Meeting the Bold Decadal Vision

Update from the DIII-D National Program

Presented by

RJ Buttery

on behalf of the DIII-D team

To

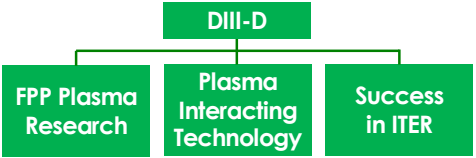
Fusion Power Associates Annual Meeting

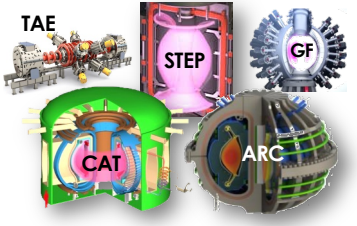
Dec 20th 2023

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

DIII-D Embracing Long Range Plan & Bold Decadal Vision

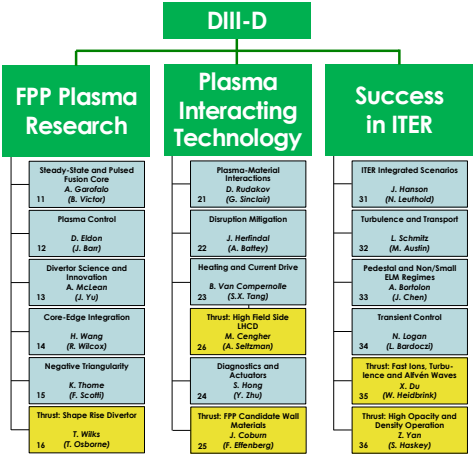
- **Restructured to close gaps on FPP & ITER**
  - **Goal oriented decision making structures ➔**
  - TRL approach targets reactor needs





DIII-D Embracing Long Range Plan & Bold Decadal Vision

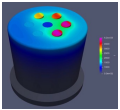
- **Restructured to close gaps on FPP & ITER**
  - Goal oriented decision making structures
  - TRL approach targets reactor needs
  - **Shared leadership model reflects participation ➔**
    - *33% Unis, 31% Nat labs, 31% GA, 4% international*
    - *13% women (6 out of 48 roles)*
    - *Many early career leadership opportunities*



DIII-D Embracing Long Range Plan & Bold Decadal Vision

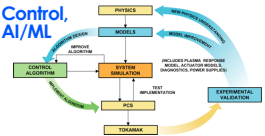
- **Restructured to close gaps on FPP & ITER**
  - Goal oriented decision making structures
  - TRL approach targets reactor needs
  - Shared leadership model reflects participation
- **Plasma Interacting Technology Program**
  - Platform approach: rapid access & support
  - Explicit FPP goal, serving wider community

Materials

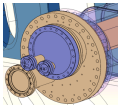


Tiles & PFC

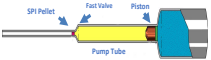
Control, AI/ML



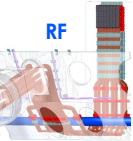
Diagnostics



Pellets



RF

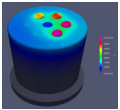


3D

DIII-D Embracing Long Range Plan & Bold Decadal Vision

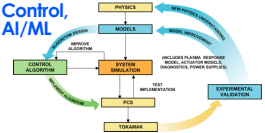
- **Restructured to close gaps on FPP & ITER**
  - Goal oriented decision making structures
  - TRL approach targets reactor needs
  - Shared leadership model reflects participation
- **Plasma Interacting Technology Program**
  - Platform approach: rapid access & support
  - Explicit FPP goal, serving wider community
- **Outreach to private sector & wider community**
  - New user framework - open, free, supported. IP protected
  - Workshops, consultations, Program Advisor Committee
    - *7 institutions signed up already*

Materials

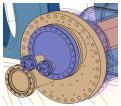


Tiles & PFC

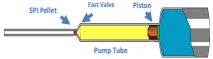
Control, AI/ML



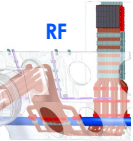
Diagnostics



Pellets



RF



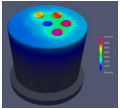
3D

DIII-D NATIONAL FUSION FACILITY

DIII-D Embracing Long Range Plan & Bold Decadal Vision

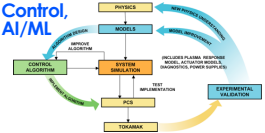
- **Restructured to close gaps on FPP & ITER**
  - Goal oriented decision making structures
  - TRL approach targets reactor needs
  - Shared leadership model reflects participation
- **Plasma Interacting Technology Program**
  - Platform approach: rapid access & support
  - Explicit FPP goal, serving wider community
- **Outreach to private sector & wider community**
  - New user framework - open, free, supported. IP protected
- **Independent oversight**
  - New User Board of PIs, chaired by university
    - *Representative Research Council selected run priorities*
  - All projects determined & owned by DOE

Materials

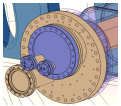


Tiles & PFC

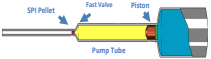
Control, AI/ML



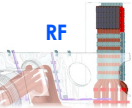
Diagnostics



Pellets



RF



3D

DIII-D NATIONAL FUSION FACILITY

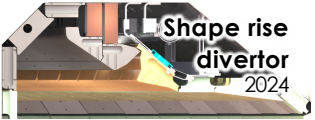
Serving the national interest as an SC User Facility

Developments Underway Close Key Gaps on Fusion Energy

- **Gyrotron upgrade to 10 lines, doubling power**
  - Scope steady state and pulsed FPP limits & develop control in burning plasma relevant regimes

Developments Underway Close Key Gaps on Fusion Energy

- **Gyrotron upgrade to 10 lines, doubling power**
  - Scope steady state and pulsed FPP limits & develop control in burning plasma relevant regimes



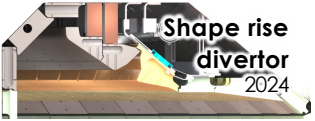
- **New shape & volume rise divertor being installed**
  - Extend pedestal density & pressure limits & test slot principles

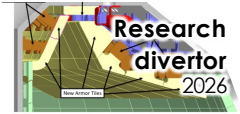
DIII-D NATIONAL FUSION FACILITY

Developments Underway Close Key Gaps on Fusion Energy

- **Gyrotron upgrade to 10 lines, doubling power**
  - Scope steady state and pulsed FPP limits & develop control in burning plasma relevant regimes

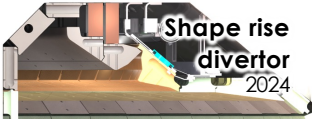
- **New shape & volume rise divertor being installed**
  - Extend pedestal density & pressure limits & test slot principles
  - *Successor research divertor to isolate detachment in planning* ➔

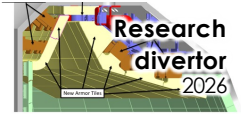


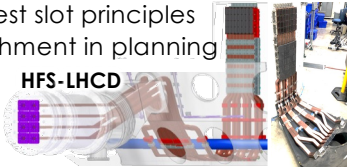


Developments Underway Close Key Gaps on Fusion Energy

- **Gyrotron upgrade to 10 lines, doubling power**
  - Scope steady state and pulsed FPP limits & develop control in burning plasma relevant regimes
- **New shape & volume rise divertor being installed**
  - Extend pedestal density & pressure limits & test slot principles
  - Successor research divertor to isolate detachment in planning
- **New high field side LHCD system**
  - Efficient high density current for reactors



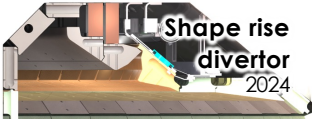


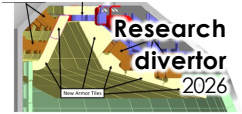


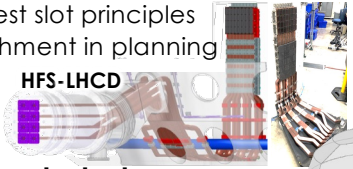
← *built*

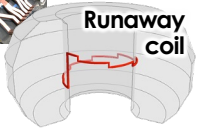
Developments Underway Close Key Gaps on Fusion Energy

- **Gyrotron upgrade to 10 lines, doubling power**
  - Scope steady state and pulsed FPP limits & develop control in burning plasma relevant regimes
- **New shape & volume rise divertor being installed**
  - Extend pedestal density & pressure limits & test slot principles
  - Successor research divertor to isolate detachment in planning
- **New high field side LHCD system**
  - Efficient high density current for reactors
- **Runaway electron mitigation coil design started**



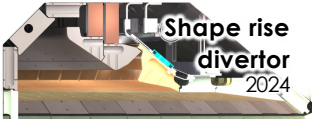


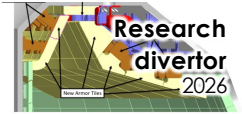


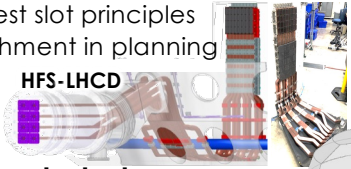


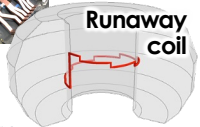
Developments Underway Close Key Gaps on Fusion Energy

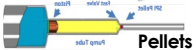
- **Gyrotron upgrade to 10 lines, doubling power**
  - Scope steady state and pulsed FPP limits & develop control in burning plasma relevant regimes
- **New shape & volume rise divertor being installed**
  - Extend pedestal density & pressure limits & test slot principles
  - Successor research divertor to isolate detachment in planning
- **New high field side LHCD system**
  - Efficient high density current for reactors
- **Runaway electron mitigation coil design started**
- **Pellet upgrades to raise density & solve disruptions**







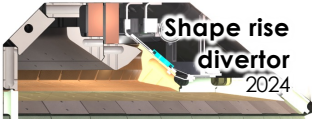


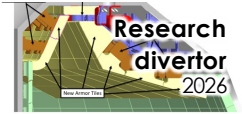


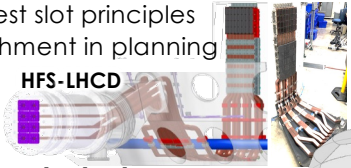
DIII-D NATIONAL FUSION FACILITY

Developments Underway Close Key Gaps on Fusion Energy

- **Gyrotron upgrade to 10 lines, doubling power**
  - Scope steady state and pulsed FPP limits & develop control in burning plasma relevant regimes
- **New shape & volume rise divertor being installed**
  - Extend pedestal density & pressure limits & test slot principles
  - Successor research divertor to isolate detachment in planning
- **New high field side LHCD system**
  - Efficient high density current for reactors
- **Runaway electron mitigation coil design started**
- **Pellet upgrades to raise density & solve disruptions**
- **Planning full wall change out & technology tests**
  - *Address fusion technology needs including innovation in plasma confinement with relevant wall material – materials choice by community*







DIII-D NATIONAL FUSION FACILITY

Exciting capabilities in next 1 – 4 years

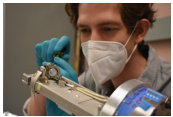
Supporting Development of Workforce & Addressing DEIA

- **Early career opportunities**
  - Leading science, talks, papers, systems
  - New mentorship program

Prof. Livia Casali
"Innovative Core-Edge Solutions for Tokamaks"
Co-lead DIII-D Core-Edge Task Force
Now Professor at UT Knoxville
Early career award

Shaun Haskey
"Main Ion Transport and Fueling in the Pedestal: From Formation to Sustainment"
Leader of key DIII-D CER diagnostic
Early career award

Mike Van Zeeland
APS Fellow



A. Rosenthal
MIT PhD
DOE SC Highlight

DIII-D NATIONAL FUSION FACILITY

Supporting Development of Workforce & Addressing DEIA

- **Early career opportunities**
  - Leading science, talks, papers, systems
  - New mentorship program
- **Strong student engagement**
  - Dedicated PhD run time supported 18 theses
  - Learning seminars & social connection
  - Year round internships thru' SULI & CCL
  - 254 postdocs & students; 36 uni PIs

Prof. Livia Casali
"Innovative Core-Edge Solutions for Tokamaks"
Co-lead DIII-D Core-Edge Task Force
Now Professor at UT Knoxville
Early career award

Shaun Haskey
"Main Ion Transport and Fueling in the Pedestal: From Formation to Sustainment"
Leader of key DIII-D CER diagnostic
Early career award

Mike Van Zeeland
APS Fellow

A. Rosenthal
MIT PhD
DOE SC Highlight

FY23 universities

Graduate	123
Undergrad	78
Uni PI awards	36

DIII-D NATIONAL FUSION FACILITY

Supporting Development of Workforce & Addressing DEIA

- **Early career opportunities**
  - Leading science, talks, papers, systems
  - New mentorship program
- **Strong student engagement**
  - Dedicated PhD run time supported 18 theses
  - Learning seminars & social connection
  - Year round internships thru' SULI & CCL
- **Addressing DEIA**
  - Code of conduct with consequences
  - Open opportunities policy w/ career pathways
  - Implicit bias and bystander training
  - SWE, HSIs, CuWiP, GEM interns, Preuss school, girls TechTrek
  - Pioneering double anonymized XP review

Prof. Livia Casali
"Innovative Core-Edge Solutions for Tokamaks"
Co-lead DIII-D Core-Edge Task Force
Now Professor at UT Knoxville
Early career award

Shaun Haskey
"Main Ion Transport and Fueling in the Pedestal: From Formation to Sustainment"
Leader of key DIII-D CER diagnostic
Early career award

Mike Van Zeeland
APS Fellow

A. Rosenthal
MIT PhD
DOE SC Highlight

FY23 universities

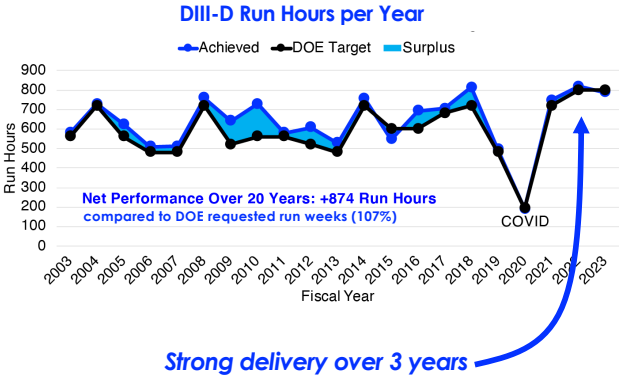
Graduate	123
Undergrad	78
Uni PI awards	36

Ongoing path – more work needed

DIII-D NATIONAL FUSION FACILITY

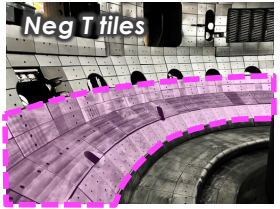
Research is Rapidly Advancing the Field

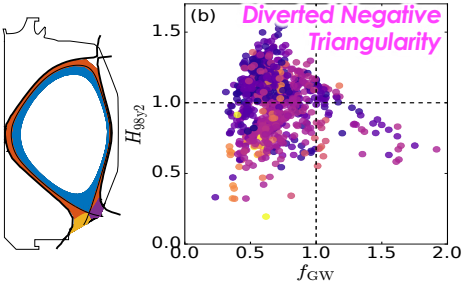
- **Record 1604 hours in last 2 years**
  - 140 scientific studies, 18 PhD theses
  - Hybrid remote operation developed



Research is Rapidly Advancing the Field

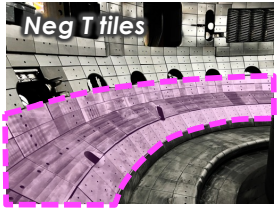
- **Record 1604 hours in last 2 years**
- **Strong delivery of projects**
  - **Negative triangularity armor enabled transformational insights into exciting potential reactor configuration ➔**



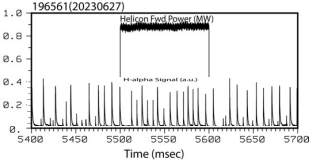


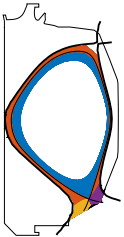
Research is Rapidly Advancing the Field

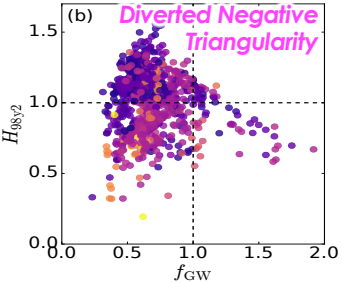
- **Record 1604 hours in last 2 years**
- **Strong delivery of projects**
  - Negative triangularity armor enabled transformational insights into exciting potential reactor configuration
  - **New helicon ultrahigh harmonic fast wave with innovative traveling wave antenna provided heating & current drive**



Over 500kW helicon coupled in H mode



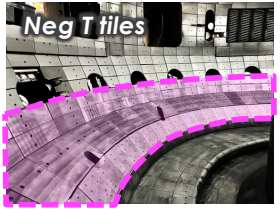




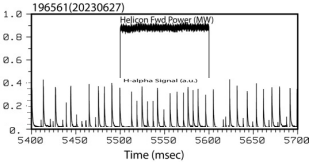
DIII-D NATIONAL FUSION FACILITY

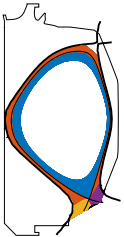
Research is Rapidly Advancing the Field

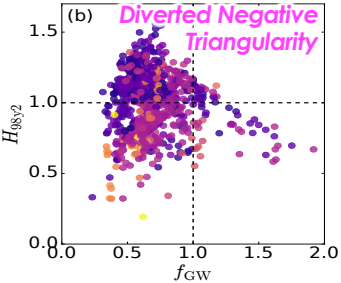
- **Record 1604 hours in last 2 years**
- **Strong delivery of projects**
  - Negative triangularity armor enabled transformational insights into exciting potential reactor configuration
  - New helicon ultrahigh harmonic fast wave with innovative traveling wave antenna provided heating & current drive
  - **Vent on track & budget for 2024-25 operation**



Over 500kW helicon coupled in H mode



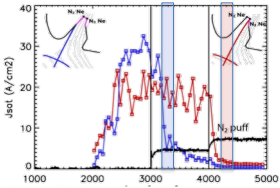




DIII-D NATIONAL FUSION FACILITY

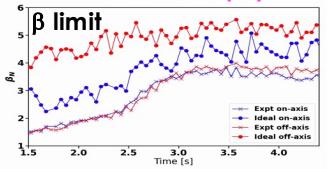
Research is Rapidly Advancing the Field

- Record 1604 hours in last 2 years
- Strong delivery of projects
- Exciting scientific results

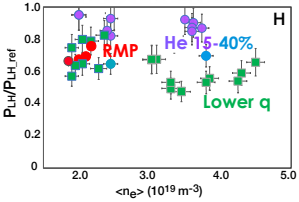


Small Angle Slot divertor improved performance with detachment

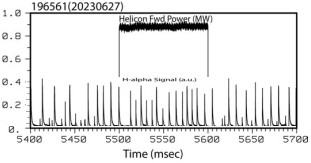
Off-axis beams & ECH show path to improved stability in ideal MHD and EP physics

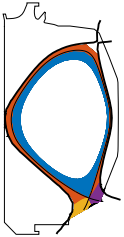


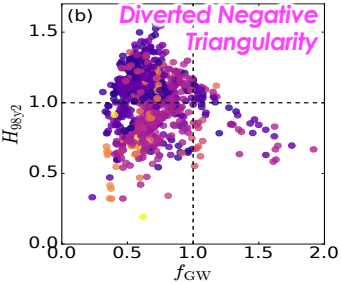
H mode access for ITER



Over 500kW helicon coupled in H mode







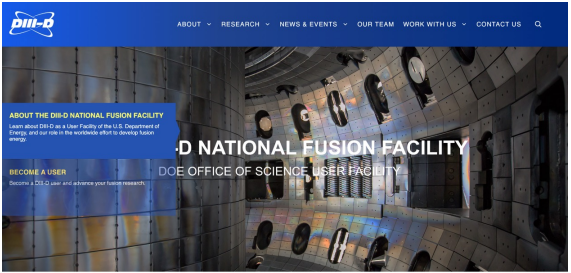
Research is Rapidly Advancing the Field

- **Record 1604 hours in last 2 years**
- **Strong delivery of projects**
- **Exciting scientific results**
- **International engagement**
  - ***New joint task forces on:***
    - **Long pulse with Tungsten**
    - **High beta AT**
  - ***Support by DIII-D team members to many international facilities***
  - ***Strong & accelerating engagement with ITER***

imas

Research is Rapidly Advancing the Field – *Open to More*

- **Record 1604 hours in last 2 years**
- **Strong delivery of projects**
- **Exciting scientific results**
- **International engagement**



A DOE OFFICE OF SCIENCE USER FACILITY HOSTED BY GENERAL ATOMICS

Call for proposals:

- **Fusion:** d3dfusion.org
- **Frontiers:** callforruntimeproposals.org
- **Technology:** Tyler Abrams & Andrew Dvorak
  - *abramst@fusion.gat.com dvorako@ornl.gov*

Diagnostics: *Suk-Ho Hong hongsukho@fusion.gat.com*
RF: *Bart Compernolle vancompernolle@fusion.gat.com*
Disruptions: *Jeff Herfindal herfindalj@fusion.gat.com*
Materials: *Dmitri Rudakov rudakov@fusion.gat.com and Greg Sinclair sinclairg@fusion.gat.com*

Get in touch to develop ideas

DIII-D NATIONAL FUSION FACILITY

DIII-D Working to Rapidly Advance US Fusion Agenda

- **High productivity research program with rapid upgrade capability**

- **Re-oriented to address goals of the Long Range Plan and Bold Decadal Vision**

- **Available, open, supported User Facility for the whole nation**

Come join us – we are here to help

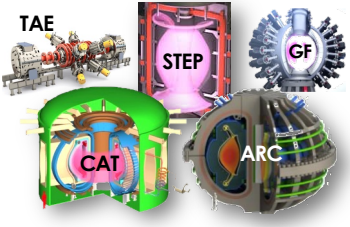
DIII-D NATIONAL FUSION FACILITY

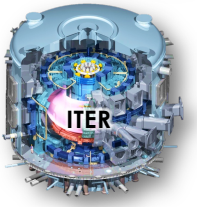
Additional Information Slides

DIII-D is Being Redeveloped for the Fusion Era

Pursue rapid progress and goal-oriented approach

- **A high volume, effective research facility**
- **Close the necessary research gaps for an FPP**
  - Execute 'the EXCITE mission'
- **Testbed for fusion technology and private sector**
- **Enable ITER to rapidly reach its potential**
- **Basis for international collaboration and leadership**





Critical infrastructure to rapidly advance fusion goals

DIII-D NATIONAL FUSION FACILITY

Compact Fusion Pilot Poses Critical Plasma Research and Integration Challenge

Compact scale requires higher power densities:

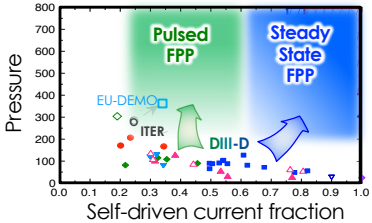
- **High pressure** and **energy confinement**
  - To fuse sufficiently in smaller volume & retain heat
- **Power handling** and **wall compatibility**
  - To mitigate hot plasma exhaust at high duty cycle
- **Plasma interacting technologies** and **control**
  - To resolve in plasma & fusion environment

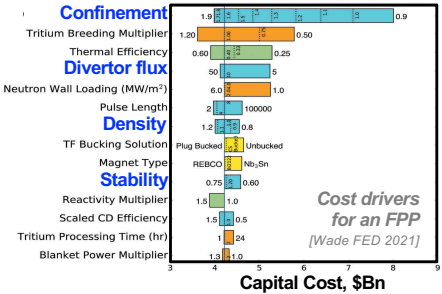
Accounts for key cost drivers in the FPP ➔

- Each needs better solutions than what we know now, requiring physics investigation

Different elements trade off against each other

- Test tog



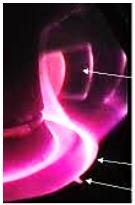


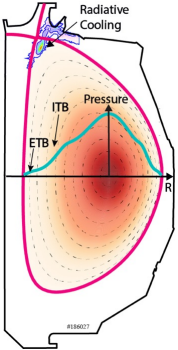
Plasma research vital to FPP design

DIII-D NATIONAL FUSION FACILITY

FPP Requires an Integrated Core-Edge-Technology Solution

- **Tokamak solution optimizes down two paths**
  - **Steady state:** Exploit natural improvements in stability & transport through **shaping**, **profiles** & **high β**
    - *Lower current, self-driven solutions decrease loads and can be sustained noninductively*
    - ***Need to validate projected solutions***
  - **Pulsed:** High confinement through **high current**
    - *Robust performance but increased instability, heat & stress*
    - ***Can stability be maintained?***
- **Common research needs to address power handling, transients, control, and required technologies**
  - Resolve compatibility between different parts of solution





Proposed upgrades enable DIII-D to explore these challenges & discover solutions

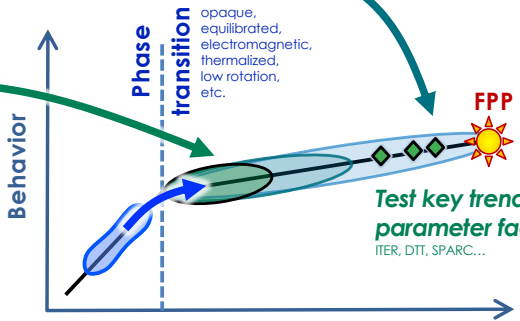
DIII-D NATIONAL FUSION FACILITY

Basis of Approach

(1) Directly access some phenomena at reactor values for physics-governing parameters
e.g. β_N, q_{min}, collisionality

(2) Resolve techniques & science in relevant regimes to project solutions

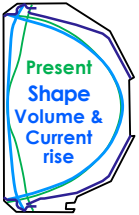
(3) Upgrades needed to access some phenomena in relevant regimes

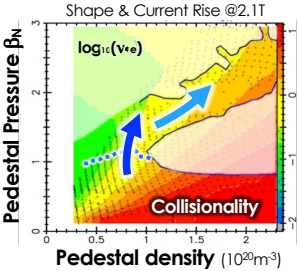


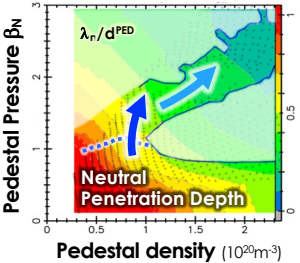
Working with other funded facilities, DIII-D can close required gaps for ITER and FPP

DIII-D Can Close the ITEP Gap on a Fusion Pilot Plant

- **Five year plan sets out the research necessary**
- **Shape and volume rise opens up the potential**
  - Higher pressure and density
  - Opaque regimes at low collisionality
    - → ***Expand limits & access relevant regimes***





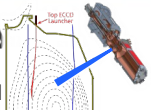


EPED, EIRENE, SOLPS

DIII-D Can Close the ITEP Gap on a Fusion Pilot Plant

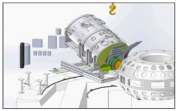
- **Five year plan sets out the research necessary**
- **Shape and volume rise opens up the potentia**
  - Higher pressure and density
  - Opaque regimes at low collisionality
- **RF rise expands to relevant physics regimes**
  - **Supports high density at low collisionality in reactor relevant conditions:**
    - *Thermalized low rotation core*
    - *Divertor-SOL-pedestal-core interaction with short mean free paths & penetration depths*
  - Flexibility to scope & resolve core solutions

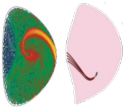
Basis to explore high dissipation exhaust regimes with high performance core



ECH provides electron heating & current drive without fueling or torque

93kV beams provide 25MW heating with low fueling & high current drive





Helicon or HFS LHCD provide high density core heating & current drive

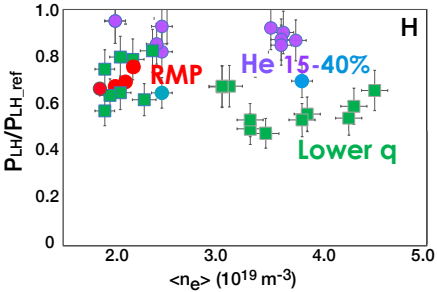
Steady State FPP Core-Edge regimes

H_{98}~ 1.2 β_N~4.5 5-6keV f_{BS}~60-75%
f_{th}~89% ν^*_{ped}~0.1 $q_{||}$~11GW/m²
$\langle n_e \rangle$~8-9E19m^{-3} f_{GW}~60-70% P_{eped}~40kPa $\langle P \rangle$~130kPa
$n_iT_i\tau$~7E19 2.2T 2.1-1.7MA q_{95}~5.2-6.5

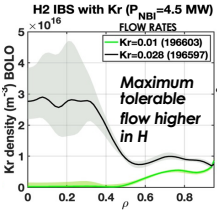
Pulsed FPP regimes that push Core-Edge further

ν^*_{ped}~0.01-0.2 f_{th}~85-97% T_e~T_i Ω~150-50 krad/s,
$q_{||}$~10 GW/m² f_{GW}~ 30-90% Neut. Pen. Depth 4%
$\langle n_e \rangle$~1-2E20m^{-3} P_{ped}~40–60kPa $\langle P \rangle$~150kPa
$n_iT_i\tau$ ~1–2E20 H_{98}~ 1-1.3 β_N~3.5 q_{95}~3.7
2.2T 3MA 42MW (25 NB, 14 EC, 3 HEL) 5MJ

DIII-D NATIONAL FUSION FACILITY



Hydrogen tolerates high Z much better than D



FLOW RATES