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

by
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for the DIII-D Team

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

1. Advances in Fusion Energy Science

2. Core-Edge Integration

3. Scenario Development
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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

Boron-filled diamond shell
3.6mm diameter 40\(\mu\)m thick

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

Whistler modes ($\omega \gg \omega_{ci}$) 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
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 \( \rho^* \) scaling of intrinsic angular momentum is found for ECH and NBI H-mode plasmas

Gyrokinetic simulations find enough \( E \times B \) shear to double the D-T fusion gain in ITER compared to no shear simulations
Energy Transport in Detached Divertors is Carried by Convection

- Flat $T_e$ profiles below 10 eV for detached divertors indicate convection-dominated transport
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
  - Modeling shows $E \times B$ drift contributes significant poloidal transport

Convection expands radiating volume, increasing dissipation for high power devices
**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.
\(E \times B\) Drifts Can Also Drive Step-Like Onset of Divertor Detachment

- UEDGE simulations highlight the nonlinear interaction between \(E \times B\) drifts and particle fluxes, causing a sudden jump to detachment.

\[\text{Experiment}
\]

\[\text{Simulation, UEDGE}
\]

\[\text{Detachment bifurcation makes control of detachment front more challenging}
\]
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.**
Outline

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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

- Closed divertor can maintain high $\nabla T_e$ even for large outward shift of $\nabla n_e$

- Closed divertors give insight to pedestal structure with opaque SOL

A. Moser, APS 2018

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

- Critical radial location of $\omega_E$ 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 $\geq 0.4$ krad/s (expect 3-10 krad/s from intrinsic torque)**
H-Mode Threshold Power Increases More With $n=3$ RMP at Low $\nu_*$
Due to Reduced $E_r$ Well From Edge Stochasticity

- $P_{\text{LH}}$ can increase by >50% at ITER-relevant $\nu_*$
  - Of concern for H-mode access in ITER
H-Mode Threshold Power Increases More With $n=3$ RMP at Low $\nu_*$ Due to Reduced $E_r$ Well From Edge Stochasticity

- $P_{LH}$ can increase by >50% at ITER-relevant $\nu_*$
  - 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 $\nu_*$ dependence
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
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
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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
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
- Stable zero-torque operation obtained, but fusion gain ($\beta_T \tau_E$) doesn’t improve below $q_{95}=3.7$

ITER baseline achieved with correct torque, $q_{95}$, $\beta_N$, $H_{98y2}$, $T_e/T_i$, but needs lower $v_s$. 

Luce PPC/2-1
Wide-Pedestal (ELM Stable) QH-Mode Initiated and Sustained With $\approx 0$ NBI Torque, Also With Dominant Electron Heating

- New zero-torque startup replaces strong counter NBI torque with $n=3$ NTV torque
Wide-Pedestal (ELM Stable) QH-Mode Initiated and Sustained With $\approx 0$ 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 ($T_e \approx 12$ keV)

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

Ernst EX/2-2
High $\beta_p$ Scenario Extended to Reactor-Relevant $q_{95}\sim6$ While Maintaining an ITB Using Negative Magnetic Shear

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

**First time achievement: self-consistent simulation evolving $n_e, T_e, T_i, q$ predicts non-inductive $Q\sim5$ in ITER with day-one heating, zero rotation**
Off-axis ECH gives Neon density peaking factor of ~2.6 while central ECH gives flat Neon profile

- $\beta_N$ up to 3.8, $H_{98y2}=1.6$, $q_{\text{min}} \approx 1$
DIII-D is Integrating Radiative Divertor into “Steady State” High-$\beta_N$ Hybrid Scenario

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  - $\beta_N$ up to 3.8, $H_{98y2}=1.6$, $q_{\text{min}} \approx 1$
- Both Neon-based and Argon-based mantles achieve 40% reduction in between-ELM divertor heat flux

\[
\begin{align*}
\rho & \quad ECH \at \rho = 0.45 \\
\rho & \quad ECH \at \rho = 0.20 \\
\end{align*}
\]

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

<table>
<thead>
<tr>
<th>Determine Path to Steady-State</th>
<th>Enabled by DIII-D Enhancements</th>
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<tbody>
<tr>
<td>Increased co-NBCD, off-axis NBCD</td>
<td>Increased EC power, top launch current drive</td>
</tr>
<tr>
<td>Helicon wave current drive</td>
<td>Inside launch lower hybrid current drive</td>
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</tbody>
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## 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