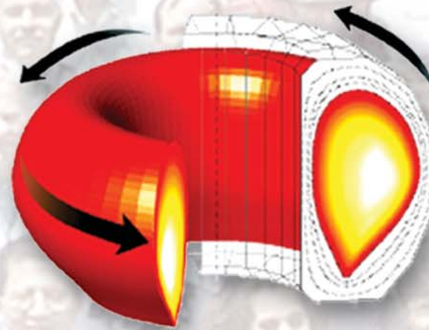
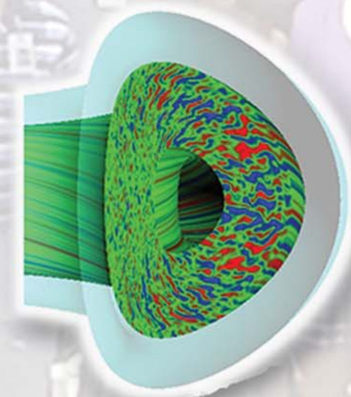
Review of Previous PAC Recommendations and Program Overview

by
T.S. Taylor



Presented to
DIII–D Program
Advisory Committee



January 31– February 2, 2006

Outline

- **Review of 2005 DIII–D PAC conclusions and recommendations**
  - The DIII–D program appreciates comments and advice and is responsive to PAC's recommendations

- **Overview of DIII–D program plans**
  - Broad community participation in the DIII–D program planning and execution supports a vigorous DIII–D research program
  - The DIII–D program plan takes advantage of new capabilities provided by Long Torus Opening Activity (LTOA)
  - The DIII–D program elements are focused on supporting ITER research needs

2005 DIII–D PAC Conclusions/Recomendations

- **Endorses the LTOA plan**
  - "Anticipated results from the physics program permitted by these modifications will be valuable to both the design and operation of ITER as well as the development of the physics basis of an attractive reactor"

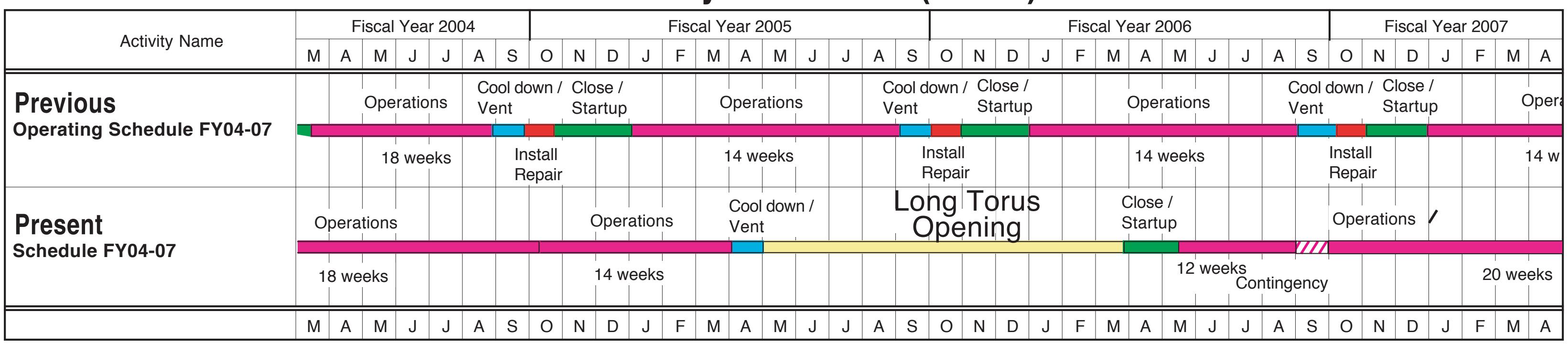
- **DIII–D is clearly a world leader in providing support to the ITER physics design**

We Are Nearing Completion of the Long Torus Opening Activities (LTOA)

— Made possible by an alternate operations schedule —

- **Collects three vent periods (4 months each) into one 12 month torus opening**
- **Enables effective use of existing staff to take on some major upgrades**
- **Preserves run time capability**
  - FY05 (14 weeks)
  - FY06 (12 weeks)
  - FY07 (20 weeks)

DIII–D Facility Schedules (04–07)



- **Anticipate completion of:**
  - ECH- 6 long pulse gyrotrons
  - Rotation of 210 degree beamline to counter
  - Lower divertor modification
  - Cooling water tower replacement
  - MG refurbishment
  - TF belt bus cooling for 10 s ops (partially done)

The PAC Fully Endorses LTOA Plan

- **Agrees first priority should be given to three major elements**
  - Procurement and installation of three additional CPI 1 MW, 10 s gyrotrons
  - Rotation of two-source beamline
  - Lower divertor modification

  Proceeding with these elements as highest priority
  High level DOE milestone for 210 counter beam

- **10 s TF belt bus upgrade**
  - **Proceeding as resources and time allow; ~50% planned work will be completed**

- **FW provides important new tool, but PAC understands the FW upgrade depends on collaborator budgets**
  - **Refurbished 285° antenna (ORNL) and 1 Eimac tube (PPPL) proceeding**
  - **Operations support impacted by budget**

- **It is important not to neglect diagnostic capability**
  - **Many diagnostic improvements undertaken ⇒ consequence of concerted and coordinated effort of collaborators, scientific research staff, and engineering support**

DIII–D is Among the World Leaders in Providing Support to the ITER Physics Basis

- **In general, the comprehensive coverage of tokamak physics in theory and experiment is an outstanding feature of the DIII–D program and is an important element in supporting the ITER physics basis**

- **INTERNATIONAL: The PAC commends the DIII–D team for its strong participation in the ITPA and encourages its continuation**
  Strong ITPA participation remains a priority

  – Encourages DIII–D team to carry out ITER Physics Tasks defined by the ITER-IT
    completing tasks as requested, willing to do more

  – PAC recommends participation in similarity experiments performed in other machines, even with tight budgets
    Significant participation planned, even with highly constrained budgets

DIII–D Researchers are Strongly Engaged in International Tokamak Physics Activity (ITPA)

— 40 team members, 3 international chairs/co-chairs, 8 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	Lehigh
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

Scientific Personnel Exchanges Enhance International Collaborations and Joint Experiments

2004–2005

to DIII–D

Current hole experiments
- E. Solano (CIEMAT)
- N. Hawkes (UKAEA)

Critical T_e gradient
- F. Ryter, A. Manini (MPI)

RWM stabilization
- M. Takechi (JAERI)
- R. Buttery (UKAEA)
- S. Pinches (MPI)

NTM stabilization
- R. Buttery (UKAEA)
- A. Isayama (JAERI)
- Y-S. Park (Seoul National Univ.)
- O. Sauter (CRPP)
- M. Maraschek (MPI)

Edge stochastization
- P. Thomas, M. Becoulet (CEA-Cadarache)
- P. Monier-Garbet (CEA-Cadarache)
- E. Nardon, F. Dubois (CEA-Cadarache)
- J. Harris (ANU, Australia)
- K-H. Finken, M. Lehmen (TEXTOR)
- N. Nishino (Hiroshima Univ.)

Error field effects
- D. Howell (UKAEA)

Current profile measurement control
- R. Giannella (CEA-Cadarache)
- D. Mazon (JET)

Beta scaling of confinement
- D. McDonald (UKAEA)

Hybrid scenarios
- A.C.C. Sips (MPI)
- E. Joffrin (CEA-Cadarache)

EHO identification and QH–mode
- F. Nave (JET)
- Y. Sakamoto (JAERI)
- H. Urano (JAERI)

Disruption mitigation
- D. Howell (UKAEA)

Plasma control system development
- J-Y. Kim (KSTAR)

Pedestal similarity
- A. Kirk (UKAEA)

33 international scientists to DIII–D

from DIII–D

Thomson scattering at JET
- T. Carlstrom
- B. Bray

Remote participation in QH–mode (JT–60U)
- P. Gohil
- L. Lao
- P. West

RWM at JET
- R. La Haye, H. Reimerdes

AT and hybrid scenario (JT–60U)
- M. Wade
- T. Luce
- M. Murakami

Confinement studies (ANU)
- T. Luce

Hybrid scenarios (ASDEX Upgrade)
- M. Wade

Boundary physics (ASDEX Upgrade)
- M. Groth

Error field harmonics (JET)
- T. Scoville

DIII–D Plans to Participate in International Experiments in 2006 (IEA/ITPA Joint Experiments)

JET	Advanced Tokamak Scenario Development	May 06
	NTM Physics	Mar 06
	Hybrid Scenario Development	Mar-Apr 06
	Pedestal Comparison	Jun 06
	Plasma Control	May 06
AUG	Hybrid Scenario Physics	
JT-60U	Advanced Tokamak Scenario Development Effect of Rotation on QH-mode Access	Jun 06
TEXTOR	Ergodic Divertor	
EAST	Plasma Control and Plasma Startup	Jun 06

DIII–D is Among the World Leaders in Providing Support to the ITER Physics Basis

- **ADVANCED SCENARIOS: Development of AT Discharges has high relevance to ITER and provides optimism that ITER may even exceed its goals**
  - Relevance of these scenarios improves with upgraded ECH and FW
    Hybrid Plan T_e/T_i - 1, and V_ϕ - 0 (Petty)
  - Comparisons with similar scenarios in larger machines are important
    Participation in JET and JT-60U experiments planned

- **TRANSPORT: Work on confinement physics is outstanding and has high relevance to ITER**
  - Both experimental and theory work among the best worldwide, including diagnostic capability
    Seminars held to improve theory/experiment coupling (Burrell)
    Strong effort to continue diagnostic improvements; collaborator cooperation and support critical (Boivin)
  - Experiments with low momentum input, both inductive and steady state, are very relevant to ITER
    Are planning; (Burrell, Petty)

DIII–D is Among the World Leaders in Providing Support to the ITER Physics Basis (continued)

- **RWM: audio amplifiers will enhance stabilization capability for RWM**
  - Essential that sufficient audio amplifiers are available to test feedback
    FY06: 6 ⇒12 amplifiers: 12 ⇒ 24 presently limited by funding (Garofalo)
- **Carbon migration is important contribution to the choice of first wall material in ITER**
  - PAC recommends O_2 bake followed by recovery
    DIII–D plan: O_2 bake in lab (Toronto); Option of O_2 bake prior to vent in 2007 (Allen)
- **Disruptions: Characterization of disruptions, their prediction and mitigation continue to be crucial for ITER**
  - More analysis of DIII–D fast current quench needed
    ITPA disruption database
    Continuing DIII–D analysis (Strait)
  - PAC recommends continuing disruption mitigation work via collaborations between C-Mod, JET, JT-60U
    Improved diagnostics and improved gas valve
    Continued collaboration through ITPA and joint research

Topical Areas: Specific Comments

- **Toward steady-state performance**
  - Significant progress on steady-state scenarios
  - Goal of sustainable high performance AT scenarios for next generation devices is appropriate
  - Necessary to integrate additional aspects
    - Compatibility of AT scenarios with steady-state divertor
      Hybrid and radiative divertor; Hybrid and RMP control of ELMs (Allen)
      AT plan: develop ⇒ long pulse sustainment ⇒ integration with divertor
    - Extend to $T_e \sim T_i$
  - Assess importance of plasma rotation after counter-NB becomes available. Planned for this year (hybrid) (Petty)
- **Plasma control**
  - PAC impressed with progress on the plasma control system
  - Coordinate with ITPA to facilitate development of advanced control for ITER
    Collaborative work through SSO and control working group
    Control and operations group planned through US BPO

Topical Areas: Specific Comments

- **Resistive wall mode**
  - DIII–D historically a world leader in MHD stability research
  - RWM research is world-class and has clear ties with other programs
  - Concerned if balanced NBI sufficient for direct feedback stabilization
    Calculations indicate adequate, option to operate at lower B_T (Garofalo)
  - Clarify needs for 24 audio amplifiers
    12 sufficient for initial n=1 feedback
    24 required for n=2 and for testing different feedback schemes (Garofalo)

- **Neoclasical tearing modes**
  - PAC would like to see an integrated presentation on the plans for NTM stabilization research; not given at 2005 PAC
    Integrated plan will be presented (La Haye)

Topical Areas: Specific Comments

- **Energetic Particle Physics** (Strait)
  - PAC is pleased that DIII–D is again emphasizing fast particle research
  - Emphasis on validating theory is commendable

- **Confinement Physics** (Burrell)
  - DIIII–D continues to make major contributions to the fundamental understanding of plasma confinement by exercising a strong coupling between theory and experiment

    Seminars held to foster continued strong experiment/theory coordination
  - A stronger interaction of particle transport studies with other aspects of confinement in DIII–D is a continuing priority

    Particle transport work part of 32 week plan for 2006–2007

Topical Areas: Specific Comments

- **Pedestal physics**
  - DIII–D team makes key contributions in the the critical area of pedestal physics
  - Control of ELMs by ergodic fields is a technique of great interest to ITER
    - Extend to lower ν_* and q — complete stabilization is robust at low ν_* (Fenstermacher)
    - Clarify physical mechanism UCSD/GA Theory Grant, work with stellarator community
  - Experiments with co plus counter to clarify the role of rotation in QH-mode, experiments planned for 06 (Fenstermacher)
  - Add data to new pedestal profile database to facilitate comparison with models. Improved data analysis tools being developed and analysis underway (Leonard)

- **Boundary Physics**
  - ^{13}C experiments are a fertile source of data for understanding flows and material migration. H-mode carbon-migration completed in FY05 (Allen)
  - PAC recommends contouring inner wall tiles for improved divertor diagnostics and physics interpretation: We are doing (Allen)
  - Concern that AT compatibility with divertor not being adequately addressed. Argon enhanced radiation in hybrid discharges (Allen)
  - PAC recommends consideration of in-situ O_2 bake
Plan: Lab bake (Toronto), work with international community (TEXTOR)
consider O_2 bake prior to vent FY07

DIII–D Program Uses an Open Planning Process

- **Research Council selected ~30 scientific staff representing broad cross section of DIII–D staff**
- **Research Council reviews and advises on the near-term direction of the DIII–D program: thrusts**
  - Program goals, milestones, ITPA, international, ... As background
  - Importance and impact of ITER a major consideration
- **Research thrusts and thrust leaders selected**
- **Research Opportunities Forum to generate and collect proposals for experiments — over 600 proposals**
- **Detailed experimental plan developed by experimental staff**
- **Research leaders present plan to Research Council and the council advises on the balance of the program (run time)**
- **Run time allocated**

DIII–D Research Council

Chair	T.S. Taylor	Experiment Coordinator	M.R. Wade
Vice Chair	S.L. Allen (LLNL)	Asst Exp. Coordinator	J.S. deGrassie

K.H. Burrell
V.S. Chan
E.J. Doyle (UCLA)
T.E. Evans
M.E. Fenstermacher (LLNL)
J.R. Ferron
C.M. Greenfield
A.M. Garofalo (Columbia)
R.J. Groebner
W.W. Heidbrink (UCI)
E.M. Hollmann (UCSD)
A.G. Kellman
R.J. La Haye
L.L. Lao
A.W. Leonard
T.C. Luce
G.R. McKee (U. Wisc.)
M. Murakami (ORNL)
R. Nazikian (PPPL)
P.I. Petersen
C.C. Petty
R. Prater
H. Reimerdes (Columbia)
D.L. Rudakov (UCSD)
P.B. Snyder
R.D. Stambaugh
E.J. Strait
D.M. Thomas

DIII–D Research Program Consists of Research Thrusts and Enduring Topical Science Areas

2006 and 2007 Research Thrusts and Leaders

	AT-1 Advanced Scenario Development	IT-1 ELM Control for ITER	IT-2 ITER Hybrid Scenario	IT-3 NTM Control for ITER	IT-4 RWM Control for ITER	SC-1 Pedestal Width Physics
Topical Area Manager	T. Luce C. Greenfield	M. Fenstermacher T. Jernigan	C. Petty J. Jayakumar	R. La Haye D. Humphreys	A. Garofalo M. Okabayashi	A. Leonard G. Staebler R. Groebner
Stability physics E. Strait	✓	✓	✓	✔	✓	✓
Confinement, transport physics K. Burrell	✓	✓	✓			✓
Boundary physics S. Allen	✓	✓	✓			✓
Heating and current drive physics R. Prater	✓		✓			✓

Table shows areas of strong overlap

- **Program leadership reflects the national character of the DIII–D Program**
- **Topical science areas provide broad scientific base**
- **Research thrusts focus efforts on critical scientific issues and integrated scenario development**

~600 Proposals at the DIII–D Research Opportunities Forum Demonstrates Strong National and International Interest

Columbia University	22
FarTech	4
Georgia Tech	2
General Atomics	283
Lehigh University	2
LLNL	44
MIT	3
ORISE	4
ORNL	21
PPPL	68
SNL	7
UC Irvine	6
UCLA	31
UCSD	32
Univ. Texas	4
Univ. Wisconsin	16
	549

CEA Cadarache	6
EFDA-CSU	8
ERM-KMS	1
Euratom	2
FSZ Julich	7
IPP Garching	7
JAEA	1
Univ. Toronto	8
UKAEA	11
	51

From Int'l Labs	51
From Universities	122
From Nat'l Labs	140
From Industry	287
Total	600

Significant Progress will be Made in FY06–07, But a Large Backlog of Experiments Will Remain

Area	Proposals Received	Unique Proposals	Proposals in 12 week plan	Proposals for 32 week plan (06/07)	Backlog of Proposals
Stability	70	64	5	14	50
Confinement	93	83	7	15	68
Heating and Current Drive	50	40	1	13	27
Boundary	60	60	5	14	46
Advanced Scenarios	59	37	4	17	20
ITER Hybrid Scenarios	47	37	5	14	23
Pedestal Width Physics	29	22	1	6.5	15.5
RWM Control for ITER	56	40	9	20	20
NTM Control for ITER	13	7	3.5	6	1
ELM Control for ITER	109	94	6	16	78
Total Proposals	586	484	46.5	135.5	348.5

The LTOA are Providing Additional Capabilities for Exciting Scientific Research on DIII–D

	2005	2006
ECH long pulse	3 LP gyrotrons (2.1 MW, 5 s) 3 SP gyrotrons (~1.6 MW, 2 s)	6 LP gyrotrons (4.5 MW, 10 s) 1 LP & 1 SP as backup
Lower divertor modification	Density control in upper SND	Density control in DND, upper SND, and lower SND
210 CNTR NBI	17.5 MW co-injection	5 MW counter-injection 12.5 MW co-injection
Cooling water tower	Upgrade Infrastructure	Sufficient cooling for 10 s full power operation
TF belt bus	TF coil – 5 s at full field	TF coil — 10 s at full field (half completed)
Fast wave	3 MW, 2 s	4 MW total 2 MW, 2 s; 2 MW, 10 s
RWM actuators	6 audio Amp.	12 audio Amp.
Diagnostics		Co + cntr viewing CER, MSE, improved FIR, ECE, …

Installation of New Cooling Towers

Co Plus Counter NBI will Provide Unique Capability in the US Fusion Program

PROVIDES

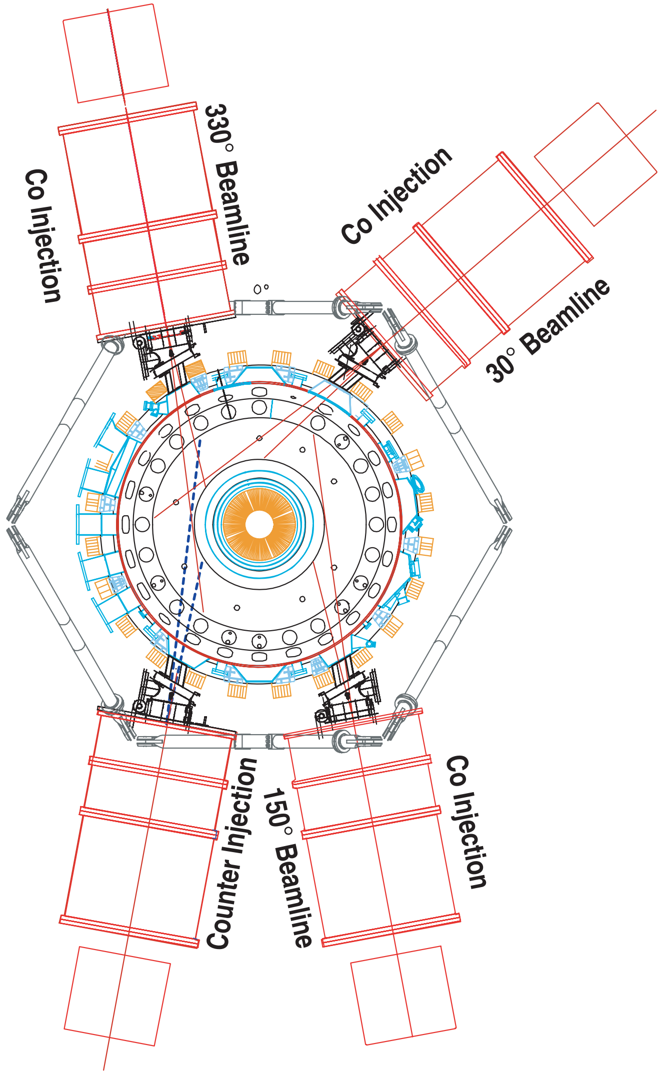
- Plasma heating
- Current drive and current profile control
- Rotation control

ENABLES

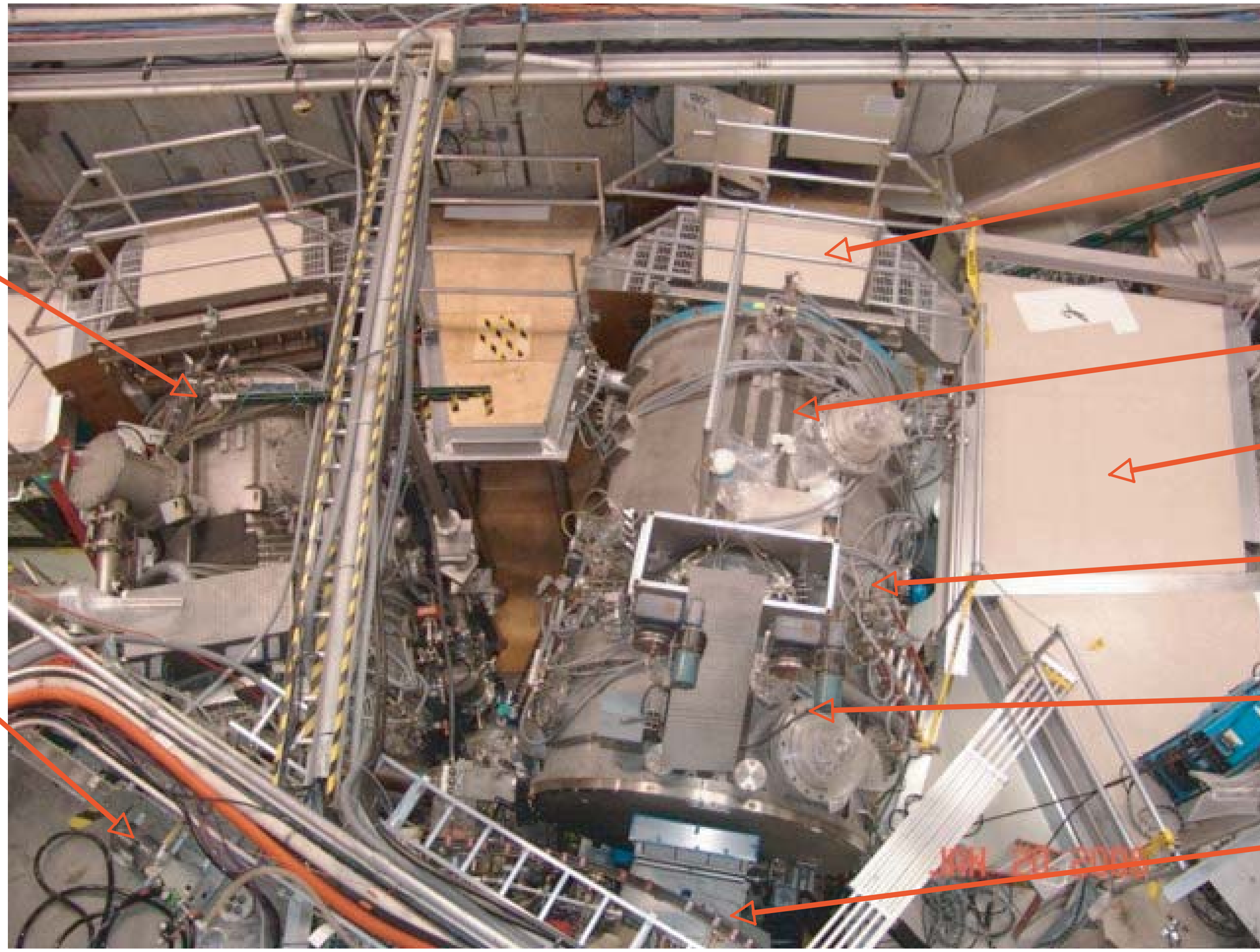
- QH-mode with central co-rotation (Fenstermacher)
- Physics of rotation (Burrell)
- RWM stability at low rotation (Garofalo)
- NTM stabilization with modulated rf (La Haye)
- Fast ion distribution control (Strait)
- Full bootstrap discharges (Prater)
- Physics of NBCD (Prater)
- Transport barrier control
  (ExB and Shafranov shift) (Burrell)

DIAGNOSTICS (Boivin)

- Co plus counter viewing MSE, J(ρ) and E_r with high resolution
- Co plus counter CER, improved poloidal and toroidal rotation



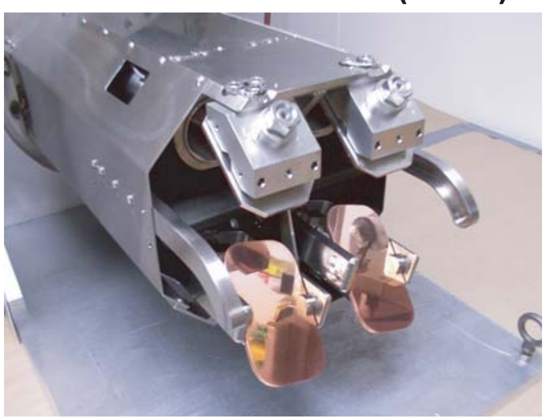
Installation of Rotated 210 Beamline



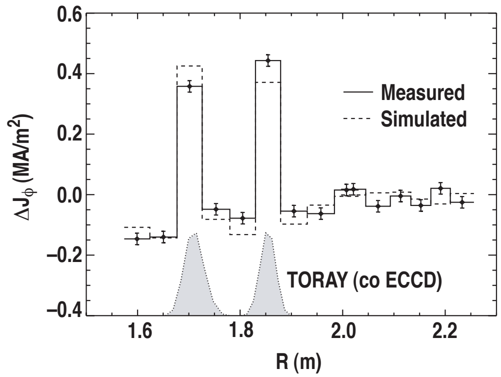
The DIII–D EC System will Provide Enhanced Off-axis Current Profile Control and Important Physics Capability

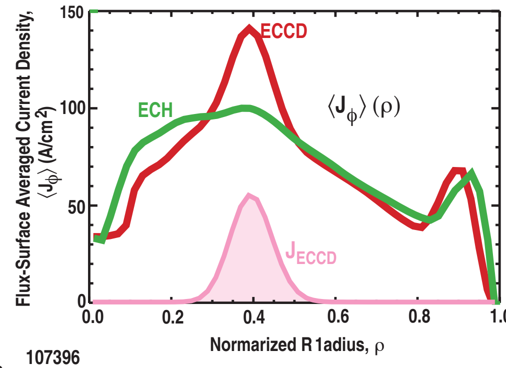
CPI Gyrotron

Steerable Launcher (PPPL)

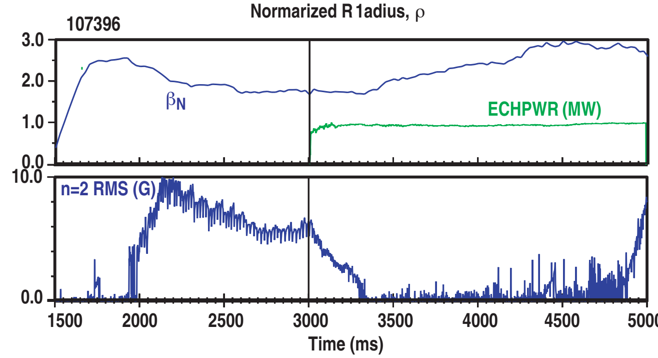


Current Drive and Current Profile Control (Luce)

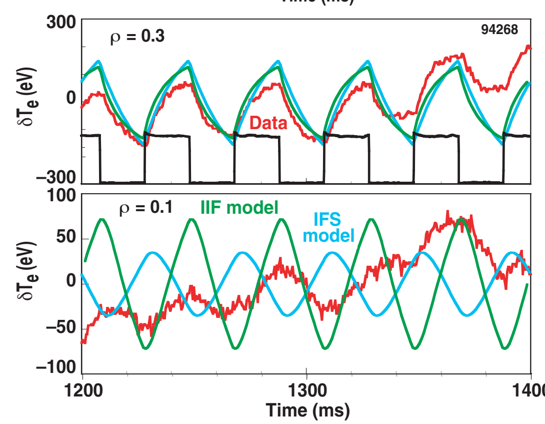




MHD Stabilization Control (La Haye)



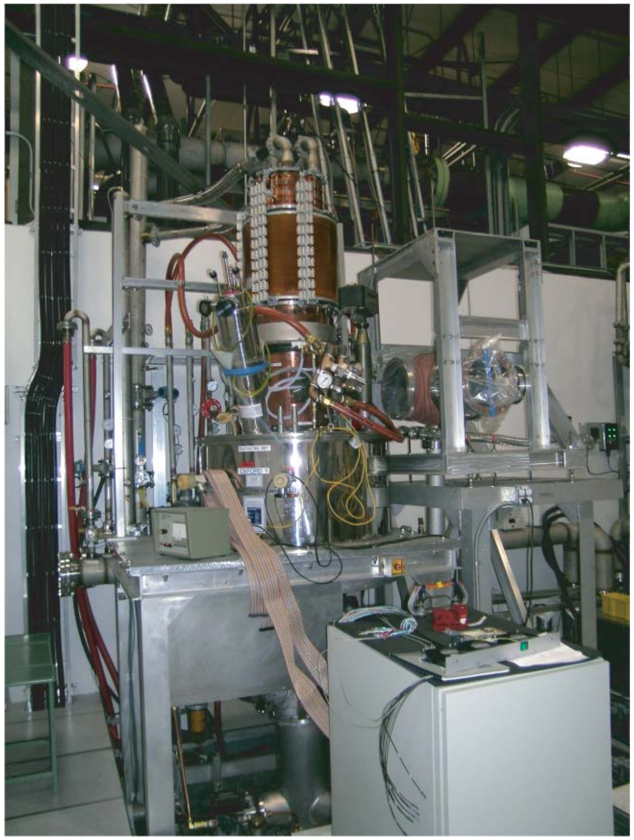
Transport Science and Transport Barriers (Burrell)



Continuing ECH Gyrotron Installation and Start-up

First replacement gyrotron installed in refurbished "socket" and started up

Refurbished "socket" for second replacement gyrotron in background

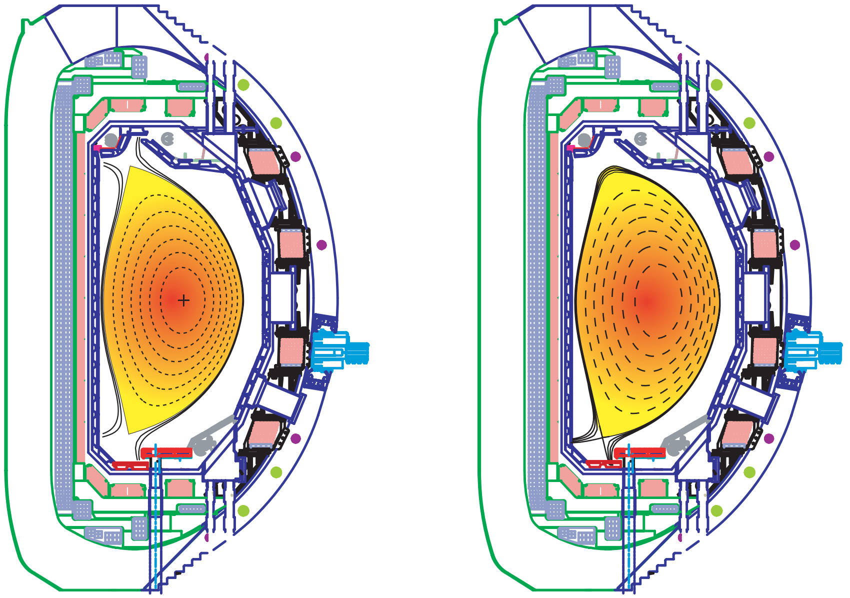


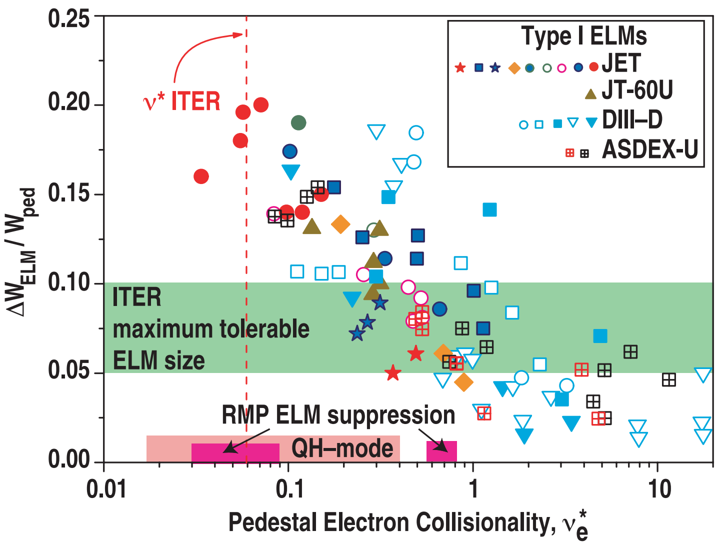
Developmental depressed collector gyrotron installed in new "socket"

The Divertor Modification will Provide Density Control in Both DND and SND

PHYSICS ENABLED:

- **Improved density control in *AT* DN plasmas (Luce)**
- **Transport and stability over range of ν^* (n_e) (Burrell)**
- **Pedestal physics with range of ν^*, SND and DND (Fenstermacher, Leonard)**
- **Plasma flow and impurity retention in the plasma boundary (Allen)**
- **Attachment/detachment control (Allen)**





Significant New Measurement Capability Will Be 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

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)

Presently Unavailable Capability

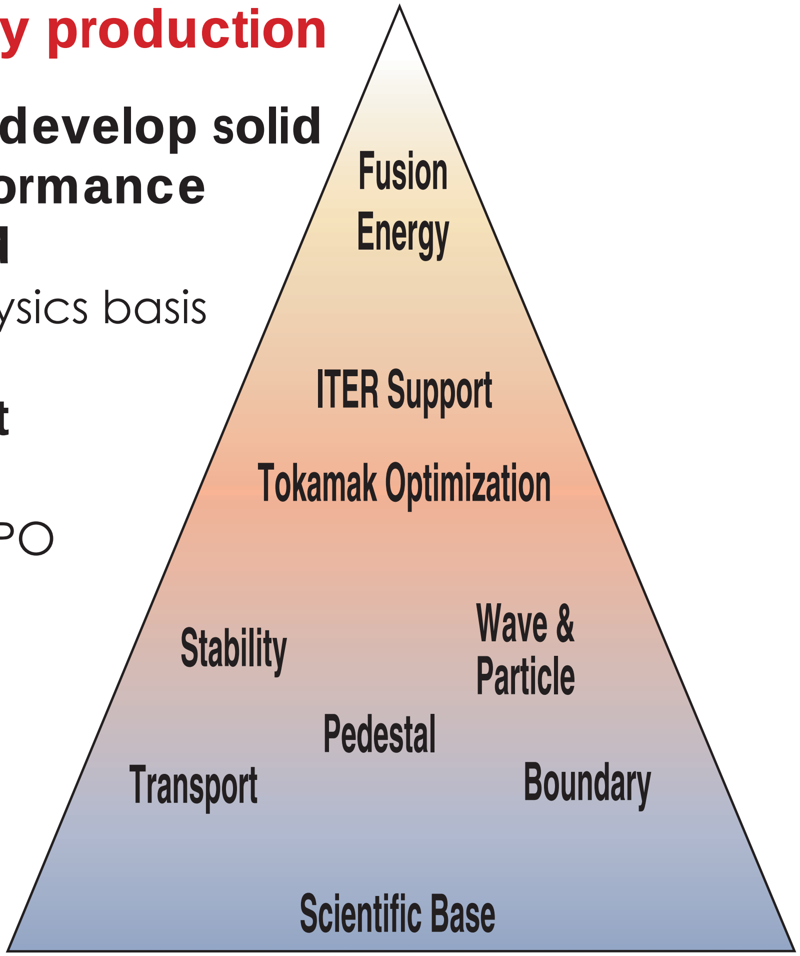
- Lower Tile current array
- NPA active CX

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

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

- **Advanced tokamak: DIII–D Program will develop solid scientific base for steady-state high performance discharges in support of ITER and beyond**
  – DIII–D has unique capability to establish physics basis
- **ITER support: DIII–D Program will carry out key scientific research in support of ITER**
  – Strong collaboration with ITPA, US BPO, US IPO
- **Science: DIII– Program will play a lead role in enhancing plasma science**
  – Transport: understanding and control of turbulence



⇒ The knowledge gained is the program's enduring contribution

A Key Goal of the DIII–D Program is to Advance the Fundamental Science Understanding of Fusion Plasmas

— A Key Role on Research in the Topical Science Areas —

Transport:

- **Develop a predictive understanding of transport ⇒ Toward predicting and guiding ITER operations**
  - Momentum transport (co+counter NBI)
  - Transport barrier physics and control (core and edge)
  - Electron thermal transport (high k turbulence)
  - Turbulence characterization (zonal flows)

Stability:

- **Establish the scientific basis for predictive understanding and control of MHD stability in toroidal plasmas: Many issues directly relevant to ITER**
  - Disruption characterization and mitigation (new gas valve, diagnostics)
  - Physics of and transport by Alfvén eigenmodes
  - Sawtooth physics and control
  - Multivariable control development
  - Plasma response to error fields
  - Physics of NTM onset and stabilization (IT-3)

A Key Goal of the DIII–D Program is to Advance the Fundamental Science Understanding of Fusion Plasmas

H&CD:

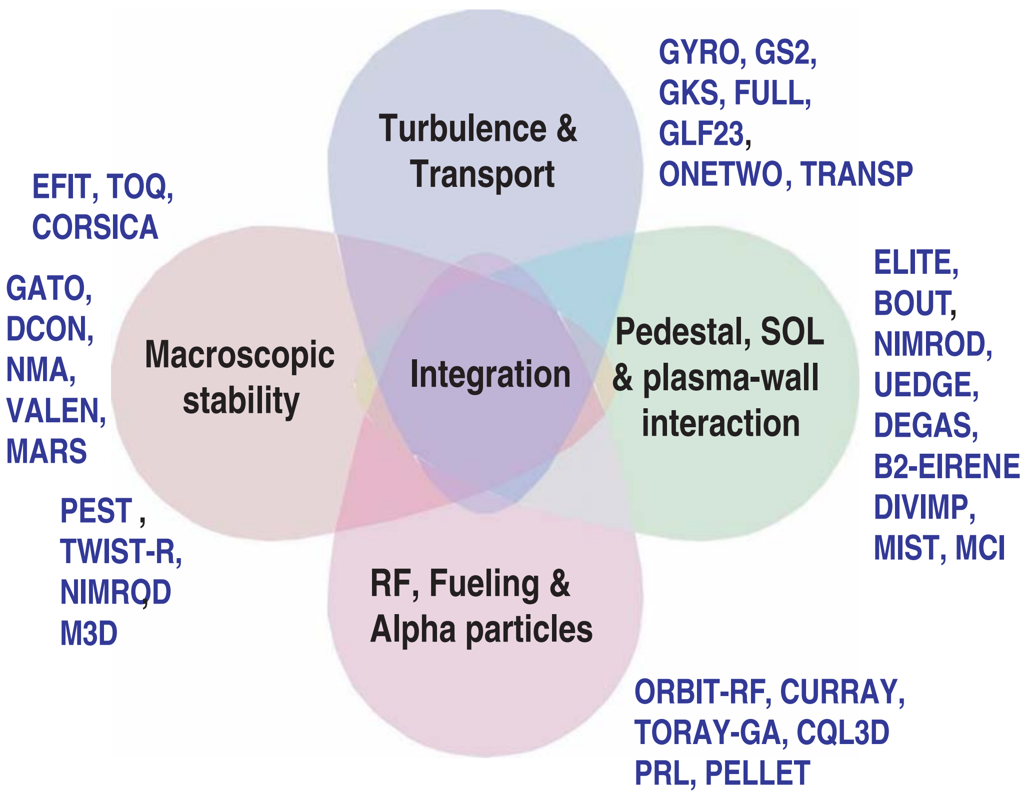
- **Develop comprehensive validated predictive models for H&CD, (ECH/ECCD, FWCD, NBCD, bootstrap)**
  - Validate neutral beam physics and current drive (co + counter NBI)
  - Measure high harmonic FW absorption and compare to theory
  - Fully noninductive discharges high f_{BS}(EC + FW + co + counter NBI)
  - Preionization and start-up assist with 2nd harmonic ECH
  - Extend ECCD model validation to far off-axis and high T_e

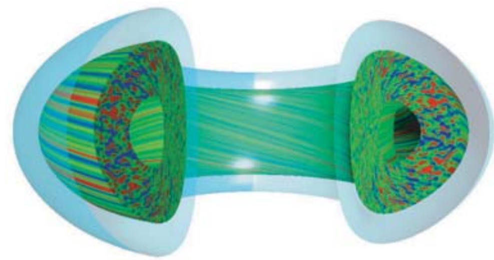
Boundary: Use detailed 2-D edge diagnostic

- **Develop a validated model of the edge plasma toward predicting boundary performance on ITER**
  - ITER tritium inventory: ^{13}C experiments, wall gap experiments, modeling
  - ELM flux measurements with new diagnostics
  - Understand exhaust in AT DN and ITER SN shapes, dome/no dome
  - Measure main chamber recycling and impurity generation with new camera and midplane probe
  - Further develop radiative divertor in hybrid
  - Compare data to models — UEDGE, DIVIMP, Bout, Kinetic Bout

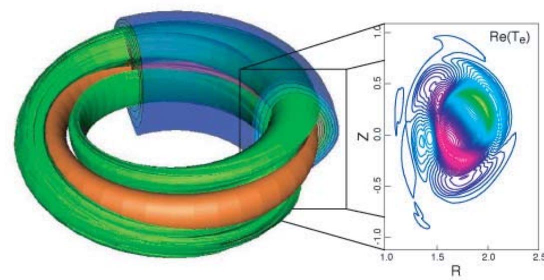
A Close Coupling Between Theory and Experiment is Essential for Advancing Fundamental Plasma Science

- **Detailed comparison of DIII-D results with theory are facilitated by:**
  - Outstanding diagnostic set
  - Precise plasma control
  - Strong multi-institutional team
  - Innovative experiments and theoretical models

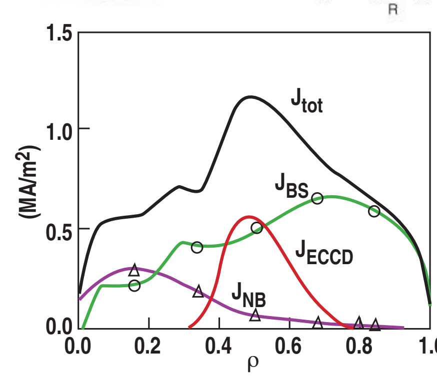




Transport GYRO



Stability NIMROD



ONETWO Integration of transport and CD modules

The DIII–D Program Will Carry Out Important Scientific Research in Support of ITER

- **Ensure the success of ITER by providing solutions to key ITER issues**
- **Enrich the ITER physics program through development and characterization of advanced scenarios**
- **Develop the physics basis for high performance, steady-state operation for ITER and beyond**
- **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 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**
  - ELM suppression/control ⇒ Non-axisymmetric coil set
  - RWM stabilization ⇒ Non-axisymmetric coil set
  - 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**
  - 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
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ELM Control

Thrust IT-1, ELM Control for ITER

IMPORTANCE: Erosion of ITER divertor and resultant lifetime

- **ELM control with RMP's**
  - ITER PRIORITY: Urgent, design issue for ITER (non-axisymmetric coils)
  - DIII–D CAPABILITY: Non-axissymetric coil set and boundary diagnostics
- **ELM free QH–mode: with dominant co-injection**
  - ITER PRIORITY: Urgent, potential design issue wrt counter NBI
  - DIII–D CAPABILITY: co + counter NBI low BT ripple, excellent core and edge diagnostics
- **ELM pace making**
  - DIII–D CAPABILITY: New pellet dropper (ORNL), diagnostics
- **Small ELM regimes**
  - ITER PRIORITY: Urgent
  - DIII–D CAPABILITY: Range of shapes, n_e control, diagnostics

Thrust IT-4, RWM Control for ITER

IMPORTANCE: provides margin in β for ITER steady-state scenarios

- ITER PRIORITY: High: Possible design issue (internal coils)
- DIII–D CAPABILITY: low rotation with co + counter, internal and external coils, high bandwidth actuators

PLAN

– Demonstrate sustained stabilization of RWM at low rotation

– Characterize stability versus rotation

– Compare effectiveness of internal and external coil set

– Validate models for RWM control on ITER

NTM Stabilization

Thrust IT-3, NTM Control for ITER

IMPORTANCE: Capability to achieve design parameters (β, τ), and disruption-free operation

- ITER PRIORITY: High; power requirement for EC
  Possible antenna reconfiguration/relocation
- DIII–D CAPABILITY: Sufficient power to vary effective width, co+cntr NBI to slow rotation for effective modulation of EC, core diagnostics

PLAN

– Validate advantage of modulated ECCD for stabilization of m/n = 3/2, 2/1 NTM’s; dependence on deposition width

Tritium Retention: Physics of Impurity Tritium Mass Transport and Removal of Co-Deposited Layers

IMPORTANCE: choice of first wall materials for ITER, and device availability

- ITER PRIORITY: Urgent divertor material decision in ~3–5 years
- DIII–D CAPABILITY: All carbon device, excellent divertor diagnostics, "axisymmetric" source
- ISSUE: Recovery after O_2 bake

PLAN

– Complete analysis of tiles for H-mode carbon migration

– ITER mirror and tile gap experiments

– Plan for ^{13}C exposure and possible O_2 bake in 07 work with international (TEXTOR)

Disruption Characterization and Mitigation

Stability

IMPORTANCE: Thermal and mechanical stress on in-vessel components, device availability

- ITER PRIORITY: Urgent, for both database and mitigation research
- DIII–D CAPABILITY: Quick recovery after high beta disruptions, high throughput gas valve, improved diagnostics

PLAN

- ITPA disruption database, continue analysis
- Mitigation with high pressure gas injection
  - Understand impurity penetration
  - Validate higher delivery rate suppresses runaways
- Measure particle and heat flux to first wall (boundary)
  - Disruptions
  - ELMs

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

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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

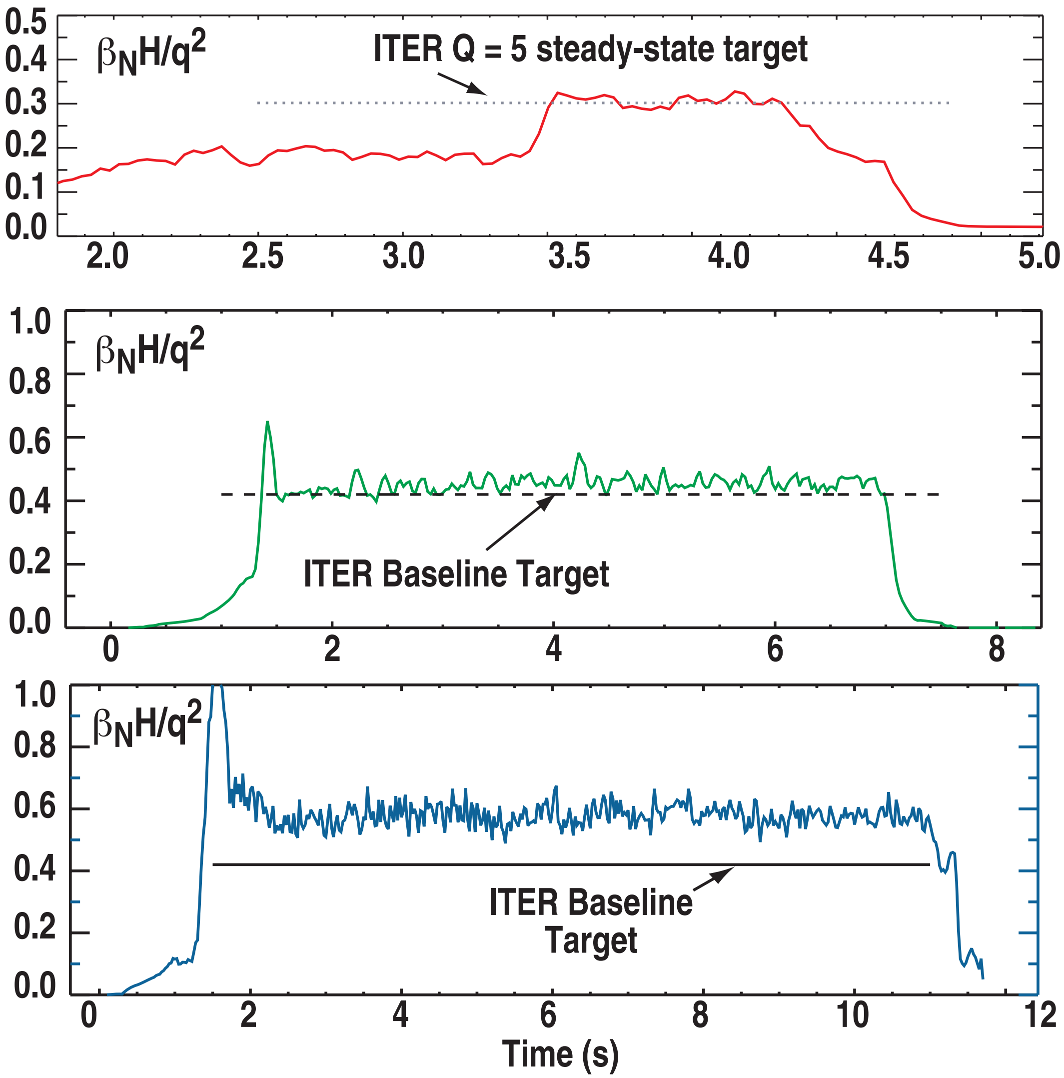
- **Advanced scenarios will extend the scientific benefit gained from ITER**
  – Advanced Inductive (Q > 40) ⇒ Plasma physics
  – Hybrid (Q ~ 10) ⇒ Materials testing
  – Fully non-inductive (AT) (Q ~ 5) ⇒ Steady state operation

- **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 aggressively forward with DEMO**

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

Operational Scenarios Being Developed on DIII-D Will Enhance the Scientific and Technological Benefit of ITER



- **Steady-state scenarios**

  $Q_{ITER} \sim 5$, t_{dur} (phys) $= \infty$,

  $I_p^{(ITER)} \approx 9$ MA

- **Hybrid scenario**

  $Q_{ITER} \sim 10$, $t_{dur} > 1$ hr,

  $I_p^{(ITER)} \approx 11$ MA

- **Advanced H-mode**

  $Q_{ITER} \sim 40$, $t_{dur} > 30$ min,

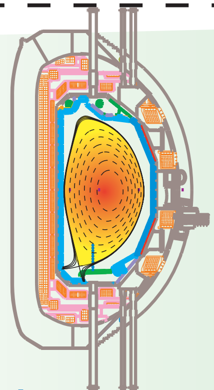
  $I_p^{(ITER)} \approx 14$ MA

DIII–D Research Will Provide a Validated Physics Basis for Steady-State Operation in ITER

2004

Long Pulse

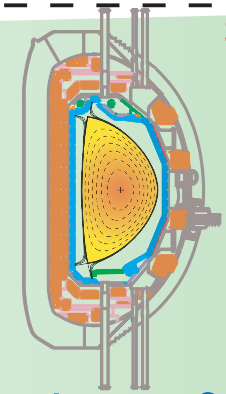
f_{BS} ~55%
β_N ~ 3.5
f_{NI} = ~90%, 2 s
100%, 0.6 s



2009

Next Step Steady State

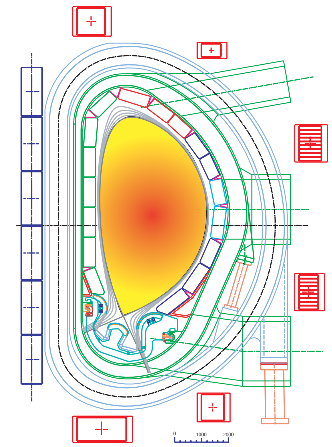
f_{BS} ~ 70%
β_N ~ 4
t_{DUR} ~ 5 s



2014

Steady-State

$f_{BS} \rightarrow$ 90%
$\beta_N \rightarrow$ 5
$t_{DUR} \rightarrow$ 10 s



Application to ITER and beyond

Development ⟶ Integration and Sustainment ⟶ Optimization

Shaping
MHD stability control
n_e control strong shape
Rotation control
q profile control (core and off-axis)
Evaluate SN vs DN
ELM control
Pressure profile control
AT divertor solution
Develop ITER prototype scenarios

Integrated Modeling

Long Pulse High Performance Discharges; Steady-State AT-1, Advanced Scenario Development

IMPORTANCE: Support key ITER steady-state objective
increase scientific benefit from ITER research
provide base for attractive tokamak optimization for ITER and beyond (CTF, Demo)

- ITER PRIORITY: High, potential ITER design implications, plasma control tools (CD). Q = 5 is #2 ITER priority
- DIII–D CAPABILITY: Shape, stability control, current profile control, n_e control, integrated plasma control

PLAN

– Shape optimization of high q_{min} scenarios

– q-profile optimization of high q_{min} scenario

– Extend duration, $1.5 < q_{min} \lesssim 2$, $q_{min} \gtrsim 2$

– Develop n_e control

– Develop model-based current profile controller

– Evaluate alternate scenarios, as time permits, high ℓ_i, QDB

Long Pulse High Performance: Hybrid
IT-2, ITER Hybrid Scenarios

IMPORTANCE: Increase scientific benefit from ITER research potential to increase performance and duration of ITER operation

- ITER PRIORITY: High, ITER performance, confinement understanding
- DIII–D CAPABILITY: Controlled discharge evolution, instability control, range of H&CD tools, diagnostics

PLAN

– Expand operating regime, ρ^*, lower SN, increase β

– Improve physics understanding
  - Role of MHD in current profile evolution (q_0 ~1)
  - Role of H-mode pedestal

– Validation in reactor conditions
  - Low rotation
  - $T_i/T_e \Rightarrow 1$

– Extrapolation issues
  - Dependence of τ on ρ^*
  - Divertor and ELM solutions

Transport Scaling of Conventional H-Mode

IMPORTANCE: Reduction of uncertainty in performance projection

- ITER PRIORITY: High,
- DIII–D CAPABILITY: rotation control, excellent profile and turbulence diagnostics, computer cluster for transport simulations (GYRO)

PLAN

- Contribution to ITER data base activities
- Non-dimensional scaling studies
  - β scaling of confinement recently completed
  - Aspect ratio — completed last year
  - ρ^* scaling at low rotation
- H-mode Threshold
  - Data base activities
  - DIII-D efforts are focused on detailed physics of transition
    2 days planned in 32 week plan
- DIII-D efforts focus on developing and testing theory-based transport models

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Transport Models to Validate Performance Projections
Transport and SC-1, Pedestal Width Physics

**IMPORTANCE: Improve scientific productivity,
control may lead to performance enhancement and risk reduction**

- ITER PRIORITY: High, understand and optimize (reduce) transport
- DIII–D CAPABILITY: A key scientific focus, experiment/theory comparisons, excellent diagnostics

PLAN

– Develop and test physics based core models
  - GYRO, GLF23, TGLF. . .

– Understand the pedestal height (SC-1, pedestal width physics)
  - Pedestal width + stability ⇒ height
  - Cross machine comparisons
  - Develop database, analysis, prepare models
  - Experiments that change width (test models)
  - Detailed characterization

Reduction of Heat Flux to the Divertor

IMPORTANCE: Boundary radiation needed in ITER to reliably handle heat flux, especially lower n_e AT scenarios

- ITER URGENCY:Longer term operational issue
- DIII–D CAPABILITY: Long pulse AT discharges, cryopumps, comparison of dome/no dome

PLAN

– Argon puff and pump in long pulse hybrid discharges and AT discharges
  - Compare to models

– Model development and validation

Fast Ion Physics and Fast Ion Instabilities

IMPORTANCE: Potential loss of alphas and damage to first wall

- ITER PRIORITY: High, possible operational issue (advanced modes) first wall protection issue
- DIII–D CAPABILITY: Excellent instability diagnostics, fast ion profile diagnostic and heating tools to alter fast ion distribution

PLAN

- Evaluate stability of Alfvén eigenmodes
- Measure fast ion transport,
- Validate codes

Sawtooth Control

IMPORTANCE: Avoidance of giant sawteeth, NTMs, and disruptions; loss of performance

- ITER URGENCY: Longer term operational concern
- DIII–D CAPABILITY: Core diagnostics, fast ion profile, FW to stabilize, EC to control

PLAN

– Evaluate ECCD near q = 1 for reducing sawteeth amplitude

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ITPA High Priority Research Tasks and ITPA/IEA Experiments 2005-2006

	Research Tasks	ITER Relevance	DIII–D Plan	Area
MHD	• Investigate underlying NTM physics including their seeding; stabilization of (3,2) and (2,1) NTMs by direct control and by indirect methods (seed island control and FIR mechanism); and identify requirements for ITER plasmas.	High	✓✓	IT-3
	• Enhance understanding and mitigation of the effects of RWMs by analysis, experimental verification of control, determination of role of plasma rotation and error fields. Determine control system requirements for diagnostics.	High	✓✓	IT-4
	• Construct new disruption DB including conventional and advanced scenarios and heat loads on wall/targets	Urgent	✓✓	Stability
	• Develop disruption mitigation techniques, particularly by noble gas injection.	Urgent	✓✓	Stability
	• Understand intermediate-n AEs; losses of fast particles from AEs; and perform theory-data comparisons on damping and stability	High	✓✓	Stability
	• Specify for ITER the low frequency noise in the diagnostic signals used in feedback loops of – the plasma vertical stabilization (noise in dZ/dt, f < 600-100 Hz) and – the RWM stabilization (poloidal field component n=1, f < 300-500 Hz)	Urgent	✓	Stability IT-4 (analysis)
Divertor and SOL	• Understand the effect of ELMs/disruptions on divertor and first wall structures	Urgent	✓	Boundary
	• Improve understanding of tritium retention and the processes that determine it and development of efficient T removal methods	Urgent	✓✓	Boundary
	• Improve understanding of Sol plasma interaction with the main chamber	Urgent (esp. with ELMs)	✓	Boundary
	• Develop improved prescription of SOL perpendicular transport coefficients and boundary conditions for input to BPX modeling	High	✓	Boundary

Pedestal and Edge	• Improve predictive capability of pedestal structure through profile modeling of joint experimental comparisons – Dimensionless cross machine comnparisons to isolate physical processes; rotation, E_r, shape, etc. – Measurement and modeling of inter-ELM transport – Establish profile database for modeling joint experiments	High	✓✓	SC-1
	• Physics based empirical scaling – Collaboration with CDBM to improve scalar database characteristics and utilization	High	✓	Transport
	• Predict ELM characteristics and develop small ELM and quiescent H-mode regimes and ELM control techniques	Urgent	✓✓	IT-1

Diagnostics	• Assessment of the various options for vertical and a radial neutron camera to measure the 2D n/a source profile and asymmetric in this quantity	High	—	
	• Development of methods of measuring the energy and density distribution of confined and escaping α's	High	—	
	• Assessment of the radiation effects on coils and for measurements of the plasma equilibrium and development of new methods to measure steady-state magnetic fields accurately in a nuclear environment	High	—	
	• Determine the lifetime of plasma facing mirrors used in optical systems	High	✓✓	Boundary
	• Development of measurement requirements for measurements of dust, and assessment of techniques for measurement of dust and erosion.	High	✓	Boundary
Steady-State Operation	• Focus the modeling activity on ITER hybrid and steady-state cases, using standard (and common) sets of input data	High	✓	IT-2
	• Assessment of real-time control of advanced scenarios in ITER, with collaboration on experiments and modeling	High	✓✓	AT-1
Transport Physics	• Understand and optimize transport properties of hybrid and steady-state demonstration discharges	High	✓✓	IT-2
	• Address reactor relevant conditions and dimensionless parameters, e.g., electron heating, T_e~T_i, low momentum input, He/impurity transport, edge-core interaction	High	✓✓	IT-2
	• Utilize international experimental databases in order to test commonality of transport physics in hybrid, steady-state scenario and reactor relevant conditions	High	✓	IT-2
	• Test simulation predictions via comparisons to measurements of turbulence characteristics, code-to-code comparisons and comparisons to transport scalings	High	✓✓	Transport

Confinement	• Resolve the differences in β scaling in H-mode confinement	High	Mostly done ✓✓	Transport
Database and Modeling	• Define a program to understand the density peaking	High	—	Stability
	• Develop a reference set of ITER scenarios for standard H-mode, steady-state and hybrid operation and submit cases form various transport code simulations to the profile DB.	High	Participating ✓	
	• Resolve which is the most significant confinement parameter, ν^* or n/n_G	High	✓	
	• Understand the aspect ratio dependence of the L-H power threshold	High	—	Transport

✓✓ — Major DIII-D plan element.
✓ — Some DIII-D effort.
— — Not planned near term.