DIII-D NATIONAL FUSION FACILITY

DIII-D National Fusion Facility Upgrade to Prepare for the Burning Plasma Era

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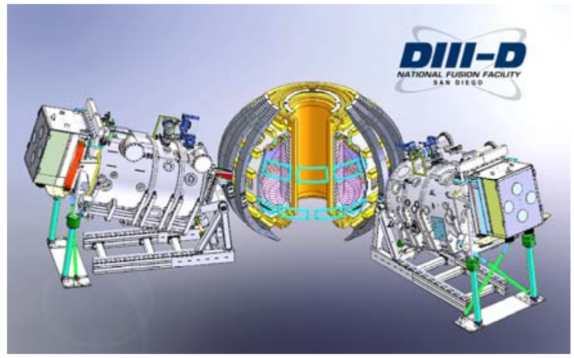
Upgrade of the DIII-D National Fusion Facility heating, current drive, and 3D shaping systems will significantly expand the technical reach of the facility to include conditions expected in future fusion energy systems and provide the framework to discover the underlying dynamics of performance-defining phenomena, test emerging theoretical concepts, and validate state-of-the-art simulations of burning plasma conditions in preparation for ITER.



The DIII-D National Fusion Facility Upgrade is *absolutely central* to the U.S. fusion program retaining its scientific leadership role in 1) advancing the fundamental understanding and predictive capability of performance-defining physics in burning plasmas; 2) providing solutions to ITER physics and operational issues that enable rapid progress to full performance at reduced risk; and 3) establishing the physics basis and promise of steady-state operation required for a decision on a Fusion Nuclear Science Facility and for future, economical deployment of fusion energy. With each Upgrade element providing compelling scientific opportunities to fusion scientists worldwide, the full package will be transformational, enabling the physics integration of several capabilities important to the success of ITER (e.g., ELM control in burning plasma conditions) and providing definitive U.S. world leadership in six ReNeW Thrusts. DIII-D Upgrade is *ready to initiate construction* with no technical barriers identified and systems of similar type and scope already deployed on DIII-D and other devices.

World-Leading Science: DIII-D Upgrade provides unique capabilities within the world fusion program, enabling access to new operational regimes with parameters relevant to burning plasmas. These new capabilities, combined with a comprehensive diagnostic set, will provide a scientific platform to resolve the most pressing scientific issues of fusion science, including:

- **Exploring the physics of the burning plasma state –** Torque-free, electron heating from alpha-particles will be a key distinguishing feature of burning plasma devices, resulting in significant changes to turbulence dynamics and associated transport from that experienced in present-day devices. A factor of 3 increase in absorbed electron cyclotron heating to 10.4MW and toroidally steerable neutral beam injection will permit access to this physics in relevant high performance regimes – dominant electron heating, low injected torque, low collisionality, and high β. The flexibility, precise deposition, and perturbative capabilities of these systems, combined with multiple profile and fluctuation diagnostics, will enable validation of turbulence transport models as T_e/T_i, ∇T_e, ∇T_i, and ExB shear are varied over a range spanning those expected in burning plasmas. These can then be utilized to guide and exploit ITER operation.
- **Understanding the conditions required for steady-state operation –** Realizing the promise of efficient, steady-state tokamak operation hinges on the ability to produce high β plasmas with self-consistent transport, stability, and bootstrap current profiles. Increased neutral beam power, deposition breadth, and duration (26MW total, 12MW off axis, 6s) and ECCD will enable examination of the non-linear coupling of current drive, transport, and stability in fully non-inductive plasmas for a range of current profiles as well as the ability to probe the steady-state performance limits ($\beta_N \sim 5$) of the best candidates. The high P/R~25 MW/m will also enable exploration of compatible exhaust mitigation solutions through radiation and geometry to test the principles of isolating a cold divertor plasma from the high performance fusion core.

- **Developing 3D optimization of the tokamak concept -** Due to enhanced effects of 3D fields at high β and low rotation, optimizing 3D fields is critical to successful operation of ITER. Enhanced flexibility from a new 3D coil set and power supplies will enable tests of predicted ideal, resistive, kinetic, and neoclassical responses by varying the toroidal/poloidal spectrum, resonant vs non-resonant fields, and radial localization. This knowledge will then be used to improve access to promising regimes such as QH-mode, and the simultaneous 3D optimization of ELM and rotation control while avoiding deleterious effects such as locked modes.
- **Anticipating effects of energetic fusion αs and high energy beams -** An upgraded diagnostic suite together with the ability to vary fast ion distributions enabled by heating upgrades will provide an unparalleled capability to explore non-linear evolution and redistributive effects of energetic particle instabilities to avoid deleterious effects in ITER and FNSF.
- **Eliminating the disruption risk for the tokamak –** Avoiding disruptions and mitigating those that do occur represents a grand challenge for burning plasma research. The 3D field and electron cyclotron upgrades will enable development of advanced control tools for disruption avoidance. New material injection systems will enable resolution of key ITER physics issues on thermal quench symmetry/duration and runaway electron dissipation and control. Together with improved 3D diagnostics and non-linear modeling, these capabilities will enable tailoring of the plasma quench to robustly protect against disruptive events.

Facility Upgrades: This research is enabled by significant enhancements in the DIII-D heating, current drive, 3D shaping, disruption mitigation, and diagnostics systems. The new capabilities, associated hardware elements, and unique physics accessed are summarized in the table below.

Table 1: DIII-D Upgrade Will Provide Access to Physics Unique Within the World Program

New Capability	Hardware Elements	Unique Physics Accessed	Other Facility Capabilities	Readiness
x3 Increase in EC Power *(10.4 MW absorbed)*	8 new 1.5 MW gyrotrons+ infrastructure	Ability to vary T_e/T_i, ∇T_e, and ∇T_i at ITER-like collisionality and β	AUG: 4 MW ECH	First article designed and on order
x2 Increase in Off-Axis NBI *(12 MW)*	2nd Off-Axis NBI	High β solutions with q_{min} from 1-2.5 for multiple τ_R	AUG: 5 MW OANB	First article deployed
35% Increase in Neutral Beam Power *(26 MW for 6 s)*	Increase NBI voltage to 105 keV	Access to high β_N (~5) with ITER relevant divertor heat flux (P/R~25)	JET: 35 MW, β_N ~3, P/R~12 NSTX: 8 MW, β_N ~7, P/R~10	Conceptual Design Phase – No Barriers Identified
High Power, Variable Torque NBI *(-8 N-m → 8 N-m with P_{NBI}=10-26 MW)*	Toroidally steerable NBI	Access β_N ~4 with a large range of rotation spanning expected ITER values		Conceptual Design Phase – No Barriers Identified
Expanded 3D Field Flexibility *(rotating n=1-4 & fixed n=6)*	New 3D coil set (2x12) & power supplies	Simultaneous ELM, multi-mode error field & RWM control	AUG: 2x8 coil - rotating n=1-2 & fixed n=4	Similar Type System Previously Deployed
Multiple Disruption Mitigation Systems	MGI (3x), SPI Rupture disks	Ability to vary/probe thermal quench and runaway dissipation	C-Mod, JET & AUG: MGI	Similar Type Systems Previously Deployed
Enhanced Measurements	Turbulent Flux 3D structure Fast Ion Imaging SOL flows	New insights into transport, 3D physics, fast ion transport, and boundary solutions		Conceptual Design Phase – No Barriers Identified

Impact on Research Needs, Gaps, and Opportunities: DIII-D Upgrade will enable the U.S program to establish definitive world leadership in several key research areas identified by recent FESAC reports (see table below). In particular, the facility upgrades will provide the U.S. with capabilities unparalleled in the world program in six ReNeW thrusts including:

- *Thrust 2*: The Advanced 3D coil set (large amplitude, rotatable n=1-4 perturbations) and toroidally steerable NBI (low NBI torque at high β) will enable quantitative understanding and optimization of the 3D physics leading to RMP ELM suppression and QH-mode while new rapid shutdown systems and diagnostics will provide unparalleled capability to develop suppression and dissipation solutions to disruption-induced runaway generation.
- *Thrust 4*: High power EC, increased off-axis NBI, toroidally steerable NBI and the Advanced 3D Coils will enable the fidelity required to simulate ITER scenarios characterized by dominant electron heating, low NBI torque, low ν^*, moderate-high β, and ELM suppression.
- *Thrust 6:* Highly flexible heating and torque input, Advanced 3D coils and substantial diagnostic upgrades will enable extensive validation of theory and simulation across a wide range of areas, including turbulent transport, 3D pedestal and ELM physics, disruption avoidance and mitigation, fast particle physics and boundary physics.
- *Thrust 3 and 8:* Increased off-axis heating and current drive (profile control) and total input power ($\beta_N \sim 5$) will enable unparalleled flexibility and capability in understanding the dynamics and control requirements of highly integrated, high β, fully-non-inductive plasma solutions, including fast particle physics.
- *Thrust 9 and 12:* Very high power input, increased shaping capabilities, and new diagnostics will provide unique opportunities to develop the science of SOL heat/particle flow and to explore the compatibility of high performance regimes with advanced divertor concepts.

Table 2: DIII-D Upgrade World-Leading Science on ReNeW Thrusts

Renew Thrusts (with Prioritization from 2012 Priorities Panel Report)	**Anticipated DIII-D Position in 2020** A=Definitive World Leader; B=World Leader; C=Strong Contributor; D=Moderate Contributor	**No Upgrades**	**EC 14.4 MW**	**NBI Upgrades**	**3D Upgrades**	**Disruption Mitigators**	**New Diagnostics**	**All Upgrades**
1 (Low)	Measurement techniques to understand and control burning plasmas	C					B	B
2 (High)	Control transient events in burning plasmas	B	B	A	A	A	A	A
3 (Mid)	Understand the role of alpha particles in burning plasmas	C	B	B	B		A	A
4 (Mid)	Qualify operational scenarios and the supporting physics basis for ITER	C	A	A	A			A
5 (Mid)	Expand the Limits For Controlling and Sustaining Fusion Plasmas	B	B	B				B
6 (High)	Develop predictive models for fusion plasmas supported by theory and challenged with experimental measurement	C	A	B	A		A	A
8 (Low)	Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas	B	A	A	B		B	A
9 (High)	Unfold the physics of the boundary layer plasma	D		B	C		B	B
10 (High)	Decode and advance the science and technology of plasma-surface interactions	D		B	C		B	B
12 (Low)	Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma	C	B	A	A		A	A
16 (Mid)	Develop the spherical torus to advance fusion nuclear science	D		C				C

International Context: Each of the Upgrade elements will provide research capabilities beyond what is available on any device worldwide (see Table 1 for comparative information). Collectively, DIII-D Upgrade will provide unparalleled capability in the world program to explore and optimize integrated performance limits under constraints expected in future devices such as ITER and FNSF (e.g., dominant electron heating, low NBI torque, ELM suppression).

Impact Beyond FES Mission: In addition to the obvious benefits to fusion energy research, the 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.

Cost and Schedule: The full project cost for the proposed set of upgrades is estimated to be ~$130M + ~$20M contingency. Opportunities exists which could offset a significant fraction of these costs through cost sharing of some Upgrade elements with ASIPP and conversion of DIII-D operating funds to project costs, resulting in an incremental cost to DoE of ~ $70M w/o contingency. This is a modest investment considering the value of the existing DIII-D facility is ~ $1B. Based on the maturity of the design and previous, practical experience with the various Upgrade elements, there is high confidence in the cost estimates. The total project execution time is scheduled for 4.5 years including design, fabrication, installation and system commissioning. Operation of DIII-D will continue in parallel with the design effort for the first 1.5 years of the project after which research operations will cease for 3 years with all efforts focused on the upgrade. Subsequently, the completion of DIII-D Upgrade will provide researchers with many new opportunities for scientific exploration at the 'full utilization' level of 26 weeks of research operation, 2 weeks of testing, and 4 weeks for calibration. The remaining time is required for preventive maintenance and system enhancements. Total annual facility operating costs are estimated at ~ $40 M.

Readiness: DIII-D Upgrade is *ready to initiate construction* with no technical barriers identified and systems of similar type and scope already deployed on DIII-D. See Table 1 for more information on each Upgrade element.

As the world program begins to prepare for the burning plasma era, the U.S. program is the world leader in several areas critical to the success of ITER. DIII-D Upgrade will provide U.S. researchers with a highly flexible facility capable of world-leading science that will enhance U.S. leadership and influence in the ITER research program while simultaneously resolving issues to reduce risk in realizing ITER Q=10 operation. As ITER is the #1 priority of the Office of Science, the "most important scientific questions" [*] *to address are those that will ensure ITERs success; DIII-D upgrade fulfills this role. In addition, DIII-D Upgrade will enable world-leading science in "many areas of research", "address needs of the broad community of users" within the U.S. fusion program, and generate a very high "level of demand" of that community.*

[*] B. Brinkman Charge to Chairs of the Office of Science Federal Advisory Committee, Dec '12