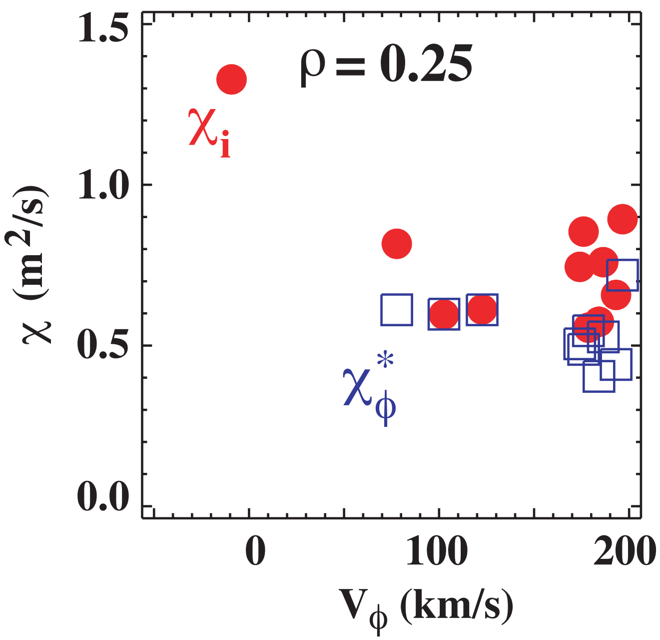
Zero Rotation With Finite Torque ....



Allows Determination of Anomalous Torque...

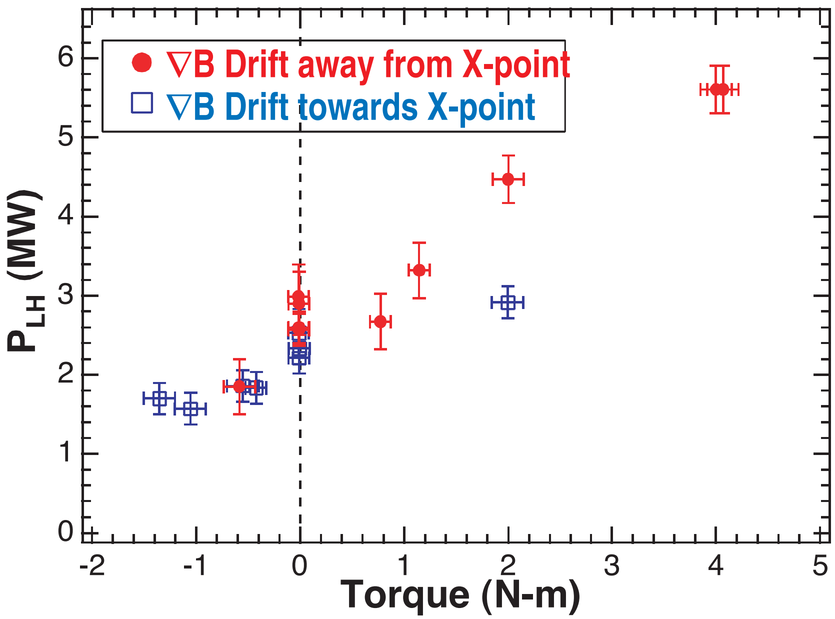


Enabling inferrence of momentum diffusivity

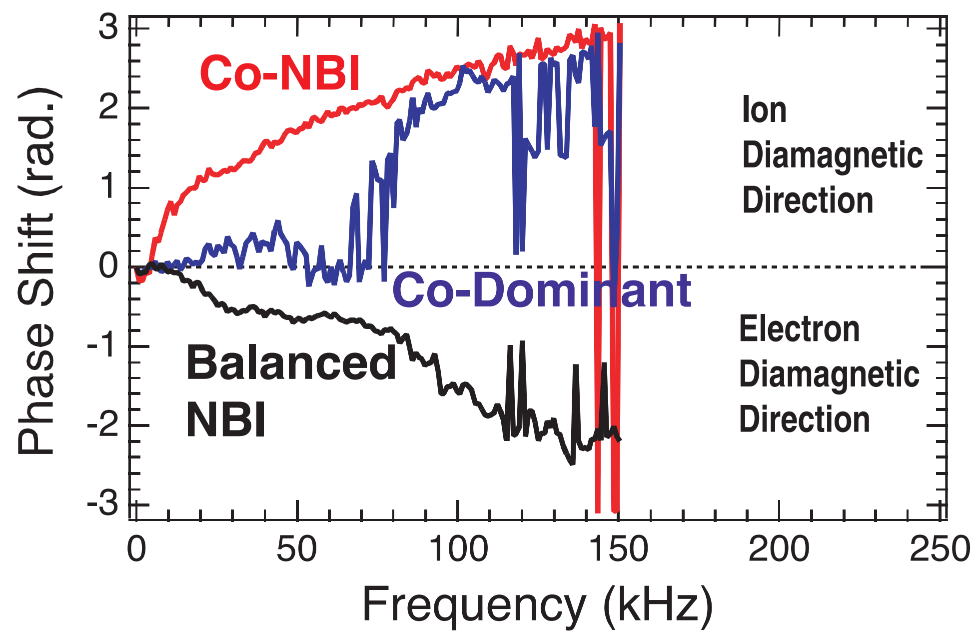


Power Threshold for L-H Transition Sensitive to Rotation; Turbulence Characteristics Vary Markedly with Rotation

- A factor of two increase in L-H transition power threshold observed in going from co-NBI to balanced NBI

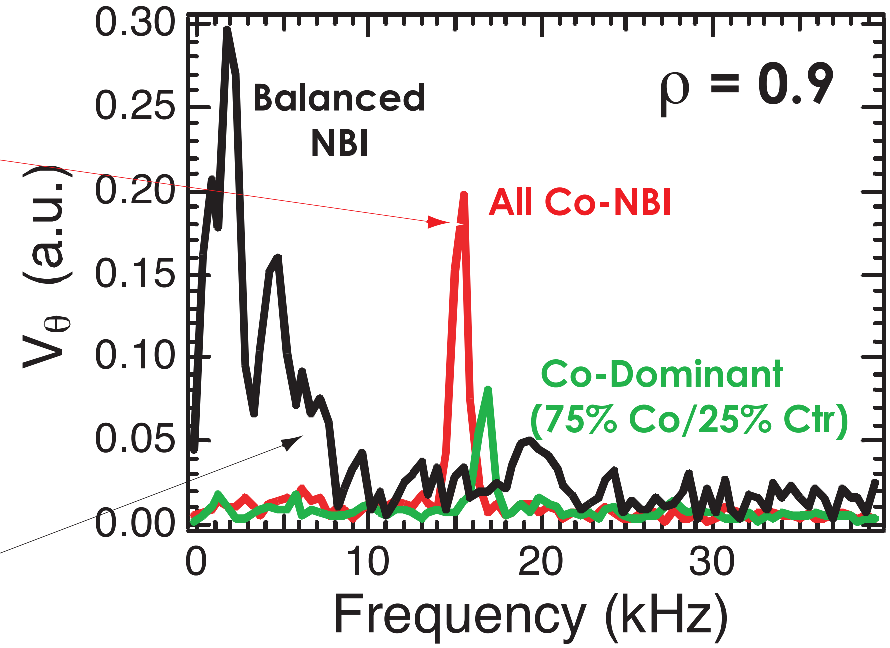


- Phase shift of turbulence reverses as rotation is decreased with multiple modes found at intermediate rotation levels



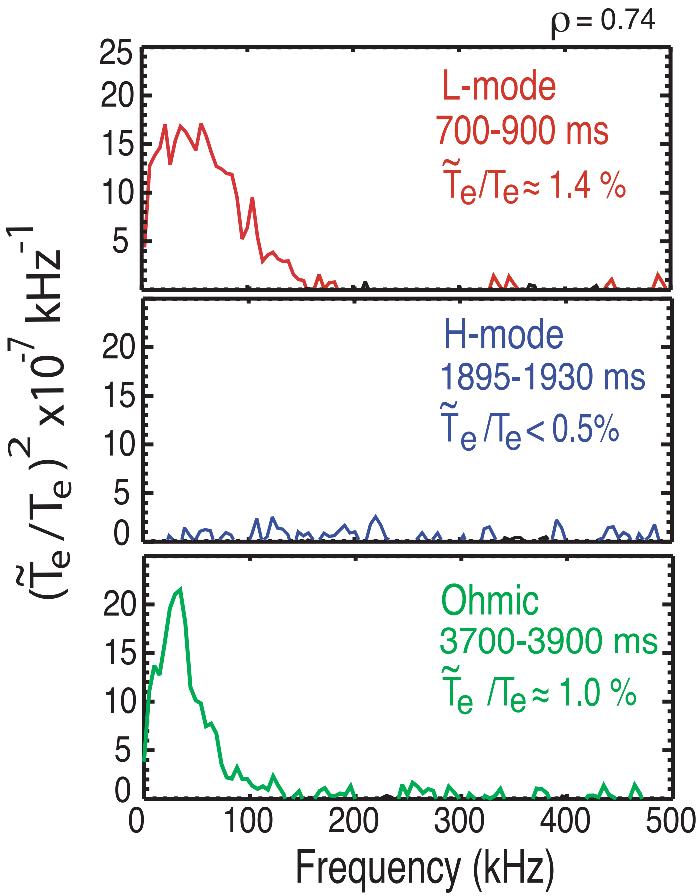
Analysis of BES data Indicates Zonal Flow Character in Edge Region Changes Markedly as Rotation is Redeuced

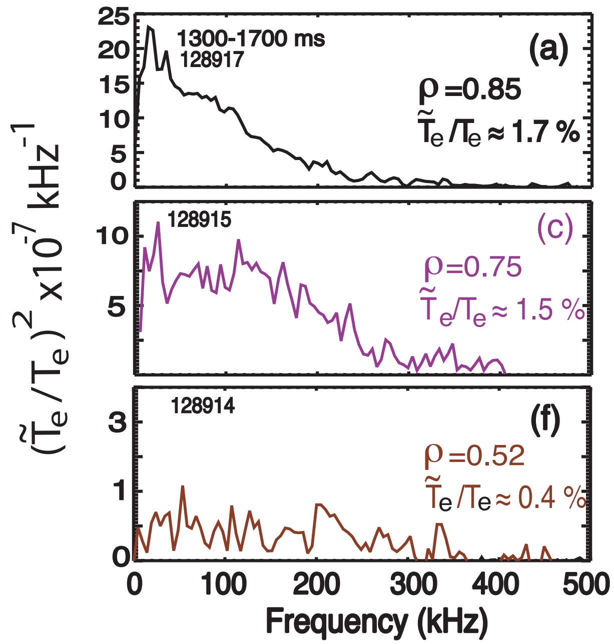
- Zonal Flow/GAM signatures identified from time-delay-estimate (TDE) analysis of BES data
- At high rotation (all co-NBI), GAM dominates the v_θ spectrum
- As rotation is reduced, prominence of GAM decresases
- At low rotation (balanced NBI), v_θ spectrum dominated by zero-mean-frequency (ZMF) zonal flow

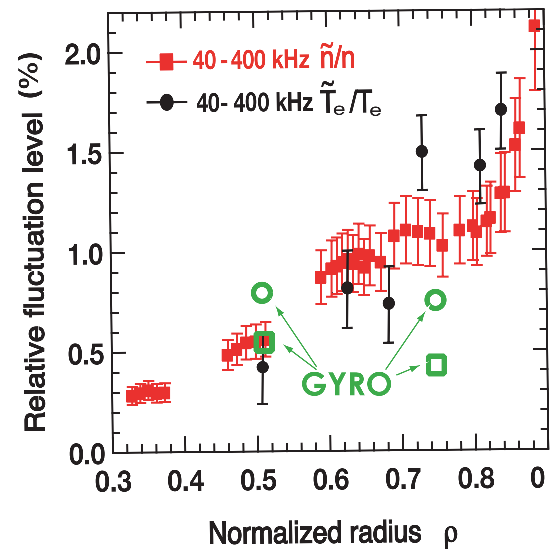


Correlation ECE Measurements of T_e Fluctuations Have Enabled Detailed Comparisons with Theory

- $\tilde{T}_e$ substantially reduced in H-mode relative to L-mode and Ohmic
- Radial variation in $\tilde{T}_e/T_e$ observed in L-mode
- Radial variation in $\tilde{T}_e/T_e$ and $\tilde{n}_e/n_e$ similar



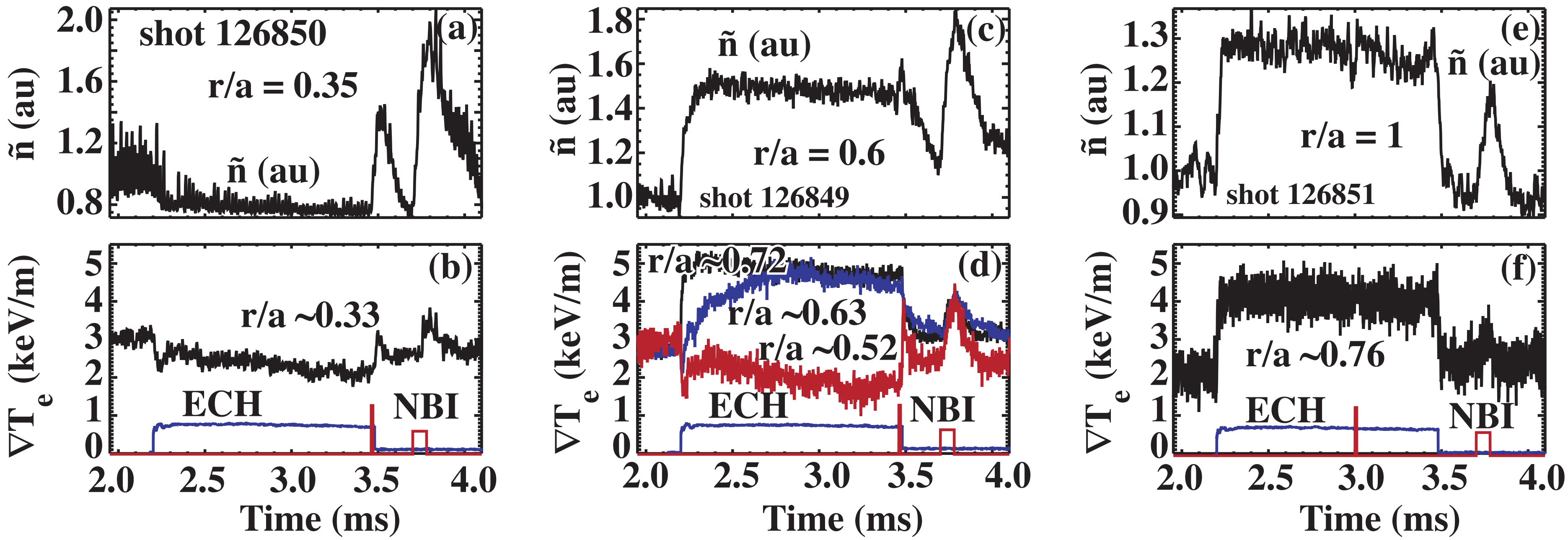




- Amplitude of $\tilde{T}_e/T_e$ and $\tilde{n}_e/n_e$ consistent with GYRO @ ρ=0.5

Localized High-k Turbulence Measurements Show Strong Correlation With Electron Temperature Gradient

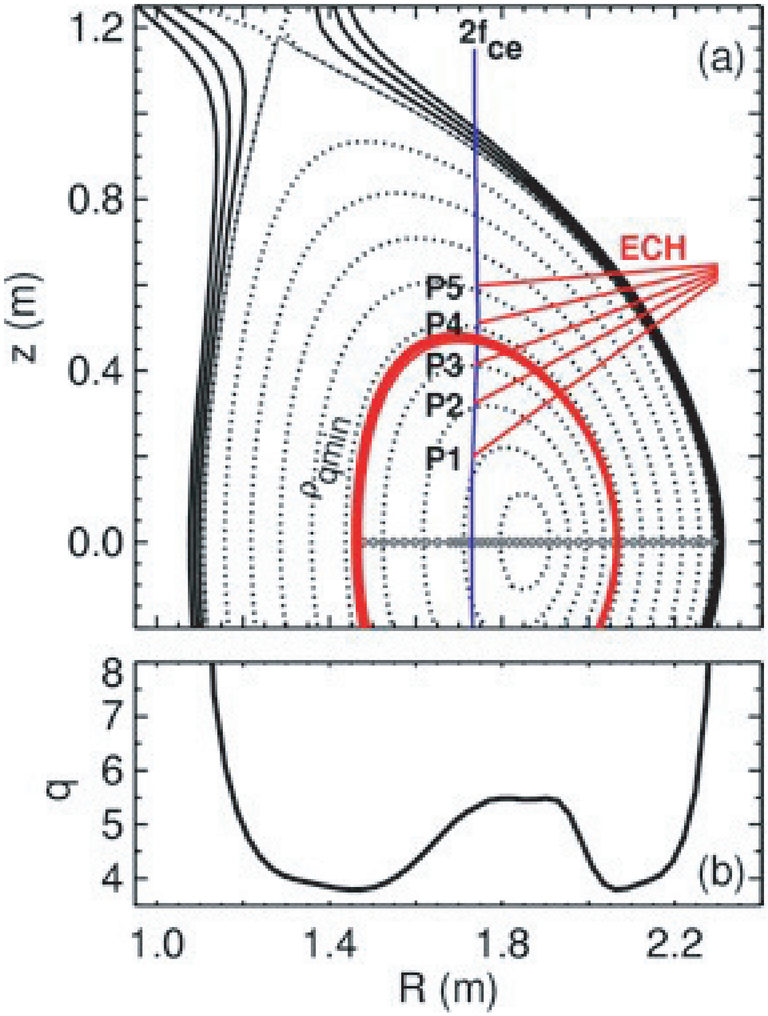
- High k (k_r = 35 cm^{-1}) measurements made by mm-wave back scattering (UCLA)



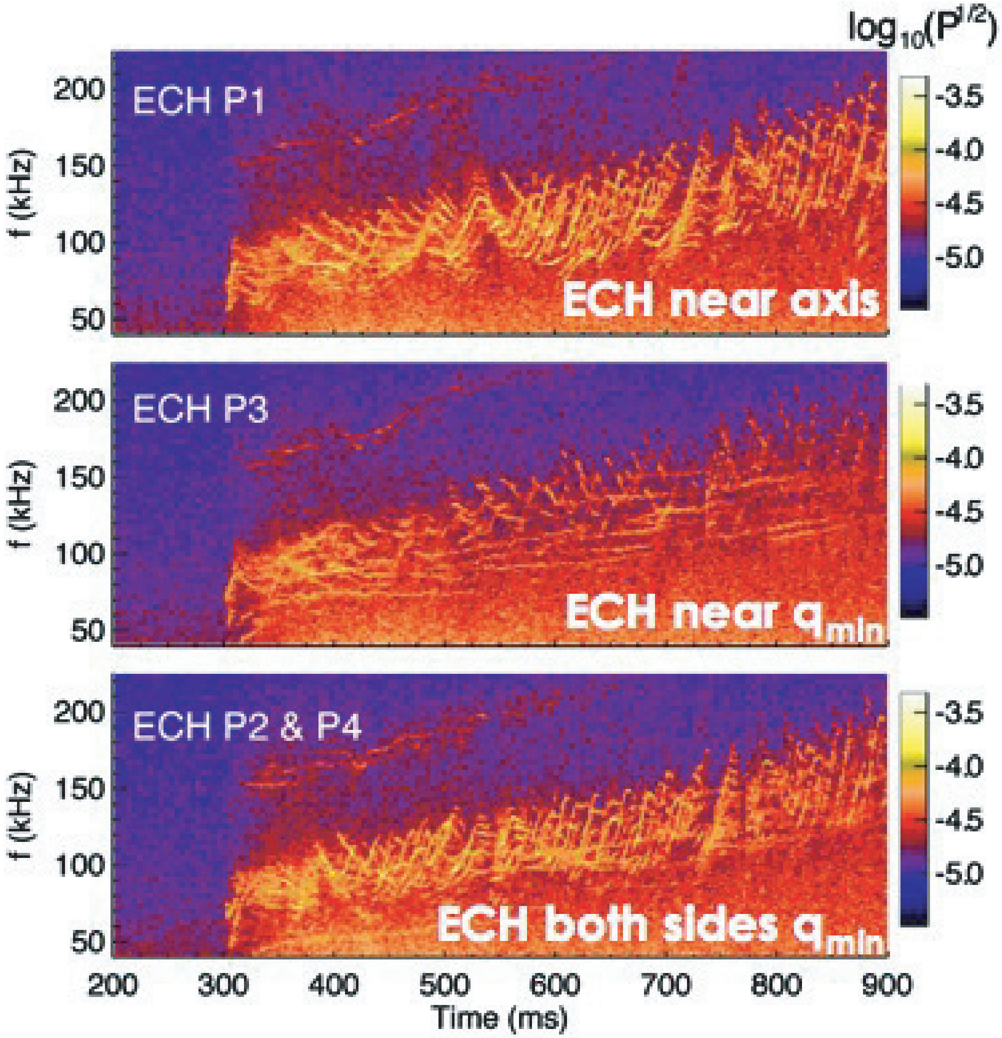
- Observed trends consistent with TGLF modeling
- GYRO comparisons ongoing

RSAE Stability Found to Be Highly Sensitive to Electron Heating Near ρ_{qmin}

- Pure radial heating by ECH at various locations

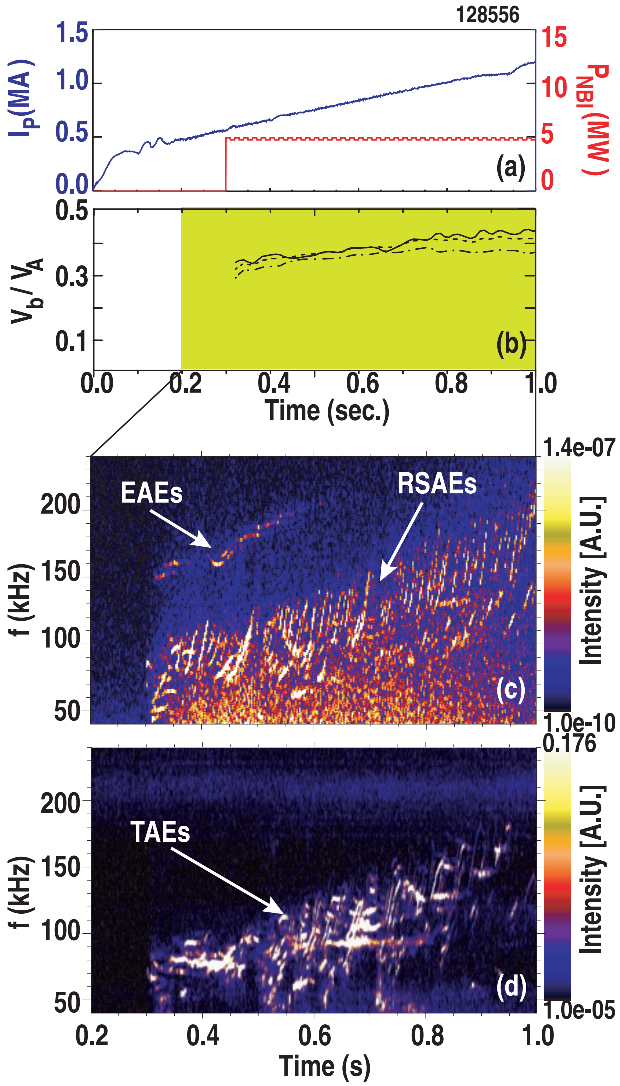


- TAE activity in all cases; RSAE activity changes markedly as ECH deposition is varied

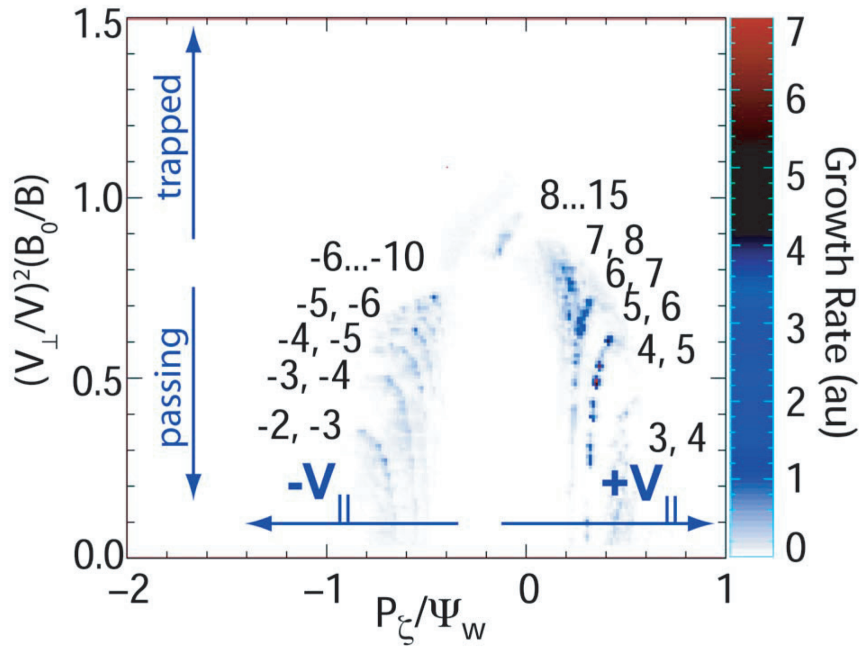


NOVA-K Analysis Indicates Importance of Low-Velocity Energetic Beam Ions on AE Stability

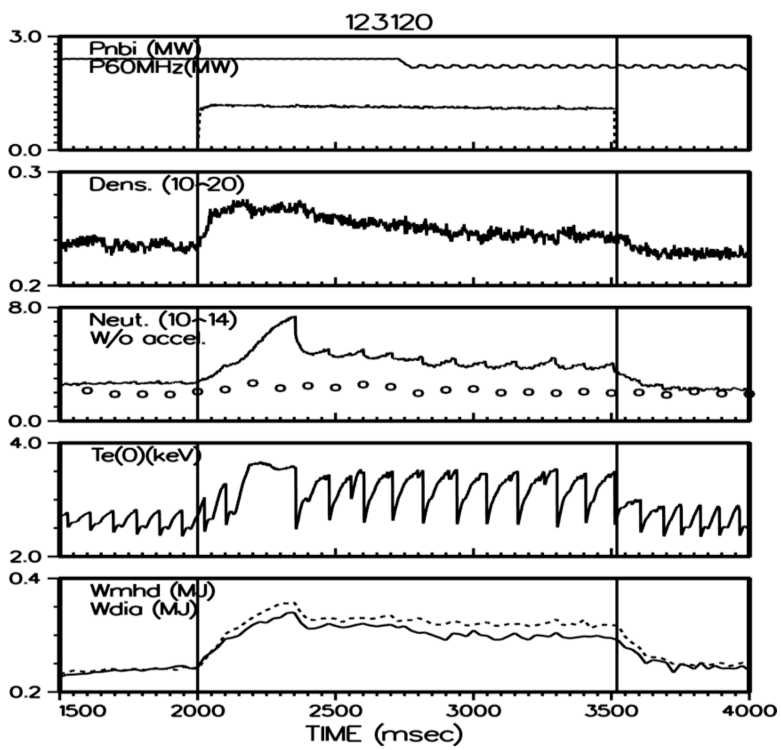
- **Significant AE activity observed with $V_b/V_A << 1$**

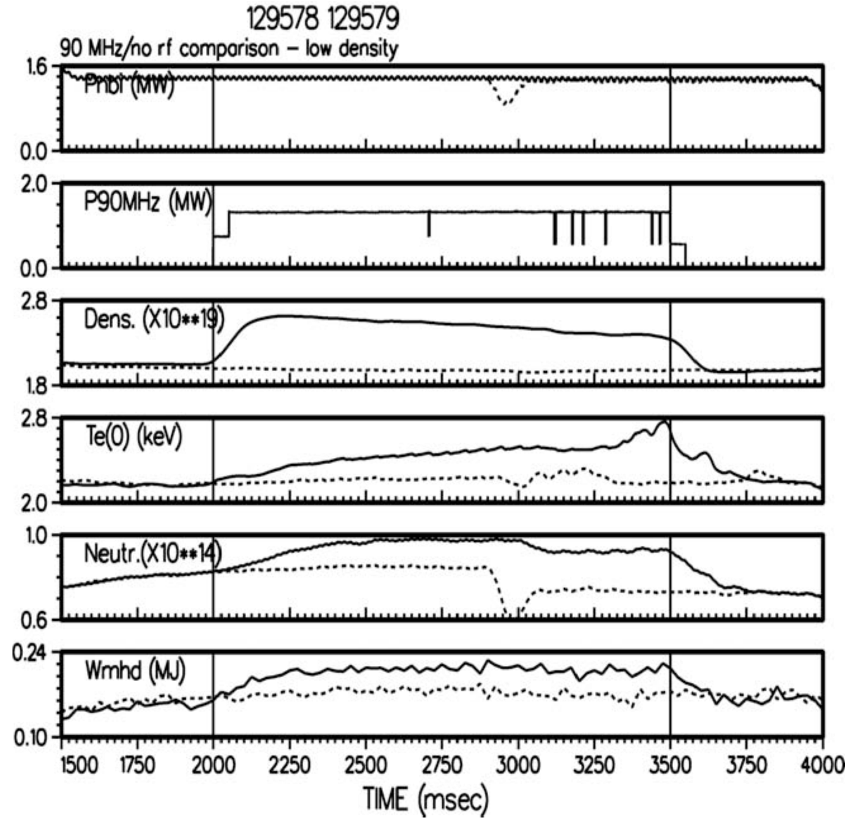


- **NOVA-K indicates many higher order resonances exists as beam ions slow down**



6th harmonic FW absorption on beam (90 MHz, 2 T) weaker than 4th harmonic (60 MHz, 2 T); core heating by direct electron absorption strong for both





- **Left panel: 60 MHz (2005), right panel: 90 MHz (2007)**
- **4th harmonic absorption results in partial sawtooth stabilization; no such effect in 6th harmonic case**
- **FIDE system shows strong beam ion acceleration in 4th harmonic case, only weak in 6th harmonic case**

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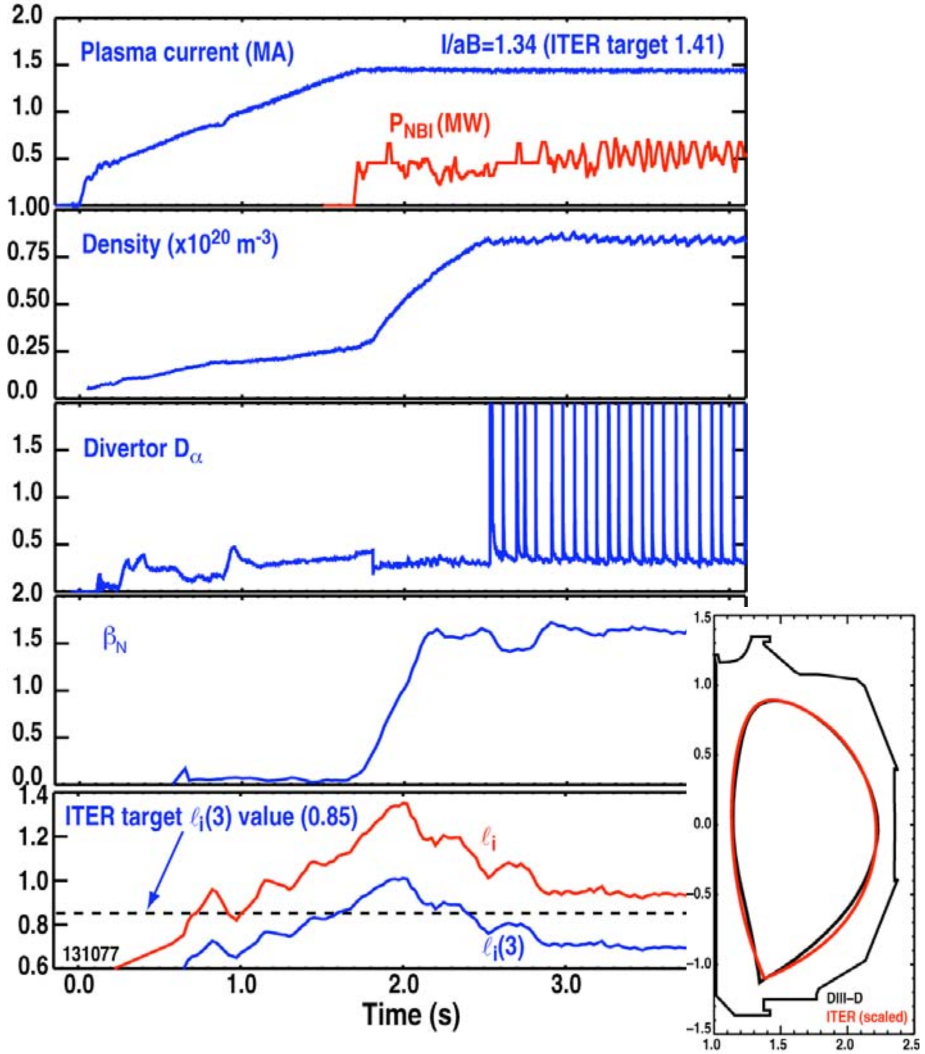
DIII-D Status and New Capabilities

- **DIII-D physics operations started January 8, 2008**
  - Three month shutdown in fall 2007
  - Startup phase completed in Dec. 2007
- **New tools available for 2008 experiments**
  - Increased ECH power (5 gyrotrons)
  - All three fast wave systems at full capability
  - New diagnostics: BES linear array, fast divertor thermocouples, fast IR TV (late in year)

Initial 2008 Experiments Highly Focused on ITER



- **More than 2/3 of experiments in January address ITER research needs**

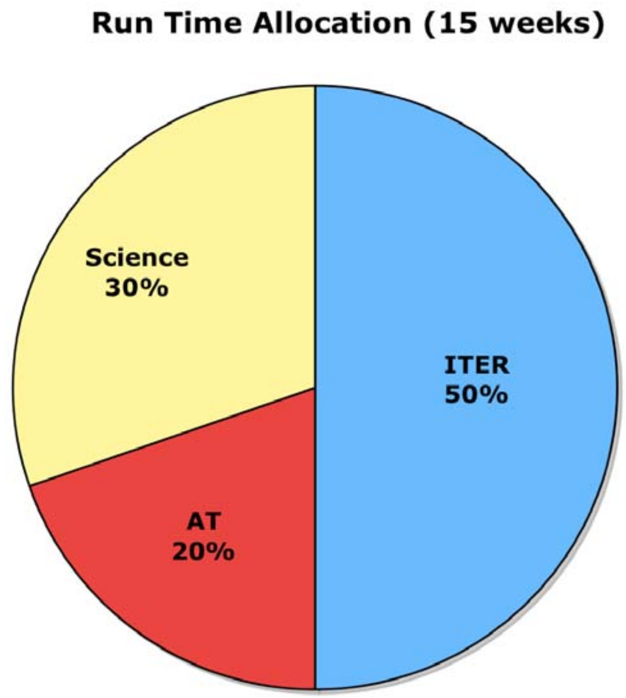
- **First 2008 experiment: ITER ELMy H-mode baseline scenario (Scenario 2). Seek to match key parameters, e.g.**
  - Shape
  - Aspect ratio
  - Normalized beta
  - Rotation

High Priority Research Topics Emphasize ITER and Fusion Science Research

	ITER	AT	Fusion Science
• ITER demonstration discharges (task force)	✓		
• ELM control and pedestal physics (task force)	✓		✓
• Rotation physics (task force)	✓		✓
• Steady-state high-beta operation		✓	
• Transport model validation			✓
• Thermal transport in the plasma boundary			✓
• Hydrogenic retention	✓		
• ITER startup, shutdown, and vertical stability	✓		

2008 Experimental Plan Addresses Important ITER Issues While Maintaining Strong Emphasis on Science

Area/Task Force	Total days	ITER	AT	Fusion Science
ITER Physics	10	10		
Steady State Integration	11		11	
Fusion Science	12	2		10
Integrated Modeling	1			1
Plasma Control	3	3		
Rotation Physics	8	2		6
ITER Demo Discharges	4	4		
ELM Control & Pedestal	7	7		
Totals	56	28	11	17



Outline

- Recent results aimed at:
  - Addressing urgent ITER design issues
  - Developing long-pulse and steady-state scenarios
  - Advancing the understanding of fusion plasmas
- Present Status
  - 2008 Experimental Emphases
- Brief Overview of DIII-D 5-Year Program Plan

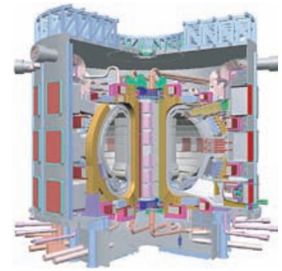
The DIII–D Research Program Has Three Research Goals

- **ITER support: Enable the success of ITER by providing physics solutions to key issues**

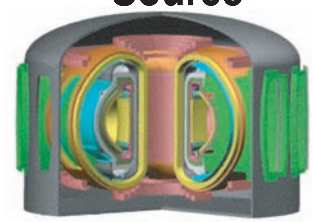
- **Advanced tokamak: Establish the physics basis for steady-state high performance operation for ITER and beyond**

- **Science: Advance the fundamental understanding of fusion plasmas along a broad front**

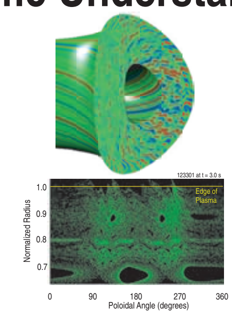
Fusion Demonstration



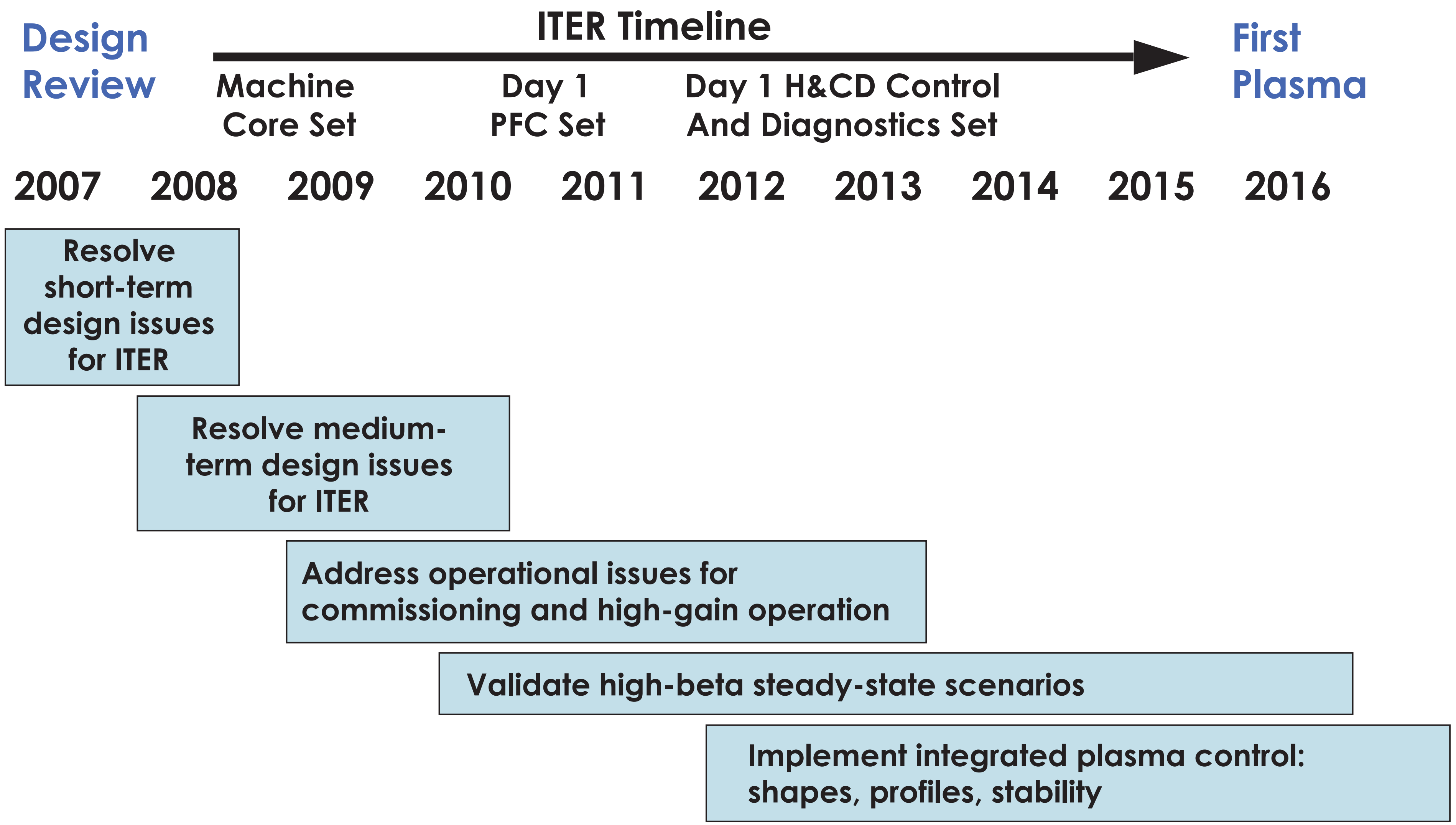
Attractive Energy Source



Scientific Understanding



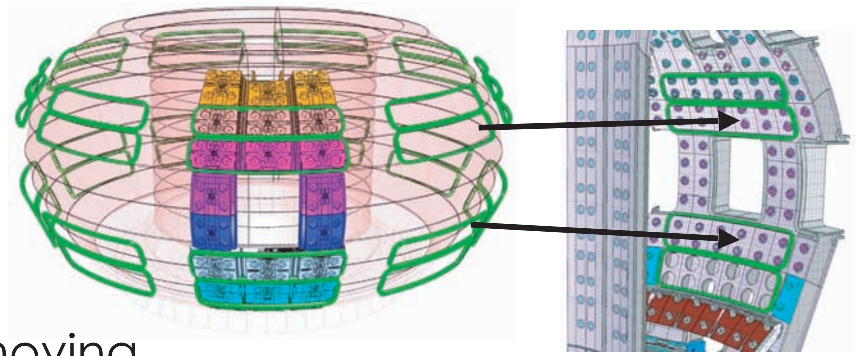
The Focus of DIII–D Research Will Evolve with ITER's Changing Needs



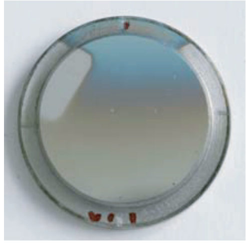
Near-Term ITER Program Focused on Resolving Key Issues for Built-In Components

- **ELM and RWM control:**
  - Establish physics basis for choice of ELM and RWM control coils in ITER
- **Hydrogenic retention:**
  - Quantify techniques for mitigating/removing tritium from carbon PFCs in ITER
- **Disruption mitigation:**
  - Evaluate capability of various delivery systems in producing necessary density for runaway suppression
- **NTM control:**
  - Validate requirements for ECCD for suppression of NTMs; test viability of using internal coil to control locked modes

ELM Control Coils for ITER

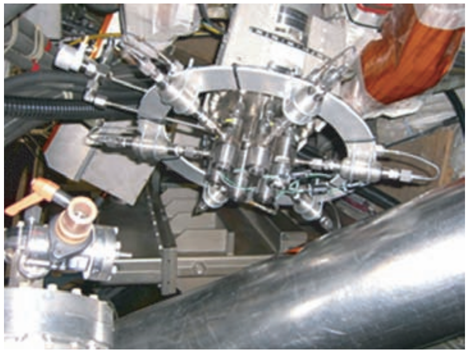


Non-Heated Mirror



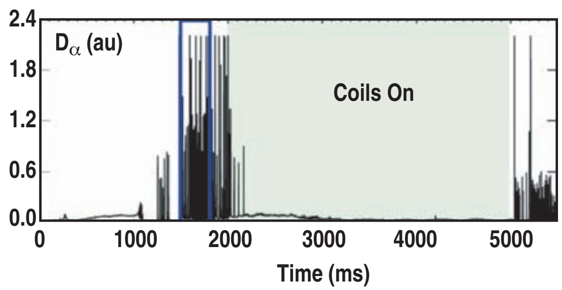
Heated Mirror

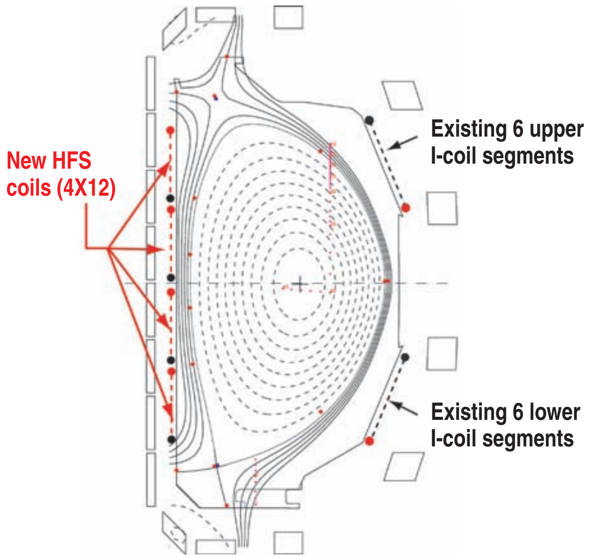
Medusa Valve



ELM Control Studies Will Focus on Identifying Best Means for ELM Mitigation in ITER

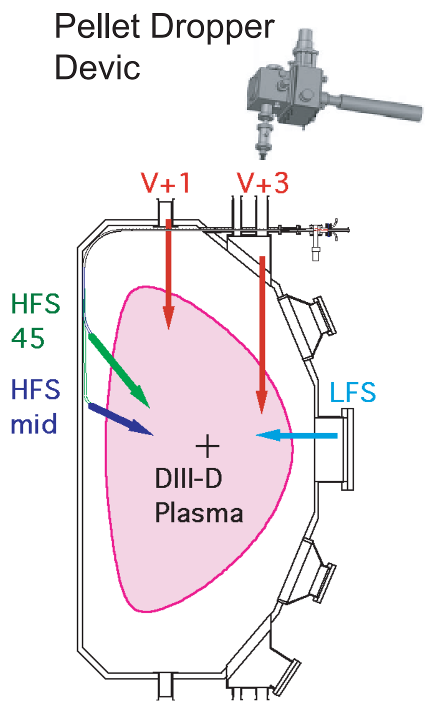
RMP ELM Suppression





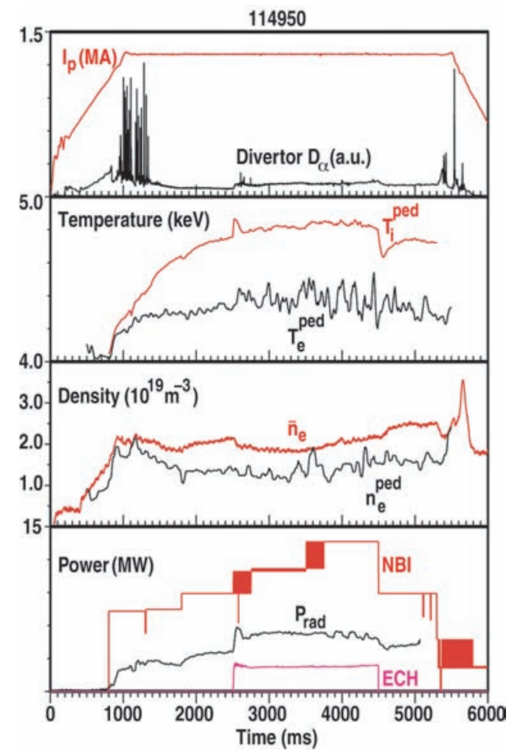
- Determine physics mechanism(s) leading to ELM suppression

Pellet Pacing



- Characterize penetration requirements
- Assess impact of successful ELM mitigation on pedestal

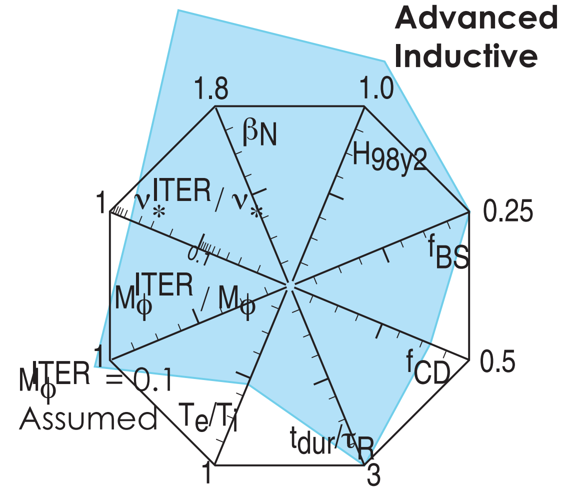
QH-mode

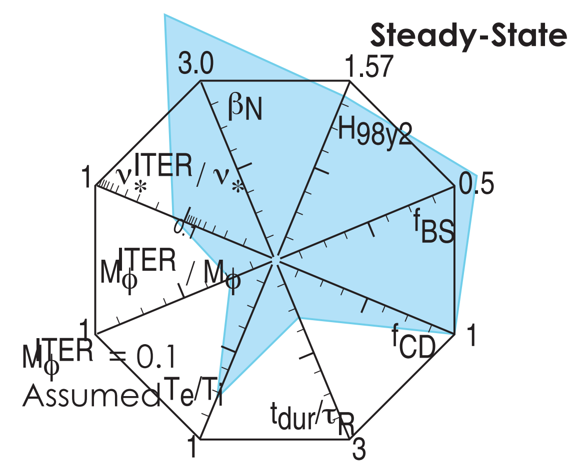


- Identify mechanisms responsible for EHO
- Expand operating space to balanced and co-NBI

Scenario Development, Validation, and Characterization for ITER Will Continue as a Primary Emphasis of the DIII–D Program

- **Conventional ELMing H–mode**
  - Evaluate impact of low rotation, $T_e \approx T_i$ on extrapolation to ITER and address limiting processes (e.g. NTMs, ELMs)
- **Hybrid**
  - Establish validity of hybrid regime in burning plasma conditions
    - Low rotation, $T_e \approx T_i$ at ITER collisionality, ELM suppression, radiative divertor
- **Steady-state high performance**
  - Provide proof-of-principle demonstration of steady-state high performance operation
  - Assess capability of ITER to achieve steady-state with chosen H&CD tools





DIII–D Will Address Operational Issues Specific to ITER as Identified by the Development of the ITER Research Plan

- **Hydrogen operation**
  – Characterize L–H transition, confinement in H plasmas
- **Current ramp simulation**
  – Develop comprehensive data set on proposed ITER startup scenarios through simulations on DIII–D
- **Disruption avoidance**
  – Develop and validate methods for real-time stability control
- **Error field correction**
  – Develop and test methods for determining the necessary error correction on ITER
- **Diagnostic development**
  – Develop and test ITER-prototype diagnostics

Steady-state Scenario Development is Staged to Successively Achieve the Performance Requirement of Future Devices

2007 2008 2009 2010 2011 2012 2013 2014 2015

ITER

$Q \geq 5$

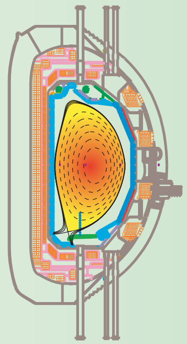
t_{DUR} ~1000 s

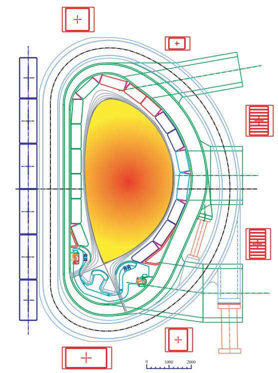
Steady-State Scenario for ITER

f_{BS} ~55%, β_N ~ 3.5

f_{NI} = 100%, t_{DUR} ~5s,

LSN ITER Shape





FDF

AT for DEMO

Net Tritium

Blanket Testing

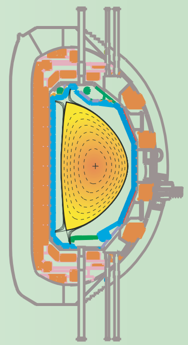
$\Gamma_N \rightarrow 2$ MW/m^2

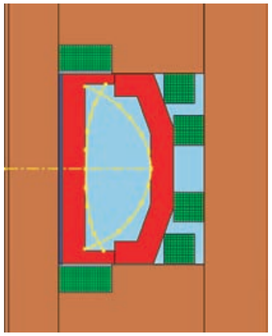
Steady-State Scenario for FDF

f_{BS} ~ 70%, β_N ~ 4

f_{NI} = 100%, t_{DUR} ~ 10 s,

High δ, DN Shape





DEMO-AT

Plant Q > 1

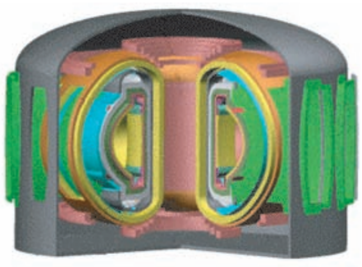
Develop Boundary Solutions

Establish Physics Basis for Steady-State Powerplant Optimization

f_{BS} ~ 90%

$\beta_N \rightarrow 5$

$t_{DUR} \rightarrow 10$ s



Proposed Hardware Upgrades Are Aimed at Providing Capability to Demonstrate β_N ~ 5 for Extended Duration

	2007	2008	2009	2010	2011	2012	2013	2014
Heating & CD	NB: 12.5 MW co, 5 MW ctr		+2.5 MW co		Off-Axis	10 s		
	EC: 4 MW	6 MW			9 MW		12 MW	
	FW: 3 MW				new antenna			
Tools				Inner Wall RMP		Div. Coils		

ITER

$Q \geq 5$

t_{DUR} ~1000 s

- Demonstrate $\beta_N > 3$, $f_{NI} = 1$ for $> \tau_R$
- Evaluate scenario at $T_e = T_i$, low torque input
- Evaluate potential boundary solutions

FDF

AT for DEMO
Net Tritium
Blanket Testing
$\Gamma_N \rightarrow 2$ MW/m^2

- Shape, bootstrap current optimization
- Demonstrate $\beta_N = 4$, $f_{NI} = 1$ for $> \tau_R$
- Integrate boundary solution

DEMO-AT

Plant $Q > 1$

- Transient exploration of routes to $\beta_N \rightarrow 5$
- Develop advanced current profile control techniques
- Demonstrate $\beta_N \rightarrow 5$, for $>5\ \tau_E$

Edge Integration

- ELM mitigation in advanced performance plasmas
- Evaluate heat flux reduction techniques

Proposed Hardware Upgrades Are Aimed at Providing Capability to Demonstrate $\beta_N \sim 5$ for Extended Duration

		2007	2008	2009	2010	2011	2012	2013	2014
Heating & CD	NB	NB: 12.5 MW co, 5 MW ctr		+2.5 MW co		Off-Axis	10 s		
	EC	EC: 4 MW	6 MW			9 MW		12 MW	
	FW	FW: 3 MW				New Antenna			
Tools					Inner Wall RMP		Div. Coils		

ITER
$Q \geq 5$
$t_{DUR} \sim 1000$ s

- Demonstrate $\beta_N > 3$, $f_{NI} = 1$ for $> \tau_R$
- Evaluate scenario at $T_e = T_i$, low torque input
- Evaluate potential boundary solutions

FDF
AT for DEMO
Net Tritium
Blanket Testing
$\Gamma_N \rightarrow 2$ MW/m^2

- Shape, Bootstrap Current optimization
- Demonstrate $\beta_N = 4$, $f_{NI} = 1$ for $> \tau_R$
- Integrate boundary solution

DEMO-AT
Plant $Q > 1$

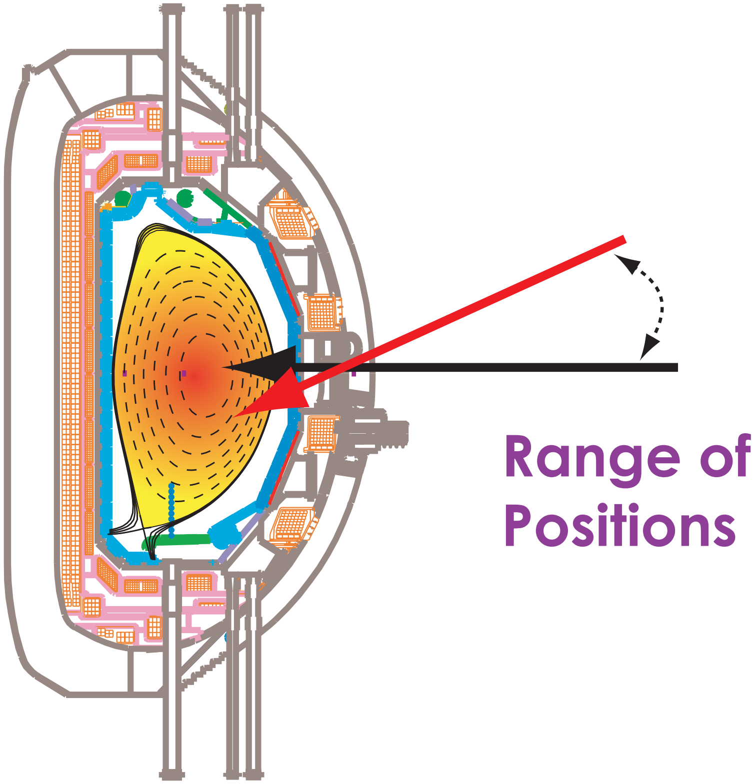
- Transient exploration of routes to $\beta_N \rightarrow 5$
- Develop advanced current profile control techniques
- Demonstrate $\beta_N \rightarrow 5$, for $> 5\ \tau_E$

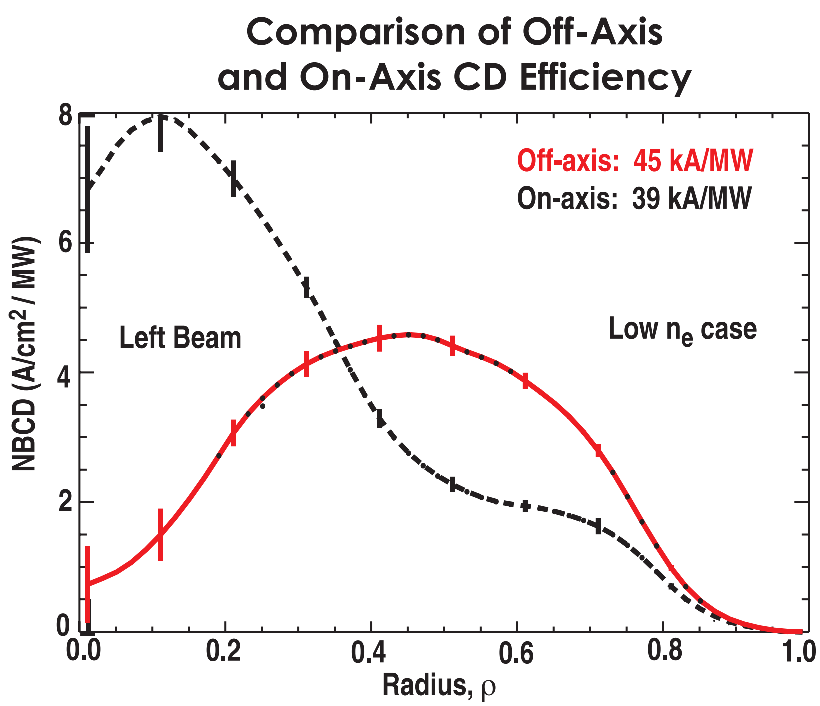
Edge Integration

- ELM mitigation in advanced performance plasmas
- Evaluate heat flux reduction techniques

Providing Required Off-Axis Current Drive for Sustained High Performance is a Key Component of 5-Year Plan

- **Off-axis current drive required to maintain favorable current profile for high β operation near the ideal stabililty limit**
- **DIII-D 5-Year Plan:**
  - Upgrade of ECCD system to 12 MW
  - Off-axis neutral beam (10 MW)

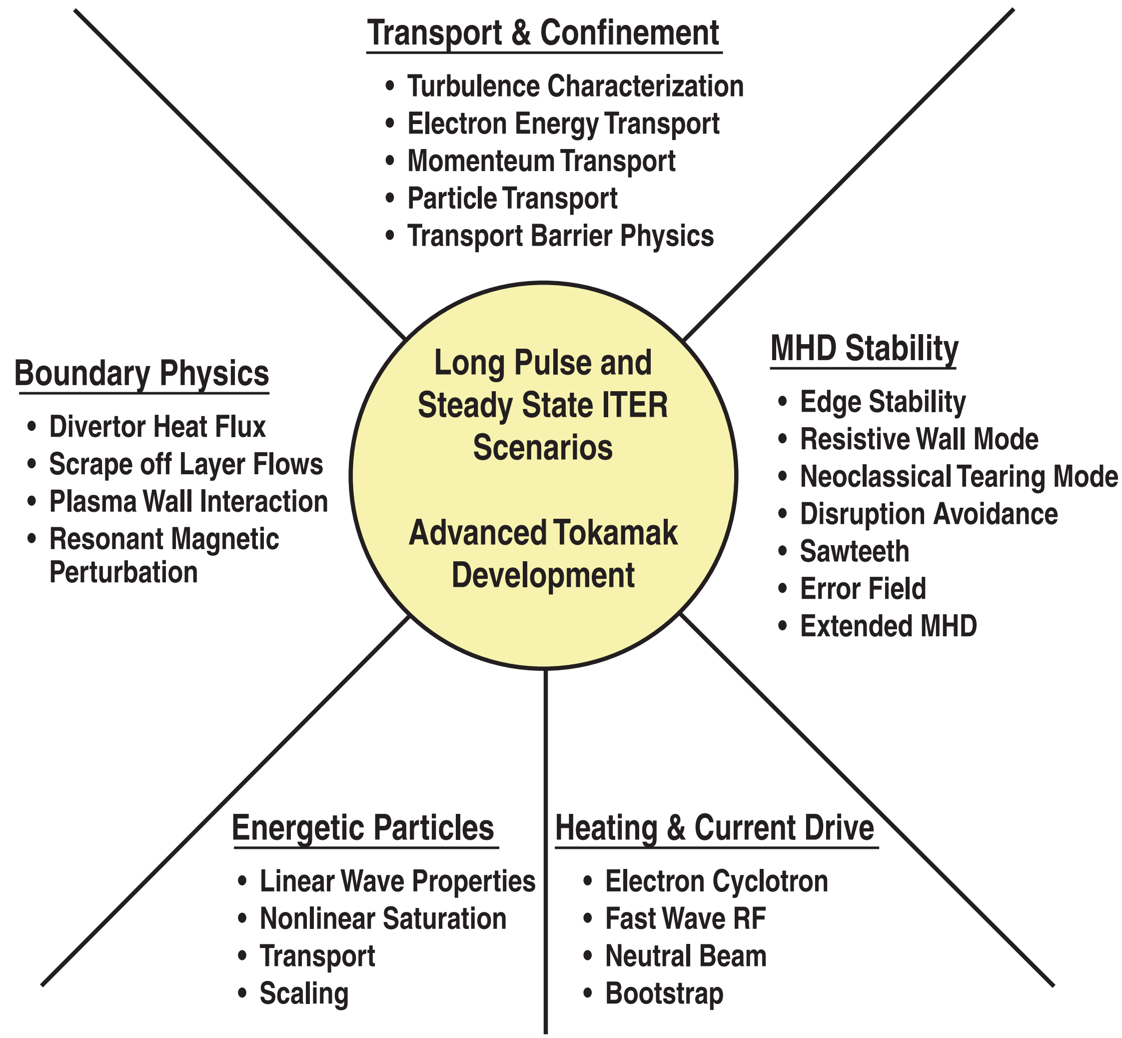




Fusion Science Research Program Seeks to Advance the Understanding of Fusion Plasmas Along a Broad Front

- **Primary goals of fusion science program on DIII-D**
  - Test and validate models of important physical processes
  - Discover and characterize new physics phenomena
  - Seek out transformational breakthroughs

- **Basic research strongly supports both ITER and Advanced Tokamak missions of DIII-D**



The knowledge gained is most enduring contribution of the DIII-D program

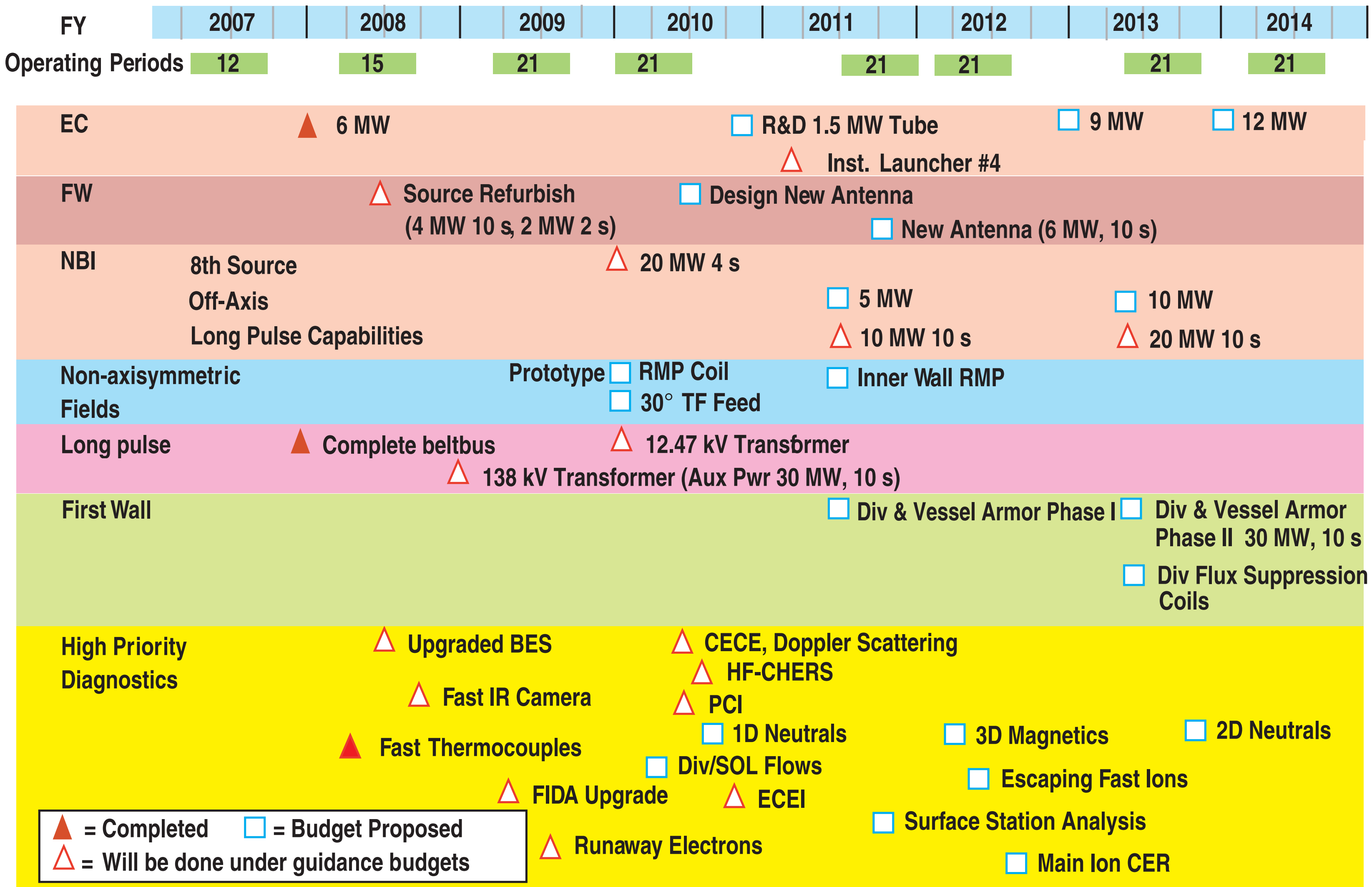
Transport Research is Entering a New Era of Detailed Comparisons of Experiment and Theory

- **Previous 5 years marked by tremendous advances in both measurement and simulation capability of transport processes**
  - Diagnostics
    - Density fluctuation measurements over a wide range of spatial scales
    - Detailed measurements of zonal flows
    - T_e fluctuations
    - High temporal and spatial resolution profile diagnostics
  - Simulation
    - Gyrokinetic codes (e.g., GYRO) capable of computing fully nonlinear saturated turbulence state
    - Reduced transport models (e.g., GLF23, TGLF) used to predict kinetic profiles consistent with the power and particle sources
- **Next 5 years will seek to validate transport codes**
  - Direct tests of GYRO predictions of turbulence characteristics through detailed comparisons with turbulence measurements
  - Test transport models through steady-state and modulated transport studies

New Capabilities Will Enable Multiple Research Activities

Hardware	Research Elements
NBI: 10 MW, off-axis	J(ρ), energetic particles, Tor/Pol rotation
20 MW, 10 s	Long pulse AT
ECE (12 MW, 10 s)	J(ρ), NTM, $T_e \sim T_i$
FW (6 MW, 10 s)	J(ρ~0), $T_e \sim T_i$, energetic particles
Inner Wall RMP	ELM control, heat and particle control
Divertor control coils	Heat and particle control
Divertor and vessel armor upgrade	10 s high performance, physics of heat removal
Hot wall operation	Hydrogenic co-deposition and removal
Custom pellets, inverse jet, liquid jet	Disruption mitigation
RWM amplifier/network	Dynamic error field control, n=1, 2 RWM stability
Improved and new diagnostics	Fusion science, control, optimization

DIII–D Five-Year Plan Hardware Schedule



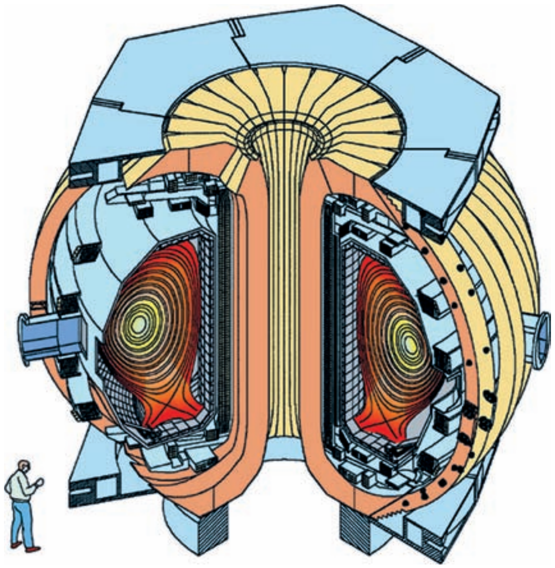
- Capabilities will provide excellent platform for ITER support, advanced tokamak development, and fusion science for the next decade

DIII-D NATIONAL FUSION FACILITY

002-08/MRW/jy

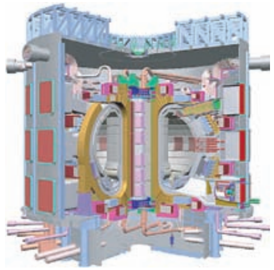
DIII–D 5-Year Plan: An Exciting Opportunity for Significant Scientific Advances Aimed at the Success of Fusion Energy

DIII–D

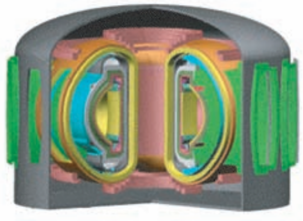


Progress on DIII–D in 5-Year Plan Will Lead to...

Increased Confidence in Success of ITER



Improved Basis for Steady-state Tokamak



Improved Scientific Understanding of Key Issues