Development in the DIII-D Tokamak of Advanced Operating Scenarios and Associated Control Techniques for ITER

by
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for
The DIII-D Team

Presented at the
21st IAEA Fusion Energy Conference
Chengdu, China

October 16–21, 2006

DIII-D
NATIONAL FUSION FACILITY

GENERAL ATOMICS

271-06/MRW/jy

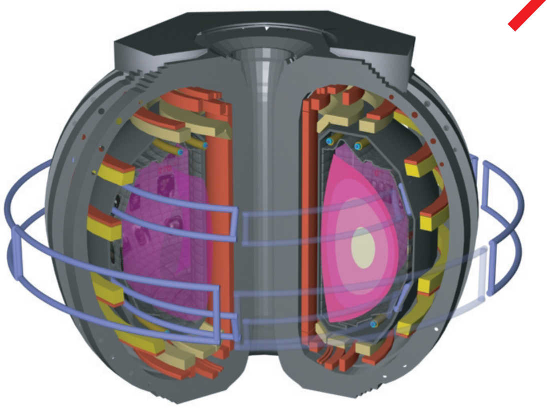
DIII–D's Research Program is Aimed at Maximizing the Scientific Benefit from ITER

DIII–D Research Elements are:

- Ensuring the success of ITER through development of physics solutions to key ITER issues
- Enriching the physics program on ITER through the development and characterization of advanced operating scenarios
- Advancing the physics understanding of issues critical to the success of ITER

DIII-D Has Advanced the Physics Basis and Confidence in ITER Achieving Its Physics Objectives

DIII-D



Plasma Control

NTM stabilization
ELM suppression
RWM stabilization
Profile Control

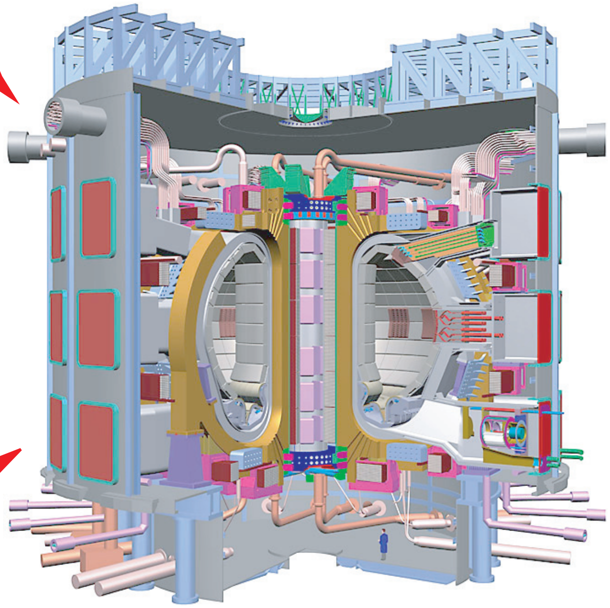
Advanced Scenario Integration

High β, steady-state (Q=5)
Hybrid (Q≥10)

Improvement of Scientific Understanding

Energetic particles
Turbulence-driven transport

ITER



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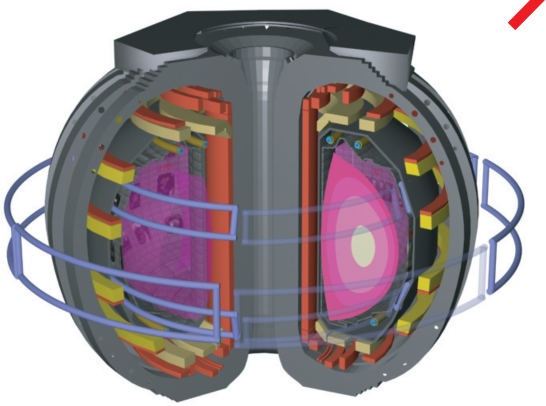

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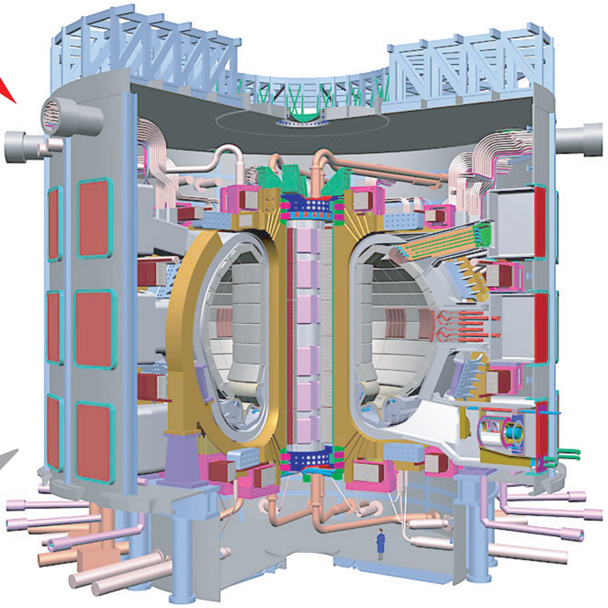
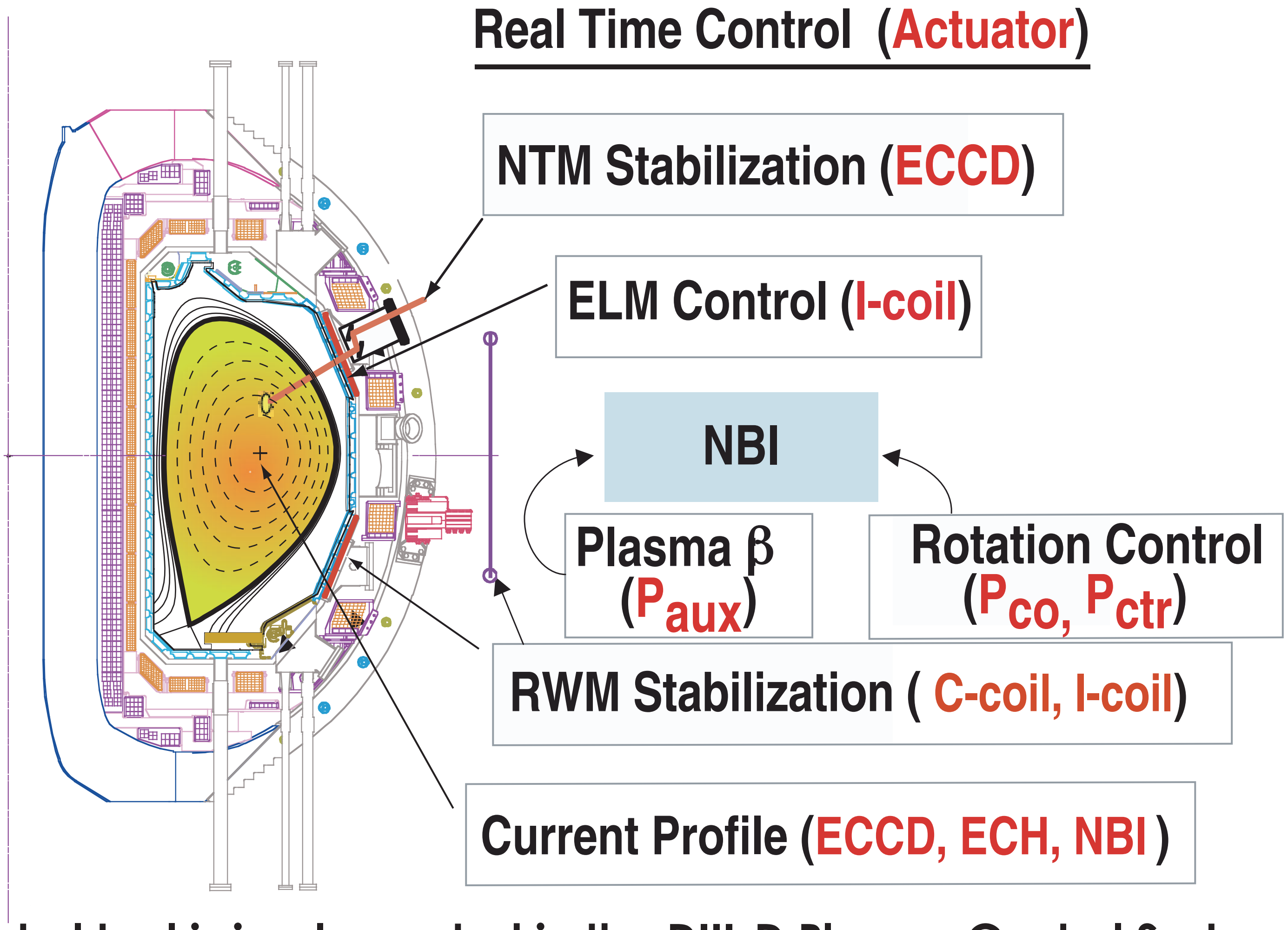


Real-Time Control of Key Plasma Properties Enabled by Extensive Set of Control Tools



Real Time Control (Actuator)

NTM Stabilization (ECCD)

ELM Control (I-coil)

NBI

Plasma β (P_{aux})

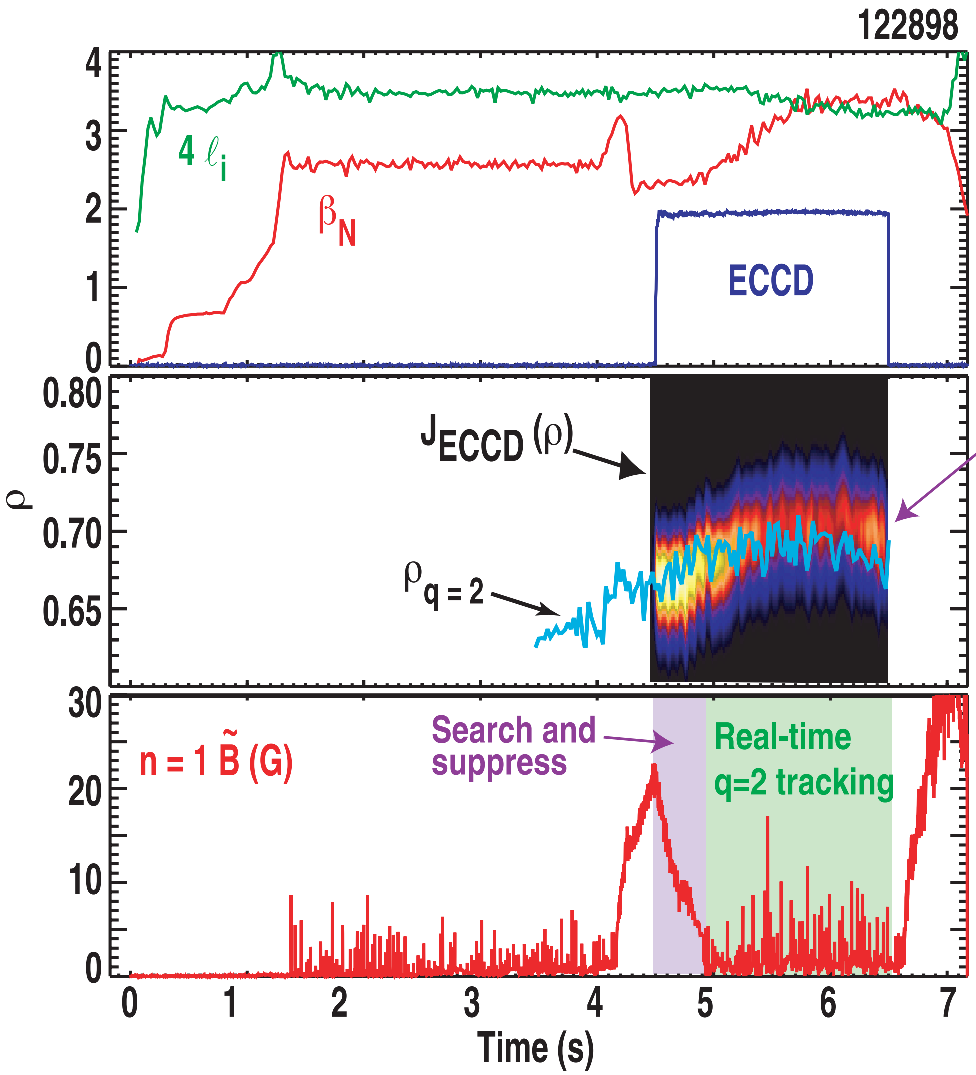
Rotation Control (P_{co}, P_{ctr})

RWM Stabilization (C-coil, I-coil)

Current Profile (ECCD, ECH, NBI)

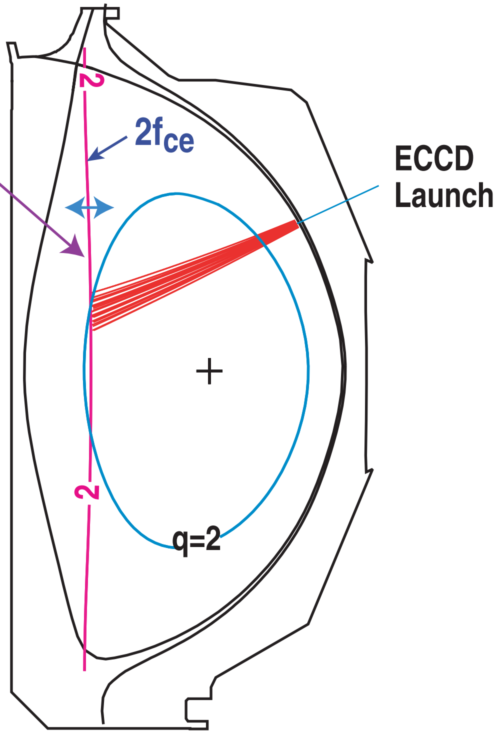
- Each control tool is implemented in the DIII-D Plasma Control System, allowing real-time integrated control

Sustained Operation at $\beta = \beta^{\text{no-wall}}$ Without m=2/n=1 NTM Demonstrated Using Real-Time Positioning of ECCD



- **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)**

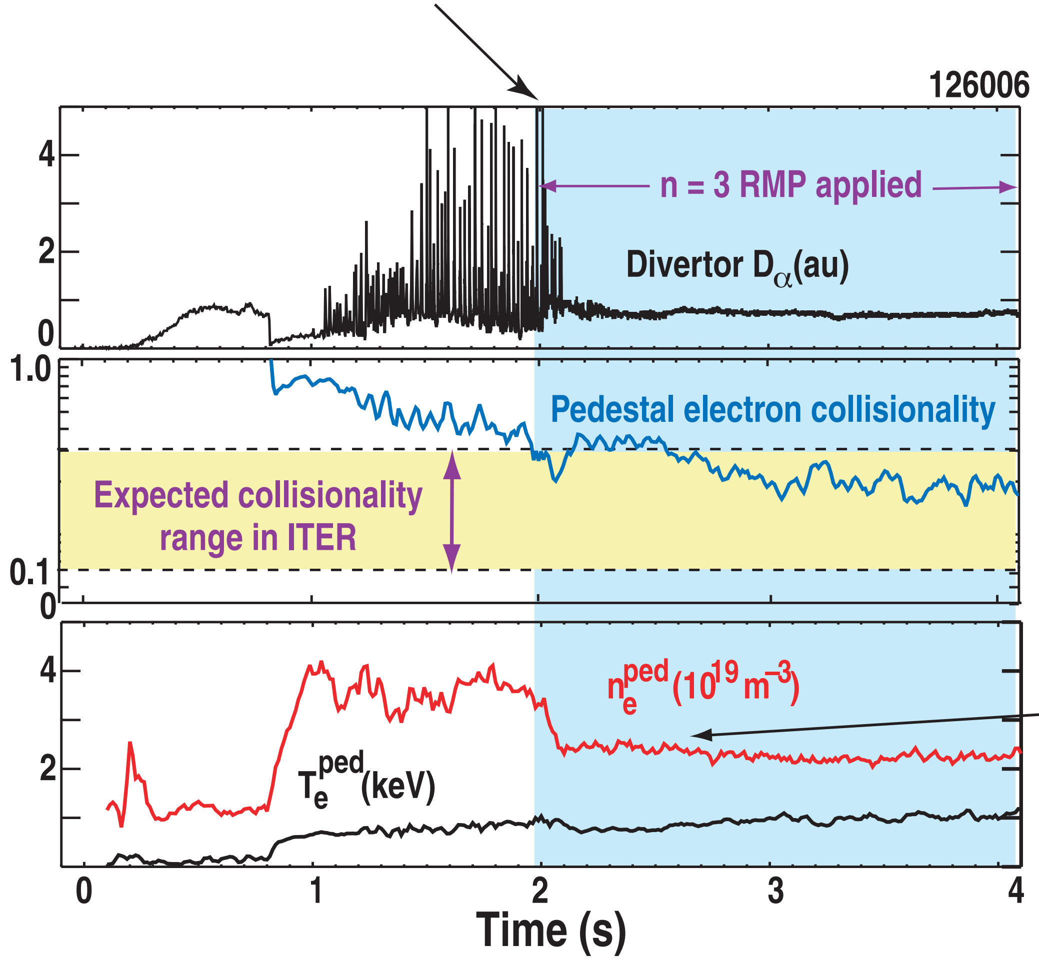
ECCD deposition location controlled by moving 2nd harmonic resonance



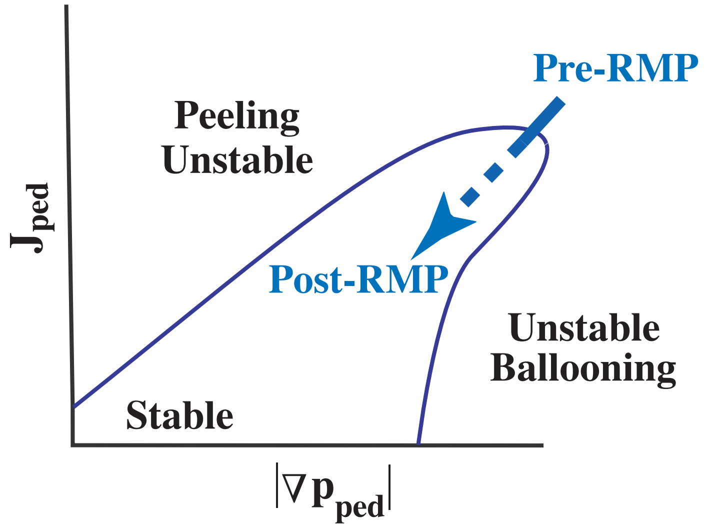
Prater, EX/4-2, Thurs a.m.

Complete ELM Suppression Achieved in an ITER-like Shape and Collisionality Using n=3 Resonant Magnetic Perturbations

- Type I ELMs suppressed when n=3 RMP is applied



- RMP reduces pressure gradient below peeling-ballooning stability limit

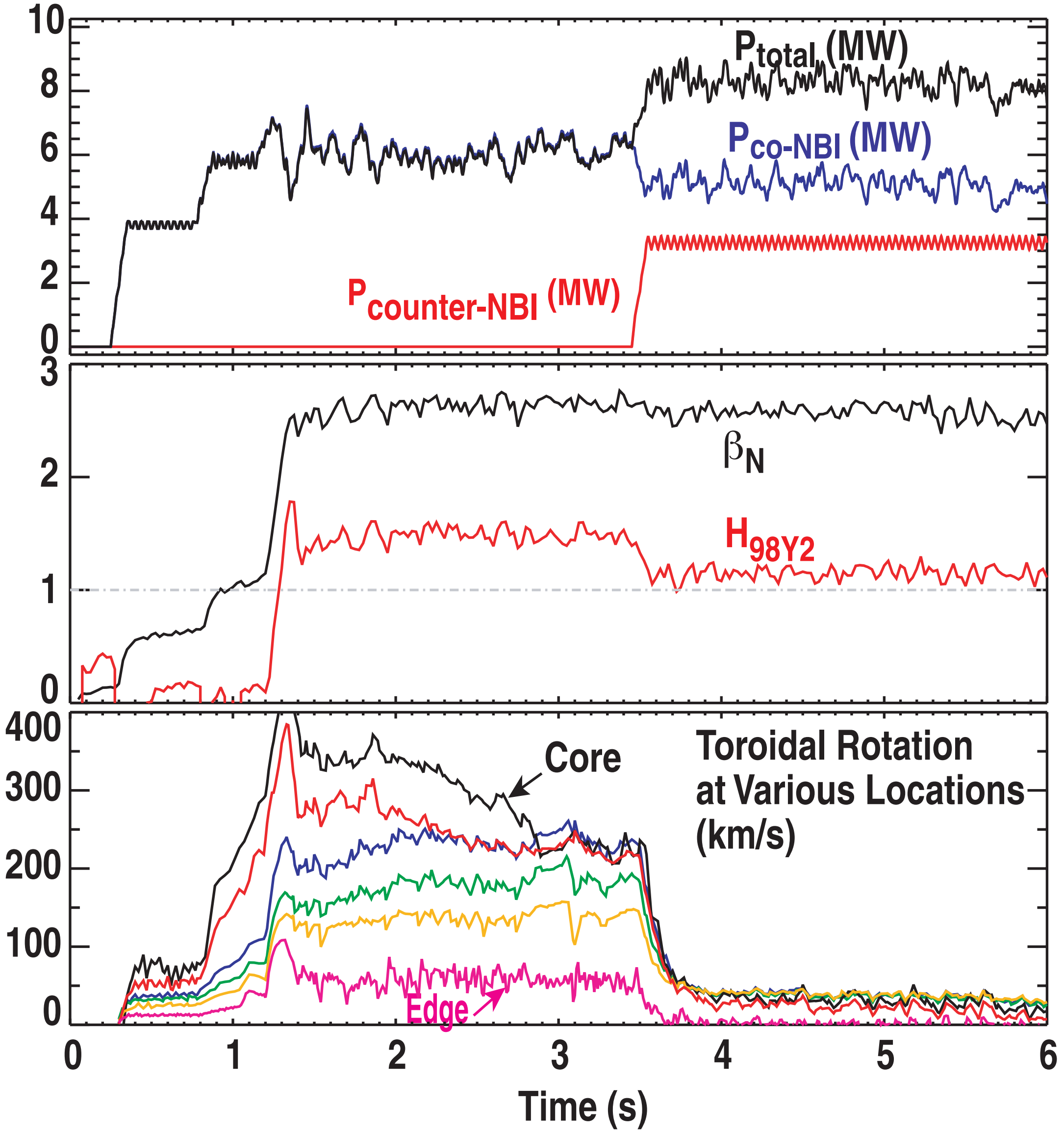


- Pressure gradient reduction due to changes in particle transport

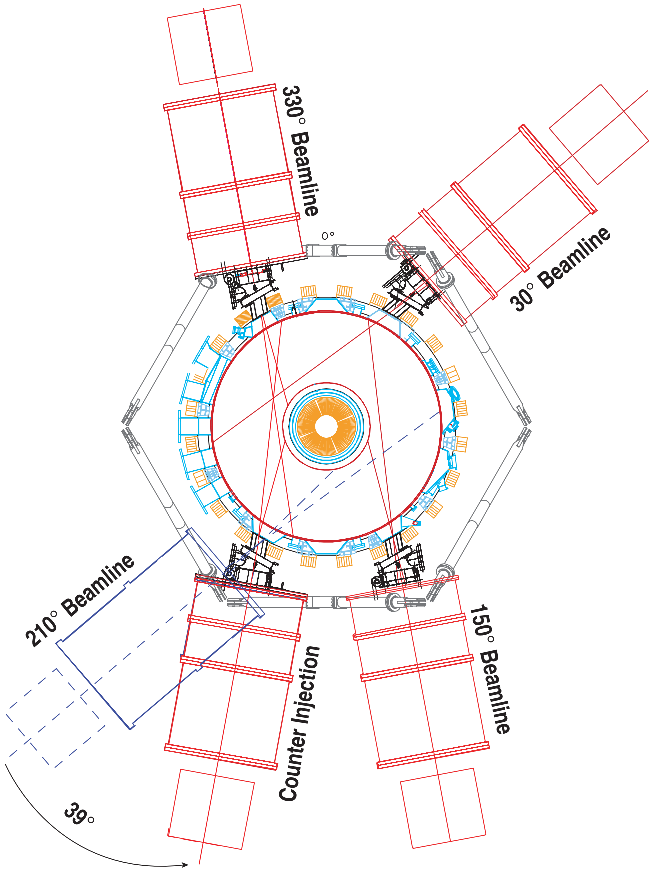
Moyer, EX/9-3, Fri. p.m.

Snyder, TH/4-1, Fri. p.m.

Reconfigured NBI System Provides Fine Control of Plasma Rotation



- Re-orientation of beamline allows 5 MW counter-NBI and 12.5 MW co-NBI



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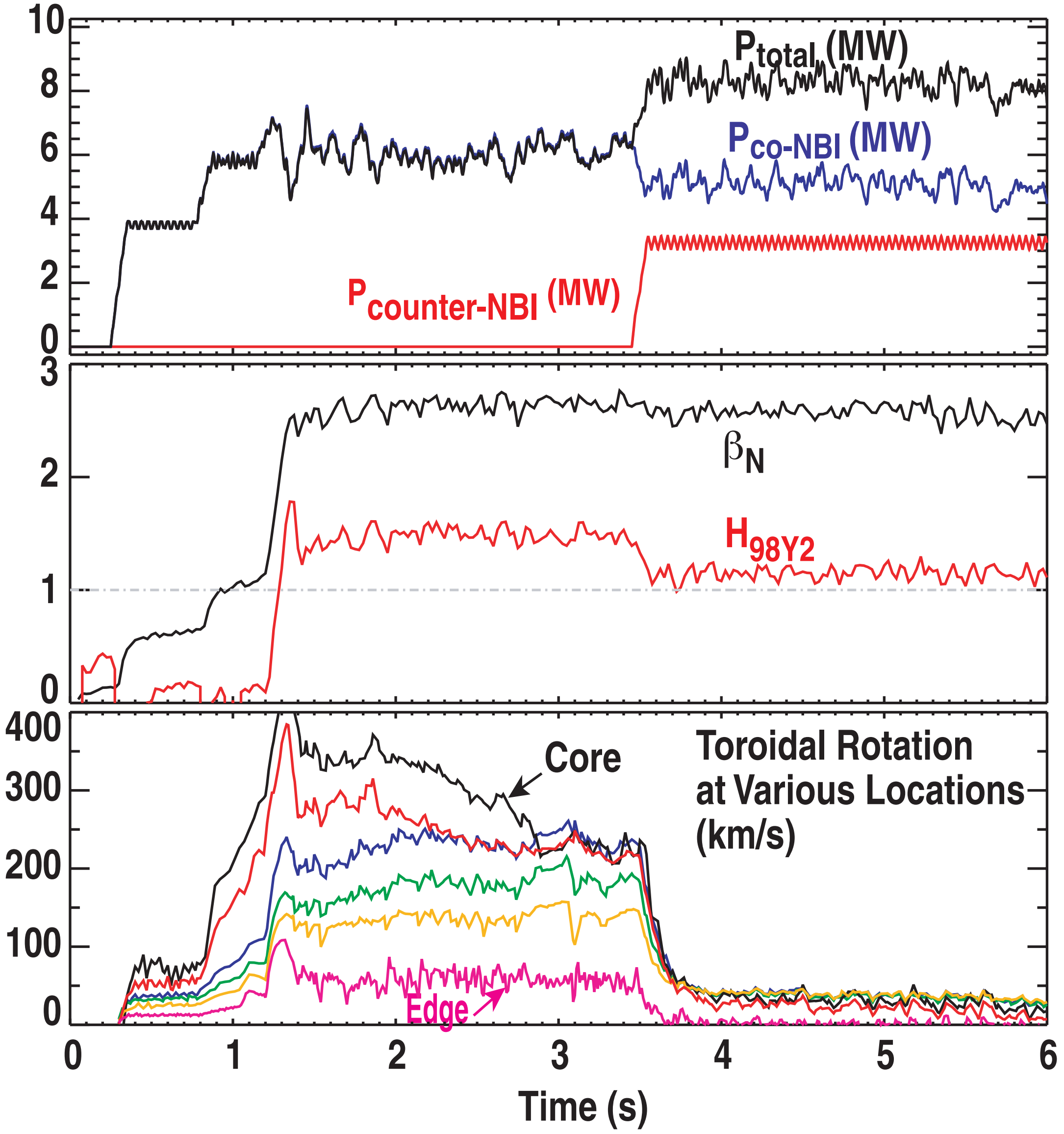
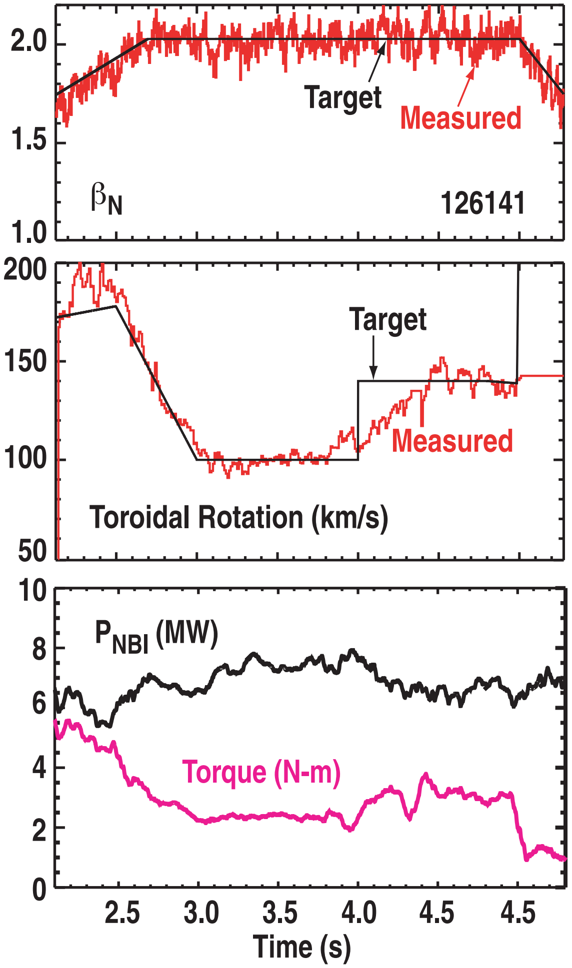


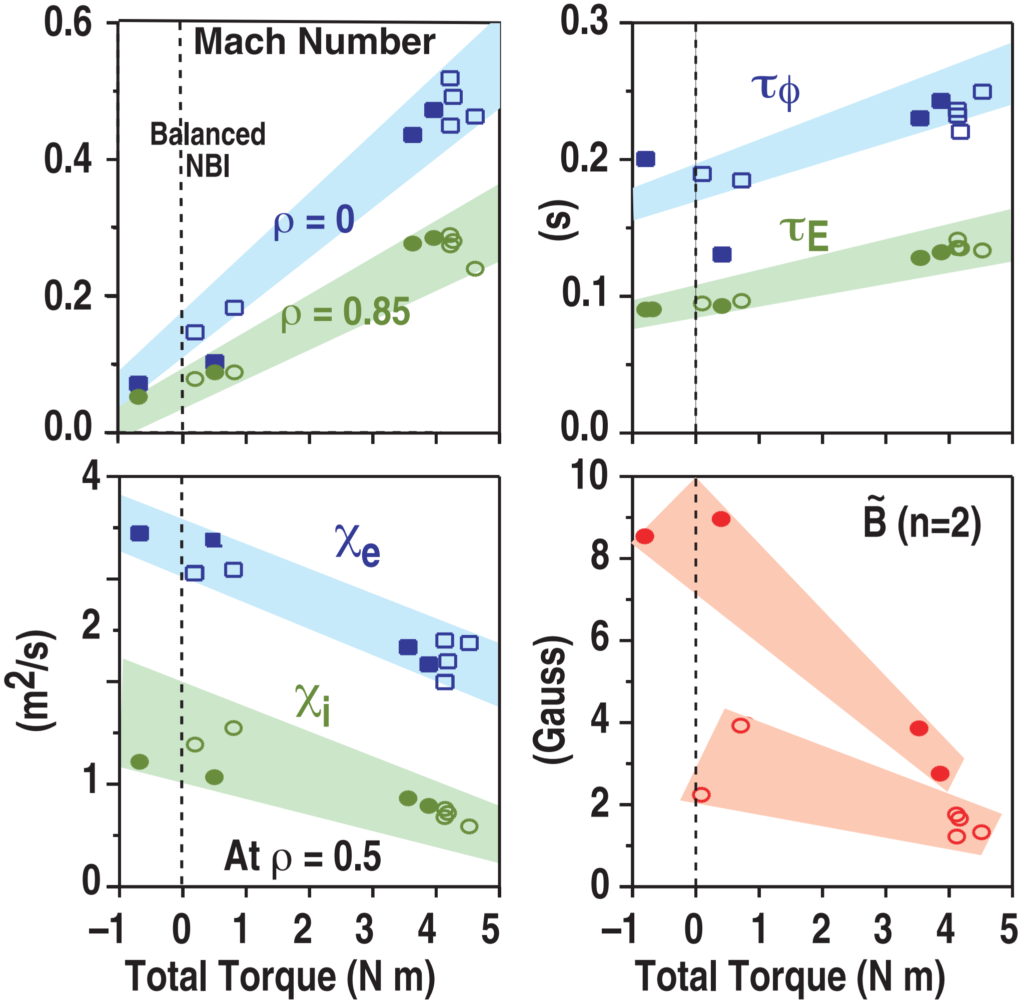
- **Simultaneous feedback control of β_N and toroidal rotation demonstrated**



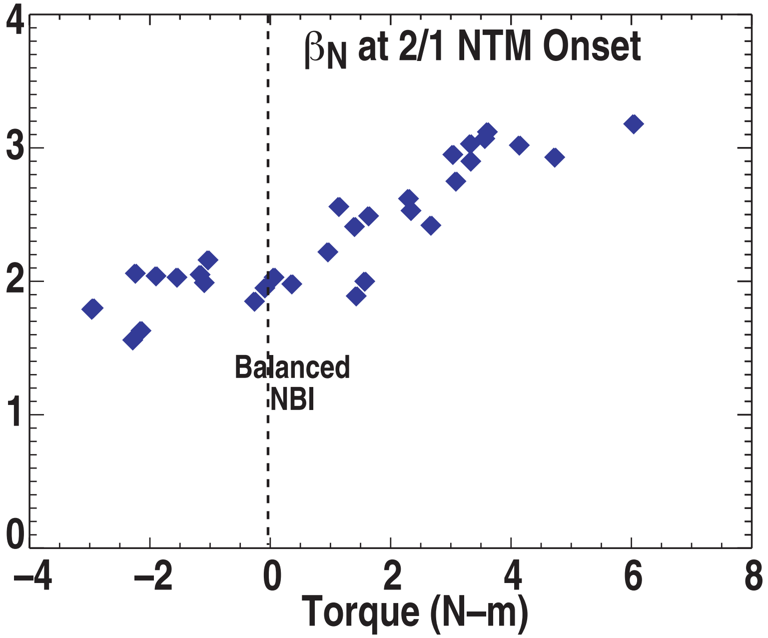
Transport and NTM Physics Shown to be Sensitive to Applied Torque and Resulting Rotation

- Hybrid discharges with β_N = 2.6

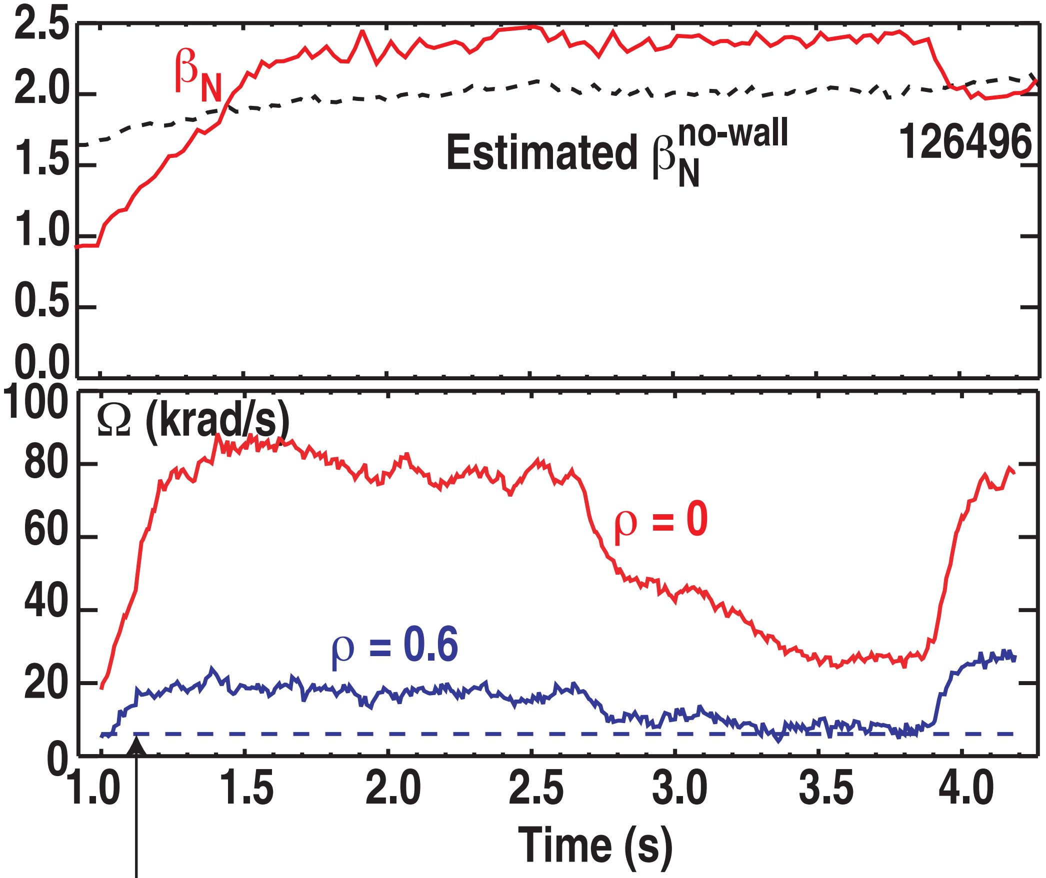
q_{95} = 4.0 (closed) q_{95} = 4.5 (open)



- β_N limit for m=2/n=1 onset decreases as torque decreases

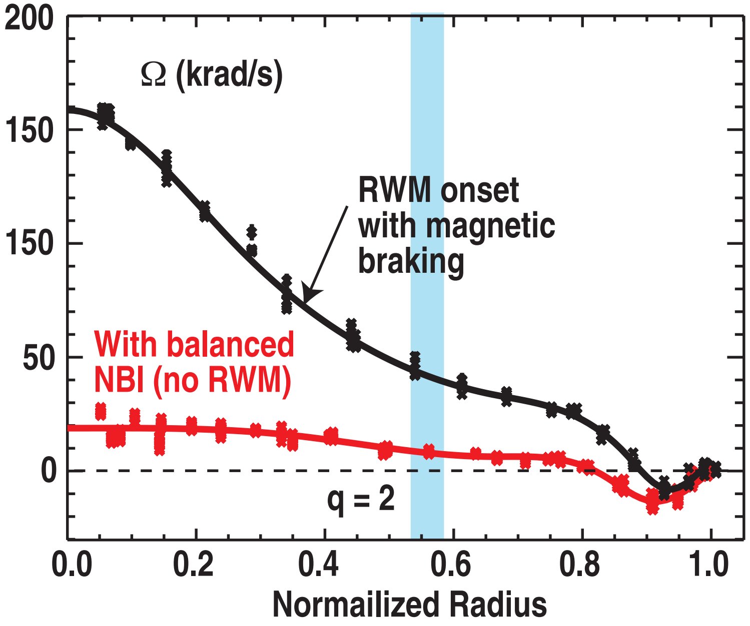


Threshold for Rotational Stabilization of RWM Found to Be Comparable to Expected Rotation in ITER



Predicted rotation at ρ = 0.6 in ITER

$\Omega_{ITER} = 0.003\ \Omega_A$



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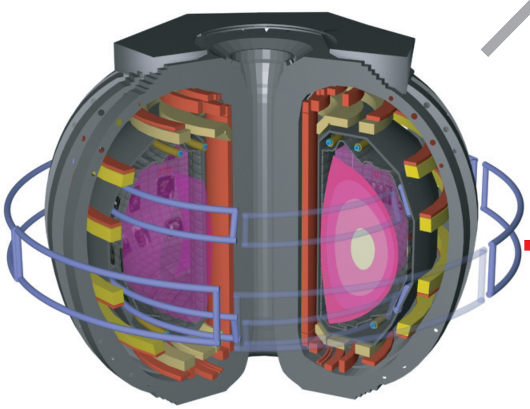

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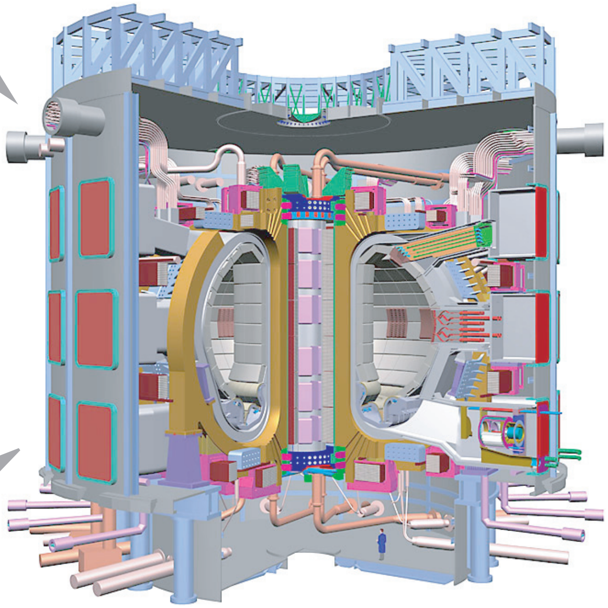
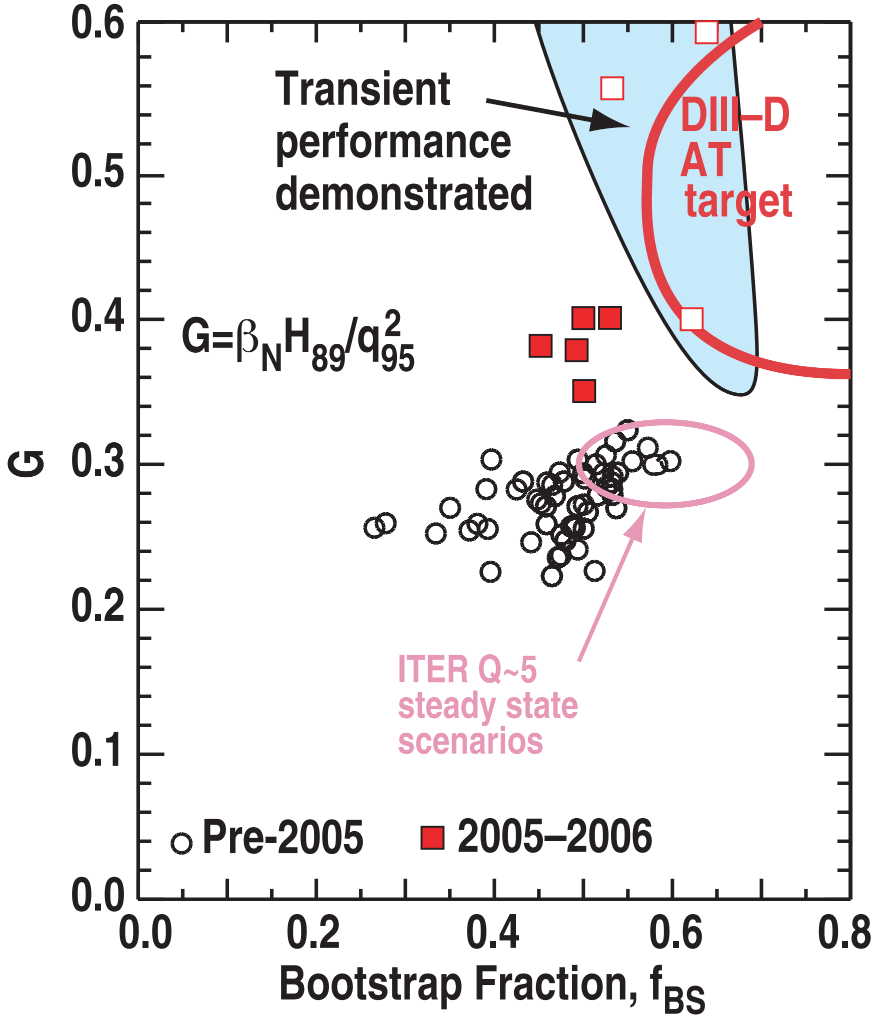


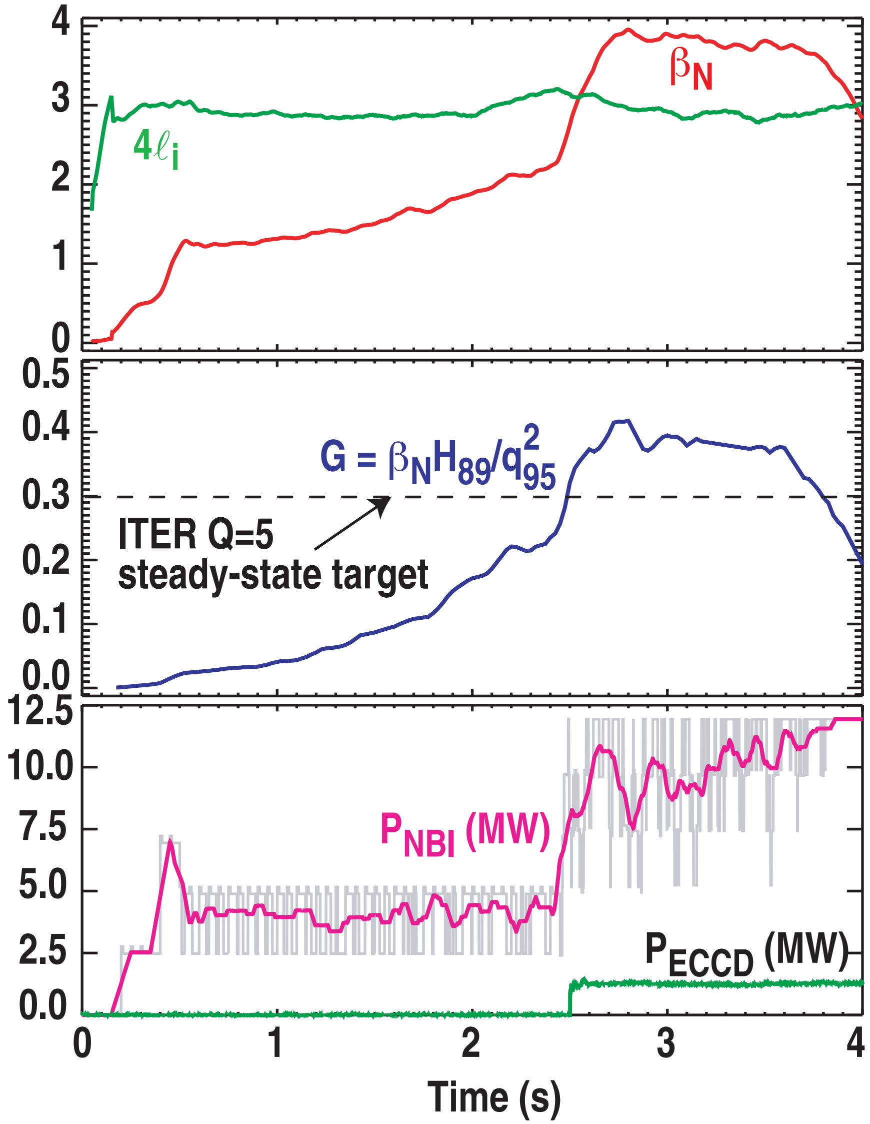
Performance Routinely Achieved Above Requirements for Q=5 Steady-state Scenario in ITER



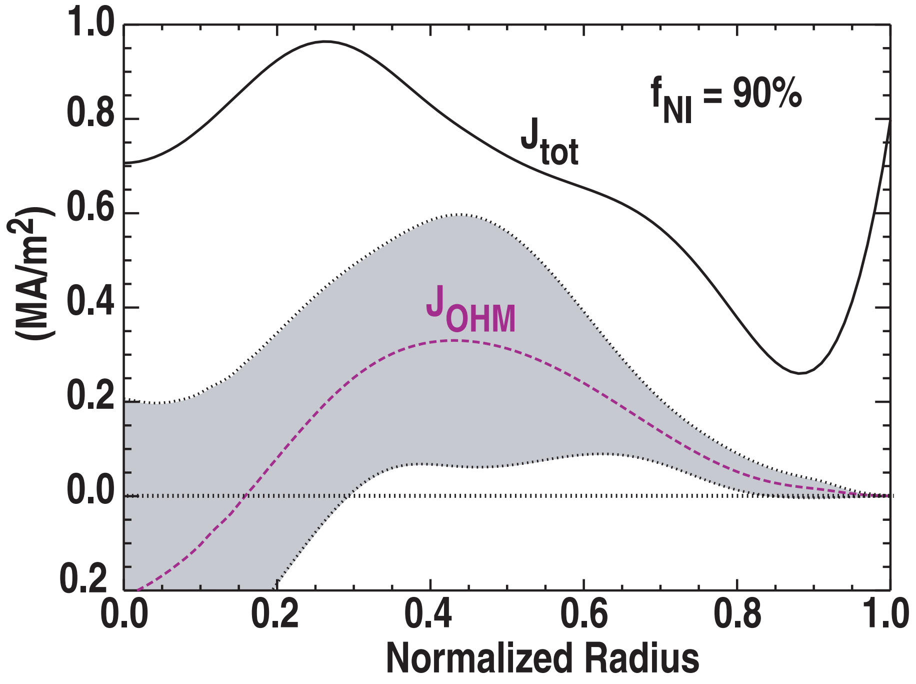
- $G > G^{ITER}_{Q=5}$ achieved in two separate lines of research
  1) Weak negative central shear utilizing current drive tools compatible with steady state
  2) Moderate negative central shear through continuous ramps in I_p and B_T
- Both methods utilize:
  - Highly shaped, double-null configurations
  - Rotational and feedback stabilization of RWM

Greenfield, EX/1-2, Mon. p.m.

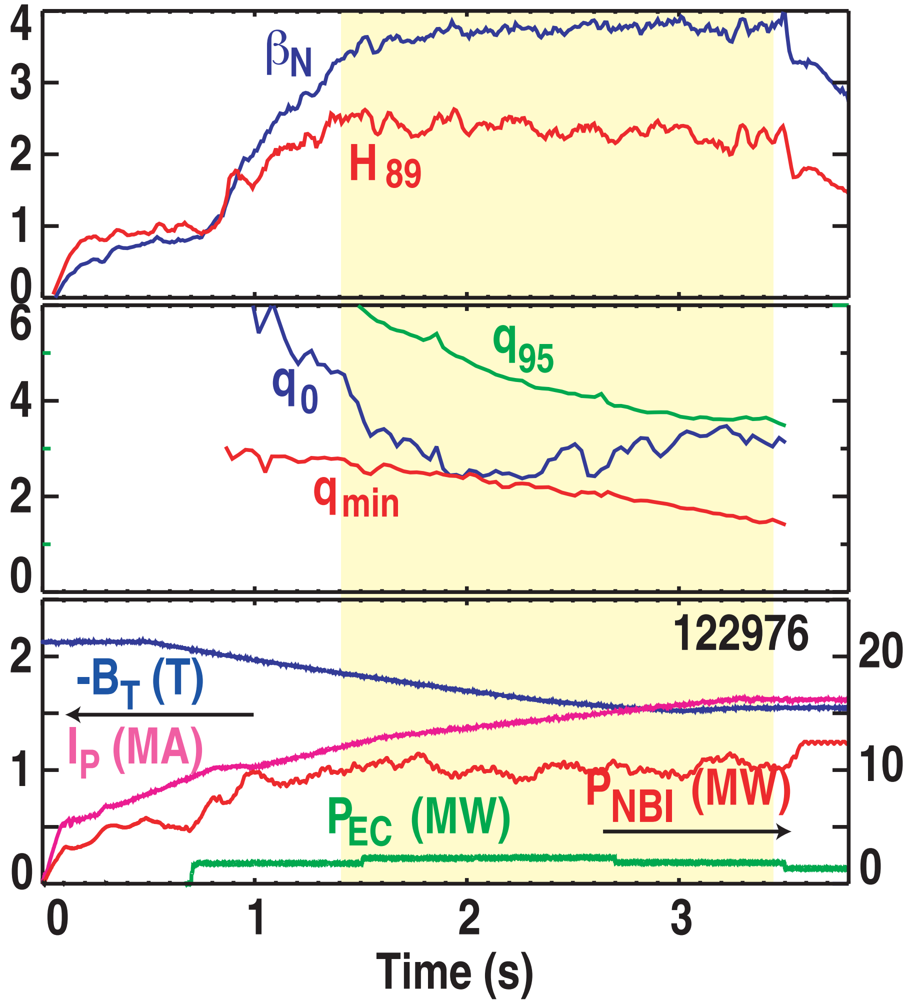
Nearly Fully Noninductive Plasmas Achieved with $\beta_N \approx 4$



- **High triangularity double null operation allows operation 25% above no-wall limit**
- **Future availability of higher ECCD power should allow fully non-inductive operation**



Sustained High Performance ($\beta_N \approx 4$ for ~2 s) Achieved in Discharges with an Internal Transport Barrier



- β_N = 3.8 is approximately 50% above conventional no-wall limit
- Broad current density profile obained by early heating, off-axis ECCD, and ramps in I_p and B_T
- Excellent confinement ($H_{89} \approx 2.5$) maintained throughout

Greenfield, EX/1-2, Mon. p.m. Garofalo, EX/7-1Ra, Fri. a.m.

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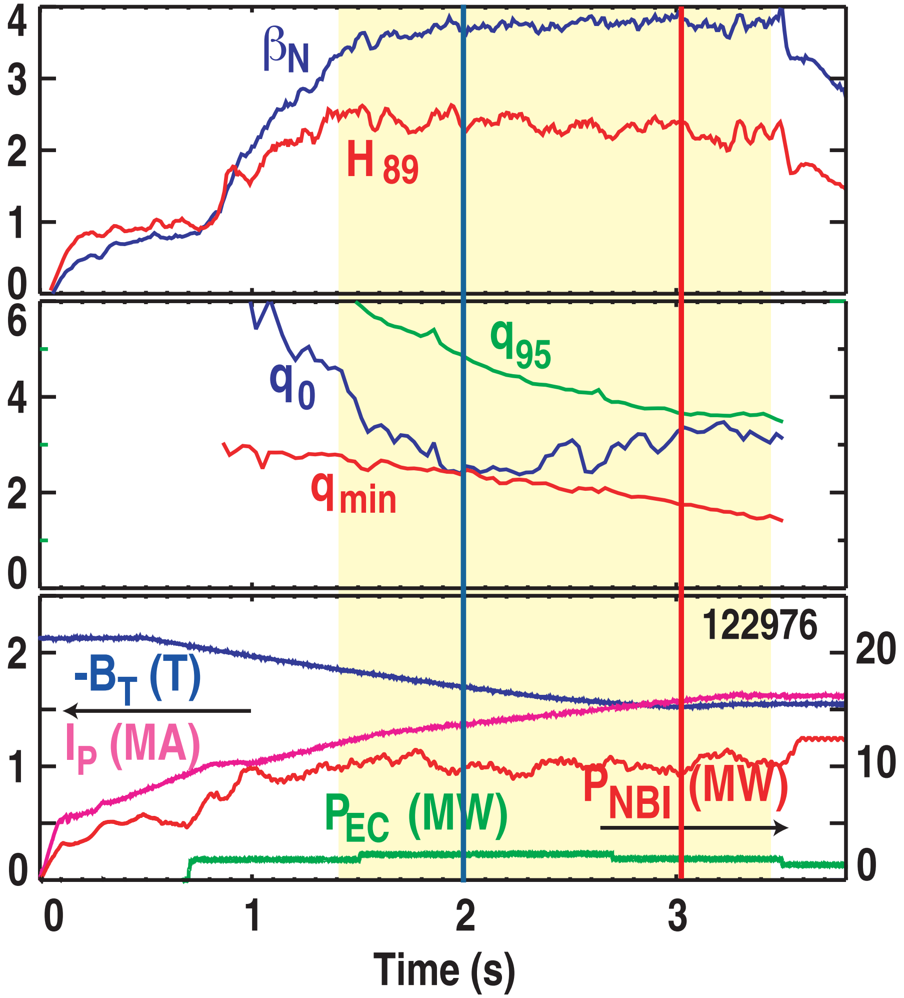
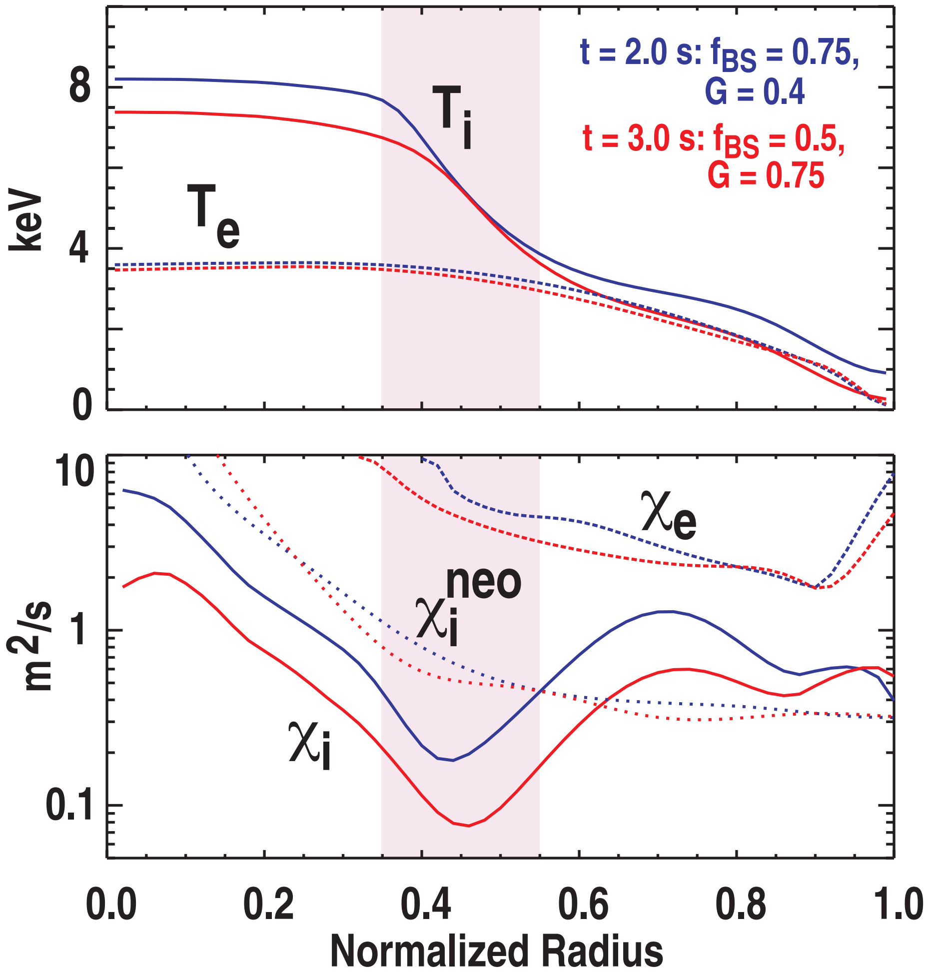


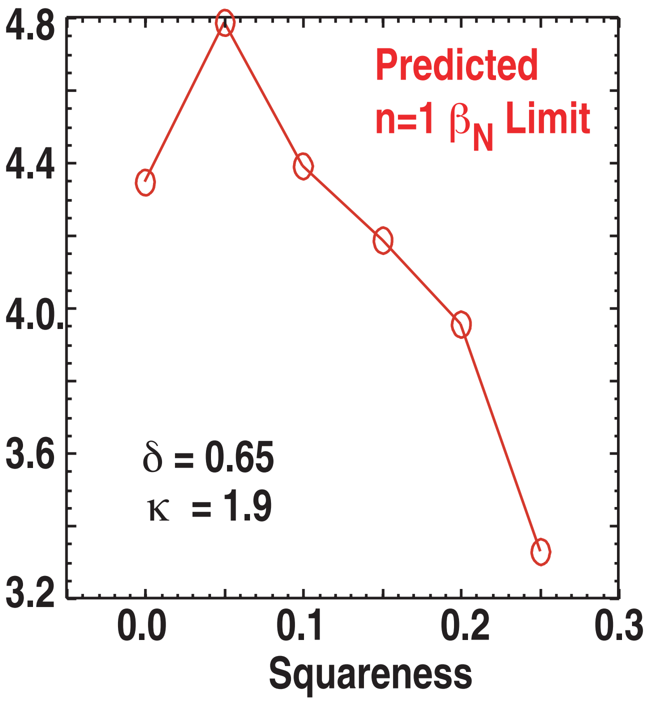


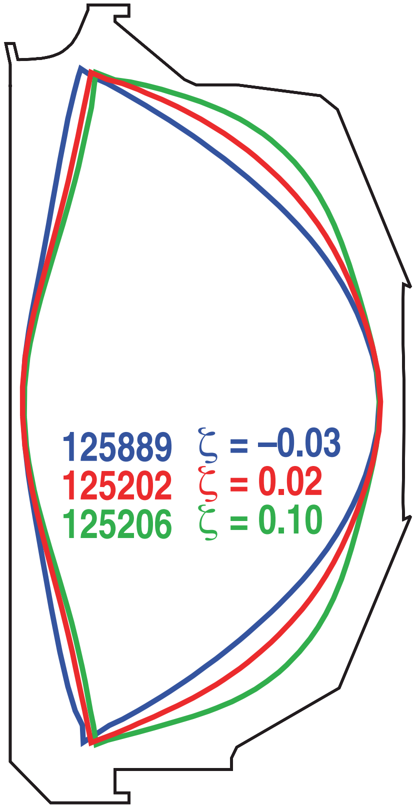
Greenfield, EX/1-2, Mon. p.m.

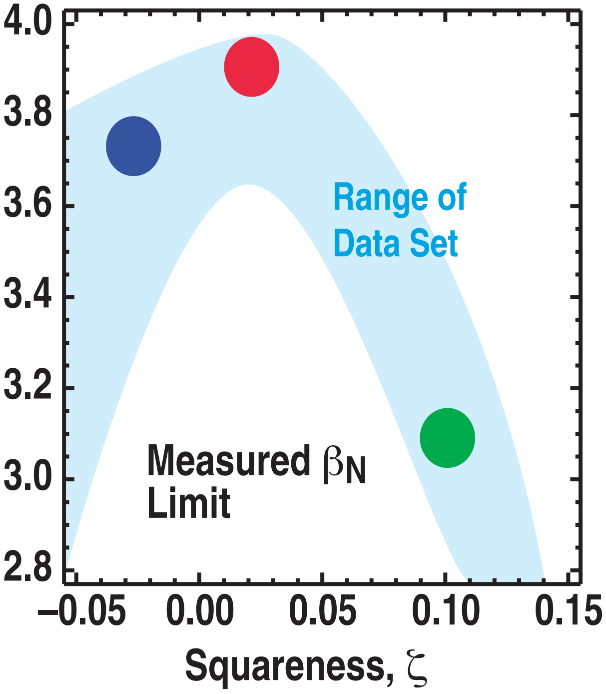
Plasma Performance Shown to be Sensitive to Details of the Plasma Shape

- Stability analysis indicates n=1 stability limit has a narrow optimum in plasma "squareness"

- Measured long pulse β limit shows similar dependence



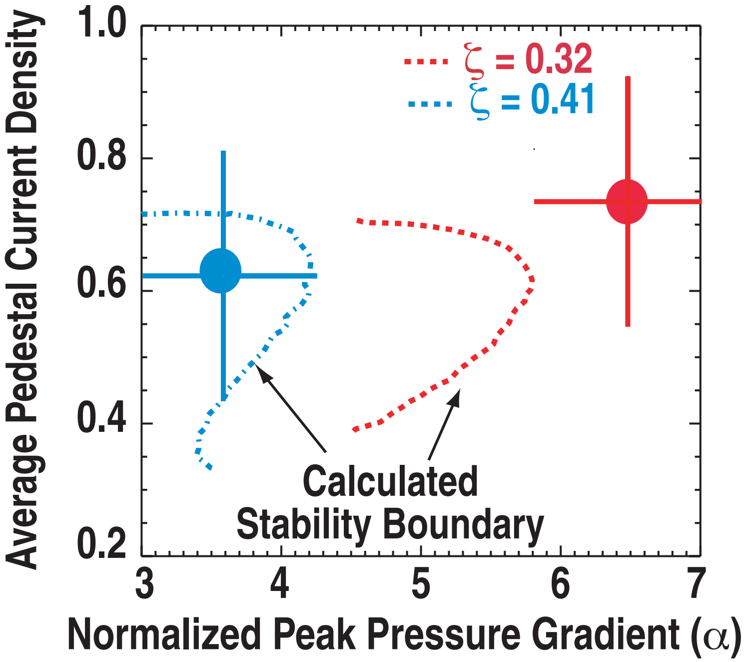


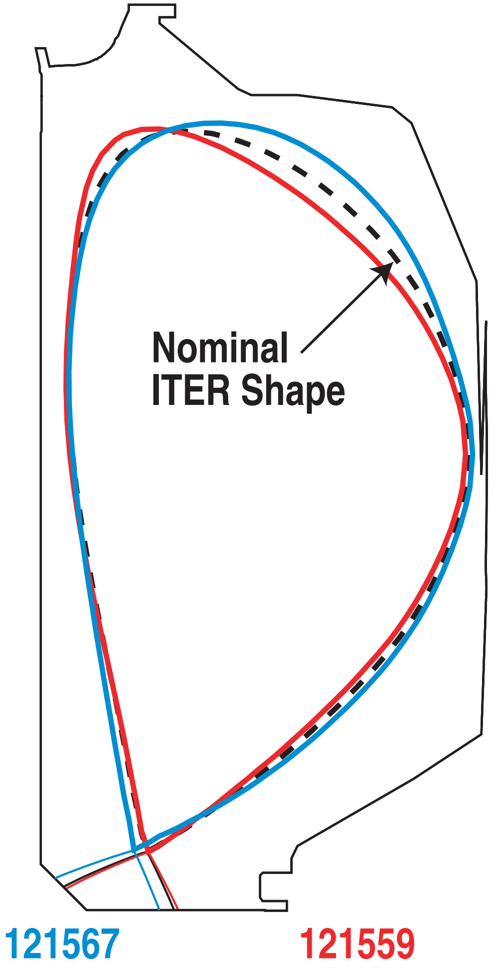


Greenfield, EX/1-2, Mon. p.m.

Details of the Plasma Shape Near the ITER Design Shape are Important

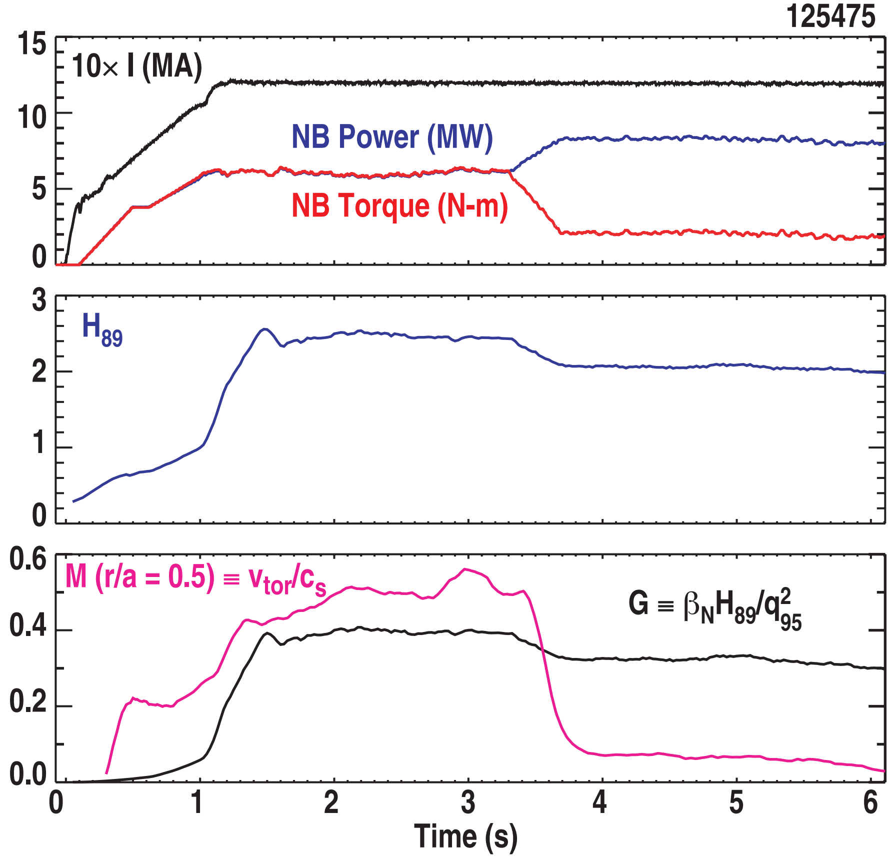
- **In ITER shape, significant change in edge pressure gradient associated with change in squareness**
  - Factor of 2 in measured pressure gradient
  - 50% in calculated stability boundary (ELITE)

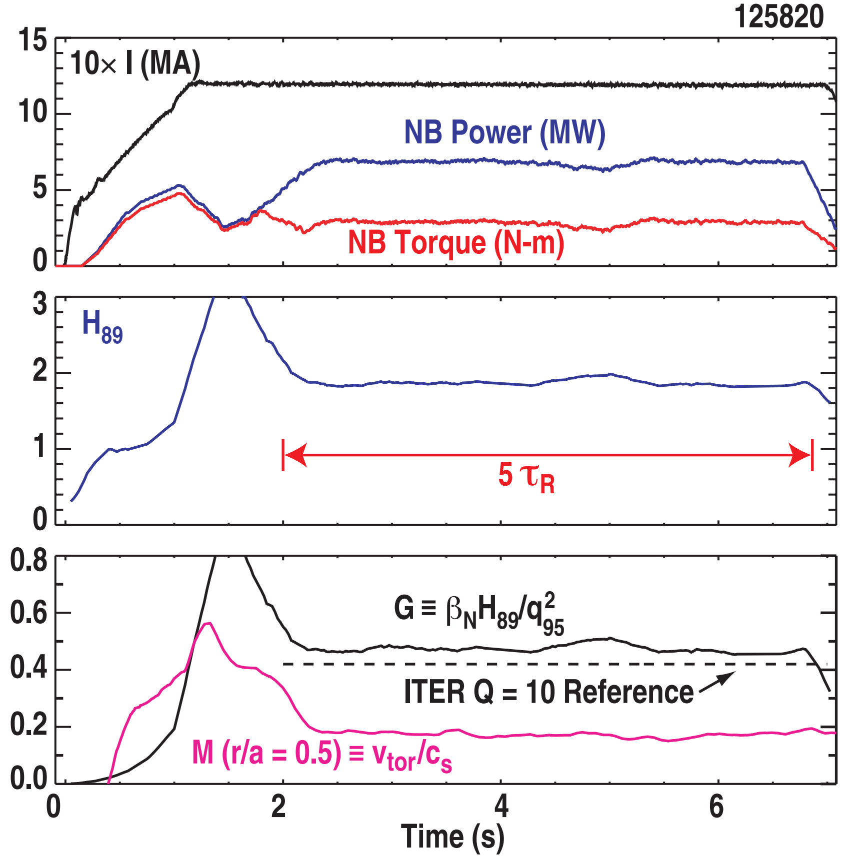




Leonard, EX/P8-3, Sat. a.m.

Performance Above ITER Q=10 Baseline Scenario Achieved in Low-Rotation Hybrid Plasmas





- $q_{95} = 4.5$
- $\beta_N = 2.6$
- $G = 0.8\ G_{ITER}$

- $q_{95} = 3.2$
- $\beta_N = 2.6$
- $G = 1.25\ G_{ITER}$

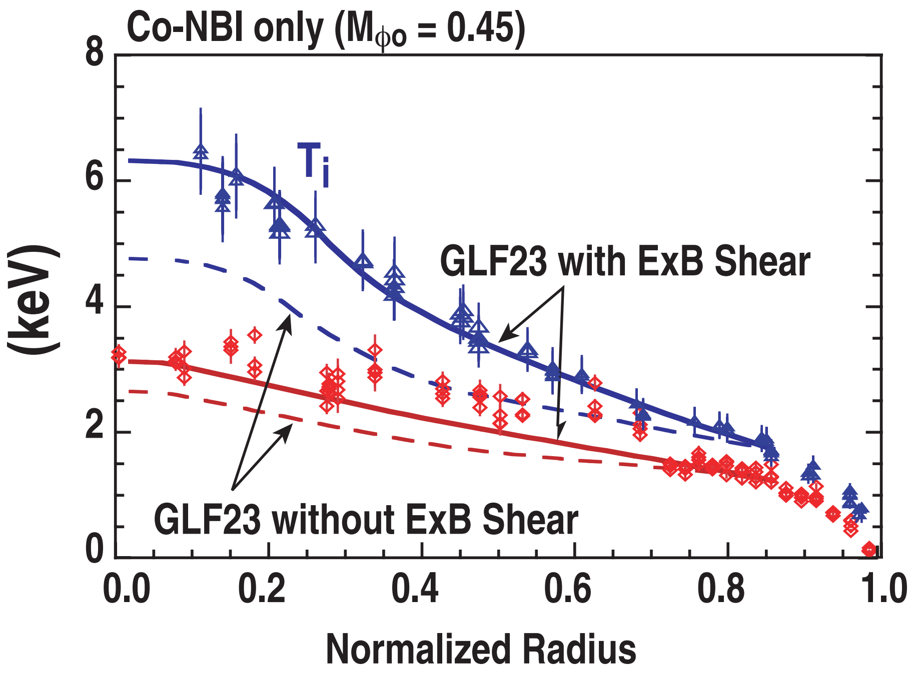
Projected Q for 15 MA ITER
89P: Q = 10.3
98y2: Q = 10.2
DS03: Q = ∞

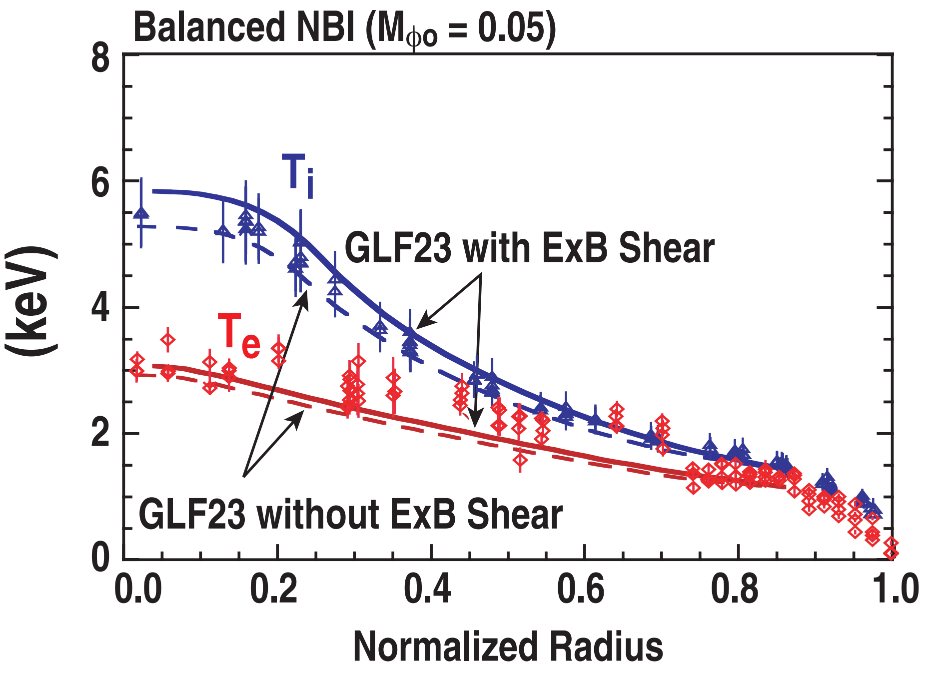
Petty, Politzer, EX/P1-9, Tues. p.m.

Comparison of Measured Profiles with GLF23 Confirm Importance of ExB Shear on Transport

- With high toroidal rotation, ExB shear required in GLF23 to reproduce measured profiles

- At low rotation, ExB shear is much less important





- H_{98y2} = 1.5 – excellent confinement!

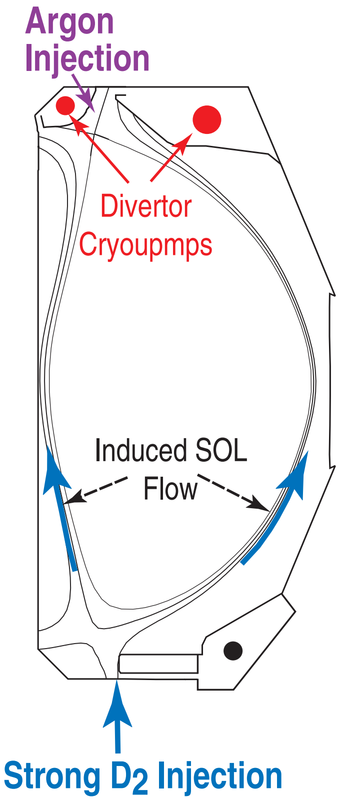
- H_{98y2} = 1.2 – good overall confinement still maintained

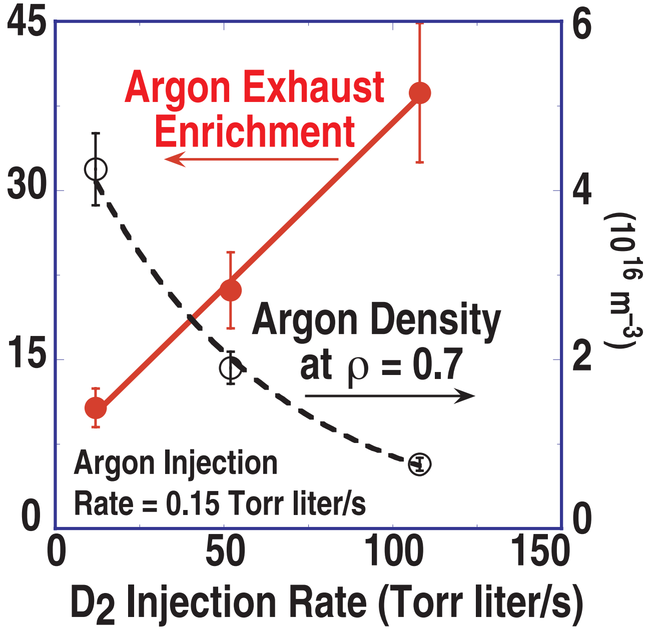
DIII-D NATIONAL FUSION FACILITY

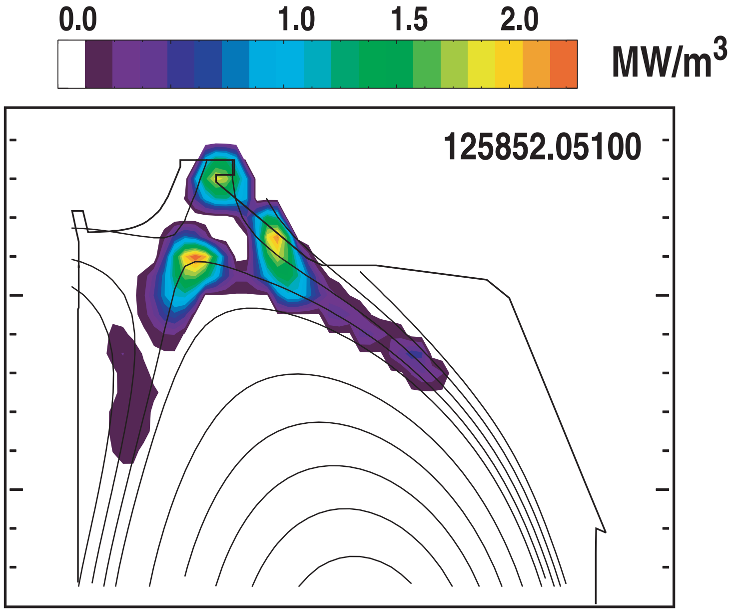
Petty, Politzer, EX/P1-9, Tues. p.m.

Compatibility of Hybrid Regime with Radiative Divertor Demonstrated Using "Puff and Pump" Technique

- Upstream gas puffing and divertor exhaust induce strong SOL flow ⇒
- Very high enrichment value obtained ⇒
- P_{rad}/P_{NBI} ~ 60% with $Z_{eff} \simeq 2.0$







- $\beta_N = 2.6$, $H_{89} = 2.0$, G = 0.4 maintained

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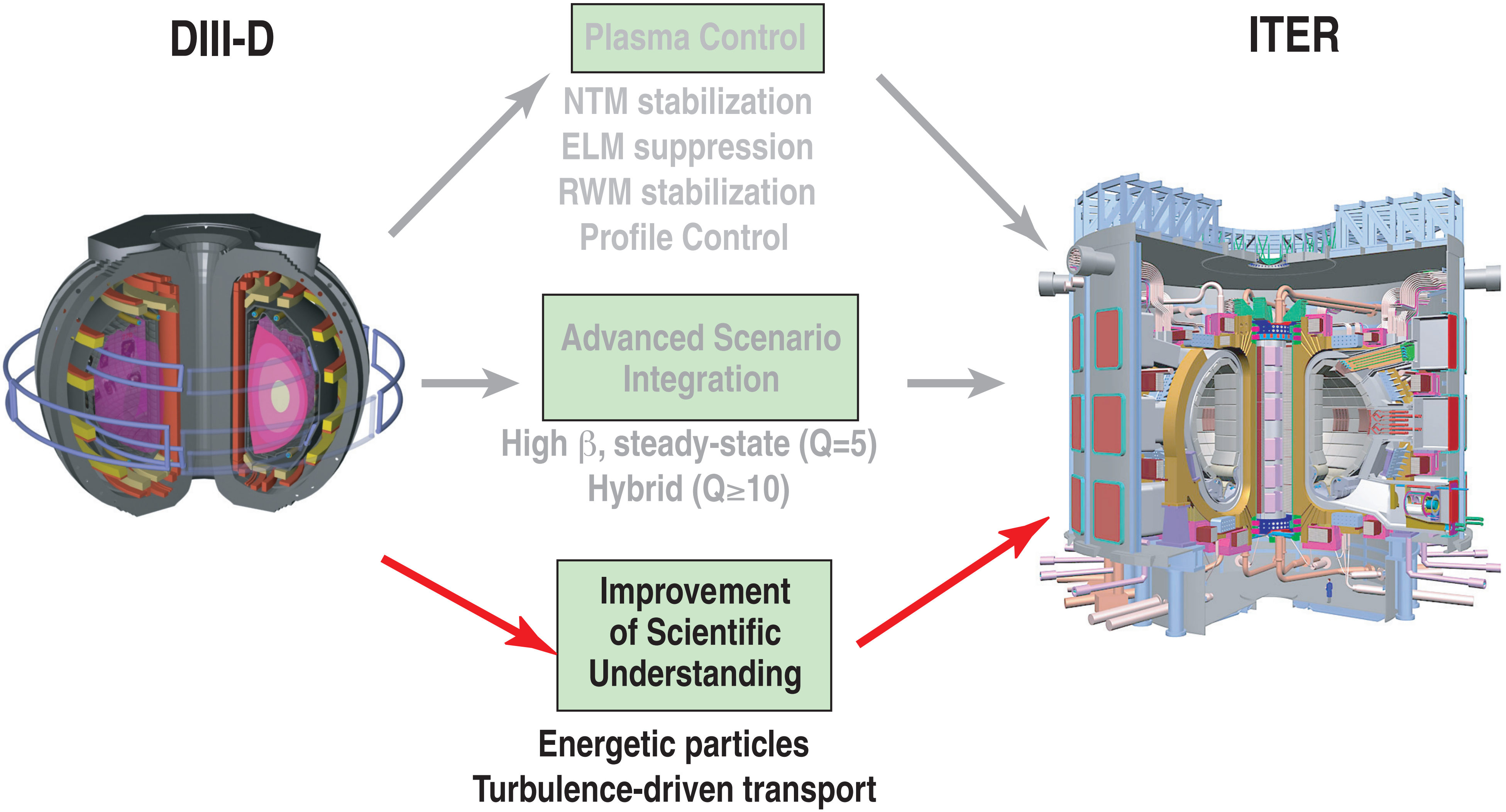

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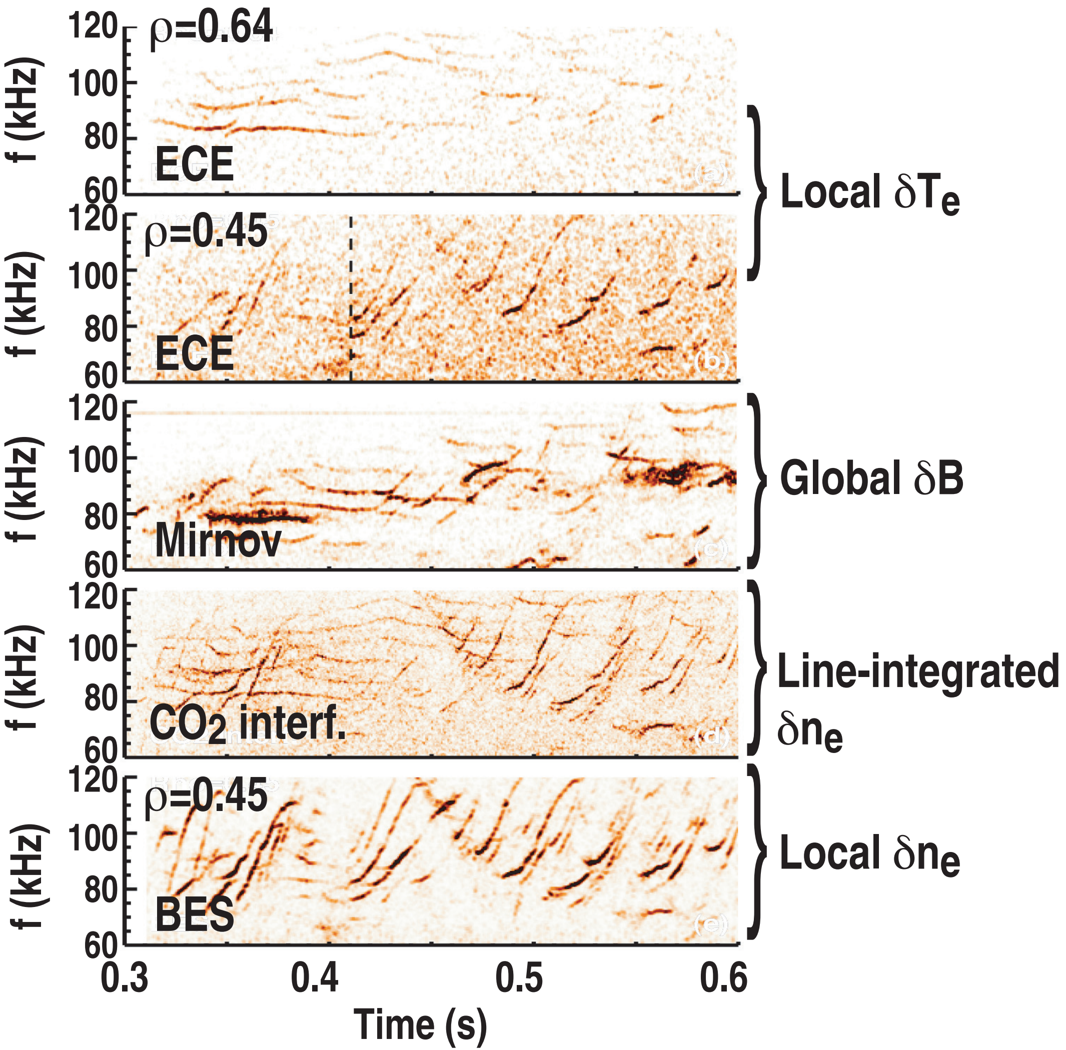
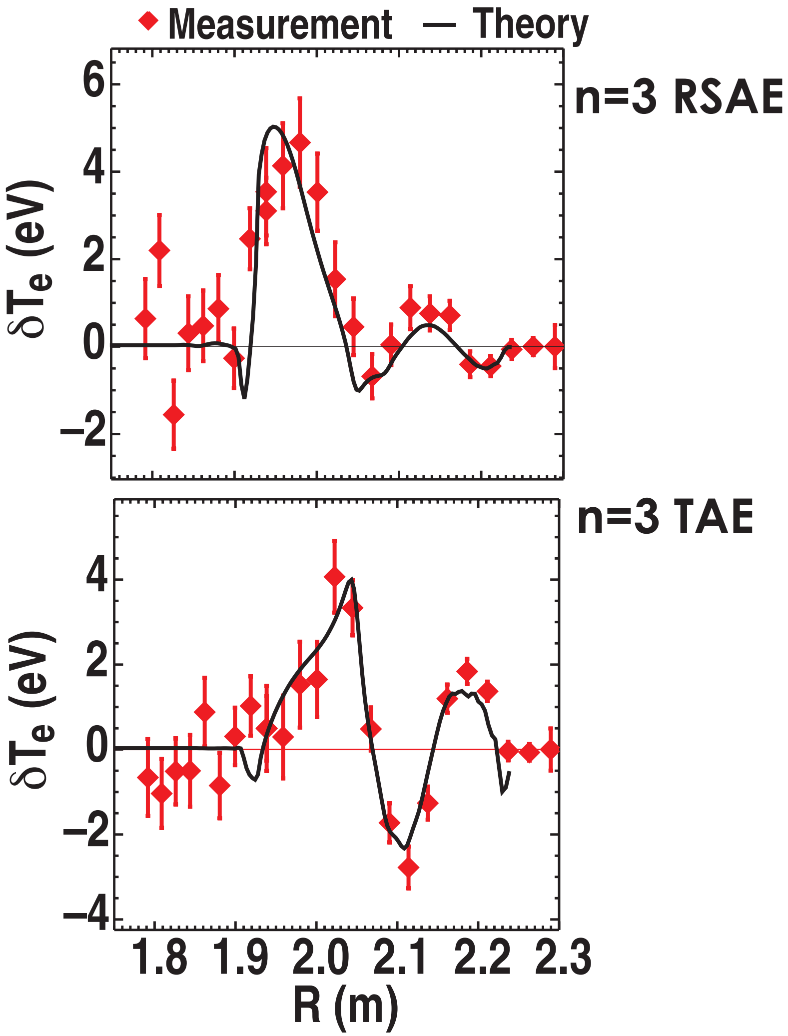
New Diagnostic Capabilities Enable Detailed Comparisons with Alfvén Eigenmode Theory

- Diagnostics probing different regions of plasma observe different MHD activity



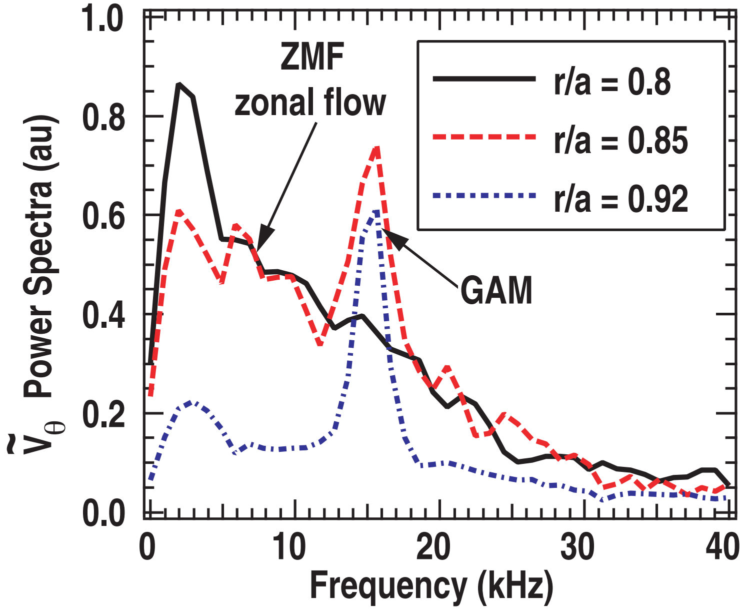
- Measured radial structure consistent with theoretical predictions (NOVA)



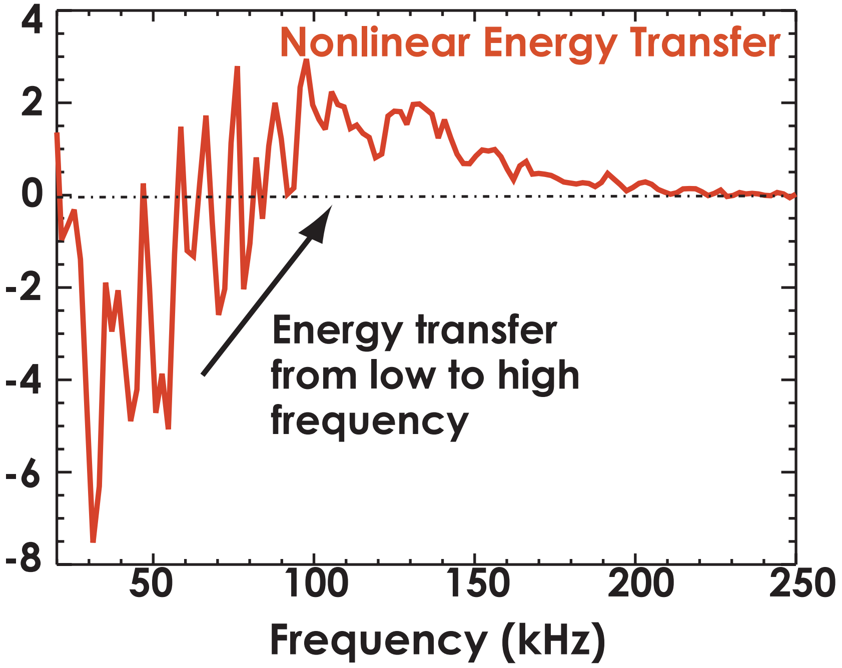
Heidbrink, EX/6-3, Thurs. p.m.

High Sensitivity BES Measurements Enable Detailed Characterization of Zonal Flow Structure and Dynamics

- Geodesic acoustic modes (GAMs) dominant near edge (r/a > 0.85)
- Zero-mean-frequency (ZMF) zonal flow dominant in core ($0.6 \lesssim r/a \lesssim 0.85$)

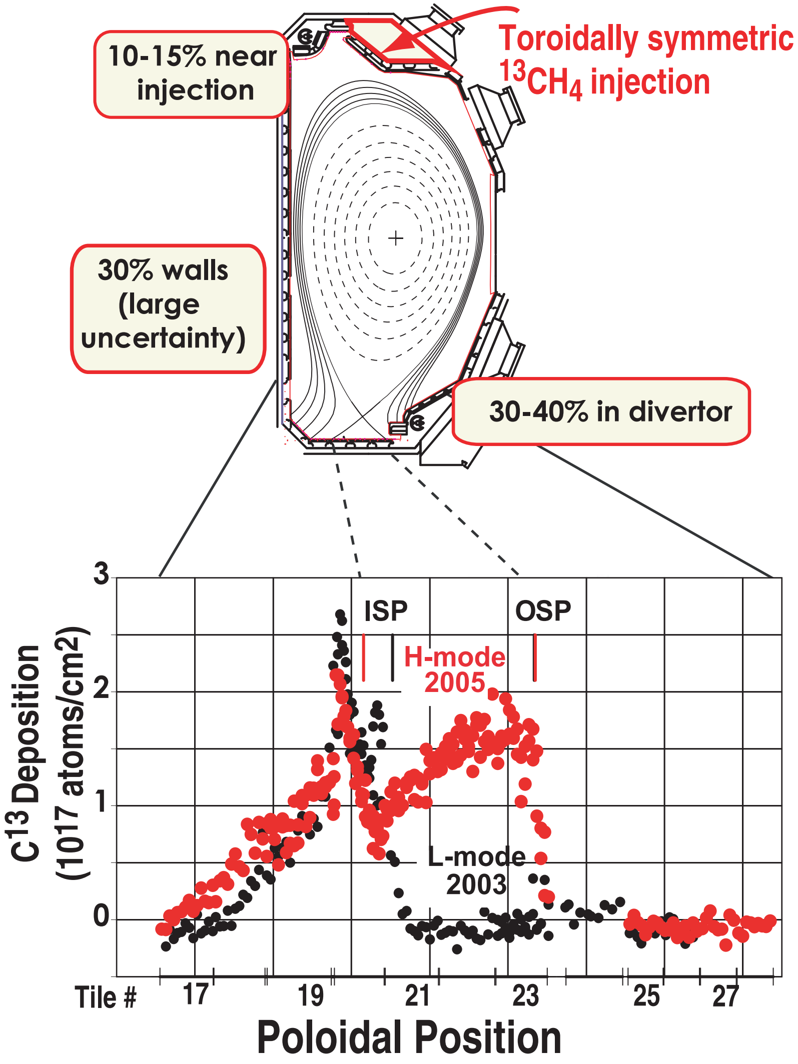


- GAMs couple energy to high frequency turbulence



$$\text{Turbulent Energy Transfer} = -\mathrm{Re}\left\langle n(f) V_y (f-f') \frac{\partial n(f')}{\partial y} \right\rangle$$

Recent Experiments Suggests Tritium Uptake in Carbon Facing Surfaces May be Controllable



Toroidally symmetric $^{13}CH_4$ injection

10-15% near injection

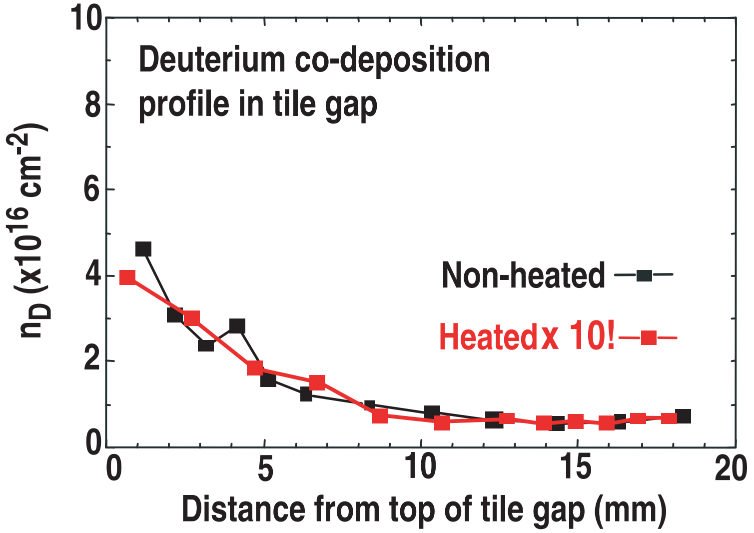
30% walls (large uncertainty)

30-40% in divertor

- **DiMES experiments show large reduction in C and D deposition on heated materials**

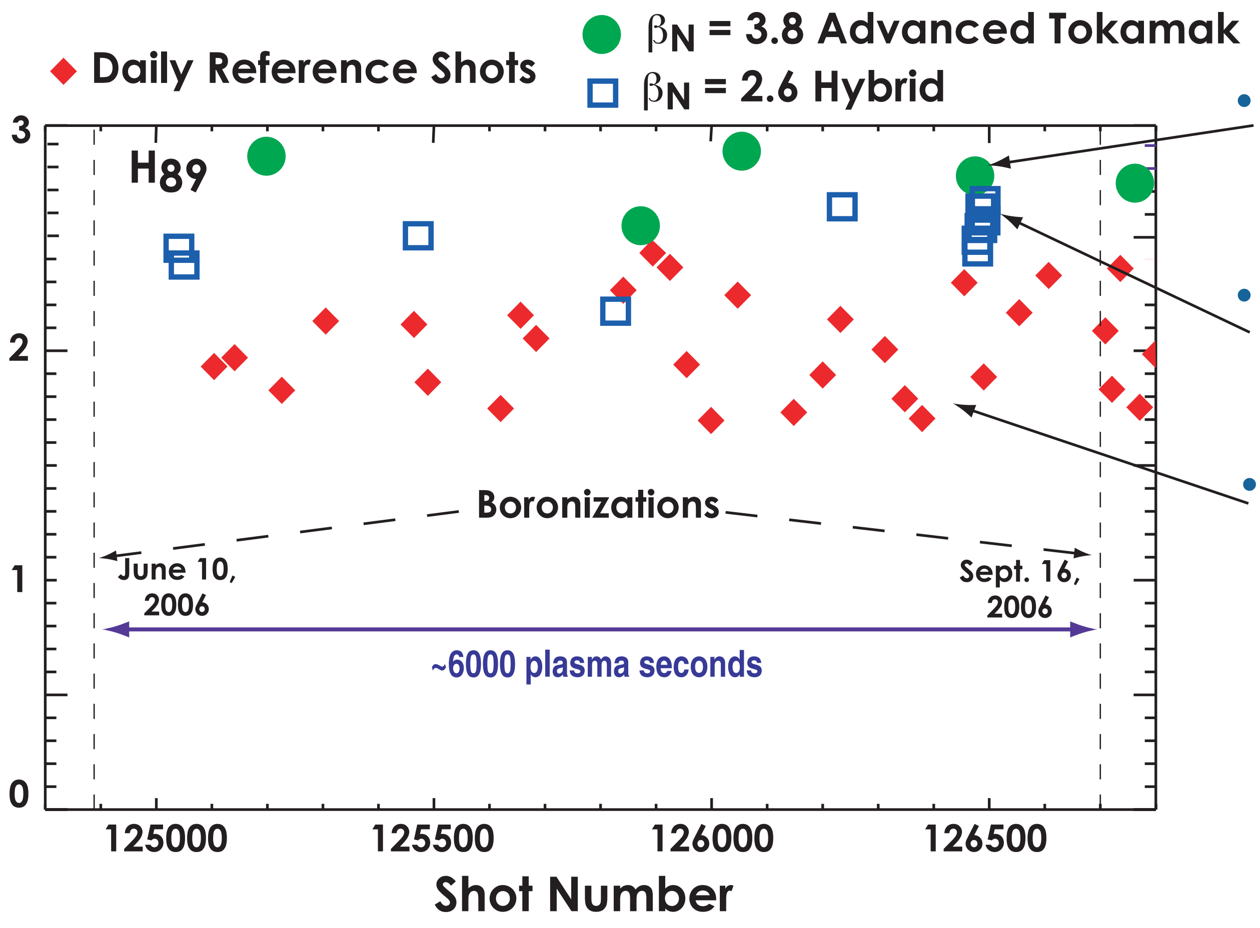
Non-Heated Mirror

Heated Mirror



Allen, EX/P4-1, Thurs. a.m.

Access to High Performance Regimes on Graphite Tiles Does Not Require Frequent Wall Conditioning



- Access to high β demonstrated after ~ 6000 s of plasma operation without boronization
- Demonstrated reproducible hybrid discharges without between-shot wall conditioning
- No systematic degradation observed in daily reference shots

- Results are distinctly different from recent results indicating the need for frequent wall conditioning of metal walls from Alcator C-Mod and Asdex-Upgrade

DIII–D's Research Program Has Made Significant Progress in Increasing the Potential Scientific Benefit of ITER

The DIII–D Research Program has:

- **Developed physics solutions to issues key to the success of ITER**
  - NTM stabilization using ECCD ⇒ **Sustained $\beta_N > 3$ operation**
  - ELM suppression via n=3 RMPs ⇒ **Longer divertor lifetime**
  - Low RWM rotation threshold ⇒ **High β operation for Q=5 steady-state**

- **Developed and characterized advanced operating scenarios that offer significant potential benefit to the ITER physics program**
  - Fully noninductive operation with $\beta_N = 3.5$
  - Demonstrated $\beta_N = 3.8$ for ~2 s with internal transport barriers

  $\}$ ⇒ **Increased confidence in Q=5 steady-state scenario**

  - Demonstrated $G > G_{ITER}$ at low rotation
  - Demonstrated compatibility of radiative divertor operation and hybrid performance

  $\}$ ⇒ **Potential for Q > 10**

DIII–D's Research Program Has Made Significant Progress in Increasing the Potential Scientific Benefit of ITER

The DIII–D Research Program has:

- **Advanced the physics understanding of issues critical to the success of ITER**
  - Energetic particles: Documented structure and impact of Alfven eigenmodes on fast-ion distribution
  - Turbulence-driven transport: Characterized zonal flow structure and impact on ITB formation

Future research will continue to focus on resolving near-term ITER design issues, qualifying advanced scenarios for use in ITER, and advancing the understanding of fusion plasmas.