

DIII-D: A Public Facility's Role in Enabling Fusion Commercialization

R. J. Buttery¹, T. Abrams¹, J. Coburn², F. Effenberg³, S. Hong¹, D.C. Pace¹, C.C. Petty¹, A.C.C. Sips¹, D. Schissel¹, F. Scotti⁴, D. Shiraki⁵, G. Sinclair¹, B. Van Compernelle¹, R. Wilcox⁵, S. J. Wukitch⁶ and the DIII-D Team.

¹General Atomics, San Diego, USA, ²Sandia National Laboratory, NM, USA, ³Princeton Plasma Physics Laboratory, USA, ⁴Lawrence Livermore National Laboratory, USA, ⁵Oak Ridge National Laboratory, TN, USA, ⁶Massachusetts Institute of Technology, MA, USA.

Abstract. The U.S. Fusion Roadmap [1] envisages the first fusion power plants to be delivered by the private sector. This goal requires major advances not only in the plasma core, which must attain much better energy confinement, control and power handling than devices today, but also in a range of even more challenging technology innovations. Also, the compatibility between these techniques, which interact with and constrain each other, must be resolved, as well as their projection to the reactor scale. The strength of DIII-D as a publicly funded facility is its broad capabilities to experiment to learn what works, and to measure and understand how to project and integrate solutions. DIII-D has thus pivoted its program to support the private sector and accelerate fusion technology testing [2].

I. Capabilities to Address Commercialization

To assess new fusion technologies, DIII-D is increasing its heating, current drive and shaping capabilities, with new RF schemes, increased electron cyclotron power and neutral beam RF sources to provide reactor-relevant conditions in core and divertor in terms of collisionality, opacity, β , rotation, plasma equilibration and current distribution (Fig. 1). This combines with an agility to rapidly install components, and develop new configurations, and an unparalleled, comprehensive diagnostics set with over 50 different measurement techniques. This combination of relevance, flexibility and measurement provides a unique platform to rapidly develop and test new techniques for fusion, provide a basis to understand and project them to fusion reactors, and resolve compatibility with and constraints on core solutions. Further, a new framework has been developed to enable private sector companies to sign up to use DIII-D, engaging on a non-proprietary and equal basis to other users, with commitment to publish any DIII-D derived data in the public domain – 19 have joined and are actively engaged in research.

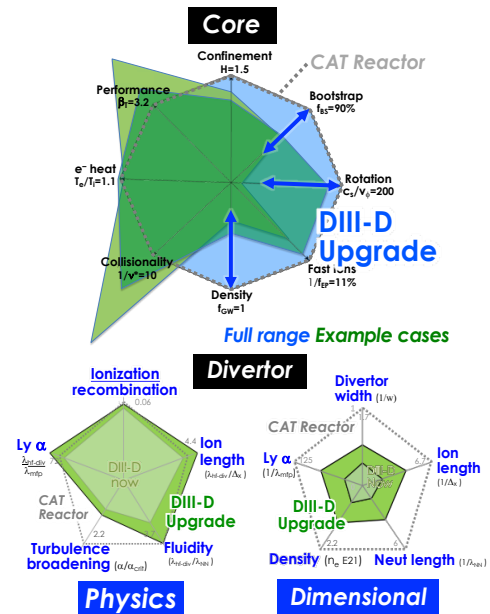


Fig. 1: Physics parameter access in DIII-D

II. Fusion Technology Testing at DIII-D

II.1 Materials

Materials development is a key technology gap for commercial fusion pilot plants (FPPs). Exposure testing of plasma-facing materials (PFMs) in an integrated fusion environment (high heat/particle flux, B-field, surface temperature, E&M forces, etc.) is essential for qualification and technology readiness level advancement. DIII-D is uniquely equipped to conduct such studies, with tests ranging from ~mm samples to full tile installments, supported by world-leading PMI diagnostics [3].

DIII-D recently completed a 2-year materials testing campaign for systematic qualification and down-selection of novel PFM candidates from public and private industry users. This exposed 61 novel materials in 180 samples from 17 institutions (e.g. Fig. 2), including 4 private industry users, in the Divertor Materials Evaluation System (DiMES) [4] using repeatable reference Ohmic, L-mode, and

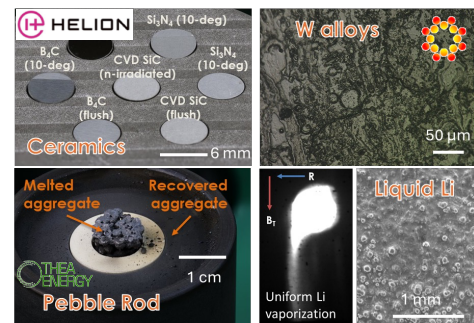


Fig 2. Some material samples tested on DIII-D.

ELMy H-mode plasmas for comparability across exposures. Conditions mimicked power plant first wall (0.2-2.5 MW/m²) and divertor (10-15 MW/m² inter-ELM) loadings.

A selection of noteworthy results [5,6] emerged: The first exposure of a liquid lithium (Li) capillary porous structure (CPS) in a tokamak demonstrated uniform Li vapor emission and suppression of droplet ejection when pre-heated to 350 °C, which has motivated interest in larger-scale liquid-metal testing. A variety of tungsten (W) architectures demonstrated good material integrity, with additively-manufactured W, W-Re(3%) alloys, and industry-developed K-doped W exhibiting near ITER-W-like resilience. On the private industry side, the first tokamak demonstration of a boron pebble rod concept was conducted by Thea Energy to test pebble ejection and recapture. A variety of ceramic candidates were tested by Helion Energy. High frequency (~75 Hz), high energy ELM impacts (>40 MW/m² on angled samples) provided a clear down-selection to CVD SiC under conditions close to those expected in Helion’s Polaris device. Tokamak Energy tested a variety of industrial W alloys and additively-manufactured W-Ta alloys, with the W-Ta alloys exhibiting a unique near-surface damage morphology. Finally, Avalanche Energy tested a variety of multi-principle element alloys (MPEAs) to assess preferential sputtering under conditions relevant to their Orbitron device.

Together, these results identify class-specific performance limits and provide benchmarks for predictive PMI modeling, material down-selection, component validation, and standardized DiMES/MatDB4Fusion datasets for AI/ML-guided plasma-facing materials development.

II.2 Power Handling

A new divertor has been designed to address the challenge of robust divertor detachment while maintaining a hot plasma core. This “Chimney divertor” will be installed in 2026 and employs a pump duct positioned part way up the leg in a tightly baffled divertor slot (Fig. 3). By allowing recycled neutral particles from the exhaust plasma to accumulate near the target, they contribute to dissipation processes that are proportional to neutral density, cooling the plasma before it contacts the material surface. Neutrals are then removed further upstream before they migrate back to the main chamber, so that the neutral density is low approaching the core plasma.

Simulations (Fig. 4) predict a passively stabilized detachment front and detachment access at lower $n_{e,sep}$ relative to a pump duct positioned closer to the target [7,8]. This has potential to reduce requirements on the plasma-facing materials in a reactor. Experiments will explore detachment access, pumping characteristics, T_e -dependent dissipation processes and core-edge integration with multiple plasma scenarios to assess the characteristics of mid-leg divertor pumping for future tokamaks. A future upgrade including reactor-relevant materials in the divertor slot is being planned.

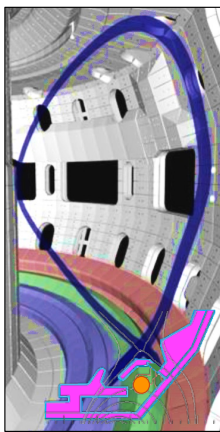


Fig. 5: Negative Triangularity closed pumped divertor.

Separately, a closed and pumped divertor is now planned for negative triangularity plasmas (Fig. 5), providing a vital test of it’s potential to radiatively reduce heat flux into the SOL and ease thus detachment, without ELMs in 2028.

II.3 RF Systems and Current Drive

Efficient off-axis current drive (CD) is key for economical steady-state fusion. The optimal choice of an actuator is not straightforward; each has pros and cons in terms of efficiency, launcher survivability and footprint, and ease of power coupling and steering. Three current drive technologies have been pioneered: top launch electron cyclotron CD, high-field-side lower hybrid CD (LHCD), and helicon ultrahigh harmonic fast wave. ECCD is easy to launch, steerable and highly localized, but its efficiency is low. However, experiments at DIII-D have demonstrated how a near-vertical ray increases the resonant

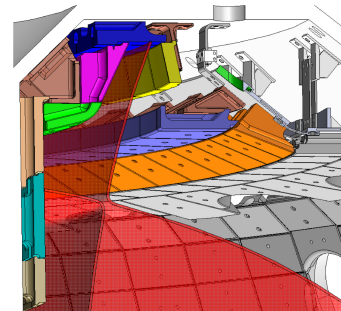


Fig 3. CAD of Chimney divertor with separatrix.

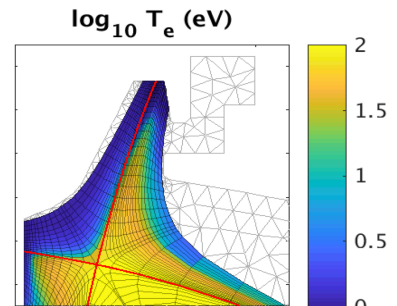


Fig 4. Simulated T_e contours in the Chimney divertor using SOLPS-ITER[7] demonstrating a cold divertor target and hot separatrix with 10eV detachment front stabilized near the pump duct.

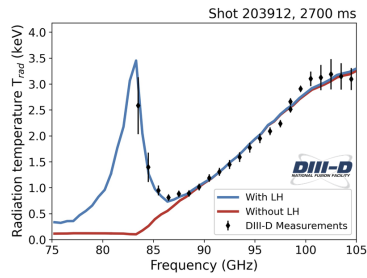


Fig. 6: Predicted and measured response on the ECE diagnostic for HFS LHCD absorption

interaction length, allowing for absorption further out in the tail of the electron distribution, boosting CD efficiency by 50-100% [9].

LHCD has the highest efficiency with a narrow profile, but typically drives current far off-axis. A first-of-a-kind high-field-side (HFS) LHCD system is operational which is predicted to have improved wave penetration to the core and high single-pass absorption. Initial results corroborate these predictions [10] (Fig 6). HFS encounters more quiescent edge conditions providing easier coupling and lowering the thermal load on antenna structures.

Helicon CD (fast waves at lower hybrid frequencies) is a third new RF actuator [11], with intermediate efficiency but propagation into higher density plasmas than LHCD. Experiments featuring a comb-line traveling wave antenna have shown clear heating signatures in L- and H-mode, and demonstrated helicon CD for the first time [12] (Fig. 7).

DIII-D is further opening up its RF infrastructure for dedicated tests, e.g., high-power microwave drilling (Terrawave), and gyrotron conditioning (MPP). Training of private industry staff on operation is another area of support expected in the near-term.

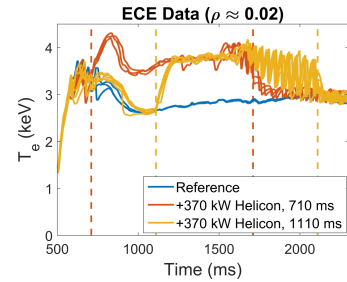


Fig. 7: Core T_e evolution in L-mode plasmas showing strong heating and early onset of sawteeth due to core current drive.

II.4 Pellets Fueling and Safe Quenching of Fusion Plasmas

Pellet innovations have been developed to fuel and safely quench fusion plasmas. Burning plasmas will be highly opaque to neutrals, necessitating pellet injection as a core fueling source, which along with heating and current drive, is a key actuator for controlling plasma profiles to optimize performance. Capabilities for real-time control of the pellet size and injection rates have been implemented on DIII-D, allowing variation of the particle source to meet control requirements based on plasma conditions.

Adaptive model-based control of the pellet and gas injection have been designed via simulation and tested in DIII-D plasmas, demonstrating robust results that can be applied to future devices. In addition to core fueling applications, DIII-D continues to explore new particle injection methods for safely quenching fusion plasmas. Novel particle delivery via room-temperature solid pellets consisting of payloads within a thin-walled “shell”, the addition of lithium coatings to minimize perturbation of the plasma edge prior to core particle delivery, as well as layering of conventional cryogenic pellets, are being explored.

II.5 Power Plant Diagnostics

Fusion power plants (FPPs) require compact, neutron-hard, non-optical, continuously operating diagnostics. DIII-D serves as a critical platform to test these, validating against established techniques.

A good example is the Fiber Optic Bolometer (FOB), engineered with Nusenics.

Conventional bolometers are susceptible to temperature fluctuations and electromagnetic interference (EMI), and optical fibers experience degradation and darkening under neutron irradiation. The FOB architecture mitigates this utilizing a Fabry-Perot interferometer that measures the phase shift induced by the thermal expansion of a silicon pillar, coupled to a gold disk to convert incident radiation into temperature variations (Fig. 8). The phase shift is unaffected by darkening of the optical fibers, thereby enabling robust, in-situ calibration (Fig. 9).

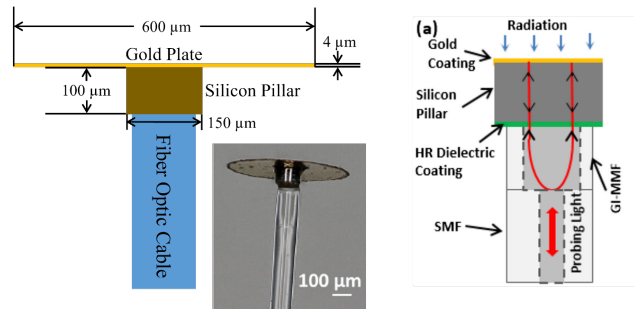


Fig. 8: Fiber Optic Bolometer tested at DIII-D with Fabry-Perot interferometer concept developed by Nusenics.

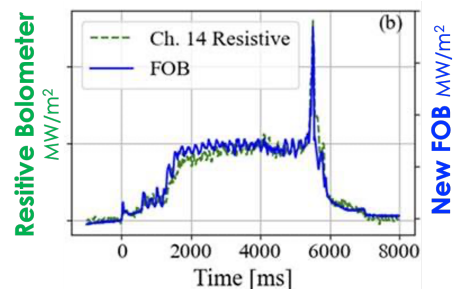


Fig. 9: Validation of new diagnostic against conventional bolometer array.

DIII-D is now working with industry partners to make a standardized, modularized, and miniaturized diagnostics to control plasma, with a modular diagnostic platform with the Next Step Fusion, and a diagnostics embedded divertor cassette with X-wave innovation and Vitzro NexTech.

II.6 AI and Digital Twin (DT) Technology

DIII-D provides an ideal platform for the development and validation of DT technology. DTs have emerged as transformative tools, able to provide real-time insights into operations and prediction, potentially revolutionizing experiment planning, control, and optimization in fusion. The DIII-D DT [13] leverages existing digital infrastructure and new capabilities, integrating advanced modeling, machine learning surrogate models, and real-time diagnostics. This will facilitate the validation of new models and control strategies, reducing risks associated with experimental trials and accelerating the development of novel technologies. At the heart is the virtual Plasma Control System (vPCS), derived from the facilities existing PCS. This representation includes GUI interface and is compatible with the experimental PCS. Thus, it is possible to run both historical experiments as well as new plasma scenarios in the DT. For any successful virtual scenario, vPCS inputs can be provided to the experimental PCS to run the same plasma discharge in DIII-D. A fast neural net representation of a kinetic equilibrium reconstruction code calculates the plasma evolution based on vPCS outputs while a different neural net leverages this equilibrium data to calculate fast ion heat flux deposition to the first wall. This usage of very fast surrogate model allows the DIII-D DT to be highly interactive.

Integration with NVIDIA Omniverse is a central component of the DT enabling detailed 3D visualization of tokamak plasma behavior and heat flux deposition to the first wall (Fig. 10). Digital models of DIII-D components, such as the neutral beam system, combined with high-fidelity geometry derived from laser scans of the tokamak's first wall, ensure accurate representation of the physical device. This newly created DT framework leverages DIII-D's advanced control systems and extensive diagnostics to demonstrate the feasibility of coupling predictive modeling capabilities directly to experimental workflows, actively informing operations in real time. Based on the very successful initial version, work has begun on extending these capabilities, incorporating enhanced models, refining the PCS integration, and expanding visualization features. By providing a flexible and robust framework, this research lays the foundation for future developments in tokamak modeling, while also serving as a backbone for other groups to integrate their workflows and models into a unified DT infrastructure.

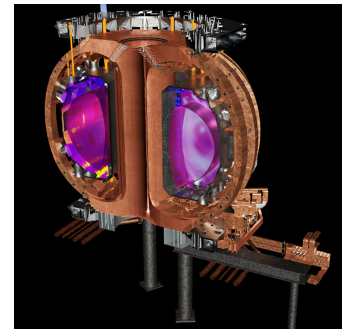


Fig. 10. The DIII-D digital twin utilizes the virtual PCS, fast surrogate models, and NVIDIA Omniverse to achieve a rapid interactive capability to explore new plasma scenarios.

III. Discussion and Conclusion

This paper has identified some of the key ways in which DIII-D is developing vital fusion technologies, utilizing unique flexibilities and diagnostics to test and understand behavior in the plasma environment. This work also includes with extensive plasma research, not discussed in this paper, to address critical challenges of performance and core behavior. These elements combine with an opening up of the facility to private sector engagement with 19 private fusion companies now exploiting DIII-D to test critical elements of their approach. DIII-D is thus providing unique and critically needed data for the fusion commercialization agenda to accelerate the path to fusion energy.

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