Overview of FY19-22 DIII-D Program Plans Towards Advancing Development of Cost-Effective Fusion Power Plants for the US

by
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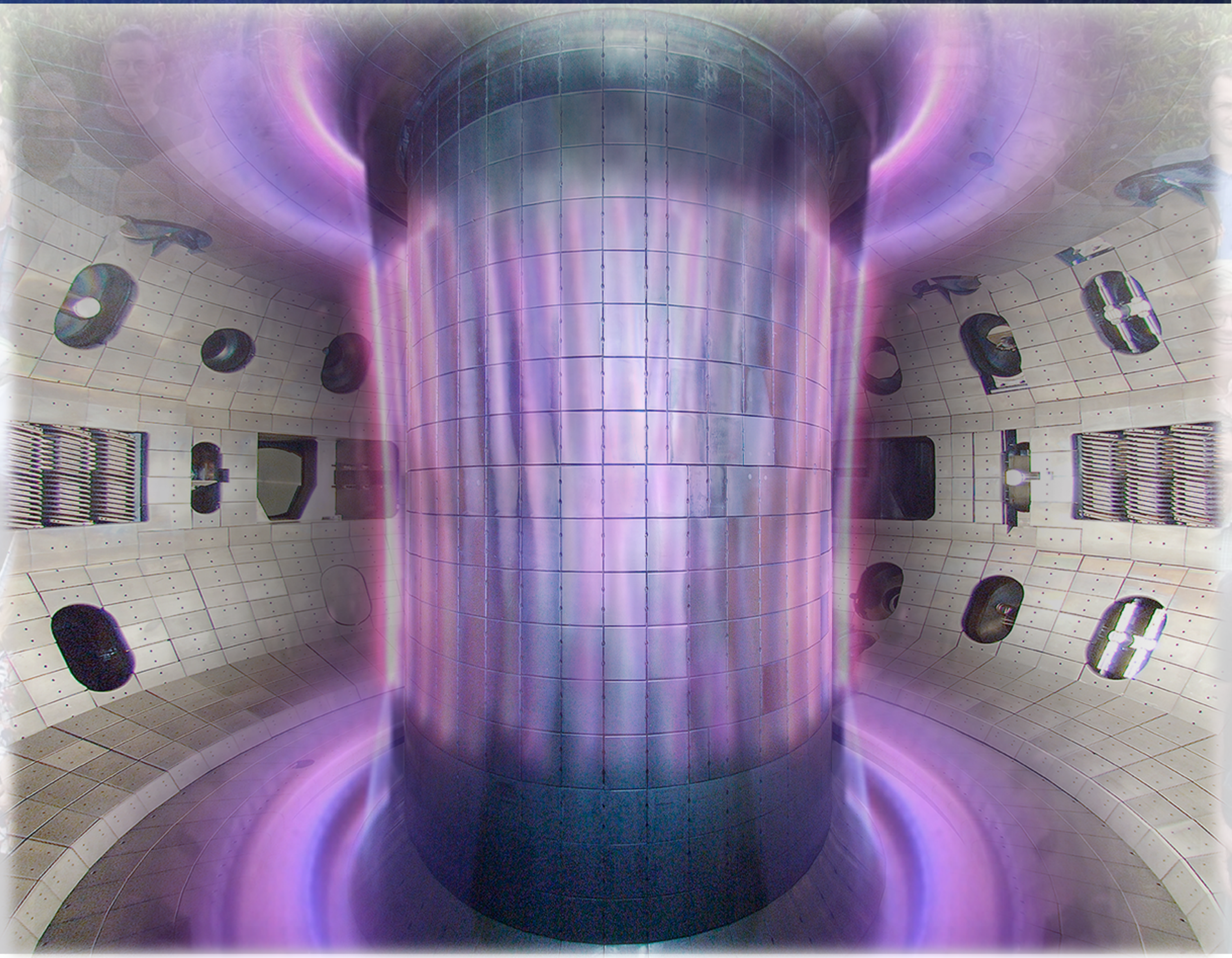
Presented at the
DOE Fusion Energy Sciences
DIII-D Budget Planning Meeting

via Zoom Videoconference

May 28, 2020



DIII-D Is Preparing for Physics Experiments Week of June 29th

- **Operations Group took measured, deliberate approach to completing vent closeout and startup tasks**

- **Helium liquefier returned to operation, supporting neutral beam operation.**

- **Plasma Cleanup completed**
  - Beams conditioned
  - Vessel cleanup completed.

- **No confirmed CV-19 cases within DIII-D group, 3 cases at Torrey Pines (non-fusion) and 16 across all of General Atomics.**

DIII-D Is Preparing for Physics Experiments Week of June 29th

Plasma clean-up operation

- **Limit to essential on-site presence in the Control Room**
- **Evaluating and adapting earning new tools for remote participation**

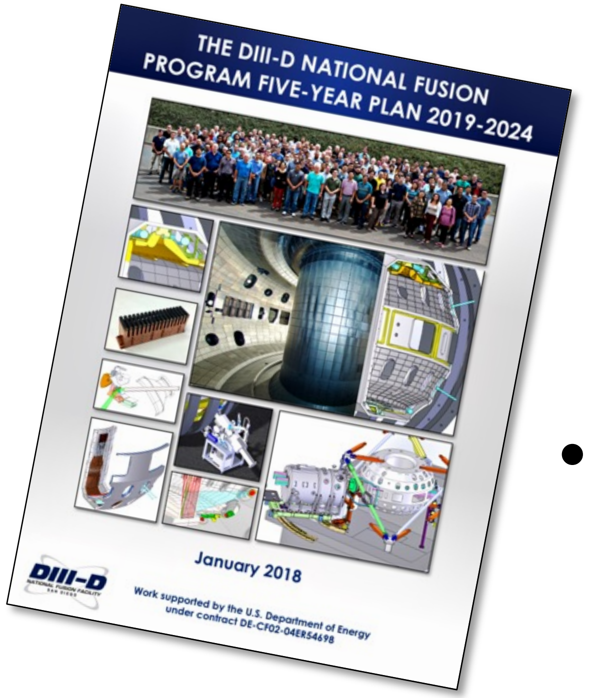
Dedicated team GA + collaborators enabled steady progress

Preparation Under Way for Restarting FY20 Physics Operations to Complete 11 Operating Weeks in FY20

- **Physics Ops starting June 29 (4wks on, 2 off)**
- **Procedures developed to allow research operations with COVID-19 restrictions in place**
  - GA guidelines for “Returning to a Secure and Healthy Workplace”
  - DIII-D Operations “COVID-19 Work Procedures”
    - Approved by GA LSNC, released to DEC
  - Physics Operations Restart Working Group (pictured) developing procedures for continuing research with most/all remote physics participation
    - Identifying technical requirements
    - Configuring tools (communications, etc.)

Valuable Learning Opportunity for ITER Participation

DIII-D Research Accelerates Progress Toward Fusion Energy


THE DIII-D NATIONAL FUSION PROGRAM FIVE-YEAR PLAN 2019-2024

January 2018

DIII-D

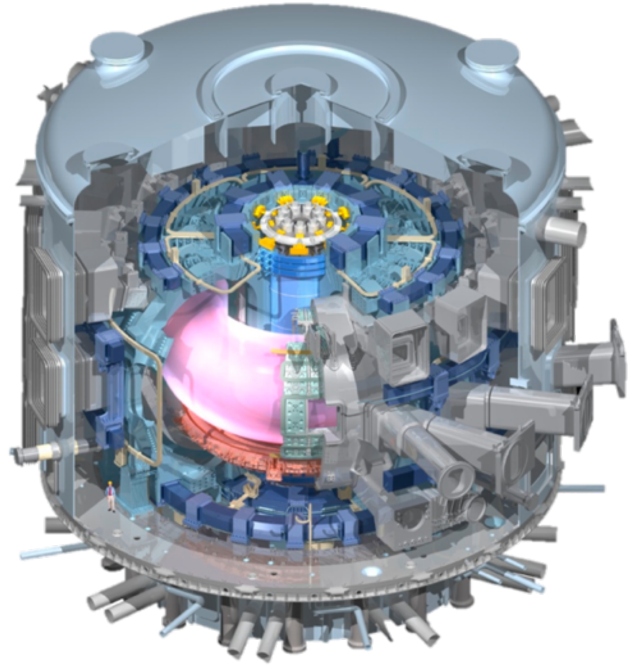
Work supported by the U.S. Department of Energy under contract DE-FC02-04ER54698

- **Accelerate Progress on ITER**
  - Prepare for effective operation & scientific exploitation

- **Realize the Path to steady-state power plants**
  - Establish physics & technical basis

Resolve Critical Physics and Technology

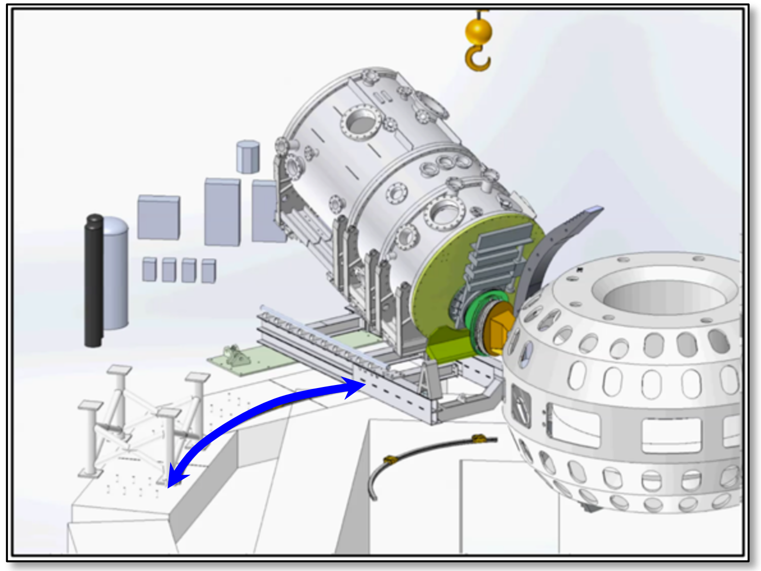
- *Burning plasma conditions (self-heated)*
  - *Self-consistent fully non-inductive*
    - *Integrated divertor solutions*
      - *Transient control (ELMs, disruptions)*



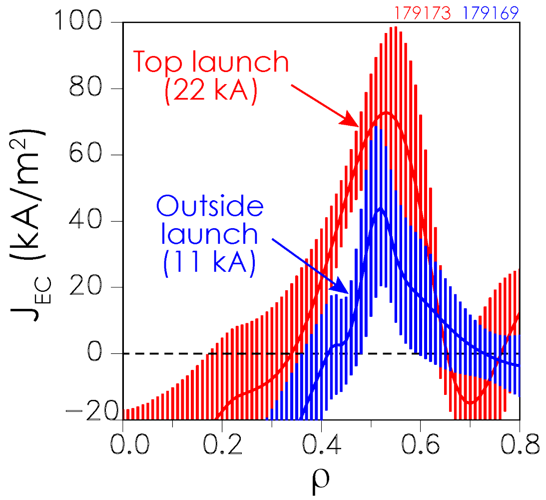
US Fusion Focus: Science → Solutions

FY20 Operations Will Exploit Off-Axis Heating and Current Drive Options For AT and Low Torque for ITER Scenarios

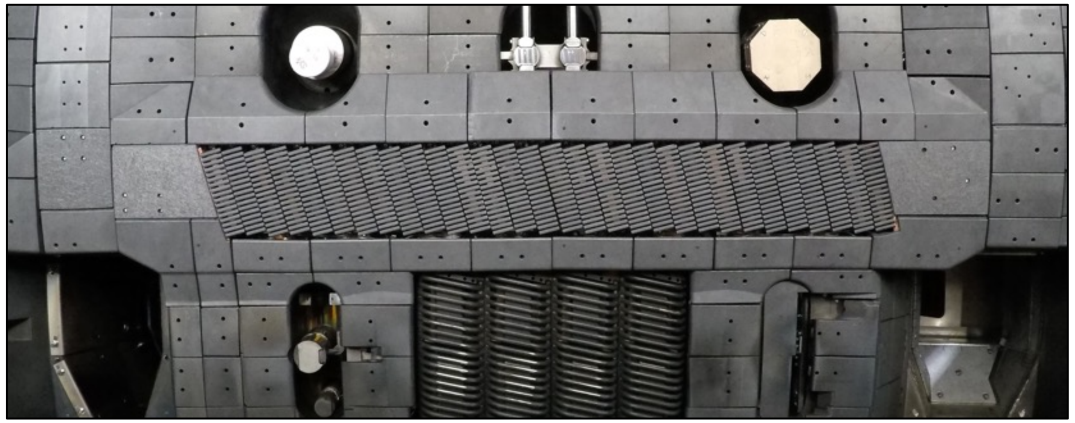
- **Off-axis co-counter NBCD with pressure broadening for high β_N**



- **Top-launch ECCD for increased efficiency**



- **Helicon Current Drive Experiments**



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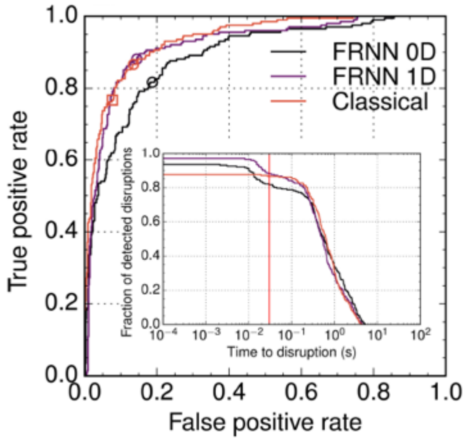
DIII-D Will Continue to Prioritize Research to Enable Success in ITER

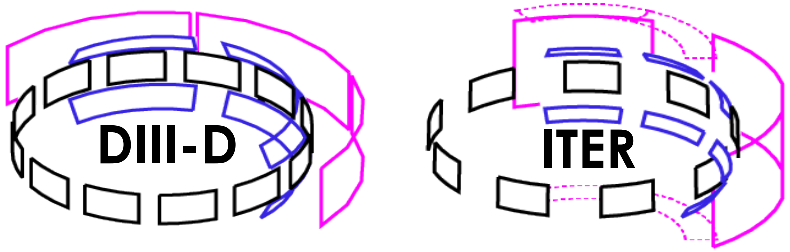
- **Develop comprehensive solutions to the disruption challenge**
  - Disruption free protocol: robust real time control of plasma operation
    - *Machine learning leading to significant successes* ➔
  - Accelerate development of disruption mitigation tools and science
    - *Cryo launcher, passive runaway mitigation coil, fast disruption diagnostics*



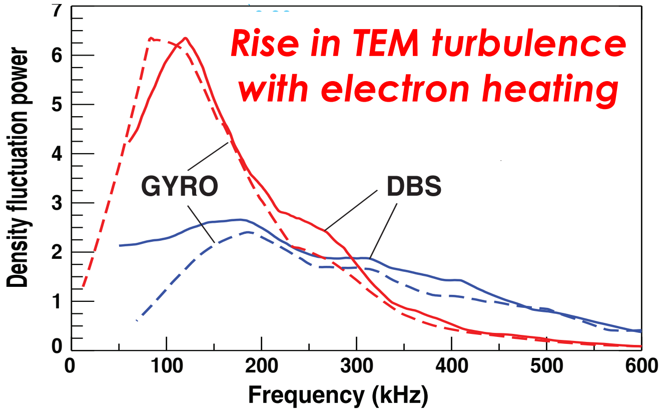
Deep learning disruption prediction on DIII-D

Kates-Harbeck, **Nature 2019**

- **Understand 3D optimization to control transients**
  - New coils and power supplies will resolve ITER optimization for RMP-ELM suppression & QH access
    - *Unique tools to probe stability & 3D physics (ELM, TM, RWM, rotation)*



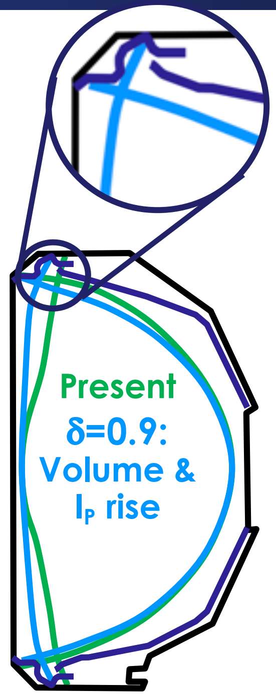
- **Optimize ITER performance and underlying physics tools**
  - Isotope campaign: H mode access, ELM suppression & confinement
  - New EC strategy (see later) plays critical role in ITER preparation
    - *Understand transport and stability in low torque electron dominant regimes*
    - *Optimize path to high performance & required stability or mode control tools*

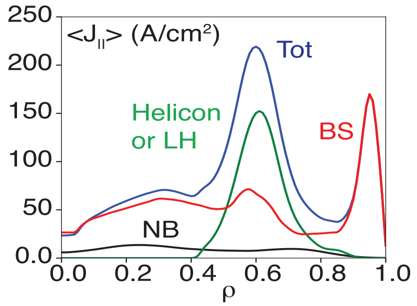


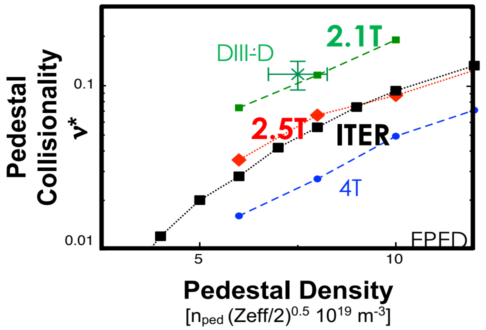
Position U.S. to lead on ITER with scientific tools to optimize performance and learn from ITER plasmas

Developing Integrated Solutions For Future US Compact Pilot Plant Requires Major Upgrades and/or Next Step Tokamak Facility

- **Critical challenges:**
  - Dissipative divertor _with_ high confinement core
  - Confident projection of reactor solutions
    - *Requires higher field, power and particle density*
- **A major upgrade to DIII-D is projected to close gaps & enable study of critical reactor physics**
  - Increased shape, field & current drive → x2-3 energy & density, making more reactor-relevant transport, EP and bootstrap regimes
  - Combine with closure to assess high dissipation divertor compatibility with opaque collisionless radiative high performance pedestal
- **A new facility would self-consistently test and optimize solutions at relevant reactor parameters to retire pilot plant risks**
  - Scoping studies indicate modest size 1.25m 4-7T facility address this
  - GA developing potential NTUF concept & evaluating GA site capability



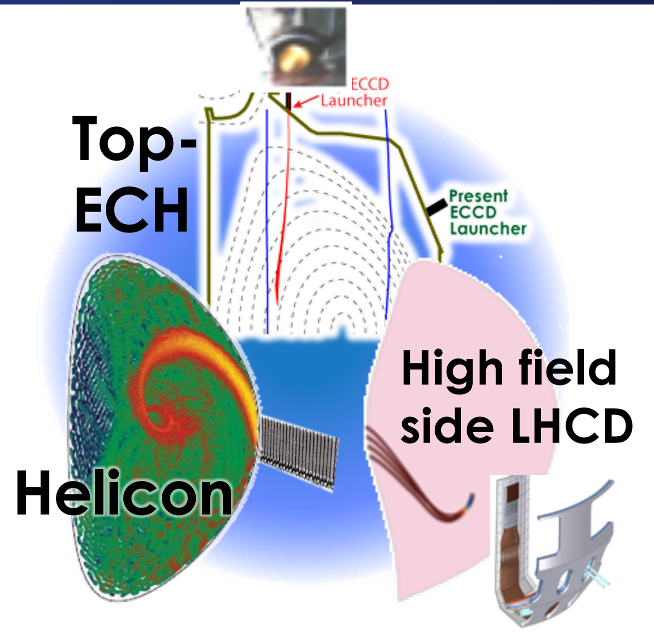


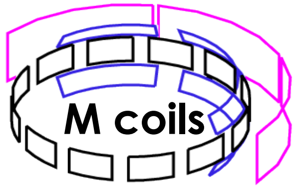


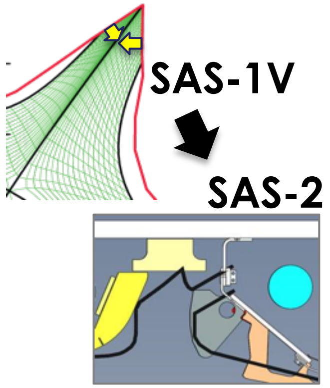
Our Goal: Inform US Pilot Plant and potential NTUF Designs

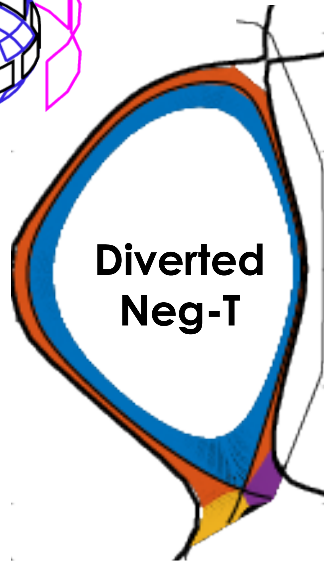
DIII-D Can Develop Transformative Solutions to Meet the Pilot Plant Challenge over the Next Decade

- **Critical needs:**
  - High confinement steady state core (current profile & current drive efficiency are key)
  - Highly dissipative divertor to handle fluxes
    - *How to achieve? How to marry together?*
- **DIII-D near term plan responds to CPP to lay foundations for pilot path**
  - Fully commit to EC expansion
    - *Key to AT, transport, stability, EP & ITER lines*
  - Develop more efficient current drive
  - Optimize closure & assess at high power
  - 3D and disruption mitigation tools
  - Negative triangularity as a game changer critical to its potential for an FPP
    - *DIII-D to address the critical questions – world first*









Continued U.S. leadership in fusion research

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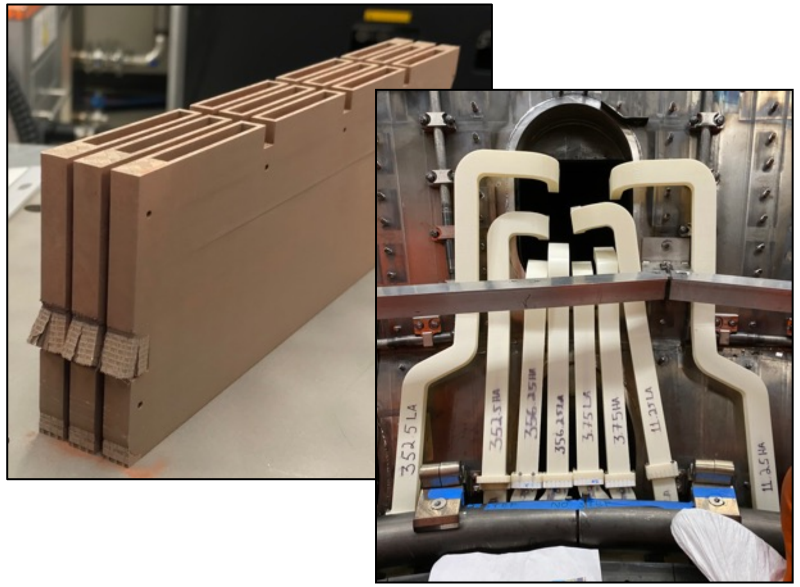
Requested Funding for FY21-22 Supports Investigation of New Capabilities for Non Inductive Current Drive: Helicon & HFS-LHCD

- **Helicon Experiments will begin in FY20**
  - Completing control system
  - Helicon system commissioning has started
  - High power operation starts in September and fully developed in FY21

- **HFS-LHCD in FY21 for efficient off-axis current drive**
  - MIT and GA collaboration
  - Site Prep and final design tasks are progressing



- **FOAs are providing advanced diagnostic capabilities supporting RF wave-plasma science**

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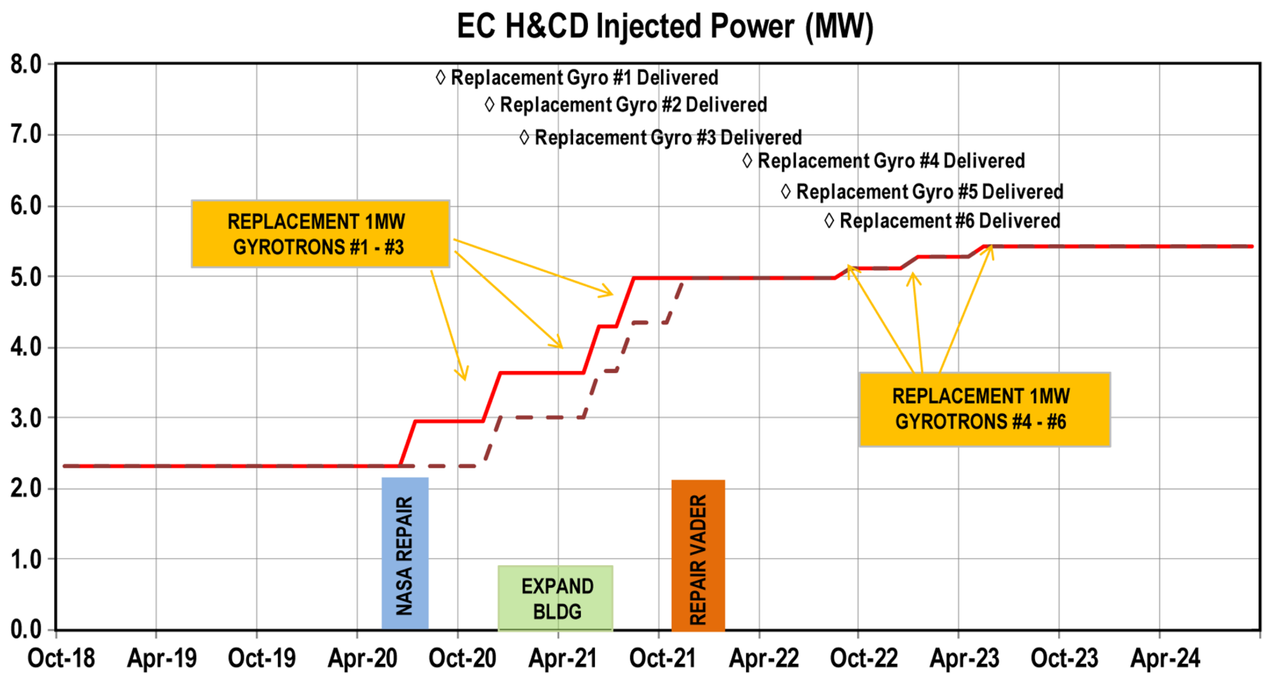
EC System – Revised Strategy for EC System Focusses on High Efficiency Top Launch and Improved Reliability

- **8 gyrotron System - Gyro #9,10 delayed; replaced with two additional higher efficiency Top Launch systems**
  - 3 Top launch systems provide equivalent ECCD as 6 side launch
- **Accelerate replacement of all old tubes**
- **Improve quality and timeliness of existing vendor (CPI)**
- **Develop alternate gyrotron supplier**
  - Purchase 2 gyrotrons from new supplier
- **Build test stand and HVP/S to enable off-line conditioning to full power**
- **Required funding: FY19 carryover and FY21/22 Incremental funding**



Longer-Range Non-Inductive Current Drive Strategy For AT Development Depends On Technology and Physics

Present Five Year Plan

Next Five Year Plan

Gyrotrons: Flexibility motivates largest spend

Vendor performance and product reliability determine future investments.

Top-launch success motivates further investment now

Limited easy top-launch access

Additional helicon systems (1 or 2)

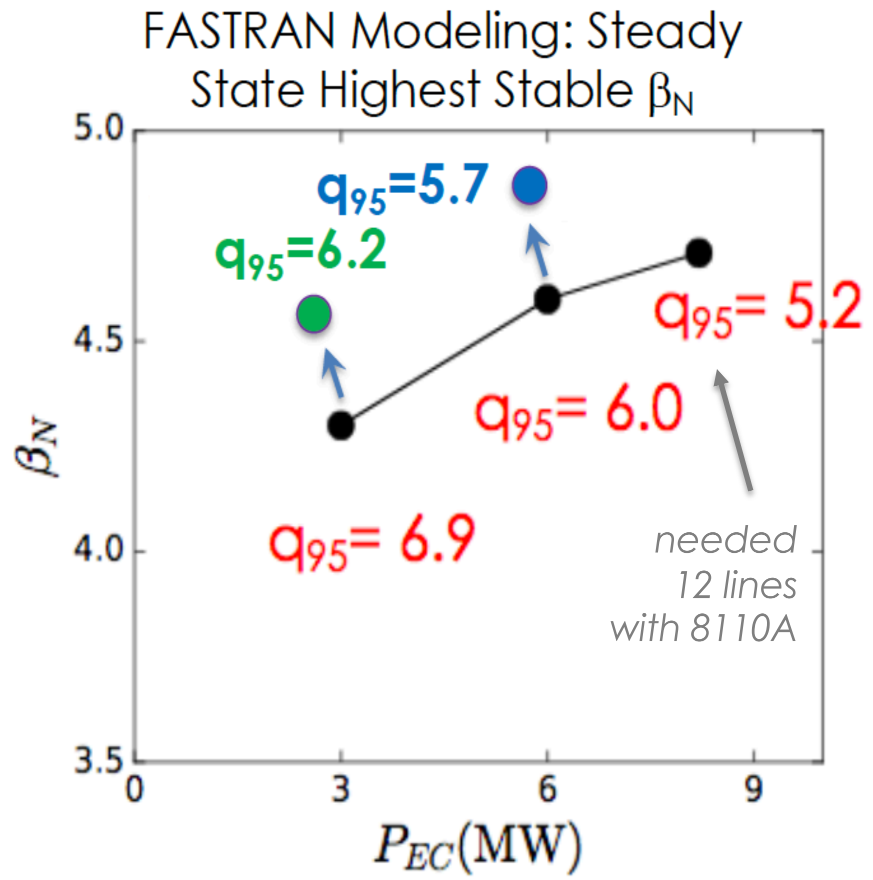
Future investments in RF current drive technologies dependent on efficiency, reliability, and flexibility.

Second HFS-LHCD system

2^{nd} co-cntr beam

Maximizing Top Launch EC Advances High – β Steady-State Goals With Some Modest Compromises

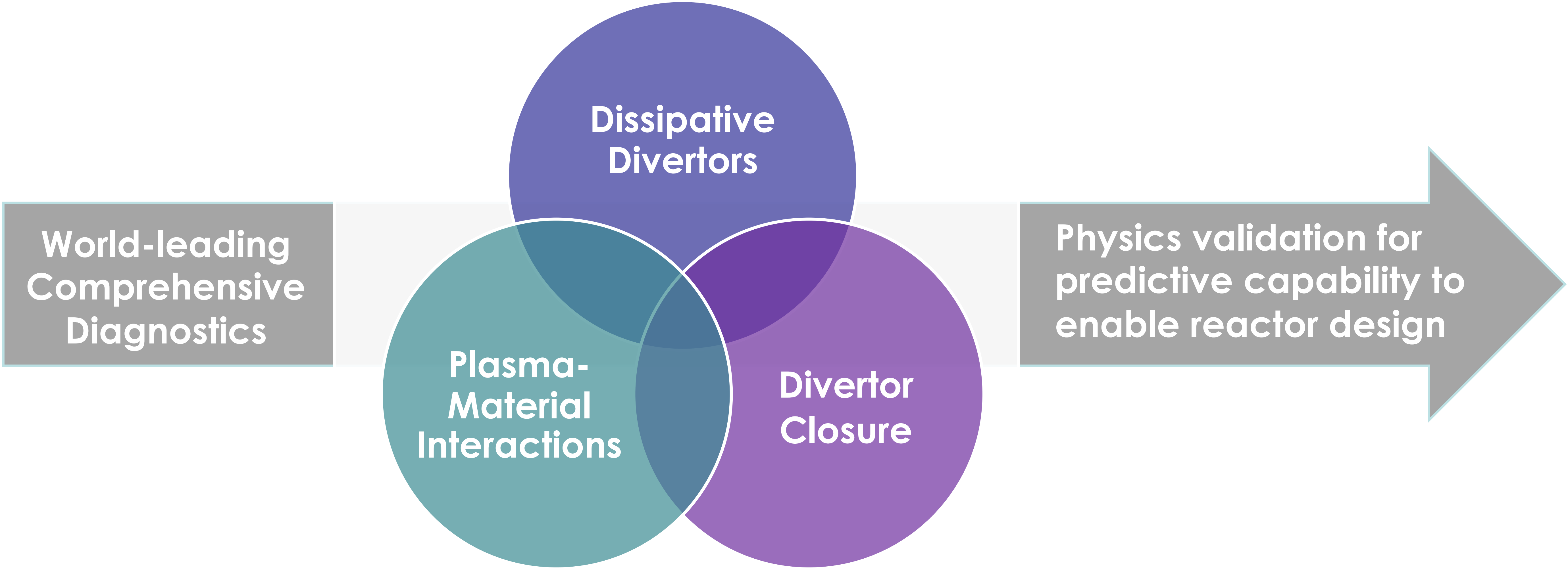
- **Advanced tokamak requires strong off axis CD**
  - Increased efficiency of 3 top launchers puts enough current where needed → higher β with less EC power
  - Outboard launchers provide needed flexibility
- **ITER baseline & variants:** 8 lines gives ample power for dominant electron heating regimes
- **Stability:** 6MW good for ITER baseline NTM control
  - *More limited scope at high β for TM optimization or more relevant low fast ion content RWM physics tests*
- **Perturbative transport studies challenged as β rises**
  - Highest power demand: core e^- heating + off axis EC gradient modulation
  - 6MW good for β_N=1.9 ITER baseline. EC demands rise rapidly with β_N



Challenge eased if helicon/LHCD work → more transport & profile control, higher B

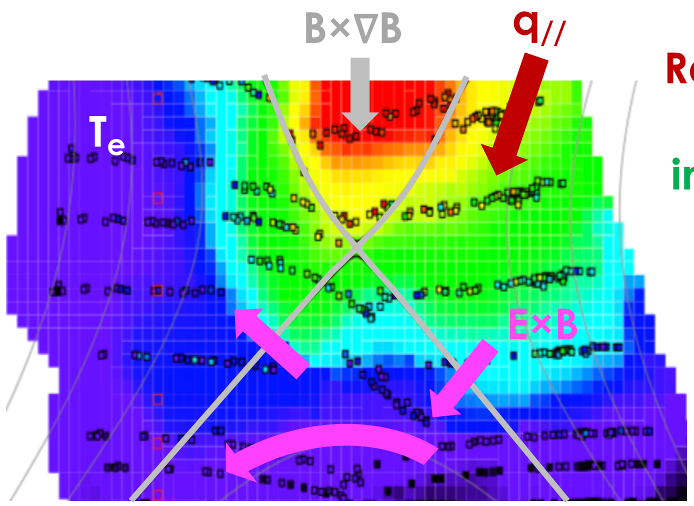
New strategy gets key power and current drive for priority goals sooner and cheaper. Retain option for 2 more lines later

DIII-D Strategy Links Configuration Changes, Diagnostic Development, and Model Validation to Build Predictive Capabilities for Advanced Divertor Design



DIII-D Boundary Program Is Providing Essential Input Needed to Develop Divertor Solutions For Steady-State Fusion Reactors

- **Understand Dissipative Divertors**
  - *Impurity radiation*
  - *Role of ExB drift and plasma flow*
  - *Turbulence transport*



Radial transport (λ_q)

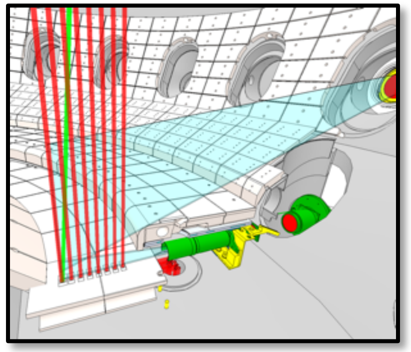
impurity radiation (T_e ~ 10-30 eV)

Ionization, Charge exchange (T_e <~ 5 eV)

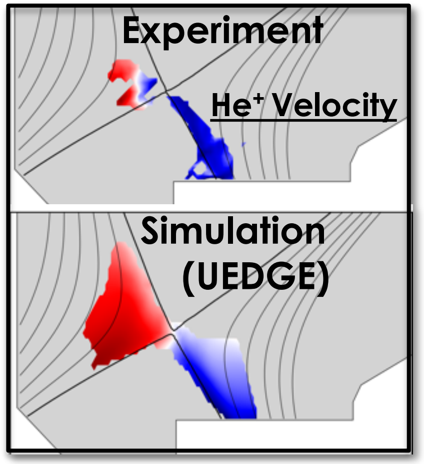
Particle transport (Parallel and ExB)

Recombination (T_e < ~ 1eV)

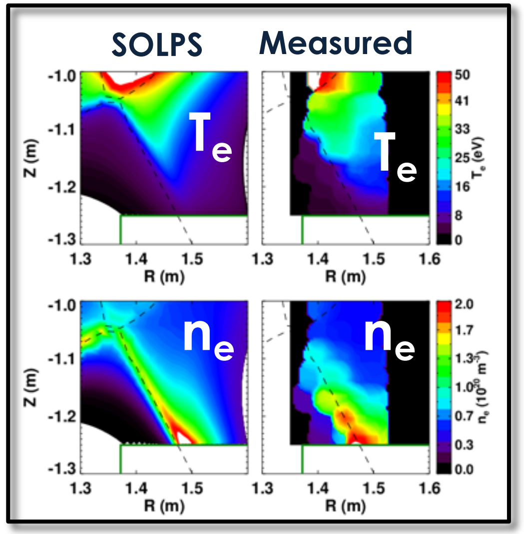
2D Div Thomson



2D Flow Imaging



SOL Model Validation



Close interaction between experiment/measurement and simulation is key to developing predictive capability

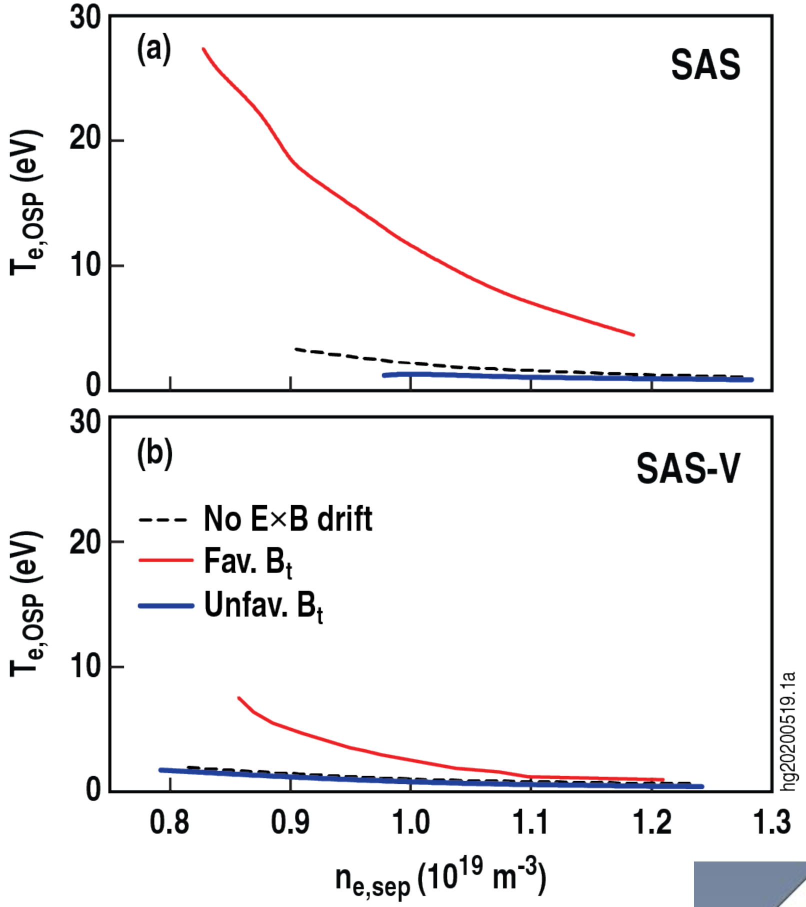
DIII-D Boundary Program Is Providing Essential Input Needed to Develop Divertor Solutions For Steady-State Fusion Reactors

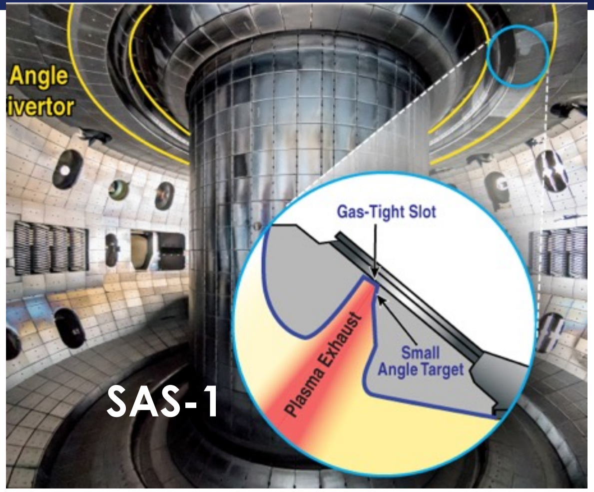
- **Understand Dissipative Divertors**
  - *Impurity radiation*
  - *Role of ExB drift and plasma flow*
  - *Turbulence transport*

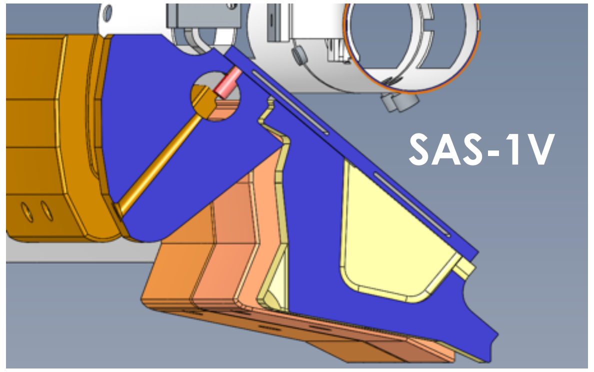
- **Evaluate Divertor Closure**
  - *Manipulate E ×B drifts in SAS to optimize detachment for both B-directions (**SAS-1V**)*
  - *Inform **SAS-2** design and optimization*

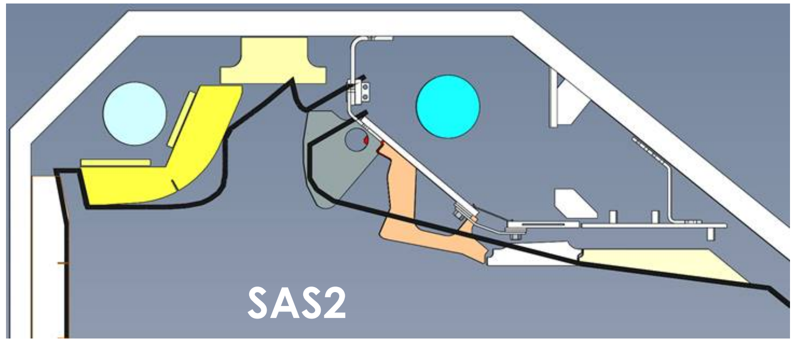
- **High-triangularity, High-elongation option**
  - *Maximize core performance by removing inner cryopump and shifting **SAS-2V** inward*
  - *Decision factors: Significantly higher cost, diagnostic impacts vs. core performance gain*

SOLPS Simulations





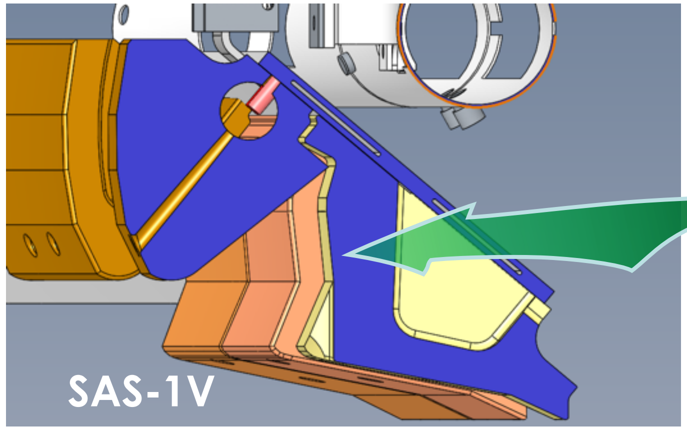


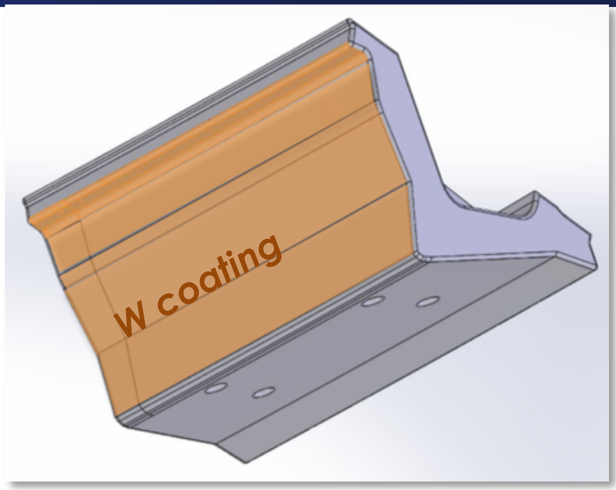


Use staged divertor changes motivated by modeling to stress-test codes & advance predictive capability

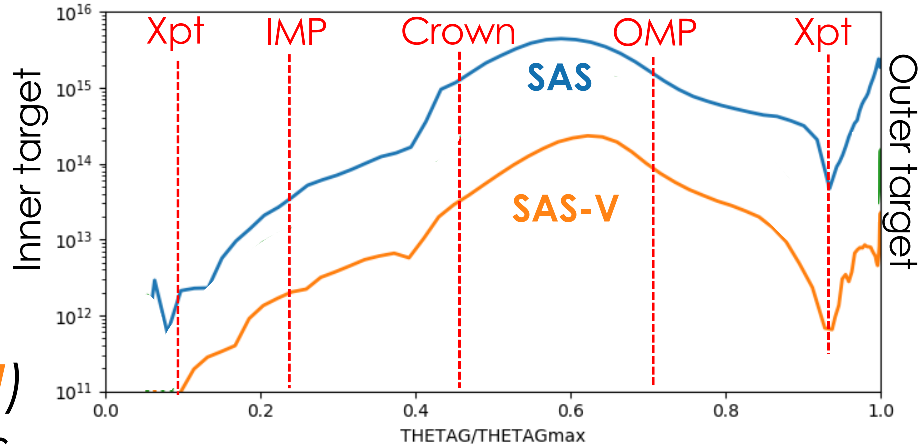
DIII-D Boundary Program Is Providing Essential Input Needed to Develop Divertor Solutions For Steady-State Fusion Reactors

- **Understand Dissipative Divertors**
  - *Impurity radiation*
  - *Role of ExB drift and plasma flow*
  - *Turbulence transport*
- **Evaluate Divertor Closure**
  - *Manipulate E ×B drifts in SAS to optimize detachment for both B-directions (**SAS-1V**)*
  - *Inform **SAS-2** design and optimization*
- **Address Critical PMI issues**
  - *Understand impact of divertor closure on W sourcing and transport (**SAS-1VW**)*
  - *Evaluate new main chamber materials for DIII-D and next-step devices (**WITS**)*

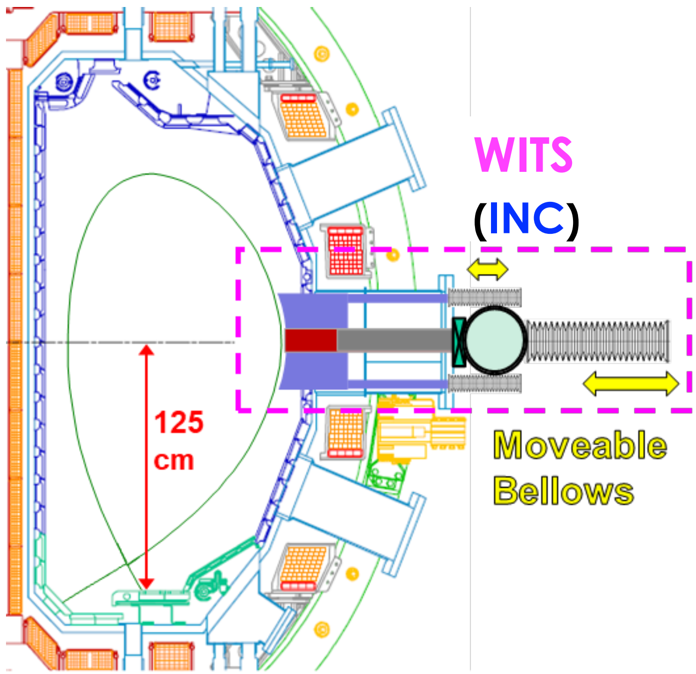




Poloidal profile of n_W (at/m³) near Separatrix



(Y-Axis: Logarithmic)



Develop a viable PMI solution compatible with high-performance core for ITER and beyond

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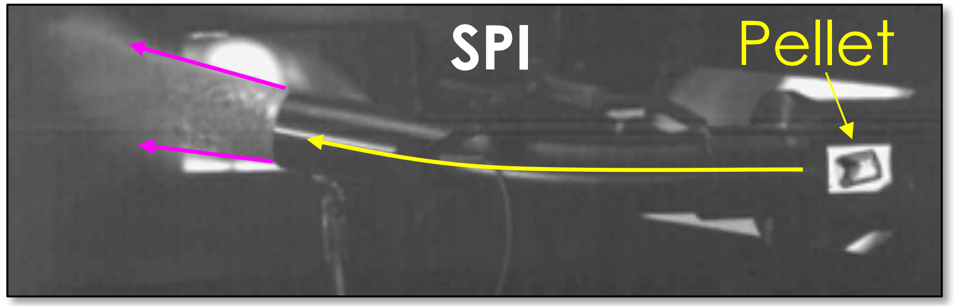
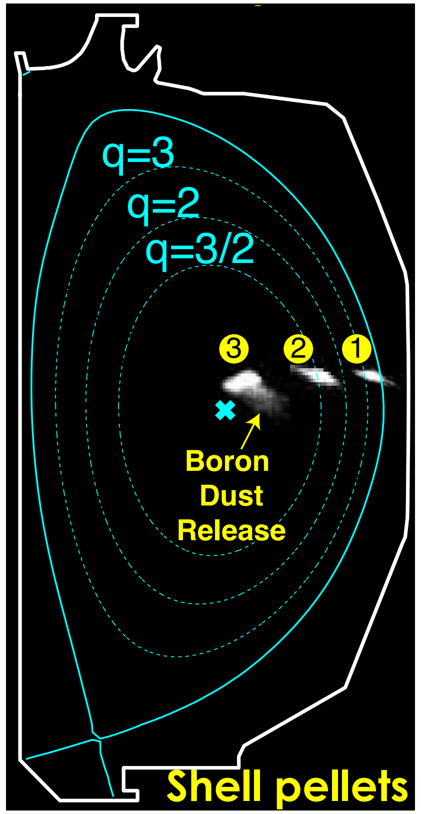
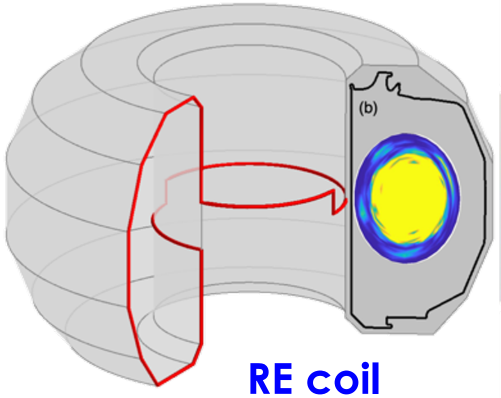
Generate Basis for Reactor Disruption Mitigation System and Demonstrate Path for Disruption-Free Operation FY20-22 plans

- **DIII-D remains lead innovator establishing credible DMS design**
  - Verify adequacy of SPI for ITER DMS
    - *INC: Camera & bolometry upgrades*
  - Pursue reactor-relevant alternatives to SPI
    - *INC: Magnetically shielded shell pellet*
  - New solutions for runaway electron control
    - *INC: Passive runaway deconfinement coil*

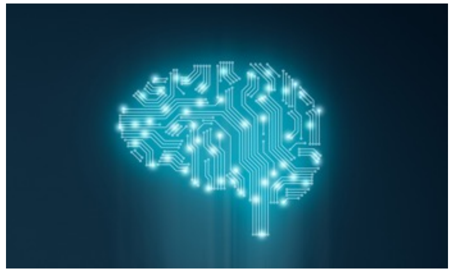




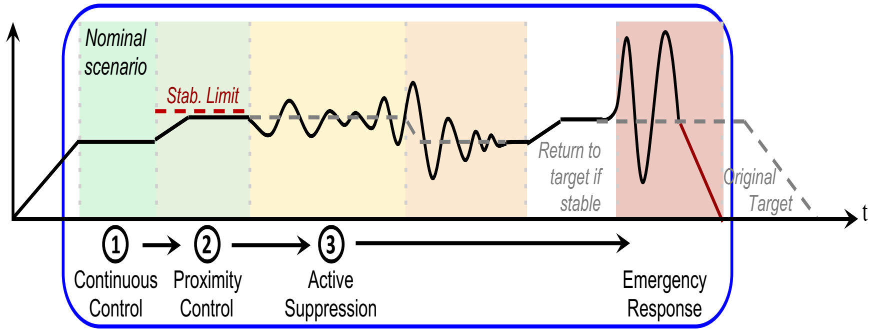


RE coil

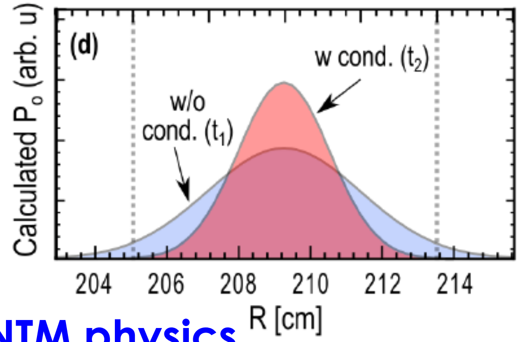
- **Must demonstrate robust solutions to finalize requirements for ITER & CPP**
- **Developing new methods for disruption-free operation**



Machine learning for disruption avoidance & detection



Disruption-free protocol



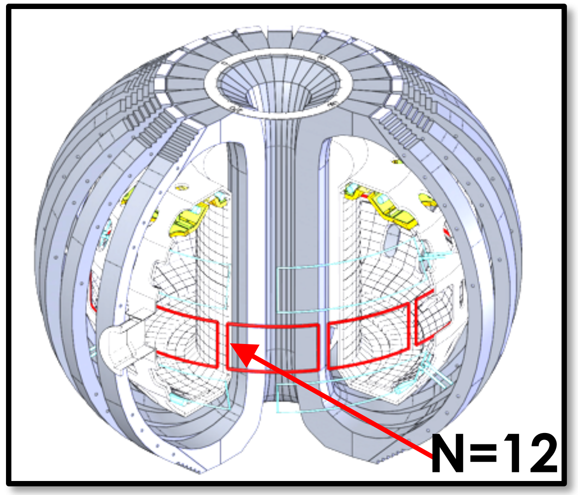
NTM physics

DIII-D Will Provide a Scientific and Technical Basis for Robust ELM-Control Solutions for ITER and Steady-state Reactors

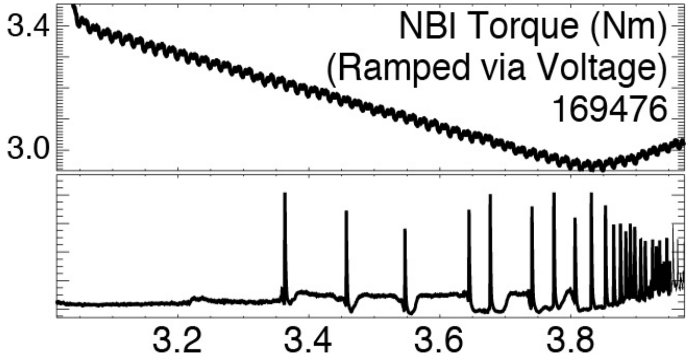
DIII-D Strengths and Capabilities Include
- Broad set of actuators
- Wide range in pedestal collisionality
- Comprehensive diagnostic set
- Close connection to theory

- **Expand operating space for ELM-free regimes, *including negative triangularity***
- **New M-coils (FY23) and second PS will provide more spectral flexibility and better match to ITER**
  - ***Explore Quasi-symmetric optimizations – possible collaboration opportunity with stellarator community***
- **ELM pacing with impurity granules or fuel pellets**

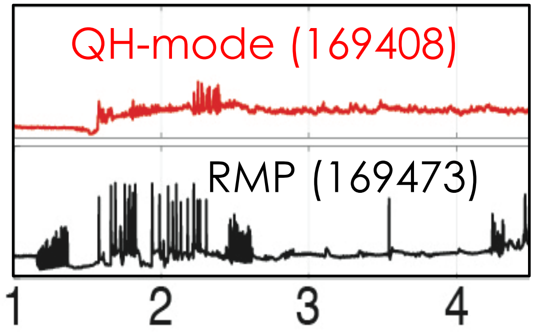
2nd 3D P/S & New 3D coils



Rotation Control



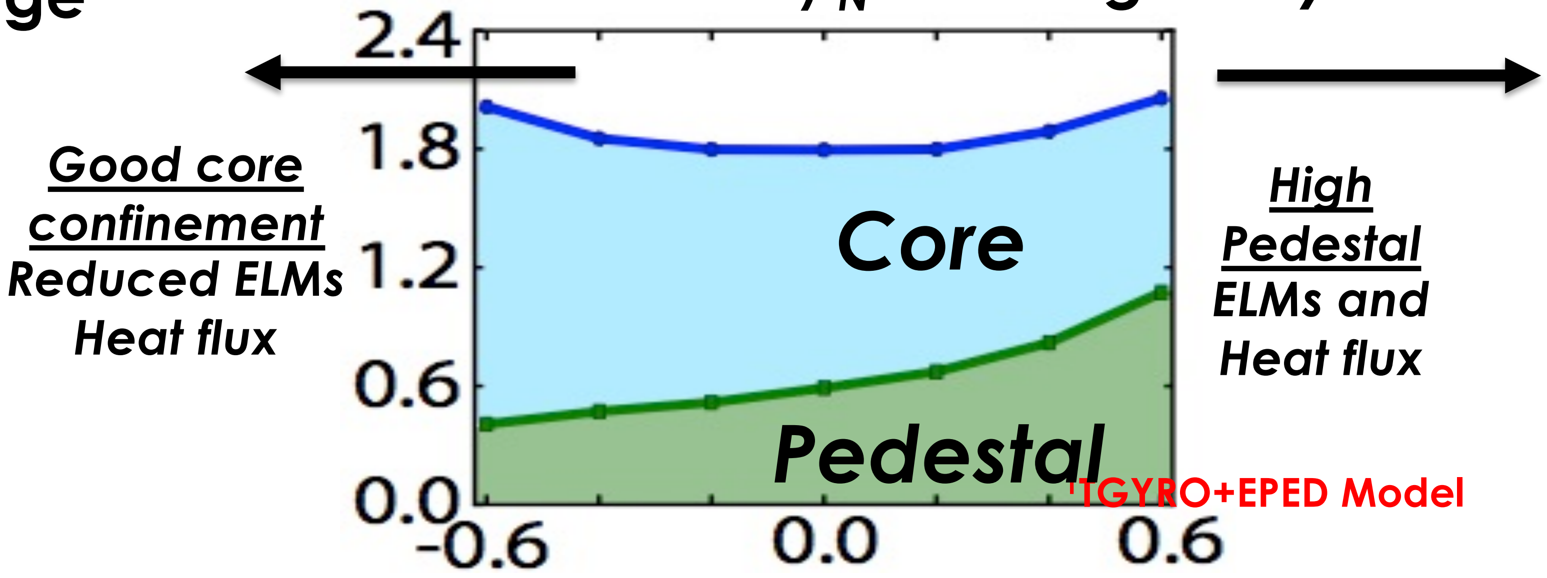
ELM-free Regimes



MTC test winding

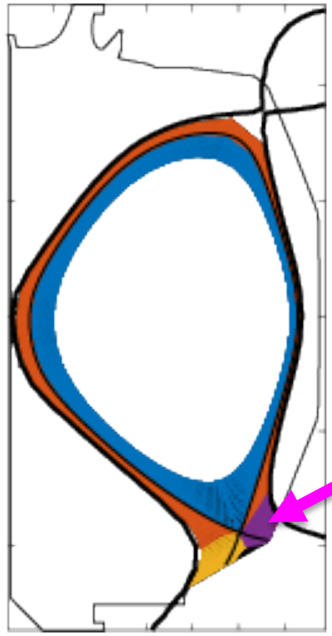
Qualification of New Path to Core-edge Integration Via High Performance L-mode Enabled By Tile Modification

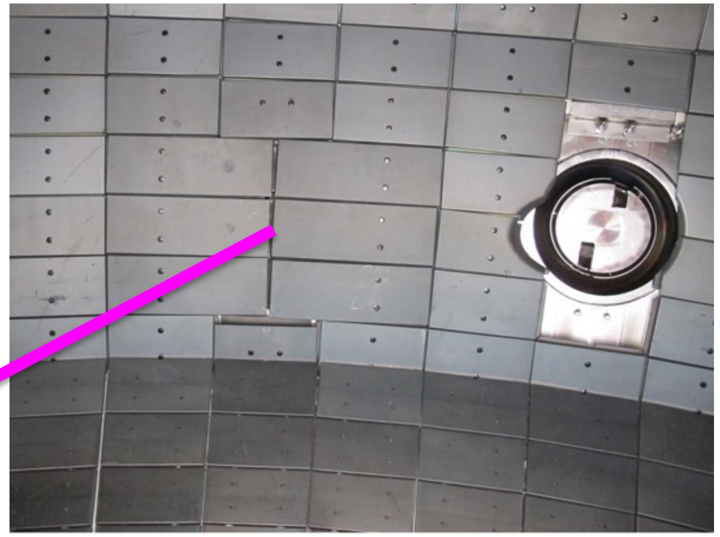
- **Negative-Dee L-mode →attractive edge solution: low P_{sep}, high f_{rad}, no ELMs**
  - Promising results from early experiments and simulation
- **Targeted mini-campaign provides**
  - Sufficient power to evaluate confinement.
  - Evaluate edge pressure limits (no ELMs).
  - Stress-test radiative edge capabilities.
- **DIII-D uniquely flexible, powerful & well-diagnosed to accomplish this task**
  - Can demonstrate a core-edge solution
- **Informs key <u>five-year plan research lines</u> with potentially transformational results.**
  - β limits, edge stability, transport, Divertor heat flux



[1]TGYRO+EPED Model

Cantilevered Tile Armor

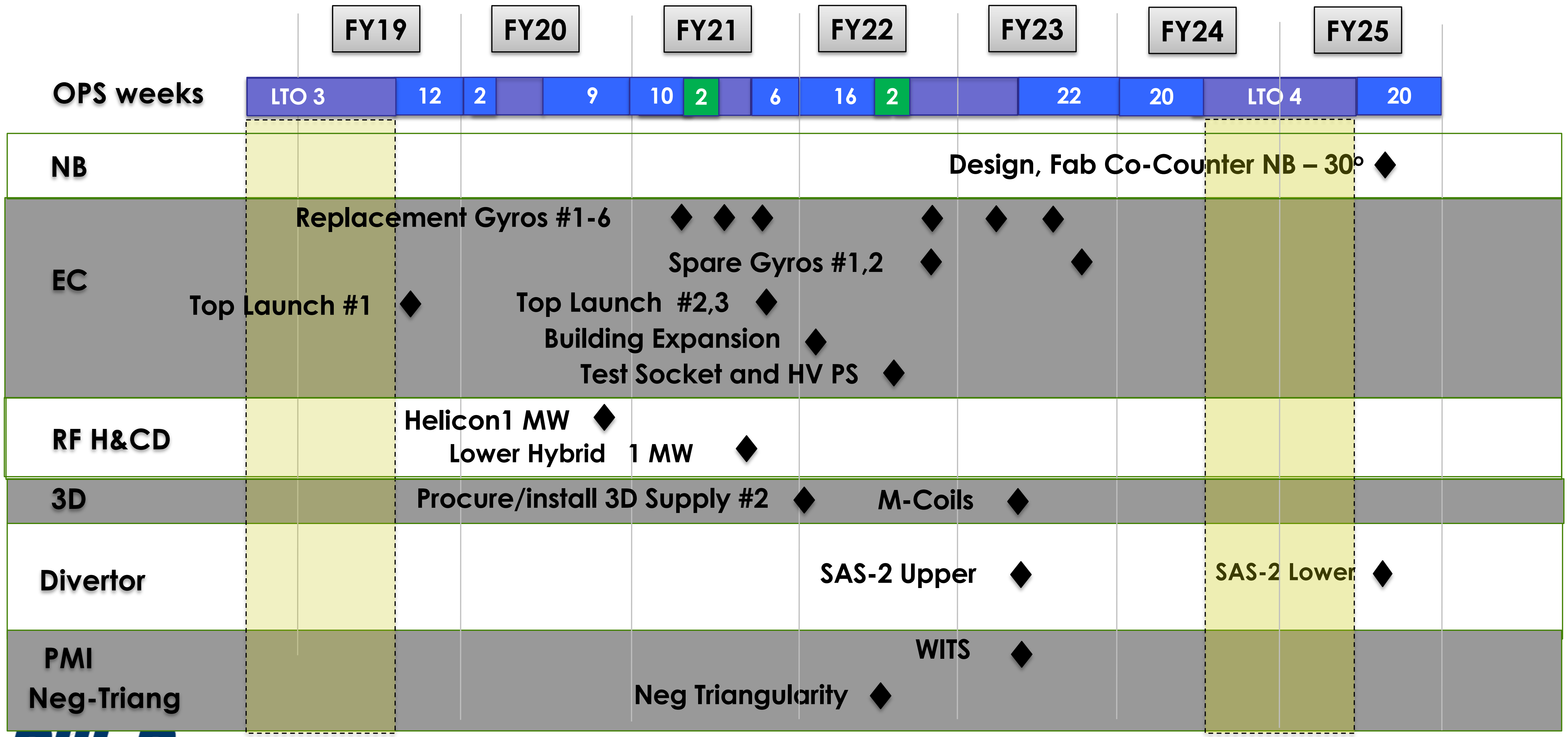




Impacts NTUF & FPP plans

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DIII-D Operations and Enhancements Schedule for FY19 – FY22 Incremental Funding



Guidance | FY21/22 Incremental

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Investments in DIII-D Supports Large National and International Research Teams To Enable World-Leading Scientific Research

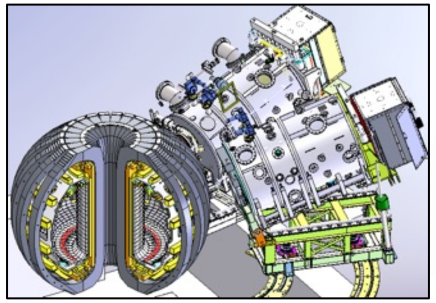
- **718 Scientific – Technical Users from 126 Institutions**
- **410 US citizens, 308 non-US citizens from 37 countries**
- **274 affiliated with educational institutions, 444 other**
- **56 post-docs, 96 Ph.D. students, 9 Masters degree, 26 undergraduates**

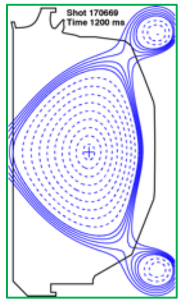
Enthusiastic DIII-D team is key to program success

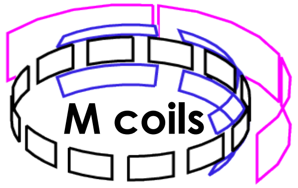
Source: Active DIII-D Cyber Access Accounts in October 2019

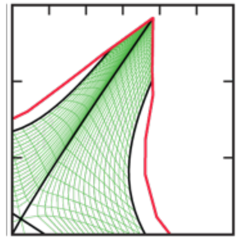
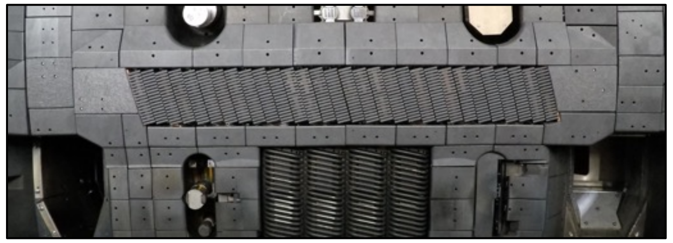
DIII-D Research Plan Offers Compelling Opportunity to Advance The World Towards Fusion Energy

Highly Flexible Operating Capability with Extensive Plasma Control Tools

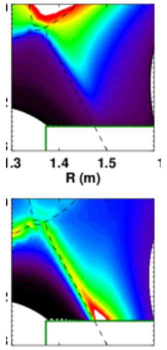


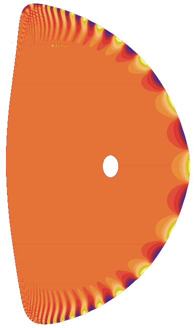




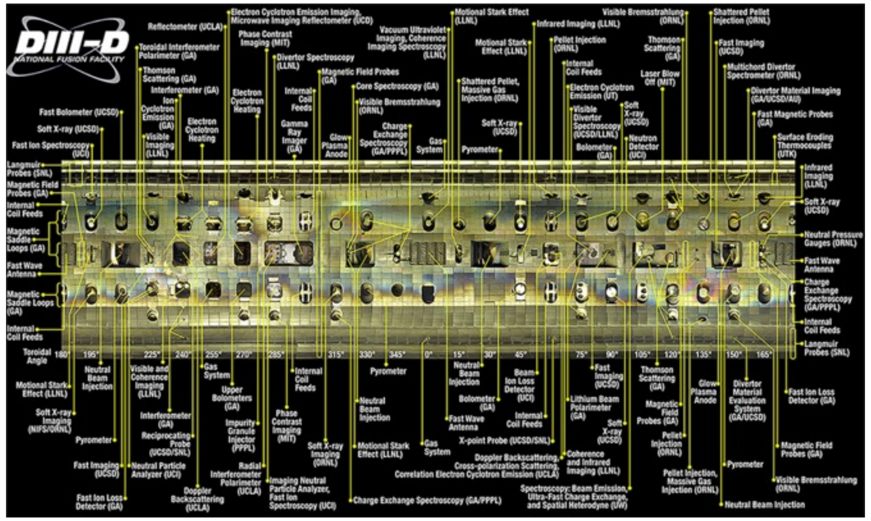



State-of-the-Art Predictive Models





Comprehensive Diagnostics



Highly Capable International Research Team

- **Address critical ITER preparation, transients and development of validated simulation capability**
- **Develop basis for tokamak path beyond ITER with high performance core & compatible boundary solution**

Proposed FY20-22 DIII-D Program Milestones

TITLE OF MILESTONE	DUE	PI	MS #	YEAR
Evaluate efficacy of disruption mitigation by core impurity deposition using shell pellet injection	2020	Eidietis, Hollmann, Bardoczi	2020-1	2020
Evaluate impact of divertor closure on particle transport and heat dissipation	2020	Shafer, Moser, Wang	2020-2	2020
Test impurity transport models and control solutions in reactor relevant plasma conditions (JRT)	2020	Howard, Abrams, Grierson, Samuell	2020-3	2020
Commission and conduct preliminary physics assessment of helicon current drive with ~1MW system	2020	Garofalo, Pinsker, Moeller, O'Neill, Lau, Porkolab	2020-4	2020
Characterize assimilation limits for deuterium SPI in parallel with high-Z neon injection (JRT)	2021	Eidietis, Hollmann, Shiraki	2021-1	2021
Unraveling the physics of high-Z leakage in a slot-like divertor configuration	2021	Abrams, Sinclair, Unterberg, Nichols	2021-2	2021
Evaluate tradeoffs between core performance and divertor power handling with shaping	2021	Grierson, Jarvinen, Snyder	2021-3	2021
Complete construction of LHCD system and commence initial powered tests in plasmas	2021	Wukitch, Pinsker, Ops	2021-4(I)	2021
Mitigate E×B effects in SAS by change of tile shape to improve power dissipation for both B_t directions	2021	Guo, Ma, Thomas, Wang	2021-5(I)	2021
Impact of Isotope Mass on Tokamak Performance	2022	McKee, Osborne, Turco	2022-1	2022
Improved understanding of Pedestal and ELM transport characteristics through identification of turbulence drives and damping, and through code validation and prediction	2022	Saarelma, Rhodes, Groebner, Mahajan	2022-2	2022
Test models of divertor impurity density required for dissipative divertor operation	2022	Samuell, Leonard, Lore	2022-3	2022
Evaluate effectiveness of disruption prevention and avoidance algorithms in ITER and fusion power plant-relevant plasma conditions	2022	Barr, Olofsson, Humphreys	2022-4(I)	2022
Use upgraded off-axis current drive sources to understand requirements for fully non-inductive core scenarios with broad profiles and $\beta_N \geq 4$	2022	Holcomb, Park, Collins	2022-5(I)	2022
Evaluate Negative Triangularity as an Integrated Reactor Scenario	2022	Austin, Paz-Soldan, Marinoni, Scotti	2022-6(I)	2022

DIII-D Facility Enhancements Significantly Advance Core and Boundary/PMI Research To Accelerate Fusion Energy Science

	Facility Upgrades	Research Goals
Core Plasma	Co-Counter NB	Increased co- power for high β scenarios, Increased power with balanced torque Low rotation high β SS scenarios
	Helicon/ HFS Lower Hybrid Top Launch EC, CCOANBI	High efficiency off-axis current drive at higher density
	Expanded EC	Increase Te/Ti; Zero-torque H&CD; Off-axis j(r); NTM stabilization; Perturbative transport
	NB Pulse/Power Extension	$T \longrightarrow 2\tau_R$; Higher β scenarios
Boundary/PMI	New 2D/3D Power Supplies, New 3D coils	Improved divertor shaping RMP and 3D physics
	Divertor Geometry Modification	Heat flux and density control; detachment physics
	Divertor diagnostics, LBO, pedestal Lyα arrays	Dissipative physics, SOL flows and momentum, turbulence and transport, fueling, impurity transport
	W inserts & PFCs tests	Understand sources and develop mitigation techniques