DIII–D National Fusion Program Status and Plans

by
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Presented at
Fusion Power Associates
Annual Meeting and Symposium
Oak Ridge, Tenessee

December 4–5, 2007

Outline

- **DIII–D mission and program elements**

- **Recent results**
  – ITER
  – Fusion science
  – Advanced tokamak

- **Five year program plan 2009-2013**

The DIII–D National and International Team: Key to the Scientific Excellence of the DIII-D Program

Active Collaborations

US Labs

ANL (Argonne, IL)
LANL (Los Alamos, NM)
LBNL (Berkeley, CA)
LLNL (Livermore, CA)
ORNL (Oak Ridge, TN)
PPPL (Princeton, NJ)
SNL (Sandia, NM)

Industries

Calabasas Creek (CA)
CompX (Del Mar, CA)
CPI (Palo Alto, CA)
Digital Finetec (Ventura, CA)
DRS (Dallas, TX)
DTI (Bedford, MA)
FAR-TECH, Inc. (San Diego, CA)
GA (San Diego, CA)
IOS (Torrance, CA)
Lodestar (Boulder, CO)
SAIC (La Jolla, CA)
Spinner (Germany)
Tech-X (Boulder, CO)
Thermacore (Lancaster, PA)
Tomlab (Willow Creek, CA)
TSI Research (Solana Beach, CA)

US Universities

Auburn (Auburn, Alabama)
Colorado School of Mines (Golden, CO)
Columbia (New York, NY)
Georgia Tech (Atlanta, GA)
Hampton (Hampton, VA)
Lehigh (Bethlehem, PA)
Maryland (College Park, MD)
Mesa College (San Diego, CA)
MIT (Cambridge, MA)
New York U. (New York, NY)
Palomar (San Marcos, CA)
SDSU (San Diego, CA)
Texas (Austin, TX)
UCB (Berkeley, CA)
UCI (Irvine, CA)
UCLA (Los Angeles, CA)
UCSD (San Diego, CA)
U. New Mexico (Albuquerque, NM)
U. Rochester (NY)
U. Utah (Salt Lake City, UT)
Washington (Seattle, WA)
Wisconsin (Madison, WI)

European Community

CEA (Cadarache, France)
CFN-IST (Lisbon, Portugal)
Chalmers U. (Göteberg, Sweden)
CIEMAT (Madrid, Spain)
Consorzia RFX (Padua, Italy)
CRPP (Lausanne, Switzerland)
EFDA-NET (Garching, Germany)
FOM (Utrecht, The Netherlands)
Frascati (Frascati, Lazio, Italy)
FZ (Jülich, Germany)
Helsinki U. (Helsinki, Finland)
IFP-CNdR (Italy)
IPP (Greifswald, Germany)
ITER (Cadarache, France)
JET-EFDA (Culham, United Kingdom)
Kharkov IPT (Ukraine)
MPI (Garching, Germany)
U. Dusseldorf (Germany)
UKAEA (Culham, United Kingdom)
U. of Kiel (Kiel, Germany)
U. Naples (Italy)
U. Padova (Italy)
U. Strathclyde (Glasgow, Scotland)

Japan

JAEA (Naka, Ibaraki-ken, Japan)
Hiroshima U. (Japan)
NIFS (Toki, Gifu-ken, Japan)
Tsukuba U. (Tsukuba, Japan)

Russia

Ioffe (St. Petersburg)
Keldysh (Udmurtia, Moscow)
Kurchatov (Moscow)
Moscow State (Moscow)
St. Petersburg State Poly (St. Petersburg)
Triniti (Troitsk)
Inst. of Applied Physics (Nizhny Novgorod)

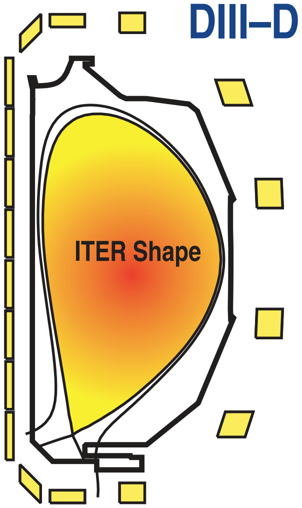
Other International

Australia National U. (Canberra, AU)
ASIPP (Hefei, China)
Dong Hau U. (Taiwan)
IPR (Gandhinager, India)
NFRC (Daegon, S. Korea)
Nat. Nucl. Ctr (Kurchatov City, Kazakhstan)
Pohang U. (S. Korea)
Seoul Nat. U. (S. Korea)
SWIPP (Chengdu, China)
U. Alberta (Alberta, Canada)
U. Toronto (Toronto, Canada)

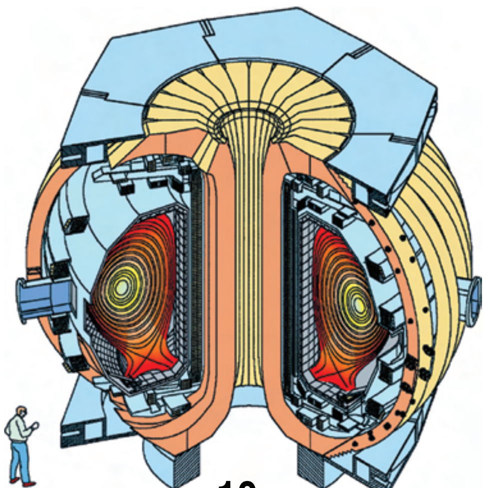
- **90 institutions participating**
  – 28 universities
- **355 scientific authors (2006)**

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

DIII–D



DIII–D PHYSICS BASIS AND OPTIMIZATION

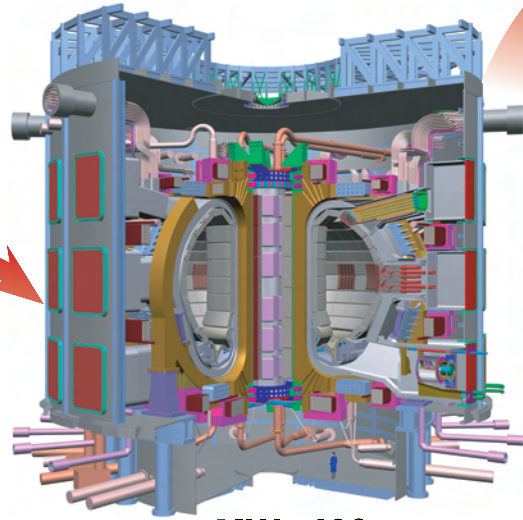


10 s

4X

Science Program – Energy Goal

ITER
FUSION DEMONSTRATION

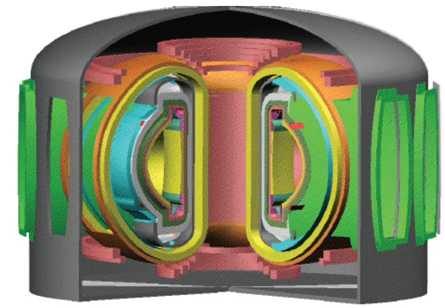


500 MW, 400 s

Developing the scientific understanding for the success of ITER and DEMO

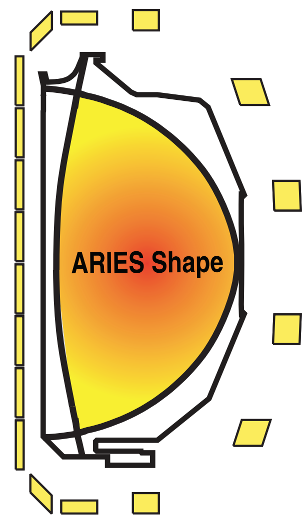
~1X

ARIES-AT
ATTRACTIVE FUSION ENERGY



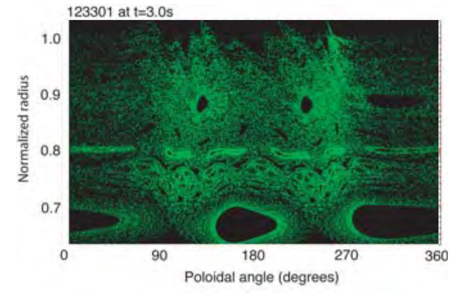
2000 MW Steady-State

DIII–D

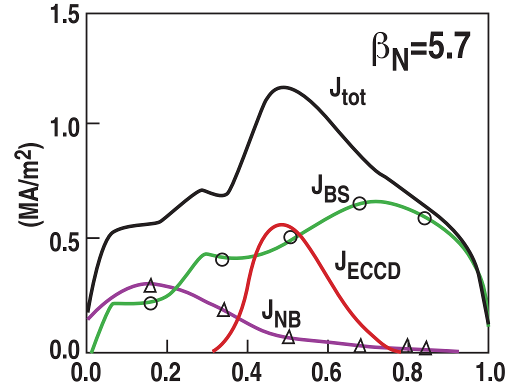


DIII–D Program Has Three Main Research Themes

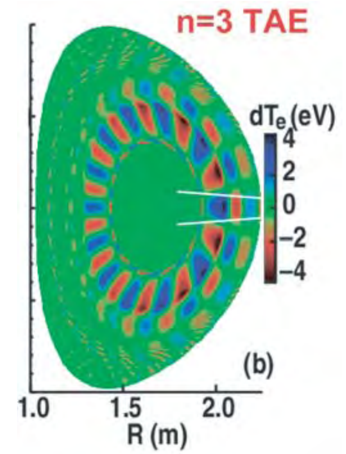
- **ITER Support: Enable the success of ITER by providing physics solutions to key issues**



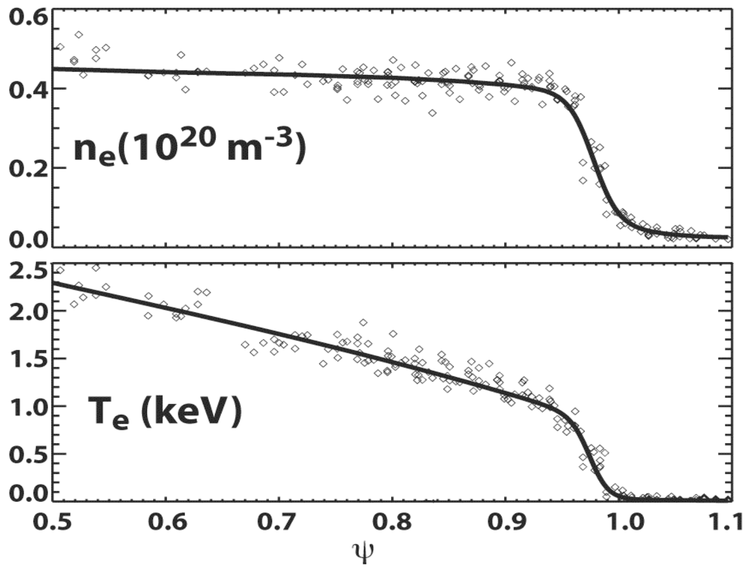
- **Advanced Tokamak: Establish the physics basis for steady-state high performance operation of ITER and beyond**
  - Core and edge

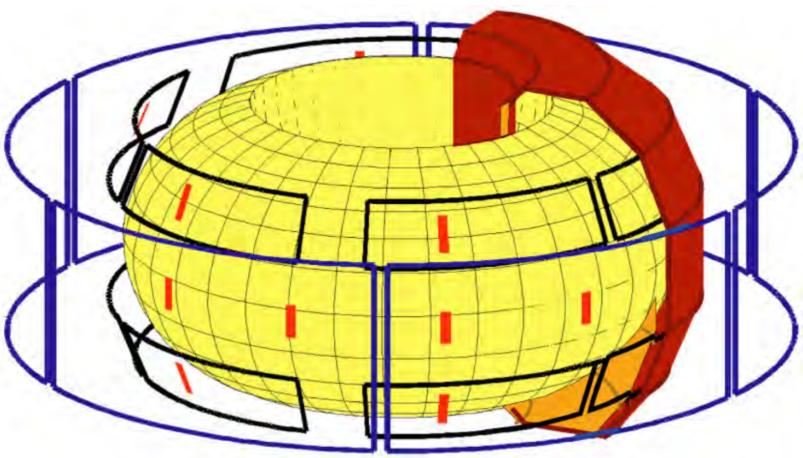


- **Fusion Science: Advance fundamental understanding of fusion plasmas along a broad front**
  - Validate predictive models
  - Transport and Stability
  - Energetic particles
  - Divertor
  - Heating and current drive

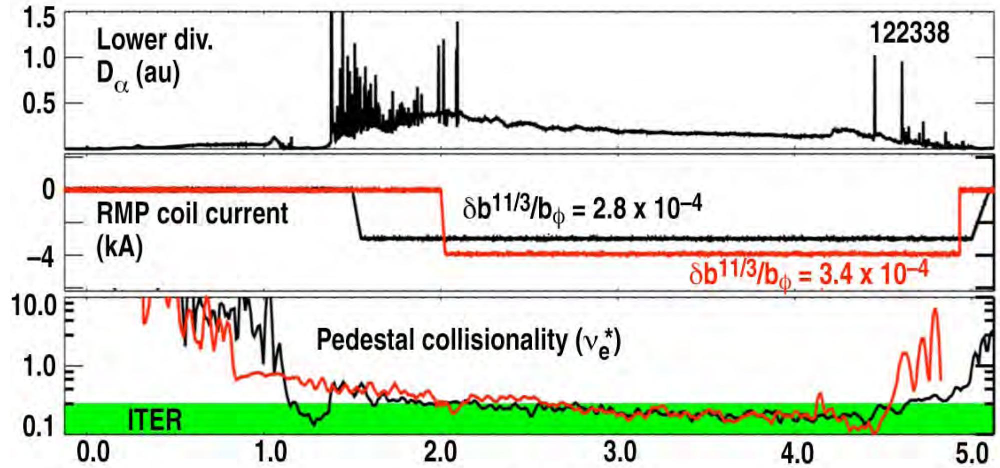


ELMs Are Eliminated Using Resonant Magnetic Perturbations (RMP): Consistent with ELITE Code

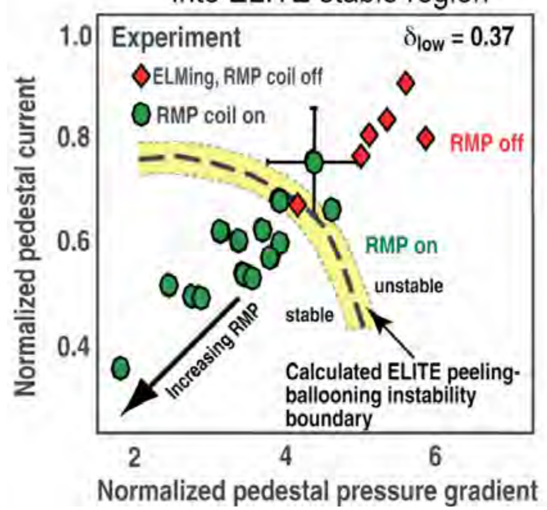




Complete ELM Stabilization in ITER Shape



RMP moves pedestal
Into ELITE stable region

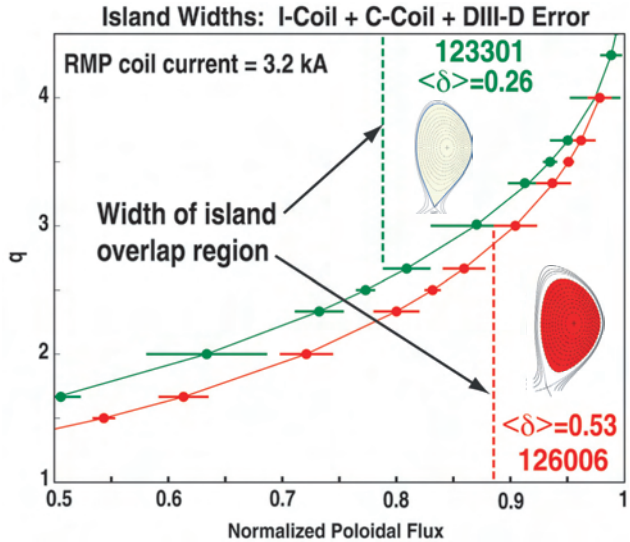


Pellet pacemaking experiments

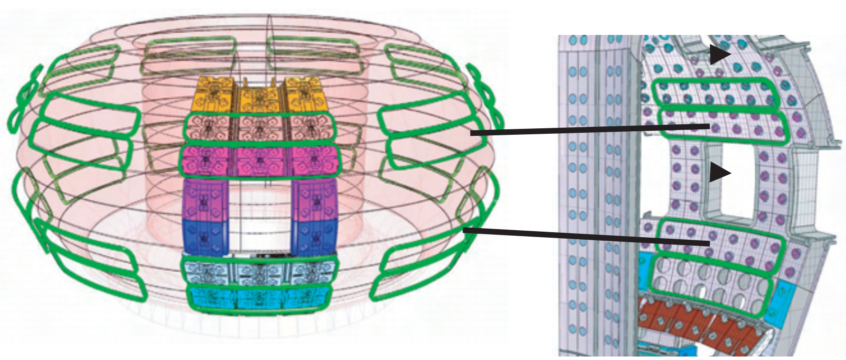
ELM-free QH-mode experiments

DIII-D Research Strongly Supported the Evaluation of ELM Control Coils for ITER

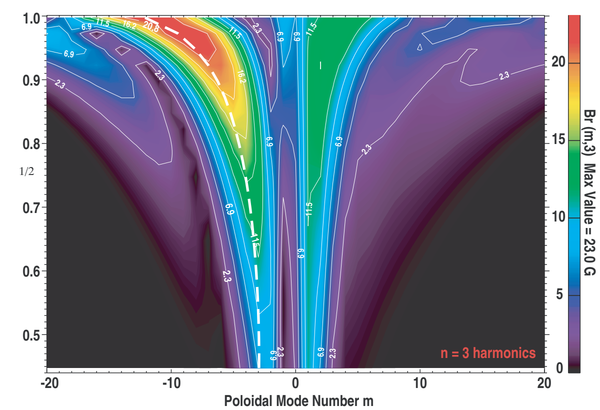
- **2007 experiments focused on providing quantifiable physics criterion for RMP ELM suppression**
  - "Island overlap" ansatz tested
- **Codes developed to treat 3-D fields in actual DIII-D and ITER geometry**
  - TRIP3D, SURFMN
- **Codes applied to ITER to determine tradeoffs in coil location number and location of coils**



ELM Control Coils for ITER

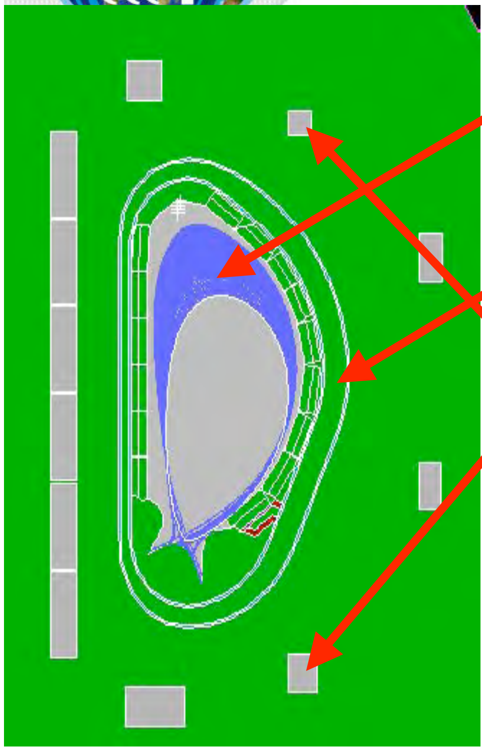


SURFMN Calculation for ITER



ITER, 72-Coil Array (4 rows x 18 coils*)

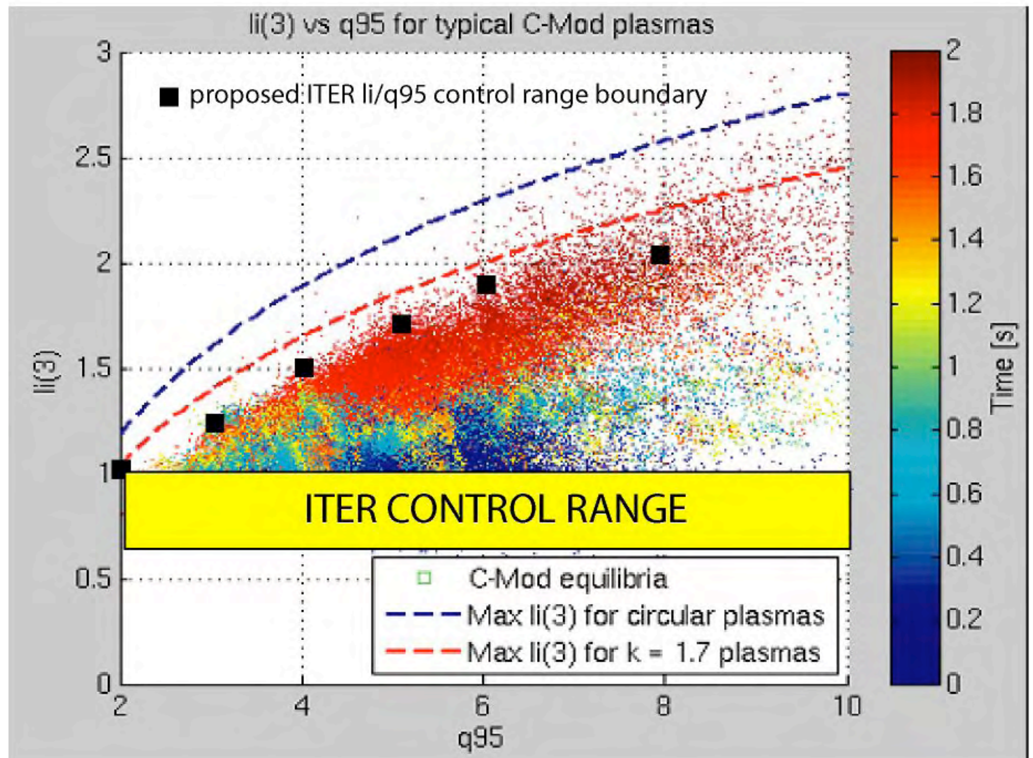
Vertical Stability



High elongation ~ 1.85 (1.7 in "Big ITER")

Thick *double-walled* vacuum vessel

Saturation of P2 and P5 in certain conditions

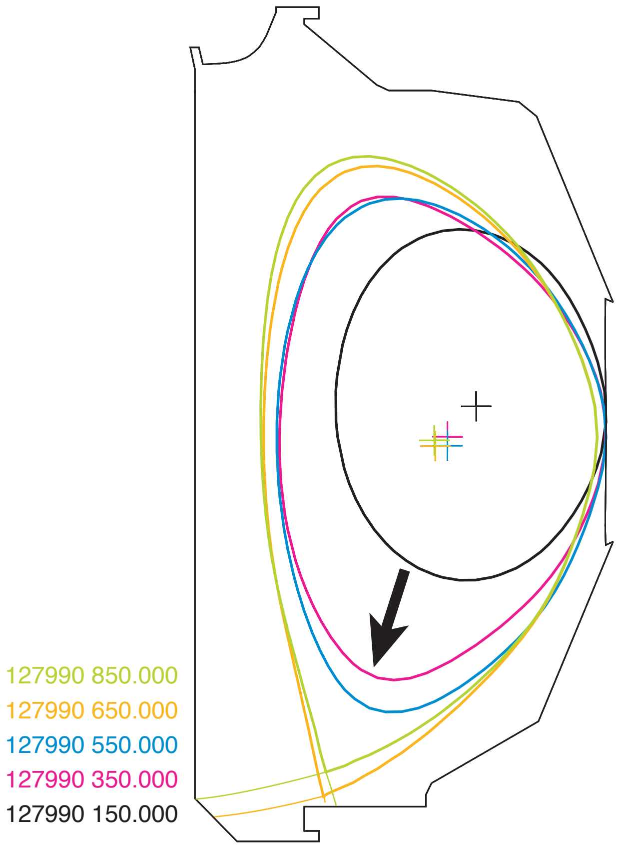


- **The range of *li*(3) between 0.7 and 1.0 has been specified for the design of the ITER PF system**

- **There is a problem with vertical stability in most discharge phases but they are gravest in Ip ramp-up and ramp-down (high l_i)**

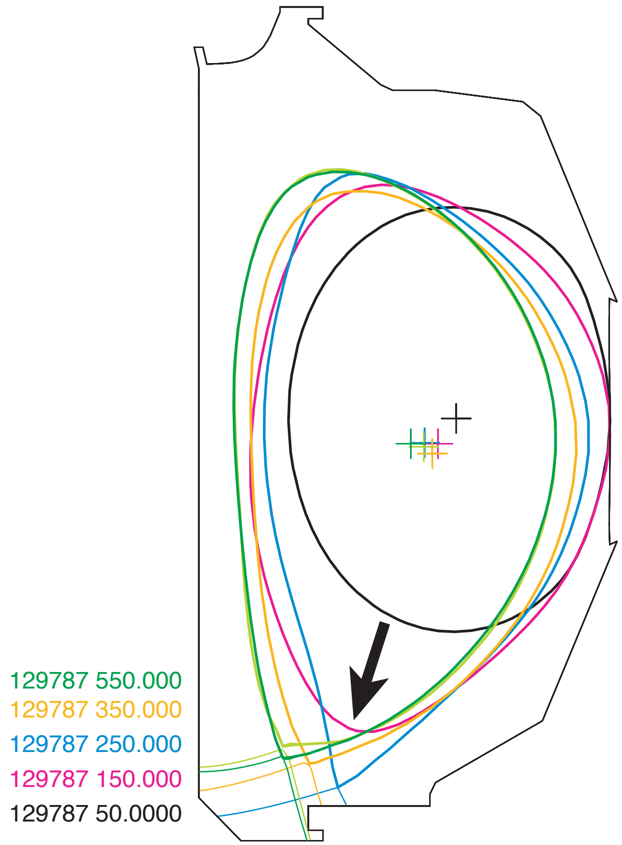
DIII–D Experiments Examined Two ITER Startup Scenarios

- Original scenario



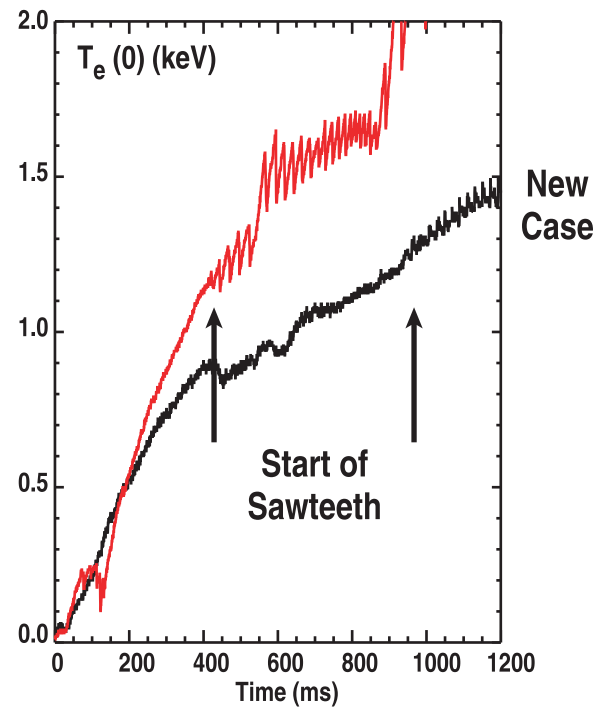
Shape variation for constant qℓ_i and X-point formation at 7.5 MA in ITER

- New scenario



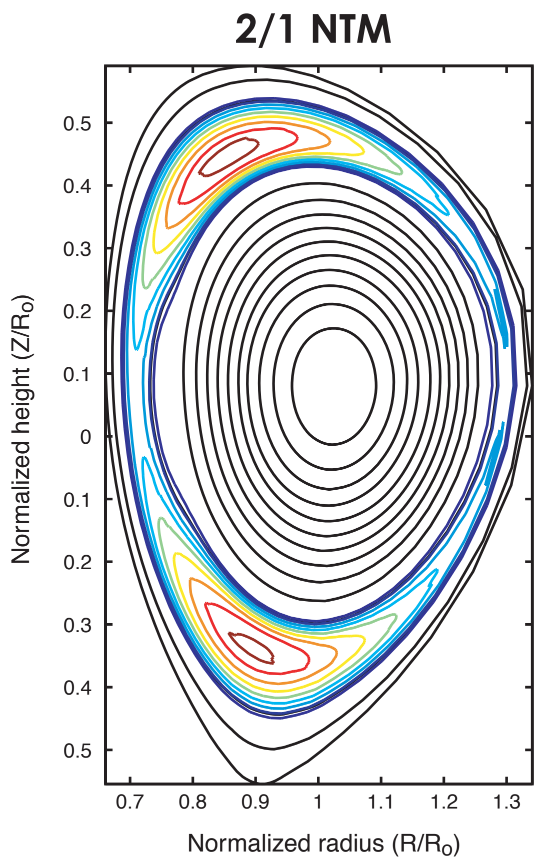
Large plasma from breakdown and X-point formation at 3.5 MA in ITER

- New startup results in lower ℓ_i and later sawtooth appearance
- Early X-point formation allows application of ℓ_i control and auxiliary heating in ITER



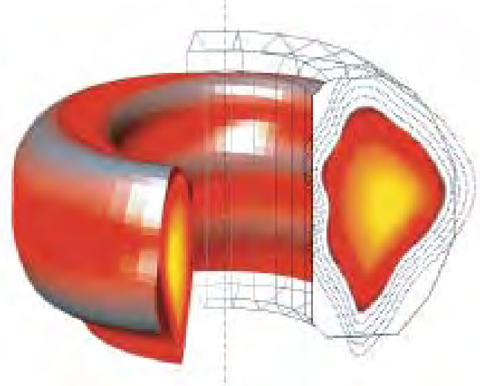
Resistive Wall Modes and Neoclassical Tearing Modes May Limit ITER Performance

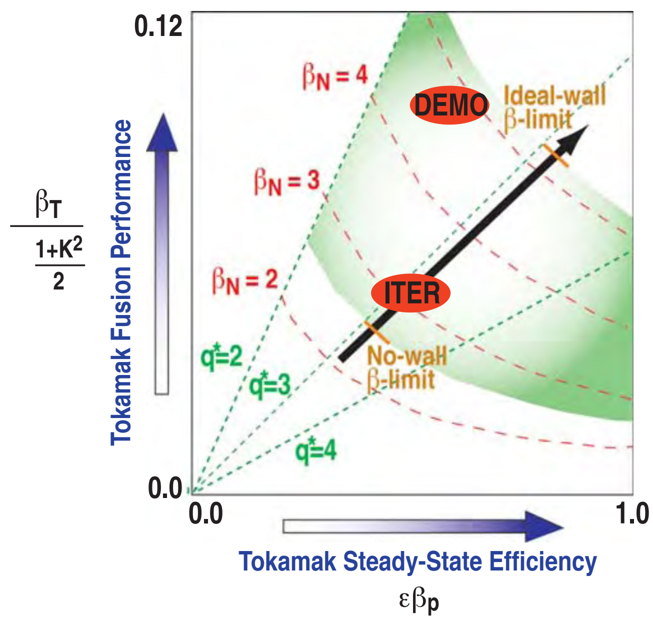
Neoclassical Tearing Modes



- Positive magnetic shear profile
- Seed Islands
- ITER ELMing H-mode $\beta_N \gtrsim 2$
- Controlled by localized ECCD

Resistive Wall Modes

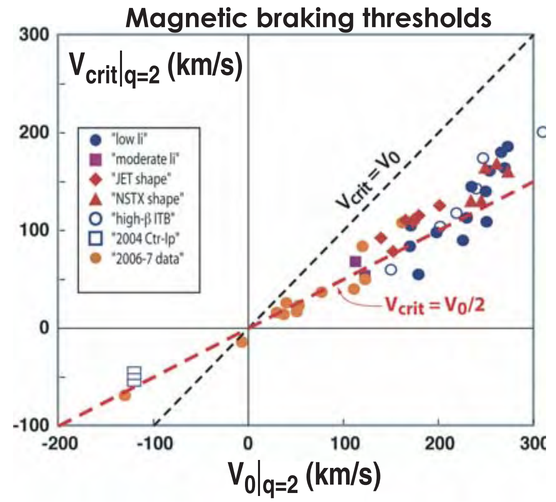




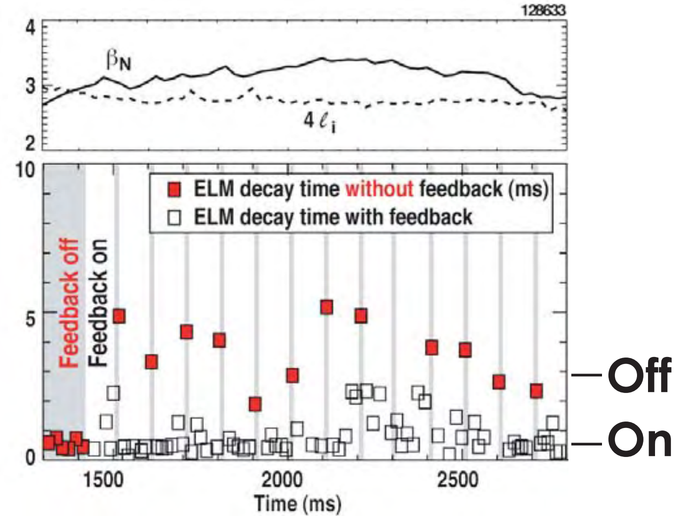
Rotational Stabilization

RWM-Control Experiments Reveal Complex Interaction Between Error Fields, Rotation, and Stability

- **Experiments show RWM stability depends largely on rotation**
  - critical velocity depends on torque (initial velocity)
  - Suggests strong role of error field screening



- **Experiments show benefit of feedback at high β and low rotation: reduced duration of ELM-induced n = 1 perturbations**



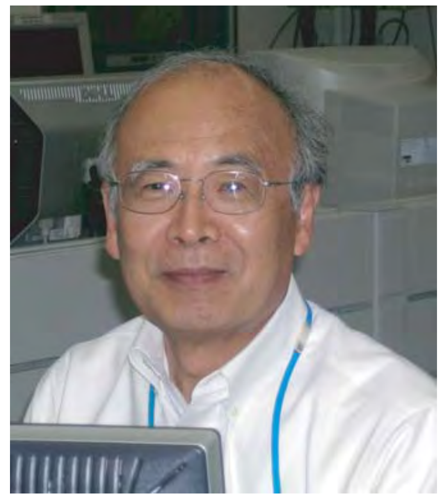
CONGRATULATIONS

for

Excellence in Plasma Physics Research

Andrea Garofalo
(Columbia)

Gerald Navratil
(Columbia)



Michio Okabayashi
(PPPL)

Edward Strait
(GA)

"For experiments that demonstrated the stabilization of the resistive wall mode and sustained operation of a tokamak above the conventional free boundary stability limit."

252-07/DH/rs

Collaborations are Vital to the Long-Term Success of DIII–D Scientific Research

- Fast ion profile (UCI)
- Tile current array (PPPL)
- DISRAD (UCSD)

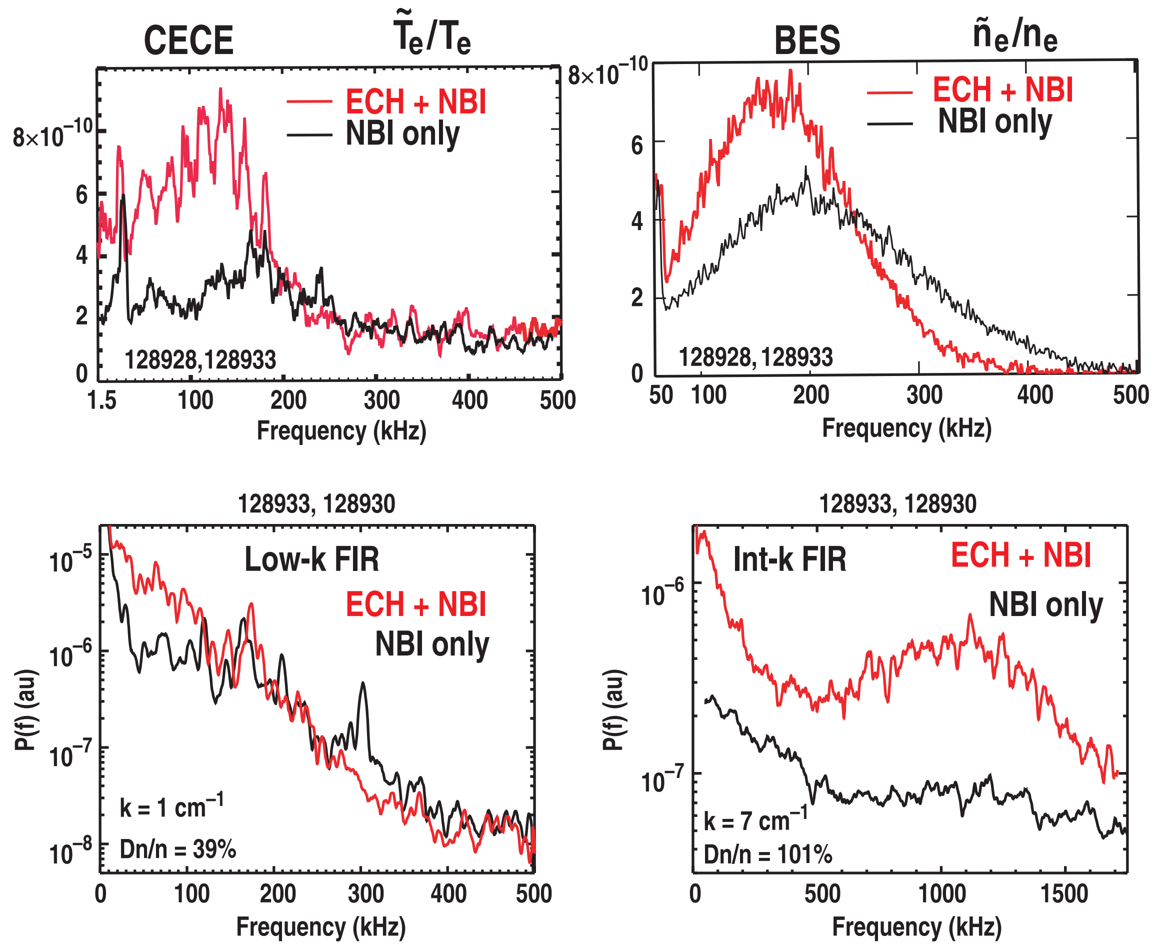
- IR cameras (LLNL)
- Fast ion collectors (UCI)
- SXR (UCSD)
- Filterscopes (ORNL)
- FIR scattering (UCLA)

- SXR (UCSD)
- BES (UW)
- VUV cameras (LLNL)
- ASDEX gauges (ORNL)
- MSE (LLNL)
- Fast framing camera (UCSD)
- QMB (UW, MIT)

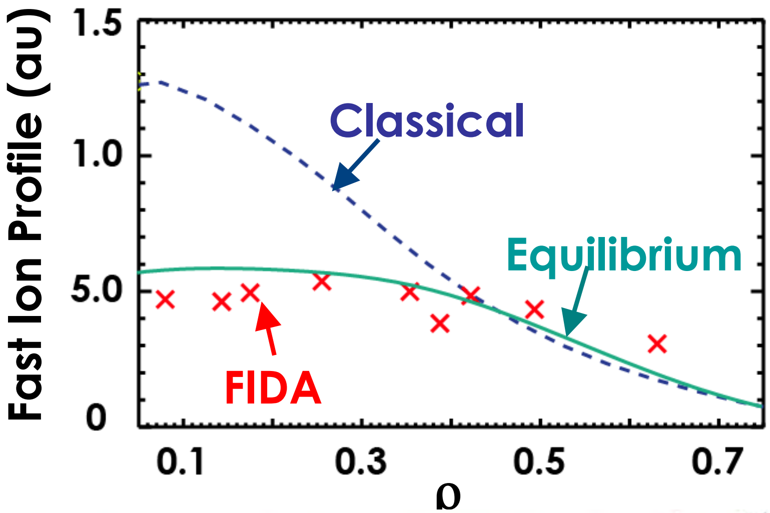
- Vertical scanning probe (UCSD, SNL)
- Radial scanning probe (SNL, UCSD)
- ECE (UT,UM)
- Neutrons (UCI)
- Phase contrast imaging (MIT)
- Langmuir probes (SNL)
- Reflectometers (UCLA)

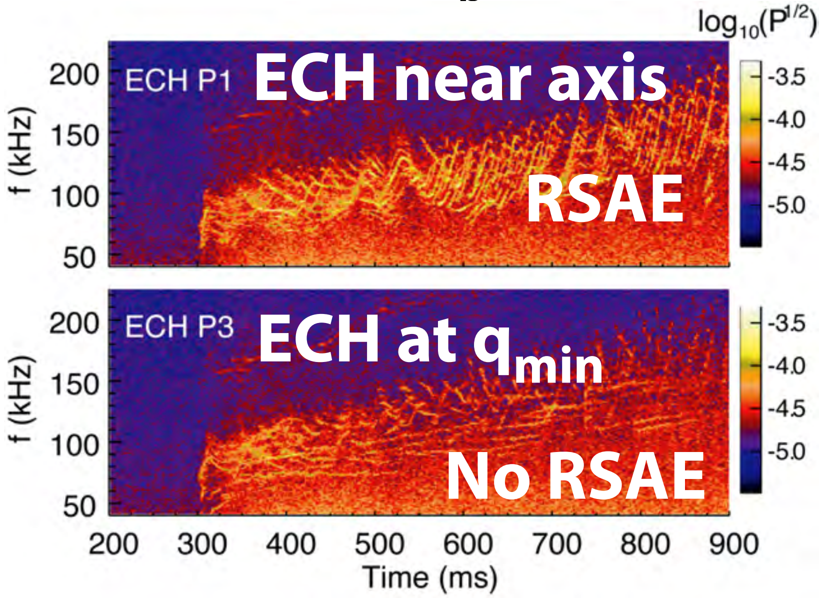
New Turbulence Measurements Provide a Uniquely Detailed Test for Gyrokinetic Transport Simulations

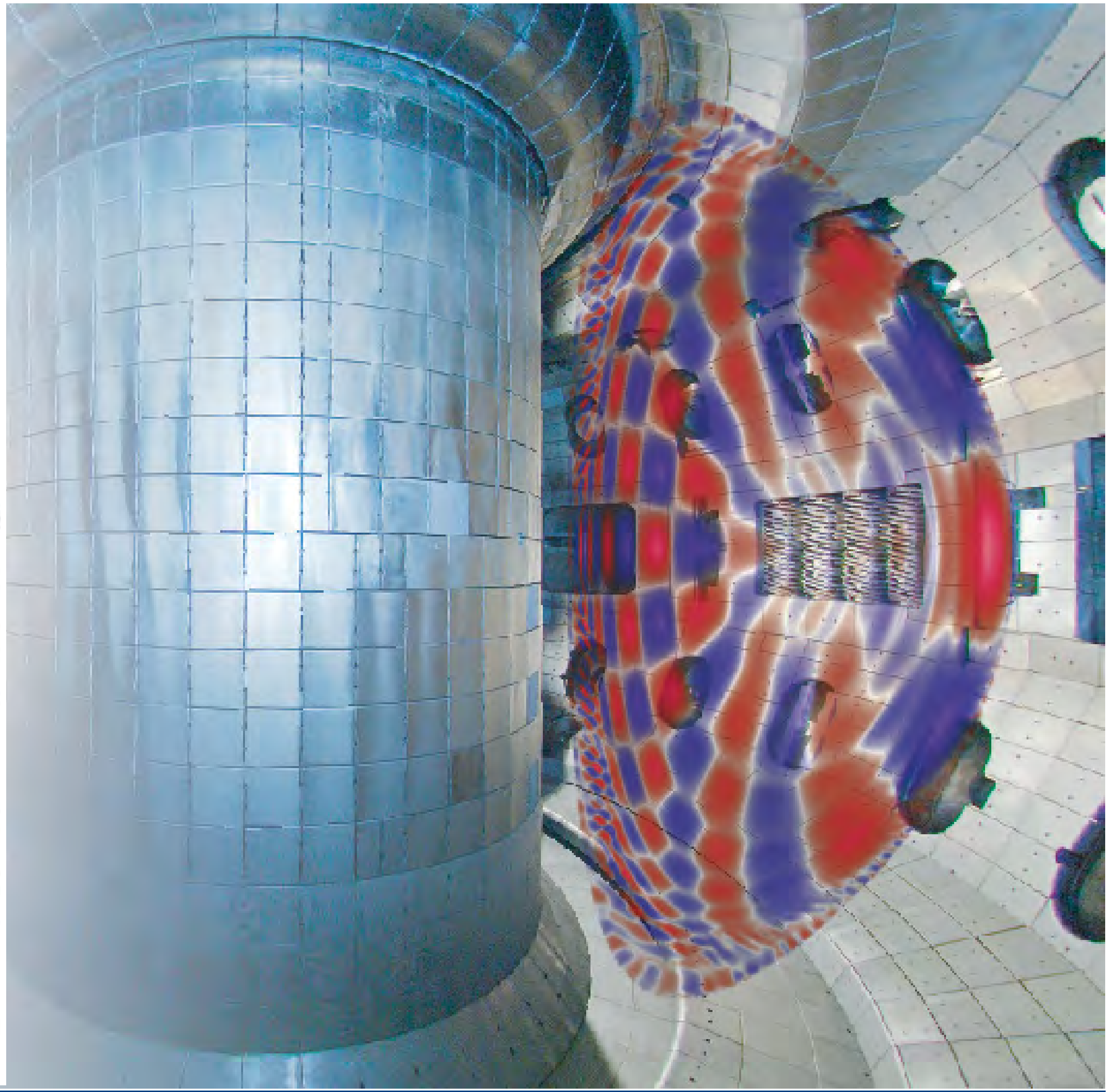
- **Multiple fluctuating fields now available**
  - $\tilde{T}_e$, $\tilde{n}_e$, $\tilde{v}$
- **Measurements show complex response to ECH**
- **GYRO simulations of $\tilde{n}_e/n_e$ and $\tilde{T}_e/T_e$ are consistent with new turbulence measurements**
- **Strong university participation**



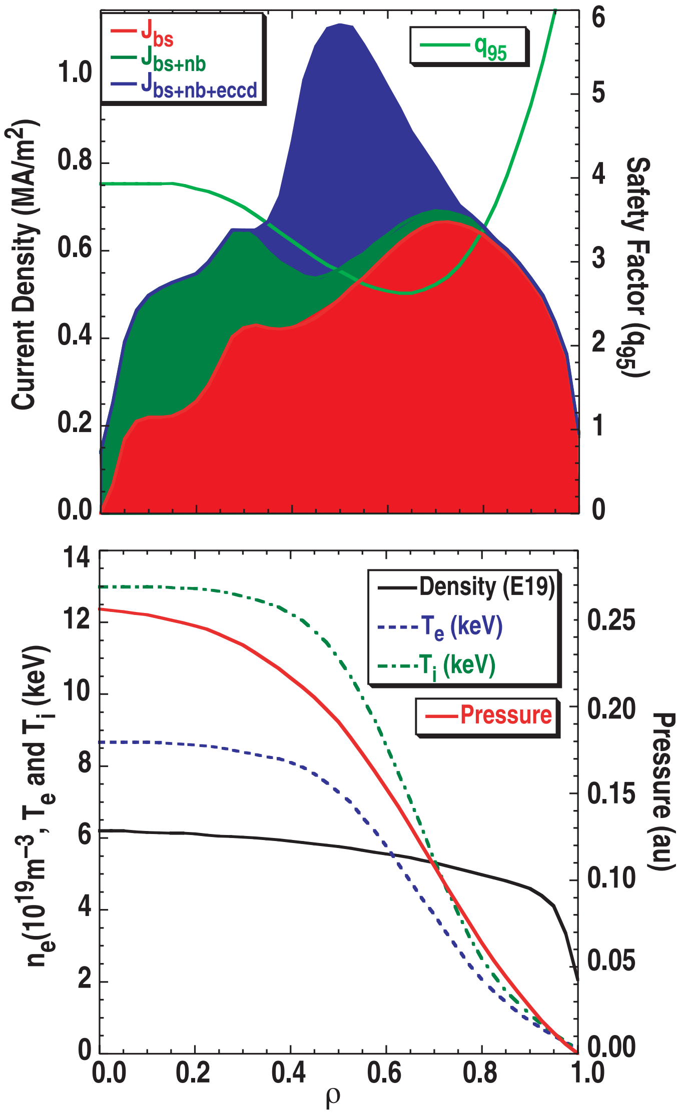
Alfvén Eignmodes Can Affect Fast Ion (Fusion Product) Confinement: New Tools Enable Research







Steady-state Advanced Tokamak Operation with Fully Non-inductive Current Drive: Developing Physics Basis



- **Simulated DIII–D discharge, 100% NICD**

  $\beta_N = 5.7$ $P_{TOT} = 20MW$ $B_T = 1.95\ T$ $I_p = 1.6MA$

  $I_{BS} = 1.07MA$ $I_{ECCD} = 0.35MA$ $I_{NBCD} = 0.18MA$

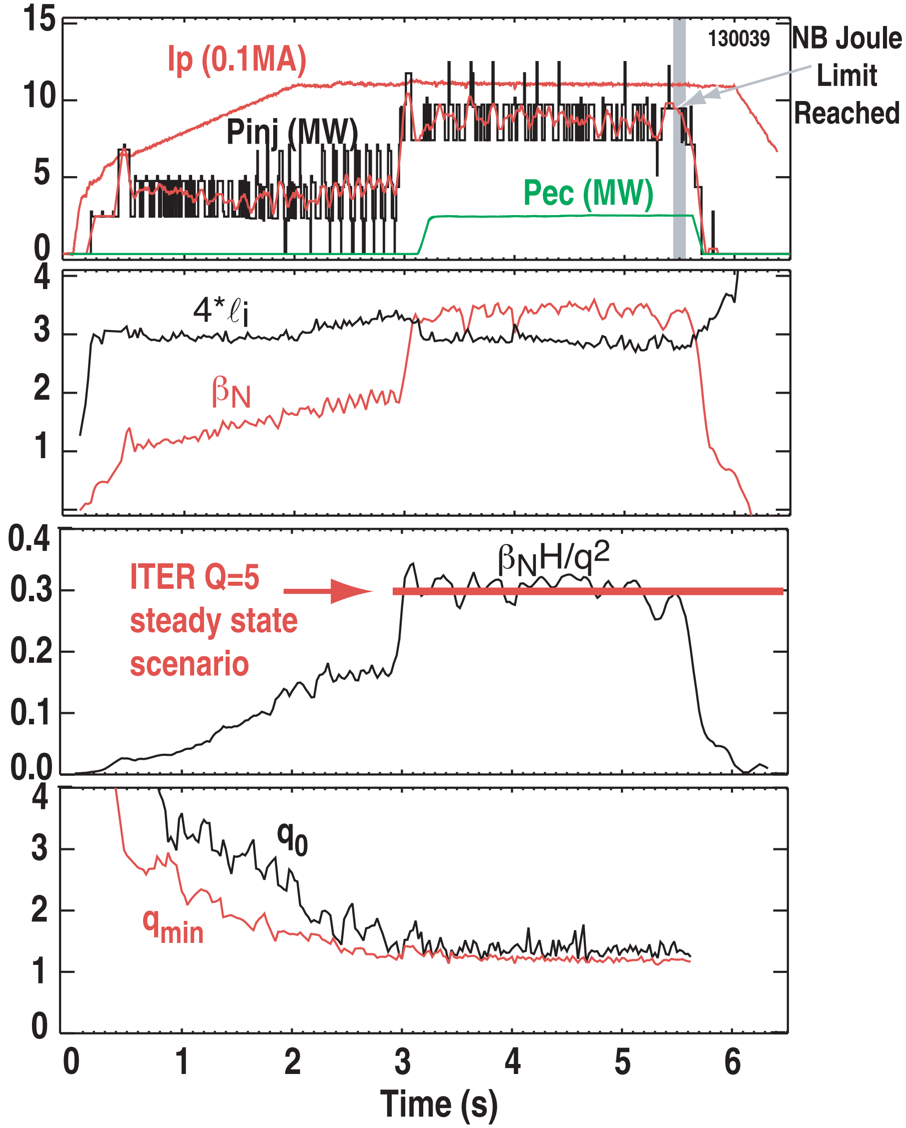
- **Off-axis current drive required for optimum q-profile**

- **Bootstrap current depends on**

$$j_{bootstrap} \sim -\frac{\varepsilon^{1/2}}{B_\theta}\frac{dp}{dr} \qquad \varepsilon = \frac{r}{R}$$

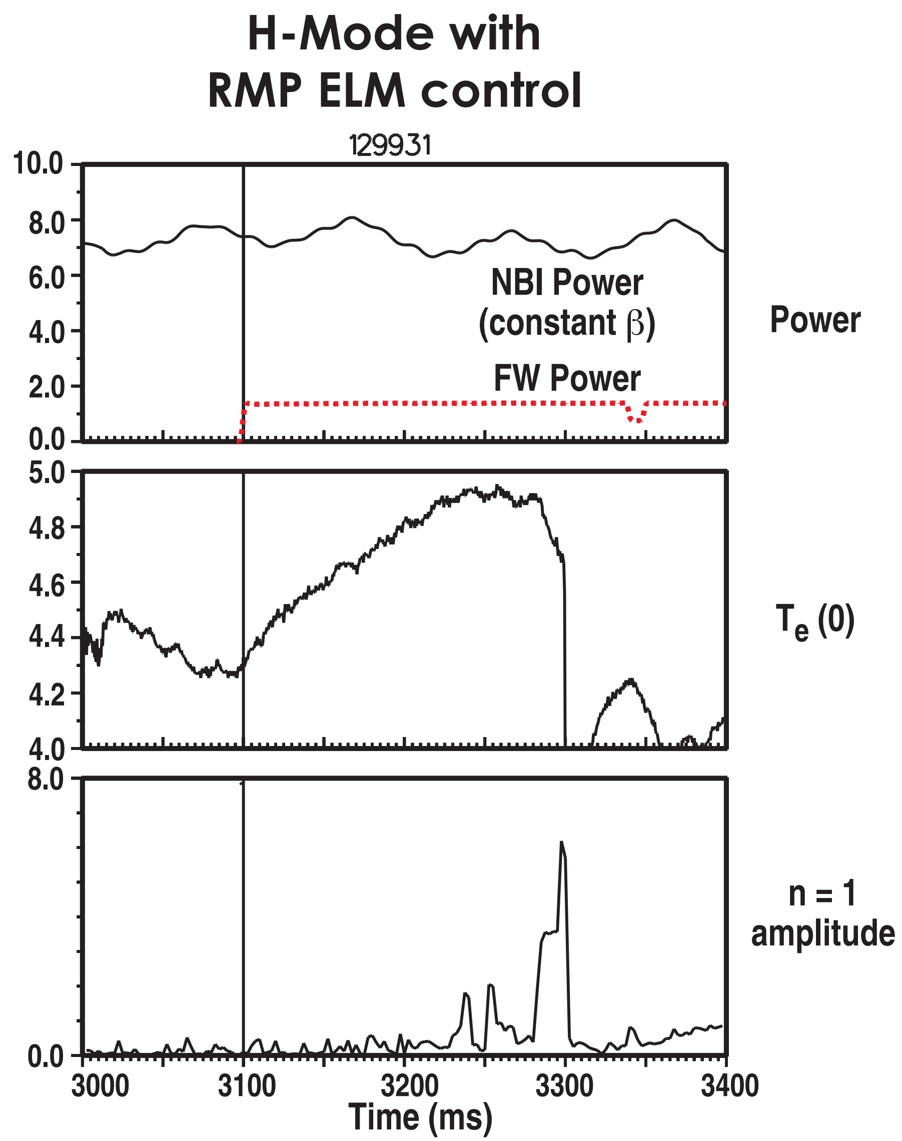
- **Self-consistent profiles must be developed and understood**

Duration with 90%, Non-Inductive CD, β_N > 3.5 Extended to 2.5s; Limited by Neutral Beam Pulse Length



- Increased ECH power extends previous results
- $f_{NI} \geq 90\%$ for > 1 τ_R
  $\beta_N = 3.4$; $f_{BS} = 60\%$
  $G = \beta_N H/q^2 = 0.3$
- Internal field measurements show stationary current profile

Refurbished Fast Wave Systems Used to Succesfully Heat ELM-Suppressed H-Mode Discharges



- **Three fast wave systems**
  - 60 to 110 MHz
  - 6 MW total source power
  - GA, ORNL, PPPL partnership
- **H-mode ELM pulses create challenging environment for RF heating**
- **Steady FW coupling provided by RMP-ELM suppression resulting in heating of H-mode core plasma**

We Are Developing the Next Five Year Program Plan for DIII–D (2009–2013)

- **Builds upon present capabilities and results**
- **Supports ITER, addresses AT development, and strengthens fusion science research**
- **Key hardware elements:**
  - Off-axis neutral beams (10 MW)
  - Increased ECH power (6–12 MW)
  - Increased capability for 30 MW 10 s operation
  - New non-axisymmetric coils for improved ELM control
  - Improved diagnostics for advancing fusion science and model validation
- **Key elements discussed at national Tokamak Planning Workshop at MIT in Sept. 2007 (www.psfc.mit.edu/tpw2007)**

DIII–D Five Year Plan (2009-2013) Emphasizes Validating Physics Basis for Advanced Scenarios for ITER and Beyond

2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015

ITER

$Q \geq 5$

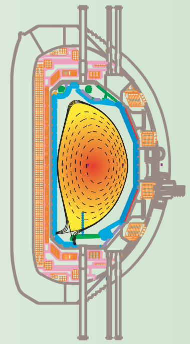
t_{DUR} ~1000s

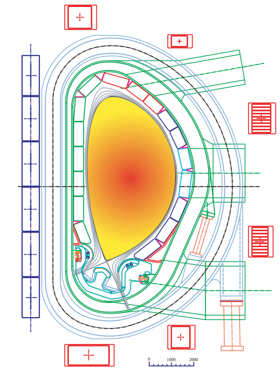
Steady-State Scenario for ITER

f_{BS} ~55%, β_N ~ 3.5

f_{NI} = 100%, t_{DUR} ~5s,

LSN ITER Shape





FDF

AT for DEMO

Net tritium

Blanket testing

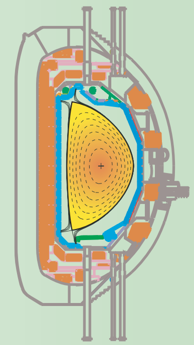
$\Gamma_N \rightarrow 2$ MW/m^2

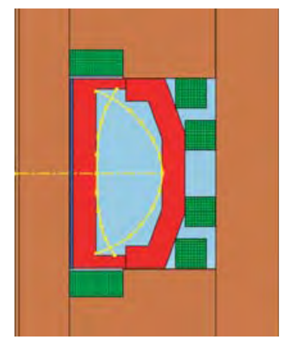
Steady-State Scenario for FDF

f_{BS} ~ 70%, β_N ~ 4

f_{NI} = 100%, t_{DUR} ~ 10 s,

High δ, DN Shape





DEMO-AT

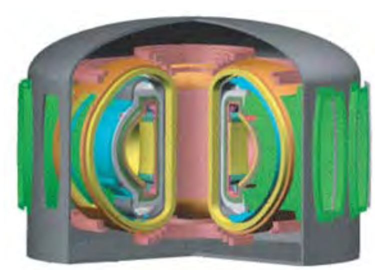
Plant Q > 1

Establish Physics Basis for Steady-State Powerplant Optimization

f_{BS} ~ 90%

$\beta_N \rightarrow 5$

$t_{DUR} \rightarrow 10$ s

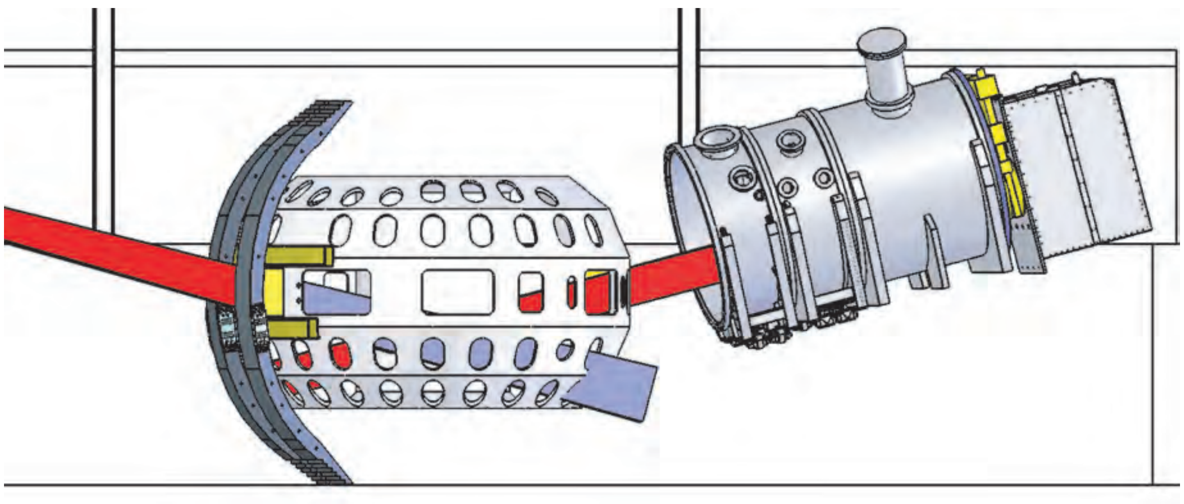


DIII-D NATIONAL FUSION FACILITY

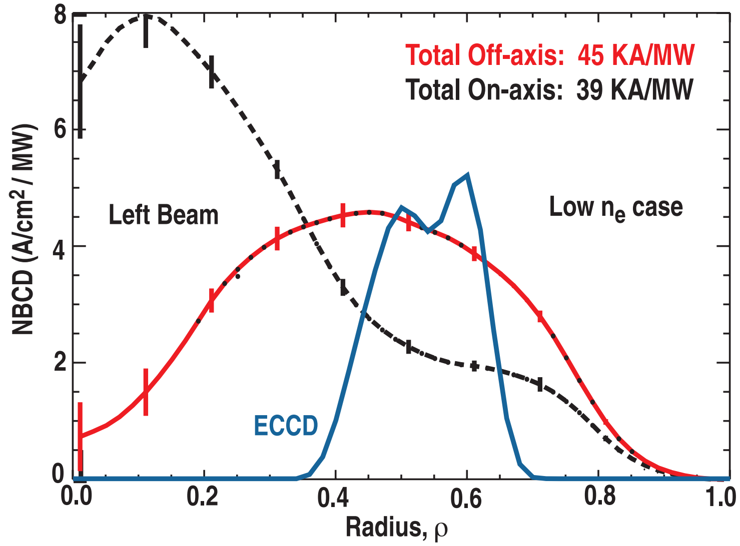
252-07/DH/rs

Providing Required Off-Axis Current Drive for Sustained High Performance is a Key Component of 5-Year Plan

- **Off-axis current drive required to maintain favorable current profile for high β operation near the ideal stabililty limit**
- **DIII-D 5-Year Plan:**
  - Upgrade of ECCD system to 12 MW
  - Off-axis Neutral Beam (10 MW)



Comparison of Off-Axis and On-Axis CD Efficiency

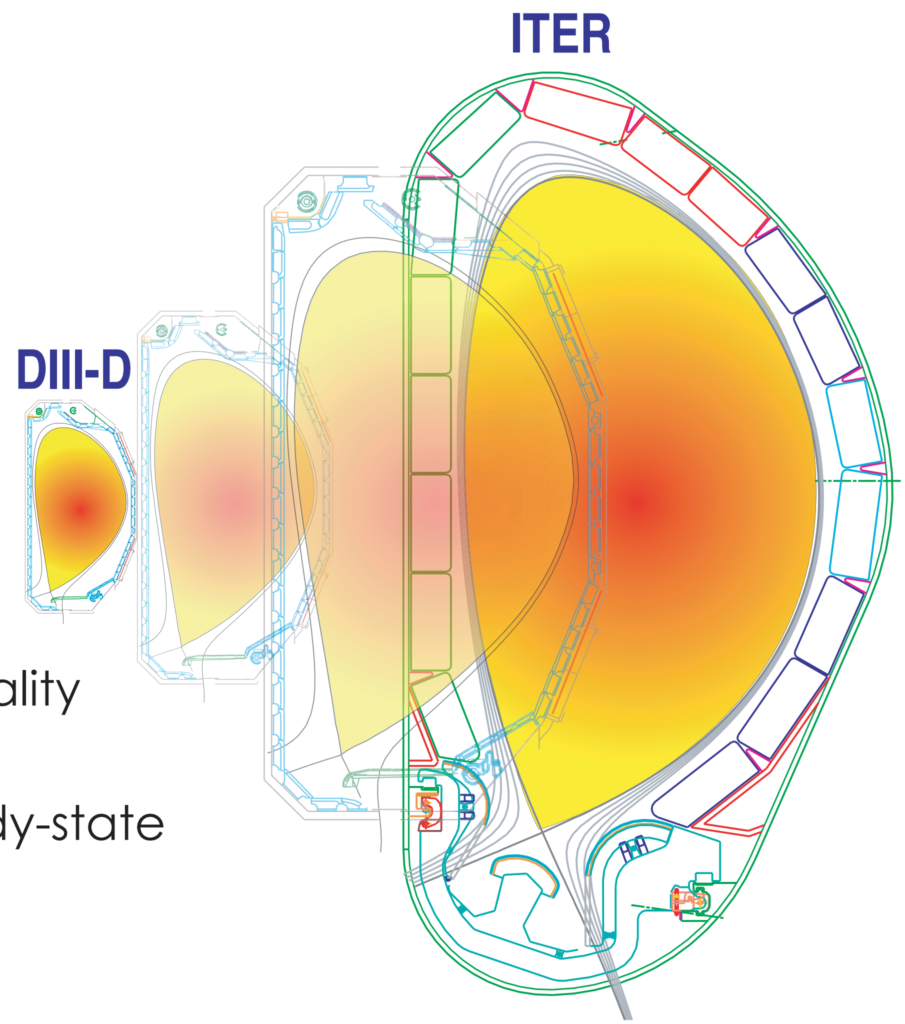


Proposed Hardware Upgrades Will Enable Multiple Research Activities

Hardware	Research Elements
NBI: 10 MW, off -axis	$J(\rho)$, energetic particles
20 MW, 10 s	Long pulse AT
ECE (12 MW, 10 s)	$J(\rho)$, NTM, $T_e \sim T_i$
FW (6 MW, 10 s)	$J(\rho{\sim}0)$, $T_e \sim T_i$, energetic particles
Inner Wall RMP	ELM control, heat and particle control
Divertor control coils	Heat and particle control
300 MJ heat removal	10 s high performance, physics of heat removal
Hot wall operation	Hydrogenic co-deposition and removal
Custom pellets, Ludwieg tube, liquid jet	Disruption mitigation
RWM amplifier/network	Dynamic error field control, n=1, 2 RWM stability
Improved and new diagnostic	Fusion science, control, optimization

DIII–D's Capabilities and Versatility Can Provide Important Contributions Towards Successful ITER Operation

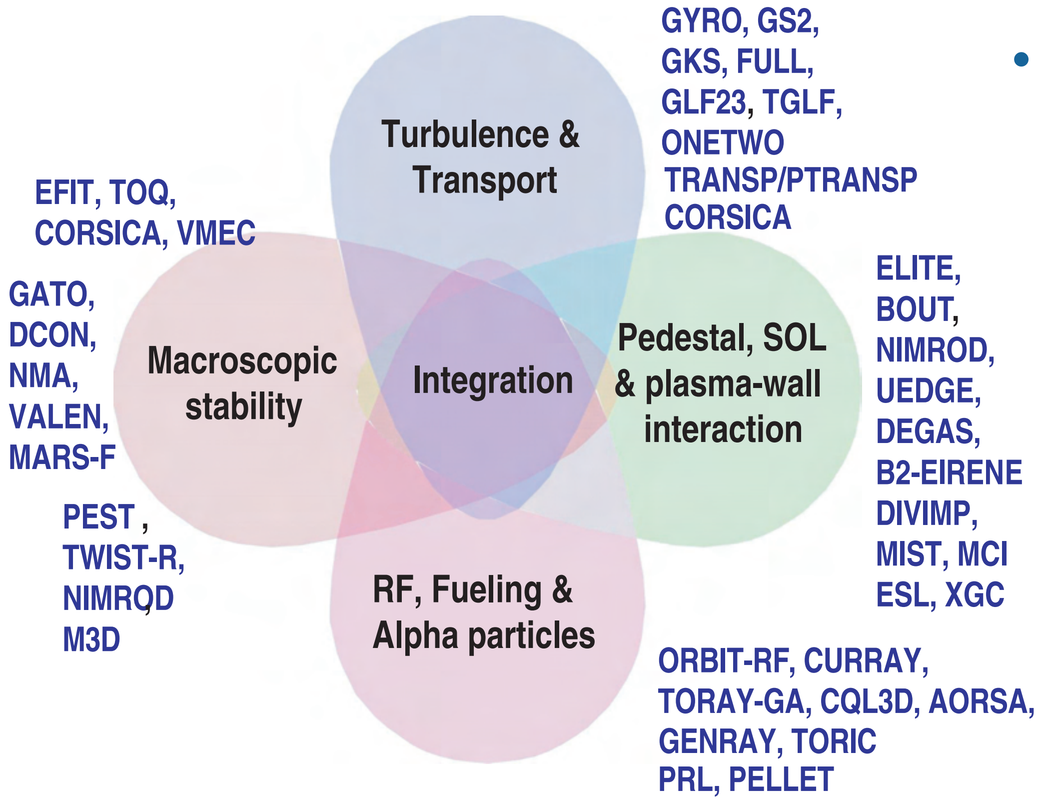
- **DIII-D is a 1/4 size ITER prototype capable of achieving ITER-like plasma conditions**
  - Collisionality
  - Mach number
  - β
  - $T_e \approx T_i$



- **Versatility enables a range of activities:**
  - High density ($f_{GW}>1$), radiative divertor ⟶ ITER collisionality
  - Conventional, ELMing H-mode ⟶ High β, steady-state
  - $\omega^{\Omega}_{E\times B} >> \gamma_{turb}$ ⟶ $\Omega \approx 0$
  - $T_i >> T_e$ ⟶ $T_i \sim< T_e$

DIII–D Will Validate Complex Theoretical Models for Fully Integrated Simulations of Future Fusion Devices

- **DIII–D Strengths**
  - Outstanding diagnostic set
  - Precise plasma control
  - Strong multi-institutional

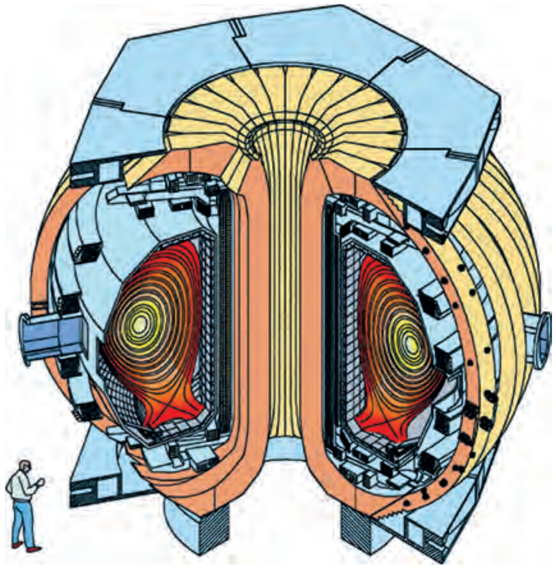


- **Near-term activities**
  - Validate complex models individually
    - GYRO, NIMROD, TGLF, BOUT,...

- **Longer term activities**
  - Validate models of interactions at multiple spatial scales
  - Integrate models into fully predictive code for use on ITER, FDF,...

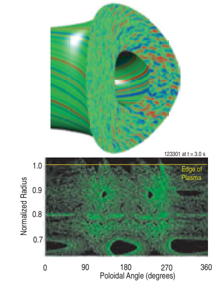
DIII-D 5-Year Plan: An Exciting Opportunity for Significant Scientific Advances Aimed at the Success of Fusion Energy

DIII-D

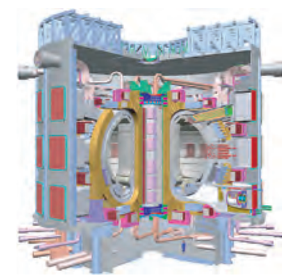


Progress on DIII–D Over Next 5 Years Will Lead to...

Improved Scientific Understanding of Key Issues



Prepare for ITER Operation



Improved Basis for Steady-state Tokamak