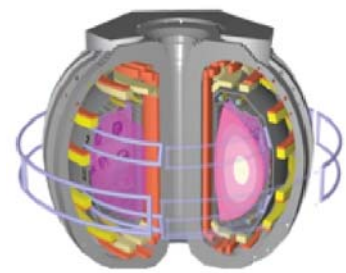
DIII-D National Fusion Facility

M.R. Wade, D.N. Hill, and R.J. Buttery for the DIII-D National Team

The DIII-D National Fusion Facility is the largest magnetic fusion research experiment in the U.S. with the mission to establish the scientific basis for the optimization of the tokamak approach to fusion energy production. The DIII-D National Fusion Facility has considerable experimental flexibility and extensive world-class diagnostic instrumentation to measure the properties of high-temperature tokamak plasmas. This provides scientists worldwide with an experimental platform to push performance boundaries, resolve specific challenges for ITER and future devices, and advance the knowledge of fusion plasmas on a broad front. Capabilities of DIII-D include a highly flexible field-shaping coil system to produce a wide variety of plasma shapes, a broad range of auxiliary heating and current drive systems, coil sets both inside and outside the vacuum vessel which are used to correct error fields and study the plasma response to perturbing magnetic fields, over 50 state-of-the-art diagnostic systems to examine plasma parameters, and an advanced digital control system for feedback control of the plasma. These capabilities, together with a broad international Team and close cooperation with theory and simulation provide an excellent facility for educating and training the next generation of fusion scientists.



The DIII-D National Fusion Facility is *absolutely central* to the U.S. fusion program retaining its scientific leadership role in 1) resolving physics issues critical to the success of ITER; 2) developing the physics basis for steady-state operation required for efficient power production, 3) addressing key issues that will form the technical basis for a Fusion Nuclear Science Facility (FNSF) and 4) advancing the fundamental understanding and predictive capability of fusion science on a broad front. Ongoing studies using the facility will enable preparation of U.S. scientists for ITER, and help advance the scientific basis for ITER exploitation. Nevertheless, without further upgrades to the facility, the U.S. will gradually cede leadership in several ReNeW Thrust areas related to burning plasma behavior and the exploitation of ITER (see Table 1). It will also limit the availability of a physics basis for a decision on the best way to proceed with a Fusion Nuclear Science Facility.

Excellent Science: The existing DIII-D facility is a world-class fusion research device with several unique capabilities enabled by a comprehensive diagnostic set, close liaison with theory through model validation, and a high degree of device flexibility. These capabilities have led to numerous advances in the tokamak concept over the past two decades including the importance of plasma shaping, sustained operation above the free-boundary kink stability limit, and ELM suppression using non-axisymmetric coils.

With its existing capabilities, DIII-D is positioned to provide key scientific studies to explore the physics of performance-limiting phenomena in its present operating regimes:

- **Reducing disruption risk –** Tearing and locked mode control with ECCD and 3D fields, plus active MHD spectroscopy, will develop individual elements of a disruption avoidance strategy at performance levels consistent with the ITER baseline scenario. Two-dimensional measurements of plasma thermal/current quench and radiation profile with various injector locations and impurity deposition depths will inform the design of the ITER disruption mitigation system. Measurements of the spatial and temporal evolution of runaway electrons during the current quench and plateau phases will provide a better understanding of dissipation and an improved physics basis for runaway handling in ITER.

- **Quantifying turbulence-driven energy, particle, and momentum transport –** Utilizing DIII-D's extensive diagnostic set and variable ion/electron heating and torque input, the role of turbulence in setting the transport characteristics of candidate ITER H-mode regimes will be explored including (i) the baseline scenario at β_N~2 with T_i~T_e and low toroidal rotation, or and (ii) advanced scenarios with elevated β_N>3 with T_i>T_e and high toroidal rotation from dominant co-NBI heating. L-mode perturbative transport studies will continue to test fundamental turbulence models, while the connection of core transport to edge pedestal models (the "shortfall") will be addressed. Evaluation of this physics in low-torque, H-mode conditions similar to those expected in burning plasmas will require additional electron heating. Existing turbulence diagnostics will also be used to develop physics-based models for the L-H power threshold and intrinsic, poloidal and neoclassical ('NTV') rotation, where control tools such as further use of 3D fields will be tested.
- **Exploring trends for steady-state operation –** Off-axis neutral beam injection and moderate power off-axis ECCD will provide the tools needed to develop the physics basis of steady-state operation in high torque, ion-heated, stationary discharges up to $\beta_N \approx 4$ with q_{min} up to 2.4. Studies will investigate transport and stability properties and explore the potential for self-consistent fully non-inductive solutions. Tests of the access requirements for a non-inductive scenario for the ITER Q = 5 mission will be possible. The variable off-axis current drive will enable assessment of a modest range of current profiles in fully non-inductive conditions with high bootstrap fraction. Evaluation and control of a broader range of profiles for FNSF/DEMO applications will require additional power and off-axis current drive.
- **Improving understanding of 3D field interactions with tokamak plasmas –** DIII-D's existing coil arrays will be used to apply rotating n=1 or n=2 magnetic fields with variable poloidal spectrum to correct error fields, control kink stability, and probe the plasma response. The application of n=3 fields with fixed poloidal spectrum will continue to be used to study the magnetic and kinetic response leading to ELM suppression as well as rotation control for QH-mode optimization. Radial and poloidal components of plasma response fields, both static and rotating, will be measured using recently expanded external magnetic diagnostics, and single-location profile and imaging systems. Improved isolation and optimization of 3D effects will require the capability to independently control each 3D coil element and a new internal coil set.
- **Advancing the physics of the plasma boundary and pedestal –** Existing diagnostics will enable tests of theory-based pedestal transport models and the role of ionization source in determining the density profile. Utilizing combined density, shape and β control, a possible path to optimize pedestal performance utilizing QH-mode operation will be explored. MHD stability models of heat flux width will be tested, together with divertor detachment and radiative dissipation models to P/R~14, including the effects of divertor geometry changes (e.g. snowflake), and compatibility with 3D fields for ELM control. Plasma surface interactions on ~1-cm scale samples at room temperature will be explored.
- **Exploring energetic ion physics** – Off-axis beams and ECH will vary fast ion distributions in regimes ranging from L-mode ramp-up to high rotation ion heated steady state plasmas, where present diagnostics will enable low-order tomographic inversions to test models though new diagnostics would provide more detailed information on the ion distributions. The ability to rotate n=1 or n=2 non-axisymmetric fields past fast ion loss detectors will enable researchers to test the effects of error fields on fast ion loss and transport. Upgraded 3D coils would enable the study of these effects during RMP ELM suppression.

Impact on Research Needs, Gaps, and Opportunities: DIII-D's existing capabilities will enable a range of research that will address many needs, gaps, and opportunities identified by recent FESAC reports. Early in the 2014-2024 time frame, these capabilities will enable definitive U.S. leadership in several areas. Specific areas in which DIII-D will play world-leading roles include:

- *Thrust 2*: The existing 3D coil capabilities and disruption mitigation/diagnostic sets will enable researchers to contribute to the physics basis for ELM control and disruption mitigation design decisions on ITER.
- *Thrust 4*: A flexible H&CD set, multiple NTM and ELM control tools, and the ability to operate at ITER-like torque and ν^* at moderate β_N will provide the capability to inform the ITER Research Plan on access requirements of the ITER baseline scenario.
- *Thrust 5 and 8*: DIII-D is the world leader in steady-state research and the existing capabilities will enable continued development of the physics basis of high β, fully non-inductive operation.
- *Thrust 3 and 6:* Flexible heating and torque input, 3D coils, and an extensive diagnostic set will enable tests of theory and simulation of turbulent transport, pedestal and ELM physics, disruption mitigation, fast particle physics and SOL physics in presently accessible regimes.
- *Thrust 9 and 12:* DIII-D's extensive diagnostic set and ability to assess a variety of divertor configurations will allow researchers to develop an improved physics basis of SOL heat/particle flow and geometric effects at moderate P/R values.

As new capabilities become available on international devices, DIII-D's leadership role will be reduced though it will remain a strong contributor in many areas (see Table 1).

Table 1: Anticipated DIII-D impact on ReNeW Thrusts over the next 10 years

Renew Thrusts (with Prioritization from 2012 Priorities Panel Report)	Anticipated DIII-D Position During Next 10 Years A=Definitive World Leader; B=World Leader; C=Strong Contributor; D=Moderate Contributor	2013	2017	2020*	2024
1 (Low)	Measurement techniques to understand and control burning plasmas	C	C	C	C
2 (High)	Control transient events in burning plasmas	A	A	B	B
3 (Mid)	Understand the role of alpha particles in burning plasmas	B	B	C	C
4 (Mid)	Qualify operational scenarios and the supporting physics basis for ITER	A	B	C	C
5 (Mid)	Expand the Limits For Controlling and Sustaining Fusion Plasmas	A	A	B	C
6 (High)	Develop predictive models for fusion plasmas supported by theory and challenged with experimental measurement	A	B	C	C
8 (Low)	Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas	A	A	B	C
9 (High)	Unfold the physics of the boundary layer plasma	B	C	D	D
10 (High)	Decode and advance the science and technology of plasma-surface interactions	B	C	D	D
12 (Low)	Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma	B	B	C	C
16 (Mid)	Develop the spherical torus to advance fusion nuclear science	D		D	D

* Equivalent to 'No Upgrades' column in Table 2 of DIII-D National Fusion Facility Upgrade white paper

International Context: DIII-D is a moderate sized, moderate aspect ratio device with arguably the best complement of heating, current drive, and diagnostic capabilities worldwide. Within the world program, there are three tokamaks of comparable size – ASDEX-Upgrade, EAST, and KSTAR. The mission of these three devices is distinctly different than that of DIII-D. ASDEX-Upgrade pioneered research on the compatibility of tungsten walls as a plasma facing material while EAST and KSTAR are superconducting devices focused on long-pulse development. The moderate size of DIII-D enables ρ^* scaling studies with larger devices such as JET (and eventually JT-60SA) that will enhance performance projections for ITER.

Impact Beyond FES Mission: In addition to the obvious benefits to fusion energy research, DIII-D Upgrade will provide a world-leading research facility for students, post docs, and scientists to conduct innovative plasma physics experiments. Research on the physics of 3D fields, magnetic reconnection, energetic particle stability and transport, and nonlinear MHD has far-reaching implications for understanding magnetospheric, solar, planetary, and larger-scale astrophysical plasmas. The cutting edge technologies required for RF and microwave systems, diagnostic development and model validation, enable training of a new generation of scientists with skills which will have broad impact beyond fusion and astrophysical research.

As the largest magnetic fusion facility in the U.S., DIII-D is a critical asset in maintaining U.S. leadership as the world fusion program prepares for the burning plasma era. DIII-D provides U.S. researchers with a highly flexible device capable of world-class science that will enhance U.S. influence in the ITER research program while simultaneously resolving issues to reduce risk in realizing ITER Q=10 operation. Additionally, the DIII-D program is well positioned to address key research gaps that are necessary to prepare the path for fusion energy development beyond ITER. While further progress can be made on critical issues with the existing facility, continued U.S. leadership in preparing for ITER operation is predicated on enhancing DIII-D capabilities (electron heating, off-axis current drive, advanced 3D coils, disruption mitigators, and diagnostics) to address the new challenges of burning plasma conditions.