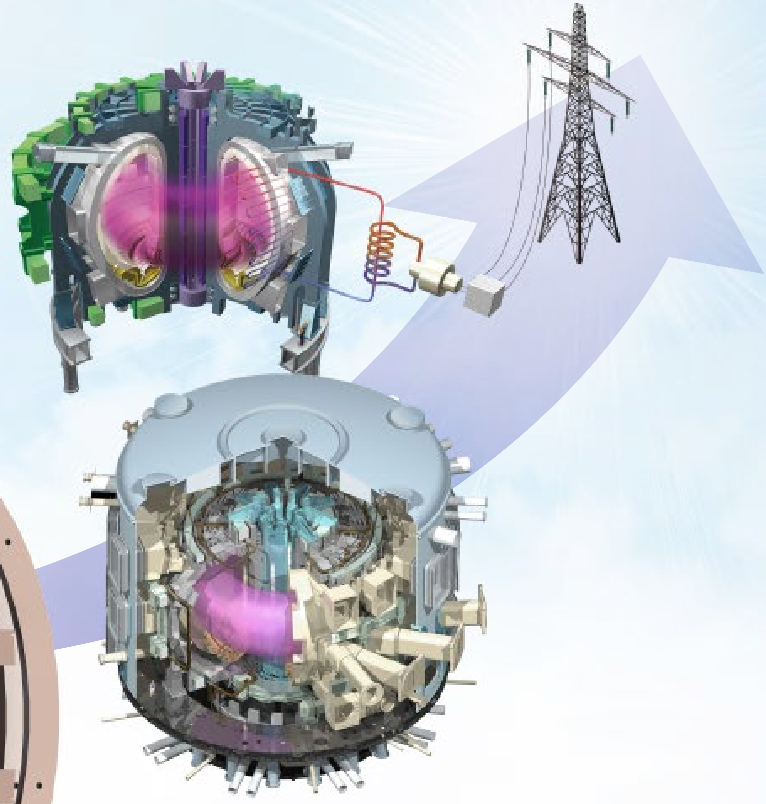
Opportunities for Collaboration with DIII-D

Our future plans, and thoughts on our common goals

presented by

RJ Buttery

with thanks to
many DIII-D colleagues



Plasma Seminar
10th US-PRC Workshop
Mar 22nd 2021

DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

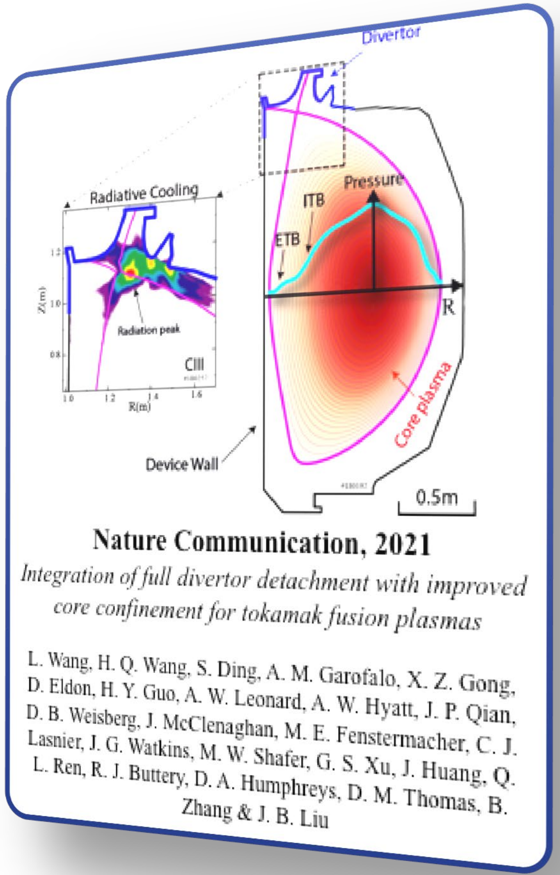
Work supported by US DOE under DE-FC02-04ER54698.

Strong and Effective, Appreciated Partnership Between DIII-D & PRC

- **Deep meaningful engagement on most important issues of fusion energy**

- **True partnership as equals with leadership opportunities on both sides**
  - Unique capabilities in each partner which inform each others path
  - Shared project leads, invited talks, papers

- **Leading to major advances that inform our path**
  - Reactor scenarios, transient control, current drive core-edge integration



Our partnership has added enormous value to our research programs in the US and PRC

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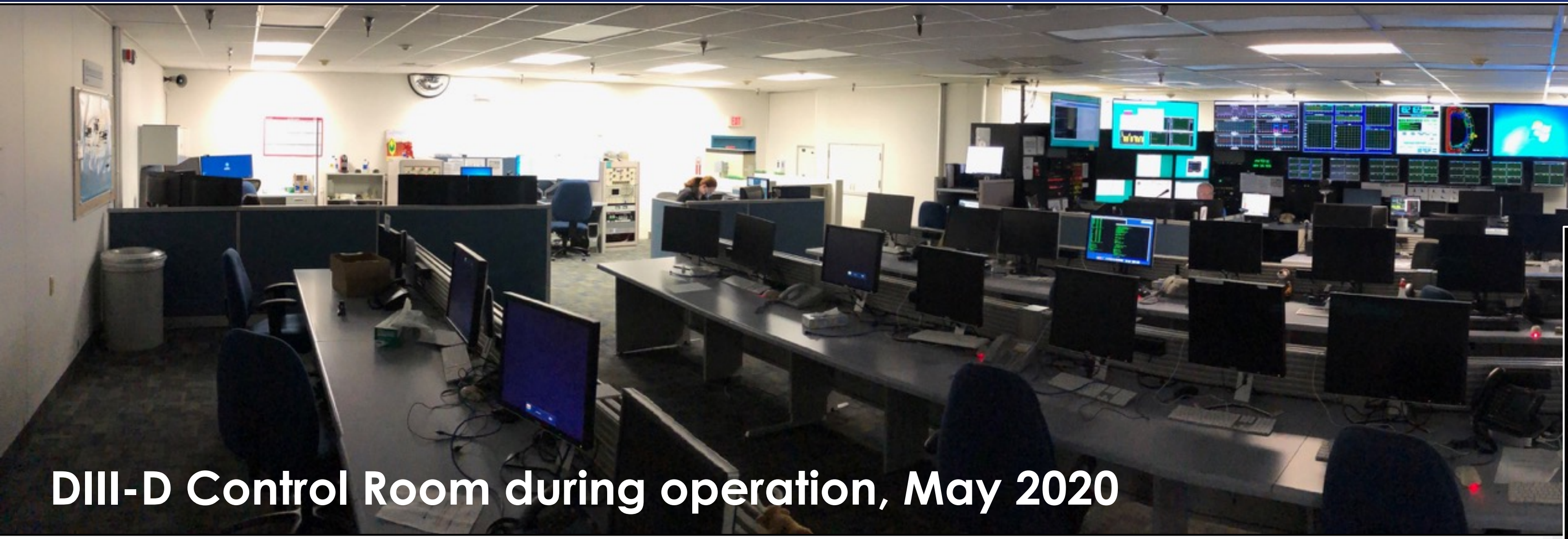
ASIPP

DIII-D has Re-Developed Operation for Remote Participation



DIII-D Control Room during operation, May 2020

- **New tools replicate the "control room experience"**
  - Team communication using Discord (gaming software!)
  - Specialized web tools developed
  - All meetings moved to Zoom
- **Procedures to keep people safe when on-site**
- ***Remote participation is easier!***

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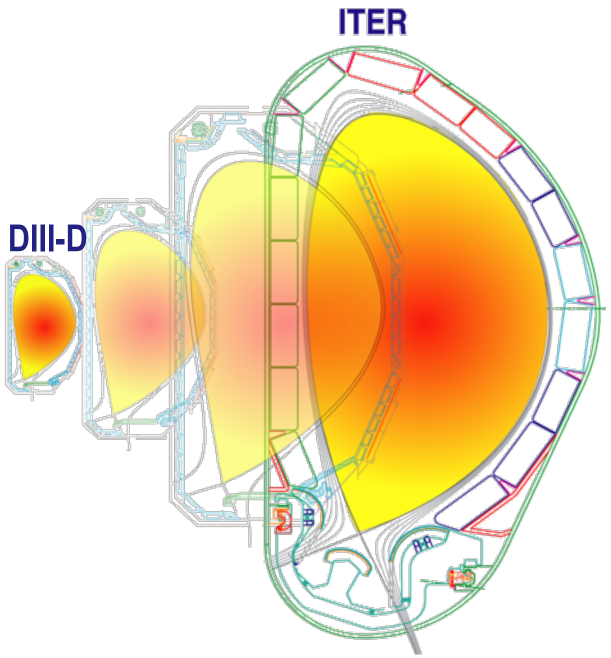
Developing models of international collaboration and preparation for ITER and other facilities

DIII-D Plans and Opportunities

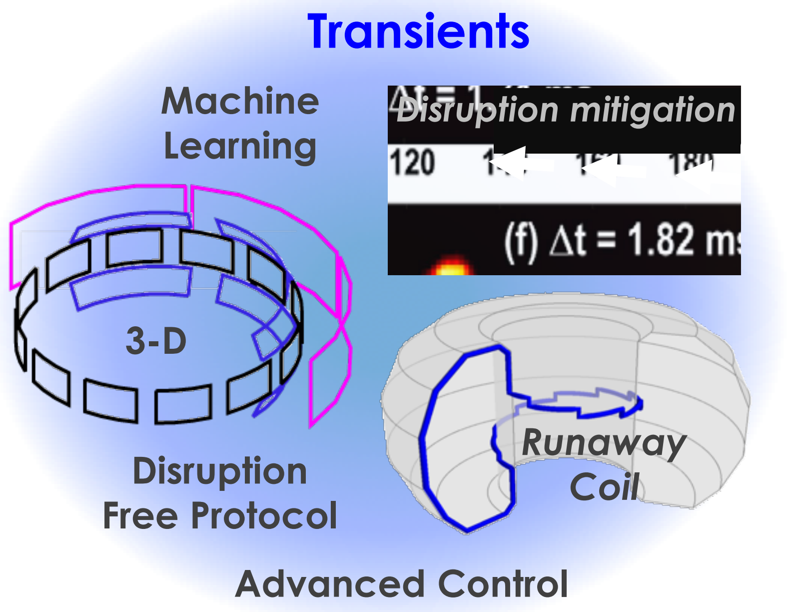
- **Research Needs**
- **Long Range Directions & DIII-D Mission**
  - *What is the potential of the facility*
- **Near Term Plans**
  - *Opportunities to Engage*
- **Conclusions**

Strong Focus Maintained on Enabling Success in ITER

DIII-D can



- **DIII-D is the U.S.'s ITER simulator**
  - Relevant parameter, shape, physics & control
- **Make ITER better**
  - Address transients & raise performance – *Q>10!*
- **Rapidly resolve ITER issues when running**

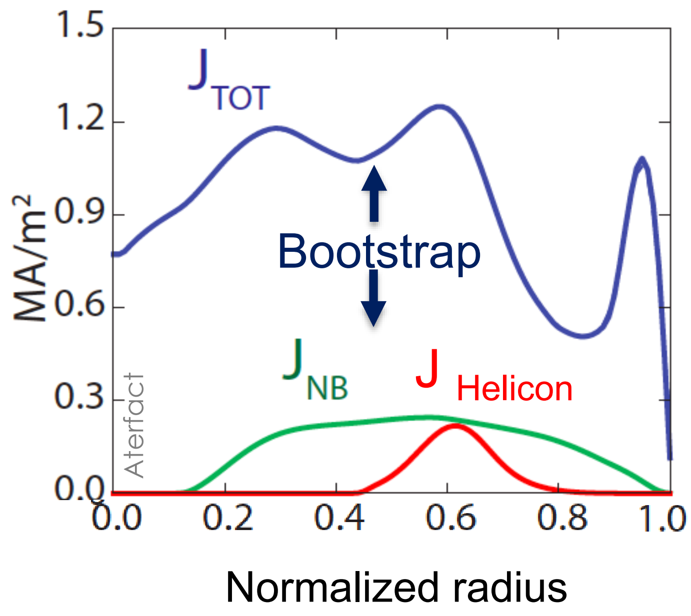


- **Validate techniques, theory & simulation**
  - Develop on DIII-D → test on ITER
  - Gain leadership. Develop tools for U.S. reactor

Develop techniques, codes & personnel
Bring learning back from ITER to U.S. program

DIII-D also Targets Advanced Tokamak Path to a Compact Fusion Pilot Plant

- **Fully integrated physics simulations project range of Compact AT pilot plant solutions**
  - State of the art models validated on DIII-D
  - High shape, broad current, high pressure
    - ***High bootstrap self-driven solutions***



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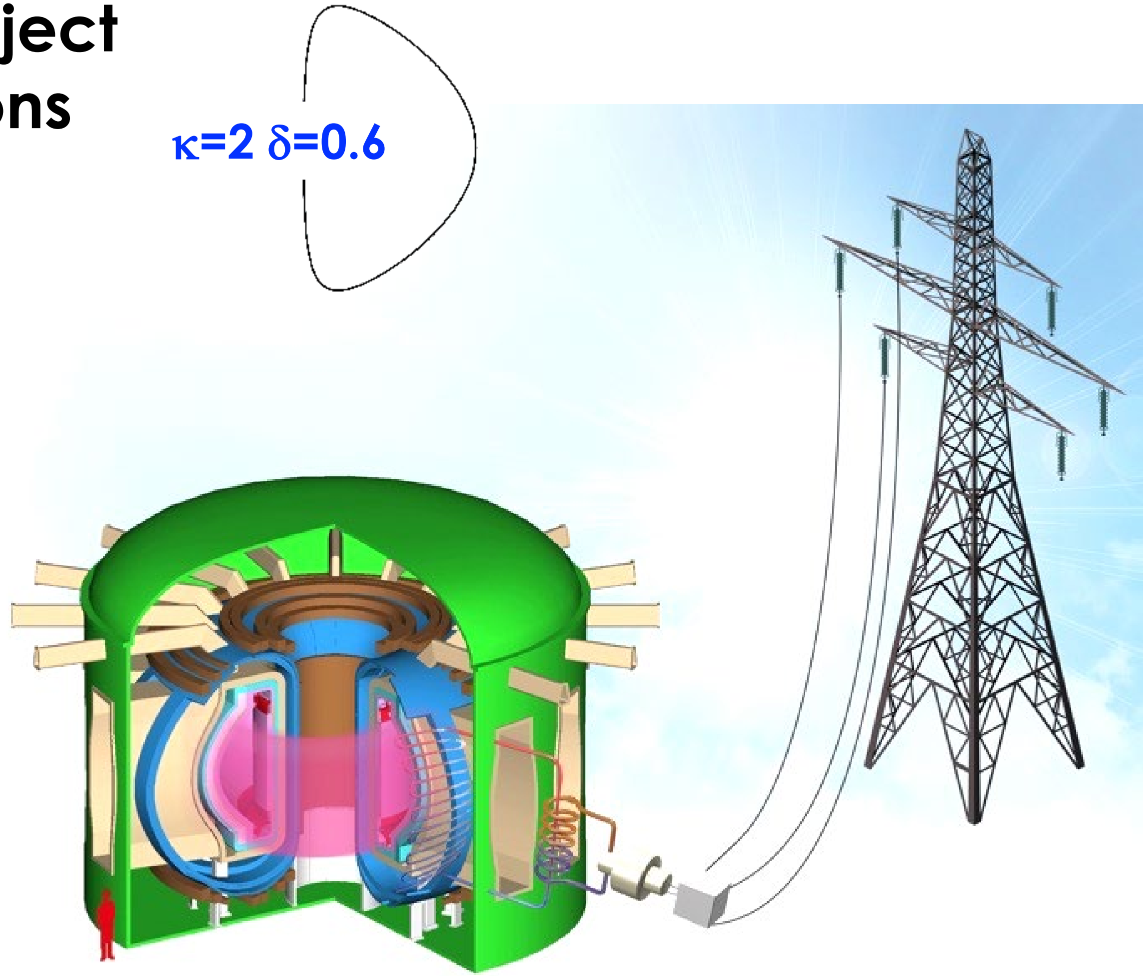

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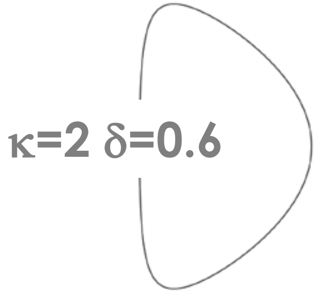
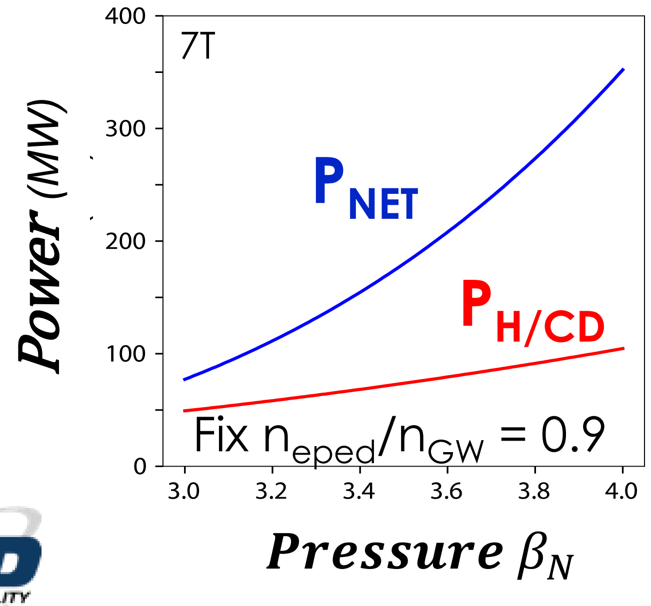
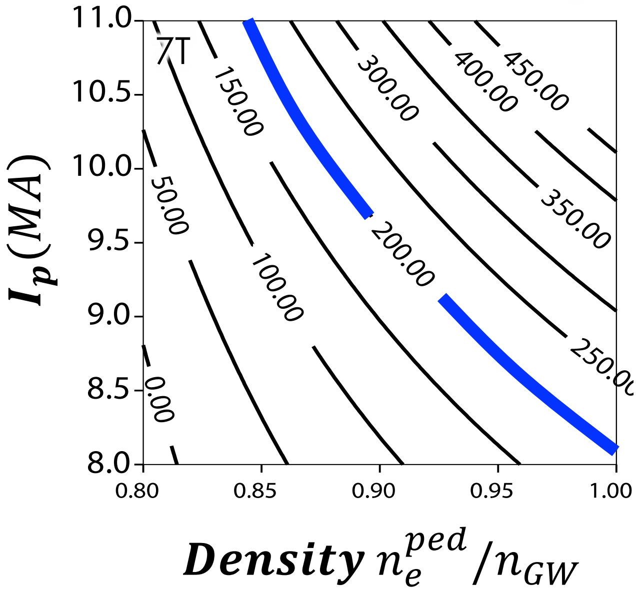


- ***Family of fully non-inductive solutions at R~4m, 200MWe***

Net & Heating Power (MW)



Net Electric Power (MW)



200MW Net Electric Solutions:

	6T	7T
I	9.4	8.1
q	4.9	6.5
β_N	4.2	3.6
H_{98}	1.3	1.5
Q	10	17
P_{heat}	84	38
P_{fus}	870	660
Neut.	2.3	1.8

R=4m, $\eta_{TH} = \eta_{CD} = 0.4$
n_e^{ped}/n_{GW}=1, 200MWe

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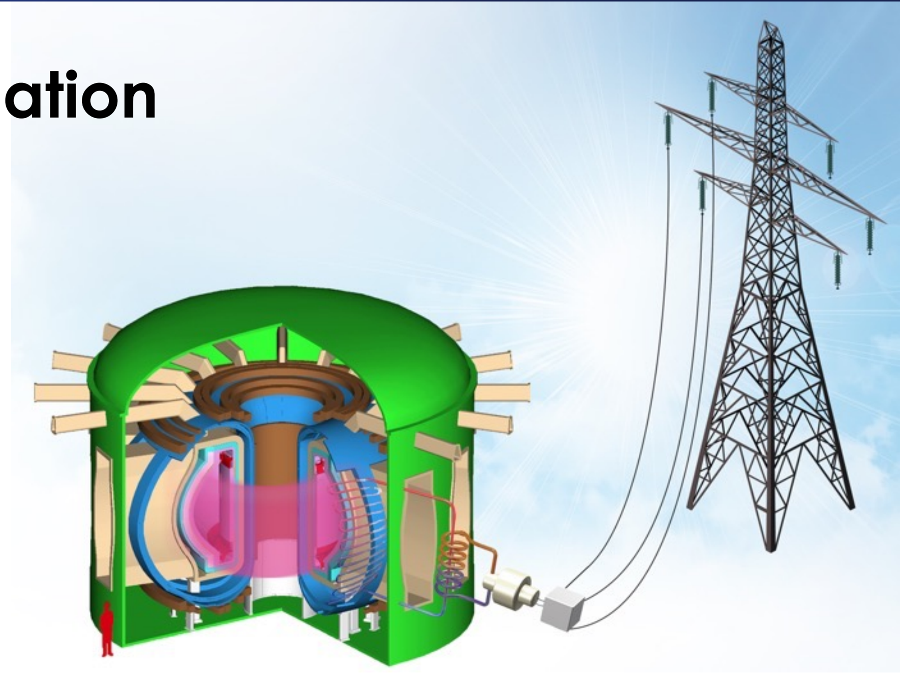
[Buttery et al., NF 2021]

Pilot Plant Concept Poses Key Research Challenges

- **Core solution needs development & physics validation**
  - Scope the limits of density, pressure, confinement
  - Turbulence, stability, energetic particle confinement
  - Required control tools & safe landing (disruptions, ELMs)
  - Viable current drive solution
- **Power handling solution compatible with core**
- **Resolve wall materials and plasma interaction**



➔ ***Compatibility between core and edge is the key challenge***

➔ ***Develop the high pressure & density solutions needed for a fusion reactor***

DIII-D aims to confront these challenges

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DIII-D Plans and Opportunities

- **Research Needs**
- **Long Range Directions & DIII-D Mission**
  - *What is the potential of the facility*
- **Near Term Plans**
  - *Opportunities to Engage*
- **Conclusions**

Key Challenge for Pilot is to Identify Plasma Solution That Delivers the Performance and Handles the Power Loading

Core and divertor physics are governed by different parameters:

Core ⟷ Pedestal	—— Separatrix ——	Divertor, $q_{||}$ ⟷ Wall
Low collisionality, $\nu^* \sim \boldsymbol{n}^3/\boldsymbol{P}^2$	n_{sep}	High n_{div} + *impurities*
⬇		⬇
PERFORMANCE		**DISSIPATION**

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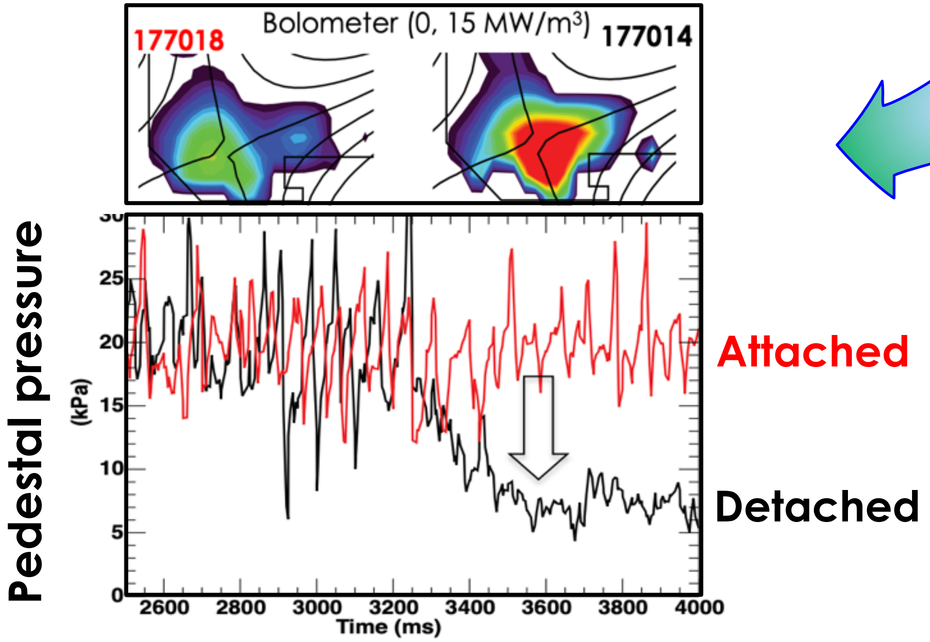
PERFORMANCE — **DISSIPATION**

Dissipative solutions in tension with high performance core



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PERFORMANCE — DISSIPATION

high <u>pressure</u> & high <u>density</u> required to reconcile performance & dissipation

This is the central focus of DIII-D upgrades and mission

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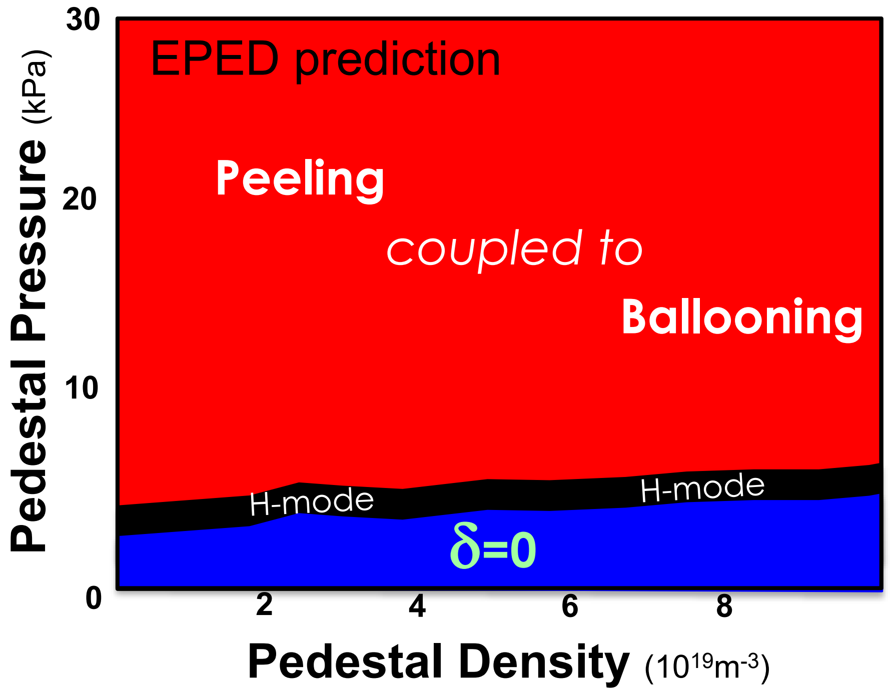
Pedestal Model Projects Strong Shaping Raises Performance

- **Peeling-ballooning instability couples**
  - Fine scale ripple-like interchange
  - Low order peel off of edge



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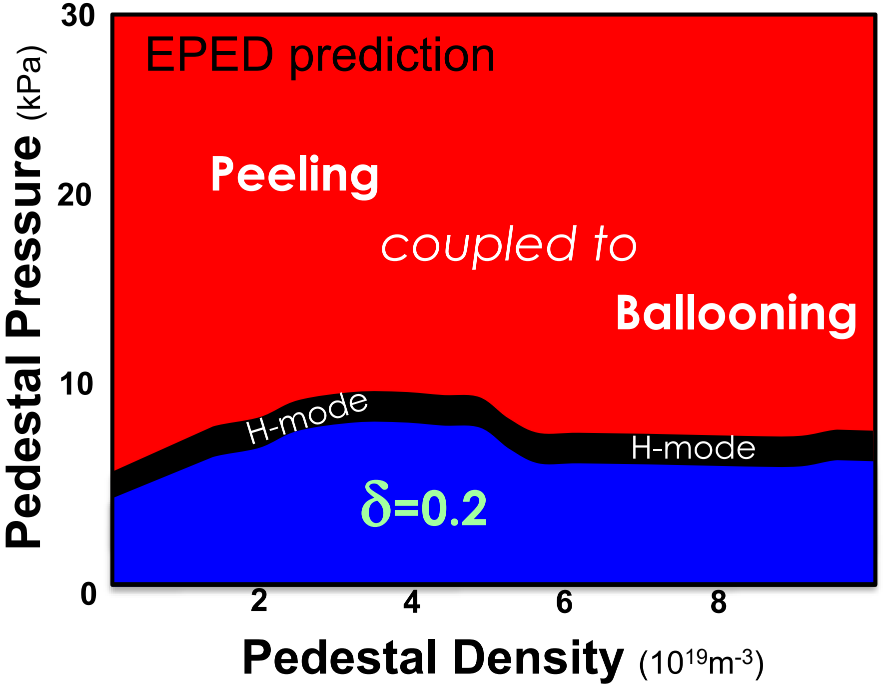

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Snyder

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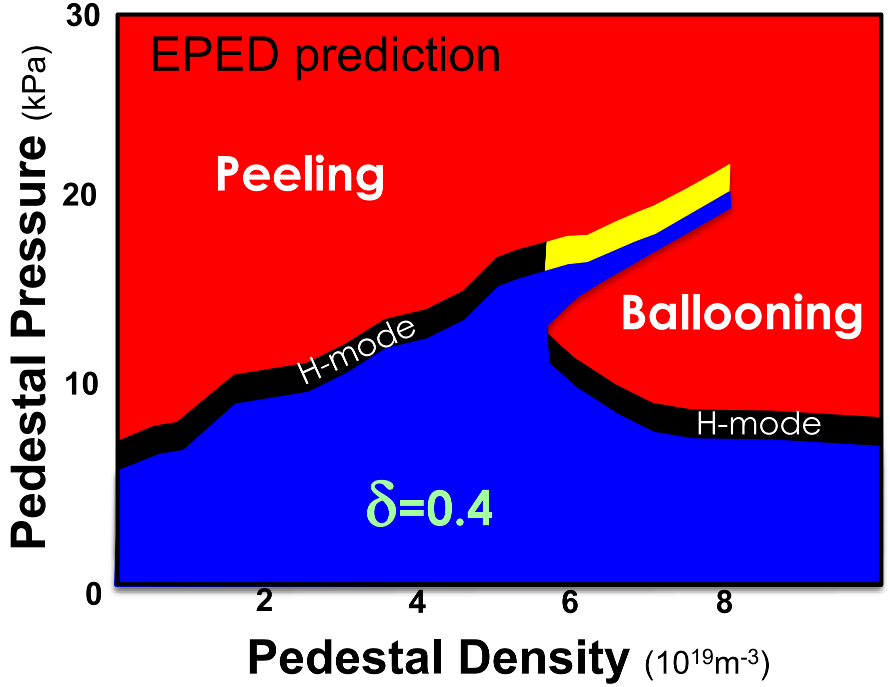

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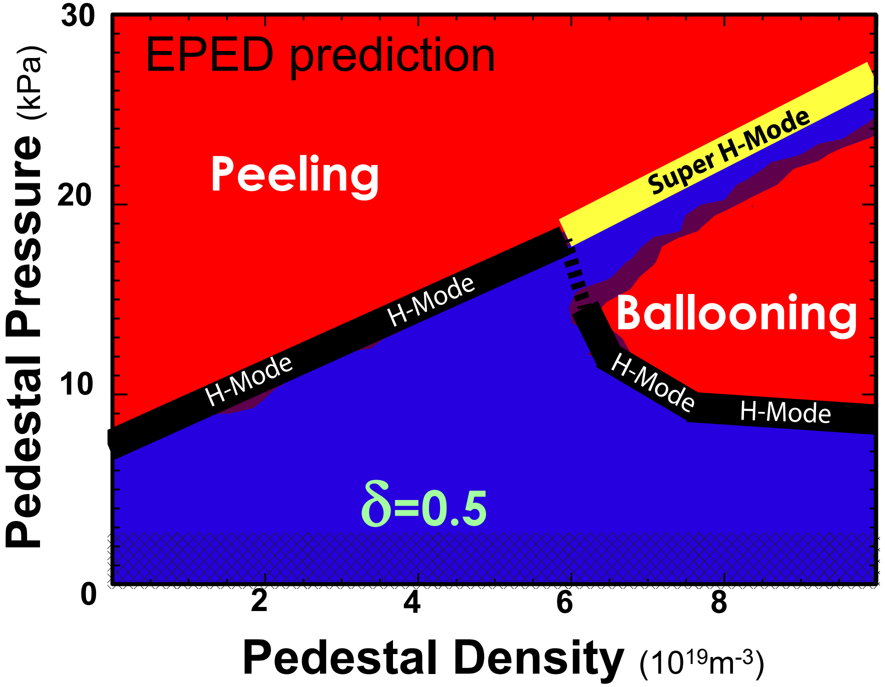
- **Super H-Mode**



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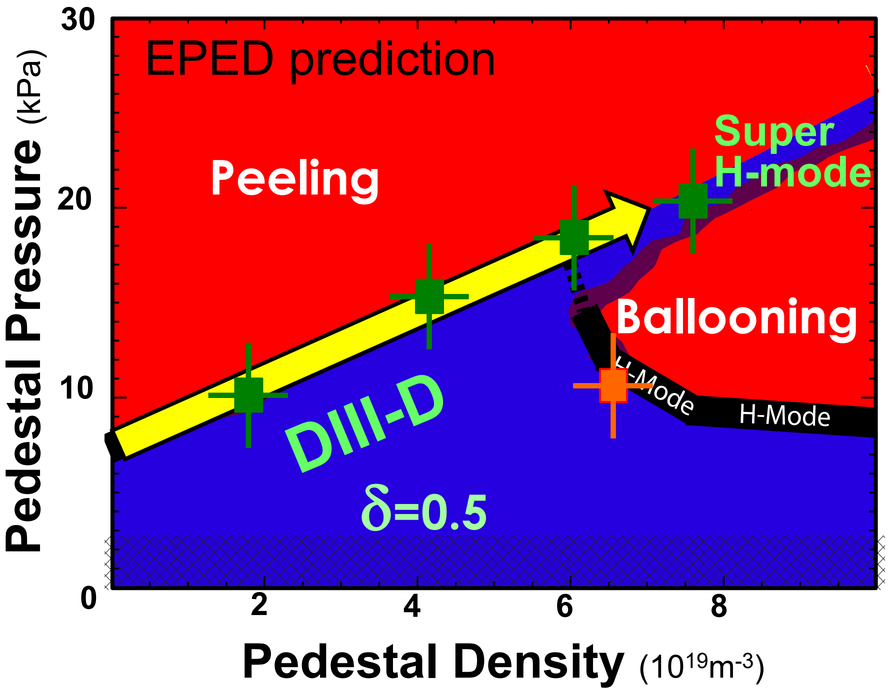
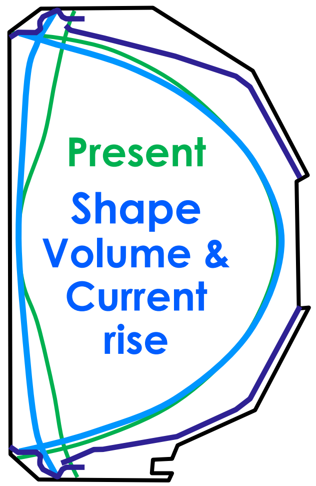
- **Super H-Mode discovered on DIII-D**
  - Record β_N=3.1 with a quiescent edge



Provides a means to raise performance in DIII-D

A Shape Rise Provides a Key Step in Confronting Challenges of the Pilot Plant

- **Raise shape, volume and current to open large expanse in operational space**
  - Install a compact divertor



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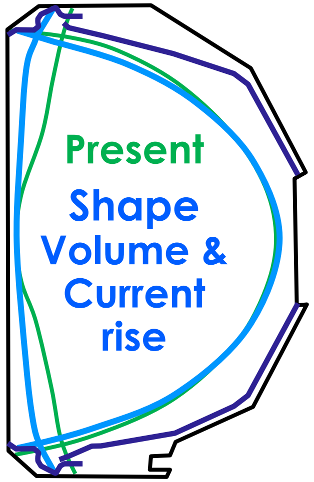
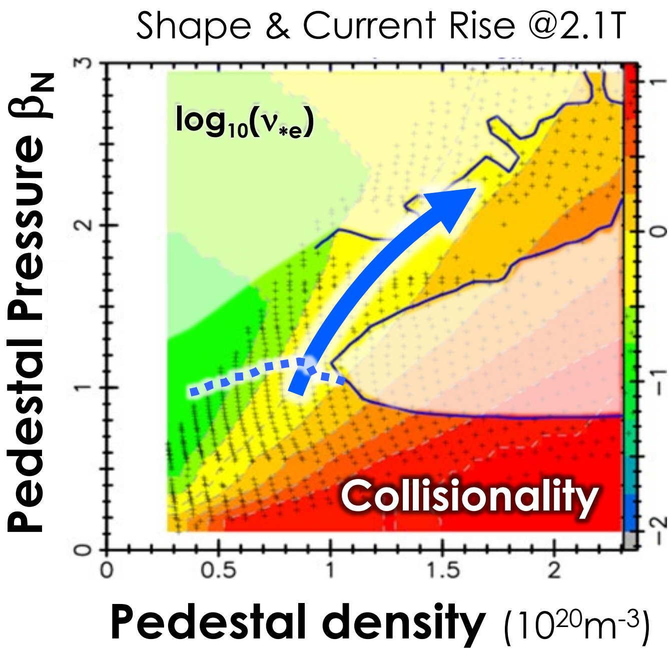
- **High pressure ➔ low collisionality at high density**
  - Explore dissipative edge with high performance





EPED, EIRENE, SOLPS

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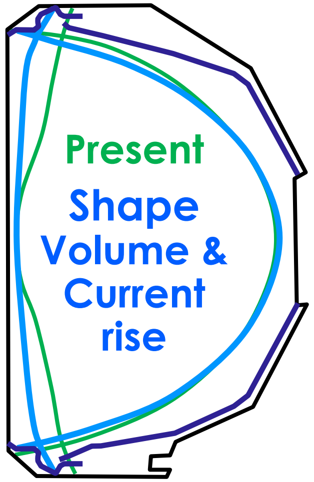
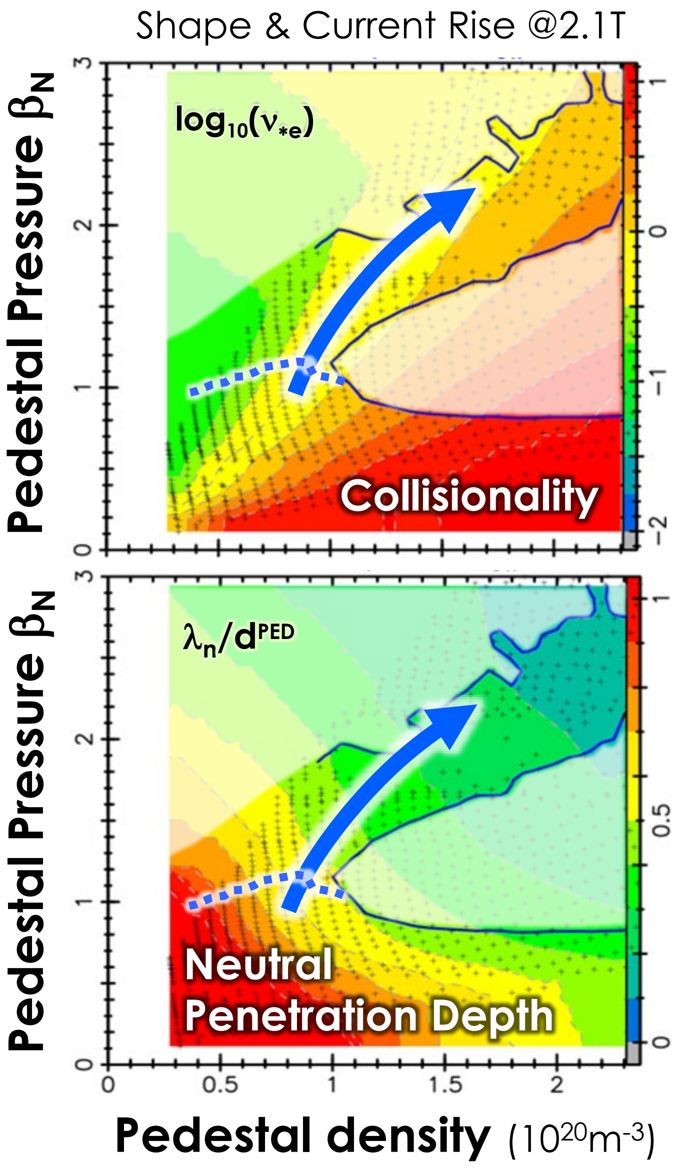
  - Capture particle transport dynamic of a reactor





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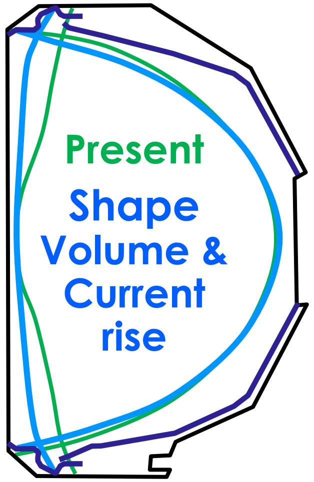
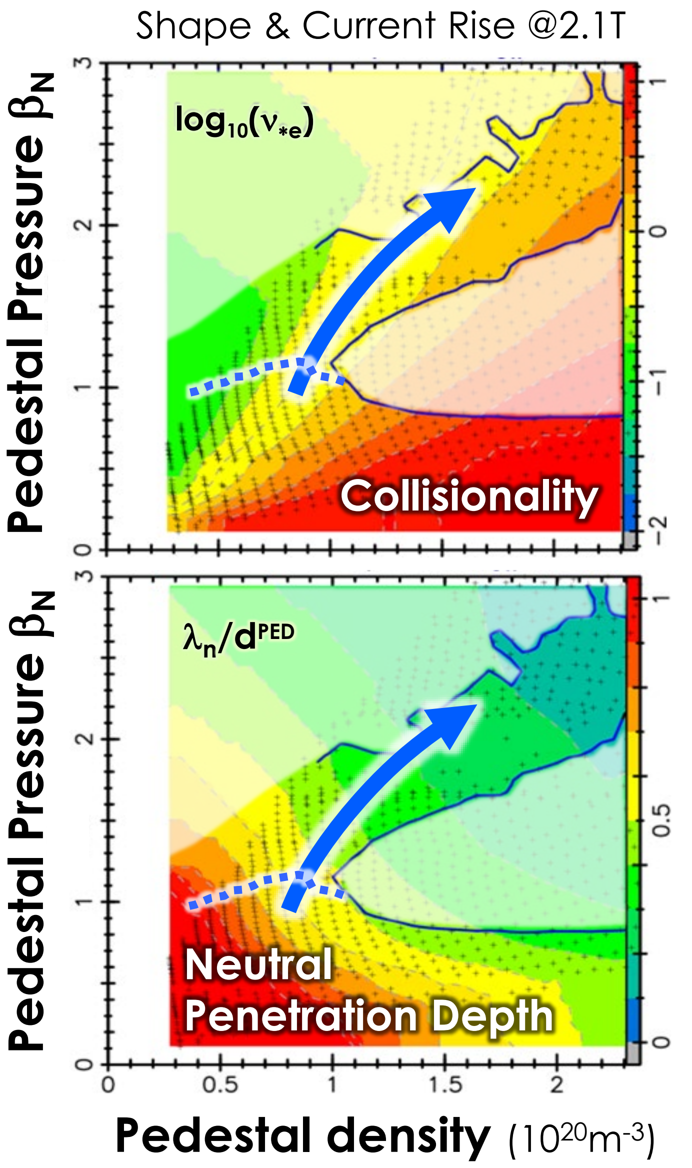
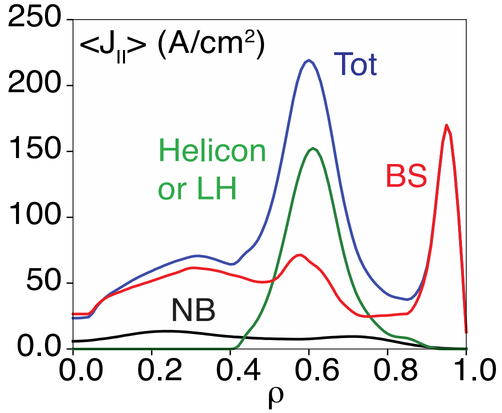
Fundamentally transforms DIII-D capabilities to study core-edge interactions & solutions





Shape Rise Part of Wider Performance Upgrade to Discover Reactor-Relevant Core-Edge Solutions

- **Additional heating & current drive needed to explore the expanded operational space**
  - 20MW RF inc. high density current drive: *Helicon, LHCD, ECH*
- **Steady states with x2 density, x3 energy ➔**
  - → **Relevant core:** High thermal & bootstrap fraction, low rotation, coupled ions & electrons



Key parameters:
2.17T, 2MA, q_{95}=5.5, 3.8MJ,
P_{ped}=41kPa, β_N=4.1(limit 10),
ν^*_{ped}~0.14, n_{ped}=8.7E19,
T_e~5keV, T_i~4keV,
Ω~21krad/s δ=0.9,
28MW beams, 12MW helicon,
11% fast ions, 61% bootstrap.

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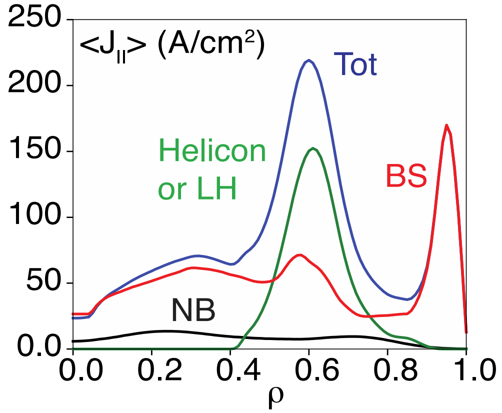

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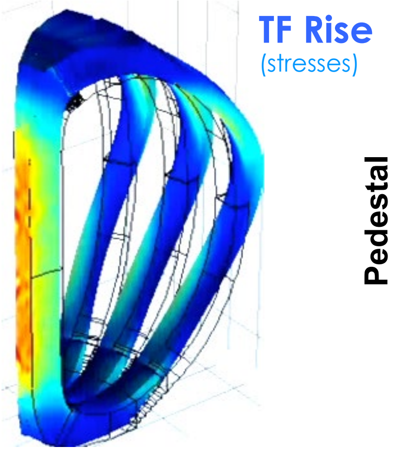
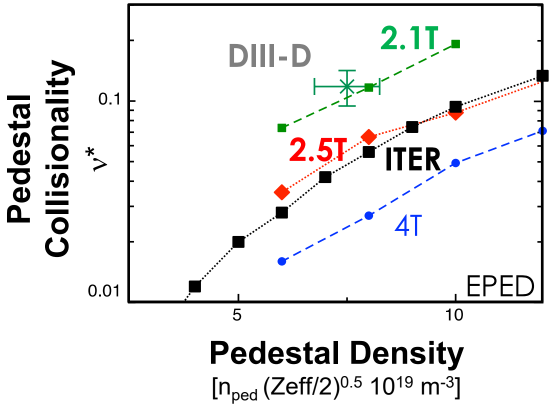
- **TF rise to 2.5T advances core-edge path further**
  - $\nu^* \sim B^{-4}$: Fully scope low ν* space to high density
    → ***ITER-like pedestal-core optimization***
- **Heat fluxes ~3GW/m² with high density**
  → **Assess reactor relevant div/SOL processes**





Dramatic change in physics capabilities to address pilot mission

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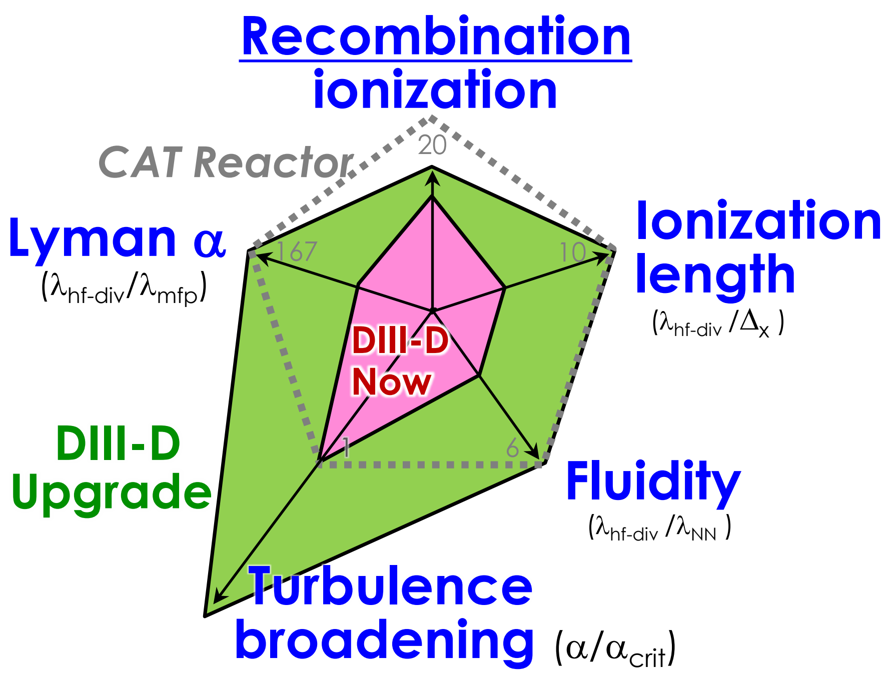
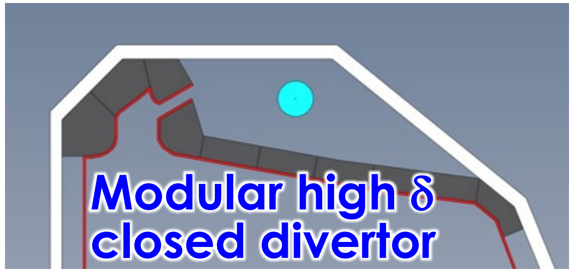
Performance and Closure Rise Enables DIII-D to Explore Reactor Divertor Solutions

- **Closes gaps on key metrics governing physical mechanisms in divertor**
  - Closure raises local density & dissipation further



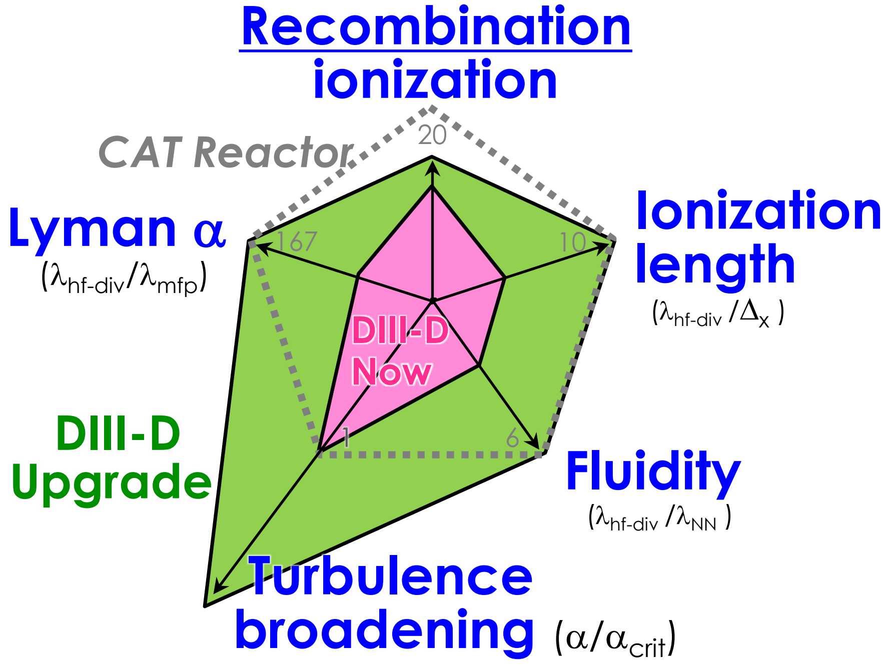
Key Divertor and Core-Edge Physics:

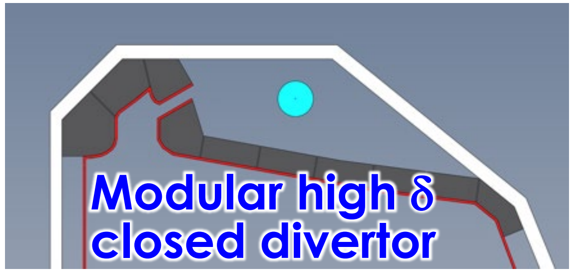
- **Lyman α:** photon trapping by particles
- **Ionization length:** how far neutrals get compared to divertor structures
- **Recombination/ionization:** governs proportion of neutrals at the edge
- **Fluidity:** as divertor plasma becomes more fluid
- **Turbulence broadening:** at high heat fluxes radial gradients drive turbulence in scrape-off layer

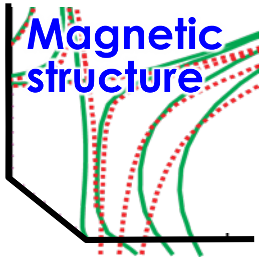


Performance and Closure Rise Enables DIII-D to Explore Reactor Divertor Solutions

- **Closes gaps on key metrics governing physical mechanisms in divertor**
  - Closure raises local density & dissipation further
- **Utilize flexibility and diagnostics to discover reactor divertor solution**
  - Variable physical and magnetic geometry
    - ***Stabilize high levels of detachment***
  - Outstanding diagnostics & theory partnership
    - ***Resolve key physics***
  - Relevant SOL/pedestal parameters and wall
    - ***Identify compatibility with fusion core***







Unique basis to develop projectable understanding for reactor

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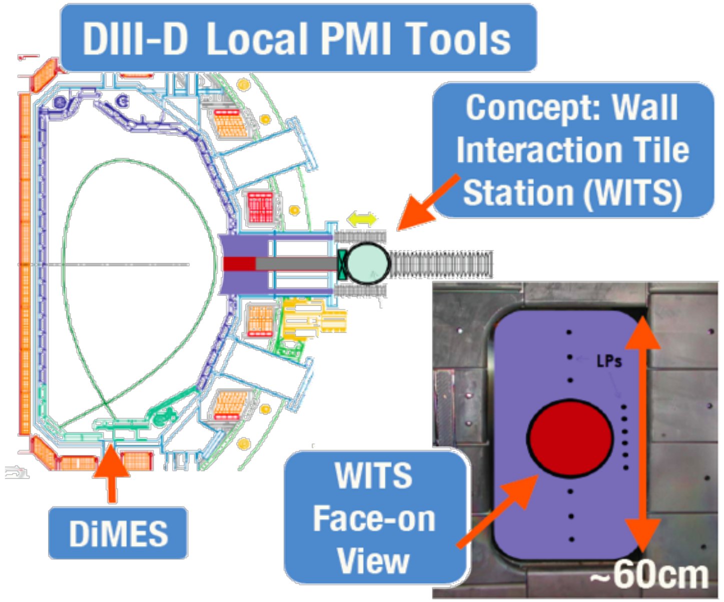
Plasma Wall Interaction is Critical in Overall Solution

- **Goal: Assess materials in relevant conditions**
  - **Qualify new materials in tokamak plasmas**
  - **Resolve constraints on divertor and core**
    - *Physics of migration and transport*
  - **Ensure suitable conditions for high performance**
    - *Radiative optimization (without carbon)*



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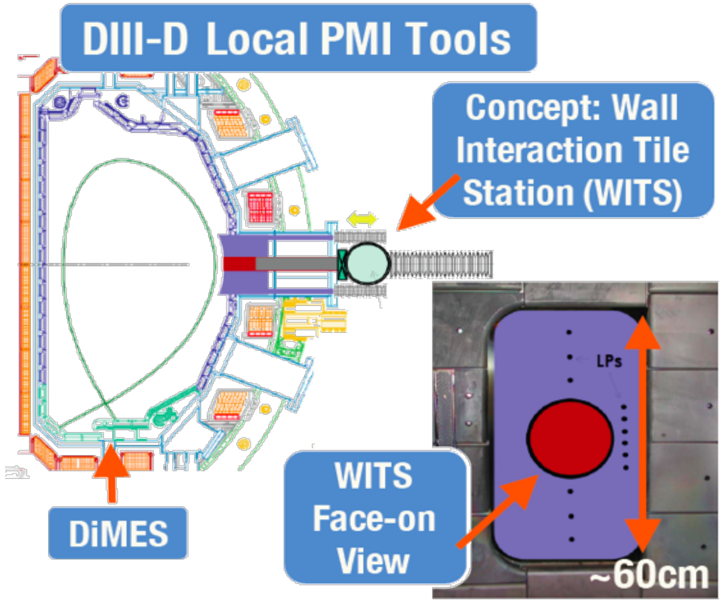
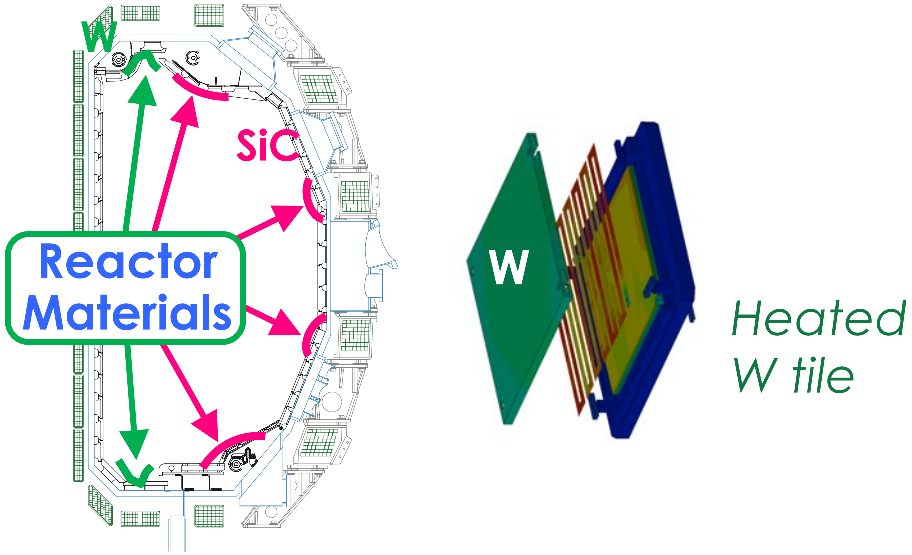
- **Key Elements**
  - **Tile Test facilities** – PMI with realistic tokamak plasma
  - **Tungsten divertor** – erosion and leakage
  - **Wall conditioning** – innovative/real time techniques
  - **SiC limiters/wall** – reduce carbon influx & PMI
    - *SiC an exciting potential reactor material*

DIII-D can help establish compatibility of core-wall solution





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New Reactor Current Drive Techniques Being Pioneered to Access New Regimes and Develop Reactor Solutions

- **Reactor Challenge**
  - **High efficiency** is key to net electric goal
  - **Reactor environment** – antenna survivability
  - **Effective coupling**

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- **DIII-D Approach**
  - **Innovative launch:** traveling wave, HFS, top
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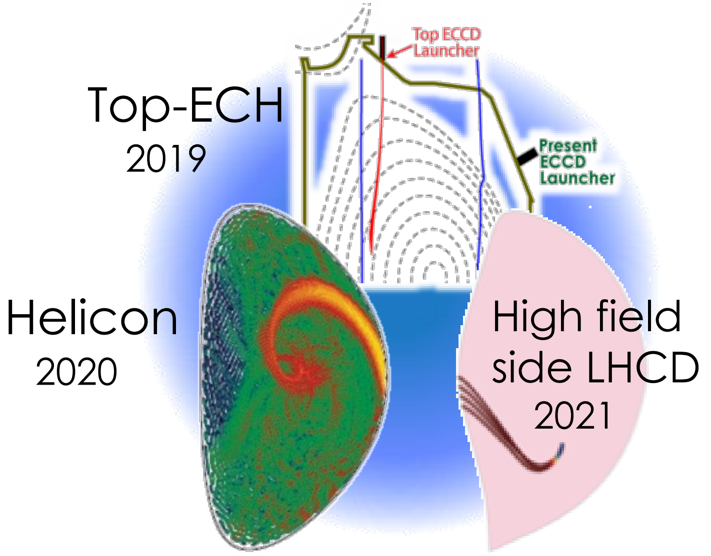

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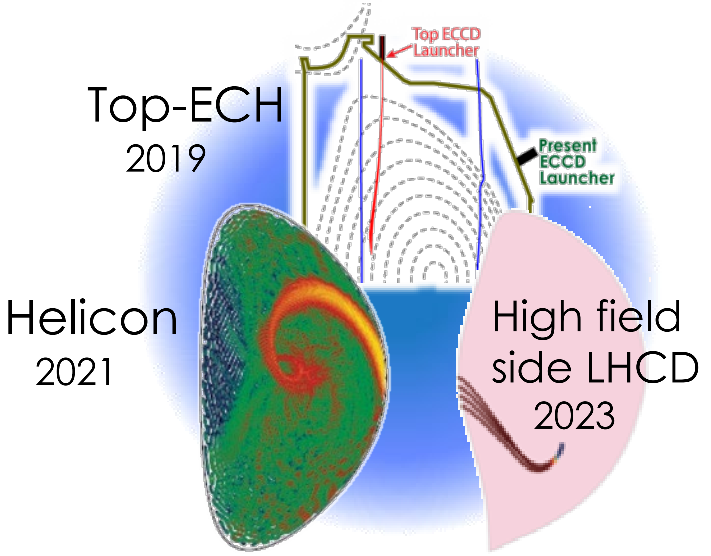
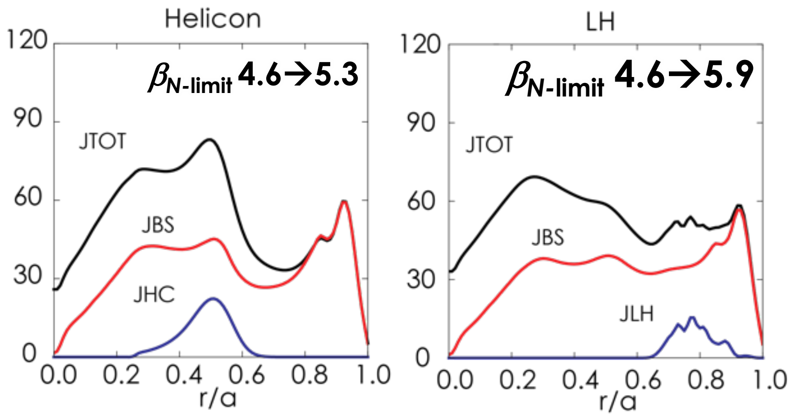
- **DIII-D Approach**
  - **Innovative launch:** traveling wave, HFS, top
  - **High density current drive:** helicon, LHCD, EC
- **Transforms Capabilities**
  - Steady states at high density & low rotation
  - Raises β_N limits
  - Viable schemes for a reactor



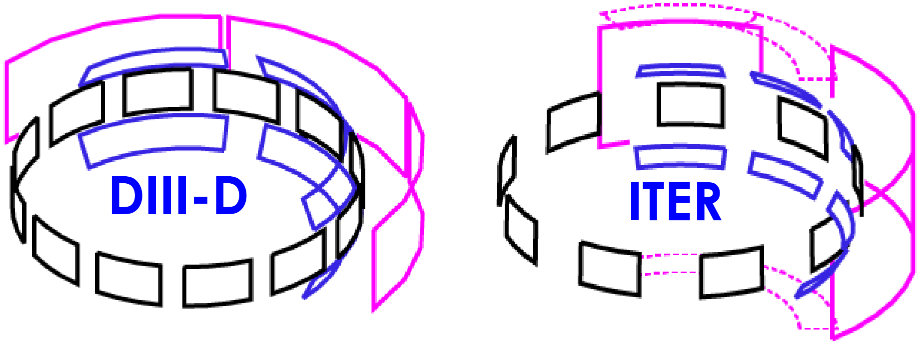


Modest investments at DIII-D can resolve critical questions for pilot

New Control Techniques Being Pioneered to Eliminate Transients Events in ITER and Beyond

- **Utilize 3D flexibility to resolve the 3D optimization of the tokamak to control transients**
  - Probe the physics and understand requirements for stability, rotation and ELM control

New ASIPP power supplies



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  - New pellet and runaway mitigation schemes

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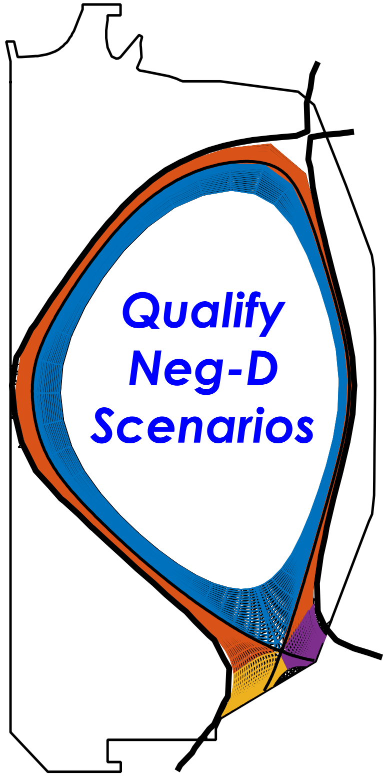
Low-Z Shell Pellet



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ASIPP

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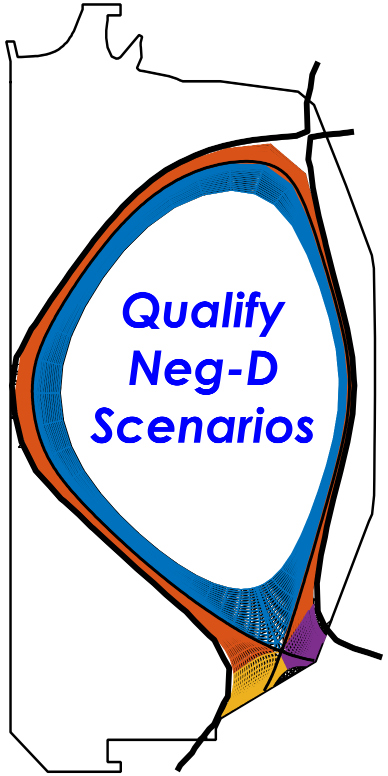
  - Probe the physics and understand requirements for stability, rotation and ELM control
- **Test novel solutions**
  - Edge-friendly negative triangularity scenarios
  - New pellet and runaway mitigation schemes
- **Disruption free protocol**
  - Combine ML, active sensing & real time control for robust avoidance & safe quenching
    - *In 40% of shots this year*

Flexible: try new things quickly
Powerful: qualify in relevant regimes

New ASIPP power supplies

Low-Z Shell Pellet



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ASIPP

Proposed Upgrades Combine to Address the Core-Edge Challenge

Higher shape & TF permit high P & n_e at low ν*

Closed divertor increases dissipation

Core ⟷ Pedestal —— Separatrix —— Divertor, $q_{||}$ ⟷ Wall

Low collisionality, $\nu^* \sim n^3/P^2$

n_{sep}

High n_{div} + *impurities*

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H&CD & transient control to reach relevant regimes

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Stable, high confinement, burning plasma relevant core

Compatible solution between core and edge

Discover & project divertor solution

Discover the solutions needed for ITER & Pilot Plant

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DIII-D Plans and Opportunities

- Research Needs
- Long Range Directions & DIII-D Mission
  - *What is the potential of the facility*
- Near Term Plans
  - *Opportunities to Engage*
- Conclusions

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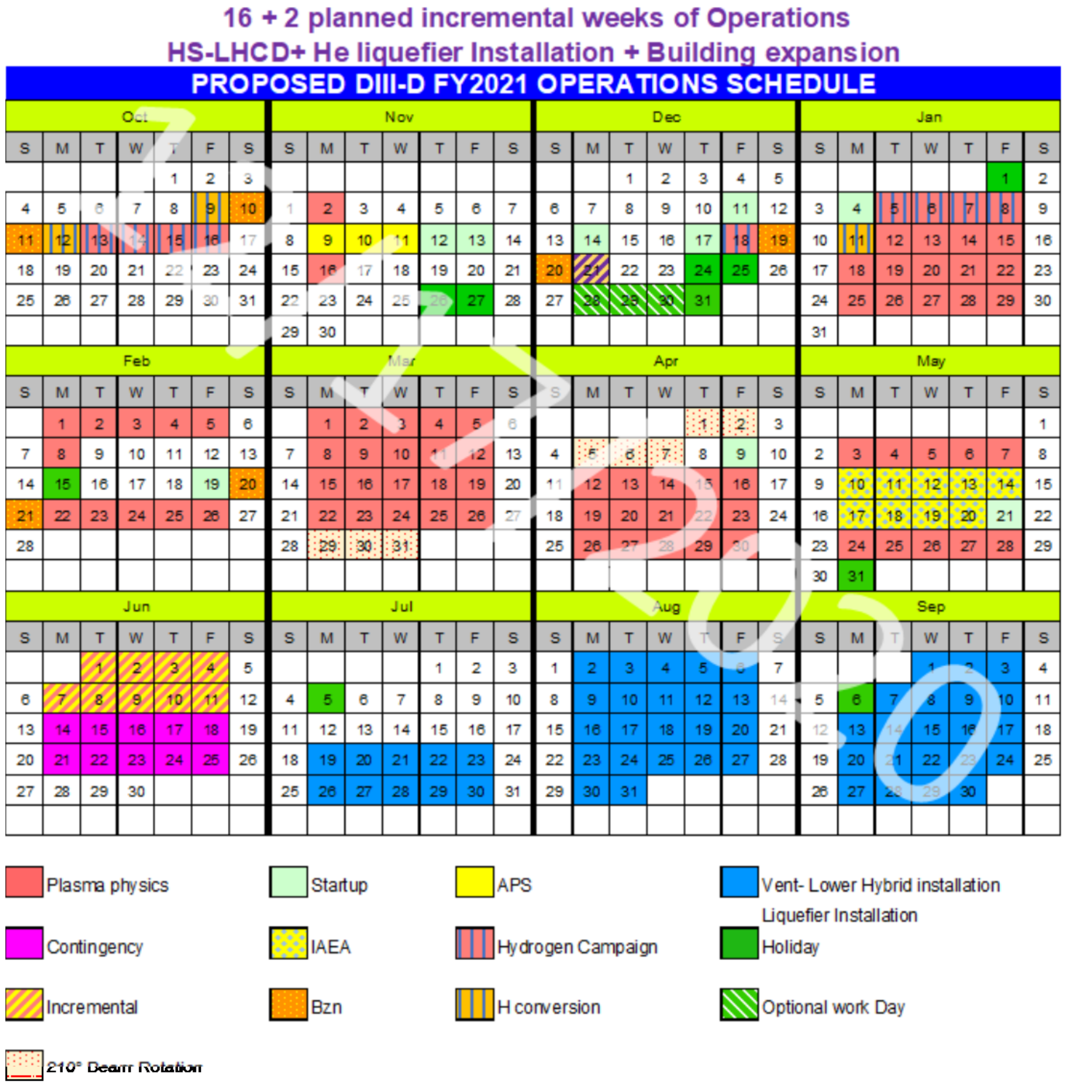
DIII-D FY21-22 Research Addresses High Priority Issues for ITER & Lays the Foundation for the Fusion Pilot Program



- **Key Priorities in 2021**
  - Hydrogen campaign for ITER
  - Disruption free protocol
  - Helicon Commissioning
  - Pedestal understanding, divertor optimization & core-edge integration
  - ITER scenarios & control
- **Upgrades in 2022-23**
  - Revised slot divertor with Tungsten
  - New helium liquefier
  - HFS LHCD
  - Negative triangularity armor
  - New 2D/3D power supply

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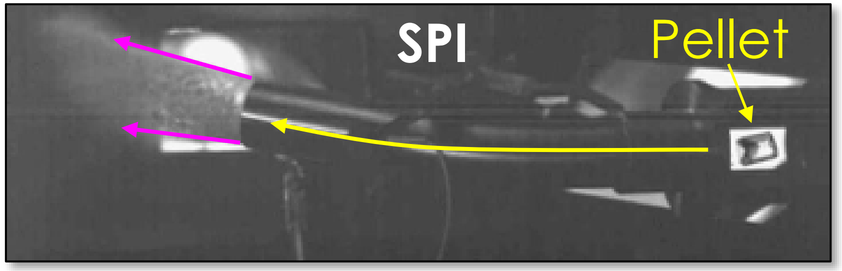
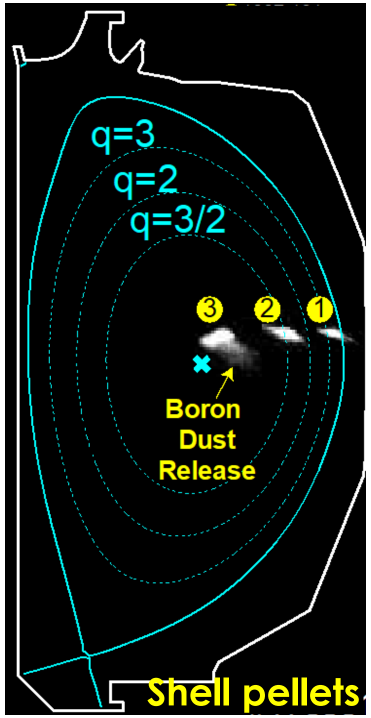
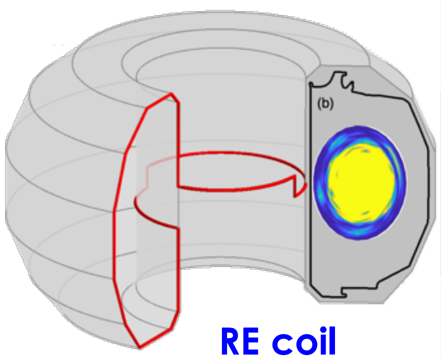
GENERAL ATOMICS

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

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

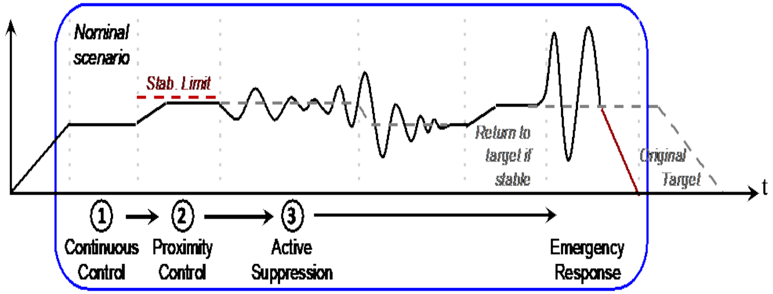




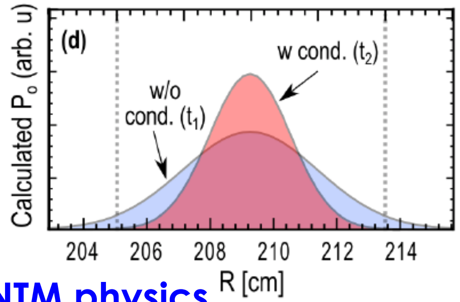


RE coil

Machine learning for disruption avoidance & detection



Disruption-free protocol

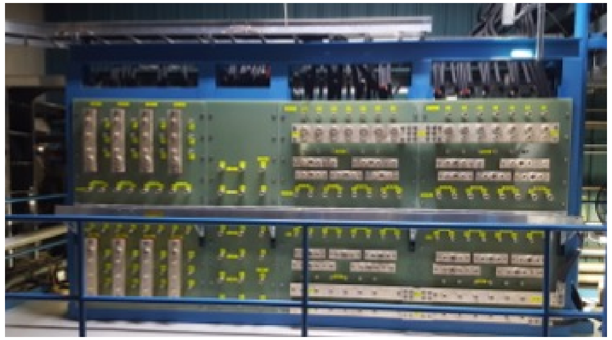


NTM physics

Second New Power Supply Through ASIPP Collaboration Significantly Enhances 3D Control and 2D Shaping

- **SSPA#1 commissioned and in routine use**
- **Supplies provide:**
  - Greater flexibility for 3D magnetic spectra
  - Improved 2D shaping capabilities for new divertor and ITER research
- **Procurement of 2nd supply underway – order placed for late FY21 installation**
- **Building expansion will be provided by GA**
- **Patch panel (expansion) by PPPL**

Power Supply #1 (FY17)



Patch Panel (FY16)

Major capability for transient and core-edge missions

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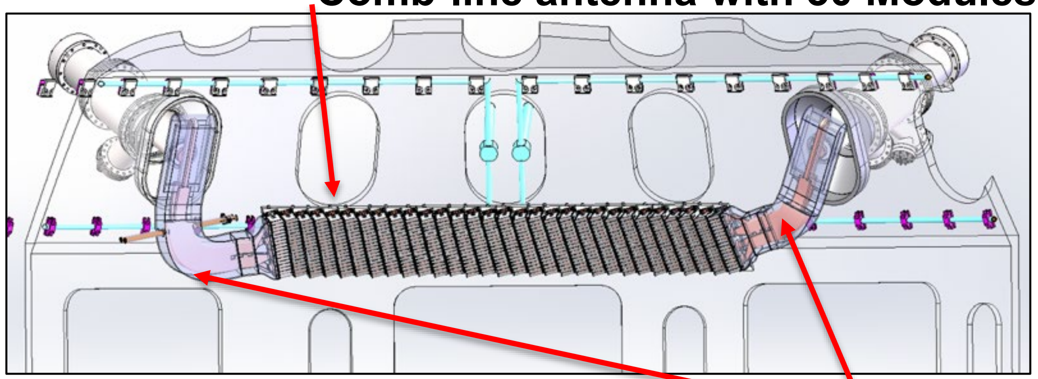
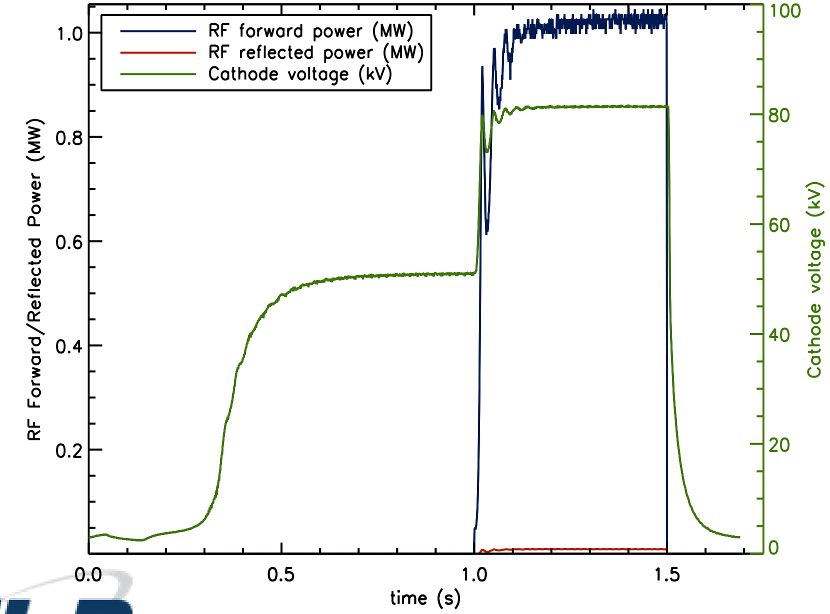
ASIPP

Helicon: 1 MW Higher Efficiency Off-Axis Current Drive
Currently being commissioned





- **Antenna installation completed**
- **Ex-vessel components installed with commissioning beginning in late 2020**
  - Klystron conditioned up to 1MW RF output power.
  - Antenna conditioning with hundreds of MW applied in progress
- **Strong coupling to plasma observed, >80% of power incident on first module**
  - Coupled power responds both to density changes during L-H/H-L transitions, and to changes in outer gap

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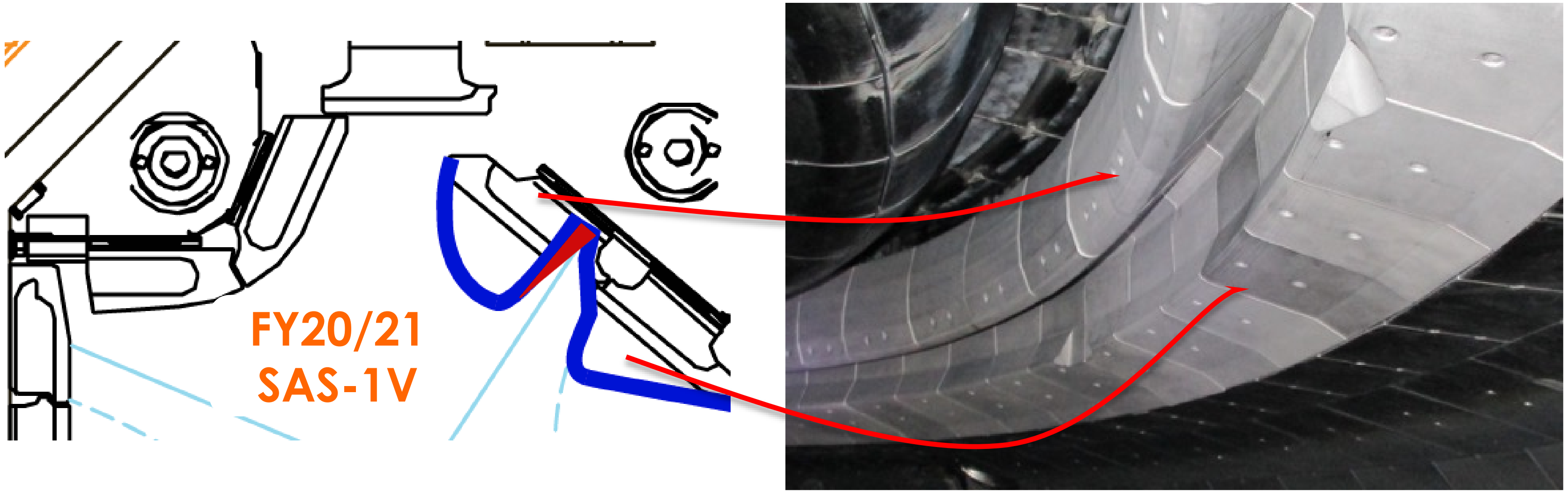
ASIPP

SAS-1V – A Small Change in Tile Profile Tests Prediction of Improved Divertor Closure

FY20	FY21

Design/Fab | Install | ◆

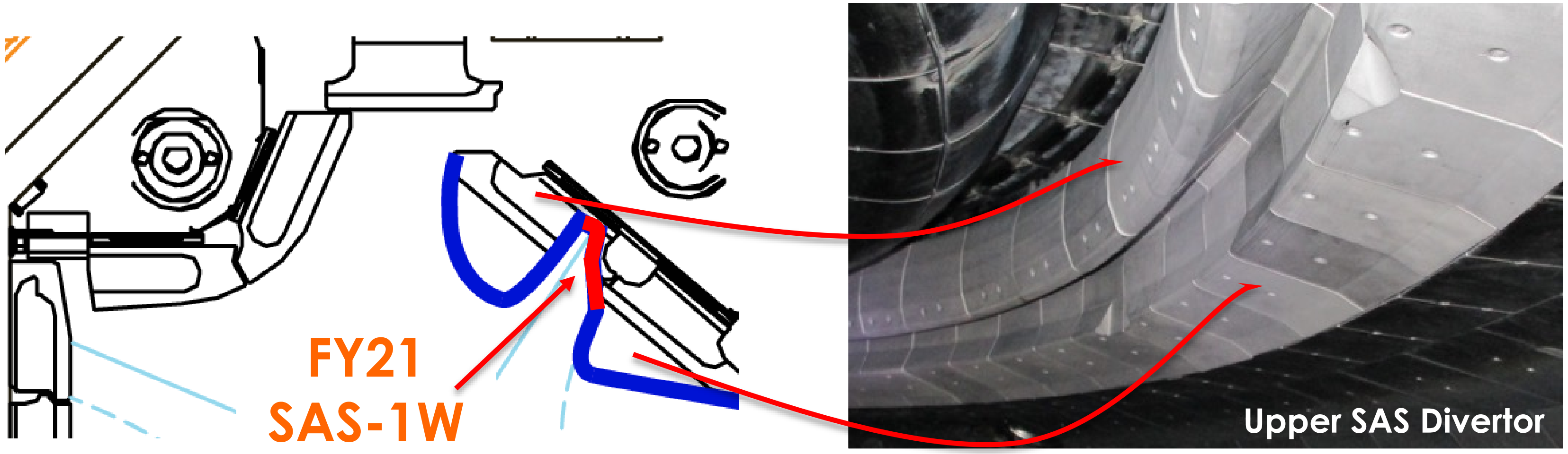


Upper SAS Divertor

- **SAS-1V – design in FY20; procure FY20/21; install FY21 vent with SAS-1W (tungsten)**
- **Diagnostic Enhancements (spectroscopy, density, temperature)**

Tungsten in SAS-1 Slot Will Enable Study of High-Z Leakage from a Closed Divertor

FY20	FY21
Design/Fab/Coat	Install ◆



- 1 row of Tungsten coated tiles will be installed in the FY21 vent.
- Tiles will remain in vessel for FY21/22 experimental campaign
- Experiment is compatible with proposed SAS-1V shape
- Diagnostic Enhancements (spectroscopy)

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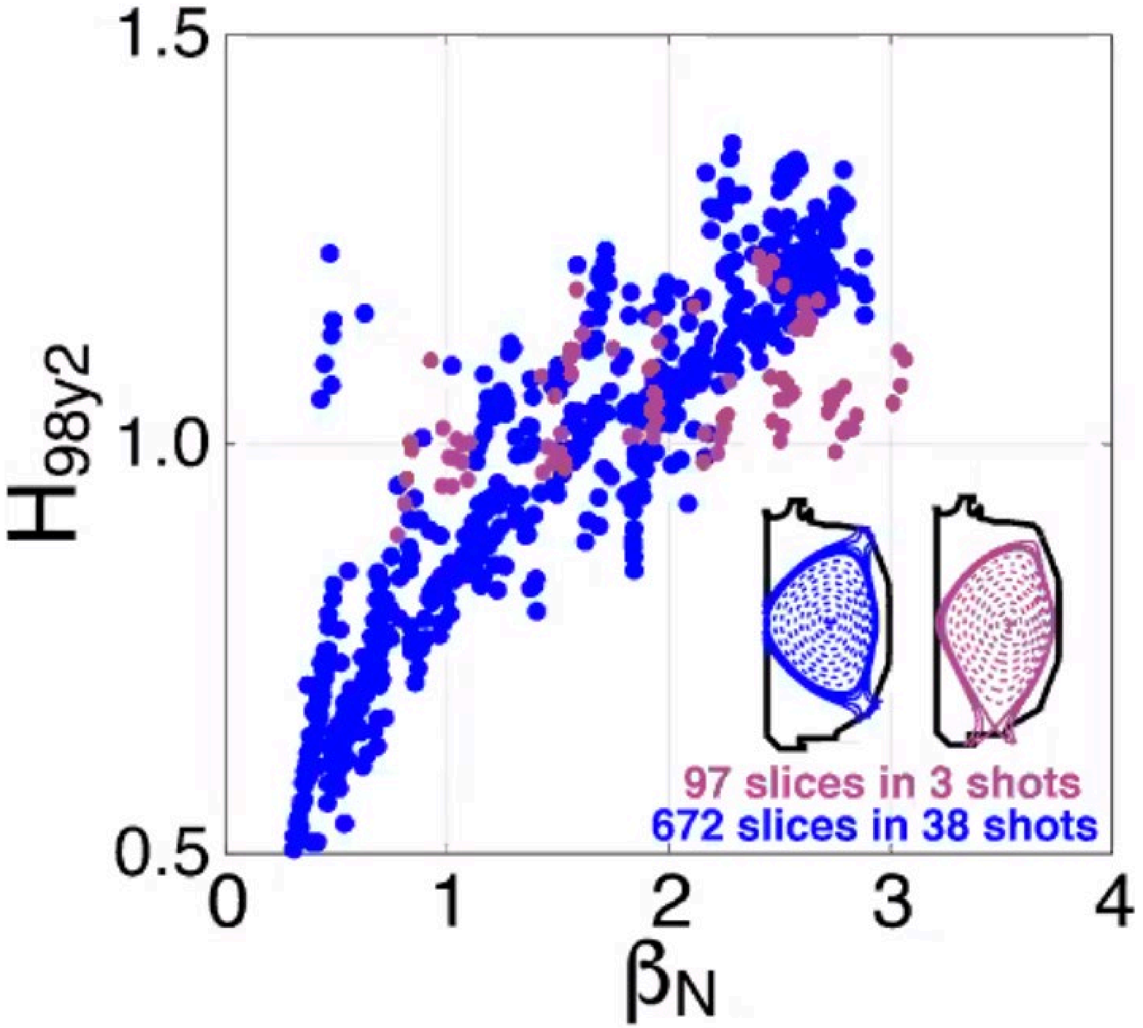
High Power, Diverted Negative Triangularity Discharges Show High Confinement, Significant β_N and ELM-free L-mode Edge



- **No ELMs L-mode edge with up to 5x P_{L-H}, high-confinement and up to β_N=3.0**
  - **Combination of shape-induced effects that weaken turbulent transport**
  - **Only got H-mode at less negative triangularity**
- **Promising candidate for core-edge integration**
  - **Robustly ELM-free with divertor at large R**
  - **Broad λ_q and low P_{Sep}**

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Negative Triangularity – Temporary Installation of Armor in FY22 Will Enable Strikepoint on Outer Wall and Protect Diagnostics

Negative Triangularity Armor

FY19	FY20	FY21	FY22	FY23

2 · 10 · 5 · 11 · 16+6 · 22

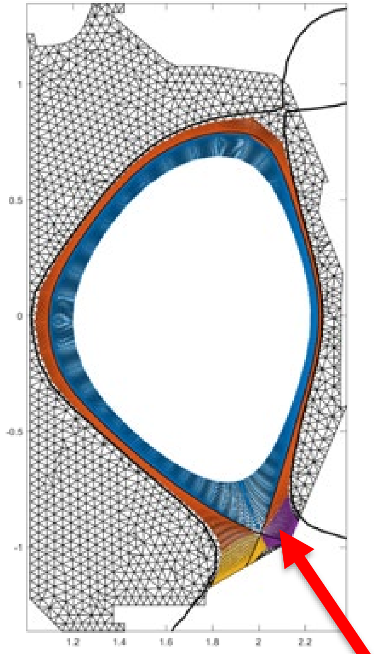
IR&D

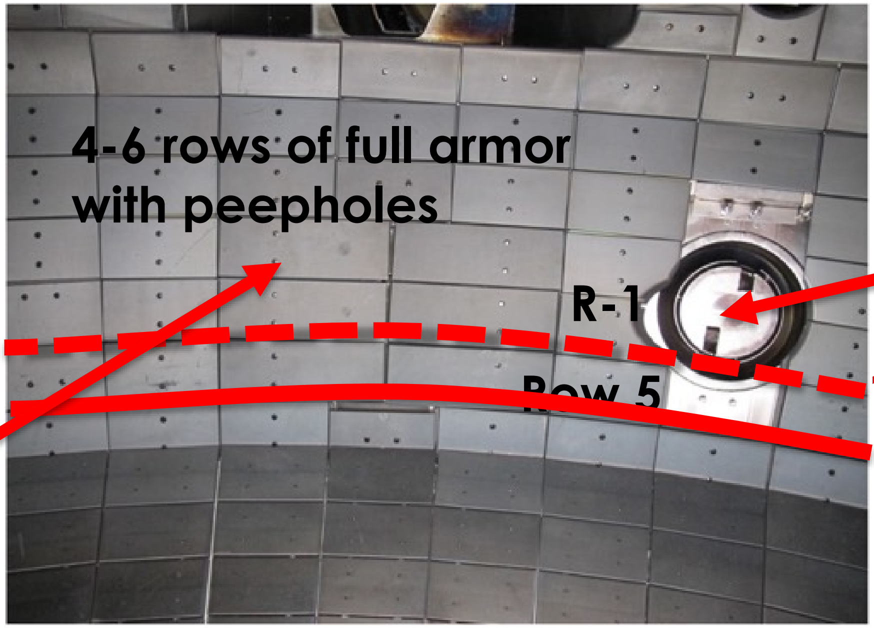
Design/Fab

Test fit prototype tile

Install in mini-vent

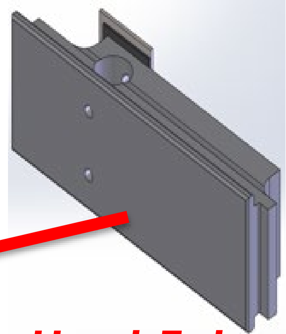
Mini-campaign





~ *Heat Extent*

Strikepoint



Cantilevered tiles protect diagnostic ports

Temporary carbon armor tiles

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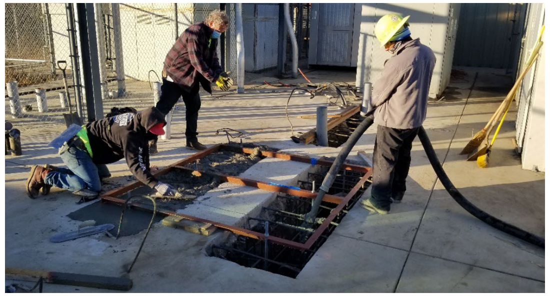
Assess viability of potentially transformational approach

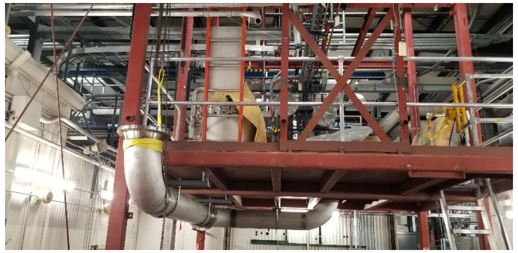
High Field Side Lower Hybrid Current Drive System in Preparation for Operation during FY23 Campaign

- **Ex-vessel installation in progress**
- **In-vessel components being prepared for installation in Summer 2022 vent**
  - New manufacturing techniques
  - Novel copper alloy, GRCop-84 to meet challenging disruption loads and thermal requirements
  - 3D printing, assembling and finishing techniques

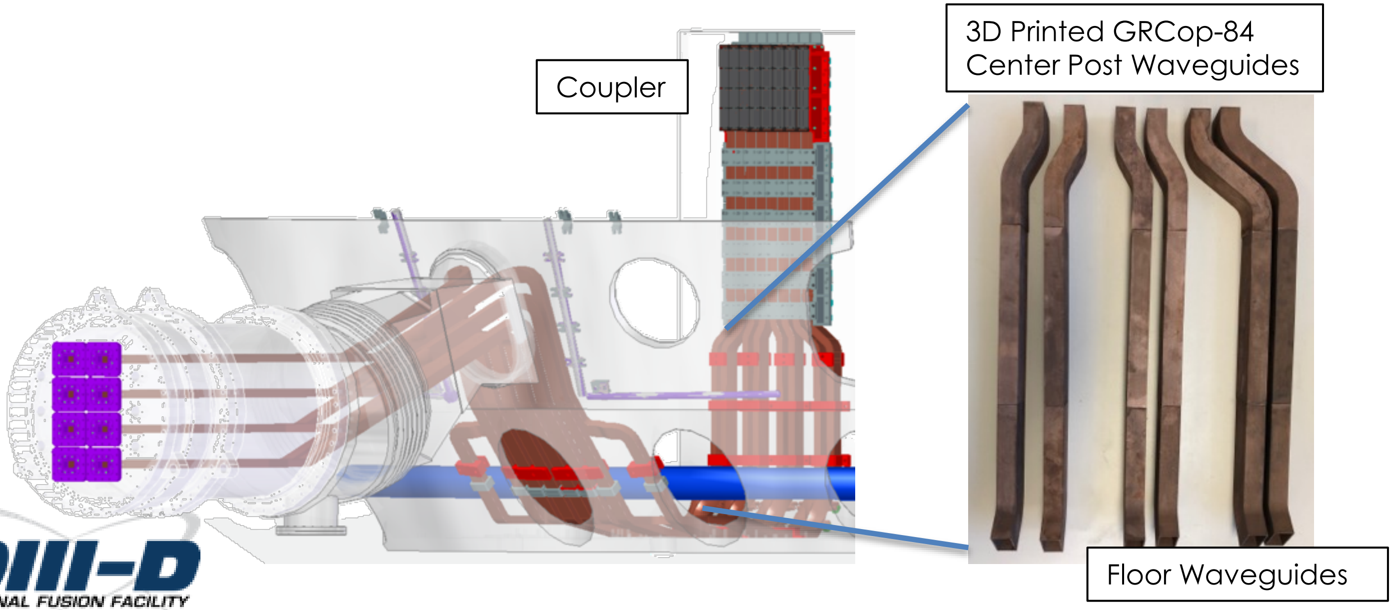


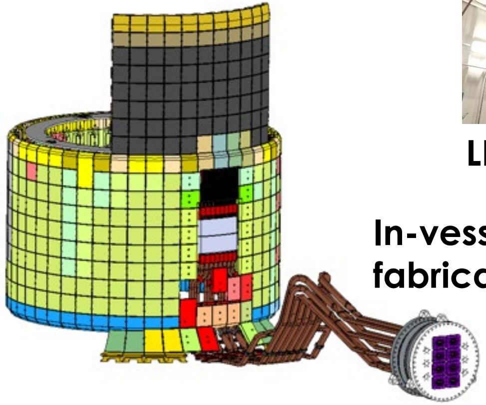
Boost Transformer foundation

HV Deck Installation



LHV water system Installation





In-vessel designs complete, fabrication in progress

Principle Near Term Foci at DIII-D Continue to Prioritize Joint US-PRC Interests

- **Key physics priorities**
  - Pioneer physics basis and techniques for integrated core-edge solutions
  - Resolution of transient control (disruptions and ELMs)
  - High performance fusion core
  - Innovative heating and current drive
  - Develop assess and project power handling solutions
- **Key partnerships**
  - Joint EAST-DIII-D Task Force remains a top priority management level initiative
    - *Collaborative experiments with EAST & DIII-D complement each other*
    - *New opportunities with HL-2M would be welcomed*
  - Development on new hardware & physics approaches (3D, helicon, …)
  - Focus on design and requirements of new facilities in US and China

Our continued partnership provides great opportunities to advance our research programs in the US and PRC

Strong and Effective, Appreciated Partnership Between DIII-D & PRC

- **Deep meaningful engagement on most important issues of fusion energy**
- **True partnership as equals with leadership opportunities on both sides**
  - Unique capabilities in each partner which inform each others path
  - Shared project leads, invited talks, papers
- **Leading to major advances that inform our path**
  - Reactor scenarios, transient control, current drive core-edge integration

Our continued partnership provides great opportunities to advance our research programs in the US and PRC

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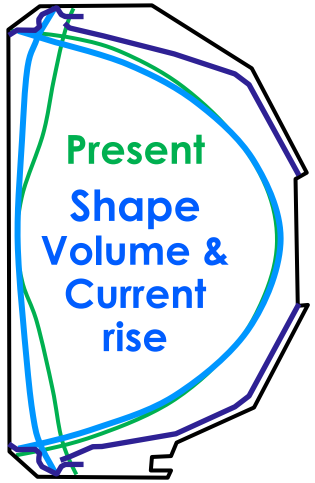
GENERAL ATOMICS

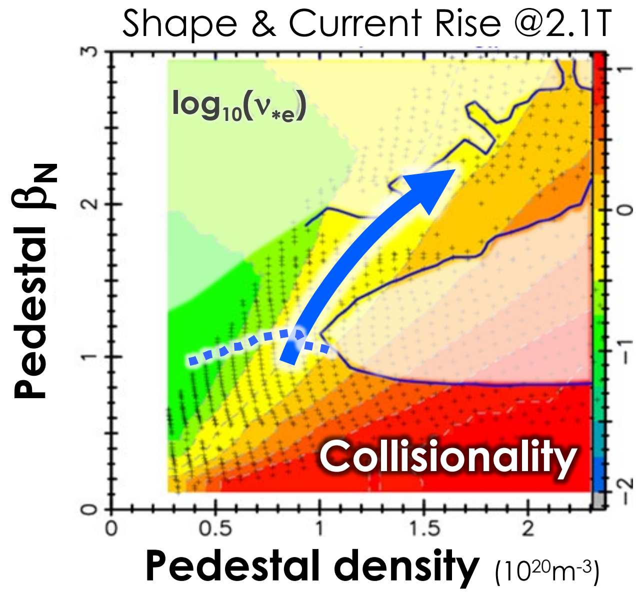
BONUS MATERIAL

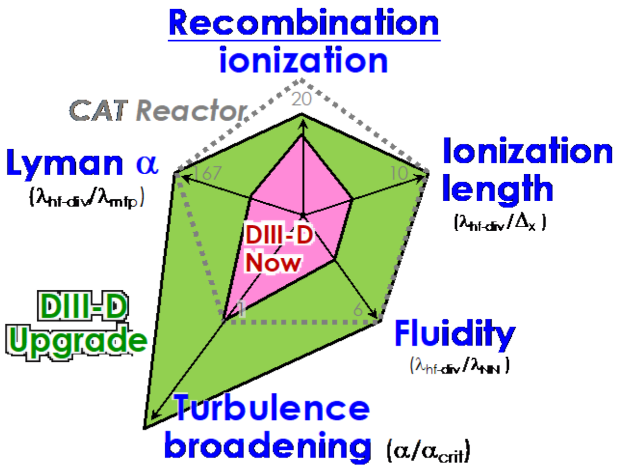
Longer Range, we are Exploring Options to Close Gaps on the Fusion Pilot Plant

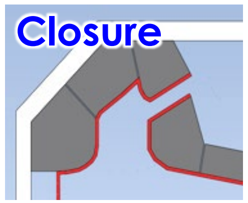
- **Path identified to reactor physics regimes**
  - **Increase shaping**, **field** & **current drive** to raise energy and density
  - **Closed divertor for power handling** to raise local density and radiate heat
  - **New wall materials** to reduce impurities & test compatibility of reactor solutions

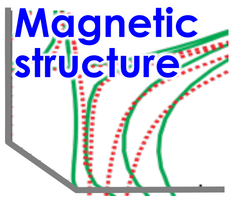
➔Reactor-relevant core & edge simultaneously
  - Raises pressure & density in steady states
  - Find techniques and technologies that work











Flexibility & relevance to find core to edge physics solutions & project to reactor

Recent and Planned Facility Enhancements Strengthen Core and Boundary/PMI Research

	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	$T \longrightarrow 2\ |_R$; 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 xport
	W inserts & PFCs tests	Understand sources and develop mitigation techniques

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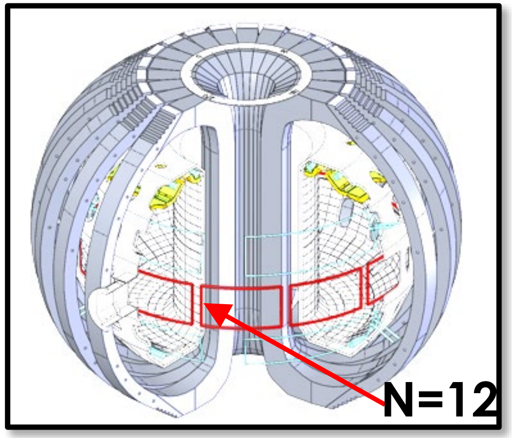
DIII-D Developing Scientific and Technical Basis for Robust ELM-Control Solutions for ITER and Steady-state Reactors

DIII-D Strengths and Capabilities Include

- Broad set of actuators
- Wide range in pedestal collisionality
- Comprehensive diagnostic set
- Close connection to theory

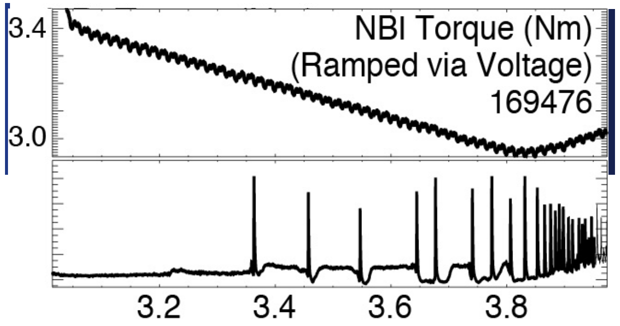
- **Expand operating space for ELM-free regimes, *including negative triangularity***
- **New M-coils (FY23) and second PS will provide more spectral flexibility and better match to ITER**
  - ***Explore Quasi-symmetric optimizations – possible collaboration opportunity with stellarator community***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

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

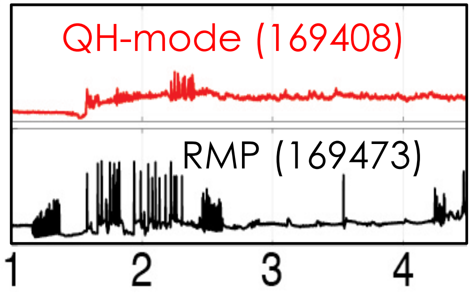


MTC test winding

Rotation Control

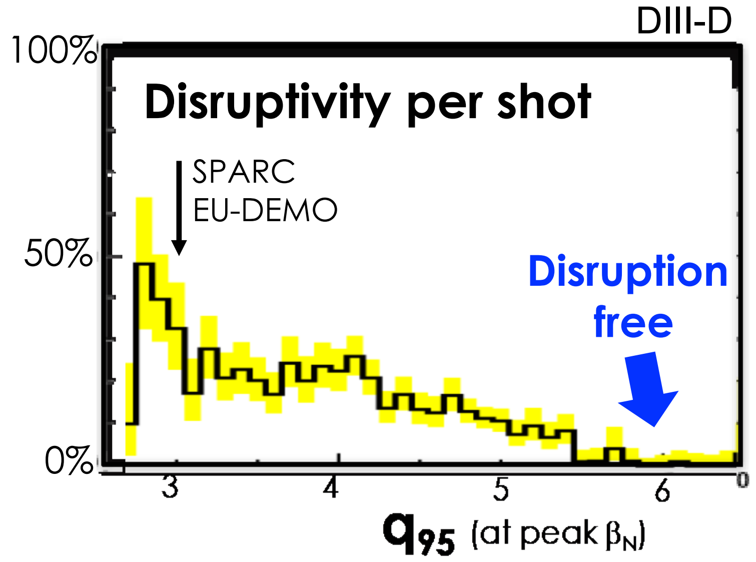


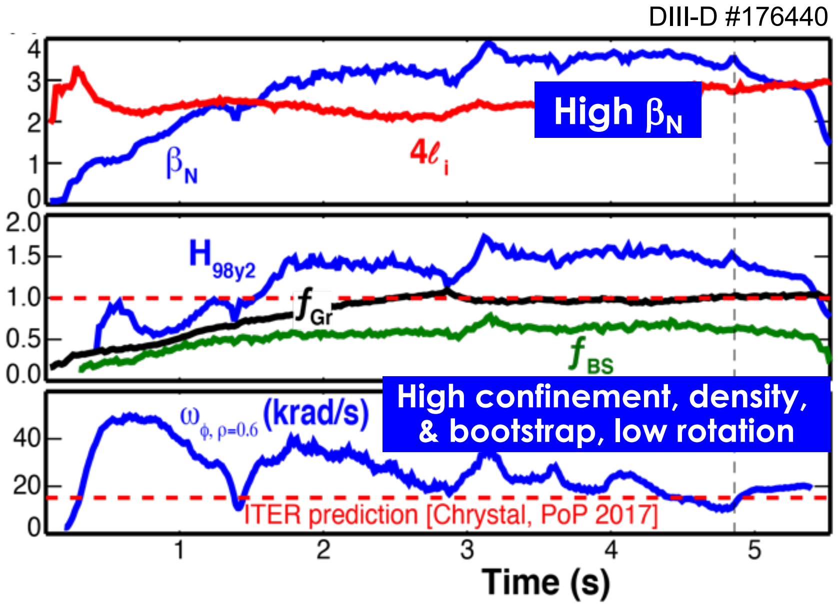
ELM-free Regimes



Steady State Path is Easier than the Pulsed Tokamak

- **Current is the key challenge for the tokamak**
  - β~few % – most energy in electromagnetic channel
  - Drives narrow heat flux width challenging divertor
- **Advanced tokamak improves stability & transport**
  - High shaping, high beta, broad current profiles
  - Permits high safety factor / low current approach
    - *Attributes demonstrated in world's tokamaks*
- **Meets key requirements of pilot plant**
  - Eliminates disruptions
  - Achieves high confinement – *key for compactness*
  - Enables stationery solutions, without cycling to reduce stresses & required size





Reduces cost, size risk, raises performance

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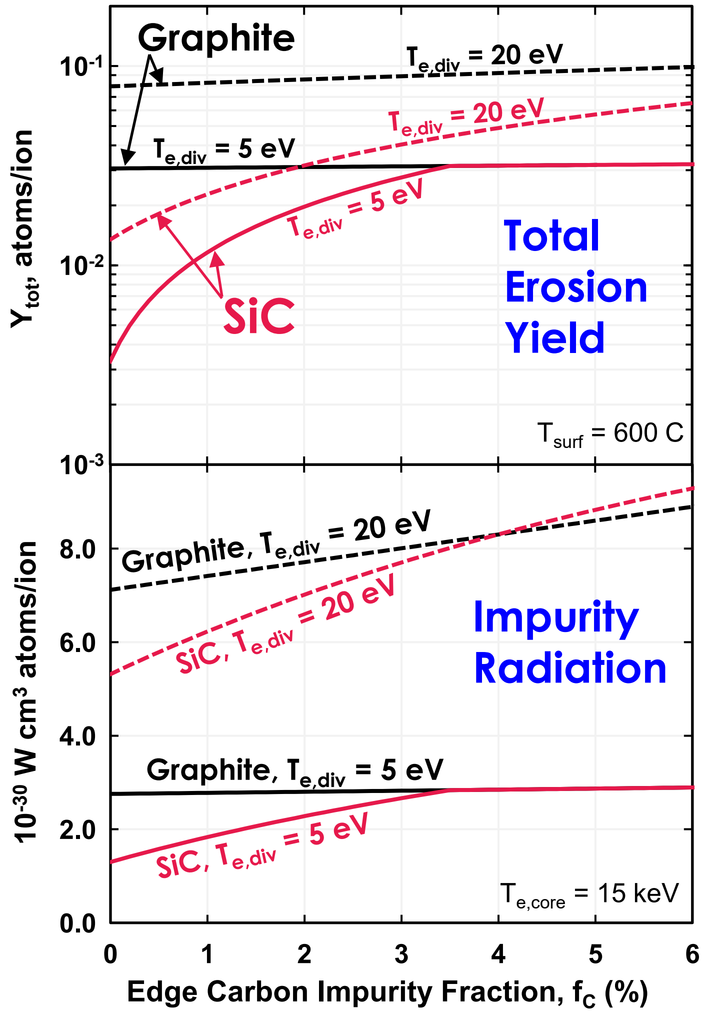
Silicon Carbide PFCs may enable reduction of C impurity content and increase of core performance

- **SiC PFCs decrease impurity sourcing relative to graphite**
  - Total erosion yield decreased by order of magnitude at low C impurity fraction
  - More pronounced decrease for detached conditions (low $T_{e,div}$)
  - Effect mostly due to low chemical sputtering yield of SiC
- **SiC may substantially decrease core radiation relative to graphite**
  - Factor of 2 decrease in Prad at low T_e and low C impurity fraction
- **SiC could represent significant benefit for DIII-D by enabling a more reactor-relevant impurity mix**

Predicted Impurity Source & Radiated Power, Graphite vs. Silicon Carbide



Abrams NF 2020, internal review

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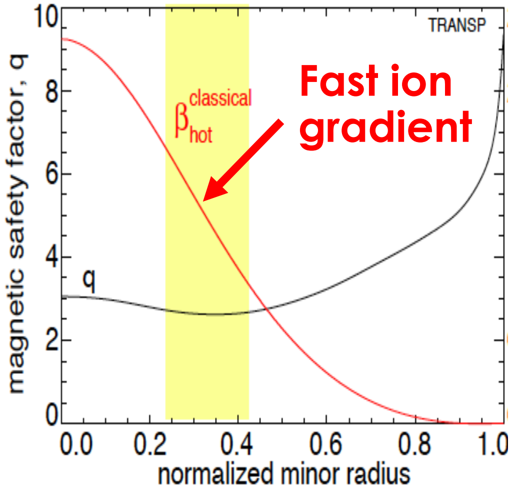
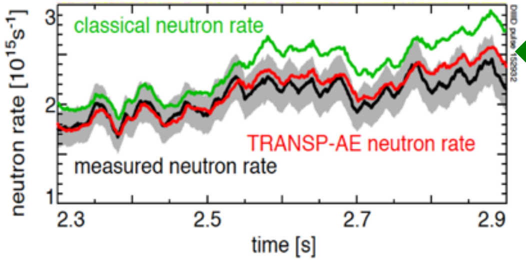
Broad Current Profile Ensures Fusion Products Stay Confined

- **Potential for Alfvénic resonances in weak magnetic shear regions**
  - Overlapping modes lead to transport

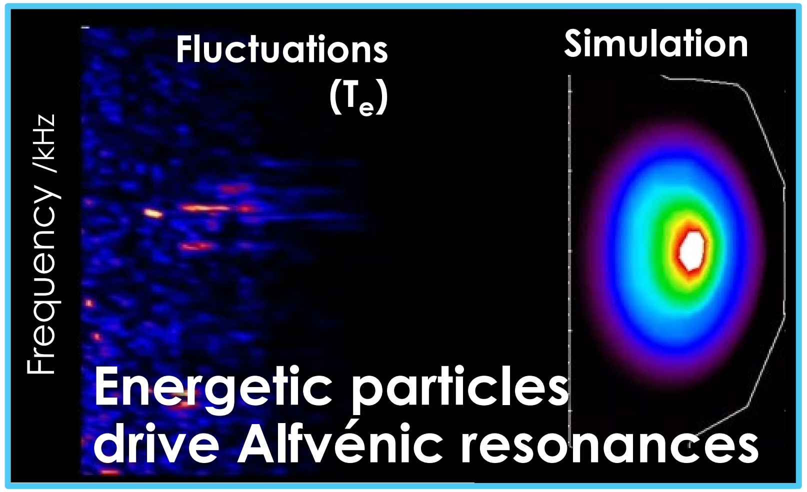
Weak shear



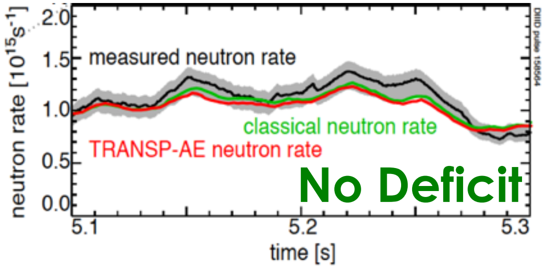
Neutron rate

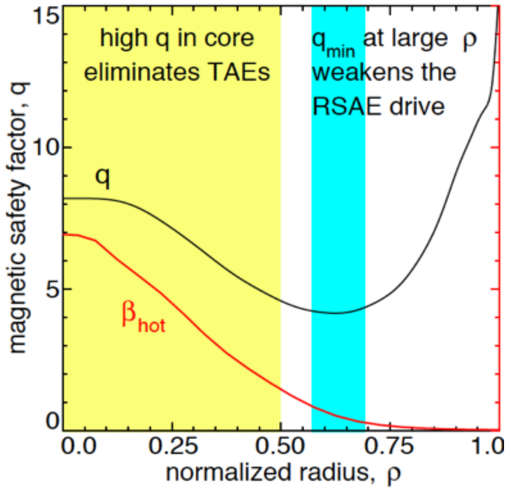


Deficit



- **Broaden current profile**
  - ***Moves weak shear out →***





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[Kramer 2018]

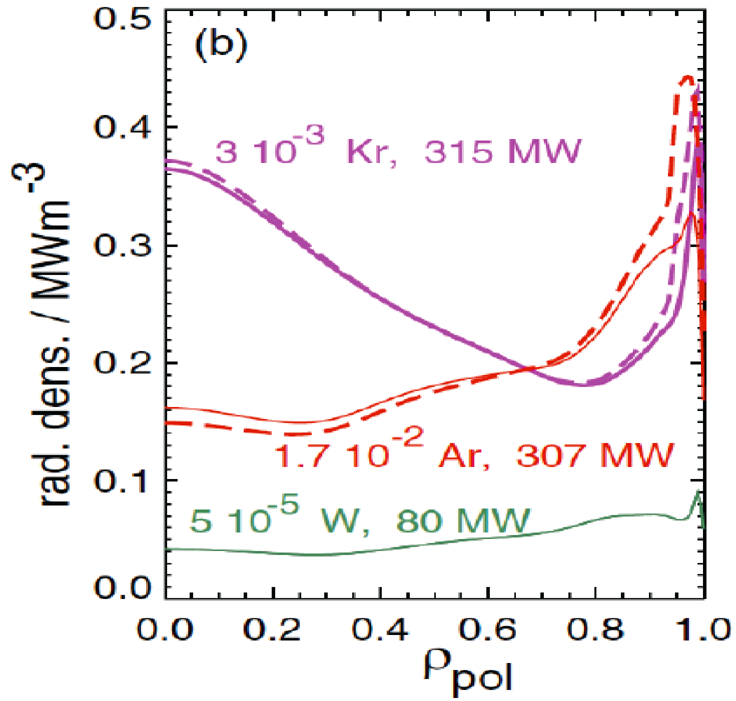
Fuel dilution due to core radiation remains a challenge for all DEMO concepts

- **As core impurity fraction is increased, higher Z_{eff} drives down fuel ion fraction**

$$f_i = 1 - 2f_{He} - Z_{imp}f_{imp}, \qquad P_{fus} \propto f_i^2 n^2 T^2 V_p$$

  - even a small change in f_i dramatically reduces fusion power

- **Kallenbach et. al. have predicted impurity profiles for a R = 9m, a = 2.25m DEMO**
  - scaling to C-AT DEMO parameters results in a 60% reduction in fusion power, 2x more than the 33% assumed in this study
  - $f_{Kr} = 1\times10^{-2}$ needed for 172 MW of core radiation
- **a radiative model is needed in GASC to ensure self-consistancy**

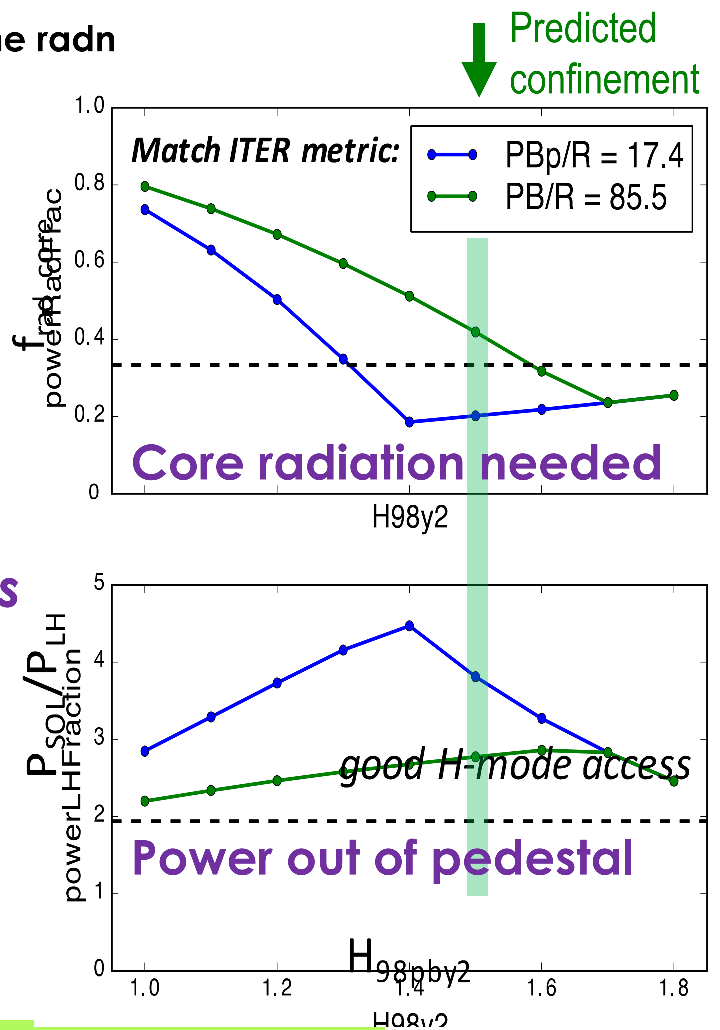


Kallenbach *et al* 2013 PPCF **55**

Power Handling Challenge Benefits from Advanced Tokamak Approach with Low Recirculating Power

- **Power escaping plasma: $P_{Separatrix} = P_{alpha\ heat} + P_{H\&CD} - P_{brems/synch/line\ radn}$**
  - Goes into layer, $\lambda_q = 1.35 B_\theta^{-0.92} \varepsilon^{0.42} P_{SOL}^{-0.02} R_0^{0.04}$, which is $\propto\ 1 / B_\theta$
  - Leads to poloidal heat flux $\mathbf{q_\theta \sim P_{SOL}\ B_\theta\ /\ N\ R}$
- **Map power to flux along field line** (B_θ / B_T): $\mathbf{q_{\|} \sim P_{SOL}\ B_T\ /\ N\ R}$
  - If power dissipates on tiles, key challenge metric is $\mathbf{q_{\|}}$
  - If power must be radiated, then connection length plays role $(B_T / B_\theta)^X$ introducing $B_\theta{}^X$ again: $\mathbf{q_\theta{}^X q_{\|}{}^{(1\text{-}X)}}$
    - ➢ ***Bracket problem with $q_{\|}$ and q_θ ←divertor challenge metrics***
- **Increase core radiation to reduce divertor challenge metric**
  - Match ITER $\mathbf{q_{\|}}$ with 50% radiation
  - Match ITER $\mathbf{q_\theta}$ with 20% radiation

  } **Both maintain good pedestal with pedestal power flux, P_{SOL}**
- **But steady state reactor may need to go further**



Low recycling power & double divertor alleviates heat flux challenge

η_{th}=0.4, n_{ped}/n_{GW}~1, 7T

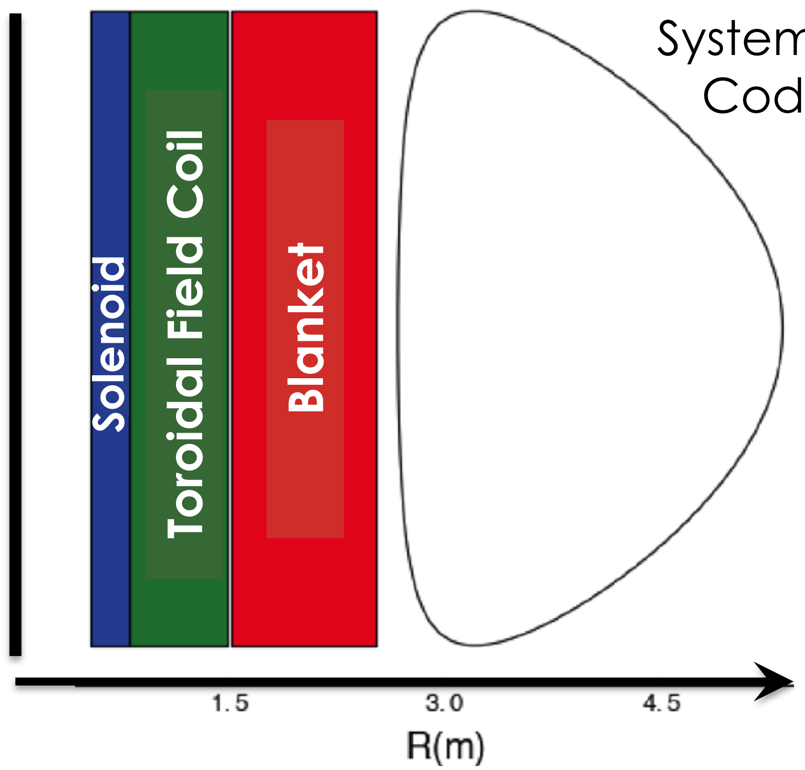
Structure Appears Viable Though Requires Advanced Approach for Stress Handling

- **Requires advanced bucking approach to deal with forces (like ARC)**
  - 'Buck' toroidal field coil forces off solenoid & central plug to cancel out stress by >50%

- **Project 4m leaves sufficient space for breeding, shielding, toroidal field coil & solenoid**

Still challenging engineering requiring research

GA Systems Code



[*Stambaugh FST 2011]

Higher Field High T_C Superconductors Offer Advantages for Maintenance & Testing Program

- **High Temperature Superconductors potentially enable demountability**
  - Enables wall to be rapidly changed for nuclear science mission

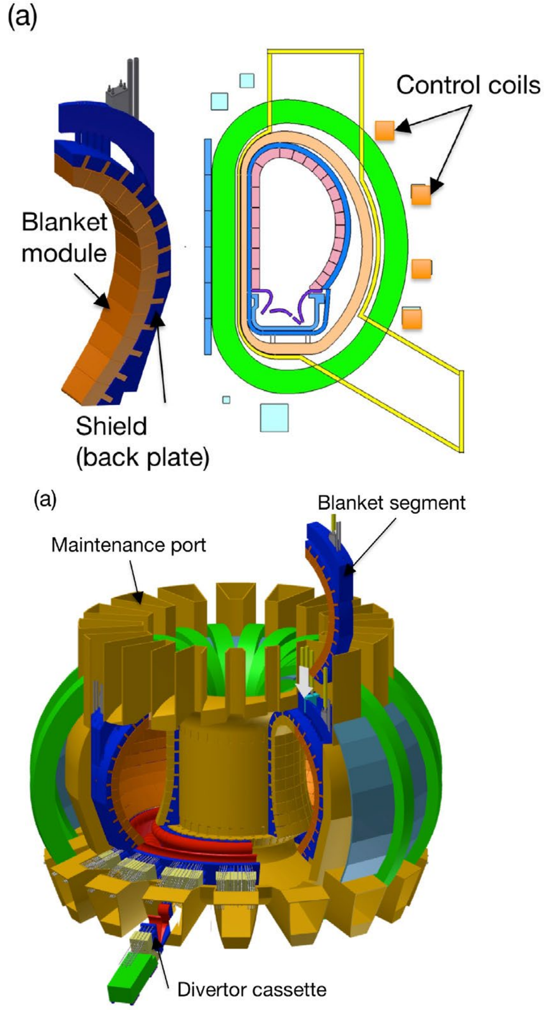
- **Propose staged approach:**
  - Net electric demonstration

    then

  - Long pulse for materials & breeding tests

HTS enables facility to combine net electric and nuclear science mission

EXAMPLE: Vertical change out scheme in Japanese SN design (C-AT is DN)



[Utoh, Fus. Eng. Des. 2017]