

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

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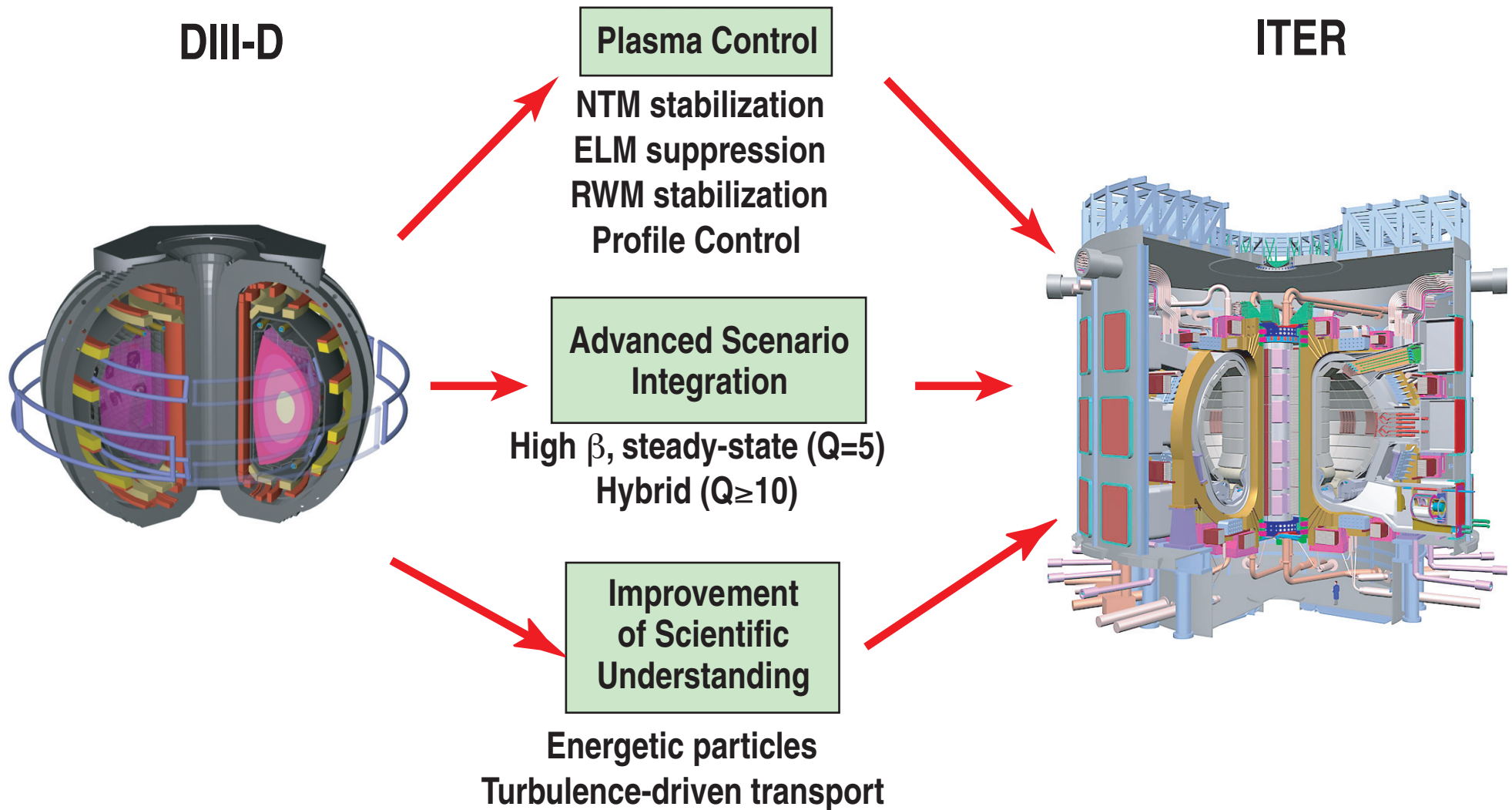


DIII-D's Research Program is Aimed at Maximizing the Scientific Benefit from ITER

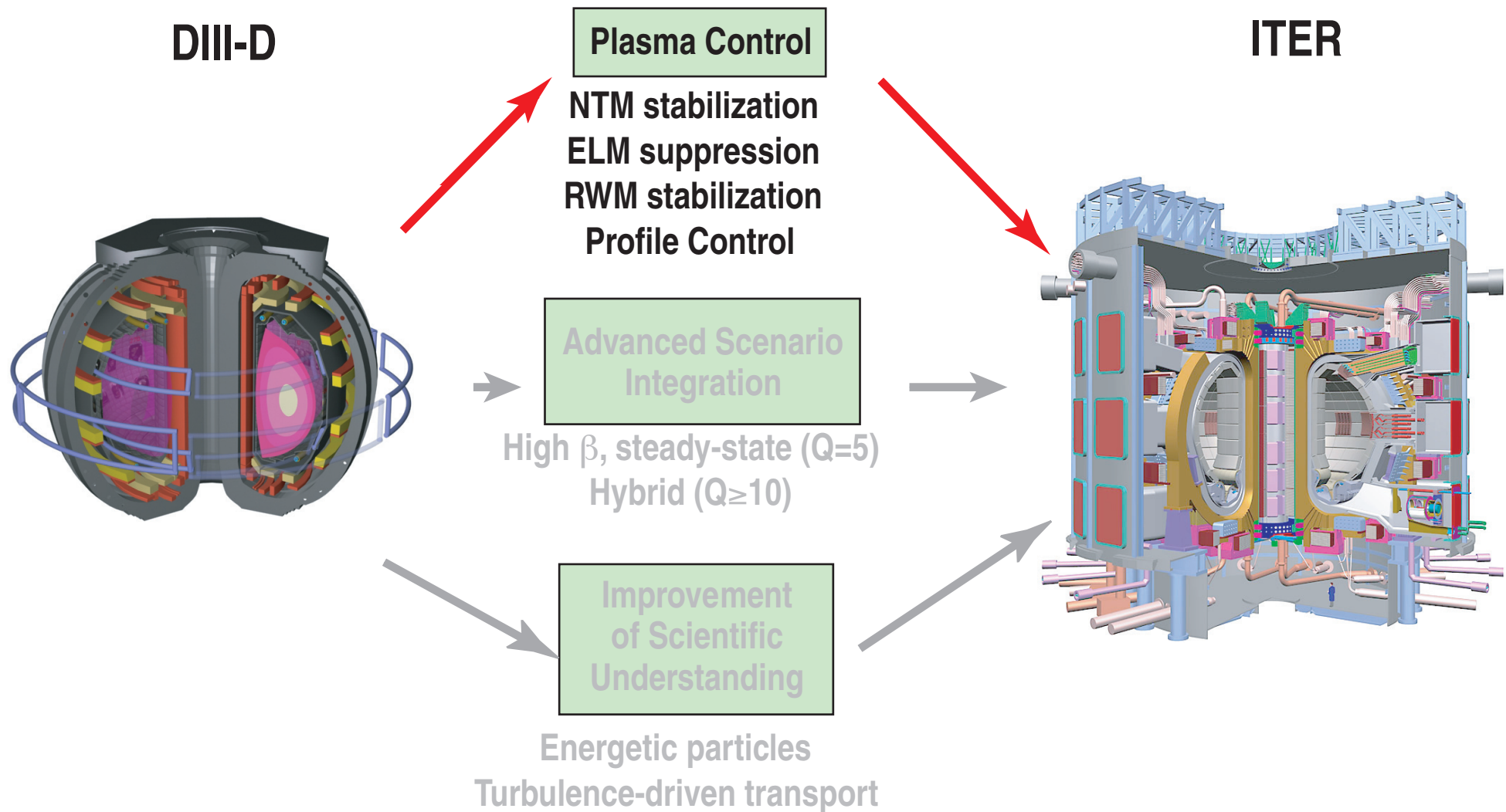
DIII-D Research Elements are:

- **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**

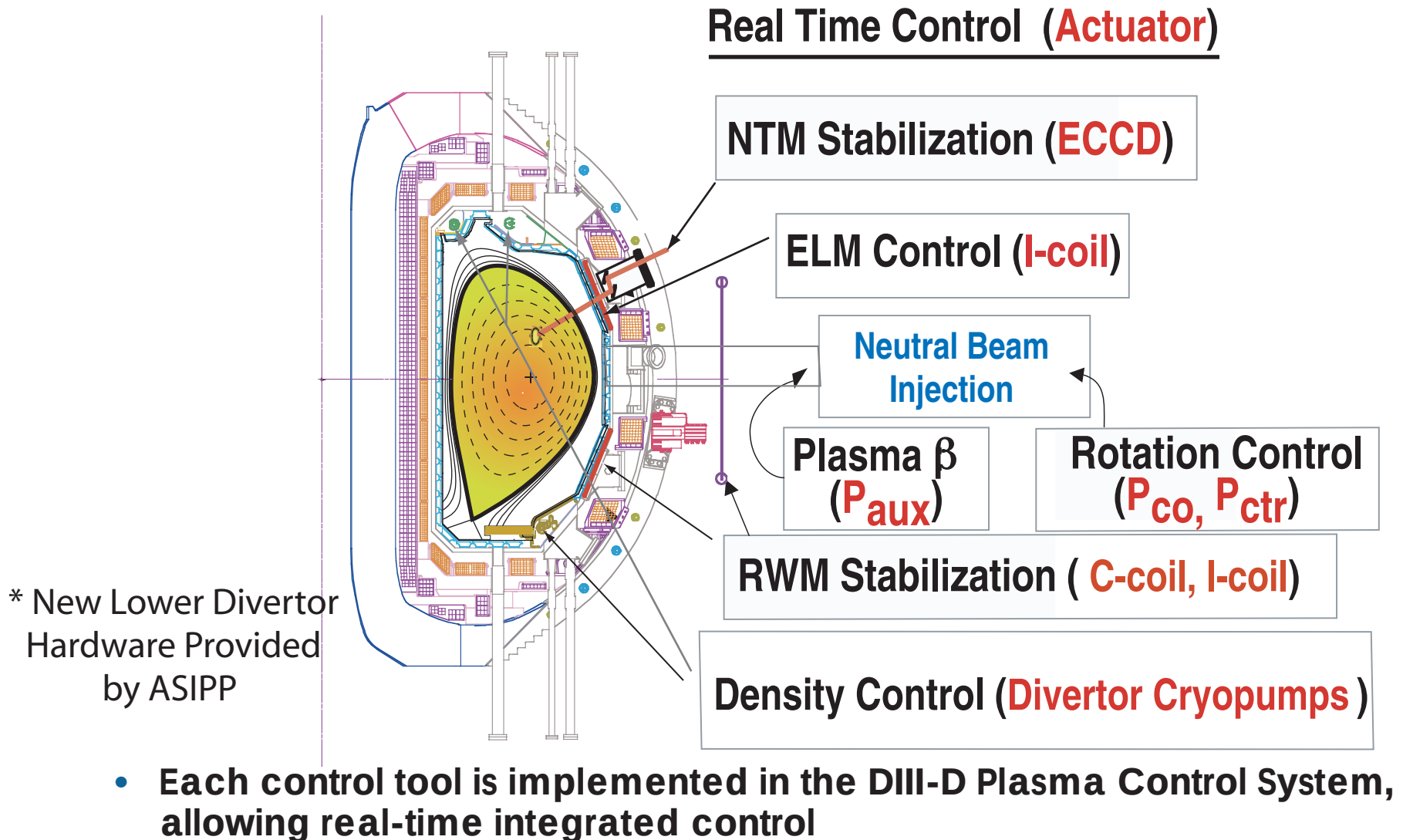
DIII-D Has Advanced the Physics Basis and Confidence in ITER Achieving Its Physics Objectives



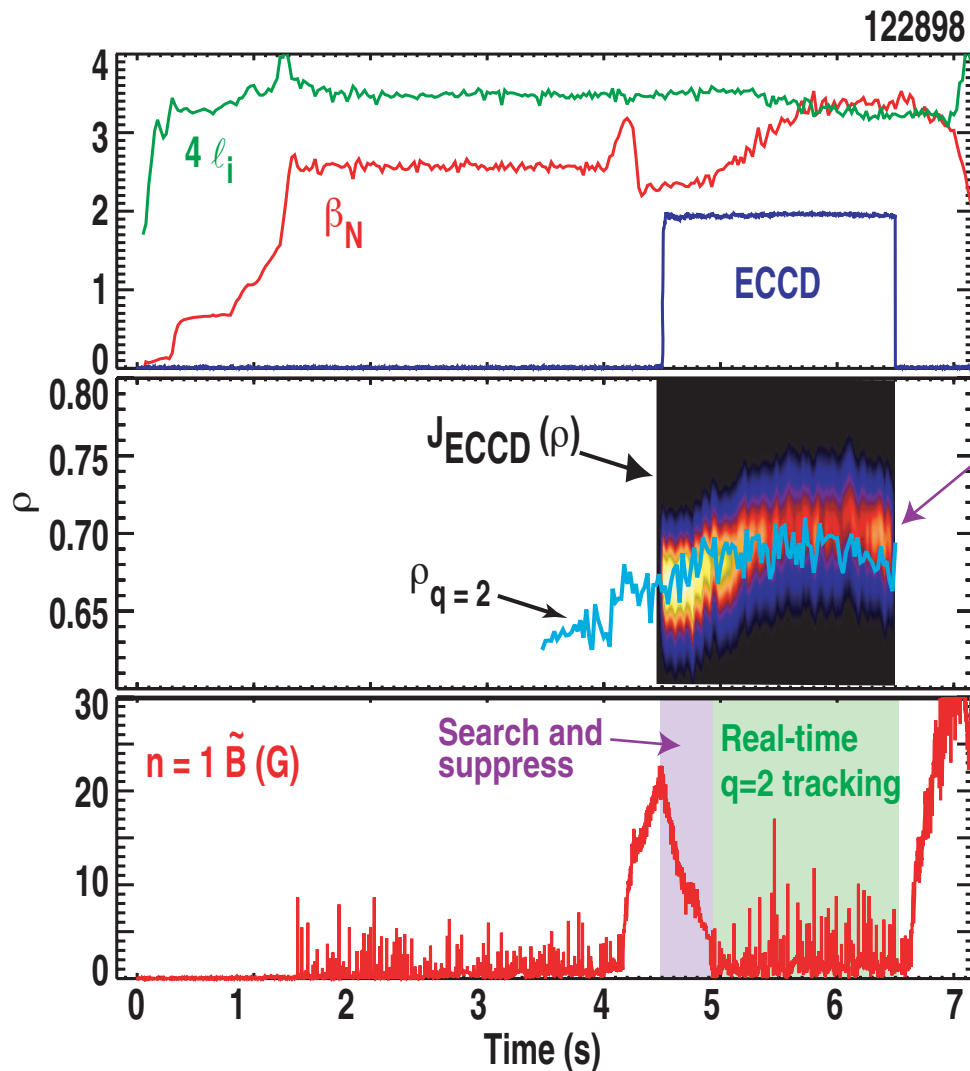
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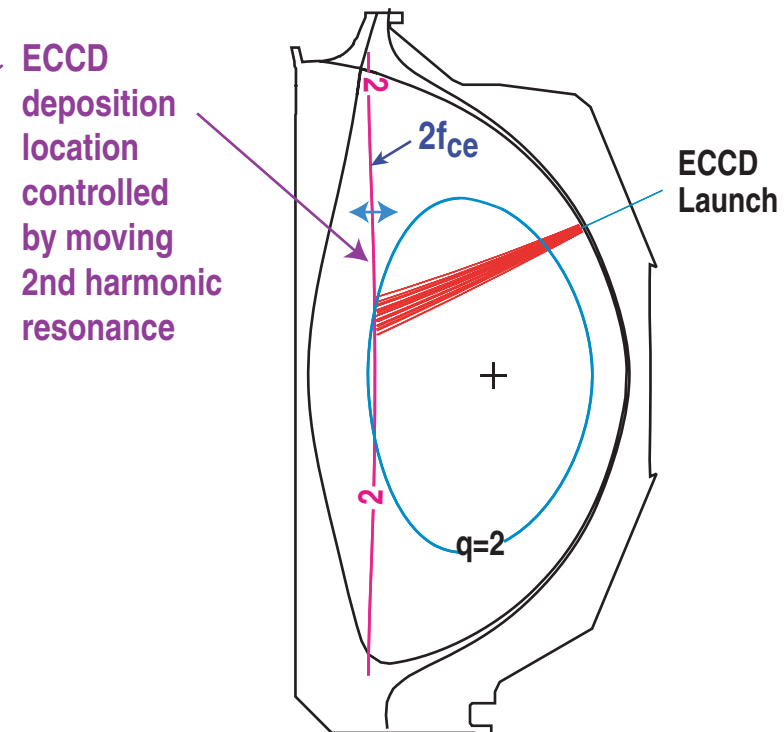
Real-Time Control of Key Plasma Properties Enabled by Extensive Set of Control Tools



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

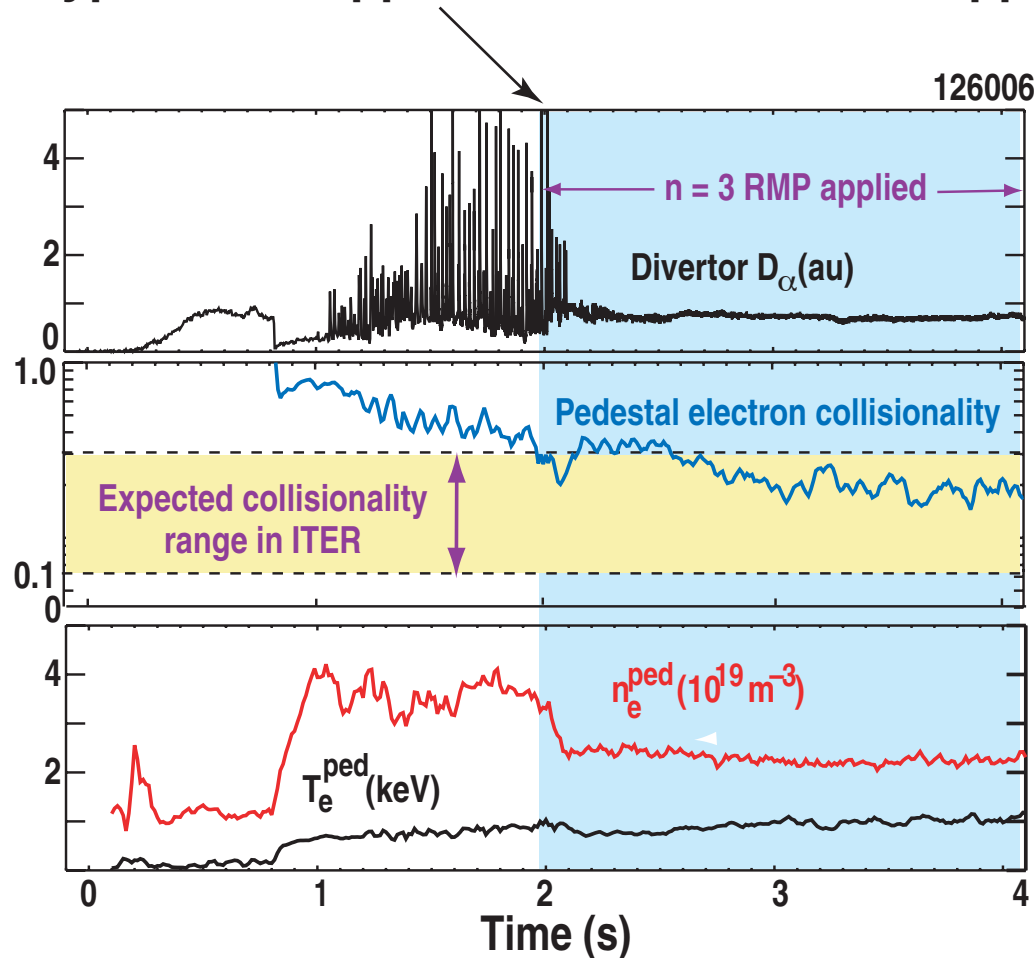


- Optimal location for NTM suppression found by real-time searching and maintained by tracking of $q=2$ surface using real-time equilibrium reconstructions including MSE (every 6 ms)

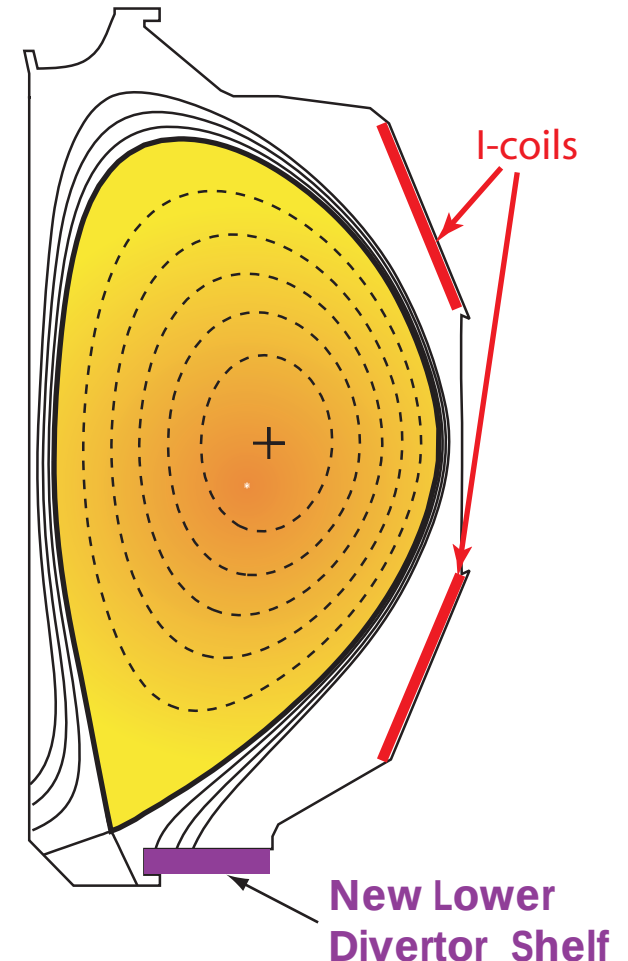


Complete ELM Suppression Achieved in an ITER-like Shape and Collisionality Using $n=3$ Resonant Magnetic Perturbations

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

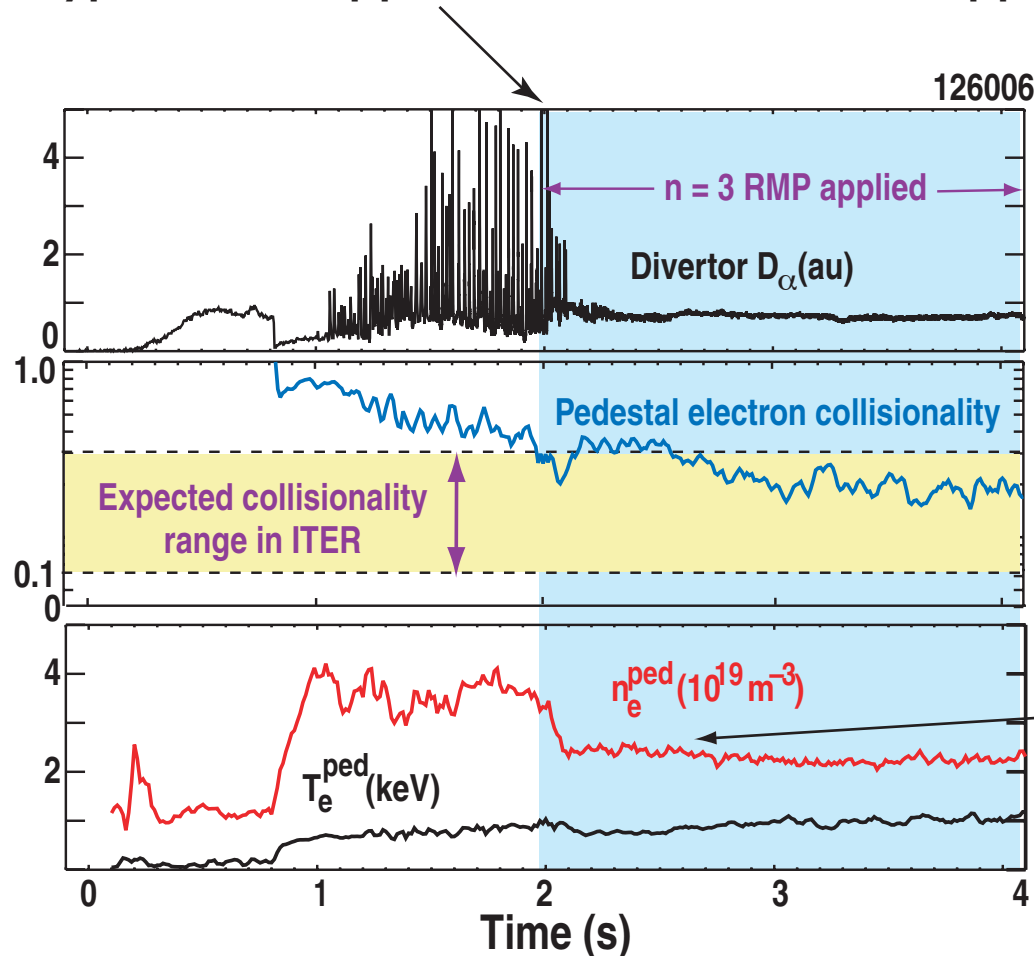


$$\kappa = 1.8, \delta_{\text{top}} = 0.36, \delta_{\text{bot}} = 0.71$$

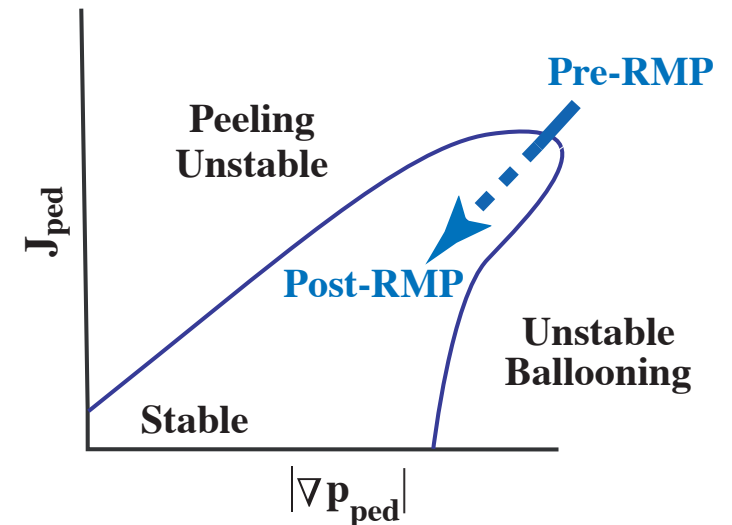


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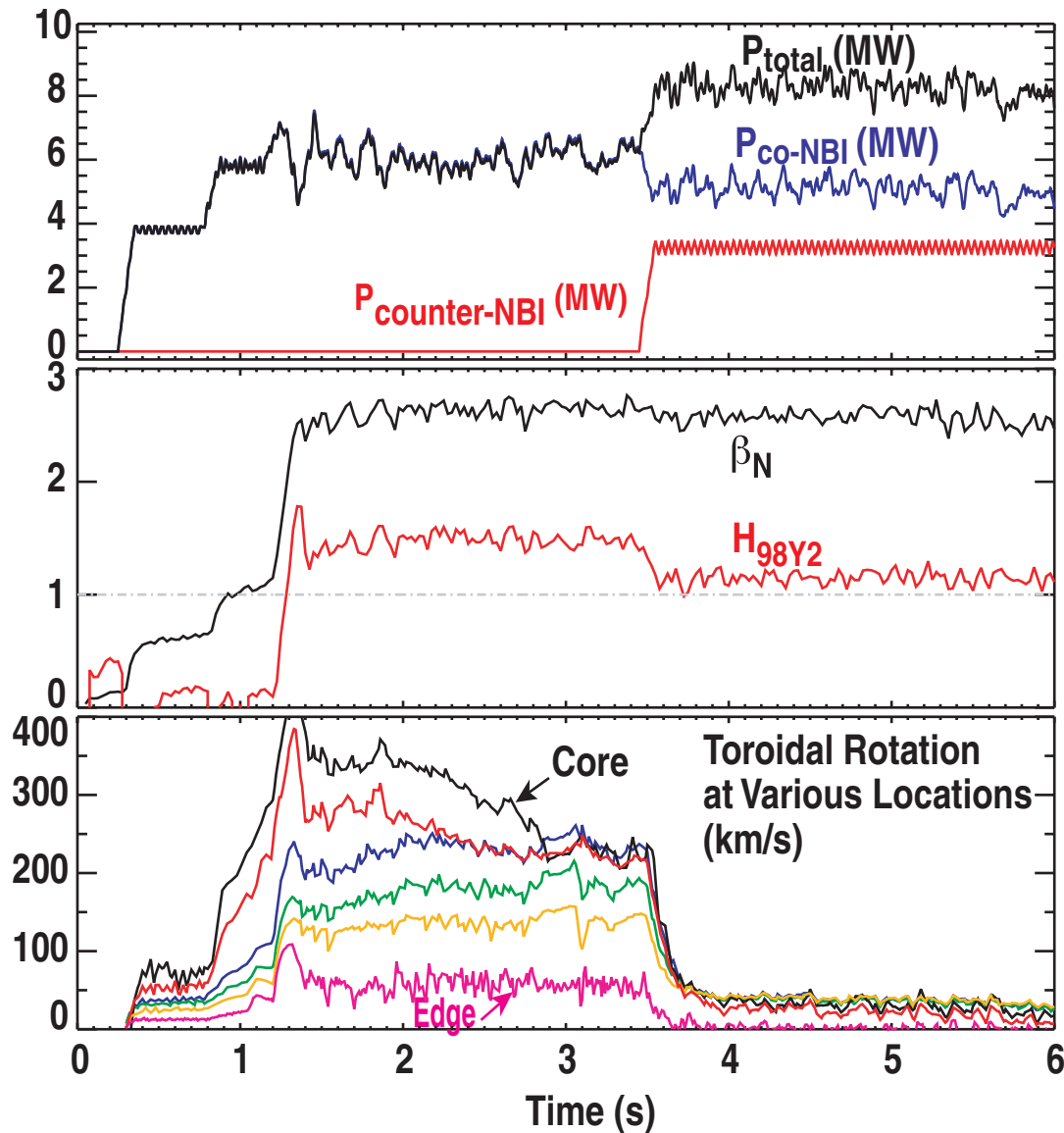


- RMP reduces pressure gradient below peeling-ballooning stability limit

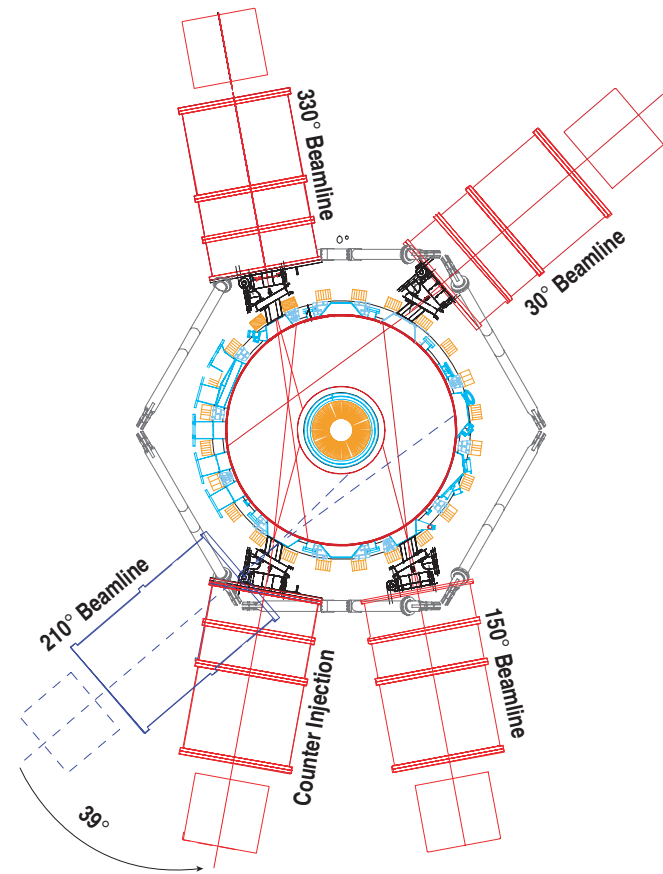


- Pressure gradient reduction due to changes in particle transport

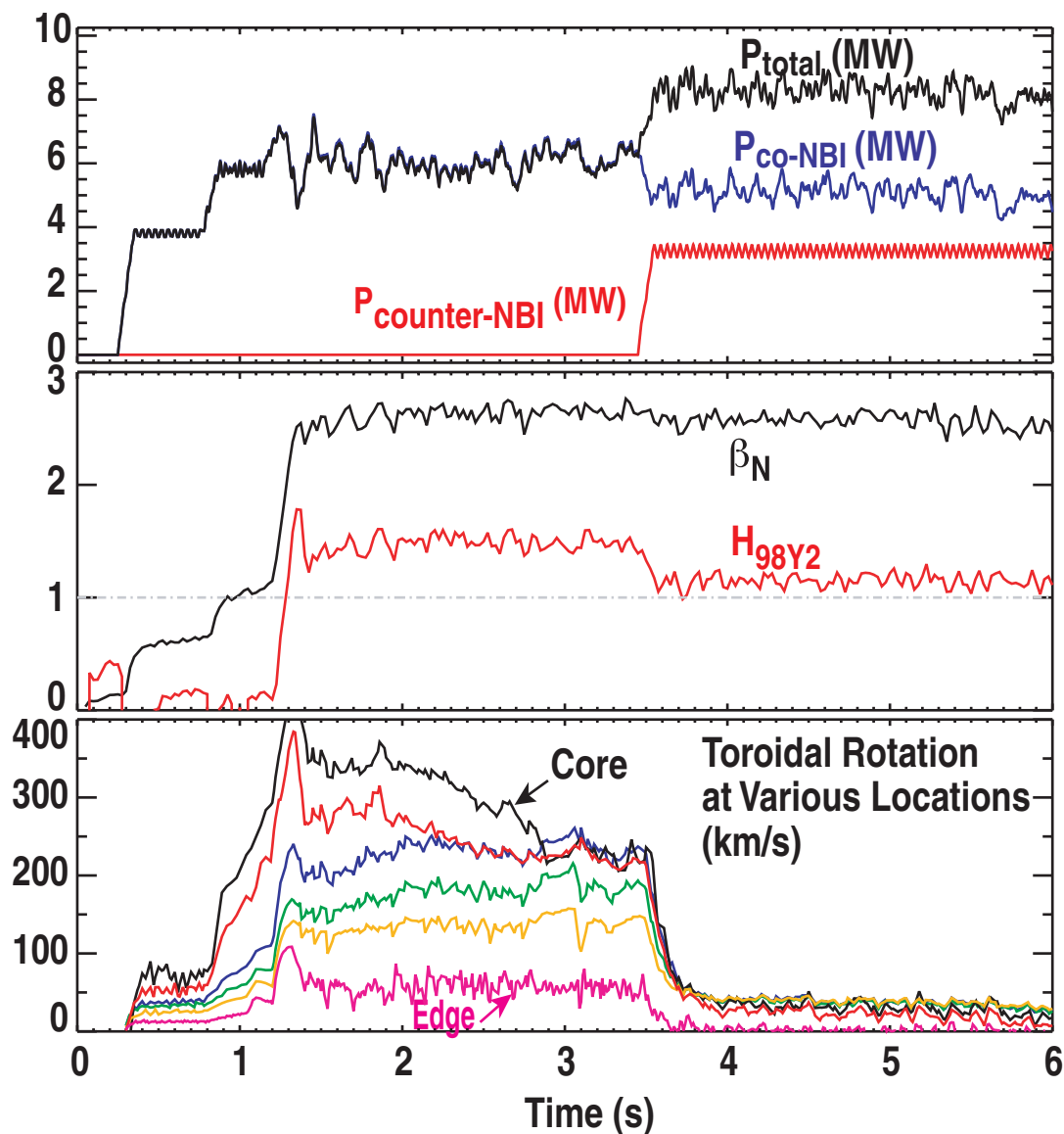
Reconfigured NBI System Provides Fine Control of Plasma Rotation



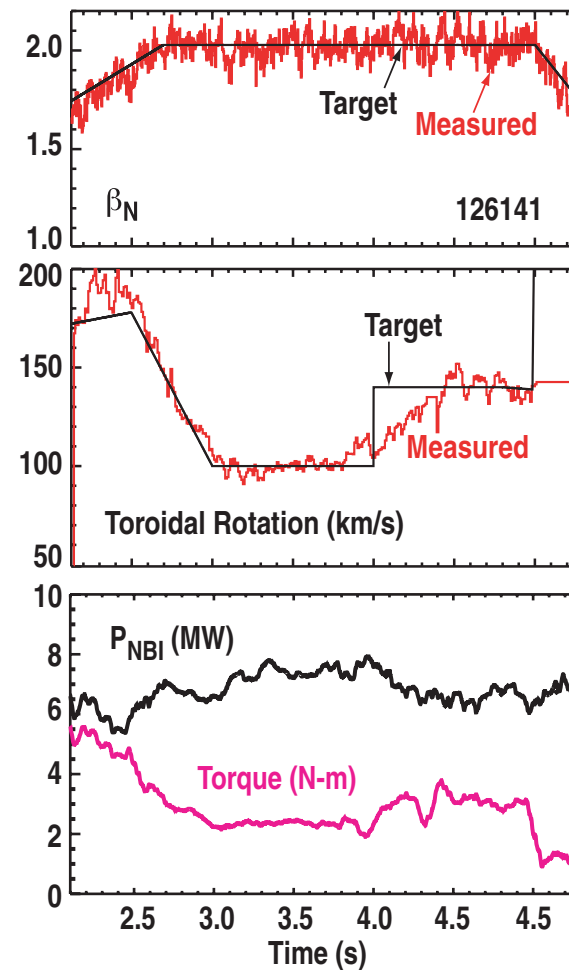
- Re-orientation of beamline allows 5 MW counter-NBI and 12.5 MW co-NBI



Reconfigured NBI System Provides Fine Control of Plasma Rotation



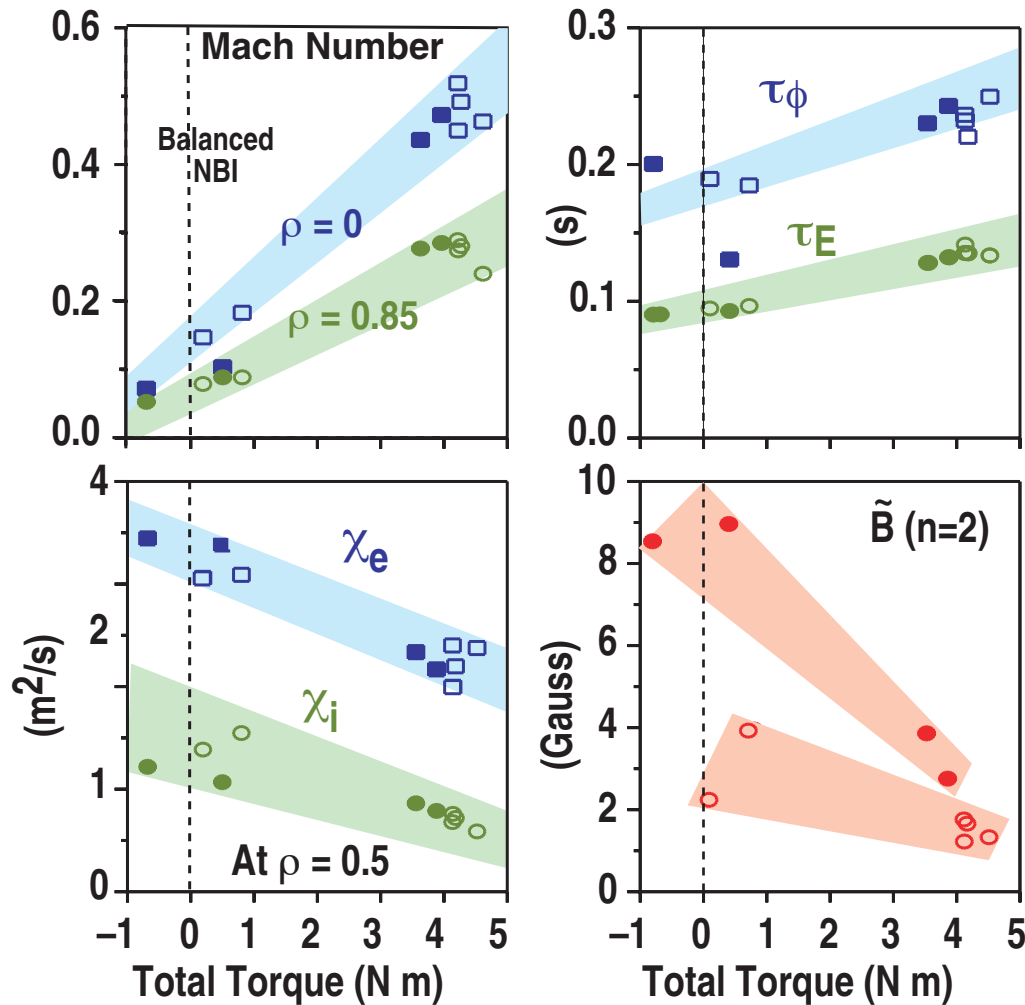
- Simultaneous feedback control of β_N and toroidal rotation demonstrated



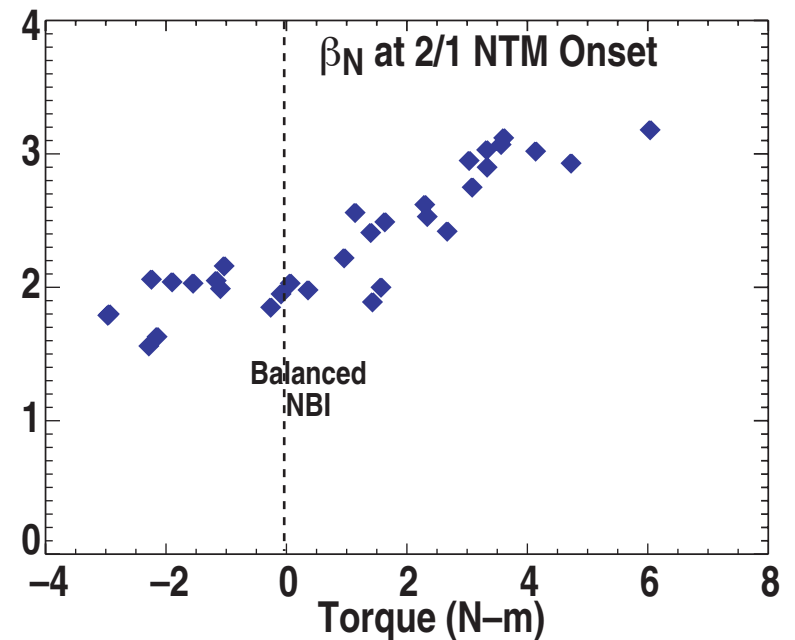
Transport and NTM Physics Shown to be Sensitive to Applied Torque and Resulting Rotation

- Hybrid discharges with $\beta_N = 2.6$

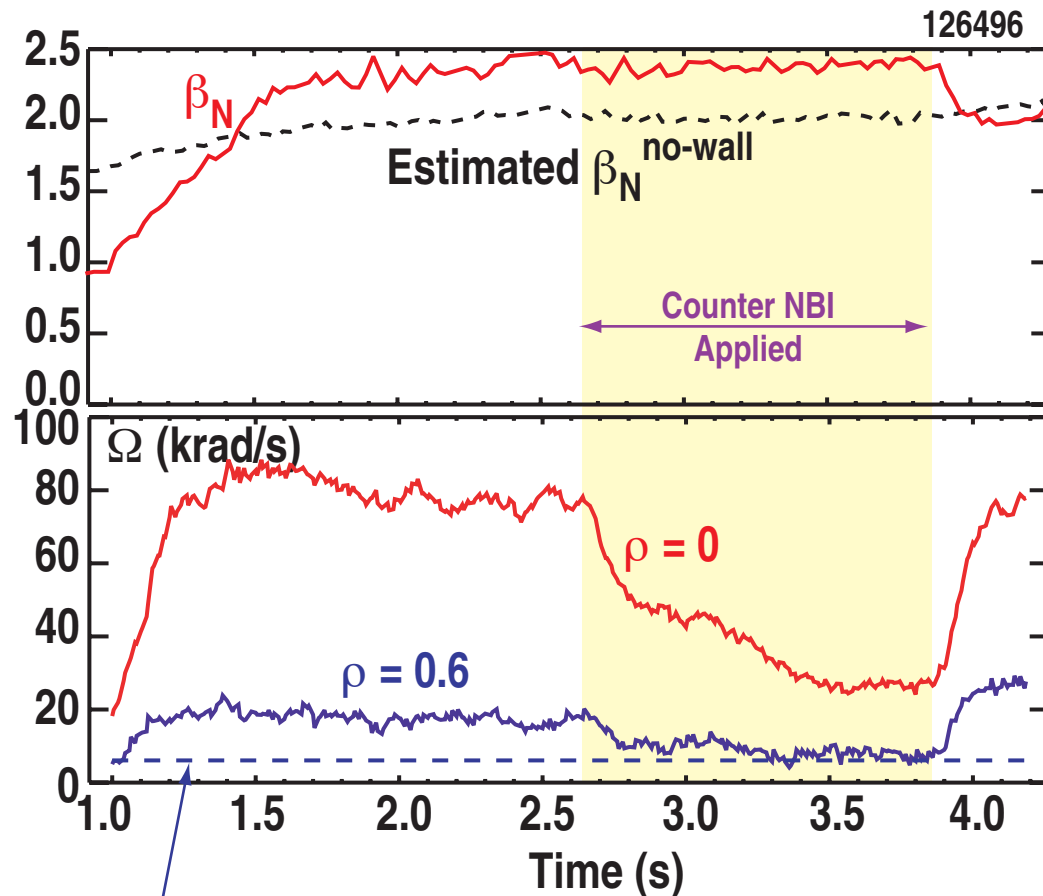
$q_{95} = 4.0$ (closed) $q_{95} = 4.5$ (open)



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

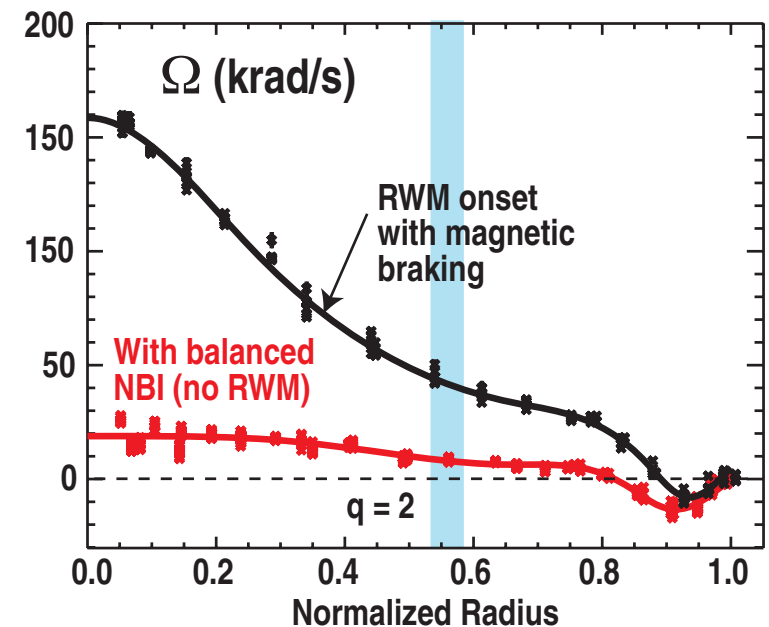


Threshold for Rotational Stabilization of RWM Found to Be Comparable to Expected Rotation in ITER

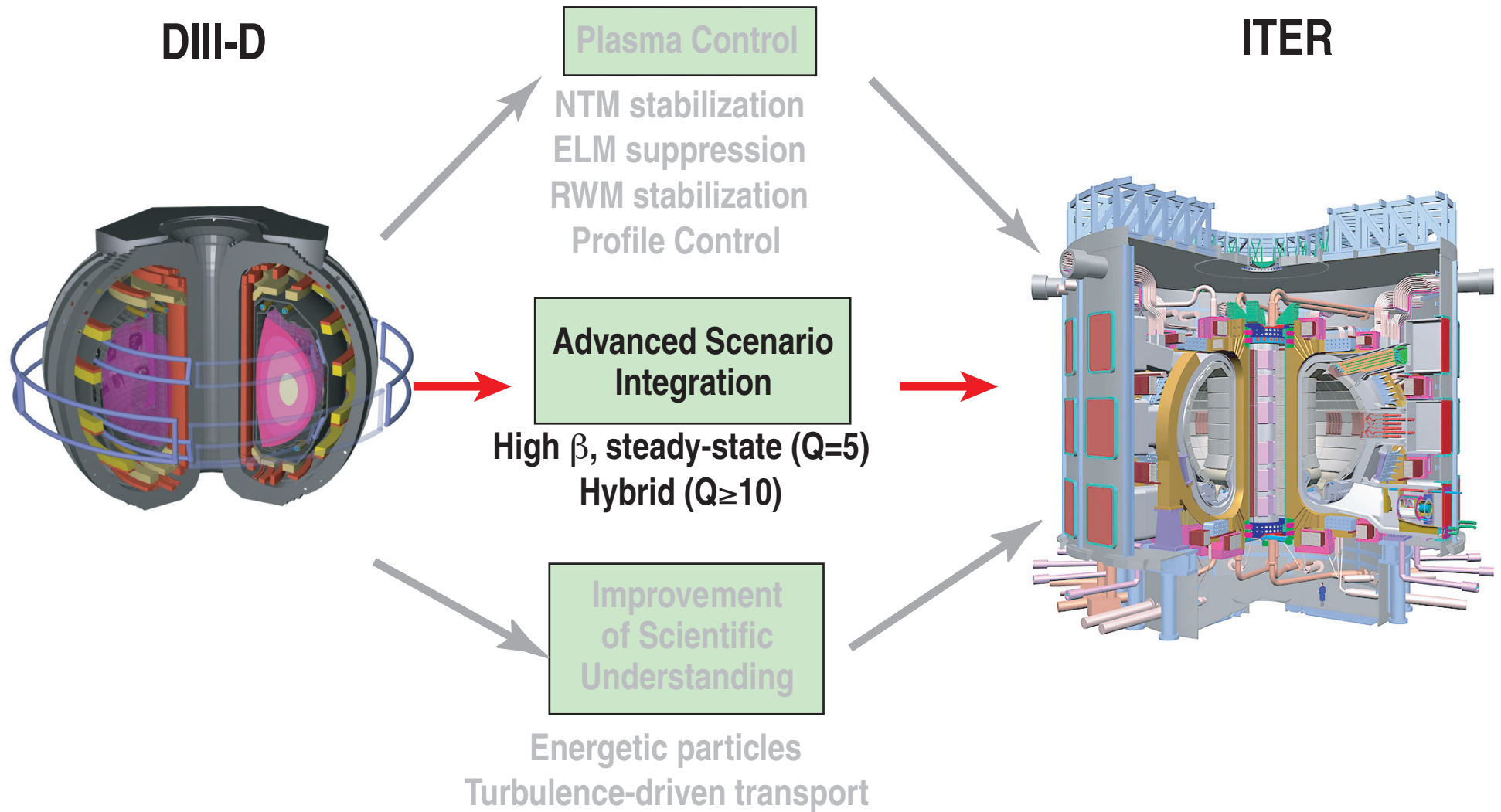


Predicted rotation at $\rho = 0.6$ in ITER:
 $\Omega_{\text{ITER}} = 0.003 \Omega_A$

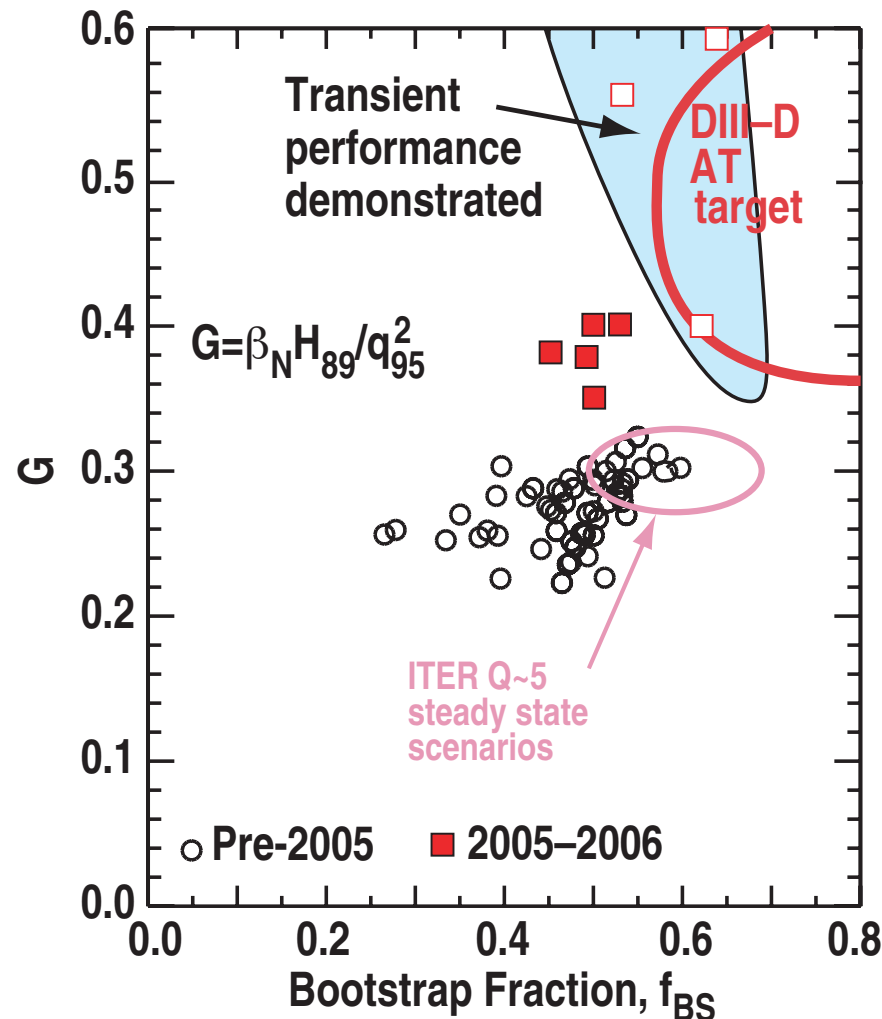
- Previous measurements using magnetic braking suggested a high rotation threshold for RWM stabilization ($\sim 1\text{-}2\%$ of Ω_A at $q = 2$)



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

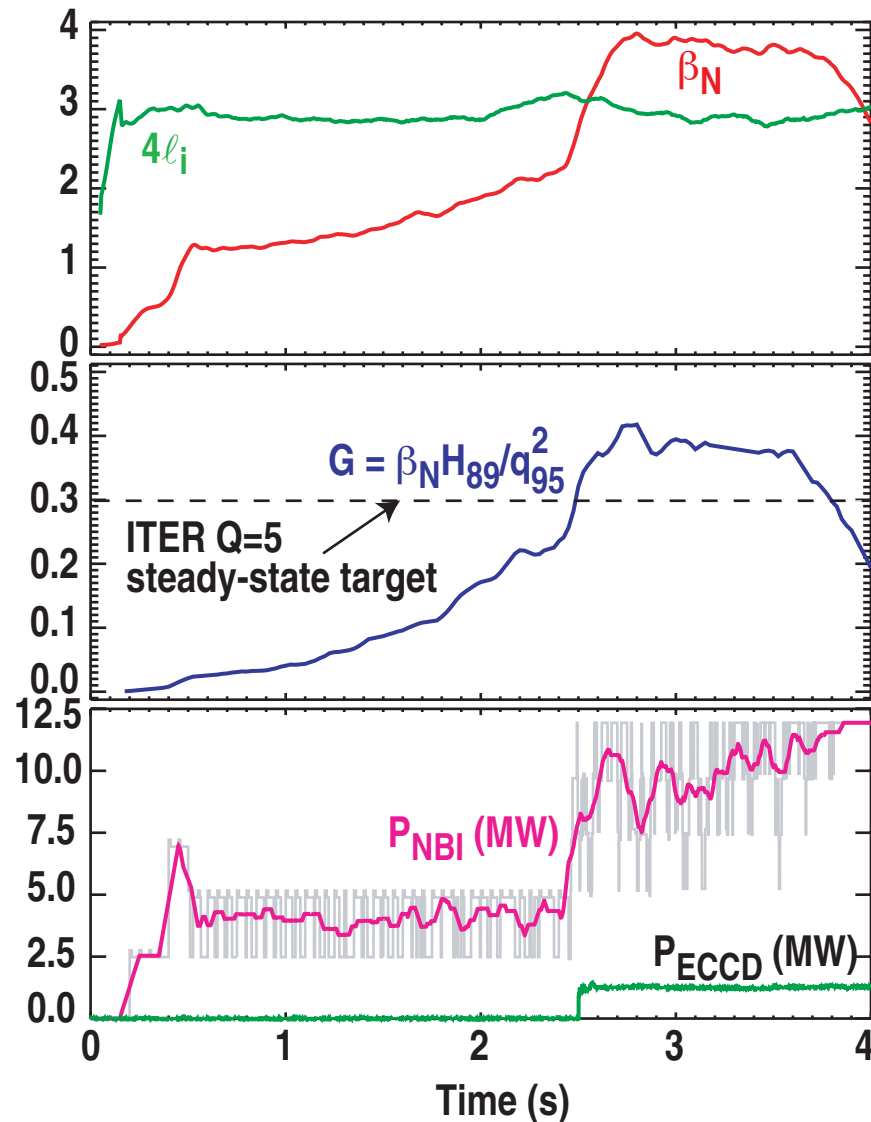


Performance Routinely Achieved Above Requirements for Q=5 Steady-state Scenario in ITER

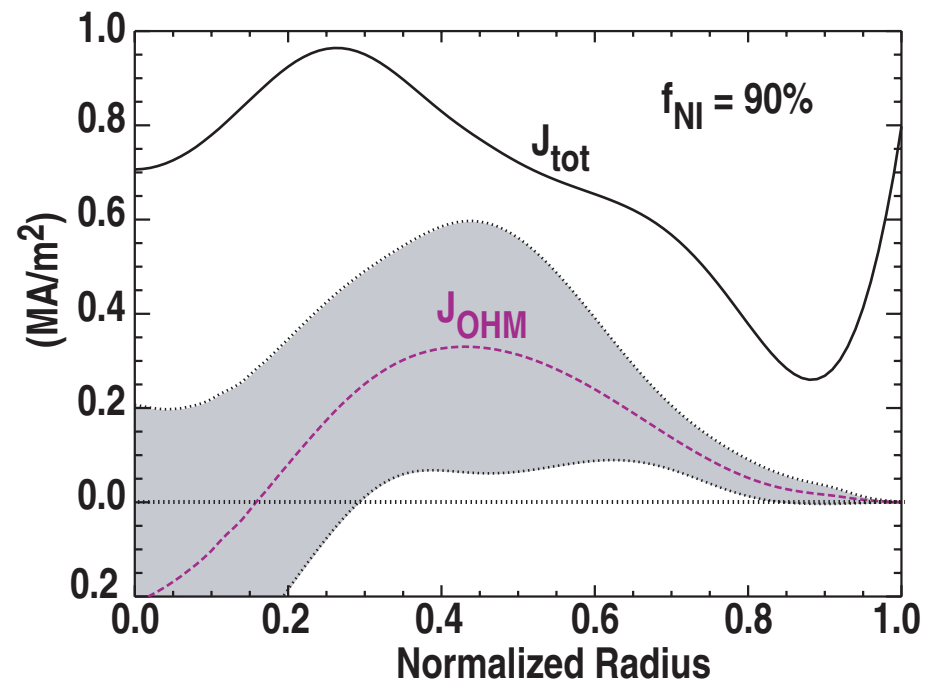


- $G > G_{Q=5}^{ITER}$ achieved in two separate lines of research
 - 1) Weak negative central shear utilizing current drive tools compatible with steady state
 - 2) Moderate negative central shear through continuous ramps in I_p and B_T
- Both methods utilize:
 - Highly shaped, double-null configurations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

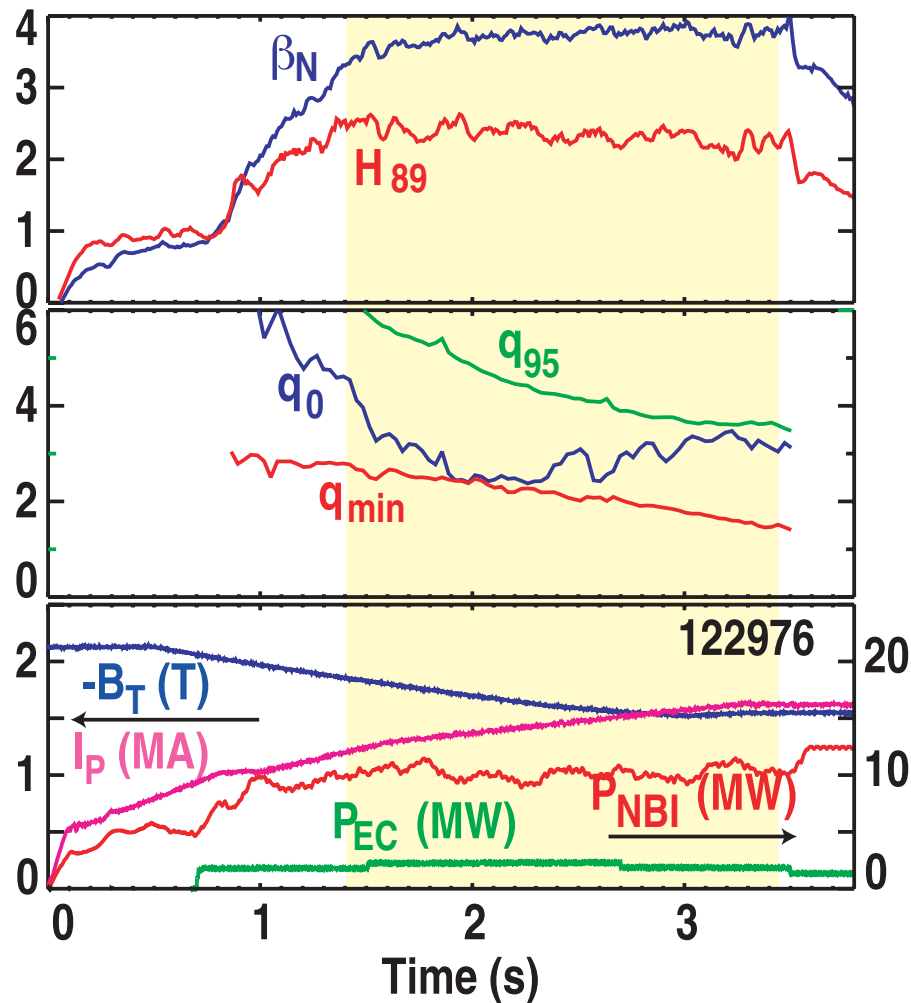
Nearly Fully Noninductive Plasmas Achieved with $\beta_N \approx 4$



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

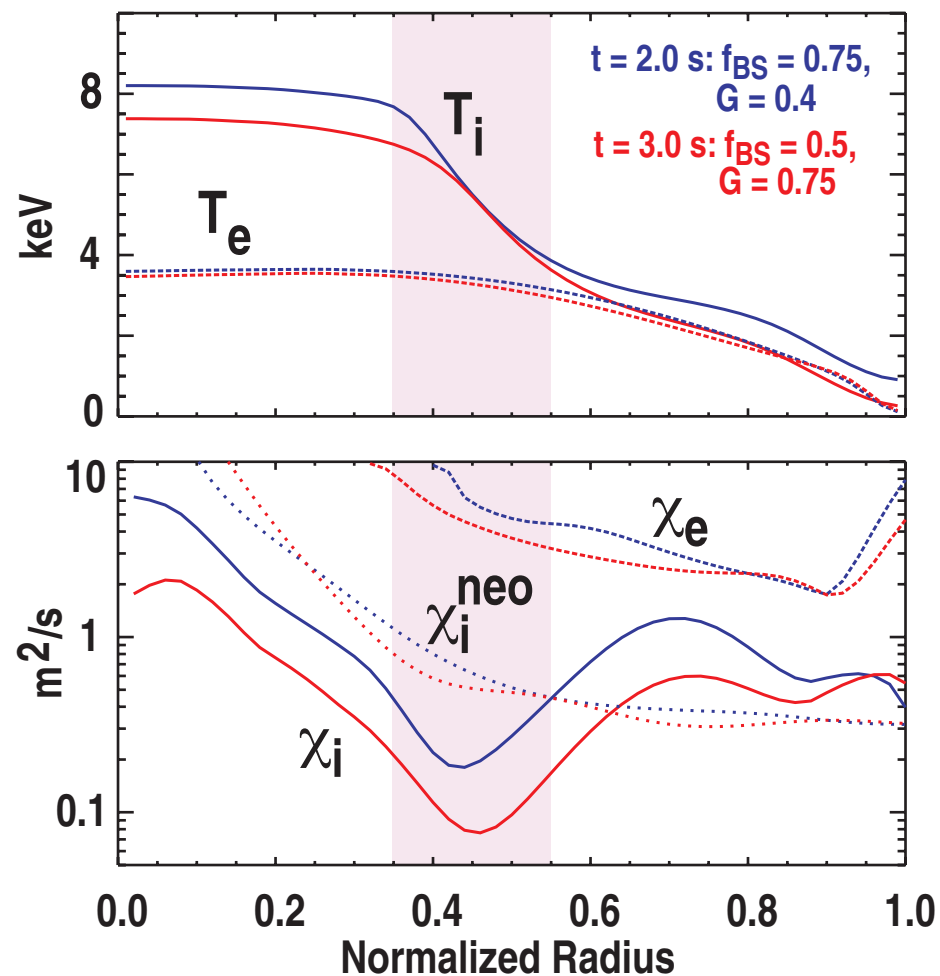
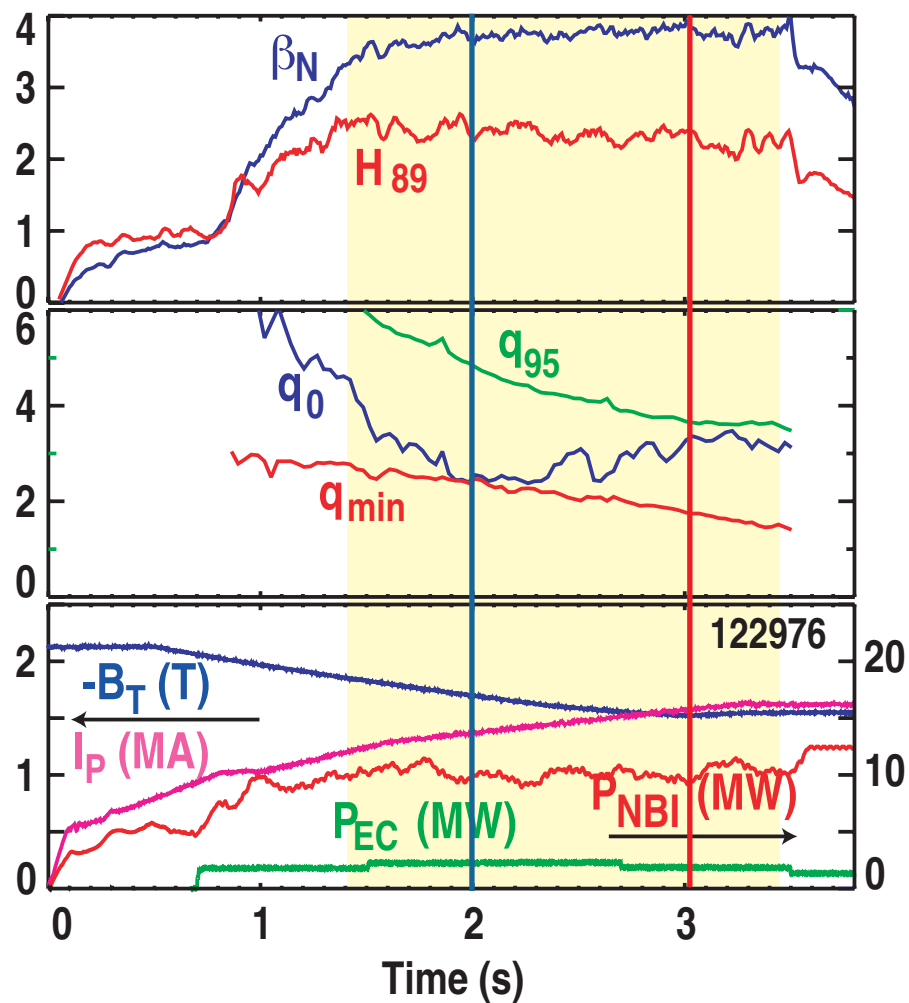


Sustained High Performance ($\beta_N \approx 4$ for ~ 2 s) Achieved in Discharges with an Internal Transport Barrier



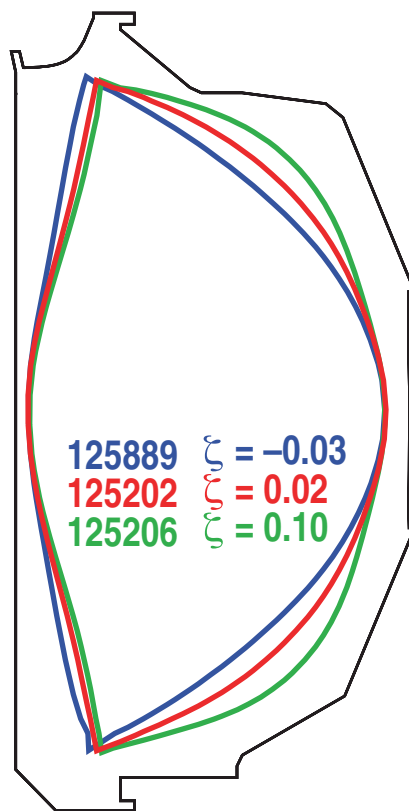
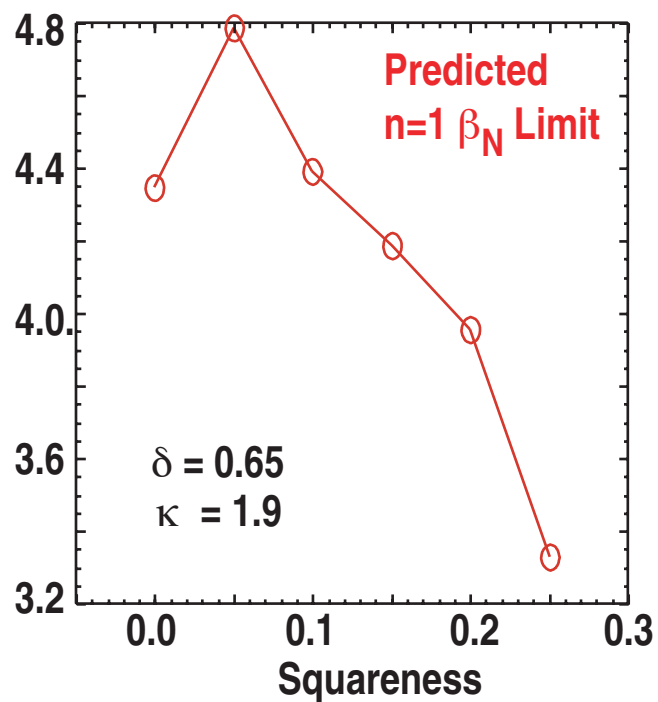
- $\beta_N = 3.8$ is approximately 50% above conventional no-wall limit
- Broad current density profile obtained by early heating, off-axis ECCD, and ramps in I_p and B_T
- Excellent confinement ($H_{89} \approx 2.5$) maintained throughout

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

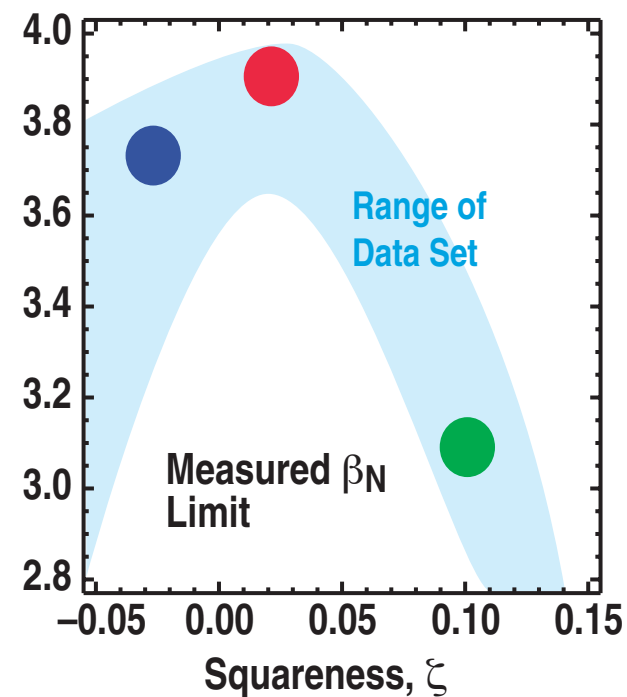


Plasma Performance Shown to be Sensitive to Details of the Plasma Shape

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

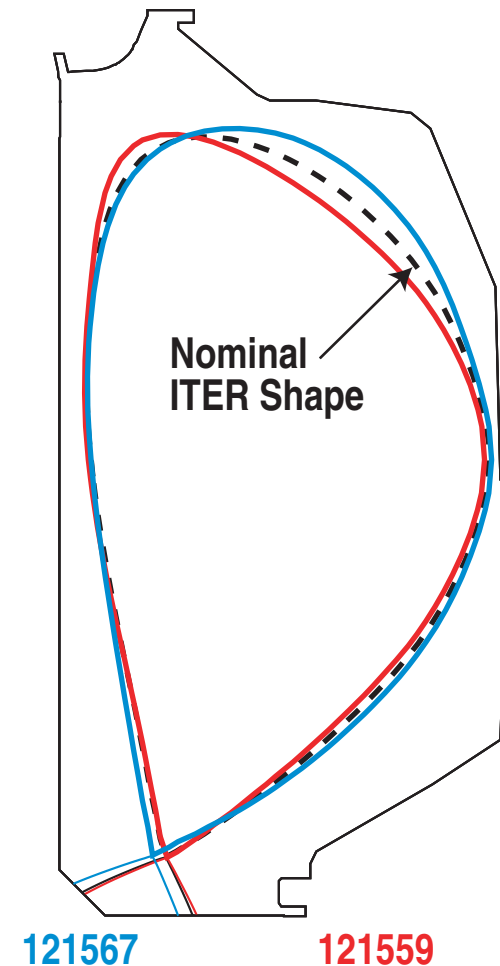
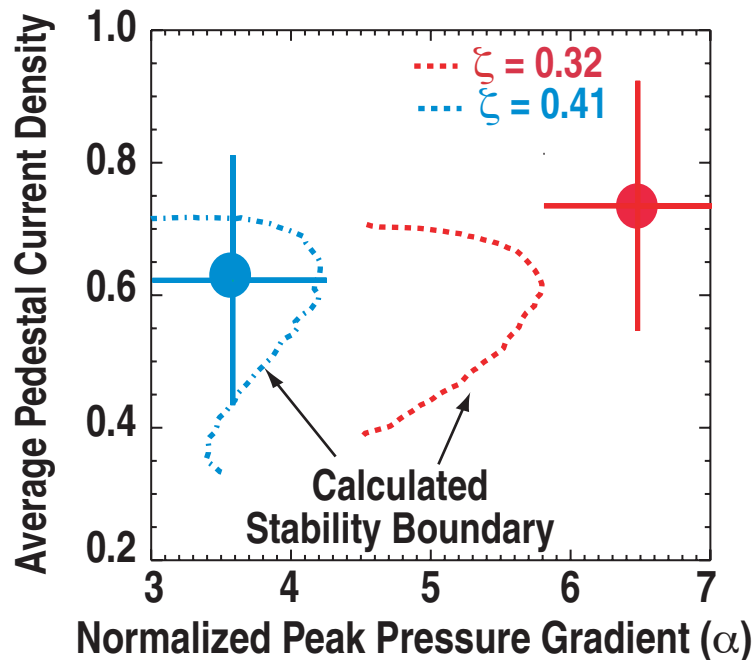


- Measured long pulse β limit shows similar dependence

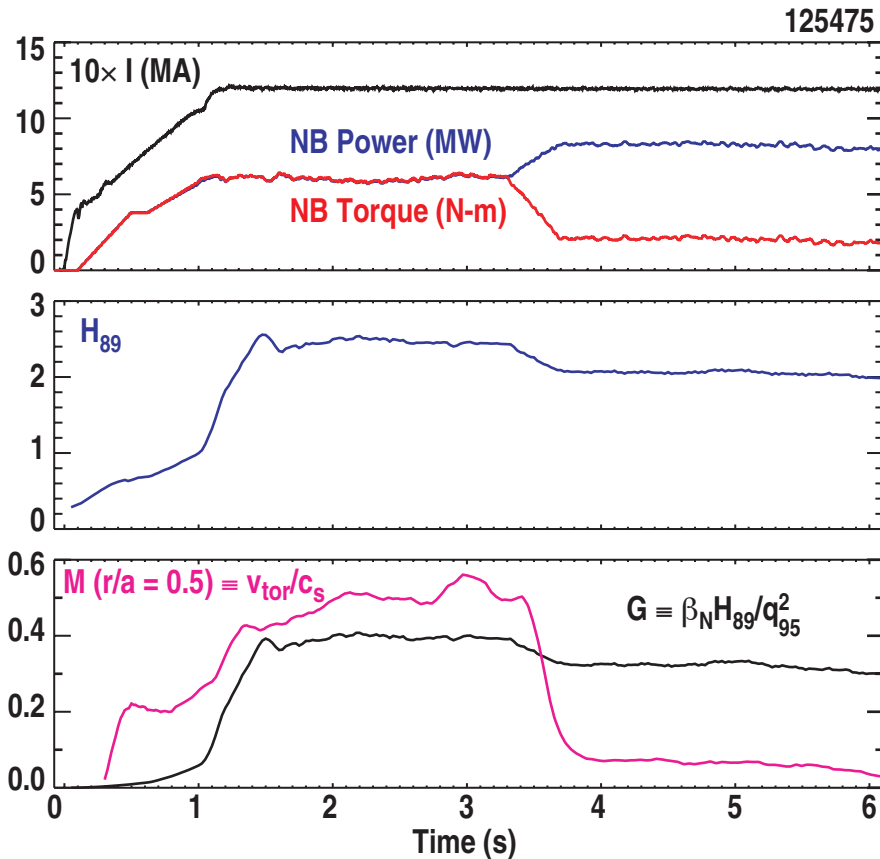


Details of the Plasma Shape Near the ITER Design Shape are Important

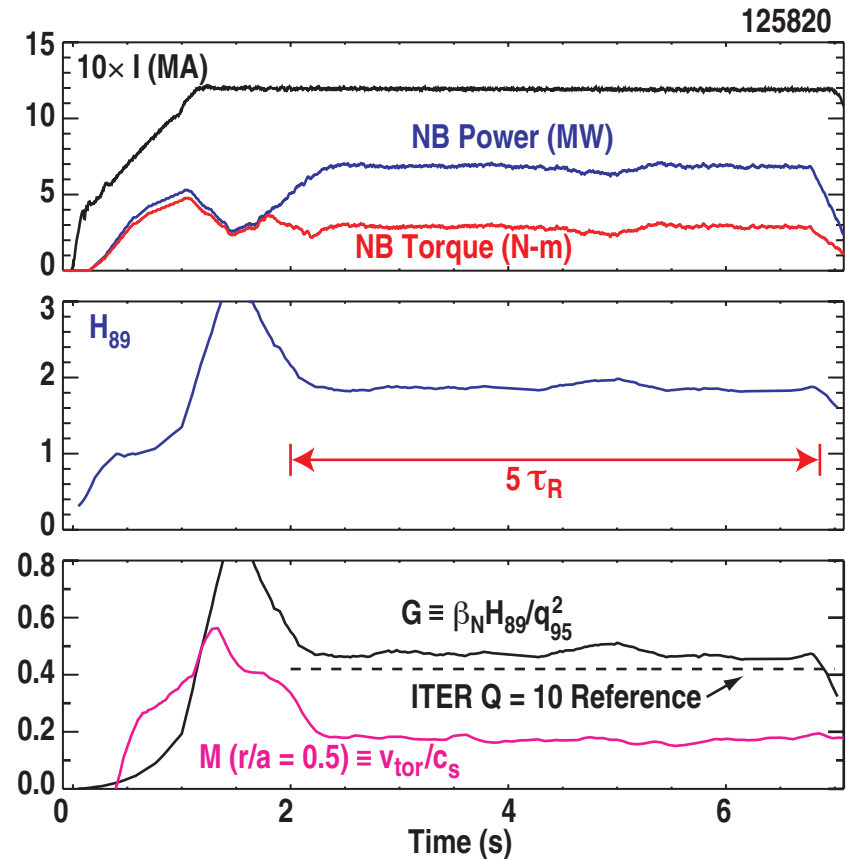
- In ITER shape, significant change in edge pressure gradient associated with change in squareness
 - Factor of 2 in measured pressure gradient
 - 50% in calculated stability boundary (ELITE)



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

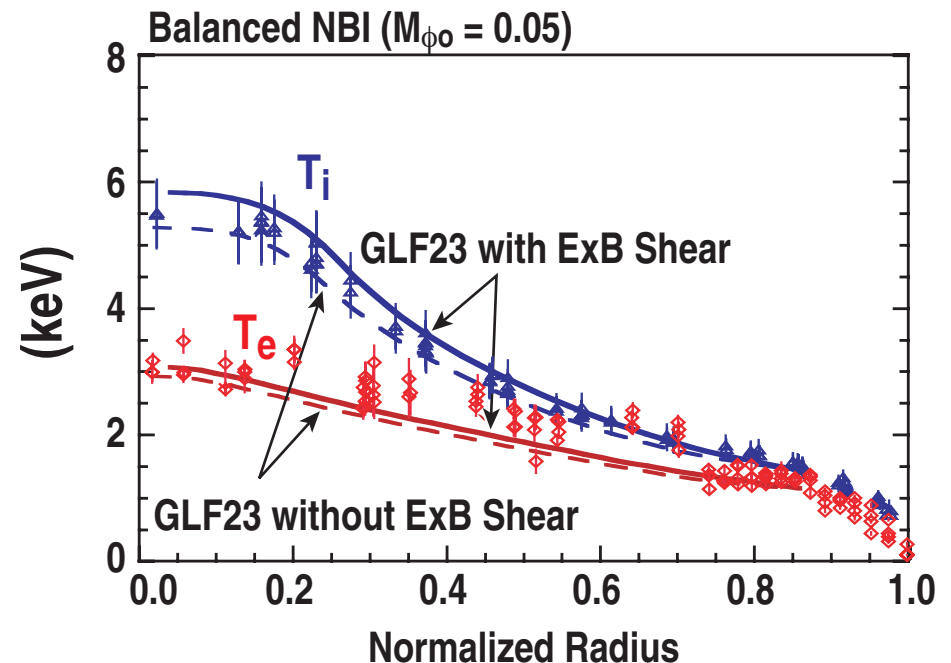
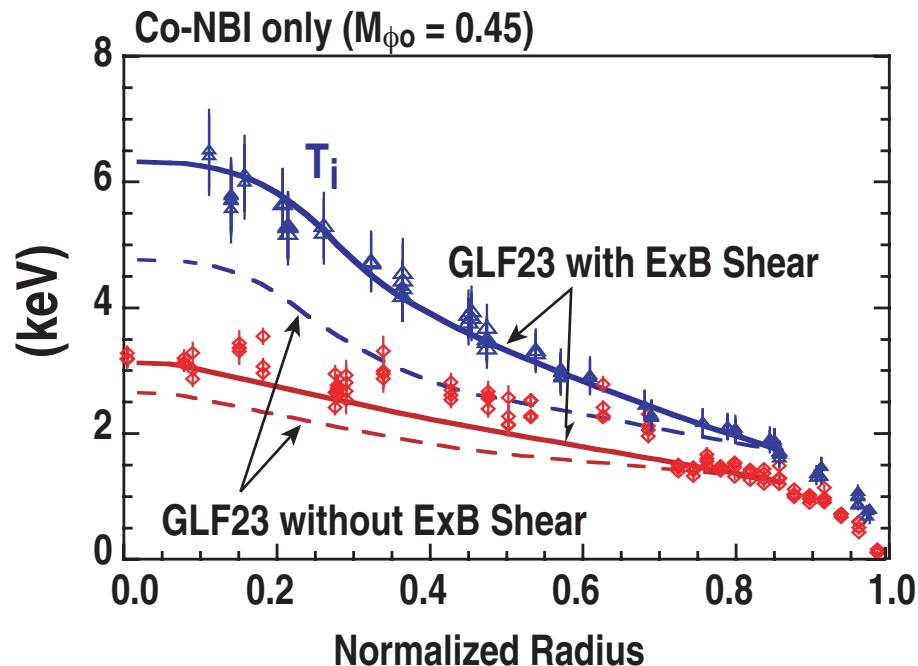
89P: $Q = 10.3$

98y2: $Q = 10.2$

DS03: $Q = \infty$

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

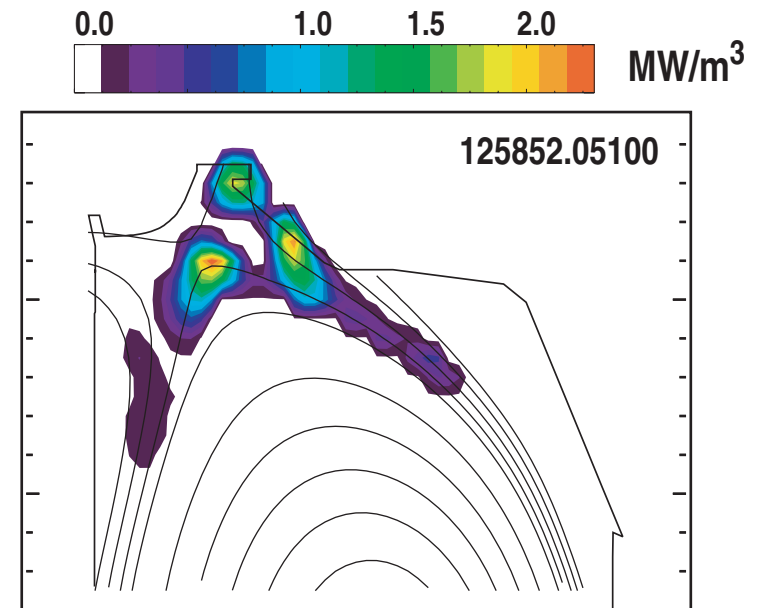
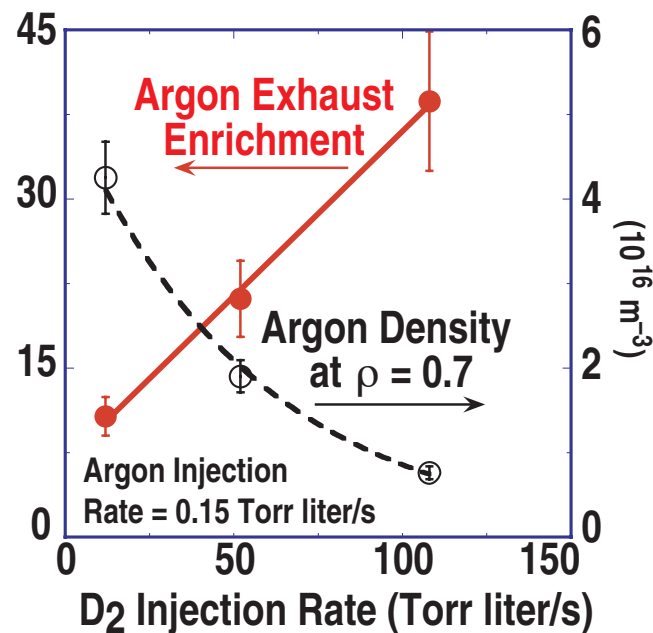
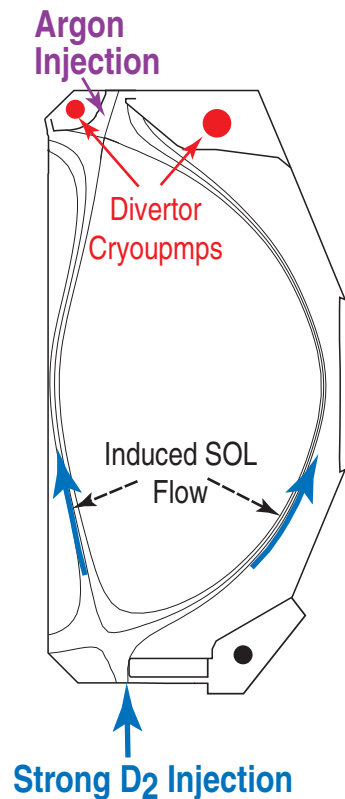
- With high toroidal rotation, ExB shear required in GLF23 to reproduce measured profiles
- At low rotation, ExB shear is much less important



- $H_{98y2} = 1.5$ – excellent confinement!
- $H_{98y2} = 1.2$ – good overall confinement still maintained

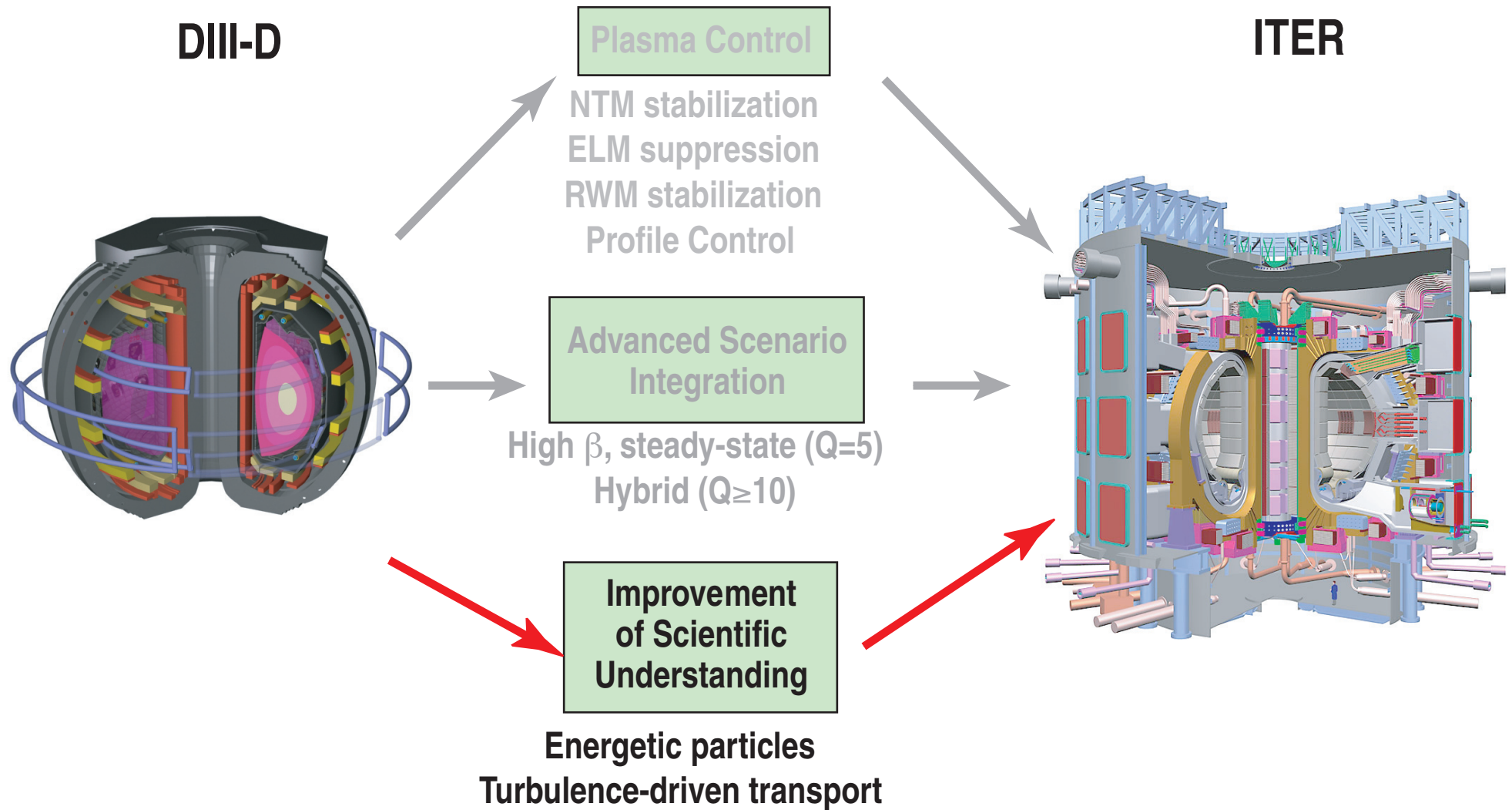
Compatibility of Hybrid Regime with Radiative Divertor Demonstrated Using “Puff and Pump” Technique

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



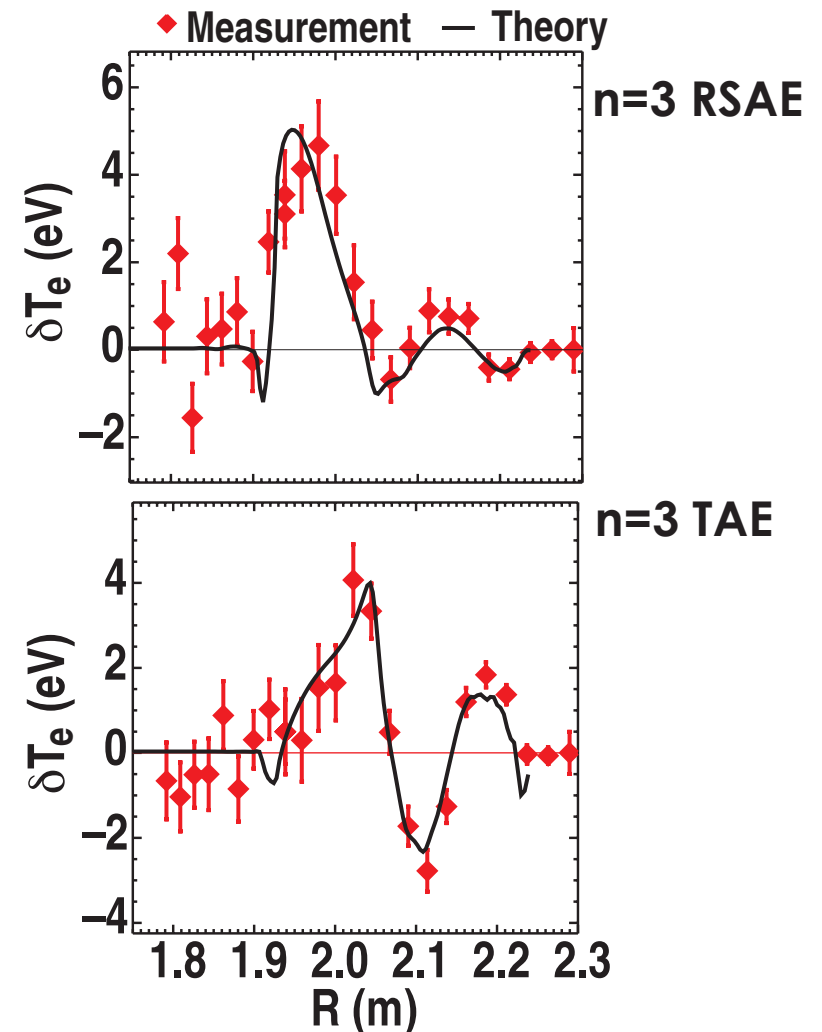
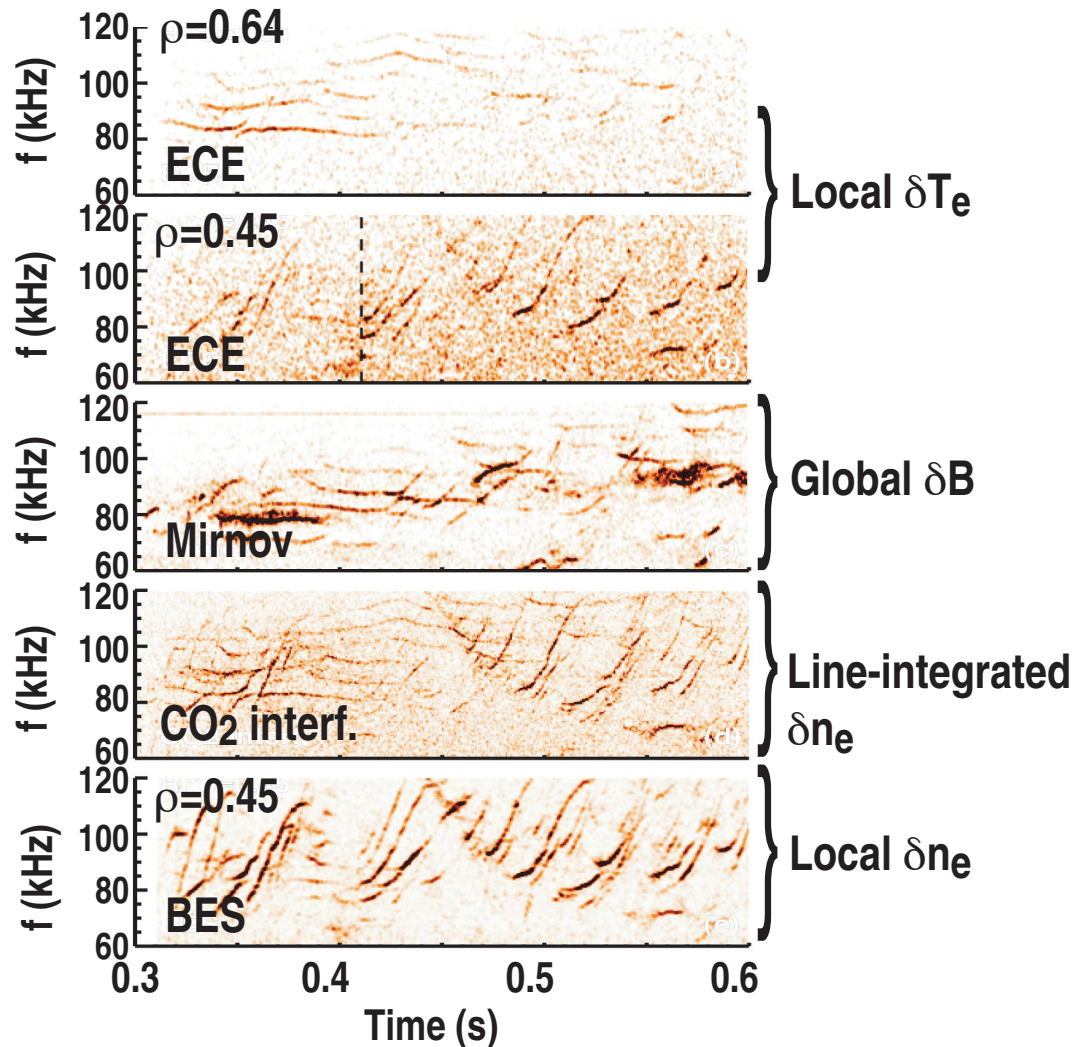
- $\beta_N = 2.6$, $H_{89} = 2.0$, $G = 0.4$ maintained

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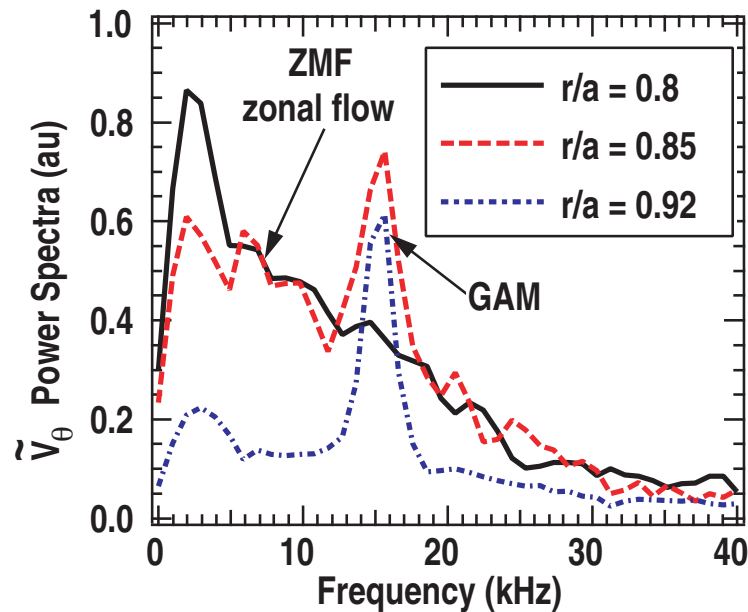
New Diagnostic Capabilities Enable Detailed Comparisons with Alfvén Eigenmode Theory

- Diagnostics probing different regions of plasma observe different MHD activity
- Measured radial structure consistent with theoretical predictions (NOVA)

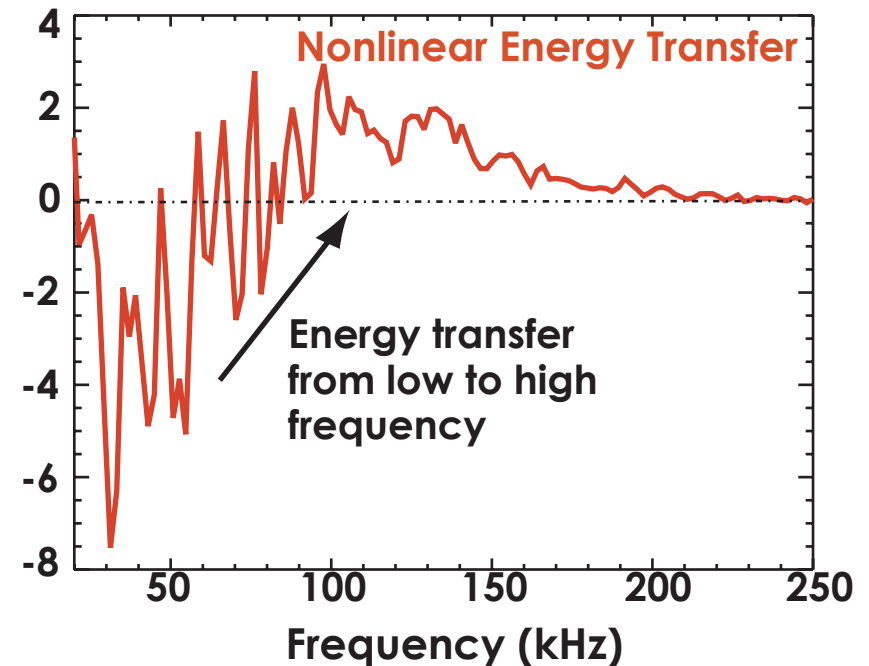


High Sensitivity BES Measurements Enable Detailed Characterization of Zonal Flow Structure and Dynamics

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

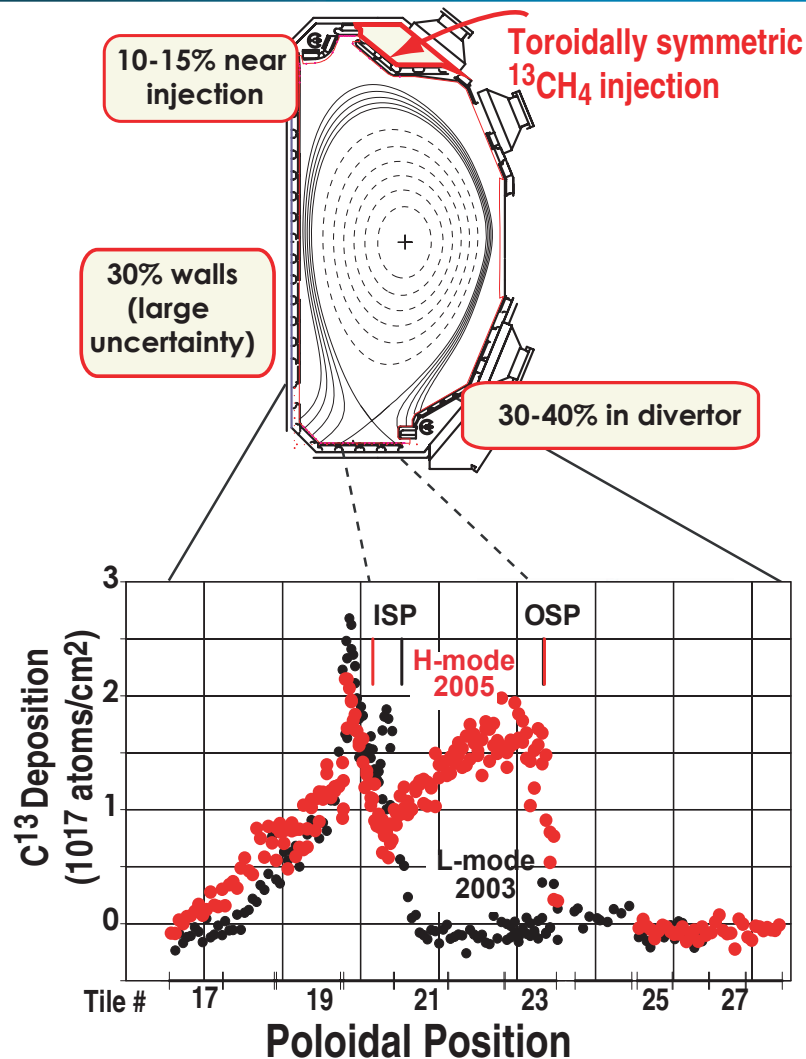


- GAMs couple energy to high frequency turbulence



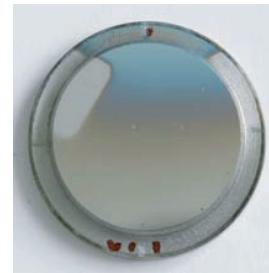
$$\text{Turbulent Energy Transfer} = -\text{Re} \left\langle n(f) V_y(f-f') \frac{\partial n(f')}{\partial y} \right\rangle$$

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

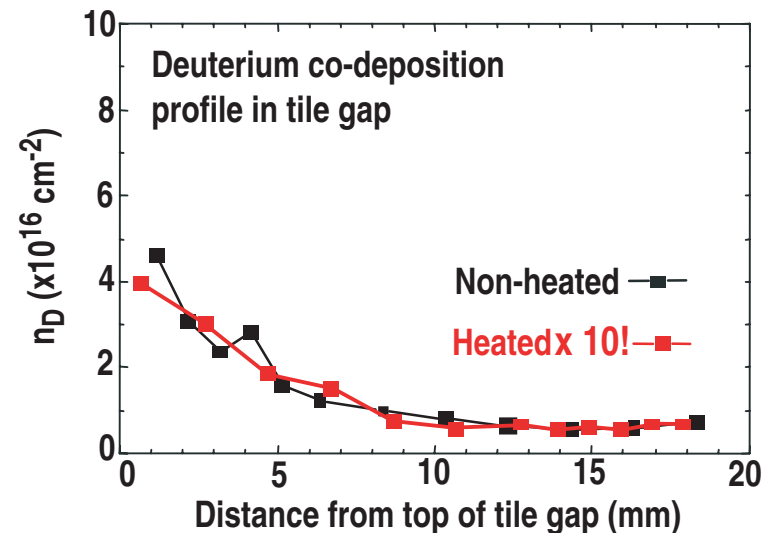


- DiMES experiments show large reduction in C and D deposition on heated materials

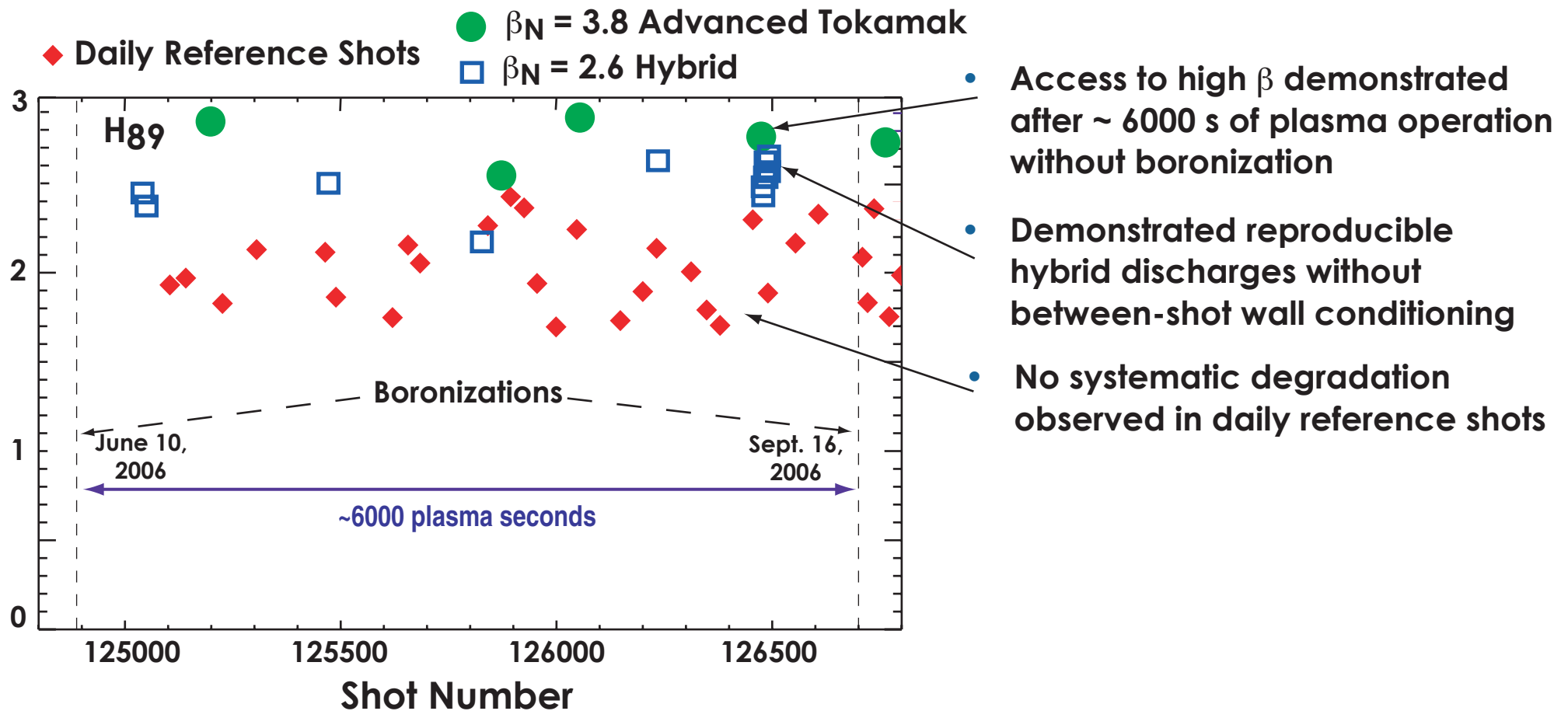
Non-Heated Mirror



Heated Mirror



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



- 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 $\Rightarrow$ **Sustained $\beta_N > 3$ operation**
 - ELM suppression via n=3 RMPs $\Rightarrow$ **Longer divertor lifetime**
 - Low RWM rotation threshold $\Rightarrow$ **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
 - Demonstrated $G > G_{\text{ITER}}$ at low rotation
 - Demonstrated compatibility of radiative divertor operation and hybrid performance

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

$\Rightarrow$ **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 Alfvén 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.

The Success of DIII-D Is Made Possible by the Hard Work of Many Scientists, Engineers, and Technicians

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