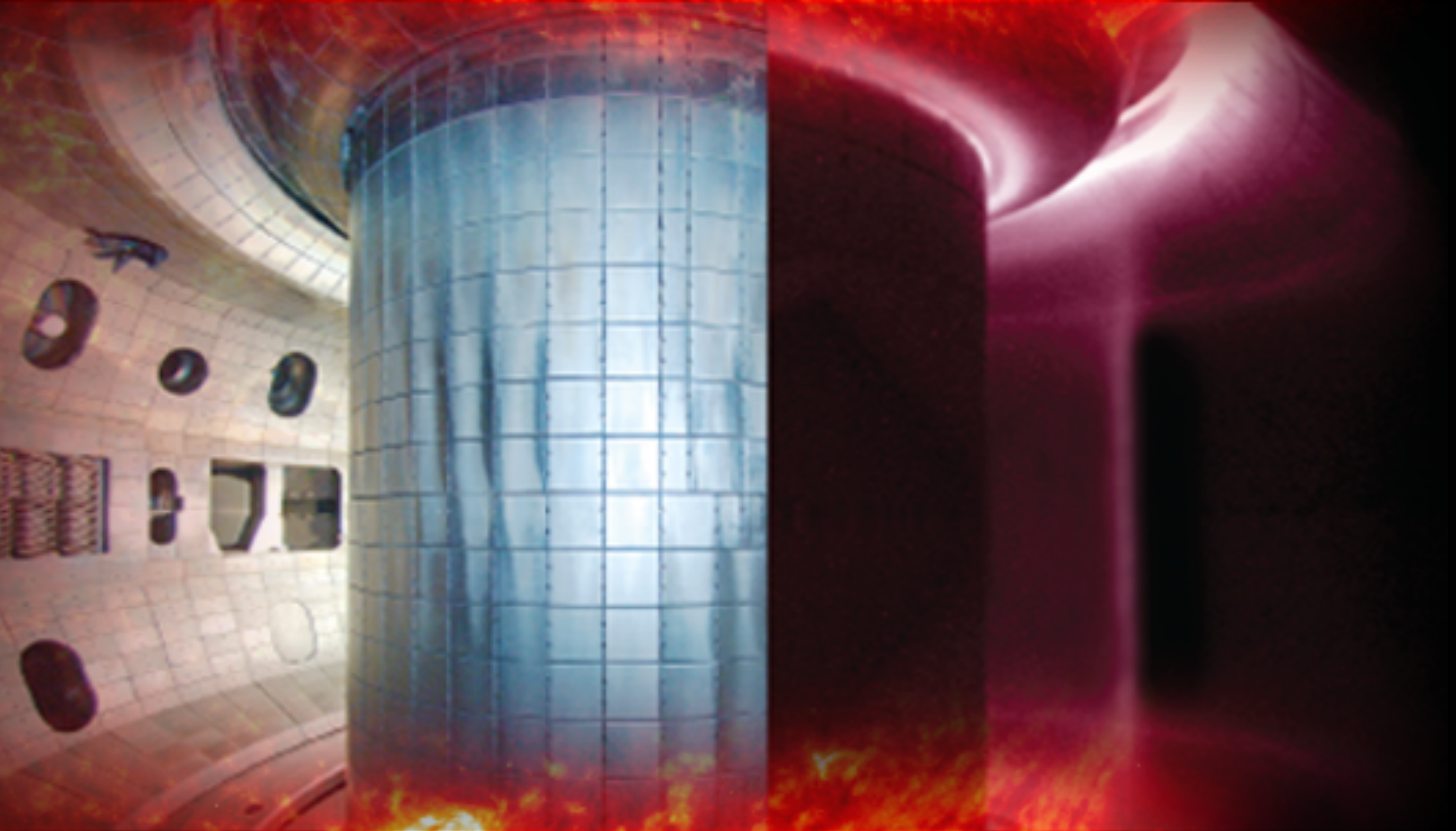
A Mission to Discover the Plasma Solutions for Future Fusion Reactors



presented by

RJ Buttery

with thanks to the DIII-D team

for the

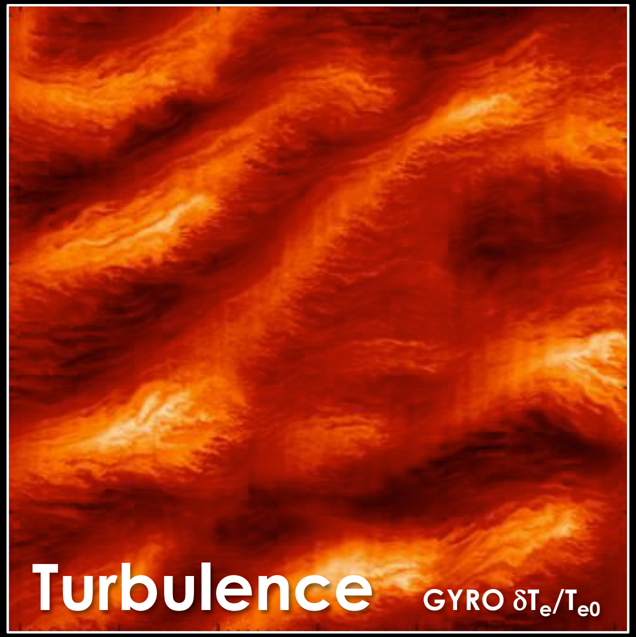
National Academies Committee for a Strategic Plan for U.S. Burning Plasma Research

Feb 26th 2018

GENERAL ATOMICS

DIII-D NATIONAL FUSION FACILITY

Fusion Reactors Encounter New Physics Challenges



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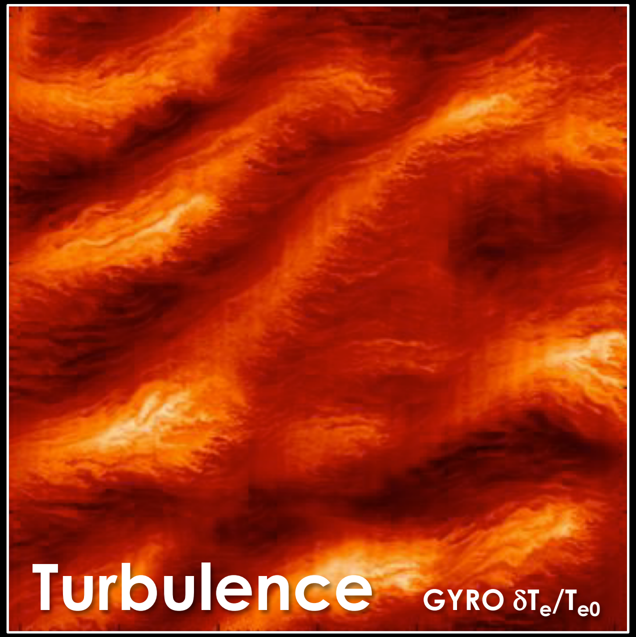

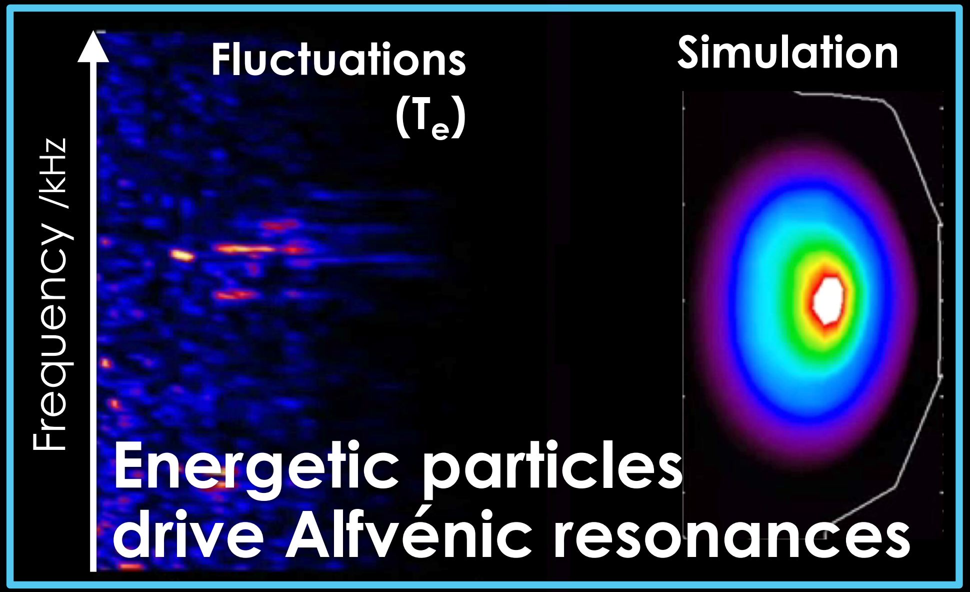

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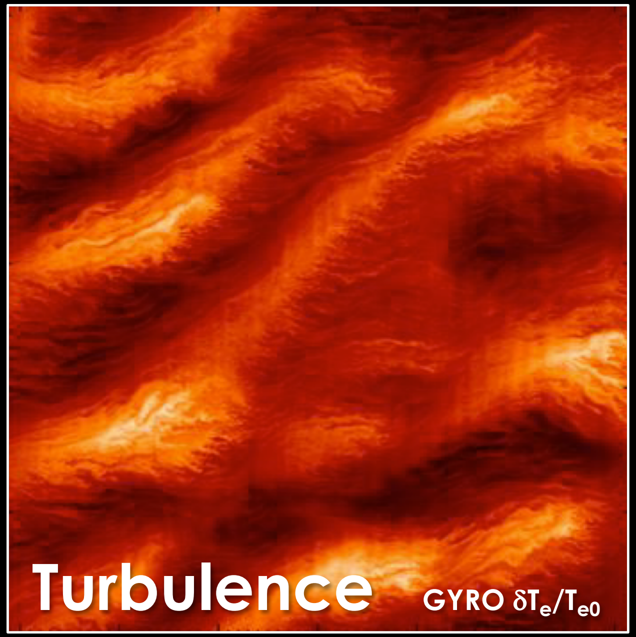

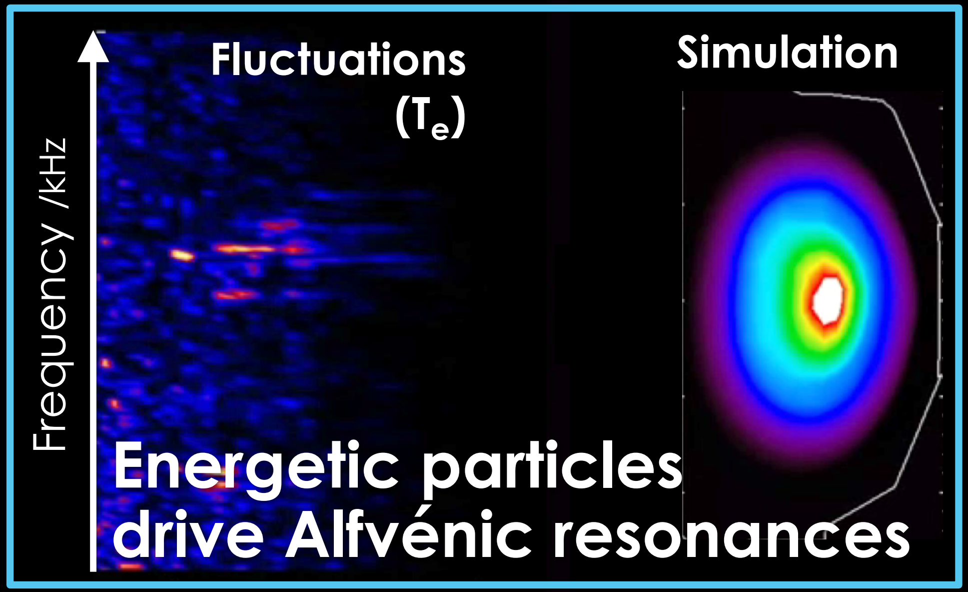

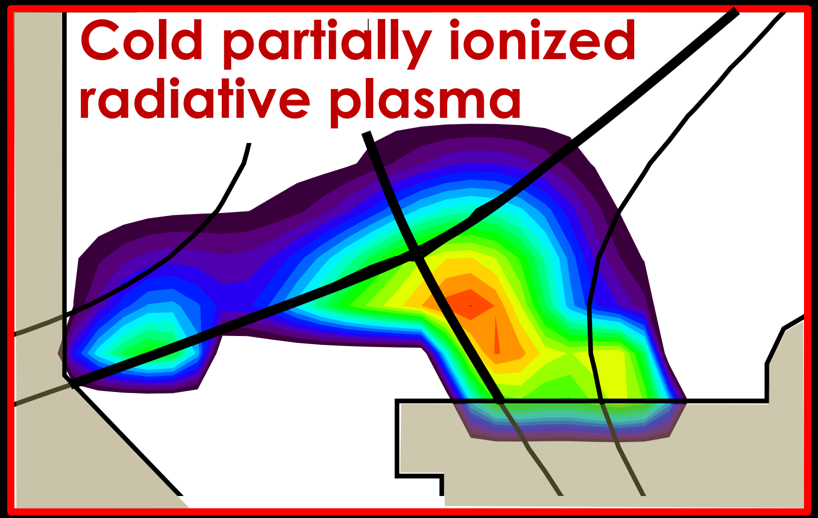

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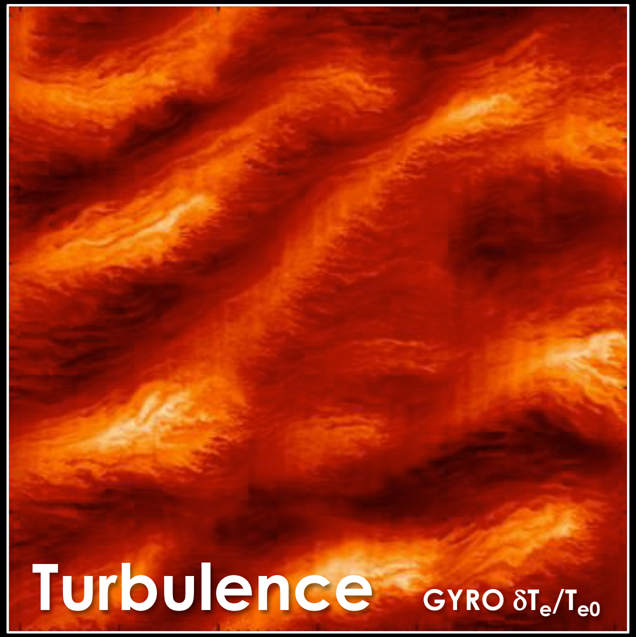
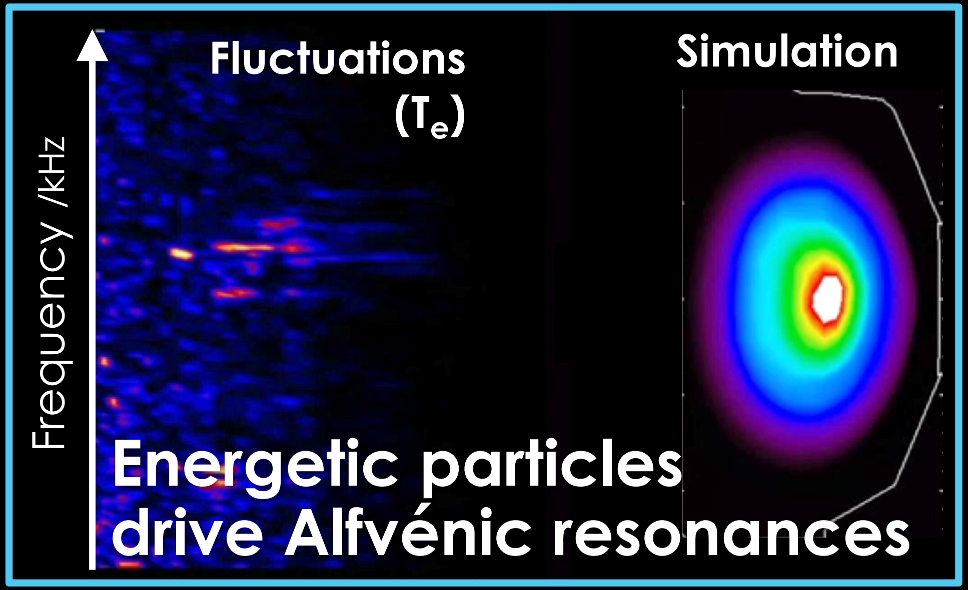
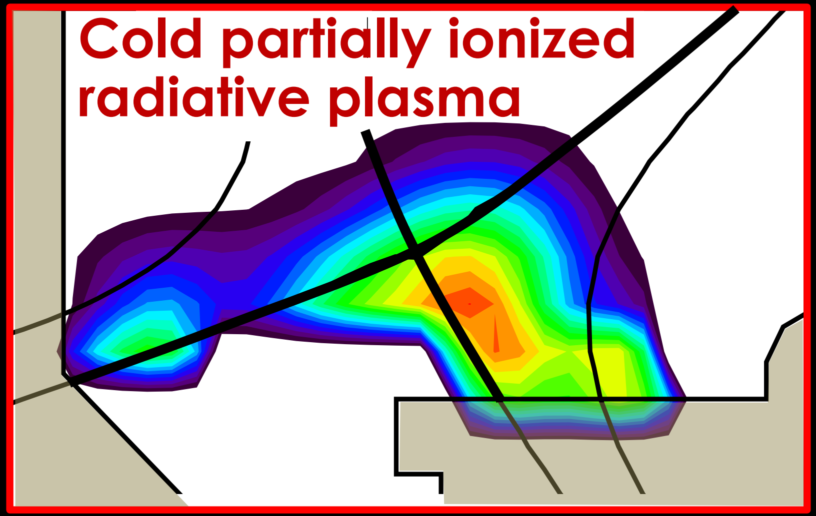


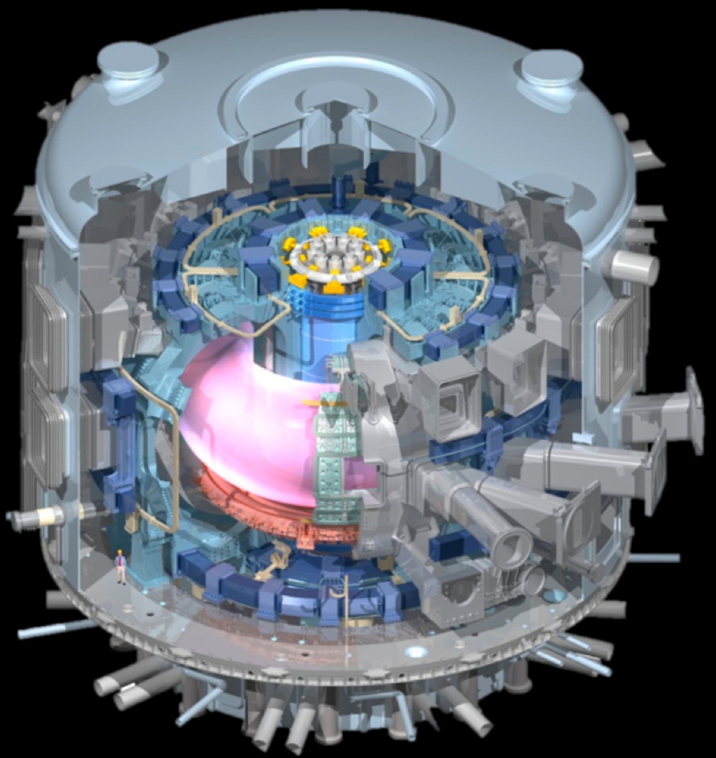




US Strength

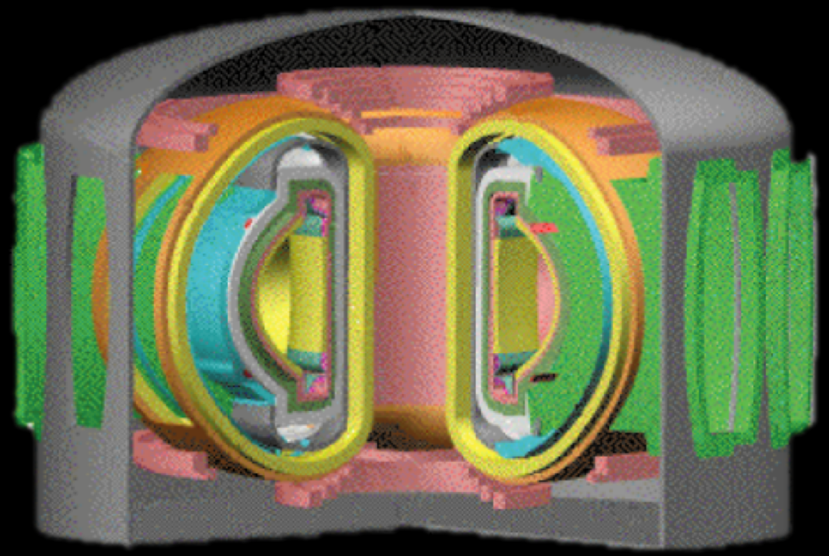
Science → Solutions

U.S. Missions in Fusion Energy



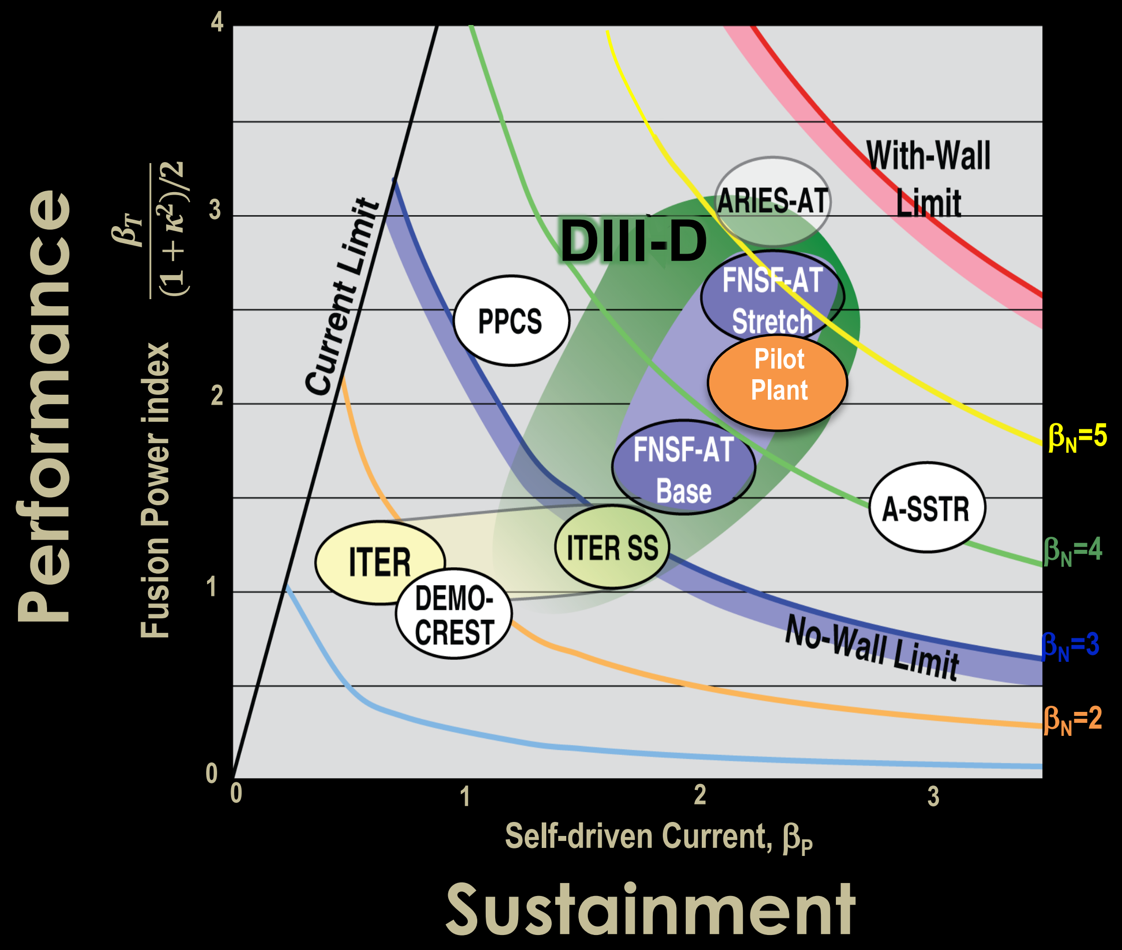
- **Make ITER better**
  - U.S. learning from ITER

- **Path to a steady state reactor**
  - U.S. should have a path
  - Establish physics & technical basis



Our Vision is to Transform DIII-D to Meet the Unique Challenges of Burning Plasma Regimes

Address in D-D so that we can proceed with D-T

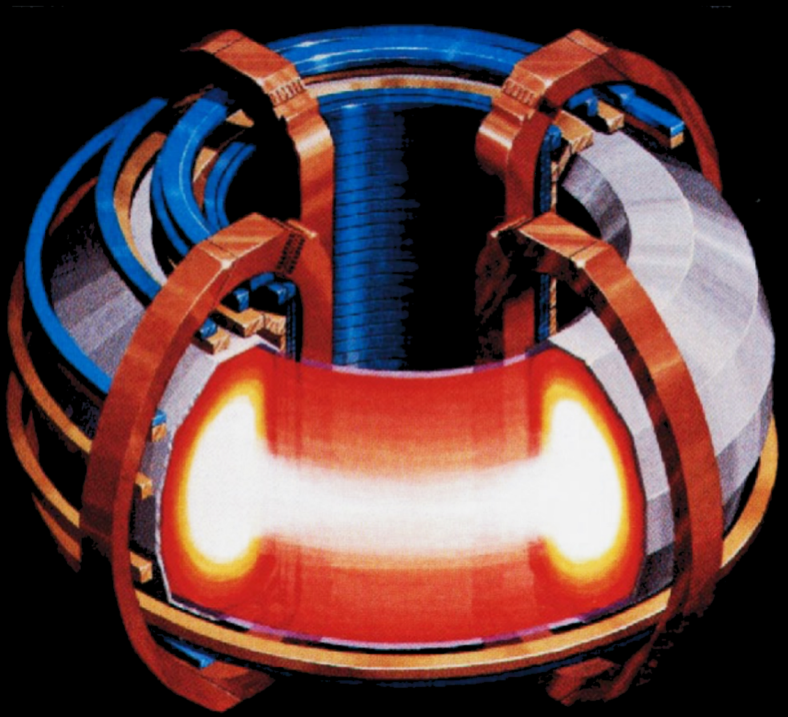


- Develop integrated core-edge solution:
  - *Performance, transients, steady state, divertor-PMI*
- DIII-D is the right scale to execute this mission
  - *Can access relevant parameters and physics mechanisms*
  - *High flexibility & diagnosis*
  - *Meaningful integration of core and edge*
- Explore how to configure plasma to make fusion solutions

- Enable scientific breakthroughs to discover fusion solutions
  - *Make ITER better and enable U.S. to benefit from ITER*
  - *Basis to proceed with steady state fusion reactor*

DIII-D NATIONAL FUSION FACILITY

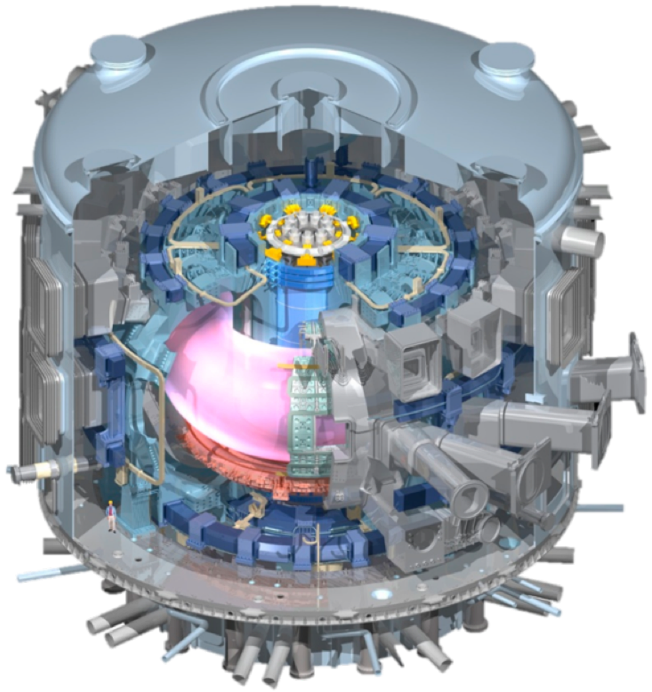
Contents



- ✓ New physics challenges
- Strategic needs for U.S. fusion path
- DIII-D plan to meet critical challenges
- Conclusions

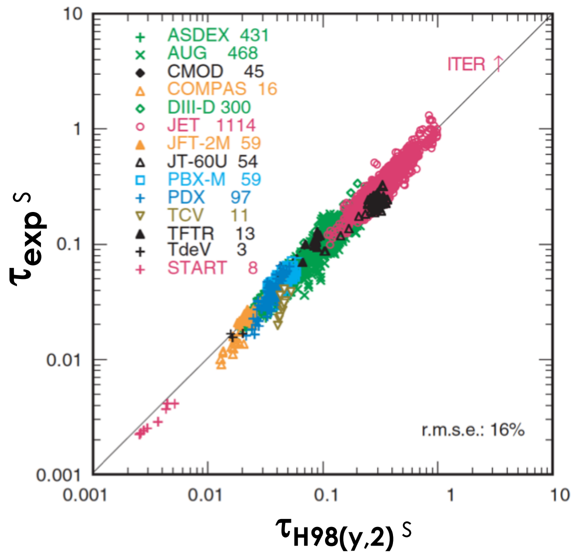
DIII-D NATIONAL FUSION FACILITY

The World Program is Focused on the Tokamak Path to Fusion Energy

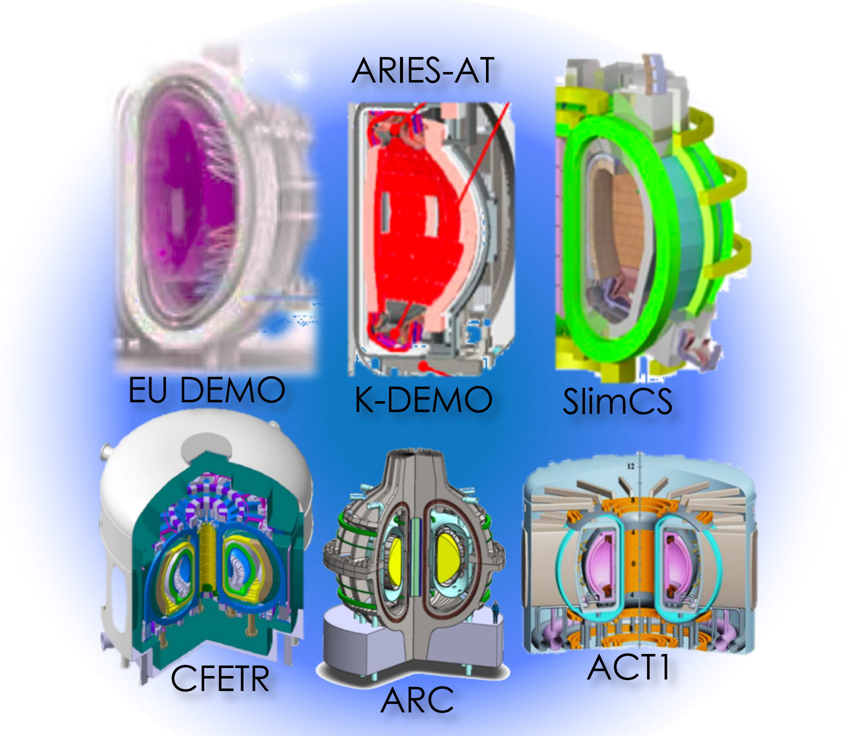


ITER

- **Demonstrate and explore physics of the self-heated burning plasma state**
  - Based on enormous body of work to project solution



- **Sustain the burning plasma non-inductively and breed tritium in high flux environment**
  - High bootstrap & RF replace inductive current
  - Detached divertor to handle heat flux

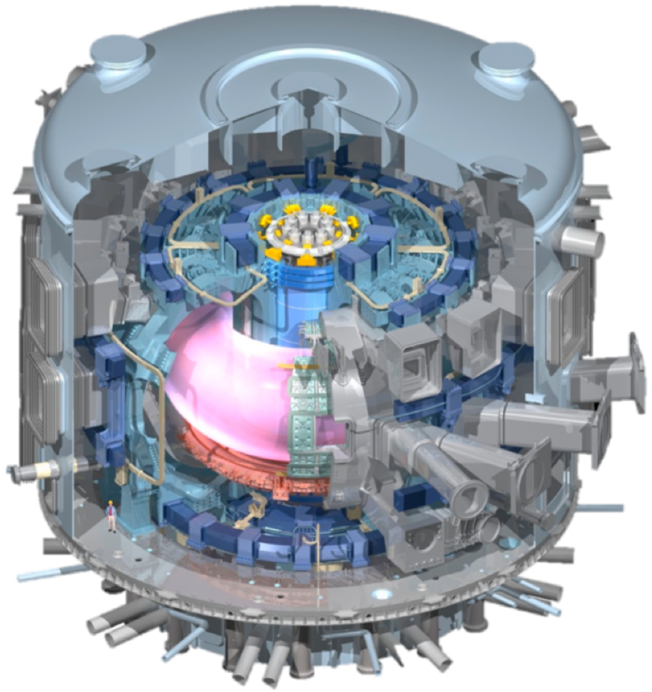


Steady State

An Integrated Path to Fusion Energy

DIII-D NATIONAL FUSION FACILITY

ITER Provides Vital Learning for Path to a Fusion Reactor



ITER

- Exploration of the burning plasma concept !
- Testing physics & techniques at reactor scale
- Development of validated predicted models
- Test steady state configurations
- How to build and operate a large scale nuclear fusion facility

ITER participation is vital if the U.S. is serious about fusion energy

- *Crucially informs U.S. approach to a D-T reactor*
- *Know-how you don't get from just reading the papers*

Steady State

How does the U.S. get to fusion energy and what is DIII-D's role?

– Enable U.S. ITER success & learning

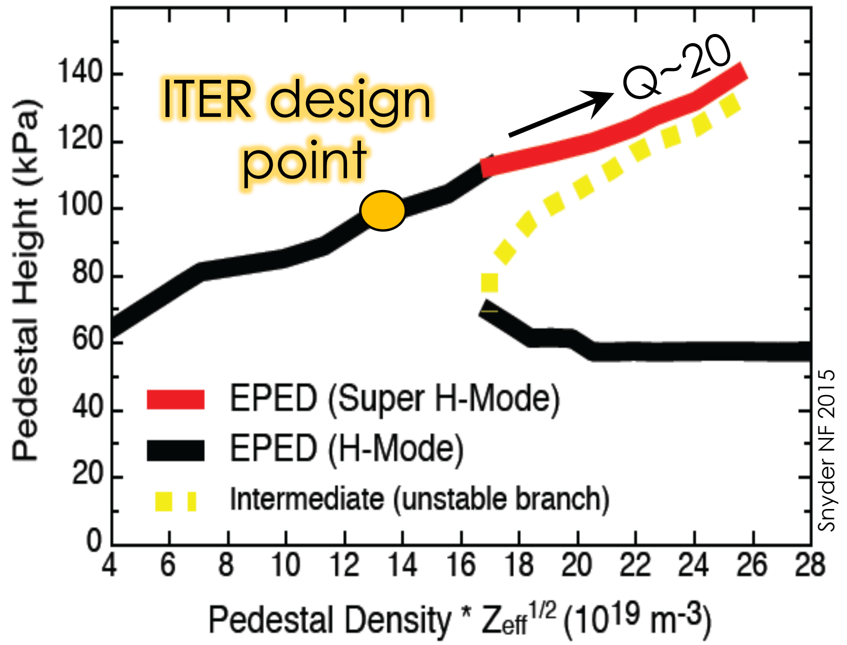
– Establish plasma basis to specify and decide on progression to U.S. D-T reactor

DIII-D NATIONAL FUSION FACILITY

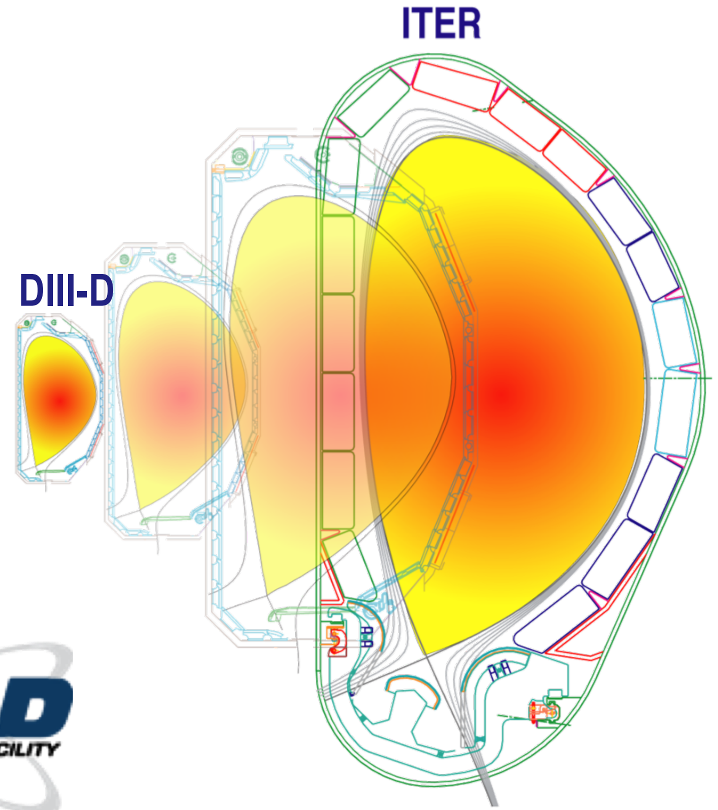
DIII-D is The Vital Tool for U.S. ITER Engagement – to Enable ITER's Success and Bring Back Learning to U.S.

DIII-D can

- **Make ITER work – Make ITER <u>better</u>**
  - Physics to raise performance
  - Stable, ELM controlled regimes
  - Disruption mitigation
- **Validate simulation to design discharges**
  - Gain U.S. leadership on ITER
  - Provide predictive tools for U.S. reactor



Improved pedestal may raise ITER Q



- **Resolve ITER issues when it is running**
  - High flexibility: can be rapidly configured & deployed
- **DIII-D is the U.S.'s ITER simulator**
  - Relevant collisionality, ω, T_e/T_i, β, q_{95}, shape, aspect ratio & control
  - Gaps on core-edge understanding & pedestal addressed here

Tight DIII-D–ITER coupling levers U.S. program and provides unique opportunities for U.S. in ITER

Without ITER Path?

• Make ITER work – Make ITER better

These topical issues and this need for validated models are all also crucial needs for a steady state tokamak reactor

– Disruption mitigation

Without ITER, the DIII-D program would pivot to address these issues in the context of steady state reactor scenarios

(we are already looking at these issues for steady state scenarios, but would accelerate this)

– High flexibility: can be rapidly configured & deployed

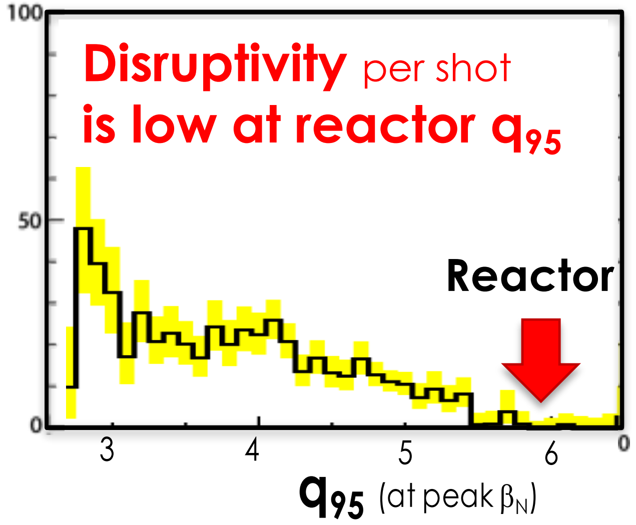
The loss of ITER participation would be a huge blow to the U.S., eliminating access to the world's first serious nuclear fusion reactor

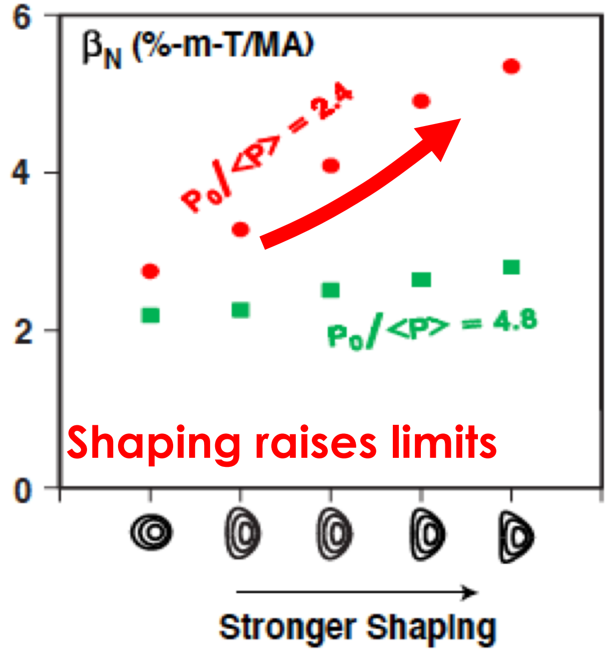
➔ Sets back U.S. ability to construct & operate a D-T device, and would likely add a generation to the U.S. path

and provides unique opportunities for U.S. in ITER

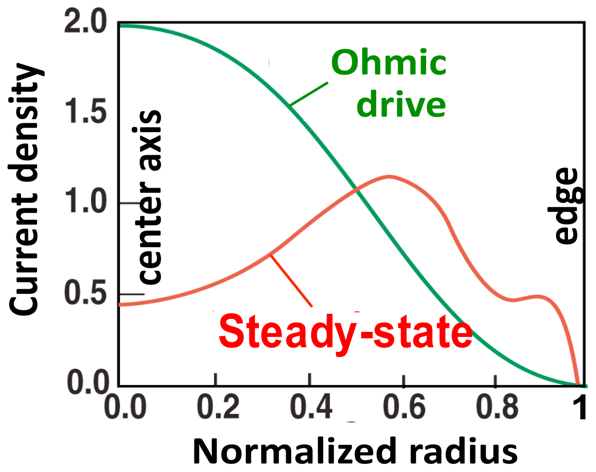
Tokamak Provides Promising Path to Steady State Fusion

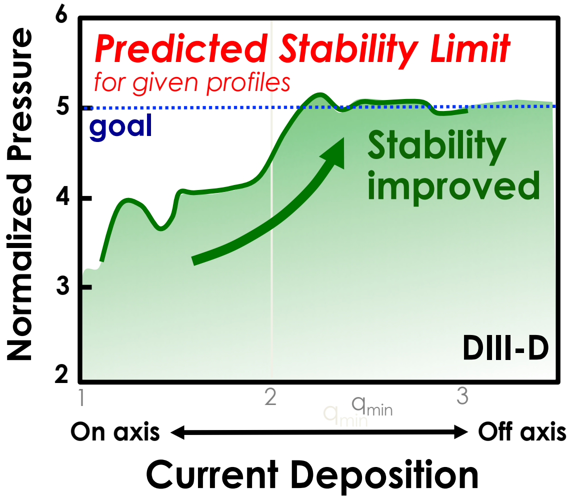
- **High q_{95} raises stability**
- **Strong shaping raises performance**

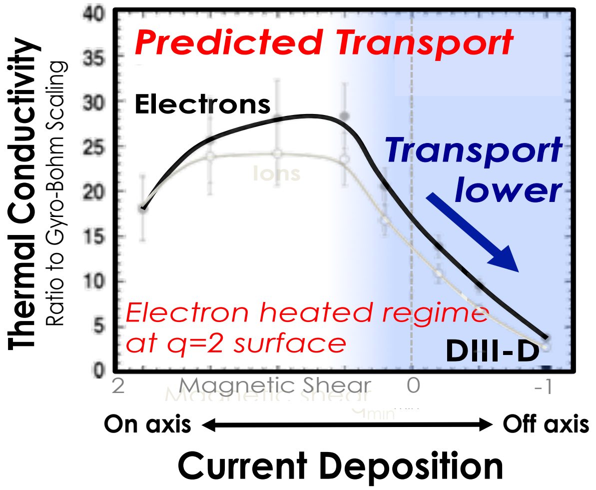




- **Favorable synergy of broad current profile, stability & transport:**







How can the U.S. accelerate this path to fusion energy?

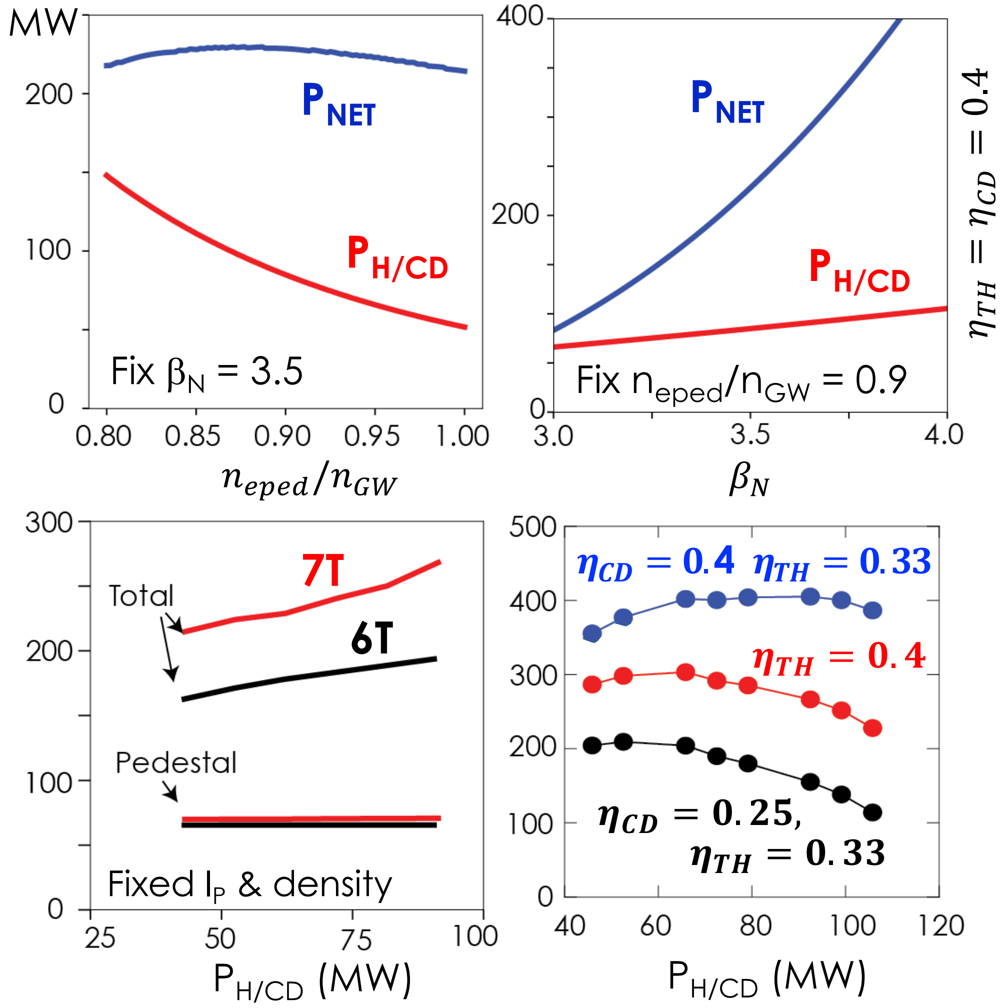
DIII-D NATIONAL FUSION FACILITY

Full Physics Simulations Show Potential of Steady State Tokamak as an Efficient Compact Reactor

- **Projects H_{98}~1.3-1.5 leading to solutions at 4m 6-7T**
  - Converged self-consistent fully non-inductive plasmas
- **Trade-offs & optimizations:**
  - **Shaping** is key: Q~shaping^2
  - **Higher density** reduces H&CD needs
  - **Higher β_N** raises fusion performance
  - **Higher B_T** improves confinement
  - **Higher efficiencies** raise $P_{net\text{-}electric}$
  - **Dissipative divertor** vs core radiation
  - **Transients** must be controlled

➢ ***Important to develop and validate these solutions***

FASTRAN 4m 7T fully non-inductive plasmas stationary TGLF-EPED-CD-EFIT solutions



Improved physics & technology reduces required scale, fusion power, fluxes and cost

DIII-D NATIONAL FUSION FACILITY

U.S. Should Innovate to Enable *Low Capital Cost* Net Electric Pilot Plant

- **Key challenges for self-sustaining reactor:**
  - **Breeding**
  - **Nuclear materials**
  - **Net electricity**
- **Should address these in a compact 'pilot plant' test facility**
  - Combine missions to remove a generation → more compelling
  - Low capital cost so affordable to go forward
  - Do not need to be at large, low-COE scale to prove approach for that scale

Power plants	ACT1	SlimCS	Korea DEMO	EU DEMO
R m	6.3	5.5	6.8	7.9
I_P MA	11	17	17	14
Pfus GW	1.8	3	2.9	2
Pnet GW	1	1	0.5	0.5

- **U.S. proposals for ARC, Compact-AT and ST-pilot**
  - *All at scale 100-200MWe, R~3-4m, A~2-3 & benefit from high temperature superconductors*
- **A pilot plant would lever U.S. ITER participation**
- **But requires additional 'enabling research'**
  - To raise fusion performance & provide required technologies

Distinctive window of opportunity for U.S.

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← U.S. would not have the expertise to proceed without its ITER participation

May need additional facility & time to develop skills and physics basis

Distinctive window of opportunity for U.S.

DIII-D NATIONAL FUSION FACILITY

Research Required in Seven Areas to Enable Low Capital Cost Pilot Plant

1. **ITER participation**
   – Validated physics models & reactor knowhow
2. **Stable high performance fully noninductive core**
3. **Dissipative Divertor**
4. **Efficient current drive**
5. **Reactor materials**
6. **Demountable high temp superconducting magnets**
7. **Engineering design & breeding concepts**

Tokamak research enables ITER & pilot plant missions (items 1–4)

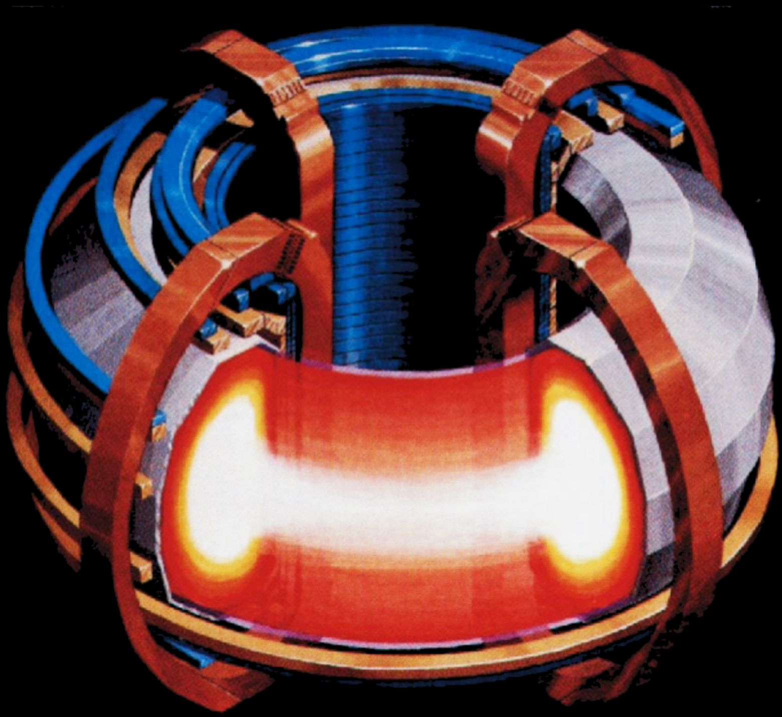
- ***DIII-D provides key opportunity to advance ITER and pilot plant research agendas***

Work on engineering & technologies to advance pilot plant approach (items 5–7)

These 7 missions provide opportunities for breakthroughs in understanding & performance that transform fusion prospects

DIII-D NATIONAL FUSION FACILITY

Contents



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DIII-D NATIONAL FUSION FACILITY

Understanding an Integrated Solution Requires Improved Performance

- Core and divertor physics are governed by different parameters:

core $\leftrightarrow$ **Pedestal** ——— **Separatrix** ——— **Divertor** $\leftrightarrow$ $q_{||}$

Collisionality, $\nu^*_{ped} \sim n^3_{ped}/P^2_{ped}$

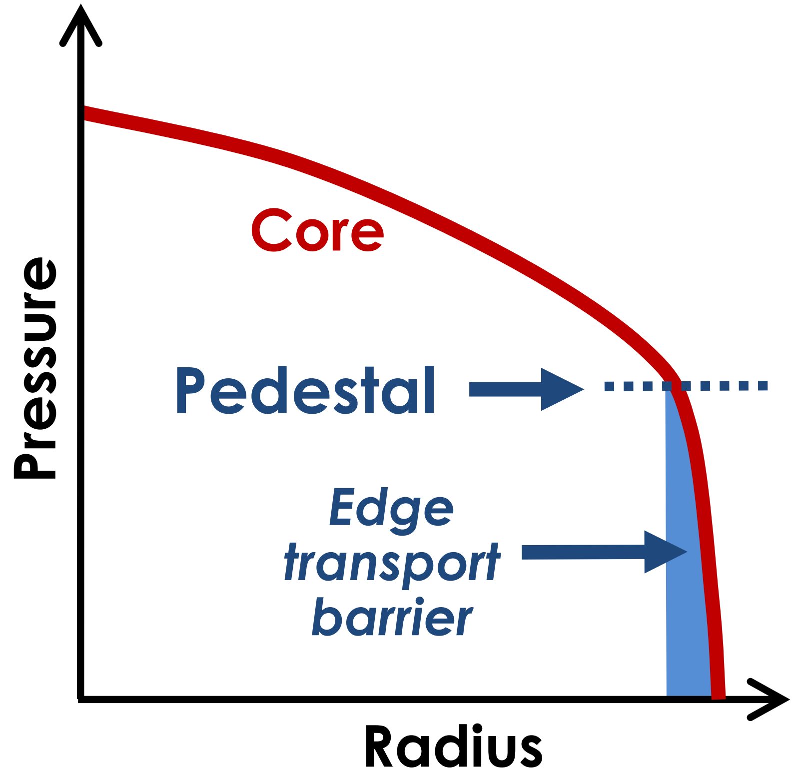
$\beta_{Nped} \sim Shaping. f_{GW}$

Pedestal physics

n_{sep}

Closure & neutrals

n_{div}



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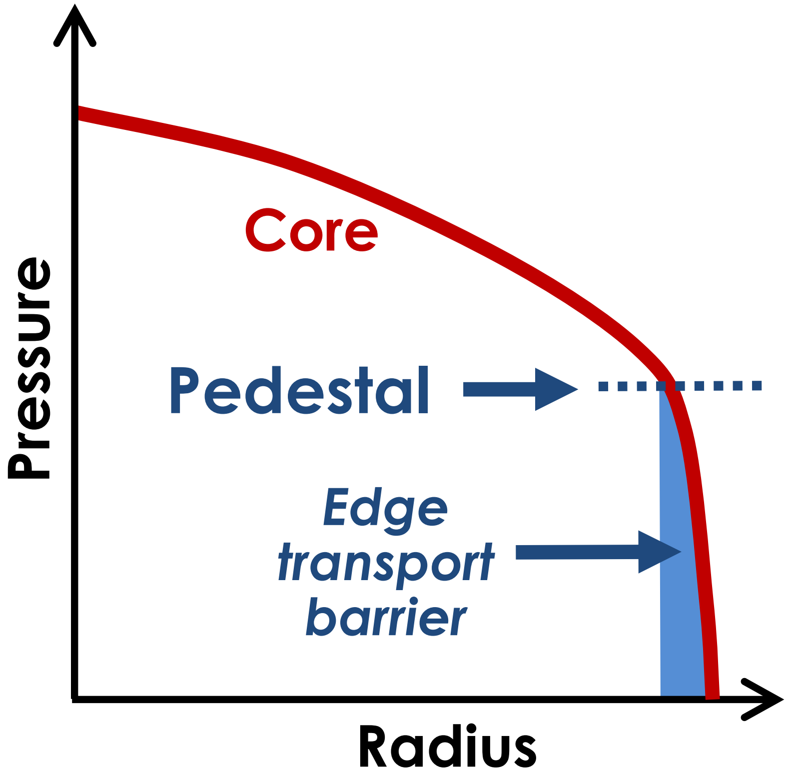

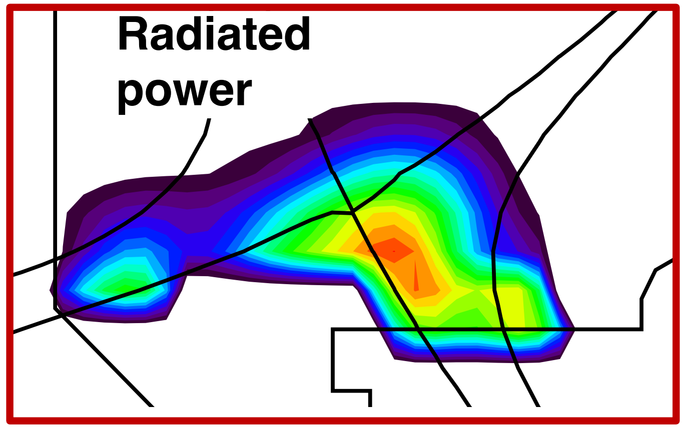

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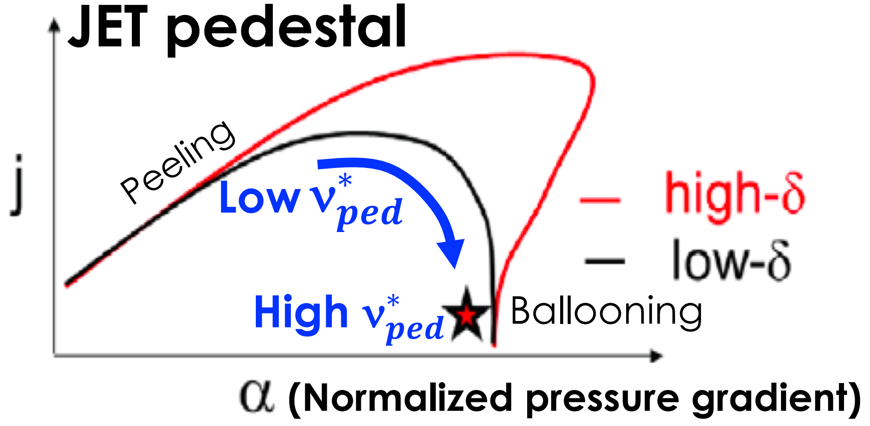

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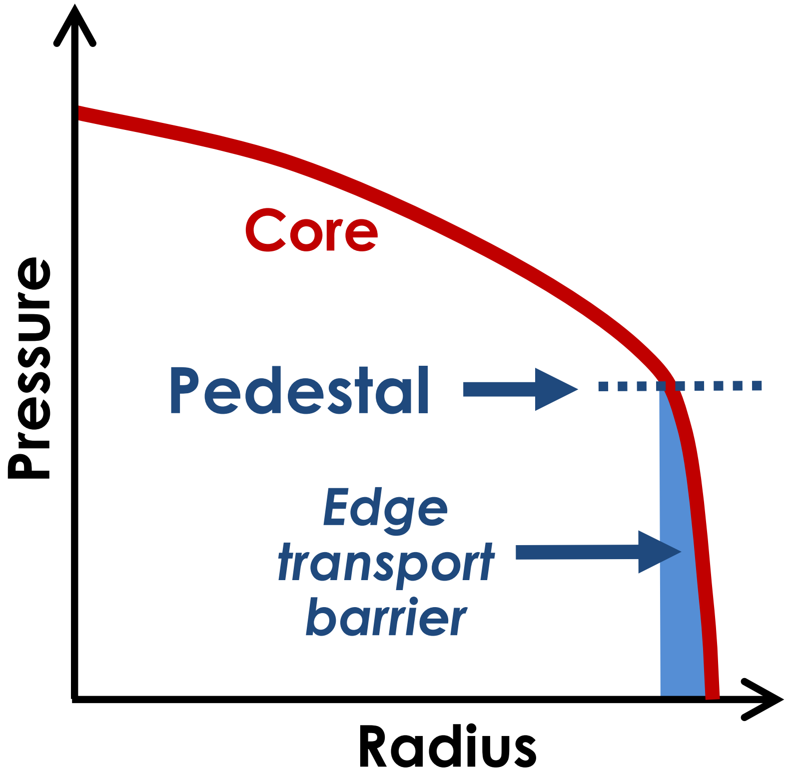

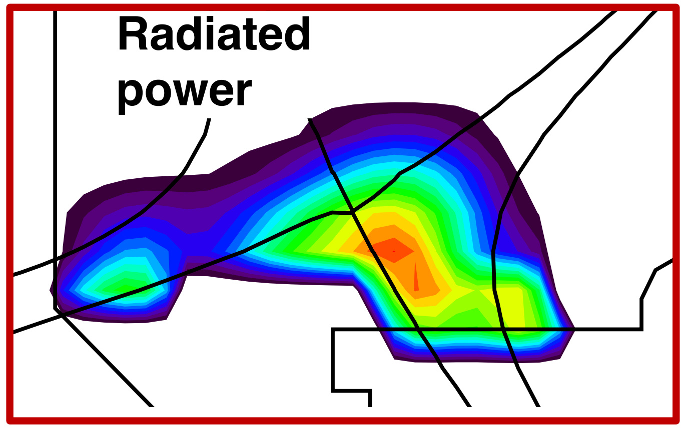

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Pedestal physics

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Closure & neutrals

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- **Core-edge solution depends on progress in each region**
  - Improved **pedestal (n_{sep}:n_{ped})** and **divertor (n_{div}:n_{sep})** solutions play a key role

DIII-D NATIONAL FUSION FACILITY

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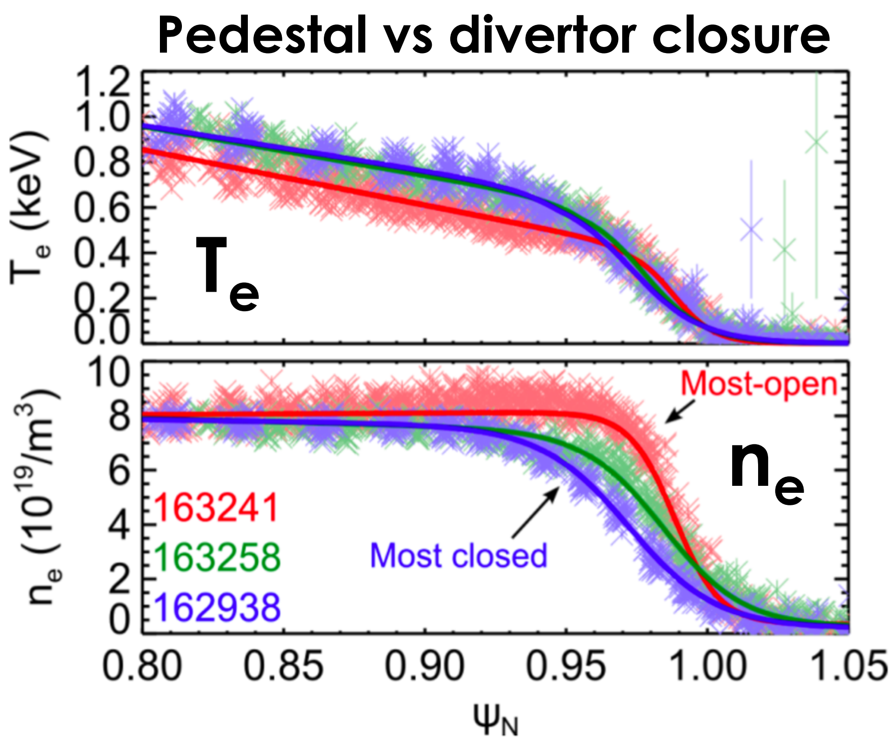
n_{div}

- **Core-edge solution depen**
  – Improved **pedestal (n_{sep}:n**



- **Strong interaction between these regions**
  – Depends on opacity

➡ ***High density an important governing parameter***

Understanding an Integrated Solution Requires Improved Performance

- **Core and divertor physics are governed by different parameters:**

core ⟷ **Pedestal** —— **Separatrix** —— **Divertor** ⟷ $q_{||}$

Collisionality, $\nu^*_{ped} \sim n^3_{ped}/P^2_{ped}$ | **Pedestal physics** ↑ | n_{sep} | **Closure & neutrals** ↑ | n_{div}

$\beta_{Nped} \sim Shaping.f_{GW}$

- **Core-edge solution depends on progress in each region**
  - Improved **pedestal (n_{sep}:n_{ped})** and **divertor (n_{div}:n_{sep})** solutions play a key role

- **Progress in underlying parameters is important**

$$n_{ped} \sim (Shaping\ f_{GW}\ I\ B\ /a)^{3/2} \quad \text{(fixed } \nu^*_{ped}\text{)}$$

⇒ **Shaping**, **field**, **current** & **power** are key levers to get to reactor-like physics regimes

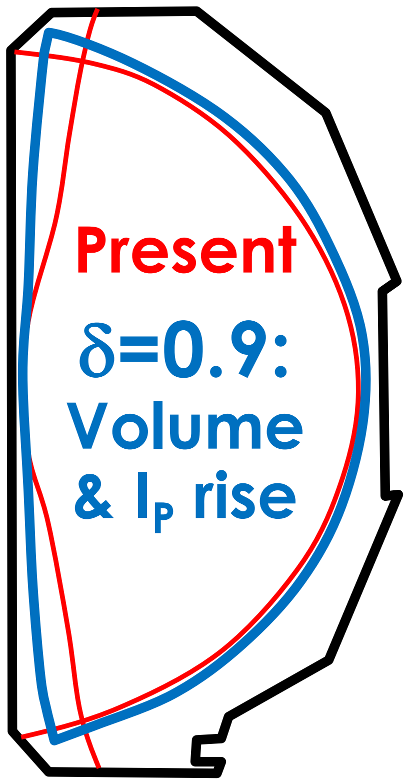
Need to increase flexibility and performance

DIII-D NATIONAL FUSION FACILITY

A Performance Upgrade Provides an Opportunity to Explore Integrated Core-Edge Solutions

Key elements:

- **Shaping increase** – raises pedestal height, volume & current carrying capacity



DIII-D NATIONAL FUSION FACILITY

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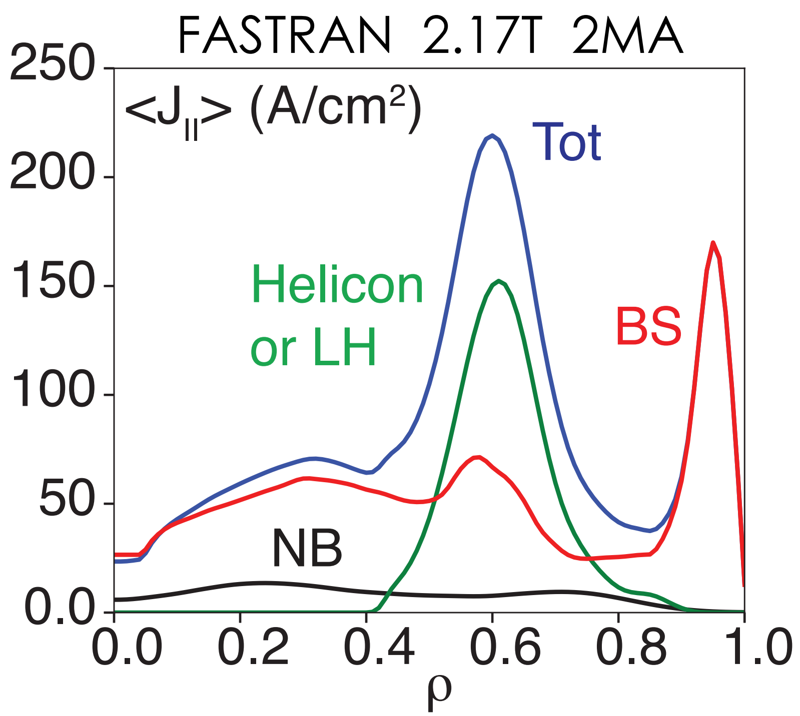
Key elements:

- **Shaping increase** – raises pedestal height, volume & current carrying capacity
- **Heating & current drive upgrade** – exploit shaping rise to higher pressure & high density steady state
  - *28MW balanced beam + 12.5MW helicon (750MHz) fully non-inductive solution at 2.2T*
    - **~3x pedestal height & stored energy in steady state**
    - **ITER-like ν^*_{ped} with much higher density**



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>T_i Ω~21krad/s
11% fast ions 61% bootstrap

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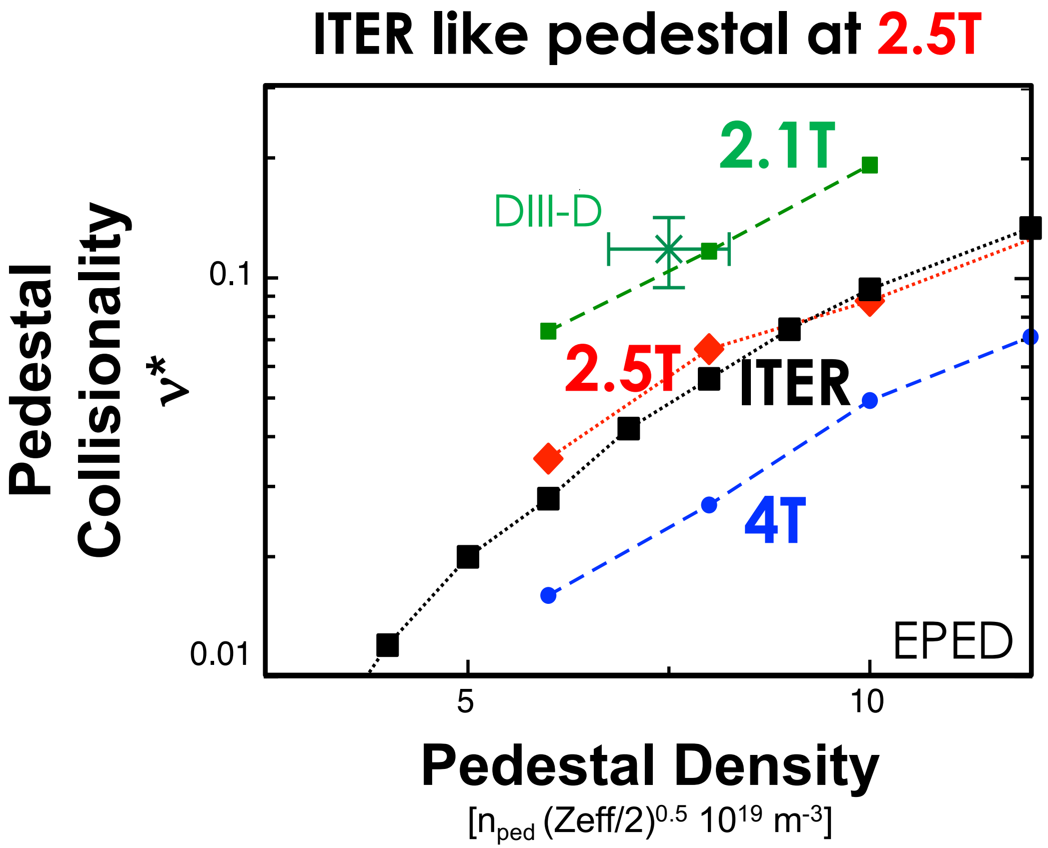
- **Higher field** – higher density & power flux at low ν*
  - *Extend existing TF→~2.5T or replacement →4T*
  - *Increases opacity*



*present steady state

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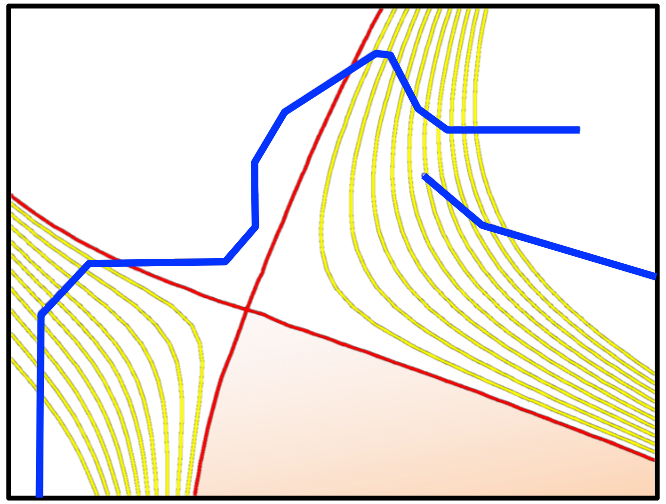
  - *Extend existing TF→~2.5T or replacement →4T*
- **Double null closed divertor** – isolate dense detached divertor from high performance core

Optimized divertor



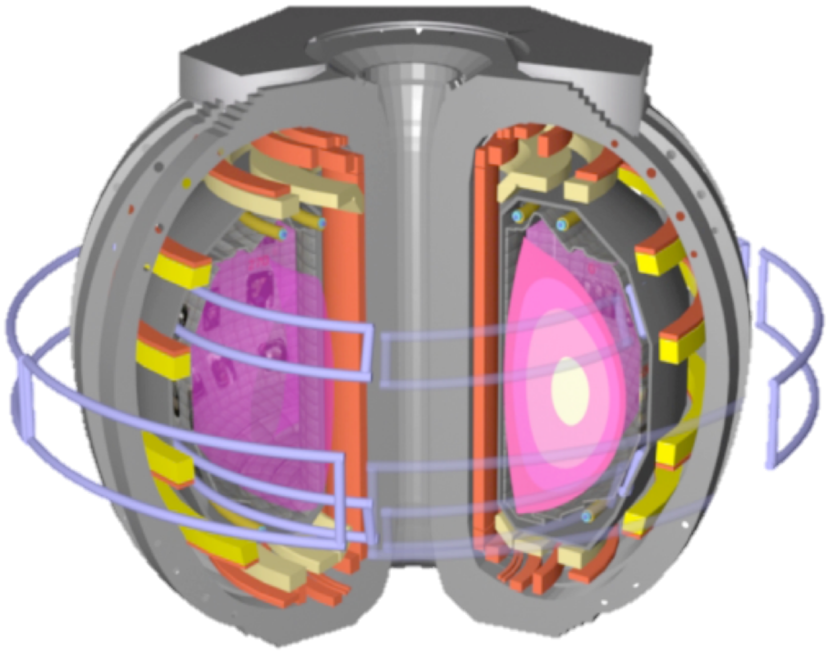
Directs neutrals to improve detachment

DIII-D NATIONAL FUSION FACILITY

A Performance Upgrade Provides an Opportunity to Explore Integrated Core-Edge Solutions

Key elements:

- **Shaping increase** – raises pedestal height, volume & current carrying capacity
- **Heating & current drive upgrade** – exploit shaping rise to higher pressure & high density steady state
- **Higher field** – higher density & power flux at low ν*
  - *Extend existing TF→~2.5T or replacement →4T*
- **Double null closed divertor** – isolate dense detached divertor from high performance core



Supporting research elements establish basis for high performance stable core & dissipative divertor:

- Low ν* 'burning plasma' core regimes
- Transients
- Steady state sustainment
- Divertor science, PMI & core interactions

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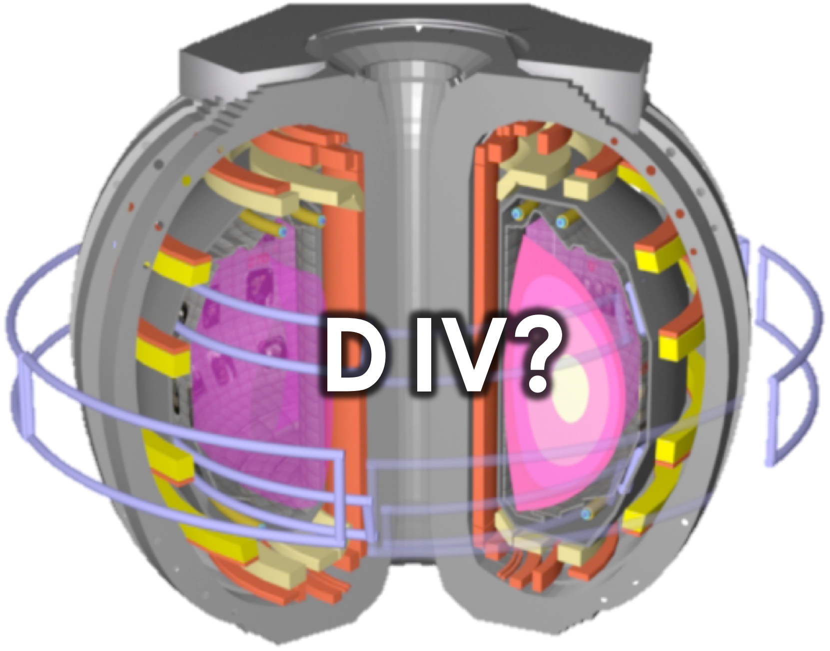

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Provide the plasma physics basis to decide on a D-T device and to lead on & learn from ITER

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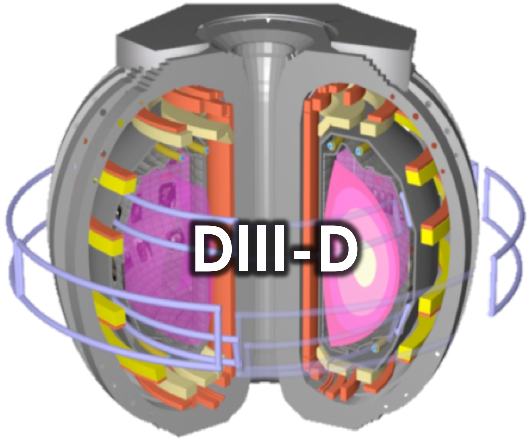
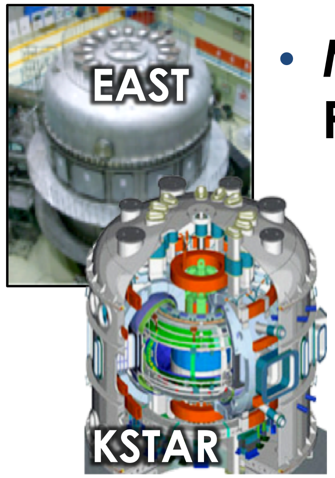
Plan Provides Distinctive & Needed Capability in World Context



- Core-edge interaction with closed divertors
- Low ν^* & rotation with reactor-like core conditions
- 3-D optimization of the tokamak
- Steady state configuration & current drive

Flexibility & diagnosis to explore physics and develop candidate solutions

Superconducting



- Material & PFC evolution
- Long pulse control

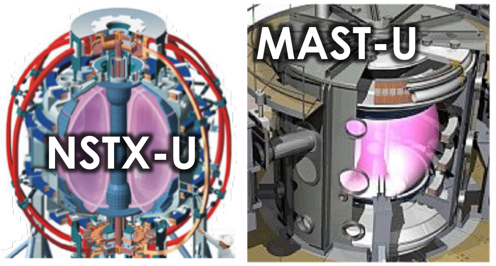
Larger scale

- Projection to reactor
- Operational techniques

Metal walls

- High Z behavior
- Bulk W influx
- RF

Key physics



- Aspect ratio effects
- Divertor magnetic geometry
- Super Alfvénic ions & high β

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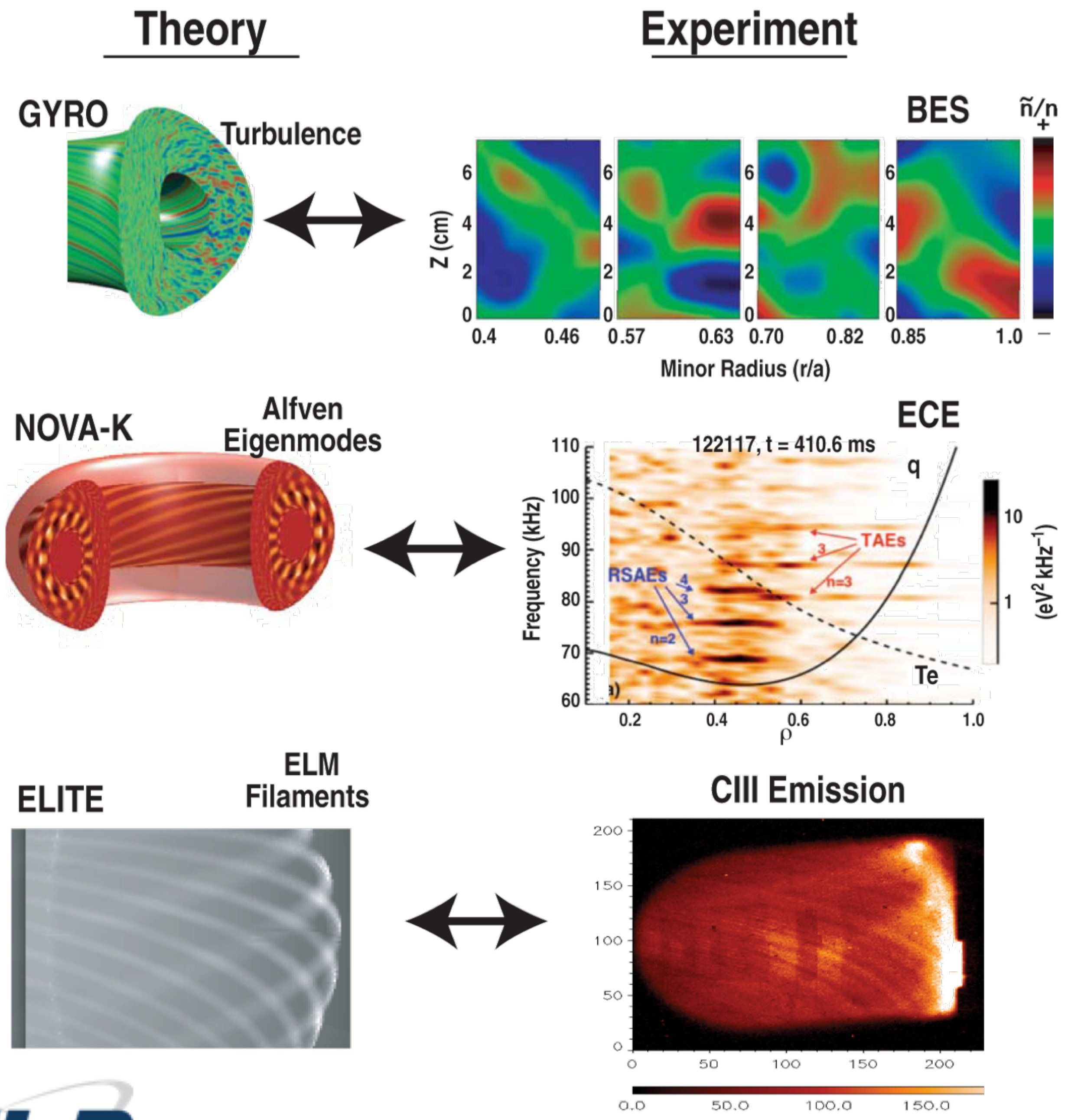
Innovative Diagnostics and Modeling Enable Tests of State-of-the-Art Theoretical Models

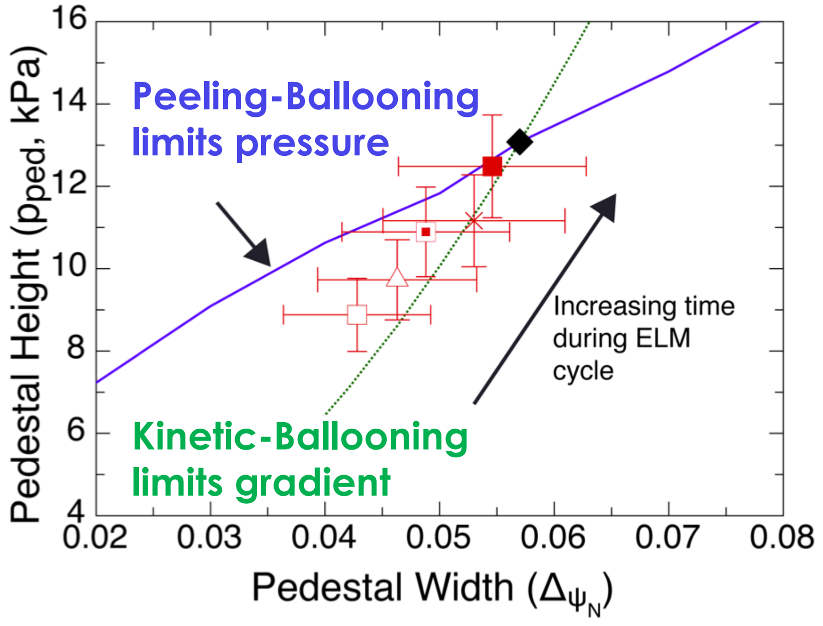


- **Comprehensive, high resolution diagnostics**
- **High speed computing & cutting edge simulation**
- **Strong collaborative approach – e.g.:**
  - Turbulence: GA, UCLA, Wisconsin, MIT, UCSD
  - Alfvén eigenmodes: UCI, PPPL, GA
  - ELMs: UCSD, LLNL, ORNL, SNL, GA

Heart of our approach:
Understanding to develop predictive capability & better solutions

Example of Science Leading to Solutions: Pedestal Improvement

- **DIII-D research validated a model of the pedestal based on two instabilities**



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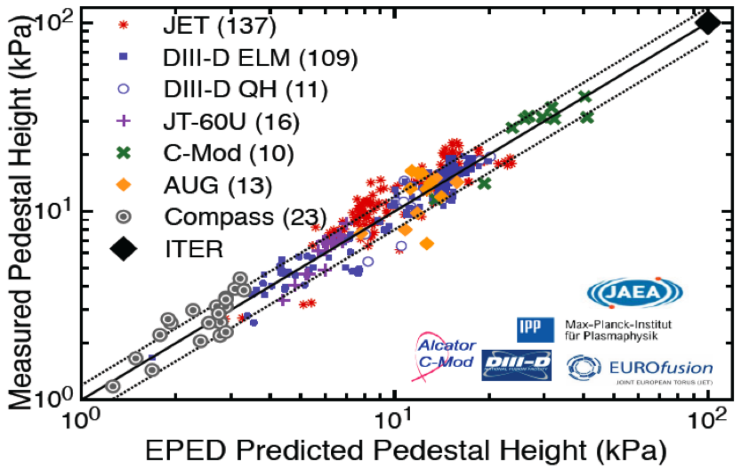
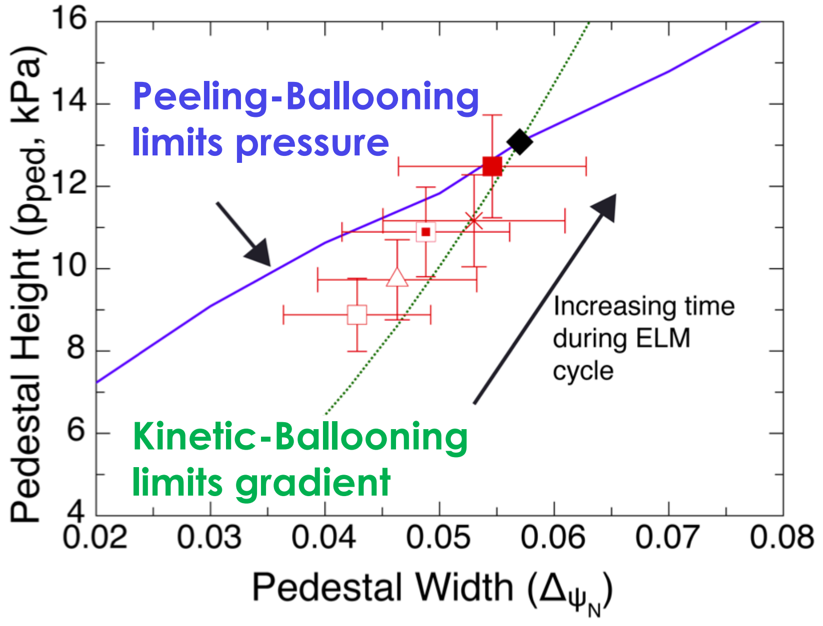
Accounts for behavior on 6 devices





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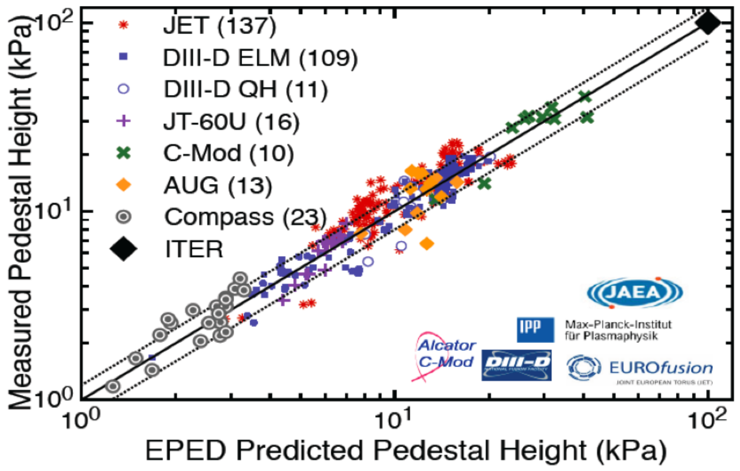
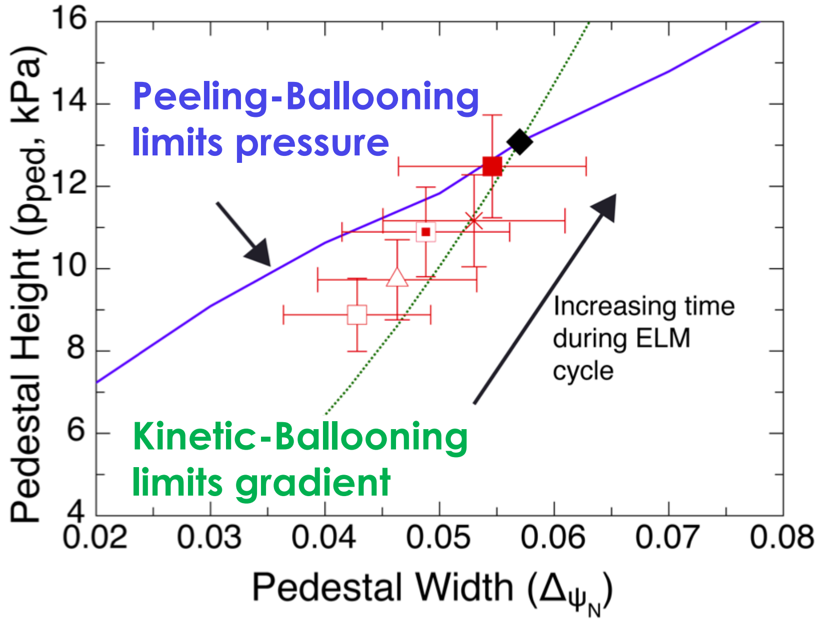
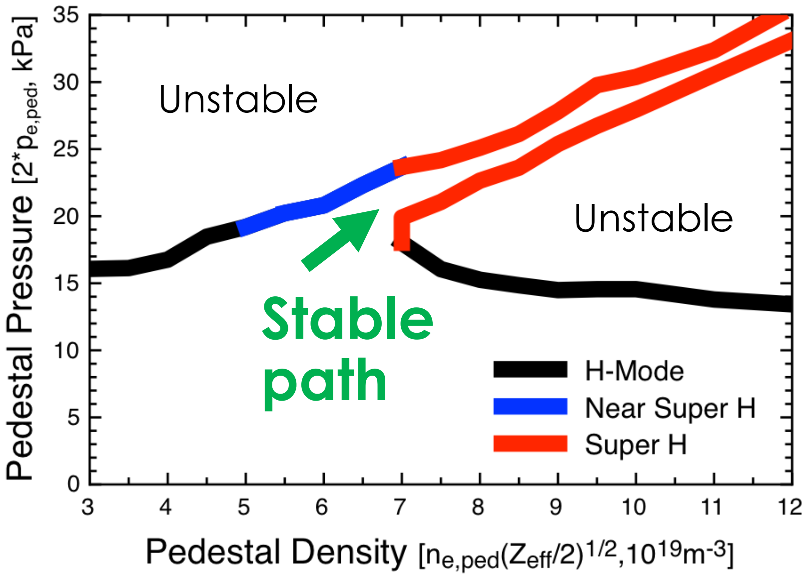


- **Used model to predict access to improved pedestals**
  - Shaping decouples modes → stability





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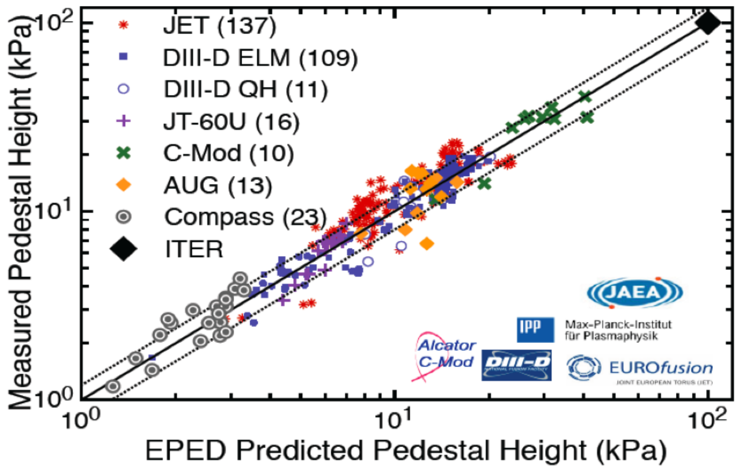
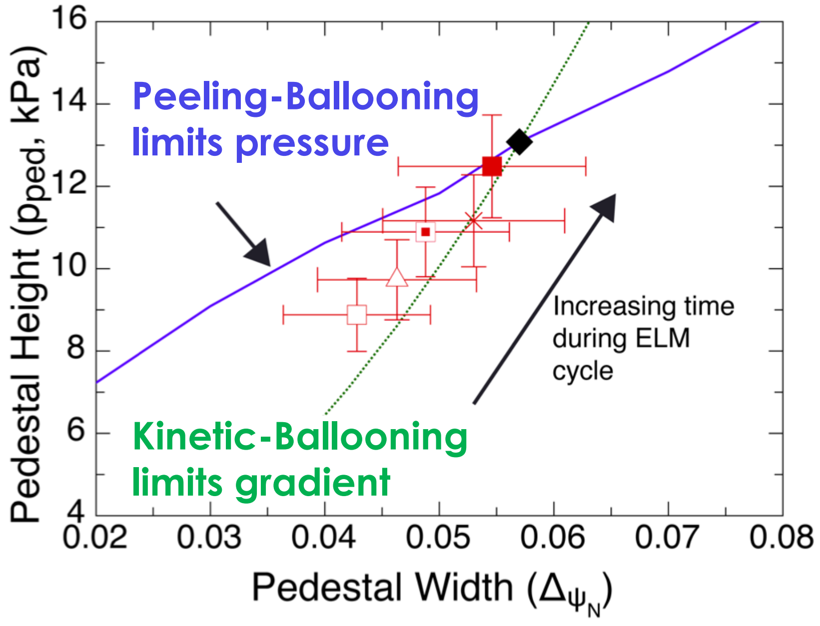
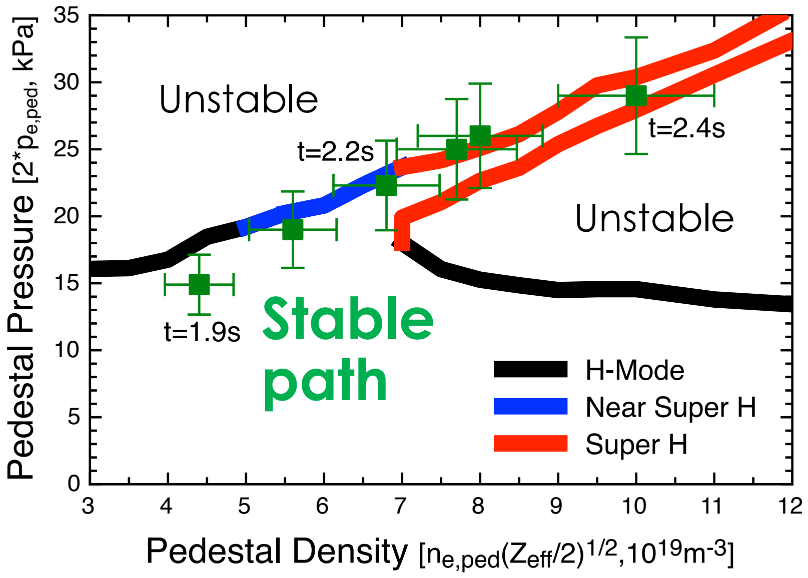




- **Used model to predict access to improved pedestals**
  - Shaping decouples modes → stability
  - Leads to record DIII-D pedestal pressure and highest Q_{DD}/IaB in a tokamak



DIII-D has relevant flexibility, parameter space & diagnostics to develop pioneering solutions

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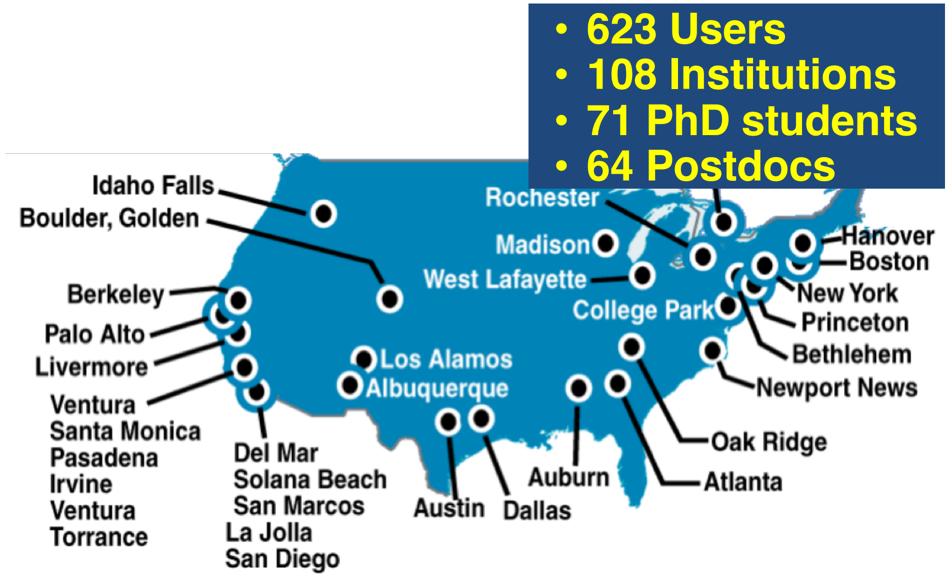
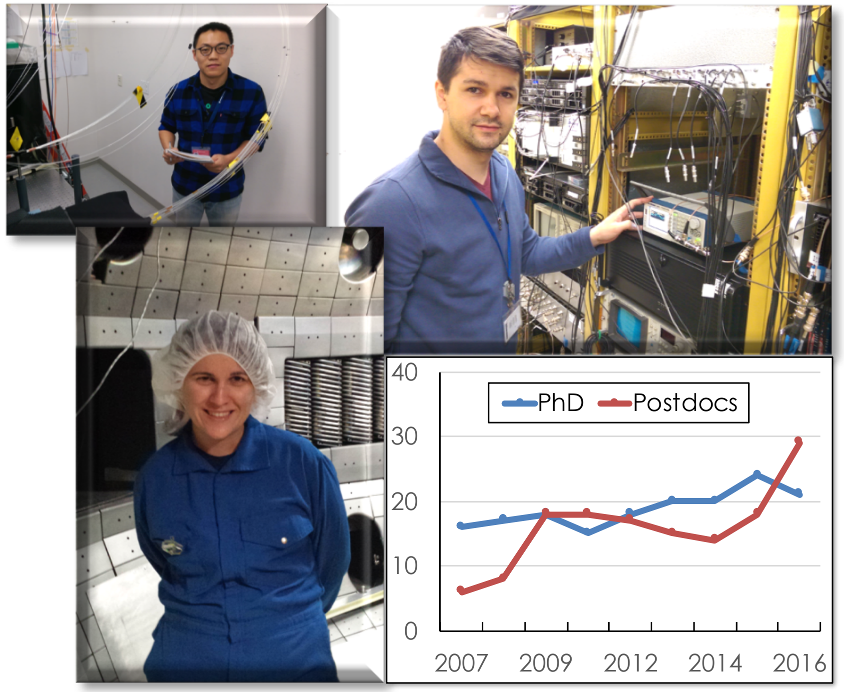
DIII-D Benefits from a Diverse and Broad Community Engagement

- **Hosts collaborative partners from across community**
  - High level of run time and broad research capabilities
  - Center for theory collaboration & simulation validation
  - Strong international & ITER engagement
- **Integrated scientific organization**
  - Opportunities for leadership across the program
  - 100 onsite scientists: $^1/_3$ Universities $^1/_3$ Labs $^1/_3$ GA
    - *Hundreds more visiting/remote*
- **Training next generation of scientists**
  - Hands on access





Collaboration is key to DIII-D's success

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Supporting Research Elements

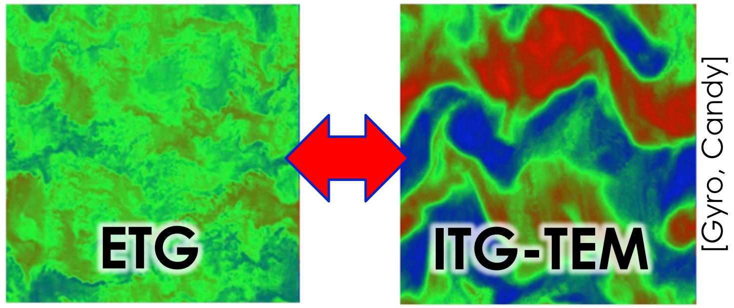
- Burning Plasma performance
- Transients
- Steady State
- Divertor/PMI

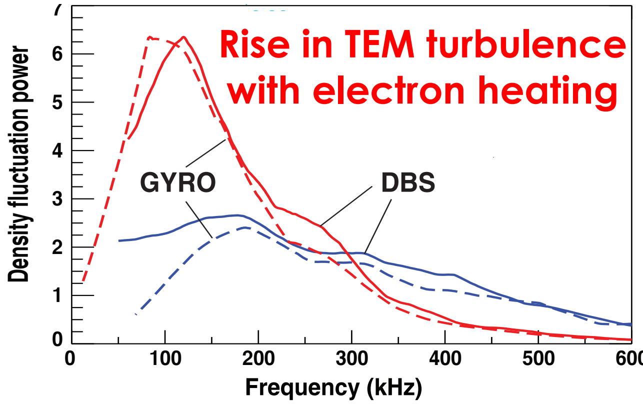
All these issues require progress for a steady state reactor, with or without ITER

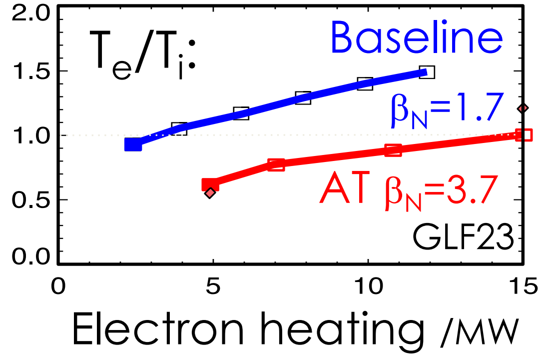
DIII-D Plans to Understand How to Project & Improve Turbulent Transport for Low ν^* Burning Plasma

- **Turbulence driving instabilities change as burning plasma parameters approached**
  - Strong nonlinear coupling across scales & fields
  - ***Need to access underlying phenomena, understand dependencies and interactions between them***

- **Research plan addresses the key elements:**
  - Changes with low ν^*, rotation & $T_e \sim T_i$ through electron heating & balanced beams
    - *Study multi-field interactions between flows, particles & energies*
  - Coupling of ions & electrons through performance (density) upgrade
  - New diagnostics to simultaneously measure multi-scale interactions
  - Electromagnetic (β) and magnetic shear with current drive upgrades







Achieve predictive capability to design & optimize ITER discharges (confinement, L-H access, rotation, isotope effect) **and fusion reactor**

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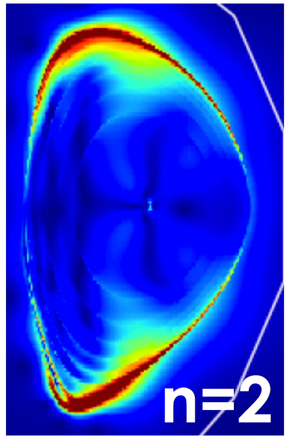
A 3-D Upgrade Provides Unique Basis to Optimize ELMs & Stability for ITER & Reactor Design

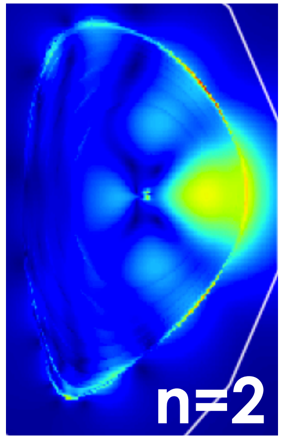
- **DIII-D discovered multi-mode plasma response to 3-D fields**
  - Accounts for ELM suppression

➢ ***Affords selective control:*** *ELMs, Rotation profile, Error fields*
  - But ELMs & rotation control most effective with n=3,4 fields (more edge resonant)



Edge current driven mode → ELM suppression

Global pressure driven kink



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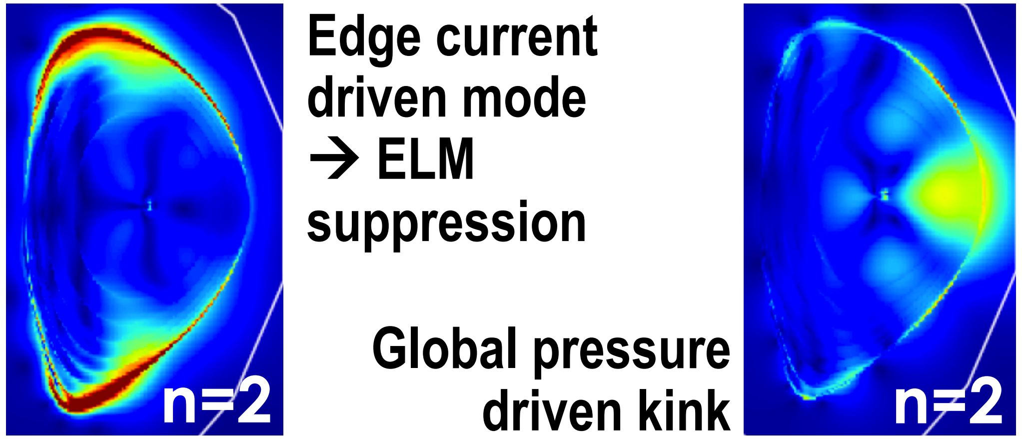
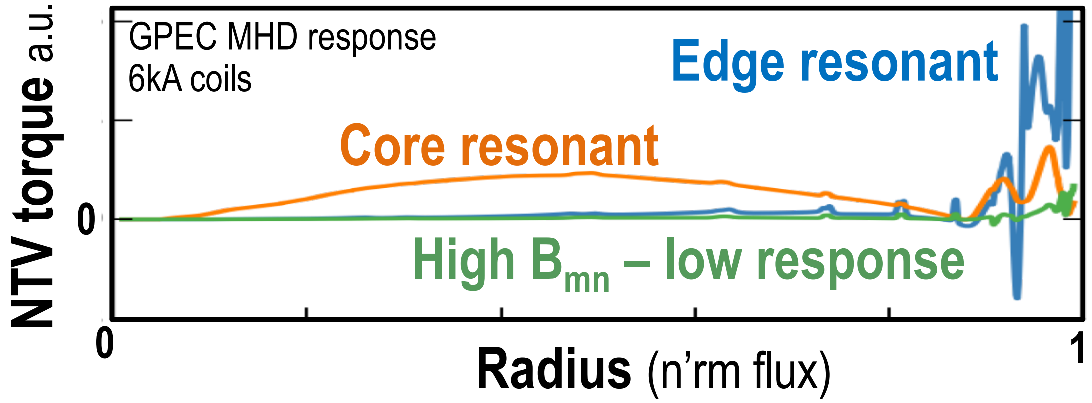
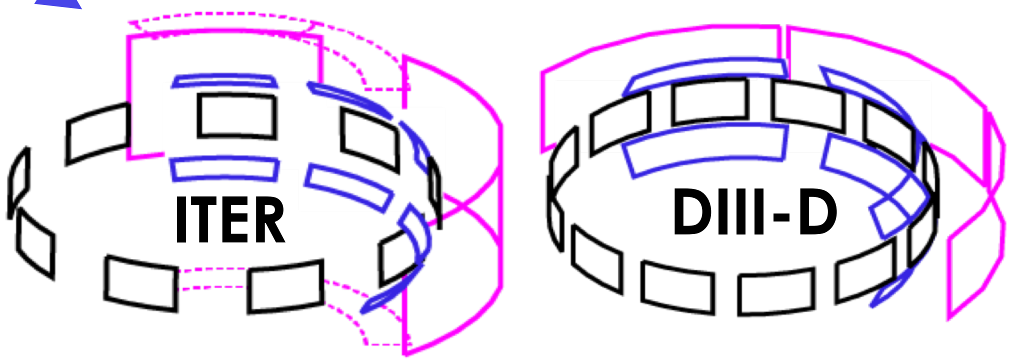
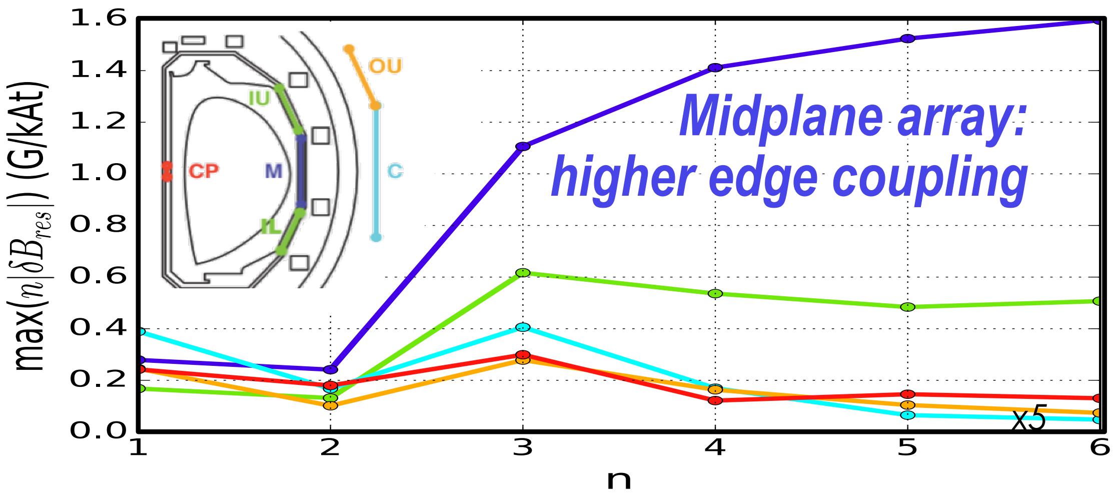




- ***New 12 coil midplane array will provide first ability to vary n=3 & 4 spectrum***
  - *Tune for ELM suppression & rotation profile control*
  - *More efficient coupling for ELMs*
  - *ITER-like coil set*



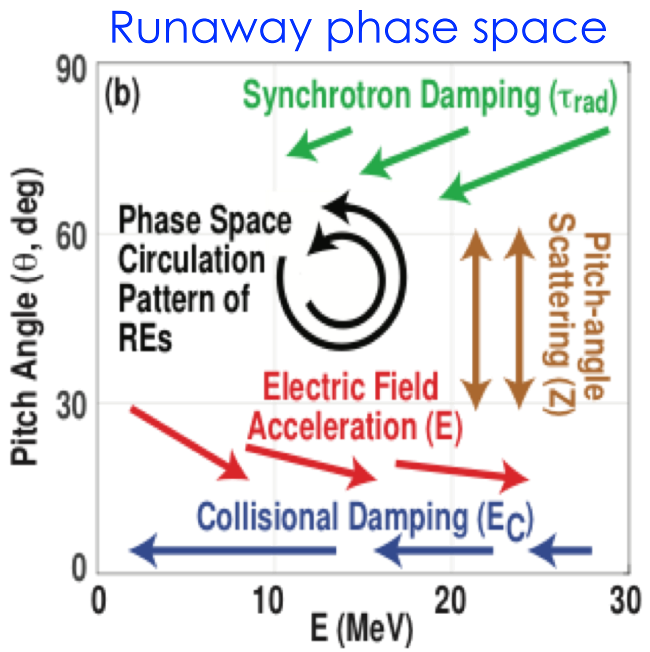


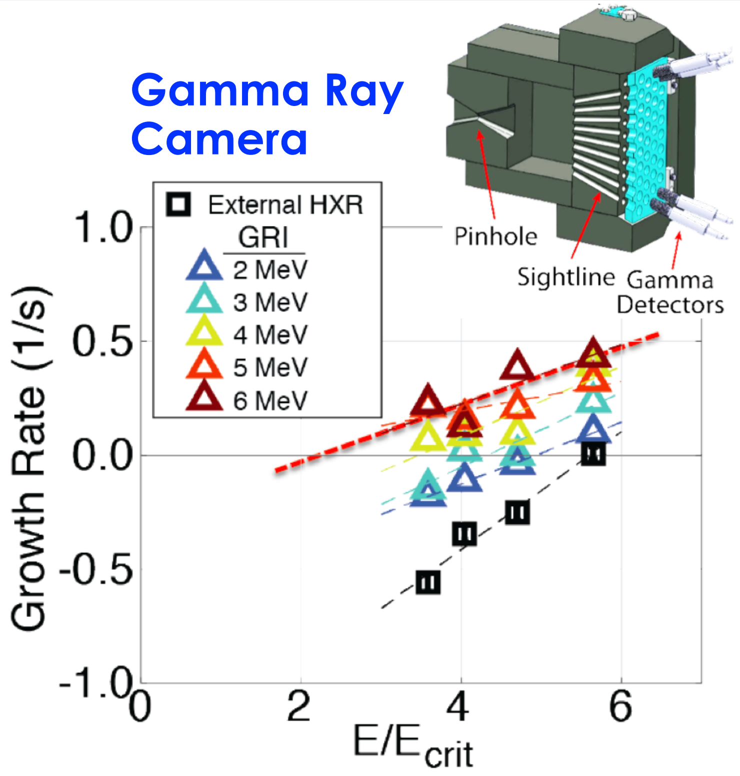
Achieving Robust Disruption Mitigation Remains Critical for the Viability Of Tokamak Reactors

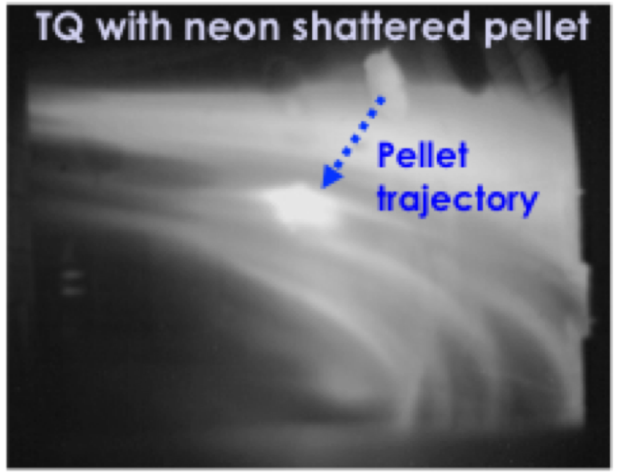
Challenge: Radiate thermal & magnetic energy while avoiding runaway electron damage

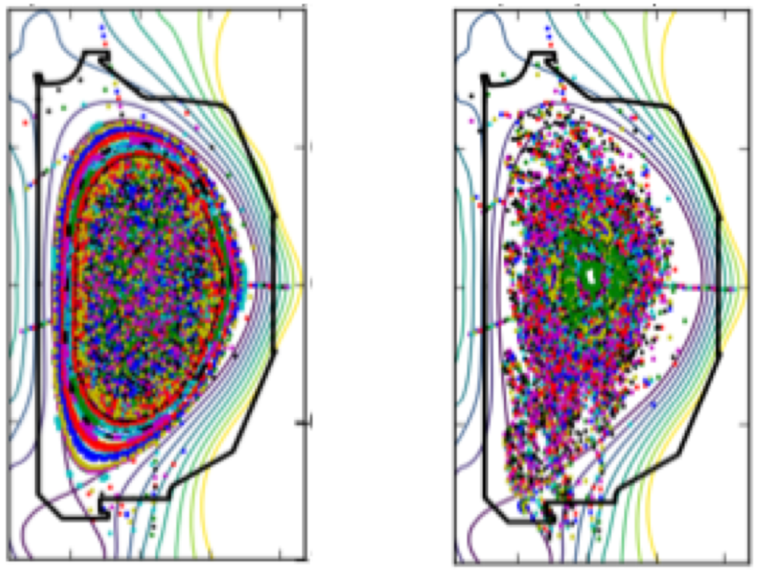
Key Development Paths

1. Linking modeling & experiment to understand runaway evolution using novel diagnostics
   – **Image real and phase space**
2. Optimize ITER shattered pellet injection (SPI)
   – **Pioneered & developed on DIII_D**
3. Core impurity deposition to simultaneously mitigate thermal, magnetic, & RE needs
   – **"Inside-out" mitigation with low-Z shell pellets**







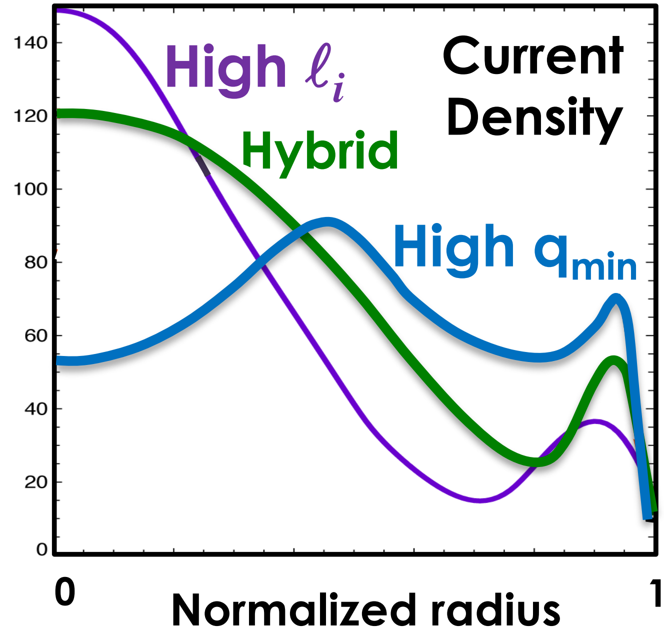


NIMROD: shell pellet stochastization

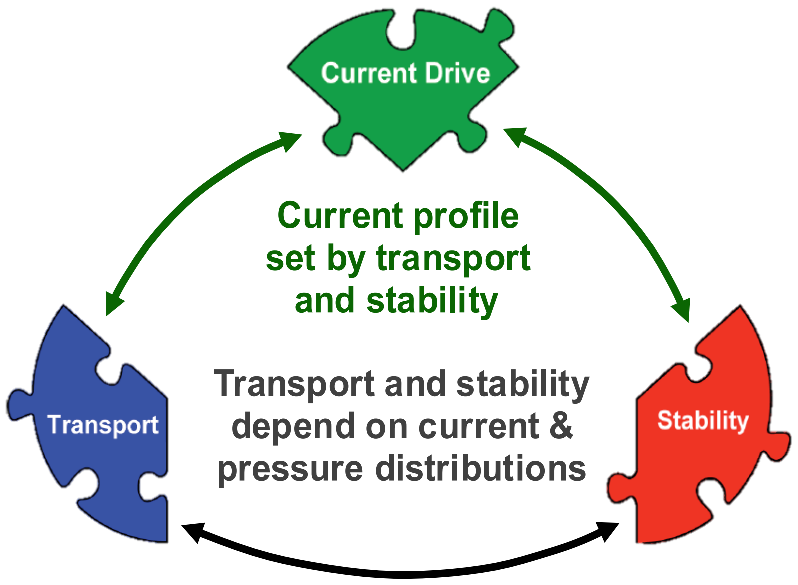
Flexible Heating and Current Drive Systems will Enable DIII-D to Discover Path to High β Steady State

- **Potential solutions from broad to peaked current profiles**
  - With **high bootstrap** or **efficiently drive on-axis**

Regime	Strength	Challenge
High q_{min}	β_N=5 potential; Low disruptivity	Fast ion transport Resistive wall mode
Hybrid	High confinement	Current evolution β_N limit
High ℓ_i	β_N=5 without RWM	Sustainment; Tearing



- **Need to find a self-consistent solution**
  - Need high β_N: β_T for performance, β_P for bootstrap
  - Transport & stability dependence on profiles & β



- **Device flexibility is key**
  - Assess physics in reactor relevant regimes

➢ ***Requirement for off-axis current drive in DIII-D***

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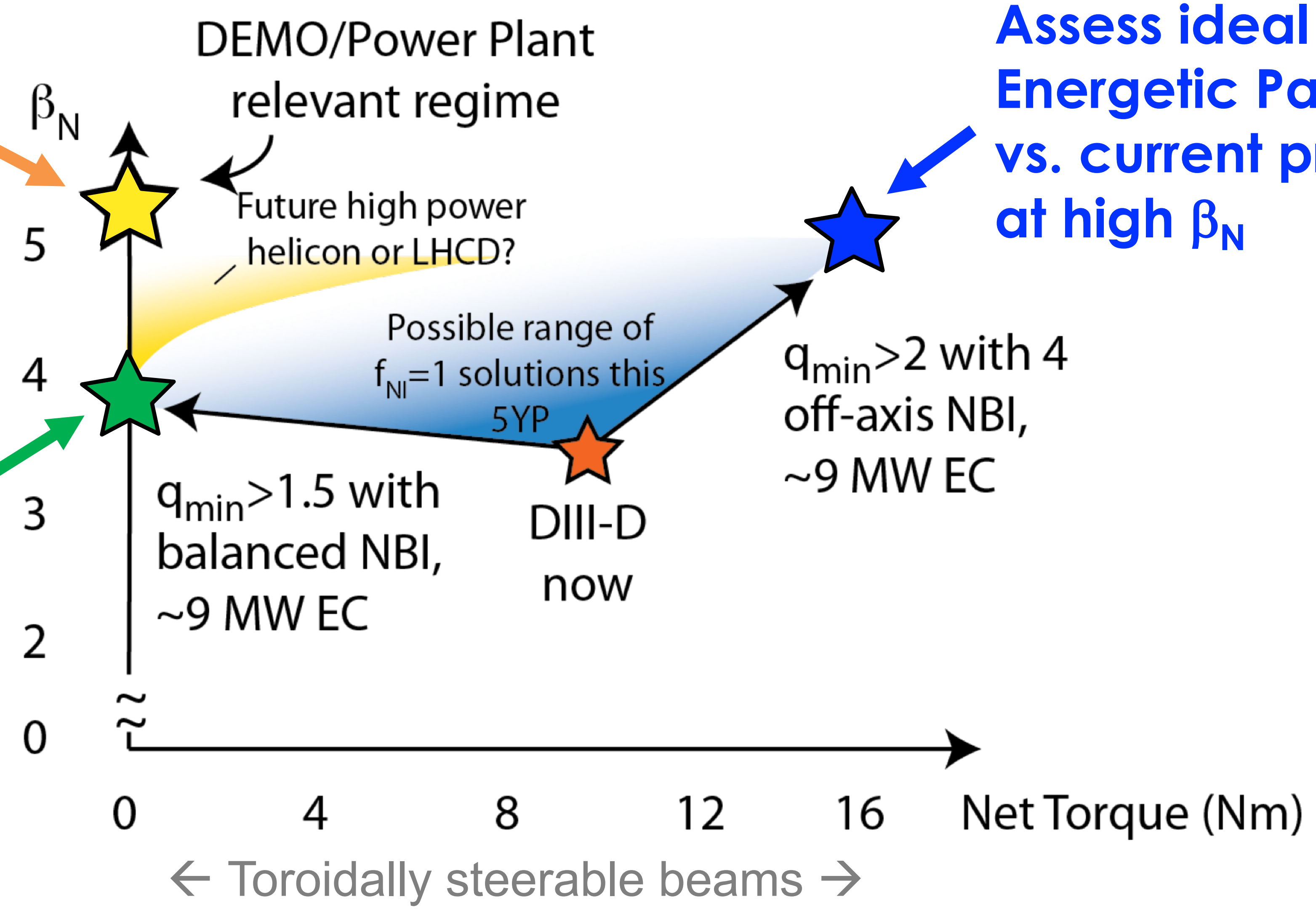
DIII-D Heating and Current Drive Upgrades Will Provide the Range to Explore Path to Steady State

Assess core-edge integration & coupled electron-ion scenarios at high density

Assess turbulent transport & ideal MHD kinetic resonances at low rotation



Assess ideal MHD & Energetic Particle transport vs. current profile at high β_N

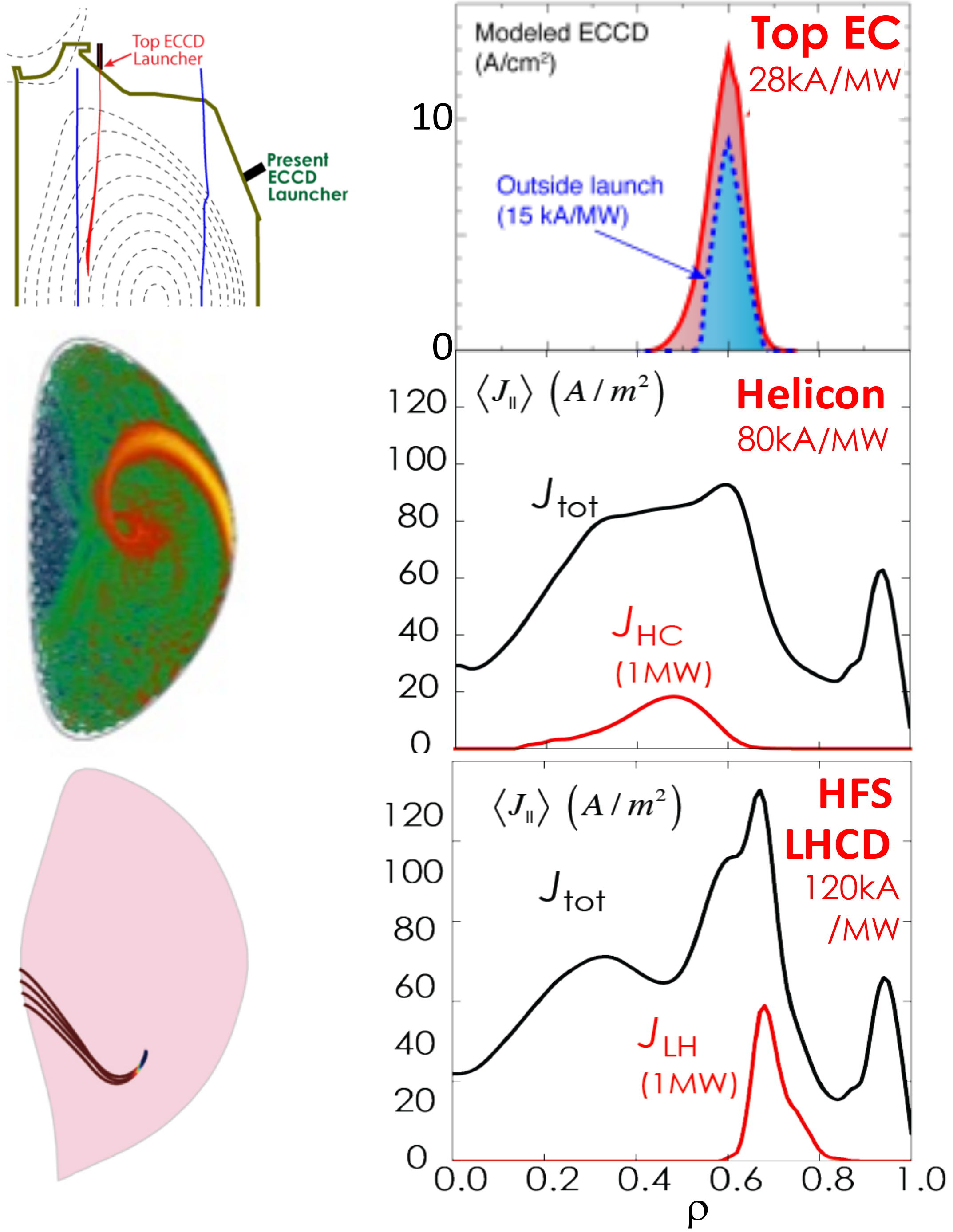
Basis to Project Steady States to Reactors

DIII-D Will Test Advanced Current Drive Methods For Reactors That Will Expand Steady State Research

- **Challenges:** Efficient reactor current drive
  - Good coupling – Harsh reactor environment

- **DIII-D will test 3 promising concepts**
  - ***Top launch ECCD***
    Doubles off-axis efficiency
  - ***High harmonic fast wave (helicon)***
    2-4x greater efficiency at high β_e
  - ***High-field side lower hybrid wave***
    HFS SOL more quiescent: Reduces flux to antenna & improves wave penetration

Extends scenarios to higher β_N, broader J, lower Ω & higher density.
Develops potential reactor technologies.



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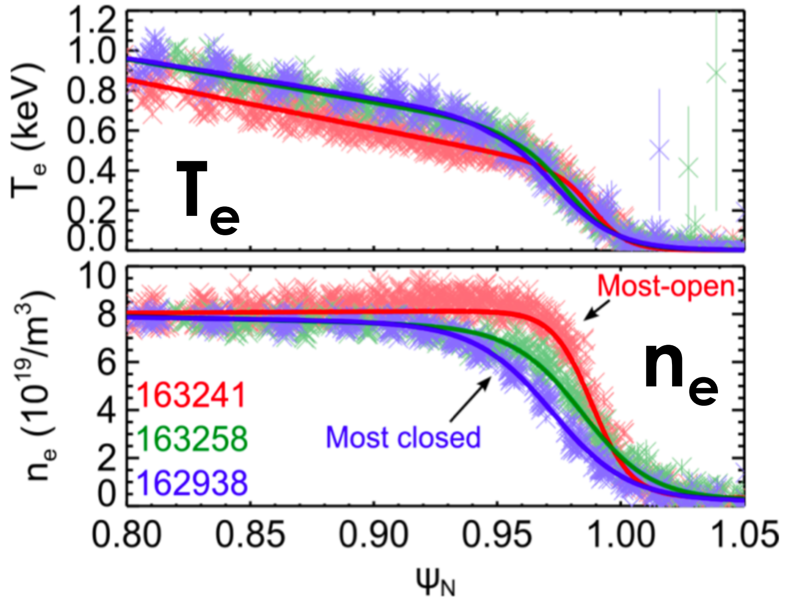
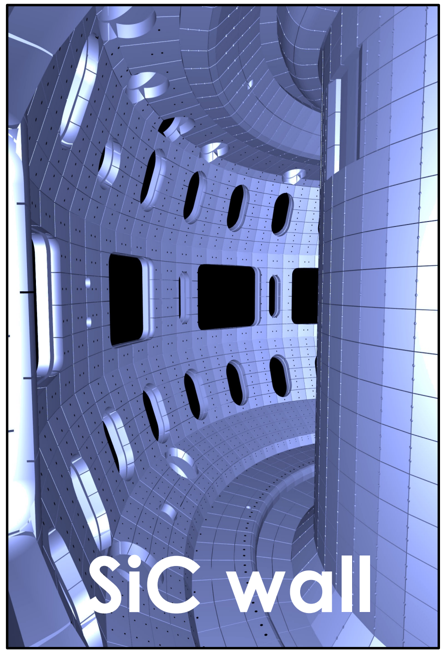
Research Will Explore How to Combine Core & Edge Solutions

- **Understand overall configuration and shape optimization**
  - High DIII-D flexibility & double null divertor
- **Test influence of divertor closure on pedestal and core**
  - Particle dynamics & pedestal turbulence
- **Develop radiative mantle techniques**
  - & understand impact of radiators on PMI
- **A SiC wall will provide a low carbon background to conduct radiative, PMI and impurity studies**
  - C impacts radiative mantle and PFC erosion

Pedestal vs divertor closure



SiC wall to assess behavior without strong C radiation

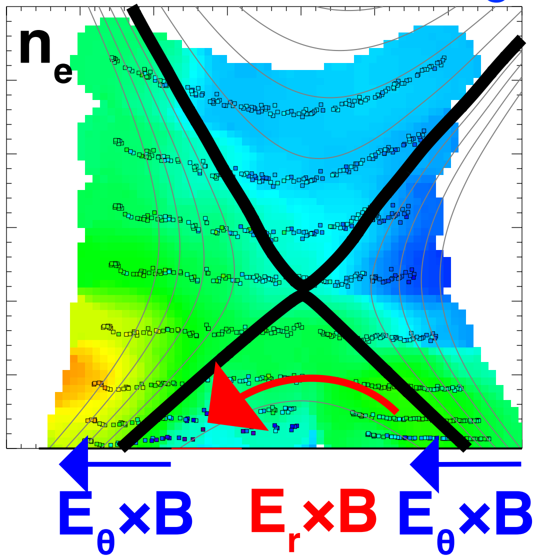


Understand physics of core-edge interaction

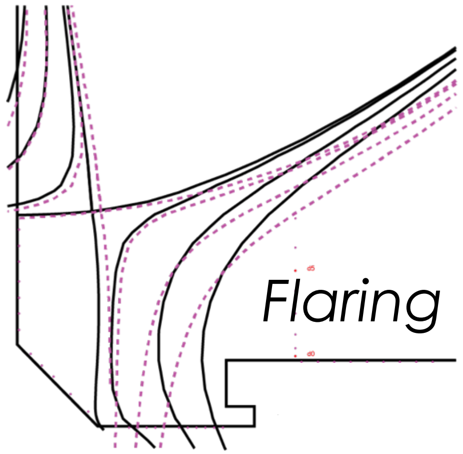
DIII-D Will Develop Physics of Dissipative Detached State and Configurations to Project Reactor Solutions

- **Key challenges**
  - Understand physics processes of dissipative divertor
  - Develop concepts for improved divertor: *full detachment compatible with low ν* reactor core*
- **Tightly coupled processes**
  - Atomic, molecular and neutral dissipation
  - Plasma drifts and parallel flows
  - Turbulent transport
- **Address critical physics**
  - Increased 2D diagnostics, especially T_i and neutrals
  - High density, high power, closed configurations
    - *Assess role of closure and magnetic geometry in containing neutrals and detachment*
  - Close coupling to model validation & development

2D Thomson scattering



Flows play key role in detachment



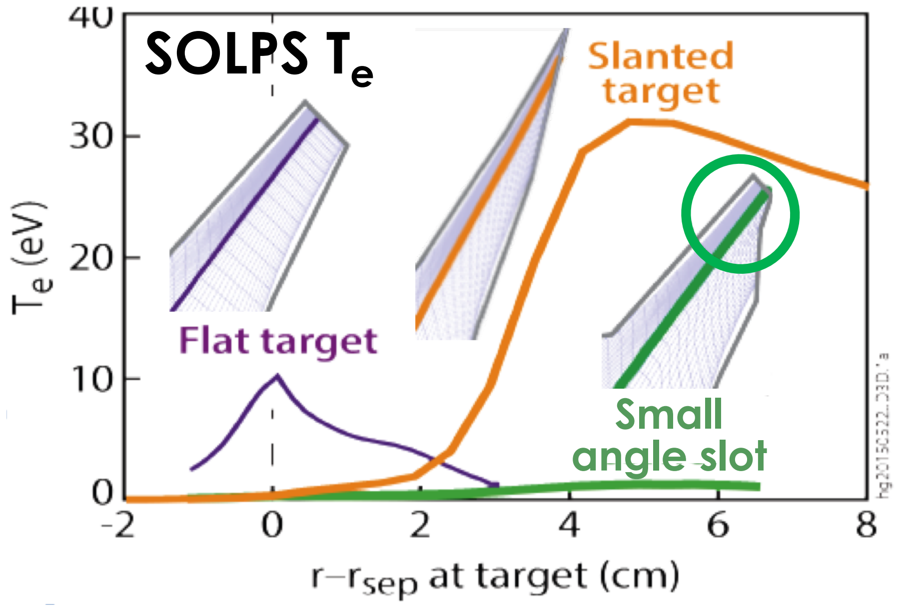
Basis to develop validated models of detachment

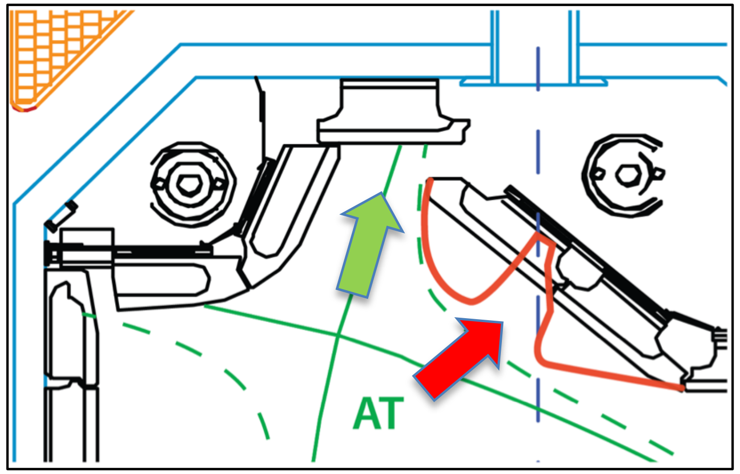
DIII-D Will Develop Innovative Closed Divertor Concepts in High Power Conditions

- **Goal: Minimize divertor volume needed for steady state operation**
  - Low plasma temperature across target
  - Compatibility with high performance core

- **Approach**
  - Close divertor
  - Direct neutrals to detach on all surfaces
  - Manipulate magnetic geometry to keep detachment front in divertor

- **Plan**
  - Explore closure geometry
  - Assess in high power main pumped divertors
  - Develop innovative particle and heat exhaust scenarios *(gas & impurity injection; magnetic geometry)*





Key contributions to the 'Divertor Test Tokamak' mission

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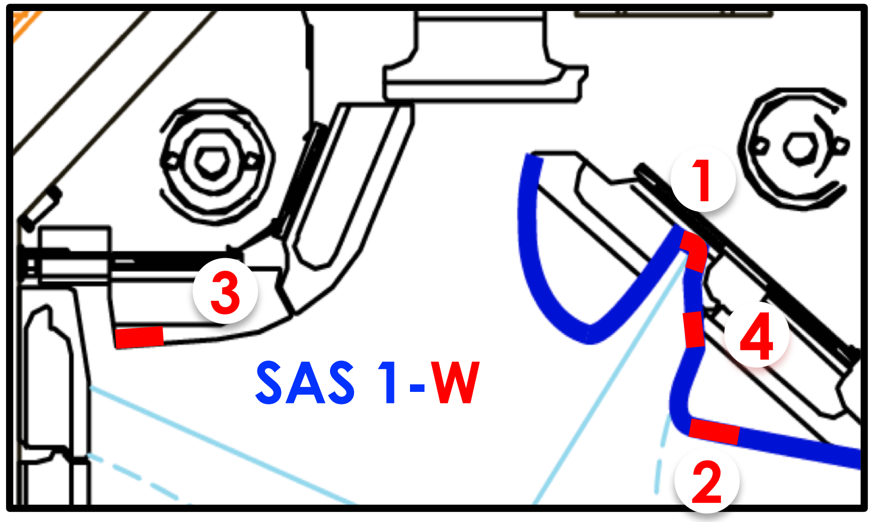
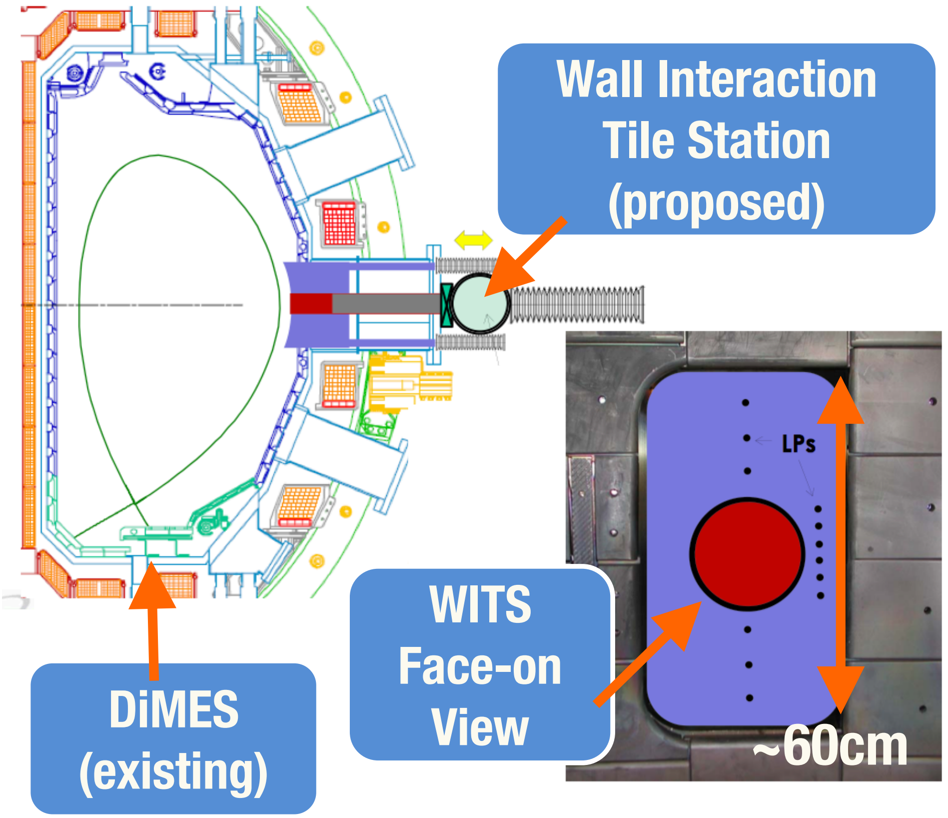
DIII-D Can Provide Unique Insights in Plasma-Materials Interaction Solutions for a Fusion Reactor

- **Focus on mixed material solution: high Z divertor with low Z wall**
- **DIII-D strength: perturbative measurement of impurity dynamics against low Z background**
  - Laser blow off & spectroscopy techniques to understand impurity transport
  - SiC wall will provide low C source background to remove low Z induced sputtering
- **Assess high-Z interaction with closed divertors**
  - Sources. Role in dissipation. Leakage
- **Test PMI & innovative materials in wall & divertor**
  - Flexible sample facilities & region tests
  - Heated tile testing





Unique opportunity to resolve physics basis with relevant materials and conditions

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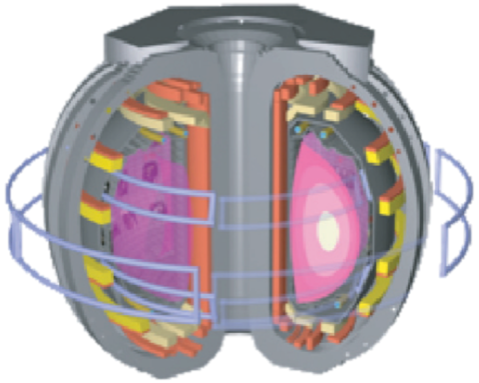
Upgraded DIII-D Addresses the Critical Challenges the U.S. Needs to Pursue for Fusion Energy



DIII-D

\+ **Core-Edge Upgrade** ⇒ **U.S. leadership on ITER** / **Basis to proceed with U.S. D-T pilot**

- **Redevelopment of facility transforms access to new physics regimes & behaviors**
  - Explore new frontiers in plasma science to meet critical challenges for fusion energy
- **Provides state of the art tool to U.S. community to enable research excellence & leadership**
- **Resolve science & solutions in D-D in DIII-D so we can succeed with D-T**
  - DIII-D 5 Year Proposal is an important first step & should be fully funded

If we didn't have a DIII-D, we would build one to address these exciting & important scientific challenges

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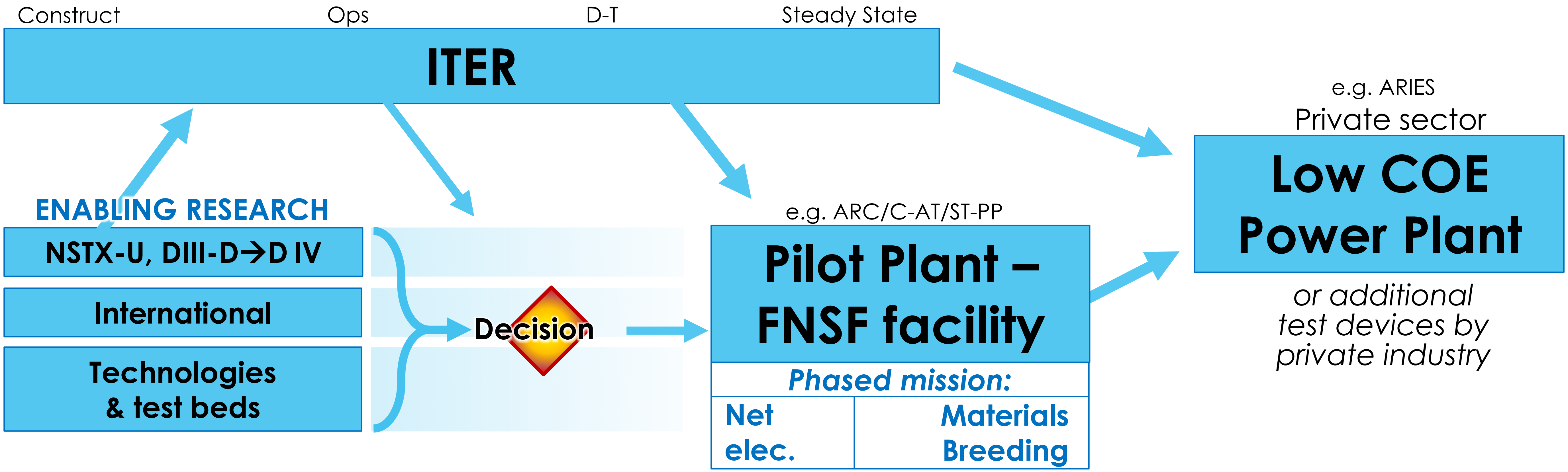
REFERENCE SLIDES

U.S. Pilot Plant Strategy Levers ITER Role with Distinctive Science & Technology Innovations



Provides key insights in world path to fusion energy

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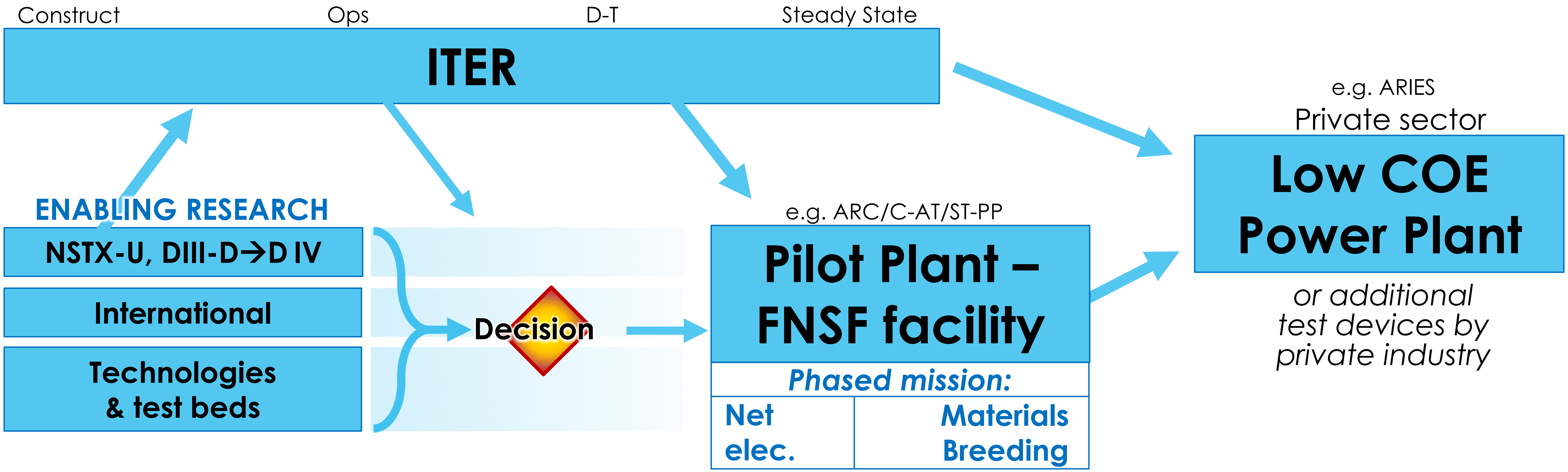
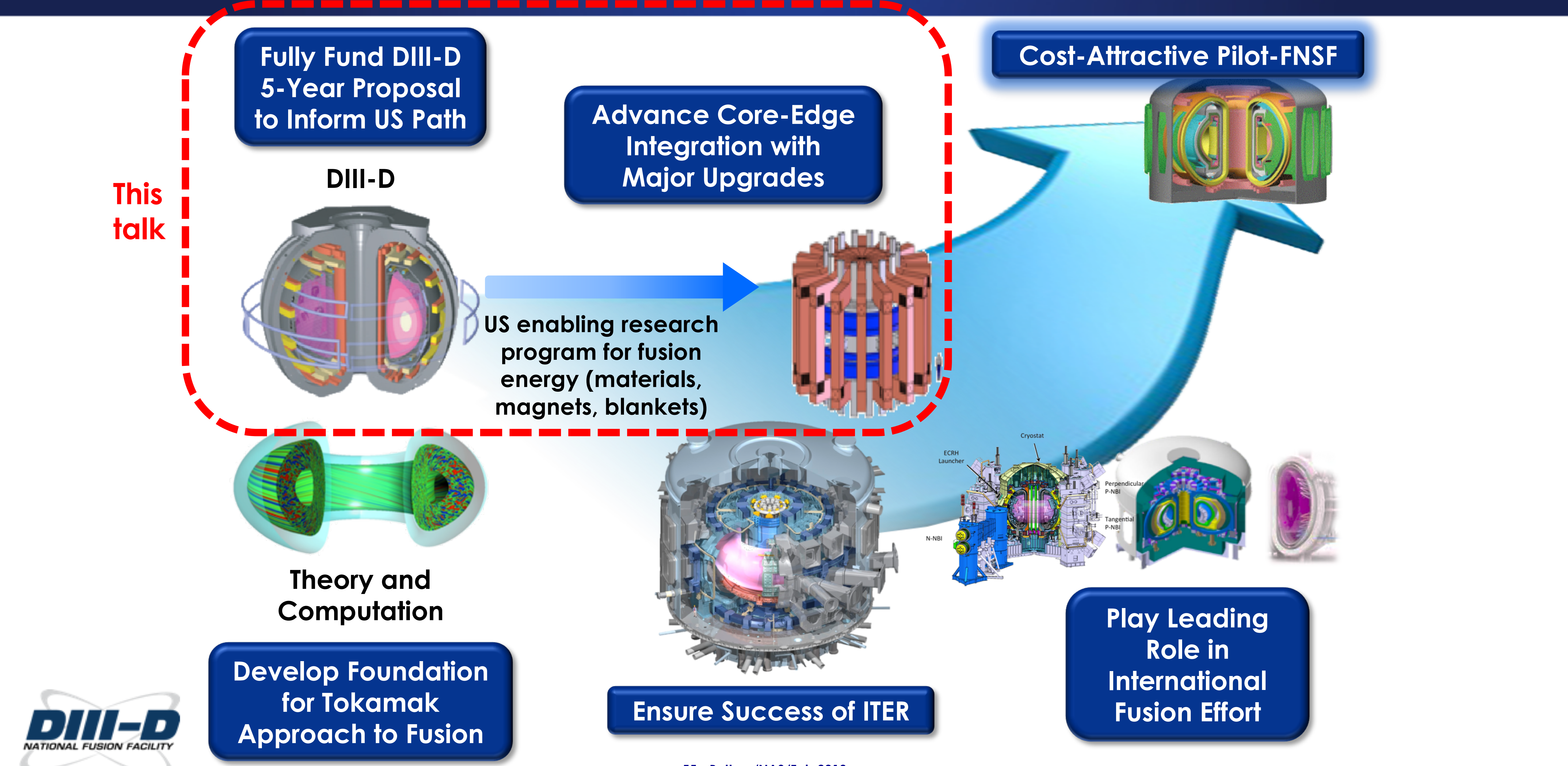


Provides key insights in world path to fusion energy

Without ITER : *Add short pulse low Q facility to gain expertise*

DIII-D NATIONAL FUSION FACILITY

GA Vision and Strategy from Scientific Excellence to Fusion Energy

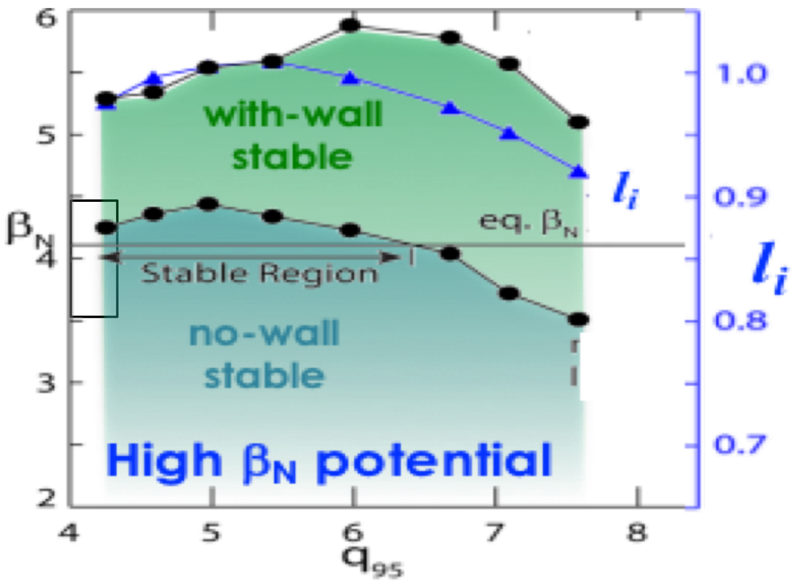


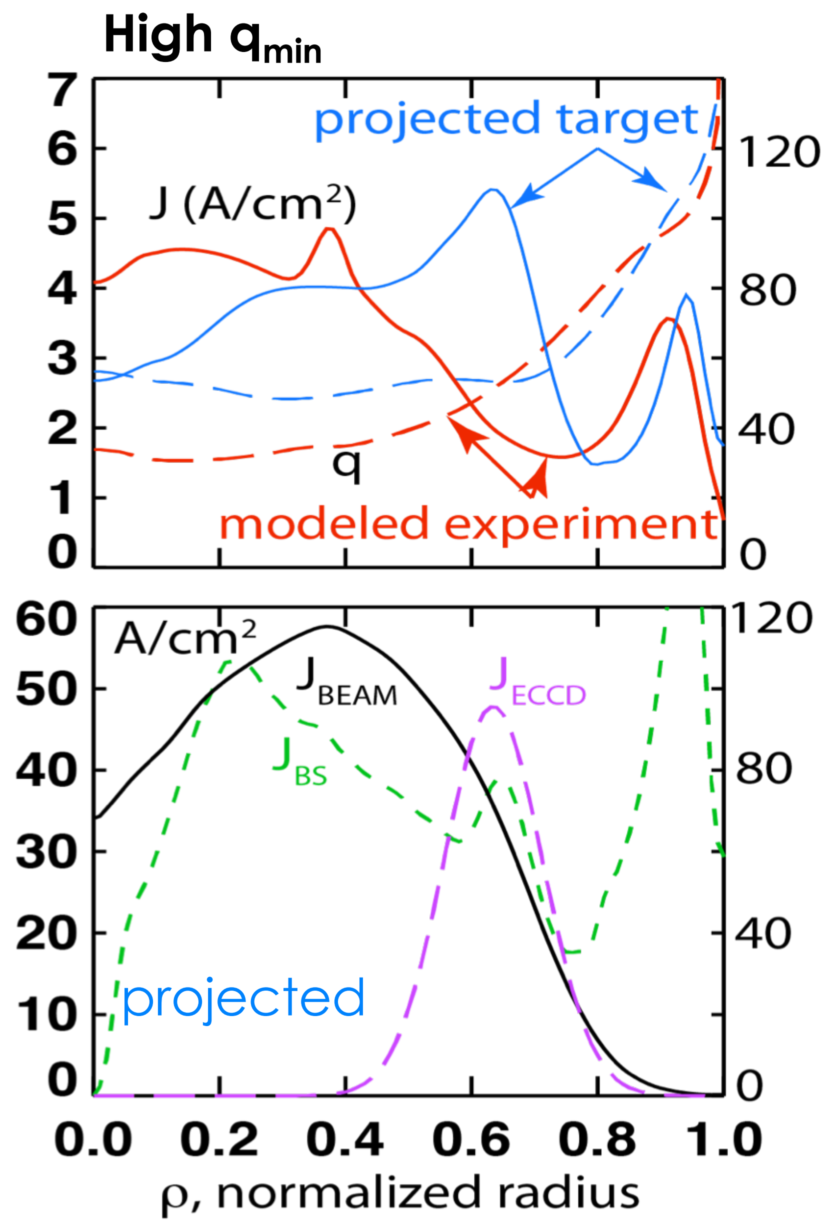
Steady State Projections with H&CD Upgrades: Co-injected beam cases

- **High q_{min} with 9MW ECCD & half beam power off axis ➔**

On-Ax NBI (MW)	Off-Ax NBI (MW)	ECH (MW)	Transport Limit in β_N	Ideal Stability β_N Limit
7.5	3.3	3.2 (FY16)	3.5 (q_{min}=1.5, f_{NI}=0.75)	3.7
9.5	10.7	9 (FY24)	5.1	4.9 (q_{min}>2, f_{NI}=1)

- **High l_i with 9MW ECCD & beam upgrade:** (see next)



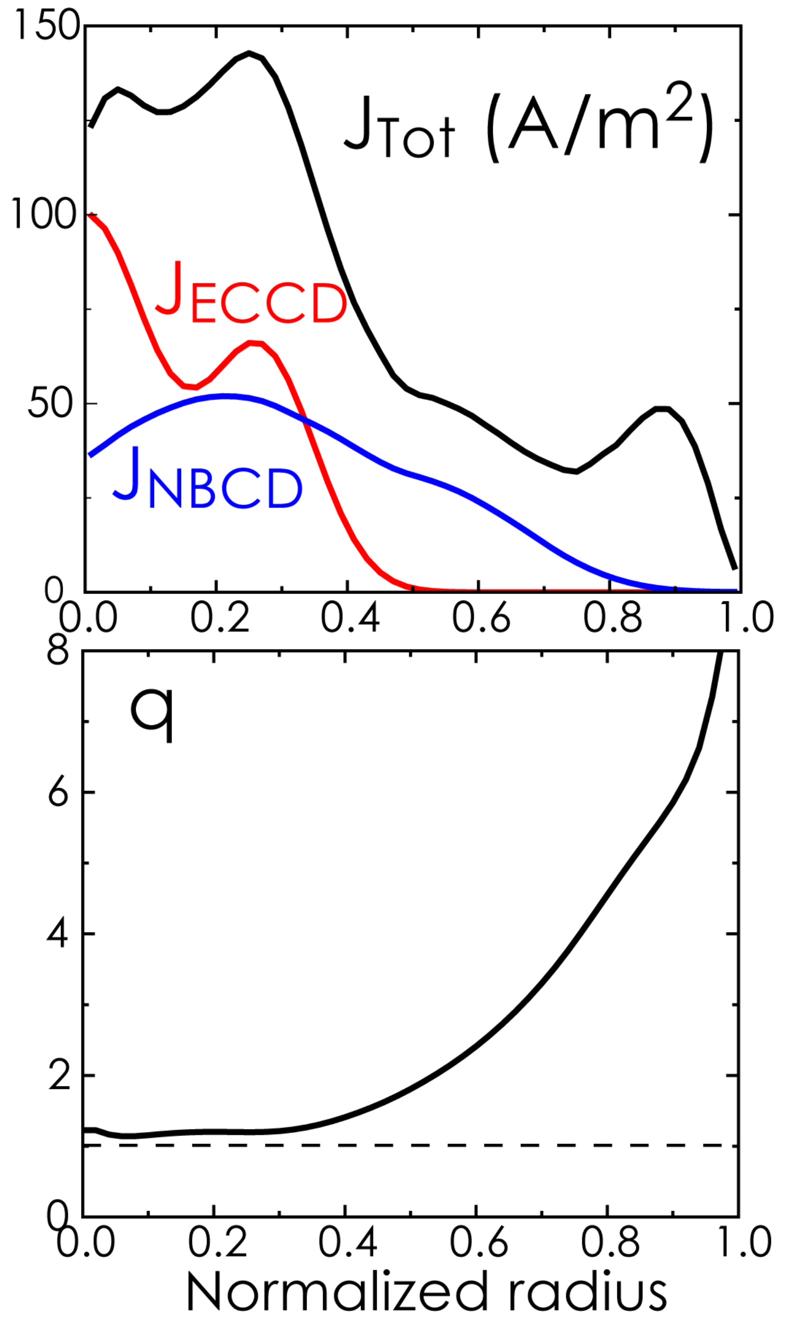


We Will Also Develop the High-*li* Scenario as an Alternative Solution for β_N~4 Without Need for Wall Stabilization

- **Peaked current gives high no-wall limit & good confinement**
- **No need for n>0 active feedback stabilization**
- **Requires more driven current**

- **Research items:**
  - Must learn to deal with sawteeth and 2/1 tearing modes
  - Benefits from reduced pedestal height

- **FASTRAN predicts same NBI & ECH upgrades enable f_{NI}=1 high-*li* at β_N=4** ⇨
  - Below no-wall limit
  - 9 MW near-axis ECCD required



9 MW gyrotrons, off-axis NBI, 3D coils & power supplies

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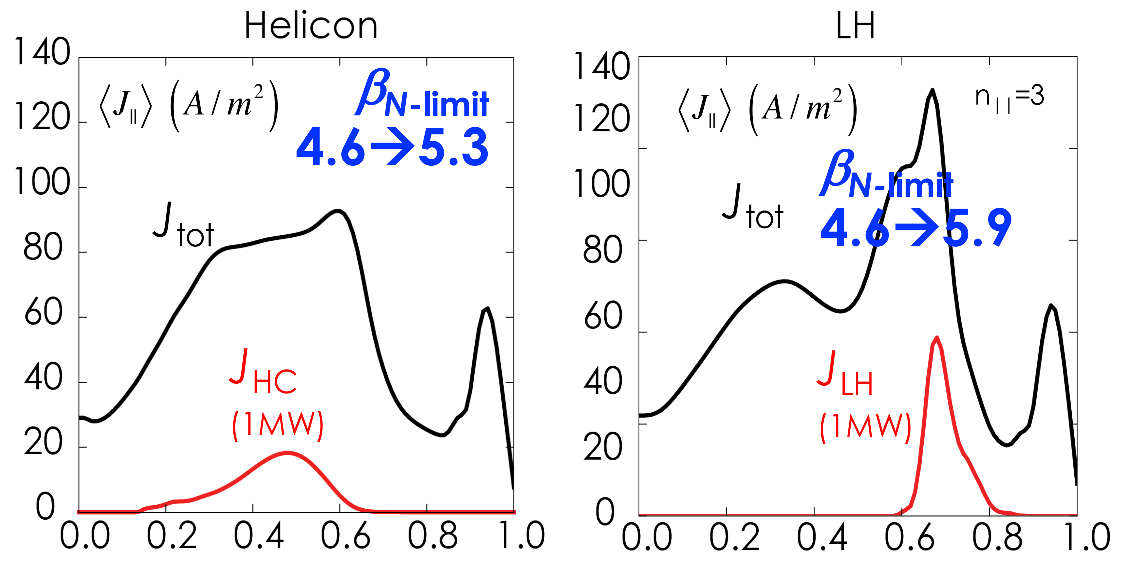
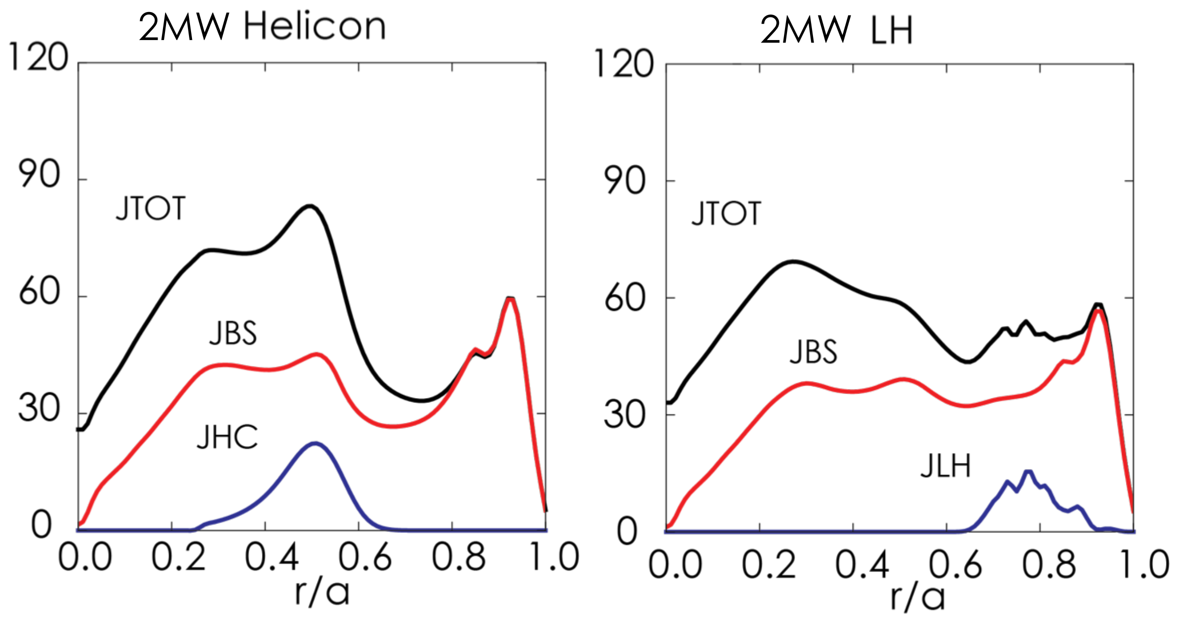
Helicon or Lower Hybrid Can Raise β_N limits & provide access to high density steady states

- **Co-injected beams β_N limit raised ➔**

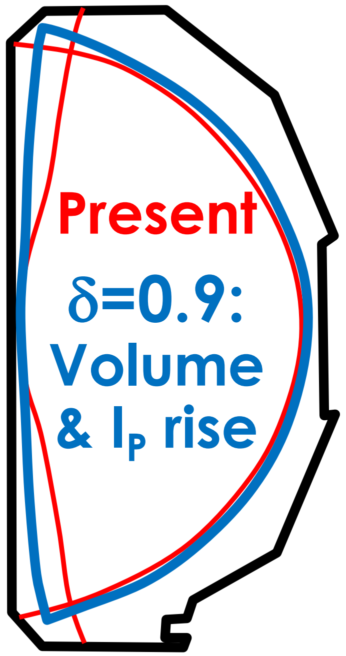


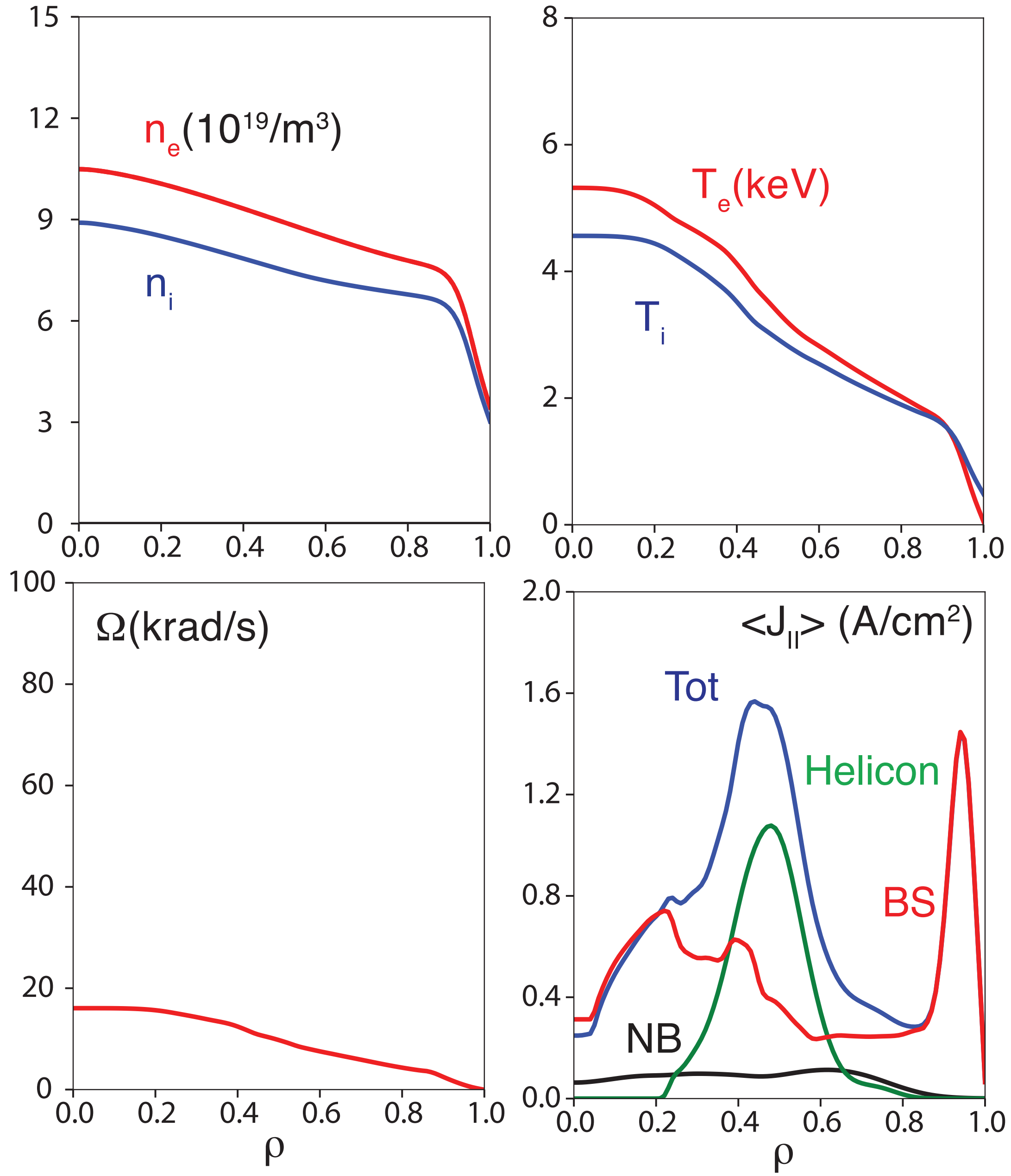
- **High density solutions without ECH and co-injected beams ➔**

FASTRAN: f_{NI}=1, f_{BS}≈0.7, β_N≈5, f_{GW}=0.9, 9.6 MW off-axis NBI, 0 MW ECH, B=1.6 T, q_{95}=6.5



High density higher volume ‘core-edge’ solution





<u>FASTRAN integrated simulation:</u>

Fully non-inductive, 65% bootstrap,
2T, 3MJ, $f_{fast\ ion}$~15%, β_N=4, $\beta_{N\text{-}limit}$=10
ν^*_{ped} ~0.24, n_{ped}=7.5E19, T_e>T_i, Ω~20krad/s
25MW balanced NBI +10MW helicon

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FASTRAN Validation vs DIII-D

- **FASTRAN routinely used in DIII-D program to interpret results, test underlying models and guide development**
  - Combines TGLF, EPED, H&CD source models and equilibria
  -

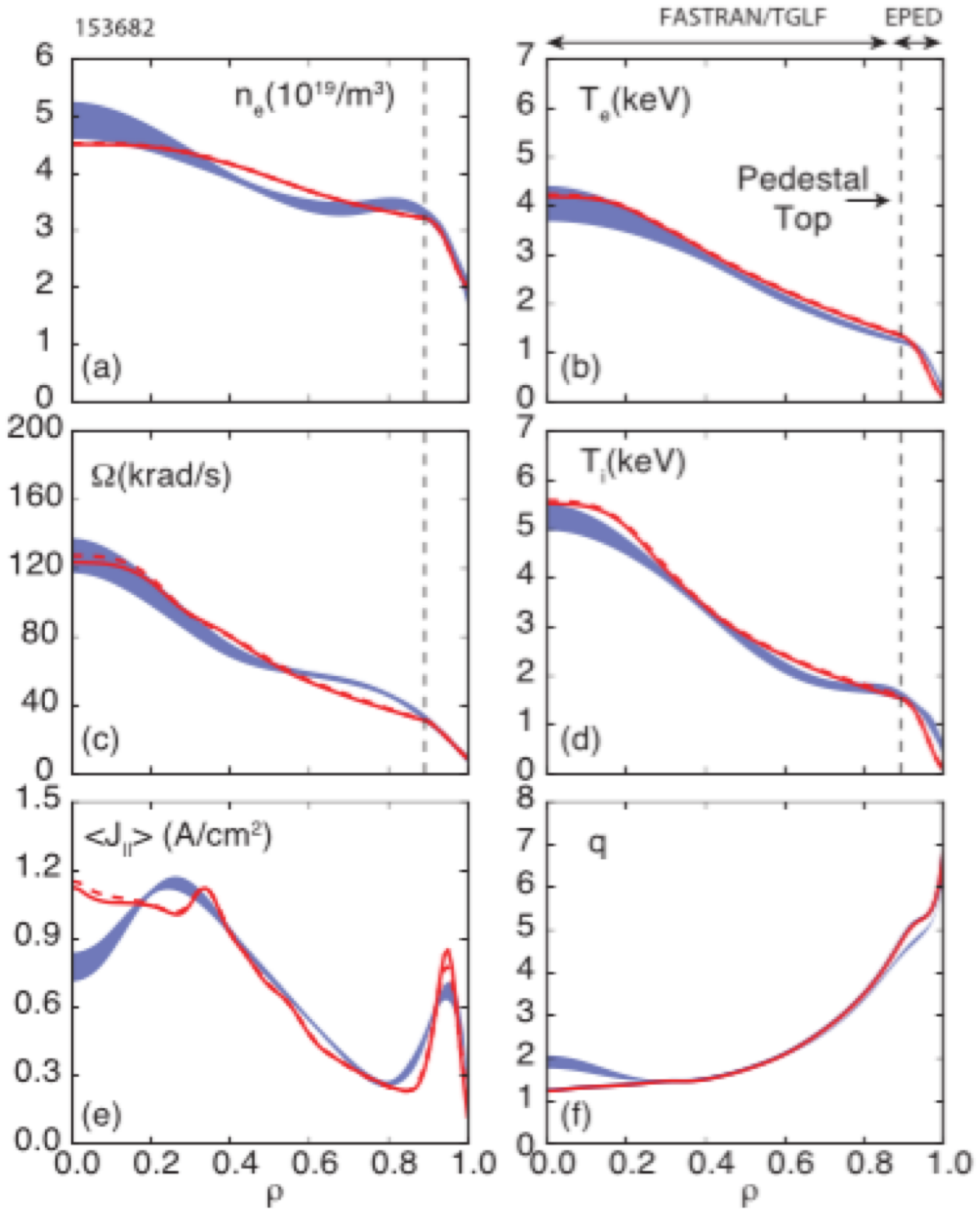

FIG. 1. Calculated radial profiles (red) compared with experimental measurements (blue): (a) electron density, (b) electron temperature, (c) toroidal plasma rotation, (d) ion temperature, (e) surface-averaged parallel plasma current density, and (g) safety factor. The shade denotes a random error bar for the time-varying experimental profile averaged over $4 < t < 5$ s during stationary high β_N phase. The calculated profiles are plotted at the end of the 4th (dashed) and 5th (solid) iterations of the steady-state solution procedures to update the sources, MHD equilibrium, and boundary conditions. The vertical line shows the location of the edge pedestal top.