# Opportunities for DIII-D/NSTX Collaborations in 2011-13

by
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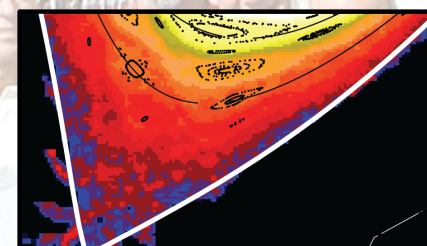
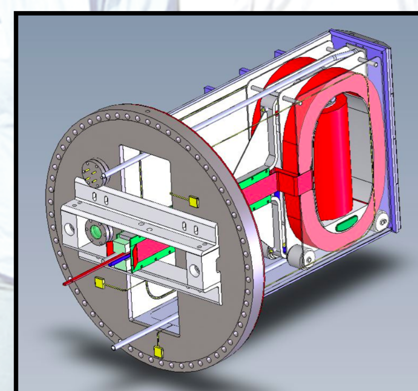
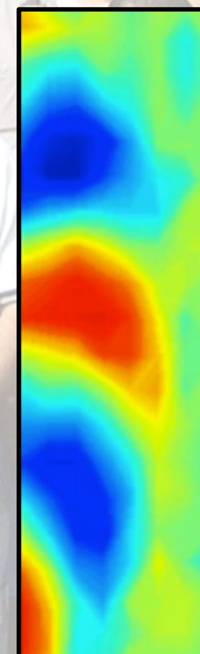
Presented at
**Princeton Plasma Physics Laboratory**
**Princeton, NJ**

**October 19, 2011**

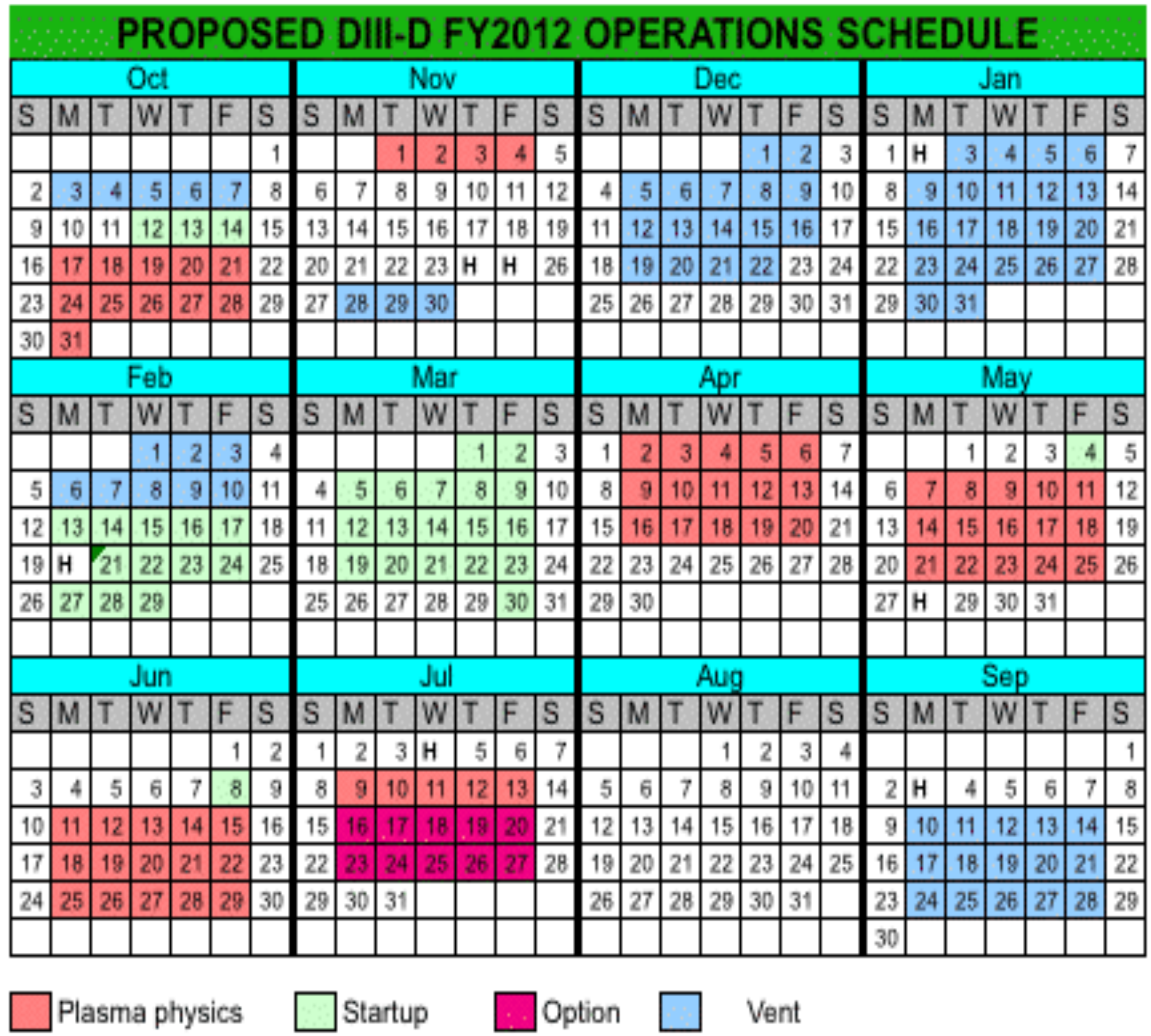






# DIII-D 2012 FWP Proposed 13 weeks of operation – Present FES Guidance is for 3 weeks

- **Plan calls for:**
  - 3 weeks in Oct.-Nov 2011
  - 10 weeks in Apr-Jul 2012



# Priorities of October 2011 Run Plan

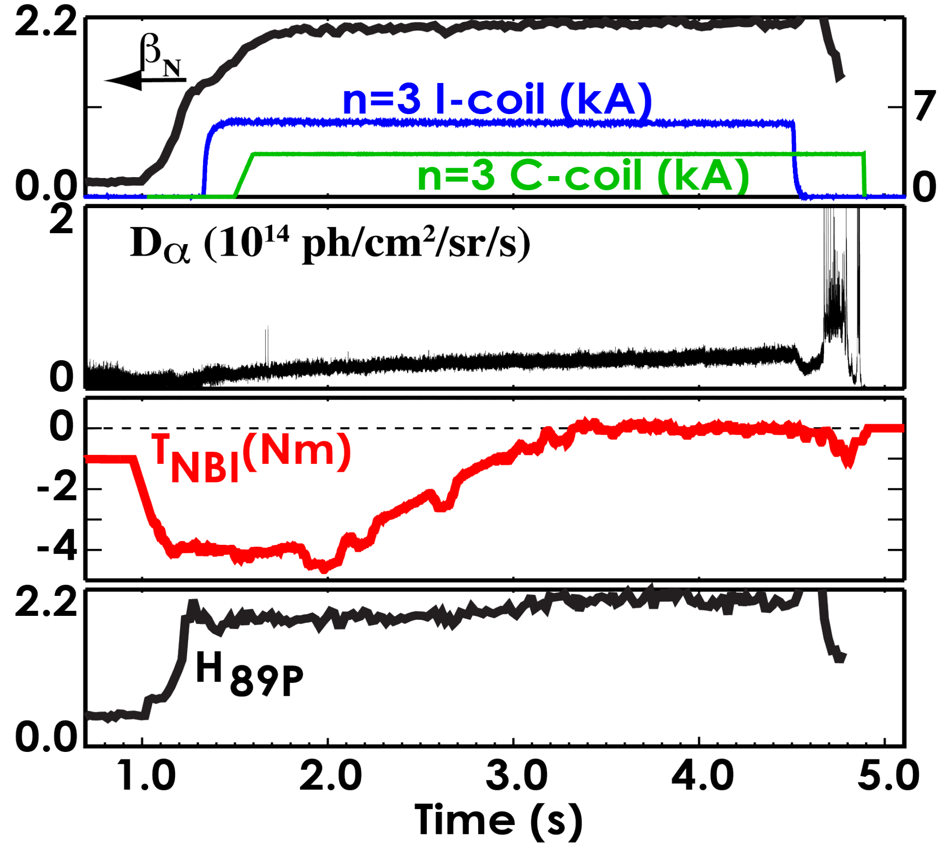
- QH-mode performance extension (co-Ip operation)
- Steady-state with off-axis NBI
- ITER baseline scenario assessment
- TBM experiment
- Pellet Pacing
- Runaway Electron Control

# QH-mode performance extension

- **Recent experiments have demonstrated capability to utilize NTV from non-resonant 3D fields to sustain QH-mode at zero NBI torque**

- **Near-term goals:**
  - Demonstrate QH-mode access with low torque startup
  - Utilize larger 3-D fields from I- and C-coils (both at 7 kA) to push QH-mode to higher fusion gain ($\beta_N H/q_{95}^2$)
    - Larger NTV will allow larger co-NBI power (and presumably higher $\beta$)

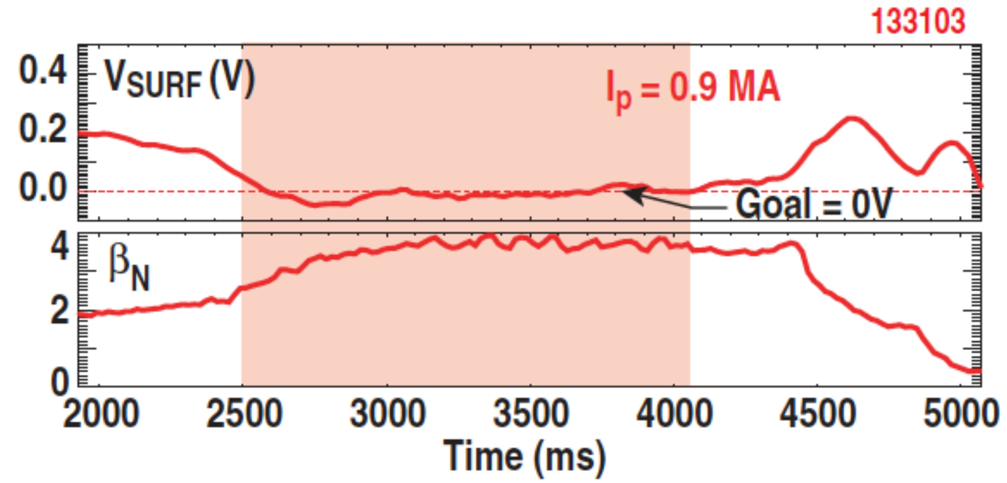
**Low Torque QH-mode**




**3 days allocated (Garofalo, Fenstermacher, Doyle**

# Steady-State with off-axis NBI

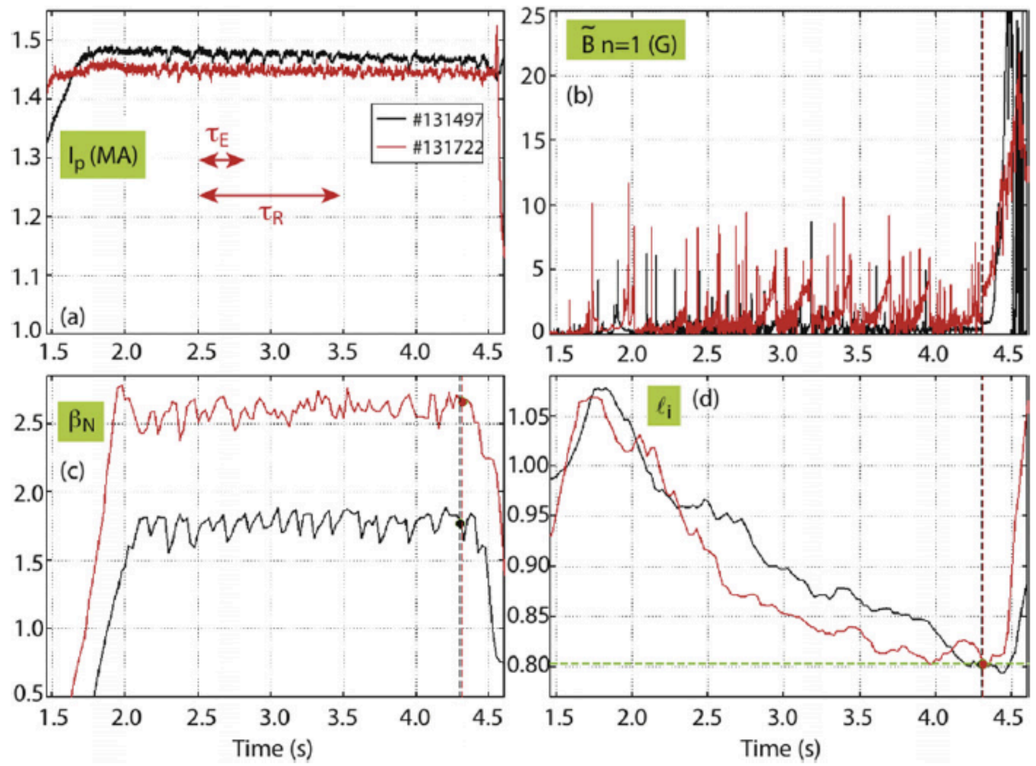
- **Experiments in 2007 have demonstrated > 1 s fully non-inductive operation at $\beta_N$ ~ 4 with $q_{min}$ ~ 1.5**
  - Conducted with on-axis NBI
  - Limited by available NBI duration
- **Experiments in FY11 with off-axis NBI focused on $q_{min}$ ~ 2**
  - $\beta_N$ ~ 3 achieved, limited by confinement
- **Near-term goal is to revisit 2007 $q_{min}$ ~ 1.5 experiments with off-axis NBI**
  - Additional off-axis CD (NBI and EC) and longer NBI pulse limits should allow ~ 3 s




- **2 days allocated (Holcomb)**

# Assessment of Long-pulse Stability and Confinement Characteristics of ITER Baseline Scenario

- **Performance consistent with ITER needs for Q = 10 demonstrated in ITER Baseline Scenario discharges worldwide**
- **Detailed examination of data set indicates tearing mode onset related to evolution of current profile (not pressure)**
- **Near-term goal is to characterize sensitivity of NTM stability and transport to long-pulse (8-sec flattop) evolution of current profille**
  - If NTMs limit duration, determine ECCD requirements for long-pulse requirements

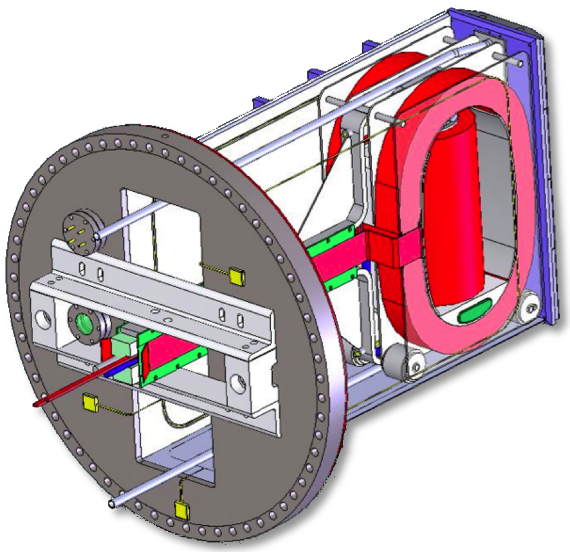


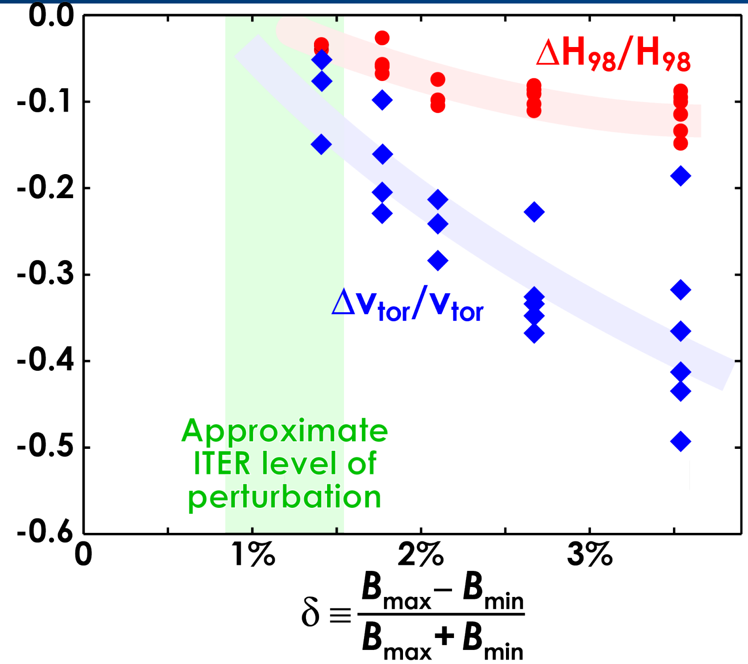

- 3 days allocated (Jackson, Solomon, Turco

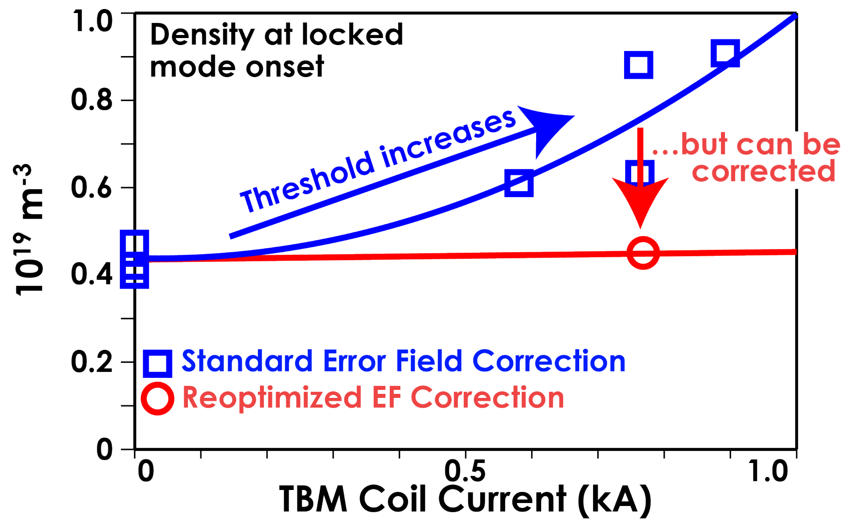
# Test Blanket Module Simulation Experiments

**Experiments in 2009 showed:**

- Little effect on most quantities of interest
- Modest effect of TBM on rotation/ confinement
- Significant n=1 response of plasma to TBM field

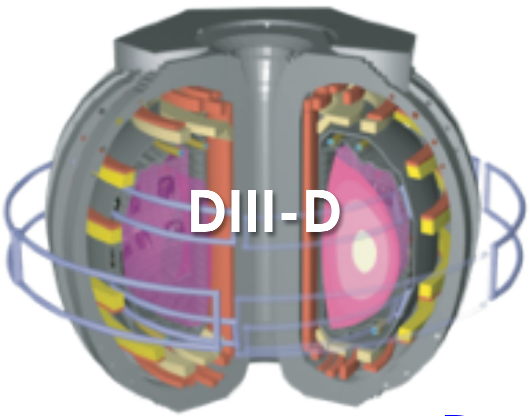




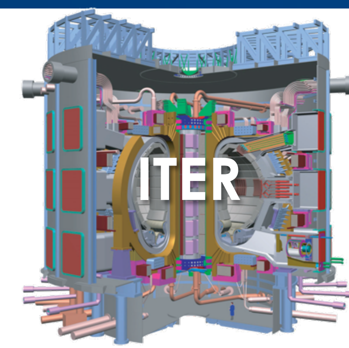

**2011: Evaluate effect of compensation TBM-induced n=1 error field on rotation and confinement (Schaffer, Snipes, Reimerdes)**

# DIII-D Has Three Major Research Themes



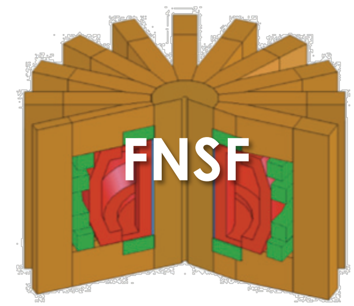

**Ensuring the success of ITER**

*Critical issues for the design and operation of ITER*



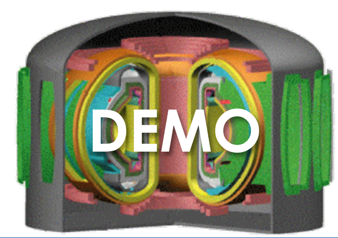

**Improving predictive capability**

*Validation studies of physics-based models of burning plasma behavior*




**Developing sustained operational scenarios**

*Advanced inductive, steady-state*



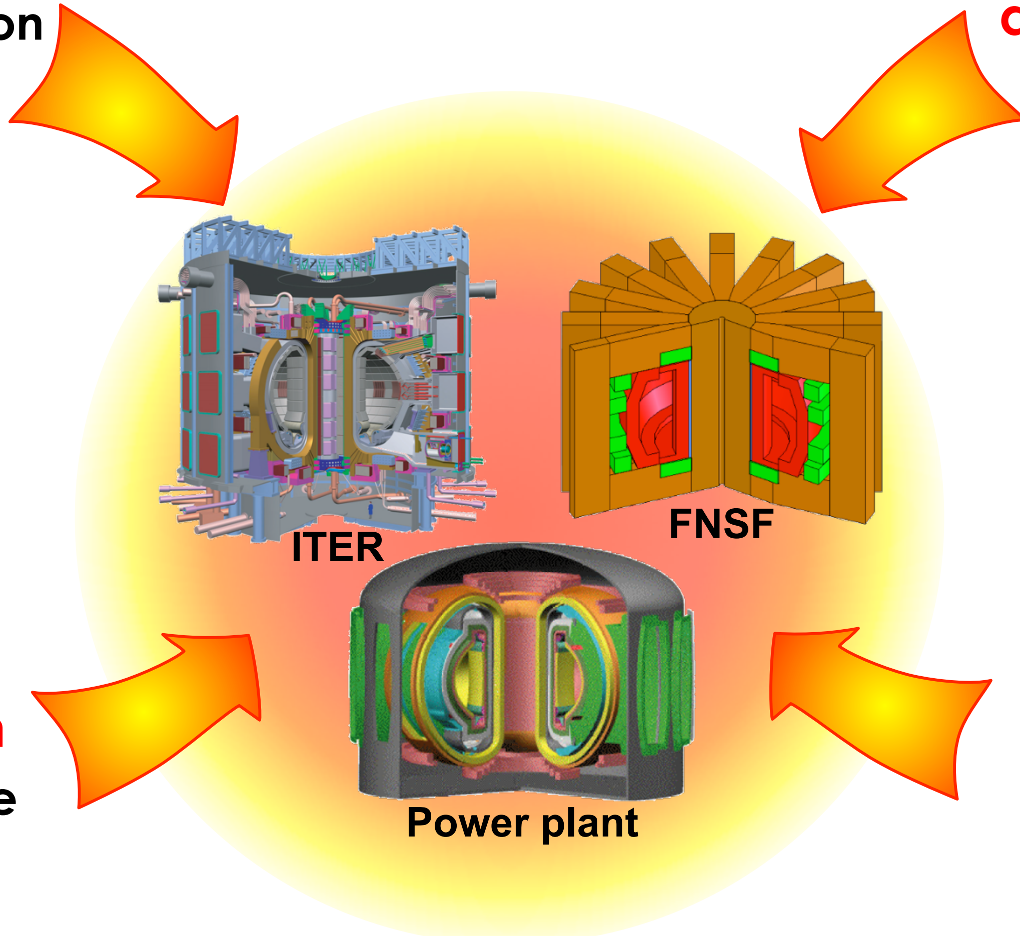
# Research Goal is To Provide Physics Basis for Design/Operational Decisions Future Devices

## Burning Plasma Conditions

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

## Stable Operation at High $\beta$

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

# 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**

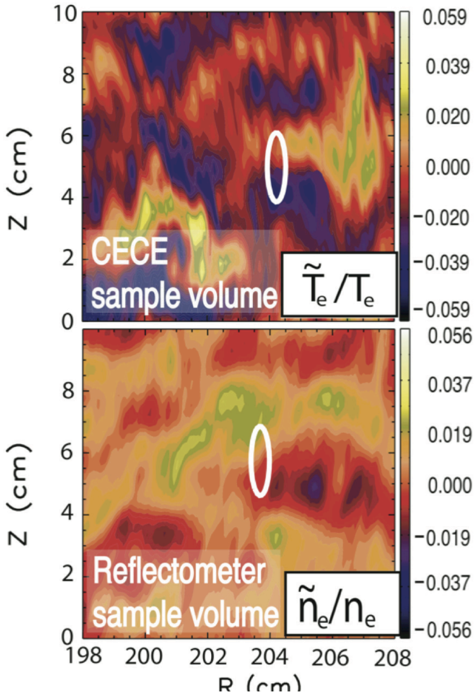
| | |
|---|---|
| **Resolve short-term design issues for ITER** | ELM control<br>Disruption mitigation<br>Startup, shape and position control<br>Hydrogenic retention & dust control |
| **Resolve medium-term design issues for ITER** | H-mode access in $H_2$ and He<br>Magnetic field asymmetries & 3D effects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

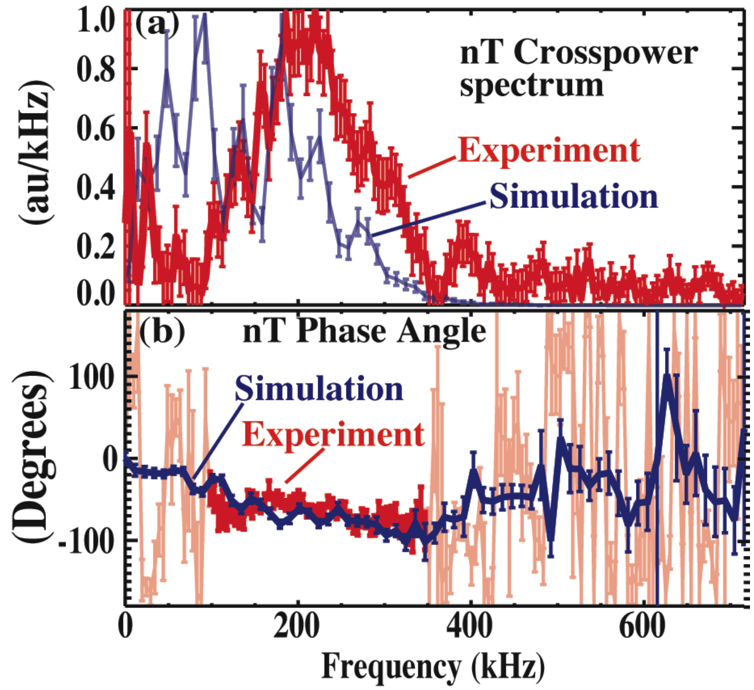
DIII-D priorities developed in consultation with ITER Organization

# Strong Partnership Between Theory and Experiment is a Central Theme of the DIII-D Research Program

## Theory | Experiment

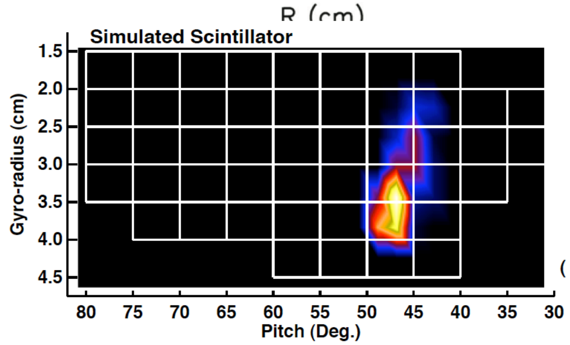
Turbulence & Transport

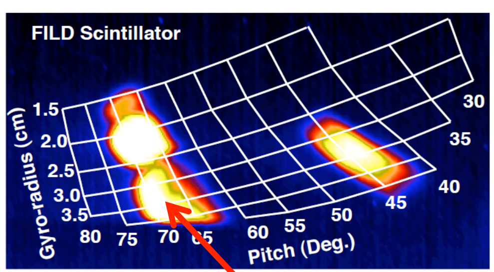



*A.E. White, APS Invited Talk 2009*

Energetic Particles




Prompt Losses

*M.A. Van Zeeland, APS Invited Talk 2010*

# Anticipated Upgrades in 2012-13

- **Heating and Current Drive**
  - 7th (2012) and 8th (2013) gyrotron (4.2 MW ECH/ECCD)
  - Real-time steering of EC mirrors (2012)
  - FW assessment in Dec 2011 → upgrades??
  - NB pulse length extension (2012-2013)
- **Particle Delivery Systems**
  - 30 Hz $D_2$ pellet pacing (2012)
  - Rupture disk (2012-2013)
  - 50 Hz LiD pacing (2013 incremental)
- **Diagnostics**
  - IRTV/periscope (2012)
  - 3D Magnetics (2013)
  - Helium Line Ratio for ne and Te (2012)
  - TALIF neutral measurement prototype (2013)
  - Swing Langmuir probe on inner wall (2012)

# DIII-D 2012 Experimental Planning Schedule

- **Early December: Research Council will meet to discuss DIII-D rolling 3-year program and develop priorities for the 2012 experimental campaign in the context of this plan.**
  - Task Forces and High Priority Working Groups announced

- **January 10-12, 2012: Research Opportunities Forum (ROF)**
  - Open Forum to discuss experimental proposals
  - Web Site should open in mid-December and be open through beginning of ROF

- **Jan 12 - ~ Feb 15, 2012:**
  - Experimental groups to discuss and prioritize proposals in each area
  - Research Council discusses overall allocation of run time
  - DIII-D management, based on Research Council advice, determines allocati on of run time

# DIII-D Physics Groups

| Area | Responsibilities (not necessarily exclusive) |
|---|---|
| **ITER Physics (Strait)** | ELM control; Disruptions; NTM control; ITER scenarios; Error-fields; ITER-specific research (e.g., He/H ops, TBM) |
| **Steady-state Integration (Luce)** | Fully non-inductive development, hybrid/advanced inductive development; core-edge integration; RWMs |
| **Fusion Science (Petty)** | Transport; Energetic Particles; General stability; H&CD |
| **Plasma Control and Operations (Humphreys)** | Physics Operations; Model-based control |
| **Integrated Modeling (Prater)** | Pedestal Physics; Model validation |
| **Boundary Plasma (Leonard)** | SOL Physics; Boundary-Material Interfaces; New Divertor Geometries |

# High Impact Areas of Opportunity for 2012-2013

- **3D Physics and ELM Control (Wade)**
- **Disruption Mitigation, Avoidance, and Characterization (Hollmann)**
- **Transport Modeling (Petty/Burrell)**
- **Off-axis NBI and steady-state integration (see earlier slide)**
- **Non-inductive startup (??)**
- **Plasma Control (Humphreys)**

# 3D Physics and ELM Control

- **While much has been learned about RMP ELM suppression, a first-principle model has not emerged.**
  - Significant opportunities exist for new insights/discoveries
- **Still remains an open physics issue for ITER design**
- **Specific areas of need are:**
  - Assistance in defining a compelling 3D magnetics diagnostic
  - Modeling of DIII-D data with state-of-the-art computational tools (e.g., IPEC, XGC0, VMEC)

# Aggressive Research Program is Envisioned to Provide Input for Critical Decisions on Future ITER and DIII-D RMP Coils

| | 2011 | 2012 | 2013 |
|---|---|---|---|
| Tools | | | Prototype RMP coil |
| Diagnostics | Edge TS, Tang. X-pt. SXR, B probes | IR/visible periscope<br>New diagnostic TBD | 3-D magnetics |

**Near-Term activities focused on improving the physics understanding of edge transport and ELM suppression**

**Plan:**

**2011.** Initial tests of models/hypotheses

- Conduct comparative n=2 studies with Asdex-Upgrade
- Measure turbulence response to RMP with edge turbulence diagnostics
- Use expanded diagnostic set to carry out rigorous tests of promising models

**2012.** Demonstrate cross-machine capability to suppress ELMs in similar regimes

New 3D Coil Physics Assessment

Provide input for ITER RMP coil decision

# Improved Understanding of the Plasma Response to 3-D Magnetic Perturbations Will Benefit ITER

| | 2011 | 2012 | 2013 |
|---|---|---|---|
| Tools | | | Prototype RMP coil |
| Diagnostics | Edge TS, Tang. X-pt. SXR, Main ion CER, B probes | IR/visible periscope<br>New diagnostic TBD | 3-D magnetics |

- **Effects can be beneficial or detrimental**
  - RMP ELM suppression, NTV rotation drive are examples of benefits
- **Key is understanding the plasma response**

**The plan leverages experience in the stellarator community, an existing suite of 3-D MHD codes, and an expanding set of 3-D diagnostics:**

**2011. Measure n=3 plasma response to test ideal/resistive models**

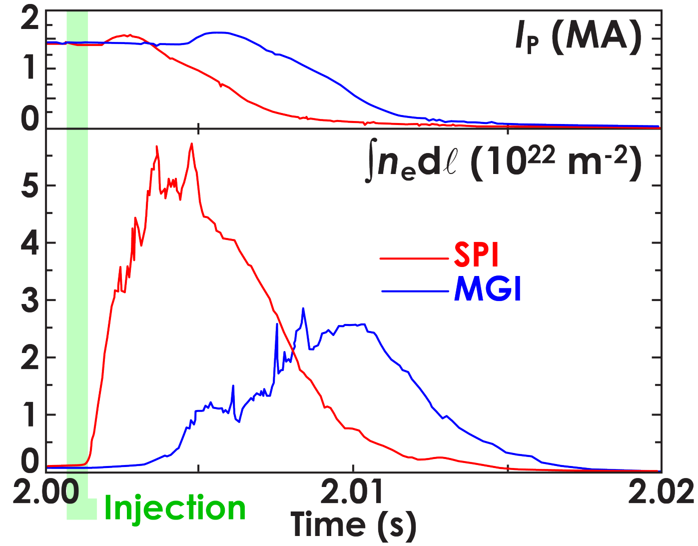
**Evaluate impact of reoptimized error field correction on TBM effects**

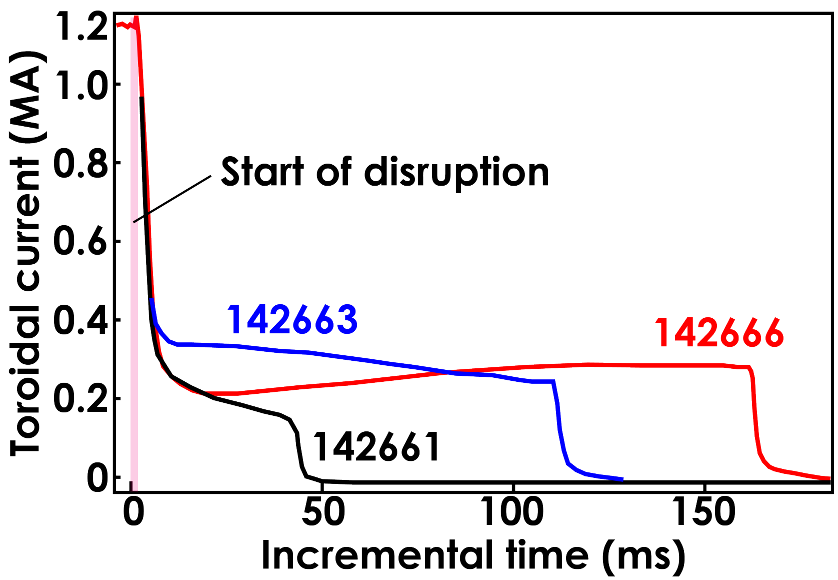
**2012. Assess plasma response to applied error fields with multiple modes**

**2013. Utilizing expanded 3-D magnetics, quantify plasma response to a wide range of externally imposed 3-D fields**

# Disruption Mitigation, Avoidance, and Characterization

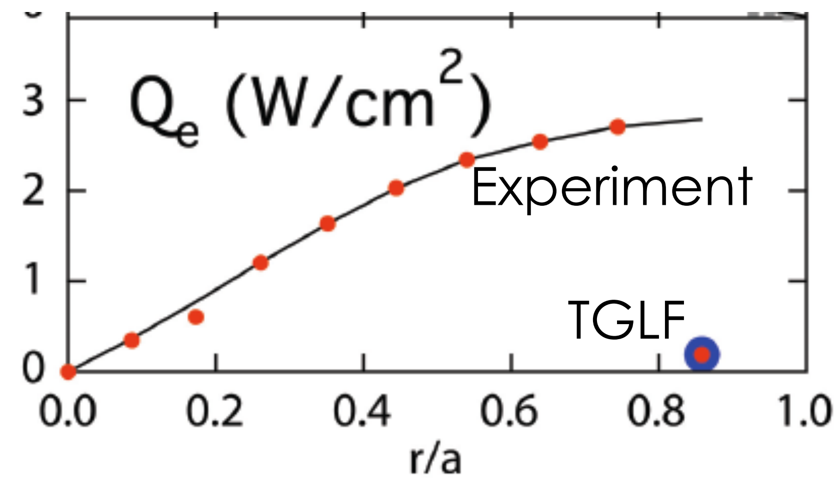
- **Avoiding and/or mitigating disruptive effects is recognized as a critical enabling element in the success of the ITER Research Plan**
- **Mitigation:**
  - Significant effort in recent years (massive gas injection, runaway channel control); some success, extrapolation uncertain
  - New schemes may still be needed
- **Avoidance:**
  - Ultimate need of any tokamak is to demonstrated robust avoidance
  - Limited effort to date; significant opportunity space in MHD detection and control
- **Characterization:**
  - ITER very interested in non-axisymmetric effects including halo currents/heat loads

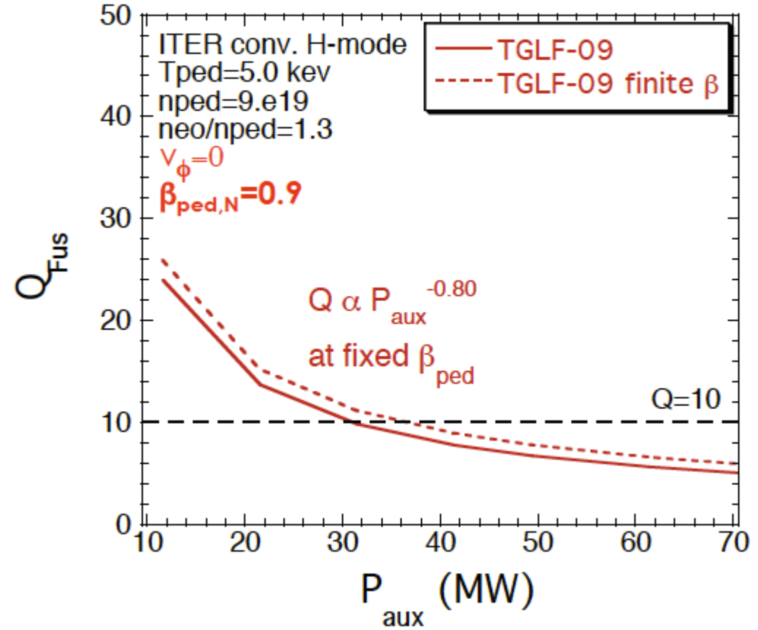


# Transport Modeling

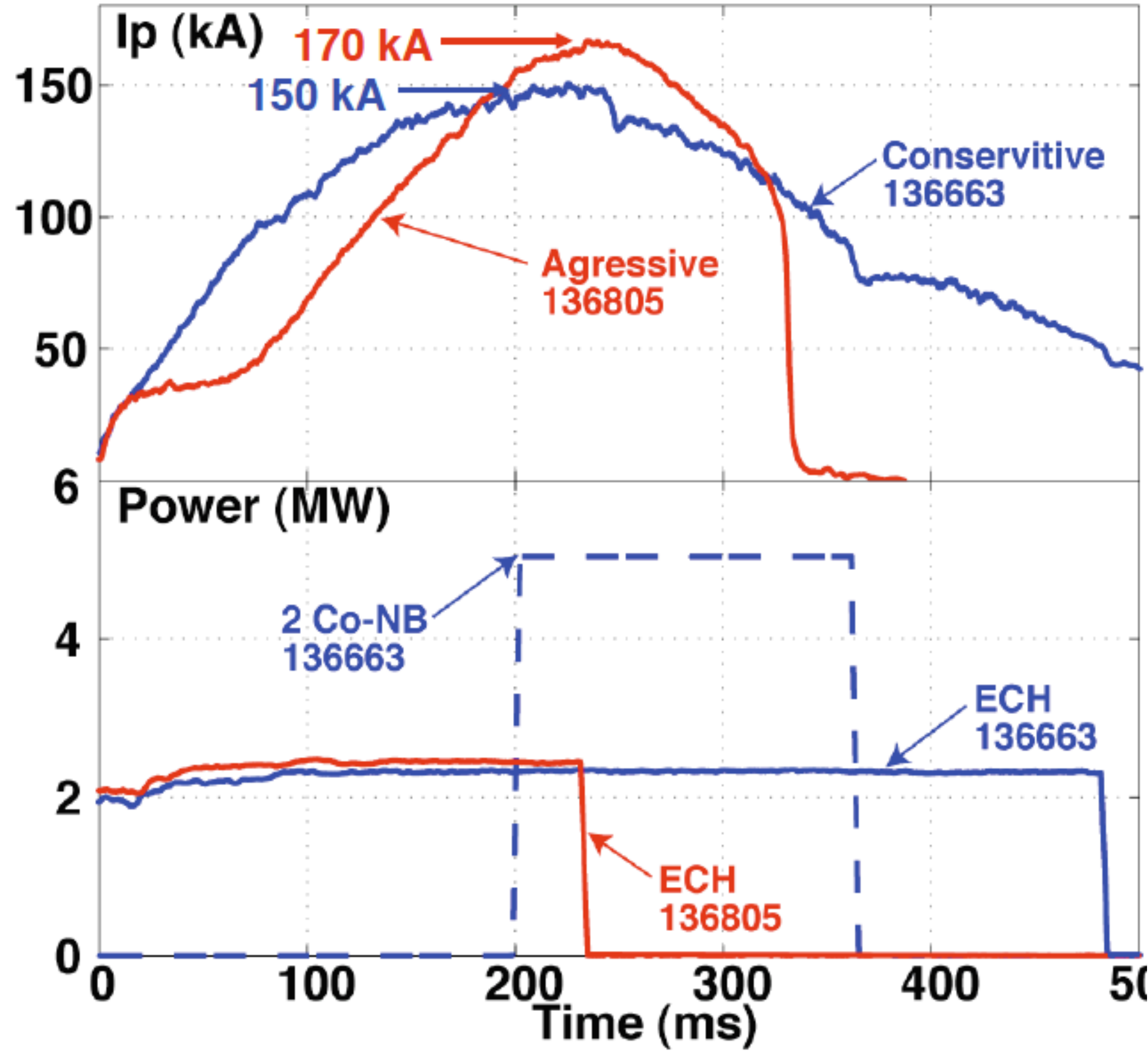
- **Large amount of data taken over past few years using extensive set of diagnostics**
  - Low-k, high-k $\delta n_e$, Low-k $\delta T_e$ , $\alpha_{<\delta ne\ \delta Te>}$
- **Comparisons show reasonable agreement between GYRO/TGLF for ρ < 0.6, but disagreement for ρ > 0.7**
  - More cases available for comparison
- **Recent TGLF modeling of ITER shows strong degradation of Q with auxiliary power**
  - Analysis indicates this is due to profile stiffness
  - Lots of data collected in 2011 – limited transport analysis/modeling done to date



# Solenoidless Startup

- **> 150 kA plasma current produced without any assistance from DIII-D coils in "center stack"**
- **Need path to get ~ 300-350 kA before NBCD can take over**
- **Primary local champion (J. Leuer) is retiring in Dec 2011**
  - Opportunity for run-time if compelling experiment is put forth



# Transport and Confinement Opportunities

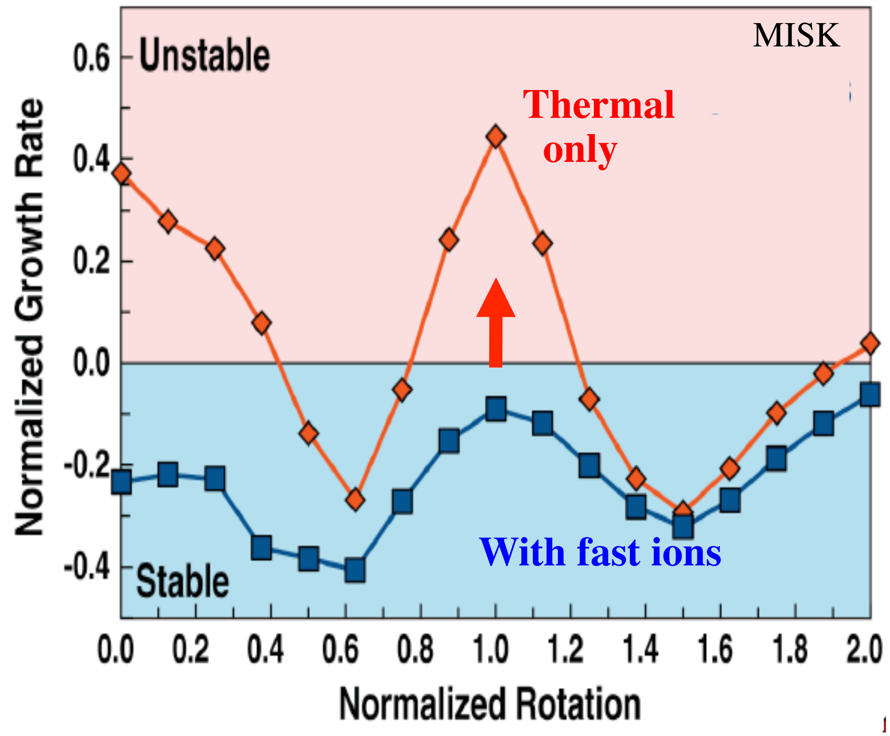
- **Model Validation (discussed previously)**
- **Test of Profile Stiffness / Critical Gradients (discussed previously)**
- **Particle/Impurity Transport (Petty)**
  - Due to lack of resources (i.e., people), currently an area with significant opportunities on DIII-D
- **Transport Analysis of Advanced Tokamak plasmas (Luce)**
  - Also lacking critical level of support

# General MHD/Stability Opportunities

- **Resistive Wall Mode (RWM) Physics and Stabilization (Okabayashi)**
- **Disruption Avoidance (Strait)**
- **Plasma Response to Error Fields (Buttery, La Haye)**

# Variable NB Aiming and Torque Should Provide Interesting Tests of RWM Fast-ion Stabilization

- **Rotation and Fast-Ion Distribution (Spatial and Velocity) can be systematically varied using off-axis and co/counter NBI**
  - Should allow detailed tests of kinetic stabilization of RWMs by fast ions
  - Also will provide platform for RWM feedback stabilization in reactor-like conditions (low torque, more isotropic fast ion distribution)

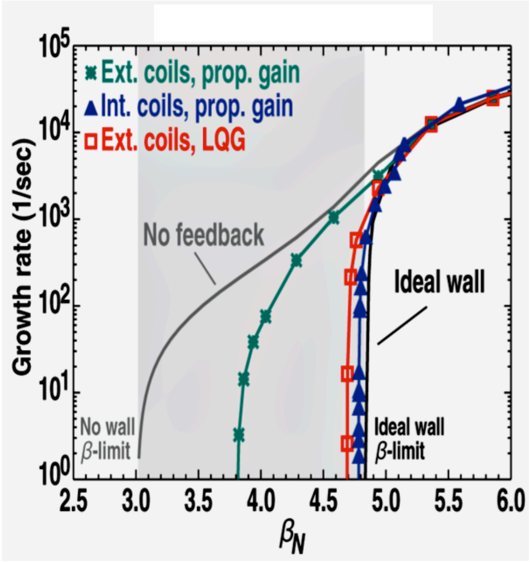


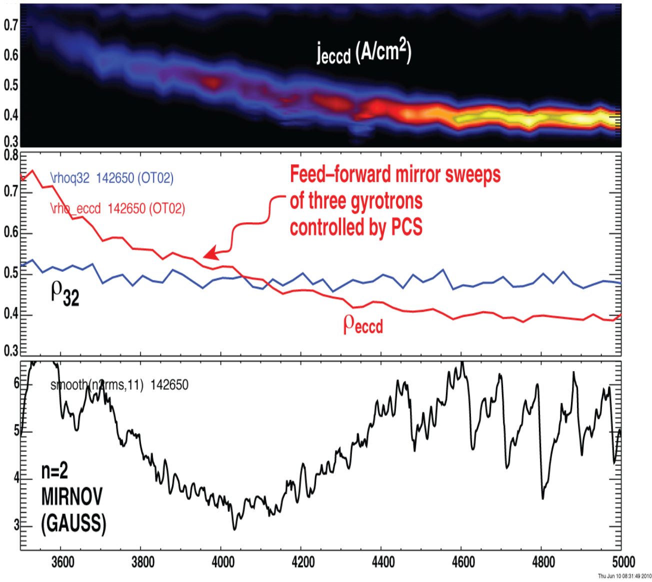
# Individual Tools for Instability Control are Nearly in Place; Next Step is Integrated Disruption Avoidance

- **RWM control: New model based 'state space' controller suggests stabilization may be possible with external coils**

- **NTM control: Utilize new steerable ECH to develop 'black box' tearing control**

- **Major challenge is to develop robust disruption avoidance algorithms that are applicable over a range of operating space. Requires:**
  - Routine implementation of stabilization tools
  - Real-time detection of instabilities
  - Hierarchical control logic to handle range of possible events



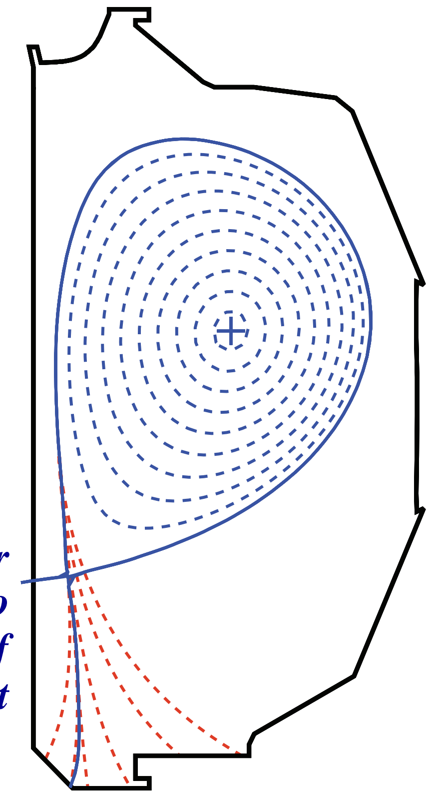



# Boundary/Pedestal Physics Opportunities

- **Basic SOL/Erosion Studies (Leonard)**
  - Takes advantage of extensive diagnostic set and ability to expose sample materials in a controlled setting
- **Heat Flux Control/Divertor Geometry Studies (Petrie, Leonard)**
- **Pedestal Structure (Groebner)**

# Divertor Experiments in 2012-13 to Focus on Physics of Detachment Onset and Configuraiton Optimizaition

- **Self-Consistent Heat and Particle Flux Control Solutions are required for next-step devices**
  - Yet, detachment thresholds, stability & asymmetry not well understood
- **DIII-D Near-Term Emphases:**
  - Determine controlling physics for detachment onset in standard configurations
  - Assess ability to reduce heat flux and improve stability of detachment using advanced configurations



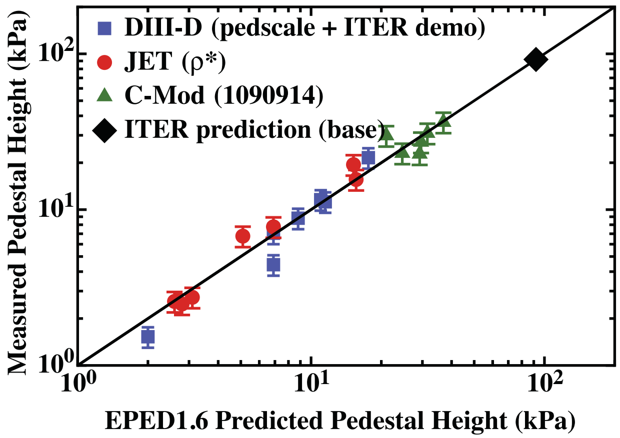

***New Diagnostics***
*Flow: 2D coherence imaging 2011*
*IR & Visible: Periscope 2012*
*Neutrals and 2013*

# 2011 JRT Has Provided the Basis for More Coordinated Effort on Understanding Pedestal Structure

| | 2011 | 2012 | 2013 |
|---|---|---|---|
| Diagnostics | Edge Thomson upgrade<br>X-pt SXR<br>Lithium beam upgrade | Line ratio ($n_e$ & $T_e$) | Neutrals /TALIF |

**Present status:**

- **Significant progress made as part of 2011 JRT**
- **Strong collaboration between NSTX and DIII-D exists now**

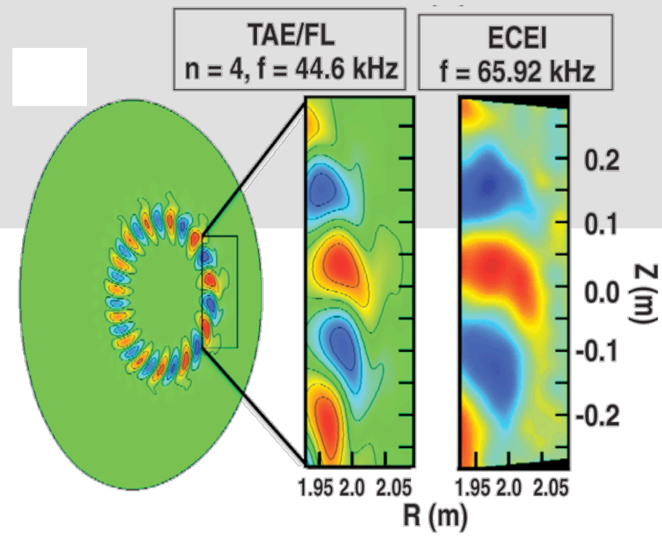



**Future potential opportunities:**

- **Compare evolution of Enhanced Pedestal H-mode on NSTX and VH-mode on DIII –D**
  - Identify mechanisms leading to enhanced performance
- **Assess impact of 3D fields on pedestal structure**
  - RMP, QH-mode, …

# Excellent Set of Diagnostics/Tools Should Provide Basis for Highly Detailed Energetic Particle Studies

| | 2011 | 2012 | 2013 |
|---|---|---|---|
| Tools | Off-axis NBI | 6 (3) MW FW | |
| Diagnostics | ECEI<br>FILD-2<br>FIDA imaging upgrade<br>BES upgrade<br>NPA upgrade | Fast FILD upgrade | |




**Present status:**

- Modes have been observed/identified, and their role on fast ion transport reasonably well understood

**Plan:**

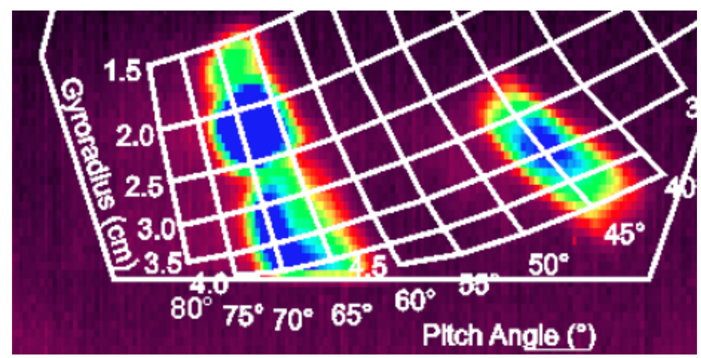
**2012.** Interplay between OANB and sawteeth

Electron thermal and EP transport by RSAE/TAE

**2013.** Super-Alfvénic ions driven by RF tail

AE validation experiments TBD

**Energy and Pitch of Loss**

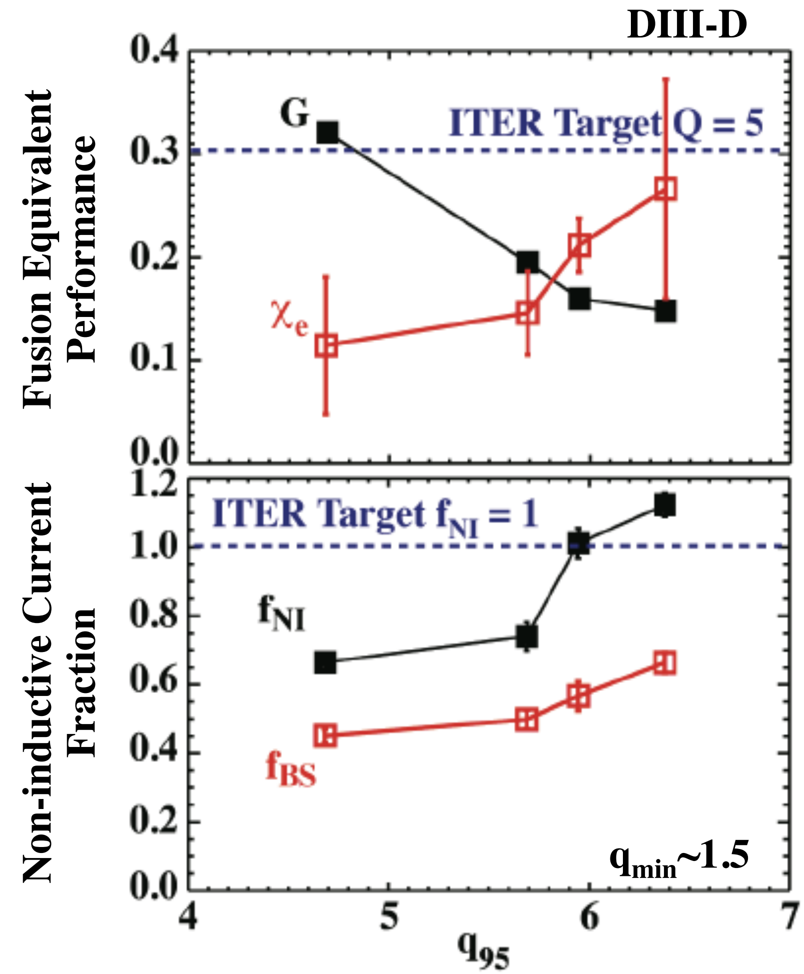


# Advanced Scenario Development Opportunities

- **Assessment of ITER Steady-State Scenarios (Luce)**
- **Demonstration of high performance solutions needed for FSNF (Luce)**
- **Transport analysis of relevant regimes (discussed previously)**

# Near-Term ITER Focus is Providing Physics Basis for Upgrade/Operational Decisions for Steady-State Ops

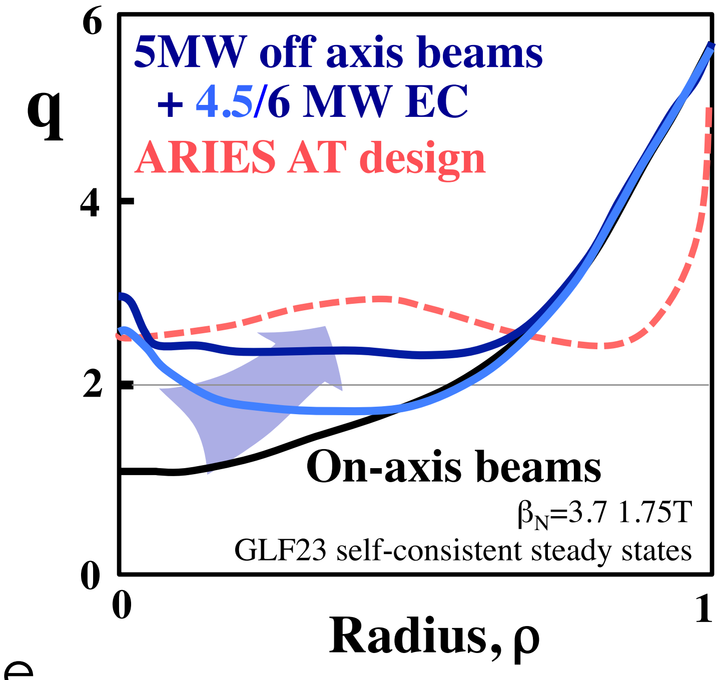
- **Trade off between fully non-inductive and Q=5 performance goals**
  - Observed in DIII-D $q_{95}$ scan ➔




- **DIII-D will identify route to raise performance:**
  - Vary current drive deposition **(2012)**
    - *Increased $q_{min}$ radius & value expected to reduce transport by weakening shear*
  - Optimization of shape consistent with ITER PF set **(2012)**
  - Define physics access requirement & develop feedback control **(2013)**
    - ***Determine how to deploy ITER's current drive systems & phase II requirements***

# DIII-D Is In Unique Position to Test Regimes Needed for FNSF and DEMO

- **Goal: Establish operating scenarios <u>and</u> design basis**
  - While FNSF parameters demonstrated in DIII-D, need to understand optimization in terms of performance and machine design
- **Issues:**
  - q profile → *Heating systems, RWM control*
  - Plasma shape → *Coil specifications*
  - Requirements for high $\beta_N$=5 (FNSF: $\beta_N$=4) for self-driven (FNSF: fully non-inductive) goals
    → *Continuous vs pulsed operation*




**Plan: First explore off-axis current regimes:**

**2011: Explore physics of $q_{min} \geq 2$ regimes**
- Assess current drive, transport & stability
- q profile tailoring for optimal current drive

**Current profile evolution & feedback control**

**2012-13: Shape optimization**

**2nd off-axis beam assessment 2012**

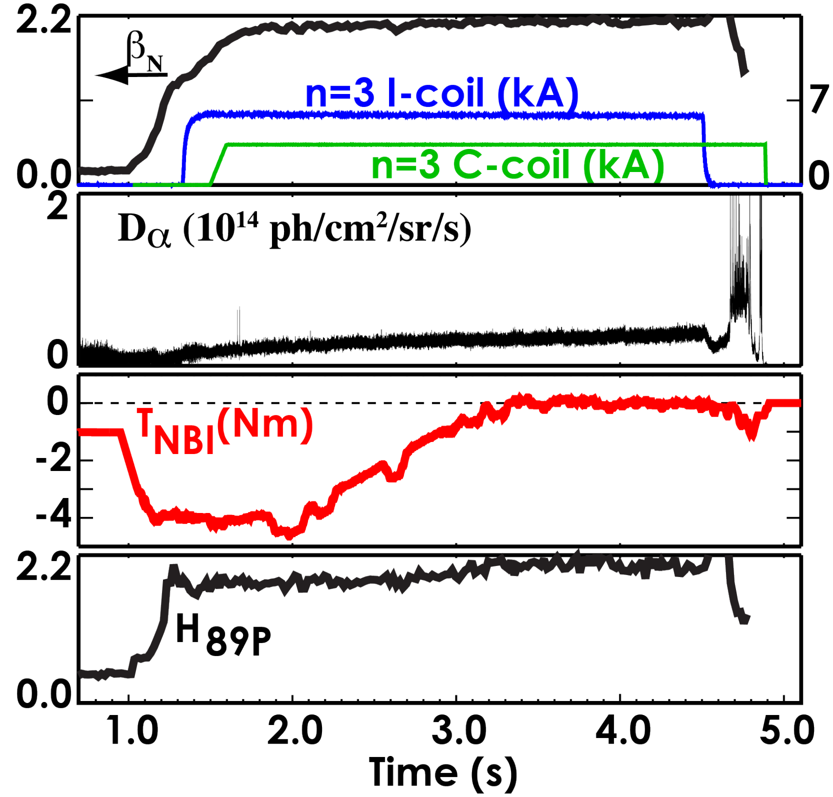
# Other Opportunities to Support ITER

- **Alternate ELM control techniques (JRT 2013) (Fenstermacher)**
- **Improved error field correction understanding (Buttery)**
- **Non-nuclear operating scenarios (Gohil)**

# Research Will Focus on Extrapolability of Using Non-Resonant Fields to Access QH-mode in ITER

**Present status:**

- QH-mode maintained with no NBI torque using non-resonant fields to drive NTB torque




**Plan:**

**2011.** Extend operation to small co-NBI torque using full non-axisymmetric coil set

**2012.** Test theory of NTV-driven shear at edge and assess extrapolability to ITER 180

**2013.** Demonstrate NTV-driven QH-mode in ITER-like conditions

Provide input for ITER RMP coil decision

# New Pellet Injection Capabilities Will Enable Testing Critical Issues for Pellet Pacing in ITER

| | 2011 | 2012 | 2013 |
|---|---|---|---|
| Tools | 30 Hz pellet injector, new guide tubes | >50 Hz LiD injector | |

**Present status:**

- 14 Hz pellets ➔ ~25 Hz ELMs
- $\Delta W_{ELM}/W$ decreases by ×3-4

**Plan:**

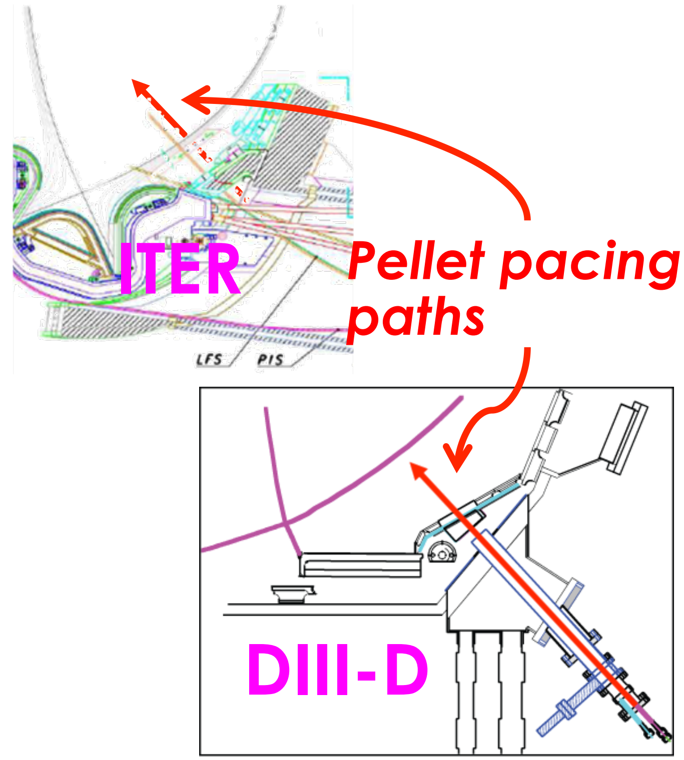
**2011.** Experiments in ITER-like shape with 30Hz pellets

Experiments to combine HFS fueling with LFS ELM pacing

**2012.** Modify pellet size as necessary to explore minimum required pellet size/penetration

Continue ITER extrapolation experiments 180

**2013.** Experiment on high rep-rate pellet ELM pacing




Provide input for ITER RMP coil decision

# DIII-D Will Continue to Assess and Qualify Scenarios for the Non-Nuclear Phase of ITER Research Plan

| | 2011 | 2012 | 2013 |
|---|---|---|---|
| Tools | Off-axis NBI | 6.7 (4.8) MW ECH<br>6 (3)MW FW | 8.2 (6.0) MW ECH |
| Diagnostics | ECEI<br>Main ion CER<br>CER poloidal rotation upgrade<br>Thomson scattering upgrade | UF-CHERS | |

**Present status:**

- **Previous isotope studies focused on L-H threshold**
  - $P_{th}$ increases by ~×2 from D to He
  - Energy confinement reduced by ~30%

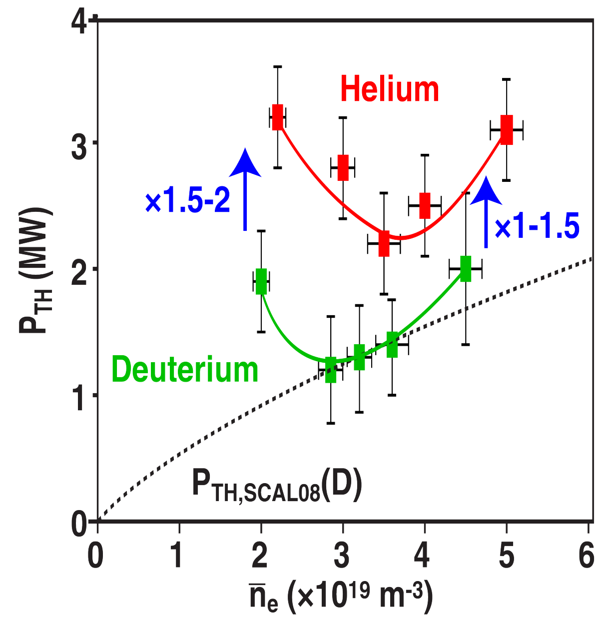
**Plan - Study with hydrogen isotopes and helium:**

**2011. Evaluate existing H and He data**

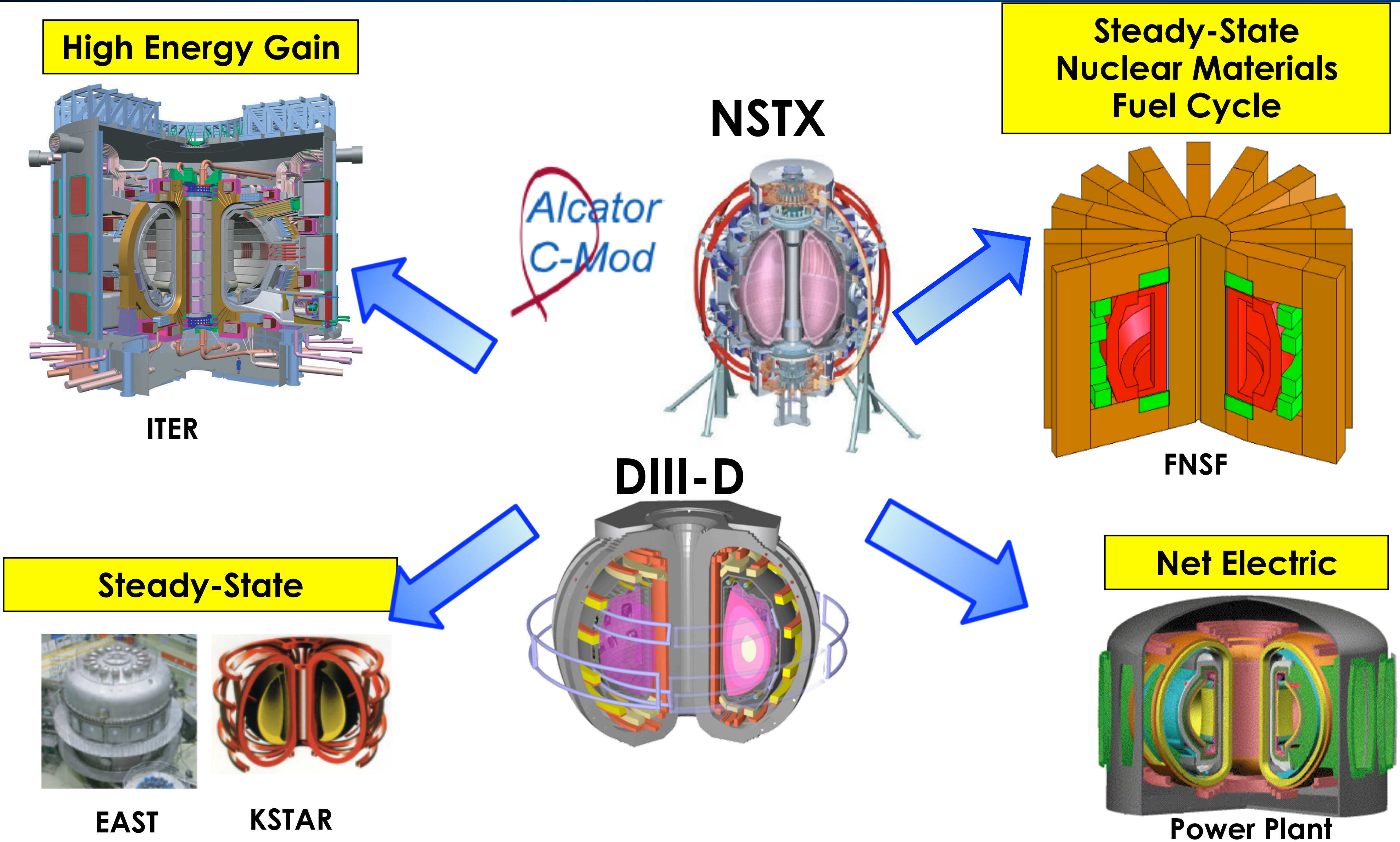
**2012. Establish conditions and power requirements for for type I ELMs**

**Evaluate $\tau_e$ and plasma performance**

**2013. Demonstrate ELM suppression in He 188(I)**

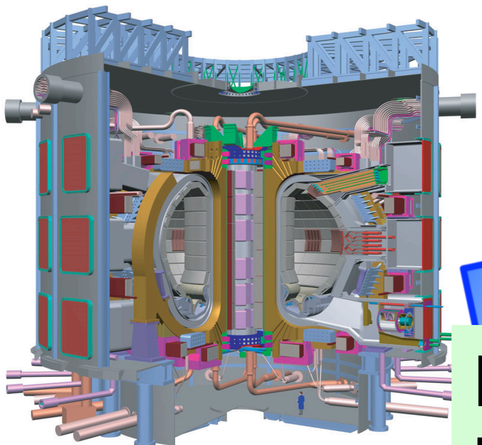


# Utilizing Strengths of Devices and Personnel, U.S. Poised to Make Significant Contributions Towards Fusion Energy



# Utilizing Strengths of Devices and Personnel, U.S. Poised to Make Significant Contributions Towards Fusion Energy

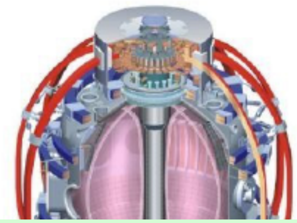
**High Energy Gain**



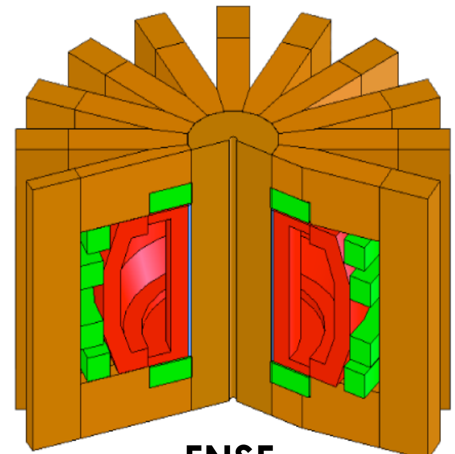
ITER

NSTX

Alcator C-Mod

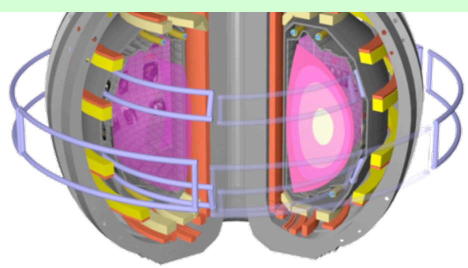


**Steady-State Nuclear Materials Fuel Cycle**



FNSF

**DIII-D Welcomes Your Ideas, Ingenuity, and Expertise - the Driving Force Behind This Progress**

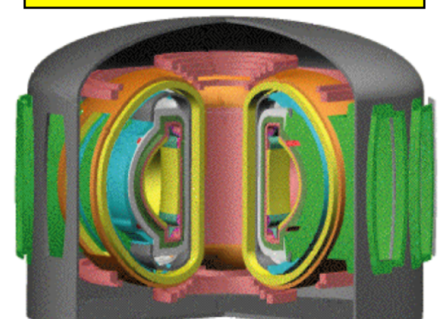


**Steady-State**

EAST

KSTAR

**Net Electric**



Power Plant