DIII-D National Fusion Program Research Directions

by
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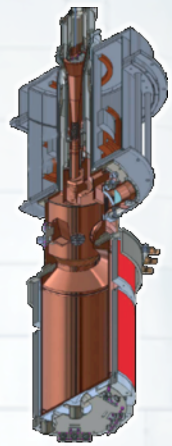
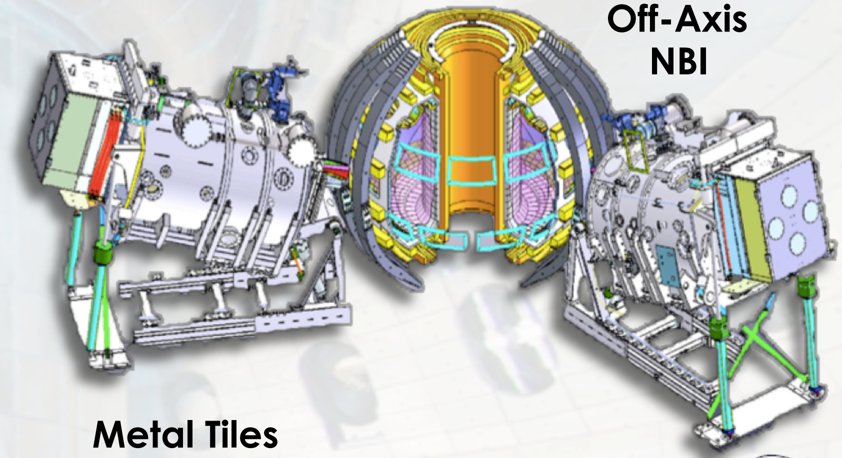
Presented to
Fusion Energy Sciences Advisory Committee
Bethesda, Maryland

January 14, 2016

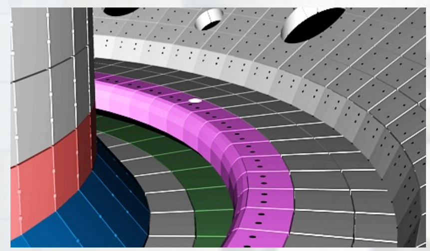
Electron Cyclotron



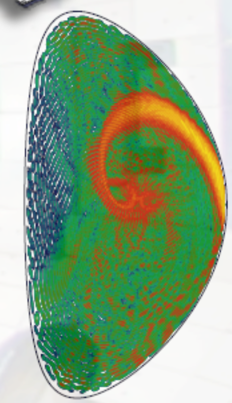
Off-Axis NBI



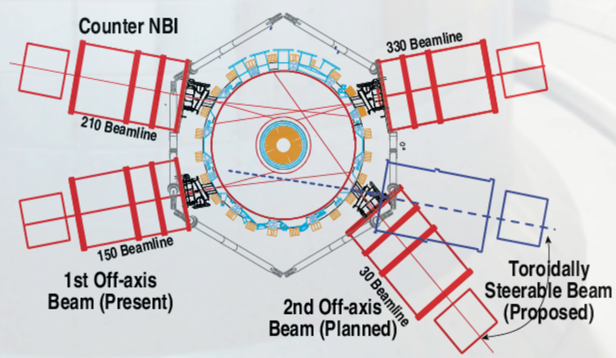
Metal Tiles



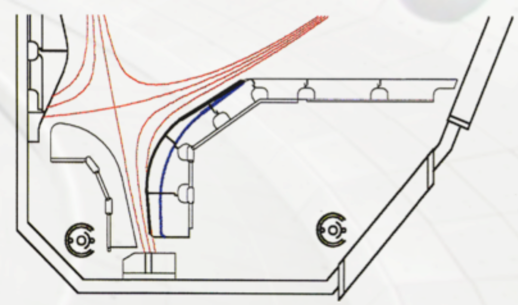
Helicon Current Drive



Co/Counter/Balanced NBI



Divertor Shape Variation



Our Vision For The DIII-D Program is Based on Three Guiding Principles

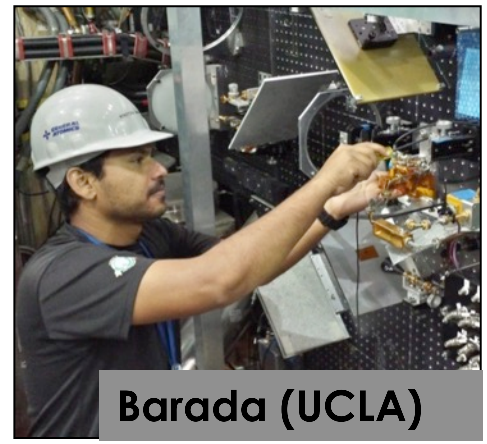
Provide exciting opportunities and stimulating work environment to recruit and train next generation fusion scientists

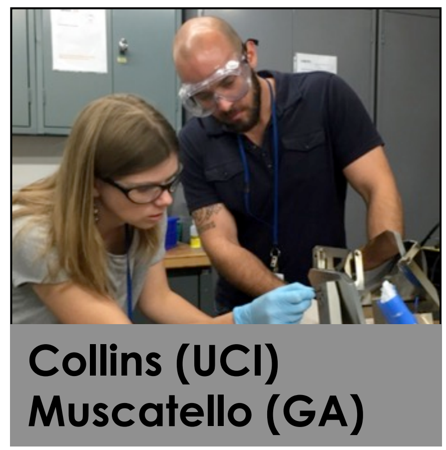
- **Research With an Energy Goal**
  Research goals address challenges to achieving fusion energy

- **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

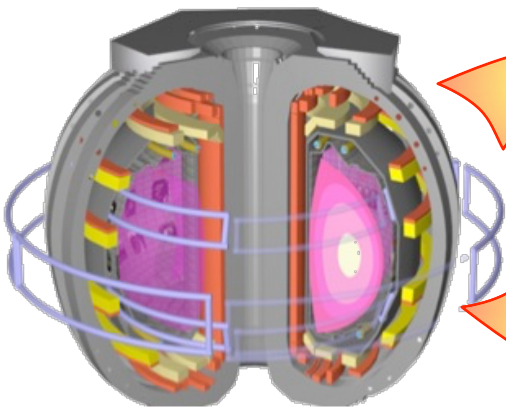

Chrystal (UCSD)


Barada (UCLA)


Collins (UCI)
Muscatello (GA)

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

DIII-D

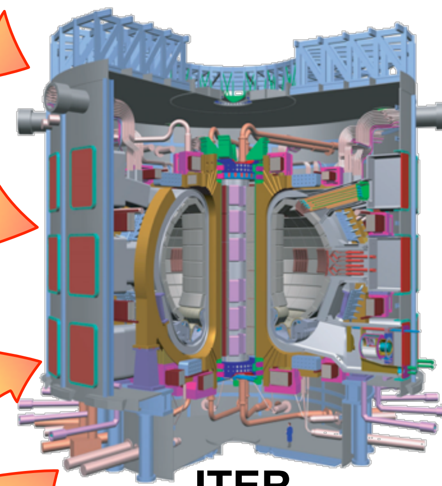


Ensure the Success of ITER

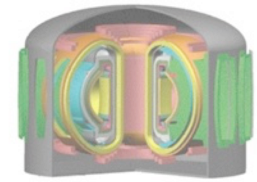
Provide Physics Basis for Fusion Development Beyond ITER

Deliver validated predictive understanding for key scientific challenges

Train a new generation of fusion scientists



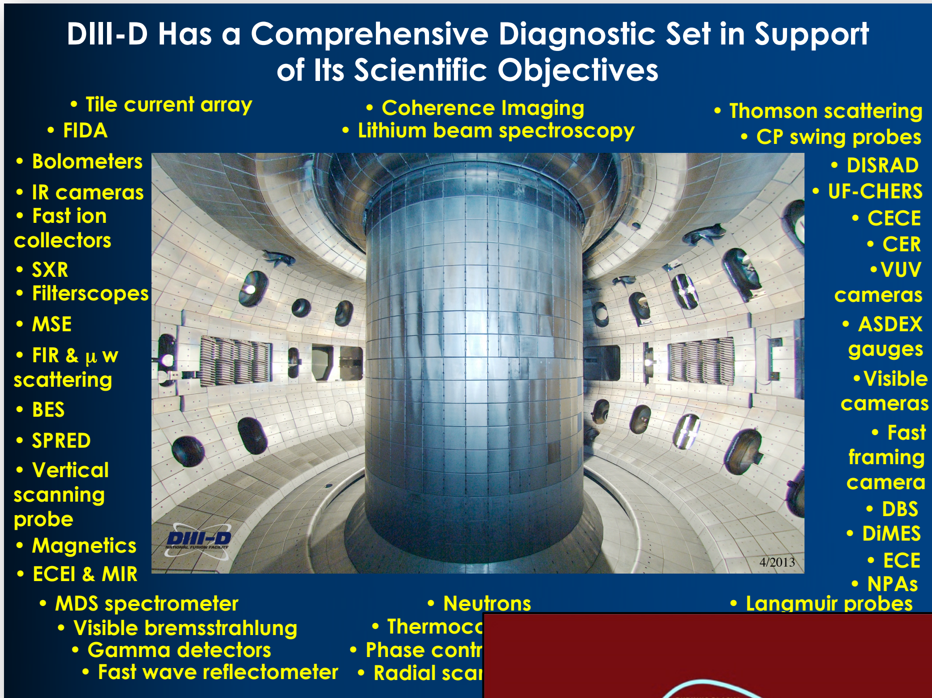
ITER

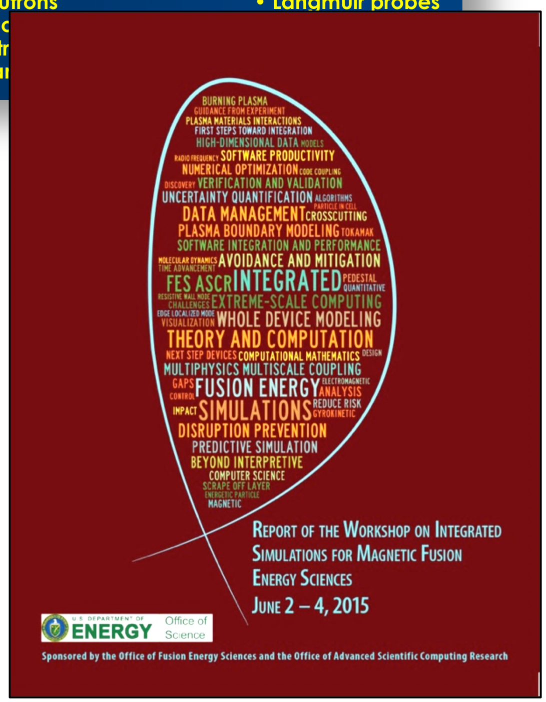


DEMO

Enabled by a highly capable facility with technical reach and flexibility to probe the relevant physics of burning plasmas

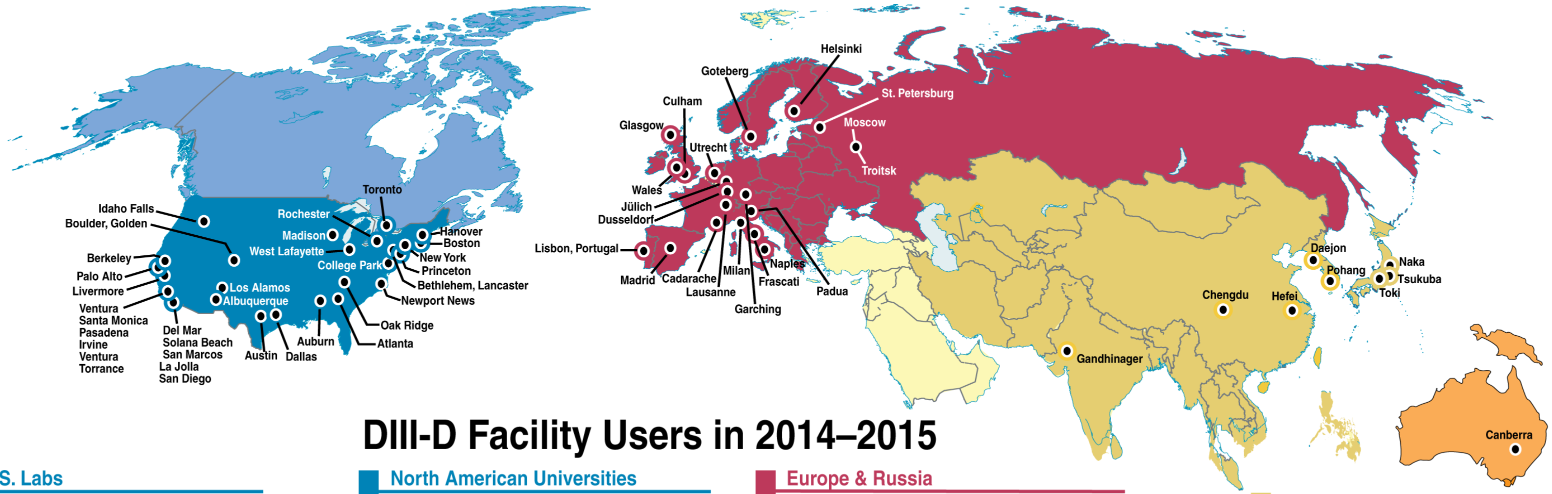
Comprehensive Diagnostics Provide a Strong Foundation to Advance Understanding Through Integrated Simulation





New predictive capabilities

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



DIII-D Facility Users in 2014–2015

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)
- Kalling 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)

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 Washington
- 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
- IFP - 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
- Università di Napoli Federico II
- University of Seville
- University of Strathclyde
- University of York
- VTT Technical Research Centre (Finland)

Asia
- ASIPP Hefei, (China)
- Dalian University of Technology, China
- Insitute 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 Unviersity
- 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 NATIONAL FUSION FACILITY SAN DIEGO

DIII-D High-Level Research Objectives Are Well Aligned With Restructured DOE-FES Program

DIII-D Research Objectives

1. **Prepare for Burning Plasmas**

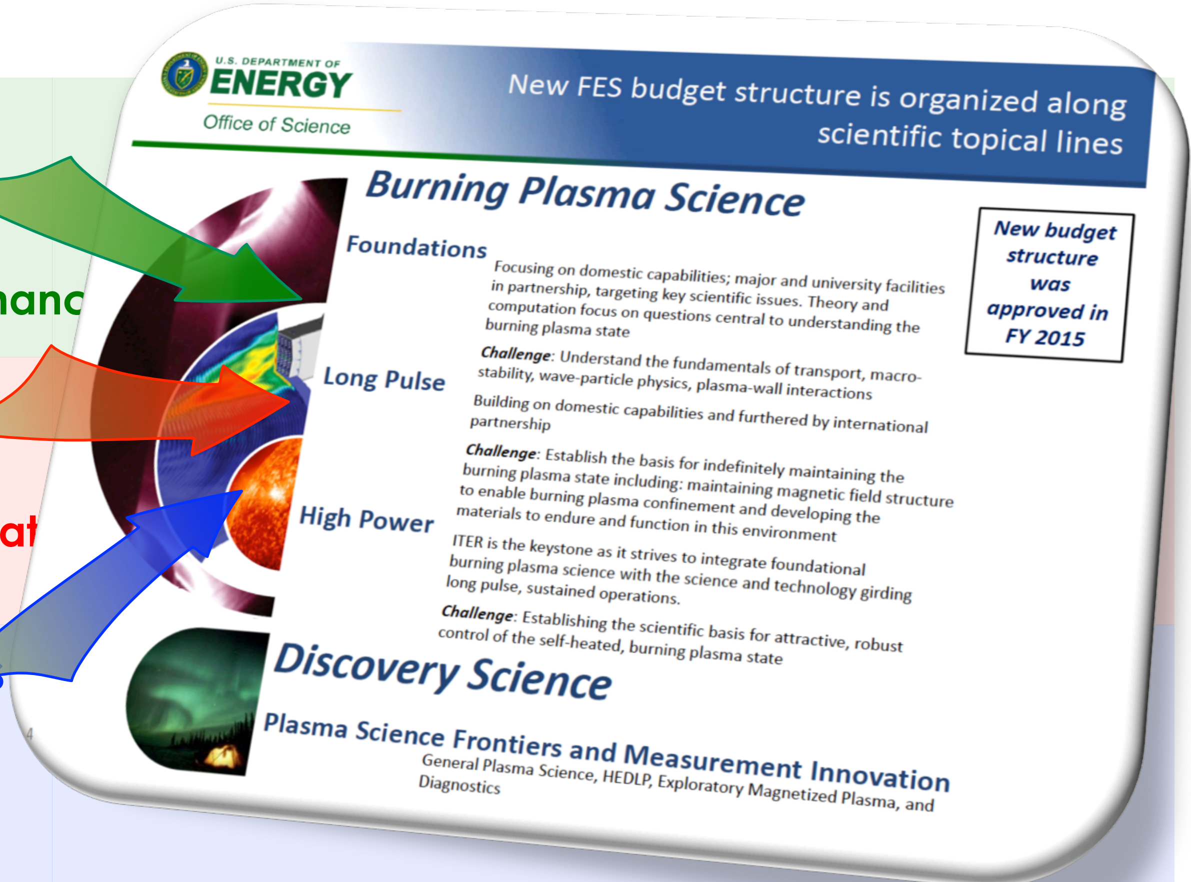
   Deliver predictive understanding of the impact & optimization of burning plasma conditions on plasma performanc

2. **Determine Path to Steady State**

   Provide requirements for achieving efficient, high performance, steady-stat 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 NATIONAL FUSION FACILITY SAN DIEGO

DIII-D Program Research Objectives Are Well Aligned With Recent Community Workshop Initiatives

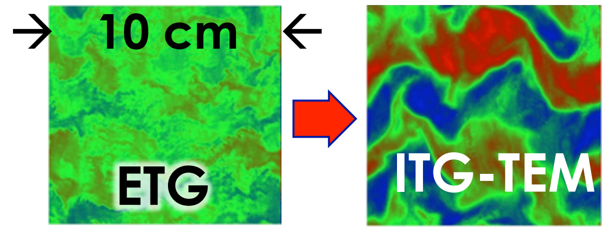
DIII-D Research Objectives	Intiatives from Planning Workshops
1. Prepare for Burning Plasmas Deliver predictive understanding of the impact & optimization of burning plasma conditions on plasma performance	Integrated Simulation Initiatives; Transients Initiatives
2. Determine Path to Steady State Provide requirements for achieving efficient, high performance, steady-state tokamak operation	Integrated Simulation Initiatives; Transients Initiatives; PMI Solutions Initiatives
3. Develop PMI-Boundary Solutions Develop and validate solutions for heat flux control including transients in ITER and future devices	Integrated Simulation Initiatives; PMI Solutions Initiatives

- **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**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

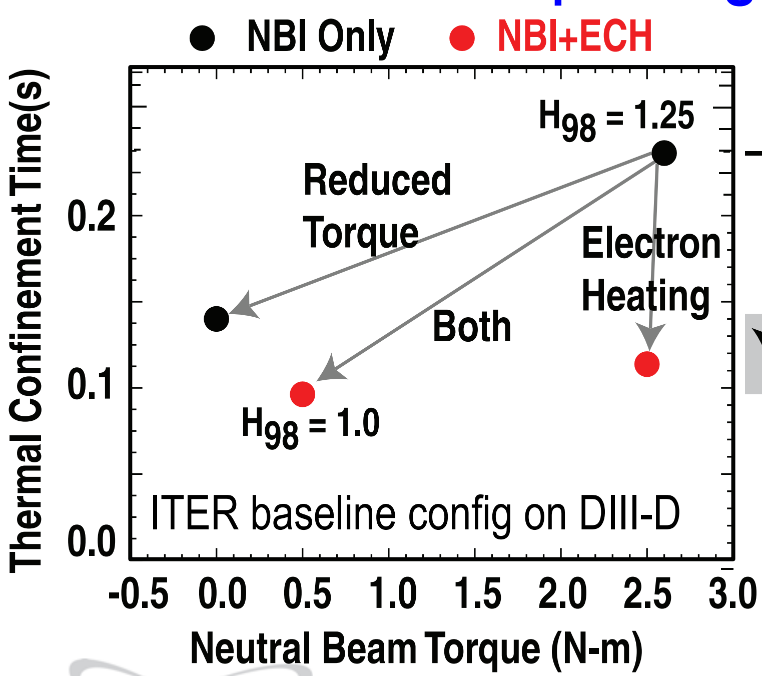
Planned Heating & Current Drive Upgrades Advance Transport Studies To Reactor-Like Conditions

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

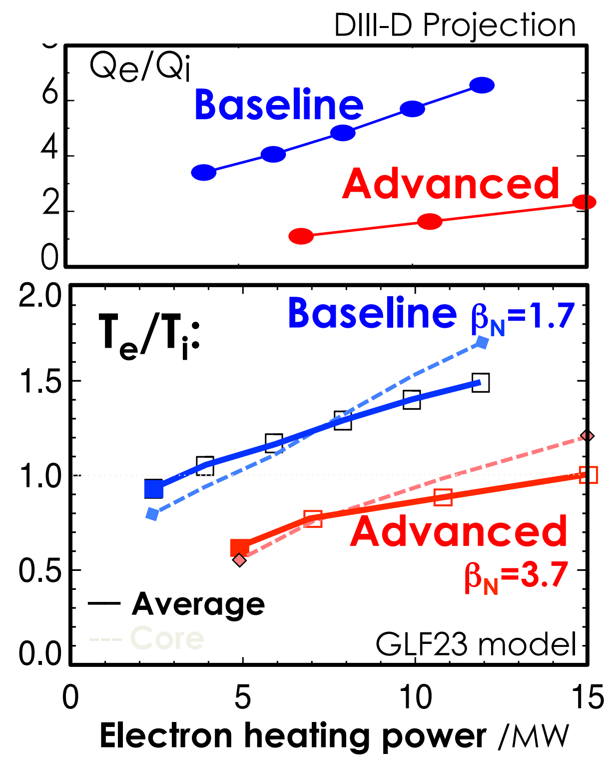


[Gyro, Candy]

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



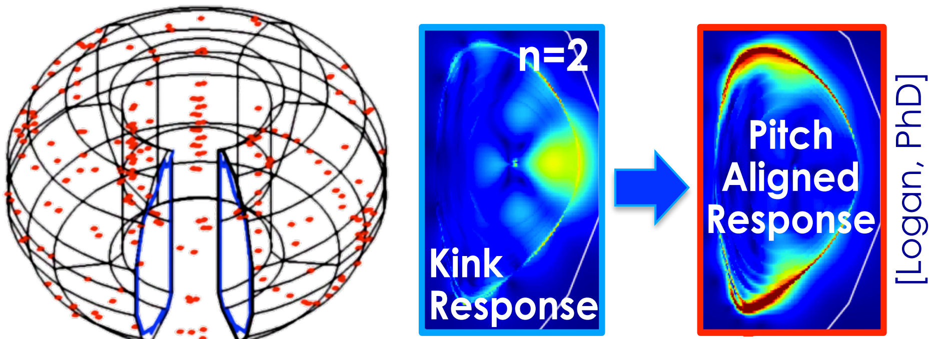
Need to develop basis for improve scenarios with low torque e⁻ heating



Simulation Initiative

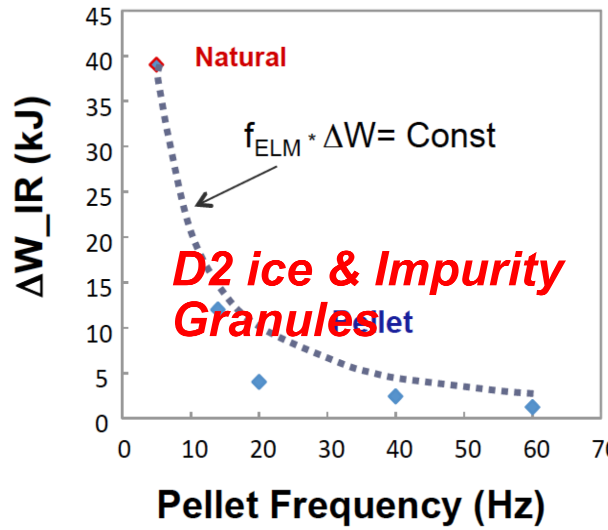
DIII-D is Discovering Physics Underlying ELM Suppression to Move Beyond Demonstration Experiments

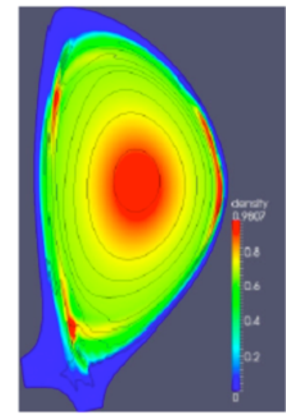
3D fields resonate with plasma to stop ELMs



- **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**

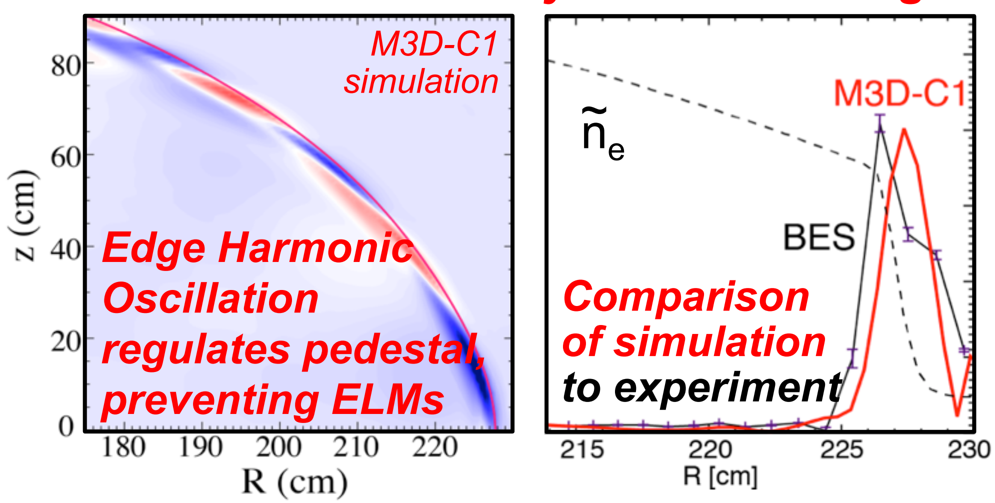
Pellet pacing reduces ELM heat loads





JOREK simulation

QH mode: an inherently ELM-stable regime



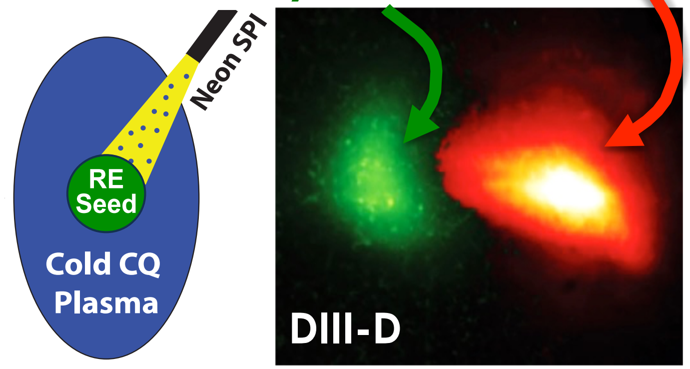
Transients and Simulation Initiatives

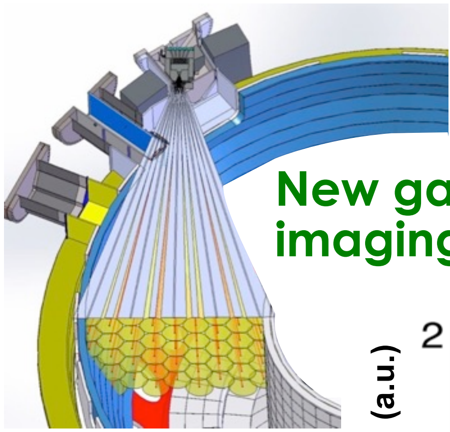
Meeting the Disruption Challenge: DIII-D Will Resolve the Physics for Safe Quenching of Tokamak Plasmas

- **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**

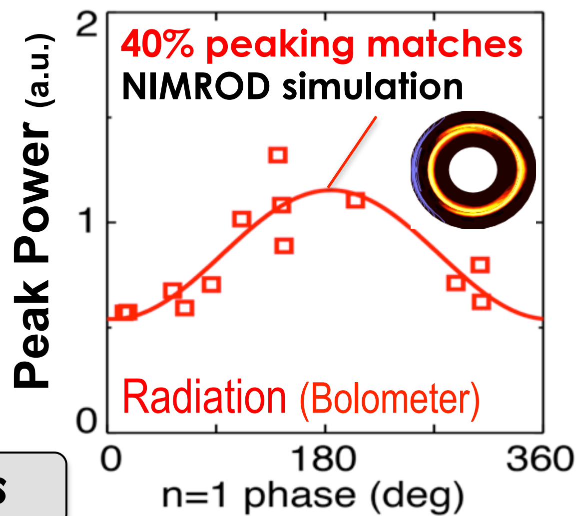
Basis for robust safe termination of plasmas in ITER & beyond

Neon shattered pellet impacts runaway electrons





New gamma ray imaging camera



Transients and Simulation Initiatives

Research Will Develop a Multi-layered Approach to Achieve Robust Reliable Operation

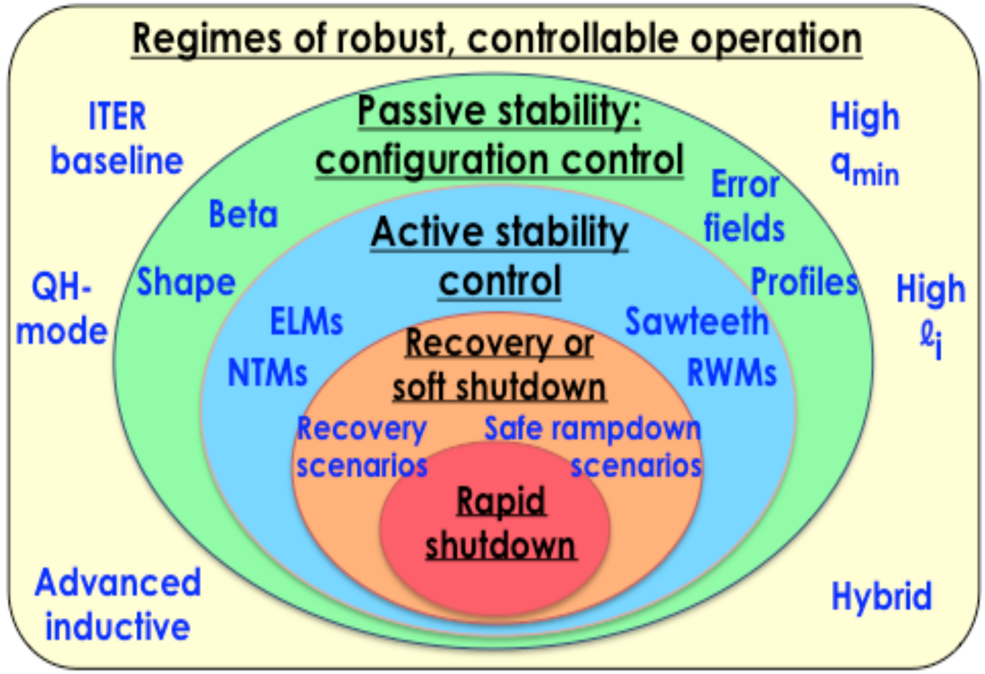
- **Research will**
  - **Understand instabilities** and how to predict or sense their onset
  - **Develop key actuators** and project to future devices
  - **Resolve integrated control strategies** in relevant scenarios

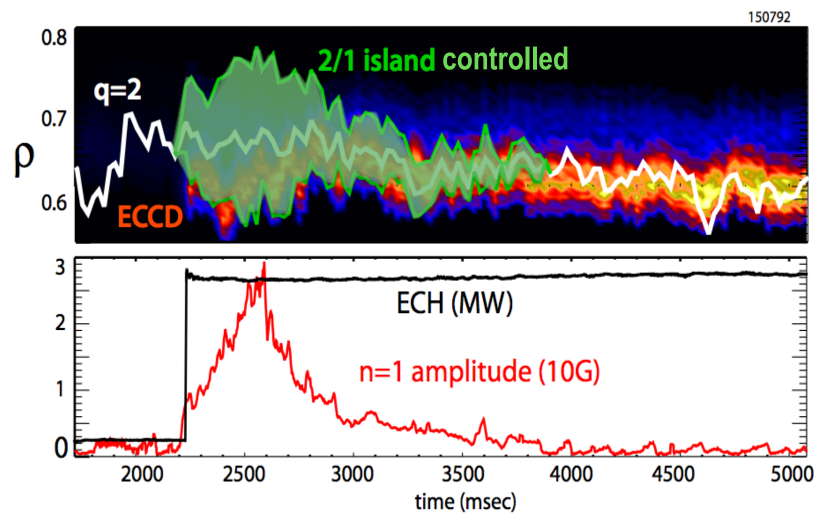
Increase EC & balanced-NBI power

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





Transients, Simulation Initiatives

A Steady State Burning Plasma Requires Both High Plasma Pressure and Self-Driven Plasma Current

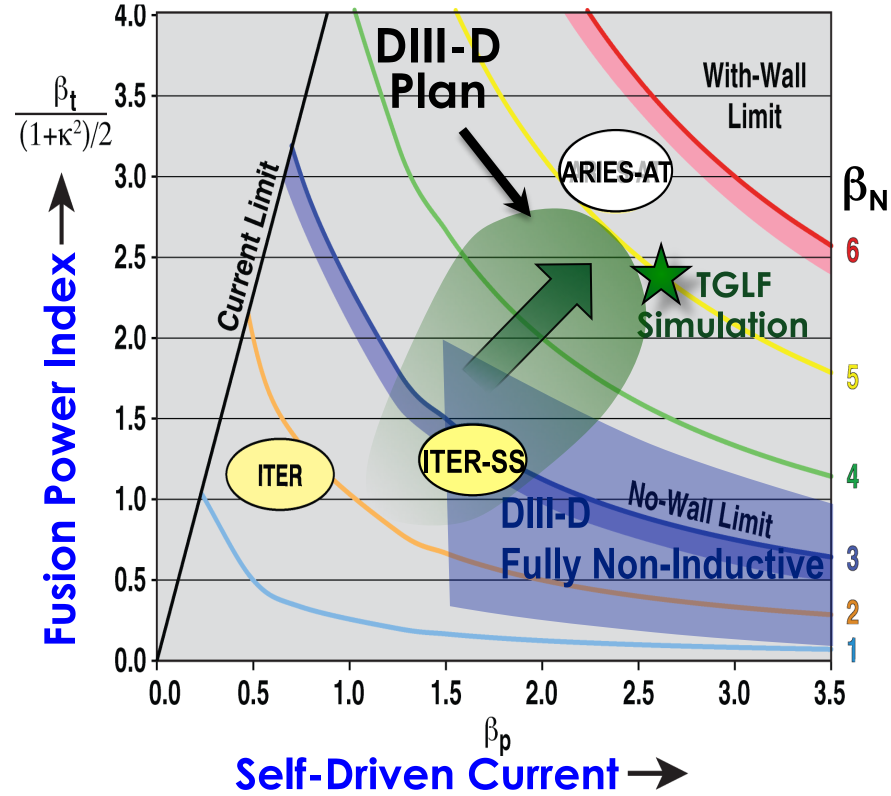
Goal

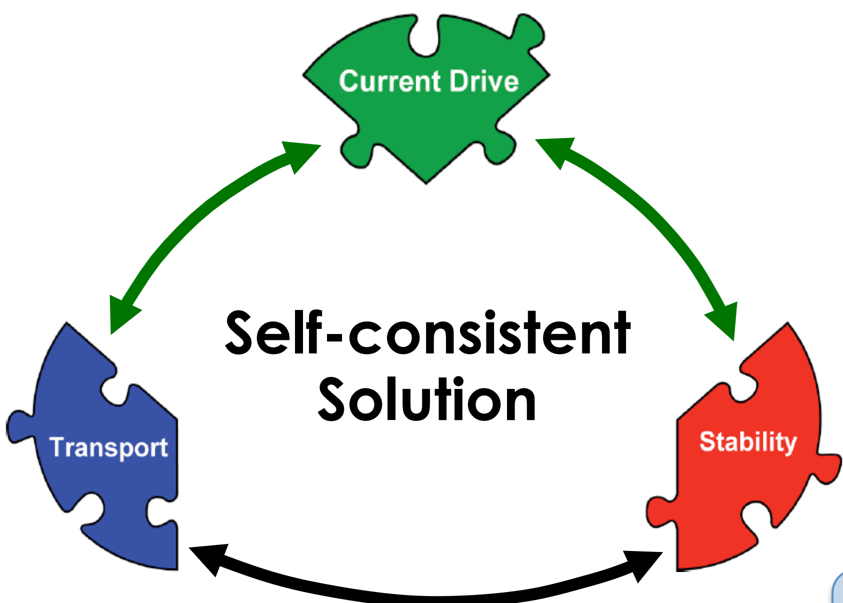
High pressure + High self-driven current

Fusion power — **Steady-state & high energy gain**

Must explore physics at high β_N to determine path for future reactors

– Increase heating power and profile flexibility through beams and ECH



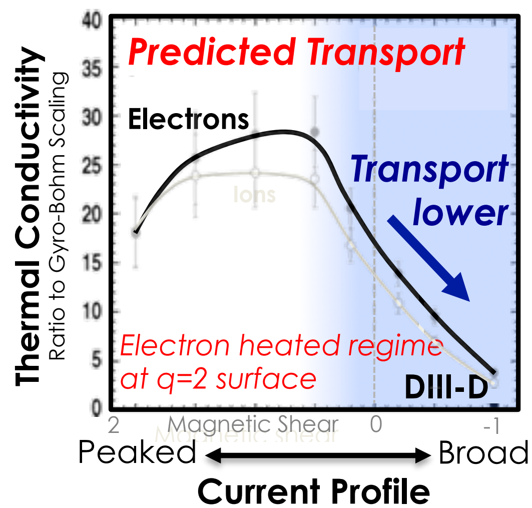


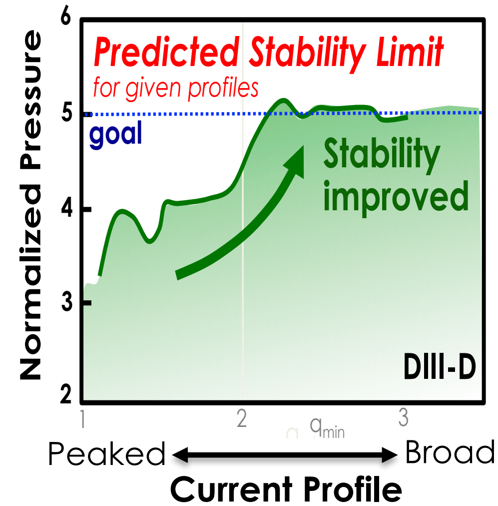
- **Tight coupling between profiles, transport and stability**
  - → Self-consistent scenario required
  - → Potential solutions with broad <u>or</u> peaked profiles

Higher β_N enables a more compact and cost-effective reactor

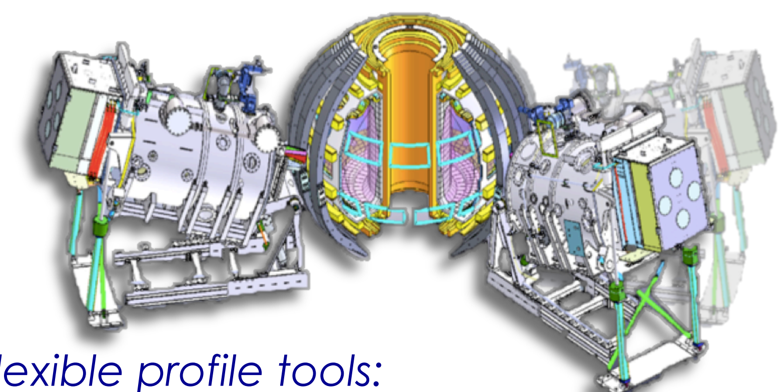
Profile Flexibility Will Enable DIII-D to Study the Key Physics at High β_N For Reactor Solutions

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

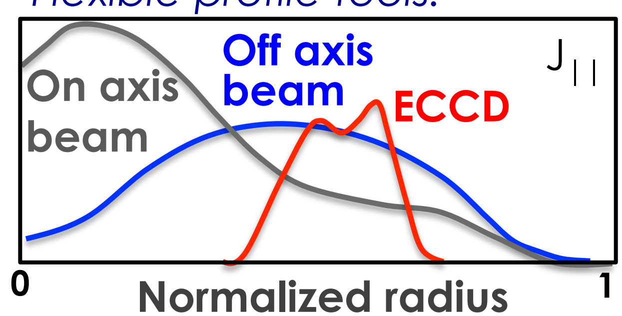




- **Enabled by 2.5x off-axis current drive and 3x electron heating:**
  - 2nd off axis beam & increased ECH
  - Toroidally steerable beams to raise co- and balanced-torque power



Flexible profile tools:



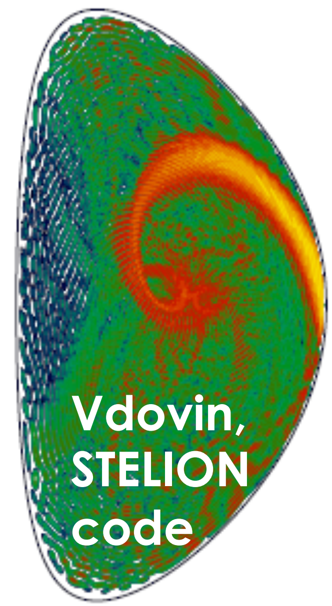
Will determine scientific foundations and existence proofs for viable steady state

Simulation, Transients Initiatives

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

Goal: Test Very High Harmonic Fast Wave (~500 MHz) as an efficient off-axis CD technique for future fusion devices

DIII-D Helicon deposition validated by 3 codes:

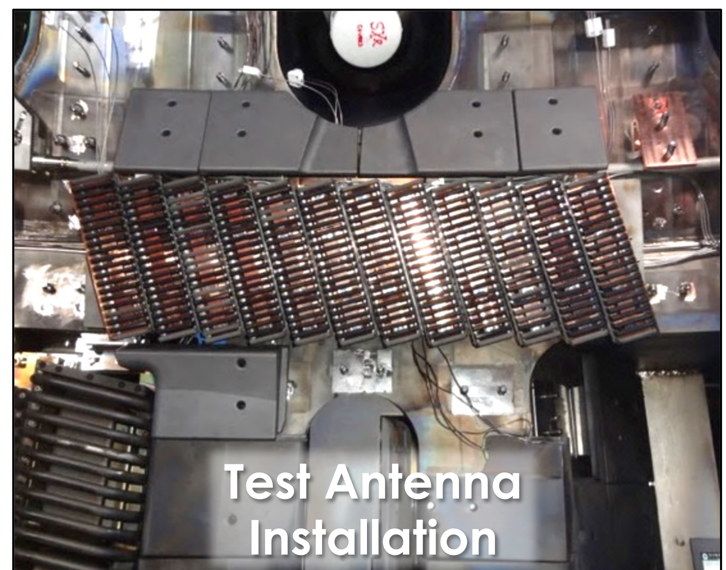


Context: Helicon & DIII-D potential

- 2-4x more efficient than ECCD or NBCD
- Comb-line antennas a tested technology
- Requires high β_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

Klystrons supplied from SLAC at modest cost



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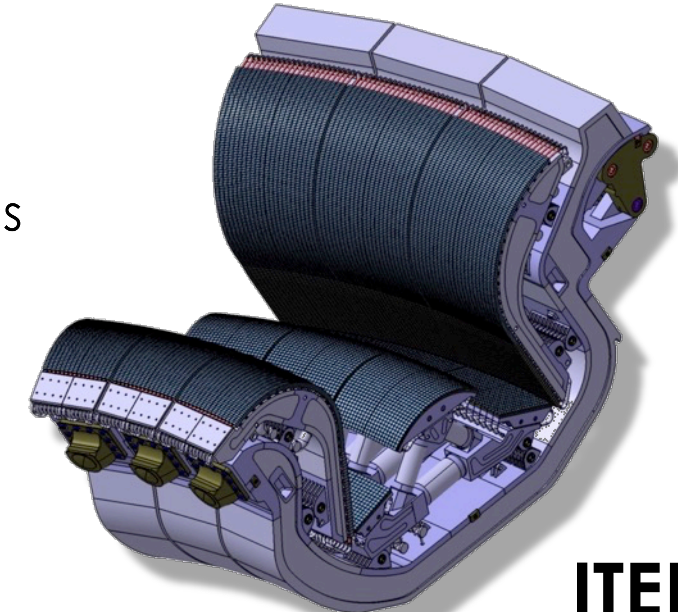
Advanced Divertors Minimize and Simplify the Volume Needed for Reliable Dissipation of Plasma Losses

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



ITER divertor module

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

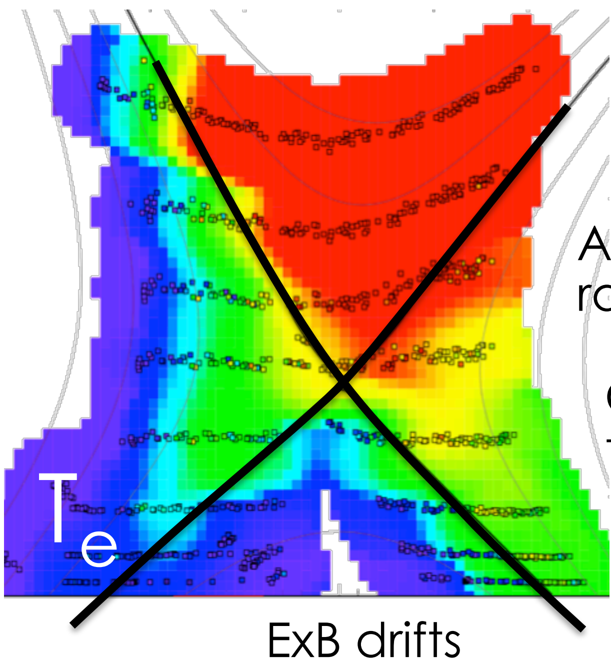
3. **Assess compatibility with high performance core**

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

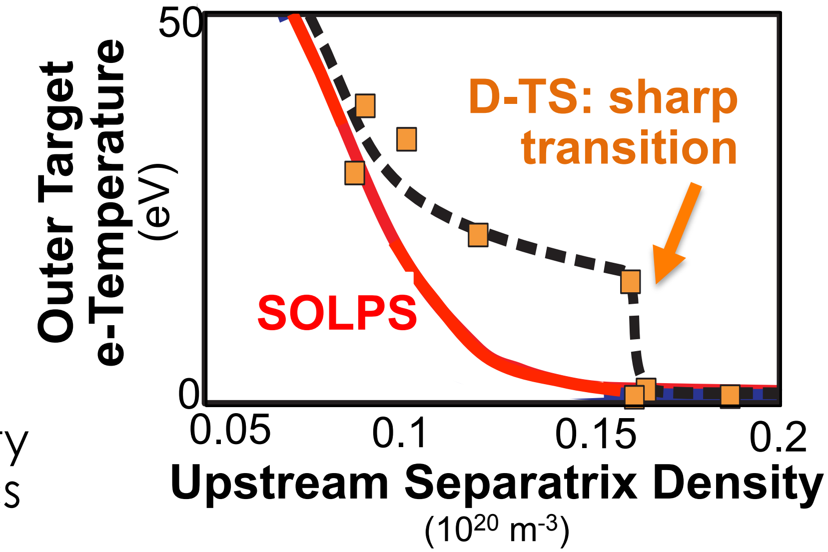


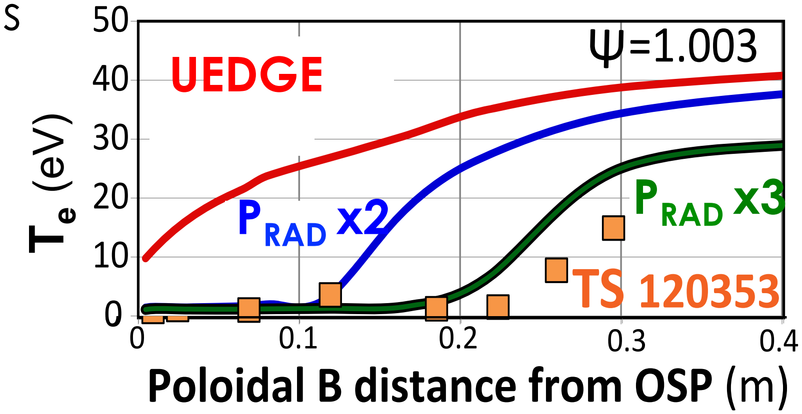
SOL turbulent transport, drift, and kinetic effects

Atomic & molecular radiation & recombination

Charge exchange, impurity transport, neutral dynamics

Sheath, surface interactions (sputtering, recycling…)



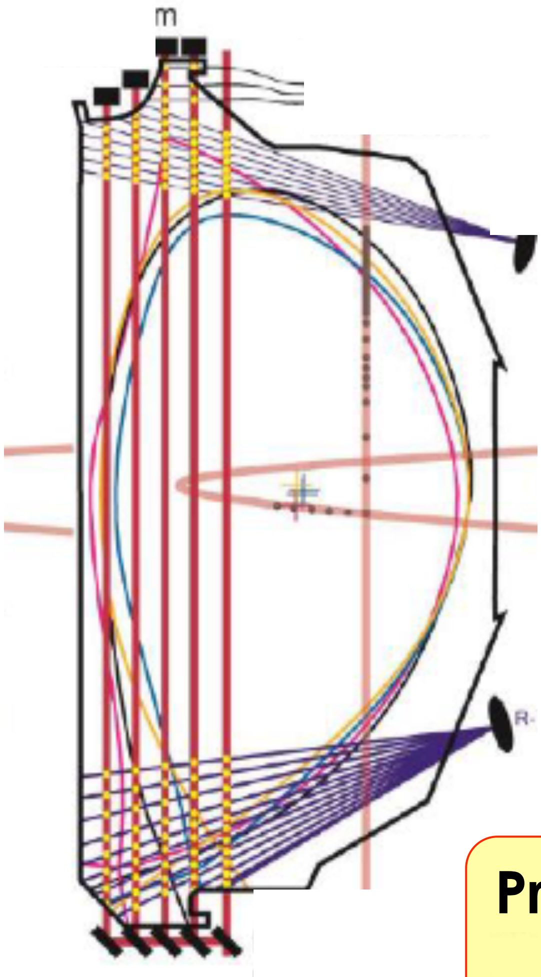


Codes must reproduce non-linearities and are key to providing predictive understanding for divertor optimization

Simulation and PMI Initiatives

Advancing Physics Understanding Requires Improved Diagnostics and Systematic Variation of Configuration

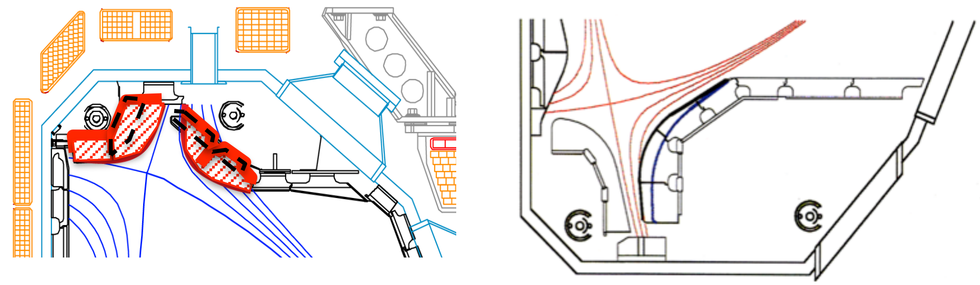
Upper & lower 2D Thomson scattering



Further enhancements

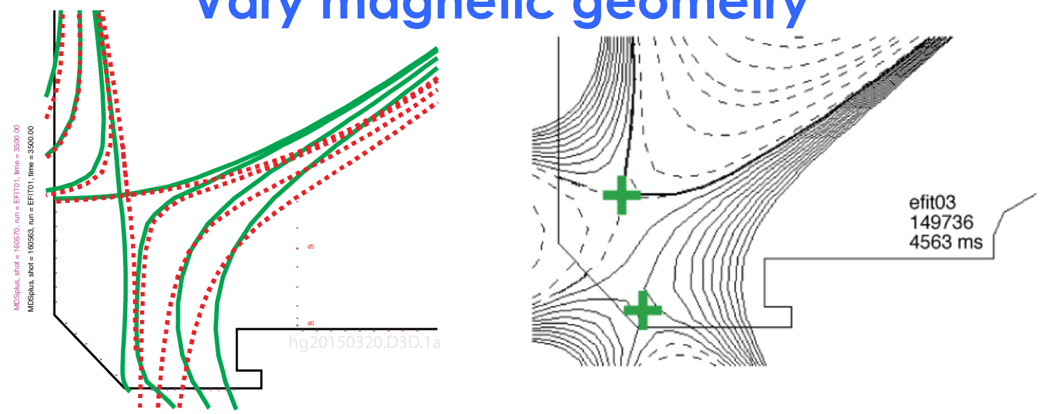
- Bolometry,
- Spectroscopy,
- Neutral pressure,
- Ion Temperature

Systematically vary closure



FY17 Joint Research Target

Vary magnetic geometry



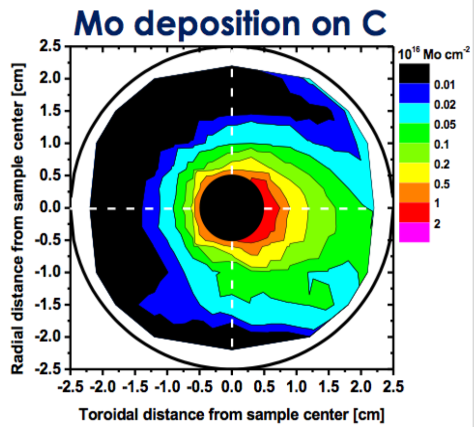
Flaring, flux expansion, connection length, additional X points

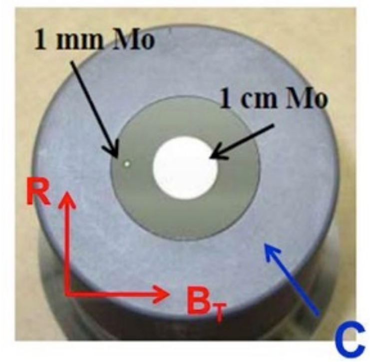
Provides basis for future optimized divertor to be tested in DIII-D

Simulation and PMI Initiatives

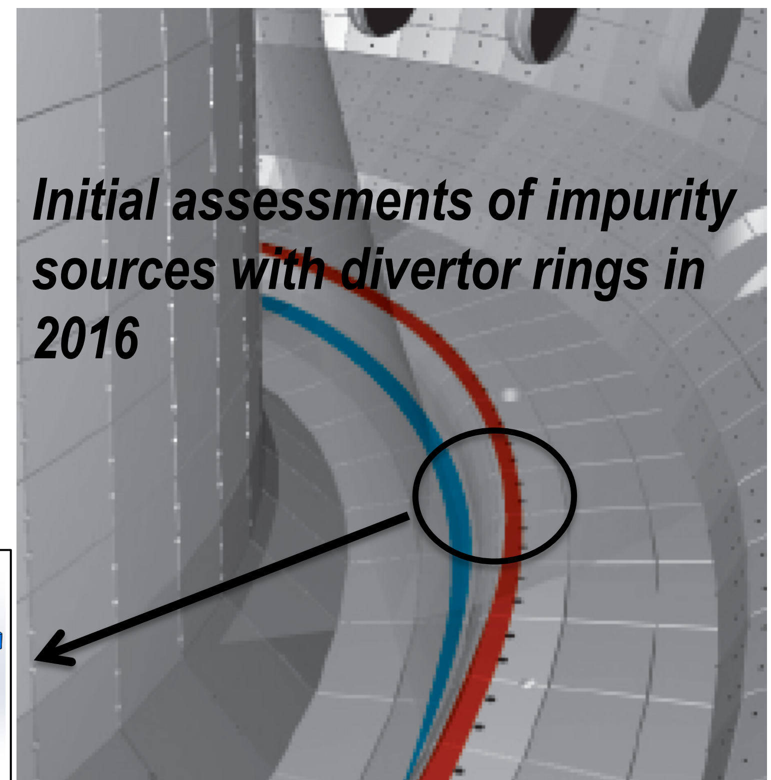
DIII-D Provides Unique Capability to Validate PMI in Reactor-Relevant Tokamak Environment

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

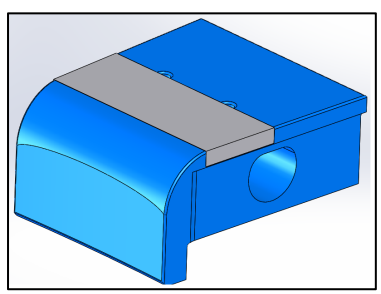




- **Assess impact on plasma performance from large scale divertor PMI**
  - High-Z core contamination & benefits of divertor optimization
  - Effects of high temperature PFCs on core and divertor operation



W-coated moly inserts



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005-16/DNH/rs

Planned Upgrades Will Provide World-Class Capabilities and Flexibility for Addressing Key Scientific Issues

DIII-D Initiatives → Enabled by DIII-D Upgrades

1. Prepare for Burning Plasmas

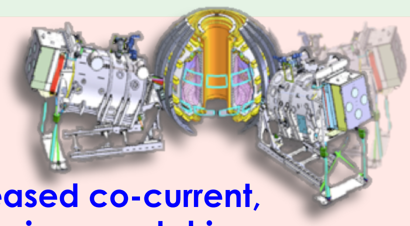
Deliver predictive understanding of the impact & optimization of burning plasma conditions on plasma performance

Increased electron Heating/current drive

Super-SPA supply (ASIPP)

2. Determine Path to Steady State

Provide requirements for achieving efficient, high performance, steady-state tokamak operation



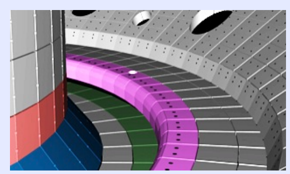
Increased co-current, off-axis current drive

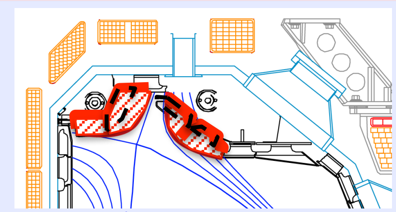
New helicon system

3. Develop PMI-Boundary Solutions

Develop and validate solutions for heat flux control including transients in FNSF and future devices

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

Cost Effective

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

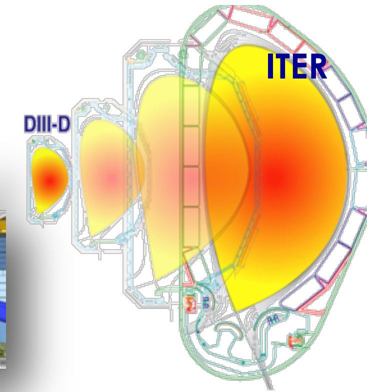
Scientific Leadership

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

Critical to FES Mission

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 (β)**
  - 20MW Co+Cntr, On/Off-axis NBI, ECH
- → **Current profile control (2-3 τ_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 (ν*)**
  - 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