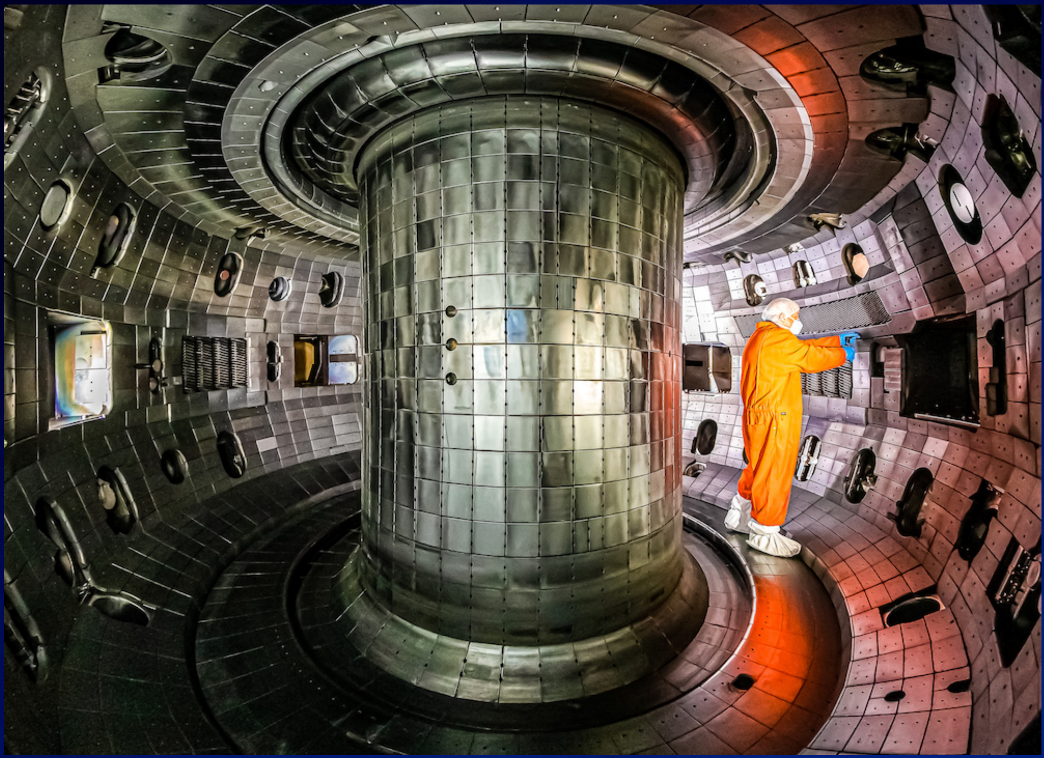


Consultation on the 5-Year Research Plan 2024 - 2029

DIII-D NATIONAL FUSION FACILITY

Purpose of this Document

This document provides an outline of the DIII-D National Fusion Facility Research Plan to be proposed for 2024 through 2029. The final proposed plan will be submitted to the U.S. Department of Energy (DOE) in September 2022, which will begin the formal DOE review process. As a DOE Office of Science User Facility, DIII-D serves the national interest and the fusion energy research targets of the DOE Fusion Energy Sciences program. The program is interested in views and ideas from across the U.S. fusion community, including public and private sector partners. Like all other Office of Science User Facilities, DIII-D is open to all interested potential users without regard to nationality or institutional affiliation.

The DIII-D 5-Year Research Plan is generated through a process of input from the User base and DOE. Consistent with the wider needs of the U.S. fusion energy program, this outline of the Plan is intended to allow feedback from prospective Users and others who participate in the development of fusion energy. Prospective Users are encouraged to submit comments on this outlined Plan, and to propose new or additional ideas. Some ideas might embed well within the Plan, and be performed under the Plan, but it is also possible to propose other activities that could use many of DIII-D platform capabilities to advance the path to commercial fusion.

Throughout the proposed Plan for the next period of performance, the facility seeks to close gaps in the design of a Fusion Pilot Plant, advance fusion materials and technology, and ensure that the ITER project is successful and that U.S. researchers are able to participate effectively. The sections below represent the research and governance areas covered by the Plan. A broad summary of each area is provided, supplemented by appendices that list specific facility capability improvements.

Over the experimental campaign of fiscal year 2021, over 400 professionals engaged directly in DIII-D research, with 230 performing their work on-site. The program presently features 50 graduate students and 41 postdoctoral scholars.

Information about DIII-D resources and capability: https://fusion.gat.com/global/diii-d/home

Submit Feedback: contact-d3d@fusion.gat.com

Closing Technical Gaps to Accelerate the Design of a Fusion Pilot Plant

In closing technical gaps for Fusion Pilot Plant (FPP) design, the DIII-D program leverages its ability for fast iteration to achieve comprehensive research advances. This includes rapid changeout of tokamak divertor geometry, and investigation of new plasma scenarios with a strong supporting cast of diagnostic and theory and modeling capabilities. A substantial rise in heating and current drive capabilities, plasma shaping and toroidal field will provide a basis to close

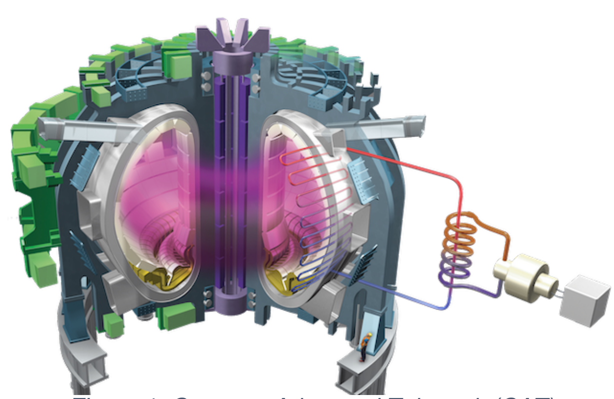


Figure 1: Compact Advanced Tokamak (CAT)

the gap on reactor physics regimes, in order to resolve the required high performance solutions and compatibility power handling and plasma facing components.

The *Advanced Tokamak* approach to magnetic confinement fusion applies strong plasma shaping and non-inductive current drive to create stationary (steady state) scenarios conducive to the performance requirements of a Fusion Pilot Plant (FPP). The proposed research plan will perform experiments that validate modeling and simulation codes necessary to design plasmas for a FPP. This includes transport of energetic particles, as the high number density of charged fusion products represents one of the unique performance aspects of any FPP.

The optimal advanced tokamak scenario for an FPP demonstrates the ability to operate in ways that passively avoid edge localized modes. Additional experiments will develop plasma control techniques to account for evolving plasma stability and other transient phenomena.

Power handling in a FPP is a high priority gap influencing design options. Application of a new *Modular Divertor* approach enables rapid iteration of divertor geometry by minimizing the in-vessel structure changes required. Over the Plan, a series of three divertors are proposed, progressively optimizing divertor closure to validate exhaust handling models for FPP design.

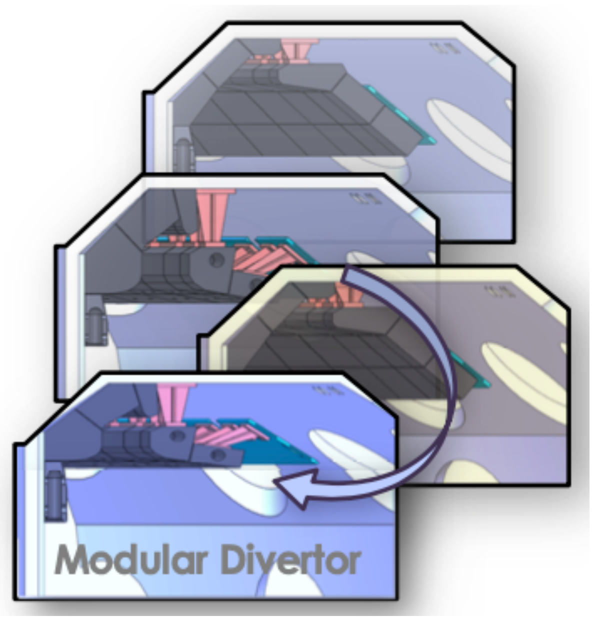


Figure 2: The Modular Divertor approach allows for rapid iteration of divertor geometry to close gaps in exhaust handling.

Within the divertor research series, the ability to cycle reactor materials allows further demonstration of erosion and material migration behaviors. Heated tiles will elevate material temperatures to the range expected across FPP parameter space. Within the main chamber, the Plan provides for installation of new limiter surfaces, including mid-Z and high-Z options (Z is atomic number, with mid-to-high Z values expected for an FPP due to high material heat flux tolerance and low tritium absorption required), and a Wall Interaction Test Station.

The Plan utilizes the control and shape flexibility of DIII-D to establish the confinement and stability properties of the *Negative Triangularity* scenario. This reverse-D type of shape provides many desirable characteristics relevant for a FPP, including the ability to direct exhaust into the low-field side of the tokamak where flux expansion reduces power handling requirements, and the potential for passive avoidance of edge localized modes.

Advancing Technologies Necessary for Future Fusion Reactors

The Plan provides new emphasis and expansion of DIII-D resources and capabilities that provide for fusion energy technology development. Just as it advances the science program, the ability to rapidly iterate systems and technologies in the plasma environment provides for fast determination of viability. Key FPP risk reduction technologies are fully accessible, including areas of runaway electron mitigation and associated plasma and tokamak control needs.

Available diagnostic coverage is expected to reduce significantly as we progress along the path to an electricity-producing fusion reactor. DIII-D research will demonstrate the ability of tokamak plasma models to act as synthetic diagnostics providing control input signals for parameters that are largely not measurable in a reactor. Dedicated tokamak access will enable technology proponents to test hardware on DIII-D plasmas such as new reactor diagnostic techniques, with the added ability to integrate their measurements into the plasma control system.

Efficient current drive is required to achieve a steady state scenario in a FPP. The Plan advances heating and current drive through three electromagnetic wave injection techniques: *High-field Side Lower Hybrid*, *Helicon*, and *Electron Cyclotron*. The Plan also establishes access such that future developments can be tested, e.g., novel antenna designs and material compositions.

Appropriate risk mitigation for an FPP requires developing high confidence in device subsystems that provide for plasma quenching in a manner that protects the facility. Shattered pellet injection technology for disruption mitigation will be advanced with an early focus on application in ITER. Passive facility responses are preferred as part of an innately protected reactor. The Runaway Electron Mitigation Coil is one such a passive device, as it would use the electromagnetic field induced by runaway electrons to create a magnetic field perturbation that deconfines them, thereby preventing the exponential growth in their population.

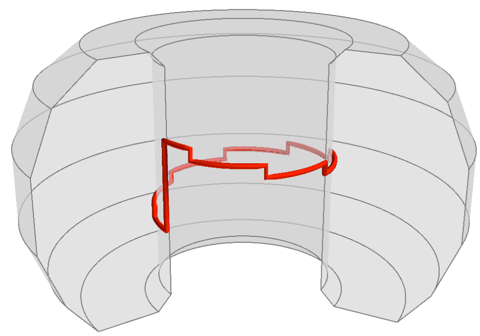


Figure 3: The Runaway Electron Mitigation coil (red) is installed across the center post to generate a helical magnetic perturbation that provides for the deconfinement of runaway electrons.

Development of technologies associated with particle and power control center on pellet fueling approaches. The injectors will interface with the plasma control system as required to demonstrate density target sustainment. Materials technology advances will utilize the same auxiliary systems (heated tiles, etc.) as employed in the FPP advanced tokamak research line, and combine with a test station, sample facilities and other tile test technologies to resolve compatibility between materials and the plasma environment.

Research to Prepare for a Successful ITER Program

The ITER research program is a designated high priority area for the U.S. Department of Energy. The DIII-D program proposes to play a meaningful role in the preparation for the early phases of ITER operation. Pre-fusion Power Operations (PFPO) of ITER require capabilities in plasma current ramp up, off-normal event response, and disruption mitigation systems. ITER scenario development within the DIII-D Plan, in conjunction with disruption mitigation technology demonstrations, serve these important needs.

As the ITER program progresses, DIII-D research will contribute to the validation of tokamak models that are used to predict (and project) its performance. This includes the prediction of heat flux widths as necessary to prepare an exhaust handling scenario. Additional work in density control scenarios will identify plasma conditions that maximize the pressure of the ITER pedestal. Integrated, high-performance scenarios that integrate core and edge will be established on DIII-D, applicable to both the Q = 10 and the Q = 5 targets of ITER.

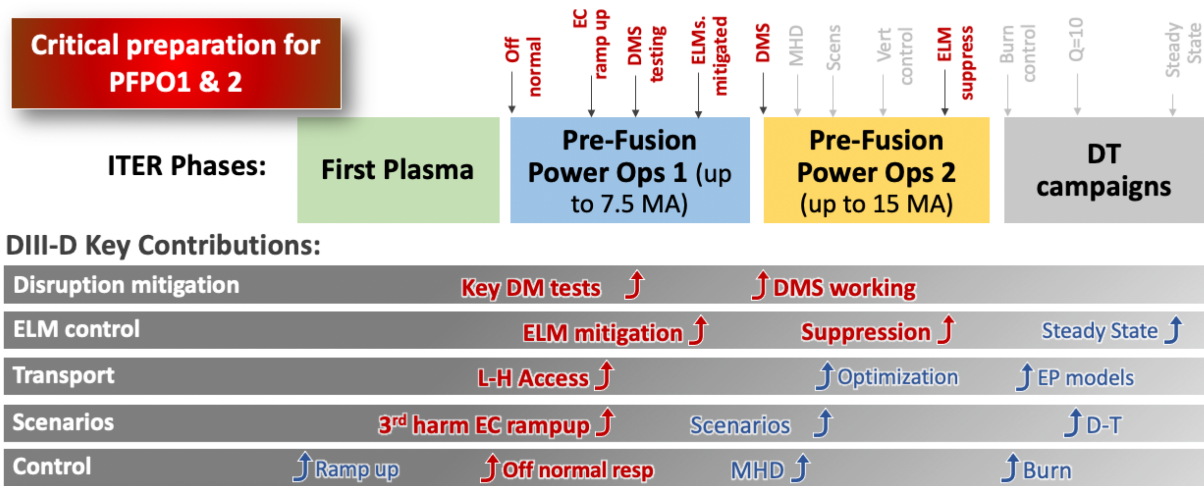


Figure 4: Sequencing of DIII-D research plan to contribute to ITER operational phases.

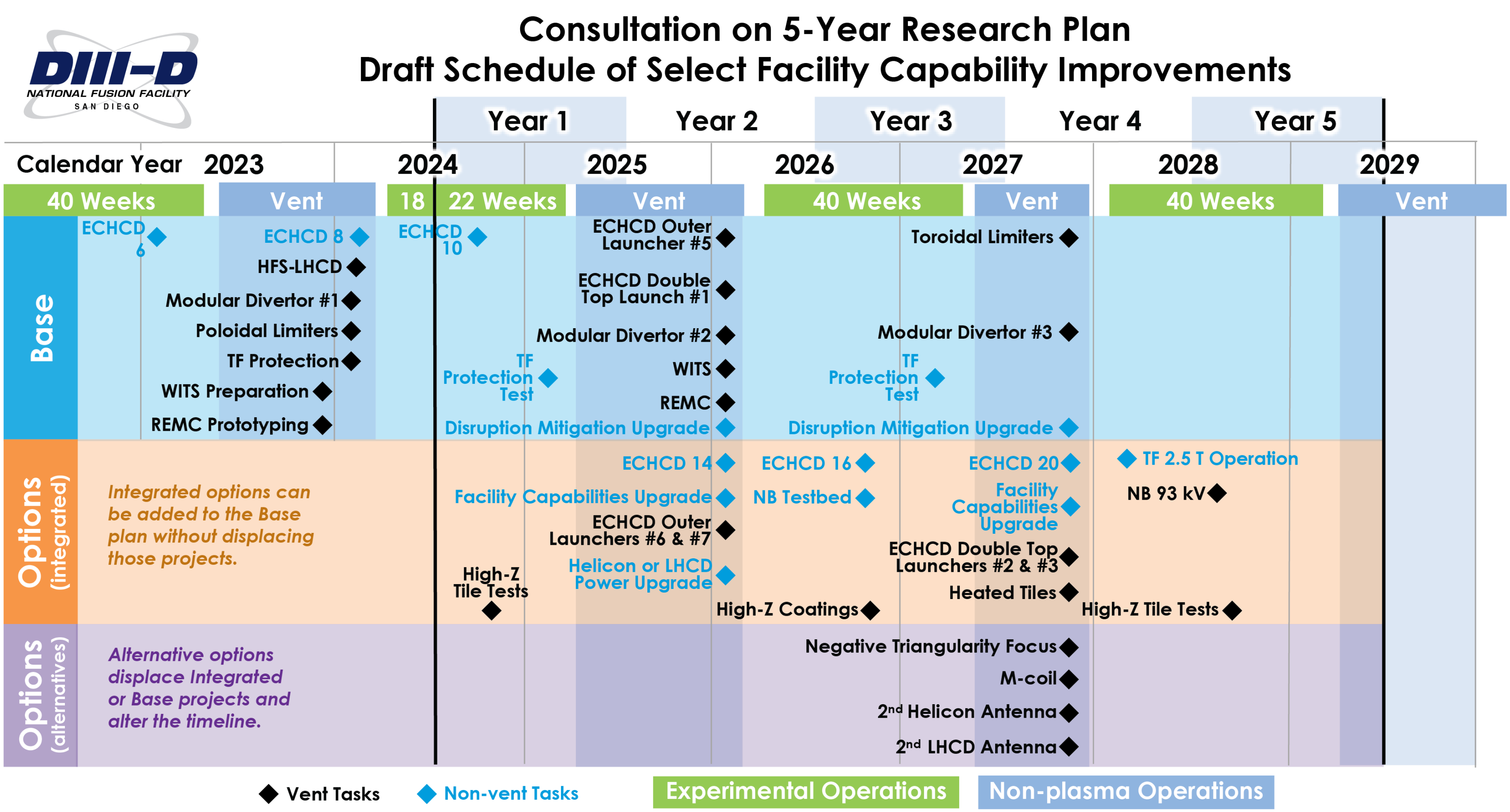
Governance and User Engagement

The DIII-D program enters the 2024 – 2029 performance period with many new opportunities for global researchers to engage with the facility. New modes of interaction include the ability to perform work that is either non-proprietary (the present standard) or proprietary. As with other User Facilities, any approved non-proprietary work is allocated resources free-of-charge, while proprietary work requires full cost recovery. Both options are available to all organizations.

The international nature of the DIII-D program is maintained in this Plan. The Program Advisory Committee continues to call upon leaders across the global fusion energy community to perform an annual review of the DIII-D program. Researchers, including engineering personnel, are welcomed to participate in facility projects.

As an open research facility, the DIII-D program dedicates resources to diversity, equity, and inclusion. The DIII-D program will continue to foster equitable opportunities to the User base through active measures. A Diversity, Equity, and Inclusion Panel will continue to operate across this new Plan, with Panel membership remaining open to all Users. Relevant seminars will continue to be made available to all Users. Dedicated resources, such as the Student Experiment Run-time allocation, are provided as necessary to ensure workforce development.

Appendix A: Draft Schedule of Select Facility Capability Improvements



Appendix B: Summary of Select Facility Capability Improvements

The following table lists the projects that are shown in the schedule of Appendix A.

Project Name	Category	Description
ECHCD 6	Address Fusion Pilot Plant and ITER Needs	**Electron Cyclotron Heating & Current Drive (ECHCD) System** Establishes capability for producing FPP and ITER relevant regimes. Increases the number of gyrotrons from 6 to 20, leading to 14 MW of injected EC power (and 20MW of RF with planned helicon and LHCD developments). Provides injection at outer (low-field) and vertical-top locations to maximize current drive effectiveness.
ECHCD 8		
ECHCD 10		
ECHCD 14		
ECHCD 16		
ECHCD 20		
ECHCD Outer Launcher #5		
ECHCD Outer Launchers #6 & #7		
ECHCD Double Top Launch #1		
ECHCD Double Top Launchers #2 & #3		
Modular Divertor #1	Demonstrate Plasma Exhaust Solution Compatible with High-performance Core	**Modular Divertor Research Program** Executes a staged divertor implementation to address issues of exhaust power handling as a function of divertor geometry. Provides for comprehensive diagnostic coverage to accelerate experimental program.
Modular Divertor #2		
Modular Divertor #3		
HFS-LHCD	Address Fusion Pilot Plant Needs	**High-field Side (HFS) Lower Hybrid Current Drive (LHCD) System** Completes first demonstration of lower hybrid current drive through injection from a launcher mounted to a tokamak center post (high-field side). Optimization of current drive informs options for FPP design.
LHCD Power Upgrade		
2nd LHCD Antenna		

Project Name	Category	Description
WITS Preparation	Demonstrate Plasma-facing Material Compatibility	**Wall Interaction Tile Station (WITS) System** Establishes capability to expose novel materials to controllable levels of plasma heat flux. Material extraction is performed through an airlock that allows for in-situ measurements prior to exposing samples to atmosphere.
WITS		
REMC Prototype	Address Fusion Pilot Plant Needs	**Runaway Electron Mitigation Coil (REMC)** Demonstrates ability to mitigate growth of runaway electron population following a disruption. Passive coil is charged by the current of the seed runaways, generating a magnetic field distortion that leads to their deconfinement.
REMC		
Poloidal Limiters	Demonstrate Plasma-facing Material Compatibility	**Plasma-facing Material Research Program** Determines compatibility of candidate materials through implementation in both main chamber and divertor exposure regions, including control of material temperature.
Toroidal Limiters		
High-Z Tile Tests		
High-Z Coatings		
Heated Tiles		
TF Protection	Address Fusion Pilot Plant Needs	**Toroidal Field (TF) Magnet System** Expands capabilities of toroidal magnetic field to support new plasma parameter regimes of relevance to FPP design.
TF Protection Test		
TF 2.5 T Operation		
Disruption Mitigation Upgrade	Address Fusion Pilot Plant and ITER Needs	**Disruption Mitigation Research Program** Two-stage capability upgrade demonstrating viability of pellet injection and alternative disruption mitigation technologies in serving requirements for FPP and ITER.

Project Name	Category	Description
Helicon Power Upgrade	Address Fusion Pilot Plant and ITER Needs	**Helicon Current Drive System** Completes demonstration of current drive through helicon wave injection. Provides flexibility in access to steady state scenarios informing FPP and ITER plasma design.
2nd Helicon Antenna		
NB Testbed	Address Fusion Pilot Plant and ITER Needs	**Neutral Beam (NB) Heating and Current Drive System** Extend the heating and current drive power from this flexible system. A testbed is accessible for related particle source technology development.
NB 93 kV		
Facility Capabilities Upgrade	Facility Support	**Site Power Upgrade** Expands site power infrastructure to support associated heating and current drive systems.
Negative Triangularity Focus	Address Fusion Pilot Plant Needs	**Negative Triangularity Focus** Demonstrates the performance characteristics of the negative triangularity plasma scenario across the exhaust parameter regime of relevance for FPP design. An integrated divertor allows for the generation of negative triangularity plasmas at full facility power and energy confinement.
M-coil	Address Fusion Pilot Plant and ITER Needs	**Midplane Coil (M-coil) for Magnetic Perturbations System** Establishes conceptual basis for the application of edge magnetic field perturbations as a pedestal and edge localized mode control mechanism. This in-vessel coil centered on the outboard midplane work in concert with existing perturbation coils to extend the spectral range of applied fields, thereby demonstrating the optimal control application as needed for FPP design.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Award(s) DE-FC02-04ER54698.