Fusion at General Atomics

By
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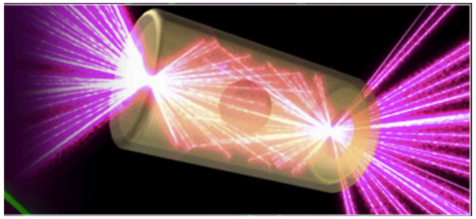
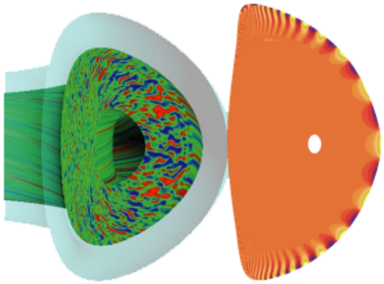
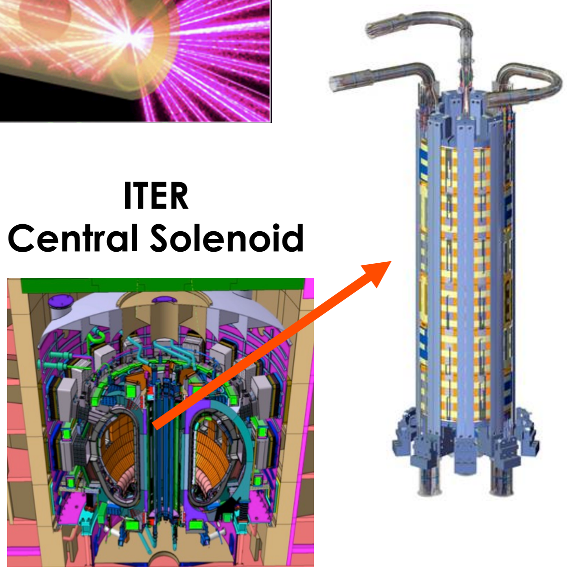
Inertial Fusion Technology

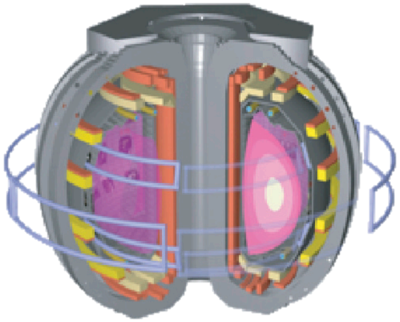


Theory &
Computation

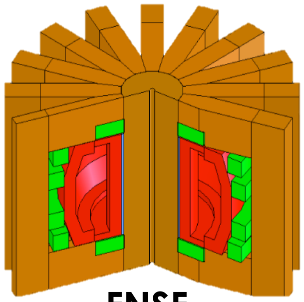


ITER
Central Solenoid





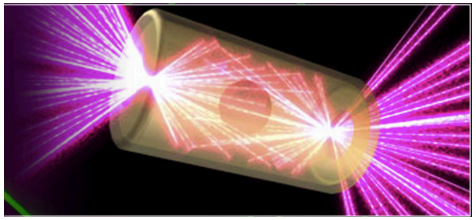
DIII-D Program



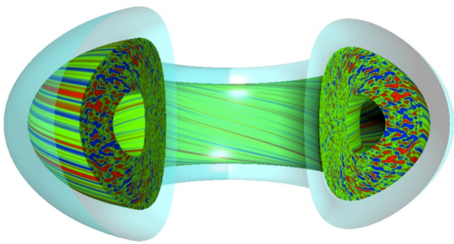
FNSF

Fusion at General Atomics: Major Contributions in Five Areas

- **Inertial Fusion Technology**
  targets for ICF

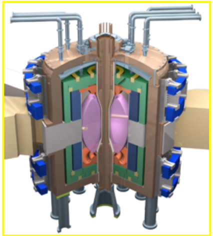


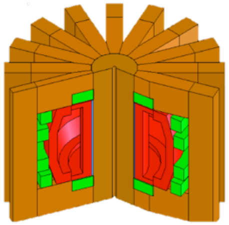
- **ITER Components**
  Central Solenoid Manufacture



- **Theory and Computation**

- **DIII-D Program**

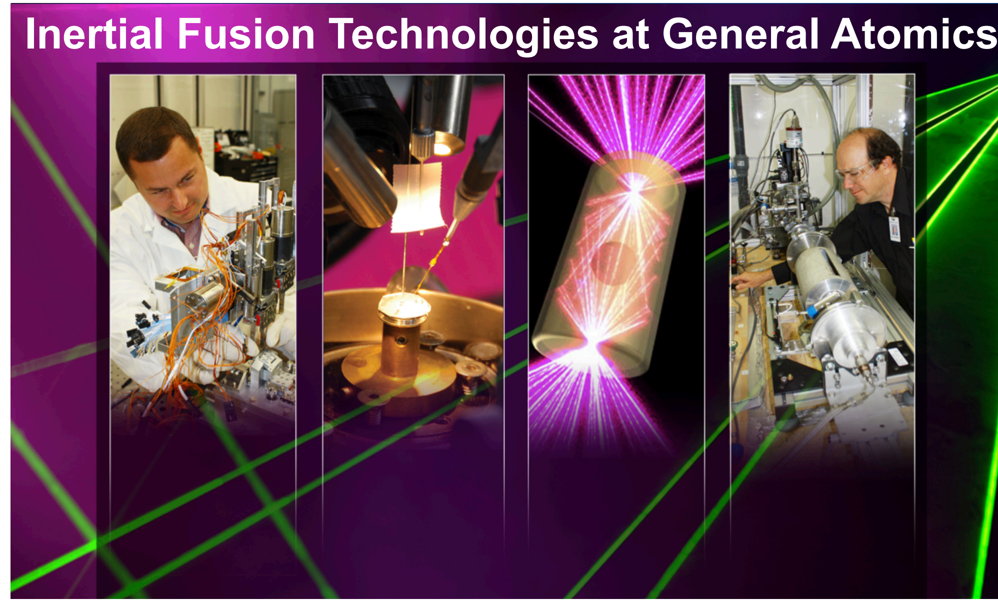




- **Fusion Nuclear Science**

GA Has a Long History Providing Inertial Confinement Fusion Targets

- **ICF target fabrication support, since 1991:**
  - Target fab & characterization techniques
  - Target cryogenic systems
  - Deliver targets
- **GA is single largest supplier of targets**
  - ~1000’s targets/year
  - Targets made for LLNL, LANL, SNL, AWE, CEA, Japan
  - IFT Staff ~115 (development)
- **DOE and General Atomics’ investments have built a unique target facility for the U. S.**
  - Strong collaboration with labs creates a central hub for target fab

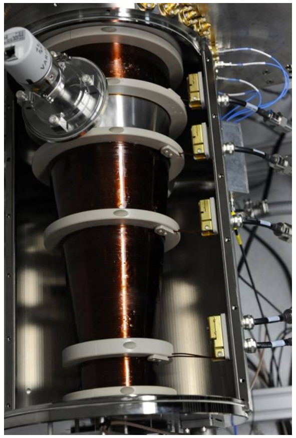


IFE target contributors

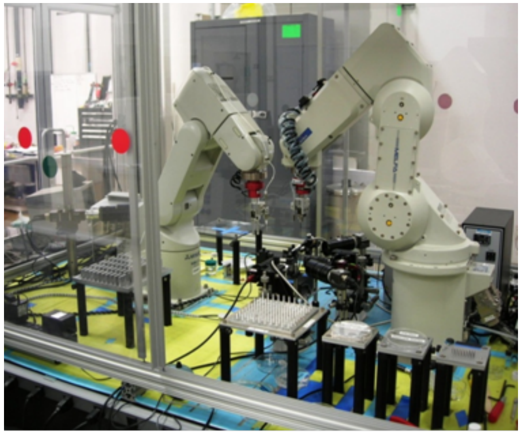
GA Inertial Fusion Technology is Developing Leading Edge Capabilities as a Target Supplier

- **Continued improvement and efficiency with modern manufacturing methods**
  - Automation and robotics for machining and characterization
  - Reduces fabrication and metrology time
  - Reduces cost – "on the pathway" to IFE
- **Preparing for Inertial Fusion Energy Targets**
  - Increased automation ➔ increased volume, reduced cost
  - Component manufacturing and assembly
- **GA IFT prepares advanced targets for NIF, Z, and Omega**
  - Develop, and supply components for the NIF cryogenic target
- **Developing ultra-fast x-ray imaging diagnostics for Omega/EP and others**

Automated Lathe

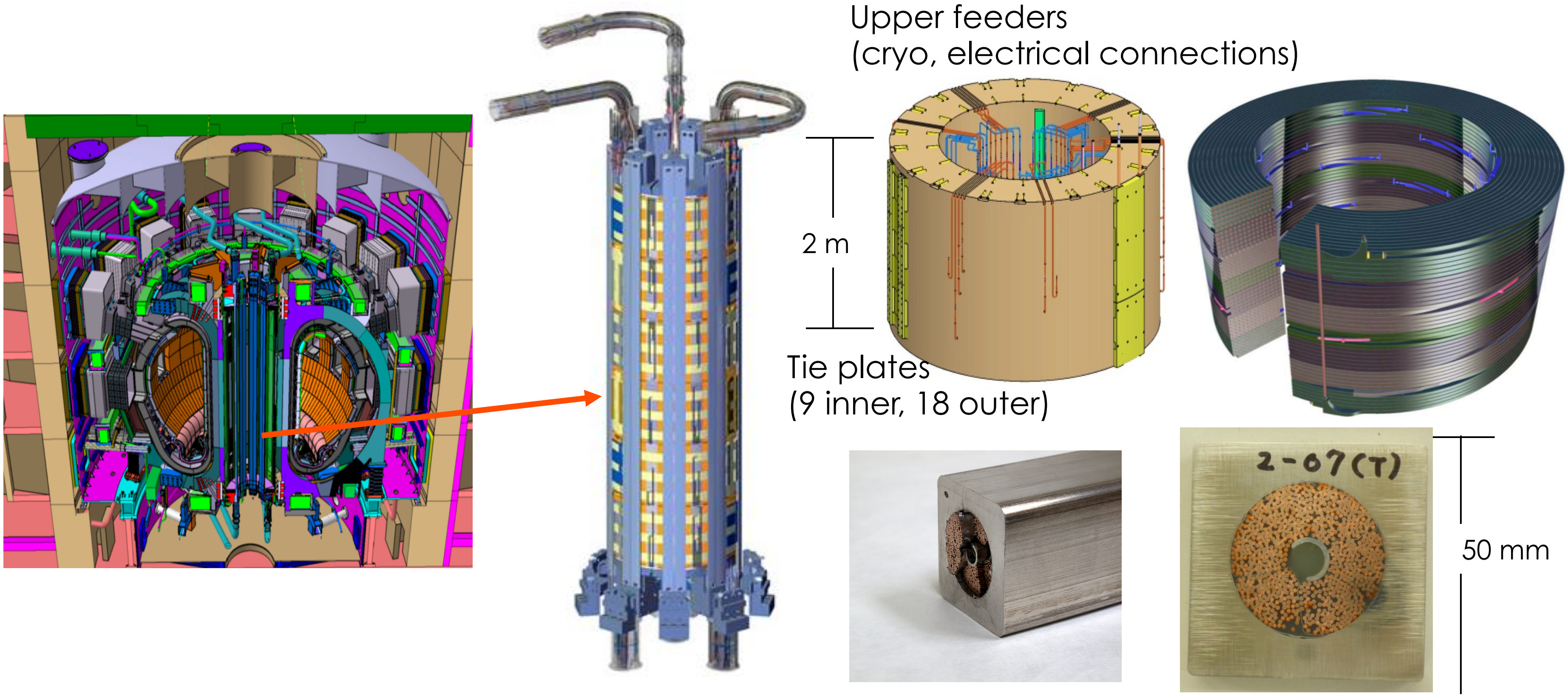


Dilation X-ray Imager



Robotic assembly and characterization

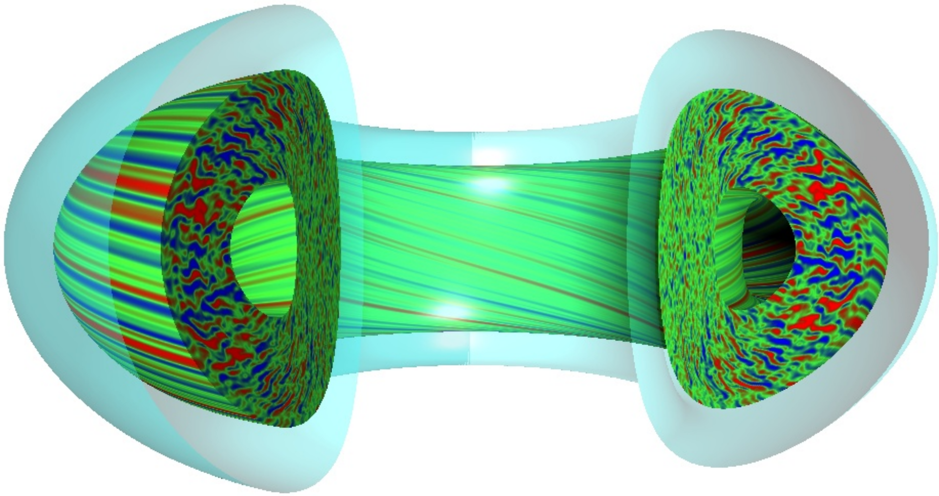
General Atomics is Manufacturing the ITER Superconducting Central Solenoid



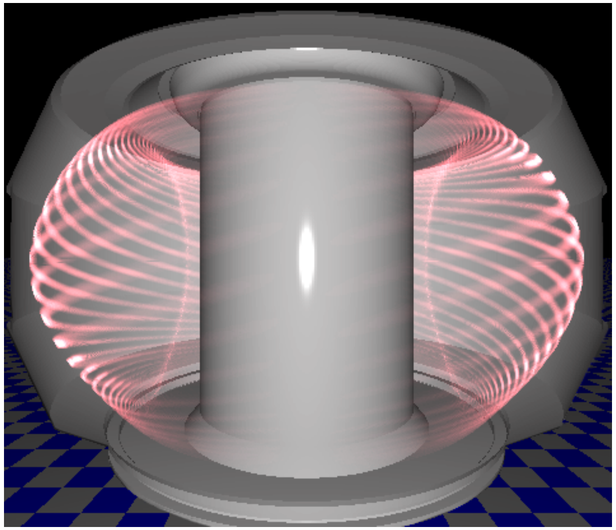
- **Six modules plus structure ~900 tonnes**
- **Each module weighing 110 tonnes has 560 turns (6.5km of conductor)**
- **Nb_3Sn CICC Conductor supplied by JAEA in 1km lengths**
- **Project duration is seven years,**

GA Theory and Computational Science Division Developing Fundamental Understanding of Fusion Plasmas

- **Advances in analytic theory and world class numerical tools, eg**
  - GYRO: electromagnetic turbulence
  - M3D-C1, ELITE, GATO: core/edge MHD
  - NEO: neoclassical transport



- **Extensive validation with DIII-D and other experiments builds confidence in understanding**
  Hierarchical validation, eg
  - Turbulence simulations compared to measurements across multiple spatiotemporal scales and multiple channels, and comparisons of predicted and observed transport
  - Predicted ELM structure and onset conditions compared to multiple high resolution measurements



GA Theory and Computational Science Division
Developing Predictive Capability for DIII-D, ITER and Beyond

- **Validated simulation and theory used to develop predictive models. eg**
  - TGLF: particle, heat and momentum transport
  - EPED: structure of H-Mode pedestal

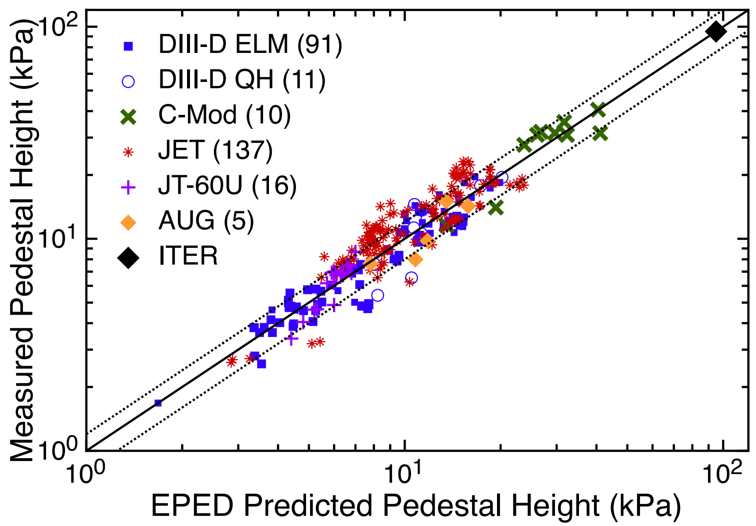
  Models extensively tested on DIII-D and other tokamaks

  Combining these models allows performance prediction and optimization for DIII-D, ITER…

- **Developing Understanding Used to Address Key Fusion Challenges**
  - Disruptions and runaway electrons
    - Assessing ITER loads and mitigation techniques
  - ELM Control
    - Developing predictive understanding of RMP ELM control and QH mode

Strong partnership between GA Theory and DIII-D Program

Comparison of EPED Model to 270 Cases on 5 Tokamaks



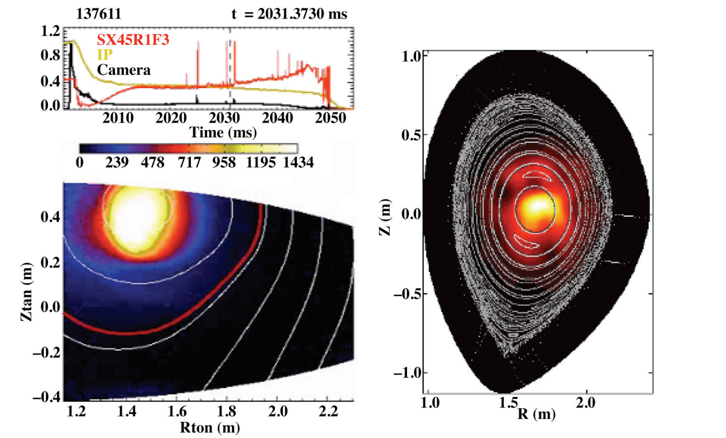
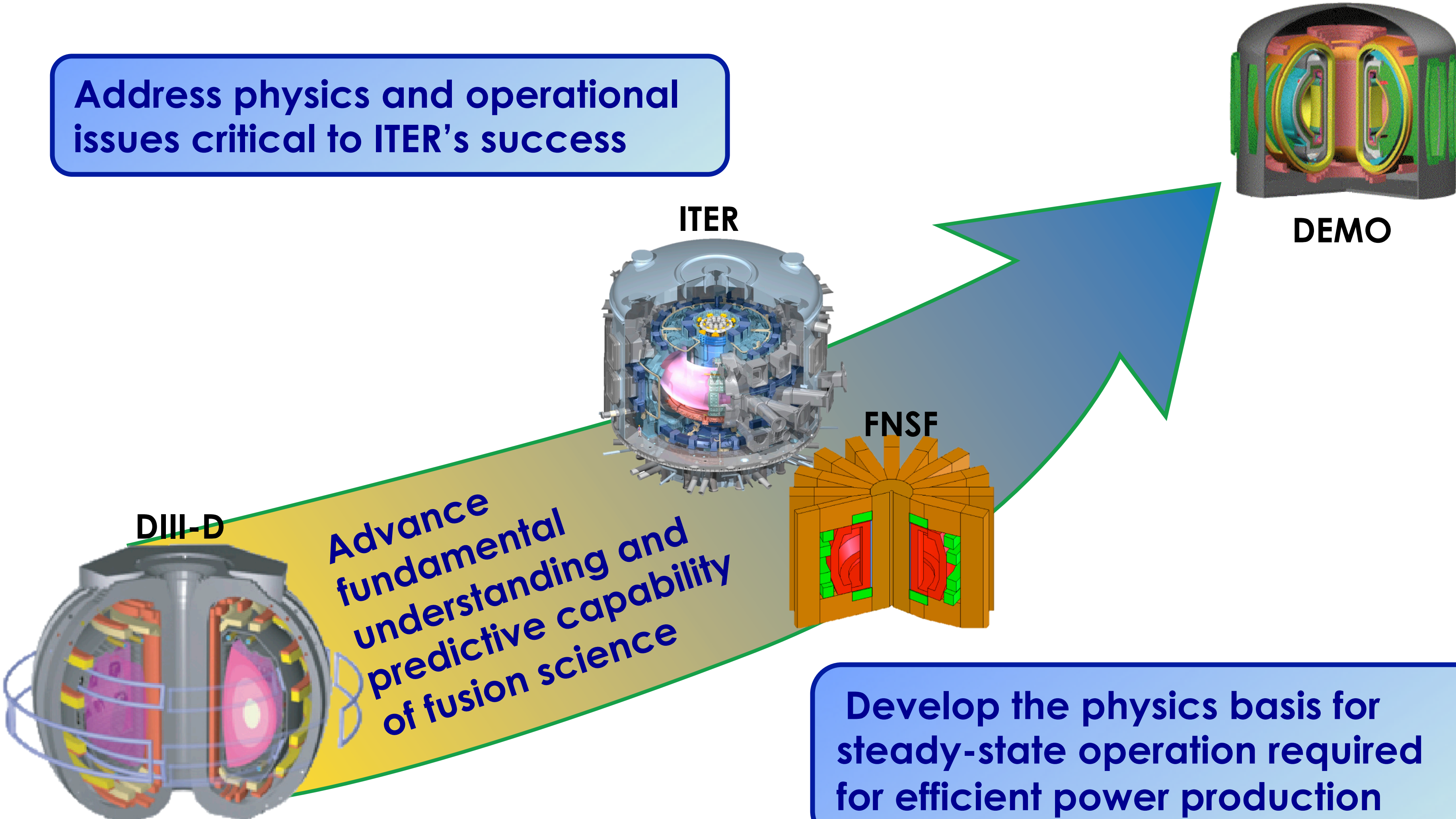


Fig. 2. (Left) Fast camera measurement of synchrotron radiation from a runaway beam in DIII-D. (Right) Synchrotron radiation brightness from a simulation with nearly 2000 electron orbits. Field lines are superimposed.

DIII-D is Advancing the Physics Basis Needed to Support Fusion Energy Development

Address physics and operational issues critical to ITER's success

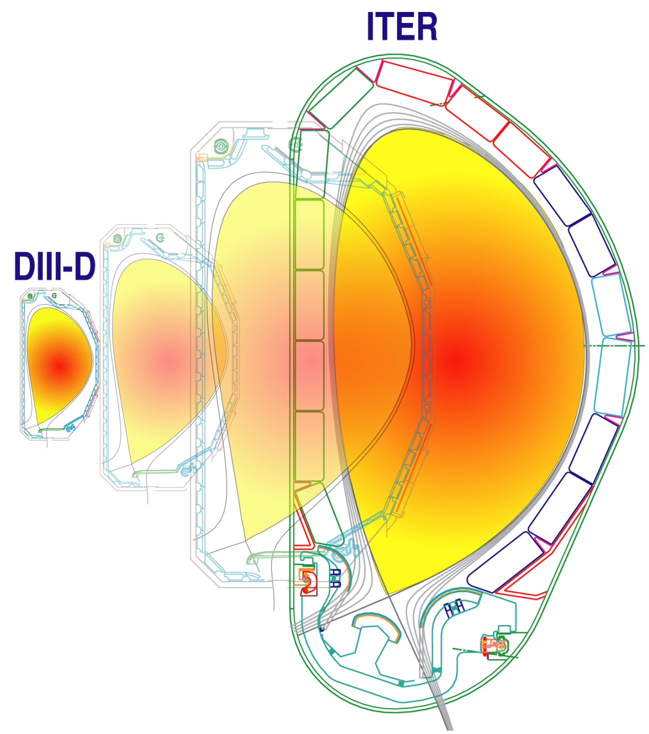


Develop the physics basis for steady-state operation required for efficient power production

DIII-D is Playing a Lead U.S. Role in Preparation for ITER

Addressing design and operational issues for ITER

- **Develop reliable plasma termination systems: runaway electron control**
- **Control Erosion from pulsed heat loads (ELMs) using 3D fields and pellets**
- **Develop ITER relevant plasma control to avoid early discharge termination:**
  - Steerable microwave for tearing modes
  - Locked modes and error field correction
- **Develop ITER relevant, electron heated scenarios, T_e~T_i, low torque, & non-nuclear**
- **Evaluate and control heat flux with new measurements, and new configurations**



DIII-D: U.S.'s ITER Simulator ~1/4 size ITER Prototype

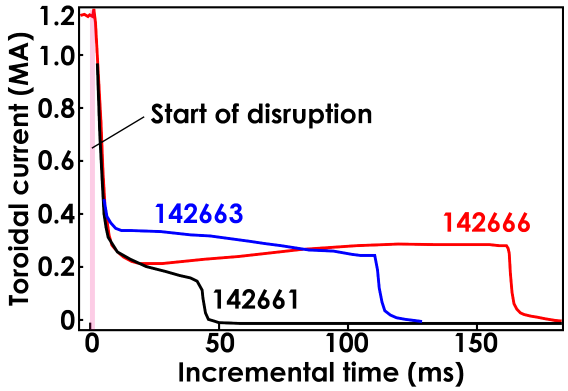
Training U.S. scientists and engineers for leadership roles in ITER

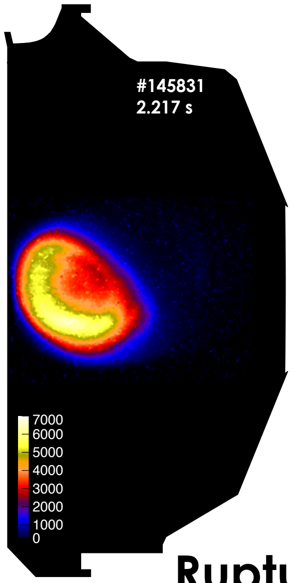
DIII-D priorities developed in consultation with ITER Organization and ITPA

DIII-D Program Targets Provide Physics Basis for Disruption Mitigation Solutions

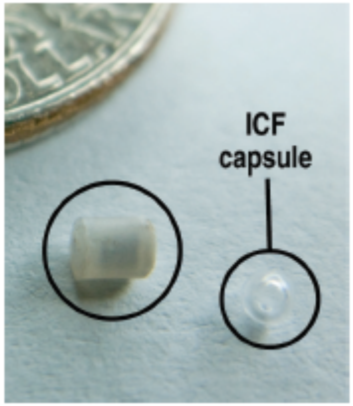
- Develop innovative techniques for runaway electron measurement, control, and dissipation
- Assess efficacy of massive particle delivery techniques
- Characterize impact of thermal, magnetic, and runaway loads on internal components

Sustained Runaway Channel

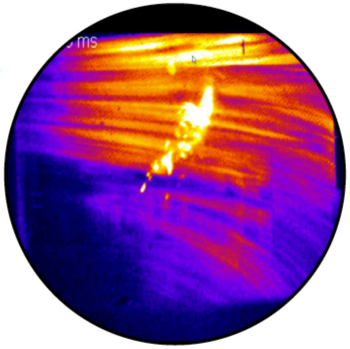




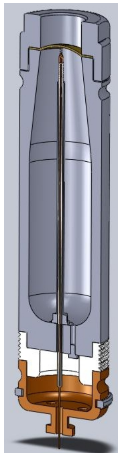
Shell Pellets



Shattered D2 Pellets

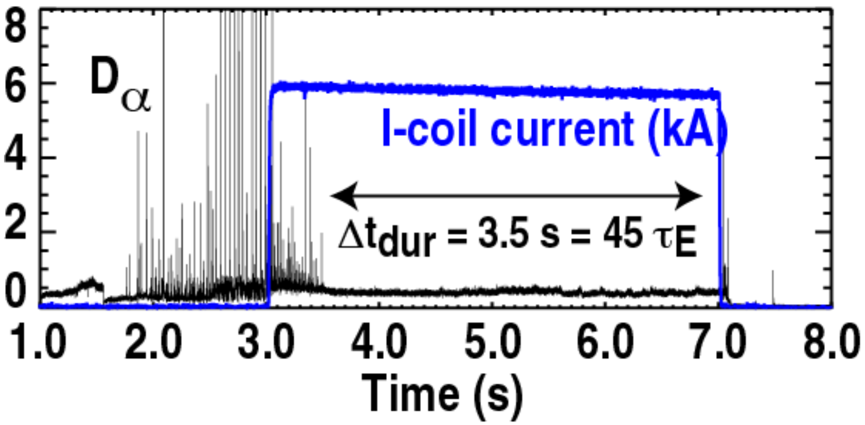


Rupture Disk

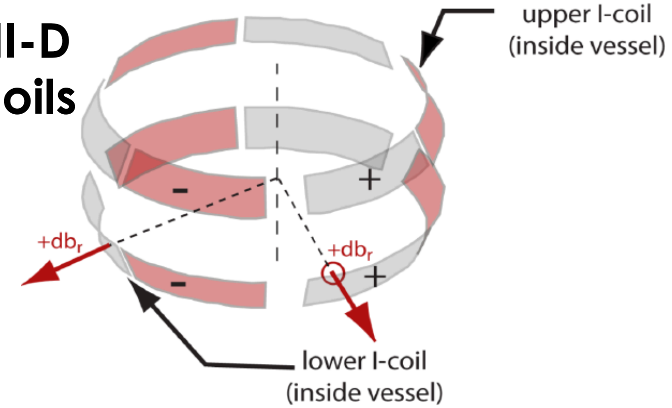


DIII-D Research Has Increased Confidence in Ability to Achieve RMP ELM Suppression on ITER

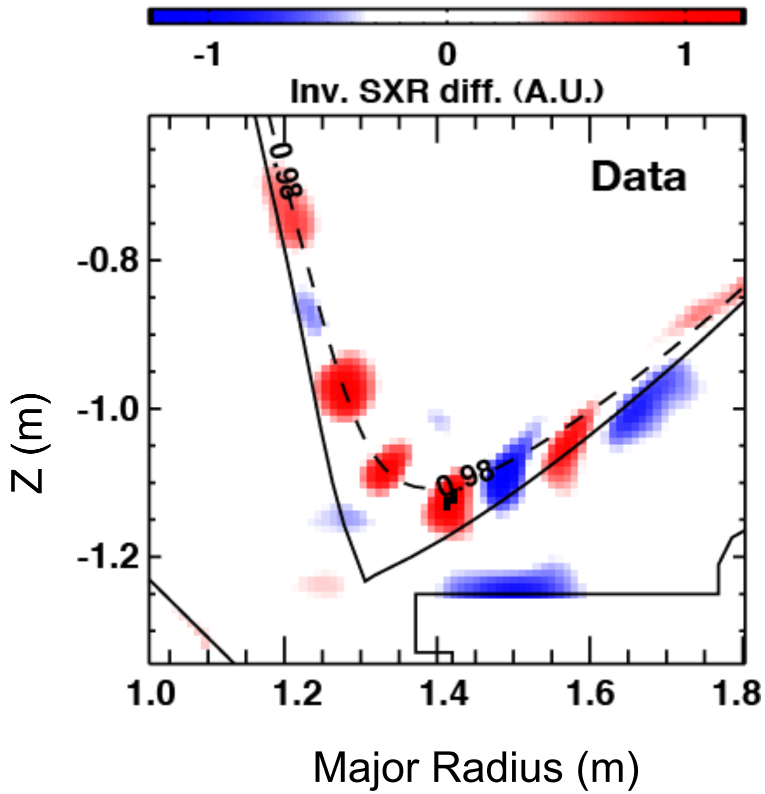
- **ELM suppression operating space expanded to include ITER baseline**



DIII-D I-coils



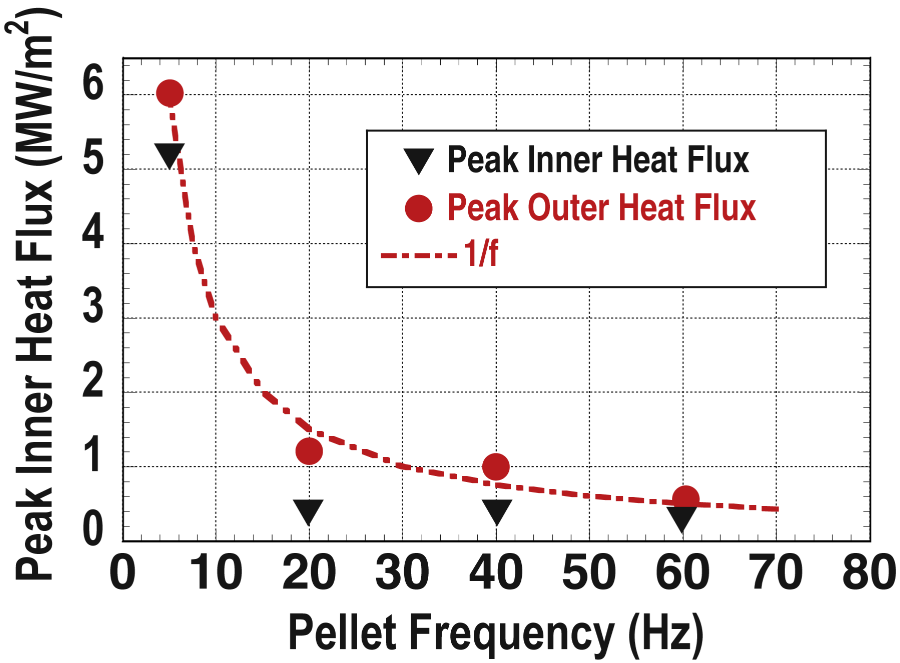
- **Significant advances in physics understanding of RMP effects**



- **Qualitative agreement with two fluid resistive MHD (M3D-C1)**

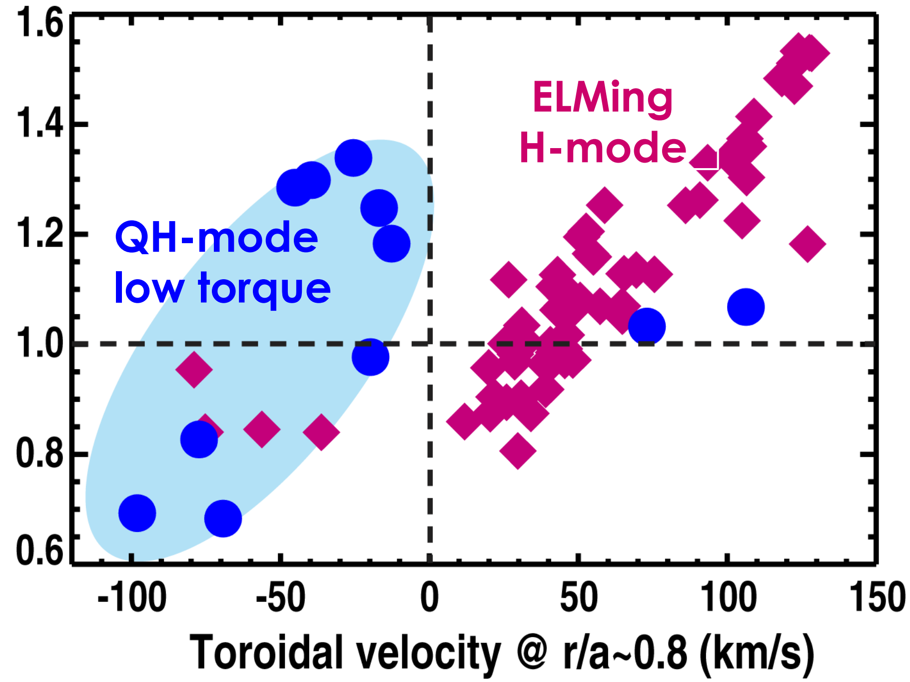
DIII-D is Demonstrating Alternate ELM Control Techniques

Pellet pacing in ITER baseline scenario yields 12x lower ELM divertor heat pulse



$f_{pellet} \times \Delta q_{div} = \text{const}$

ELM-free QH-mode Extended to ITER Relevant Torque Using External 3D Coils



QH-mode is an attractive candidate scenario for ITER

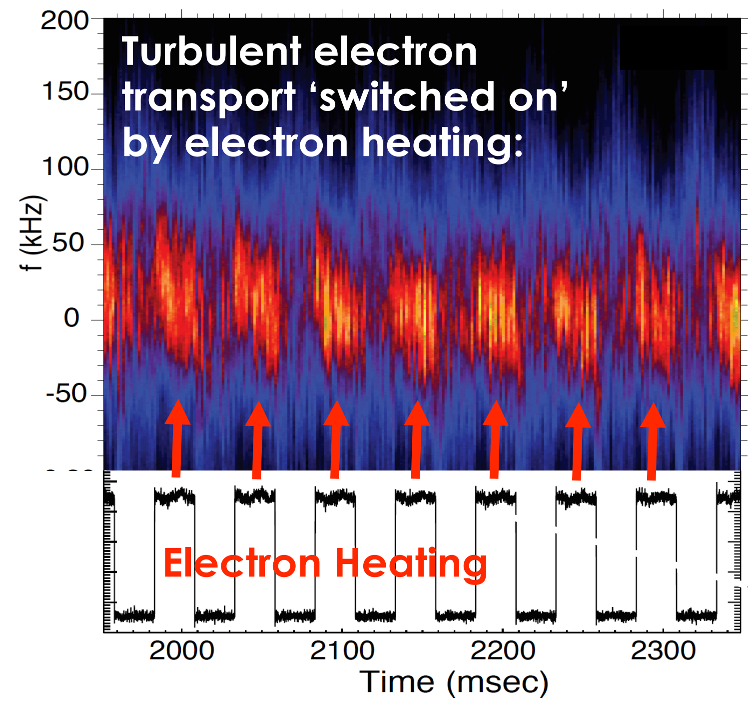
DIII-D is Proposing Modest Upgrades in 3D Field Capability to Advance Scientific Understanding and Optimize Performance

- **Proposed upgrades will enable enhanced physics capabilities:**
  - Power Supplies
    - Increased amplitude perturbation during rotation
  - New coil array
    - Broader spectrum (n=1-4) of applied fields
    - n=1-4 rotatable
  - New coil array + power supplies
    - Multi-mode control
- **Imaging enabled by rotating perturbation across fixed diagnostics**
- **QH-mode with increasing NBI torque may be possible with increased NTV torque from new coil set**

Upgrade provides scientific understanding and extrapolation to ITER

Burning Plasma Regimes Access Different Energy Transport Processes

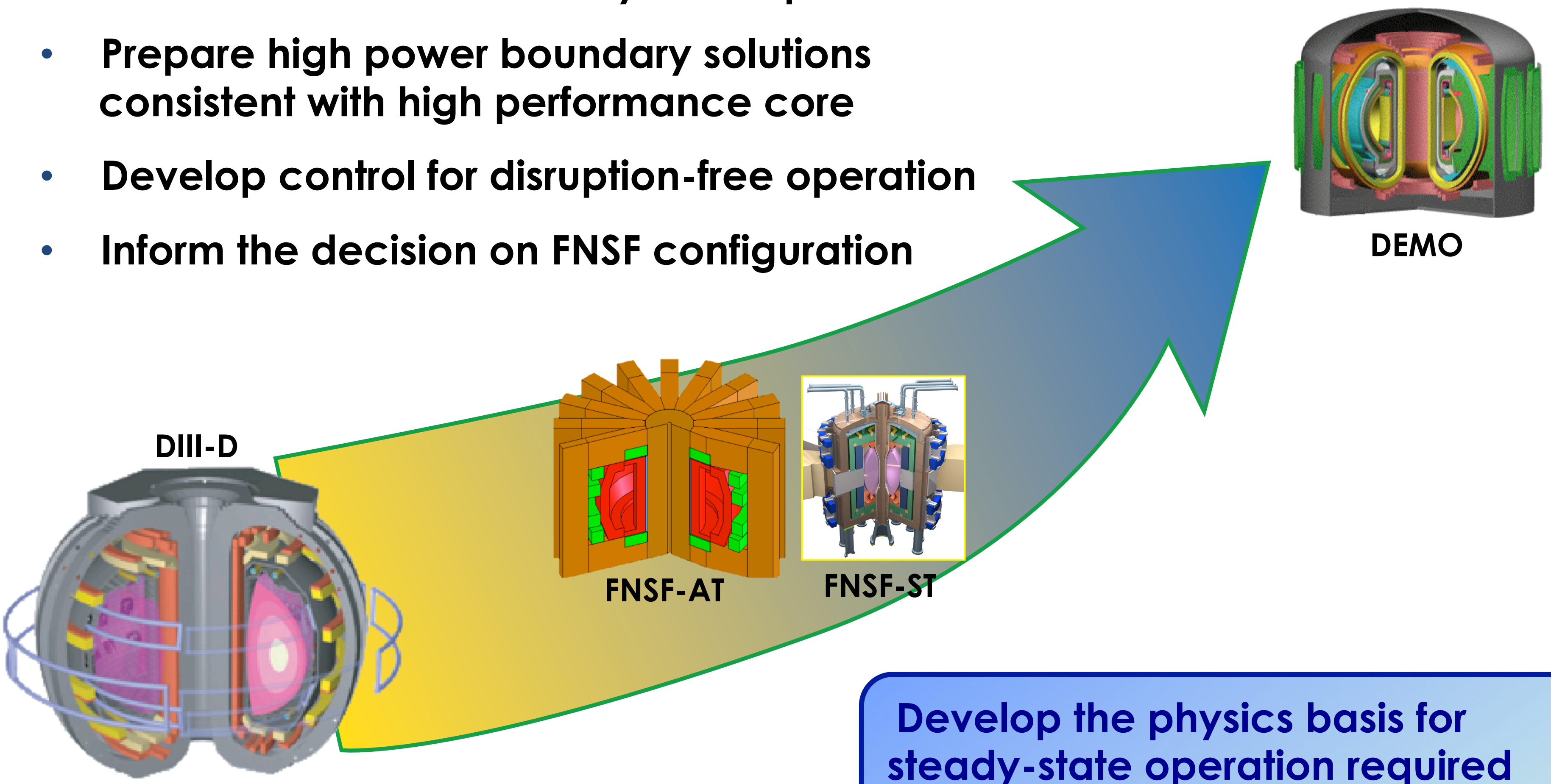
- **Burning plasmas are heated by fusion α' s**
  - Primarily heat electrons
- **Microwaves heat electrons similar to fusion α' s**
  - Relevant T_e, collisions, rotation and fuelling
- **Relevant turbulence and transport can be evaluated with electron heating**



Microwave upgrade (~ 8 MW to 15 MW) will access burning plasma relevant transport regimes

DIII-D is Advancing the Physics Basis Needed for a Fusion Nuclear Science Facility and DEMO

- Provide the basis for steady state operation
- Prepare high power boundary solutions consistent with high performance core
- Develop control for disruption-free operation
- Inform the decision on FNSF configuration

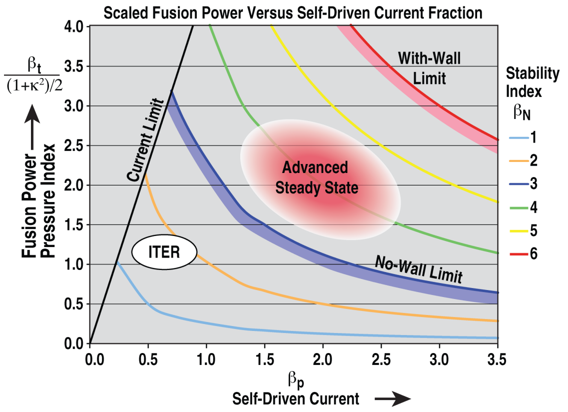


Develop the physics basis for steady-state operation required for efficient power production

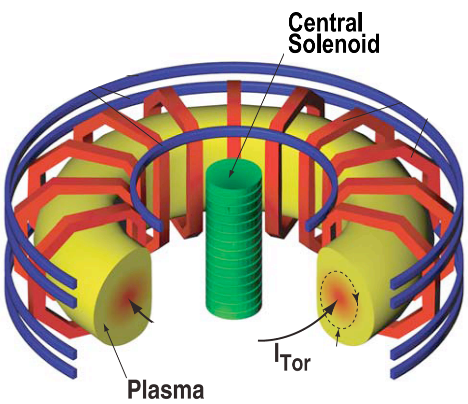
Controlling Current Distribution is Key to Steady State High Performance Plasma

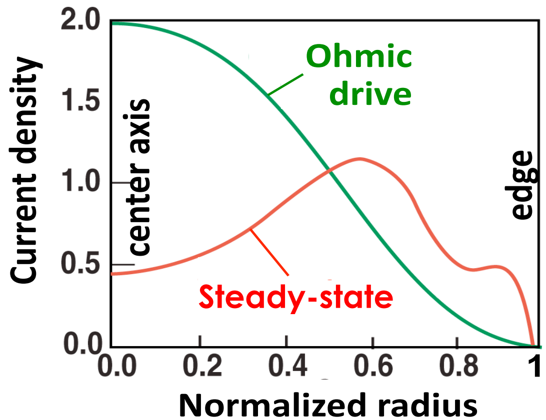
- **Goal:** High pressure (Fusion power) + High self-driven current (Steady-state & high energy gain)

$$I_{steady\ state} = \cancel{I_{CS}}^{\,0} + I_{self\text{-}driven} + (I_{NBI} + I_{waves})$$

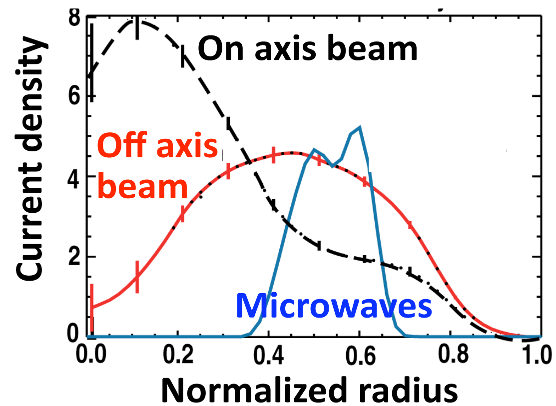


- Theory & experiment show current must be distributed off-axis to achieve optimized steady-state solutions



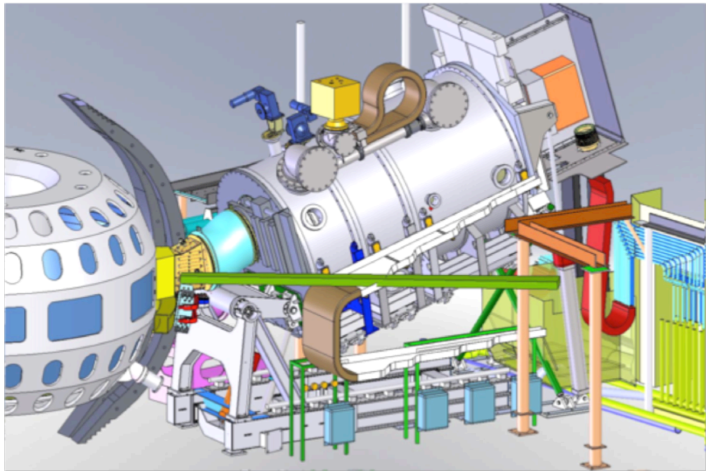


Tools:

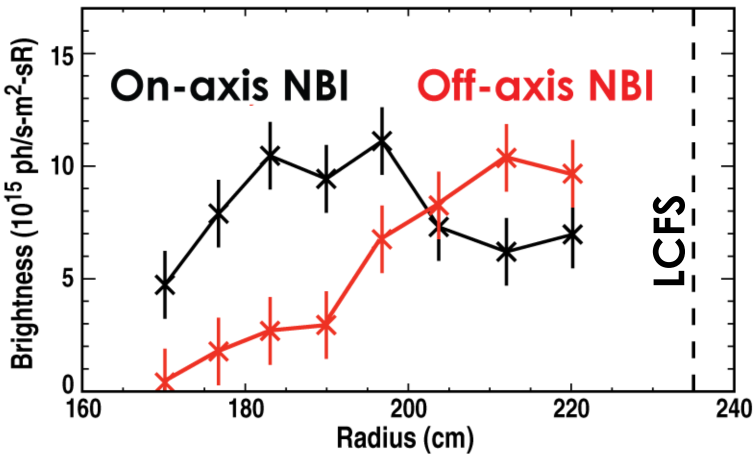


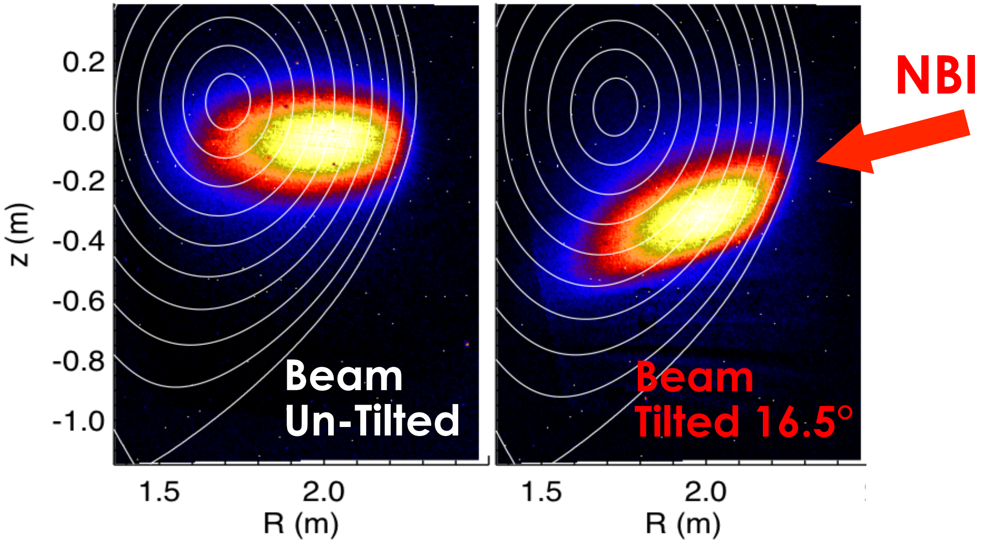
Off-axis neutral beams & microwave driven currents provide off-axis current

DIII-D Neutral Beam Successfully Modified for Off-Axis Injection, Providing H&CD for Physics Studies

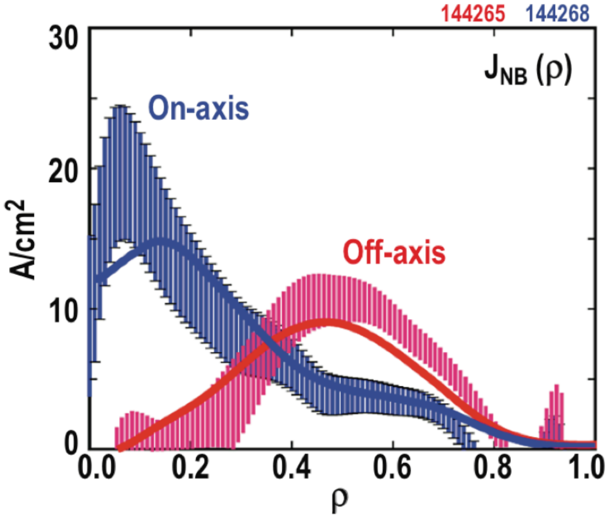


Measured Fast Ion CXR Emission

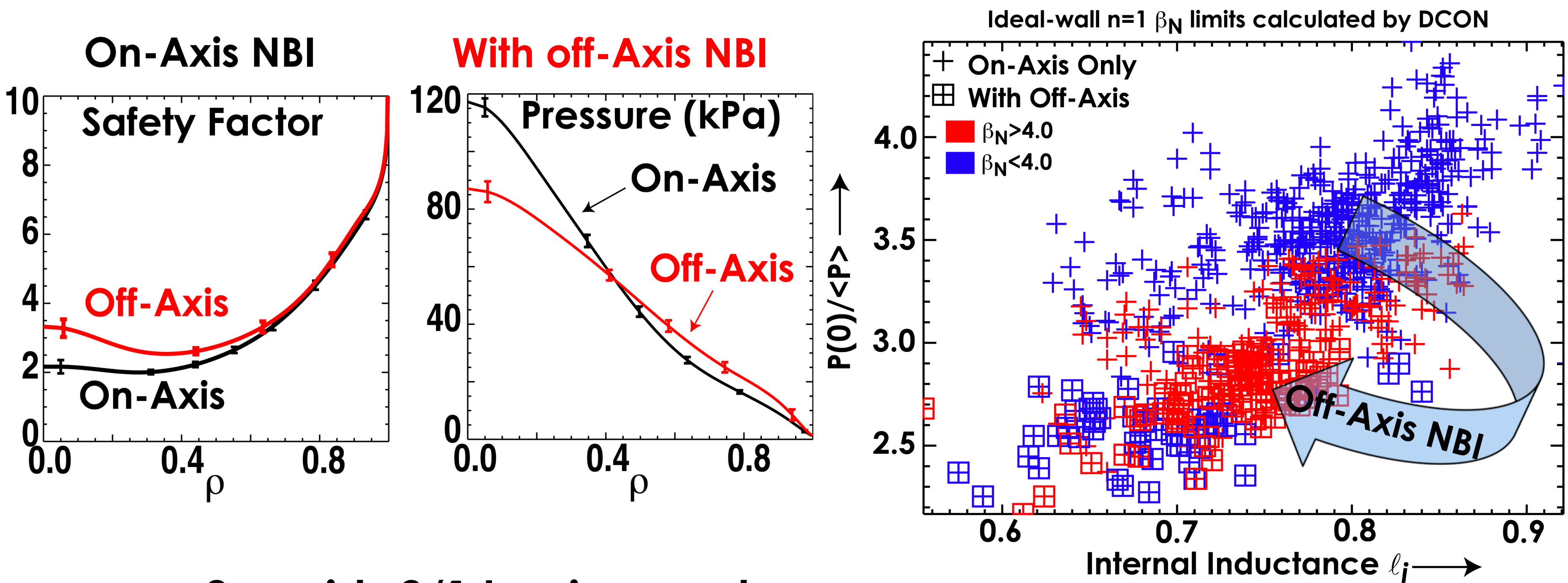




NBCD Agrees with Classical Model

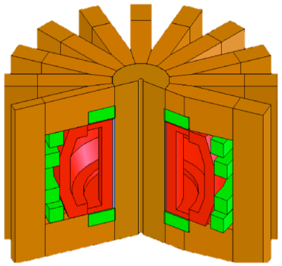


Off-Axis NBI Produces Broad Current & Pressure Profiles with Sustained q_{min}>2 for Higher β_N Stability Limits



- q_{min}>2 avoids 2/1 tearing modes
- Off-axis NBI broadens current and pressure profiles
- Plasmas have higher predicted stability limits (β_N ~4)

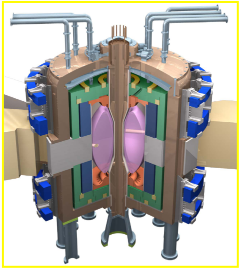
Evaluating Options for a Nuclear Fusion Science Facility to Operate in Parallel with ITER



FNSF-AT

Objectives
- **FNSF + ITER informs DEMO design choices**
- **Q = 10 in ITER leads to DEMO construction**

FNSF-ST



- **Modest effort funded by GA**
- **Evaluating mission elements, technical readiness, and risks**
  - Supporting community effort (led by D. Meade)
- **Developing self-consistent scenarios for FNSF-AT**
  - Steady-State with ECCD only
  - TBR > 1.1, H_{98y2}~1.2, β_N=3.7, f_{BS}~70%
  - Manageable peak divertor heat flux based on SOLPS and experiments
- **Developing a staged approach**
  - Demountable cooled copper coils
  - Remote maintainable with removable blankets, divertor, etc.