UPGRADING DIII-D TO CLOSE THE GAPS TO FUTURE FUSION REACTORS

[1]C.C. PETTY for the DIII-D TEAM

[1]General Atomics, San Diego, California, USA

Email: petty@fusion.gat.com

The DIII-D program is pursuing an ambitious plan to rapidly close critical design gaps to a Fusion Pilot Plant (FPP) including the crucial issue of integrating performance and exhaust solutions. Over the next several years, three major facility upgrades will allow DIII-D to access reactor-relevant physics regimes with increased flexibilities. The electron cyclotron heating will be doubled to 7 MW of injected power using 10 gyrotrons to furnish low-torque electron heating and current profile control. The upper Shape & Volume Rise divertor will be swapped out for a Dissipation Focused Divertor to investigate detachment front stability while preserving high core confinement using upstream cryopumping with a novel “chimney” divertor. Finally, as early as 2027 there will be a full wall change out of the graphite walls to decarbonize DIII-D and test the compatibility of reactor relevant materials (predominantly Tungsten) with advanced core-edge scenarios. Additional upgrades that have been proposed include a closed, pumped lower divertor at large major radius to allow negative triangularity plasmas to explore detached conditions, increasing the NBI power to 25 MW using new RF sources, installing a runaway electron mitigation coil, and the first test of spin polarized fusion in a magnetically confined fusion device. Together these elements will enable reactor solutions to be pioneered and projected with confidence.

DIII-D is a flexible platform to address plasma interacting material and technology issues in an FPP-relevant environment. Changing the plasma-facing wall from carbon to metal (predominantly Tungsten) tiles, which could occur as early as 2027, represents an exciting opportunity for DIII-D to address key plasma-material interaction and core-edge integration challenges for fusion energy [1]. Decarbonizing the wall environment in DIII-D will facilitate material testing by eliminating mixed-material uncertainties and subjecting materials to particle bombardment more representative of what is expected in a reactor (both in impact energy and particle composition). Key information on the effect of transients on erosion and core impurity accumulation (including ELM "burn-through") will be instructive in defining operational windows for ITER and other devices that maximize component lifetime and plasma stability. Using DiMES coupons or tile installations, testing of reactor-relevant, innovative materials (see Fig. 1) at low carbon levels will enable more insight into the performance of various fabrication routes and resolve key material behavioral questions. To achieve decarbonization at the earliest possible date, Tungsten tiles for primary surfaces will be supplemented with other metals tiles (e.g., stainless steel, TZM) for secondary surfaces, with the latter being upgraded to Tungsten at a later time.

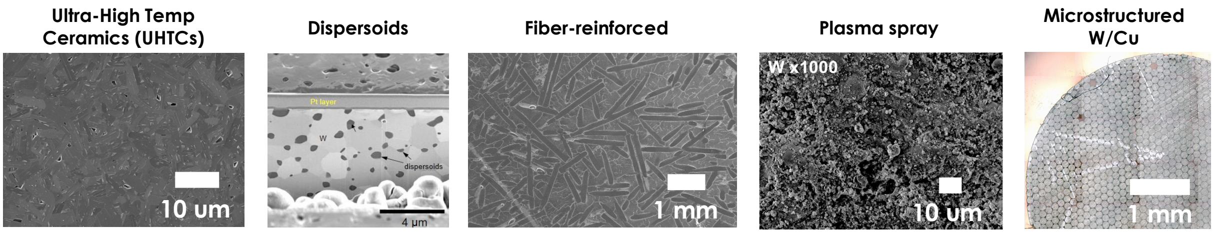

Figure 1. Examples of relevant, innovative materials that can be tested in decarbonized DIII-D environment.

Changing to an all-metal wall on DIII-D will also advance the core-edge integration mission through investigating a diverse array of feedback loops in transport, stability and radiation caused by changes in the plasma conditions. DIII-D experiments will therefore address key operational questions for ITER and FPP in the presence of reactor-relevant materials by systematically probing dissipative exhaust regimes, integrating reactor-relevant edge and pedestal conditions, as well as continuing to develop and qualify new core solutions. The all-metal wall will require new constraints for how to operate DIII-D, for example, gas puffing and/or impurity seeding may be necessary from the onset of the discharge, new and flexible wall conditioning capabilities may be needed, and the access conditions to different regions of plasma phase space may be impacted. Developing strategies to establish high performance scenarios in a decarbonized, high-Z impurity environment will enhance our integrated predictive modeling capability, including wall-to-core impurity transport, and provide critical data to develop models to project behavior to future reactors. There will also be opportunities for enhanced collaboration and joint experiments with international facilities and working groups to fill the knowledge gap and enhance key datasets.

Heating and current drive upgrades on DIII-D will address several core-physics gaps for a compact FPP. Enlarging the ECH system to 10 gyrotrons with 7 MW injected power will help control high-Z impurities and expand the range in plasma current and beta over which reactor-like conditions can be achieved, i.e. $T_e \geq T_i$, electron-ion coupling, low rotation and low collisionality. The expansion will add two gyrotrons at 117.5 GHz and two gyrotrons at 104/137/170 GHz, compared to six existing gyrotrons at 110 GHz, with the higher frequencies enabling heating and drive current in higher density plasmas and/or higher magnetic fields via top launch and/or O-mode injection [2]. Additionally, a 1 MW high-field-side LHCD system is being installed [3], which has the potential to provide efficient off-axis current drive consistent with advanced tokamak scenarios due to improved wave accessibility and penetration, and a 1 MW helicon system that has shown clear evidence of heating and current drive [4]. Research is also ongoing to develop new RF sources for the neutral beams, which could increase the power and reliability of this system in the future. The upgraded heating and current drive systems will expand the range of current profiles studied on DIII-D, the goal being to investigate the optimal profiles in FPP (both inductive and steady-state) for a high beta limit, good energetic particle stability and high confinement.

DIII-D is replacing its upper divertor with a novel "chimney" design for improved location control of divertor detachment and power dissipation while preserving high core confinement. For the past two years, a Shape & Volume Rise divertor with a core-edge integration focus has been used to investigate Super H-mode pedestal conditions with high density, high pressure and low collisionality. In 2025, a different Dissipation Focused Divertor is being installed for a unique investigation of detachment front stability from upstream cryopumping using an innovative "chimney" pump concept [5] (see Fig. 2). The goal is to maintain a hot plasma core while simultaneously achieving a cold divertor target by stabilizing the detachment front between the target and X-point via upstream pumping in a tightly baffled divertor slot. Boundary plasma and neutral modeling with both SOLPS-ITER (including kinetic neutral physics) and UEDGE (including the physics of cross-field drifts) predicts that this concept will dissipate significant power through a high-pressure region of main ion neutrals in the divertor slot, reducing the need to inject edge radiating impurities and thus minimizing core fuel dilution.

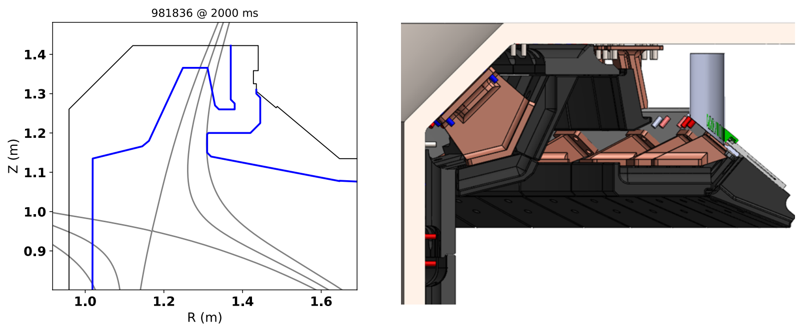

Figure 2. Drawings of new "chimney" divertor showing separatrix location.

Negative triangularity plasmas with H-mode like confinement offer a simpler path to core-edge integration, and DIII-D is designing a pumped lower divertor at large major radius with long parallel connection lengths and poloidal leg length for exploring detached conditions in negative triangularity plasmas. SOLPS-ITER and UEDGE simulations predict reduced detachment onset density and improved particle control for the closed-divertor plasma geometry with private flux region pumping, with further reduction in detachment density enabled by the outer vertical target [6]. Simulations also show higher electron temperature at the X-point before the onset of detachment in the new divertor geometry, indicating reduced confinement degradation when approaching detachment.

In summary, DIII-D research vision for the next several years, in collaboration with worldwide facilities, provides a vital opportunity to rapidly close out critical plasma research gaps to resolve design of an FPP and success in ITER. The major upgrade of the DIII-D facility discussed here represents the fastest path to close the integrated tokamak exhaust and performance gap for an FPP.

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