DIII-D Results and Plans For Research In Support of ITER and Future Steady-State Fusion Tokmaks

by
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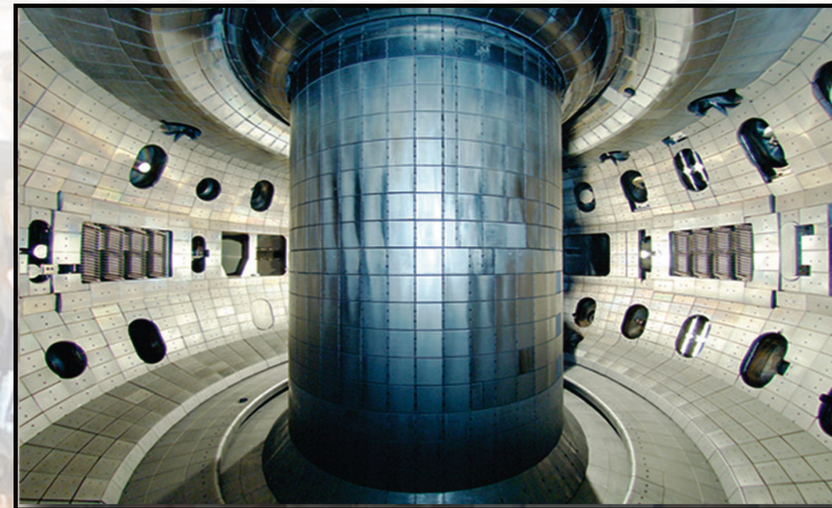

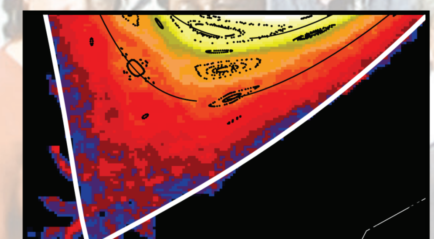

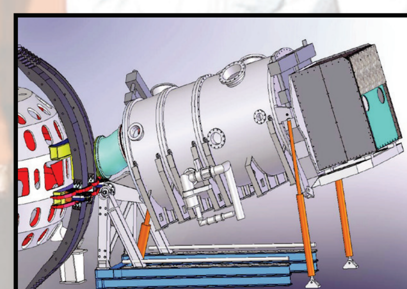

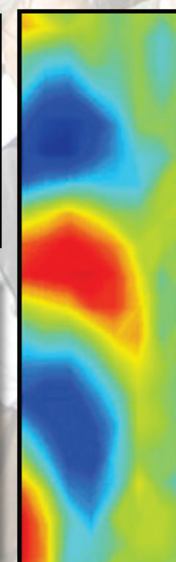

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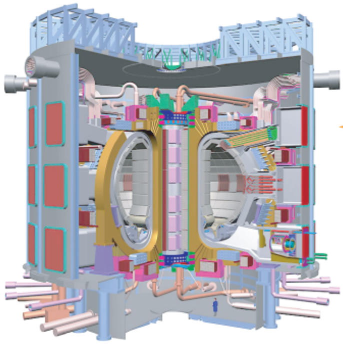
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-PRES-489137

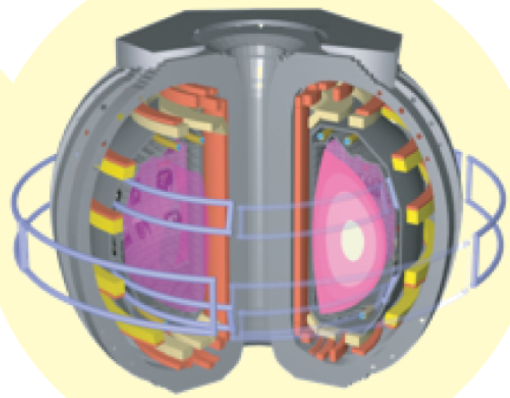
DIII-D Mission: To Establish the Scientific Basis for the Optimization of the Tokamak Approach to Fusion Energy Production

ITER: Establish the viability of burning plasma operation

500 MW, 400 s

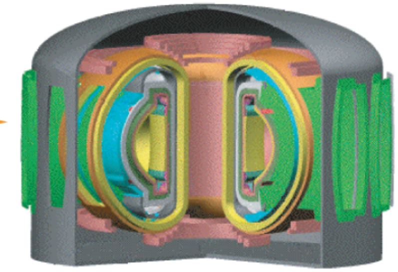


DIII-D



FNSF & DEMO: Fusion Power production

1 GW, steady-state

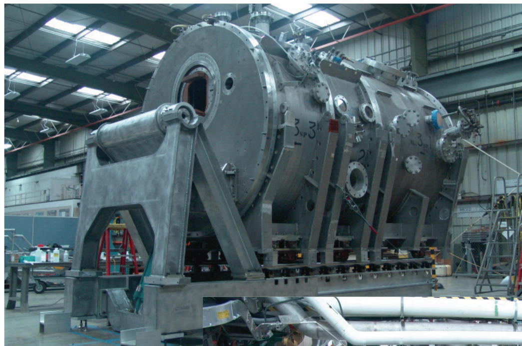
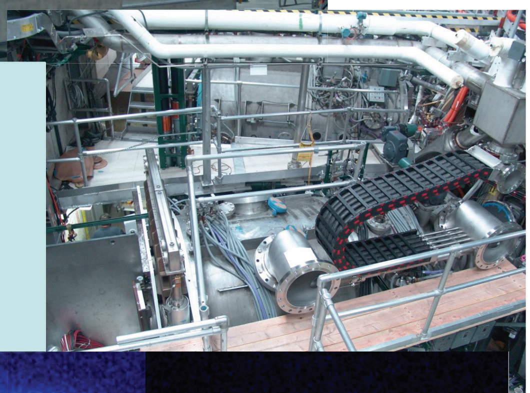


- **Design/Planning/Operation Issues:**
  - Avoidance/Mitigation of transients (ELMs, Disruptions)
  - Established operating scenarios
  - Effect of tritium breeding modules

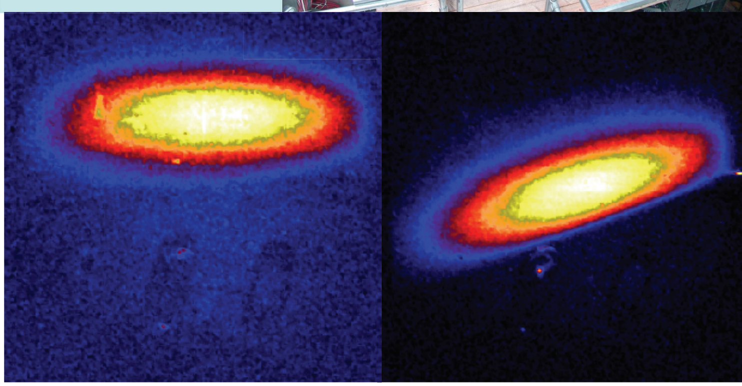
- **Physics Needs Beyond ITER:**
  - Operation near theoretical stability limits
  - Full current profile sustainment
  - Closed fuel cycle
  - Materials in extreme conditions

- **Common Elements:**
  - Transport in Burning Plasma regime ($T_e = T_i$, Low Torque Input)
  - Real-Time Stability Control
  - Effect of Energetic Particles
  - Simulation Capability

2011 Experimental Plan Utilizes Significant New Capabilities Provided by 2010 Long Torus Opening

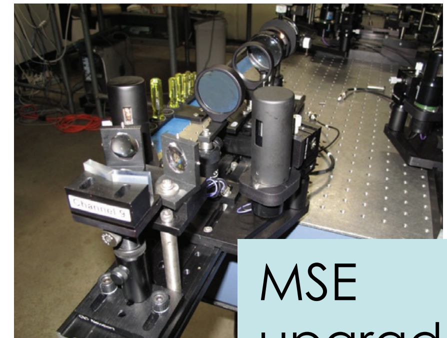



Off-axis neutral beam injection

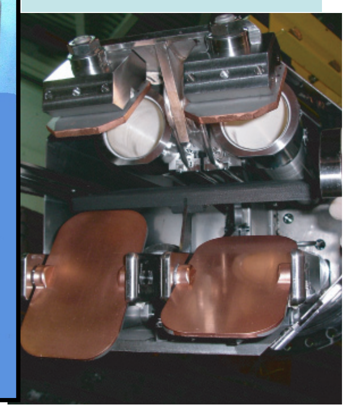


Thomson upgrade

MSE upgrade



ECH: new gyrotron, launcher upgrades



Improvements to Fast Wave heating

DIII-D Major System Capabilities for 2011 Experiments

Heating and Current Drive (injected power/pulse)

- **NB: 8 sources; 15 MW co, 5 MW counter (3 s); 5 MW off-axis**
- **EC: 6 gyrotrons; 3.8 MW (5 s); six steerable launchers**
- **FW: 2 MW (10 s), 1 MW (2 s)**

Coils

- **18 Poloidal field shaping coils**
- **6 external coils, 12 internal coils**
  - Error field control, RWM feedback
  - RMP (ELM control)

Divertor/First wall/Conditioning

- **3 cryopumps; 15-20,000 l/s**
- **ATJ graphite - 90% coverage; Reduced edge heating**
- **350° C bake, boronization, He glow between shots**

Support for ITER is the Major Focus of DIII-D Research

ITER Timeline

Design & Construction — Initial Operation 2019 — Burning Plasma

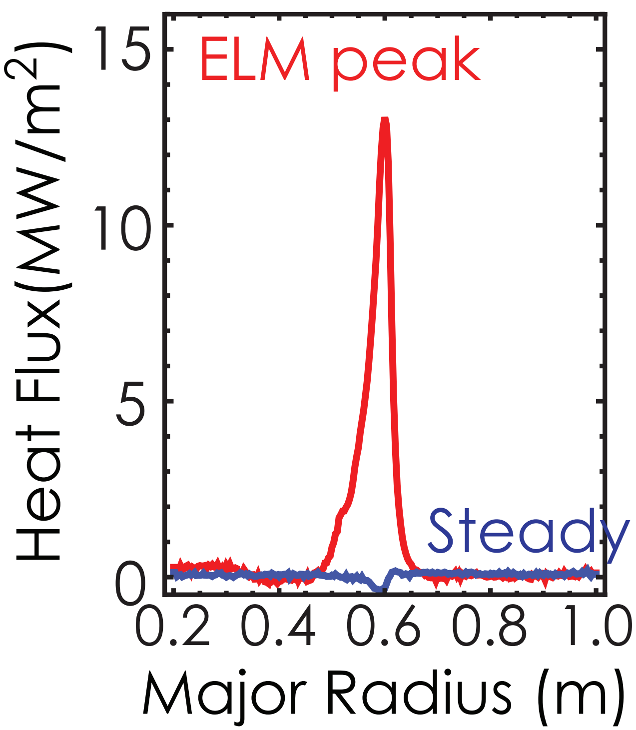
World Fusion Community Prepares for ITER Operation

Resolve short-term design issues for ITER	ELM control Disruption mitigation Startup, shape and position control
Resolve medium-term design issues for ITER	H-mode access in H_2 and He Magnetic field asymmetries & 3D effects Heating & current drive requirements
Address operational issues for commissioning and high-gain operation	Fast-ion instabilities 3D field effects Operational scenarios
Integrated plasma dynamics and control	Strong electron heating $T_e \sim T_i$ Low external torque operation Profile control, Divertor control

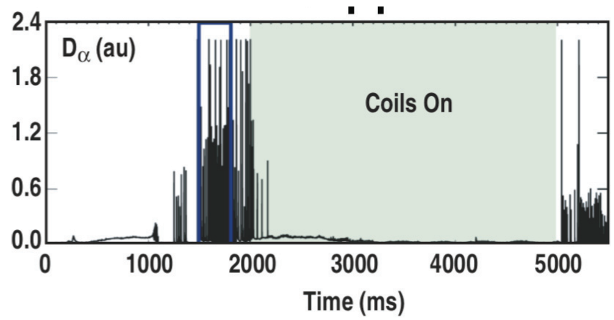
Control of Edge Localized Modes (ELMs) is Urgent ITER Issue: DIII-D is Developing Physics Basis For Control

H-mode ELMS: ~20% of energy loss arrives in rapid repetitive bursts

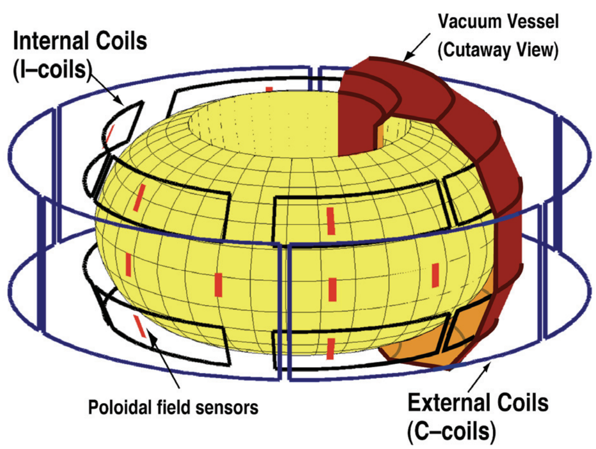
DIII-D IR TV



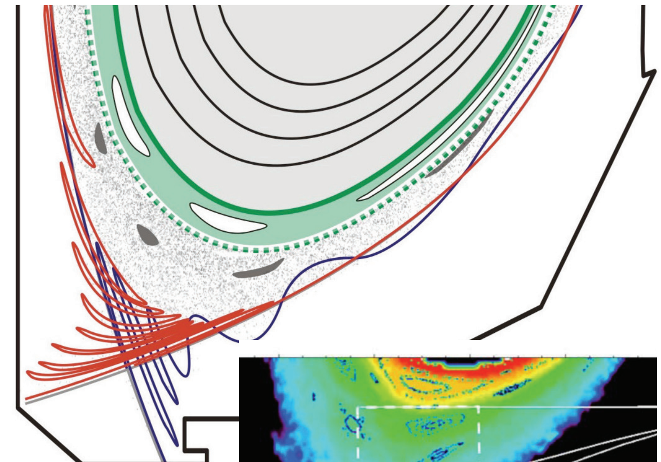
Application of 3D fields can suppress ELMs

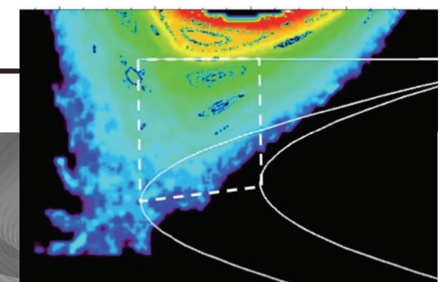


Flexible set of 3D coils

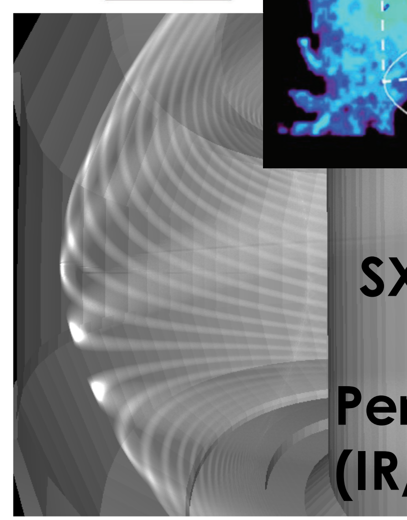


Plasma response modifies internal fields





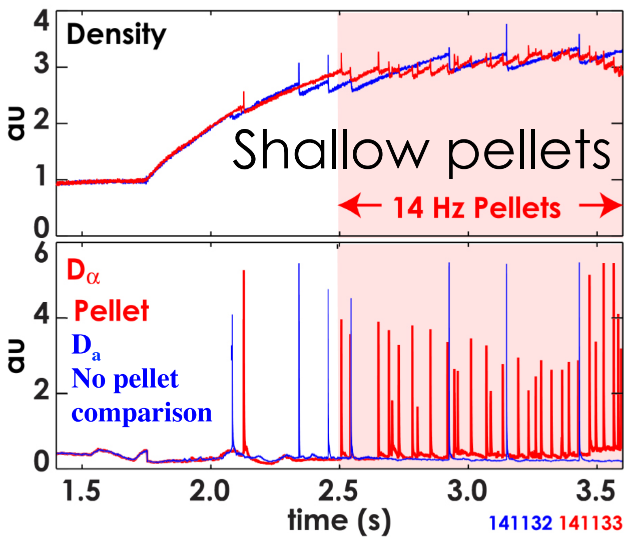
Tangential SXR Camera



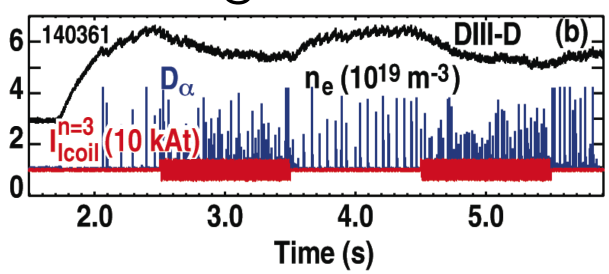
Periscope (IR/Vis)

DIII-D is Evaluating Multiple Techniques For ELM Control

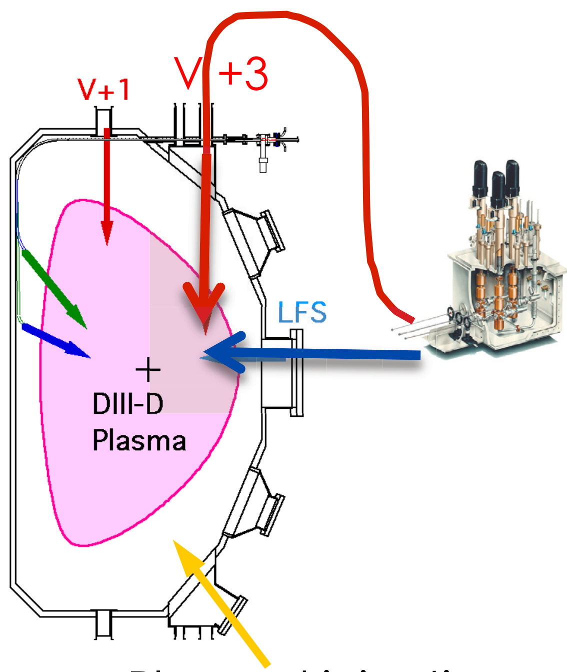
Active Pacing: Induce more frequent, but smaller ELMs



AC magnetic fields

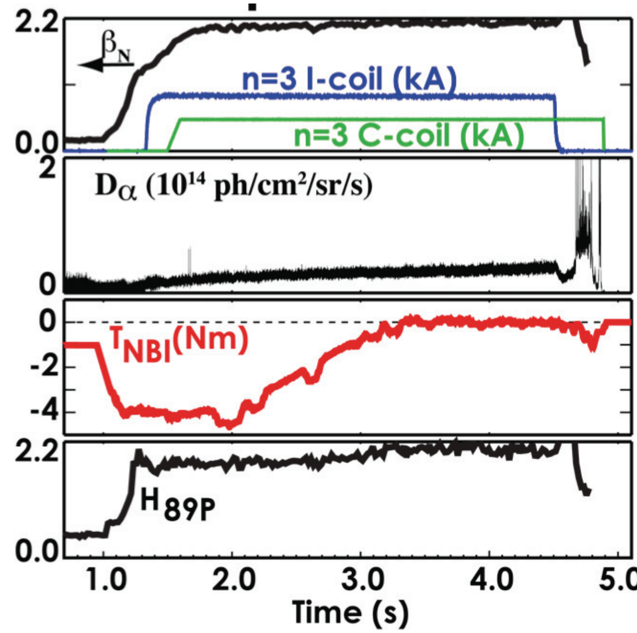


Multiple launch locations (ORNL)



Planned injection geometry for ITER

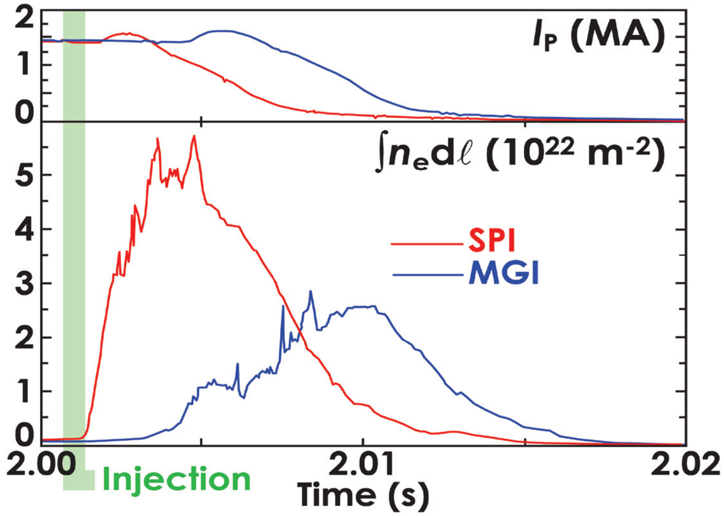
ELM-free Operation: Low-torque QH-mode

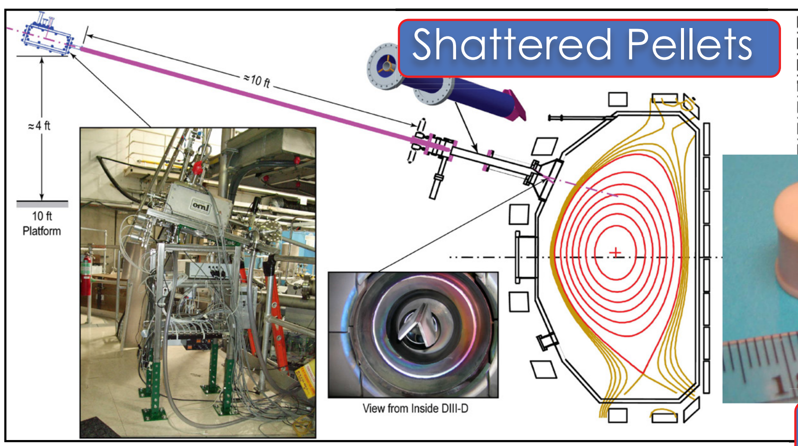


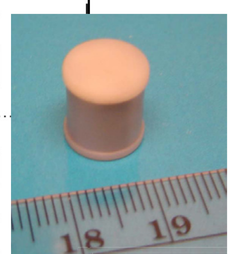
Use 3D fields to spin plasma for good confinement

High Priority Experiments Seek Robust Controls to Mitigate Consequences of Major Disruptions

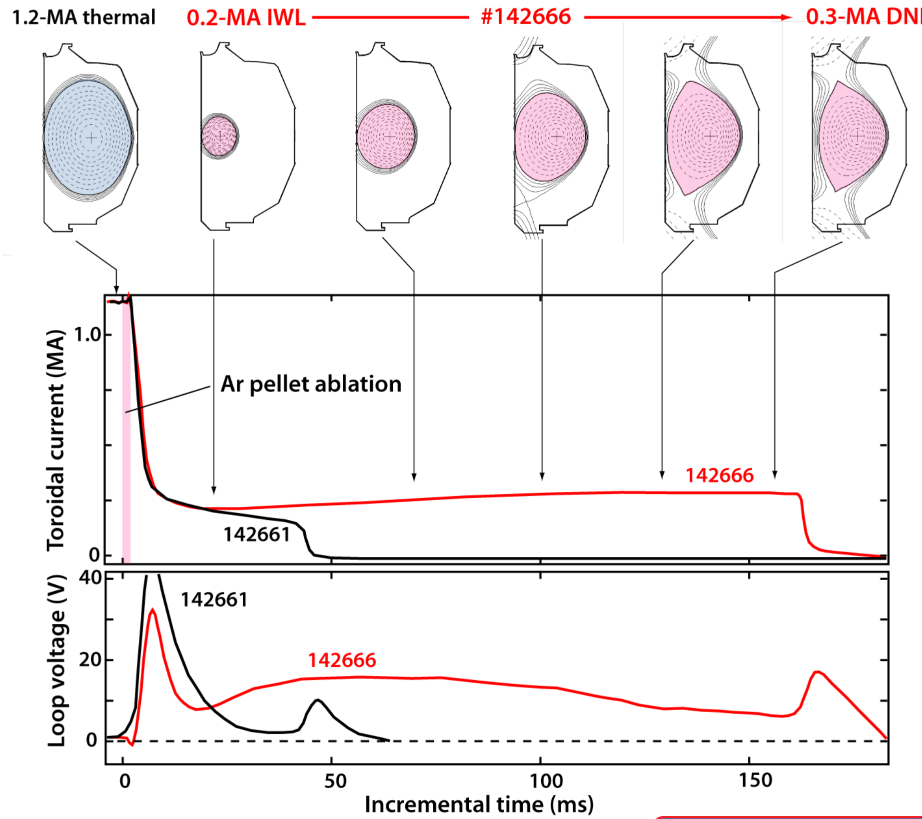
Massive Gas Injection to reduce localized heating and vessel currents

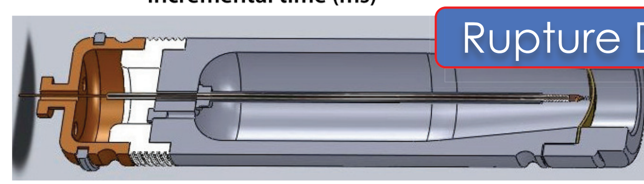






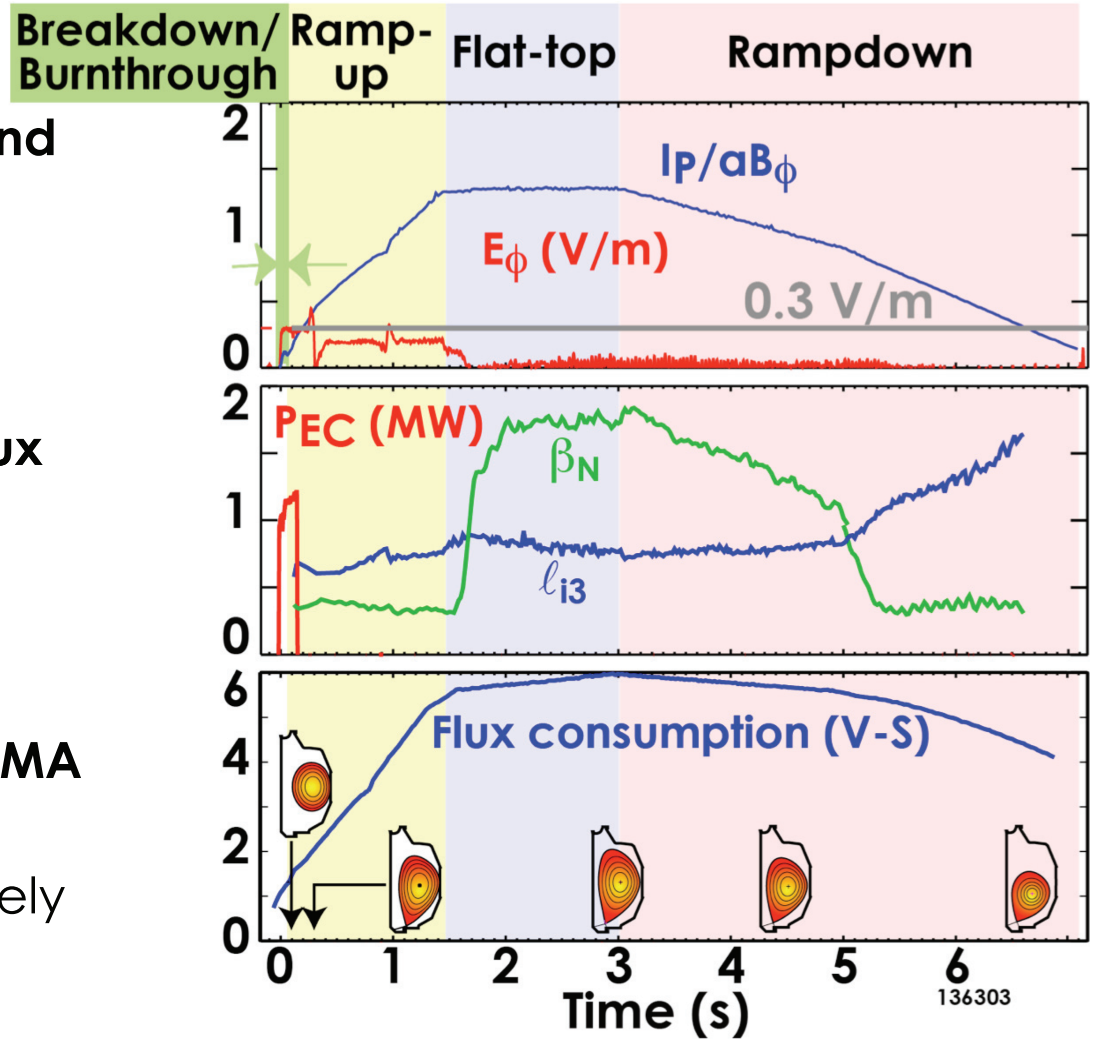
Active control of Runaway Electrons in DIII-D points to safe dissipation





Control Simulation Experiments Demonstrate Improved Scenarios for ITER Startup and Rampdown

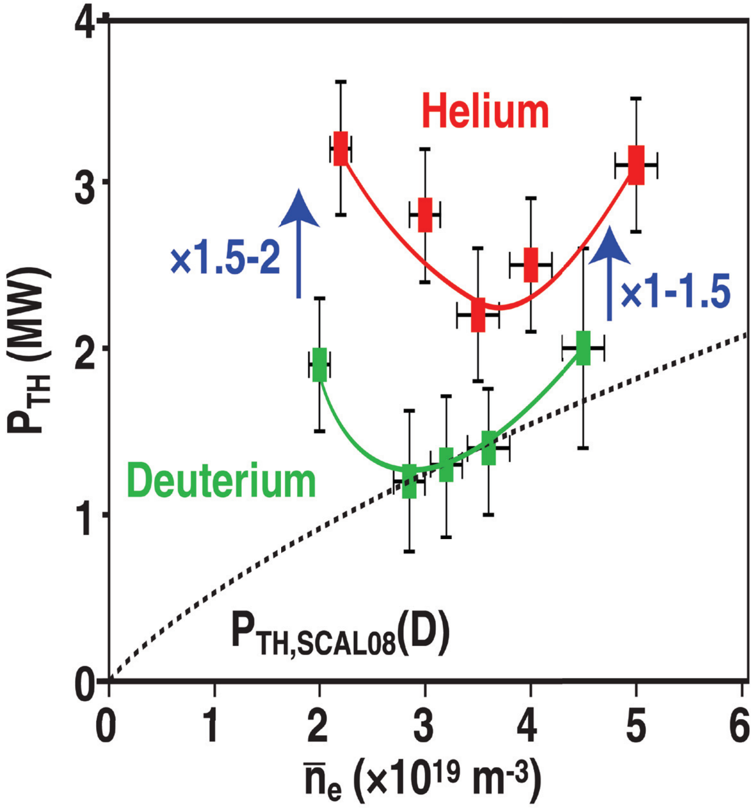
- **Reliability of ramp-up improved by EC assist during breakdown and burn-through**
- **New ITER rampdown scenario developed to avoid additional flux consumption**
- **Reliably ramped down without disruption until current below 1.4 MA (equivalent) ITER target**
  – Vertical stability limit quantitatively predicted by theory



DIII-D Hydrogen/Helium Experiments Inform Plans for Initial Non-Nuclear ITER Operation

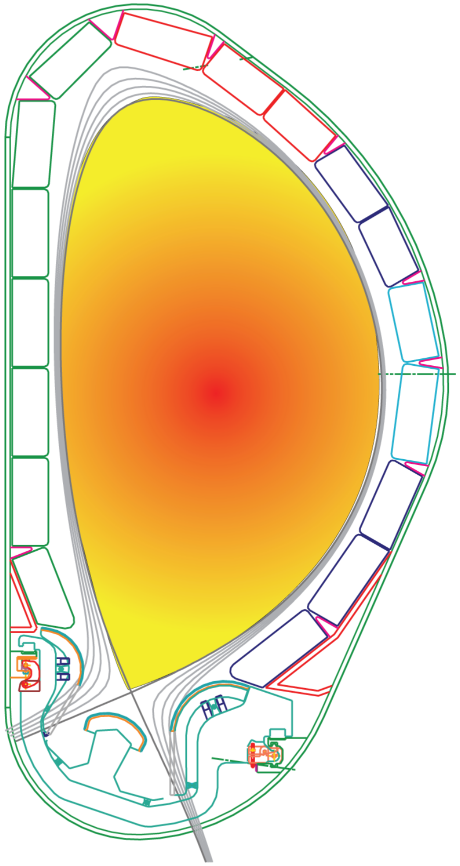
- **ITER plans to commission many control systems during non-nuclear operations**
- **Experiments in hydrogen and helium**
  - L-H transition power: H/He/D: 2.0/1.5/1.0
  - Reduced confinement in H/He (> 50%)
- **Future work**
  - Assess various ELM control techniques in He plasmas
  - Develop scenarios with improved confinement in H and He

H-mode power threshold comparison

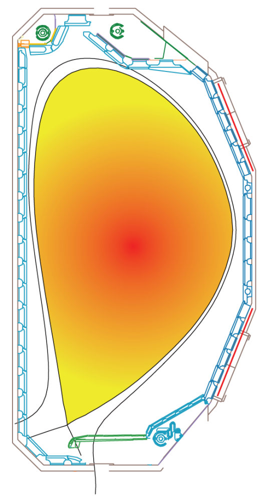


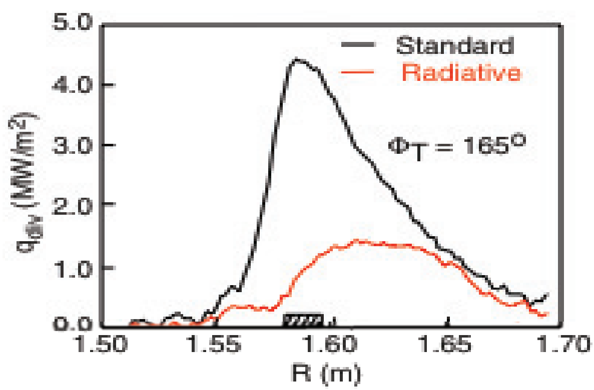
SOL Studies Focused on Identifying Key Processes Determining Divertor Heat Flux Width Scaling to ITER

ITER

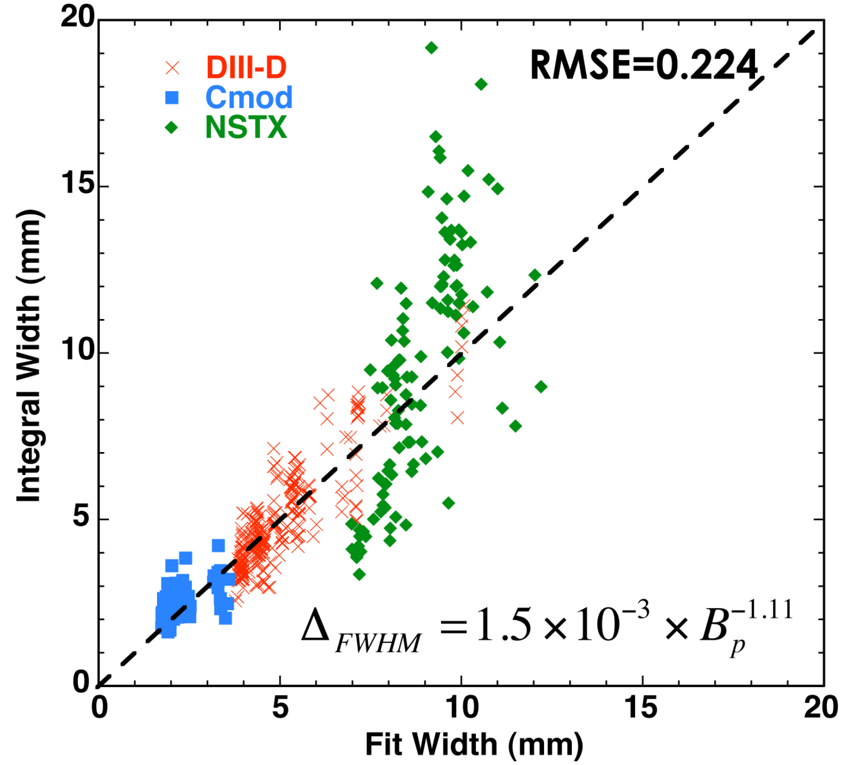


DIII-D



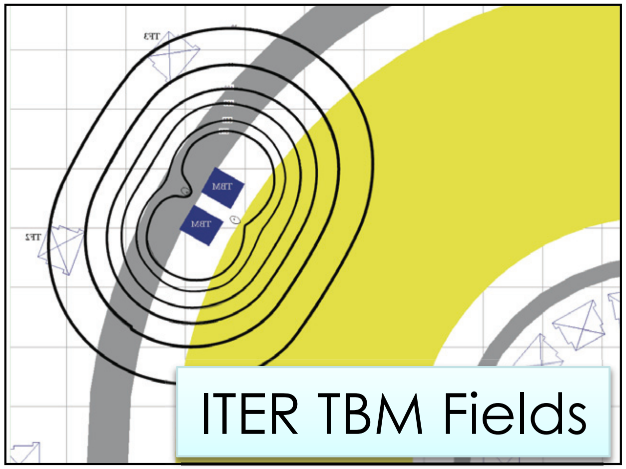


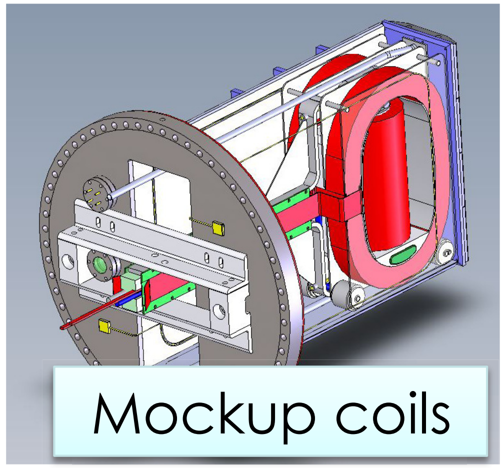
Divertor Heat Flux Width Mapped to Outer Midplane

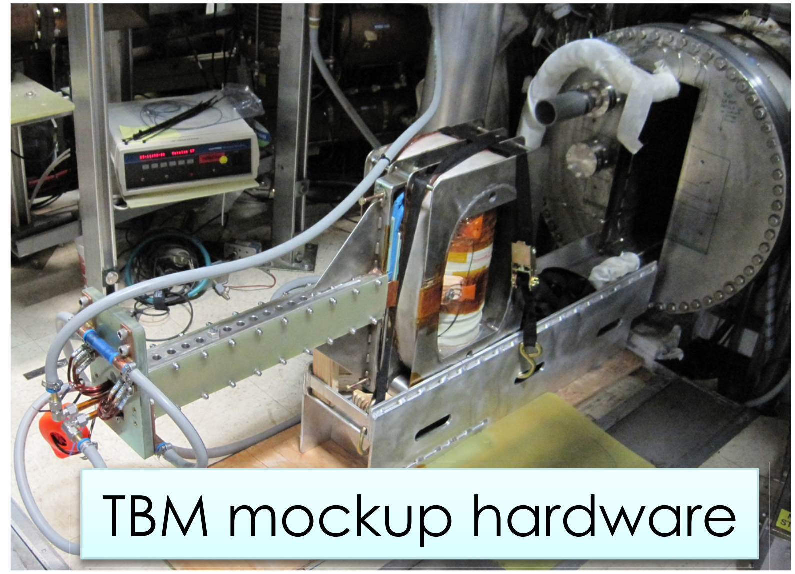


Data from 2010 joint experiments (DIII-D, C-Mod, and NSTX) points to underlying physics (width ∝ $1/B_{pol}$)

DIII-D Experiments Simulating ITER TBM Field Perturbations Showed Minimal Impact on Performance

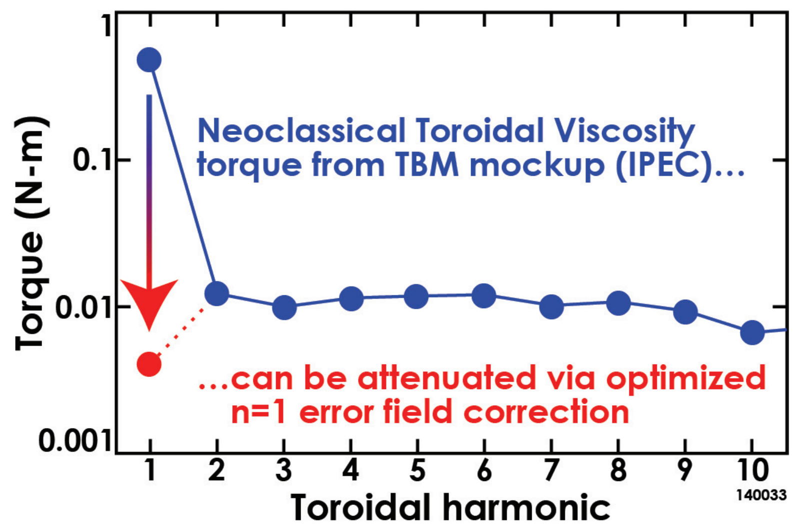






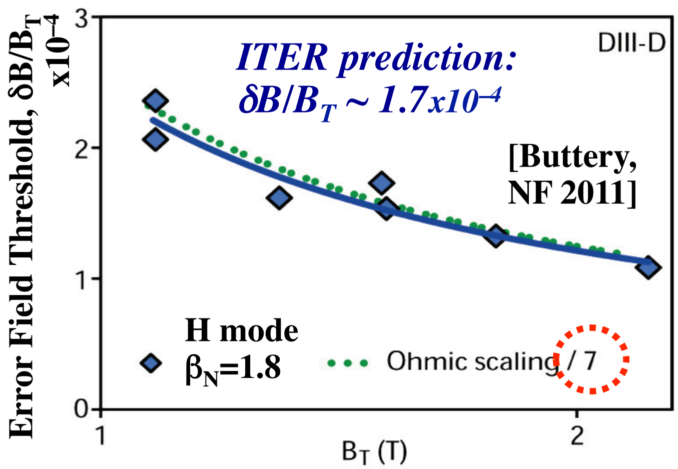
- **Little effect on confinement, but some reduction in plasma rotation, possibly from response to n=1 component**

- **2011-2013 Plan:** Reassess effect on rotation/confinement with TBM n=1 error field compensation

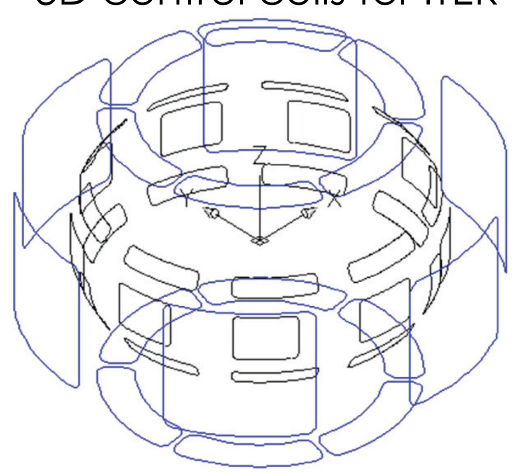


Feedback-controlled Error Field Correction Experiments Are Developing the Knowledge Base For ITER

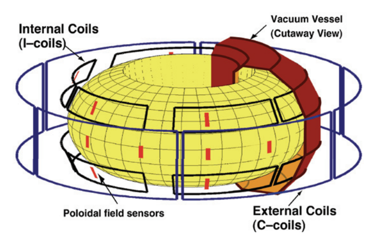
Feedback control of plasma response to applied 3D fields is key

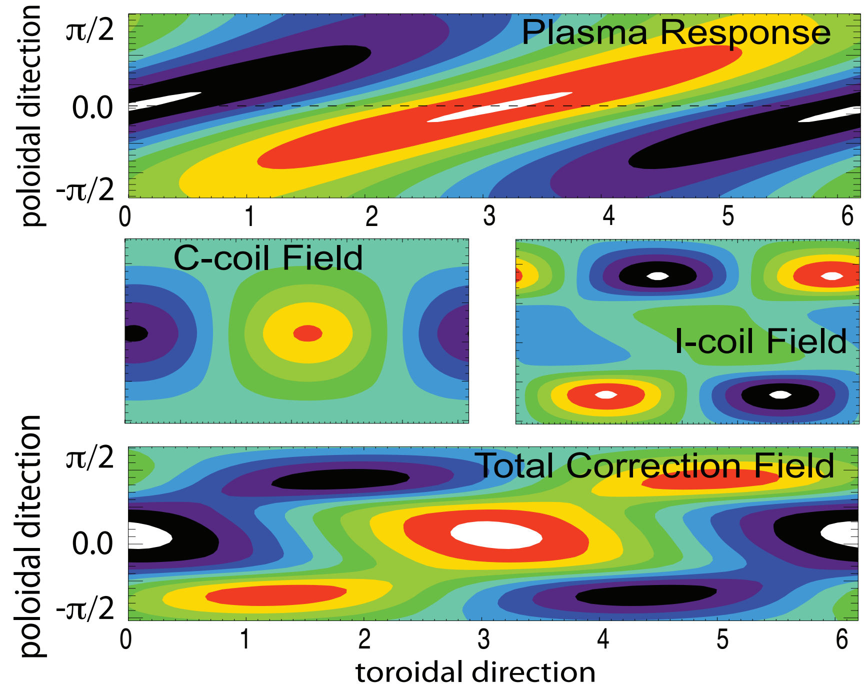


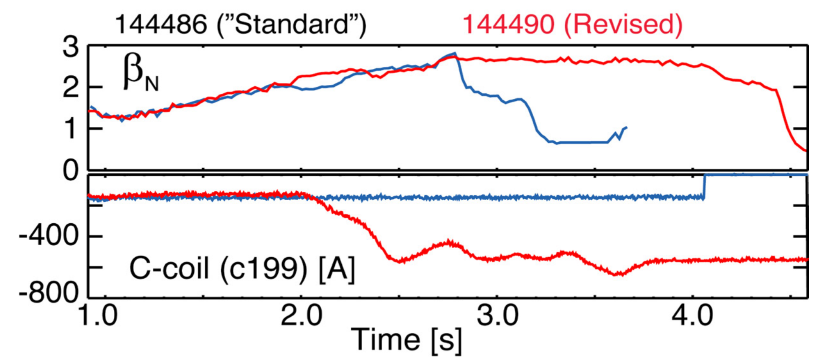
3D control coils for ITER



3D control coils on DIII-D

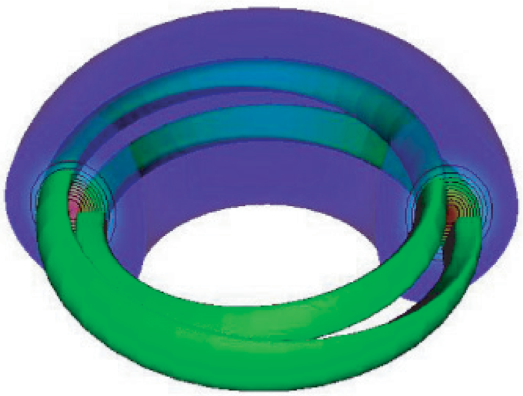






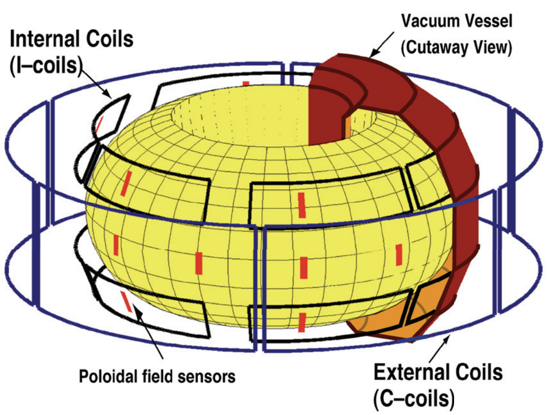
Experiments Are Developing Techniques to Suppress Disruption Precursors: ECCD Locked Mode Control

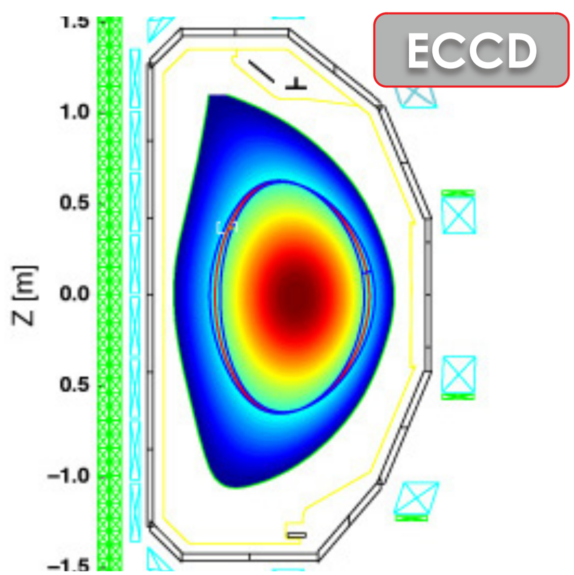
Locked 2/1 mode

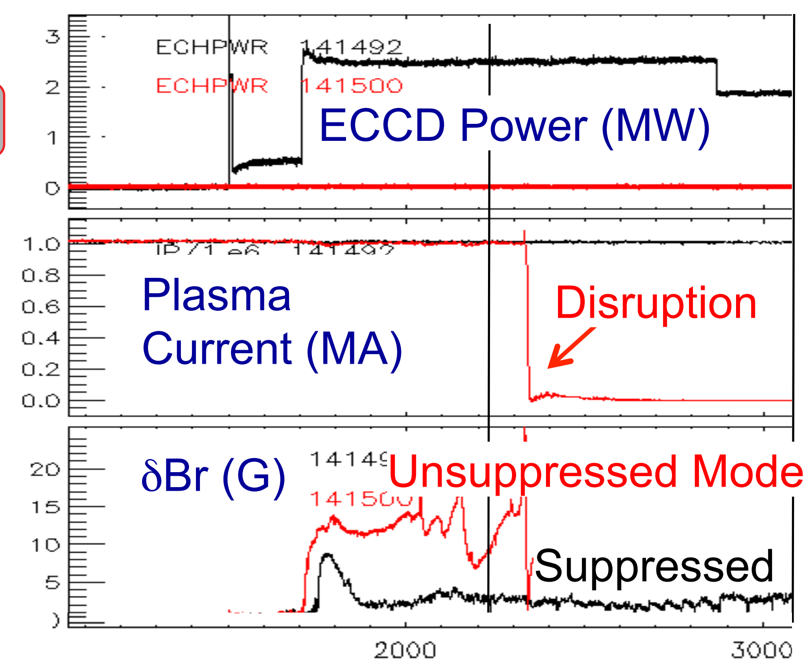


- **Locked n=1 tearing mode begins to grow**
- **n=1 RMP aligns mode's toroidal phase with ECCD**
- **ECCD suppresses mode and avoids disruption**

3D control coils on DIII-D

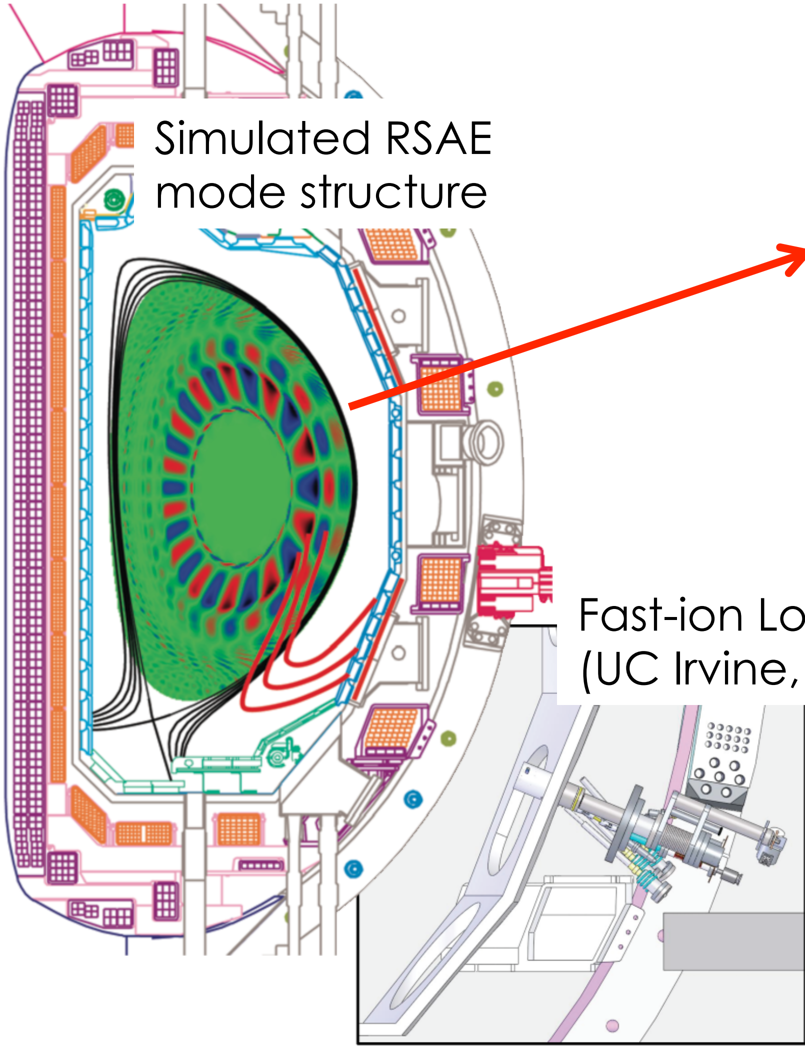


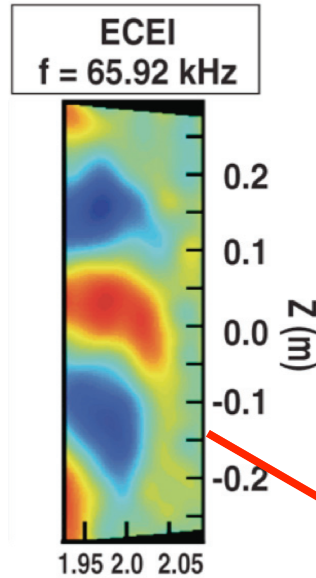




Measured Alfvén Eigenmode Activity Agrees With Simulation and is Correlated with Measured Losses

Simulated RSAE mode structure

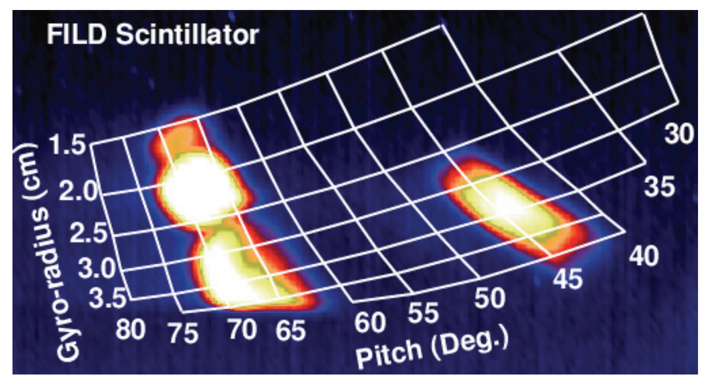




2D ECE Imaging measurement (UC Davis, GA, PPPL)

Fast-ion Loss Detector (UC Irvine, GA)

Time-correlated Fast Ion losses



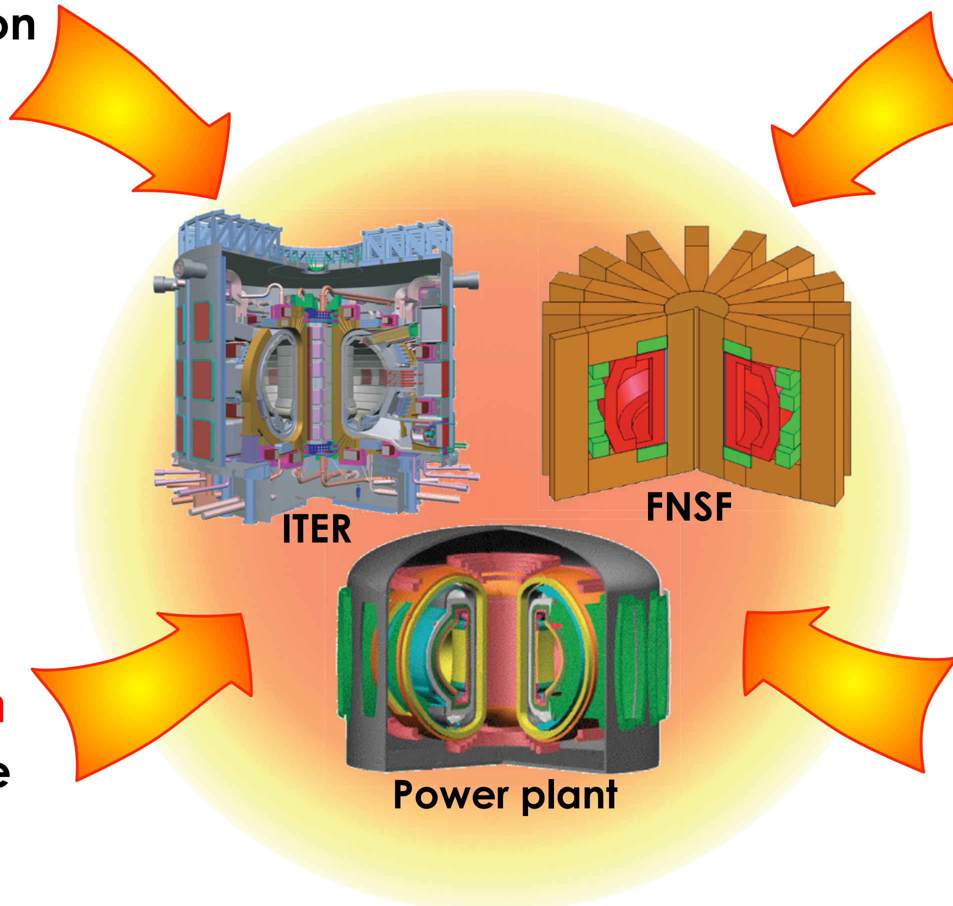
Future Steady State Tokamaks Have Common Research Needs

Burning Plasma Conditions

- Dominantly electron heated
- Low torque
- Low fuelling and collisionality
- Energetic ions

Stable Operation at High β

- Good passive stability
- Effect of energetic ions
- Active control through heating and 3D tools
- Event prediction, detection and control



Steady State Plasma Operation

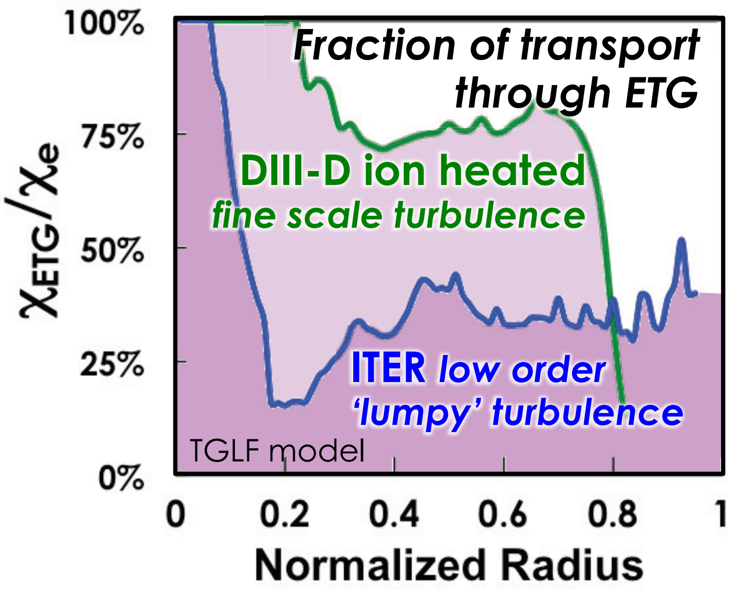
- Fully non-inductive
- Self driven well aligned currents
- High confinement
- Configuration control

High Fluence Boundary Solution

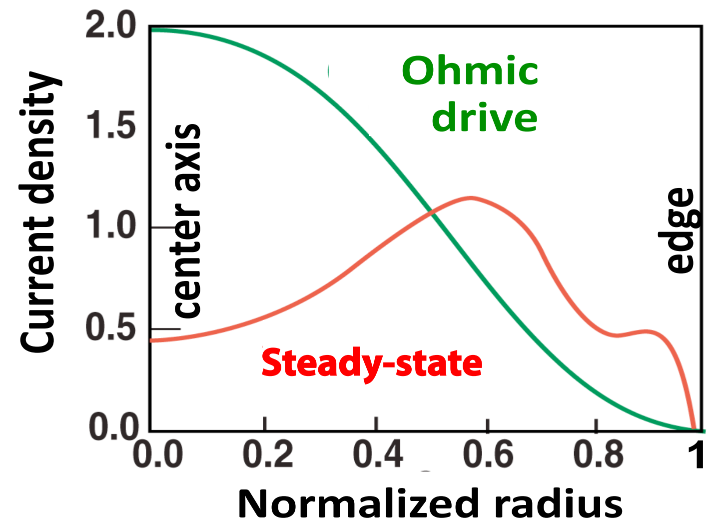
- Spread heat
- Cool exhaust to avoid erosion
- Compatible with high performance core

Plasma Behavior is Fundamentally Different in the Burning Plasma Regime

- **Transport processes change with dominant α heating of electrons:**
  - **Nature & scale of turbulence change ➔**
  - Because heat, momentum and particle throughput are very different cf NB heating
  - ITER likely different optimization to current devices



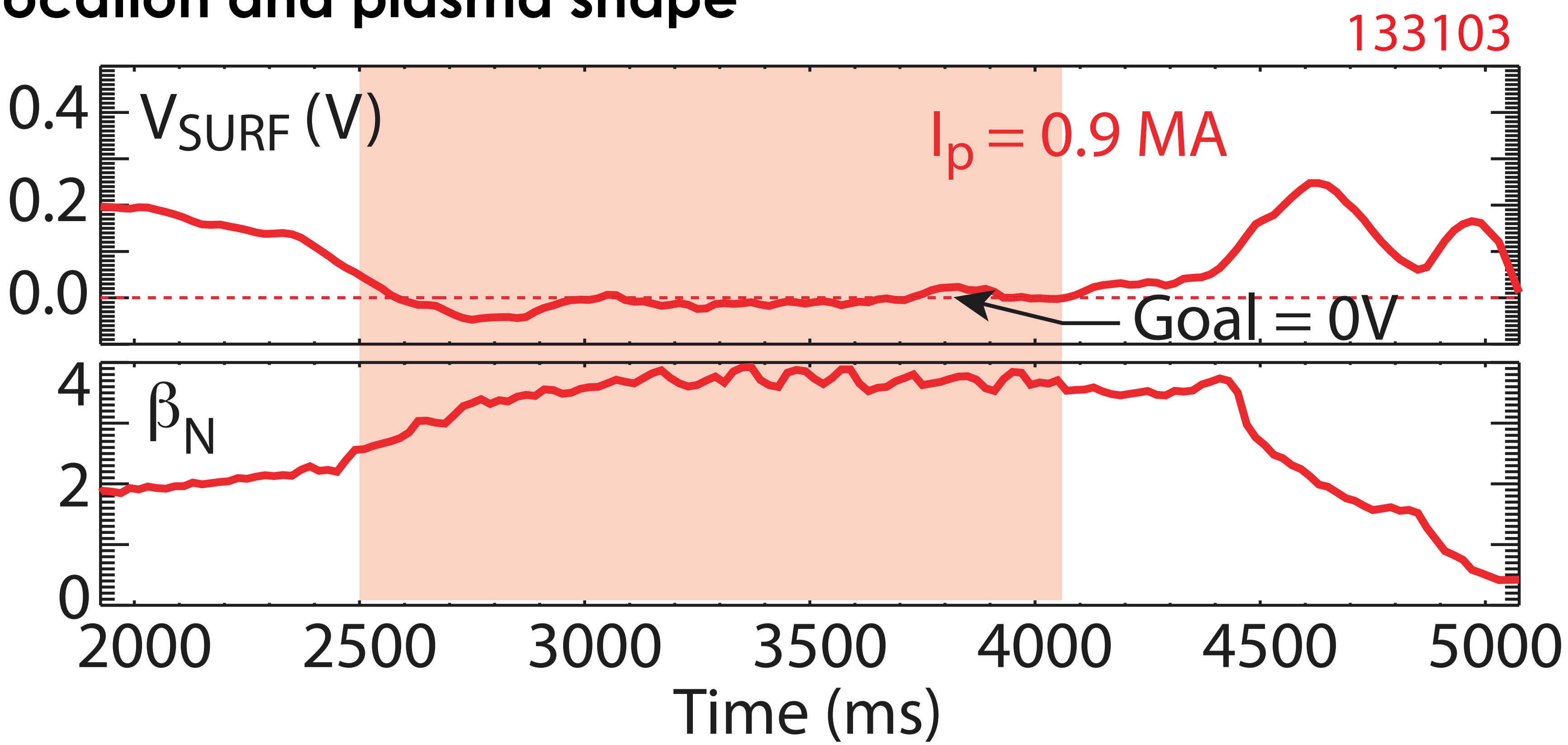
- **New stability, transport and current dynamics in high β steady state**
  - **Off axis currents change the physics**
  - Need to develop self-consistent and self-sustaining solution



Vital to prepare for this with present devices – avoid surprises or lengthy re-optimizations at the reactor scale

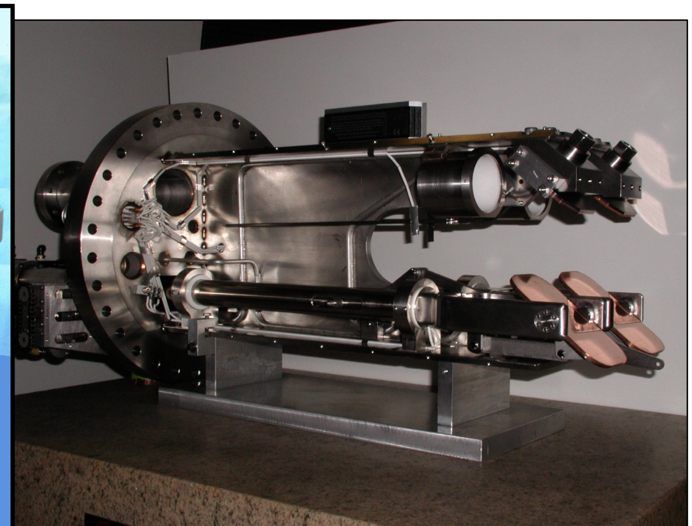
Fully Non-Inductive Operation Has Been Sustained for Approximately a Resistive Time (~1 s)

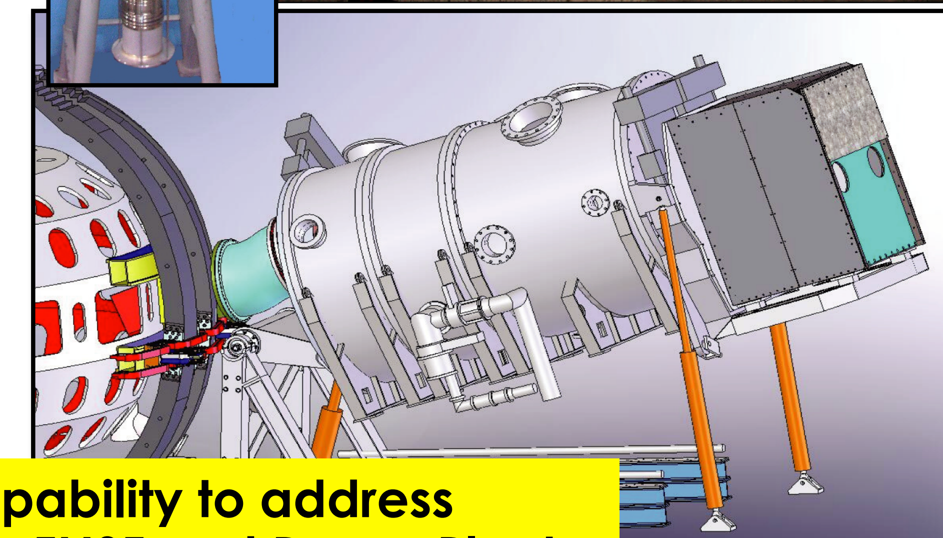
- **Scenario based on separate studies of optimal ECCD location and plasma shape**



- **Performance consistent with that required for FNSF-AT**

Adding New Heating and Current Drive Technologies To DIII-D To Address Burning Plasma Physics





Upgrades

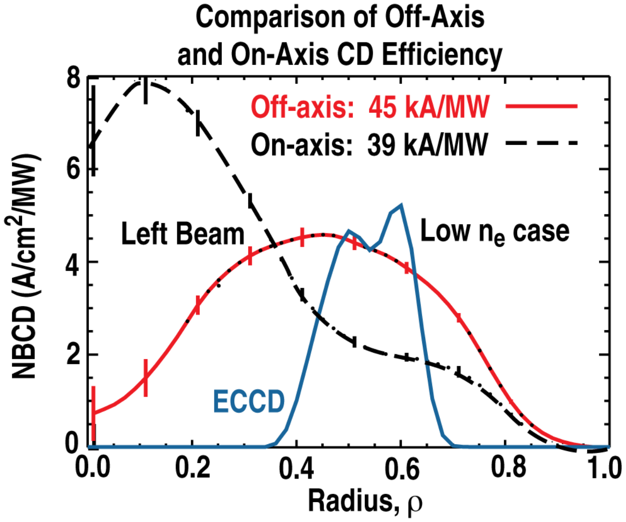
- **12 MW Microwave Heating**
  - 1.8MW 117.5GHz gyrotrons
  - Steerable launchers

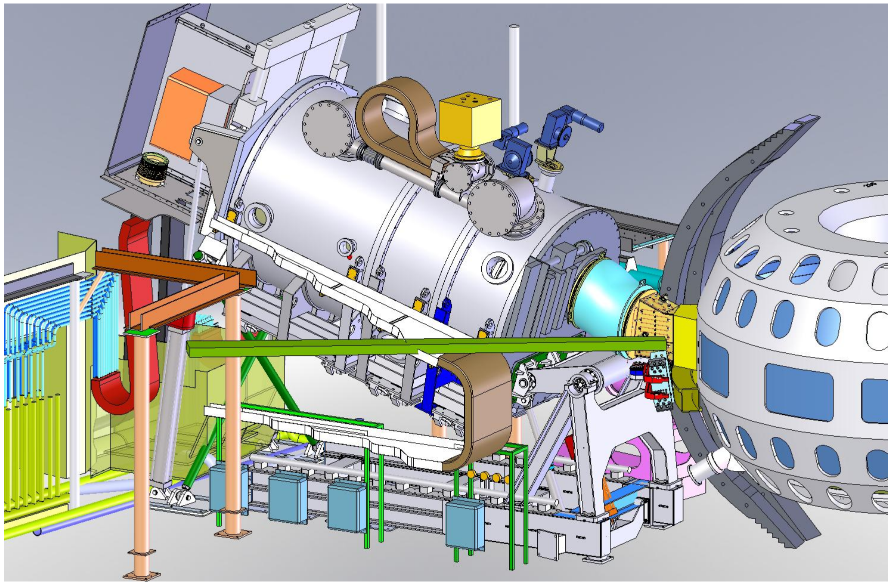
- **5+5=10 MW off axis Neutral Beams**
  - Relevant current distributions

- **Heating like fusion α's**
- **Current distributions like a power plant**

Provides unique capability to address important issues for ITER, FNSF and Power Plant

Successful Installation of Off-axis Beamline Provides 5 MW of Off-Axis Neutral Beam Current Drive

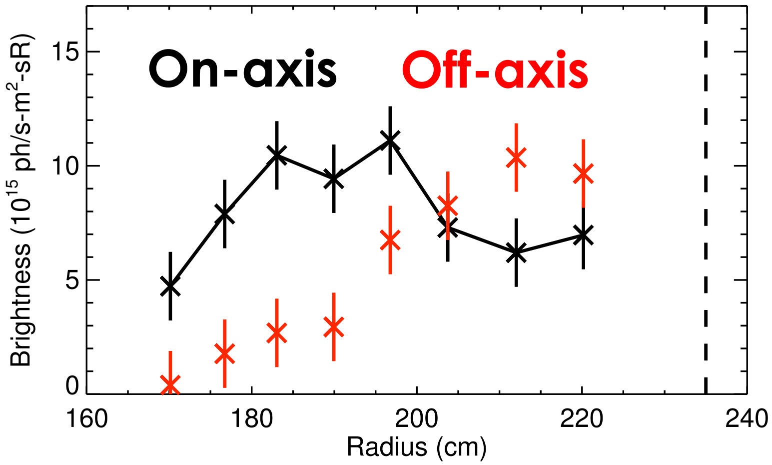


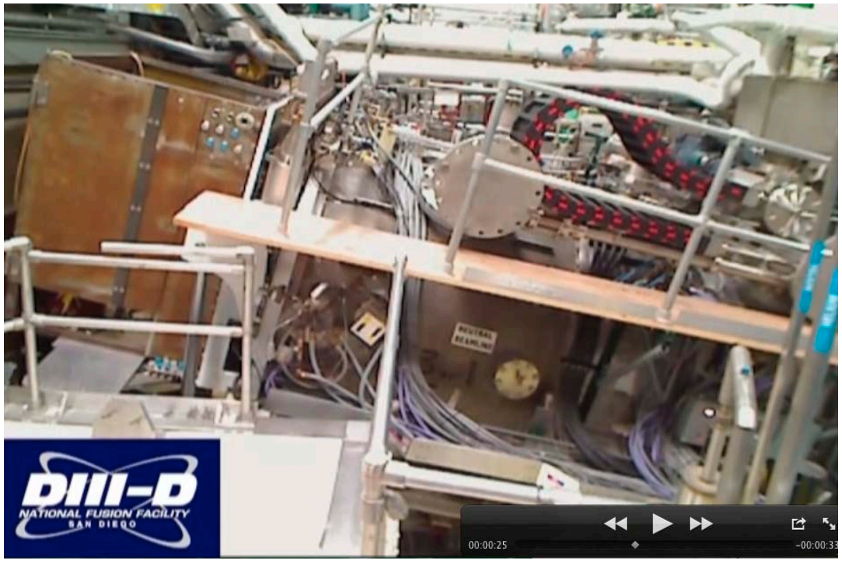


- Beamline and all support systems were removed, modified, reinstalled, and ready for operation within 1 year.
- Continuous adjustment of injection angle (0-16.5°)
- Two modified NB ion sources were built and tested in FY10. First new source fabrication in US in over 25 years.
- Decision to proceed with 2nd OANB (to 10 MW) will be made in 2012

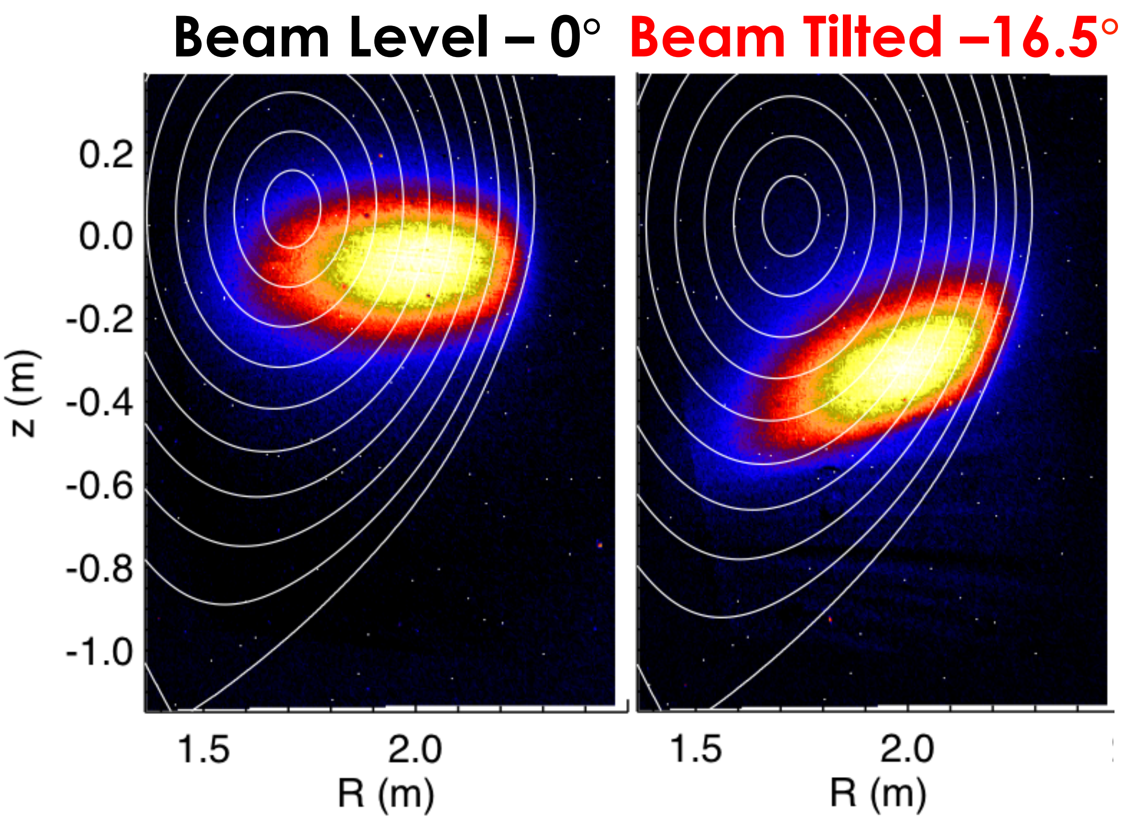
Successful Operation of Off-axis Beamline Provides 5 MW of Off-Axis Neutral Beam Current Drive

Measured Fast-Ion CXR Emission



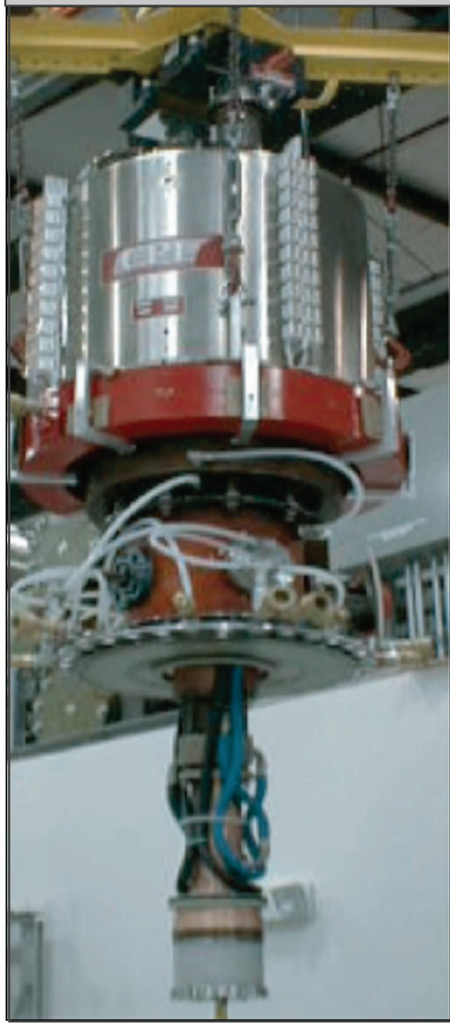


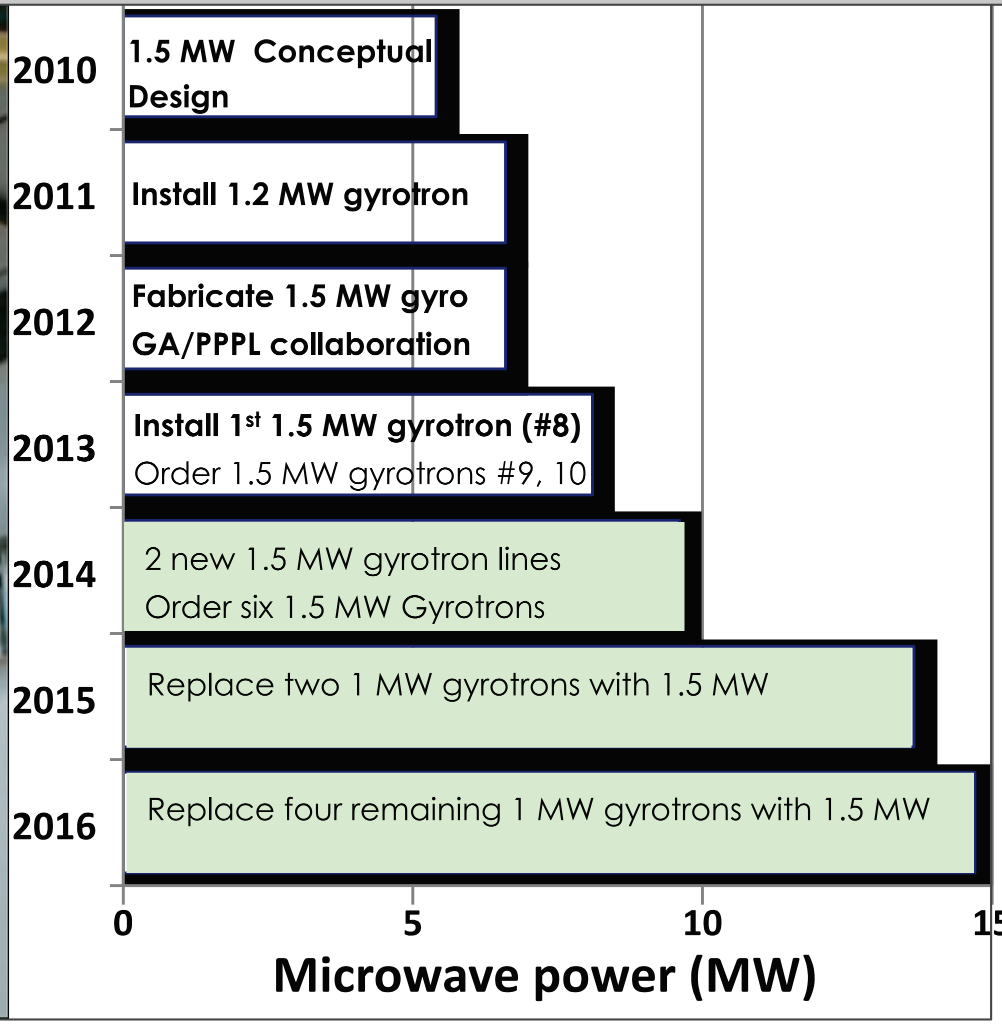
D-alpha images of beam interaction with plasma



Clear Path to Dominant Electron Heating Relies On Deployment of 1.5 MW Gyrotrons

PATH FROM 5 MW (6 GYROTRONS @ ~1MW each) to 15 MW (10 GYROTRONS @ 1.5MW each)





DIII-D Well Positioned to Address Research Needs Common to Future Steady State Tokamaks

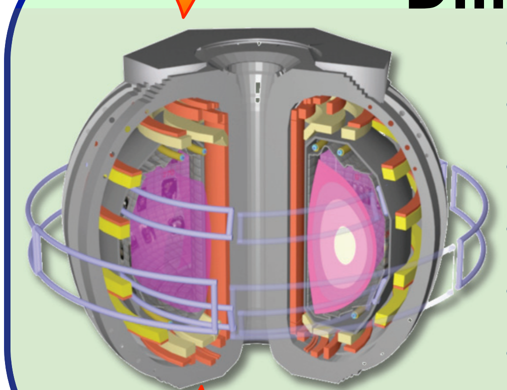
Burning Plasma Conditions

- Dominantly electron heated
- Low torque
- Low fuelling and collisionality
- Energetic ions

Stable Operation at High β

- Good passive stability
- Effect of energetic ions
- Active control through heating and 3D tools
- Event prediction, detection and control

DIII-D



- Current drive tools
- Pulse lengths > τ_R
- Electron heating
- Variable torque
- Refined diagnostics
- Divertor flexibility
- 3D fields

Steady State Plasma Operation

- Fully non-inductive
- Self driven well aligned currents
- High confinement
- Configuration control

High Fluence Boundary Solution

- Spread heat
- Cool exhaust to avoid erosion
- Compatible with high performance core