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

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

- High energy REs grow with electric fields $E/E_{\text{crit}} \sim 2$
  - Theory predicts growth at $E/E_{\text{crit}} \sim 1.6$

- Lower energy RE growth at higher $E/E_{\text{crit}} \sim 5$
  - 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
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- 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 \(\rightarrow\) 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
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

![Diagram showing $T_e$ and $n_e$ distributions](image_url)

2D Divertor Thomson Scattering (DTS)
Drifts Affect Divertor Asymmetries and Detachment Threshold

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- Reverse \( B_T \) lowers density for detachment in H-mode

- Effects understood due to interplay between radial and poloidal \( E \times B \) 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
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  – Usual approach matches upstream density
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- 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
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
Experiments with Tungsten Rings Reveals Metal Influx Is Predominantly from Strike Point Location

- Different W isotopes isolate strikepoint from divertor shelf
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**
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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
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

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
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
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
- Stiffness not observed because temperature is not kept constant

Suggests fusion gain will increase with heating more than stiffness would imply
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 $\beta_N$ to $\sim15\%$ in 200 DIII-D cases

- Enables prediction and optimization of ITER fusion gain: $Q\sim12$ possible

New frontier: Multi-scale turbulence simulations and TGLF improvement

Meneghini – TH/9-1
Holland– TH/6-1
Staebler – TH/P2-8
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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Determine Path to Steady-State

- Shafranov shift stabilization
- Fast ion transport
- Core-edge integration
Excellent Confinement in High $\beta_p$ 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 $q_{95} \approx 6$ if high confinement maintained with high $q_0$ (NCS)
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.
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

![Graph showing fast ion transport and losses](image-url)

- **Fast Ion Transport**
  - Energetic neutral particle analyzer
  - Stochasticity (Theory)

- **Fast Ion Losses**
  - $t=516-948 \text{ ms}$
  - Increasing power

**PDF (counts)**

- Fluctuation amplitude

**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
    \[ f_{\text{RSAE-min}}^2 = (f_{\text{GAM}}^2 + f_V^2) \]
    \[ f_{\text{GAM}}^2 \propto T_e \quad f_V^2 \propto \nabla T_e \]

Suggests tailoring of temperature profile can control RSAE-driven transport

- Including these effects correctly predicts existence and evolution of RSAEs
ELM Suppression Achieved in ≈1 MA Fully Non-Inductive Hybrid with Minimal Impact on Performance

- High $\beta_N$ + 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**
Future DIII-D Enhancements Provide Flexibility to Continue to Address these Key Issues

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<td><strong>Control Transient Behavior</strong></td>
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- 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

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