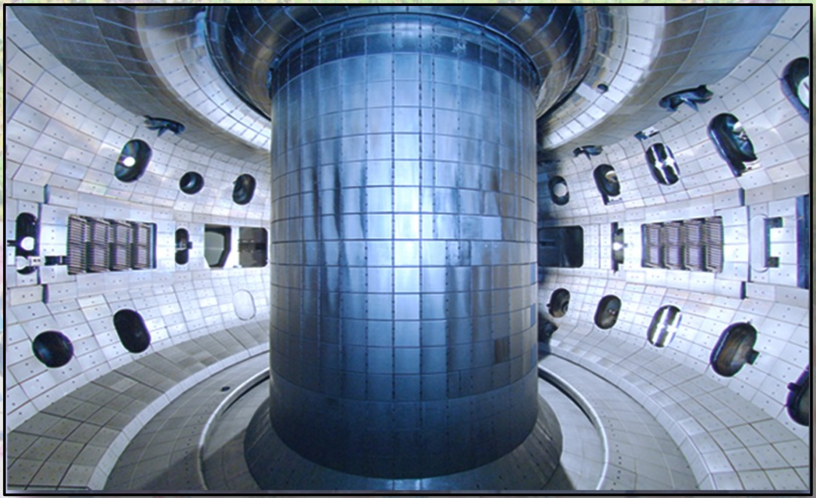
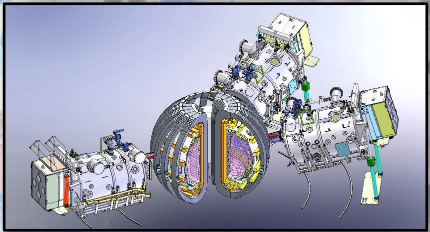
DIII-D Research Advancing the Scientific Basis for Burning Plasmas and Fusion Energy

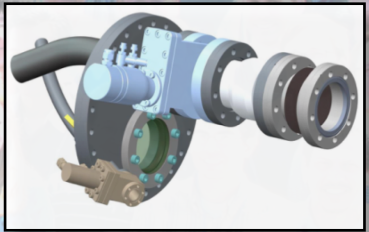
by

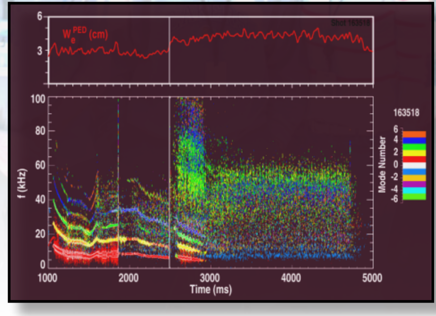
W.M. Solomon

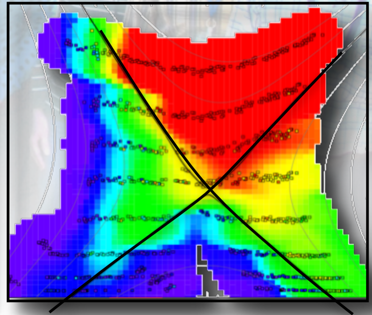
for the DIII-D Team











Presented at the

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Kyoto, Japan

October 17-22, 2016

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

072-1/WMS/rs

DIII-D Advances Fusion Energy Development By Focusing on Four Research Elements

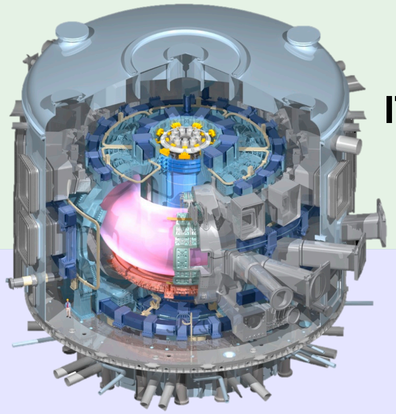
DIII-D Research Elements

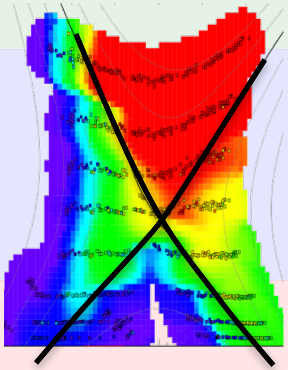
Control Transient Behavior

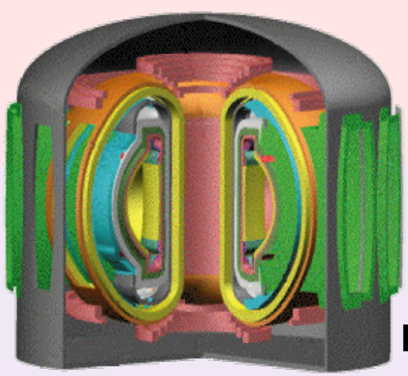
Develop Relevant Boundary Solutions

Strengthen the Basis of Fusion Science

Determine Path to Steady-State





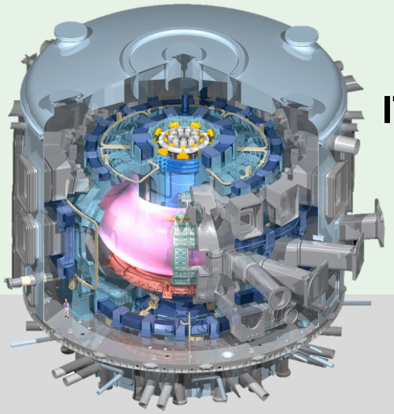


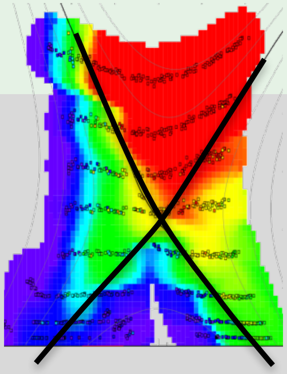
DIII-D Advances Fusion Energy Development By Focusing on Four Research Elements

DIII-D Research Elements

Control Transient Behavior

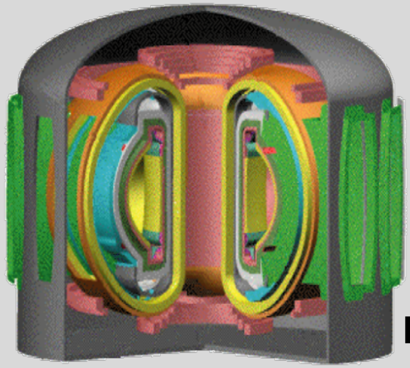
- Disruption mitigation
- Low torque stability
- ELM control





Develop Relevant Boundary Solutions

Strengthen the Basis of Fusion Science

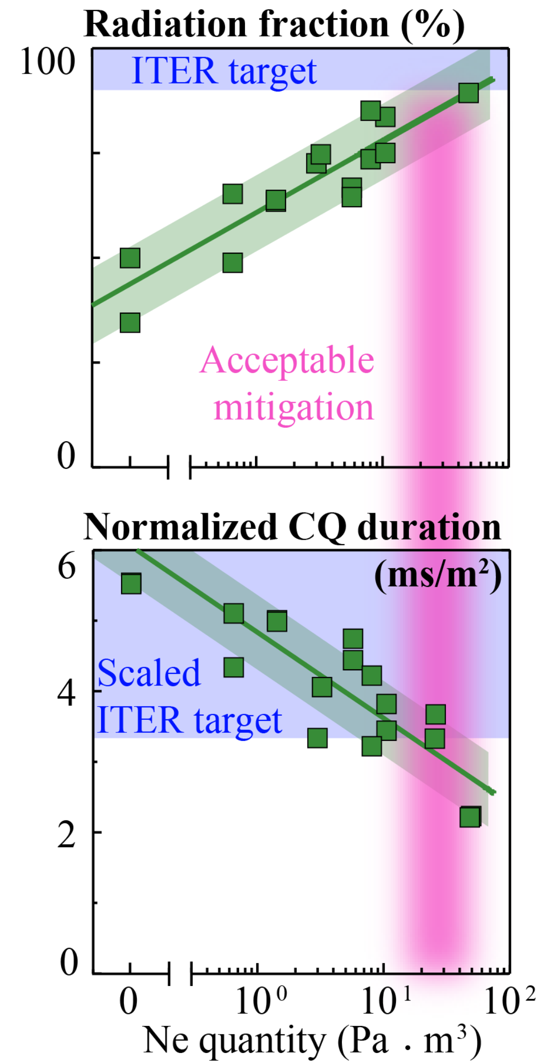


Determine Path to Steady-State

DIII-D Is Uniquely Equipped with Primary Disruption Mitigator for ITER: Shattered Pellet Injection (SPI)

- **Large cryogenic pellet shattered in guide tube provides pulse of tiny solid shards**
- **Varying deuterium / neon mix provides control of disruption characteristics**
- **Achieved first demonstration of runaway electron plateau dissipation with SPI**

Increases confidence that SPI will be an effective disruption mitigation tool for ITER



Shiraki – EX/P3-20
Commaux – EX/9-2

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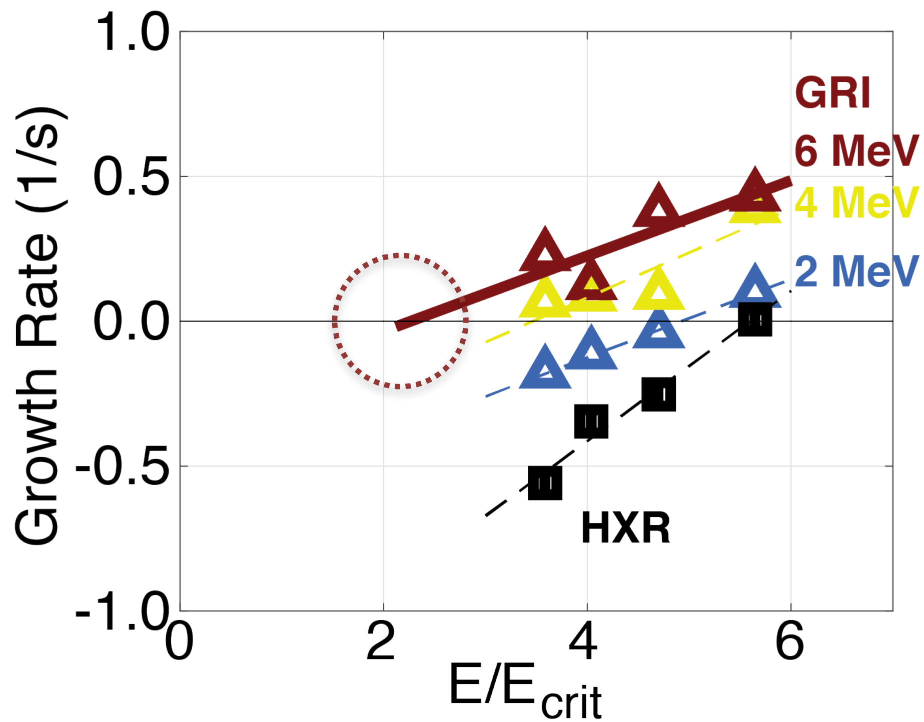
Gamma Ray Spectroscopy Reveals Growth of High Energy Runaway Electrons (REs) Matches Theory

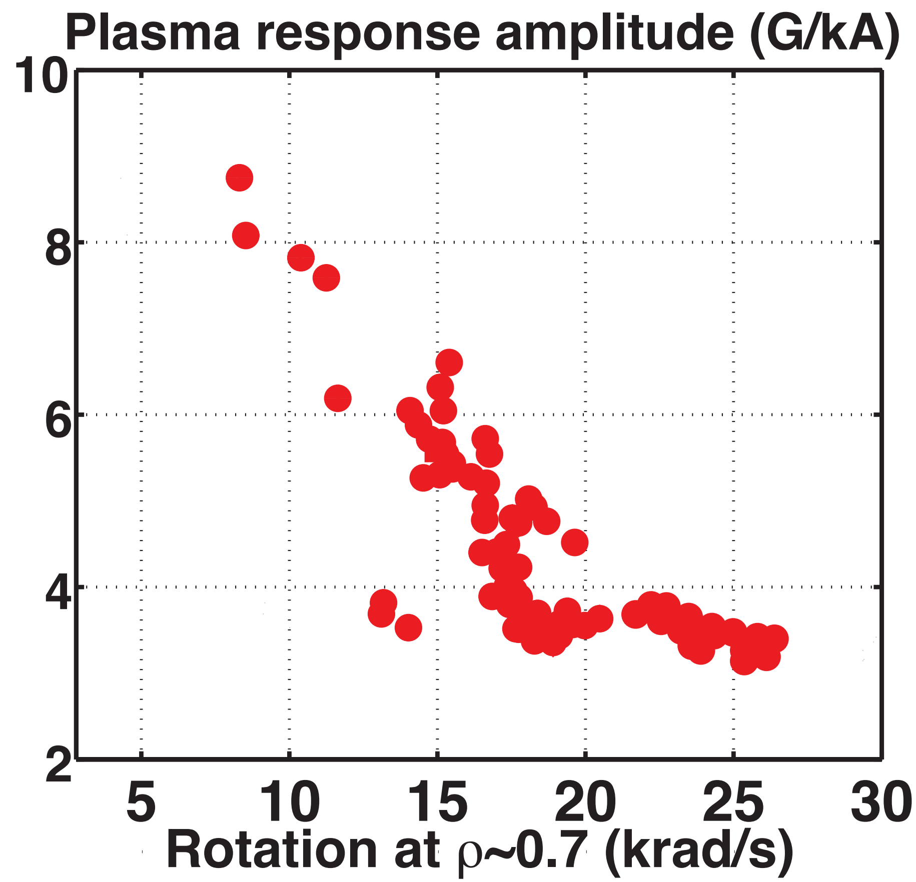
- **High energy REs grow with electric fields E/E_{crit}~2**
  - Theory predicts growth at E/E_{crit}~1.6
- **Lower energy RE growth at higher E/E_{crit}~5**
  - Similar to previous HXR measurements



More destructive high energy REs are more difficult to dissipate → better to prevent initial growth

MHD Spectroscopy Used to Identify the Approach to Instability in Low Torque ITER Baseline

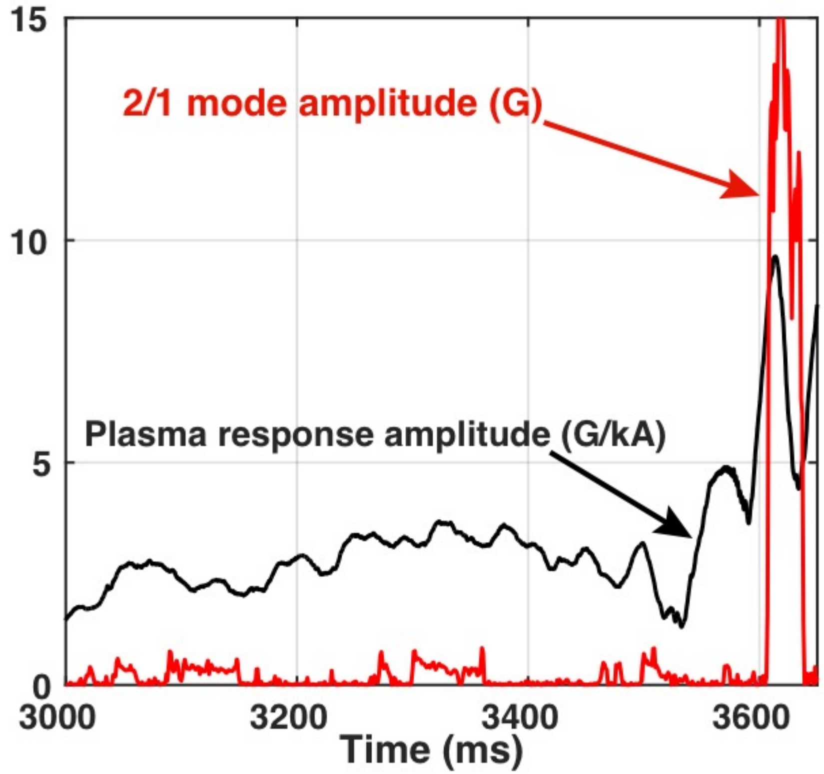
- **ITER baseline typically characterized by 2/1 tearing modes that lock at low torque**
- **Plasma response amplitude increases as rotation is reduced**



Turco – EXP/3-14

MHD Spectroscopy Used to Identify the Approach to Instability in Low Torque ITER Baseline

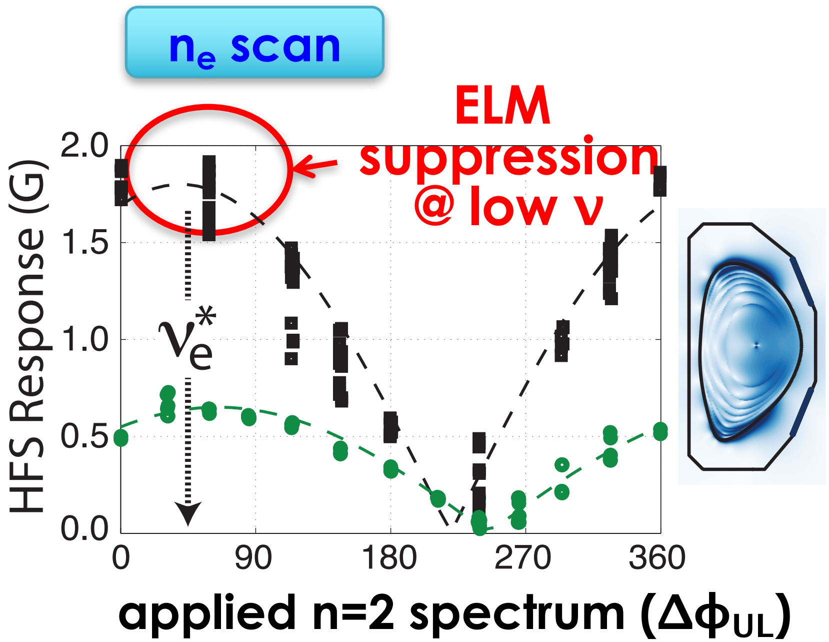
- **ITER baseline typically characterized by 2/1 tearing modes that lock at low torque**
- **Plasma response amplitude increases as rotation is reduced**
- **Onset of 2/1 instability preceded by increase in plasma response**



Potential to use real-time measured change in plasma response as part of disruption warning system

ELM Suppression in ITER Baseline Associated with Low Collisionality Edge Mode on High Field Side (HFS)

- **HFS response measurement strongest at low collisionality**
- **Control of applied mode spectrum important to optimize response for ELM suppression**

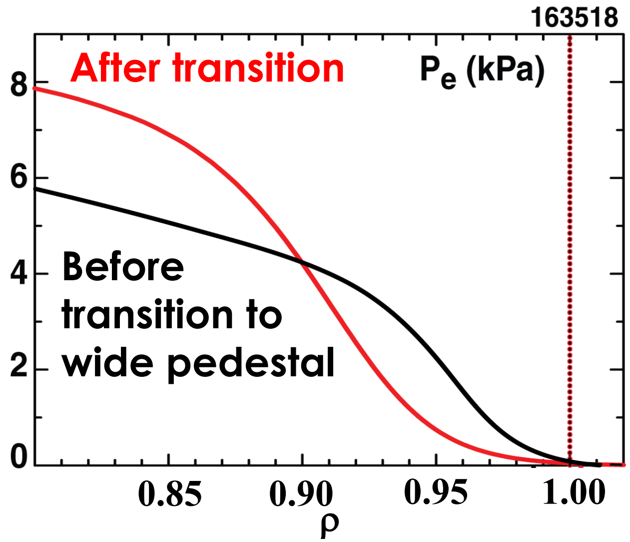


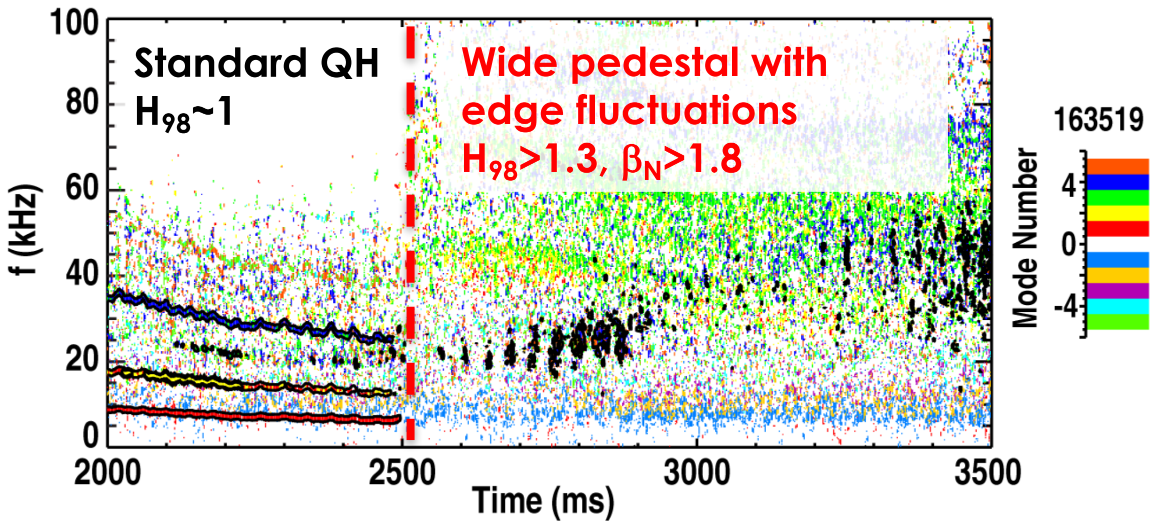
Importance of enhanced response at low collisionality confirmed by ELM suppression on ASDEX-Upgrade → favorable for ITER

Paz-Soldan – EX/1-2
Nazikian - PD

Discovered Stationary Quiescent H-mode Plasmas with Zero Net NBI Torque and High Energy Confinement

- New state with increased pedestal height, width and confinement
- Bifurcation to new regime triggered using torque ramp down
- Associated with changes in ExB shear and increased edge fluctuations





Exciting potential solution to high performance low torque ELM control

Chen – EX/3-2

DIII-D Advances Fusion Energy Development By Focusing on Four Research Elements

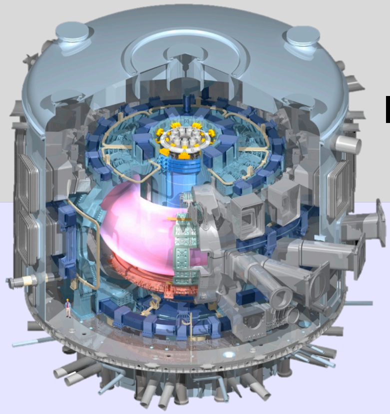
DIII-D Research Elements

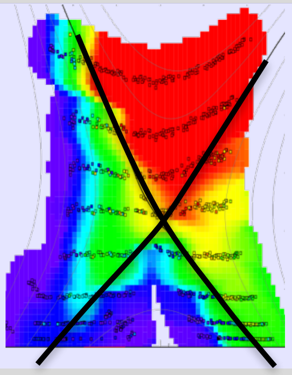
Control Transient Behavior

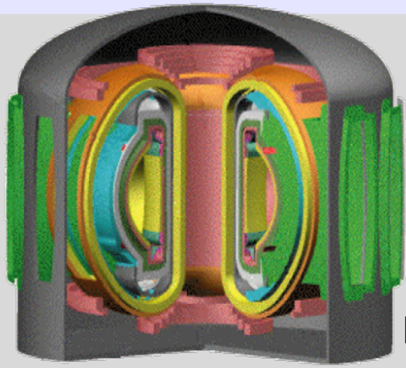
Develop Relevant Boundary Solutions
- Divertor drifts
- Radiation shortfall
- 3D divertor heat fluxes

Strengthen the Basis of Fusion Science

Determine Path to Steady-State



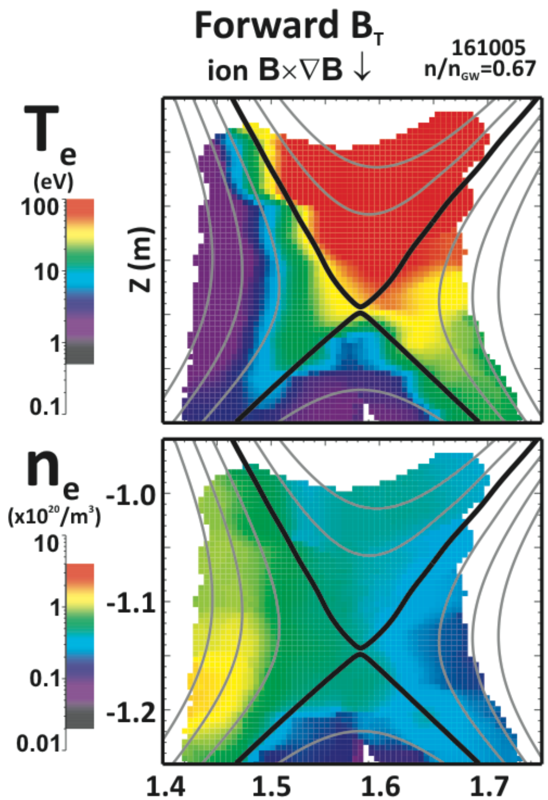




Drifts Affect Divertor Asymmetries and Detachment Threshold

- **Inner divertor exhibits higher n_e and lower T_e for normal B_T direction**

2D Divertor Thomson Scattering (DTS)



McLean – EX/2-1

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Drifts Affect Divertor Asymmetries and Detachment Threshold

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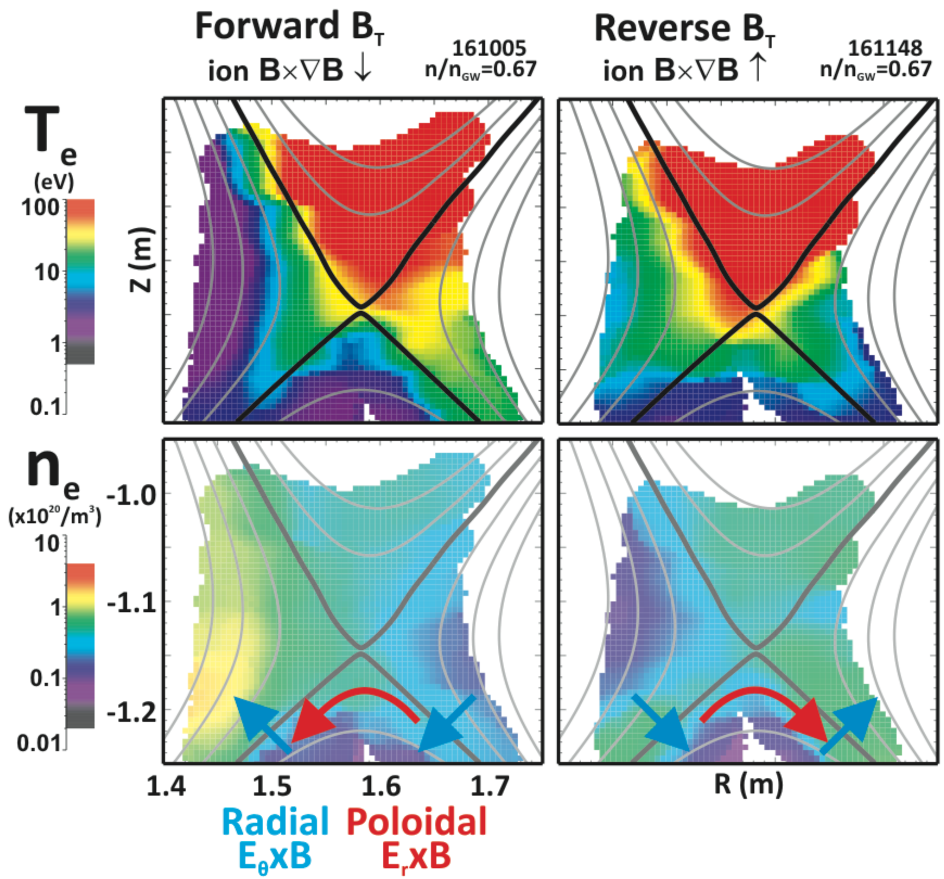
  - Reversing B_T mitigates in-out asymmetry

2D Divertor Thomson Scattering (DTS)



McLean – EX/2-1

Drifts Affect Divertor Asymmetries and Detachment Threshold

- **Inner divertor exhibits higher n_e and lower T_e for normal B_T direction**
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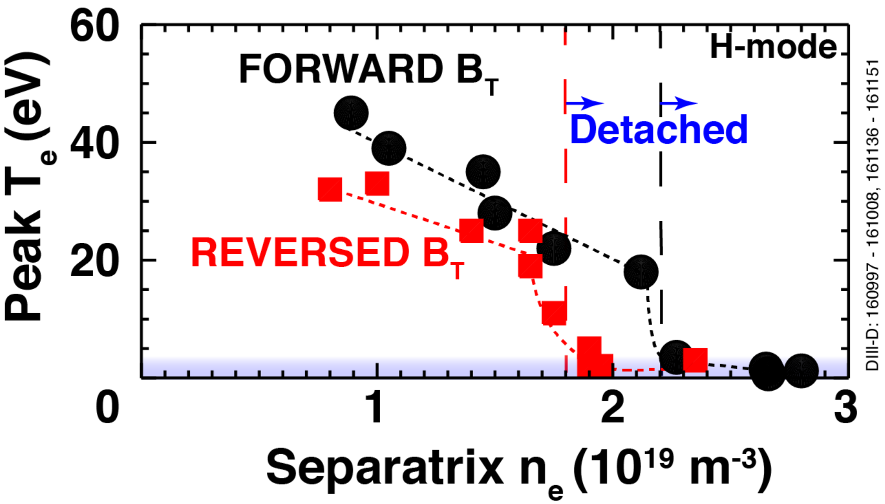
- **Reverse B_T lowers density for detachment in H-mode**

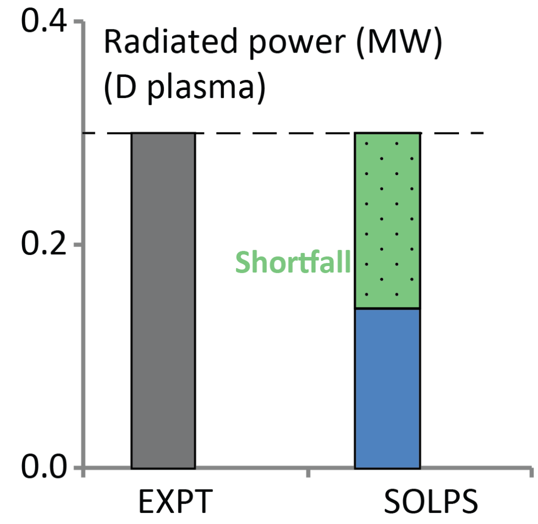


- **Effects understood due to interplay between radial and poloidal ExB drifts**
  - Reproduced qualitatively in UEDGE simulations with full cross-field drifts

Future divertor designs can be better optimized by accounting for asymmetries due to drifts

Radiation "Shortfall" Caused by Under-Prediction of the Divertor Density and Uncertain Atomic Physics

- **SOLPS and UEDGE modeling of D+C plasmas show significant "shortfall" in radiated power**



McLean – EX/2-1

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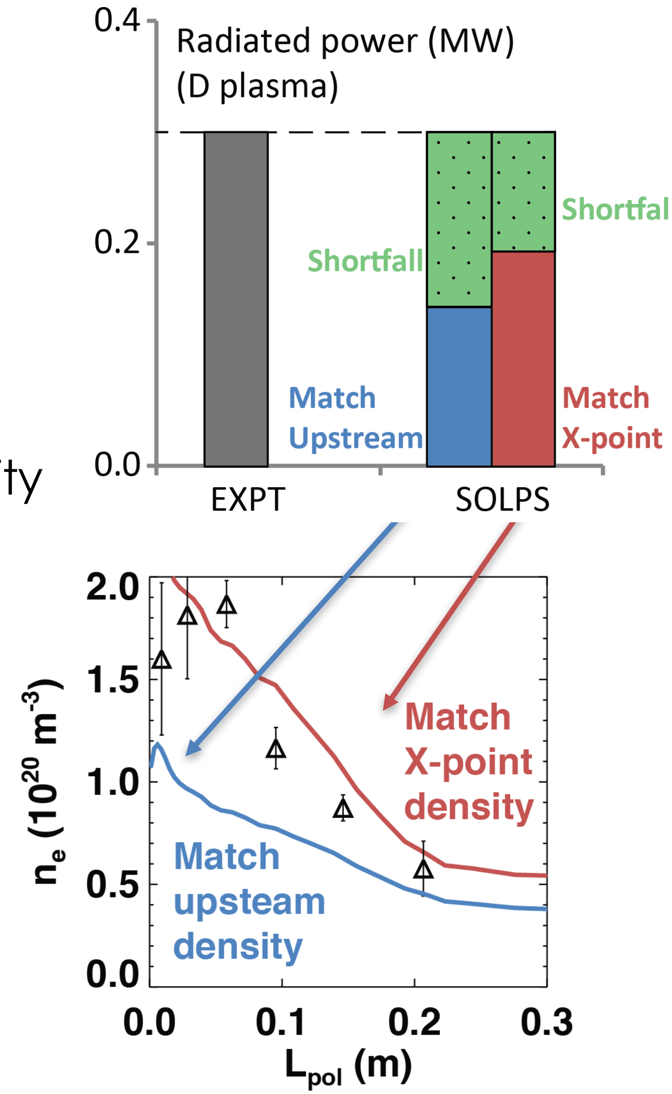
- **Shortfall can be reduced by matching the X-point density measured by DTS**
  - Usual approach matches upstream density

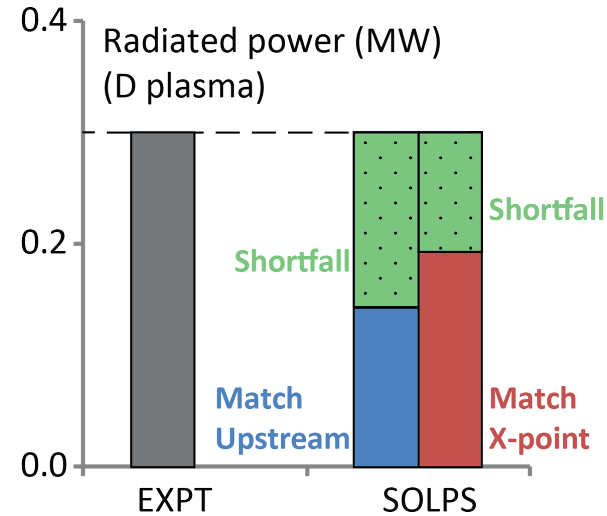


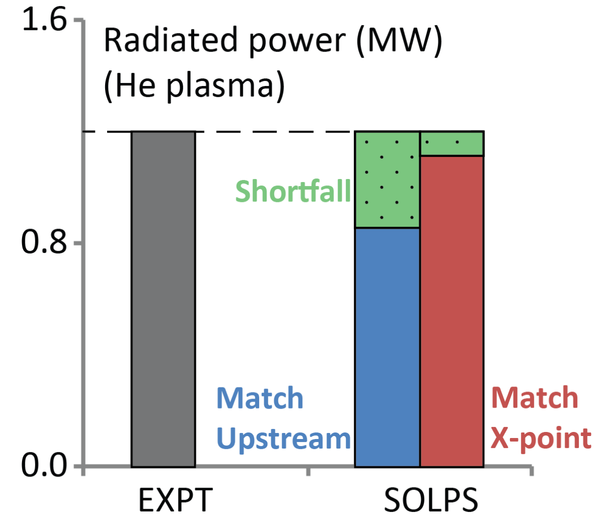
McLean – EX/2-1

Radiation "Shortfall" Caused by Under-Prediction of the Divertor Density and Uncertain Atomic Physics

- **SOLPS and UEDGE modeling of D+C plasmas show significant "shortfall" in radiated power**
- **Shortfall can be reduced by matching the X-point density measured by DTS**
  - Usual approach matches upstream density
- **Shortfall eliminated in helium plasmas**
  - No uncertainties in hydrocarbon reactions

Highlights need to improve D atomic and molecular physics and parallel transport model in the divertor



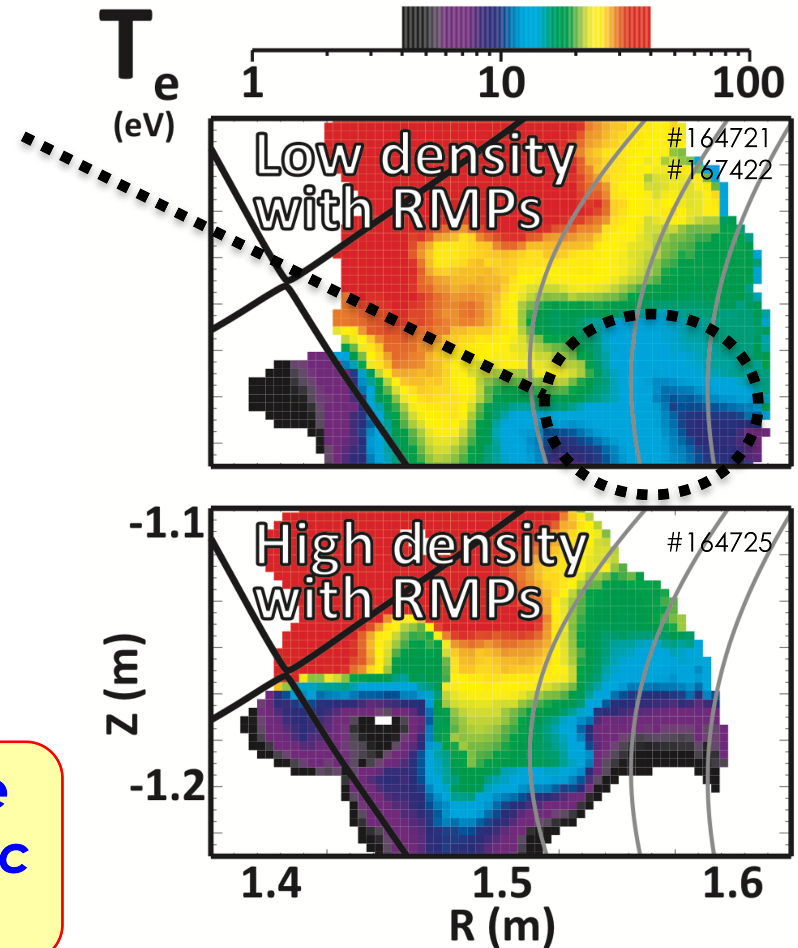


McLean – EX/2-1

Spatial Extent of Divertor Electron Temperature Lobes Due to RMP Are Reduced at High Density

- **At moderate density, lobes in T_e extend to the divertor plates, heat flux profile also shows 3D structure**

- **At higher core densities these lobes shrink and move away from target**
  - Before partial detachment and continuing through to detachment
  - May be sensitive to poloidal spectrum and plasma response

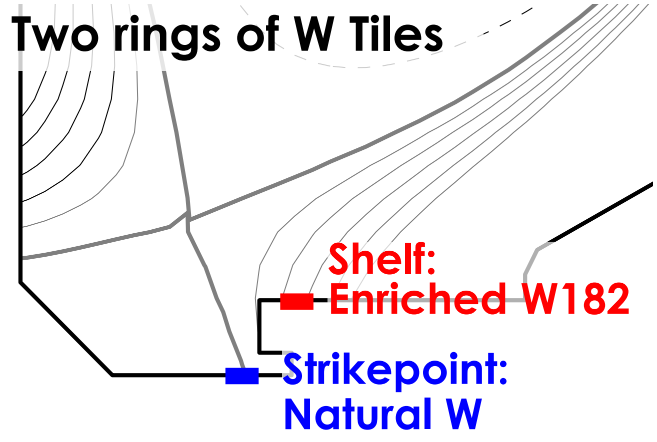


Partial detachment of divertor may be sufficient to eliminate non-axisymmetric heat flux striations in ITER

Briesemeister – EX/7-3Rb
Lore - TH/P6-12

Experiments with Tungsten Rings Reveals Metal Influx Is Predominantly from Strike Point Location

- Different W isotopes isolate strikepoint from divertor shelf

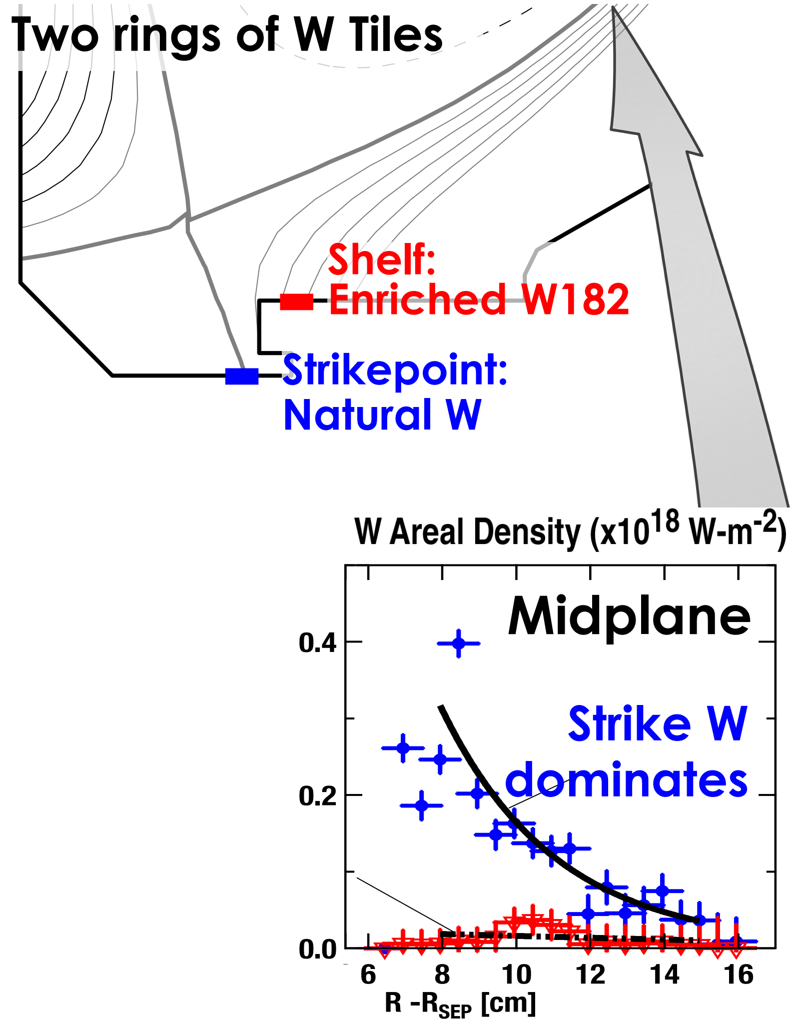


Unterberg - PD
Ding – MPT/1-2RB

Experiments with Tungsten Rings Reveals Metal Influx Is Predominantly from Strike Point Location

- Different W isotopes isolate strikepoint from divertor shelf
- Little contribution of W182 from shelf tile in high power H-mode

Suggests control of strikepoint flux is key to limiting core contamination



Unterberg - PD
Ding – MPT/1-2RB

DIII-D Advances Fusion Energy Development By Focusing on Four Research Elements

DIII-D Research Elements

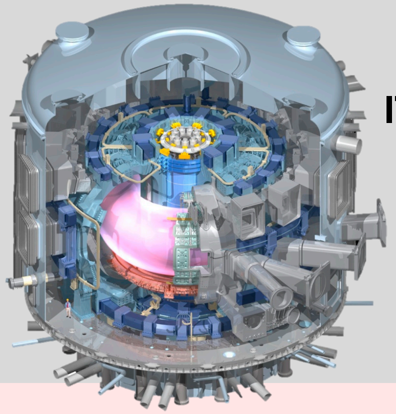
Control Transient Behavior

Develop Relevant Boundary Solutions

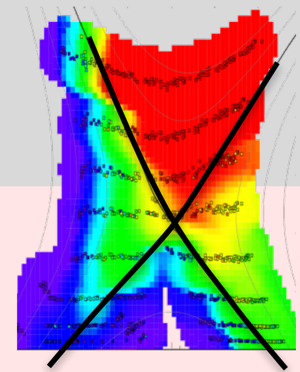
Strengthen the Basis of Fusion Science

- Intrinsic rotation drive
- Particle transport
- Stiffness
- LH physics

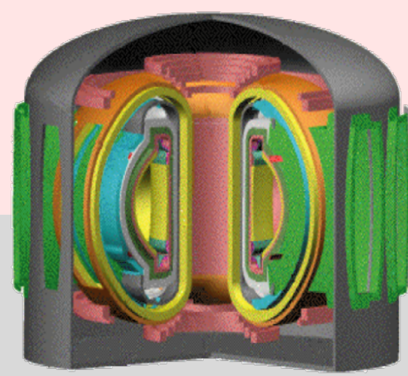
Determine Path to Steady-State



ITER



Plasma Exhaust



DEMO

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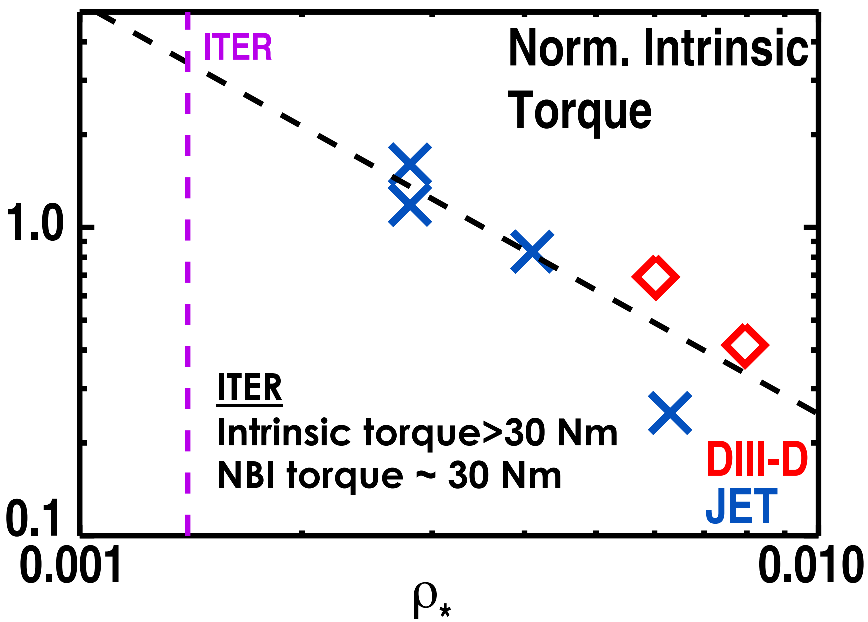
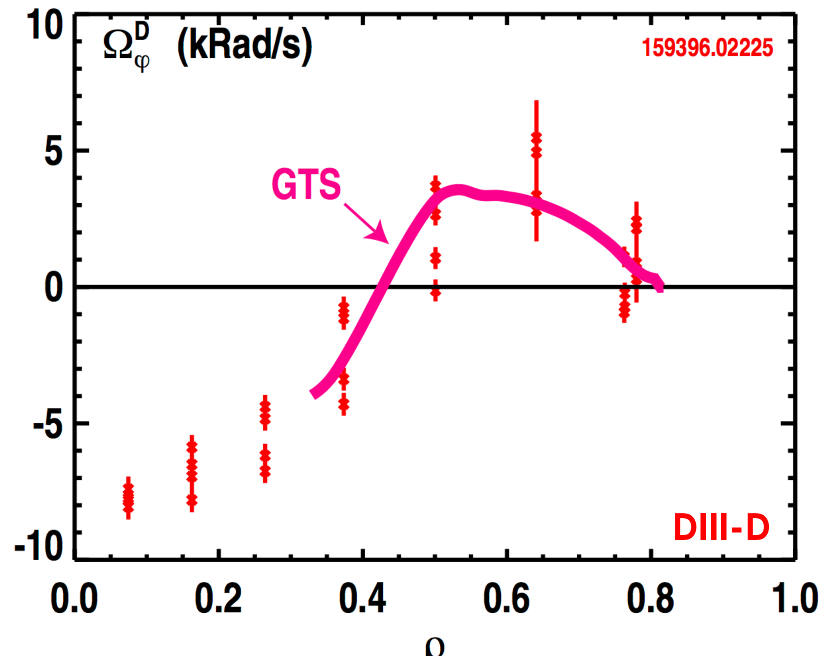
ρ* Scaling of Intrinsic Drive Projects to a Torque Comparable to that from Neutral Beams on ITER

- **Experimental scaling determined in joint study with JET**
  - Favorable scaling still leads to relatively low level of rotation



- **Simulations with GTS gyro-kinetic code reproduces reversal of core intrinsic rotation**

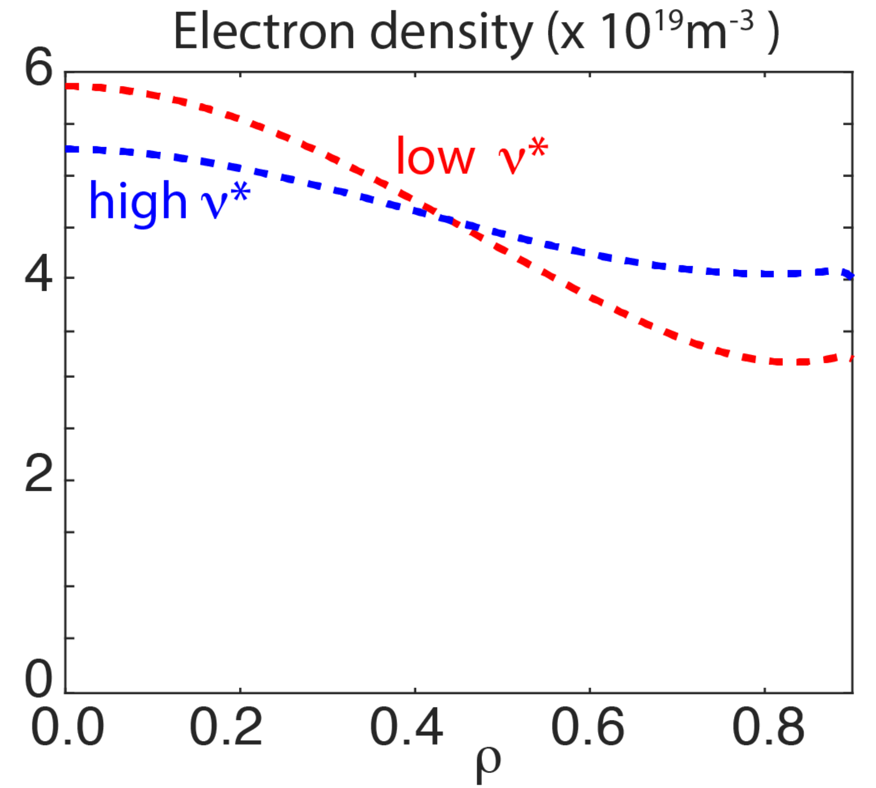


Grierson – EX/11-1
Wang - TH-C/P3-12
deGrassie – EX/P3-13

Although intrinsic rotation projected to be low, profile effects may still lead to improved performance

Increase in Density Profile Peaking at Low Collisionality Appears Due to Changes in Beam Fueling

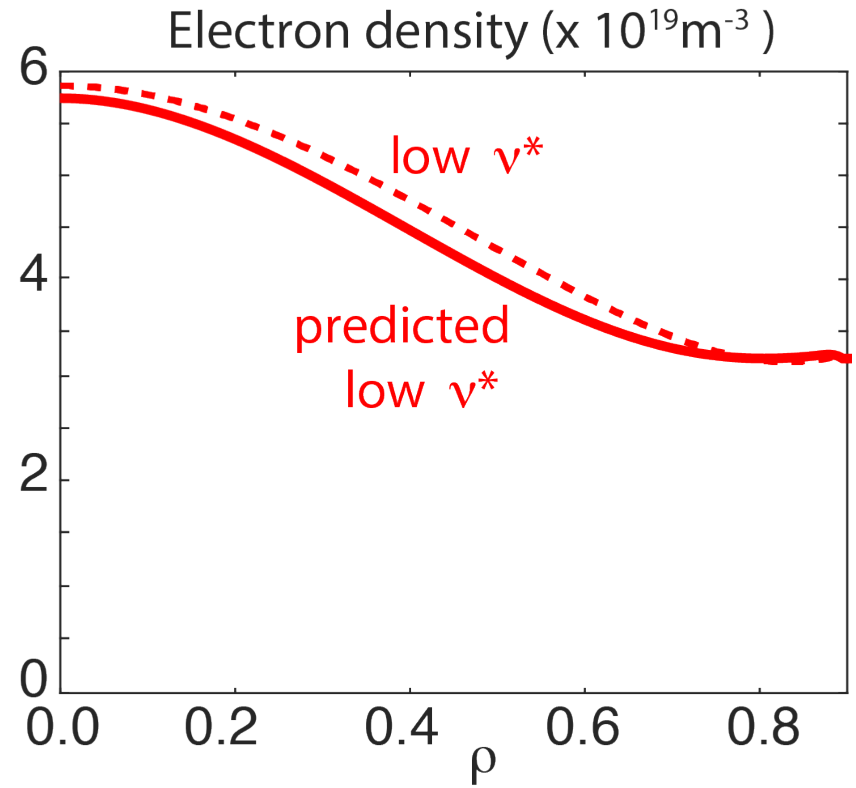
- **Increase density peaking observed in dimensionless collisionality scaling experiment**



Mordijck – EX/P3-9

Increase in Density Profile Peaking at Low Collisionality Appears Due to Changes in Beam Fueling

- **Increase density peaking observed in dimensionless collisionality scaling experiment**
- **Change in peaking is reproduced by changes in core fueling only**
  - Assuming no change in normalized transport from high collisionality case

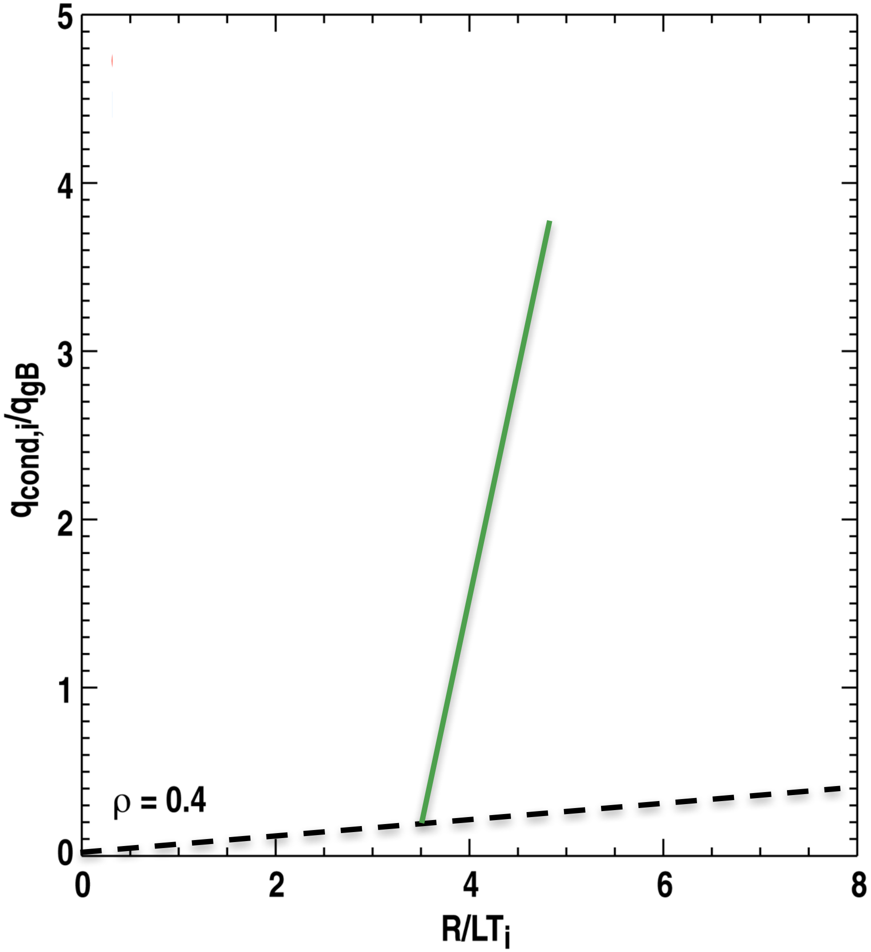


Database scalings may be too optimistic for density peaking in ITER

Mordijck – EX/P3-9

Ion Stiffness Does Not Clamp Ion Temperature Gradient in Power Scans

- **Stiffness paradigm is large incremental transport above critical gradient**



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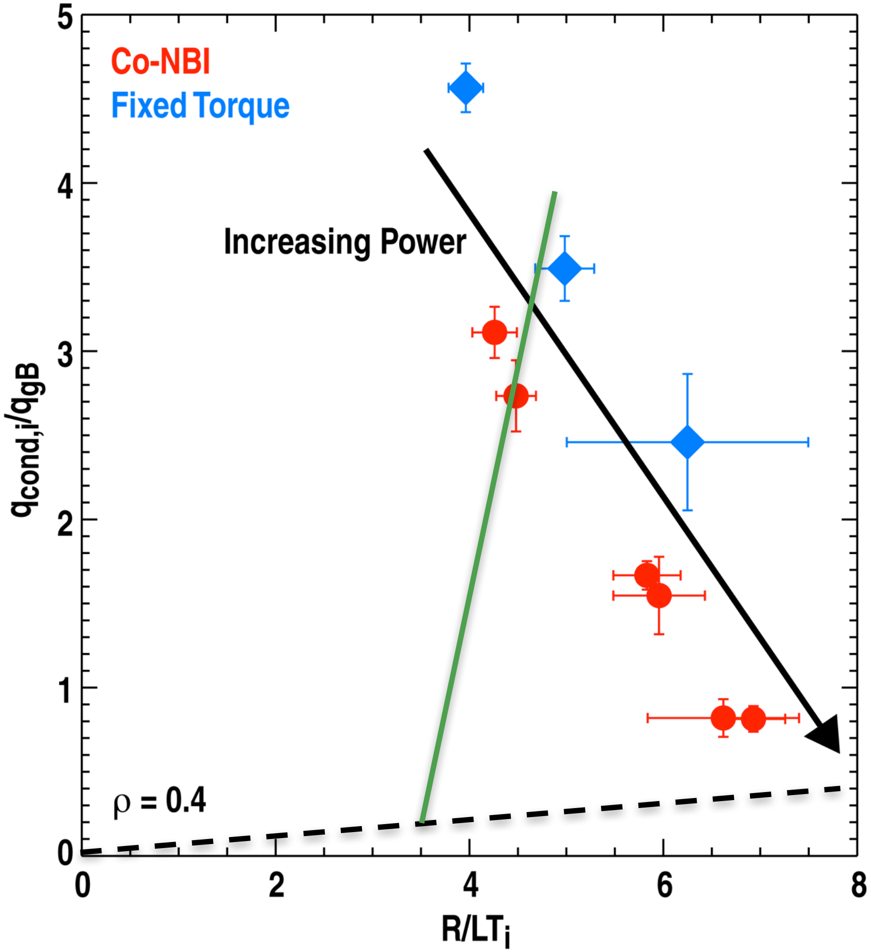
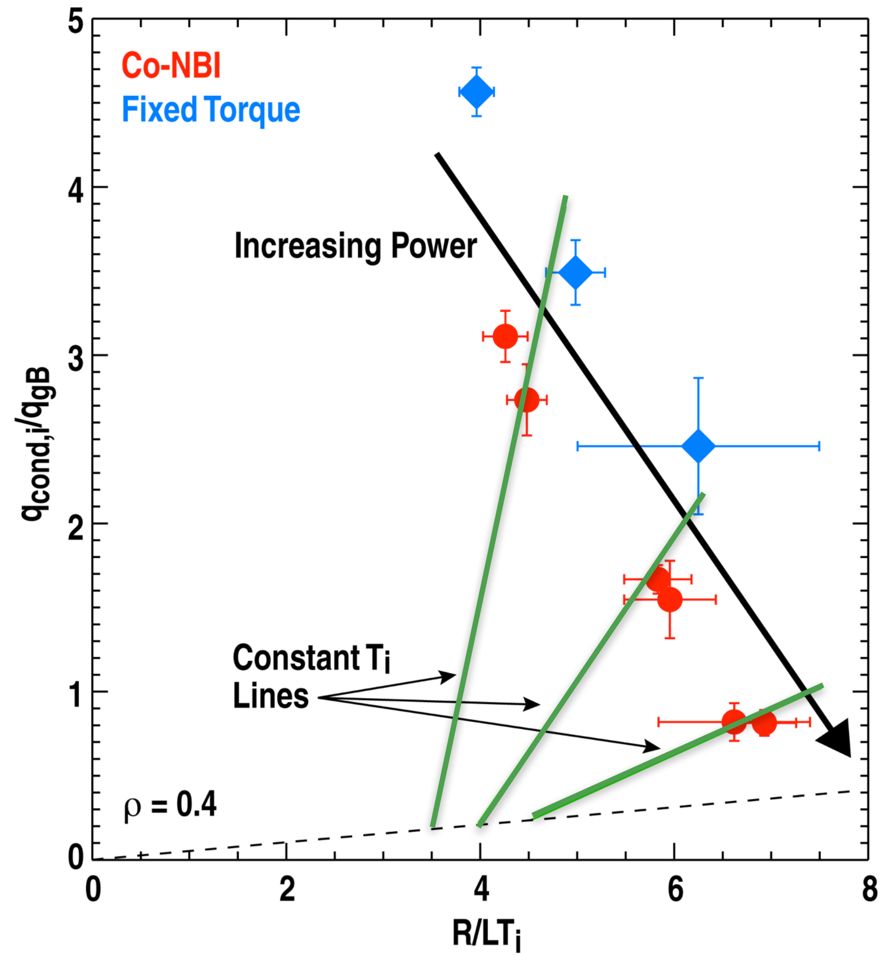
- **Stiffness paradigm is large incremental transport above critical gradient**
- **Ion thermal diffusivity drops with increasing power**



Ion Stiffness Does Not Clamp Ion Temperature Gradient in Power Scans

- **Stiffness paradigm is large incremental transport above critical gradient**
- **Ion thermal diffusivity drops with increasing power**
- **Stiffness not observed because temperature is not kept constant**

Suggests fusion gain will increase with heating more than stiffness would imply



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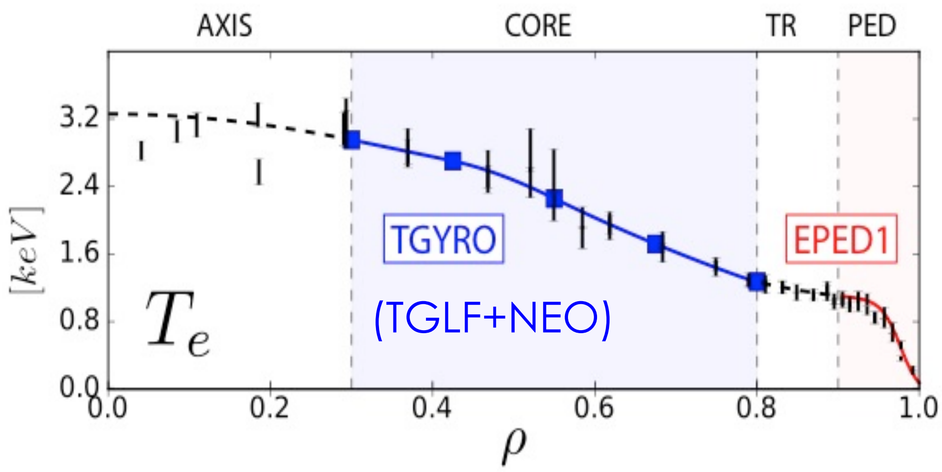
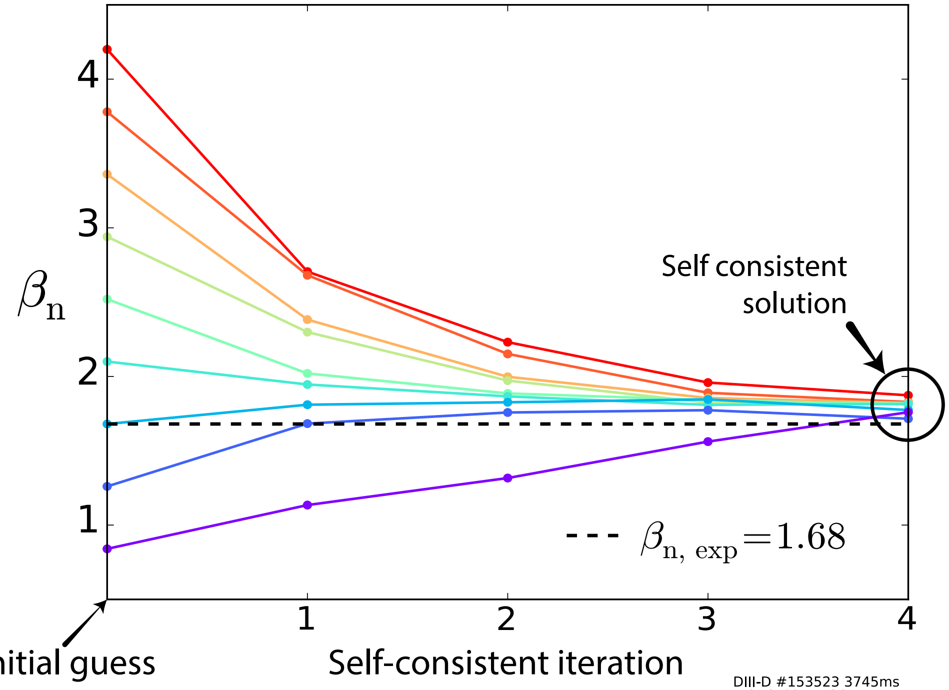
Theory-Experiment Validation Has Increased Confidence in ITER Achieving its Q=10 mission

- **Self-consistent coupling of core & pedestal theoretical models**
  - No free or fit parameters
- **Whole profile iteration converges to unique solution**
  - Predicts β_N to ~15% in 200 DIII-D cases
- **Enables prediction and optimization of ITER fusion gain: Q~12 possible**

New frontier: Multi-scale turbulence simulations and TGLF improvement

Meneghini – TH/9-1
Holland– TH/6-1
Staebler – TH/P2-8





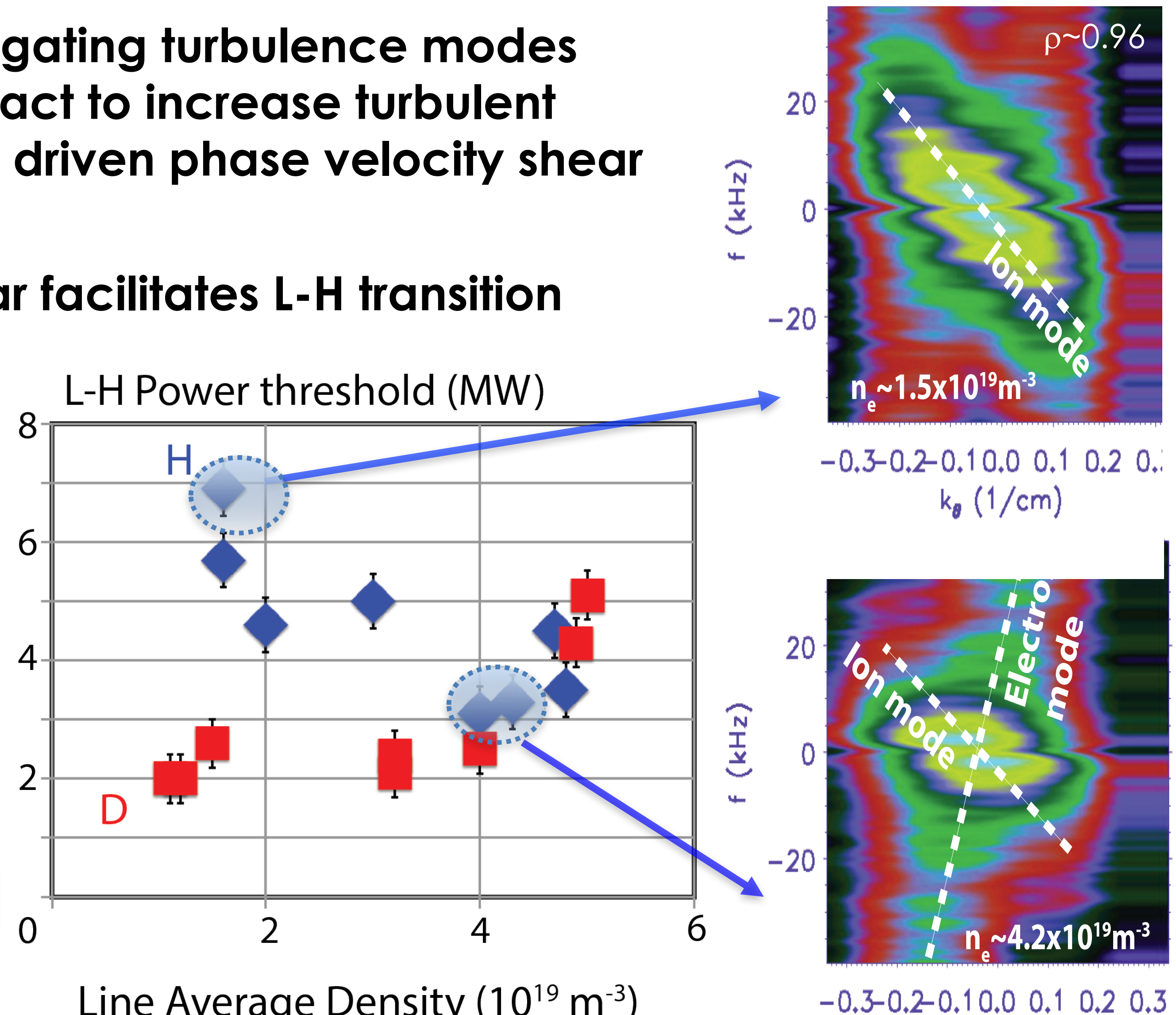
DIII-D #153523 3745ms
072-1/WMS/rs

Dual Mode Nature of Edge Turbulence May Explain Isotope and Density Scaling of L-H Power Threshold

- **Counter-propagating turbulence modes appear to interact to increase turbulent Reynolds stress driven phase velocity shear**
- **Increased shear facilitates L-H transition**

Minimum in LH power threshold correlated with dual modes

Yan – EX/5-1
Schmitz – EX/P3-11



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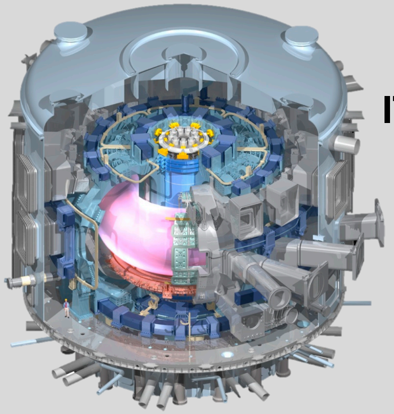
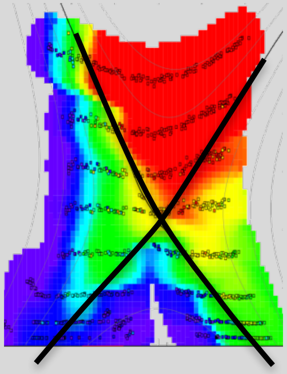
Control Transient Behavior

Develop Relevant Boundary Solutions

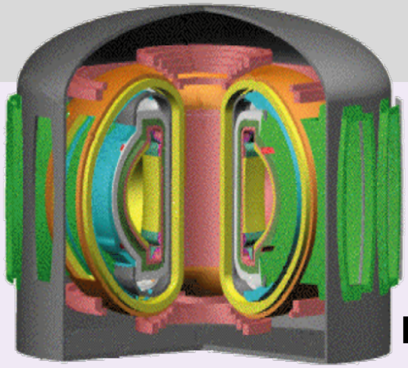
Strengthen the Basis of Fusion Science





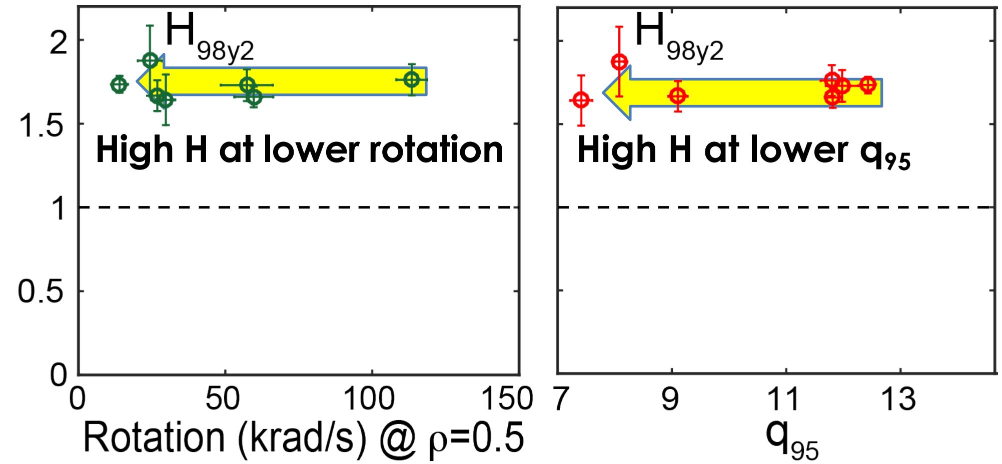
Determine Path to Steady-State

- Shafranov shift stabilization
- Fast ion transport
- Core-edge integration

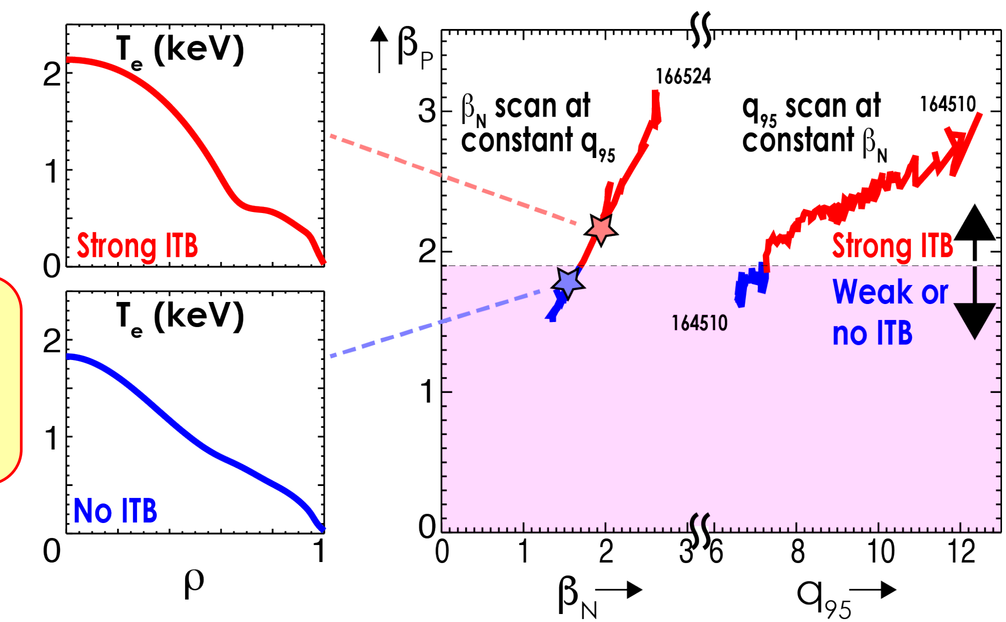


Excellent Confinement in High β_P Scenario Is Due to Shafranov Shift Stabilization

- **Large radius ITB and excellent confinement maintained at reduced rotation or q_{95}**



- **ITB lost when Shafranov shift ($\propto\beta_P$) gets too low**



Projects to ITER Q=5 at q_{95}~6 if high confinement maintained with high q_0 (NCS)

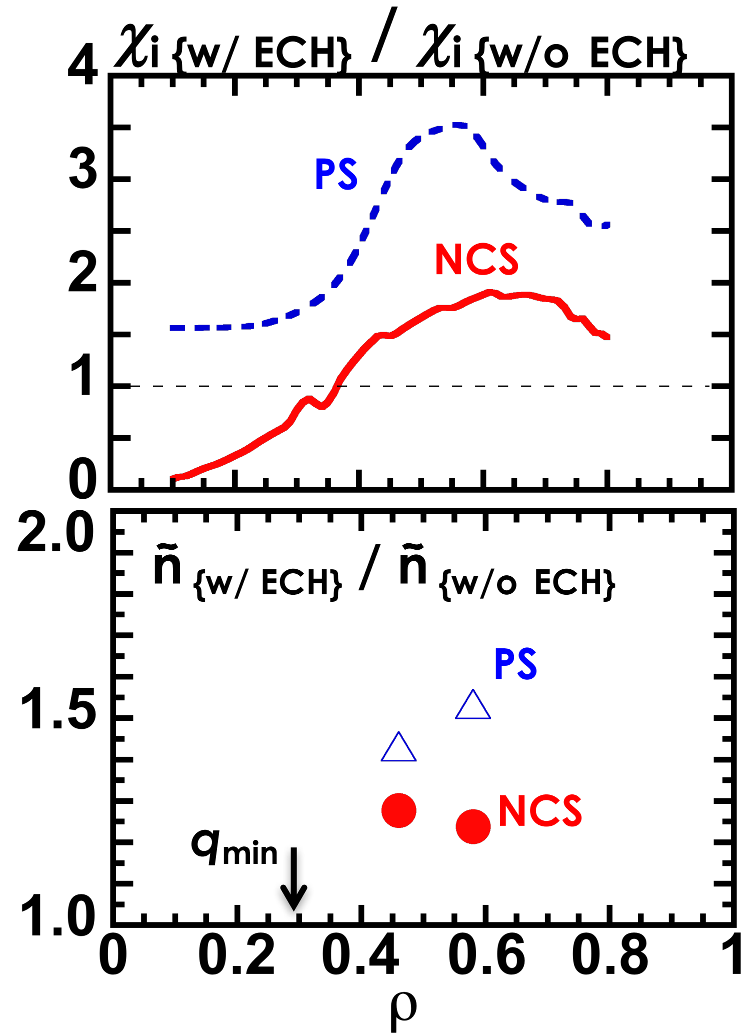
Qian – EX/4-2

Incorporating Negative Central Shear Mitigates Confinement Degradation with Increasing T_e/T_i

- **Plasmas with standard positive shear (PS) show reduced T_i when ECH power added**
- **Increase in T_e/T_i has less impact on fluctuation levels with negative central shear (NCS)**

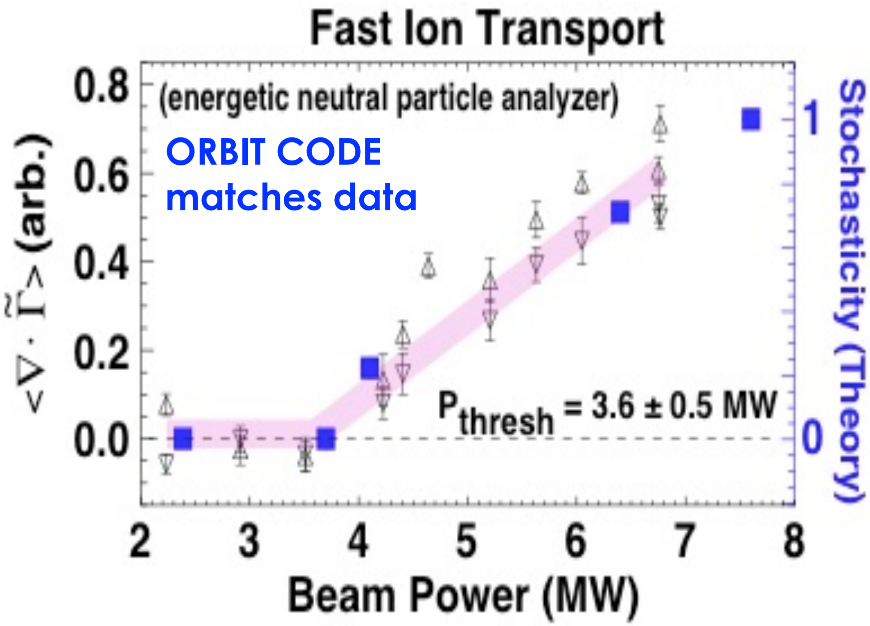
Advanced scenarios can maintain performance in burning plasma relevant conditions

Increase T_e/T_i with ECH



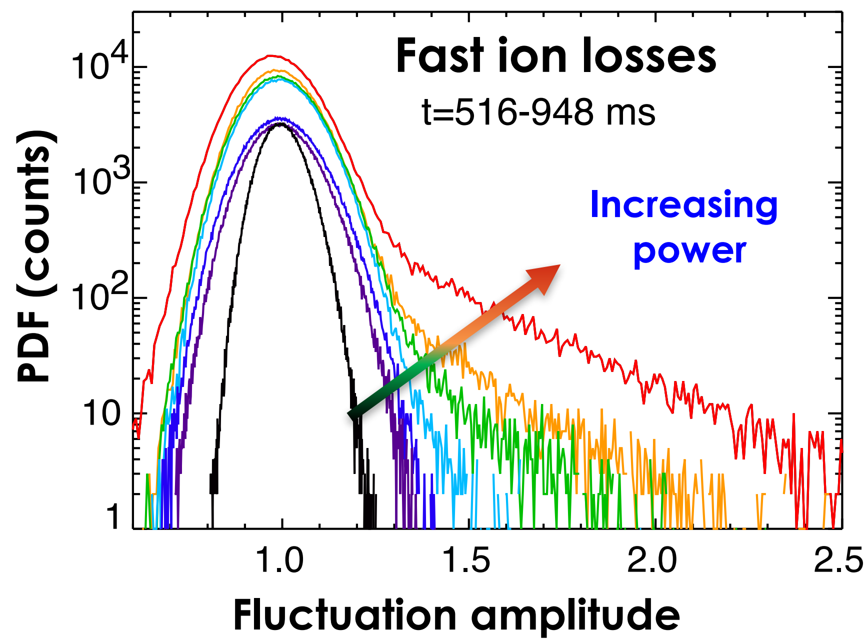
Yoshida – EX/8-1

Fast Ion Transport Exhibits a Critical-Gradient Like Behavior Driven by Overlap of Multiple Unstable Modes



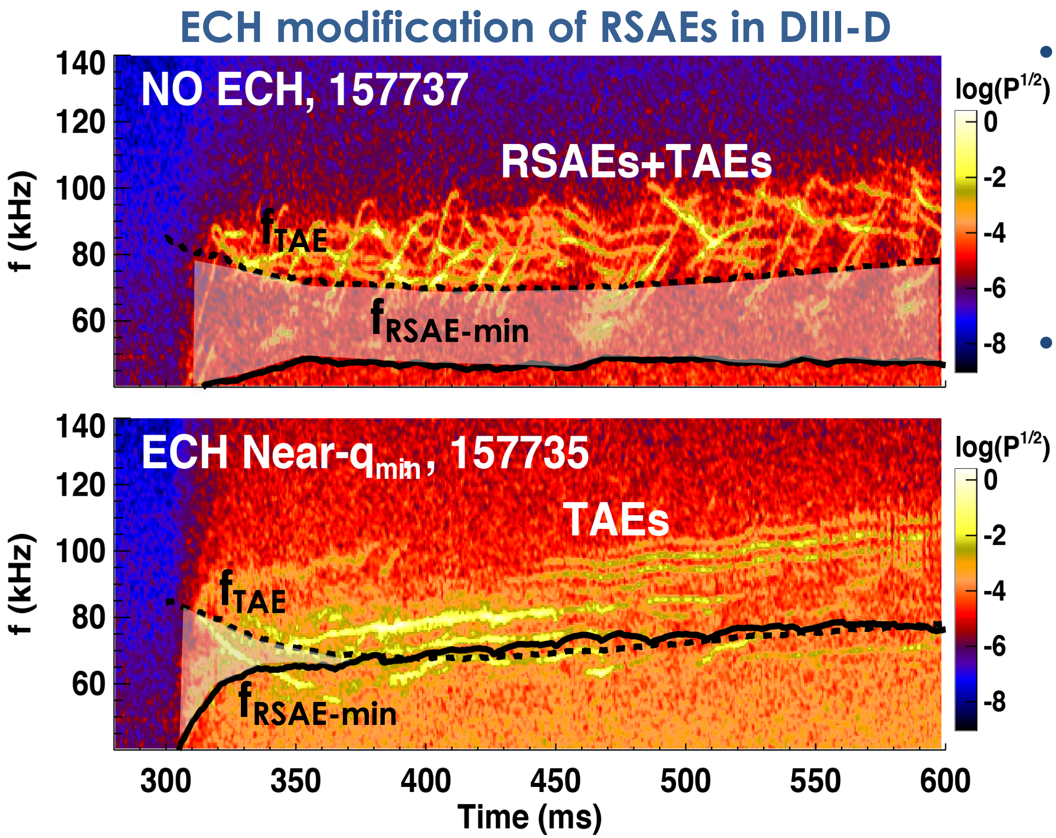
- **Rapid increase in fast ion flux above threshold in beam power**

- **Intermittent bursts of losses observed above threshold**



Collins – EX/6-2

Large Impact of ECH on Alfvén Eigenmode (AE) Activity in DIII-D Plasmas Explained by Finite Temperature Effects



- **ECH drastically alters AE activity**
  - Reverse Shear AE (RSAEs) particularly sensitive
- **RSAEs exist between a minimum frequency and the TAE frequency**
  - Temperature gradient and elongation modify minimum frequency

$$f^2_{\text{RSAE-min}} = (f^2_{\text{GAM}} + f^2_{\nabla})$$

$$f^2_{\text{GAM}} \propto T_e \qquad f^2_{\nabla} \propto \nabla T_e$$

- **Including these effects correctly predicts existence and evolution of RSAEs**

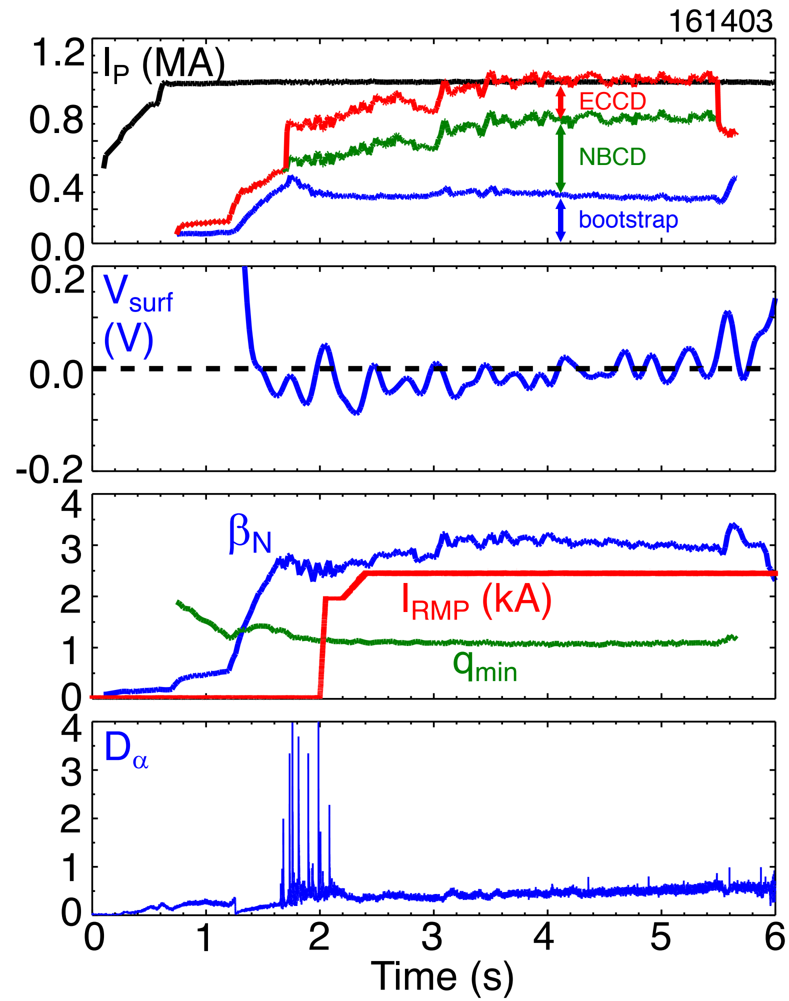
Suggests tailoring of temperature profile can control RSAE-driven transport

Van Zeeland – EX/P3-24

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

ELM Suppression Achieved in ≈1 MA Fully Non-Inductive Hybrid with Minimal Impact on Performance

- **High β_N + bootstrap, and coupling to weakly stable edge kink mode gives stronger response than in ITER baseline**
  - Wider q_{95} range (6-7.5) for suppression
  - ~5% reduction in H_{98}
- **Separately, "puff-and-pump" radiative divertor halved peak divertor heat flux**
  - Again little change in confinement (~10%)



ELM control appears more robust in steady-state scenarios

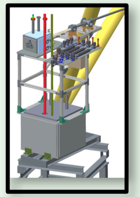
Petty – EX/4-1
Petrie – EX/P3-27

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Future DIII-D Enhancements Provide Flexibility to Continue to Address these Key Issues

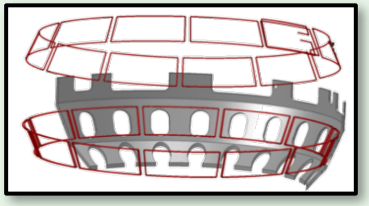
DIII-D Research Elements | **Enabled by DIII-D Enhancements**

Control Transient Behavior



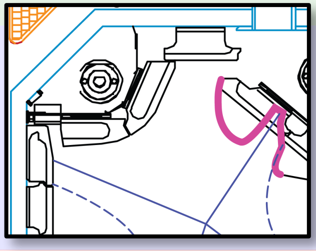
2nd SPI

Improved 3D control



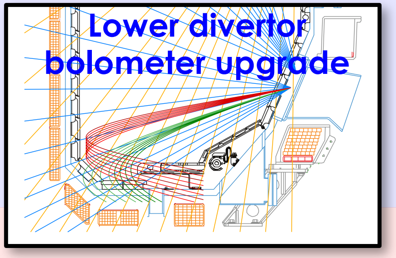
Increased electron Heating/current drive

Develop Relevant Boundary Solutions

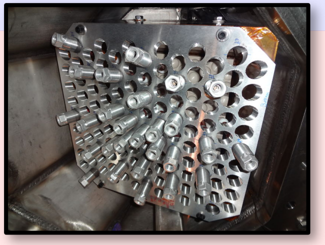


Divertor closure modifications

Lower divertor bolometer upgrade

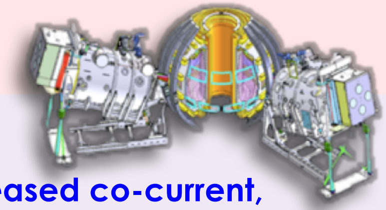


Strengthen the Basis of Fusion Science



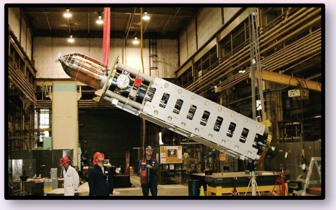
Improved diagnostics

Determine Path to Steady-State



Increased co-current, off-axis current drive

"Helicon" system



DIII-D Has Advanced the Scientific Basis for Fusion Energy: Preparing for ITER and Laying the Foundation for Steady-State

- Increased confidence in our ability to handle and control transients (disruption mitigation, ELM suppression, QH-mode)
- Improved understanding of processes relevant to divertor dynamics (drifts, radiation shortfall)
- Key advances in understanding in momentum, particle and thermal transport
- Extended steady-state scenarios to more reactor relevant regimes (rotation, Te/Ti) and integrated boundary physics solutions (ELM-suppression and radiative divertor)