DIII-D Research Toward Resolving Key Issues for ITER and Steady-State Tokamaks

by
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DIII-D is Advancing the Physics Basis Needed to Support Fusion Energy Development

- Address ITER challenges and validate scenarios
- Develop basis for steady-state operation
- Advance predictive capability for fusion
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DIII-D is Advancing the Physics Basis Needed to Support Fusion Energy Development
DIII-D is Preparing the Basis for ITER Operation

Match key plasma conditions in ITER where possible

- Address critical issues
  - Scenarios at low torque
  - Stability
  - ELMs
  - Disruptions

Shape

I/αB

β, βN

T_e/T_i

Collisionality

Rotation
Stationary Low-Torque ITER Baseline Discharges Are Maintained for Multiple Current Relaxation Times

Develop experience with low-torque operation for ITER – access, stability, and confinement at low rotation

- ITER – equivalent NBI torque
- ELMing H-mode
  - Matches shape
  - Matches I/aB
- Broad ECCD near q=3/2 controls tearing modes

G. Jackson, EX/P2-08
Successful Integration of Key Elements of Tearing Mode Control for ITER

- **Real-time** control of EC power and mirror steering to \( q=2 \) surface

- PCS detects growing 2/1 tearing mode and turns on ECCD

- **Real-time** control provides complete stabilization of m/n=2/1 tearing mode
Pellet Pacing in ITER Baseline Scenario Yields 12x Higher ELM Frequency

ITER shape, geometry

\[ \beta_N = 1.8 \]

1.3 mm pellets 100-150 m/s

- Reduced ELM energy loss
- Minimal change in confinement
- No fueling increase

L. Baylor, EX/6-2
Pellet Pacing in ITER Baseline Scenario Yields 12x Lower ELM Divertor Heat Pulse

- Reduced ELM energy loss
- Minimal change in confinement
- No fueling increase

ITER shape, geometry

\[ \beta_N = 1.8 \]

1.3 mm pellets 100-150 m/s

\[ f_{\text{pellet}} \times \Delta q_{\text{div}} = \text{const} \]

L. Baylor, EX/6-2
Sustained RMP ELM Suppression Extended to ITER Baseline Scenario

- n=3 perturbation with internal coils
- Match ITER
  - Shape and I/aB
  - $\beta_N = 1.8$ and $\nu^* = 0.12$
- Suppression at low collisionality using n=2 configuration
- ELM suppression also shown in helium plasmas
Operating Range for ELM-free QH-mode Extended to ITER Relevant Torque Using External 3D Coils

- Achieved using external n=3 coils to drive edge rotation shear

QH-mode is an attractive candidate scenario for ITER

K. Burrell, EX/P4-08
Operating Range for ELM-free QH-mode Extended to ITER Relevant Torque Using External 3D Coils

Neutral Beam Torque

-1 0 +1 (Nm)

ITER-equivalent NBI torque

• Achieved using external n=3 coils to drive edge rotation shear

QH-mode is an attractive candidate scenario for ITER

K. Burrell, EX/P4-08
Operating Range for ELM-free QH-mode Extended to ITER Relevant Torque Using External 3D Coils

Neutral Beam Torque

QH

ITER-equivalent NBI torque

• Achieved using external n=3 coils to drive edge rotation shear

Excellent energy confinement quality at low rotation: $H_{98y2} = 1.3$

QH-mode is an attractive candidate scenario for ITER

K. Burrell, EX/P4-08
Error Field Correction Strategies Must Include Full Plasma Response of All Field Components

Proxy error field experiments show that correction fields increase NTV damping

C-coil Proxy
n=1 error

I-coil Correction

IPEC calculated n=1 NTV damping

“Test Blanket Module”

Similar results with localized error field

Localized heating tests fast ion transport models

H. Reimerdes, EX/P4-09  G. Kramer, ITR/P1-32
R. Buttery, EX/P4-31  N. Ferraro, TH/P4-21
DIII-D Disruption Experiments Point Toward Controlled Dissipation of Runaway Electrons In ITER

Radial stability provides time to dissipate runaways

High-Z gas injection increases runaway electron dissipation

DIII-D experiments provide the physics basis for RE control in ITER

E. Hollmann, EX/9-2
V. Izzo, TH/P3-13
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Coordinated Pedestal Characterization Experiments are Confirming EPED Prediction of the ITER Pedestal

New High Resolution Thomson Scattering

- First-principles stability calculation uses no fitted parameters

R. Groebner, EX/11-4
Pedestal Evolution During ELM Cycle is Observed to Be Consistent With Predictions of EPED Model

New High Resolution Thomson Scattering Shows Pedestal Growth

**Graph**

- First-principles stability calculation uses no fitted parameters
- Kinetic ballooning modes (KBM) limit local pressure gradient
- Pedestal width grows at constant $\nabla P$ until ELM occurs at peeling ballooning mode limit

P. Snyder, TH/P3-17
Modulated RMP Experiments Point to Island at Top of Pedestal Inhibiting Pedestal Growth and ELMs

- **RMP rotation reveals MHD response**
  - Displacements seen in X-point SXR imaging
  - Compared with vacuum field and two-fluid MHD simulation

- **Mechanism: RMP limits width of pedestal**
  - RMP field resonant near top of pedestal
  - Island growth where $\omega_e \sim 0$
  - Island limits inward expansion of high-gradient pedestal
Edge Fluctuation and Flow Measurements Are Beginning to Reveal H-mode Transition Dynamics

- L-H transition trigger is key to predicting threshold power
- Repetitive sampling of L-H transitions during limit cycle oscillations
- New data shows interplay between HF turbulence and LF turbulent flow

G. Tynan, EX/10-3  L. Schmitz, EX/P7-17
Z. Yan, EX/P7-05  P. Gohil, ITR/P1-36
Stiffness refers to a sharp increase in transport above a critical $\nabla T$

H-mode heat flux scan shows electrons are more stiff than ions

TGLF agrees with results of dedicated H-mode stiffness experiment as it does with the broader H-mode database
Critical-Gradient Transport Experiments Test Profile Stiffness Predictions

- Vary ECH location to change L-mode $\nabla T_e$ with $T_e \sim$ constant
- Transport exhibits critical gradient threshold, agrees with simulation
- Sharp rise in measured $T_e$ fluctuations indicates TEMs are important, providing excellent test for gyrokinetic simulations

C. Holland, EX/P7-09
Critical-Gradient Transport Experiments Test Profile
Stiffness Predictions

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C. Holland, EX/P7-09
Off-Axis Beam Allows Variation of Alfvén Eigenmode Drive and Fundamental Tests of Stability Models

- Vary fast ion pressure gradient to change Alfvén Eigenmode (AE) drive/stability
- Reversed-Shear AEs mostly stable with off-axis injection
- Comparisons with kinetic codes (GTC, GYRO, TAEFL) are underway

W. Heidbrink, EX/P6-22
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DIII-D | ITER | FNSF | DEMO
Steady-State Fusion Requires Broad Current and Pressure Distributions

- Steady state fusion requires:
  High pressure + High self-driven current

- High normalized beta, $\beta_N$

- Current distributed off axis is favorable for steady-state, stability, and confinement

Off-axis NBI and ECCD enable steady-state scenario research
DIII-D Neutral Beam Successfully Modified for Off-Axis Injection to Broaden Current and Pressure Profiles

Off-axis Neutral Beam Can Be Adjusted During An Experiment

5 min to raise beam, 30 min start to finish
Off-Axis NBI Produces Broad Current & Pressure Profiles with Sustained $q_{\text{min}}>2$ for Higher $\beta_N$ Stability Limits

- $q_{\text{min}}>2$ avoids 2/1 tearing modes
- Off-axis NBI broadens current and pressure profiles
- Plasmas have higher predicted stability limits ($\beta_N \sim 4$)

C. Holcomb, EX/1-5
ITER/FNSF Equivalent Performance Demonstrated with Relaxed $q_{\text{min}} \approx 1.5$

- Off-axis beam sustains stable stationary operation
- $f_{\text{NI}} = 70\%$
- Modeling shows potential to raise $\beta_N$ and $f_{\text{NI}}$ further
\( q_{\text{min}} \approx 1.5 \) Scenario Appears Compatible with Radiating Mantle for Divertor Heat Flux Reduction

Peak divertor heat flux reduced \(~35\%\)

\( P_{\text{RAD}} \) doubles without significant performance degradation

C. Holcomb, EX/1-5
T. Petrie, EX/P5-12

Neon 5.2 t l/s
DIII-D is Developing the Physics Basis for Integrated Steady-State Divertor Solutions

- Critical issues
  - Predicting ITER requirements
  - New solutions for steady-state fusion

- New unified ITPA data base indicates narrow heat flux for ITER
  - Gradients below ballooning limits
  - Motivates and supports physics modeling

SOL heat flux width: \( \lambda_q \propto 1/B_{pol} \)

![Graph showing SOL heat flux width](Courtesy T. Eich)

- JET
- C-Mod
- AUG
- D3D

\( R^2 = 0.77 \)
Snowflake Divertor Configuration Reduces ELM and Steady-State Heat Flux

- SF configuration reduces heat flux 2-3X by flux expansion
- $\Delta W(ELM)$ reduced
- Core confinement ($H_{98y2} > 2$) and pedestal constant
Snowflake Divertor Configuration Reduces ELM and Steady-State Heat Flux

- SF configuration reduces heat flux 2-3X by flux expansion
- $\Delta W(\text{ELM})$ reduced
- Core confinement ($H_{98y2} > 2$) and pedestal constant
- ELM heat flux reduced dramatically with gas puffing
DIII-D is Advancing the Physics Basis Needed to Support Fusion Energy Development

Address ITER challenges and validate scenarios

Develop basis for steady-state operation

Advance predictive capability for fusion
DIII-D is Advancing the Physics Basis Needed to Support Fusion Energy Development

- Increased electron heating for burning plasma conditions
- Diagnostic and 3D field upgrades for fusion science
- Increased off-axis current drive and new divertor configurations
### Other DIII-D Related Talks at This Conference

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