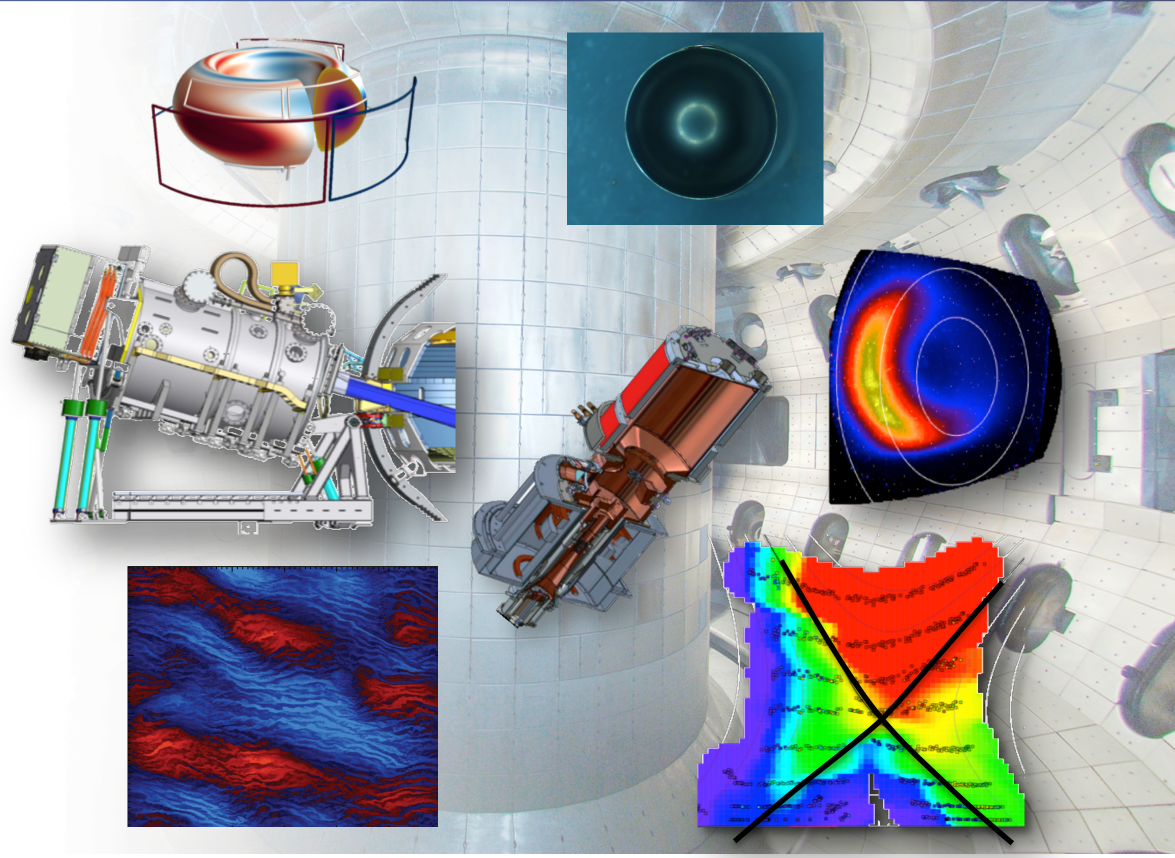
DIII-D Research Towards Establishing the Scientific Basis for Future Fusion Reactors



by

C.C. Petty

for the DIII-D Team

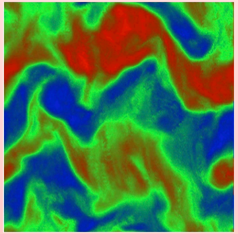
Presented at the

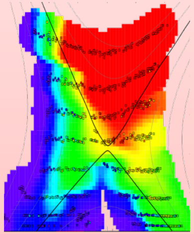
27th IAEA Fusion Energy Conference Ahmedabad, India

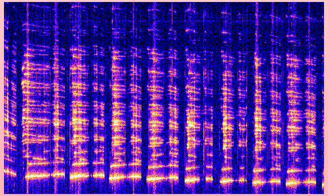
October 22–27, 2018

DIII-D Research Towards Establishing the Scientific Basis for Future Fusion Reactors

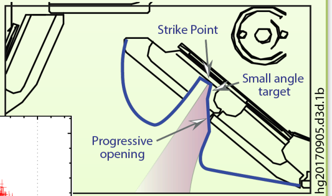
1. Advances in Fusion Energy Science

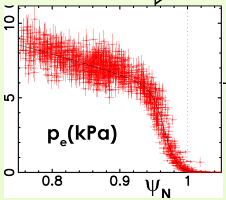


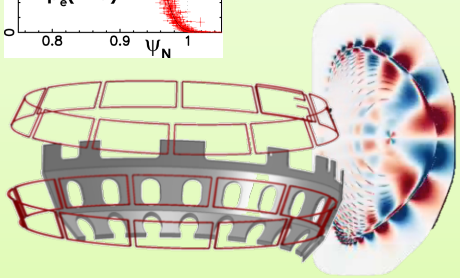




2. Core-Edge Integration







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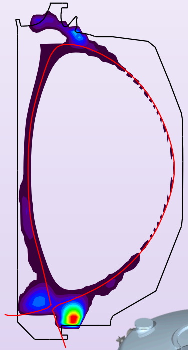

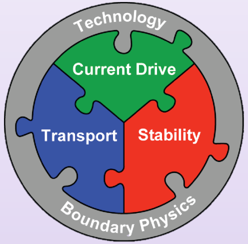

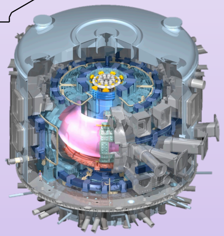

DIII-D NATIONAL FUSION FACILITY

DIII-D Research Towards Establishing the Scientific Basis for Future Fusion Reactors

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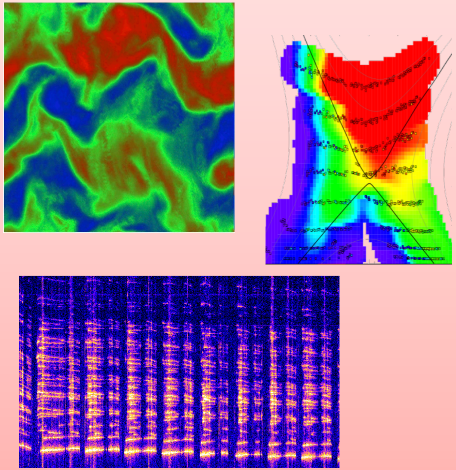

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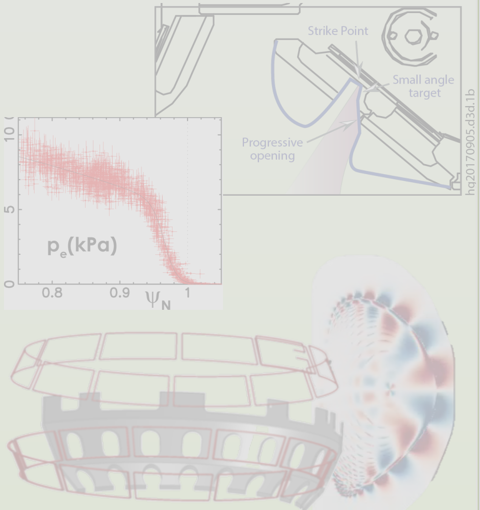

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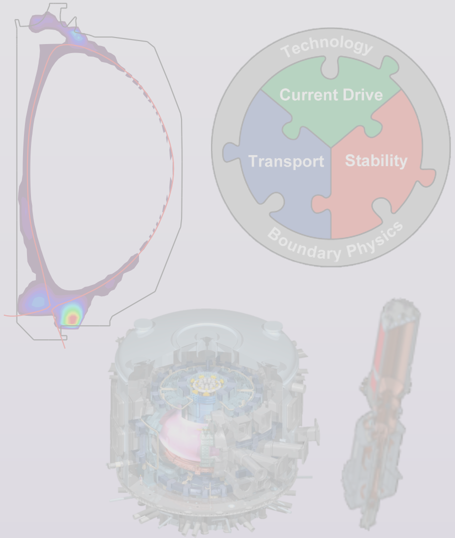
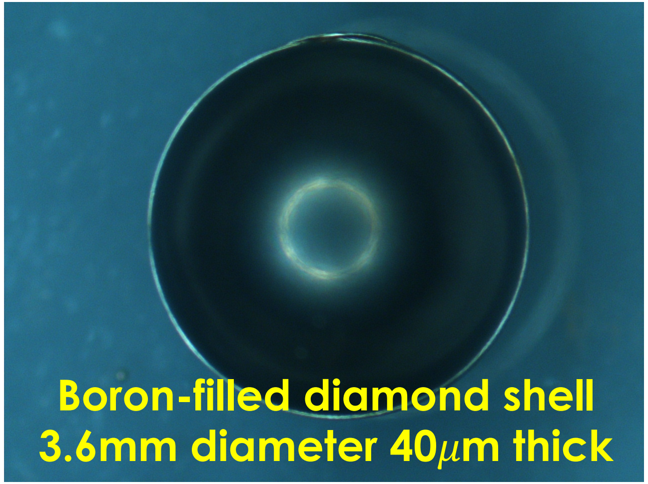


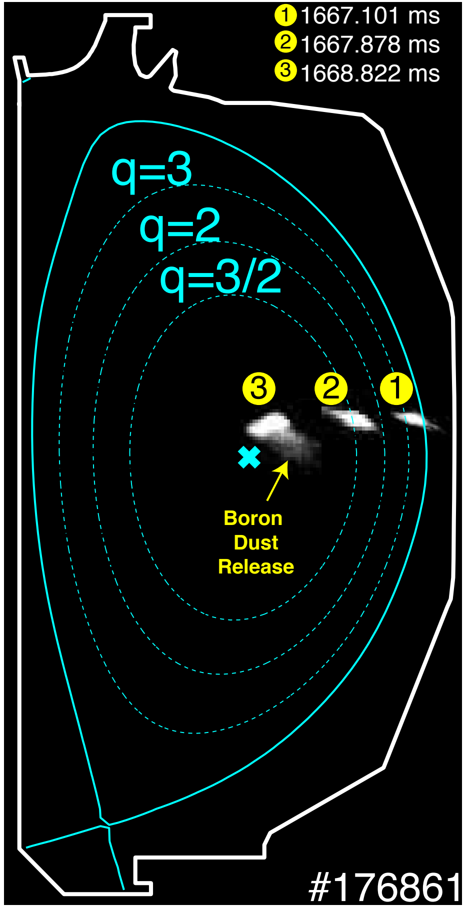
First Demonstration of Shell Pellets – a Novel and ITER Relevant Technique for Disruption Mitigation

- **Shell pellet transports impurities to core before ablating, releasing impurity payload**



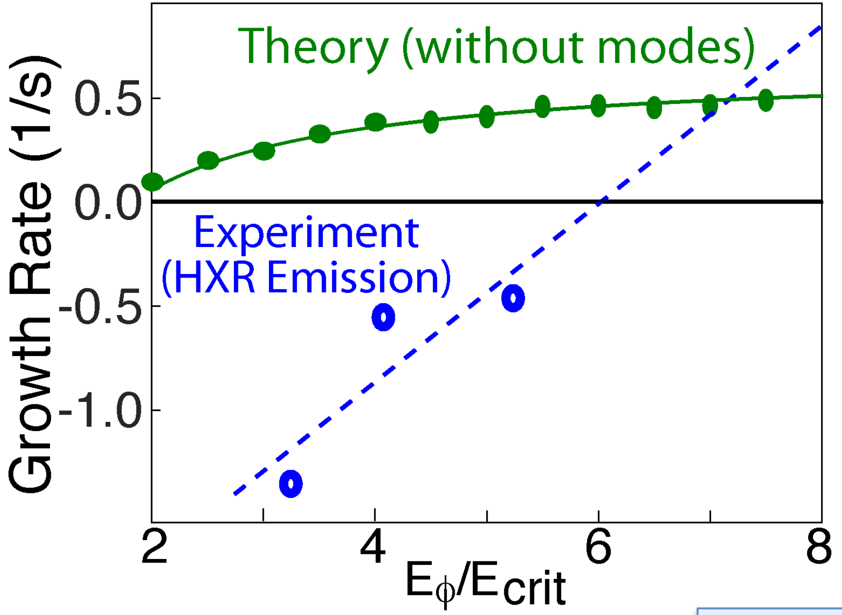
"Inside-out" thermal quench mitigation

See N. Eidietis post-deadline



Energetic Electron-Driven Whistler Modes are a Potential Cause of Runaway Electron Dissipation

- **HXR pinhole camera measurements of critical E-field threshold are reproduced by modeling when high frequency modes are included**



Paz-Soldan EX/6-1; Thome EX/P6-29; Spong TH/P8-17; Liu TH/P8-16

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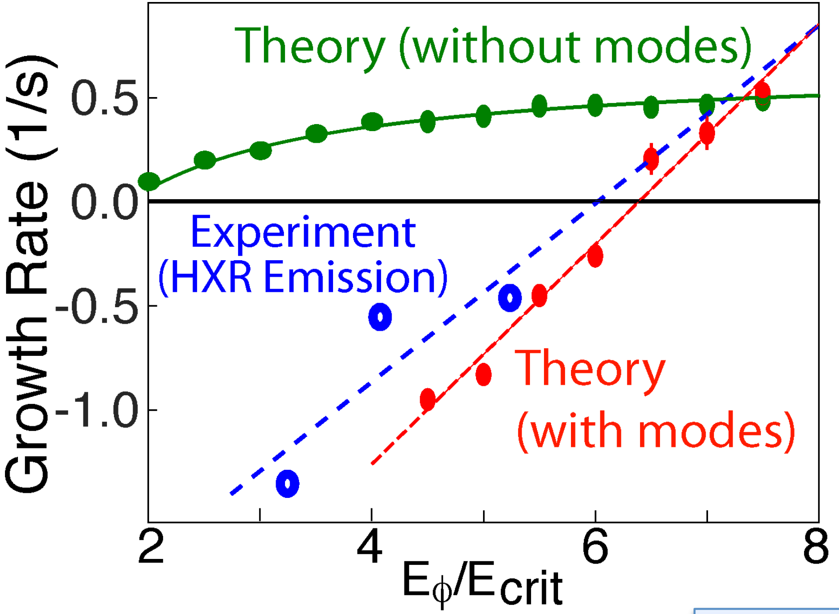
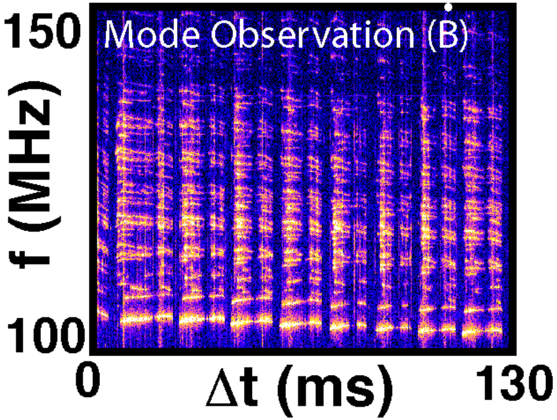


Plasma waves excited by RE can be used to dissipate RE energy

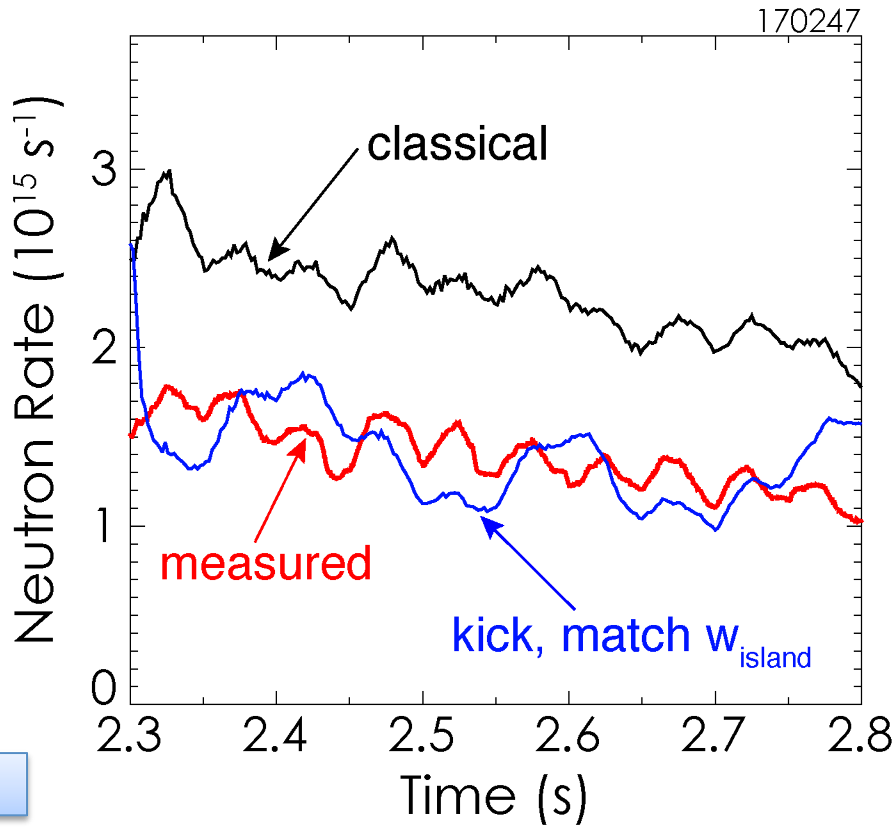
Whistler modes ($\omega >> \omega_{ci}$) are directly observed



Paz-Soldan EX/6-1; Thome EX/P6-29; Spong TH/P8-17; Liu TH/P8-16

Reduced-Physics "Kick Model" Accurately Predicts Fast Ion Transport from Tearing Modes and Strong AE Activity

- **Using experimental 2/1 island width, *kick model* in TRANSP replicates measured neutron rate reduction**
  - Good agreement also found between kick model and fast ion density profiles from FIDA



Dramatic improvement in predictive simulations of EP transport

Podesta EX/1-2

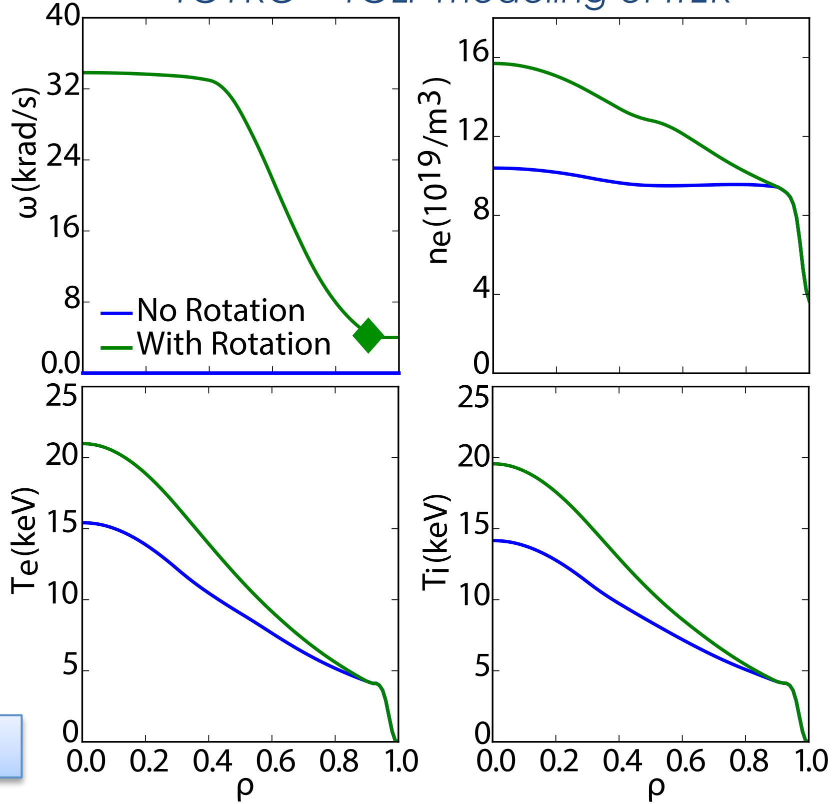
Rotation Profile Predicted for ITER With Edge Intrinsic Torque and TGLF Transport has Stabilizing Influence on Turbulent Transport

- **DIII-D experiments project ITER edge intrinsic rotation to be 3–10 krad/s (◆)**
  - Similar ρ_* scaling of intrinsic angular momentum is found for ECH and NBI H-mode plasmas

Gyrokinetic simulations find enough E×B shear to double the D-T fusion gain in ITER compared to no shear simulations

Chrystal EX/5-2

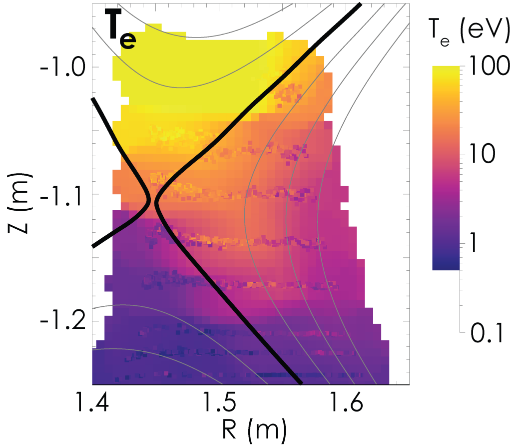
TGYRO + TGLF modeling of ITER



DIII-D NATIONAL FUSION FACILITY

Energy Transport in Detached Divertors is Carried by Convection

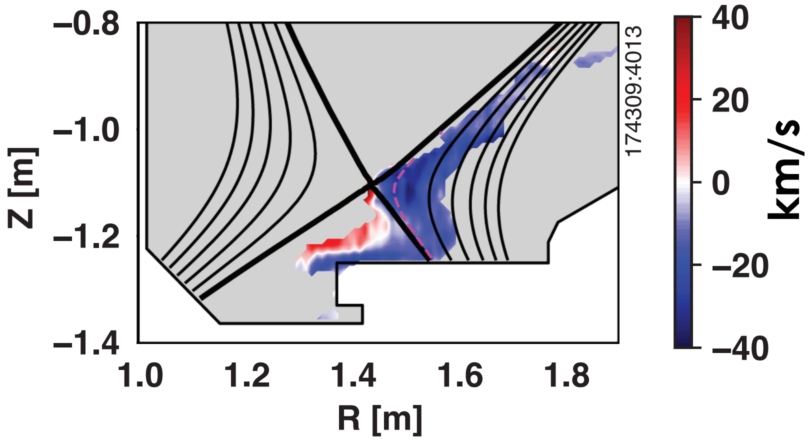
- **Flat T_e profiles below 10 eV for detached divertors indicate convection-dominated transport**

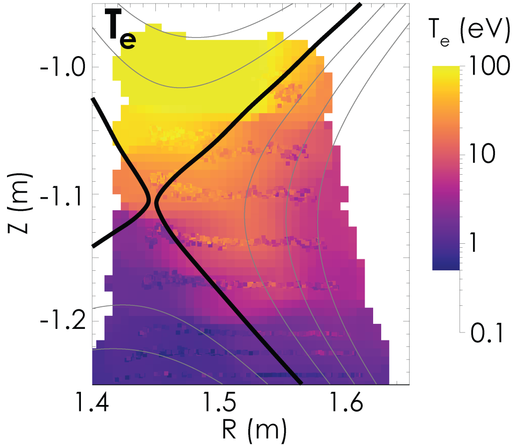


Leonard EX/P6-12

Energy Transport in Detached Divertors is Carried by Convection

- **Flat T_e profiles below 10 eV for detached divertors indicate convection-dominated transport**
  - Coherence imaging spectroscopy of C^{2+} confirms M~1 ionization-driven flow from X-point to target





Convection expands radiating volume, increasing dissipation for high power devices

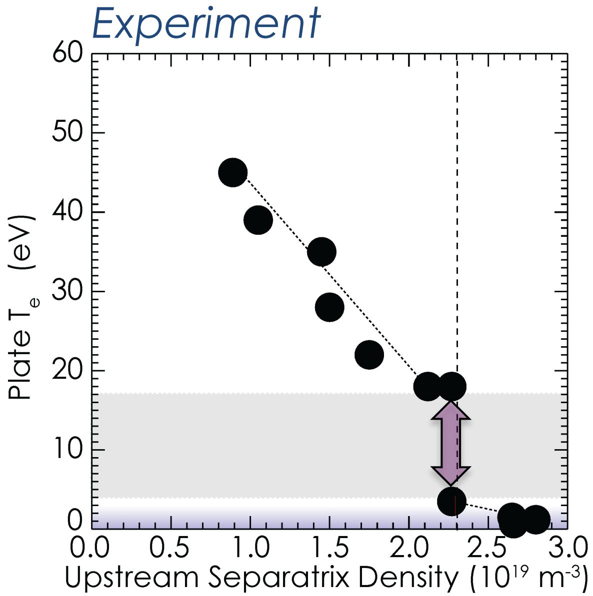
  - Modeling shows E×B drift contributes significant poloidal transport

Leonard EX/P6-12

DIII-D NATIONAL FUSION FACILITY

E×B Drifts Can Also Drive Step-Like Onset of Divertor Detachment

- **UEDGE simulations highlight the nonlinear interaction between E×B drifts and particle fluxes, causing a sudden jump to detachment**



Jaervinen EX/9-3

$E \times B$ Drifts Can Also Drive Step-Like Onset of Divertor Detachment

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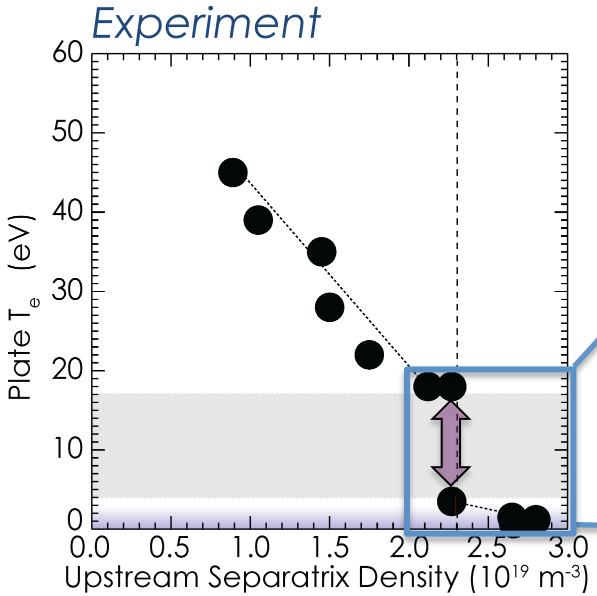
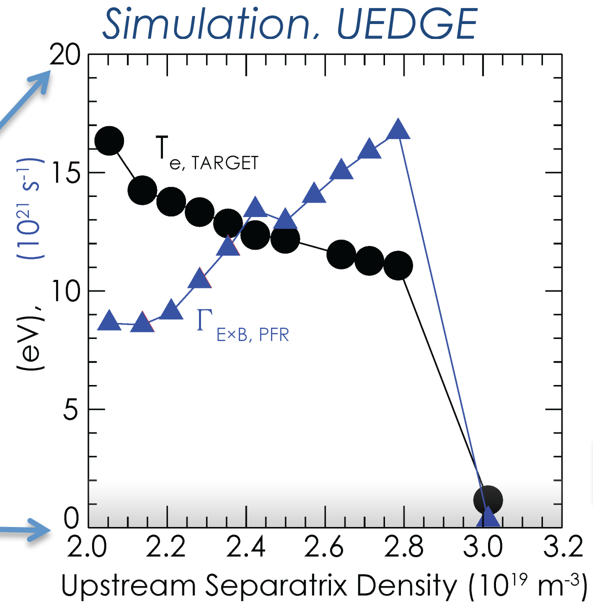




Jaervinen EX/9-3

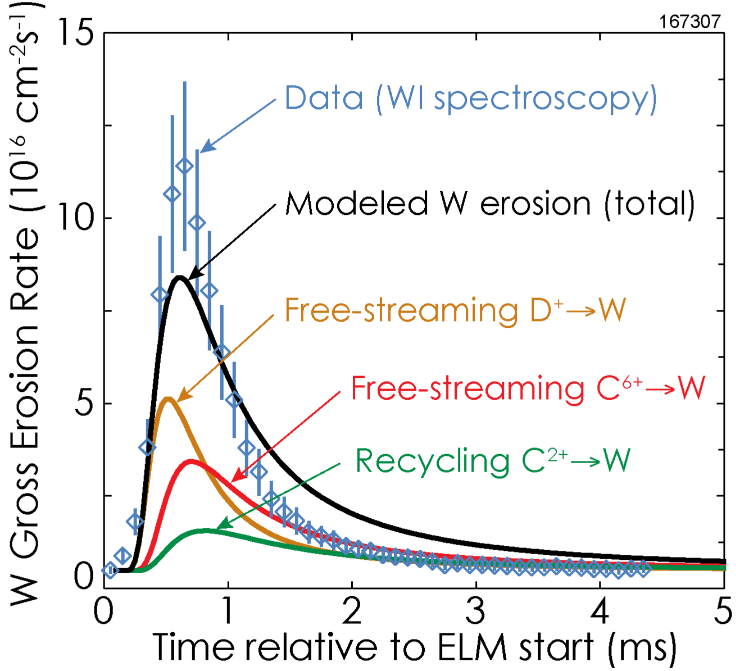
Detachment bifurcation makes control of detachment front more challenging

DIII-D NATIONAL FUSION FACILITY

Improved Understanding of High-Z Erosion in DIII-D Divertor Identifies Important Mechanisms for ITER

- **Energetic D^+ and C^{6+} from pedestal top dominate W sputtering during ELMs**

W erosion in ITER from ELMs will be mainly caused by T, D ions with pedestal energy



Abrams EX/P6-13

Ding MPT/2-2

Outline

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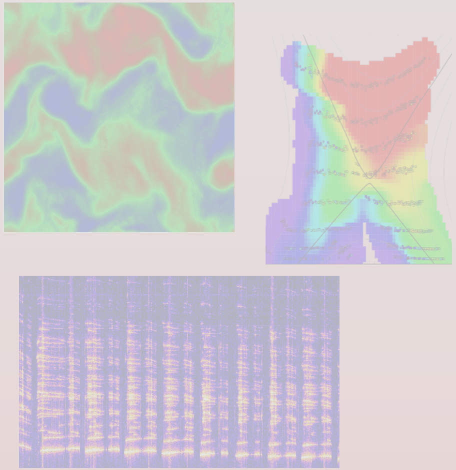

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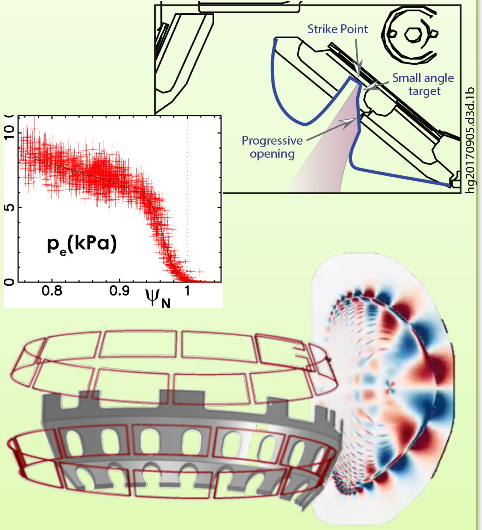

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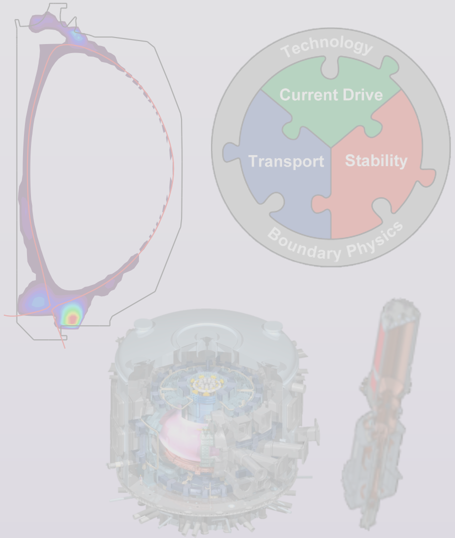
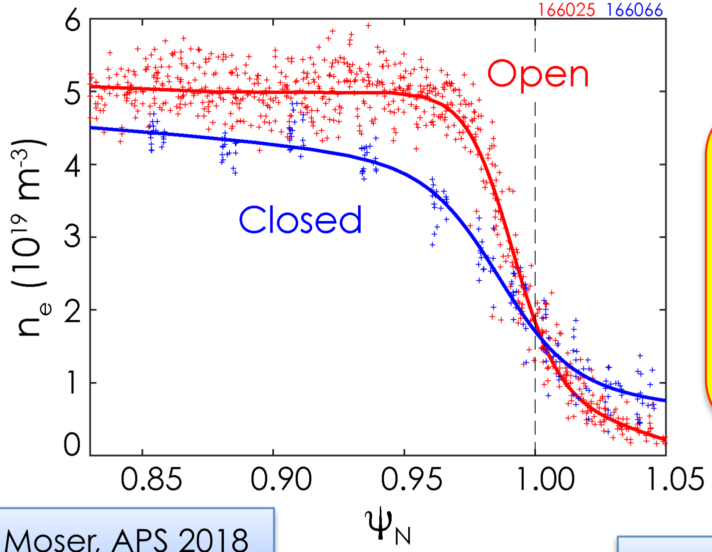


Closed Divertor Exhibits Higher Separatrix Density Relative to Pedestal Density Than Open Divertor

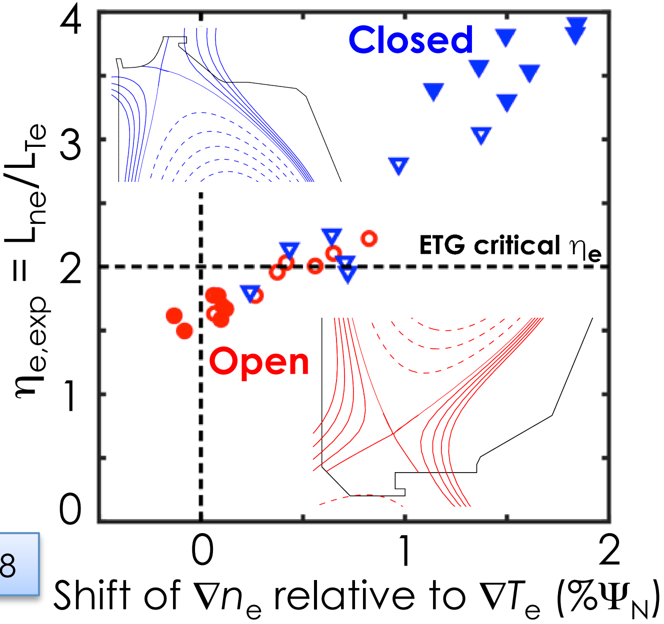
- **OEDGE and SOLPS modeling shows closed divertor has ~50% less core ionization**



A. Moser, APS 2018

Closed divertors give insight to pedestal structure with opaque SOL

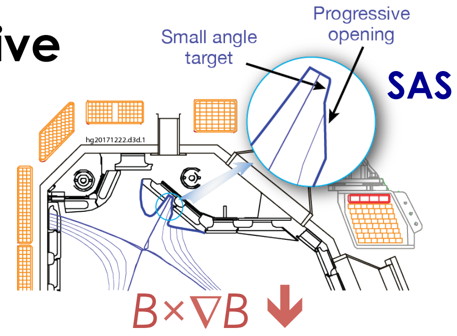
- **Closed divertor can maintain high ∇T_e even for large outward shift of ∇n_e**

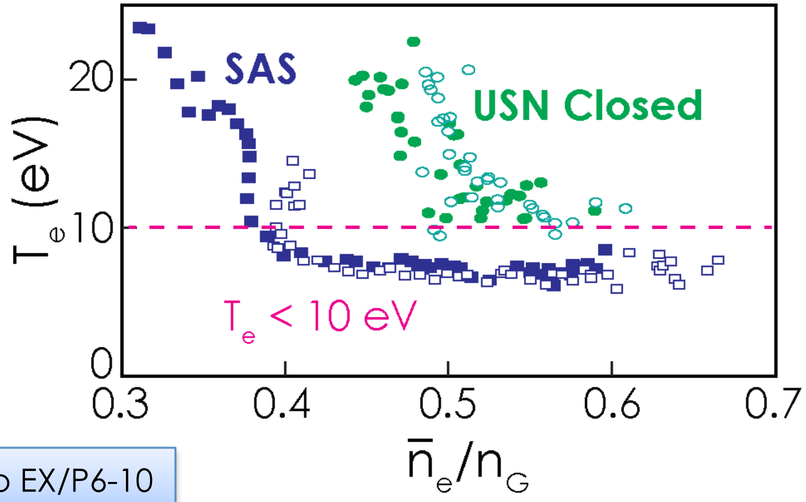


H.Q. Wang, Nucl. Fusion 2018

New SAS Divertor Concept Demonstrates Improved Divertor Power Dissipation Compatible With Steady-State Tokamaks

- **Small angle slot (SAS) divertor transitions to dissipative divertor conditions with T_e<10 eV at lower n_e**



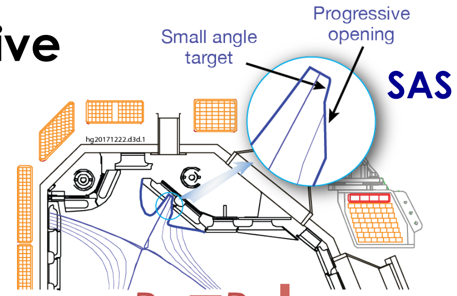


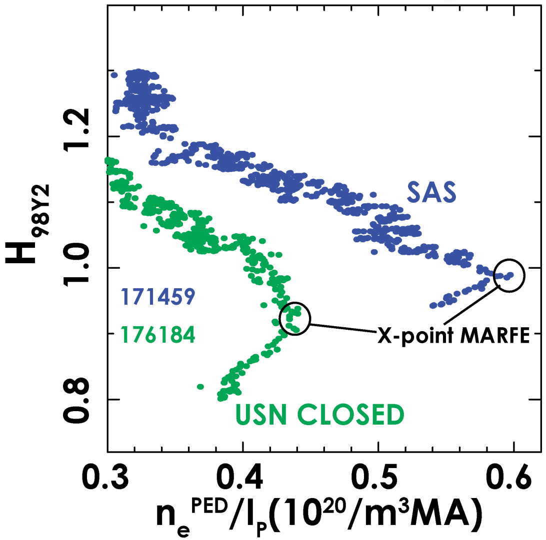
Guo EX/P6-10

DIII-D NATIONAL FUSION FACILITY

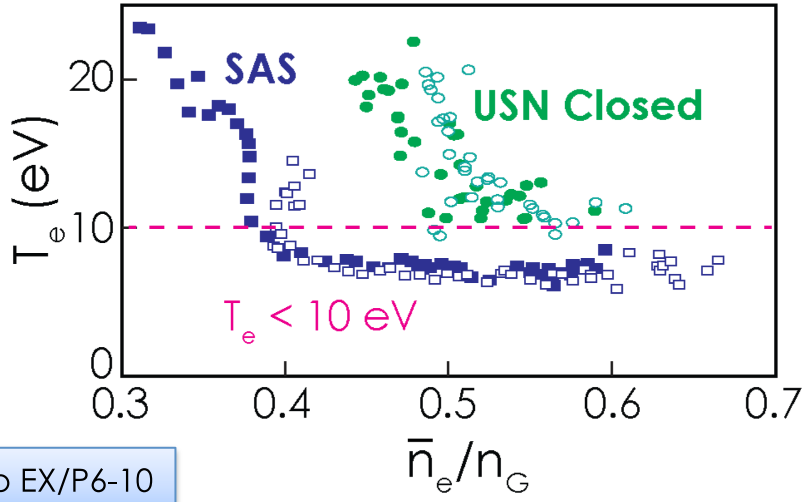
New SAS Divertor Concept Demonstrates Improved Divertor Power Dissipation Compatible With Steady-State Tokamaks

- Small angle slot (SAS) divertor transitions to dissipative divertor conditions with T_e<10 eV at lower n_e
- Exhibits better core confinement at high n_e





SAS divertor is "core friendly" with a colder divertor at low core collisionality

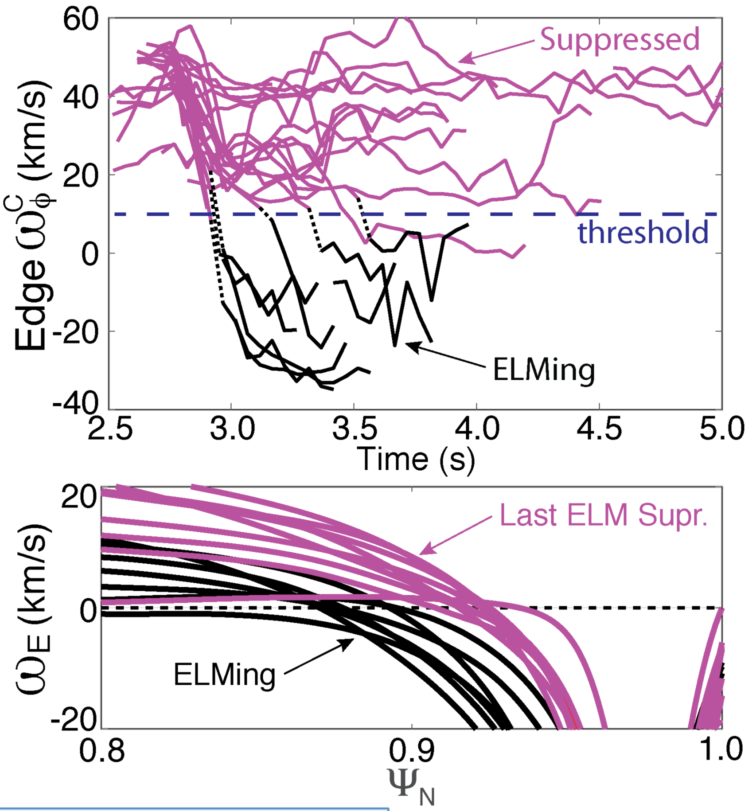


Guo EX/P6-10

Extending n=3 RMP ELM Suppression to Low Torque Finds Edge Rotation Threshold of ~10 km/s

- **Critical radial location of ω_E rotation zero-crossing (*i.e.*, E_r=0) observed at threshold**

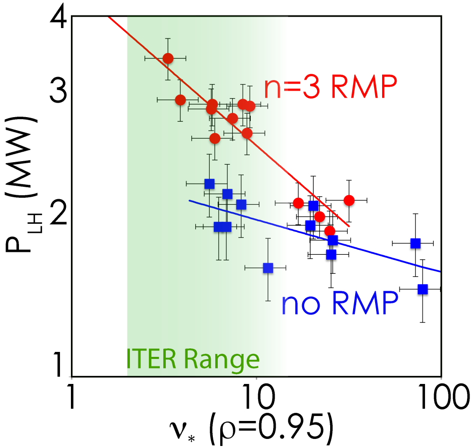
In ITER, edge rotation to maintain E_r=0 in pedestal top for ELM suppression is ≥0.4 krad/s (expect 3-10 krad/s from intrinsic torque)



Paz-Soldan, Nucl. Fusion

H-Mode Threshold Power Increases More With n=3 RMP at Low ν_* Due to Reduced E_r Well From Edge Stochasticity

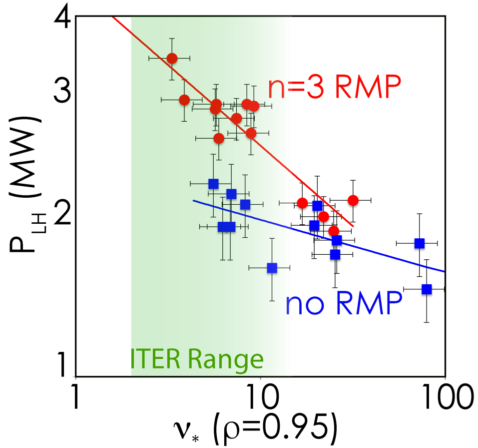
- **P_{LH} can increase by >50% at ITER-relevant ν_***
  - Of concern for H-mode access in ITER



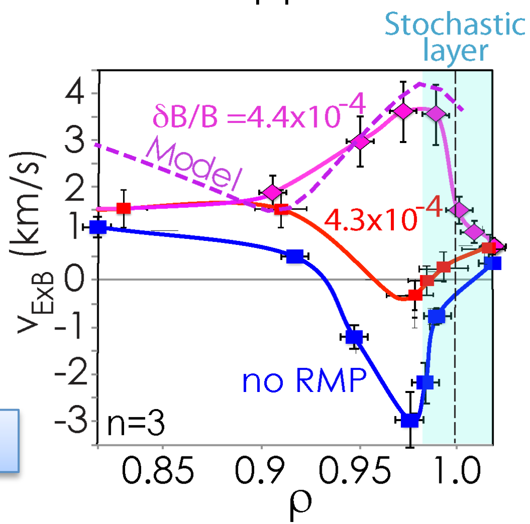
Schmitz EX/4-2

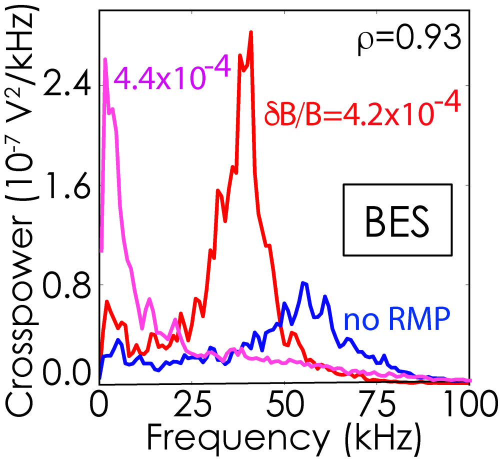
H-Mode Threshold Power Increases More With *n*=3 RMP at Low ν_* Due to Reduced E_r Well From Edge Stochasticity

- **P_{LH} can increase by >50% at ITER-relevant ν_***
  - Of concern for H-mode access in ITER
- **Significant reduction in edge E_r well by RMP fields may explain P_{LH} dependence**
  - Low-k turbulence (BES) increases with applied RMP



A simple stochastic transport model explains the E_r reversal and its ν_* dependence



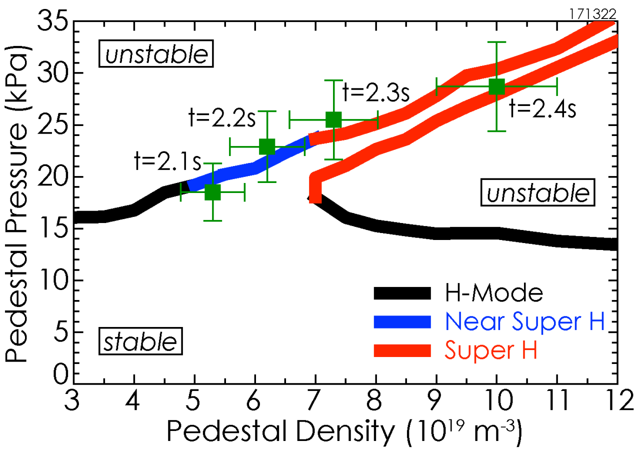


Schmitz EX/4-2

DIII-D NATIONAL FUSION FACILITY

In Super H-Mode, High Pedestal Pressure and Core Confinement Can Be Sustained With Strongly Radiating Divertor

- **Record fusion gain for DIII-D ($Q_{DT,eq} \approx 0.45$) is transiently achieved**
  - Super H-mode occurs in strongly shaped plasmas where pedestal pressure increases with density

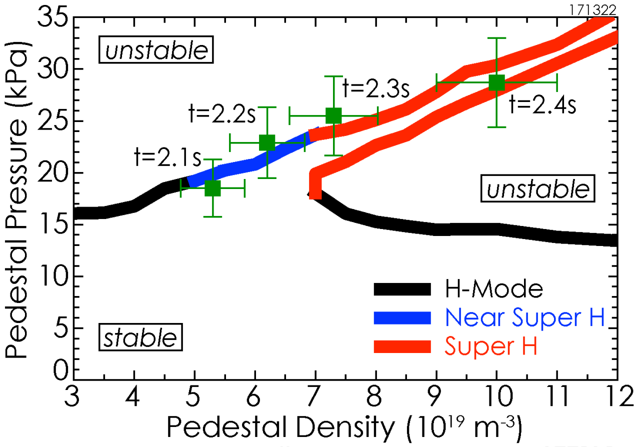


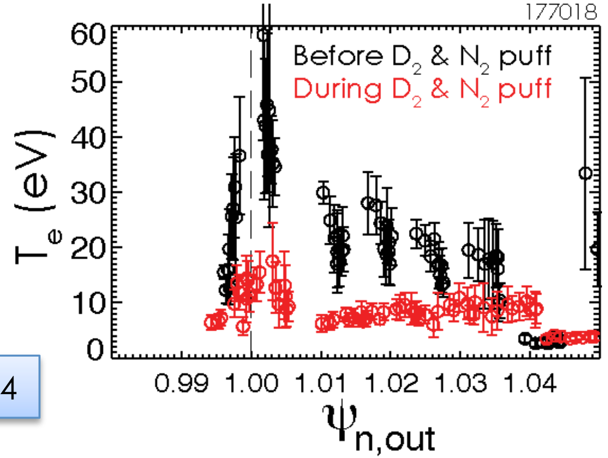
Snyder EX/2-4

In Super H-Mode, High Pedestal Pressure and Core Confinement Can Be Sustained With Strongly Radiating Divertor

- **Record fusion gain for DIII-D ($Q_{DT,eq} \approx 0.45$) is transiently achieved**
  - Super H-mode occurs in strongly shaped plasmas where pedestal pressure increases with density
- **During D_2 and N_2 puffing, high pedestal pressure (~20 kPa) is sustained in radiative divertor with large reduction in divertor T_e**

Super H-mode is compatible with both high fusion performance and high separatrix density for divertor solutions





Snyder EX/2-4

DIII-D NATIONAL FUSION FACILITY

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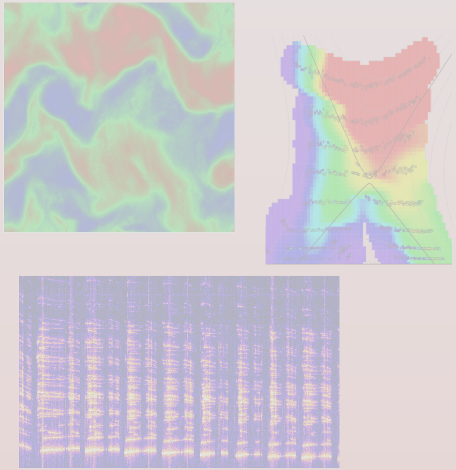

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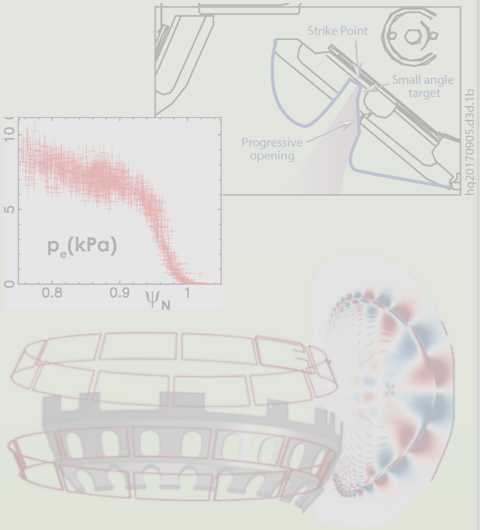

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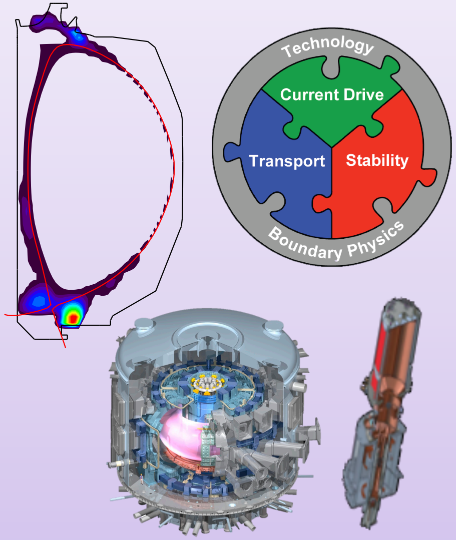
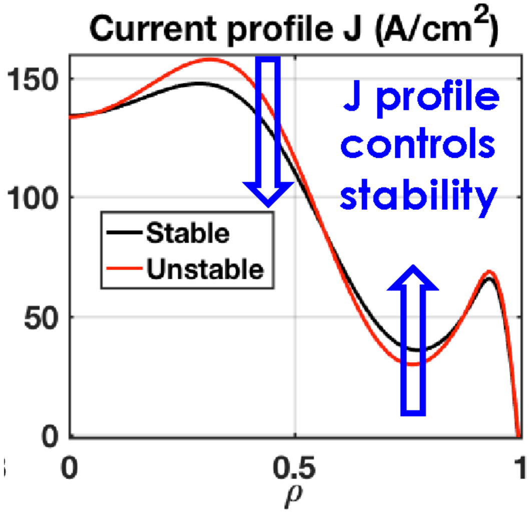


Key Advance is Stable ITER Baseline Scenario Equivalent to $Q_{fus} \approx 10$ With Zero Injected NBI Torque

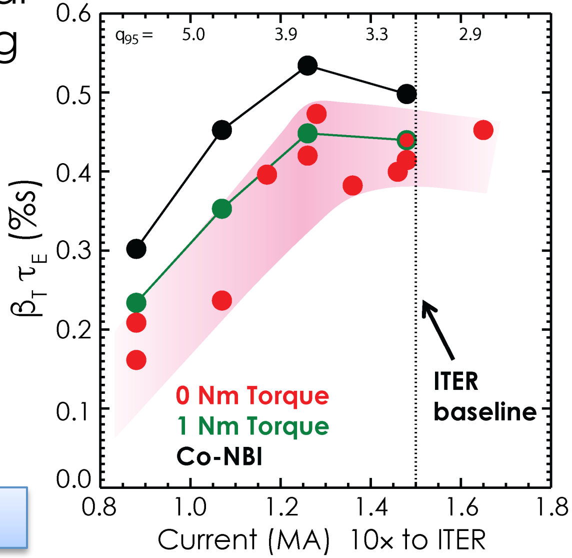
- **In past, steep "well" in current profile near *q*=2 made ITER baseline scenario at zero-torque unstable**
  - Solution is to modify initial current profile by slowing I_P ramp and delaying H-mode transition

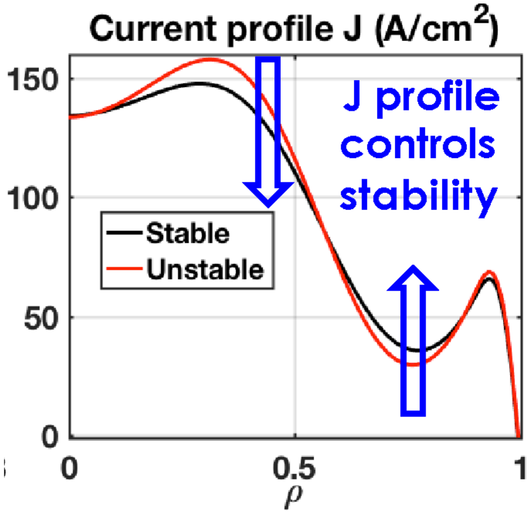


Turco, Nucl. Fusion 2018

Key Advance is Stable ITER Baseline Scenario Equivalent to Q_{fus} ≈ 10 With Zero Injected NBI Torque

- **In past, steep "well" in current profile near *q*=2 made ITER baseline scenario at zero-torque unstable**
  - Solution is to modify initial current profile by slowing I_P ramp and delaying H-mode transition
- **Stable zero-torque operation obtained, but fusion gain ($\beta_T\tau_E$) doesn't improve below q_{95}=3.7**



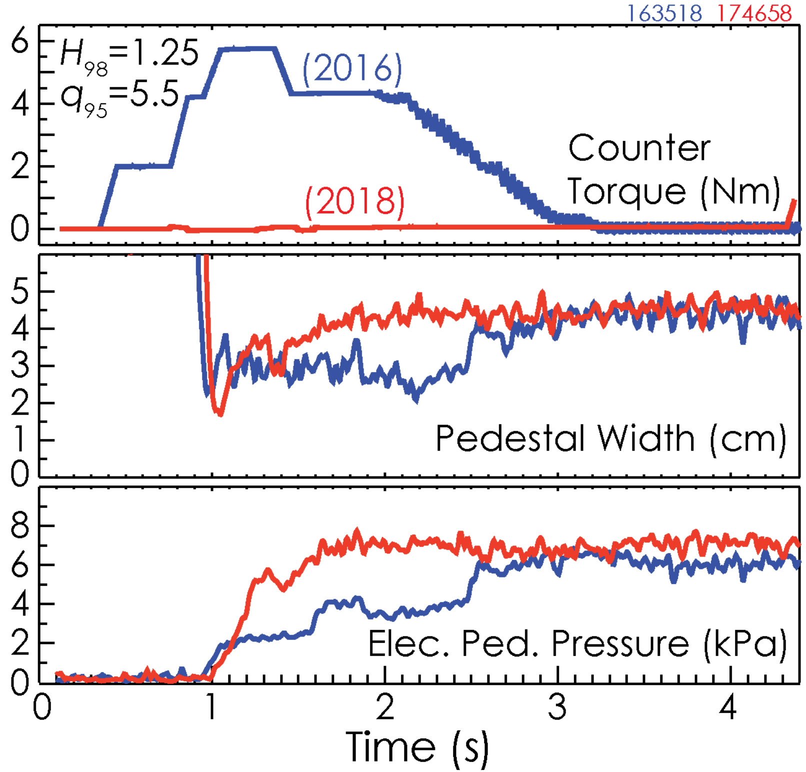


Luce PPC/2-1

ITER baseline achieved with correct torque, q_{95}, β_N, H_{98y2}, T_e/T_i but needs lower ν_*

Wide-Pedestal (ELM Stable) QH-Mode Initiated and Sustained With ≈0 NBI Torque, Also With Dominant Electron Heating

- **New zero-torque startup replaces strong counter NBI torque with n=3 NTV torque**

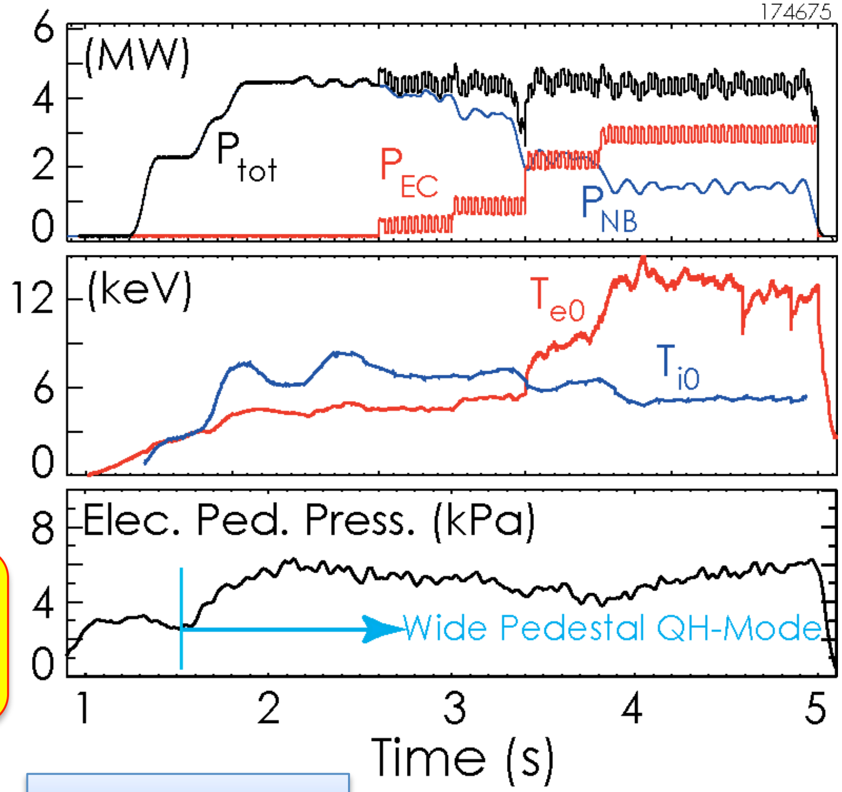


Ernst EX/2-2

Wide-Pedestal (ELM Stable) QH-Mode Initiated and Sustained With ≈0 NBI Torque, Also With Dominant Electron Heating

- **New zero-torque startup replaces strong counter NBI torque with n=3 NTV torque**
- **Wide-pedestal QH-mode also sustained by replacing most NBI power with ECH**
  - Central ECH creates electron ITB (T_e≈12 keV)

Wide-pedestal QH-mode is attractive scenario for ITER: no ELMs, low ν_*, zero torque, electron heating but needs lower q_{95}

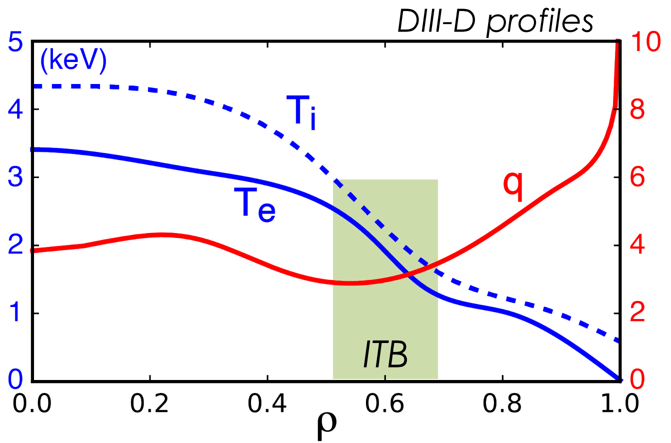


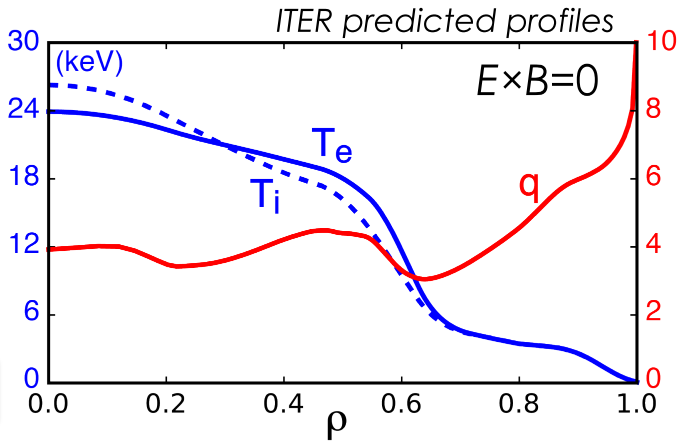
Ernst EX/2-2

High β_P Scenario Extended to Reactor-Relevant q_{95}~6 While Maintaining an ITB Using Negative Magnetic Shear

- **Enhanced confinement (H_{98y2} up to 1.8) and ITB from Shafranov shift stabilization of turbulence**
  - E×B shear is low at foot of ITB

First time achievement: self-consistent simulation evolving n_e, T_e, T_i, q predicts non-inductive Q~5 in ITER with day-one heating, zero rotation

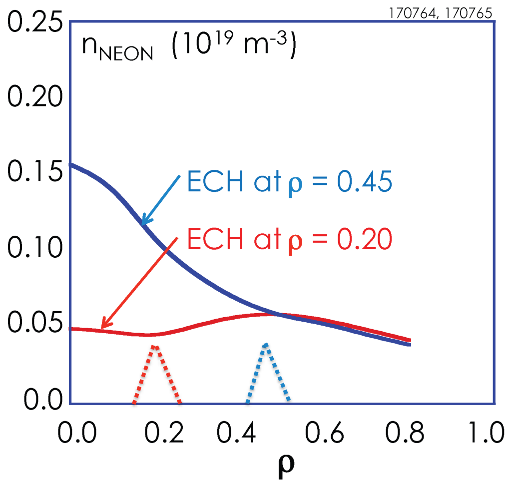




McClenaghan EX/4-3

DIII-D is Integrating Radiative Divertor into "Steady State" High-β_N Hybrid Scenario

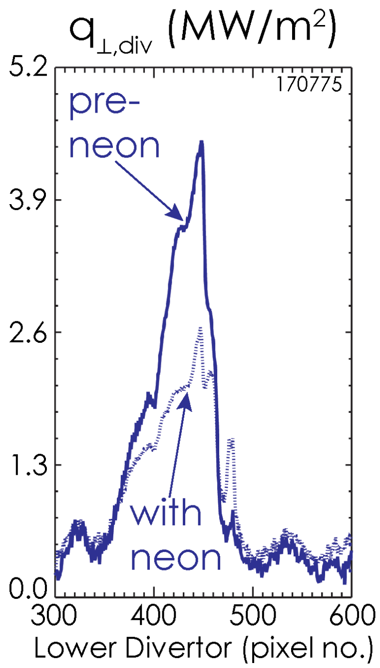
- **Off-axis ECH gives Neon density peaking factor of ~2.6 while central ECH gives flat Neon profile**
  - β_N up to 3.8, H_{98y2}=1.6, q_{min}≈1

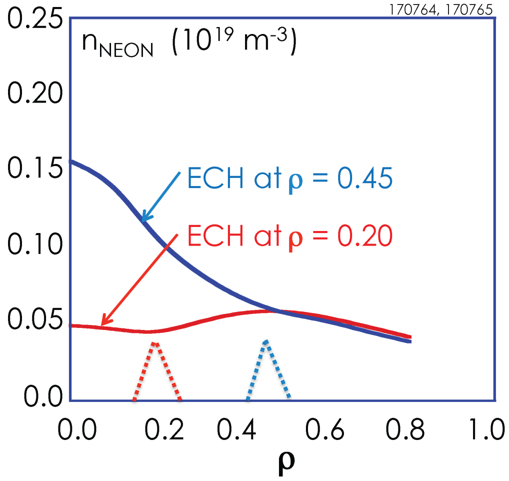


Turco EX/3-3; Petrie EX/P6-11

DIII-D is Integrating Radiative Divertor into "Steady State" High-β_N Hybrid Scenario

- **Off-axis ECH gives Neon density peaking factor of ~2.6 while central ECH gives flat Neon profile**
  - β_N up to 3.8, H_{98y2}=1.6, q_{min}≈1
- **Both Neon-based and Argon-based mantles achieve 40% reduction in between-ELM divertor heat flux**





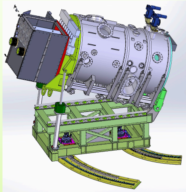
Turco EX/3-3; Petrie EX/P6-11

Good radiative divertor achieved with high beta, high confinement core

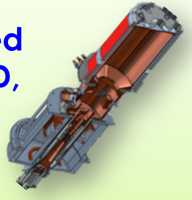
Future DIII-D Facility Enhancements Will Strengthen Steady-State and Boundary/PMI Research

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

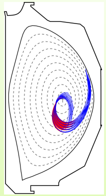
Determine Path to Steady-State



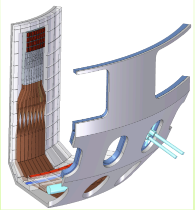
Increased co-NBCD, off-axis NBCD



Increased EC power, top launch current drive



Helicon wave current drive

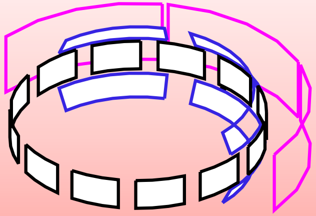


Inside launch lower hybrid current drive

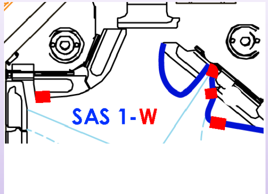
3D Fields and Stability

New ASIPP 3D coil power supplies

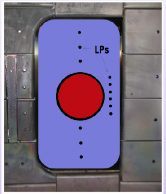
More flexible 3D fields (M-coil)



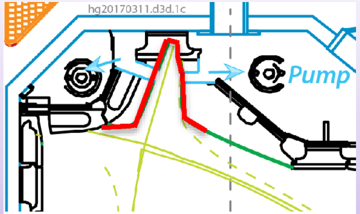
Divertor and PMI



W inserts in SAS 1



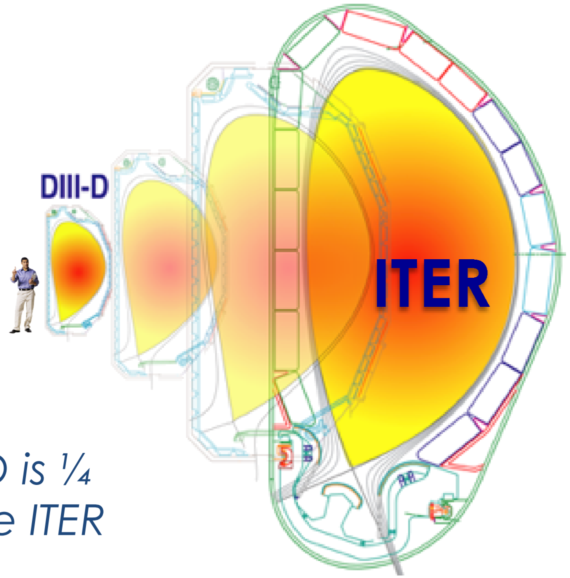
Tile station



W tiles/ closed SAS 2 divertor

DIII-D Program is Advancing the Scientific Basis for Future Fusion Reactors

- **Improving scientific basis for disruption and runaway electron mitigation**
- **Integrating detached and radiative divertors with high performance core**
- **Promising new high-gain and steady-state scenarios for ITER**



DIII-D is ¼ Scale ITER