DIII-D National Fusion Program Research Directions

by
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Presented to
Fusion Energy Sciences Advisory Committee
Bethesda, Maryland

January 14, 2016
Our Vision For The DIII-D Program is Based on Three Guiding Principles

- **Research With an Energy Goal**
  Research goals address challenges to achieving fusion energy

- **Scientific Excellence**
  Fastest route to success and developing predictive capability

- **World Class Facility for U.S. Office of Science**
  Upgrades for access to new physics
  Highly capable operations team supports expanded user group

Provide exciting opportunities and stimulating work environment to recruit and train next generation fusion scientists

Chrystal (UCSD)

Collins (UCI)
Muscatello (GA)

Barada (UCLA)
Key DIII-D Program Goals Can Motivate a Vibrant and Expanding US Fusion Program With an Energy Goal

Ensure the Success of ITER

Provide Physics Basis for Fusion Development Beyond ITER

Deliver validated predictive understanding for key scientific challenges

Train a new generation of fusion scientists

Enabled by a highly capable facility with technical reach and flexibility to probe the relevant physics of burning plasmas
Comprehensive Diagnostics Provide a Strong Foundation to Advance Understanding Through Integrated Simulation

DIII-D Has a Comprehensive Diagnostic Set in Support of Its Scientific Objectives

- Tile current array
- FIDA
- Bolometers
- IR cameras
- Fast ion collectors
- SXR
- Filterscopes
- MSE
- FIR & µ w scattering
- BES
- SPRED
- Vertical scanning probe
- Magnetics
- ECEI & MIR
- MDS spectrometer
- Visible bremsstrahlung
- Gamma detectors
- Phase control
- Fast wave reflectometer
- Radial scan
- Thomson scattering
- Lithium beam spectroscopy
- Neutrons
- Langmuir probes
- DISRAD
- UF-CHERS
- CECE
- CER
- VUV cameras
- ASDEX gauges
- Visible cameras
- Fast framing camera
- DBS
- DIMES
- ECE
- NFAs
- Fast ion loss detector
- Gamma detectors
- DBS
- Coherence Imaging
- CP swing probes
- Neutrons
- Langmuir probes

New predictive capabilities
Integrated International Team With Diverse Capabilities Is the Key Strength of the Program

DIII-D Facility Users in 2014–2015

**North American Universities**
- Auburn University
- Carnegie Mellon University
- Columbia University
- Georgia Tech (Atlanta)
- Horizon Prep (San Diego)
- Lehigh University
- Massachusetts Institute of Technology
- Oak Ridge Associated Universities
- Palomar College
- Princeton University
- The College of William and Mary
- University of Arizona
- UC Berkeley
- UC Davis
- UC Irvine
- UC Los Angeles
- UC San Diego
- University of Colorado, Boulder
- University of Maryland
- University of Texas
- University of Toronto
- University of Wisconsin
- University of Wisconsin
- West Virginia University

**Europe & Russia**
- Aalto University, Finland
- CEA Cadarache (France)
- Chalmers University of Technology (Sweden)
- Ciemat (Spain)
- Consorzio RFX (Italy)
- D-TACQ Solutions Ltd (UK)
- Eindhoven University (Netherlands)
- ENEA C.R. Frascati (Italy)
- EPFL (Lausanne, Switzerland)
- Forschungszentrum Juelich (Germany)
- Huazhong University of Science and Technology
- IFM - Consiglio Nazionale delle Ricerche (Italy)
- Institute of Control Sciences (Moscow)
- Institute of Plasma Physics AS CR, Czech Republic
- Instituto Superior Tecnico, Lisboa, Portugal
- Istituto di Fisica del Plasma CNR-EURATOM (Italy)
- ITER Organization
- Kungliga Tekniska Hogskolan (Stockholm)
- Max-Planck Institute for Plasma Physics
- Politecnico di Milano (Italy)
- RRC Kurchatov Institute
- Technical University Munich
- TRINITI lab
- United Kingdom Atomic Energy Authority (CCFE)
- Universita degli Studi di Padova
- Universita di Napoli Federico II
- University of Seville
- University of Strathclyde
- University of York
- VTT Technical Research Centre (Finland)

**U.S. Labs**
- Idaho National Laboratory
- Jefferson Lab
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Oak Ridge National Lab
- Princeton Plasma Physics Laboratory
- Sandia National Laboratory

**U.S. Industries**
- American Physical Society
- Beach Access Software (San Diego)
- CompX (San Diego)
- Eagle Harbor Technologies, Inc.
- Far-Tech, Inc. (San Diego)
- Fourth State Research (Austin)
- General Atomics (San Diego)
- IMSOL-X (San Diego)
- Kailing Software (New York)
- Tech-X Corporation (Boulder)
- Tri Alpha Energy, Inc.

**U.S. Academic Institutions**
- American Physical Society
- Oak Ridge Institute for Science Education

**South America**
- Centro Atomico Bariloche (Argentina)
- University of Sao Paulo (Brazil)

**Asia**
- ASIPP Hefei, (China)
- Dalian University of Technology, China
- Institute for Plasma Research (India)
- Ishikawa National College of Technology (Japan)
- ITER-India
- Japan Atomic Energy Agency
- KAIST (Korea)
- Korea National Fusion Research Center
- METU - Middle East Technical University (Turkey)
- National Fusion Research Institute (Korea)
- National Institute for Fusion Science, Japan
- Peking University
- Seoul National University
- Southwestern Institute of Physics, China
- Tohoku University
- USTC (Hefei, China)

**Australia**
- Australian National University (Sydney)

- 557 Users
- 32 Countries
- 95 Institutions
- 63 Grad Student Users
- 54 Post Doc Users
DIII-D High-Level Research Objectives Are Well Aligned With Restructured DOE-FES Program

DIII-D Research Objectives

1. Prepare for Burning Plasmas
   Deliver predictive understanding of the impact & optimization of burning plasma conditions on plasma performance

2. Determine Path to Steady State
   Provide requirements for achieving efficient, high performance, steady-state tokamak operation

3. Develop PMI-Boundary Solutions
   Develop and validate solutions for heat flux control including transients in ITER and future devices

DIII-D Funding provided under Foundations
# DIII-D Program Research Objectives Are Well Aligned With Recent Community Workshop Initiatives

## DIII-D Research Objectives

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<td>Deliver predictive understanding of the impact &amp; optimization of burning plasma conditions on plasma performance</td>
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- **Broad engagement by DIII-D and GA theory programs**
  - Over 40 scientists on panels
  - Chair, co-chair of Transients Workshop, working group chairs
- **Workshops: diverse, lively discussions**
Planned Heating & Current Drive Upgrades Advance Transport Studies To Reactor-Like Conditions

- **Challenge:** Theory and experiment show transport will change in burning plasmas
  - Turbulence altered with stronger electron heating and reduced flow shear

- **DIII-D** will access dominantly electron heated low rotation regimes to understand turbulence properties over wide range in \( \beta \)
  - Increase gyrotron power and toroidally steer neutral beams to triple range accessed

![Graph showing electron heating power](image)

**Simulation Initiative**

**Figure:**
- **Graph:** Simulation showing electron heating power vs. \( Q_e/Q_i \)
- **Data:** Baseline and Advanced scenarios
- **Legend:** NBI Only, NBI+ECH

**Need to develop basis for improve scenarios with low torque e\(^{-}\) heating**
DIII-D is Discovering Physics Underlying ELM Suppression to Move Beyond Demonstration Experiments

3D fields resonate with plasma to stop ELMs

- Address extrapolation issues
  - Raise 3D flexibility to isolate spectral features for ELM & stability control
  - Pellet ELM triggering mechanisms
- Produce ELM-free regimes under reactor-relevant conditions
- Utilize “3D” super-supplies (ASIPP China), possible new set of 3D coils to optimize spectrum

Pellet pacing reduces ELM heat loads

QH mode: an inherently ELM-stable regime

Transients and Simulation Initiatives
Meeting the Disruption Challenge: DIII-D Will Resolve the Physics for Safe Quenching of Tokamak Plasmas

- U.S. responsible for ITER disruption mitigation system
  - Energetic runaway electrons
  - Localized heat loads & forces

- DIII-D research seeks to
  - Resolve physics of runaway dissipation
  - Understand radiative asymmetries
  - Optimize mitigation schemes
  - Compare with non-linear models and theory for reliable projection

- Utilize 3D diagnostics & injector developments

Basis for robust safe termination of plasmas in ITER & beyond
Research Will Develop a Multi-layered Approach to Achieve Robust Reliable Operation

- **Research will**
  - Understand instabilities and how to predict or sense their onset
  - Develop key actuators and project to future devices
  - Resolve integrated control strategies in relevant scenarios

**Increase EC & balanced-NBI power**

**Increase 3D flexibility to access key regimes, do perturbative studies**

*Significant progress in proof of principle control methods*

*Basis for reliable control of burning plasmas*
A Steady State Burning Plasma Requires Both High Plasma Pressure and Self-Driven Plasma Current

Goal

High pressure + High self-driven current

- Fusion power
- Steady-state & high energy gain

Must explore physics at high $\beta_N$ to determine path for future reactors

- Increase heating power and profile flexibility through beams and ECH

Self-consistent Solution

- Tight coupling between profiles, transport and stability
  - Self-consistent scenario required
  - Potential solutions with broad or peaked profiles

Higher $\beta_N$ enables a more compact and cost-effective reactor
Profile Flexibility Will Enable DIII-D to Study the Key Physics at High $\beta_N$ For Reactor Solutions

- Research will explore key profile dependencies in high $\beta$ regime
  - Stability above the no-wall limit
  - Turbulence modification by magnetic shear
  - Fast ion redistribution physics

- Enabled by 2.5x off-axis current drive and 3x electron heating:
  - 2nd off axis beam & increased ECH
  - Toroidally steerable beams to raise co- and balanced-torque power

Will determine scientific foundations and existence proofs for viable steady state
Goal: Test Very High Harmonic Fast Wave (~500 MHz) as an efficient off-axis CD technique for future fusion devices

Context: Helicon & DIII-D potential
- 2-4x more efficient than ECCD or NBCD
- Comb-line antennas a tested technology
- Requires high $\beta_e$ and current drive measurement

Research Plan
- Test prototype antenna (100 W) in fall 2015
- Install and test 1MW system in early 2017
- Compare with simulation and assess current drive efficiencies

Helicon Implementation Progressing Well and On Track for Key Tests as a Transformational Current Drive Source

Klystrons supplied from SLAC at modest cost
Advanced Divertors Minimize and Simplify the Volume Needed for Reliable Dissipation of Plasma Losses

1. Advance physics understanding to develop improved divertor concepts
   - Enhanced measurements to isolate physics
   - Systematic divertor modifications to determine key dependencies
   - Compare against state-of-the-art numerical simulation

2. Test Advanced Materials for fusion
   - Evaluate erosion, migration and re-deposition on a variety of scales
   - Assess impact and mitigate impacts on core plasma

3. Assess compatibility with high performance core

Validated models are essential for extrapolating to future devices and to design optimized divertors

PMI Workshop Initiatives
Developing Power Handling Solution Requires Comprehensive Understanding of Detachment Physics

Complex, dynamic multi-scale physics

- SOL turbulent transport, drift, and kinetic effects
- Atomic & molecular radiation & recombination
- Charge exchange, impurity transport, neutral dynamics
- Sheath, surface interactions (sputtering, recycling...)

Codes must reproduce non-linearities and are key to providing predictive understanding for divertor optimization

Simulation and PMI Initiatives

D.N. Hill/FESAC/January 14, 2016

005-16/DNH/rs
Advancing Physics Understanding Requires Improved Diagnostics and Systematic Variation of Configuration

**Upper & lower 2D Thomson scattering**

Further enhancements
- Bolometry,
- Spectroscopy,
- Neutral pressure,
- Ion Temperature

Systematically vary closure

**FY17 Joint Research Target**

Vary magnetic geometry

Flaring, flux expansion, connection length, additional X points

Provides basis for future optimized divertor to be tested in DIII-D
DIII-D Provides Unique Capability to Validate PMI in Reactor-Relevant Tokamak Environment

- Test emergent materials in fusion relevant plasmas
  - Assess physics of erosion, re-deposition & migration
  - Measure temperature dependence
  - Evaluate surface evolution

- Assess impact on plasma performance from large scale divertor PMI
  - High-Z core contamination & benefits of divertor optimization
  - Effects of high temperature PFCs on core and divertor operation

Initial assessments of impurity sources with divertor rings in 2016
Planned Upgrades Will Provide World-Class Capabilities and Flexibility for Addressing Key Scientific Issues

**DIII-D Initiatives**

1. **Prepare for Burning Plasmas**
   - Deliver predictive understanding of the impact & optimization of burning plasma conditions on plasma performance

2. **Determine Path to Steady State**
   - Provide requirements for achieving efficient, high performance, steady-state tokamak operation

3. **Develop PMI-Boundary Solutions**
   - Develop and validate solutions for heat flux control including transients in FNSF and future devices

**Enabled by DIII-D Upgrades**

- **Increased electron Heating/current drive**
- **New helicon system**
- **Super-SPA supply (ASIPP)**
- **Increased co-current, off-axis current drive**
- **Toroidal rows of metal-coated tiles**
- **Divertor Closure Modifications**

Strong DIII-D program enables synergies with NSTX-U, long-pulse facilities, ITER, university programs, theory community, and diagnostic development
Continued Investment in DIII-D Provides a World-Leading Facility for U.S. Scientists to Pursue Fusion Energy Research

- **Leverages $1B investment in existing world-class facility**
  - Extensive, flexible control tools
  - Comprehensive diagnostic set

- **Delivers new capabilities that can transform the landscape of fusion science**
  - Burning plasma transport
  - Self-consistent high $\beta$ steady states
  - Reactor-relevant detached divertor with transients eliminated

- **Provides the foundations for success in U.S. next step devices**
  - Burning plasmas in ITER
  - Long-pulse, high performance operation in FNSF

**A world-class U.S. fusion user facility providing exciting research opportunities to scientists worldwide**
DIII-D is a Highly Flexible Facility to Develop Scientific Basis for Optimizing Tokamak Approach to Fusion Energy

- Vary, rotation, rotational shear, and pressure profiles ($\beta$)
  - 20MW Co+Cntr, On/Off-axis NBI, ECH

- Current profile control (2-3 $\tau_R$ pulse lengths)
  - Co/Cntr, On/off-axis NBI, ECCD, Helicon test

- Vary local gradients, $Te/Ti$ (steady & perturb)
  - ECH/ECCD, On/Off-axis NBI

- Wide range in density and collisionality ($\nu^*$)
  - Controllable divertor exhaust, low-Z wall

- Shaping flexibility (ITER, DEMO, exploratory)
  - 18 shaping coils, PCS, Upr/Lwr divertors

- Broad range of Transient control tools
  - 3D coils & diags, ECCD, IGI, pellets, SGI, MGI

- Systematic divertor modification, diagnosis, modeling
  - Upr/Lwr; variable config, geom, closure; cryopump

- PMI: Controlled exposure over a range of scales/times
  - DiMES, MiMES, metal rings, heated samples