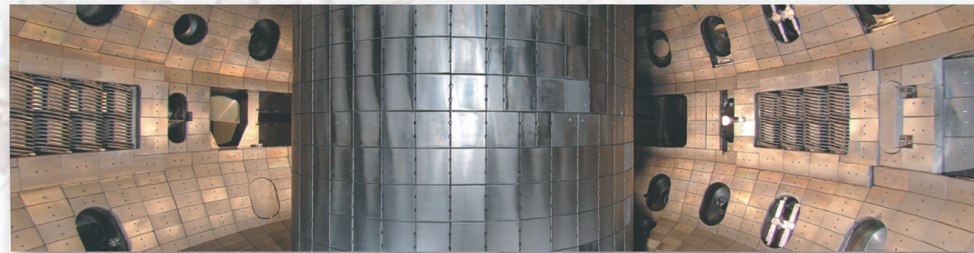
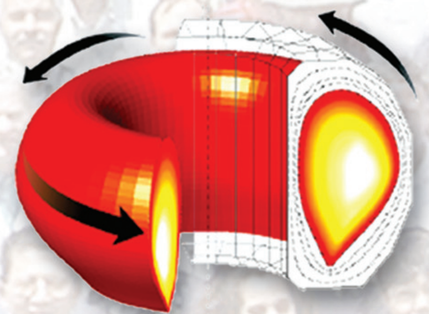
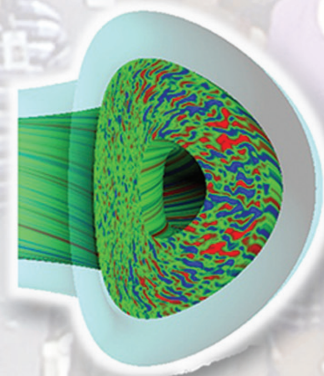
DIII-D National Fusion Program Status and Plans



Presented by
T.S. Taylor



Fusion Power Associates
Annual Meeting and Symposium
Washington, DC



September 27–28, 2006

DIII–D is a Large, International Program

Active Collaborations 2004

- 90 institutions participate
- 515 active users
  - 119 GA
  - 396 others
- 317 scientific authors (2004)
  - 577 cumulative
- 1082 visits to GA (2000–2004)
- Students and faculty have been from
  - 65 universities
  - 28 states

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 (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 (Boston, MA)
Palomar (San Marcos, CA)
New York U. (New York, NY)
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)

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)

European Community

Cadarache (St. Paul-lez, Durance, France)
Chalmers U. (Goteberg, Sweden)
CFN-IST (Lisbon, Portugal)
CIEMAT (Madrid, Spain)
Consorzia RFX (Padua, Italy)
Culham (Culham, Oxfordshire, England)
EFDA-NET (Garching, Germany)
Frascati (Frascati, Lazio, Italy)
FOM (Utrecht, The Netherlands)
Helsinki U. (Helsinki, Finland)
IFP-CNdR (Italy)
IPP (Garching, Greifswald, Germany)
ITER (Garching, Germany)
JET-EFDA (Oxfordshire, England)
KFA (Julich, Germany)
Kharkov IPT, (Ukraine)
Lausanne (Lausanne, Switzerland)
IPP (Greifswald, Germany)
RFX (Padova, Italy)
U. Dusseldorf (Germany)
U. Naples (Italy)
U. Padova (Italy)
U. Strathclyde (Glasgow, Scotland)

Japan

JAERI (Naka, Ibaraki-ken, Japan)
JT-60U
JFT-2M
Tsukuba University (Tsukuba, Japan)
NIFS (Toki, Gifu-ken, Japan)
LHD
Hiroshima University (Japan)

Other International

Australia National U. (Canberra, AU)
ASIPP (Hefei, China)
Dong Hau U. (Taiwan)
KBSI (Daegon, S. Korea)
KAERI (Daegon, S. Korea)
Nat. Nucl. Ctr. (Kurchatov City, Kazakhstan)
Pohang U. (S. Korea)
Seoul Nat. U. (S. Korea)
SWIP (Chengdu, China)
U. Alberta (Alberta, Canada)
U. of Kiel (Kiel, Germany)
U. Toronto (Toronto, Canada)

BROAD INTEREST IS SHOWN IN THE 586 RESEARCH PROPOSALS FOR CY06–07

FOREIGN

CEA Cadarache 6	FSZ Julich 7
EFDA-CSU 8	IPP Garching 7
ERM-KMS 1	JAERI 1
Euratom 2	U. Toronto 7
	UKAEA 11

Total: 50

DOMESTIC

Columbia 22	ORNL 21
FarTech 4	PPPL 66
Georgia Tech 2	SNL 7
GA 276	UCI 6
Lehigh 2	UCLA 30
LLNL 44	UCSD 30
MIT 3	U. Texas 4
ORISE 4	U. Wisconsin 15

Total: 536

DIII–D NATIONAL FUSION FACILITY

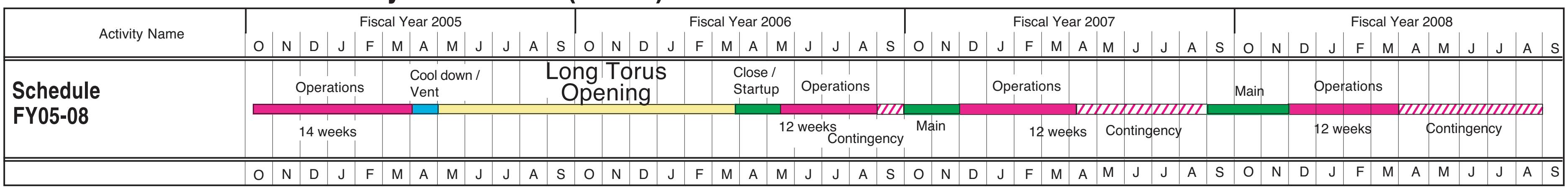
Summary/Outline

- **DIII-D has completed a very successful "long torus opening" (12 months) that has provided exciting capabilities for the future**
  - Maintained experimental operations in FY 05 and FY 06; 12 weeks
  - Flexible set of plasma control capabilities
  - Improved comprehensive physics measurements
  - New capabilities are leading to new physics results
- **DIII-D is well positioned to support ITER research needs**
  - Focused on providing important and timely research results on key issues for ITER's design and operation
  - Maintain program balance:
    - Advance fusion science
    - Develop advanced scenarios in support of ITER and beyond
    - Support ITER

The Long Torus Opening Has Provided DIII–D With Exciting Capabilities for the Future

- **Significant progress was made on major facility upgrades proposed in 5 year plan**
- **Preserved run-time capability**
  - FY05 (14 weeks); FY06 (12 weeks); FY07 (25 weeks)

DIII–D Facility Schedules (05–08)

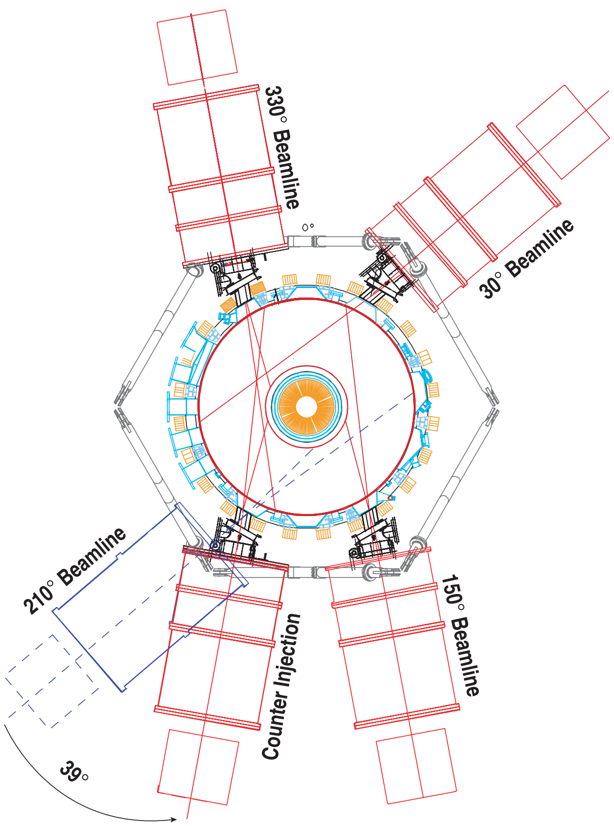


- **LTOA activities**
  - ECH- 6 long pulse gyrotrons
  - Rotation of 210 degree beamline to counter
  - Lower divertor modification
  - Cooling water tower replacement
  - TF belt bus cooling for 10 s ops*
  - Diagnostic upgrades and refurbishments*
- **Other significant work**
  - Long pulse transformer
  - Fast wave system
  - Contoured inner wall tiles
  - High band width actuators (I-Coil)
  - TF feedpoint upgrade

**best effort*

DIII–D Versatility and Capability Are Greatly Enhanced by Several Hardware Modifications/Upgrades

- **Reorientation of beamline**

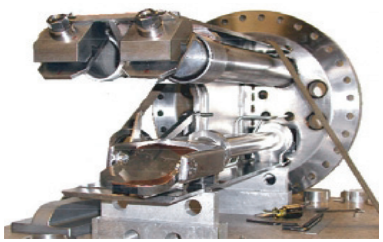


⇒ **Rotation control for**
– Stability physics
– Transport physics

- **EC upgrades**

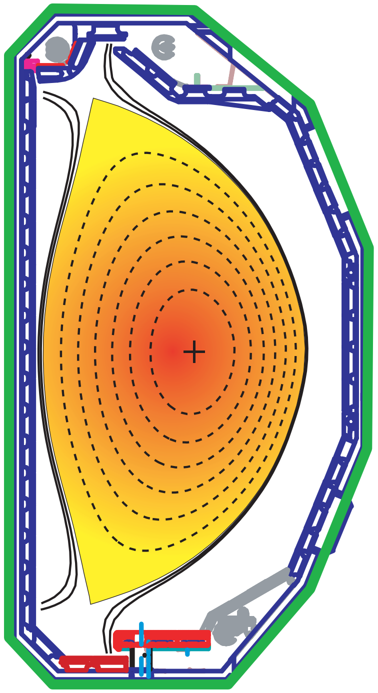
6 gyrotrons –4.5 MW for 10 s

All steerable toroidally and poloidally



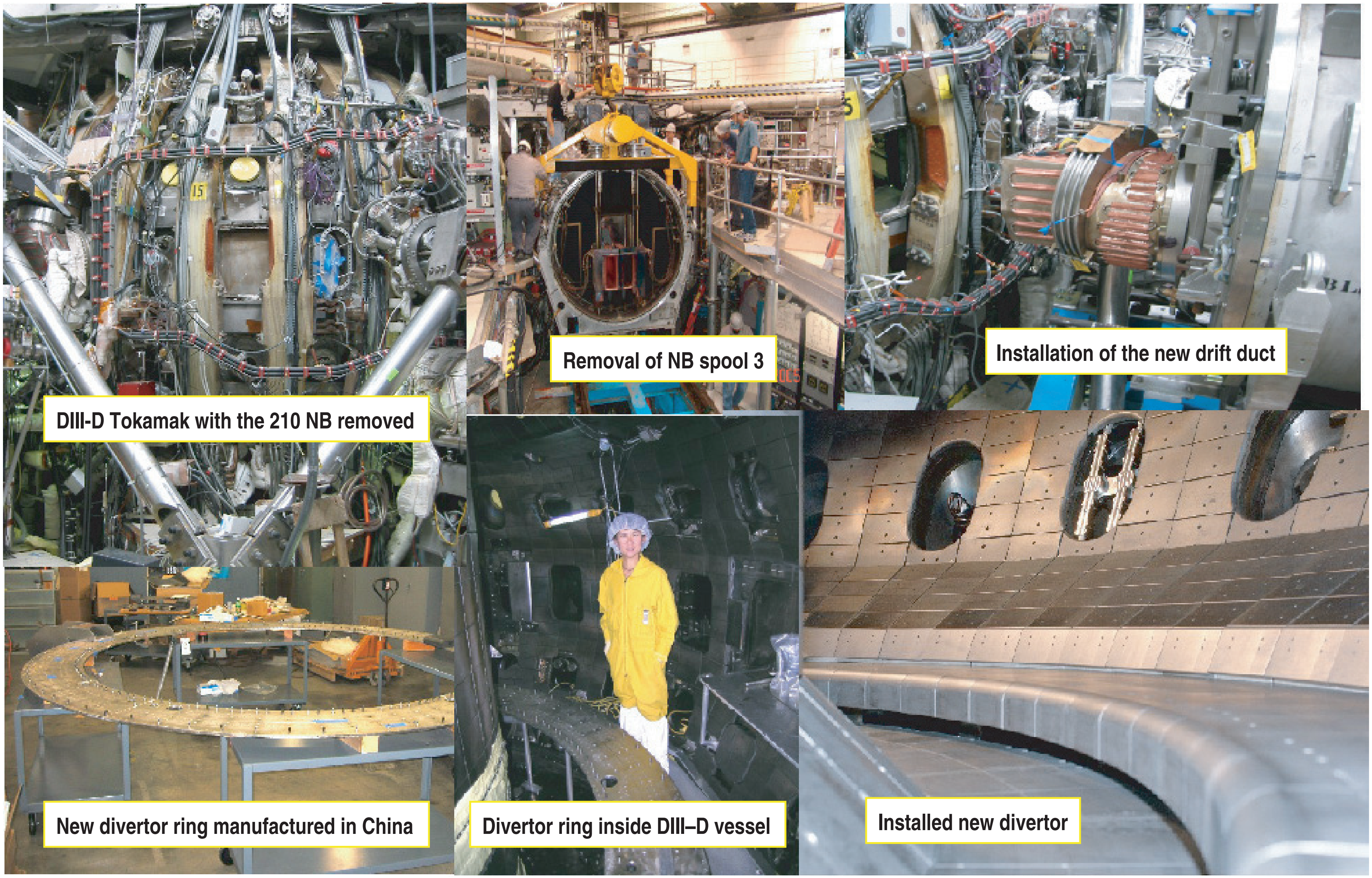
⇒ **J(ρ) control, NTM stabilization, electron transport**

- **Lower divertor modification**



⇒ **Density control in double null plasmas**

DIII–D Hardware Upgrade Performed During LTOA (1 of 2)



DIII-D Tokamak with the 210 NB removed

Removal of NB spool 3

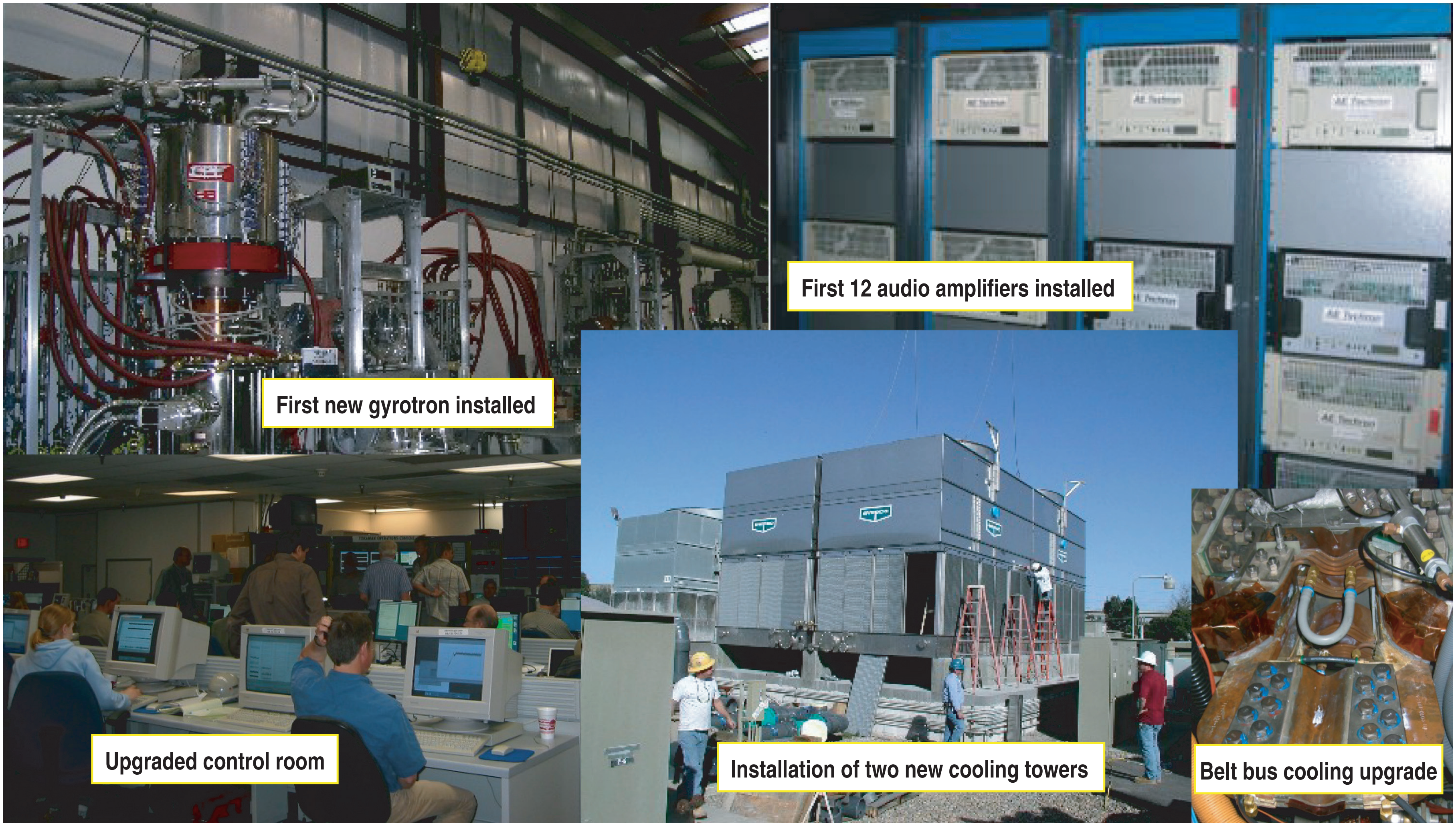
Installation of the new drift duct

New divertor ring manufactured in China

Divertor ring inside DIII–D vessel

Installed new divertor

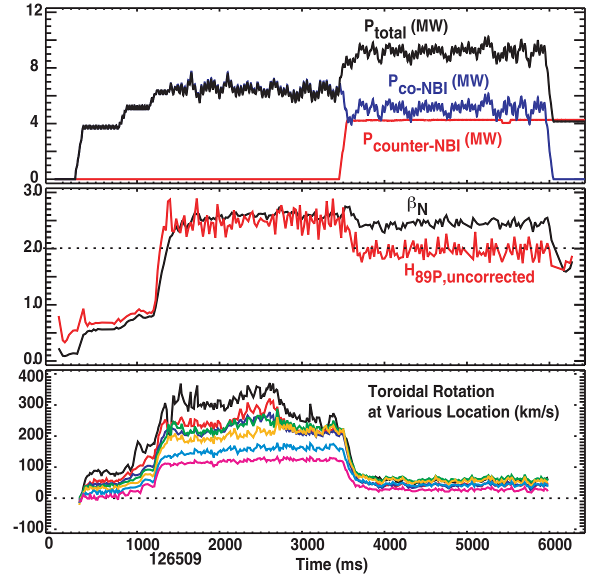
DIII–D Hardware Upgrade Performed During LTOA (2 of 2)



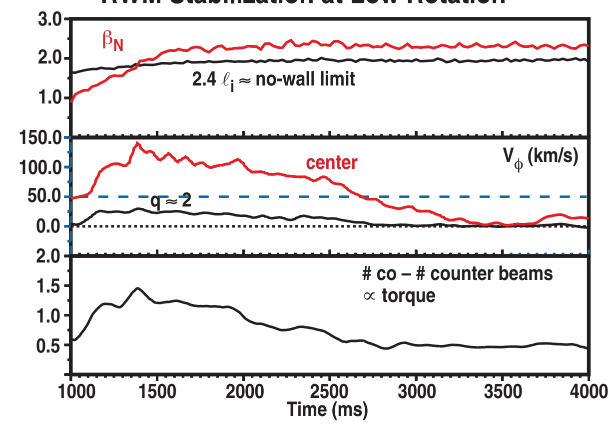
New Capabilities to Change the Plasma Rotation With Co Plus Counter NBI Has Provided New and Exciting Physics Results

- Energy confinement decreases systematically as rotation and rotational shear is reduced by adding counter-NBI power
- Robust hybrid regime operation achieved in a variety of plasma shapes and at low rotation
- Simultaneous feedback control by PCS of β and toroidal rotation demonstrated using real-time equilibrium reconstruction and CER spectral analysis
- Co-NBI shown to be more effective in driving TAEs than counter-NBI, as expected by theory
- Comparison of rotation velocities inferred from co- and counter-viewing CER confirm accuracy of cross section corrections
- β threshold for m=2/n=1 NTM onset shown to increase linearly with plasma rotation
- Significant decrease in L-H power threshold observed as rotation reduced to near zero
- Rotation threshold for rotational stabilization of RWM found to be much lower than previously obtained — good news for ITER!

Effect of Rotation on Confinement

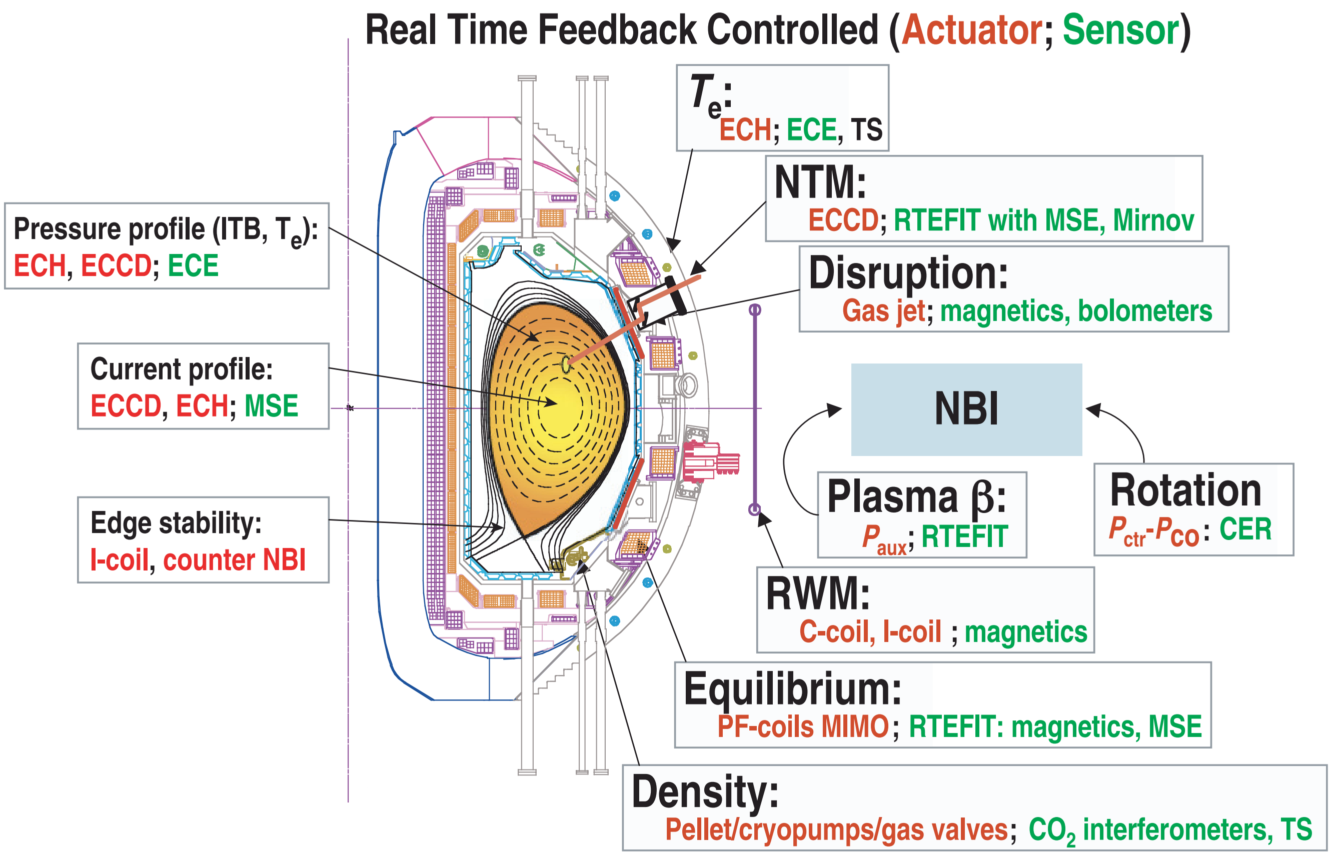


RWM Stabilization at Low Rotation



DIII-D Has Developed a State-of-the-Art Advanced Plasma Control System Used Around the World

- Real-time q-profile
- Real-time boundary display
- Real-time plasma rotation control



. . . in use on DIII–D, NSTX (US), MAST (UK), EAST (China); under development KSTAR (Korea) Pegasus (U. Wisc.)

Significant New Measurement Capability Are Now Available Following the LTOA

New Capability

*MSE, counter viewing (LLNL)
CER, counter viewing (PPPL)
BES, additional high-sensitivity channels (Wisc.)
D_α, Mod B (UCSD)
*SXR poloidal array
MDS, under shelf spectral views
MIMES (midplane) (UCSD)
QMBs (Wisc., Julich)
Shelf halo current monitors
Contoured center post tiles

*Complete installation in October

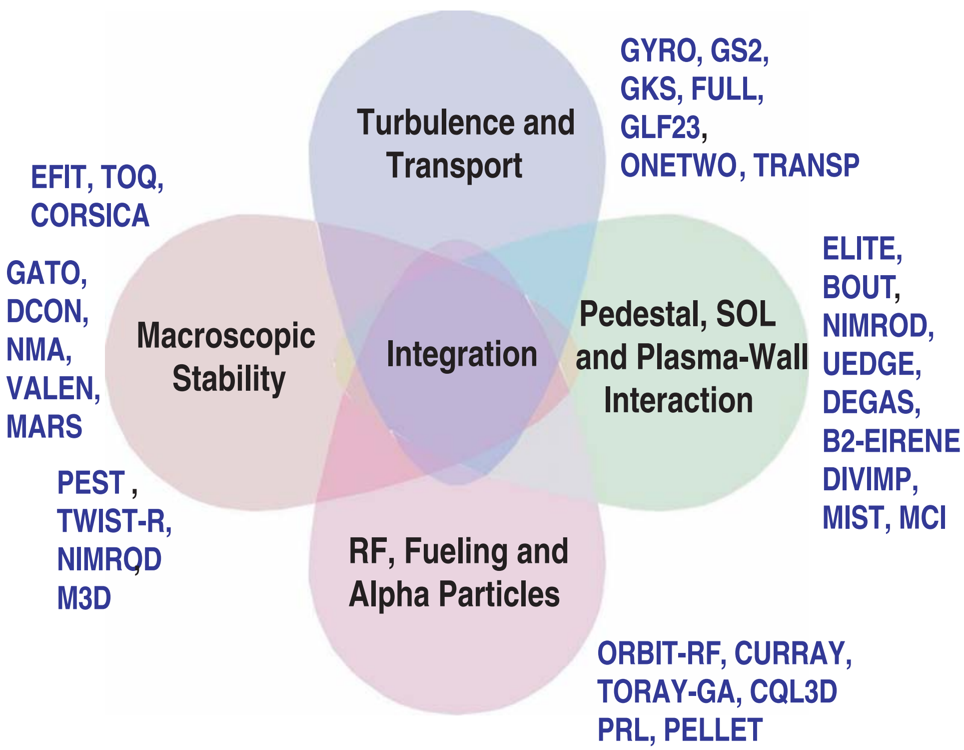
Improved Capability

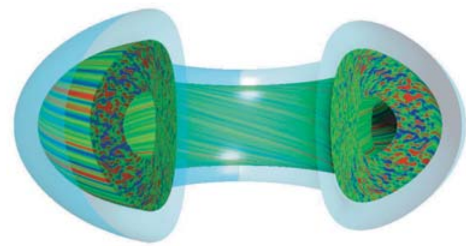
FIR Scattering (UCLA)
ECE Radiometer (UT, UM)
Langmuir Probes-floor (SNL)
Recycling camera (LLNL)
Filterscope views (ORNL)
Lithium beam
Fast framing camera (UCSD)
Divertor Thomson scattering
Reflectometer (UCLA)
Interferometer (ORISE)
Phase Contrast Imaging (MIT)

- DIAGNOSTICS: Clear example of DIII–D team effort with significant effort and contributions from collaborating institutions

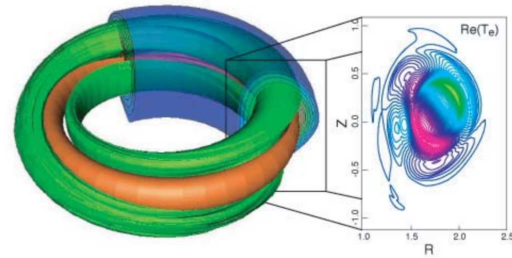
DIII–D Will Leverage State-of-the-Art Diagnostic and Computational Tools to Advance Fusion Science

- **We are increasing the emphasis on model validation and integrated modeling**
- **Detailed comparison of DIII-D results with theory are facilitated by:**
  - Outstanding diagnostic set
  - Precise plasma control
  - Strong multi-institutional team
  - Innovative experiments
  - Integrated theory/experiment team

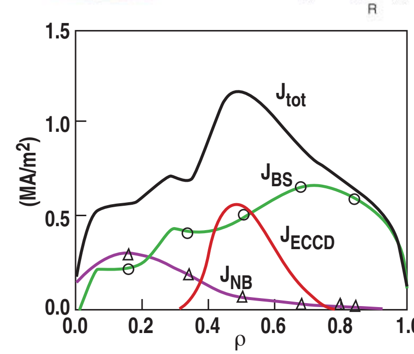




Transport GYRO



Stability NIMROD



Integration ONETWO and CD modules

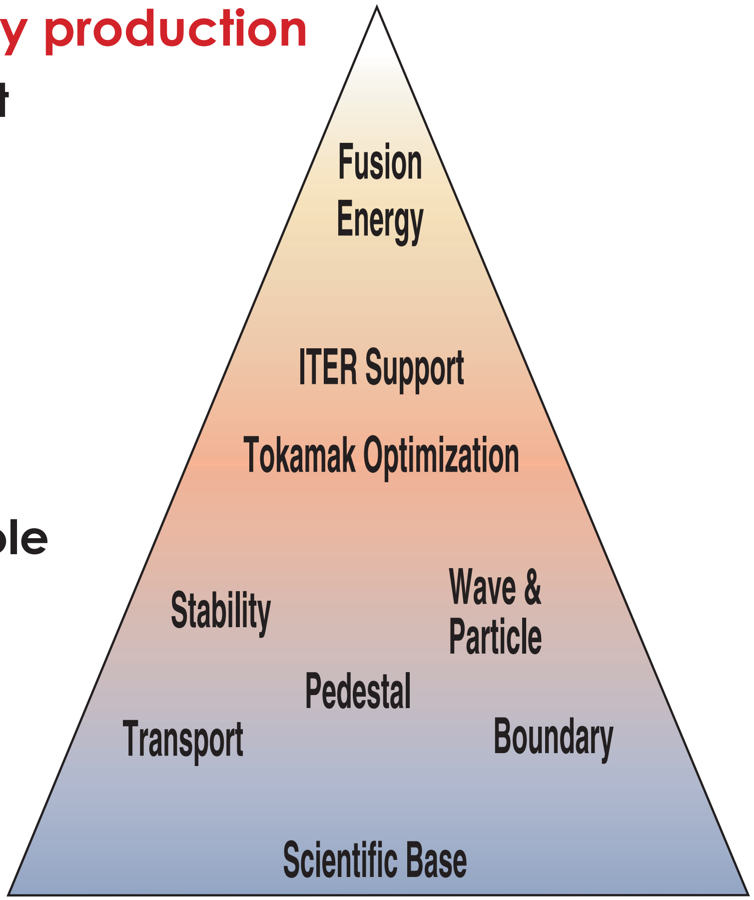
- “The new capabilities, together with an unparalleled diagnostic set and highly competent team guarantee that DIII–D will continue in its position at the forefront of the world’s fusion research program”

DIII-D Program Advisory Committee

DIII–D is an Integrated Science Program Aimed at an Energy Goal

DIII–D Mission: to establish the scientific basis for the optimization of the tokamak approach to fusion energy production

- **ITER support: DIII–D Program will carry out key scientific research in support of ITER**
- **Advanced tokamak: solid scientific base for study-state high performance**
- **Science: DIII– Program will play a lead role in enhancing plasma and fusion science**
  - Transport: understanding and control of turbulence



⇒ The knowledge gained is the program's enduring contribution

DIII–D is Well-Positioned to Support ITER

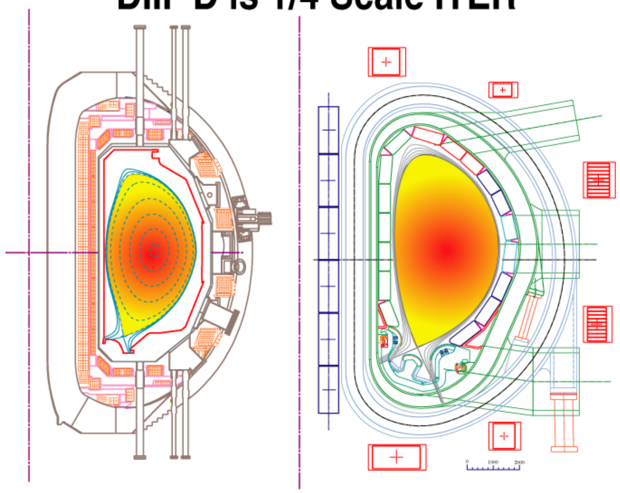
- **Recognized world leader in key ITER-relevant research**
  – Strong international and domestic collaborations
  – US BPO, ITPA (40 DIII–D participants)
    joint experiments [19(04), 20(05), 21(06)]

- **Versatility enables a wide scope of research and adaptation to new scientific developments**
  – Flexible control systems (heating, current drive, particle control, 3D fields)
  – World's best diagnostic set
  – Advanced integrated digital plasma control system
  – Large variety of operating scenarios

- **Integrated theoretical and modeling support**

- **Recognized as a world leader in fusion science**
  – Excellent scientific research record
  – A training ground for ITER scientists

ITER Physics and Design
DIII–D is 1/4 Scale ITER



DIII–D ITER

DIII–D Will Provide Important and Timely Research Results on Key Issues for ITER's Design and Operation

- **Provide the physics basis for key ITER design decisions (highest priority)**
  - ELM suppression/control ⇒ Non-axisymmetric coil set
  - RWM stabilization ⇒ Non-axisymmetric coil set, plasma rotation
  - NTM stabilization by ECCD ⇒ EC launcher design/location
  - Disruption mitigation ⇒ Mitigation system design, thermal mechanical loads
  - Tritium retention in carbon PFCs ⇒ Choice of first wall materials
- **Develop and validate integrated scenarios that meet ITER physics objectives and offer potential for an enriched ITER research program**
  - Steady-state, high beta advanced tokamak development
  - Hybrid scenarios development
  - Transport scaling of conventional, ELMing, H–mode
- **Develop a predictive understanding of issues key to ITER performance**
  - Physics based transport model – core and pedestal
  - Heat flux control
  - Fast ion physics and instabilities
  - Sawtooth control

High Performance Steady-State Fusion Plasmas are Being Pursued in Support of ITER Objectives

ITER Objectives

1. "To achieve extended burn in inductively-driven deuterium-tritium plasma operation with Q ≥ 10 (Q is the ratio of fusion power to auxiliary power injected into the plasma), not precluding ignition, with an inductive burn duration 300 and 500 s"

2. "To aim at demonstrating steady-state operation using non-inductive current drive with Q ≥ 5"

   - DIII–D is a world leader in establishing the scientific basis for steady-state operation

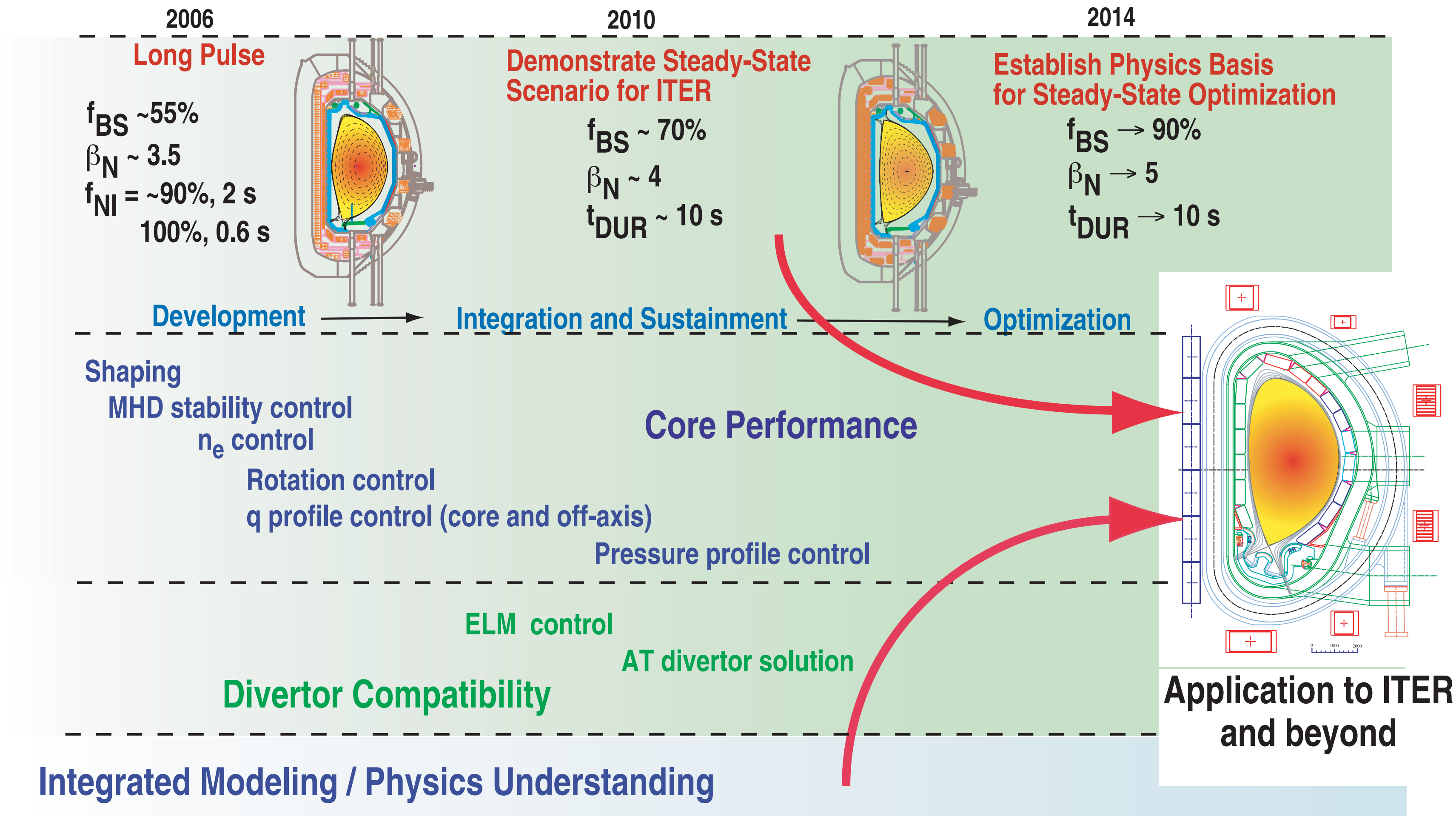
Our Vision: By the Time ITER Operates, Advanced Operational Scenarios Will Become Standard

- **Advanced scenarios may avoid issues with ITER baseline**
  - NTMs, sawteeth, high current disruptions
- **Advanced scenarios will extend the scientific benefit gained from ITER**
  - Advanced Inductive (Q > 40) ⇒ Plasma physics
  - Hybrid (Q ~ 10) ⇒ Materials testing
  - Fully non-inductive (AT) (Q ~ 5) ⇒ Steady state operation
- **Advanced scenarios will enhance the technological benefit to ITER**
  - Enable technology testing, PFC, auxiliary systems, …
  - Enable limited nuclear testing
- **Steady-State operation on ITER will establish a strong case to move forward aggressively with DEMO**

⇒ **ITER will greatly benefit from DIII-D Advanced Tokamak (*AT*) Research**

DIII–D is Positioned to Contribute Strongly to Steady-state Scenario Development for ITER

— Plasma control is a key element of the Advanced Tokamak Program —



DIII–D Research Addresses Most of the ITER Design and Pre-Operational Issues, Identified in the EPAct Report

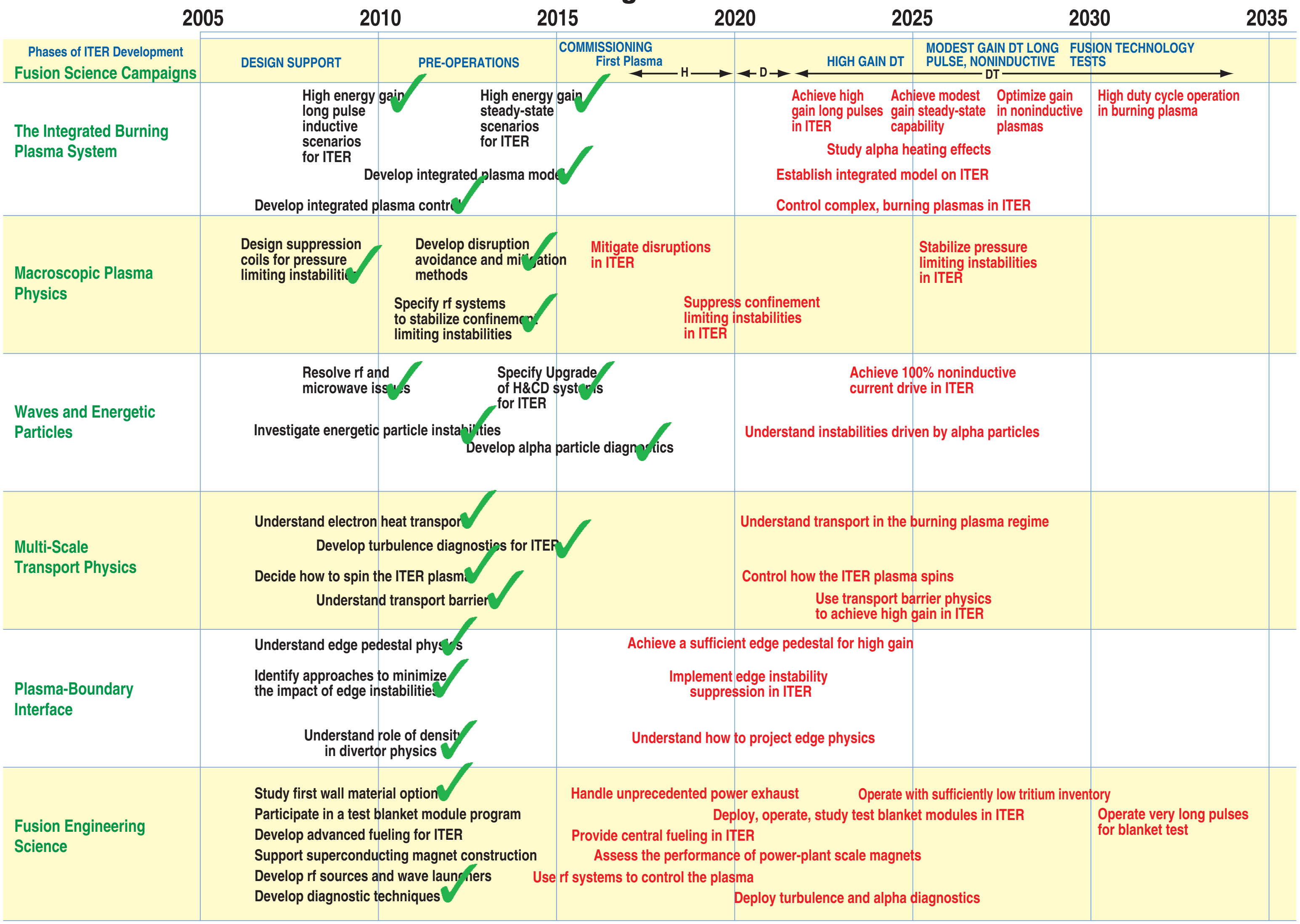
Research Agenda for ITER

Phases of ITER Development (2005–2035): DESIGN SUPPORT (2005–2010) · PRE-OPERATIONS (2010–2015) · COMMISSIONING, First Plasma (2015–2020; H) · D · HIGH GAIN DT · MODEST GAIN DT LONG PULSE, NONINDUCTIVE · FUSION TECHNOLOGY TESTS (DT)

Fusion Science Campaigns		
The Integrated Burning Plasma System	High energy gain long pulse inductive scenarios for ITER High energy gain steady-state scenarios for ITER Develop integrated plasma model Develop integrated plasma control	Achieve high gain long pulses in ITER Achieve modest gain steady-state capability Optimize gain in noninductive plasmas High duty cycle operation in burning plasma Study alpha heating effects Establish integrated model on ITER Control complex, burning plasmas in ITER
Macroscopic Plasma Physics	Design suppression coils for pressure limiting instabilities Develop disruption avoidance and mitigation methods Specify rf systems to stabilize confinement limiting instabilities	Mitigate disruptions in ITER Stabilize pressure limiting instabilities in ITER Suppress confinement limiting instabilities in ITER
Waves and Energetic Particles	Resolve rf and microwave issues Specify Upgrade of H&CD systems for ITER Investigate energetic particle instabilities Develop alpha particle diagnostics	Achieve 100% noninductive current drive in ITER Understand instabilities driven by alpha particles
Multi-Scale Transport Physics	Understand electron heat transport Develop turbulence diagnostics for ITER Decide how to spin the ITER plasma Understand transport barriers	Understand transport in the burning plasma regime Control how the ITER plasma spins Use transport barrier physics to achieve high gain in ITER
Plasma-Boundary Interface	Understand edge pedestal physics Identify approaches to minimize the impact of edge instabilities Understand role of density in divertor physics	Achieve a sufficient edge pedestal for high gain Implement edge instability suppression in ITER Understand how to project edge physics
Fusion Engineering Science	Study first wall material options Participate in a test blanket module program Develop advanced fueling for ITER Support superconducting magnet construction Develop rf sources and wave launchers Develop diagnostic techniques	Handle unprecedented power exhaust Operate with sufficiently low tritium inventory Deploy, operate, study test blanket modules in ITER Operate very long pulses for blanket test Provide central fueling in ITER Assess the performance of power-plant scale magnets Use rf systems to control the plasma Deploy turbulence and alpha diagnostics

DIII–D Research Addresses Most of the ITER Design and Pre-Operational Issues, Identified in the EPAct Report

Research Agenda for ITER



DIII–D Will Provide Crucial Fusion Science and Scenario Development in Support of ITER

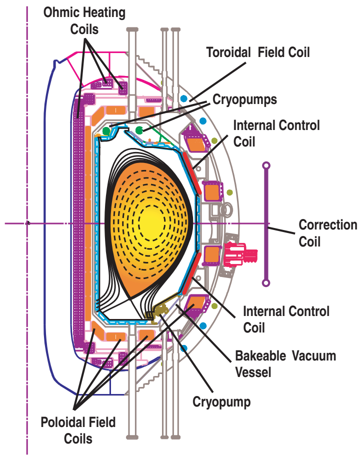
2006 | 2008 | 2010 | 2012 | 2014

ITER Timeline	Design Review	Machine Core Set	Day 1 PFC Set	Day 1 H&CD, Control, and Diagnostics Set	
ELM Control	Evaluate techniques	Propose design for ITER	Demonstrate ELM solution	Test ITER protype	
Disruptions	Test gas jet	Characterize thermal loads	Pre-disruption detection	Disruption avoidance	
NTM Stabilization	Test ECCD modulation	Develop real-time steering	ITER feedback prototype		
Tritium Retention	^{13}C transport	Co-deposition with heated walls	Test co-deposit removal techniques		
RWM Stabilization	Test feedback at low rotation	Internal vs external coils	Propose design for ITER	Optimal feedback algorithms	n > 1 stabilization
Baseline Scenario	Demonstrate performance	Test predictive models	Refine and validate predictive models	Develop and test prototype ITER simulator	
Hybrid Scenario	Validate in reactor-like conditions	Define required control tools	Develop access technique for ITER		
Advanced Tokamak	Demonstrate fully noninductive ops	Evaluate compatibility with ITER hardware set	Demonstrate *AT* scenario w/o RWM	Develop access technique with ITER Day 1 H&CD Set	

Scenario Demonstration

DIII–D is Well Positioned to Enable the Success of ITER and Advance the Science of Fusion Energy

Machine Versatility



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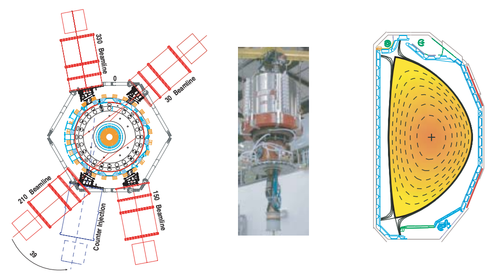
State-of-the-Art Tools



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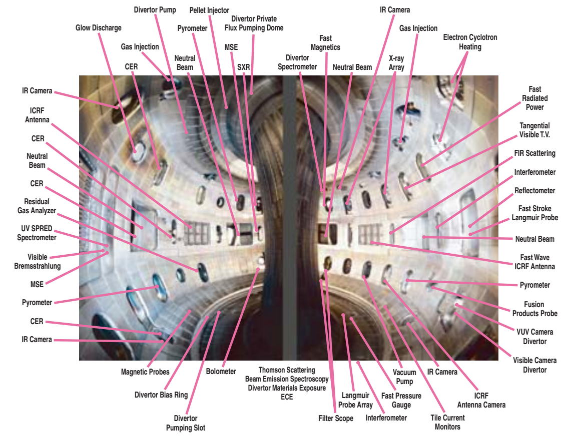
Comprehensive Diagnostics



Simulation

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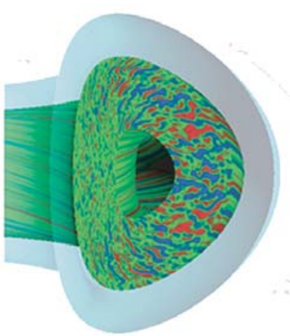

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International Research Team

=

A unique opportunity to make significant advances towards:

- A predictive understanding of fusion plasmas
- Success of ITER in its baseline mission
- An enriched ITER research program
- Realizing the potential of steady-state tokamak operation

DIII–D NATIONAL FUSION FACILITY

060-06/MW/jy