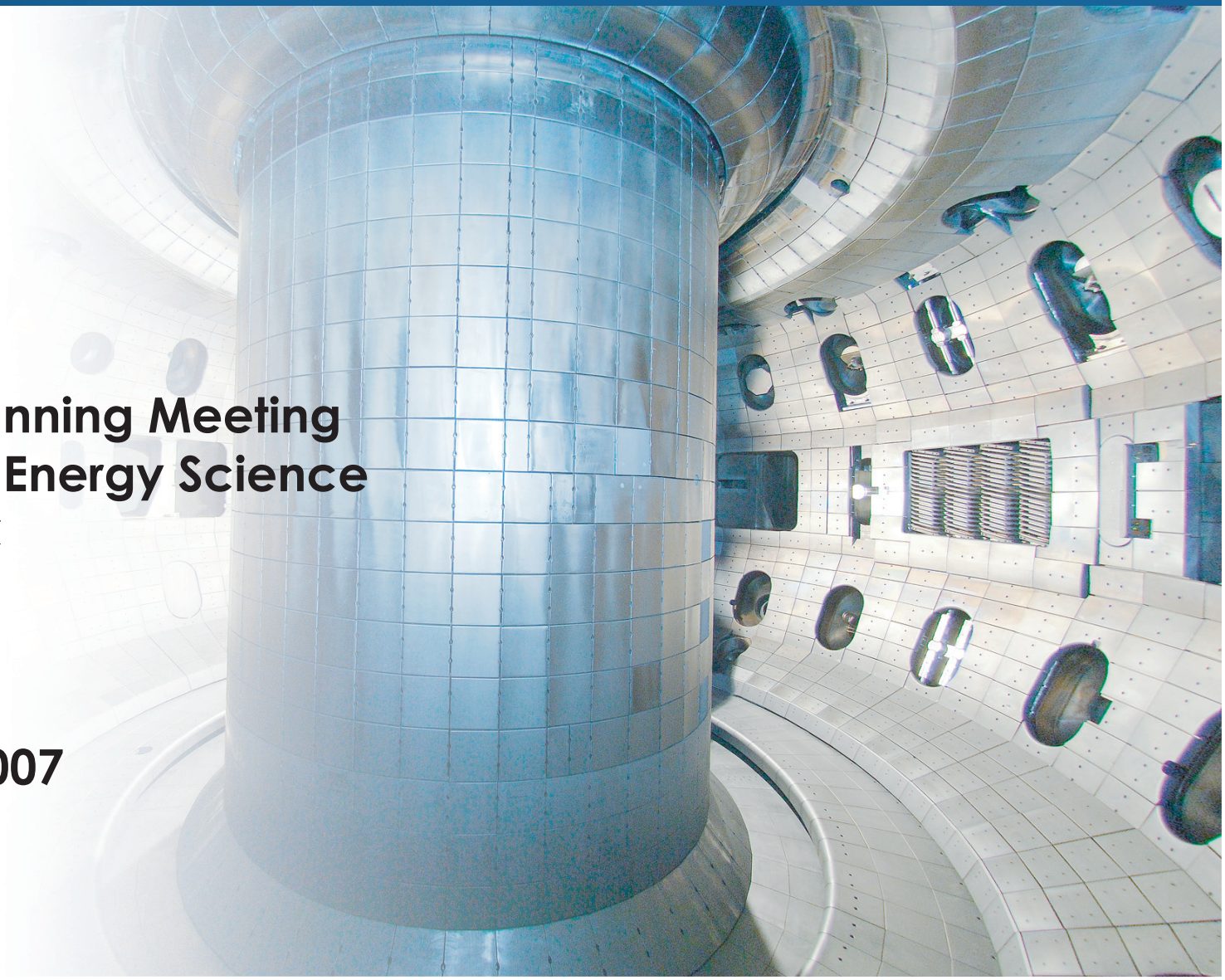
DIII–D National Fusion Program



by
D.N. Hill

Presented at
FY09 Budget Planning Meeting
Office of Fusion Energy Science
Washington, DC

March 13–14, 2007

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

038-07/DNH/jy

DIII–D is a Large, International Program

Active Collaborations 2006

- 90 institutions participate
- Over 200 active scientists
- Over 350 scientific authors (2006)
- 120 foreign national visitors (2006)
- Students, faculty, and post docs from 38 Universities

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)

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

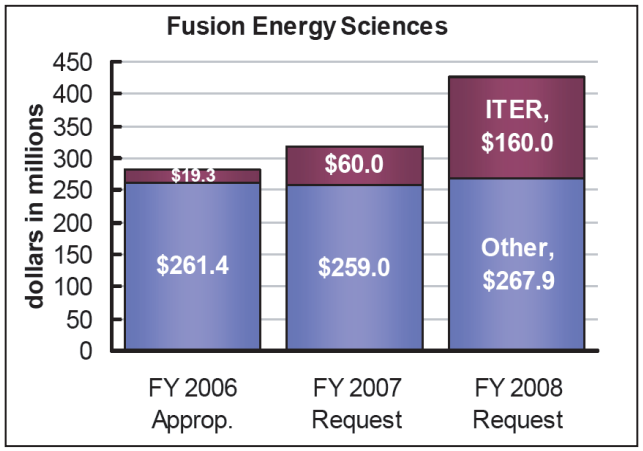
Columbia 22	ORNL 21
FarTech 4	PPPL 66
Georgia Tech 2	SNL 7
GA 276	UCI 6
Lehigh 2	UCLA 30
LLNL 44	UCSD 30
MIT 3	U. Texas 4
ORISE 4	U. Wisconsin 15

Total: 536

DIII–D NATIONAL FUSION FACILITY

038-07/DNH/jy

DIII–D is Responsive to the Changing Climate for Fusion Research



Fusion budget is growing!

- **DIII–D personnel active in process of defining ITER issues through the USBPO and ITPA**
  - USBPO deputy director, eight topical group leaders or deputy leaders, and four Council members are members of DIII–D Team
  - 40 DIII–D participants in ITPA
- **Tasks currently being defined by ITER design review working groups**
- **DIII–D is working with the USBPO and the rest of the US Fusion program to provide an effective and timely input to ITER**
  - Example: recent experiment in DIII–D simulating the ITER startup phase

DIII-D Research Responds to Urgent Needs for ITER Design Review

Response is reflected in

	DR&PO working group	USBPO issue cards
• Realignment of 2007 experimental plan		
• New milestones for FY08/09		

Experiments address immediate issues for ITER design

• Control of tritium inventory, choice of first wall material	Task 5	1.9-20
• Non-axisymmetric coils for ELM mitigation	Task 8.1	1.9-12
• Systems for resistive wall mode stabilization		
– Feedback control coils	Task 8.2	1.9-12
– Plasma rotation control	Task 8.3	1.9-18
• Disruption avoidance and mitigation	Task 4	1.9-15
• Pellet pacing for ELM control	Task 9	1.9-14
• Validation of startup scenarios	Task 7	1.9-13
• Projections of advanced operating modes	Task 2	

*ITER Design Requirements and Physics Objectives working group

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

Research Agenda for ITER

2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035

Phases of ITER Development

DESIGN SUPPORT | PRE-OPERATIONS | COMMISSIONING First Plasma | H | D | HIGH GAIN DT | MODEST GAIN DT LONG PULSE, NONINDUCTIVE | DT | FUSION TECHNOLOGY TESTS

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
- Suppress confinement limiting instabilities in ITER
- Stabilize pressure limiting instabilities in ITER

Waves and Energetic Particles

- Resolve rf and microwave issues ✓
- Specify Upgrades 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 Researchers Are Strongly Engaged in the International Tokamak Physics Activity (ITPA)

— 37 team members, 3 international chairs/co-chairs, 9 US leaders/co-leaders —

Coordination Committee	Oktay
Erol Oktay	OFES
Ned Sauthoff	PPPL
Ron Stambaugh	**GA**

Transport Physics (TP)	Bolton
Ed Doyle	**UCLA**
Ed Synakowski	LLNL
John Rice	MIT
John Kinsey	GA
Punit Gohil	GA
Dave Mikkelsen-Stell.	PPPL
Michael Kotschenreuther	Texas
Catherine Fiore	MIT
Larry Baylor	ORNL
Wendell Horton	Texas
Chuck Greenfield	GA
T.S. Hahm	PPPL
Bill Nevins	LLNL
Martin Peng	PPPL/ORNL
Ron Waltz	GA
Jim Callen	Wisconsin

Pedestal & Edge Physics (PEP)	Crisp
Tony Leonard	**GA**
Amanda Hubbard	MIT
Parvez Guzdar	Maryland
Tom Rognlien	LLNL
Mickey Wade	GA
Xueqaqio Xu	LLNL
Phil Snyder	GA
Rich Groebner	GA
Rip Perkins	PPPL
Tom Osborne	GA
Jim Drake	Maryland
Ben Leblanc	PPPL

Steady State Operations (SSO)	Oktay
Tim Luce	**GA**
Paul Bonoli	MIT
Ron Prater	GA
Chuck Kessel	PPPL
Masanori Murakami	ORNL
Randy Wilson	PPPL
Mike Zarnstorff	PPPL
Pete Politzer	GA
Joel Hosea	PPPL
Cary Forest	Wisconsin

MHD, Disruption and Control (MDC)	Dagazian
Ted Strait	**GA**
William Heidbrink	**UCI**
Robert Granetz	MIT
Jon Menard	PPPL
Jerry Navratil	Columbia
Ed Lazarus-Stellarator	ORNL
Chris Hegna	Wisconsin
Eric Fredrickson	PPPL
John Wesley	GA
Steve Jardin	PPPL
Boris Breizman	Texas
Raffi Nazikian	PPPL
Doug Darrow	PPPL
Nicolai Gorelenko	PPPL
Steve Sabbagh	Columbia

Notes:

1. **The first five persons in each group are the core members**
2. **The first person in each group is the U.S. Leader**
3. **The second person is the U.S. deputy leader**
4. **The membership is open to all members of the U.S. community**
5. **Everyone on the list will receive communication on ITPA and be able to contribute to it.**

Confinement, Database, and Modeling (CDBM)	Eckstrand
Wayne Houlberg	ORNL
Jim DeBoo	**GA**
Stan Kaye	PPPL
Joe Snipes	MIT
Robert Budny	PPPL
Tom Casper	LLNL
Craig Petty	GA
Lynda Lodestro	LLNL
Glenn Bateman	Lehigh
Dale Meade	PPPL
Arnold Kritz	Lehigh
Martin Greenwald	MIT

Divertor Physics & Scrape-off-layer (DSOL)	Finfgeld
Bruce Lipschultz	MIT
Peter Stangeby	**LLNL/GA**
Dennis Whyte	Wisconsin
Sergei Krasheninnikov	UCSD
Max Fenstermacher	LLNL
Rajesh Maingi	ORNL
Ali Mahdavi	GA
Daren Stotler	PPPL
John Hogan	ORNL
Charles Skinner	PPPL
Henry Kugel	PPPL
Jim Strachan	PPPL
Mathias Groth	LLNL
Steve Lisgo	U Toronto

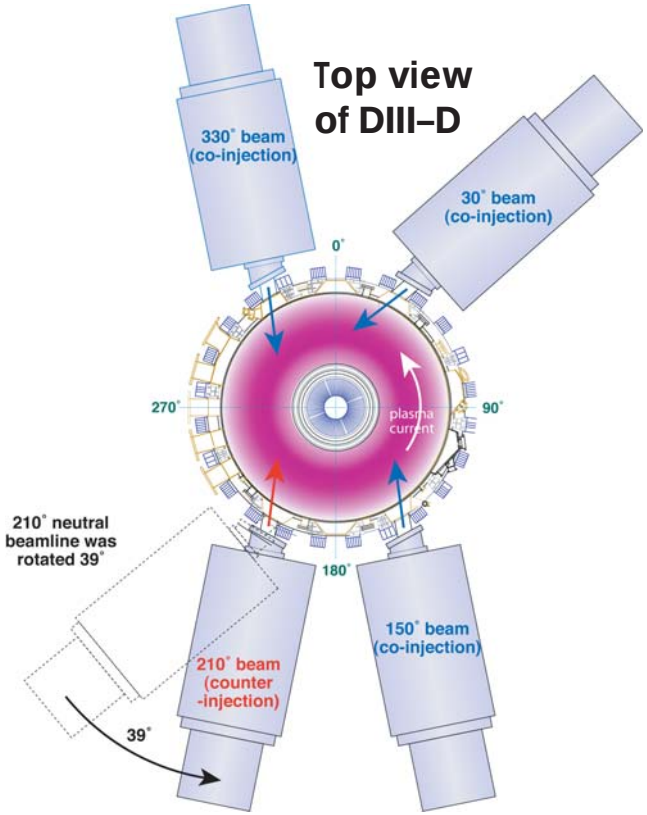
Diagnostics	Markevich
Dave Johnson	PPPL
Rejean Boivin	**GA**
Tony Peebles	UCLA
George McKee	Wisconsin
Glen Wurden	LANL
Don Hillis	ORNL
Ray Fisher	GA
Ken Young	PPPL
Jim Terry	MIT

DIII–D NATIONAL FUSION FACILITY

038-07/DNH/jy

Recent Hardware Modifications and Diagnostic Upgrades Further Increase DIII–D Capabilities for ITER Relevant Research

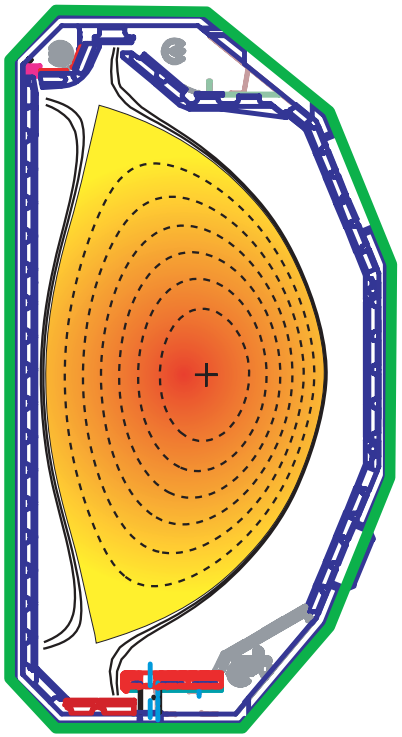
- **Reoriented beamline**



210˚ neutral beamline was rotated 39˚

⇒ ITER-like rotation

- **Extended lower divertor**



⇒ ITER-like collisionality

- **Major diagnostic upgrades (20+ systems)**

Major contributions and effort by many institutions

⇒ ITER-relevant model validation

⇒ Producing ITER-relevant people

Most Recent PAC Recognized Many Potential Contributions to ITER R&D Needs with new DIII-D Capabilities

ITER Near Term Research:

"The PAC recognizes that the DIII-D team has utilized the new capabilities after the LTOA very effectively and has investigated urgent issues concerning the ITER design following largely the recommendations given by the PAC in 2006."

"Significant progress has been made in several areas… These results, if confirmed, have a potentially large impact on the predicted ITER performance and could therefore influence the decisions to be taken in the ongoing ITER design review."

ITER Longer Term Research:

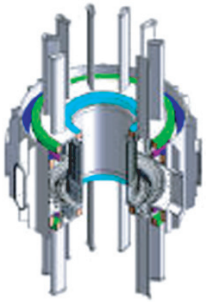
"The PAC recommends that a strong focus is maintained on the development of candidate advanced scenarios for ITER during the coming 5 years and that, in particular attention is given to exploring plasma behaviour in these scenarios under ITER-relevant conditions, …"

Fusion Science:

"The DIII–D diagnostic capability for the pedestal region is arguably unparalleled among the world's large tokamaks. Given that the scaling of the pedestal height/width is one of the key uncertainties in predicting the fusion gain for ITER and future tokamaks, this capability should be strongly exploited."

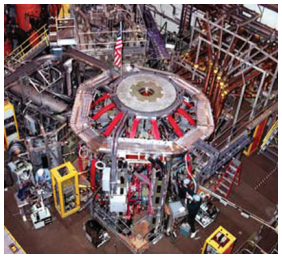
DIII–D Versatility Promotes Collaborations with Fusion Facilities Worldwide

ALCATOR C-MOD



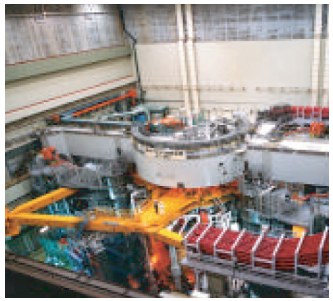
- Impurity flows
- Disruption studies
- Pedestal
- Rotation

NSTX

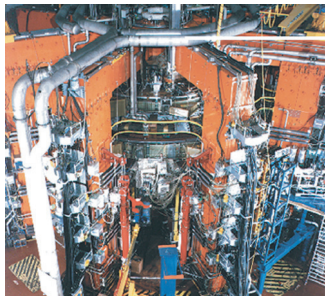


- Aspect ratio scaling
- RWM
- Plasma control
- Fast ions

JT-60U

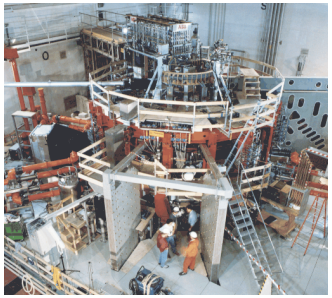


- Advanced Tokamak
- Hybrid
- QH-mode
- Effects of rotation



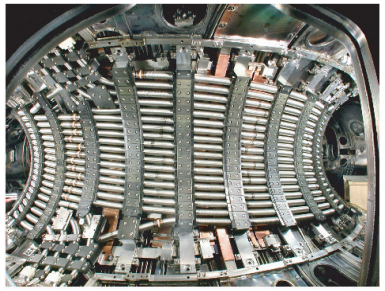
- Advanced Tokamak
- ELM mitigation
- Real-time control
- RWM, NTMs
- Hybrid

ASDEX-UPGRADE



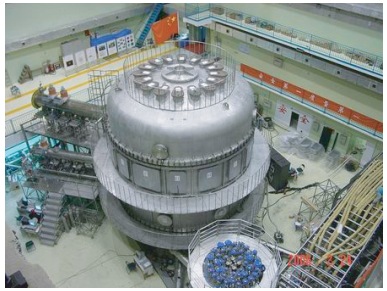
- Hybrid
- Tungsten wall
- Pedestal
- NTM

TEXTOR



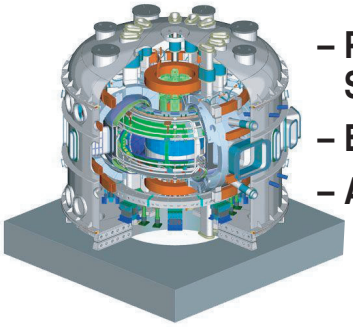
- Dynamic ergodic divertor

EAST



- Plasma Control System
- Neutral Beams

KSTAR



- Plasma Control System
- ECH
- Access Grid

A Broad Range of Scientific Personnel Exchanges Enhance International Collaborations and Joint Experiments

2006-2007

to DIII–D

Plasma Control System Development
- S-H Han (KSTAR)
- S.H. Seo (KSTAR)
- B. Xiao (EAST)
- Q. Yuan (EAST)
- J. Qian (EAST)

NTM Stabilization
- R. Buttery (UKAEA)
- F. Volpe (MPI Gesellschaft)
- A. Isayama (JAEA)

RWM Stabilization
- M. Takechi (JAEA)
- G. Matsunaga (JAEA)

Pedestal and QH-mode studies
- C. Maggi (IPP-Garching)
- Y. Kamada (JAEA)
- Y. Sakamoto (JAEA)

ELM Studies
- N. Oyama (JAEA)

AT scenarios
- T. Suzuki (JAEA)
- S. Ide (JAEA)
- Y. Sakamoto (JAEA)

Li Beam development
- K. Kamiya (JAEA)
- A. Kajima (JAEA)

Resonant Magnetic Perturbation studies
- K-H. Finken (FZ-Julich)
- M. Jakabowski (FZ-Julich)
- M. Lehnen (FZ-Julich)
- B. Unterberg (FZ-Julich)
- O. Schmitz (FZ-Julich)
- H. Frerichs (FZ-Julich)
- D. Reiter (FZ-Julich)
- D. Harting (FZ-Julich)
- D. Schega (FZ-Julich)
- E. Nardon (CEA-Cadarache)
- M. Becoulet (CEA-Cadarache)
- V. Parail (UKAEA)
- J. Lonnroth (Univ Finland)
- R. Koslowski (FZ-Julich/JET)
- Y. Liang (FZ-Julich)
- S. Pinches (IPP Garching/JET)
- R. Buttery (UKAEA)

Transport Physics
- L. Vermare (IPP-Garching)

Boundary Physics
- S. Brezinsek (IPP-Garching)

from DIII–D

Boundary Physics (ASDEX Upgrade)
- M. Groth

ITB Physics and Real Time Control (JET)
- P. Gohil

NTM studies (JET)
- R. LaHaye

QH-mode plasmas (JT-60U)
- P. Gohil
- L. Lao (Remote)

AT scenarios (JET)
- T. Luce
- J. Ferron
- M. Murakami (Remote)

Ergodic Divertor Studies (TEXTOR)
- T. Evans

Remote participation on ELM control studies (JET)
- M. Fenstermacher
- T. Evans
- P. Gohil
- R. Moyer
- T. Osborne

Pedestal (JET)
- T. Leonard
- T. Osborne

Divertor hardware development (EAST)
- M. Schaffer

Neutral Beam development (EAST)
- R. Callis

Plasma Control System development (EAST)
- D. Humphreys
- M. Walker
- J. Leuer
- G. Jackson
- D. Piglowski
- B. Penaflor
- A. Hyatt

Plasma Control System development (KSTAR)
- M. Walker
- B. Penaflor

ITER CODAC Design (ITER Cadarache)
- M. Walker
- D. Humphreys

- 38 scientists visiting DIII–D to participate in experiments, with 29 DIII–D scientist visiting international patners

Over 40 Joint Papers Including DIII–D Authors and/or Data Have Been Published Since 2003

Some of the most recent:

2005

C. Bourdelle, *et al.*, "*Impact of the α parameter on the microstability of internal transport Barriers*," Nucl. Fusion **45**, 110 (2005).

F Imbeaux, *et al.*, "*Multi-machine transport analysis of hybrid discharges from the ITPA profile database*," Plasma Phys. Control. Fusion **47**, B179 (2005).

J.C. DeBoo, *et al.*, "*Search for a critical electron temperature gradient in DIII-D L-mode discharges*," Nucl. Fusion **45**, 494 (2005).

M.R. Wade, *et al.*, "*Hybrid scenario development in DIII-D*î, Fusion Science Technol. **48**, 1199 (2005).

M.R. Wade, *et al.*, "*Development, physics basis and performance projections for hybrid scenario operation in ITER on DIII-D*," Nucl. Fusion **45**, 407 (2005).

J.G. Cordey *et al.*, "*Scaling of the energy confinement time with β and collisionality approaching ITER conditions*," Nucl. Fusion **45**, 1078 (2005).

W.A. Houlberg *et al.*, "*Integrated modeling of the current profile in steady-state and hybrid ITER scenarios*," Nucl. Fusion **45**, 1309 (2005).

2006

T.E. Evans, *et al.*, "*Edge stability and transport control with resonant magnetic perturbations in collisionless tokamak plasmas*," Nature Physics **2**, 419 (2006).

R.J. La Haye, *et al.*, "*Cross-machine benchmarking for ITER of neoclassical tearing mode stabilization by electron cyclotron current drive*," Nucl. Fusion **46**, 451 (2006).

H. Reimerdes, *et al.*, "*Cross-machine comparison of resonant field amplification and resistive wall mode stabilization by plasma rotation*," Phys. Plasmas **13**, 056107 (2006).

Y. Liu, *et al.*, "*Modeling of resistive wall mode and its control in experiments and ITER*," Phys. Plasmas **13**, 056120 (2006).

Pace is increasing

S.M. Kaye, *et al.*, "*The role of aspect ratio and beta in H-mode confinement scalings*," Plasma Phys. Control. Fusion **48**, A429 (2006)

D.C. McDonald, *et al.*, "*The impact of statistical models on scalings derived from multi-machine H-mode threshold experiments*," Plasma Phys. Control. Fusion **48**, A439 (2006).

E.J. Doyle, *et al.*, "*Progress on it advanced tokamak and steady-state* scenario development on DIII–D and NSTX" EPS invited, PPCF. **48** (2006) B39-B52

D. McDonald, *et al.*, "*Recent progress on the development and analysis of the ITPA global H-mode confinement database*," accepted for publication in Nucl. Fusion.

21th IAEA Fusion Energy Conference, Chengdu, China, October 2006:

J.E. Rice, *et al.*, "*Inter-Machine Comparison of Spontaneous Toroidal Rotation*," EX/P3-12.

R.V. Budny, *et al.*, "*Transport Physics of Hybrid Scenario Plasmas in the International Multi -Tokamak Database and Implications for ITER*," IT/P1-5.

Borba, *et al.*, "*Excitation of Alfvén eigenmodes with sub-Alfvénic neutral beam ions in JET and DIII-D plasmas*," PD-1

C.F. Maggi, *et al.*, "*Characteristics of the H-mode Pedestal in Improved Confinement Scenarios in ASDEX Upgrade*, DIII-D, JET and JT-60U," IT/P1-6.

O.J.W.F. Kardaun, *et al*, "*The tortuous route of confinement prediction near operational boundary - improvement of analysis based on ITERH.DB4/L.DB3 Database*," IT-P1-10.

R. Maingi, *et al.*, "*Dependence of the H-mode Pedestal Structure on Aspect Ratio*," IT/P1-12.

J. Wesley, *et al.*, "*Disruption Characterization and Database Activities for ITER*," IT/P1-21.

R.J. La Haye, *et al.*, "*Evaluating Electron Cyclotron Current Drive Stabilization of Neoclassical Tearing Modes in ITER: Implications of Experiments in ASDEX-U, DIII-D, JET, and JT-60U*," EX/P8-12.

Y.X. Wan, et al., *"Overview of Progress and Future plan of EAST Project"* OV/1-1 (Invited)

M. Bécoulet, et al., *"Modeling of Edge Control by Ergodic Fields in DIII–D, JET and ITER"* IT/P1–29

Summary of Papers and High Visibility Presentations of The DIII–D and GA Theory Programs in FY06

- Over 80 refereed publications
- Nature Physics cover article
- IAEA 23 papers (Luce - post deadline oral presentation)
- APS Review (Petty) and 12 invited papers (including post deadline)
- APS 9 invited papers (Petty review, Strait-post deadline invited)
- EPS 15 papers (Doyle invited)
- PSI 17 papers (Leonard invited)
- Hi Temp Plasma Diagnostics 12 papers (McKee Invited)
- TTF 10 presentations
- SOFT 7 papers (Kellman invited)
- TOFE 4 papers (Boivin invited)
- EC-14 4 papers
- 5 PRL's

DIII–D Program Recognition in FY06-07

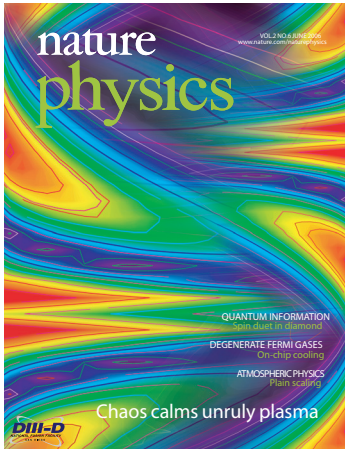
- Inaugural Nuclear Fusion Award for outstanding paper presented to Dr. Tim Luce

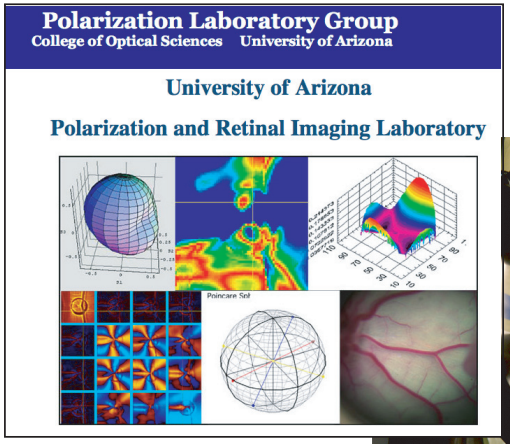
- Dr. John Ferron named a fellow of the America Physical Society
- Dr. Chuck Greenfield recently named Deputy Director of the US Burning Plasma Organization
- Dr. Vincent Chan is the Chair-elect of the Division of Plasma Physics of the American Physical Society

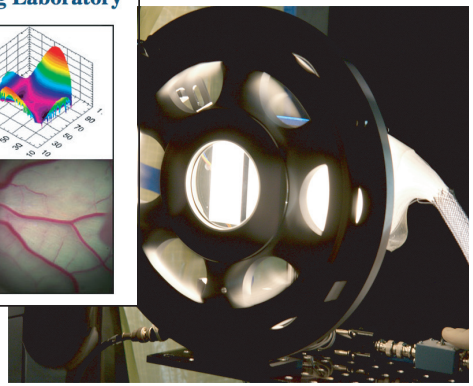
- Dr. Steve Allen is the secretary treasurer of the Division of Plasma Physics of the American Physical Society
- Dr. Keith Burrell is Chair of the Transport Task Force
- Dr. C. Craig Petty gave a review presentation on dimensionless scaling at the APS-DPP meeting, which highlighted many DIII–D experiments on this topic

DIII–D Scientists Interact with the Broader Scientific Community on Many Levels

- Seventeen attempts to publish in broader science journals (1 rejected)
- Twelve collaborations with scientists outside plasma physics
- Five presentations at colleges and universities to non-plasma majority scientific science meetings
- Seven talks at non-plasma specific science meetings
- Hosted NSF Workshop on Mathematical Models for Plasma Control
- DIII–D gyrotrons used as heat source for materials science research
- MSE calibration experiment for University of Arizona polarization and Retinal Imaging Laboratory
- Developed collaboration with Lehigh U. Mechanical Eng. Dept. on non-linear control – 2007 NSF CAREER award for Prof. E. Schuster







DIII-D Scientists Interact with the Broader Scientific Community on Many Levels (2)

Attempts to Publish in Broader Science Journals

DIII-D Program Contact	Journal	Title	Result or Reference
T. Evans, R. Moyer, K. Burrell	Nature Physics 2, 419	Edge stability & Transport control w/resonant magnetic perturbations in collisionless tokamak plasmas	Cover article, Vol 2 June 2006
M. Walker	Control Systems	Emerging Applications in Tokamak Plasma Control	Published in special issue on tokamak plasma control
D. Humphreys	Control Systems	Progress in other areas of Tokamak Plasma control	Published in special issue on tokamak plasma control
T. Evans	Physical Review Letters	Mechanisms of Edge-Localized-Mode Mitigation by External-Magnetic-Field Perturbations	Phys. Rev. Lett. 98, 095001 (2007)
H. Reimerdes	Physical Review Letters	Reduced Critical Rotation for Resistive-Wall Mode Stabilization in a Near-Axisymmetric Configuration	Phys. Rev. Lett. 98, 055001 (2007)
M. Van Zeeland	Physical Review Letters	Radial Structure of Alfvén Eigenmodes in the DIII-D Tokamak through Electron-Cyclotron-Emission Measurements	Phys. Rev. Lett. 97, 135001 (2006)
G. McKee	Physical Review Letters	Detection of Zero-Mean-Frequency Zonal Flows in the Core of a High-Temperature Tokamak Plasma	Phys. Rev. Lett. 97, 125002 (2006)
G. McKee	Review of Scientific Instruments	High sensitivity beam emission spectroscopy for core plasma turbulence imaging	Rev. Sci. Instrum. 77, 10F104 (2006)
D. Schlossberg	Review of Scientific Instruments	Velocity fluctuation analysis via dynamic programming	Rev. Sci. Instrum. 77, 10F518 (2006)
M. Shafer	Review of Scientific Instruments	Spatial transfer function for the beam emission spectroscopy diagnostic on DIII-D	Rev. Sci. Instrum. 77, 10F110 (2006)
T. Rhodes	Review of Scientific Instruments	Millimeter-wave backscatter diagnostic for the study of short scale length plasma fluctuations	Rev. Sci. Instrum. 77, 10E922 (2006)
D. Rudakov	Review of Scientific Instruments	First tests of molybdenum mirrors for ITER diagnostics in DIII-D divertor	Rev. Sci. Instrum. 77, 10F126 (2006)
D. Thomas	Review of Scientific Instruments	Signal processing techniques for lithium beam polarimetry on DIII-D	Rev. Sci. Instrum. 77, 10F515 (2006)
C. Holcomb	Review of Scientific Instruments	Motional Stark effect diagnostic expansion on DIII-D for enhanced current and Er profile measurements	Rev. Sci. Instrum. 77, 10E506 (2006)
E. Strait	Review of Scientific Instruments	Magnetic diagnostic system of the DIII-D tokamak	Rev. Sci. Instrum. 77, 023502 (2006)
T.L. Rhodes	Review of Scientific Instruments	Millimeter-wave backscatter diagnostic for the study of short scale length plasma fluctuations	Review of Scientific Instruments **77**, 10E922 2006
E.J. Doyle	Review of Scientific Instruments	Projections to ITER based on the design and performance of the DIII-D high resolution density profile reflectometer system	Rejected

DIII-D Scientists Interact with the Broader Scientific Community on Many Levels (3)

Collaborations with Scientists Outside of Plasma Physics

DIII-D Program Contact	Outside Scientist	Institution	Research Area
M. Walker	E. Schuster	Lehigh University	Nonlinear control theory
M Walker	L. Zaccarian	University of Rome	Nonlinear control theory
M. Walker	W. Helton	UCSD	Controllability theory
M. Walker	M. Krstic	UCSD	Multidisciplinary control
M. Walker	C. Kamath	LLNL	Scientific data mining
R. Fisher	Prof Victor Zacek	University of Montreal	PICASSO Project (search for dark matter) Properties of superheated drop/bubble detectors
John Lohr	Keith Thompson, John Booske	Univ of Wisconsin	Using 110 GHz microwaves for annealing of implanted junctions in silicon for CMOS applications
John Lohr	David Young	National Renewable Energy Laboratory	Crystallization of amorphous silicon using microwaves to increase photoconversion efficiency at low cost
John Lohr	Oleg Louksha, Gregory Sominski	St Petersburg State Polytechnical Institute	Low frequency parasitic oscillations in high power gyrotrons
Yury Gorelov	Kevin Felch	CPI	Infrared measurements of the temperature of CVD diamond with low emissivity
T. Evans	Dr. K.W. Roeder	Fields Institute, Dept of Mathematics, University of Toronto	Dynamical systems theory of vector fields
S.L. Allen	Prof. Russell Chipman	University of Arizona	Optical Polarization Measurements

DIII-D Scientists Interact with the Broader Scientific Community on Many Levels (4)

Presentations at Colleges and Universities to Non-Plasma Majority Scientific Audiences

DIII-D Program Contact	Venue	Date	Title
R. Boivin	University of New Mexico, weekly colloquium, Department of Electrical and computer engineering	05/05/06	Magnetic fusion, turbulence and DIII-D... or are we there yet?
C.M. Greenfield	Kansas State University	1/19/2006	Advances and New Developments in Fusion Energy Research Using the Tokamak
C.M. Greenfield	Creighton University	1/20/2006	Advances and New Developments in Fusion Energy Research Using the Tokamak
C.M. Greenfield	University of Connecticut	2/3/2006	Advances and New Developments in Fusion Energy Research Using the Tokamak
L. Baylor	Auburn University, Physics Dept. colloquium seminar	03/02/07	Fueling of Burning Plasmas-ITER

Talks at Non-Plasma Specific Science Meetings

DIII-D Program Contact	Venue	Date	Title
M. Walker	IEEE Conference on Decision and Control	12/13/06	A multivariable analysis of the vertical instability in Tokamaks
M. Walker	NSF Workshop on Mathematical Models for Plasma Control	05/11/06	Off-normal event handling
M. Walker	NSF Workshop on Mathematical Models for Plasma Control	05/11/06	Introduction to Tokamak plasma control
D. Thomas	15th International Conference on Atomics Processes in Plasmas	3/19-22/07	Lithium Polarization Spectroscopy: Making Precision Plasma Current Measurements in the DIII-D National Fusion Facility
G. McKee	16th International Toki Conference on Advanced Imaging and Plasma Diagnostics	12/5-8/06	Plasma Turbulence Imaging via Beam Emission Spectroscopy in the Core of the DIII-D Tokamak
E.J. Strait	Annual APS meeting	4/22-25/06	Magnetic reconnection in the DIII-D Tokamak
T. Evans	Intnational Conference on Chaos, Complexity and Transport	6/4-8/07	Implications of topological complexity and Hamiltonian chaos in the edge magnetic field of toroidal plasmas

Outline of the DIII–D Presentations

• Introduction	D.N. Hill (LLNL)	10 minutes
• DIII–D Research Plans	M.R. Wade	25 minutes
• University Research on DIII–D	G. McKee (Wisconsin)	15 minutes
• DIII–D Program Budgets and Schedules	T.S. Taylor (GA)	15 minutes
• GA Institutional Issues	R.D. Stambaugh (GA)	10 minutes
• Community Discussion		10 minutes

DIII–D Research Program Plans

by
M.R. Wade

Presented at
FY09 Budget Planning Meeting
Office of Fusion Energy Science
Washington, DC

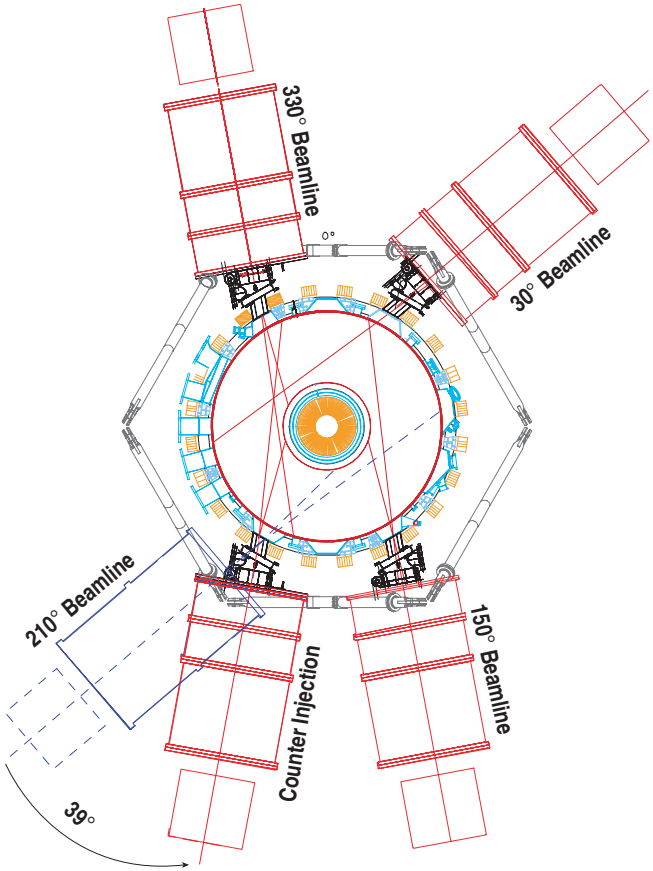
March 13–14, 2007

DIII–D Research Program is Closely Aligned with FESAC Priorities Report Overarching Themes

DIII–D Objectives	FESAC Priorities Panel
• Enable the success of ITER by providing physics solutions to key design issues	• Create a star on earth
• Establish the physics basis for steady-state, high performance operation for ITER and beyond	• Develop the science and technology to realize fusion energy
• Advance the fundamental understanding of fusion plasmas along a broad front	• Understand matter in the high temperature state

Recent Hardware Upgrades have Provided DIII–D with Exciting Capabilities for the Future

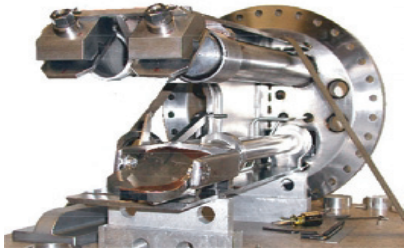
- Reorientation of beamline
- EC upgrades
- Lower divertor modification



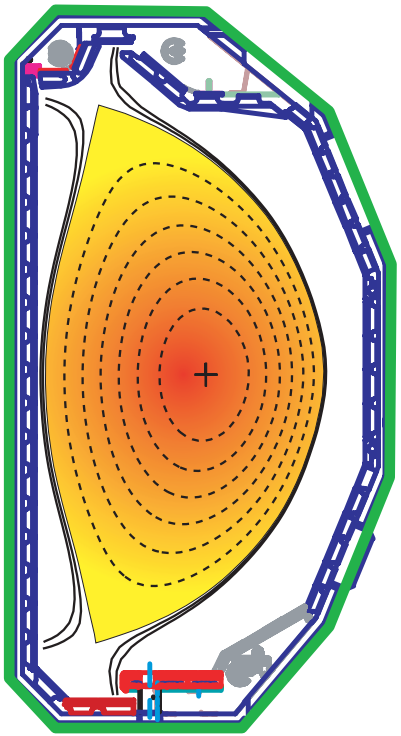
⇒ Rotation control

6 gyrotrons
–4.5 MW
for 10 s

All steerable toroidally and poloidally



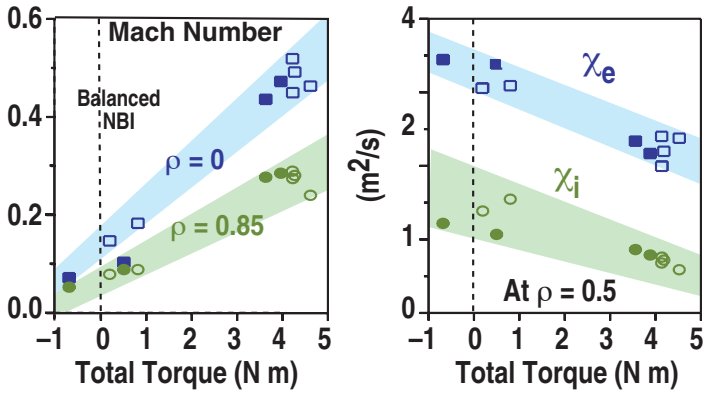
⇒ J(ρ) control, NTM stabilization, electron transport



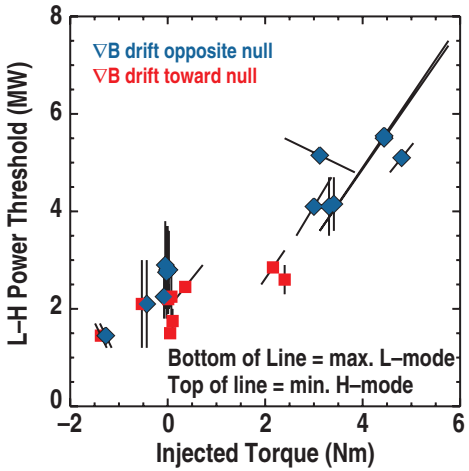
⇒ Density control in double null plasmas

New Capability to Control Torque Input Has Enabled New Scientific Research Paths

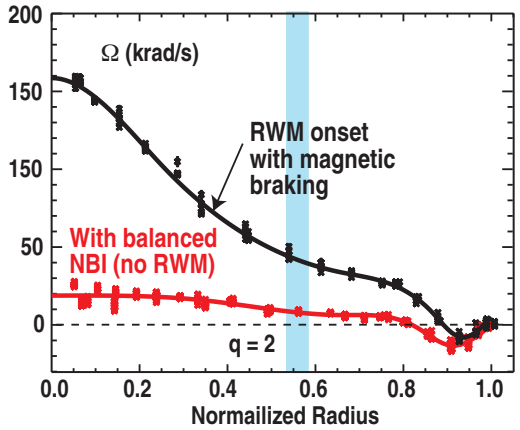
- Assessed impact of torque on rotation and transport



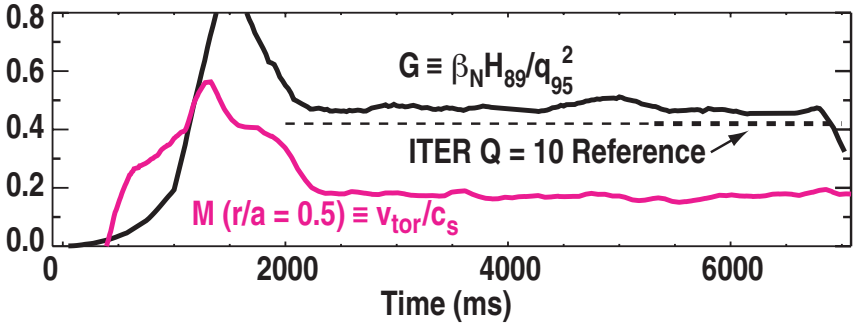
- Discovered L–H transition is sensitive to applied torque



- Discovered RWM stability threshold requires much lower rotation than previously observed

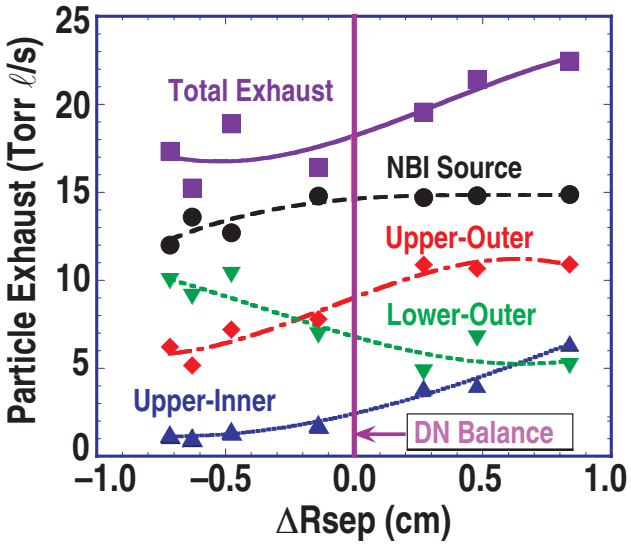


- Developed long-pulse, low rotation discharges with normalized gain better than ITER baseline

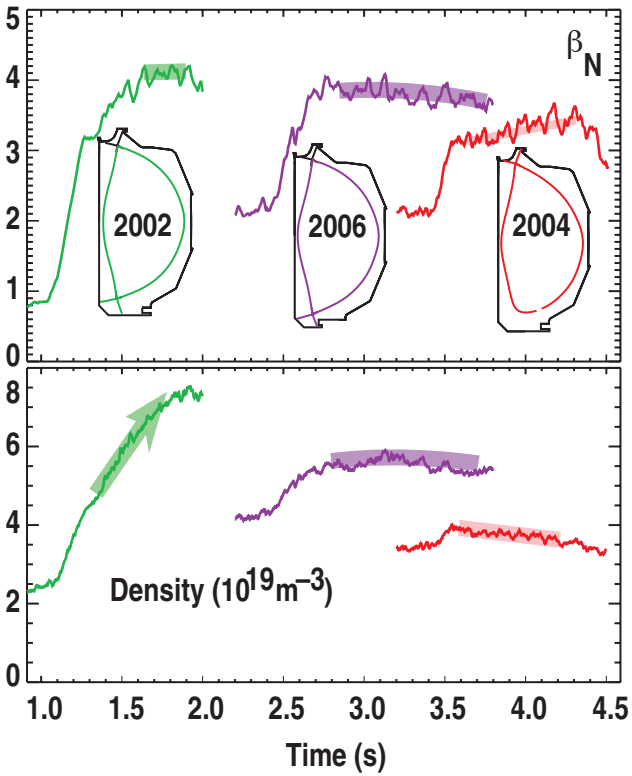


Effectiveness of New Lower Divertor Demonstrated and Utilized for Density Control in a Variety of Regimes

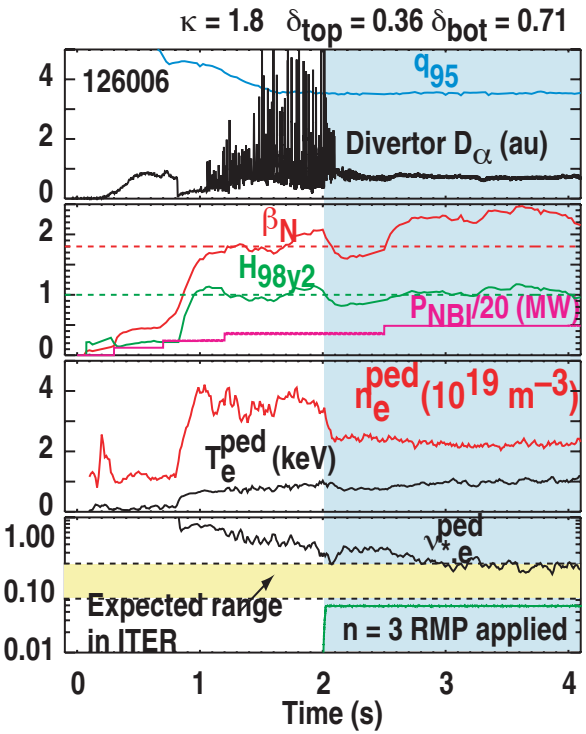
- Quantified impact of new divertor on particle control



- Used new divertor to reduce density and access high β



- Used new divertor to achieve low collisionality with ELM suppression in ITER-like shape



- Results consistent with design expectations

Research Highlights from 2006 Campaign

ITER

- Discovered that threshold for rotational stabilization of RWM is comparable to the rotation levels expected in ITER
- ELM suppression in the ITER shape and collisionality demonstrated
- 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
- Documented strong dependence of carbon redeposition on wall temperature
- Extended achievable density in QH-mode up to $n_{eped}/n_{e,GW} \approx 0.5$
- Significantly reduced density threshold for locked modes by improvements in intrinsic error and error compensation

Plasma Control

- Simultaneous feedback control by PCS of β and toroidal rotation demonstrated using real-time equilibrium reconstruction and CER
- Achievement of first plasmas in the EAST tokamak

Research Highlights from 2006 Campaign (continued)

Advanced Tokamak

- Good density control demonstrated in double-null shapes using new lower divertor in hybrid and Advanced Tokamak discharges
- Achieved normalized gain (G=0.4) comparable to the ITER Baseline scenario in double-null, Advanced Tokamak discharges
- Stability limit and confinement in Advanced Tokamak discharges shown to be sensitive to details of the plasma shape

Fusion Science

- H-mode power threshold reduced significantly with balanced NBI
- Measure radial profile and spectrum of high-k turbulence
- Confirmed theoretical prediction that zonal flows trigger sustained core barrier only when background ExB shear is sufficient
- Co-NBI shown to be more effective in driving TAEs than counter-NBI, as expected by theory
- Measured flattening of fast ion profile during Alfvenic activity
- Observed similar SOL flow velocities for deuterium and carbon
- Comparison of rotation velocities inferred from co- and counter-viewing CER confirm accuracy of cross section corrections

DIII–D Research Program Has Three Main Program Elements: ITER, Advanced Tokamak, and Science

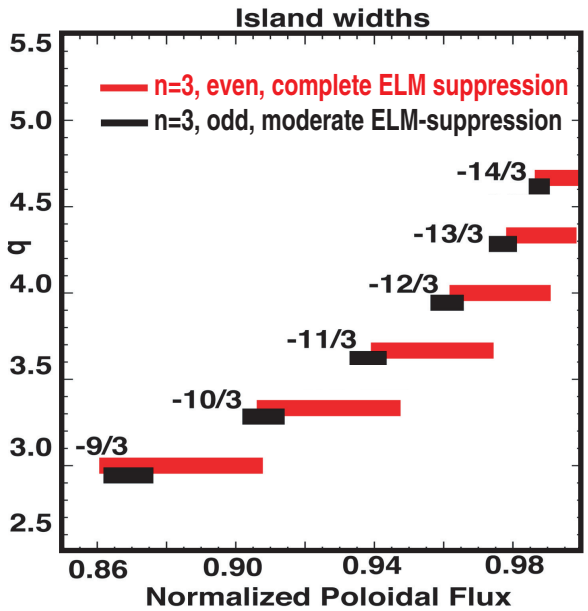
Ensure the success of ITER	Develop the physics basis for integrated, steady-state operation	Advance the fundamental understanding of fusion plasmas
• Provide physics solutions to key ITER issues	• Qualify fully noninductive scenarios for ITER	• Discover and characterize new phenomena
• Characterize advanced operating scenarios for use on ITER	• Determine ultimate potential of Advanced Tokamak operation	• Validate theoretical models for use in predictive modeling
• Improve the understanding of key physics issues	• Provide physics basis for integrated AT operation consistent with core/edge physics constraints	
ITER: Q=10 Baseline	**Q=5 Steady-State**	**Prediction and Control**

Near-Term ITER Research Focuses on Design Issues While Longer Term Activities Emphasize Operational Issues

Ensure the success of ITER	Near-term Activities	Longer-term Activities
• Provide physics solutions to key ITER issues	• ELM control • RWM stabilization • NTM stabilization • Disruption mitigation • Tritium retention	• Pedestal/ELM optimization • Disruption avoidance
• Characterize advanced operating scenarios for use on ITER	• Hybrid scenario characterization • Fully noninductive demonstration	• Establish access paths • Control specific to ITER tools • Scenarios for Q > 10 in ITER
• Improve the understanding of key physics issues	• Assess effect of rotation on operational performance	• Improved predictive capability for pedestal • Develop validated transport model

Near-term ELM Control Research Focuses on Evaluation of Non-axisymmetric Coil Requirements for ITER

- Experiment and theory suggest island overlap from RMP in pedestal region is important for ELM suppression



- Screening of RMP by Rotation also thought to be important

Research Plans

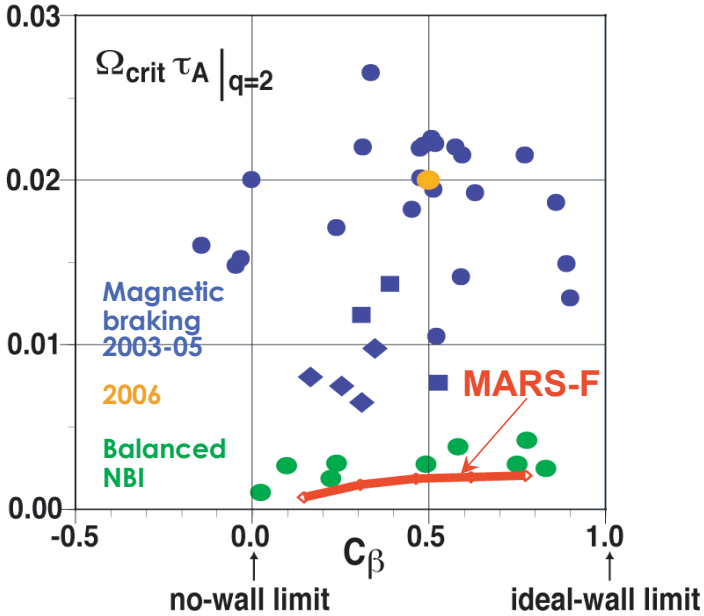
2007:
- Evaluate sensitivity of ELM suppression to RMP mode spectrum
- Measure RMP effects on pedestal turbulence and transport (PEP-19)
- Evaluate dependence of QH-mode on plasma rotation (Milestone #164, TP-5)

2008:
- Evaluate impact of plasma rotation on ELM suppression by RMP (Milestone #165)
- Assess pellet pacing as a method for ELM control in ITER

2009:
- Evaluate ELM suppression with RMPs in advance scenarios
- Evaluate options for new RMP coils on DIII–D

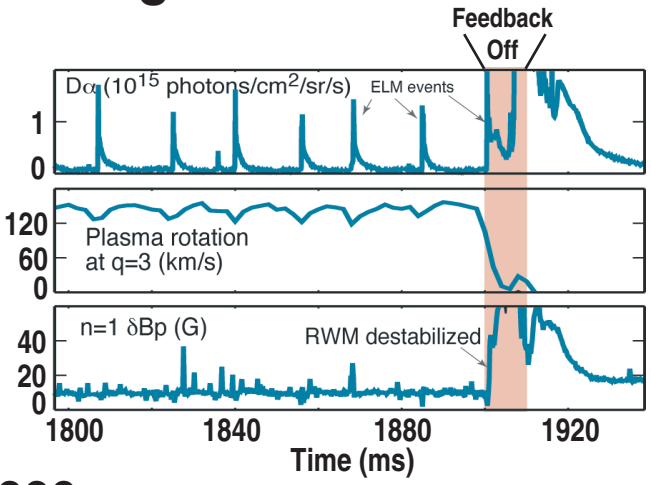
Resistive Wall Mode (RWM) Studies Focused on Providing Key Information on Feedback Coils for ITER

- Low rotation threshold found for RWM stabilization



- Significant uncertainties in measured threshold and anticipated rotation in ITER

- In addition, studies indicate transient events may cause RWMs even at high rotation



2007-2008:

- Assess the synergistic effect of rotation and feedback control on RWMs (Milestone #163, MDC-2)
- Determine rotation threshold and feedback requirements for ITER

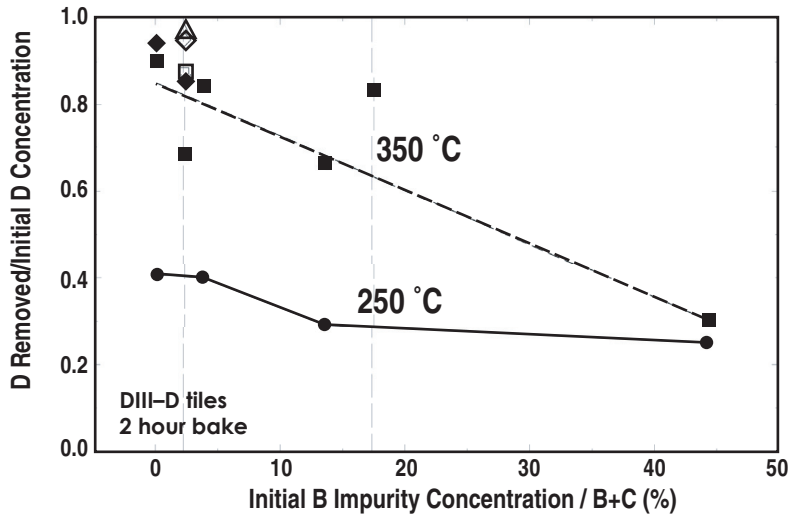
2009:

- Develop and validate advanced algorithms for optimal control

DIII–D Will Provide Important Information for the use of Carbon Materials for PFCs in ITER

DIII–D

- **Previous DIII–D experiments indicate carbon re-deposition is:**
  - localized in inner divertor
  - sensitive to material temperature
- **Tests at U. Toronto show thermal oxidation (O2 bake) is effective at removing D**



2007:
- **Demonstrate high performance without boronization**
- **Begin assessment of ability to remove co-deposits by O_2 bake (DSOL-12)**

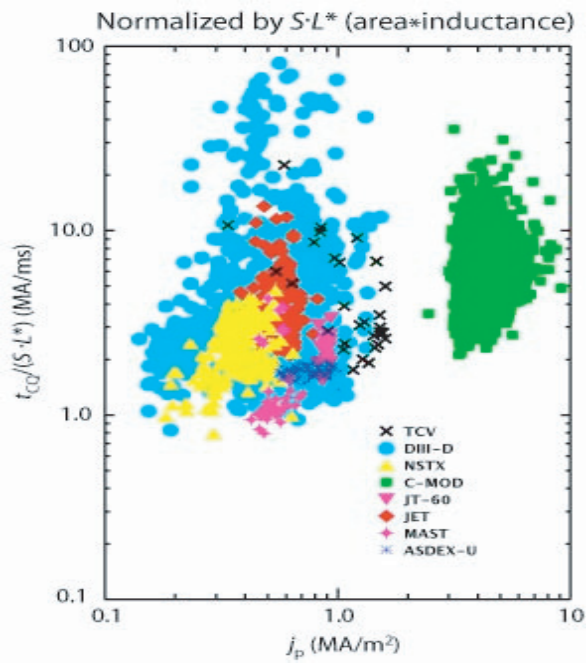
2008:
- **Operation with heated walls 120°C (DSOL-13)**
- **Characterize dust**

2009:
- **Assess other methods for co-deposit removal (O-GDC,...)**

Disruption Research Will Focus on Characterization and Mitigation of Disruptions

Characterization

- Analysis of ITPA disruption database identified expected minimum current quench duration in ITER



2008: Extend analysis to thermal quench and halo current

Mitigation

- DIII–D and C-mod experiments indicate impurity neutrals do not penetrate plasma

2007:
- Evaluate impurity assimilation vs. gas delivery rate and injected species (DSOL-11)

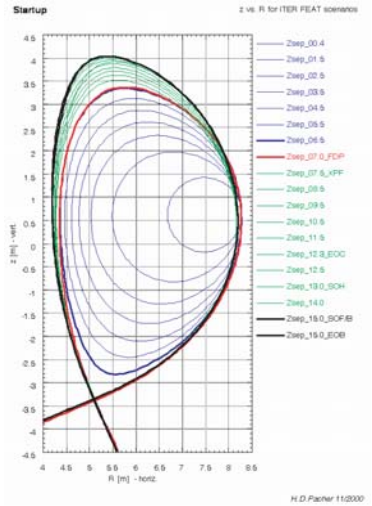
2008:
- Assess runaway electron generation during mitigated disruption (Milestone 168)

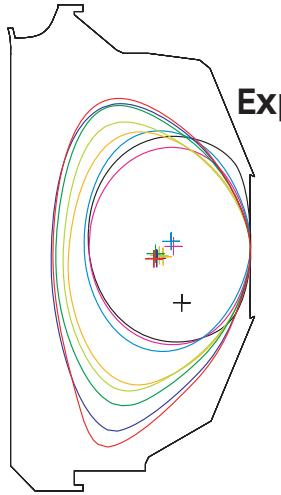
2009:
- Proof-of-principle test of alternative impurity deliver system
- Real-time stability analysis for disruption avoidance

Experiments Will Assess Requirements for ITER Start-up Scenarios Compatible with Advanced Scenarios

- Initial ITER start-up experiments conducted. . .

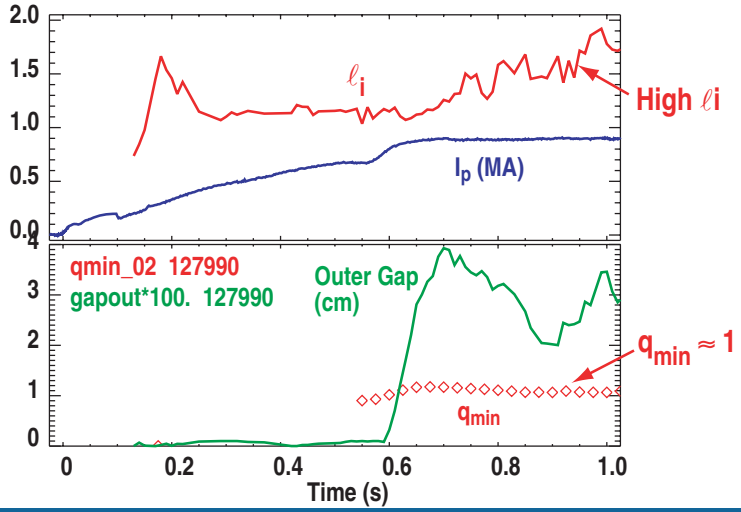
ITER "Simulation"





DIII–D Experiment

. . . Indicate rapid penetration of current



- Motivated by very recent requests by ITER team

2007: Develop plasma control and initial assessment

2008: Evaluate potential start-up scenarios for ITER (Milestone #166, SSO-5)

2009: Benchmark models for use on ITER

Other Research Activities Will Focus on Issues Important to the Success of ITER

- **Neoclassical tearing modes (NTMs)**
  2007: Initial assessment of NTM control with non-axisymmetric coils
  2008: Evaluate NTM stabilization using modulated ECCD (Milestone #170, MDC-8)
  2009: Demonstrate simultaneous stabilization of 3/2 and 2/1 NTMs

- **Intrinsic rotation (DOE level I Milestone for FY08)**
  2007: Measure sensitivity of rotation at zero input torque with β
  2008: Assess momentum damping due to intrinsic/applied error fields
  2009: Intrinsic rotation in torque-free plasmas (RF heated)

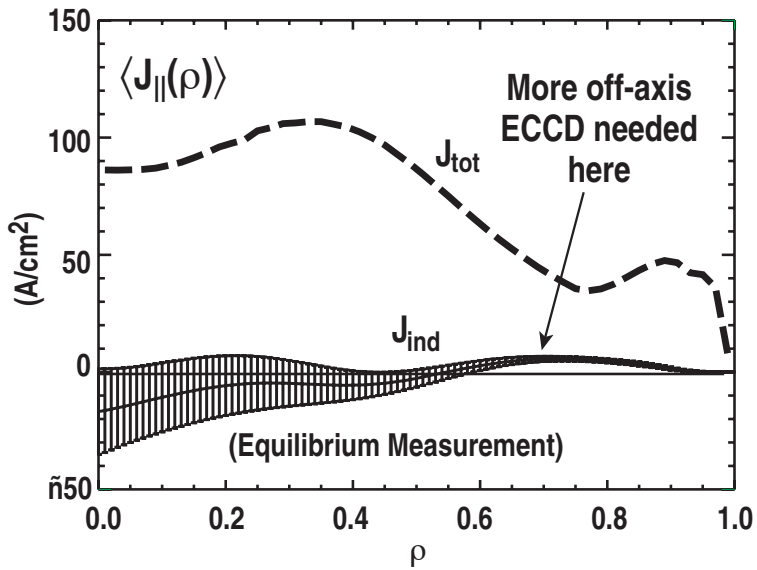
- **Pedestal Characterization**
  2007: Determine dependence on β in advanced scenarios (SSO-4, PEP-20)
  2008: Characterize turbulence in pedestal region
  2009: Compare pedestal and turbulence charateristics with TGLF (Milestone #172)

Advanced Tokamak Program Will Support ITER Development on Path to Demonstrating Steady-State Integrated Scenarios

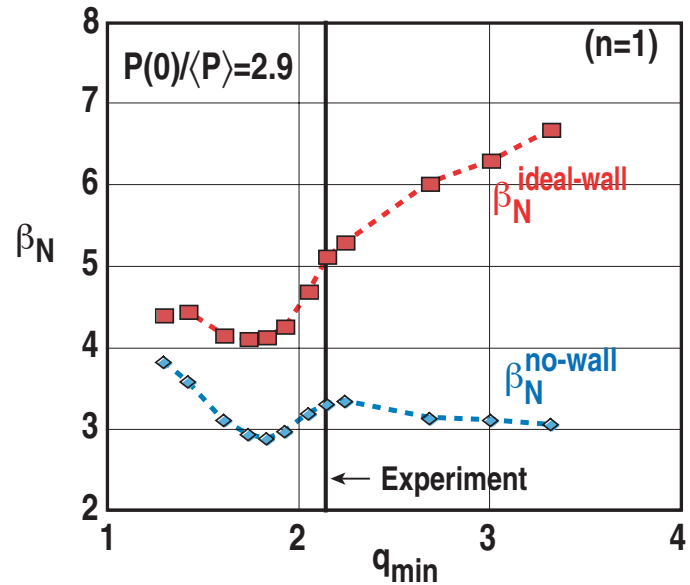
Develop the physics basis for integrated, steady-state operation	Near-term Activities	Longer-term Activities
• Qualify fully non-inductive scenarios for ITER	• Sustained operation with $\beta_N \approx 4$ • Demonstrate robust RWM stabilization • ITER start-up	• Develop control specific to ITER tools
• Determine ultimate potential of Advanced Tokamak operation	• Determine optimal magnetic configuration (i.e., shape, $J(\rho)$)	• $\beta_N \gtrsim 5$, $H_{89} \approx 3$, $f_{BS} > 80\%$ exploration
• Provide physics basis for integrated AT operation consistent with core/ edge physics constraints	• Assess method for heat flux control in AT regimes	• Demonstrate scenarios with high β and acceptable edge control

Advanced Tokamak Experiments Will Demonstrate Fully Non-Inductive Discharges for ITER and Explore Potential of Operating at $\beta_N \approx 5$

- Increased EC power should allow fully non-inductive high β operation



- Stability analysis indicates present experiments near operating window with access to $\beta_N > 4$



2007: Demonstrate fully non-inductive operation with $\beta_N \lesssim 4$ (SSO-1.1)

2008: Demonstrate fully non-inductive operation for a resistive time (Milestone #169)

2009: Optimize f_{BS} by variations in q profile

2007-2008: Explore potential route to operation with $\beta_N > 4$

Control Tool Development Will Continue to be an Important Part of Advanced Scenario Development and Integration

Current Profile Control:

2007: Continue developmement of feedback control of the current profile formation for steady-state scenarios

2008: Evaluate start-up scenarios for access to advanced scenarios in ITER (Milestone #166)

Fast Wave Heating:

2007: Evaluate coupling in steady-state scerario discharges

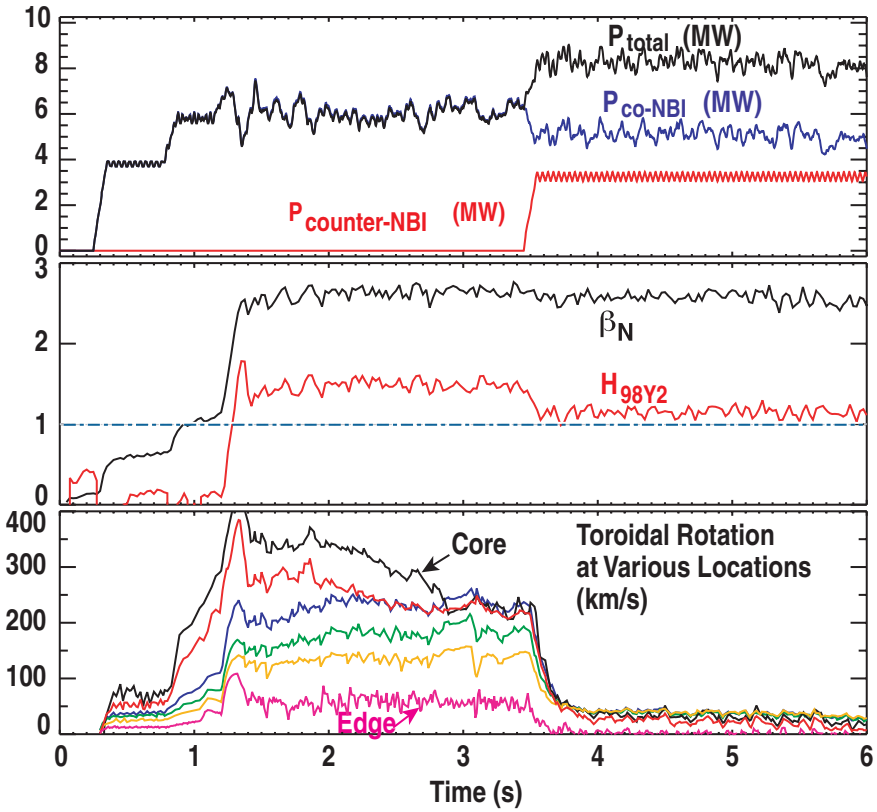
2008: Demonstrate electron heating in high performance plasmas

ELM Suppression:

2009: Apply ELM mitigation using RMPs to steady-state scenario plasmas

Hybrid Scenario Research Will Focus on Issues Critical in the Extrapolation of this Regime to ITER

- Experiments in 2006 demonstrated hybrid regime could be maintained at low rotation



- Near-term goal: Qualify this regime as alternative to the standard ITER baseline scenario

2007:
- Continue evaluation of impact of rotation, especially at $q_{95} \approx 3$ (TP-4.2)
- Explore pedestal dependence on β (SSO-4)

2008:
- Evaluate impact of strong electron heating ($T_e \rightarrow T_i$) (SSO–2.1)
- Assess compatibility of ELM mitigation

2009:
- Evaluate performance under ITER-like conditions (Milestone #171)
- Combine radiative divertor and ELM mitigation for heat flux control

Hardware Upgrades are Needed to Fully Exploit Physics of Advanced Scenarios

- **Increased electron heating for AT and $T_e \rightarrow T_i$ research**
  - 4.5 MW Long-pulse gyrotrons (+1.5 MW: '09 incremental)
  - Upgrades to FW systems (07-08)
  - Fast steerable EC launchers (09 incremental)
- **Long-pulse, high β operation**
  - Restore 8th NBI source (08-09)
  - Install upgraded 138 kV Transformer (08)

Fusion Science Research Aimed At Discovering and Understanding Important Aspects of Fusion Plasmas

Advance the fundamental understanding of fusion plasmas

- Discover and characterize new phenomena
- Validate theoretical models for use in predictive modeling

Near-term Activities

- Explore phenomena revealed by LTOA upgrades
- Continue basic tests of complex, theoretical models
- Motivate development of new theory to explain observed phenomena

Longer-term Activities

- Discover/evaluate new phenomena that have potential to transform fusion research
- Detailed test of complex models
- Develop integrated models for understanding interaction of complex phenonema

Basic Fusion Science Research is Essential for Continued Advances in the Viability of Fusion Energy

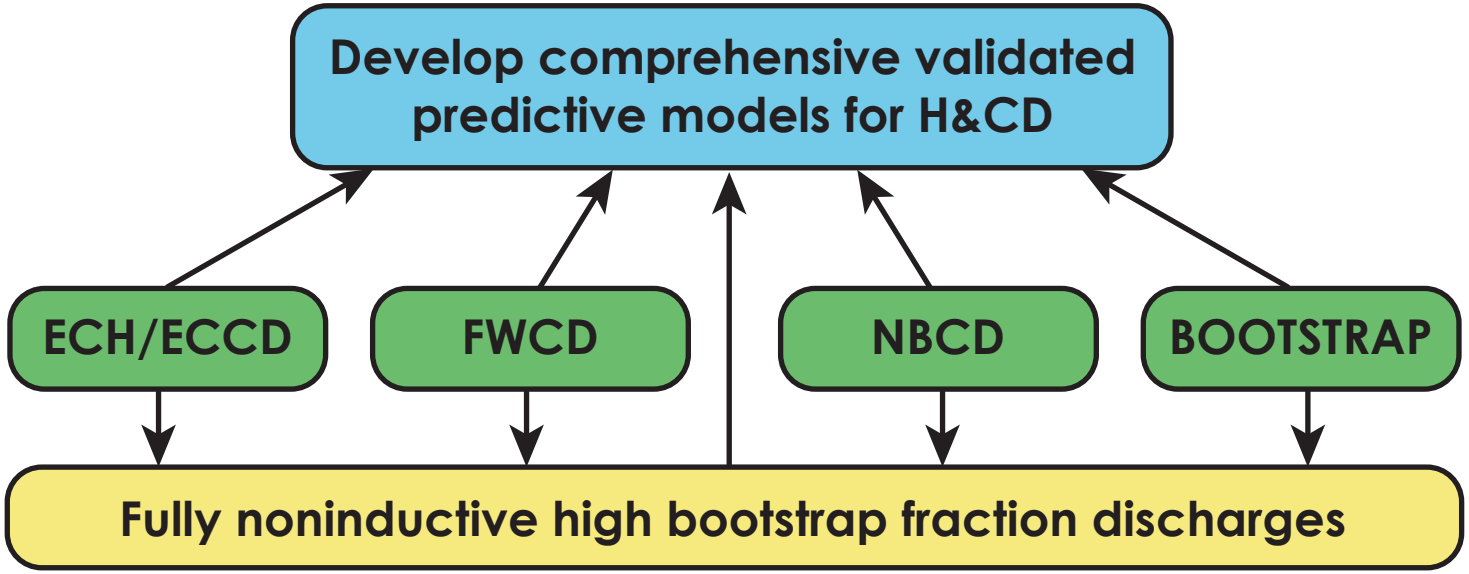
Area	Scientific Objective	Long-Term Impact
Transport	Develop a scientific basis for a predictive understanding of turbulent transport	Enhanced confinement, transport control
Stability	Establish the scientific basis to predict and control macroscopic instabilities	High pressure operation
Boundary	Develop basic understanding and advanced techniques for controlling particle and heat exhaust	Ability to handle exhaust from high performance core
Heating and current drive	Develop comprehensive validated predictive models for H&CD	Steady-state operation, transport control
Energetic particles	Provide the scientific basis of energetic particle instabilities in future burning plasma devices	Utilize alpha particles most effectively

New Tools and Diagnostics Will Promote Significant Progress Towards a Predictive Understanding of Transport

Develop scientific basis for a predictive understanding of turbulent transport

	Rotation/ Momentum	Barrier Physics	Dimensionless Scaling	Turbulence
2007	Rotation in torque-free plasmas (TP-6.1)	Impact of rotation on L-H transition	Role of shape in β scaling (CDB-2)	Separate ITG and TEM (TP-7) T_e fluctuations
2008	Rotation damping mechanisms	Differentiate E×B and magnetic shear (Milestone #167)	Particle transport vs T_e/T_i (CDB-9)	Test ExB shear stab. theory (TP-4.2)
2009	Compare χ_ϕ with χ_i	Differentiate E×B and α-stabilization	ρ_* scaling at low rotation (CDB-8)	Dependence on magnetic shear

Experiments in Heating and Current Drive Will Emphasize Tests of Theoretical Models Important in ITER Modeling



	ECH/ECCD	FWCD	NBCD	BOOTSTRAP
2007		High harmonic absorption by beam ions		
2008	Far-off-axis ECCD		Validate current drive models using new NBI (SSO-6)	Test theory in pedestal region
2009	ECH Pre-ionization	Current drive in AT plasmas	"Alpha channeling"	Test theory in core

New Diagnostics Will Provide a New Window into Energetic Particle Physics

Provide the scientific basis of energetic particle instabilities in future buning plasma devices

	AE physics	Fast Ion Transport	Application
2007	Stability vs beam injection direction	Measure fast ion profile during AEs (MDC-11)	Effect on sawtooth stability
2008	Structure of high-n AEs	Benchmark models of fast-ion transport by AEs (Milestone #174)	Control sawtooth stability
2009	Benchmark non-linear calculations	Determine phase space for fast-ion interaction with AEs	

Divertor Research Supports Advanced Tokamak, ITER, and Basic Physics Programs

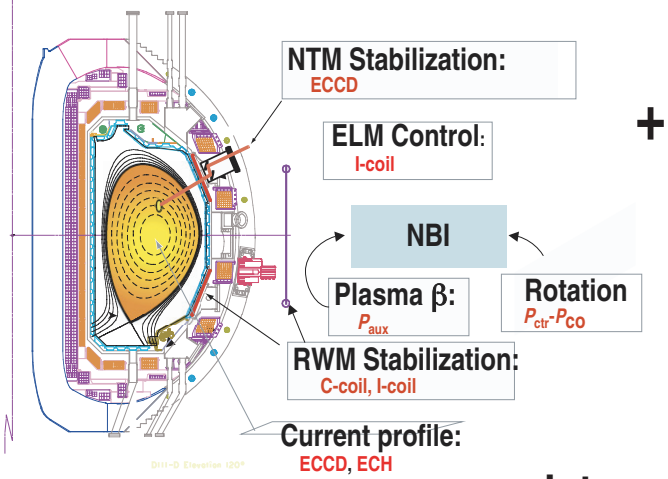
Develop basic understanding and advanced techniques for controlling particle and heat exhaust

	Particle Control	Heat Flux Control	SOL Transport	Plasma Surface Interaction
2007	Optimize density control in double null	Radiative divertor hybrid plasmas	^{13}C Transport (DSOL-9)	Chemical sputtering (DSOL-2)
2008	Effect of dome on detachment	Feedback control of radiative divertor	Poloidal dependence of transport (DSOL-6)	Possible O_2 bake (DSOL-12) for tritium control (Milestone #173)
2009		Radiative divertor in ELM suppressed plasmas	Plasma and impurity flows	

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

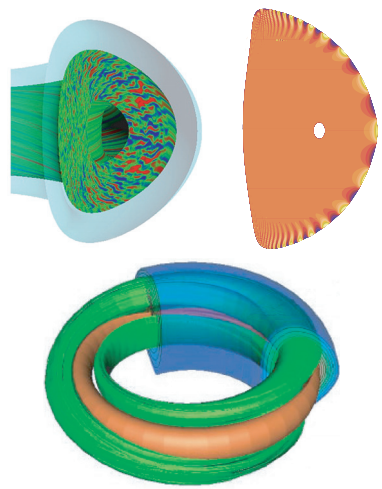
Extensive Plasma Control Tools

Real Time Control (Actuator)



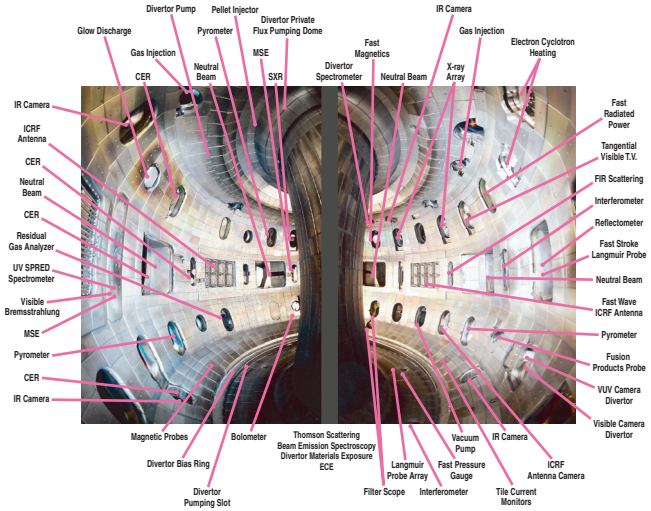
+

State-of-the-Art Predictive Codes



+

Comprehensive Diagnostics



+

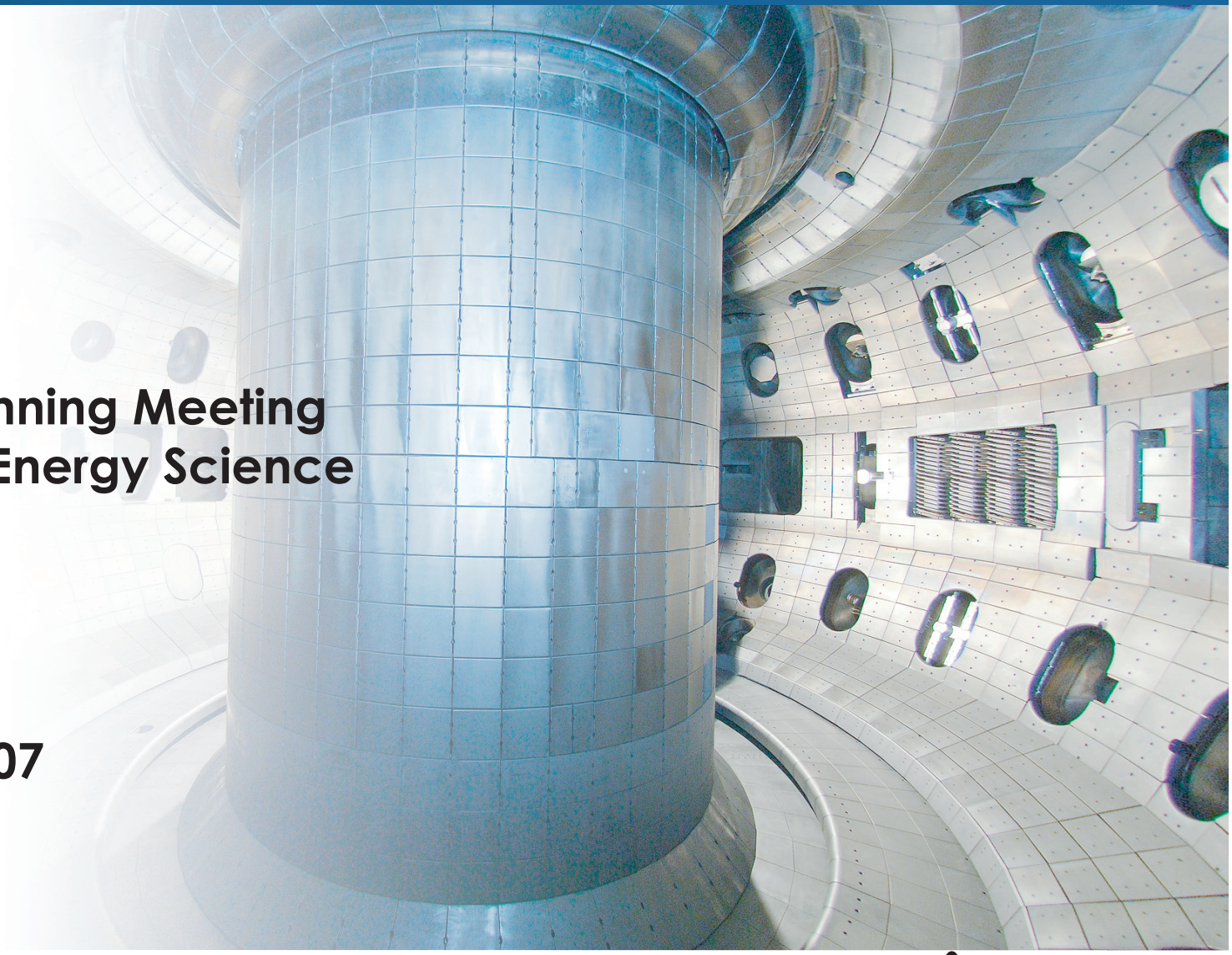
International Research Team

=

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

University Research at DIII–D



by
G.R. McKee

Presented at
FY09 Budget Planning Meeting
Office of Fusion Energy Science
Washington, DC

March 13-14, 2007

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

THE UNIVERSITY of WISCONSIN MADISON

038-07/GRM/rs

DIII–D is a Large, International Program

Active Collaborations 2006

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)

Major University Programs on DIII–D

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)

Major University Programs on DIII–D

• Columbia U.	Resistive wall mode research, AT/High-β
• Georgia Tech	Pedestal and edge physics
• MIT	Phase contrast imaging diagnostic
• Lehigh	Transport studies
• UC-Irvine	Energetic particle physics
• UCLA	Turbulence measurements, transport
• UCSD	Edge turbulence, disruptions, ELM control
• U. Maryland	EC diagnostics
• U. Texas	ECE measurements, confinement physics
• U. Toronto	Divertor physics
• U. Wisconsin	BES, turbulence and transport, MHD, Divertor/PFC

Major University Programs on DIII–D

• Columbia U.	Resistive wall mode research, AT/High-β
• Georgia Tech	Pedestal and edge physics
• MIT	Phase contrast imaging diagnostic
• Lehigh	Transport studies
• UC-Irvine	Energetic particle physics
• UCLA	Turbulence measurements, transport
• UCSD	Edge turbulence, disruptions, ELM control
• U. Maryland	EC diagnostics
• U. Texas	ECE measurements, confinement physics
• U. Toronto	Divertor physics
• U. Wisconsin	BES, turbulence and transport, MHD, Divertor/PFC

University of Wisconsin Research at DIII–D Addresses Several Topical Science Areas

Diagnostic Development for Turbulence Studies

- Beam Emission Spectroscopy
- Data Analysis
- Turbulence experiments

MHD/Transport Theory
(J. Callen, C. Hegna)

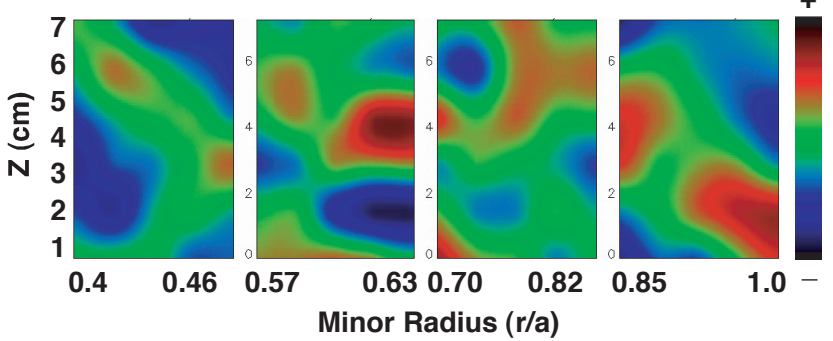
- Paleoclassical Transport
  - Electron heat transport
  - Pedestal T_e model
- Error field effects
  - Mode-locking thresholds

Divertor/ Plasma Facing Components

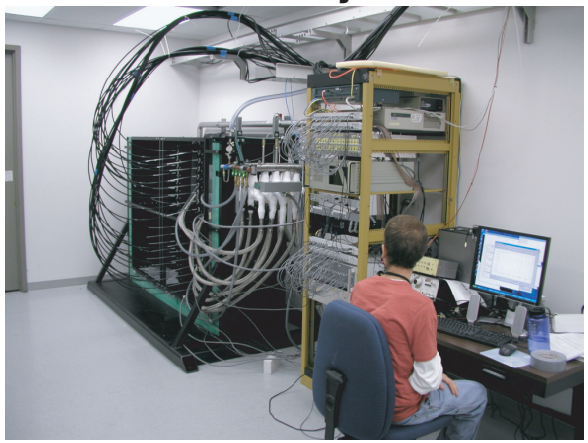
- Particle-Induced Gamma-ray Emission Analysis of Carbon Tile PFC
- Quartz Micro Balance diagnostic

UW Has Developed an Advanced Turbulence Imaging Diagnostic System at DIII-D

Beam Emission Spectroscopy probes spatio-temporal dynamics of long-wavelength turbulence

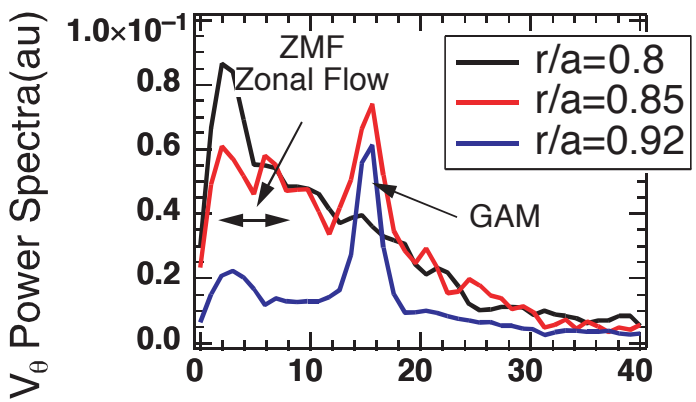


BES Laboratory at DIII-D



- 3 graduate students
- 2 post-doctorates

Zonal Flow Measurement



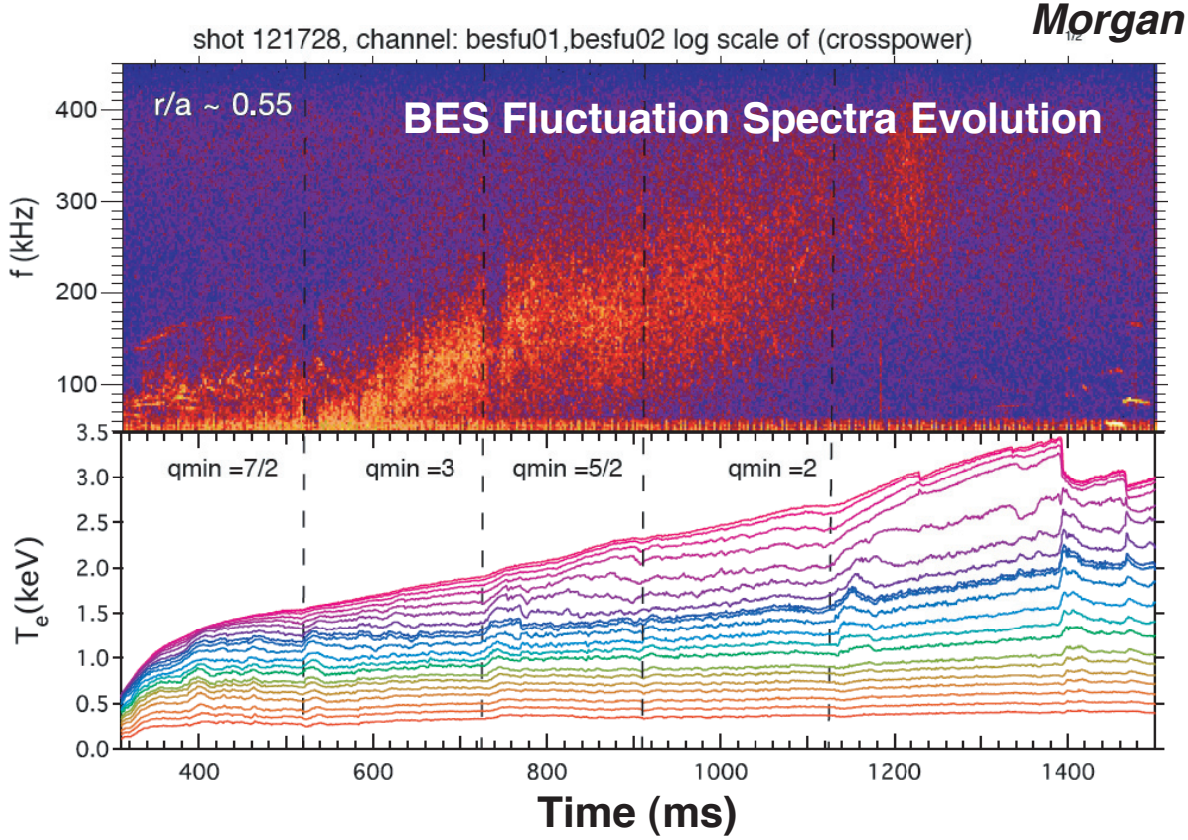
(Supported through Diagnostic Development Grant)

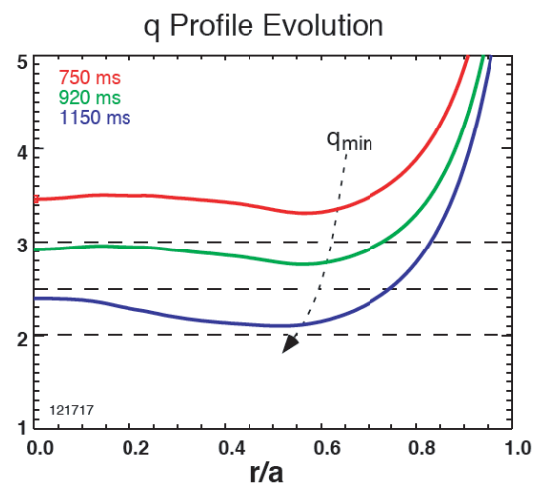
D. Gupta, et al., Physical Review Letters 97, 125003 (2006)

G. Mckee, et al., IAEA, Chengdu (2006)

Graduate Student Thesis Research: Turbulence and Zonal Flow Dynamics During ITB Formation

Morgan Shafer, Ph.D student, UW





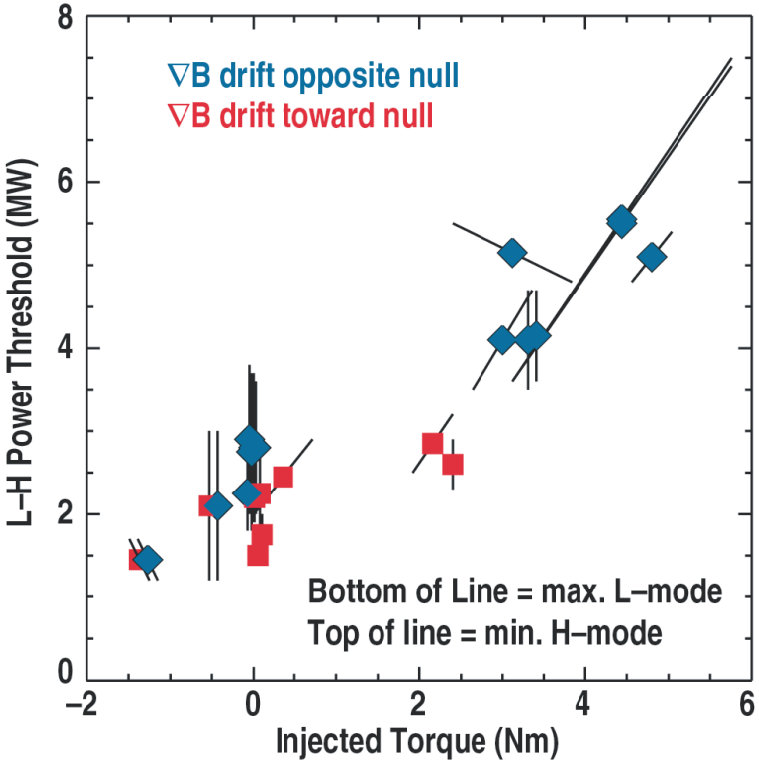
M. Austin, et al., Phys. Plasmas 13, 082502 (2006)

U. Texas, GA Wisconsin

- **Turbulence transiently reduced during q_{min} appearance**
- **GYRO predicts increased zonal flows near low-order rational q_{min} may trigger ITB** *(Waltz et al., Phys. Plasmas (2006))*
- **Challenge this prediction with BES measurements**

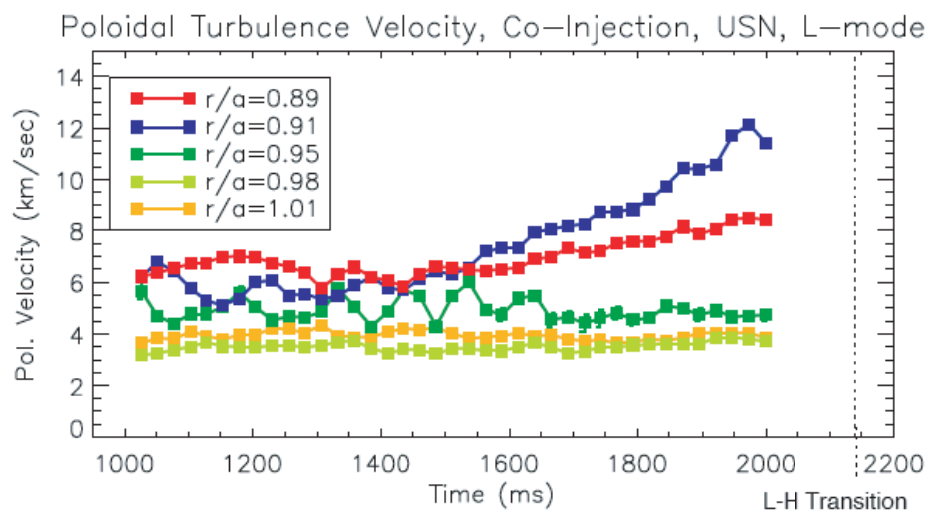
Graduate Student Research Project II: How Do Turbulence and Shear Flows Interact at LH Transition?

D. Schlossberg, Ph.D Student, UW



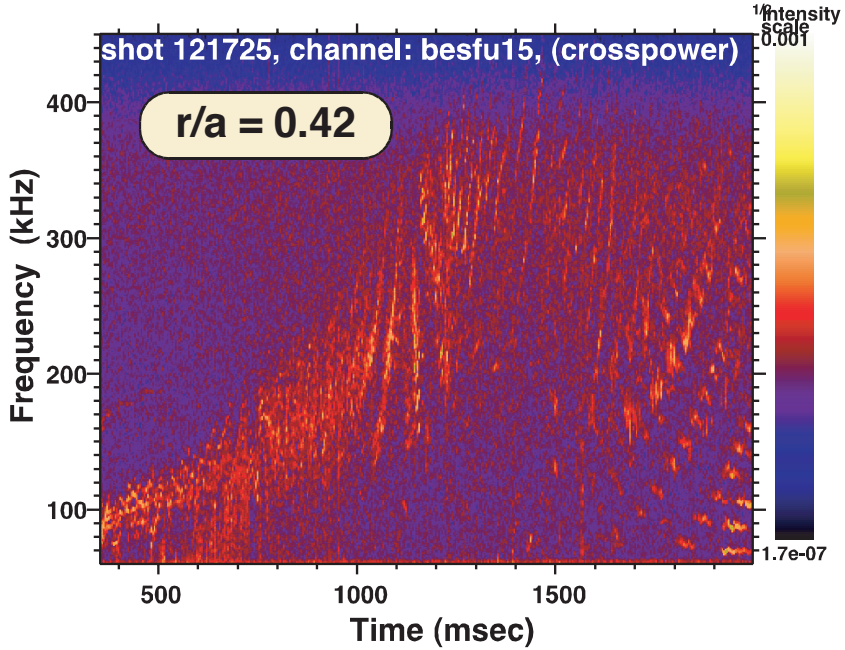
- **Student led an experiment to examine LH transition physics**
- **Discovered strong dependence of LH power threshold on rotation**
  - Understanding of this has potential beneficial implications for ITER

Gradual evolution of poloidal turbulence flows prior to LH transiton



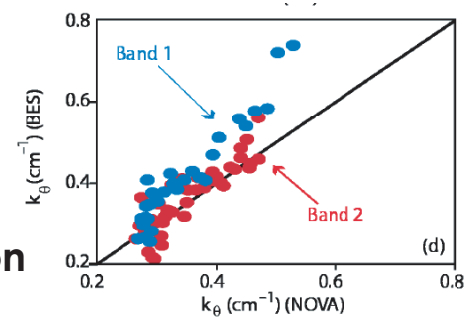
Multi-Institutional Collaboration at DIII–D Provides Opportunities For New Scientific Discoveries

- BES revealed localized Reversed-Shear Alfvén Eigenmode structure

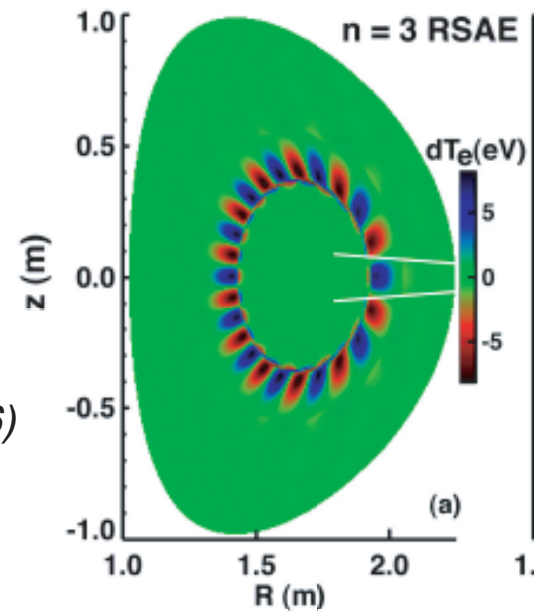


Compare with simulation

Poloidal Wavenumber



NOVA-K



References:

R. Nazikian et al., Phys. Rev. Lett. 96, 105006 (2006)
M. VanZeeland et al., Phys. Rev. Lett. 97, 135001 (2006)
W. Heidbrink, Proc. IAEA-FEC, Chengdu (2006)

THE UNIVERSITY of WISCONSIN MADISON · PPPL PRINCETON PLASMA PHYSICS LABORATORY · GENERAL ATOMICS · UCI

Inter-Institutional Collaborations Fostered by DIII–D National Fusion Facility

- **U. Wisconsin program has developed associated collaborations with:**
  - UCSD (C. Holland, G. Tynan): Nonlinear studies of turbulence and zonal flow interaction; GYRO V&V (APS Invited Talk 2006, C. Holland)
  - GA Theory group (Waltz, Candy): GYRO V&V, ρ^* scaling, q-triggered ITB
  - UCLA: Turbulence studies, experimental coordination
  - U. Texas - Austin (M. Austin, R. Bravenec): q_{min} ITB, synthetic diagnostics
  - PPPL, GA, UC-Irvine: Alfven Eigenmode studies
  - PPPL: expansion and reconfiguration of BES

- **Common aspect of collaborative research programs**

Opportunities for Increased Scientific Productivity Between Research Facilities and University Collaborations

- **Complementary goals arise between academia and laboratory facilities**
  - University student theses require investigation into fundamental research
  - Laboratories looking for cutting-edge results, contributions to experiments

- **Can achieve greater exploitation of research operations time, diagnostics, data**
  - Optimal program structure would have critical mass of researchers in home and laboratory institutions

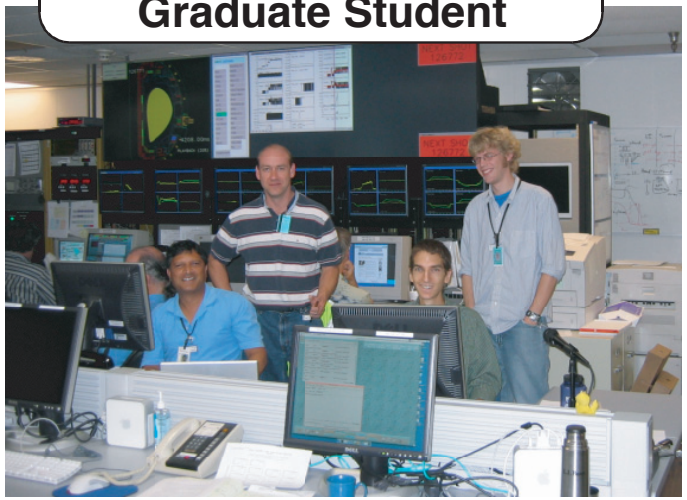
- **Diagnostic development programs are excellent entry point (3 programs at DIII-D)**
  - Targeted research in line with university mission, exploit university expertise
  - Significant overhead for student travel
  - Called upon to support wide variety of research programs
  - Requires a more effective development path to establish a scientifically coherent program

- **University collaborations should be well-aligned with campus research**
  - May require additional support to leverage strengths of university and labs

DIII–D's Scientific Productivity Could Support More Ph.D. Theses and Entry Post-Doc Research

- **Historically – 65 universities from 28 states**
- **23 U.S. universities participate in DIII–D now**
- **DIII–D has trained**
  - 36 graduate students
  - 32 post doctoral researchers
- **17 current Ph.D thesis students**

DIII-D Experiment Led by Graduate Student



- **Post-Doc's work led to significant contributions to DIII–D research**
  - E. Belli (ORISE), edge gyrokinetic simulations
  - C. Holcomb (LLNL), MSE
  - I. Joseph (UCSD), RMP ELM control
  - D. Ponce (ORISE/GA), Thomson Scattering
  - H. Schmitz (FZ Julich), DiMES camera
  - F. Volpe (GA), magnetic island structure
- **Often leading to scientific staff positions**

- **DIII–D can train more young researchers for ITER and the fusion program**
  - An incremental budget request is made for 3 additional postdocs

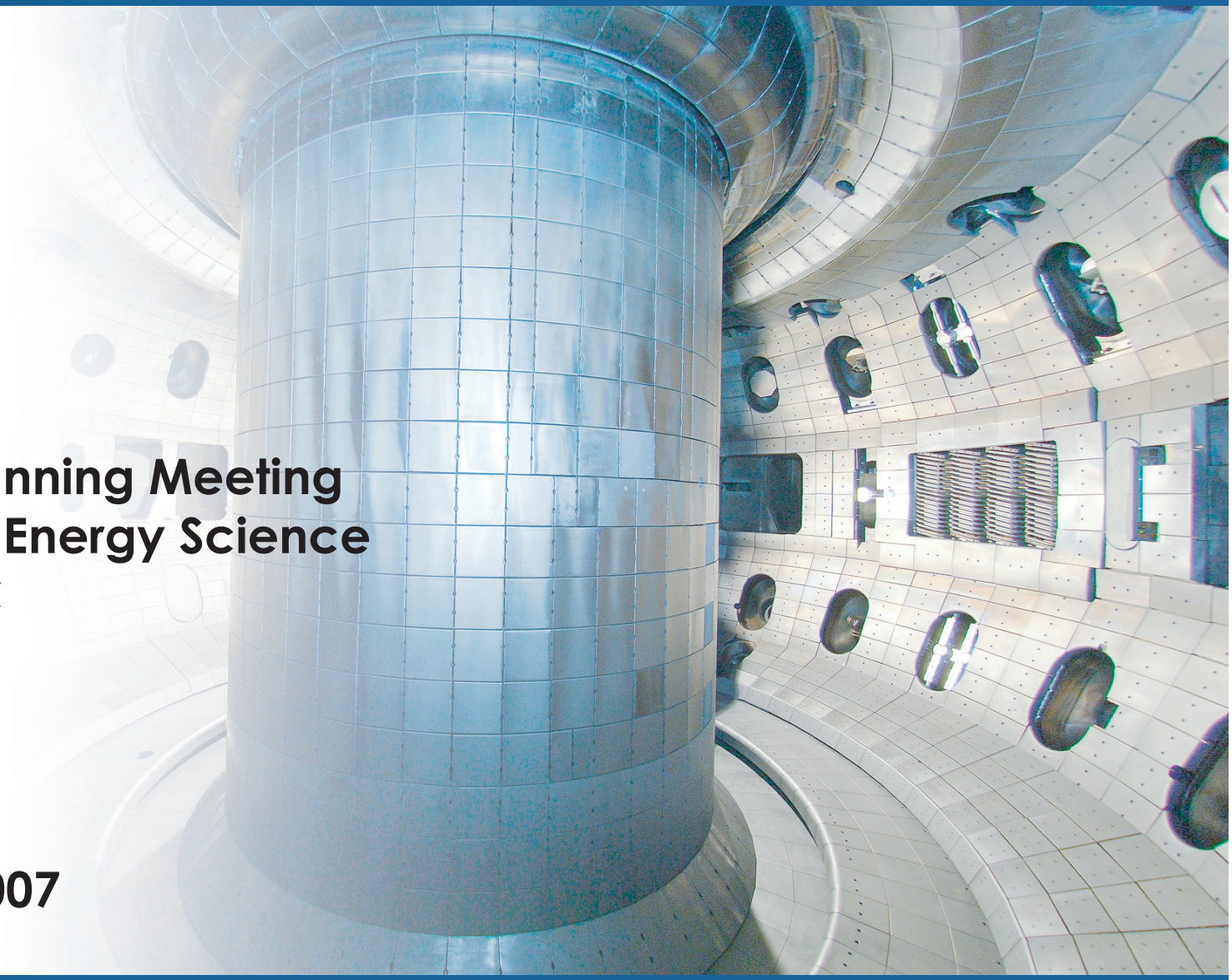
Current Ph.D Thesis Students on DIII–D

1. **A. McLean** - U. Toronto – Plasma Surface Interactions, Chemical Sputtering
2. **J. Dorris** – MIT – Phase Contrast Imaging
3. **N. Antoniuk-Pablant** – UCSD – Spectroscopy of Dalpha region for main ion T_i and internal B field
4. **Y. Luo** – UCI - Measurement of fast ion profiles using D-alpha spectra
5. **R. Rubilar** - Georgia Tech - Radiation modeling
6. **D. Schlossberg** - Wisconsin - Turbulence Velocity and Heat Flux Dynamics near the LH Transition
7. **M. Shafer** – Wisconsin – Nonlinear Turbulence Dynamics during Internal Transport Barrier Formation
8. **Z. Friis** – Georgia Tech – Thermal Instabilities in Tokamaks
9. **S. Harrison** – Wisconsin – Plasma Surface Interaction Diagnostics
10. **Y-S Park** – Seoul National University – Neoclassical Tearing Mode Detection and Control
11. **S. Mordjick** - UCSD - 2D modeling of edge transport
12. **A. White** – UCLA - Electron temperature fluctuation measurements on DIII–D via correlation ECE
13. **A. James** - UCSD - γ-ray spectroscopy of disruptions
14. **E. Nardon** - CEA - ELM Control by Stochastic Edge Fields
15. **D. Elder** - U. Toronto - OEDGE modeling of the DIII–D ^{13}C methane experiments
16. **Y. Mu** - U. Toronto - OEDGE modeling of DIII–D DiMES experiments
17. **M. Lanctot** - Columbia - Advanced Algorithms for RWM Feedback Control

DIII-D Provides Excellent Research Opportunities for Universities

- **World-class research facility that remains on the cutting edge of fusion energy sciences, AT development and ITER-relevant research**
  – Experimental facilities that are not available in most campus environments
- **Widely available program support to integrate university programs**
- **Scientifically stimulating and welcoming environment**
- **Collaborators well integrated into the experimental planning campaign**
  – Students participate in and lead experiments
  – Active program in basic fusion energy sciences
- **Growing number of graduate students and postdoctoral researchers**
- **Opportunities to increase scientific productivity and further university missions**

DIII–D Program (Budget and Schedules)



by
T.S. Taylor

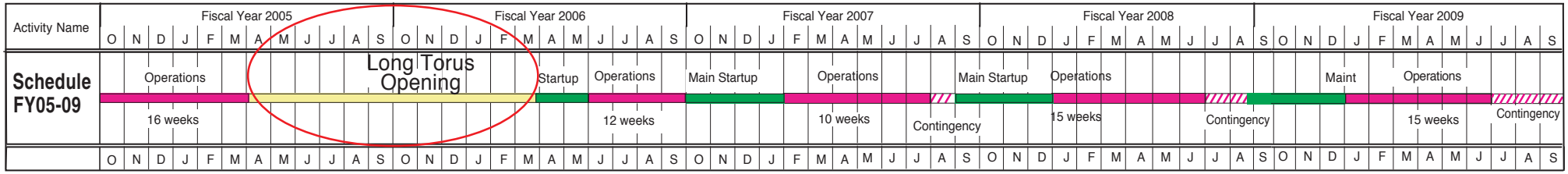
Presented at
FY09 Budget Planning Meeting
Office of Fusion Energy Science
Washington, DC

March 13-14, 2007

DIII-D Research Program is Leveraging New Capabilities Provided by the Long Torus Opening

- **LTOA completed in 2006 followed by 12.6 weeks of operation**

DIII–D Facility Schedules (05–09)

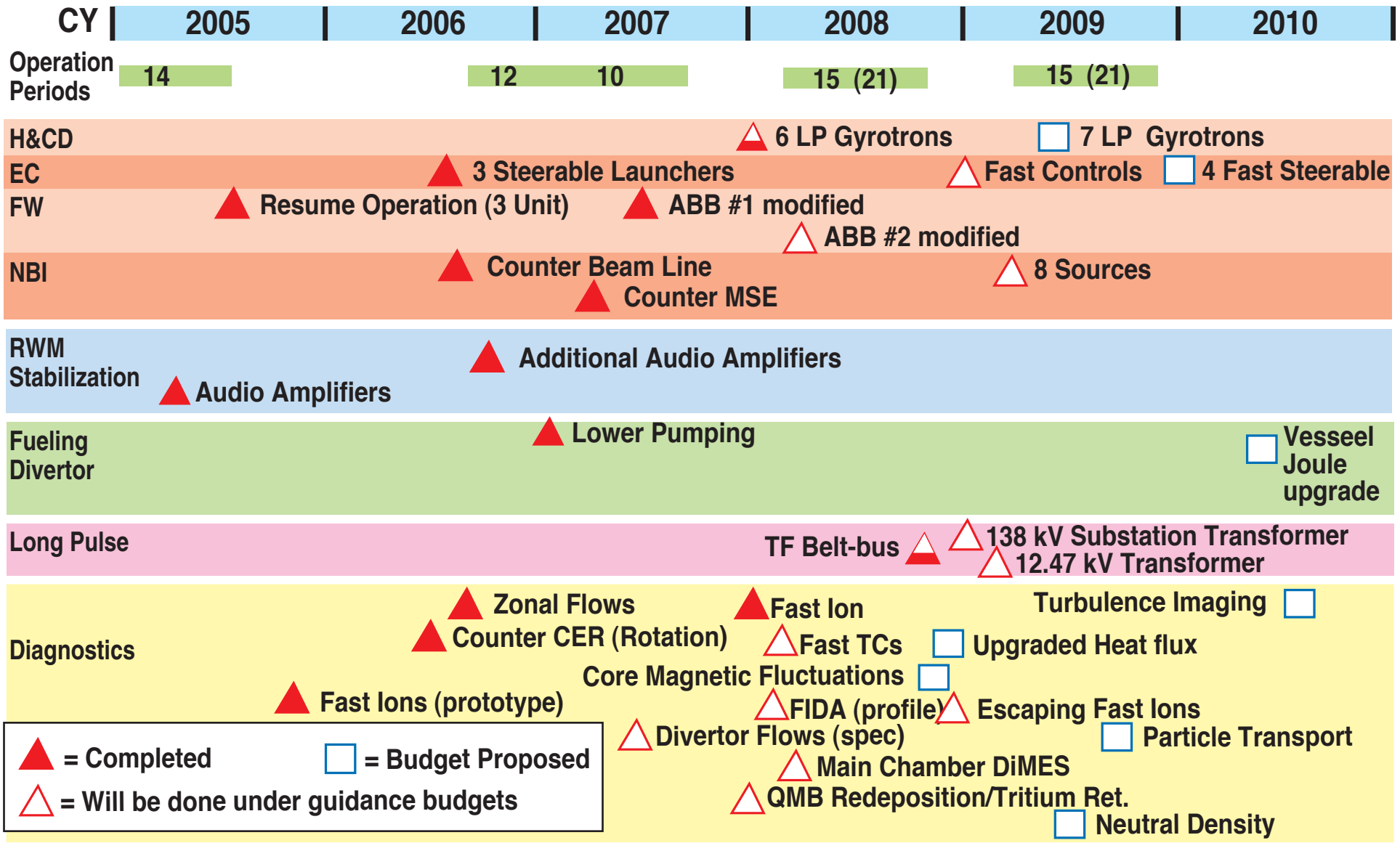


- **"The LTOA represented a significant long-term risk and committment by the DIII-D group and they are commended for successfully carrying out this activity while maintaining a vigorous research program." "a gutsy and wise decision" (Mid-Term Review of Major MFE Facilities)**

- **"The LTOA is an unqualified success and the PAC congratulates the DIII-D Team for boldly planning and executing its implementation and for the outstanding scientific results already obtained in the first operating campaign" (2007 DIII-D PAC)**

- **Now carrying out experiments to further extend these results**
  - 10 weeks planned in 2007

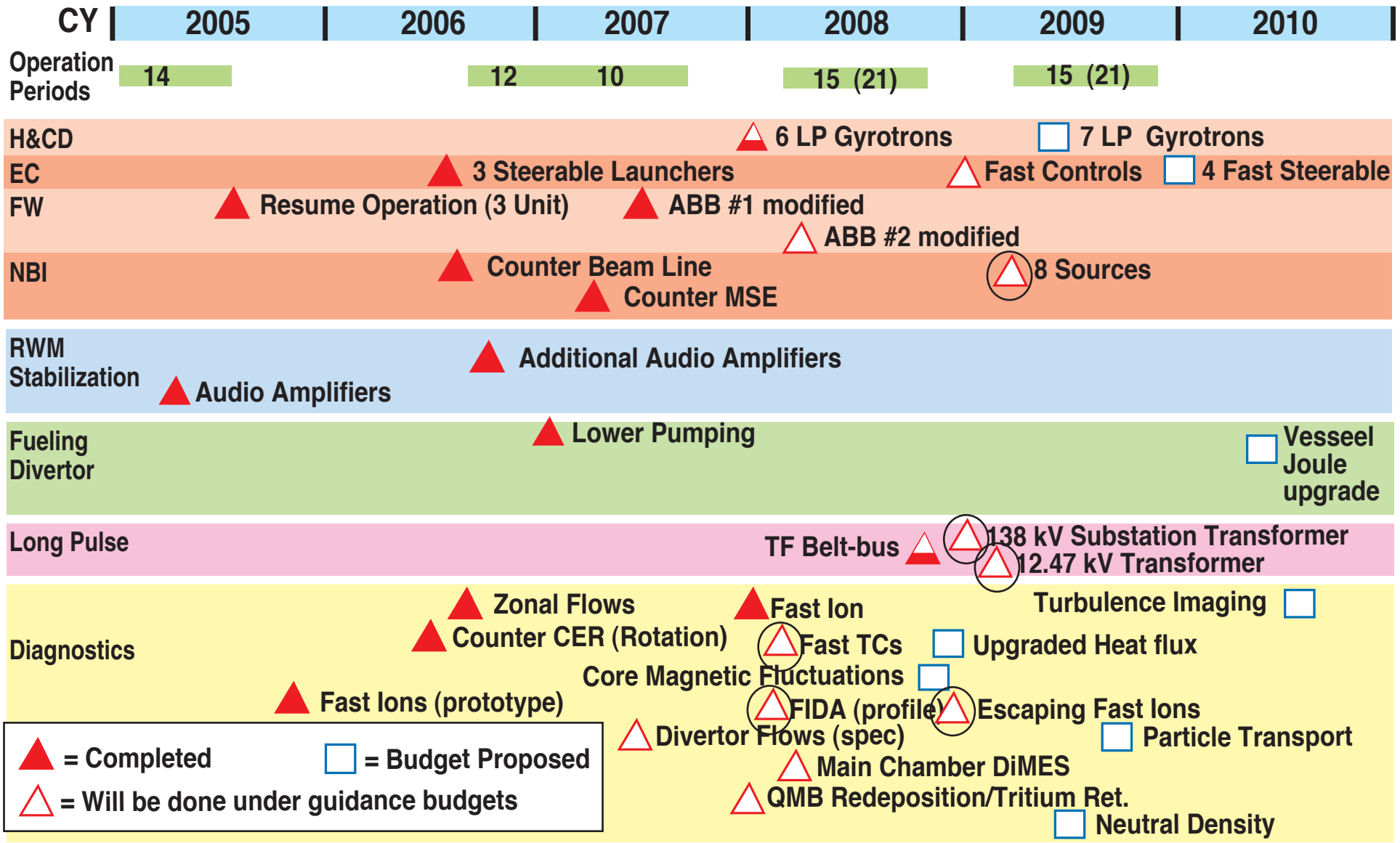
The DIII–D Facility Capabilities Plan



DIII–D NATIONAL FUSION FACILITY

038-07/DH/jy

The DIII–D Facility Capabilities Plan



DIII–D NATIONAL FUSION FACILITY

038-07/DH/jy

Refurbishments Included in the FY08-FY09 Guidance Budget

- **Restore 8 NBI source operation**
- **2nd ABB fast wave tube**
- **Power system infrastructure: 138 kV transformer**
- **Fast steerable EC launcher**
- **Rebuild auto transformer (PPPL)**
- **Data system: CAMAC → PC-based DACQ**
- **Diagnostics**
  - Thomson lasers and electronics
  - Upgrade fast ion D_α (profile)
  - Divertor fast thermocouples
  - Repair QMB
  - Upgrade BES to 48 channels

FY07 Research Goals

10 weeks of operation

- **Milestone 163 — Assess the synergistic effect of plasma rotation and feedback control on plasma instabilities**
  - Determine feedback requirements for RWM stabilization as plasma rotation is systematically decreased
- **Milestone 164 — Quiescent H-mode experiments with co- plus counter-injection**
  - Utilize neutral beam torque control to assess role of rotation in obtaining QH-mode plasmas

FY08 Research Goals

15 weeks of operation

- Milestone 165 — Evaluate the use of non-axisymmetric magnetic fields for ELM control in ITER relevant plasmas
- Milestone 166 — Assess the compatibility of ITER startup with access to advanced operating regimes
- Milestone 167 — Separating the role of plasma rotation and magnetic shear in the stabilization of turbulence

21 weeks of operation (incremental)

- Milestone 168 — Compare disruption mitigation by high-pressure gas injection with theoretical predictions
- Milestone 169 — Assessment of the optimum current profile for steady-state operation

FY08 DOE Joule Milestone

Conduct experiments on major fusion facilities leading toward the predictive capability for burning plasmas and configuration optimization. In FY2008, FES will evaluate the generation of plasma rotation and momentum transport, and assess the impact of plasma rotation on stability and confinement. Alcator C-Mod will investigate rotation without external momentum input, NSTX will examine very high rotation speeds and DIII-D will vary rotation speeds with neutral beams. The results achieved at the major facilities will provide important new data for estimating the magnitude of and assessing the impact of rotation on ITER plasmas

- **DIII-D contributions**
  - RWM stabilization at low rotation
  - NTM threshold vs rotation
  - L-H transition vs rotation
  - ExB shear stabilization of turbulence
  - RMP penetration vs rotation
  - Intrinsic rotation
  - Pedestal height/characterization vs rotation

FY09 Research Goals

15 weeks of operation

- Milestone 170 — Evaluate modulated electron cyclotron current drive for stabilizing neoclassical tearing mode
- Milestone 171 — Evaluate the impact of ITER-like conditions (low rotation, $T_e \approx T_i$) on transport in improved performance plasmas
- Milestone 172 — Compare variations in pedestal structure and turbulence characteristics with TGLF predictions

21 weeks of operation (incremental)

- Milestone 173 — Assessment of ITER tritium inventory with carbon in-vessel components: control and removal of carbon (tritium) inventory in co-deposited layers
- Milestone 174 — Compare measured fast ion transport by Alfvén eigenmodes to theoretical models

DIII–D National Fusion Program Budgets

	FY07	FY08	FY08(I)	FY09	FY09(I)
BUDGET ($000)	$56,027	$59,669	$7,016	$60,863	$8,331
SCIENCE	$24,961	$26,058	$3,325	$26,357	$3,100
OPERATIONS	$31,066	$33,611	$3,691	$34,506	$5,231
STAFFING (FTE)	167.4	172.1	13.4	170.0	14.0
SCIENCE	77.5	78.3	9.6	77.0	10.4
OPERATIONS	89.9	93.8	3.8	93.0	3.6
RUN WEEKS	10	15	+6 (21)	15	+6 (21)

Full Utilization of the DIII-D Facility Provides 25 Weeks of Operation

	FY07	FY08	FY08(I)	FY08 FULL UTILIZATION	FY09	FY09(I)	FY09 FULL UTILIZATION
BUDGET ($000)	$56,027	$59,669	$7,016	$8,836	$60,863	$8,331	$10,151
SCIENCE	$24,961	$26,058	$3,325	$3,992	$26,357	$3,100	$3,767
OPERATIONS	$31,066	$33,611	$3,691	$4,844	$34,506	$5,231	$6,384
STAFFING (FTE)	167.4	172.1	13.4	17.4	170.0	14.0	18.0
SCIENCE	77.5	78.3	9.6	11.6	77.0	10.4	12.4
OPERATIONS	89.9	93.8	3.8	5.8	93.0	3.6	5.6
RUN WEEKS	10	15	+6 (21)	+10 (25)	15	+6 (21)	+10 (25)

DIII–D National Fusion Program Funding by Institution ($000)

	FY07	FY08	FY08(I)	FY09	FY09(I)
DIII-D PROGRAM	$56,027	$59,669	$7,016	$ 60,863	$8,331
GA	**$44,100**	**$46,967**	**$5,366**	**$47,916**	**$6,706**
GA CONTRACT SUPPORTED	**$2,308**	**$2,325**	**$0**	**$2,342**	**$0**
UCLA	$480	$480		$480	
U. MARYLAND	$27	$27		$27	
U. IRVINE	$113	$113	$814	$113	TOTAL
U. TORONTO	$117	$117		$117	
OTHER GA SUBCONTRACTS	$77	$77		$77	
GA COLLABORATOR SUPPORT	$1,494	$1,511		$1,528	
DOE DIRECT SUPPORTED	**$11,927**	**$12,693**	**$1,650**	**$12,947**	**$1,625**
PPPL	$4,214	$4,330	$500	$4,416	$700
LLNL	$3,132	$3,420	$250	$3,488	$250
ORNL	$2,541	$2,610	$525	$2,662	$525
UCSD	$810	$832		$849	
U. TEXAS	$425	$437		$446	
COLUMBIA	$325	$375		$383	
SNL	$190	$215	$375	$219	$150
U. WISCONSIN	$160	$340		$347	
GEORGIA TECH	$130	$134		$137	
RUN WEEKS	10	15	+6 (21)	15	+6 (21)

DIII–D NATIONAL FUSION FACILITY

038-07/TST/wj

DIII–D National Fusion Program Staffing by Institution (FTEs)

	FY07	FY08	FY08(I)	FY09	FY09(I)
DIII-D PROGRAM	167.4	171.1	13.4	170.0	14.0
GA	**123.2**	**126.1**	**8.9**	**124.6**	**8.7**
GA CONTRACT SUPPORTED	**4.6**	**4.6**	**0.0**	**4.6**	**0.0**
UCLA	3.3	3.3		3.3	
U. MARYLAND	0.1	0.1		0.1	
U. IRVINE	0.7	0.7		0.7	
U. TORONTO	0.4	0.4		0.4	
OTHER GA SUBCONTRACTS	0.1	0.1		0.1	
DOE DIRECT SUPPORTED	**39.6**	**40.4**	**4.5**	**40.8**	**5.3**
PPPL	11.9	8.4		9.4	
LLNL	8.5	9.3	2.2	8.7	3.0
ORNL	7.3	8.6	1.3	8.6	1.3
UCSD	4.7	4.8		4.8	
U. TEXAS	1.9	2.0		2.0	
COLUMBIA	2.3	2.6		2.6	
SNL	1.0	1.1	1.0	1.1	1.0
U. WISCONSIN	1.4	3.0		3.0	
GEORGIA TECH	0.6	0.6		0.6	
RUN WEEKS	10	15	+6 (21)	15	+6 (21)

DIII–D National Fusion Program

	FY07	FY08 GUIDANCE	FY09 -10%	FY09 GUIDANCE	FY09 INCREMENTAL
BUDGET ($OOO)	$56,027	$59,669	$54,777	$60,863	$69,194
SCIENCE	$24,961	$26,058	$23,722	$26,357	$29,457
OPERATIONS	$31,066	$33,611	$31,055	$34,505	$39,737
STAFFING (FTEs)	167.4	172.1	158.0	170.0	184.0
SCIENCE	77.5	78.3	69.3	77.0	87.5
OPERATIONS	89.9	93.8	89.0	93.0	96.5
RUN WEEKS	10	15	7	15	21

Impact of 10% Budget Cut in the DIII-D National Fusion Program FY08/09

In FY08, the following actions would be taken in the order listed

1. Delay EIMAC tube replacement for fast wave
2. Delay long-pulse transformer connection
3. Delay refurbishment of data system (CAMAC)
4. Delay rebuild of auto-transformer (PPPL)
5. Delay 8th NBI source
6. Replace run-time from 15 to 7 weeks
7. Reduce staff ~12 FTE — GA (8)

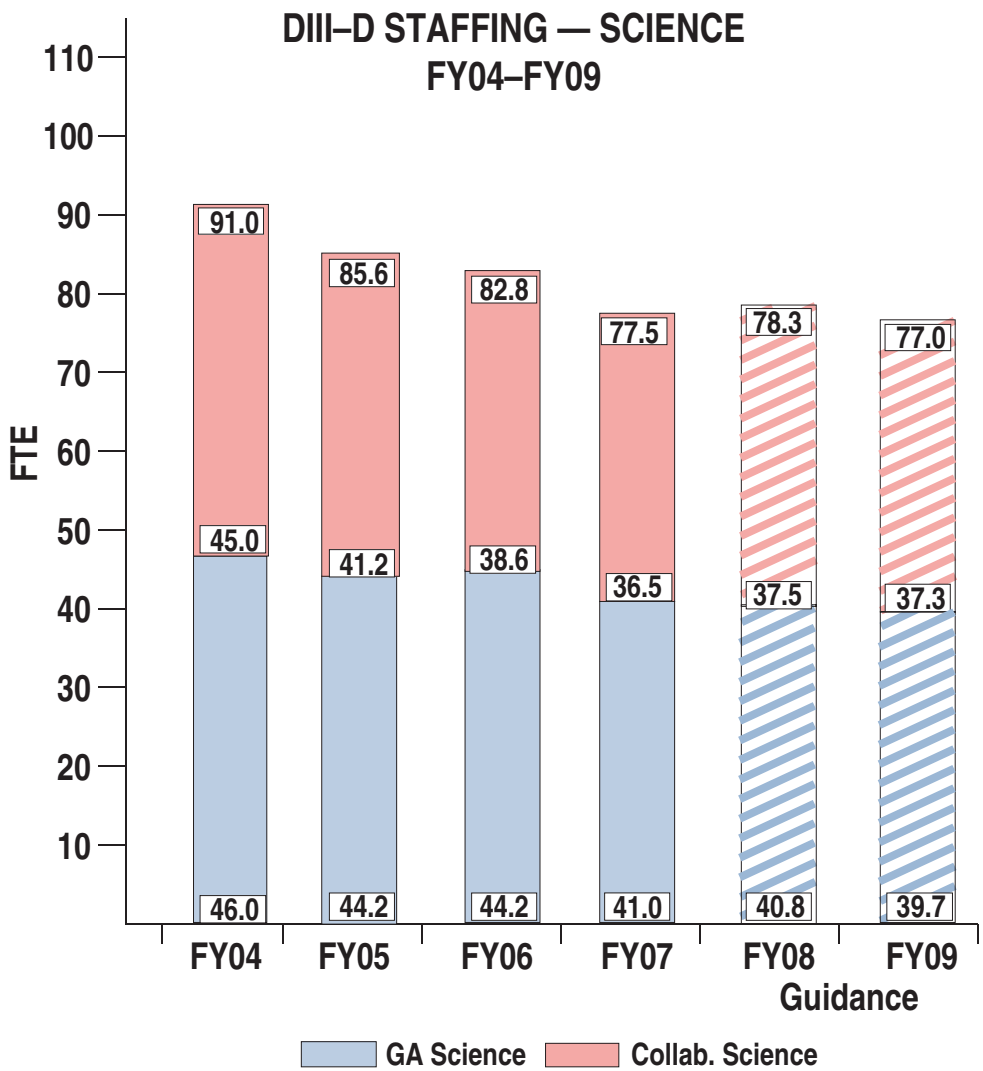
In FY09, the following actions would be taken in the order listed

1. Delay long-pulse transformer connection
2. Delay refurbishments to Thomson scattering system
3. Delay 8th NBI source
4. Reduce run-time from 15 to 7 weeks
5. Reduce staff ~12 FTE — GA (8)

Summary of DIII–D Program Incremental Budget Requests

	FY08		FY09	
Increased Operating Time	**$2,791K** (To 21 Weeks)		**$2,831K** (To 21 Weeks)	
Facility Operations	GA	$1,791K	GA	$1,831K
Science Research	GA	$1,000K	GA	$1,000K
Restore Scientific Staff	**$1,,300K**		**$1,,300K**	
	GA	$1,000K	GA	$1,000K
	ORNL	$100K	ORNL	$100K
	LLN L	$50K	LLN L	$50K
	SNLA	$150K	SNLA	$150K
Add Students/Postdocs	**$500K**		**$500K**	
	GA (5)	$500K	GA (5)	$500K
Neutral Beam Systems	**$400K**		**$0K**	
Restore 8 Source Operations	GA	$400K		
ECH	**$110K**		**$2,150K**	
Upgrade Gyrotron Socket	GA	$110K		
Installation of 7th Socket			GA	$850K
Procure 8th Gyrotron			GA	$1,000K
Long Pulse ECH Launcher for Gyrotrons 7 and 8			PPPL	$300K
Fast Wave	**$500K**		**$500K**	
Increased Operations Support	PPPL	$250K	PPPL	$250K
	ORNL	$250K	ORNL	$250K
Pellet Fueling and Disruption Mitigation	**$175K**		**$175K**	
Mitigation Pipe Gun	ORNL	$100K	ORNL	$100K
Restore Full Support for Pellet Fueling	ORNL	$75K	ORNL	$75K
Diagnostic Refurbishments/Upgrades	**$1,240K**		**$875K**	
CAMAC Replacement	GA	$250K	GA	$250K
Replacement of Thomson Lasers	GA	$110K	GA	$110K
CER Cameras	GA	$80K	GA	$80K
ECE at 2nd Toroidal Location	GA/Texas	$125K		
SXR Tomography Upgrade			GA	$85K
Restore DN Heat Flux Measurements	LLNL	$50K	LLNL	$50K
Fast Measurements of ELM Heat Flux	LLNL	$150K	LLNL	$150K
FI Scintillator Array	PPPL	$250K	PPPL	$150K
Expanded Fixed Probe Array	SNLA	$140K	SNLA	
Refurbish Fixed Probe DAQ	SNLA	$85K	SNLA	
Totals	**$7,016K**		**$8,331K**	

Rebuilding Scientific Staff is Critical to Support a Vital Research Program

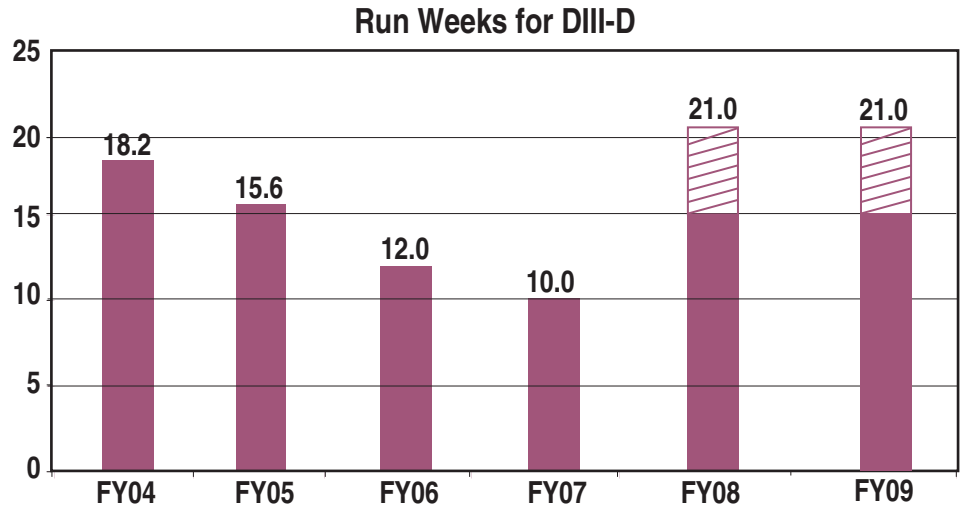


- **Decrease in scientific staff**
  - 13 over last 3 years
- **Restore scientific staff**
  - In depth analysis
  - Theory and model validation
  - Diagnostic developments
  - State-of-the-art plasma control
  - Train scientists for ITER

Increased Runtime Would Allow More Excellent Experiments to be Completed

Area	Proposals Received	Unique Proposals	Proposals in 22 week plan (06/07)	Scheduled (%)
Stability	70	64	8	12.5
Confinement	93	83	12	14.5
Heating and Current Drive	50	40	3	7.5
Boundary	60	60	9	15
Advanced Scenarios	59	37	17	32
ITER Hybrid Scenarios	47	37	8	22
Pedestal Width Physics	29	22	2	9
RWM Control for ITER	56	40	19	45
NTM Control for ITER	13	7	3.5	50
ELM Control for ITER	109	94	12	13
Total Proposals	586	484	93.5	19

- DIII-D PAC: "We strongly believe the planned 10 weeks of operation is far short (by perhaps a factor of 2) of what would allow optimum exploitation of this world class facility."



- DIII-D program is very appreciative of the proposed increase in runtime for FY08 and FY09

DIII-D: A World Class Program Committed to the Success of ITER and Advancing the Science of Fusion Energy

- **DIII-D has a demonstrated record of outstanding performance**
  - Reliable, safe, productive operation of a major U.S. scientific facility
  - Record of important, relevant research for fusion energy
  - Very successful large national and international research team
  - Bold, innovative management: successful implementation of facility upgrades enables new science

- **Budget requests provide balanced investments in**
  - Facility
  - People
  - Run time

⇒ **Continued investment in the DIII-D program is essential to ensure the U.S. position as a world leader in fusion energy research**