DIII-D's Role in Pioneering Fusion Commercialization and Technology

Presented by

RJ Buttery

*for T. Abrams[1], J. Coburn[2], F. Effenberg[3], S. Hong[1], D.C. Pace[1], C.C. Petty[1], A.C.C. Sips[1], D. Schissel[1], F. Scotti[4], D. Shiraki[5], G. Sinclair[1], B. Van Compernolle[1], R. Wilcox[5], S. J. Wukitch[6] and **the DIII-D Team.***

at the

Symposium on Fusion Technology

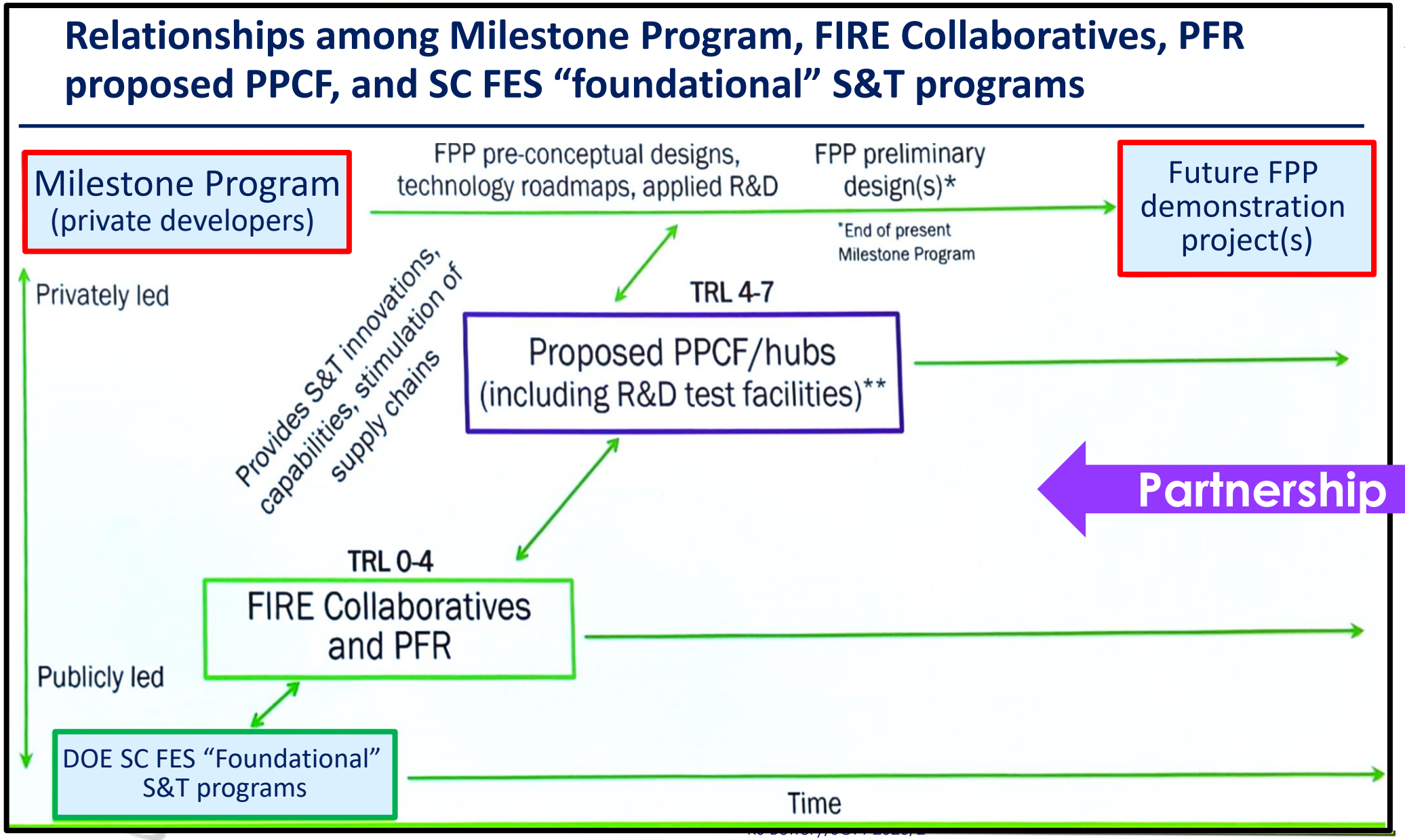
Sep 24th 2026



[1]General Atomics [2]Sandia National Laboratory
[3]Princeton Plasma Physics Laboratory
[4]Lawrence Livermore National Laboratory
[5]Oak Ridge National Laboratory [6]Massachusettes Institute of Technology

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

U.S. Vision Envisages Rich Research Infrastructure Partnering Public and Private Sector

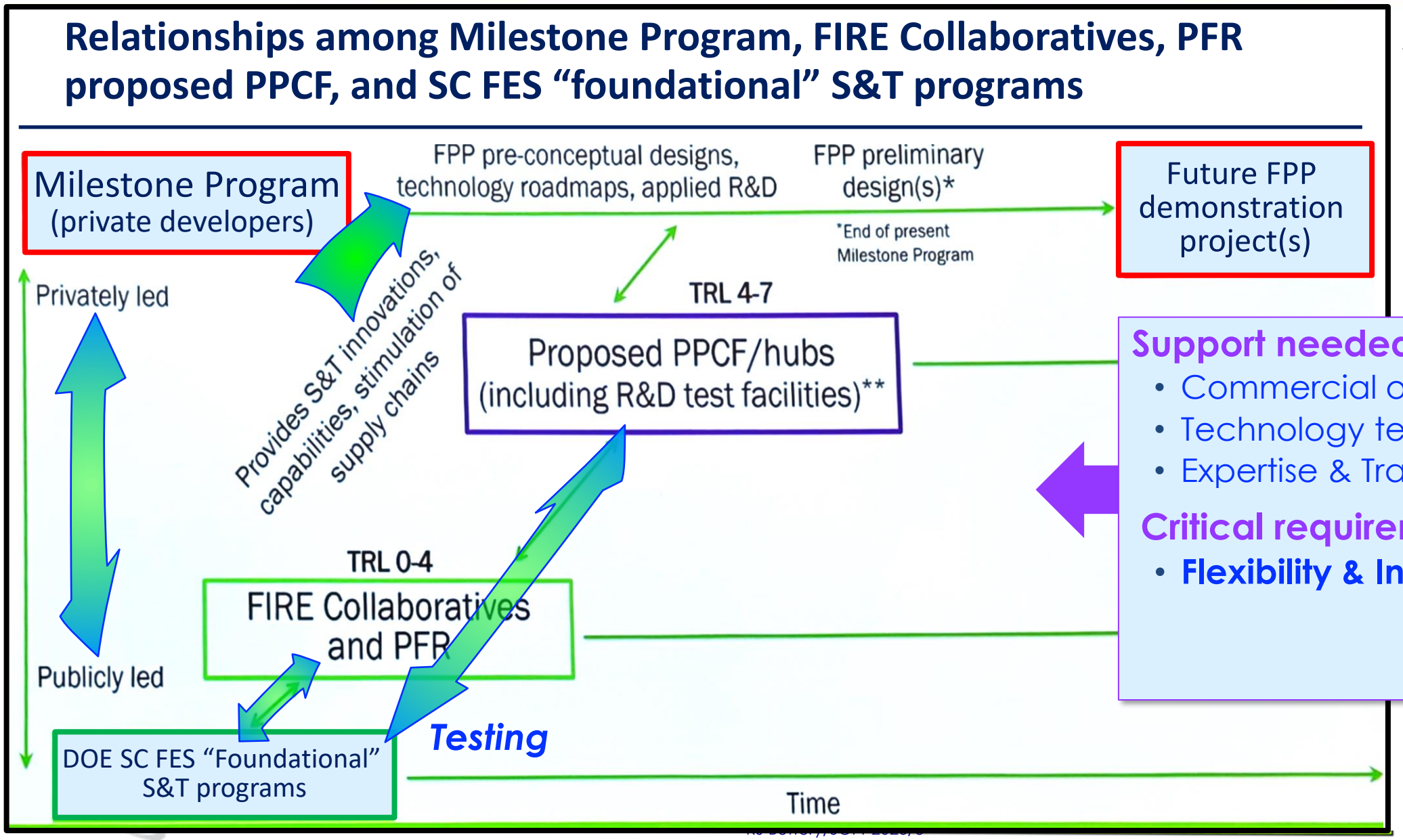


JP Allain
UFA, 2024

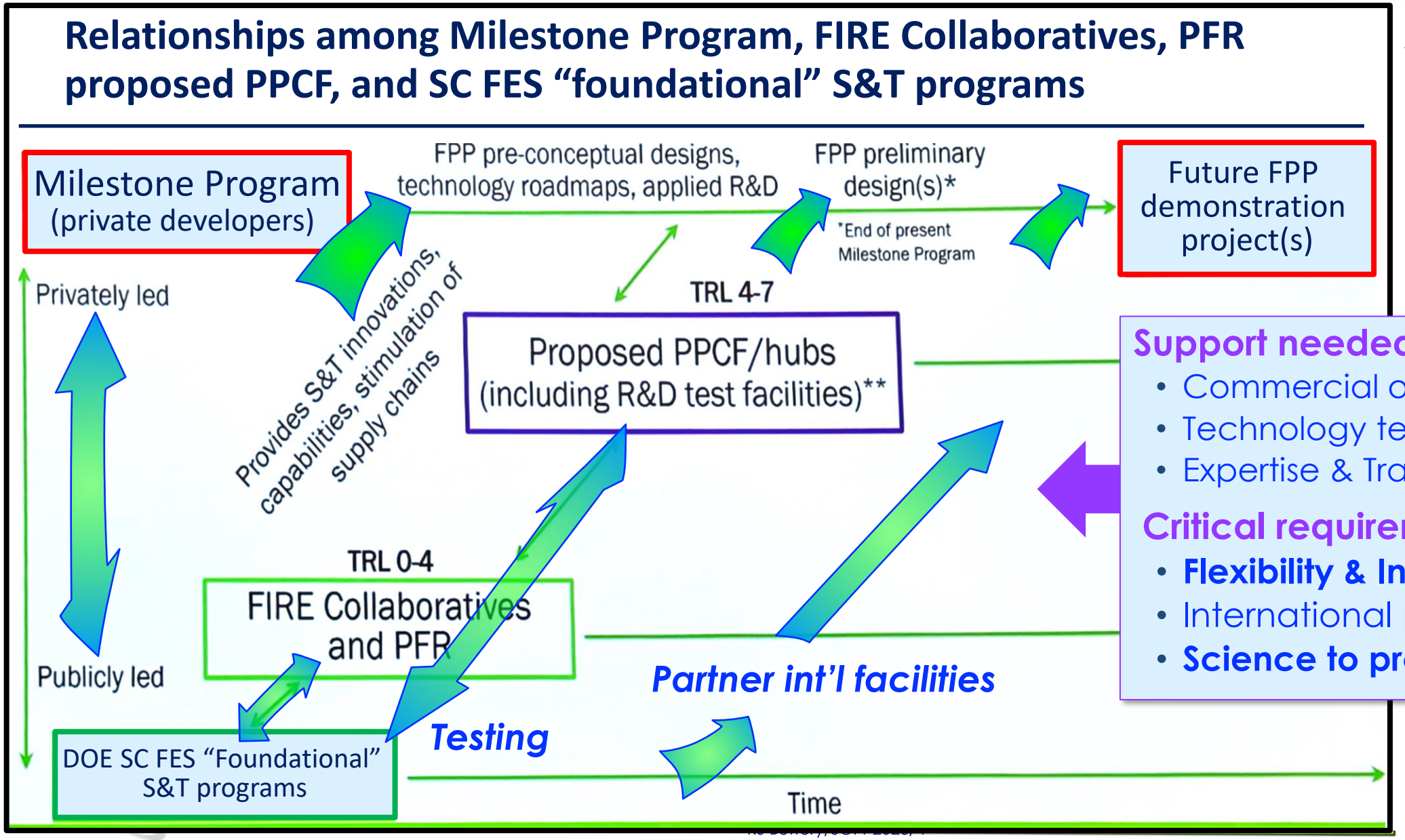
U.S. Vision Envisages Rich Research Infrastructure Partnering Public and Private Sector

Relationships among Milestone Program, FIRE Collaboratives, PFR proposed PPCF, and SC FES "foundational" S&T programs

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UFA, 2024



U.S. Vision Envisages Rich Research Infrastructure Partnering Public and Private Sector

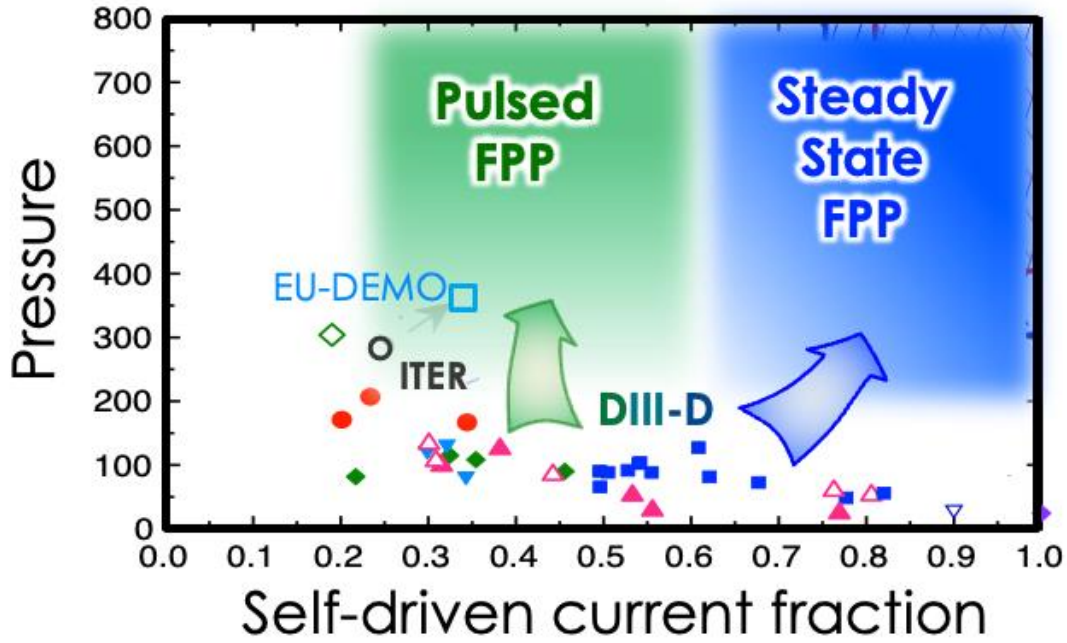


JP Allain
UFA, 2024

Compact / Low Capital Cost Fusion Pilot Poses a Plasma Research Challenge

Compact scale requires higher power densities:

- **High pressure and energy confinement**
  - To fuse sufficiently in compact device and retain heat for high gain
- **Power handling and wall compatibility**
  - To mitigate hot plasma exhaust
- **Plasma interacting technologies and control must be developed**



Tokamak a vehicle for this integration

- *Insights translate to other concepts*

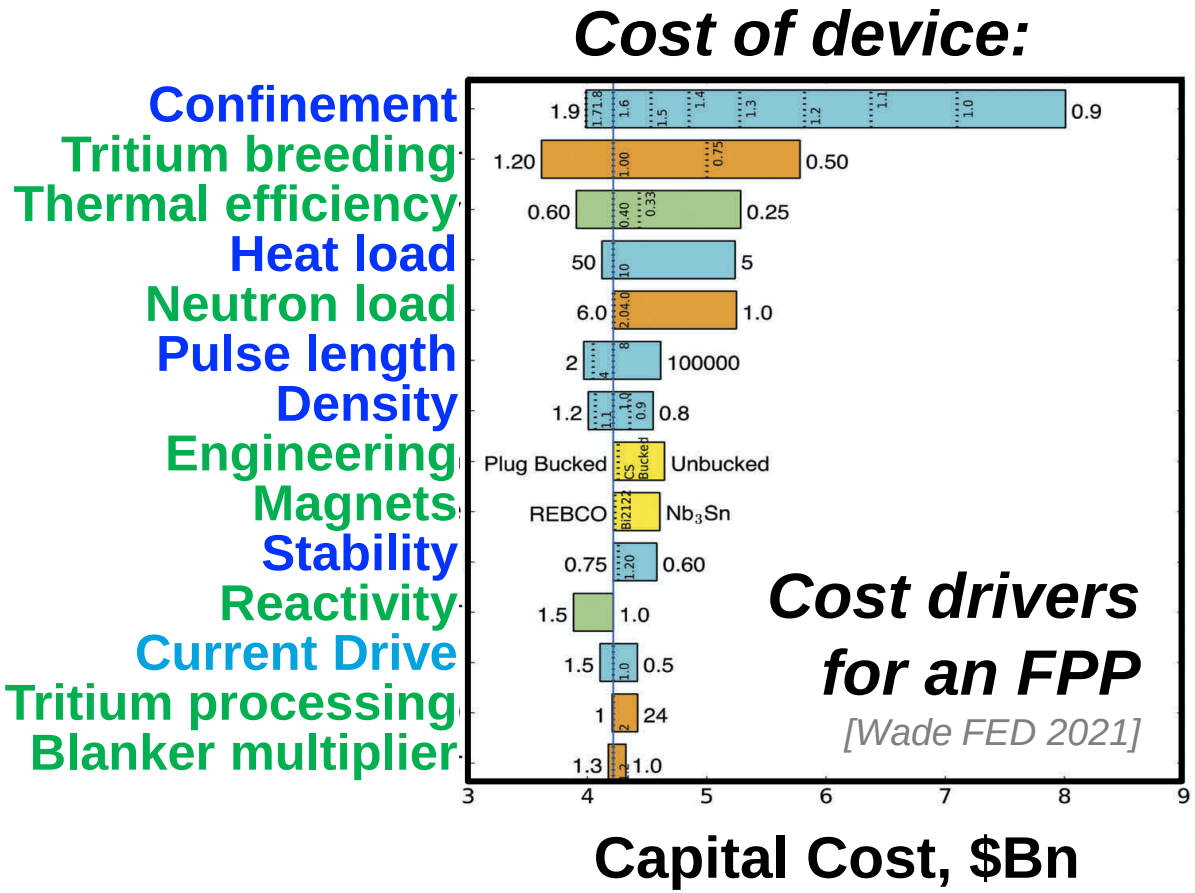
Innovation is <u>required</u> in each area

Need better solutions than we know now

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Cost Drivers of a Fusion Power Plant Driven by Science and Technology

- **Technology** bounds pushed by fusion challenge
  - *Driven by plasma solution*
  - *Compatibility with plasma a vital constraint*
- **Plasma science** is a key cost driver for fusion pilot plants
  - *Levers cost-effective approach*
  - *Vital to develop effective solutions*



Research vital to improve & understand science and technology solutions

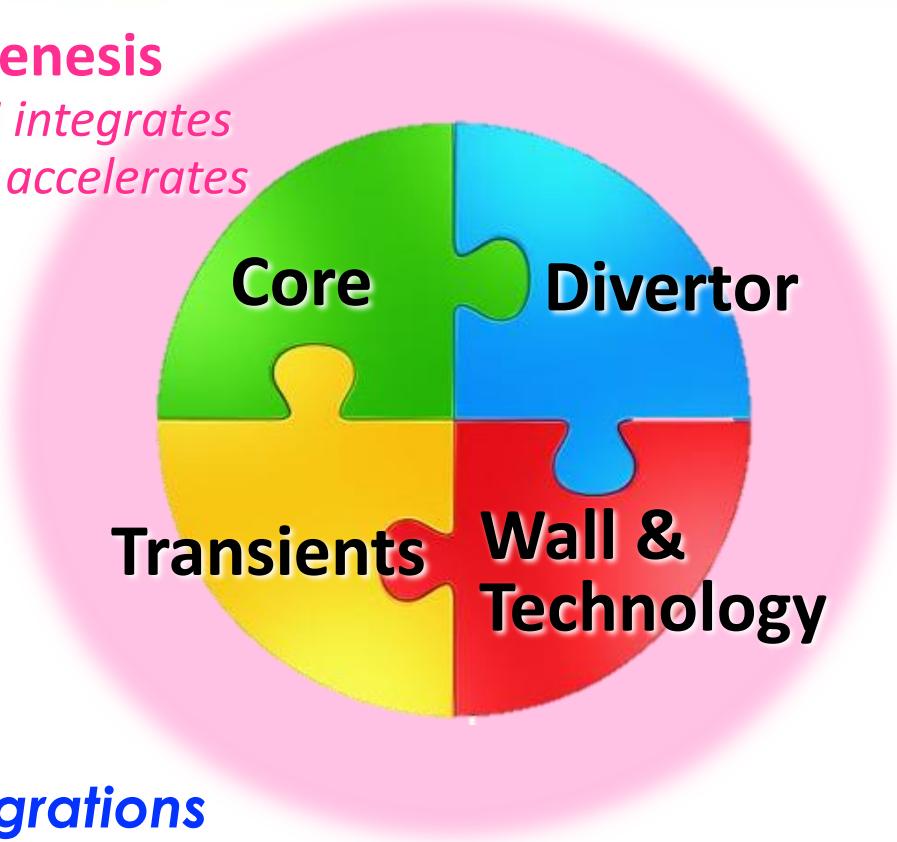
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An Integrated Solution Places Constraints on Each Element of that Solution

- **Each part interacts with and poses constraints on the others**
  - *Wall impurities ←→ core & divertor*
  - *Core solution ←→ divertor heat flux*
  - *Transients ←→ detachment & wall & core*
  - *Technology ←→ core conditions*

AI serves as the integrator & accelerator

Genesis
AI integrates & accelerates



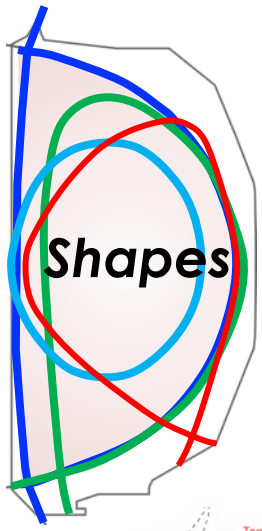
- **Vital to test interaction of elements together**
  - ***Tokamak provides an early testbed for many integrations***
  - ***Comprehensive measurement key in resolving viability & projectability***

Multiple research challenges that must be solved together

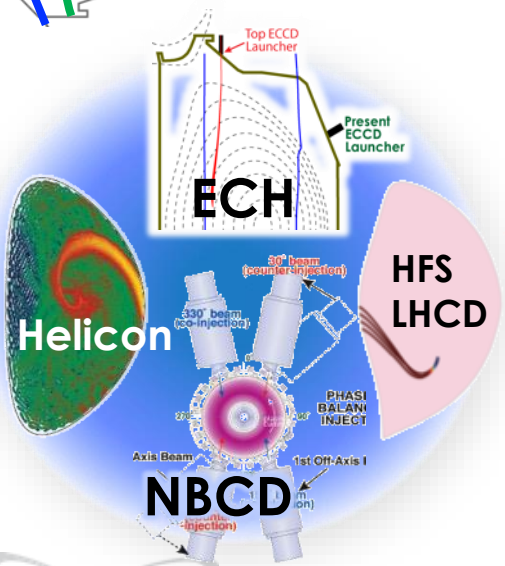
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DIII-D's role

DIII-D is a Uniquely Flexible Tool to Resolve Required Solutions

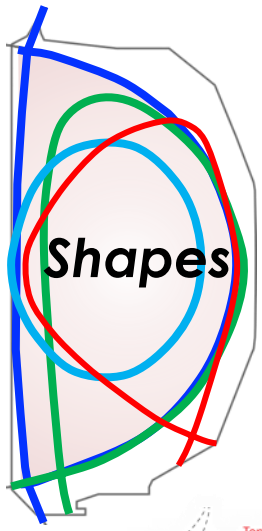


- **Huge flexibility to discover new solutions**
  - Shape, 3D fields, fueling, impurities, density control
  - Control rotation, current & heat to e⁻'s or ions
  - Rapid change out to test new technologies

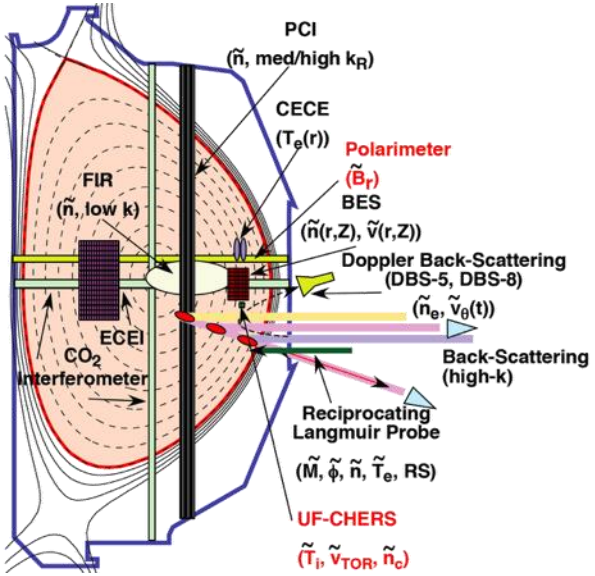


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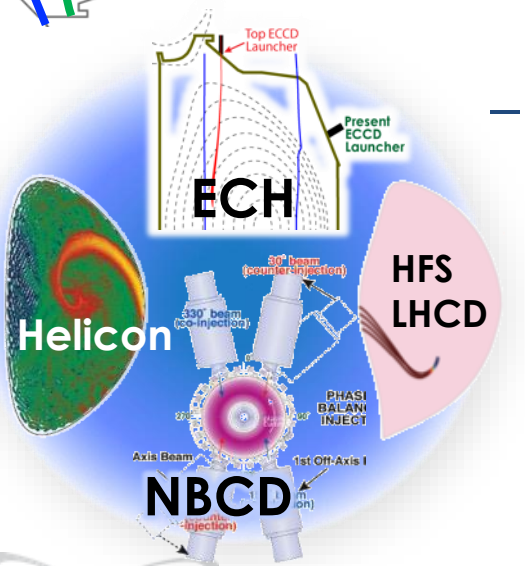
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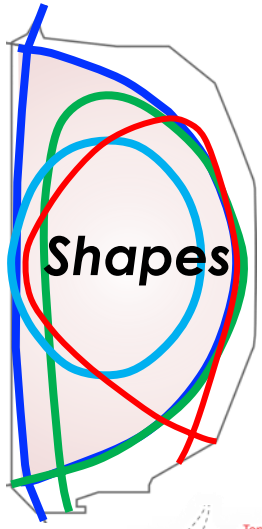


- **Comprehensive measurements**
  - Over 50 techniques: Kinetics, magnetic, particles, fast ions, neutrals, heat, impurities,
  - Profiles, 2D, 3D, and imaging

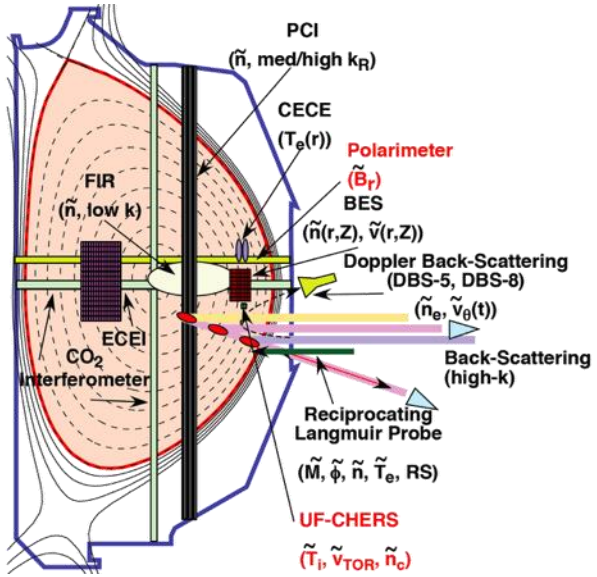


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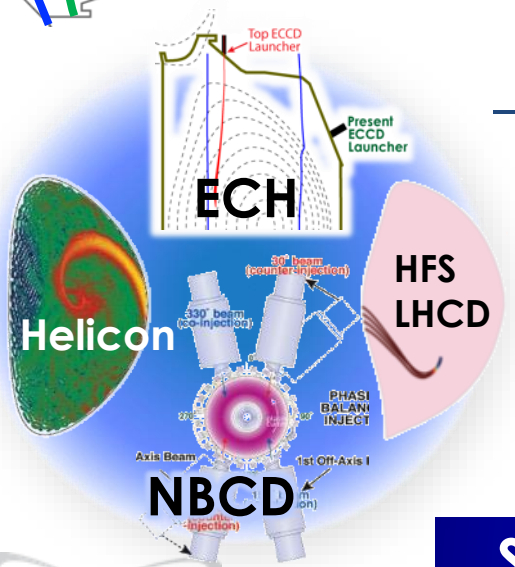
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- **Collaboratively led with over 800 users**
  - 21 areas led by uni's, Nat Labs, intl & GA
  - Joint development of strategy
  - Engaged with private industry

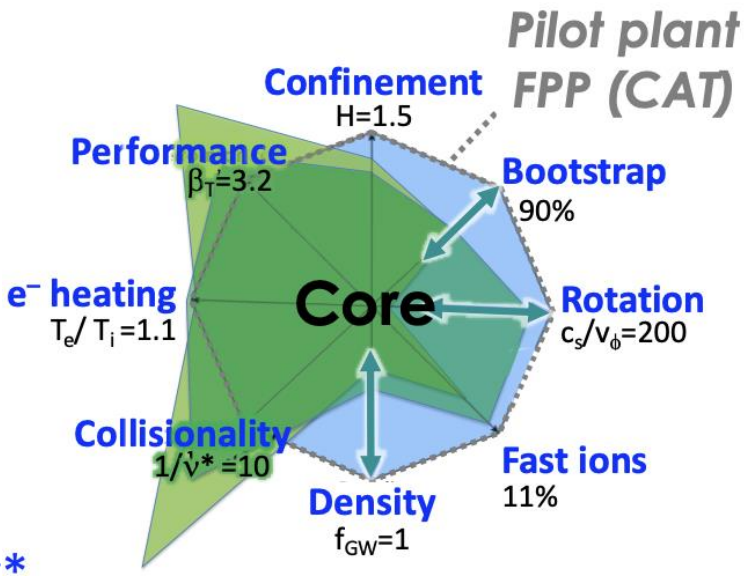


Supporting ~100 institutions to pursue <u>their</u> priorities with an effective user model

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Relevant Parameters & Physics Regimes to Address Core and Edge Plasma Challenges

- **Integrated physics simulations identify high performance core solutions**
  - 2.2T, 2.5MA, 16MW NBI + 7MW EC
  - Hot thermalized cores, $T_e \sim T_i$
- **Opaque low-collisionality edge with high density for dissipation**
  - Low neutral penetration depths at low ν^*
  - Short path lengths in divertor
  - ~30% of pilot plant $q_{||}$
- **Relevant physics regimes for core optimization and divertor dissipation**

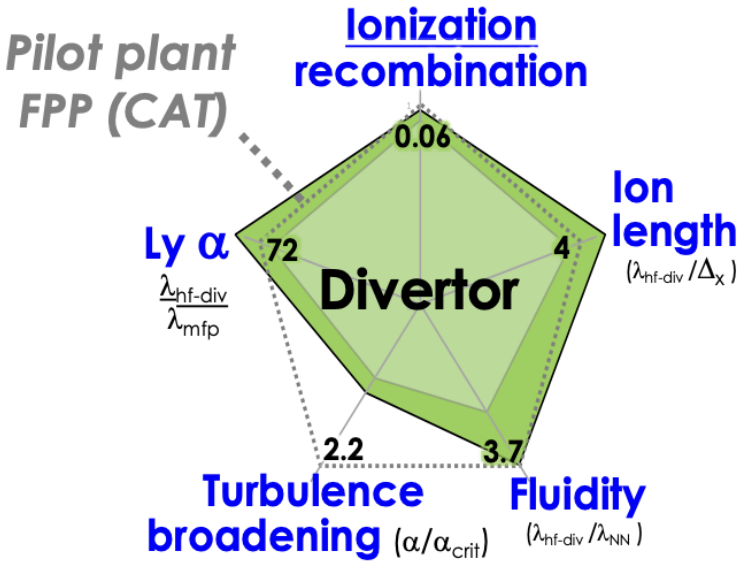


Relevant divertor & core physics metrics

DIII-D Parameters

- *Integrated*
- *Separately*

Derived physics metrics from ORNL CESOL simulations



Basis to develop & integrate wide range of fusion technology & science solutions

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Support for Fusion Technology and Commercialization

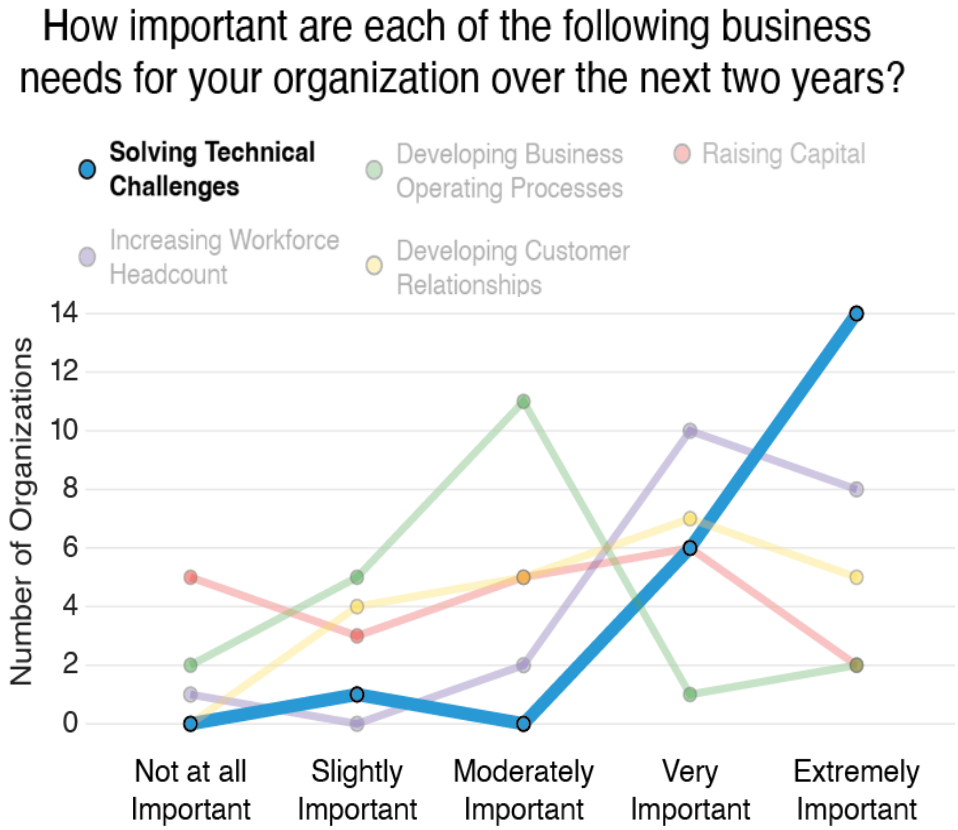
Serving multiple fusion paths

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DIII-D Now Engaged with Private Industry to Accelerate Commercialization

- **Industry research identified significant need***
  - Solve challenges to reduce timescale & risk
  - ***50% of fusion companies want a user facility***

Key D3 asks: ML, control, data, materials, diagnostics, plasma behavior, component testing, simulation, training, expertise



*Survey of 22 fusion companies, D.C. Pace, MBA thesis

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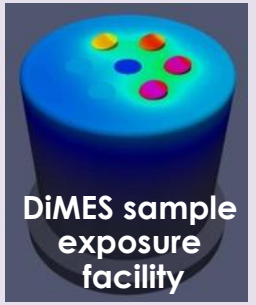
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- **DIII-D has re-oriented its program to pursue technology goals to align with private sector**

  →***Enables full non-proprietary collaboration***

Early industry examples

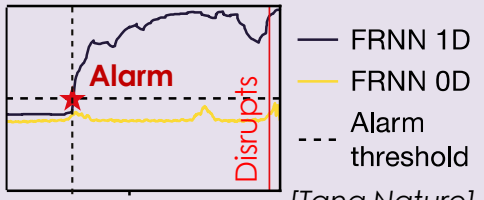


Materials Interactions

Tested SPARC wall material in fusion grade plasma with 4 month turnaround!

NVIDIA & MS Hardware for Machine Learning Disruption Prediction

Using DIII-D digital twin with deep learning & profile measurement



[Tang Nature]

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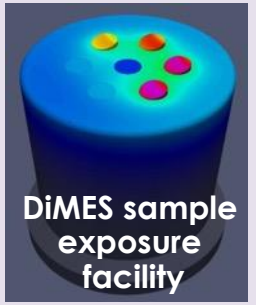
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- **New user framework enables private sector**
  - **Protects private IP** while sharing public IP
  - **Partnership approach:** equal access with support, training, expertise & shared leadership
  - ***Pre-competitive R&D with non-proprietary access is preferred industry mode***

Early industry examples

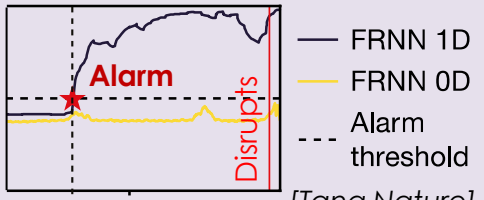


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Rapid, free, flexible access: 30 companies now engaged

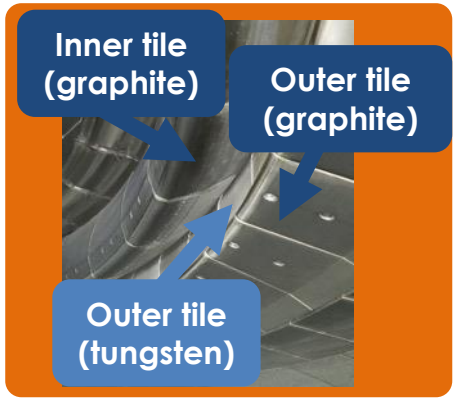
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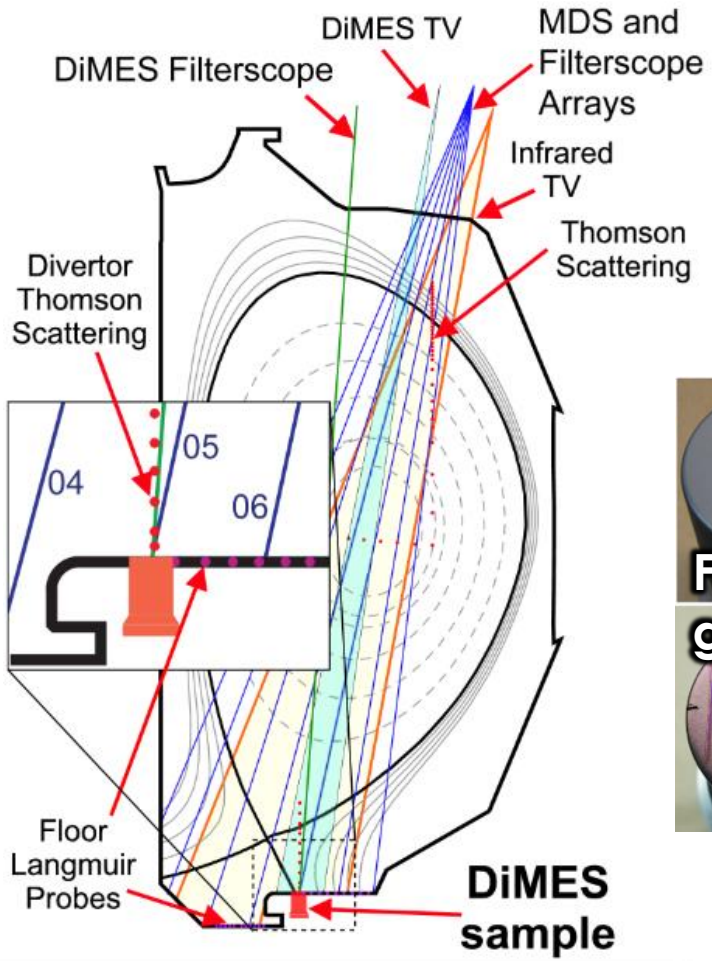
Technology Engagements at DIII-D

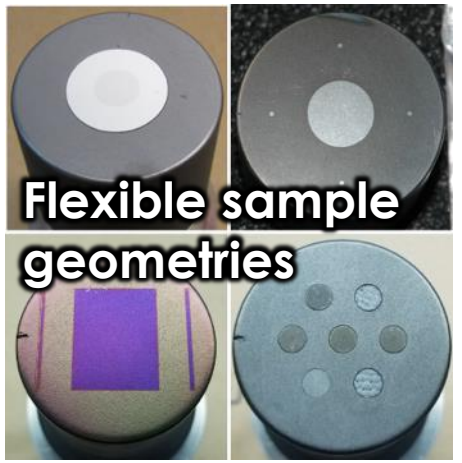
DIII-D Stress-Testing Many Innovative Materials

- **Divertor Materials Evaluation Station (DiMES)**
  - well-diagnosed – shot-to-shot replacement
  - varying geometries – sees transient events
- **Tiles and rings enable study of erosion leakage and transport about plasma**







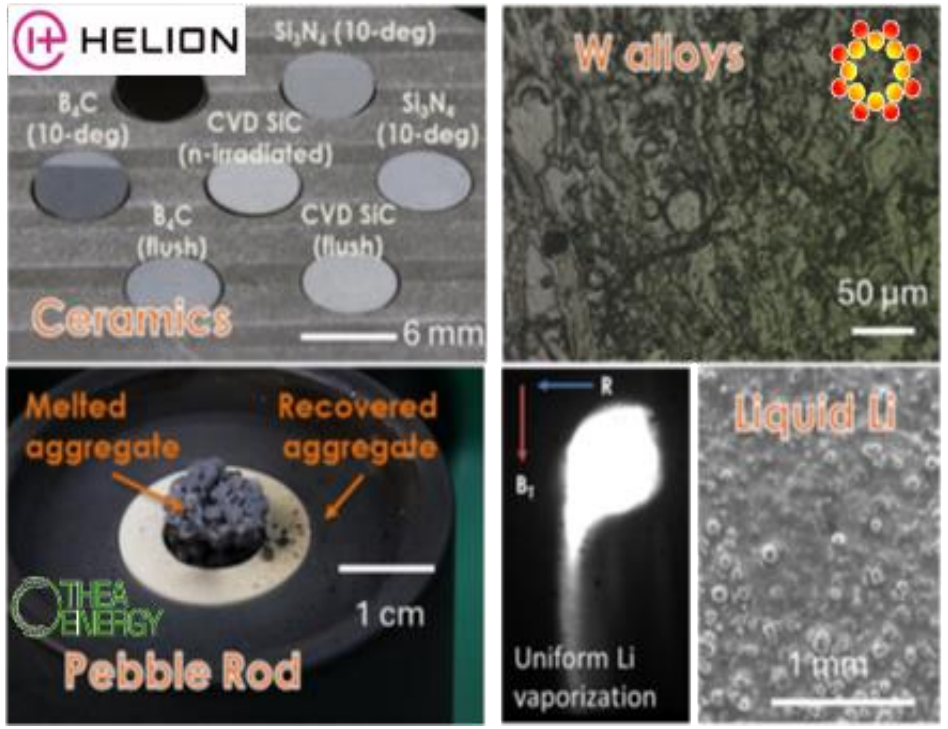


Capability to rapidly insert and test wide range of fusion materials and their compatibility with the core

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Last Two Years Seen Major Campaign of Materials Testing

- **61 novel plasma-facing materials from 12 institutions were successfully tested**
  - **Ceramics:** down-selected to bulk SiC for Helion
  - **W alloys:** Assessed k-doped W and W-Ta alloys for Tokamak Energy
  - **Multi-principle element alloys:** preferential erosion observed for Avalanche Energy
  - **Boron pebble rod divertor:** first demo for Thea Energy
  - **Liquid lithium** capillary porous structure led to uniform vapor emission & suppression of droplets at 350C
- **Tile technology campaign this week!**
  - Tungsten coatings & tile designs for DIII-D & ITER
  - Plus novel materials and surfaces for industry



Liquid lithium capillary porous system

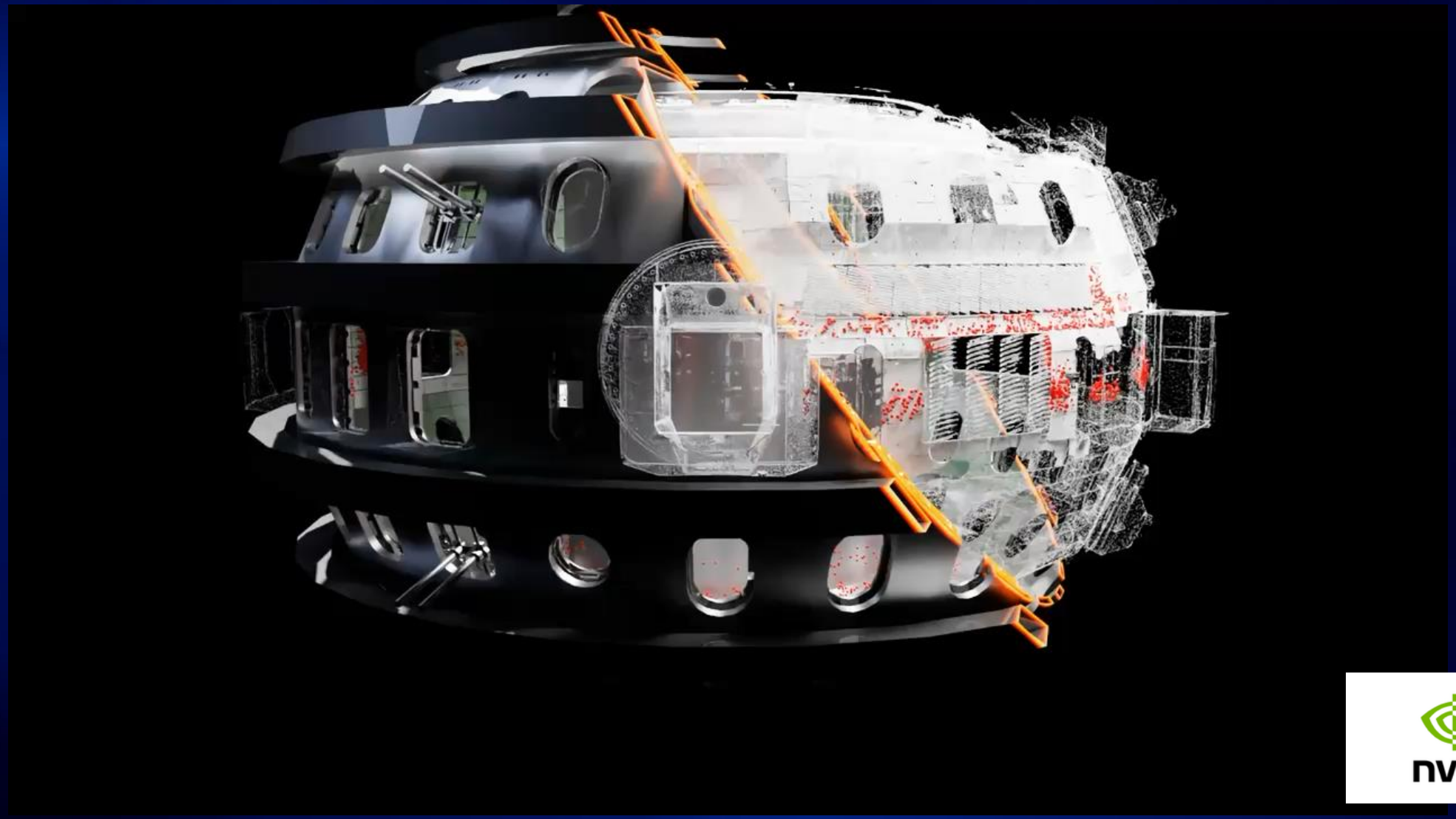


Assessing a wide range materials, novel structures & coating technologies under reactor relevant plasma conditions

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DIII-D is Pioneering Digital Twin Technology

DIII-D



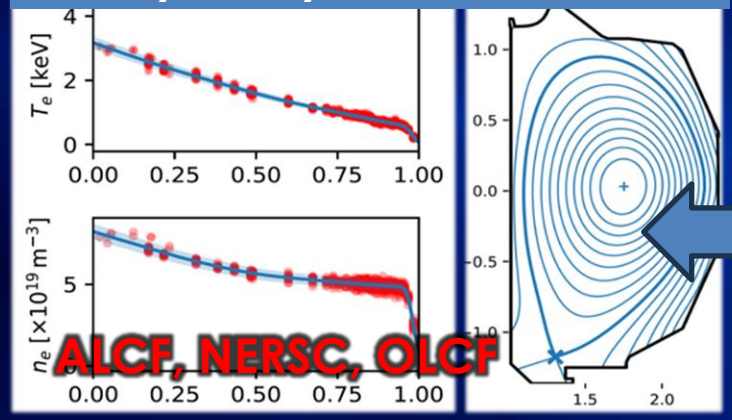
NVIDIA

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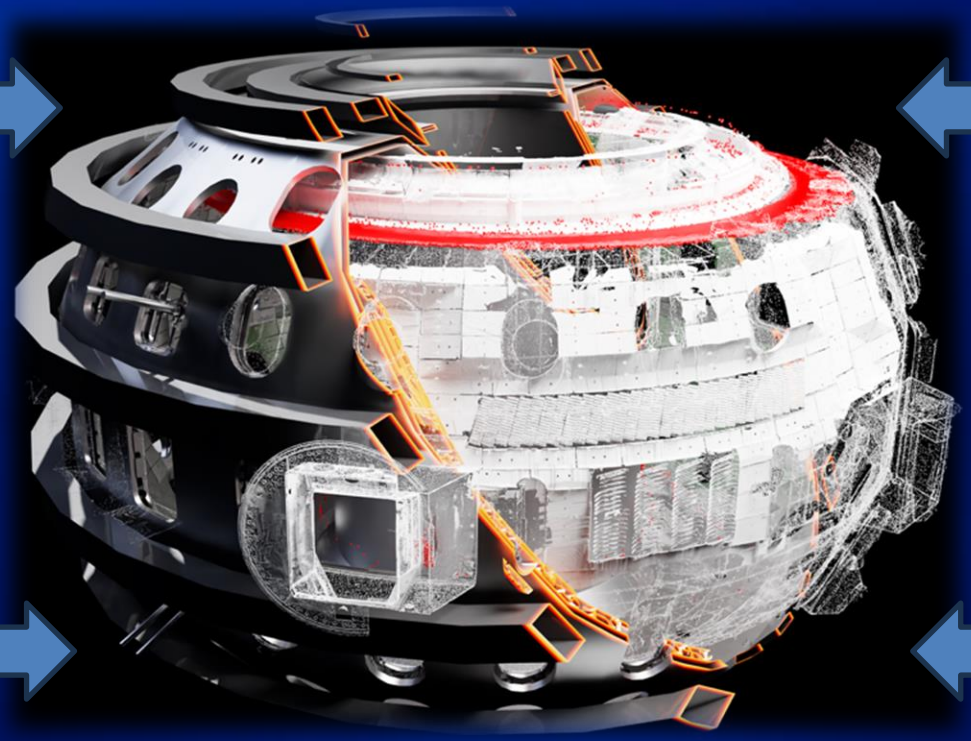
GENERAL ATOMICS

DIII-D is the Proving Ground for the FES Genesis Mission

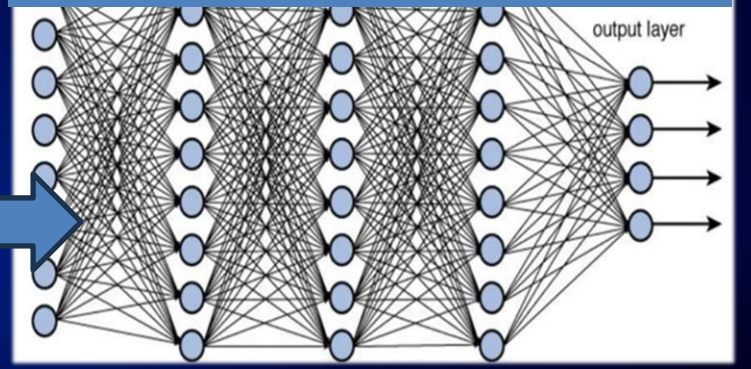
Superfacility (IRI): rapid high-fidelity analysis on demand



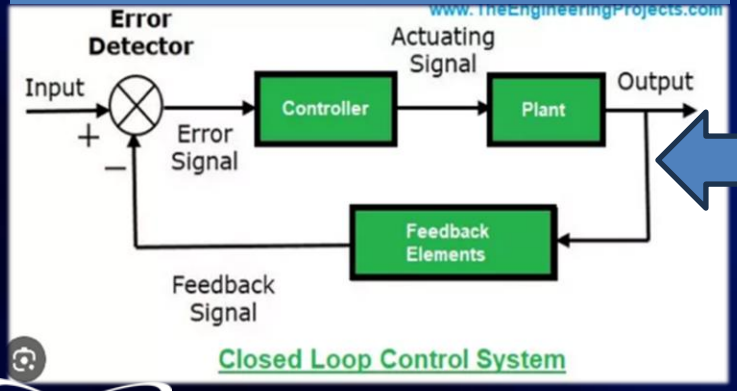
Digital & Physical Twin integrates big data, ML & supercomputing & closes loop on control



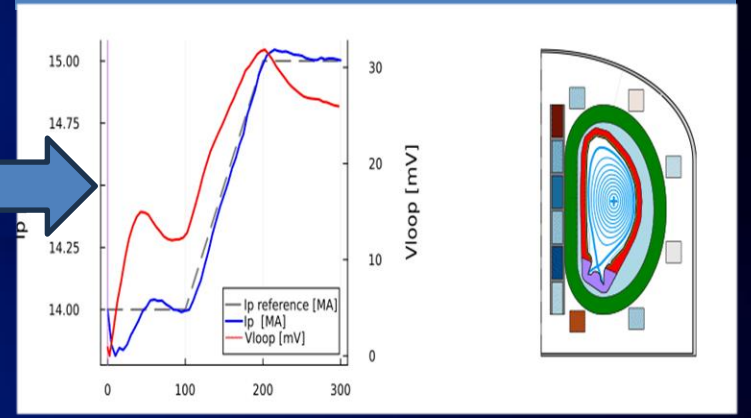
Fusion Data Platform making data available to FIRE centers



Real-time Forecasting and Actuator Control



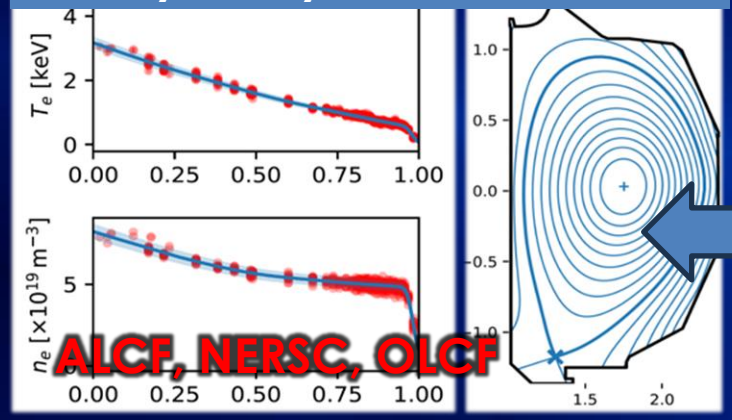
FUSE: Plant and plasma simulator with virtual PCS



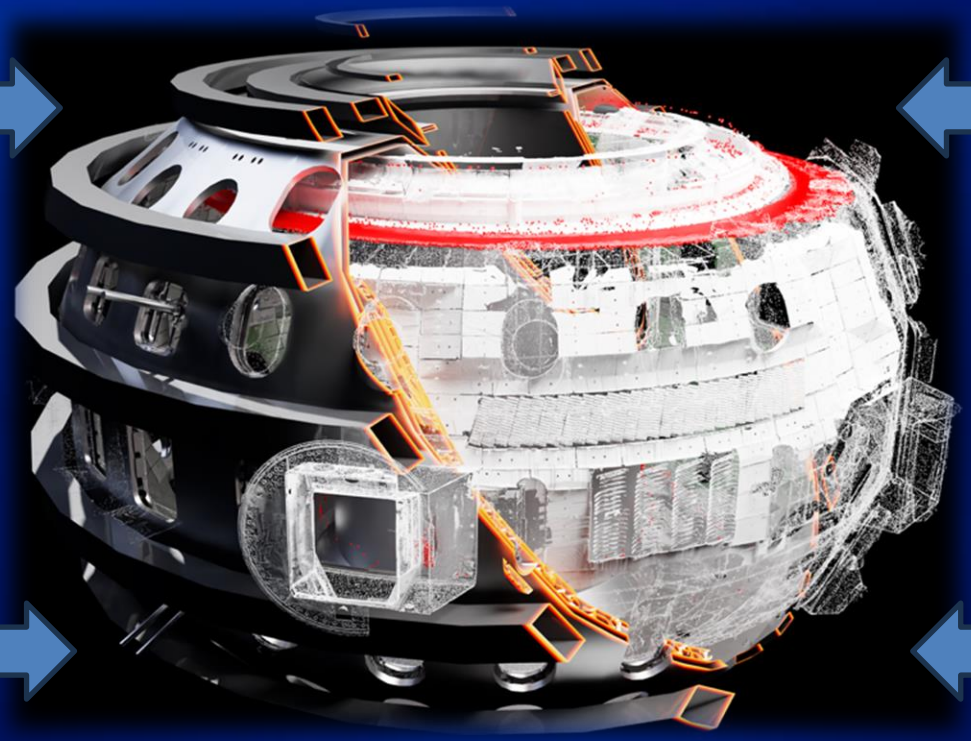
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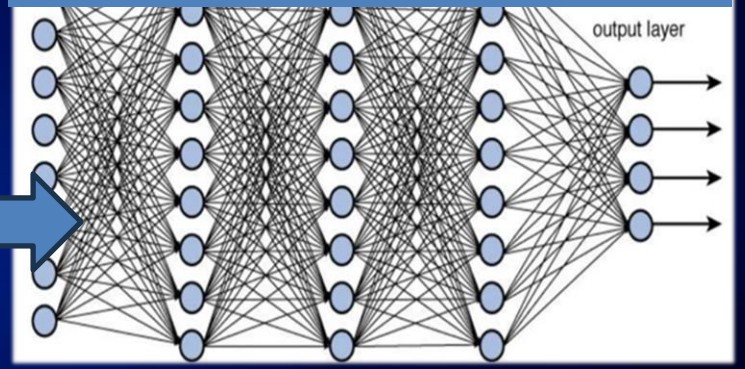
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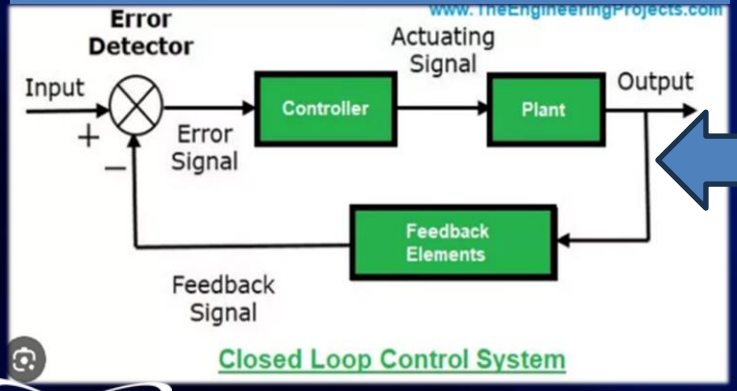
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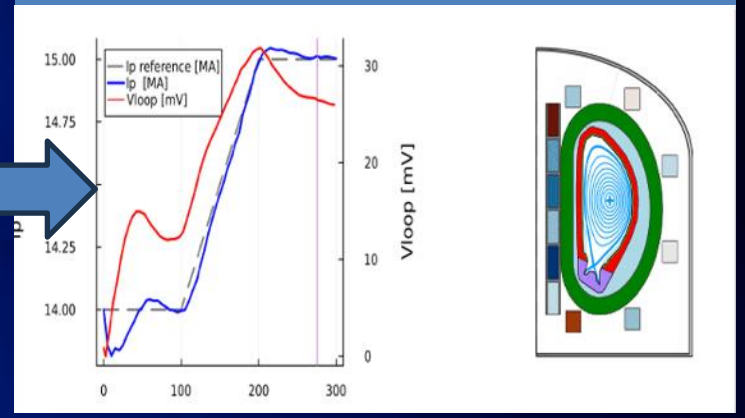
Fusion Data Platform making data available to FIRE centers



Real-time Forecasting and Actuator Control



FUSE: Plant and plasma simulator with virtual PCS



38 Genesis fusion proposals sought to use DIII-D (got 1/3rd of those awarded)

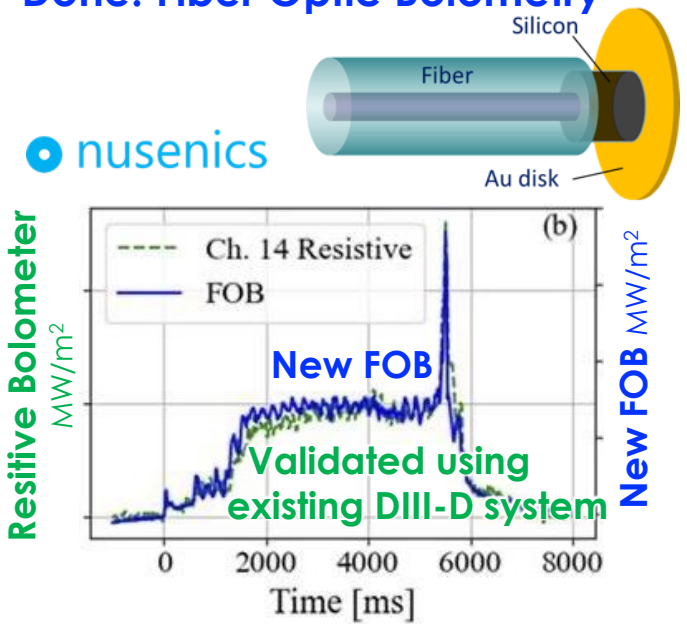
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

DIII-D seeks to pioneer the techniques of AI & Digital Twin for fusion

DIII-D Provides a Unique Testing Ground for Fusion Diagnostics

- **Fusion needs advances in diagnostics**
  - ***Plasma & neutron flux***
  - ***Miniaturization & modularization***
  - ***Reduced diagnostic set***
- **DIII-D a key proving ground**
  - Validation against proven systems ➡
  - Rapid installation

Done: Fiber Optic Bolometry*

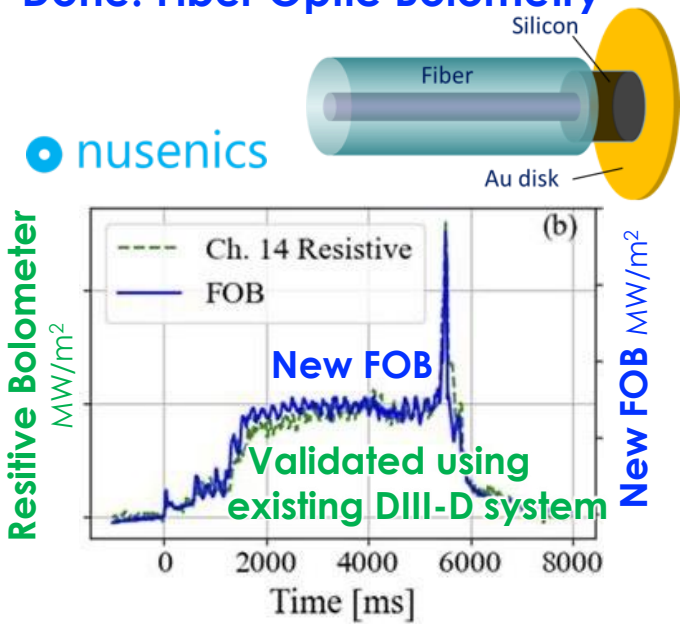


*S. Lee, et al., Rev. Sci. Instrum. 93, 123515 (2022)

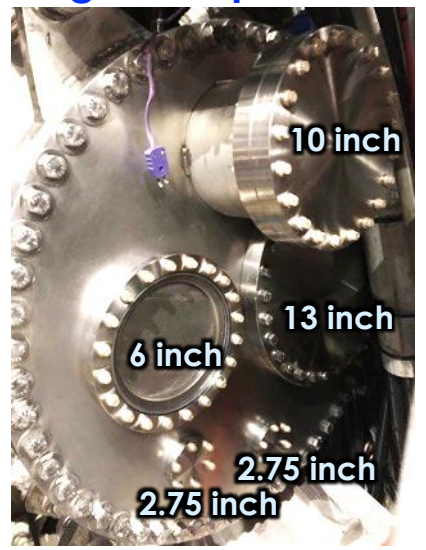
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  - Rapid installation
  - Diagnostic testing platform ➡➡

Done: Fiber Optic Bolometry*



Next Step Fusion Diagnostic platform

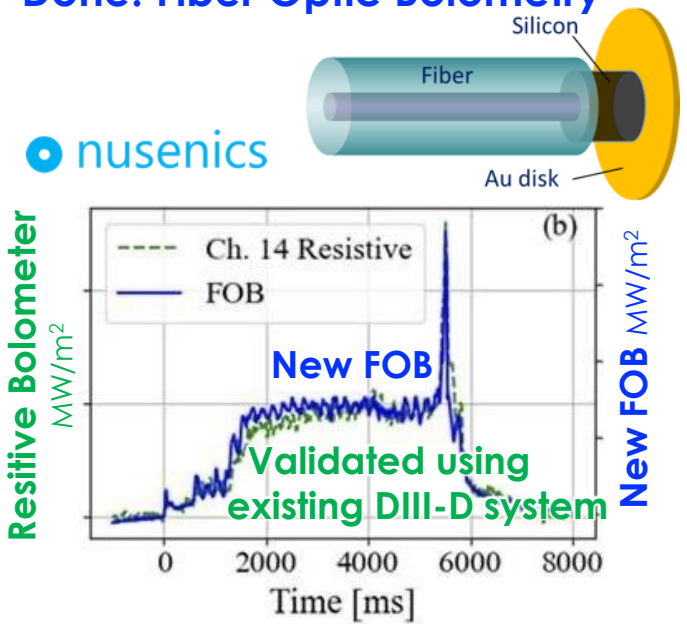


*S. Lee, et al., Rev. Sci. Instrum. 93, 123515 (2022)

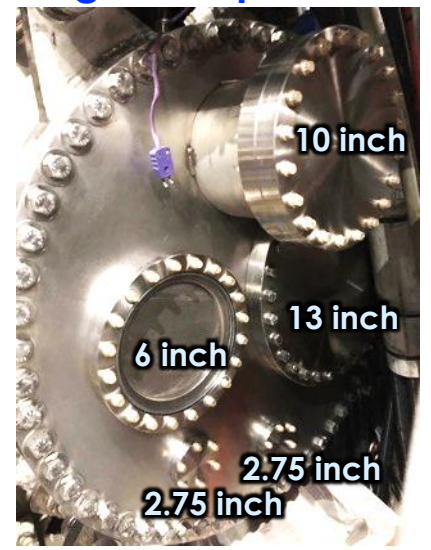
DIII-D Provides a Unique Testing Ground for Fusion Diagnostics

- **Fusion needs advances in diagnostics**
  - ***Plasma & neutron flux***
  - ***Miniaturization & modularization***
  - ***Reduced diagnostic set***
- **DIII-D a key proving ground**
  - Validation against proven systems ➡
  - Rapid installation
  - Diagnostic testing platform ➡➡
- **DIII-D now pursuing many innovations**
  - Particle detectors (Xantho), Radiation-hardened sensors ➡
  - Stray EC detectors (ITER), spin polarized fusion sensor (UCI)
  - Synthetic diagnostics & AI monitoring for real time control (P-U)

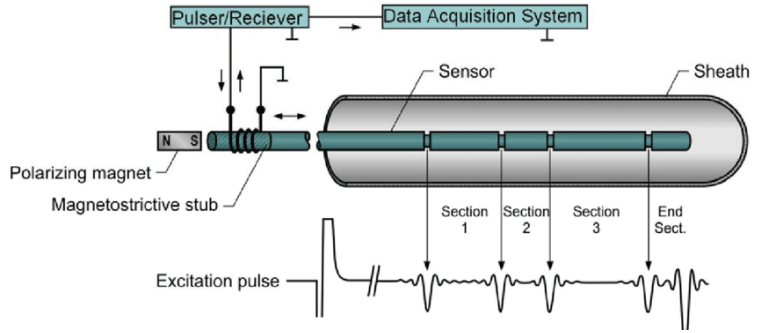
Done: Fiber Optic Bolometry*



Next Step Fusion Diagnostic platform



Doing: Radiation hardened T_e sensors



Low hanging fruit: DIII-D seeks to validate a wide range of reactor diagnostics

DIII-D NATIONAL FUSION FACILITY

X-WAVE INNOVATIONS, INC. Make state-of-the-art obsolete

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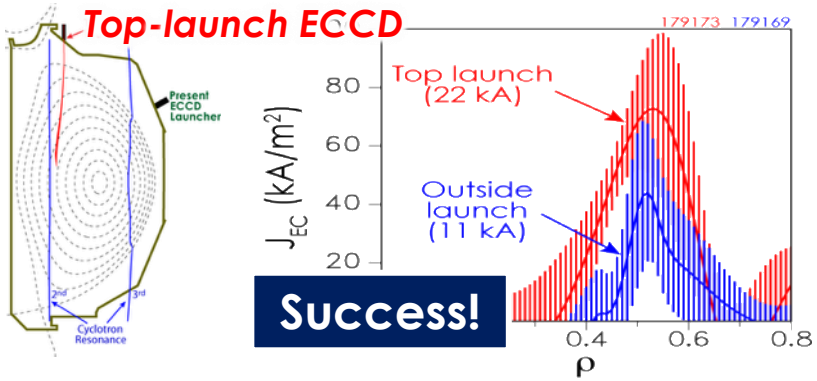
DIII-D is Pioneering Groundbreaking RF Technology

- **Key issues**
  - Efficiency
  - Coupling
  - Survivability

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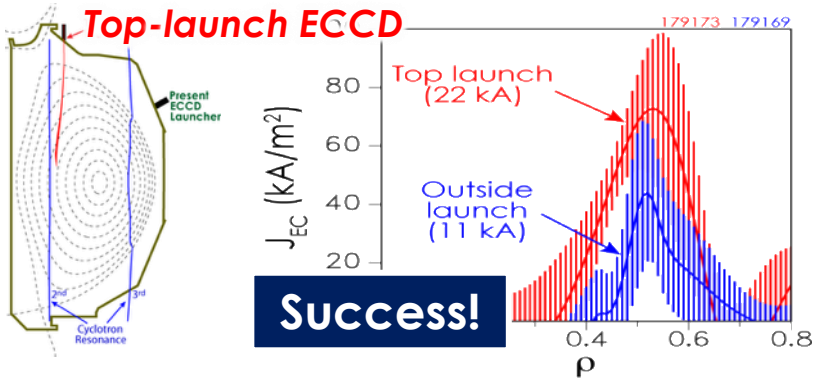
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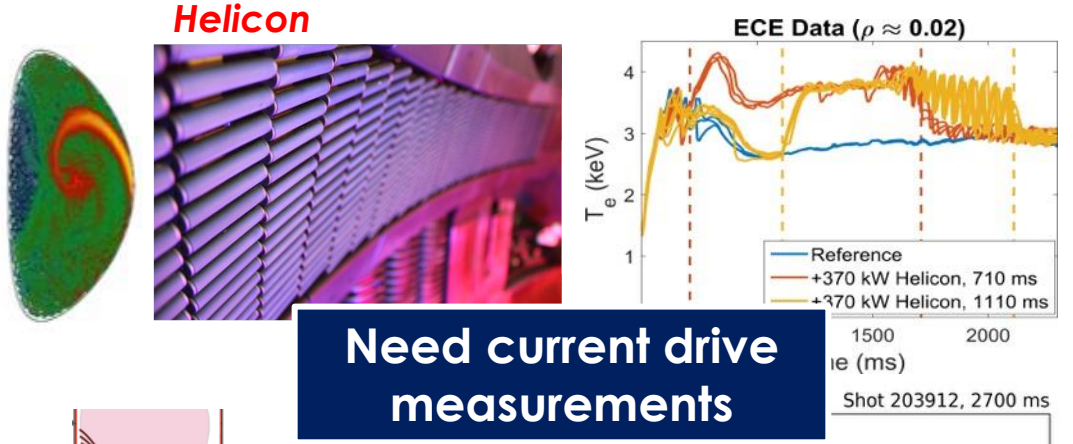
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  - **Top-launched electron cyclotron**
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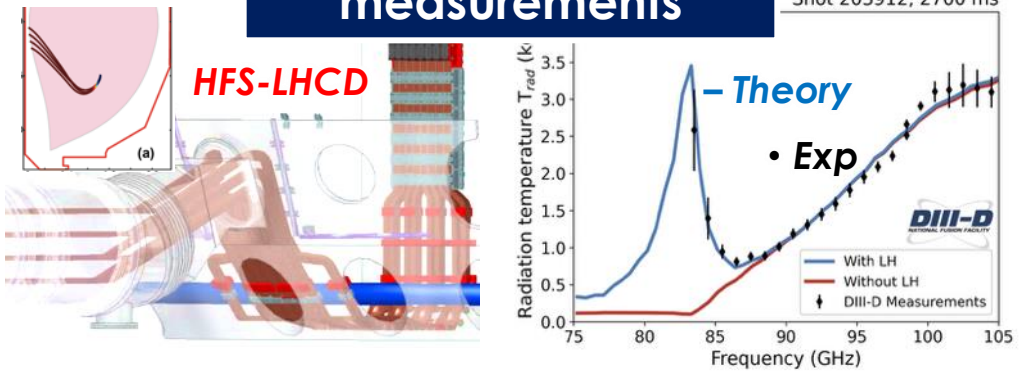


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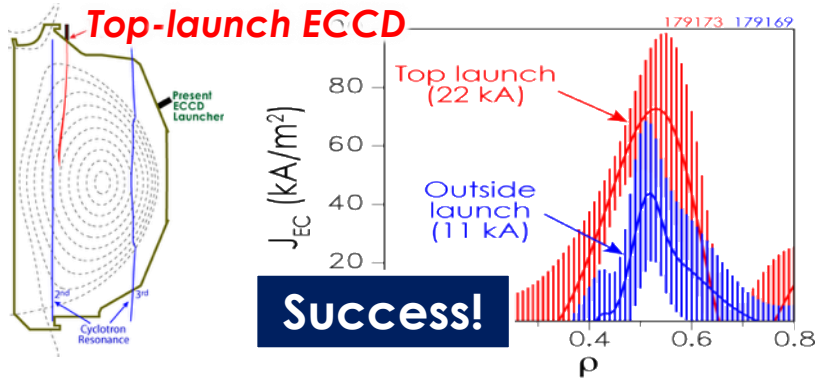


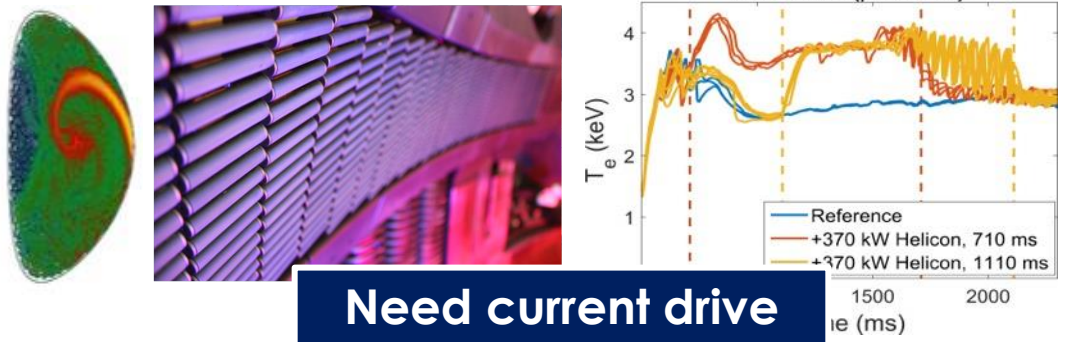


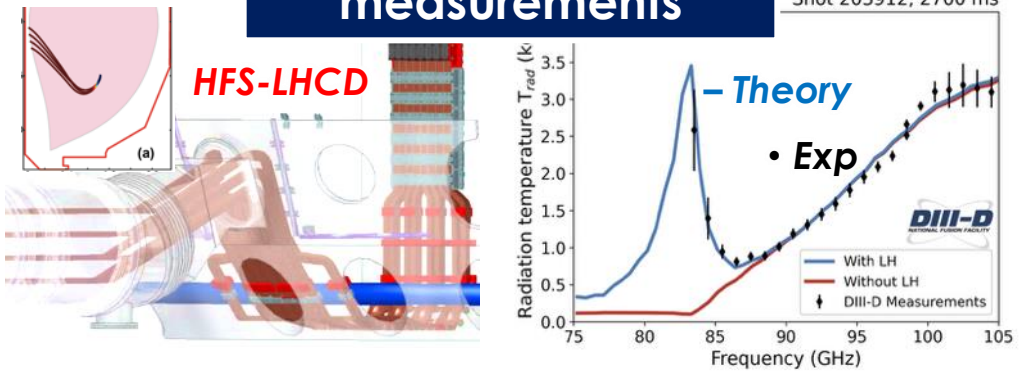
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  - **High-power microwave drilling** test planned (Terrawave)
  - \+ **Training for industry** (T1) + **Non-inductive startup?** (UKAEA)

Efficient RF key for fusion. Key tests of current drive & physics remain to be done

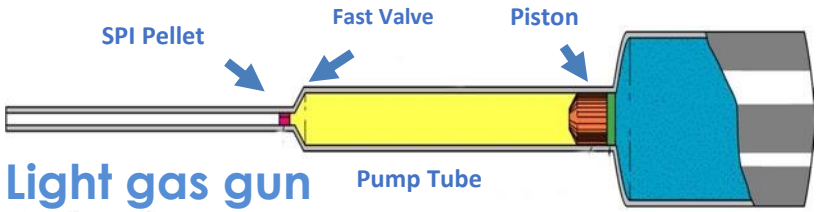




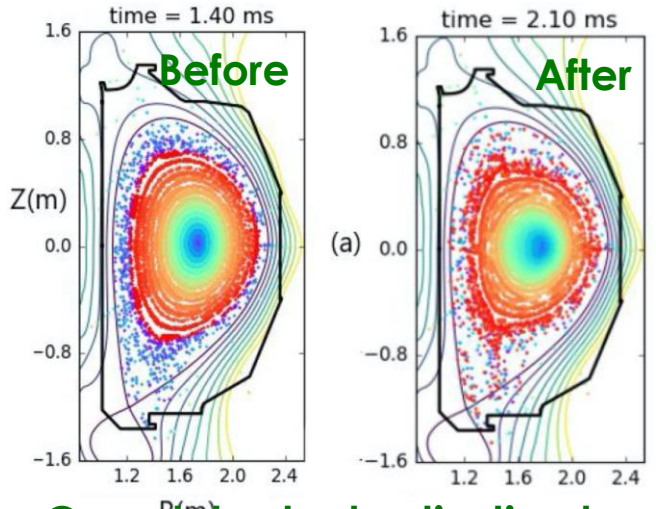


DIII-D Developing Innovative Particle Injection Technologies

- **Mitigation of plasma terminations (disruptions): High speed or coated shells to penetrate to core**
  - Rapid quench to avoid thermal & mechanical loads and prevent formation of energetic electron beams
    - *Most critical issue for tokamaks – DIII-D has pioneered the solutions*



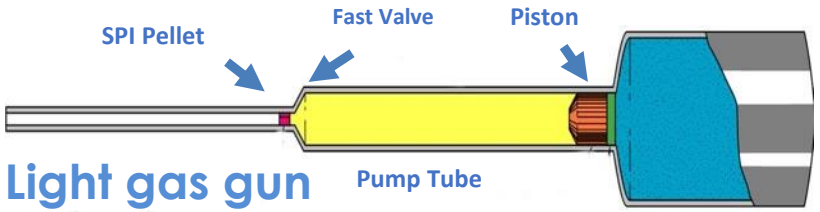




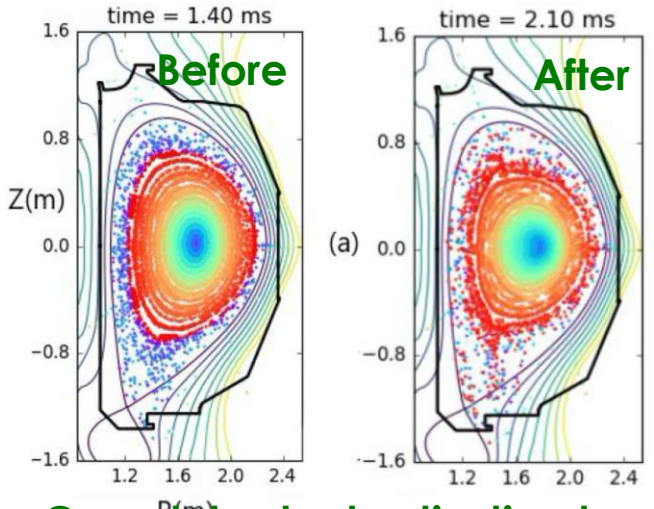
Complete stochastization by core impurity deposition

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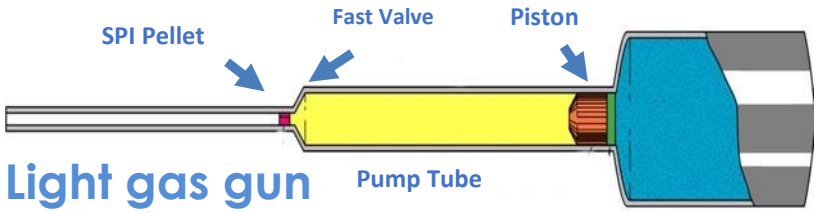




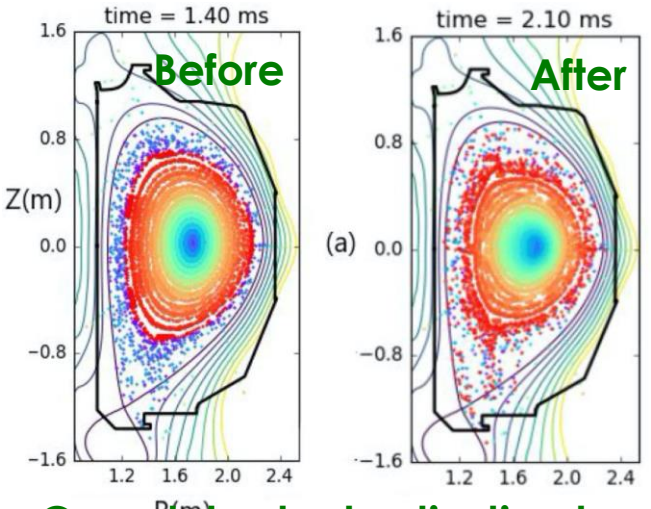
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- **Pellet fueling: innovation & model based control**
  - Lithium coated shells minimize edge perturbation







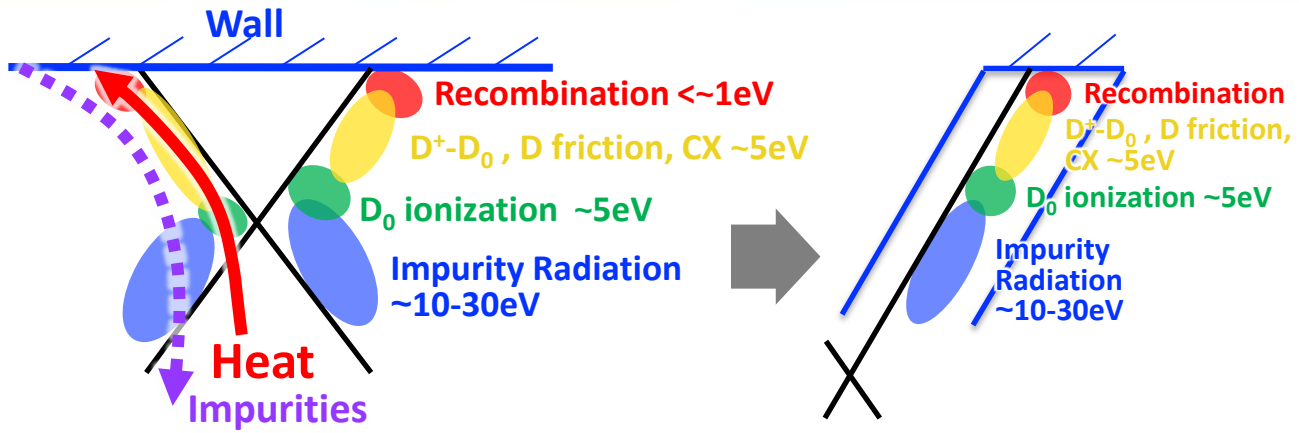
Complete stochastization by core impurity deposition

DIII-D playing critical role in resolving disruption mitigation & fueling, and testing innovative new techniques

DIII-D NATIONAL FUSION FACILITY

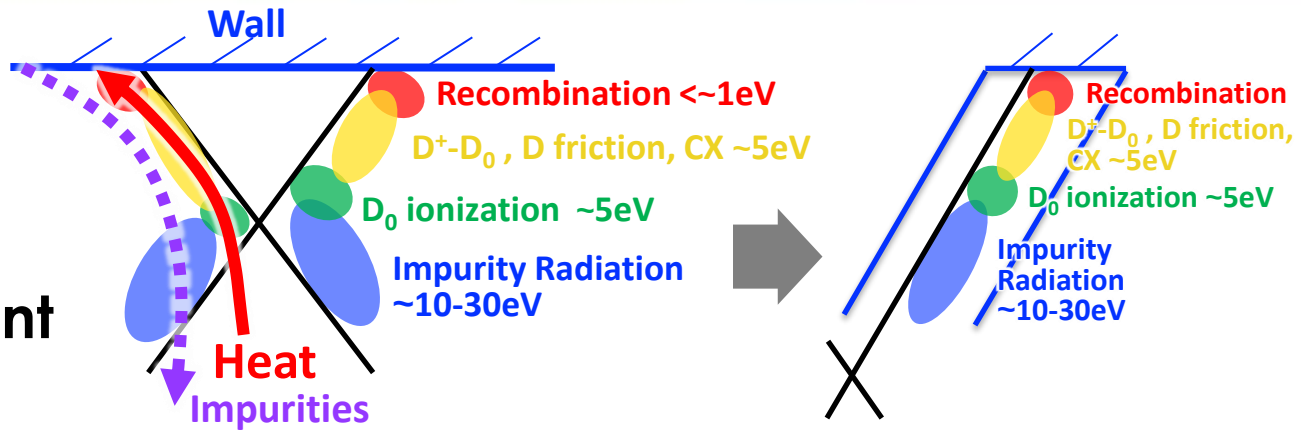
New "Chimney" Divertor Offers Improved Concept to Mitigate Heat Flux, Tungsten Erosion & Influx

- **Complex multiscale physics processes**
- **Longer leg:** isolates physics and avoids X point degradation



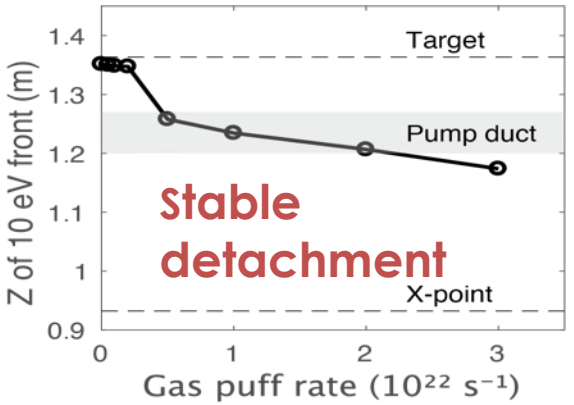
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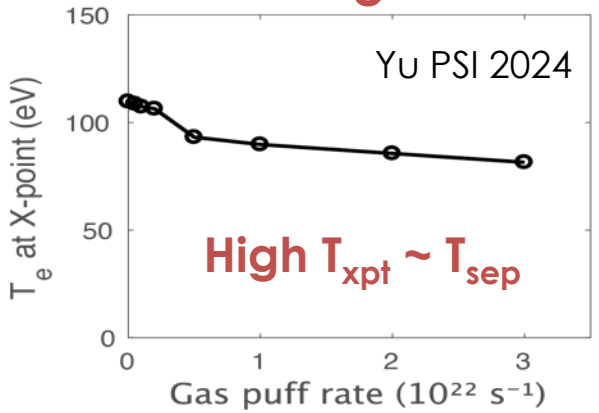
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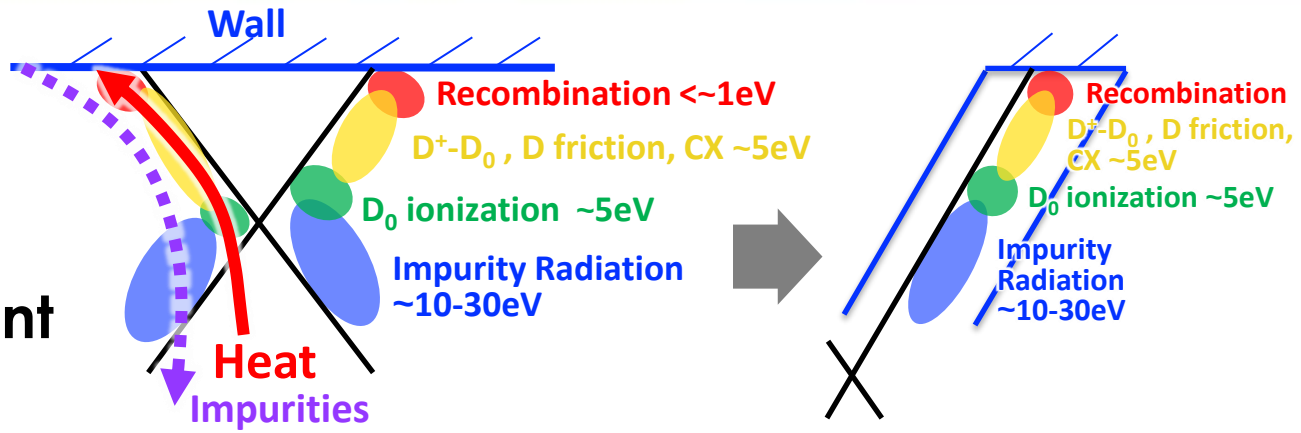
SOLPS predicts cold dense target & hot X with good stability





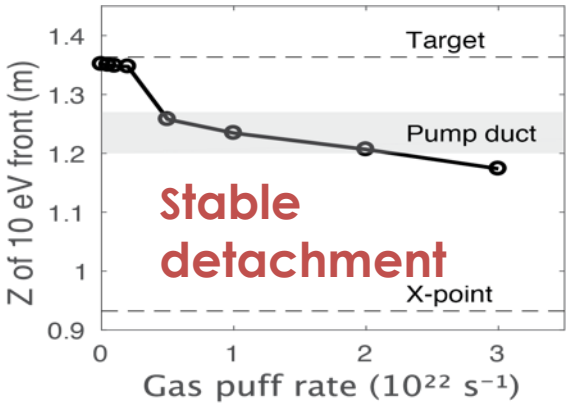
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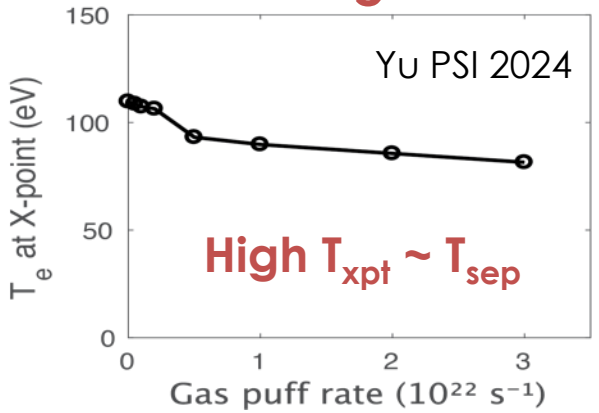
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Phase 2 envisaged with Tungsten lining

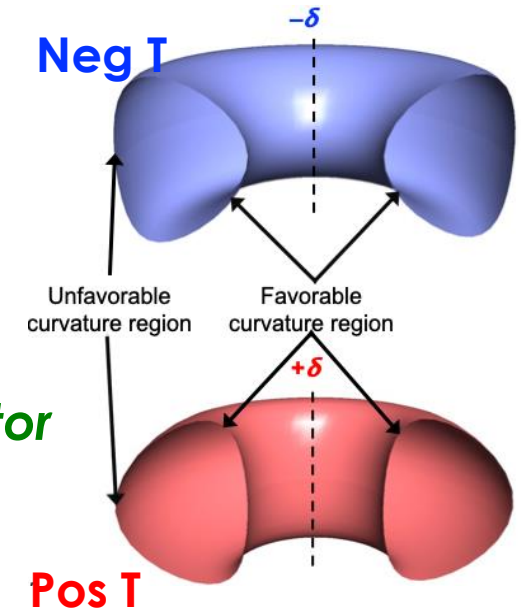
- *Assess radiation & leakage of tungsten in the divertor regime & transport to core*

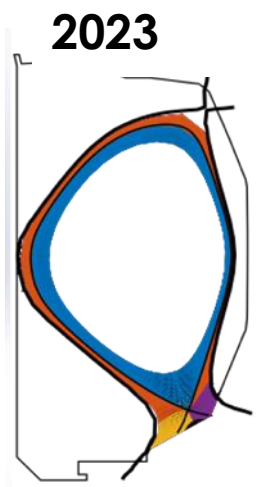
Potential to solve power handling challenge in next 5-6 years

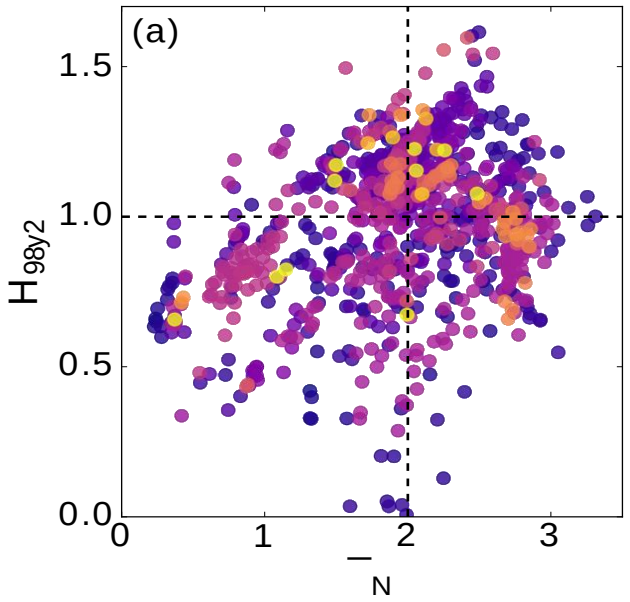
DIII-D NATIONAL FUSION FACILITY

DIII-D Will Pioneer Negative Triangularity as a Potentially Unique Core-Edge Solution

- ***'NT' removes tokamak pedestal and compensates with lower transport in core***
  - *Robust solution for ELMs (maybe only one?)*
  - *Decreases heat required into divertor*
- **TCV favorable results in limiter configuration**
- ***DIII-D great performance in H-mode w open divertor***





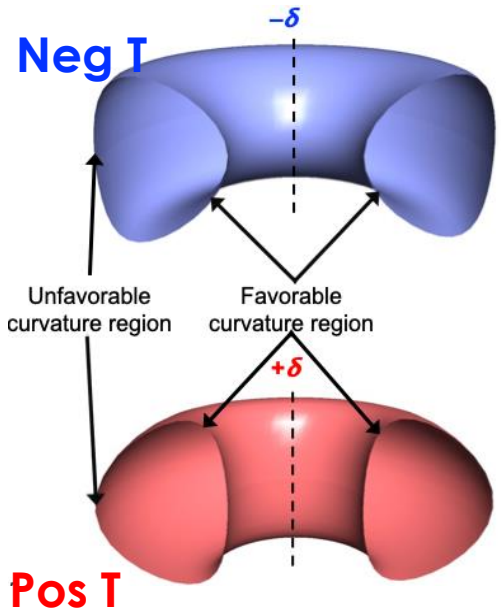


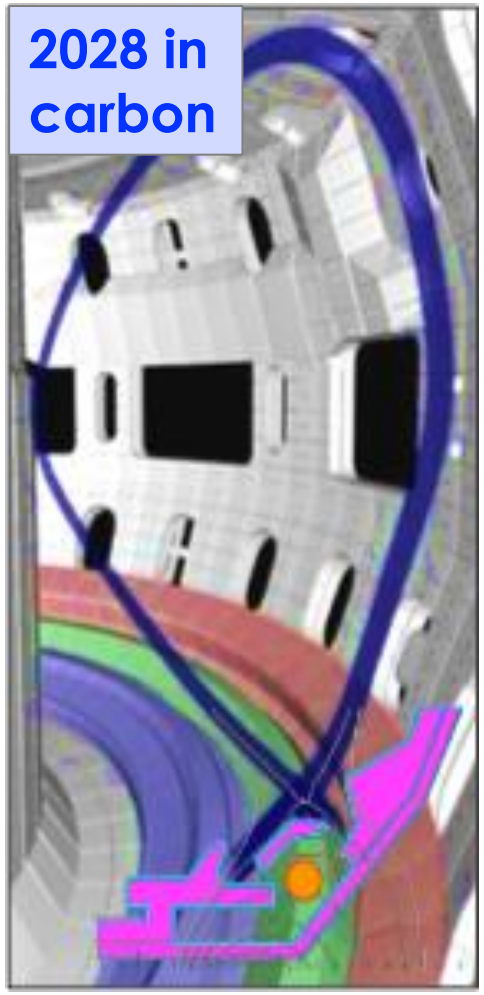
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Funded & built by KYOTO FUSIONEERING for whole DIII-D team

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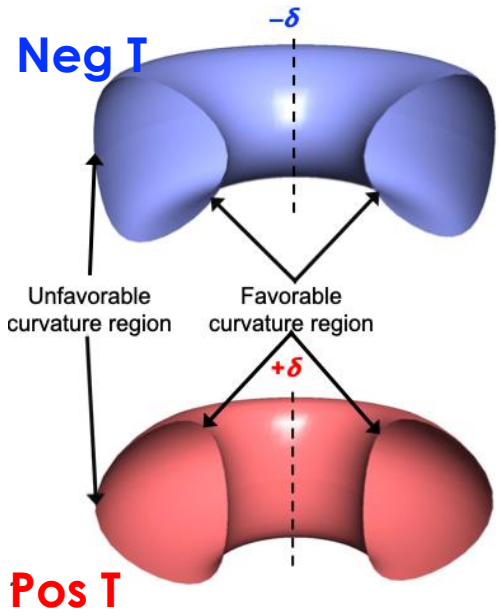


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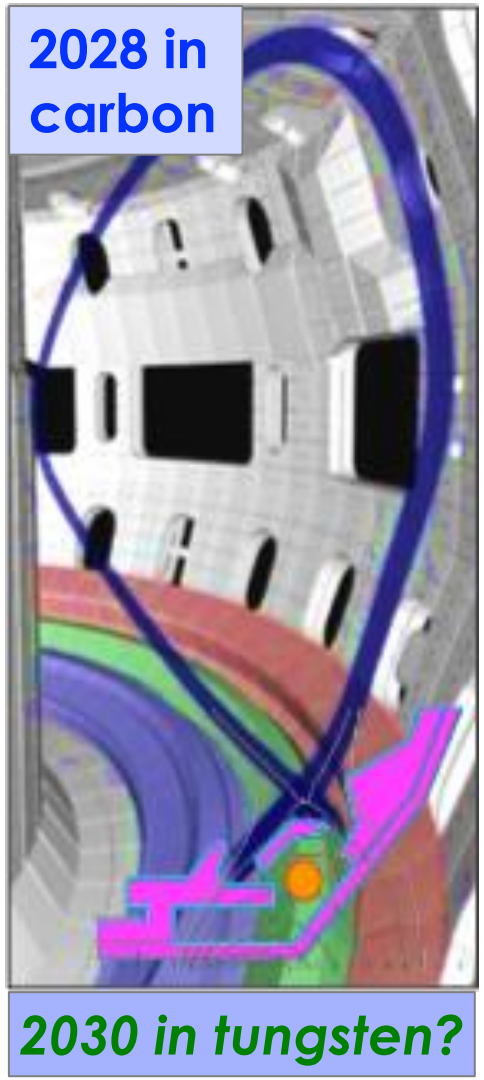
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Follow up with tungsten wall would assess heat flux mitigation on tungsten tiles and leakage of tungsten back the core



Transformational solution to two greatest plasma challenges in the Roadmap

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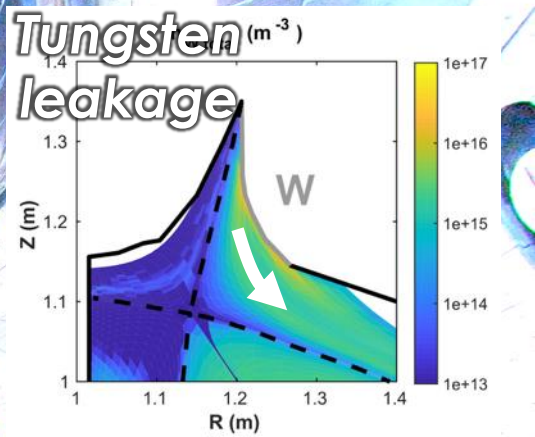
A Tungsten Wall at DIII-D Would Help Close Remaining Gap Between DIII-D and Power Plant Regimes

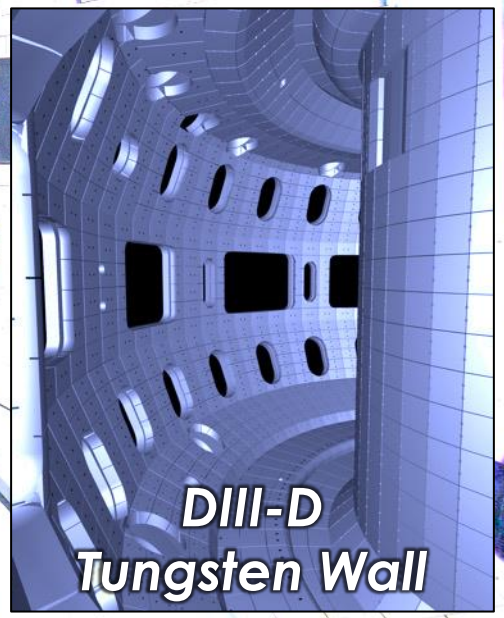
Wall a key constraint on the plasma solution

- Influences detachment, pedestal, radiators, performance & stability
- Must tolerate core scenario & places constraints on it
  - *Carbon influences behavior in ways not expected in reactor*

DIII-D proposing to move to a Tungsten wall:

- **Resolve plasma scenario & behaviors in W environment,**
- **Test innovative new materials without carbon induced erosion**
  - Better solutions are needed than tungsten
- **Pioneer integrated core-edge-wall-technology solutions**
  - Pulsed, steady state, NT with advanced divertors & transient control compatible with surrounding fusion technology





Basis to resolve a wide range of fusion science and technology solutions

DIII-D NATIONAL FUSION FACILITY

DIII-D Providing Critical Insights on Fusion Science & Technology To Enable the Commercialization Agenda

- **Highly flexible, able to rapidly implement and measure new concepts**
- **Relevant core and edge pursuing necessary innovation in each**
- **Engaged with fusion industry & pioneering multiple fusion technologies**



DIII-D supporting a faster path to fusion by levering public and private expertise to resolve techniques & science to project solutions needed

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