# Fusion Program at General Atomics

By
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Presented at the
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and Symposium

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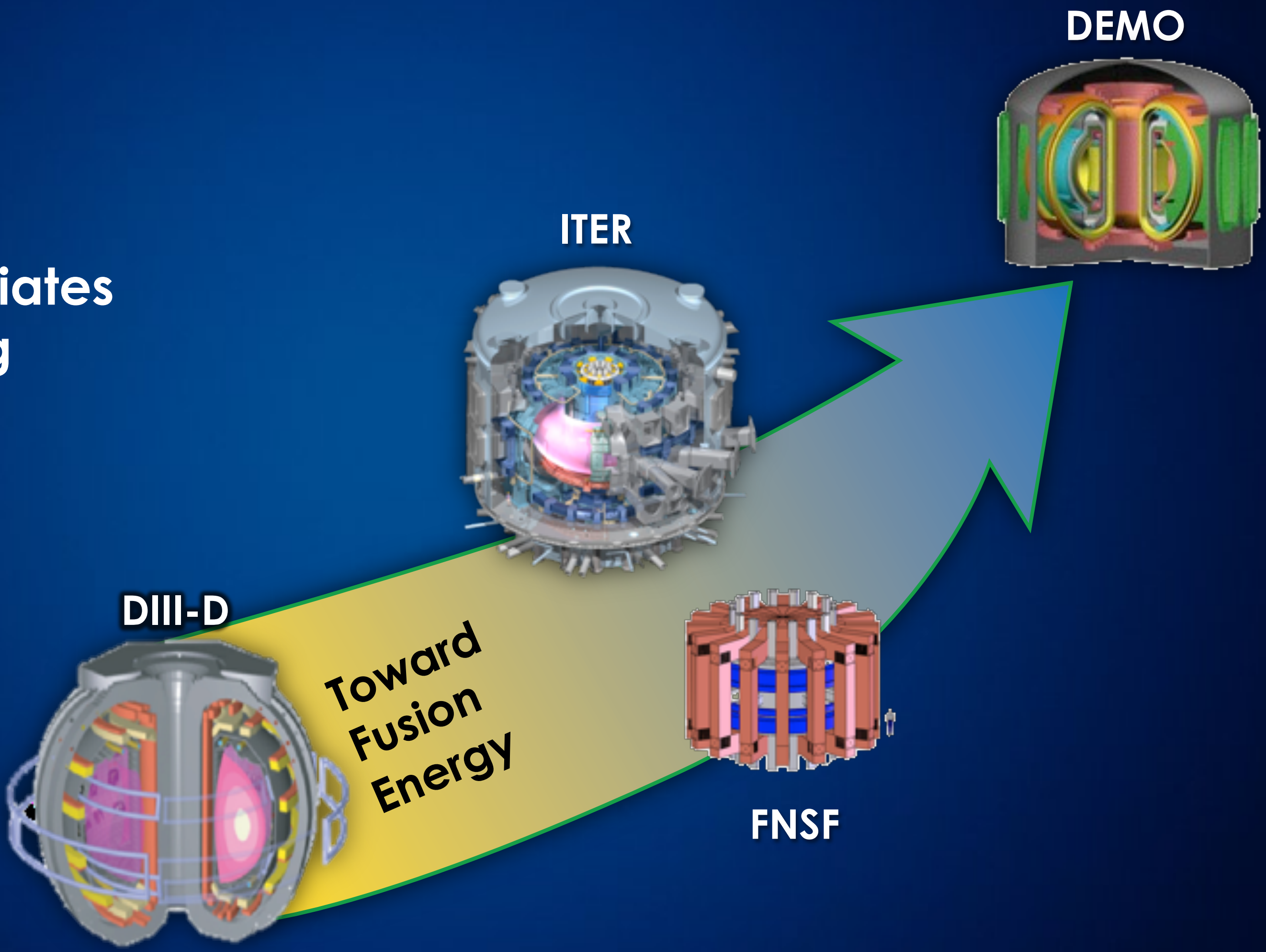
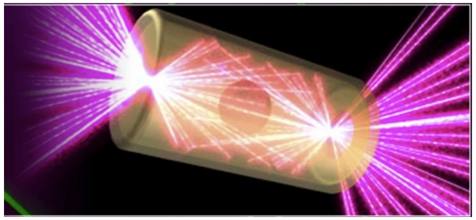




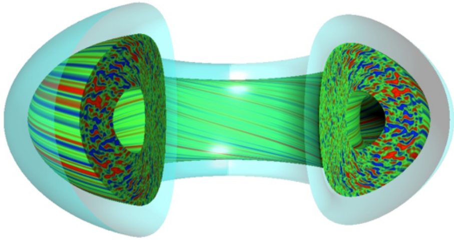
GENERAL ATOMICS

# Fusion at General Atomics: Major Contributions in Five Areas

- **Inertial Fusion Technology**
  Targets for ICF and diagnostics



- **ITER Components**
  Central solenoid manufacture
  Diagnostics



- **Theory and Computation**


- **DIII-D Program**

- **International Collaboration**

# General Atomics Provides Inertial Confinement Fusion Targets

- **ICF target fabrication support, since 1991:**
  - Target fab & characterization
  - Target cryogenic systems
  - Materials & processes development
  - Diagnostics & pinholes
  - Onsite assembly & fielding


- **GA is largest supplier of targets**
  - >10,000's targets & components / year
  - Staff ~115
  - Supporting: LANL, LLE, LLNL, SNL, SLAC, Scarlet; **International**: AWE, CEA, ILE, LULI, CELIA

| Lab | Targets or Components |
|---|---|
| LANL | 664 |
| LLE | 859 |
| LLNL | 1,445 |
| NLUF | 850 |
| LBS | 571 |
| SNL | 685 |
| NIF | 5,908 |
| SLAC | 6* |
| Diagnostics | 1,303 |
| Other | 1,537 |

*= Hundreds of target sites per target assy

**Experiments**
- ~200 at NIF (LLNL)
- ~1000 at OMEGA/EP (LLE)
- 6 series on LCLS represents >1000 shots (SLAC)
- >100 on Z machine (SNL)

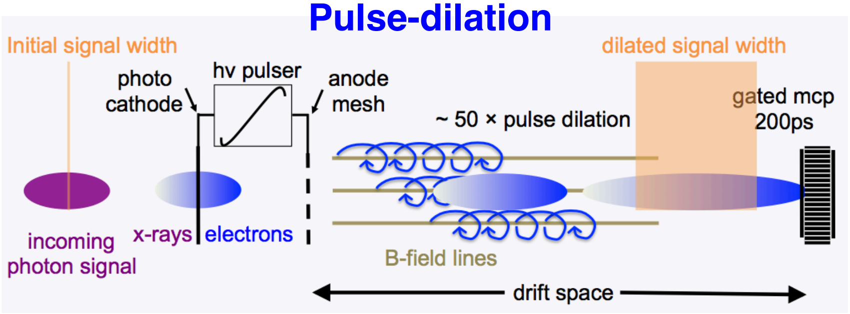
- **DOE & GAs' investments have built a unique target facility**
  - Strong collaboration with labs
  - Central hub for target fab

**University Collaborators**: M.I.T.; Princeton; U of Michigan; U of Nevada, Reno; Caltech; UCSD; UC Berkley; Stanford; Rice Univ.; ARTEP; U of New Hampshire;

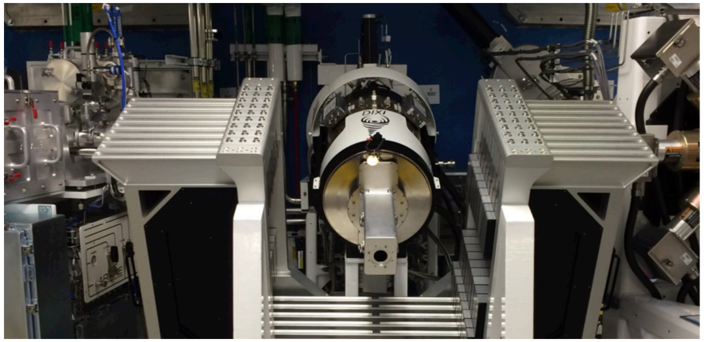
# General Atomics Develops Transformational Diagnostics for ICF and HED Experiments (with International Collaborators)

- **Pulse-dilation imaging (Kentech)**
  - Pioneered technique which gives 10X faster gates for imagers (≥5ps)
- **DIXI – Dilation X-Ray Imager (Kentech & LLNL)**
  - Designed, built and fielded a 5 ps x-ray imager for the NIF
  - Recent results reveal unprecedented levels of detail in implosion dynamics
- **Ultrafast Photodetectors (Kentech,Photek,LANL)**
  - Developing 10X faster photodetectors for upgrades to gamma detectors, optical Thomson scattering, …

**Pulse-dilation**



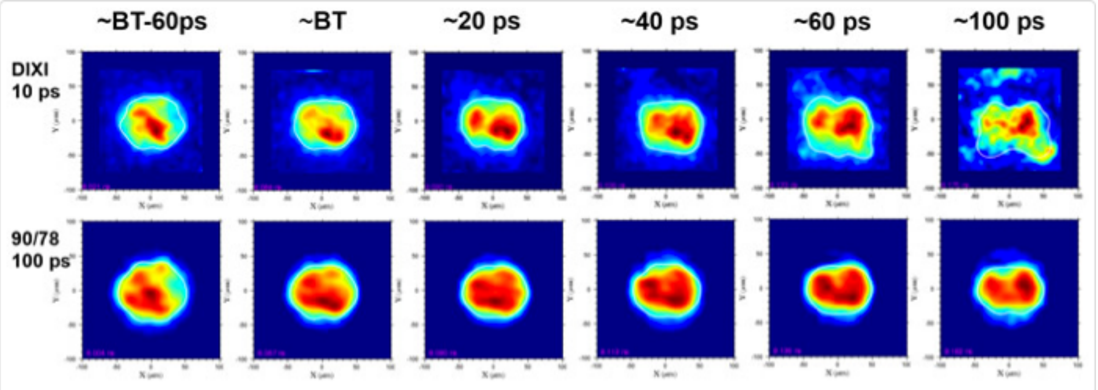

**DIXI on NIF**



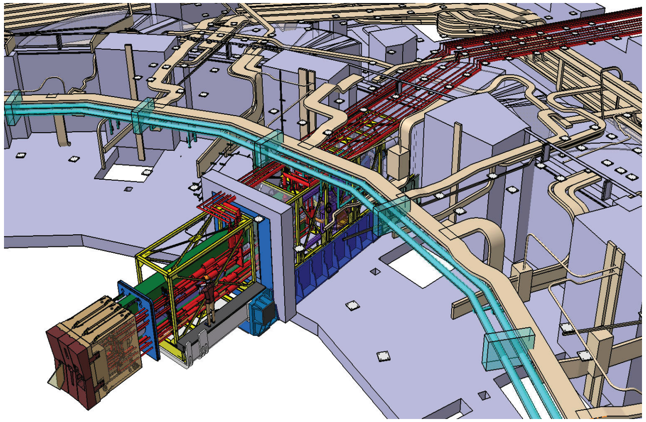
**High Fidelity Implosion Images On NIF**

**DIXI →**

**Previous →**

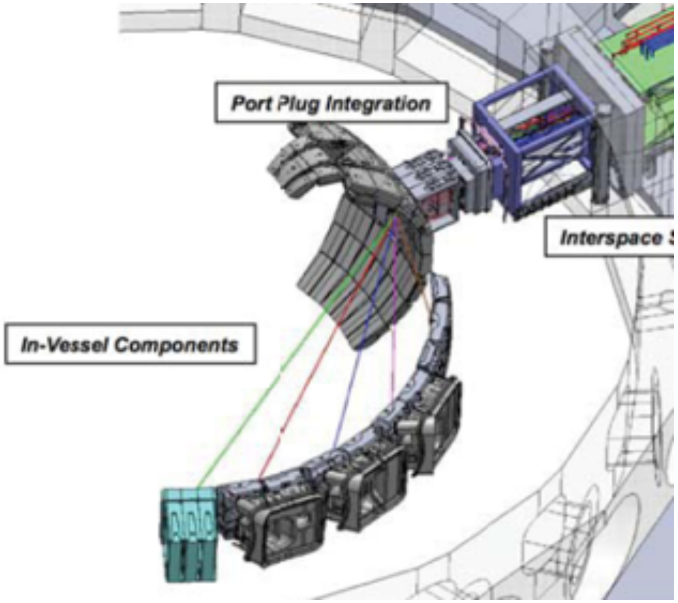


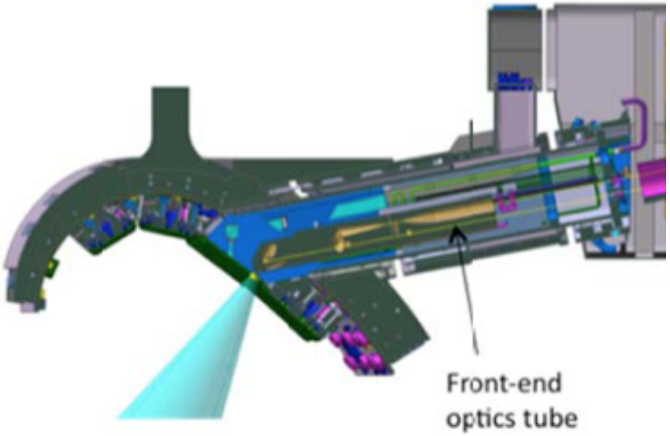
# General Atomics is Fabricating Three Diagnostic Systems for ITER



**Low Field Side Refectometer (GA/UCLA)**

**Toroidal Interferometer Polarimeter GA/UCLA/PSI)**



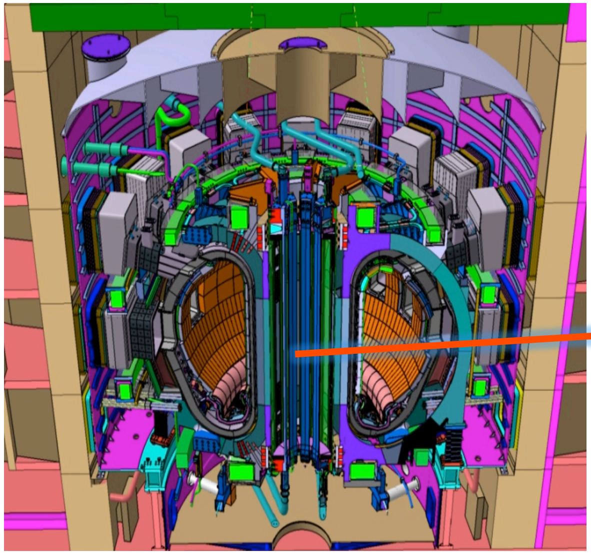




**IR/Visible Wide Angle Viewing system (GA/LLNL/TNO/Univ Ariz.)**

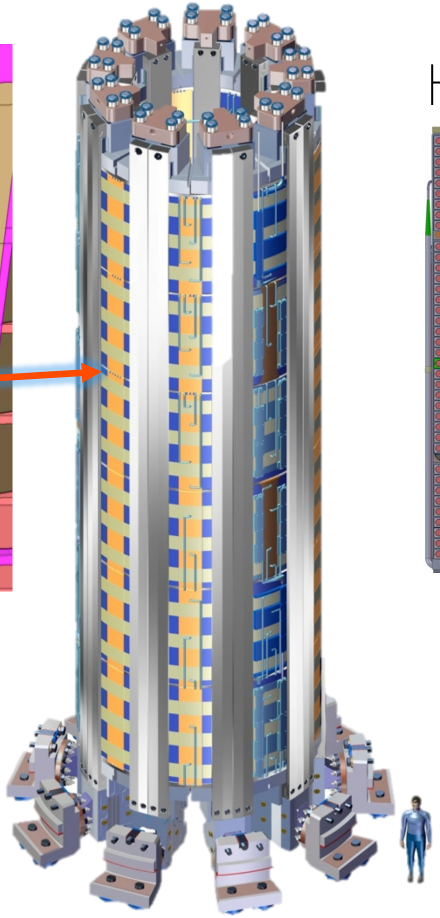
5 upper port camera systems

# General Atomics is Manufacturing the ITER Superconducting Central Solenoid

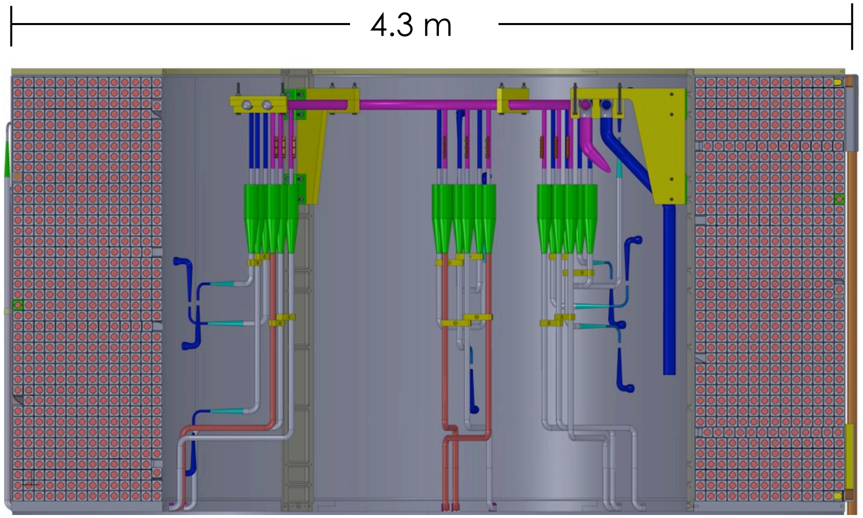
- **Six modules plus structure ~900 tonnes**
- **Each module weighing 110 tonnes has 560 turns (6.5km of conductor)**
- **$Nb_3Sn$ CICC Conductor supplied by JAEA in 1km lengths**



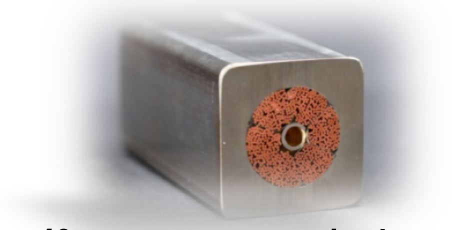
**ITER**



**CS Stack**
(6 modules)



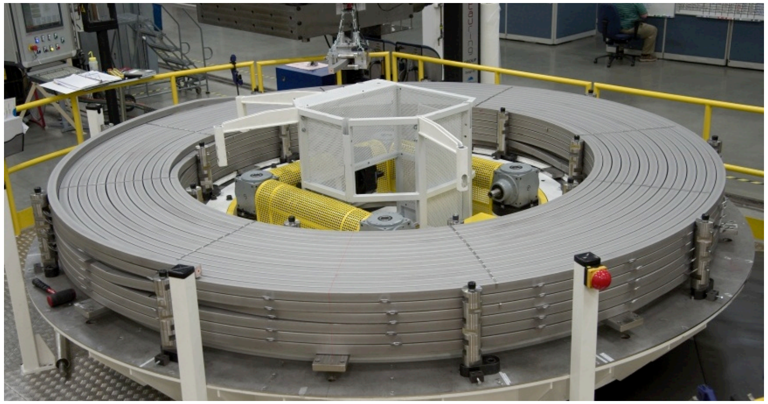

**Module cross section**



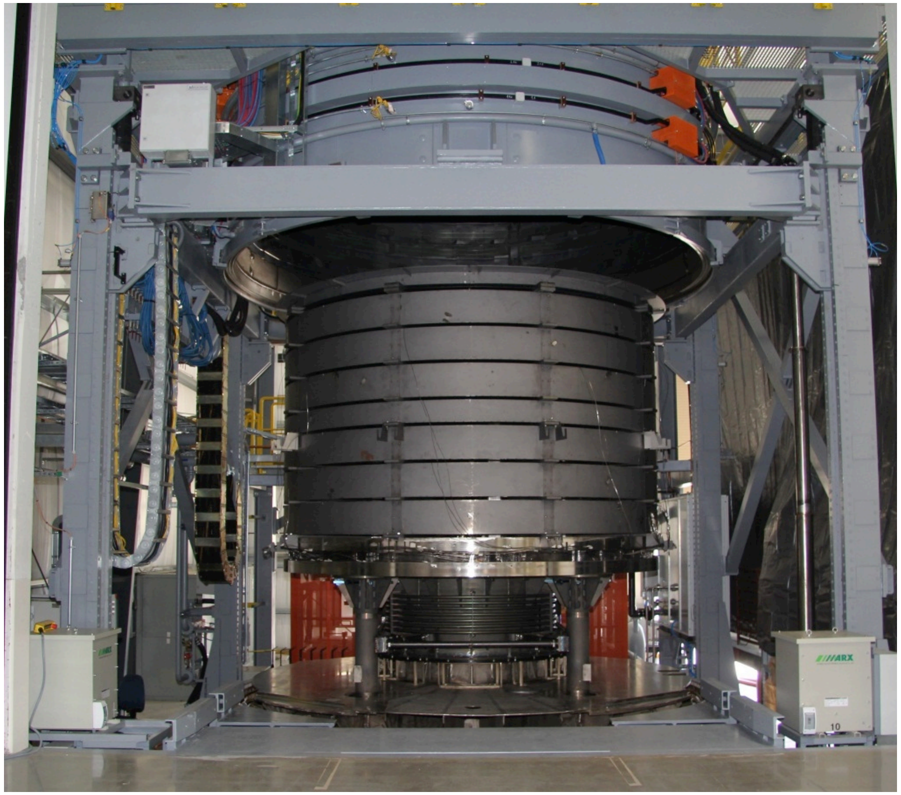
**49mm square conductor**

# Tooling is Installed and Tested for Manufacturing of CS Modules


Two parallel lines can wind the 49mm square jacketed superconductor into 14 turn pancakes

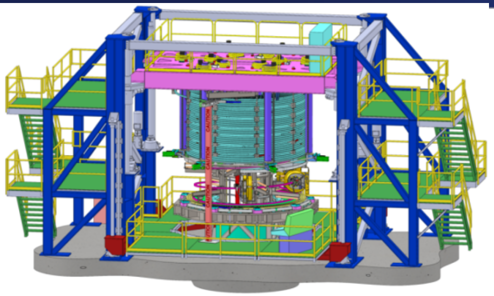


Prototype coil winding: 900m of continuous winding forms 6 out of 40 coil layers



Argon atmosphere furnace for heat treating superconductor. A geometric representation of CS Module is used to qualify the convection furnace for operation with the coils

# Insulation and Final Test Stations Are Being Completed

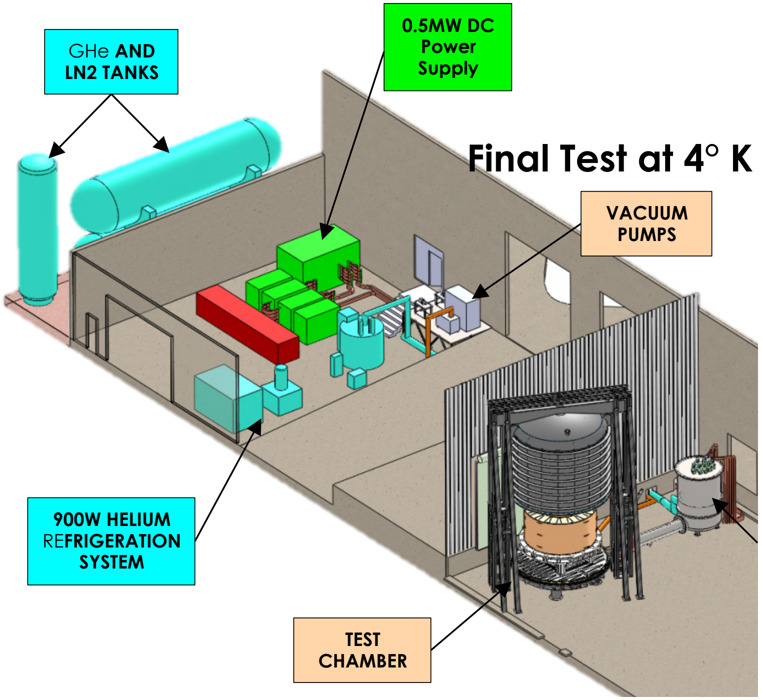


The 560 coil turns are insulated with 6 layers of glass and Kapton during four month process. 110 ton coil is suspended from steel structure while each turn is separated for insulating

Automated wrapping system for applying insulating tapes →

**Insulation Station**

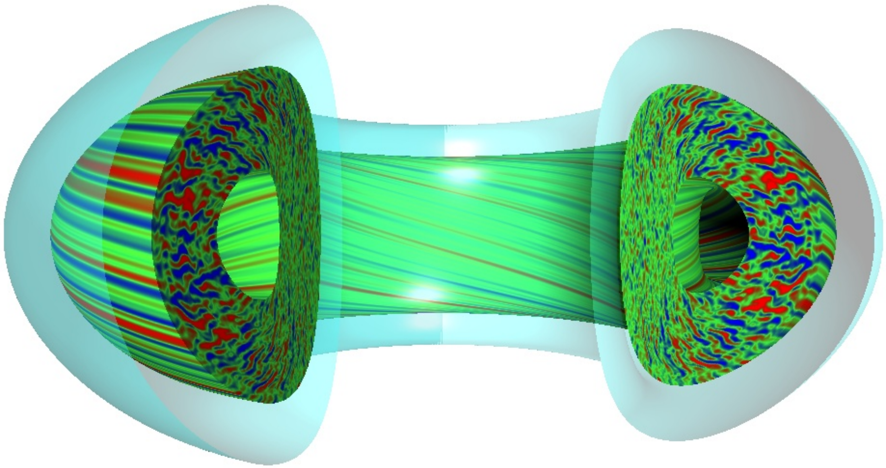
**Final Test at 4° K**

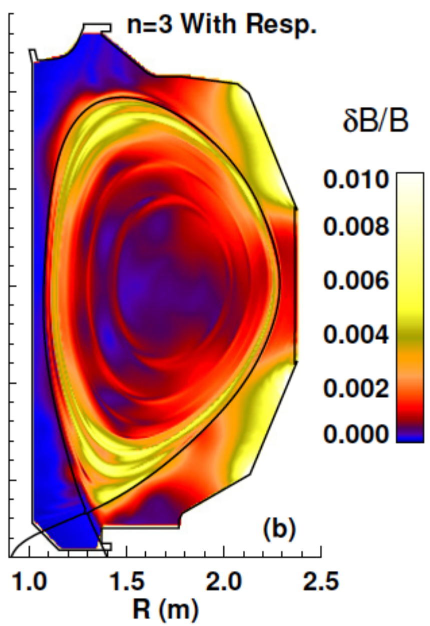


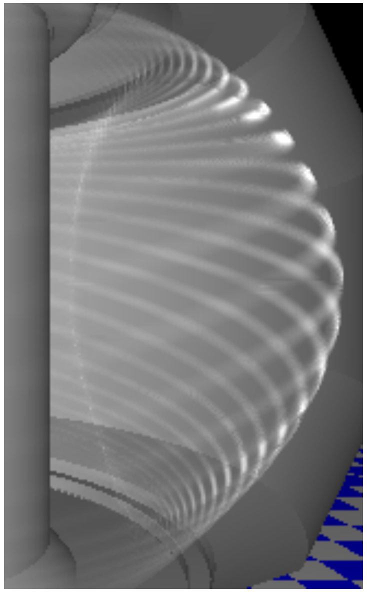

Each of seven modules is tested at 4K with full current (50kA) in Final Test Station prior to shipment to ITER

# GA Theory and Computational Science Department Developing Fundamental Understanding of Fusion Plasmas

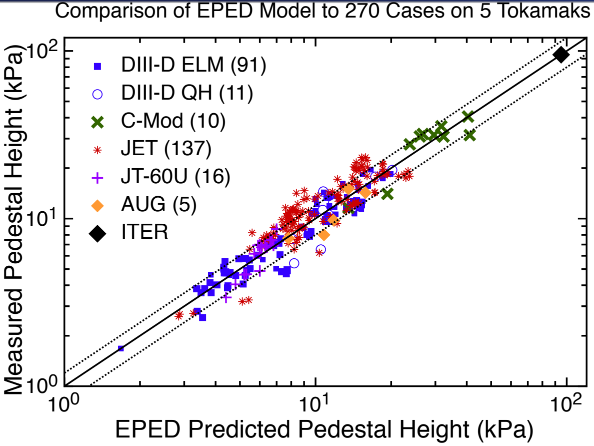
- **Advances in analytic theory and world class numerical tools, eg**
  - GYRO: electromagnetic turbulence
  - M3D-C1, ELITE, GATO: core/edge MHD
  - NEO: neoclassical transport
  - OMFIT: integrated modeling
- **Extensive validation with DIII-D and other experiments builds confidence in understanding**
  - Turbulence simulations compared to measurements across multiple spatiotemporal scales and multiple channels
  - Predicted plasma response to imposed fields, compared to meas.
  - Predicted ELM structure and onset conditions compared to multiple high resolution measurements

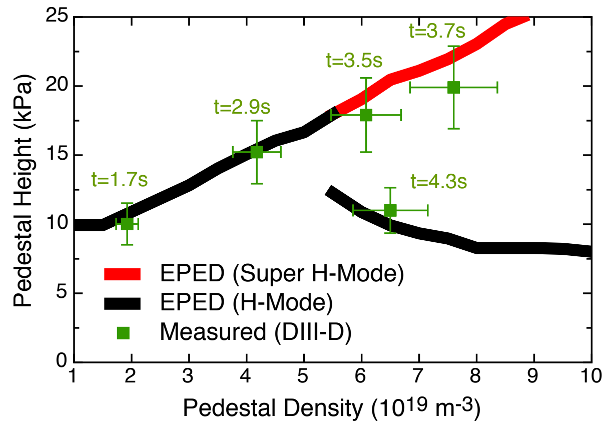




# GA Theory and Computational Science Division Developing Predictive Capability for DIII-D, ITER and Beyond



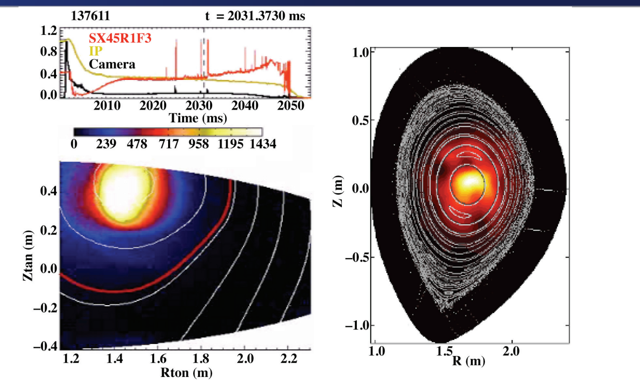




Fig. 2. (Left) Fast camera measurement of synchrotron radiation from a runaway beam in DIII-D. (Right) Synchrotron radiation brightness from a simulation with nearly 2000 electron orbits. Field lines are superimposed.

- **Validated simulation and theory used to develop predictive models and develop scientific understanding eg.**
  - TGLF + NEO: particle, heat and momentum transport
  - EPED: structure of H-Mode pedestal, used to discover new Super H-Mode regime
  - Disruptions and runaway electrons
  - RMP ELM control and QH-mode

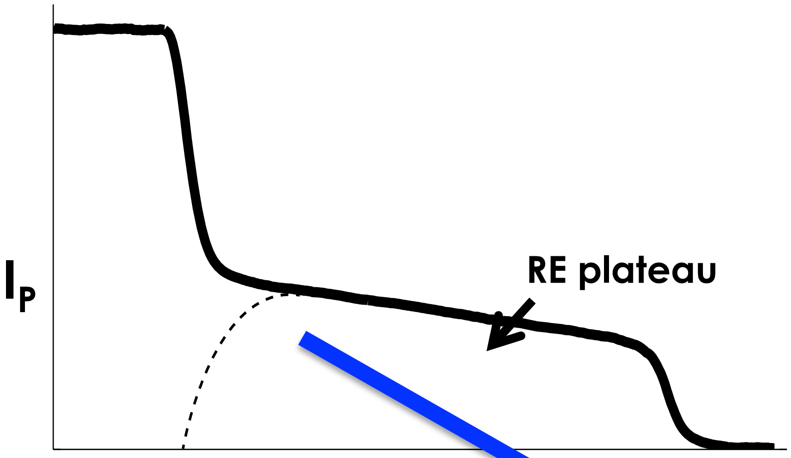
*Models extensively tested in numerous expts.*
*Combining these models (via OMFIT and AToM SciDAC Project) allows performance prediction and optimization for DIII-D, ITER…*

**Strong partnership between GA Theory and DIII-D Program**

# DIII-D Mission: to Establish the Scientific Basis for the Optimization of the Tokamak Approach to Fusion Energy Production

- **Selected Highlights of Recent DIII-D Results**
  - Addressing critical issues for ITER design and operation
  - Development of steady-state scenarios for ITER and Demo
  - Progress in detached radiative divertor solutions
- **Proposed Upgrades to DIII-D**
  - As presented to the FESAC Strategic Planning Panel

# Electron Drag (Avalanche Theory) Is Insufficient to Explain Measured Current Damping Rate

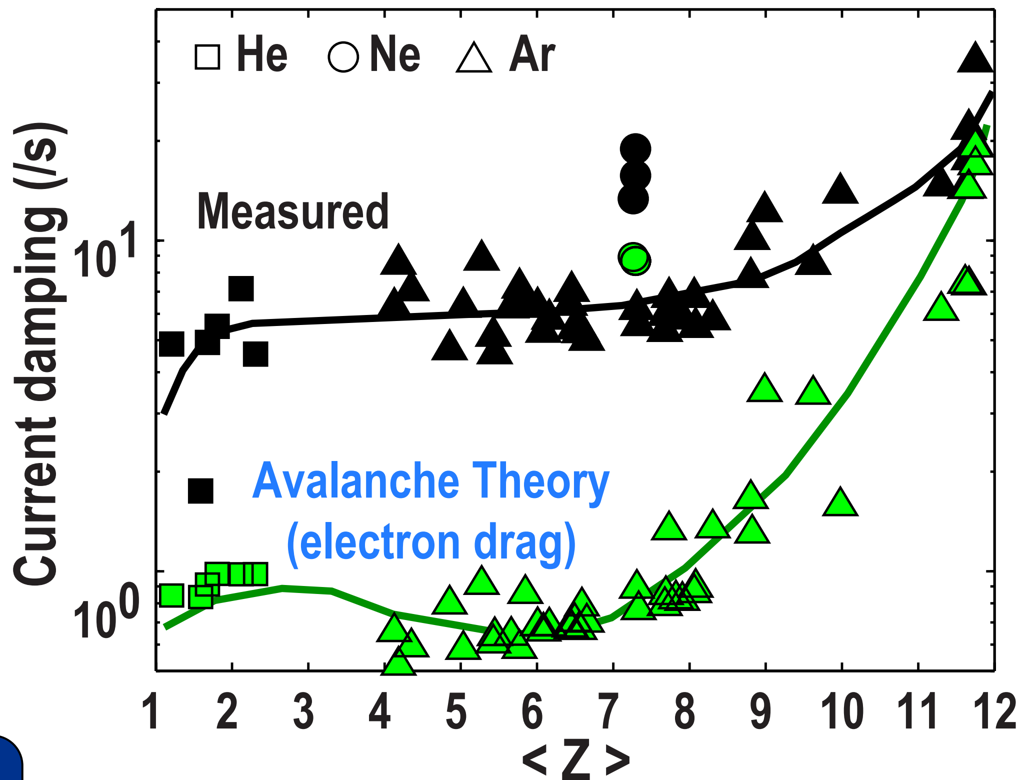



- **RE current damping rate obtained from plasma current and electric field:**

$$\nu_I \equiv eE/m_e c\bar{p} - \dot{I}_P/I_P$$

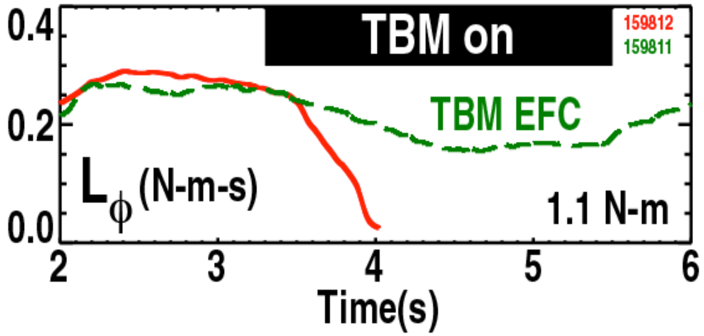
**ITER Impact: may require less impurity injected to prevent runaway electrons**

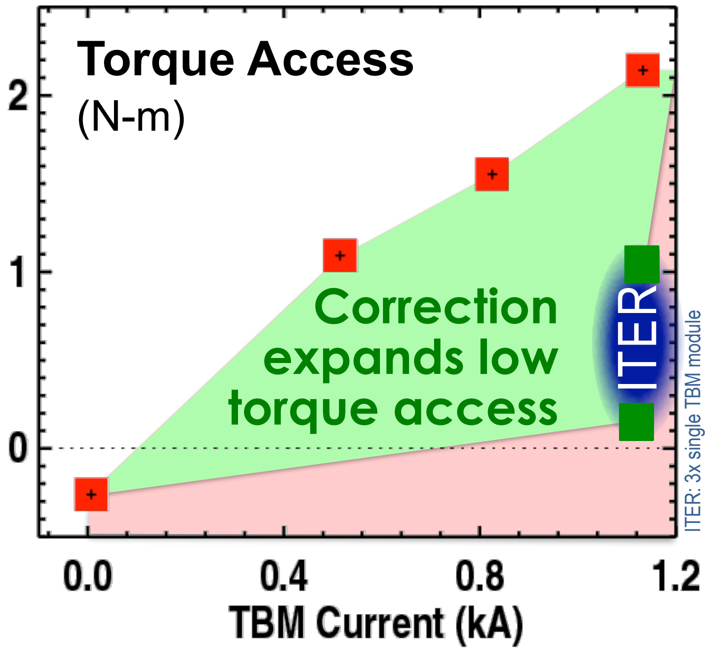
**Measured current damping rate is typically 10x larger than expected from avalanche theory (electron drag only)**



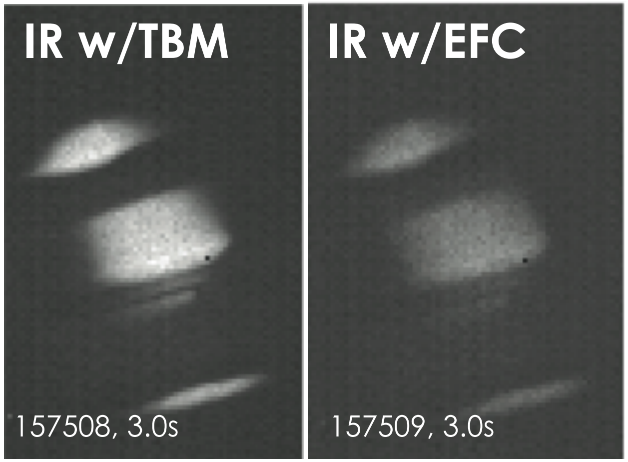

<Z> = Effective nuclear charge seen by RE

# Error Field Correction of ITER Test Blanket Module (TBM) Enable Low Torque, High β Operation



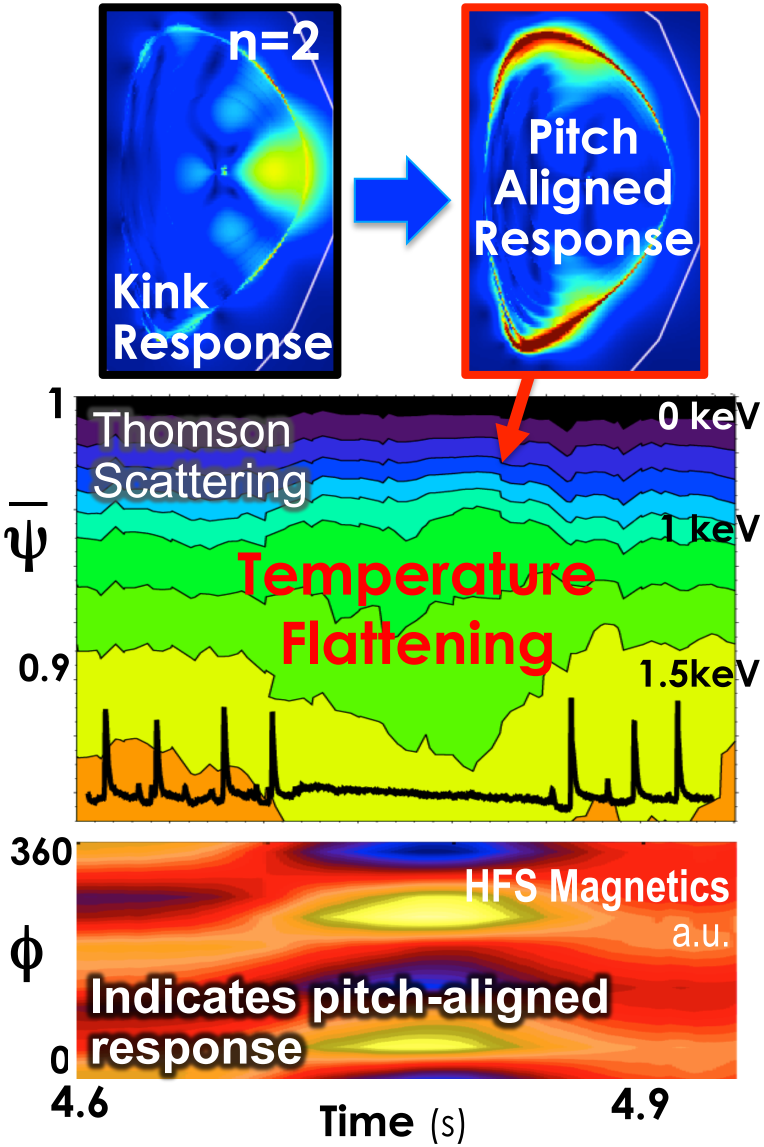




- **Low Torque: Error Field Correction (EFC) avoids locked mode and disruption**
- **High $\beta_N$: Over 60% reduction of TBM magnetic perturbation with optimal EFC**
  - Fast ion losses reduced
  - *First wall heat load reduced 80%*




**N=1 EFC necessary to access ITER equivalent regime**

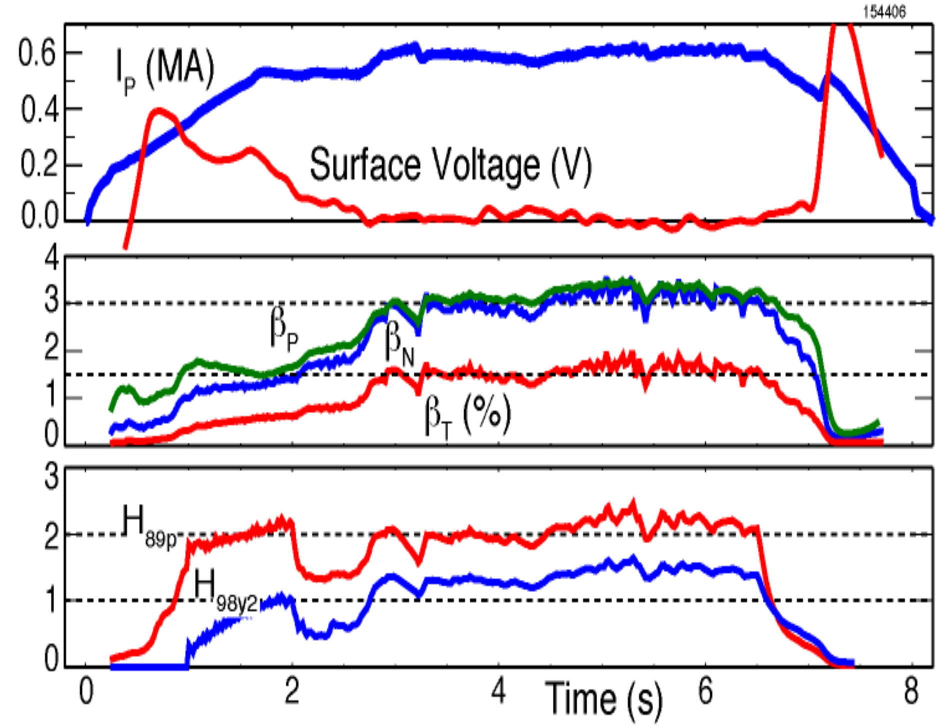
# Experiments Suggest Resonant Field Penetration Is Key to RMP-ELM Suppression




- Continuously vary n=2 field structure from kink to pitch resonant
- ELM suppression accompanied by signatures of resonant field penetration
  - $\omega_{e\perp} \rightarrow 0$ at pedestal top
  - Pedestal width narrows
  - Flattens pedestal temperature
  - Non-linear HFS magnetic response of pitch resonant field
- Validates 2-fluid MHD predictions of island formation & overlap (M3D-C1)
  - Kink response – ELM Mitigation
  - Pitch resonant – ELM suppression
- Resonant field penetration also predicted in ITER

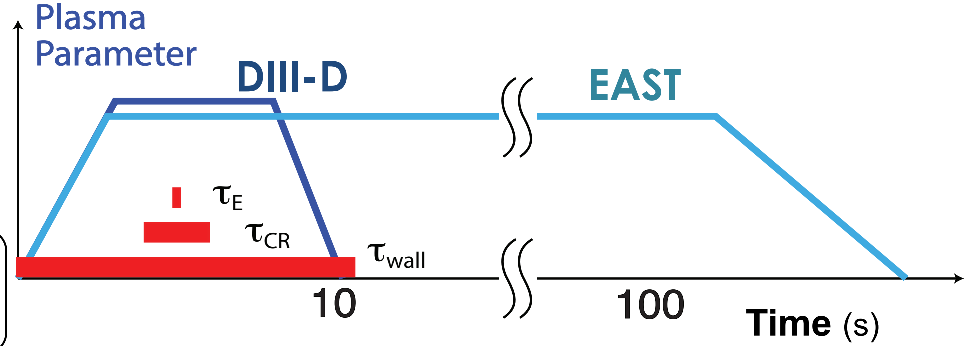
# High Bootstrap Fully Non-inductive Scenario Developed for Long Pulse Operation

- **Reduced torque and current ramp rate to match EAST**
  - Sustained for two current redistribution times
- **ρ=0.7 transport barrier gives good normalized confinement**
  - $H_{89}$>2, 80% bootstrap
  - Fast ions well confined



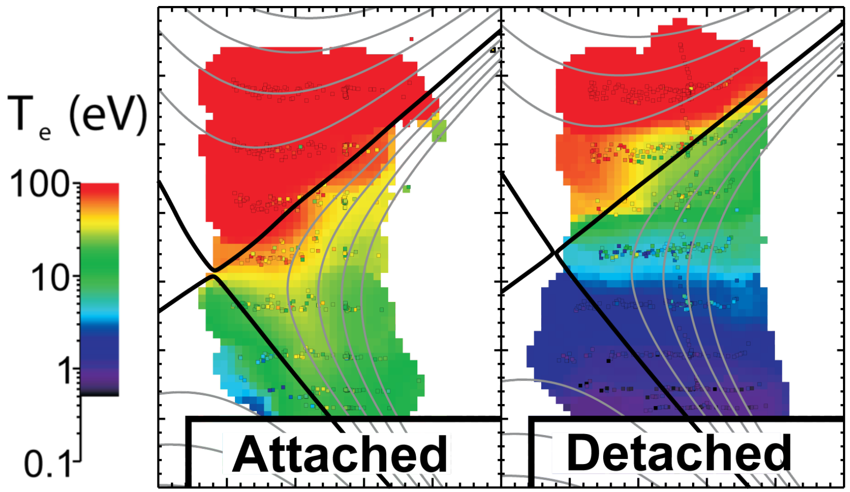

**Joint initiative with EAST**

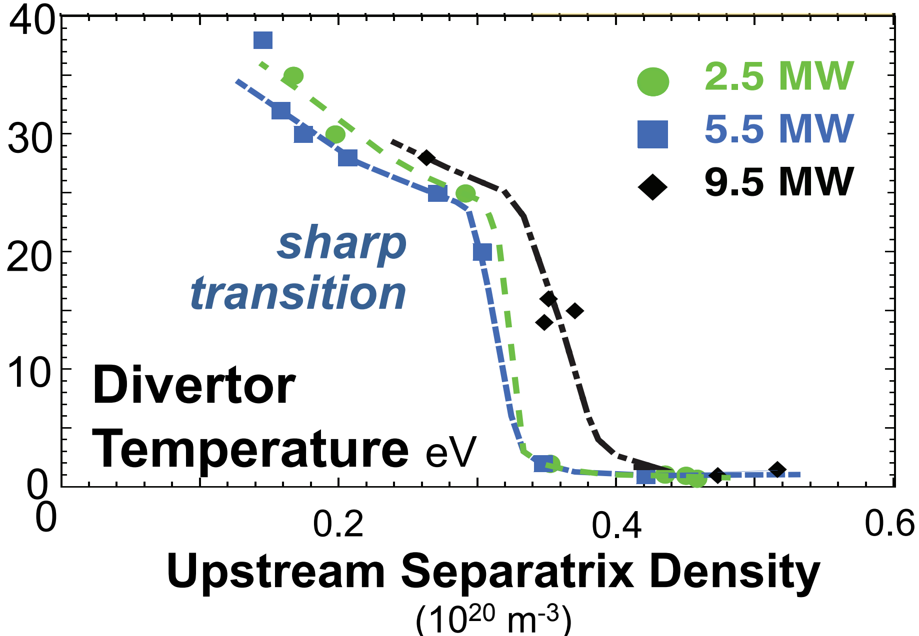
**Fully non-inductive target for EAST**



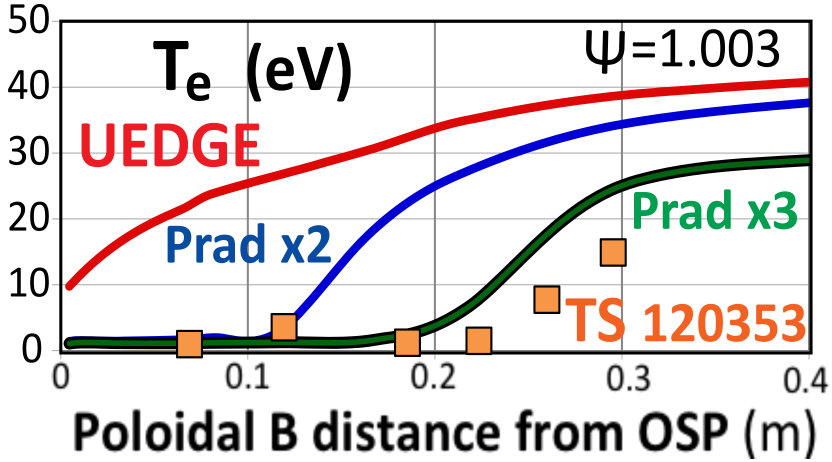

**Hybrid: 100% non-inductive, 1 MA 50% bootstrap, $\beta_N$ = 3.6, $H_{98y}$ = 1.6**

# Measured Temperature Data Show Sharp Transition to Detachment and Radiation Shortfall in Simulations




- **Sharp drop in $T_e$ vs $n_e^{sep}$ to $T_e$ < 1eV at detachment**
  - Molecular processes important
- **Detachment simulations reveal "radiation shortfall" in models**
  - Models match attached data
  - Potential issue with one of the radiation models at low $T_e$



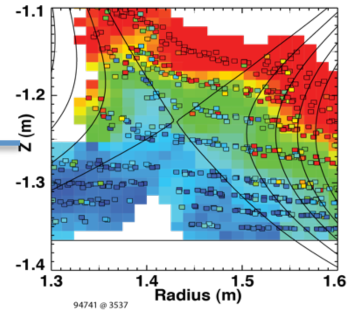
# New DIII-D Boundary/PMI Center Recently Created to Coordinate/Stimulate Increased Effort in This Critical Area

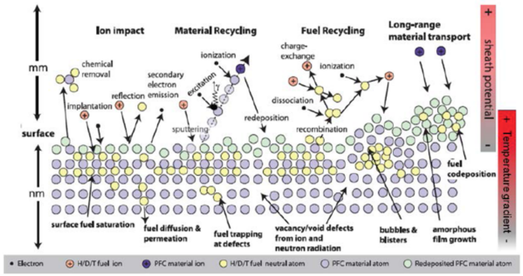
DIII-D Experiments

DiMES

**DIII-D Boundary/PMI Center**

Modeling



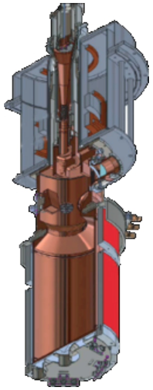

Materials (SciDAC-PSI)


Edge Theory

- **Advance scientific understanding and develop predictive capability**
  ***➔ Deliver physics basis for robust heat flux and erosion control.***
- **Develop and test advanced divertor solutions in high performance plasmas relevant for FNSF**
  ***➔ Improve divertor solution through innovation.***
- **Evaluate reactor relevant materials at high temperatures**
  ***➔ Provide data to broad materials community in fusion environment.***

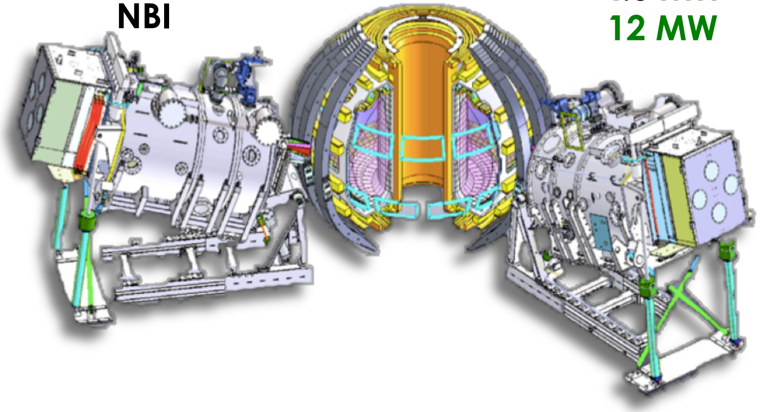
# Proposed DIII-D Upgrades to Develop the Scientific Basis for the Burning Plasma Era and Fusion Energy Development

**Electron Cyclotron**



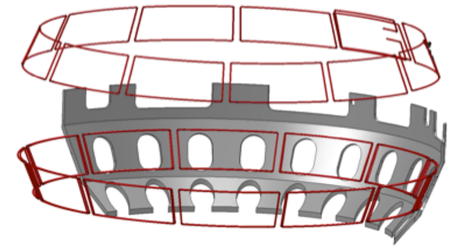
**3. 5 MW**
**10.4 MW**

**Off-Axis NBI**



**4.5 MW**
**12 MW**

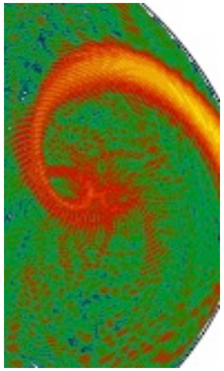
**New 3D Coils**



| | | |
|---|---|---|
| n | 1 – 3 | 1– 6 |
| n-rotate | 1 – 2 | 1– 4 |

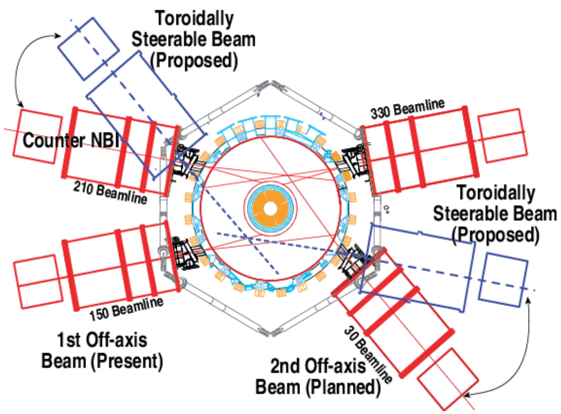
physics → RMP, NTV, EFC, RWM

**Helicon Current Drive**



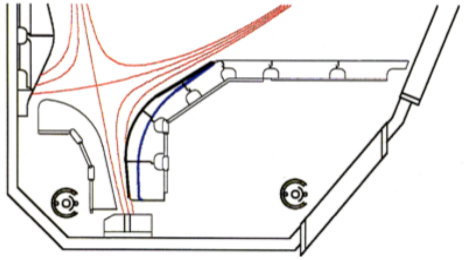
**0 MW**
**1 - 3 MW**

**Co/Counter/Balanced NBI**




| | | |
|---|---|---|
| Counter | 4.5 MW | 10 MW |
| Balanced | 9 MW | 20 MW |
| Co | 13.5 MW | 20 MW |

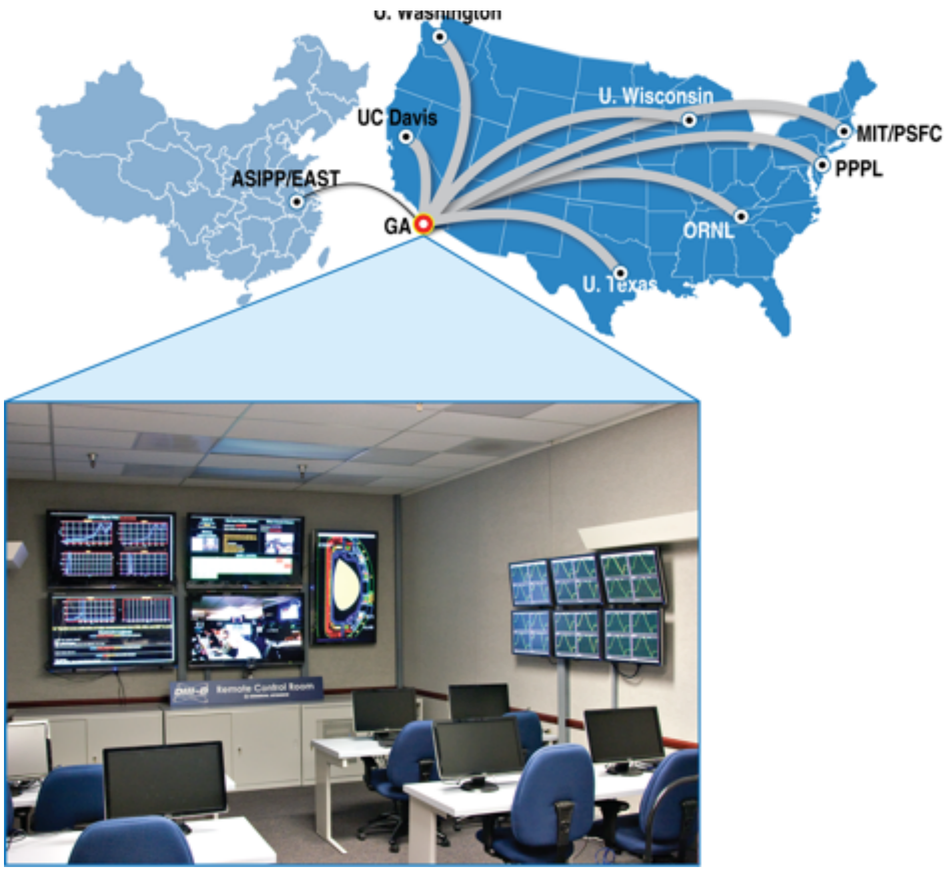
**Advanced Divertor**



Optimized geometry
Heated tiles
New wall material

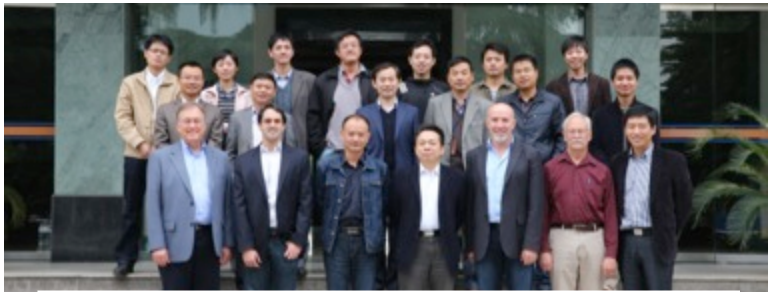
# International Collaboration: Accelerates Progress in Fusion and an Important Part of DIII-D/GA Fusion Effort

**Remote Participation Capability**
→ increases efficiency, effectiveness
→ reduces cost




Fast data transfer from EAST experiment to GA demonstrated – Increased by 300x

## Examples: EAST and ASDEX-U



1st EAST/DIII-D Joint Experiment Planning Workshop held at ASIPP
→prototype experiments on DIII-D

Landau Spitzer Award: ASDEX-U/DIII-D Collaborative effort on energetic particles