Develop the Scientific Basis for Burning Plasma Experiments and Fusion Energy Development
(A 10-Year Vision for DIII-D)

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The world fusion program is now preparing for the burning plasma era, with ITER construction well under way and broad discussion of other new facilities for fusion development, such as a Fusion Nuclear Science Facility (FNSF) in the US. The DIII-D Program has developed a 10-year vision to increase the technical reach of the facility to access conditions highly relevant for future burning plasma experiments: dominant electron heating, low-input torque, non-inductive current drive, active 3D fields for MHD control, disruption mitigation, and high radiative dissipation with a viable plasma-material interface. The proposed upgrades will enable evaluation of the underlying plasma dynamics, testing of emerging theoretical concepts, and validation of state-of-the-art models needed to prepare for ITER operation and to optimize FNSF design. The request will leverage fusion energy science funding through mutual investment by international partners that will provide DIII-D with unique capabilities within the world program, enabling DIII-D to remain a national center in the US fusion program for advancing physics and training scientists for leading US participation in ITER and designing an FNSF. In support of this 10-year vision, we propose three initiatives that will, over the next decade, provide the scientific basis to begin design of an FNSF tokamak.

Deliver Predictive Understanding of the Impact of Burning Plasma Conditions on Plasma Performance - Future burning plasma experiments will operate at low-collisionality with relatively low fast ion content, $T_e > T_i$, dominant electron heating, with heating sources with very low torque relative to the plasma inertia. Dominant electron heating and low collisionality significantly change turbulent transport and pedestal stability, while low-torque operation challenges edge localized mode (ELM)-control, error field correction, and MHD stability even at modest β_N. Proposed upgrades to the DIII-D EC heating system (going from 3.5MW now to 7.5MW and ultimately to10.5MW), along with modifications to the neutral beam system configuration (second off-axis with co-counter steering capability) will more than double the low-torque heating power, providing a robust operating range for developing and evaluating attractive operating scenarios for ITER. Iterative experiment-theory-simulation comparison and validation using a uniquely comprehensive diagnostic set is key to developing simulation tools that can be used confidently and effectively for design and operation of future devices, thereby reducing risk and improving productivity.

Quantify Requirements for Achieving High Performance, Steady-state Operation in FNSF - Designing FNSF will demand significant improvements in the physics basis for steady state operation beyond that necessary for ITER operation. The DIII-D upgrade will more than double the off-axis electron cyclotron current drive capability, evaluate 1MW of off-axis helicon-wave current drive, increase capability to study 3D field effects using new a new power supply provided by ASIPP for improved error field correction, and RMP and resistive wall mode control. Research will focus on understanding the self-consistency between transport, stability, and current drive in the steady-state regime for durations exceeding the current relaxation time τ_R, the longest plasma physics time scale. Disruption avoidance and mitigation will be optimized. Emphasis will be placed on developing and optimizing self-consistent, high-performance, steady-state core solutions for FNSF. This initiative will extend US leadership in the area and provide a compelling platform for exploiting US expertise on new superconducting devices in China and Korea.

Develop and validate solutions for steady-state and transient heat fluxes in FNSF and future devices - Steady-state burning plasma experiments must maintain high pedestal T_e for good confinement, and simultaneously achieve high radiative losses in the boundary ($P_{rad}/P_{loss} > 70\%$) to detach the divertor plasma, reducing plasma-facing component heat flux and erosion. High power density, comprehensive 2D diagnostics, operational flexibility with ELM control, and divertor configuration and material changes are key to developing the validated predictive design codes needed for FNSF and DEMO. Near-term research with improved diagnostics and increased heating power will emphasize model validation, leading toward modification of the divertor configuration to reduce detachment threshold density, followed by evaluation of operating with high-temperature plasma-facing components, and installation of reactor-relevant plasma-facing component materials (low erosion, tritium retention, and high threshold for radiation damage).