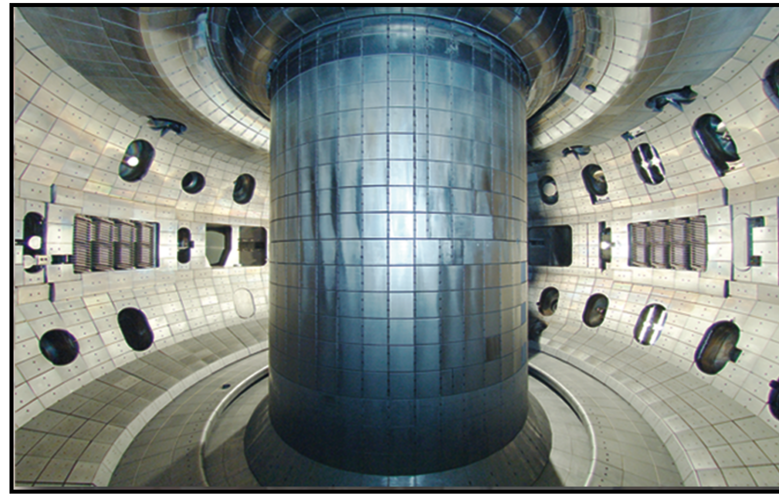
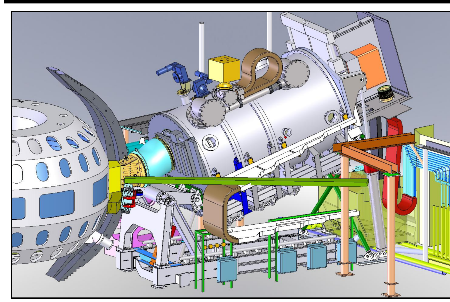
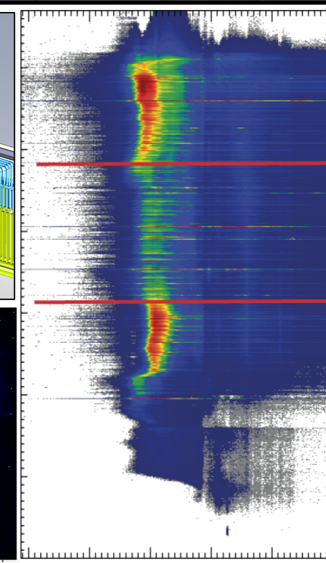
DIII-D Research Toward Resolving Key Issues for ITER and Steady-State Tokamaks

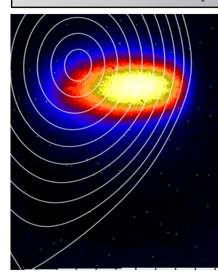


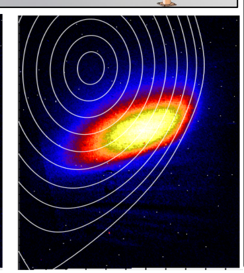
by
D.N. Hill for the DIII-D Team
Lawrence Livermore National Laboratory





Presented at
2012 IAEA Fusion Energy Conference
San Diego, California

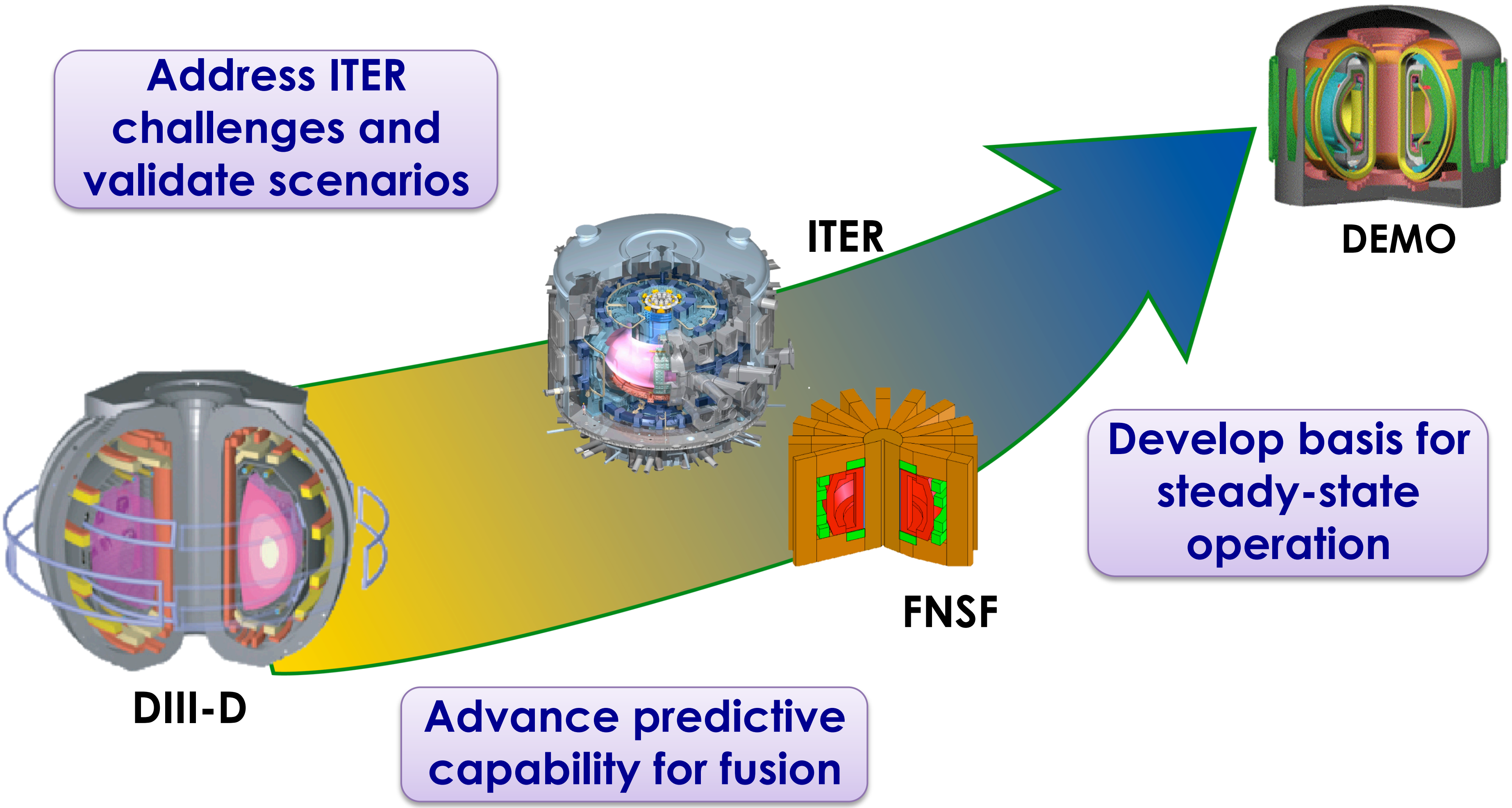




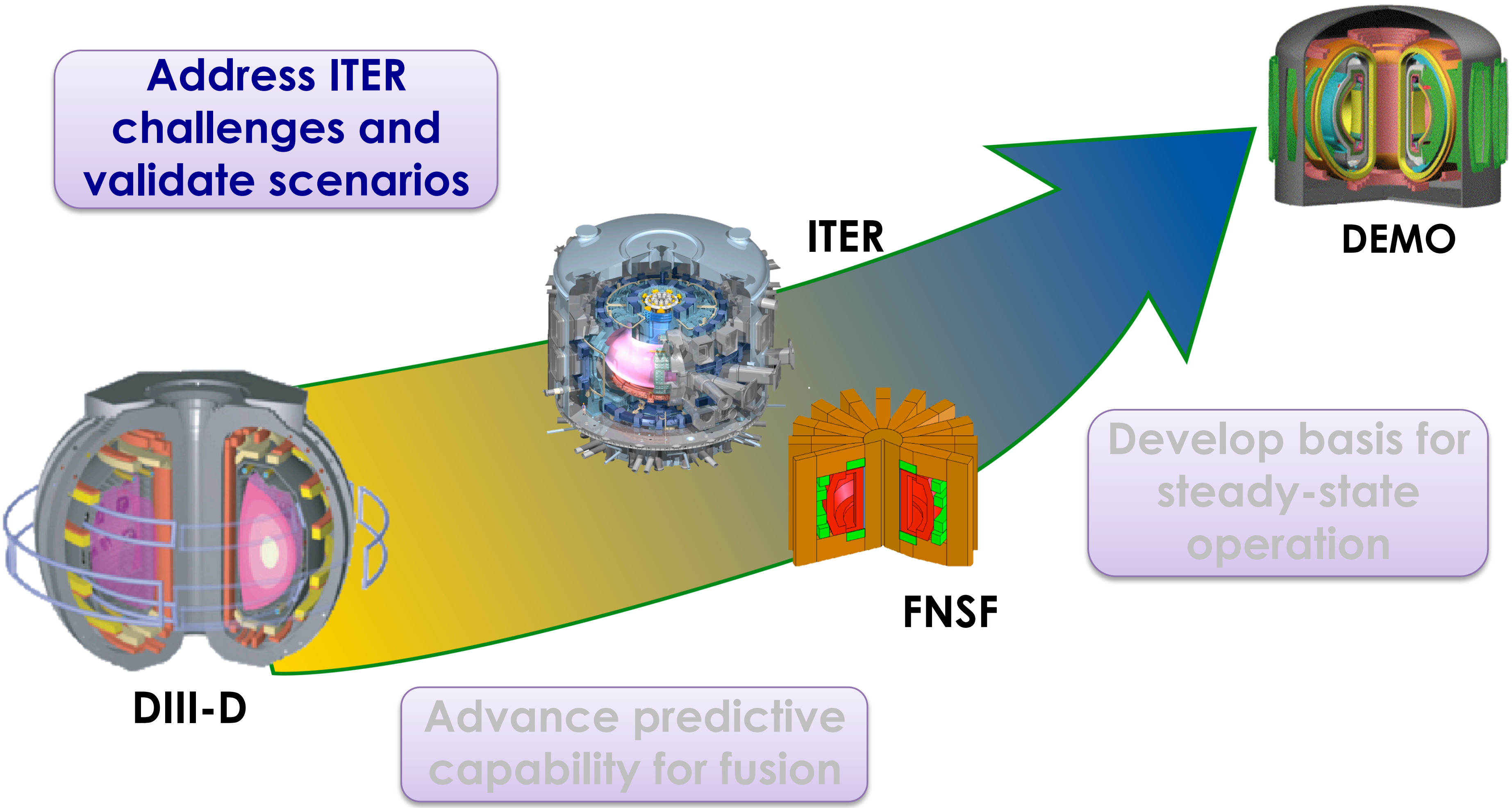
October 8–13, 2012

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and DE-FC02-04ER54698. LLNL-PRES-588692

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

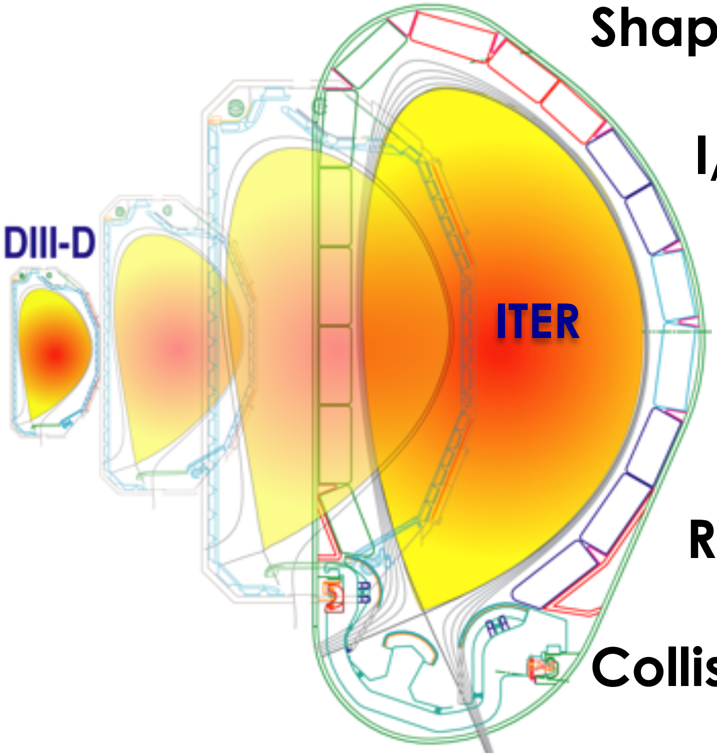


DIII-D is Advancing the Physics Basis Needed to Support Fusion Energy Development



DIII-D is Preparing the Basis for ITER Operation

Match key plasma conditions in ITER where possible



Shape

I/aB

β, β_N

T_e/T_i

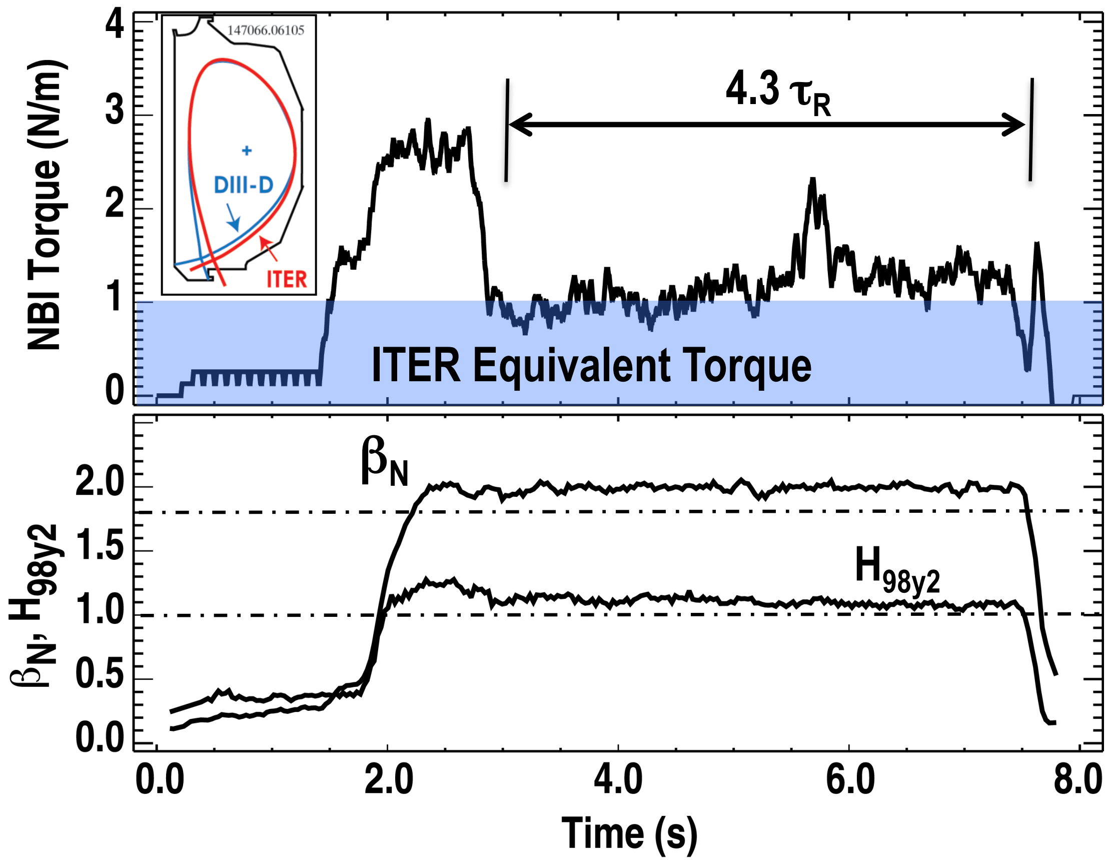
Rotation

Collisionality

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

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

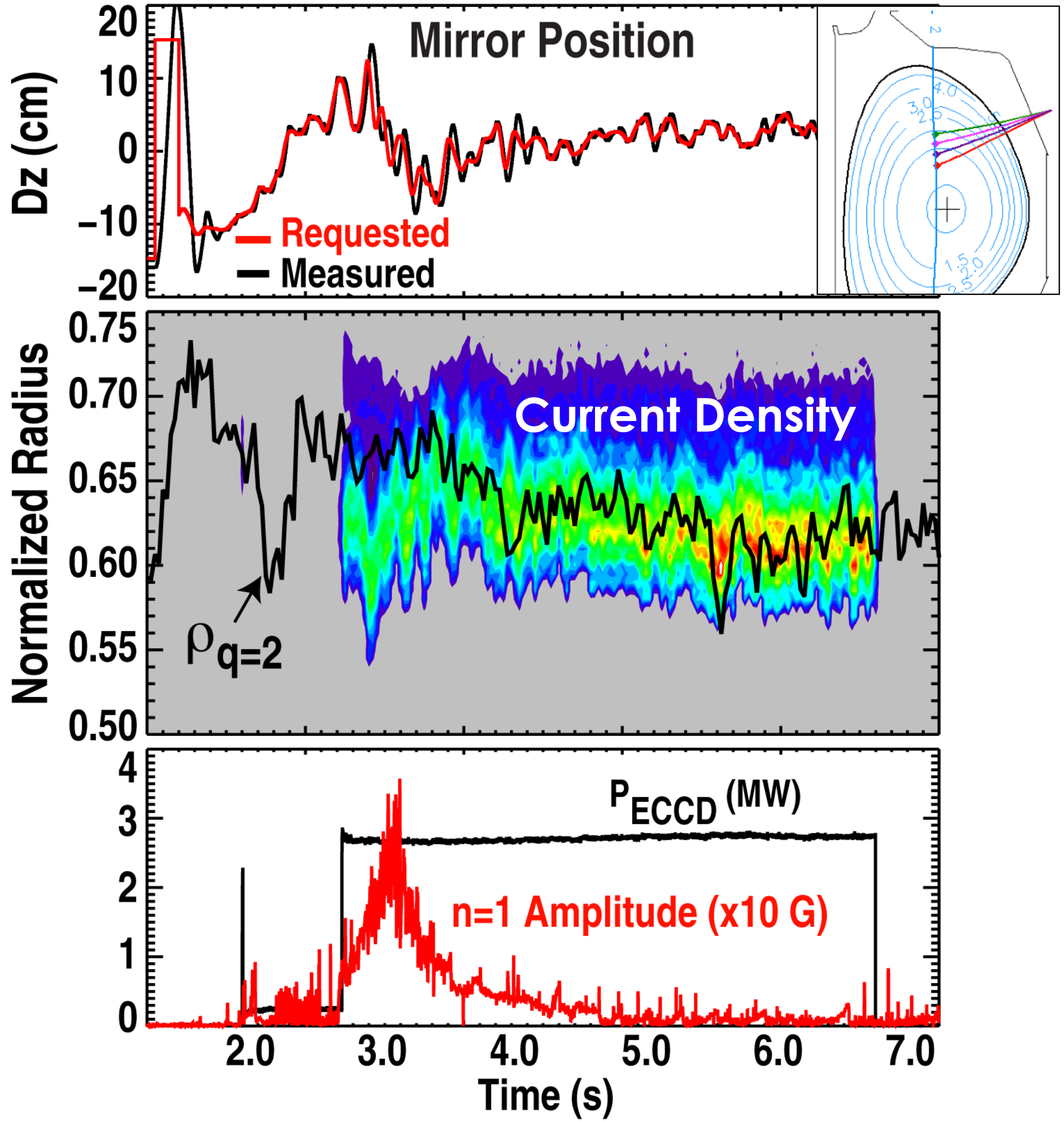


- **ITER – equivalent NBI torque**
- **ELMing H-mode**
  - Matches shape
  - Matches I/aB
- **Broad ECCD near *q*=3/2 controls tearing modes**

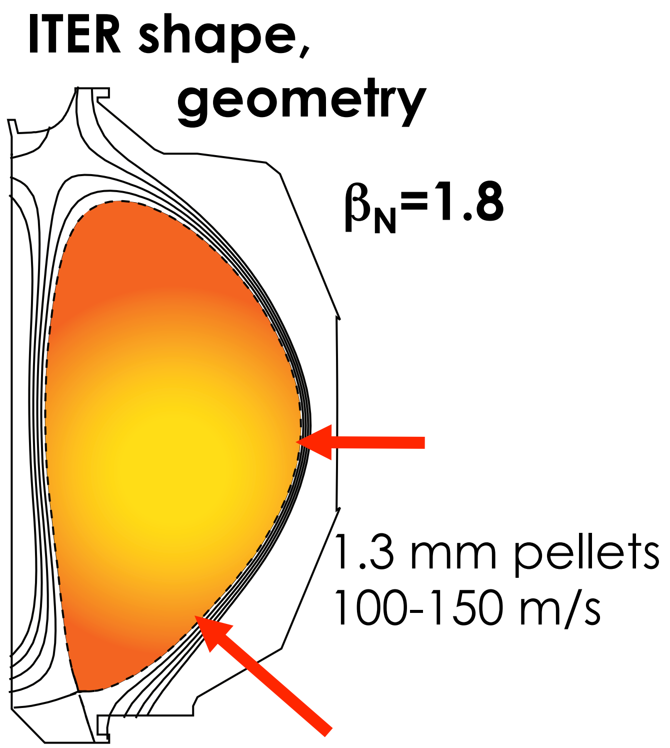
G. Jackson, EX/P2-08

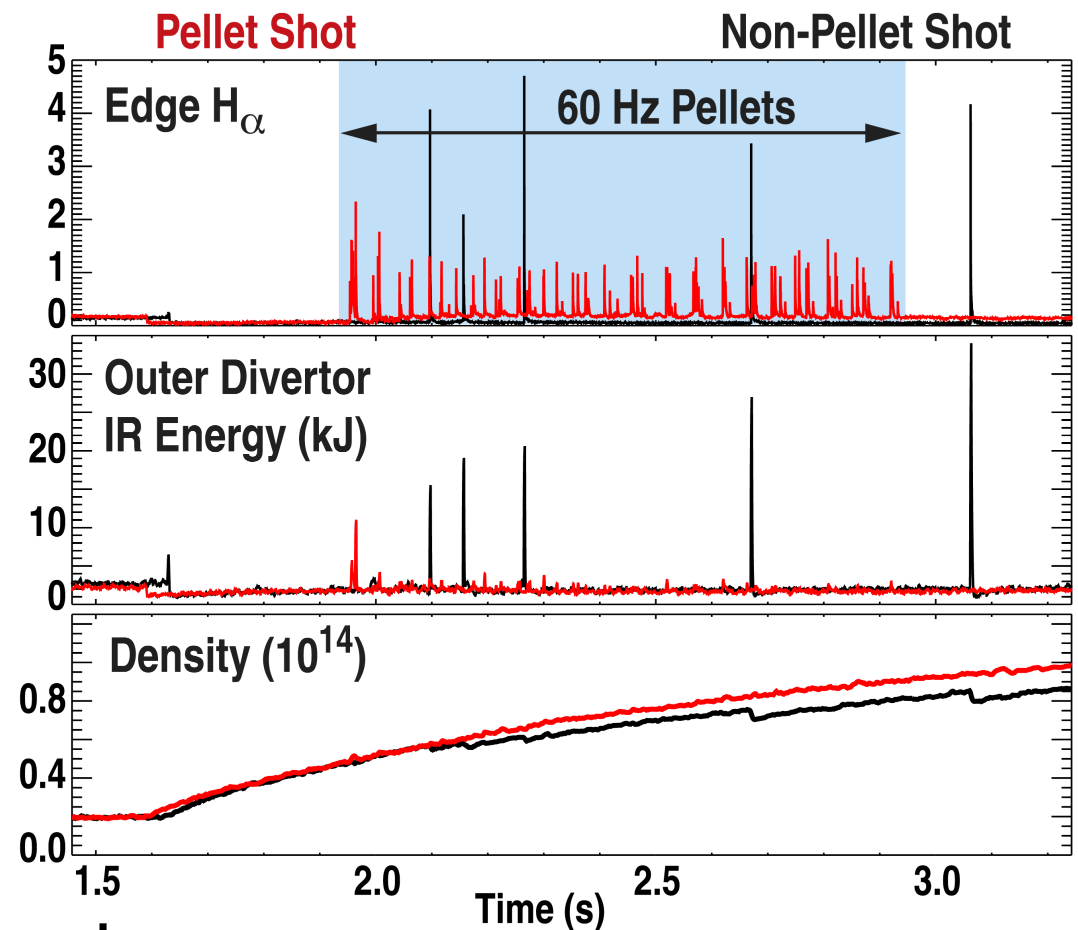
Successful Integration of Key Elements of Tearing Mode Control for ITER

- *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

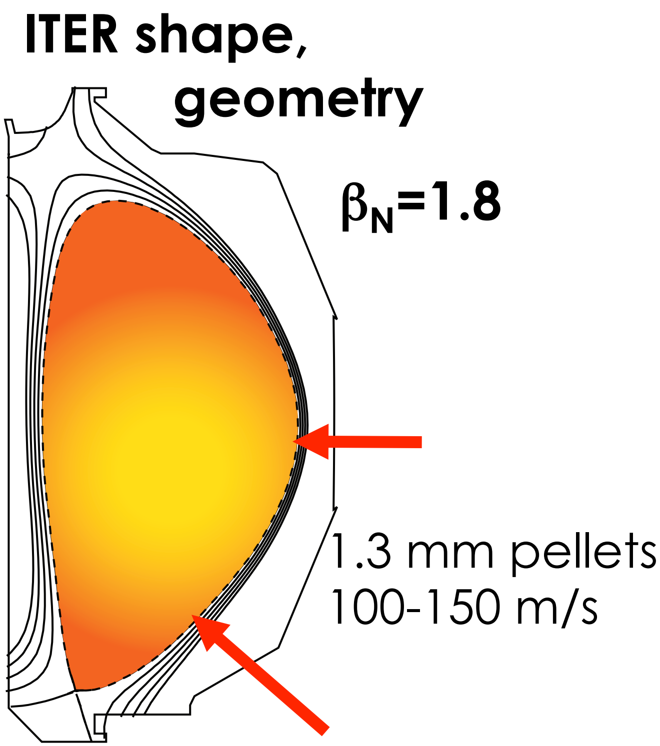


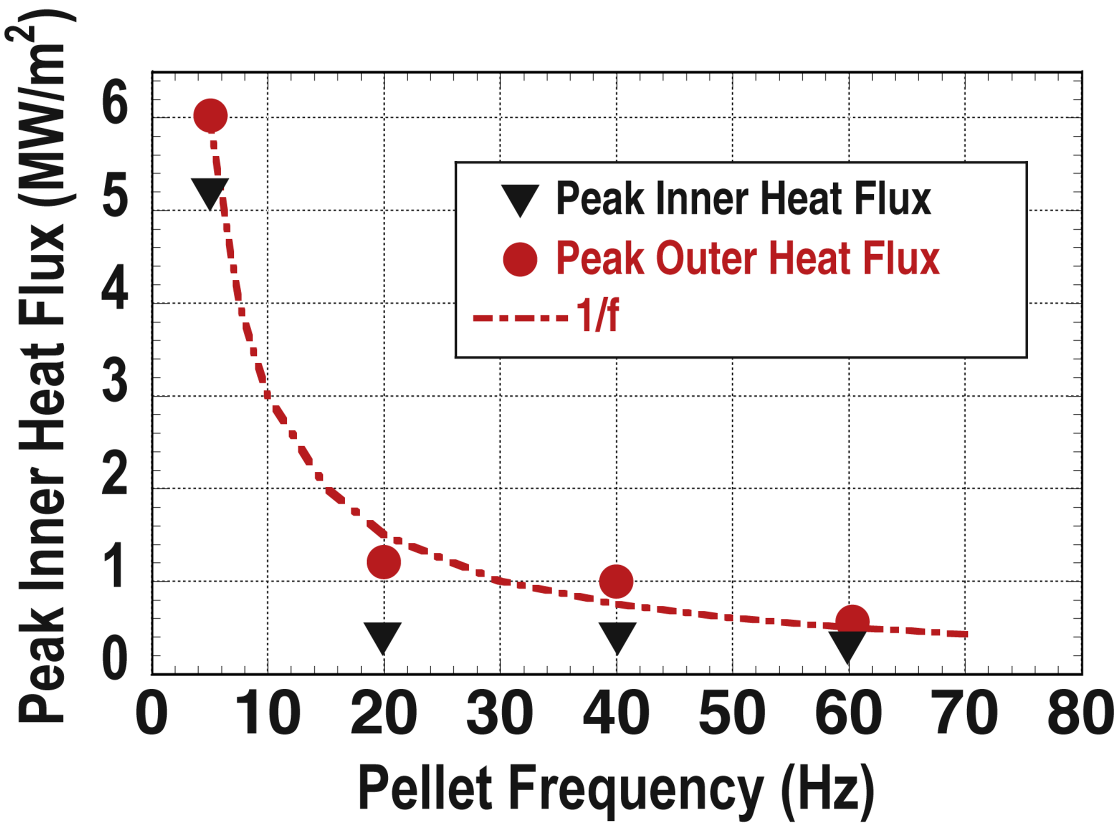


- Reduced ELM energy loss
- Minimal change in confinement
- No fueling increase

L. Baylor, EX/6-2

Pellet Pacing in ITER Baseline Scenario Yields 12x Lower ELM Divertor Heat Pulse





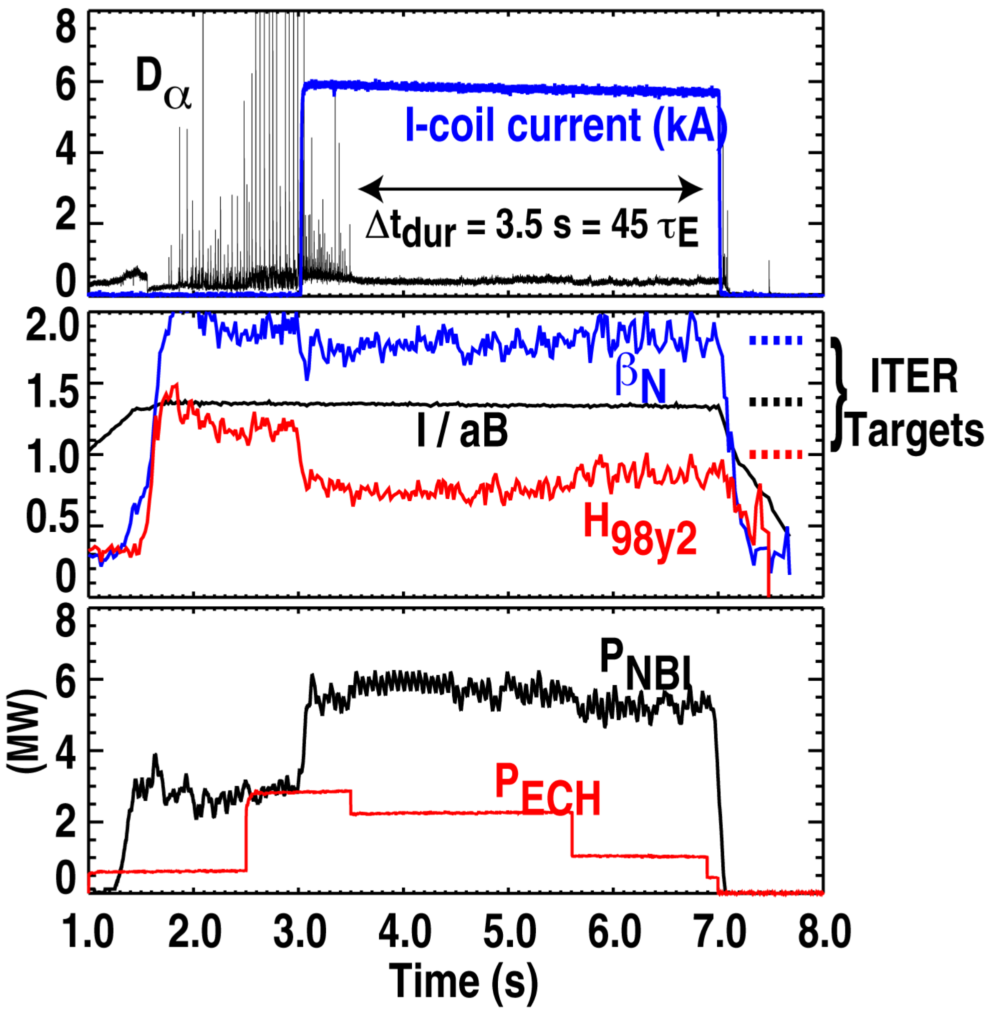
- **Reduced ELM energy loss**
- **Minimal change in confinement**
- **No fueling increase**

$$f_{pellet} \times \Delta q_{div} = const$$

L. Baylor, EX/6-2

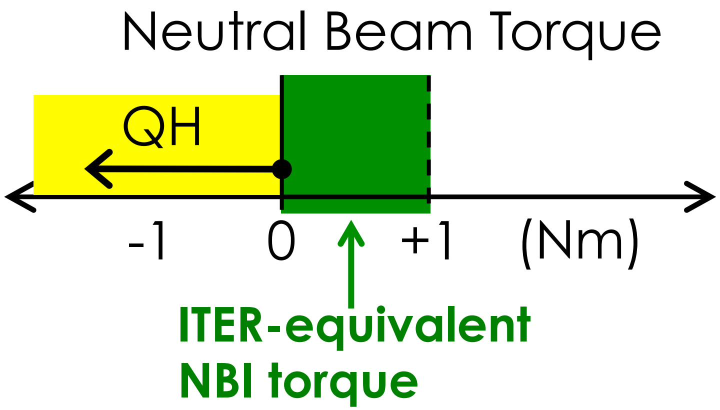
Sustained RMP ELM Suppression Extended to ITER Baseline Scenario

- **n=3 perturbation with internal coils**
- **Match ITER**
  - Shape and I/aB
  - β_N = 1.8 and ν^* = 0.12
- **Suppression at low collisionality using n=2 configuration**
- **ELM suppression also shown in helium plasmas**



M. Wade, EX/3-1
T. Evans EX/P1-25

Operating Range for ELM-free QH-mode Extended to ITER Relevant Torque Using External 3D Coils

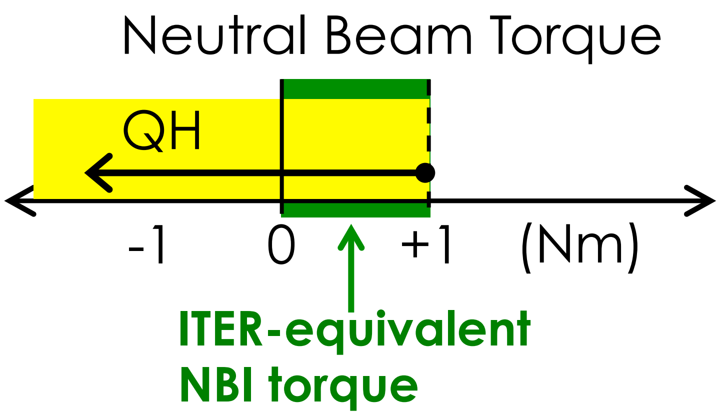


- **Achieved using external n=3 coils to drive edge rotation shear**

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

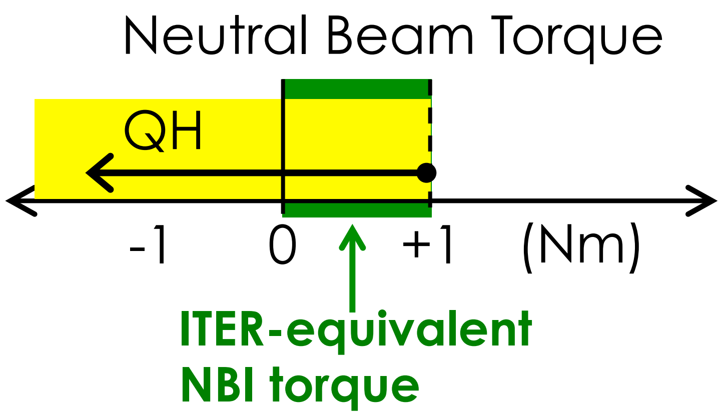


- **Achieved using external n=3 coils to drive edge rotation shear**

QH-mode is an attractive candidate scenario for ITER

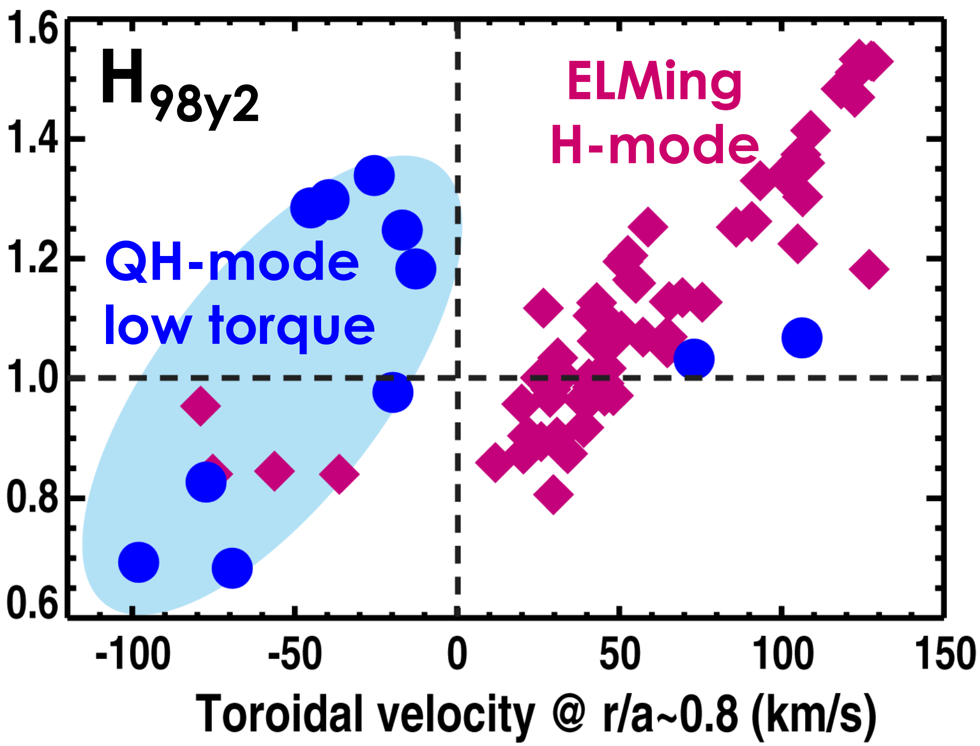
K. Burrell, EX/P4-08

Operating Range for ELM-free QH-mode Extended to ITER Relevant Torque Using External 3D Coils



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

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

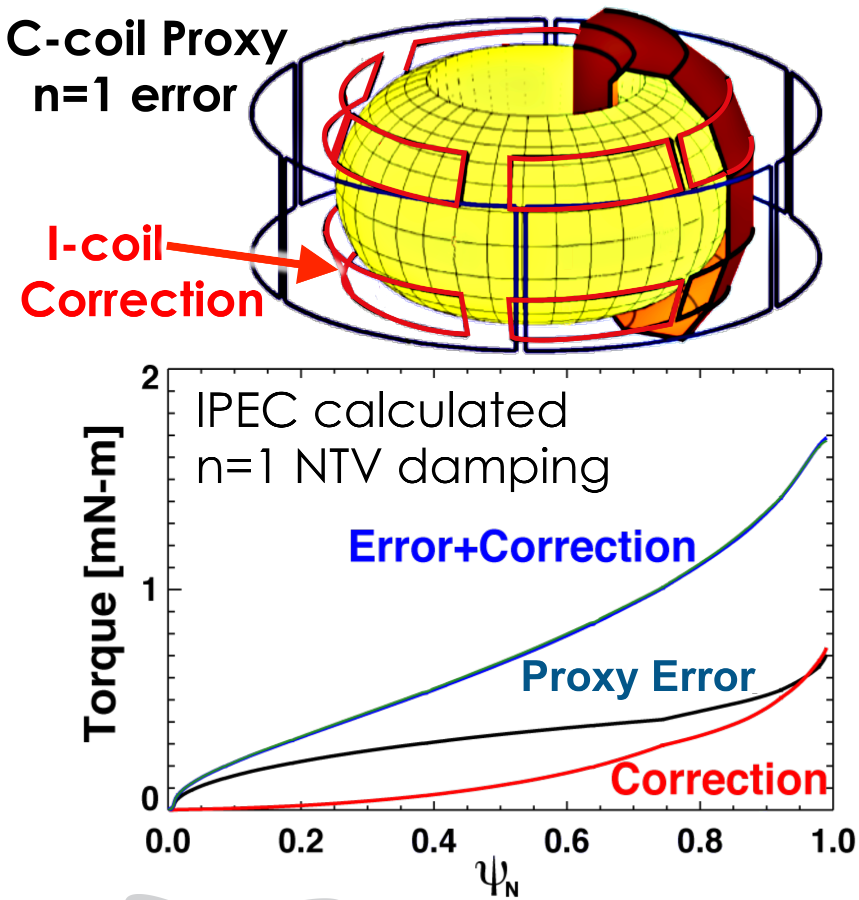


QH-mode is an attractive candidate scenario for ITER

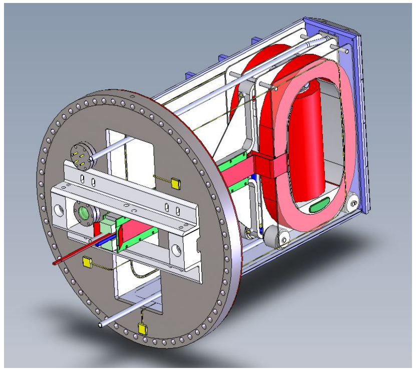
K. Burrell, EX/P4-08

Error Field Correction Strategies Must Include Full Plasma Response of All Field Components

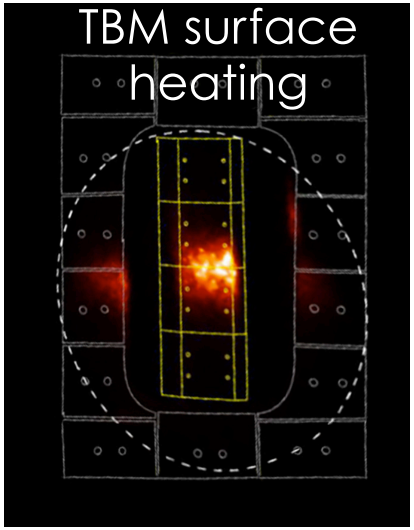
Proxy error field experiments show that correction fields increase NTV damping



"Test Blanket Module"



Similar results with localized error field



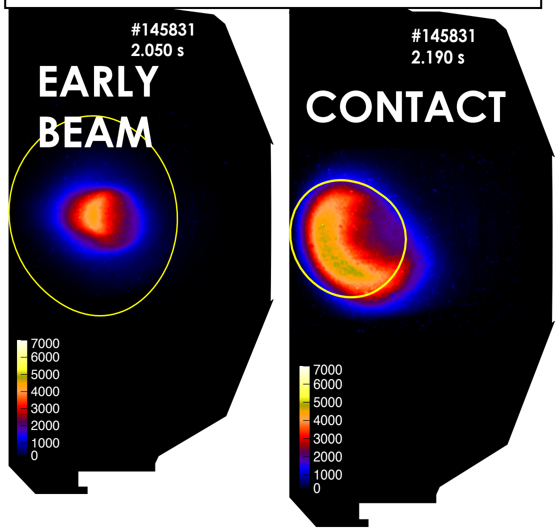
Localized heating tests fast ion transport models

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

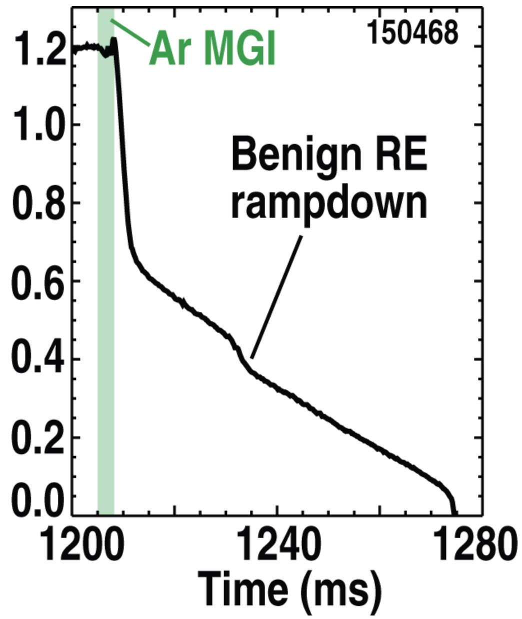
Radial stability provides time to dissipate runaways

RE Synchrotron Emission

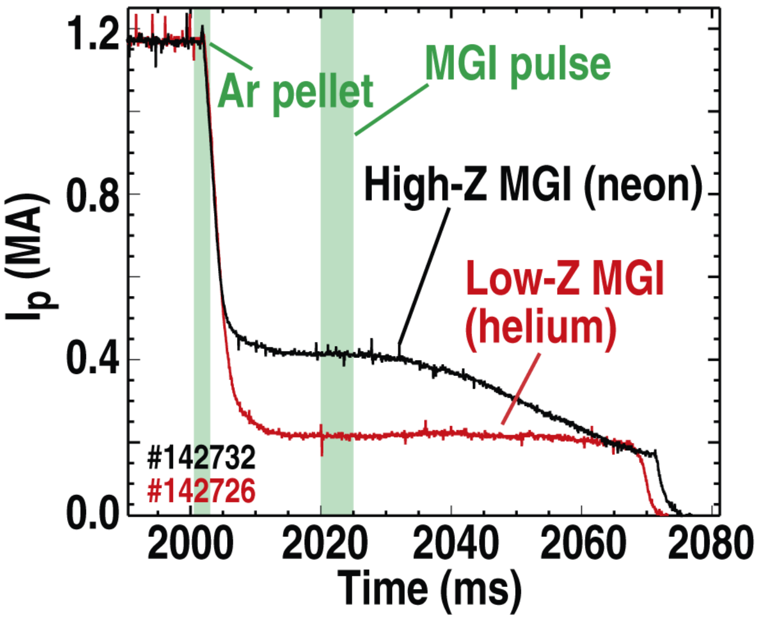


High-Z gas injection increases runaway electron dissipation

MGI ***before*** thermal quench



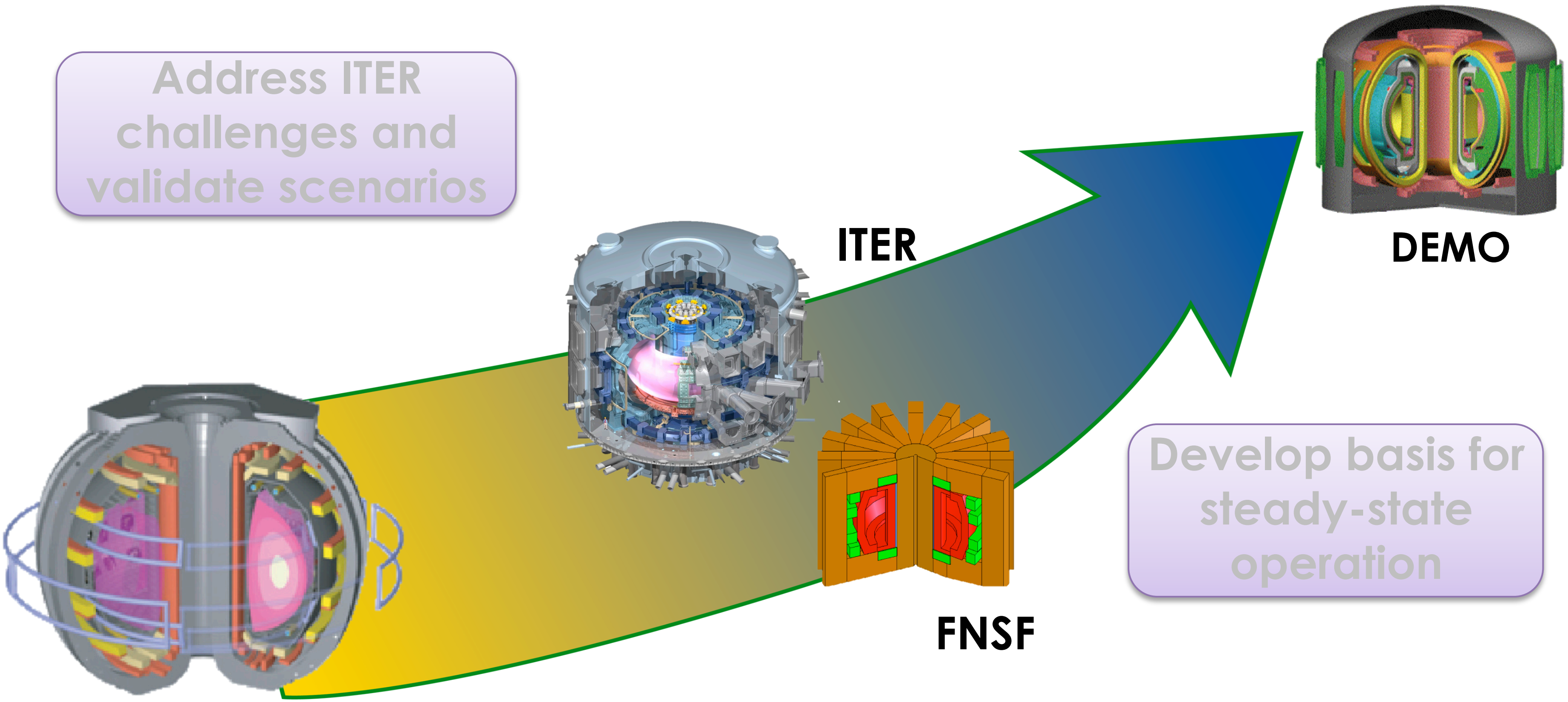
MGI ***after*** thermal quench



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

E. Hollmann, EX/9-2
V. Izzo, TH/P3-13

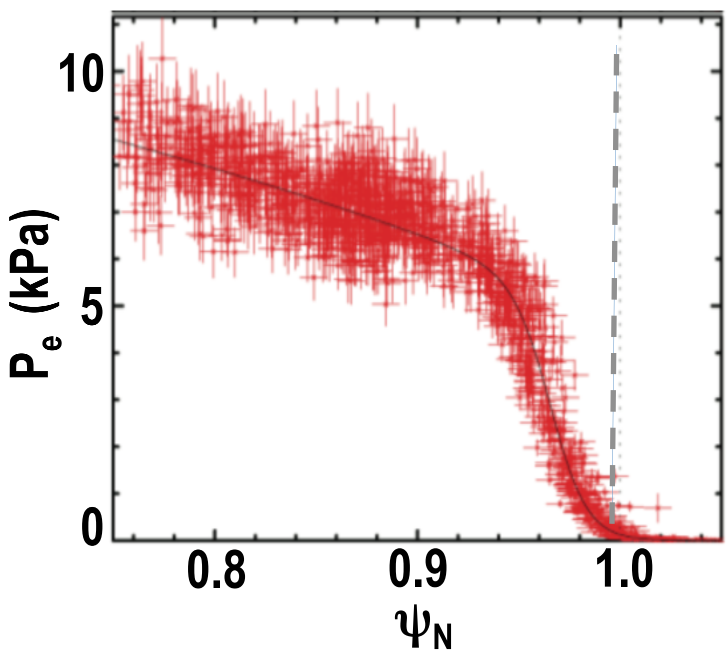
DIII-D is Advancing the Physics Basis Needed to Support Fusion Energy Development

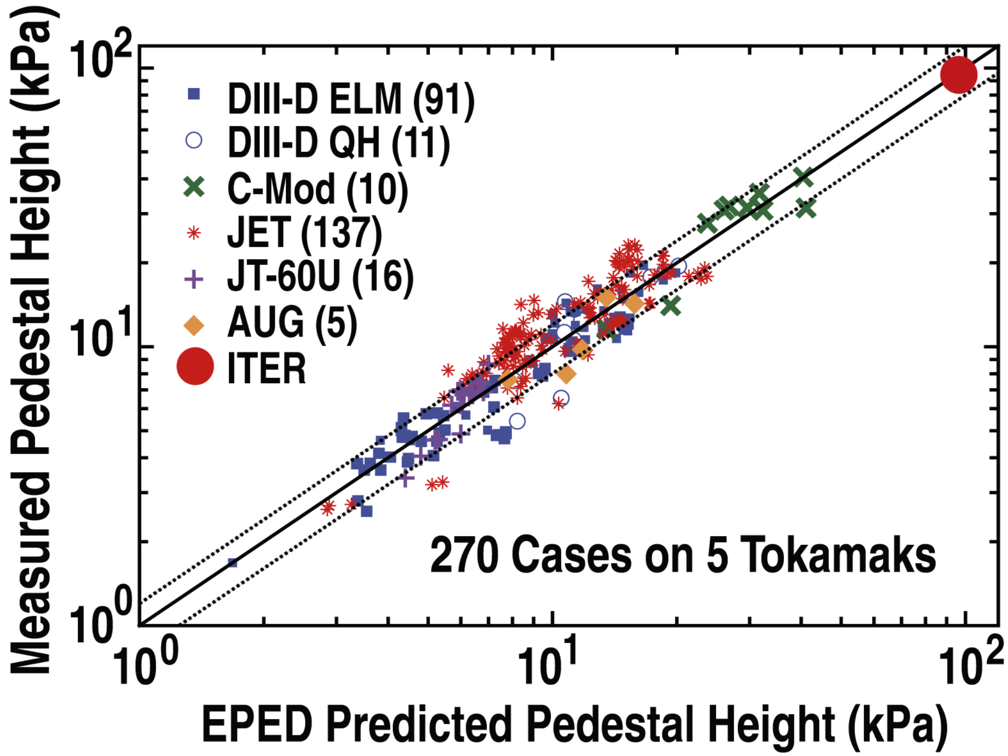


Advance predictive capability for fusion

Coordinated Pedestal Characterization Experiments are Confirming EPED Prediction of the ITER Pedestal

New High Resolution Thomson Scattering

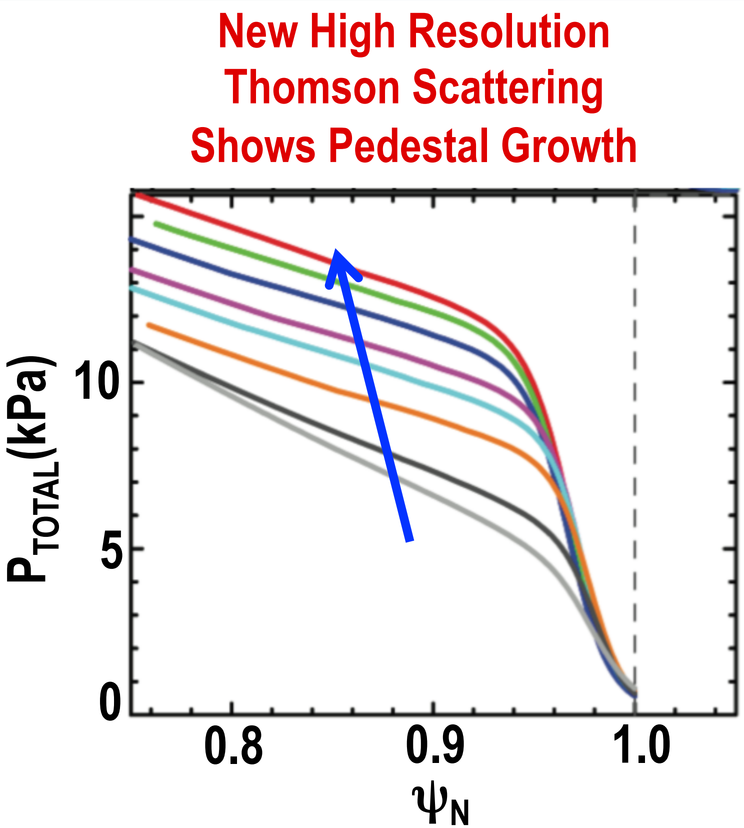


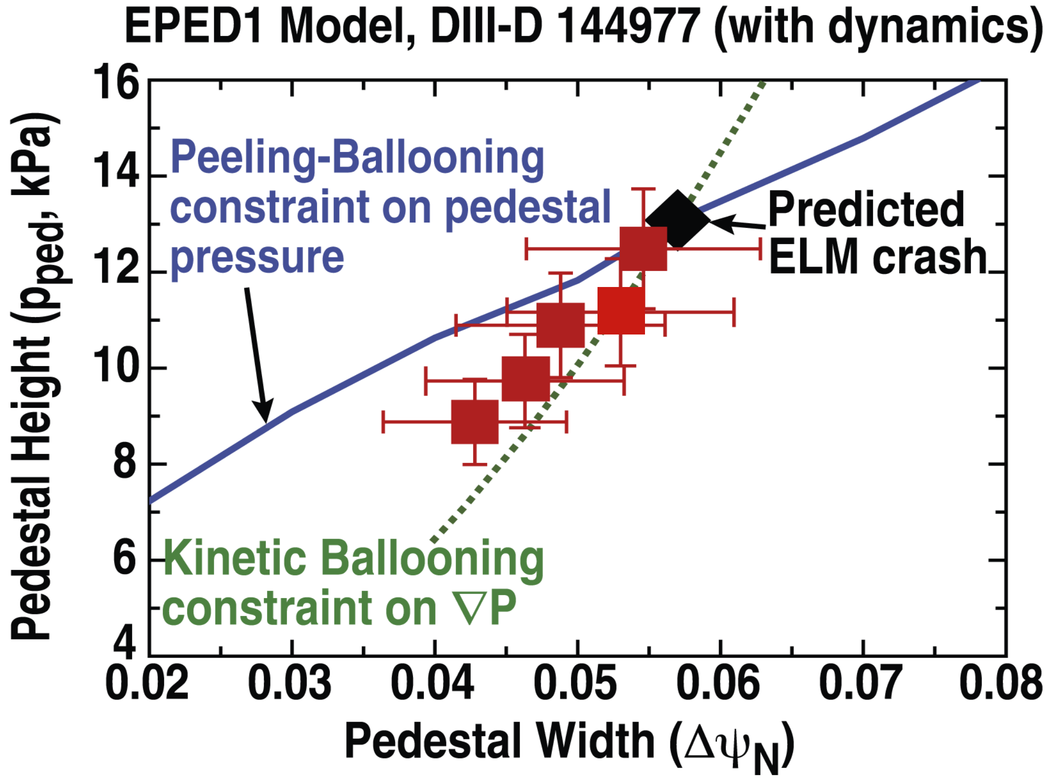


- First-principles stability calculation uses no fitted parameters

R. Groebner, EX/11-4

Pedestal Evolution During ELM Cycle is Observed to Be Consistent With Predictions of EPED Model





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

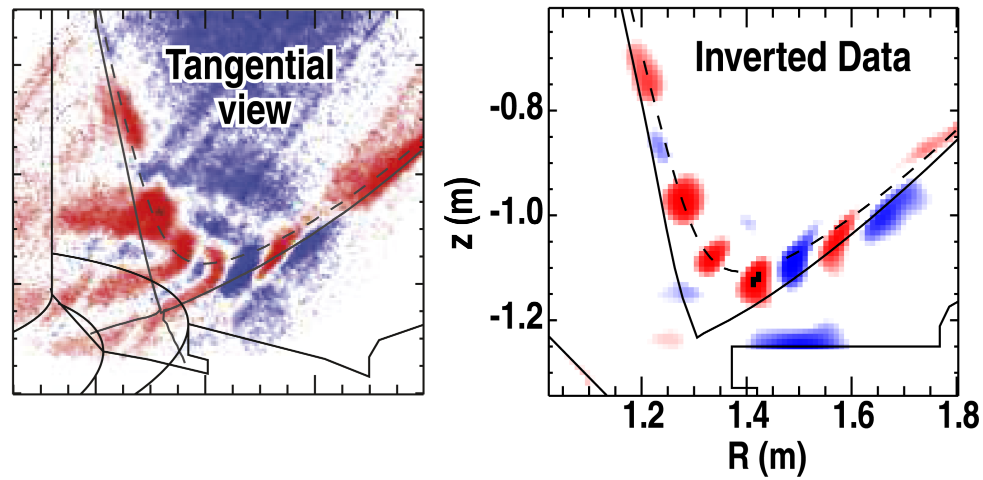
P. Snyder, TH/P3-17

Modulated RMP Experiments Point to Island at Top of Pedestal Inhibiting Pedestal Growth and ELMs

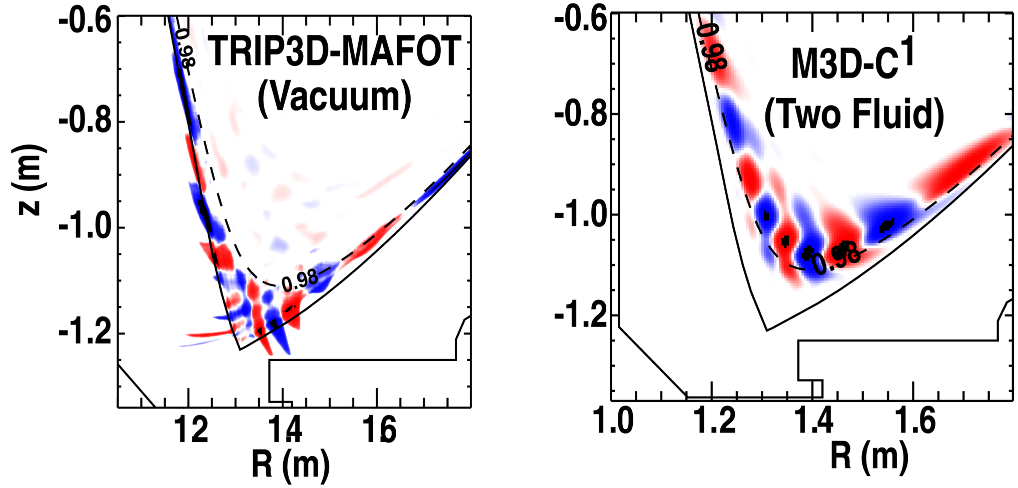
- **RMP rotation reveals MHD response**
  - Displacements seen in X-point SXR imaging
  - Compared with vacuum field and two-fluid MHD simulation

- **Mechanism: RMP limits width of pedestal**
  - RMP field resonant near top of pedestal
  - Island growth where ω_{*e} ~0
  - Island limits inward expansion of high-gradient pedestal

Experiment: SXR data

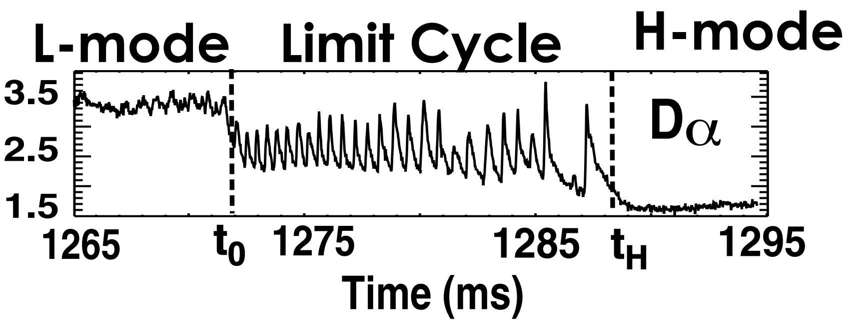


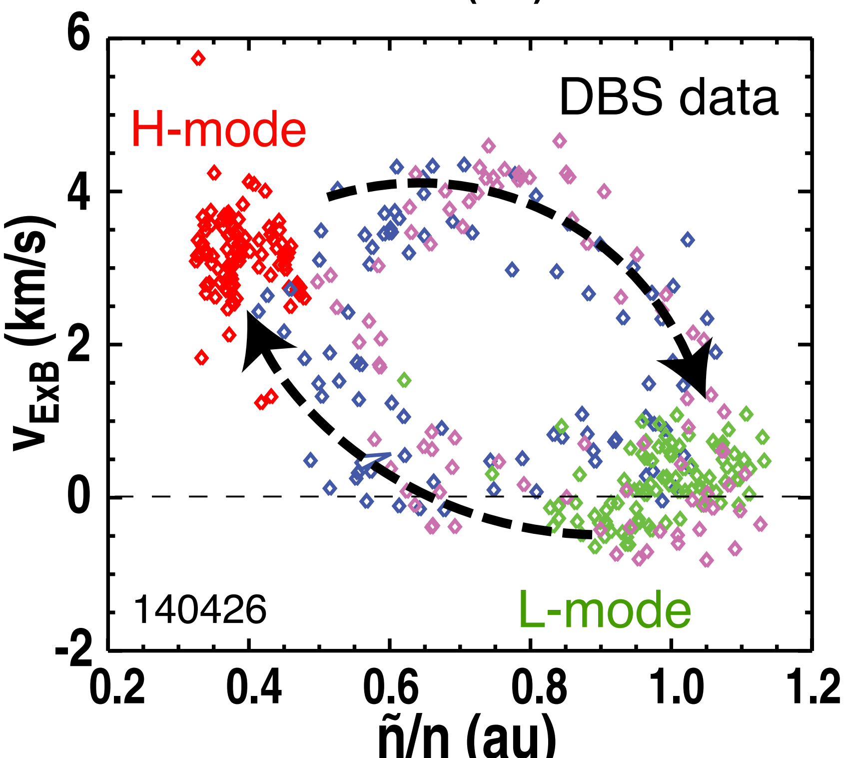
Simulation: SXR Data



N. Ferraro, TH/P4-21
G. McKee, EX/P7-06

Edge Fluctuation and Flow Measurements Are Beginning to Reveal H-mode Transition Dynamics



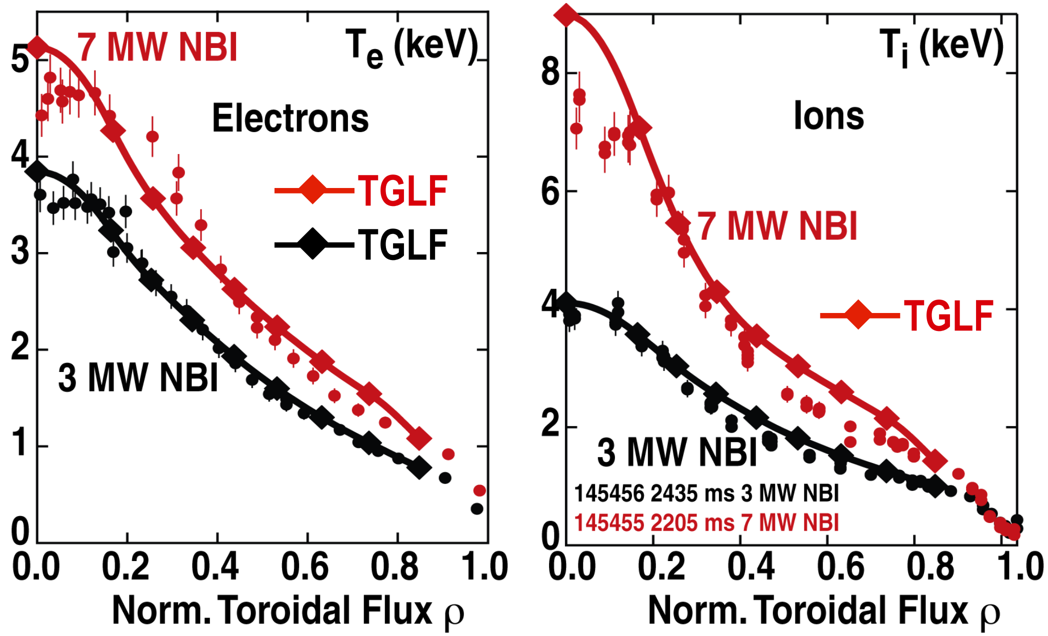


- L-H transition trigger is key to predicting threshold power
- Repetitive sampling of L-H transitions during limit cycle oscillations
- New data shows interplay between HF turbulence and LF turbulent flow

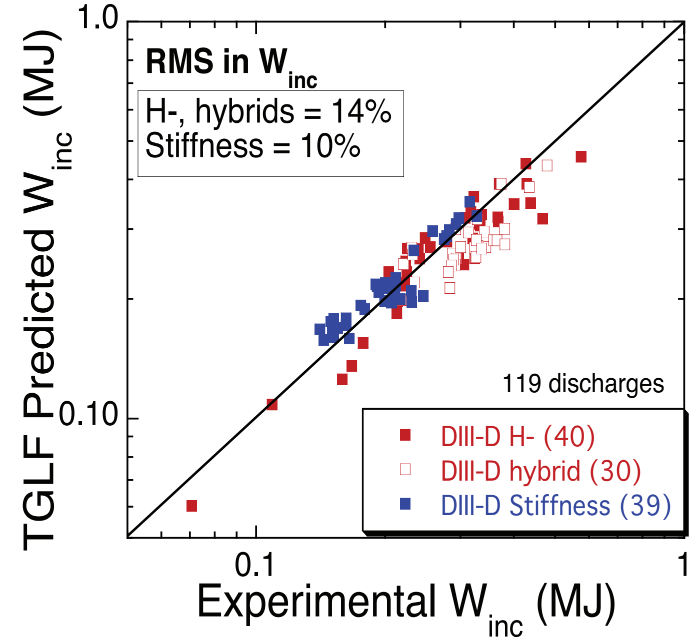
G. Tynan, EX/10-3 L. Schmitz, EX/P7-17
Z. Yan, EX/P7-05 P. Gohil, ITR/P1-36

Core Transport H-mode Stiffness Experiments Support TGLF Predictions for ITER

DIII H-mode Profiles



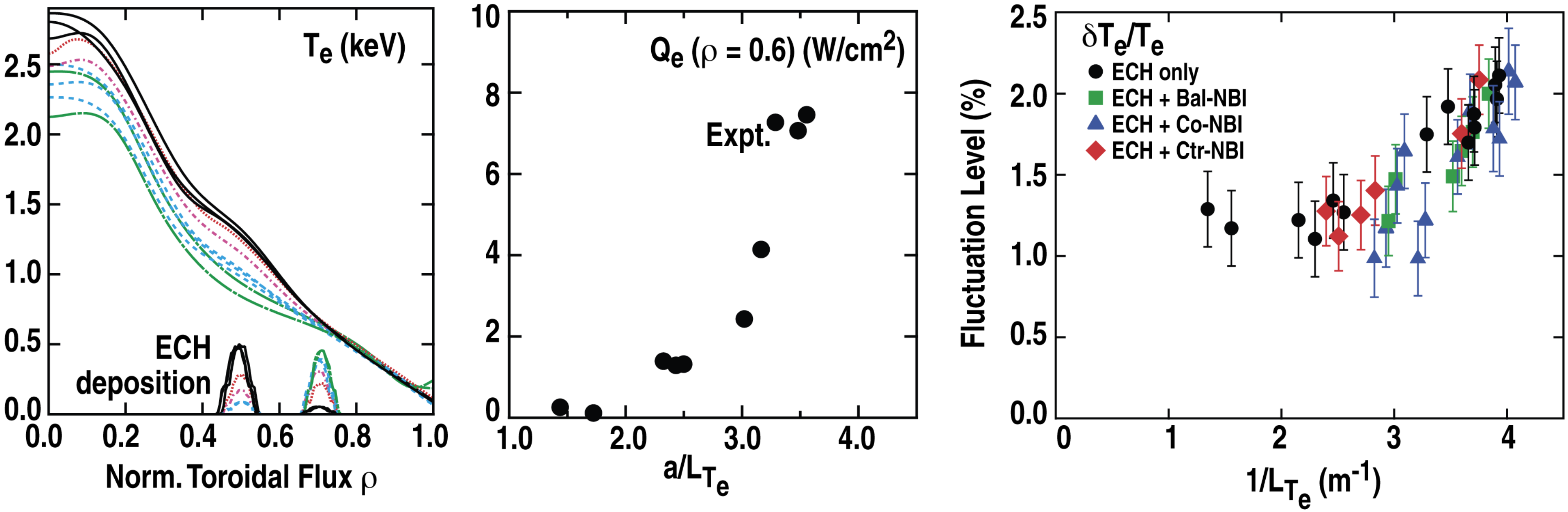
TGLF Simulations of DIII-D



- Stiffness refers to sharp increase in transport above a critical ∇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

T. Luce, EX/P3-18
G. Staebler, TH/8-2

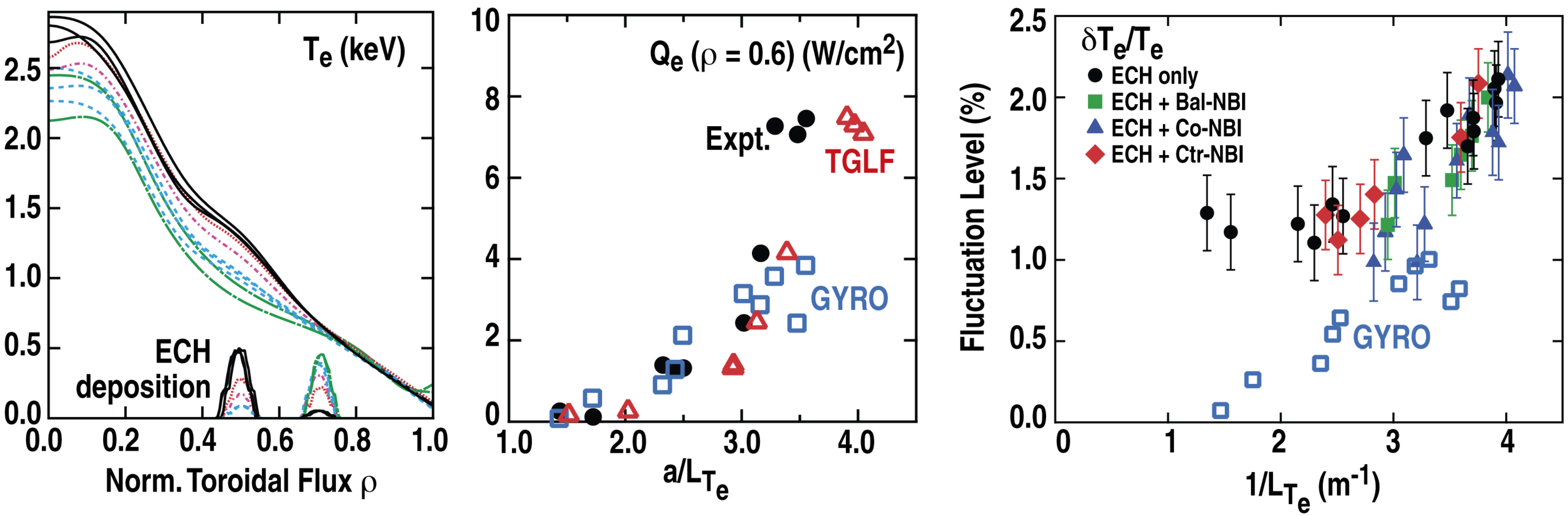
Critical-Gradient Transport Experiments Test Profile Stiffness Predictions



- Vary ECH location to change L-mode ∇T_e with T_e ~ 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

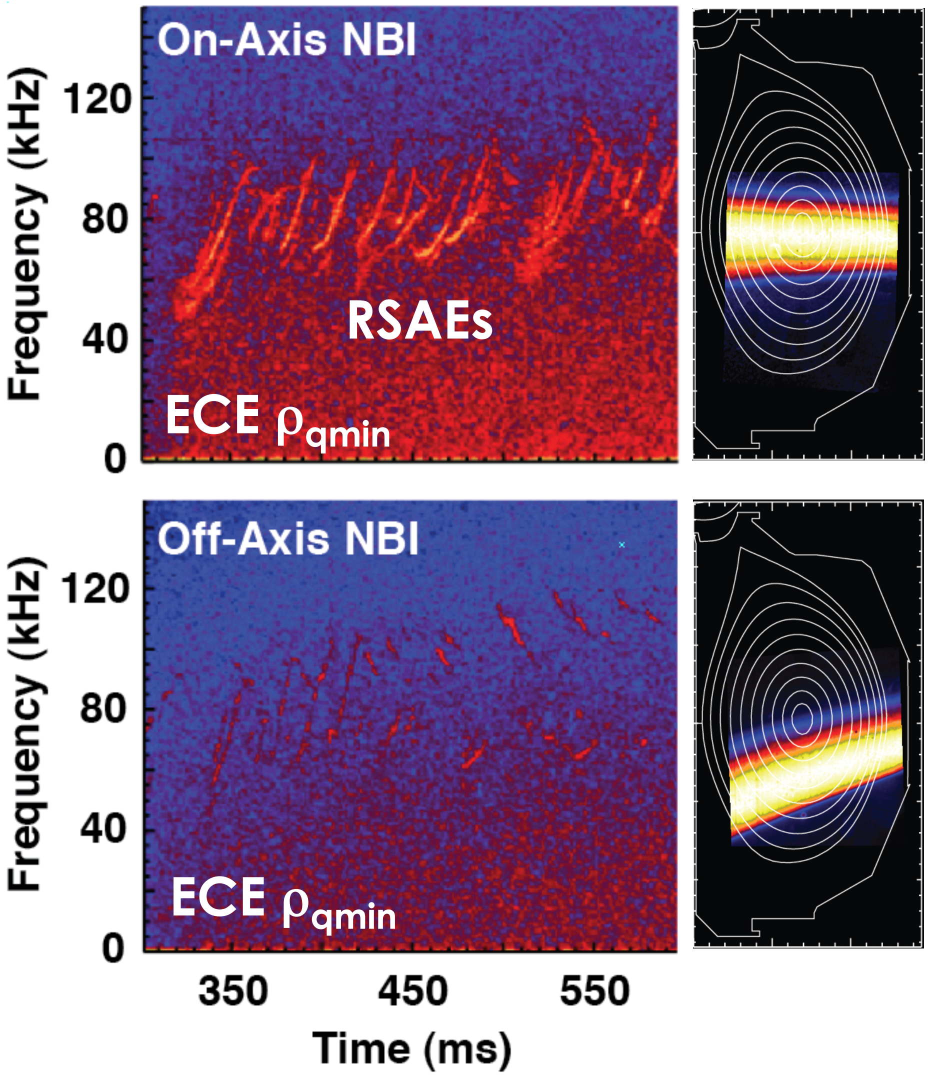
Critical-Gradient Transport Experiments Test Profile Stiffness Predictions



- Vary ECH location to change L-mode ∇T_e with T_e ~ 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

Off-Axis Beam Allows Variation of Alfvén Eigenmode Drive and Fundamental Tests of Stability Models

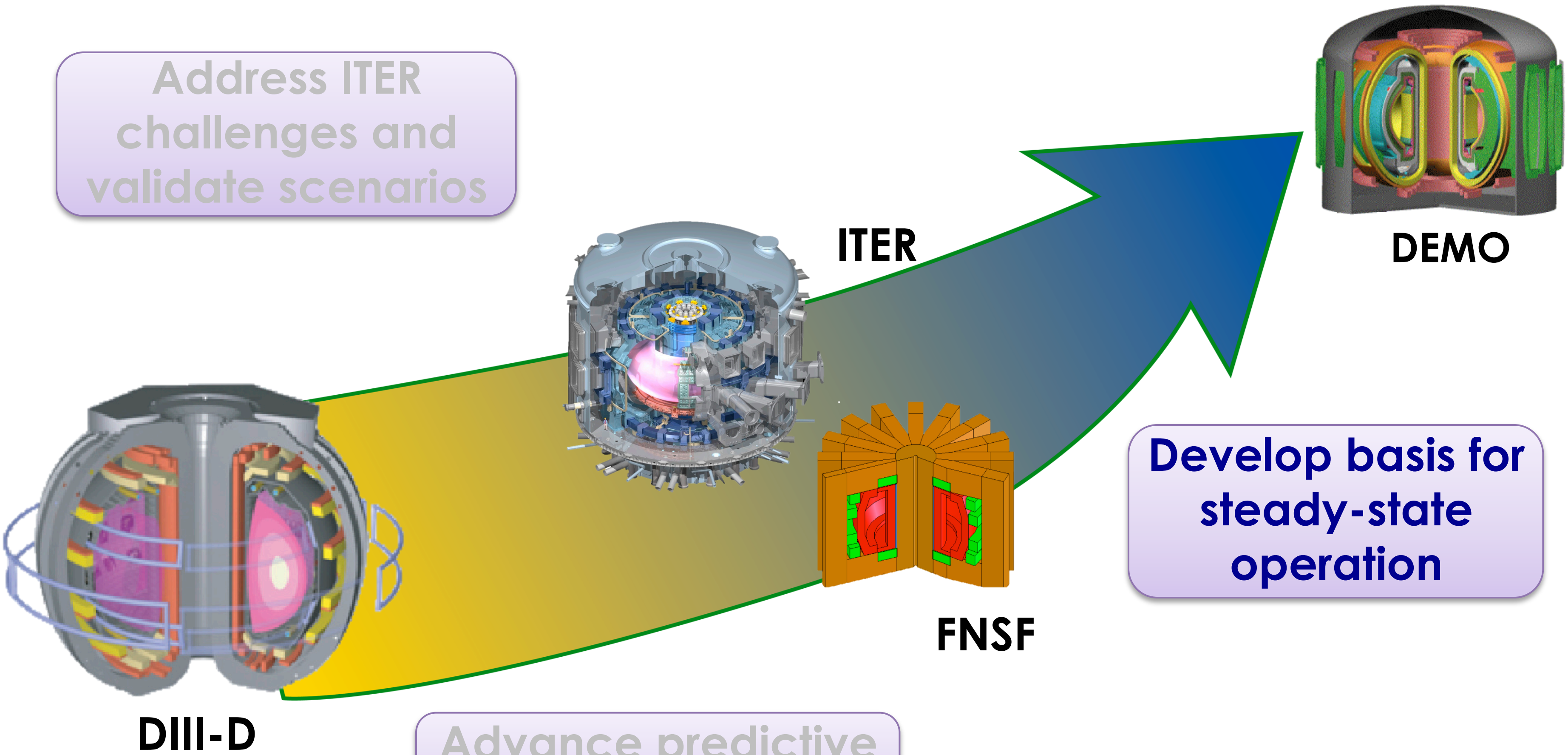


- Vary fast ion pressure gradient to change Alfvén Eigenmode (AE) drive/ stability
- Reversed-Shear AEs mostly stable with off-axis injection
- Comparisons with kinetic codes (GTC, GYRO, TAEFL) are underway

W. Heidbrink, EX/P6-22

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

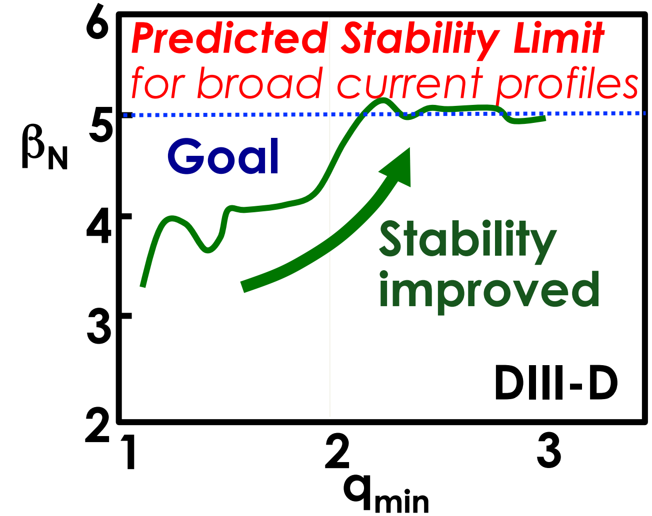
Steady-State Fusion Requires Broad Current and Pressure Distributions

- Steady state fusion requires:

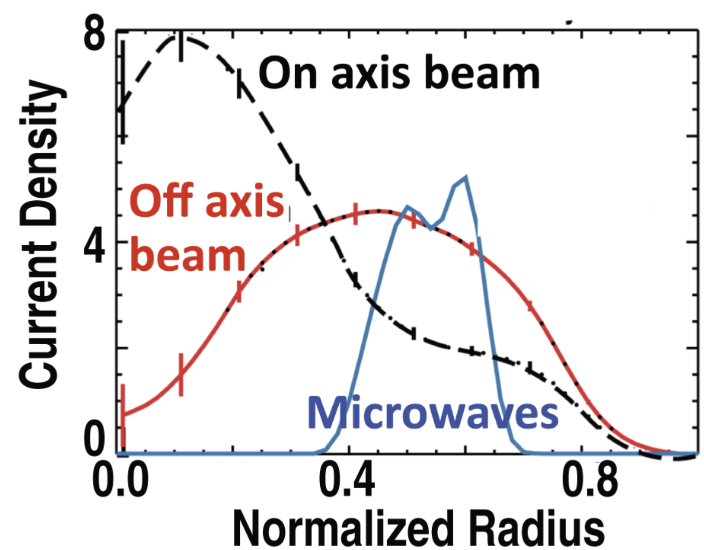
$$\underbrace{\text{High pressure}}_{\text{Fusion power}} + \underbrace{\text{High self-driven current}}_{\text{Steady-state high energy gain}}$$

➡ High normalized beta, β_N

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



Off-axis NBI and ECCD enable steady-state scenario research

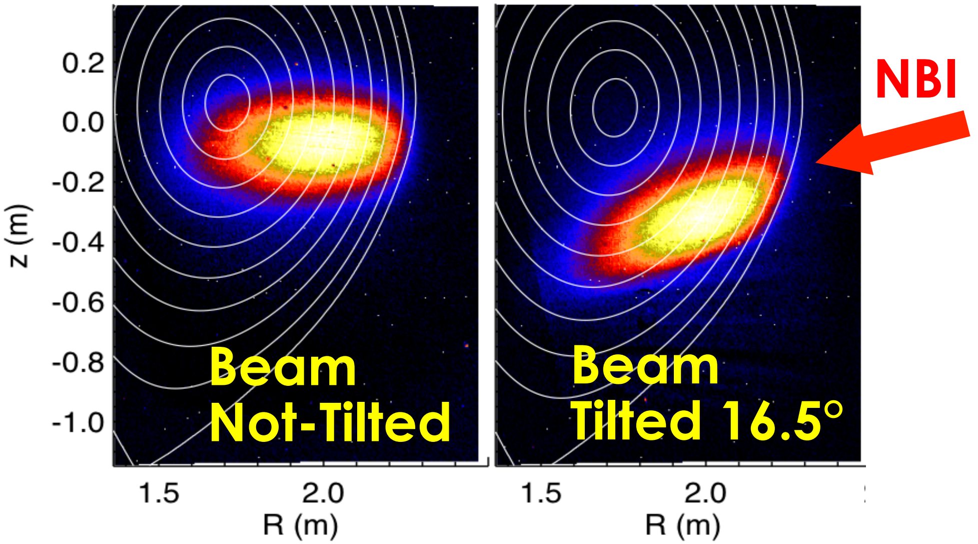


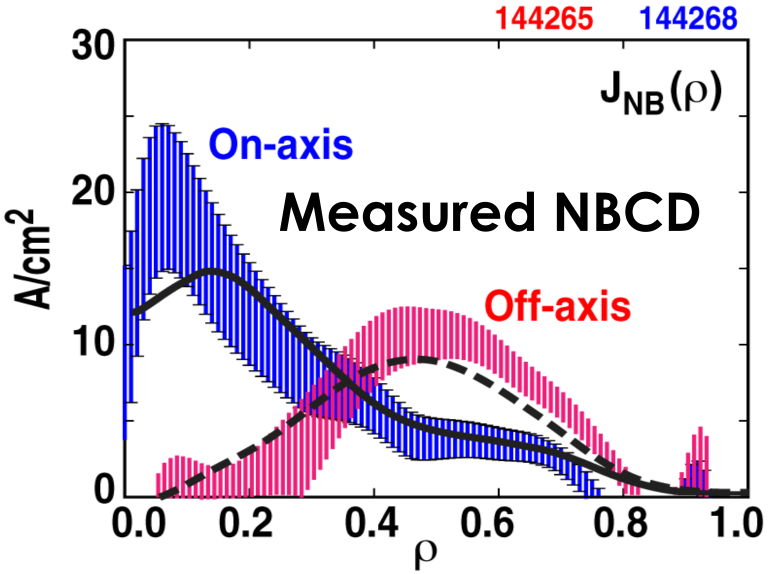
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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

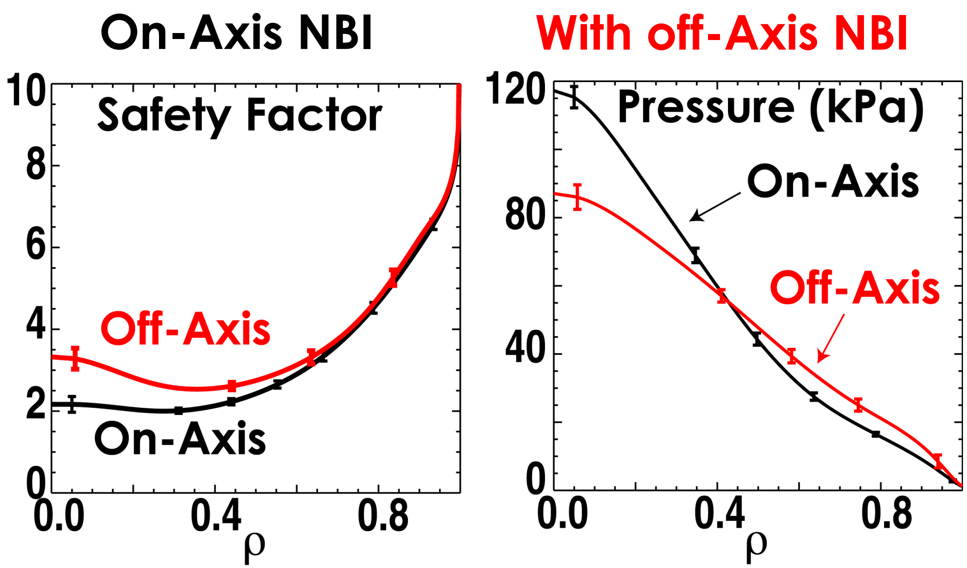
5 min to raise beam,
30 min start to finish

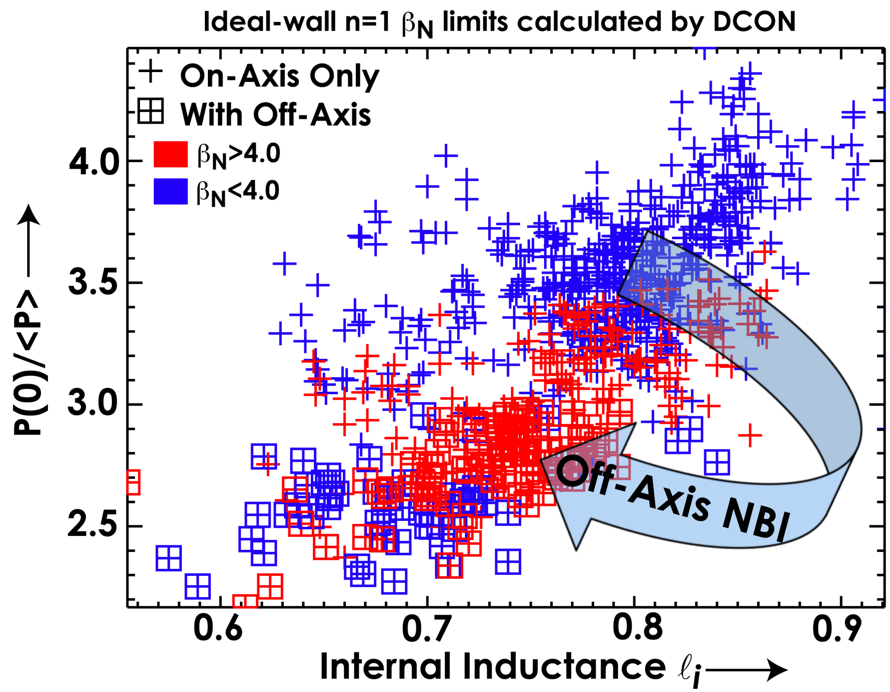




J.M. Park, EX/P2-13

Off-Axis NBI Produces Broad Current & Pressure Profiles with Sustained q_{min}>2 for Higher β_N Stability Limits



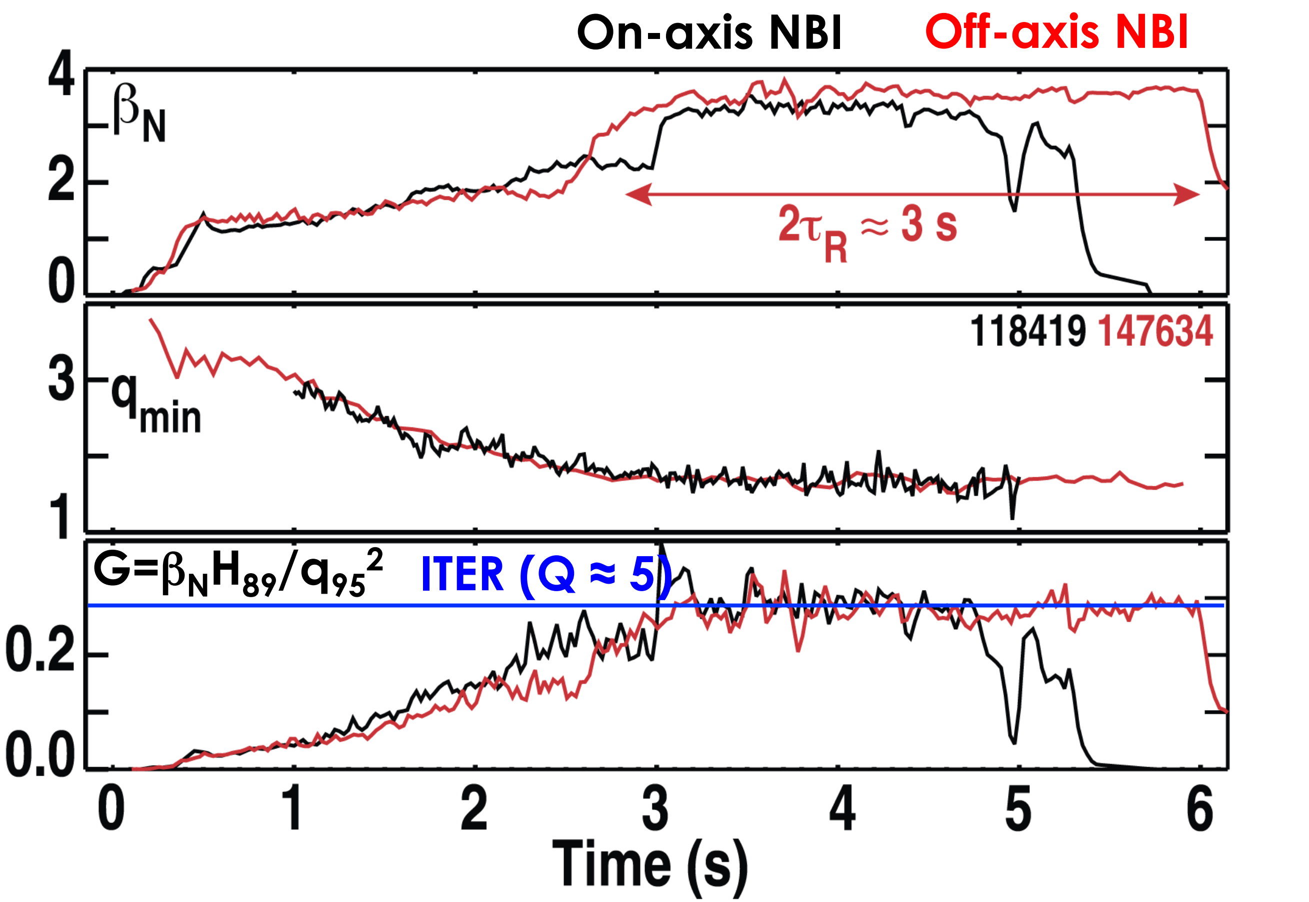


- q_{min}>2 avoids 2/1 tearing modes
- Off-axis NBI broadens current and pressure profiles
- Plasmas have higher predicted stability limits (β_N ~4)

C. Holcomb, EX/1-5

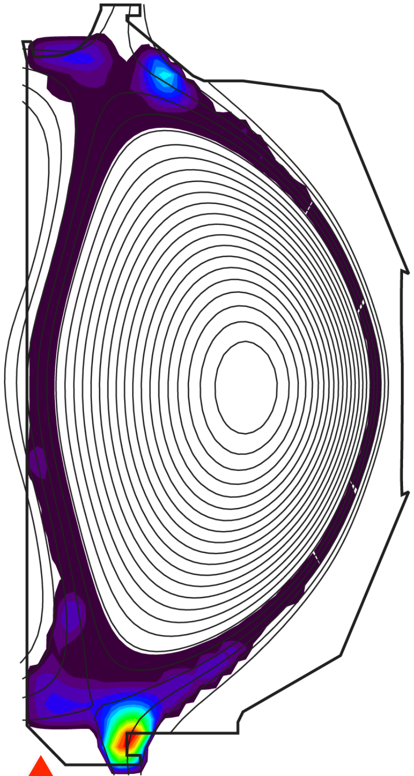
ITER/FNSF Equivalent Performance Demonstrated with Relaxed q_{min} ~1.5

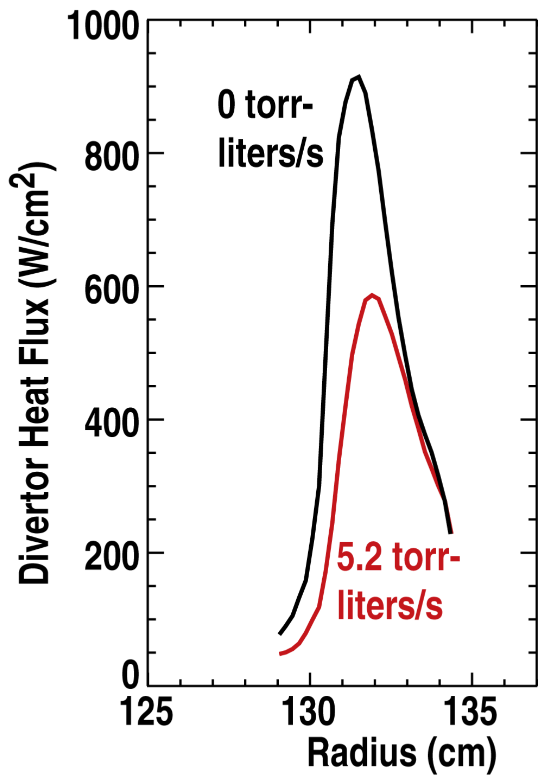
- **Off-axis beam sustains stable stationary operation**
- **f_{NI} = 70%**
- **Modeling shows potential to raise β_N and f_{NI} further**



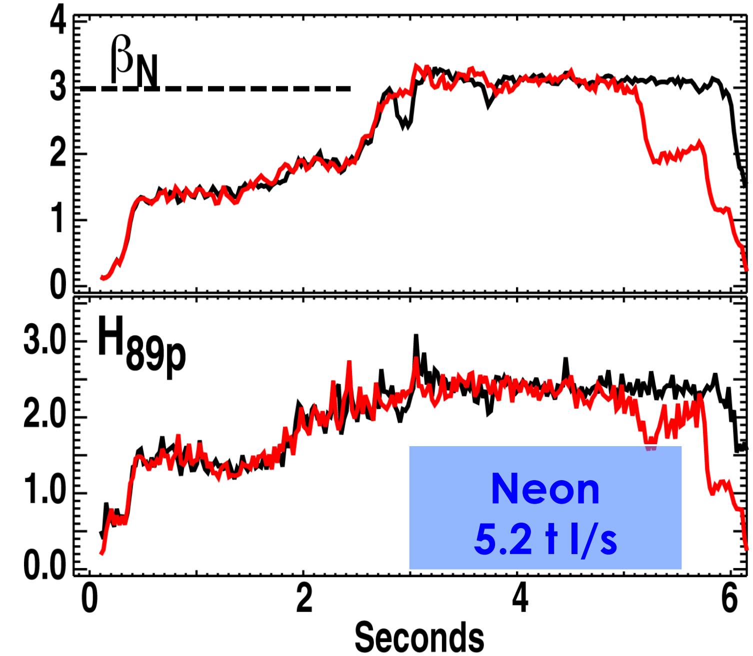
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

q_{min}≈1.5 Scenario Appears Compatible with Radiating Mantle for Divertor Heat Flux Reduction





Peak divertor heat flux reduced ~35%



***P_{RAD}* doubles without significant performance degradation**

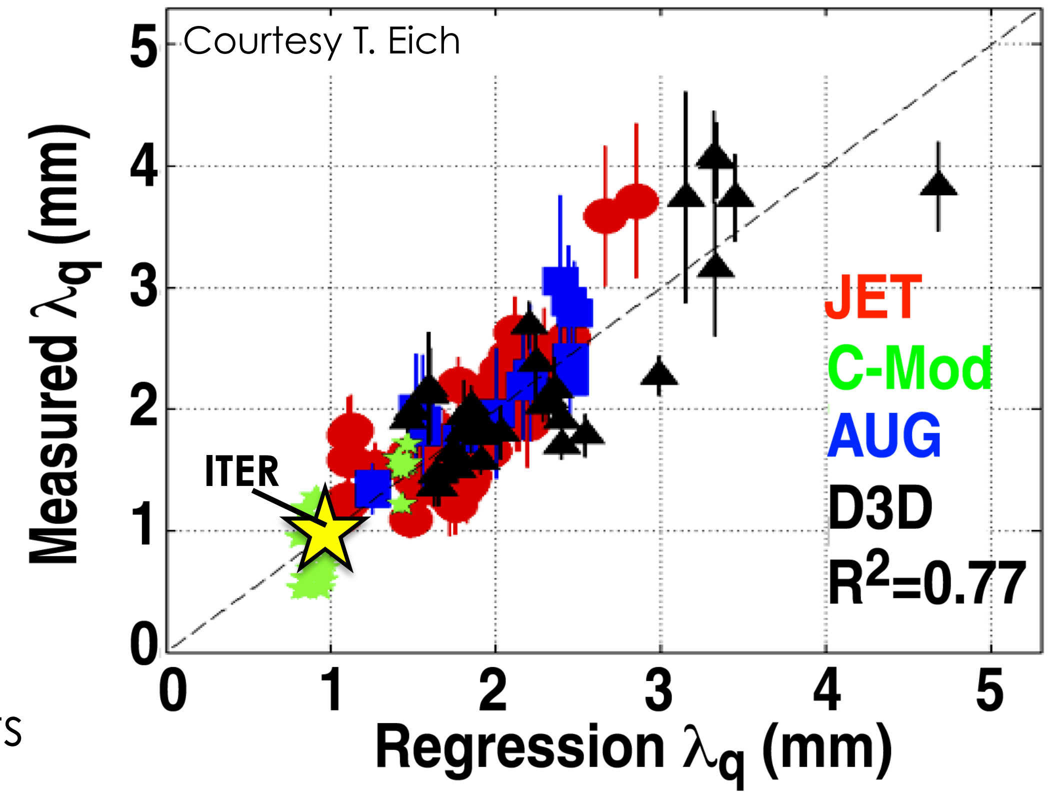
C. Holcomb, EX/1-5
T. Petrie, EX/P5-12

DIII-D is Developing the Physics Basis for Integrated Steady-State Divertor Solutions

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

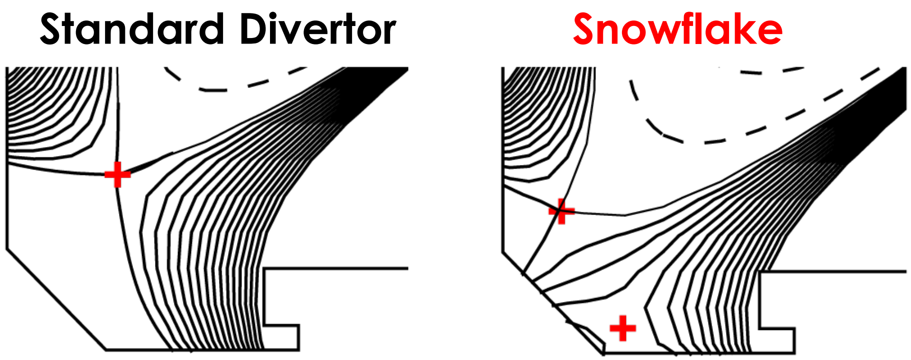
- **New unified ITPA data base indicates narrow heat flux for ITER**
  - Gradients below ballooning limits
  - Motivates and supports physics modeling

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

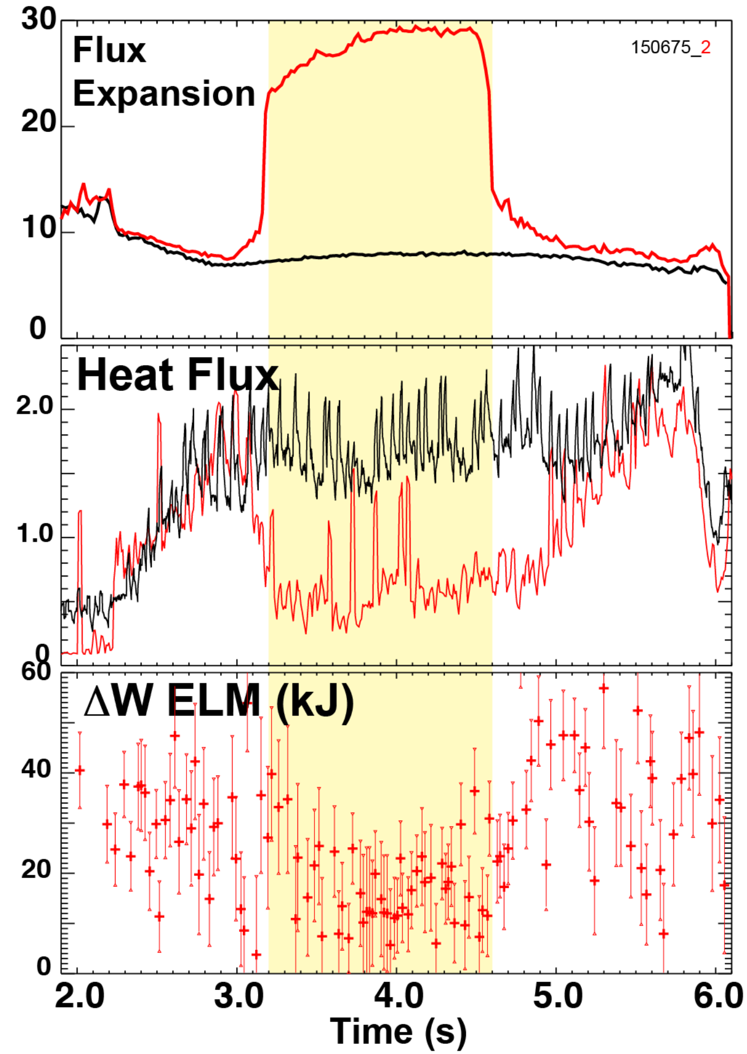


T. Eich, ITR/1-1 M. Makowski, EX/P5-16 D. Rudakov, EX/P5-11

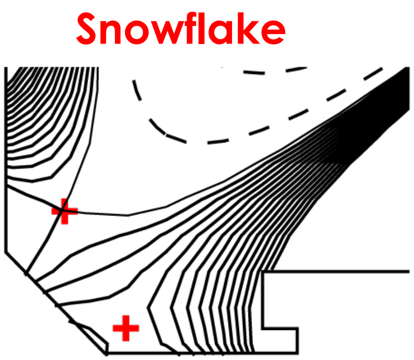
Snowflake Divertor Configuration Reduces ELM and Steady-State Heat Flux



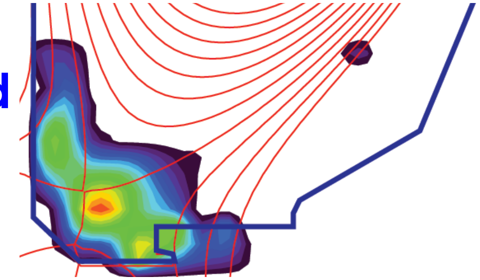
- SF configuration reduces heat flux 2-3X by flux expansion
- $\Delta W(ELM)$ reduced
- Core confinement ($H_{98y2} > 2$) and pedestal constant



Snowflake Divertor Configuration Reduces ELM and Steady-State Heat Flux

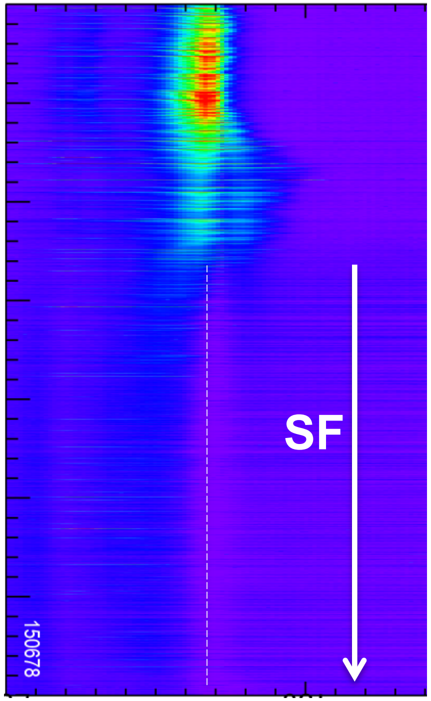


Increased Divertor Radiation

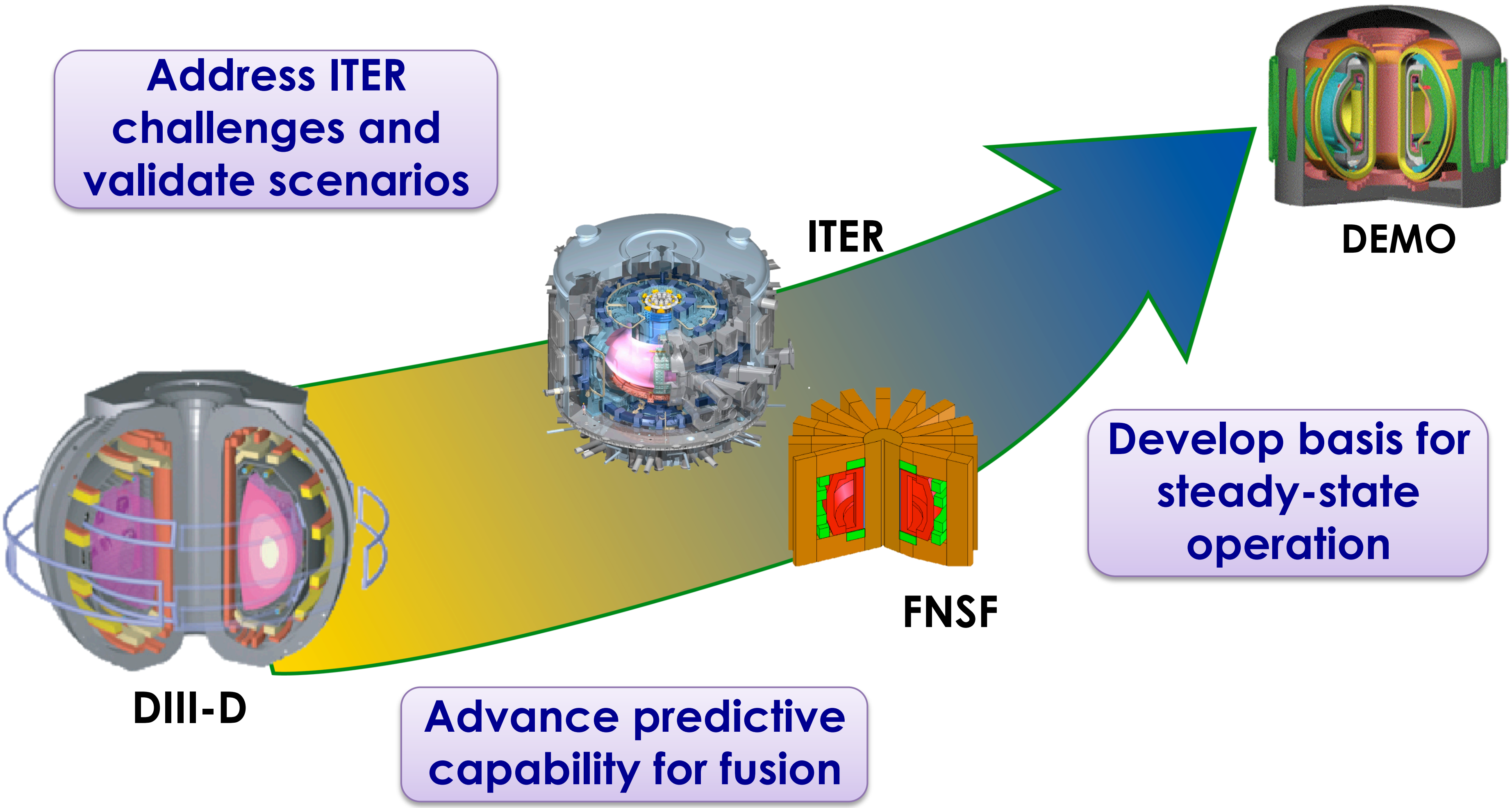


- SF configuration reduces heat flux 2-3X by flux expansion
- ΔW(ELM) reduced
- Core confinement ($H_{98y2} > 2$) and pedestal constant
- ELM heat flux reduced dramatically with gas puffing

Reduced Divertor Heat Flux

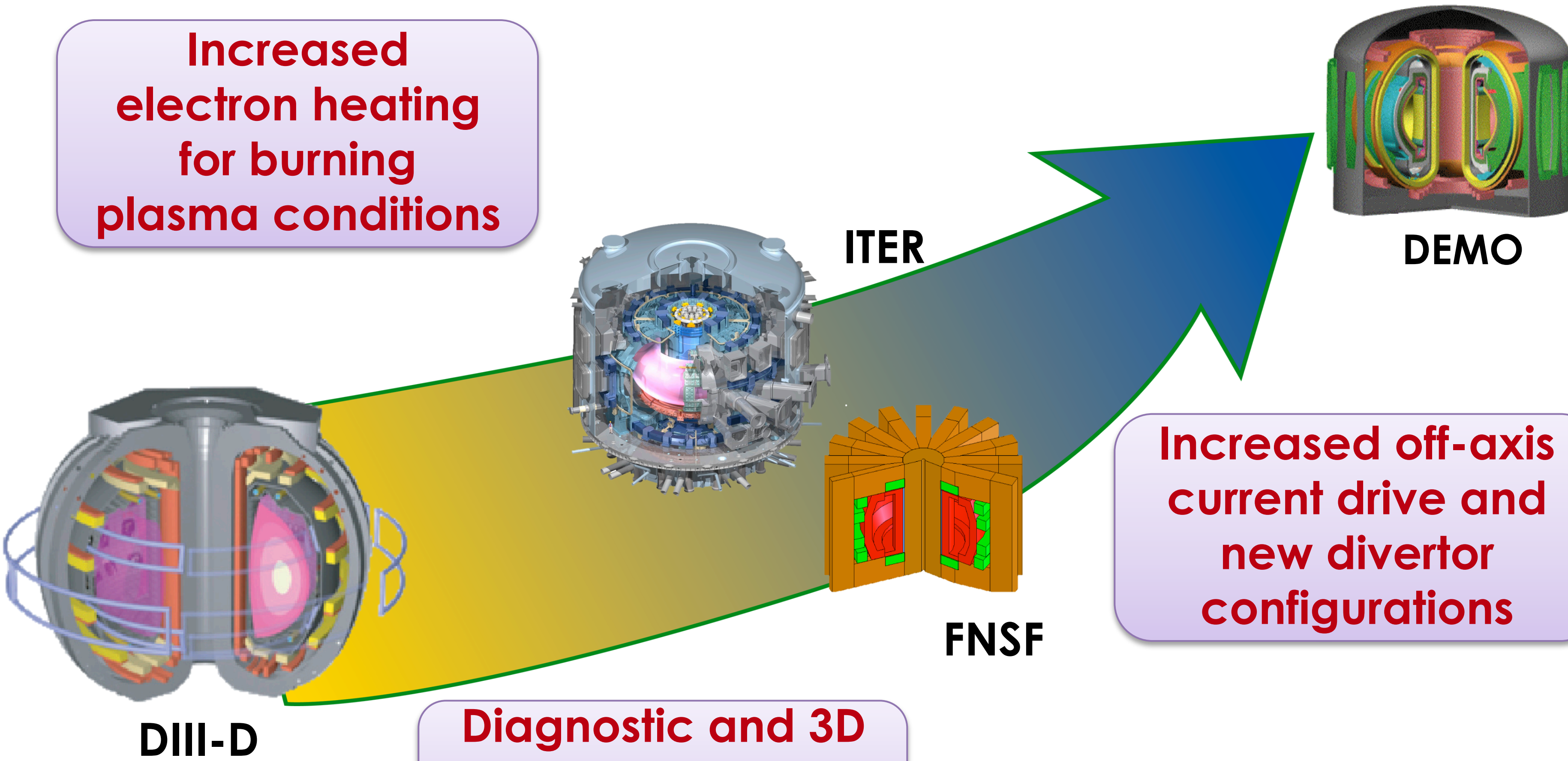


DIII-D is Advancing the Physics Basis Needed to Support Fusion Energy Development



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

Increased electron heating for burning plasma conditions



Increased off-axis current drive and new divertor configurations

Diagnostic and 3D field upgrades for fusion science

Other DIII-D Related Talks at This Conference

EX/1-5 **Tues PM**	Holcomb	Fully Noninductive Scenario Development in DIII-D Using New Off-Axis Neutral Beam Injection
EX/3-1 **Wed AM**	Wade	Advances in the Physics Understanding of ELM Suppression Using Resonant Magnetic Perturbations in DIII-D
EX/5-1 **Thurs AM**	Matsunaga	Dynamics of Energetic Particle Driven Modes and MHD Modes in Wall-Stabilized High Beta Plasmas on JT-60U and DIII-D
EX/6-2 **Thurs PM**	Baylor	Experimental Demonstration of High Frequency ELM Pacing by Pellet Injection on DIII-D and Extrapolation to ITER
TH/8-2 **SAT AM**	Staebler	A New Paradigm for ExB Velocity Shear Suppression of Gyrokinetic Turbulence and the Momentum Pinch
EX/9-2 **FRI AM**	Hollmann	Control and Dissipation of Runaway Electron Beams Created during Rapid Shutdown Experiments in DIII-D
EX/10-3 **Sat AM**	Tynan	Zonal Flows as the Trigger Event for the L-H Transition
EX/11-4 **Sat PM**	Groebner	Improved Understanding of Physics Processes in Pedestal Structure, Leading to Improved Predictive Capability for ITER