DIII-D Indicative Time Line to 2030

Presented by

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with thanks to many

DIII-D colleagues

For distribution to participants in DOE open call process

April 2025

DIII-D NATIONAL FUSION FACILITY

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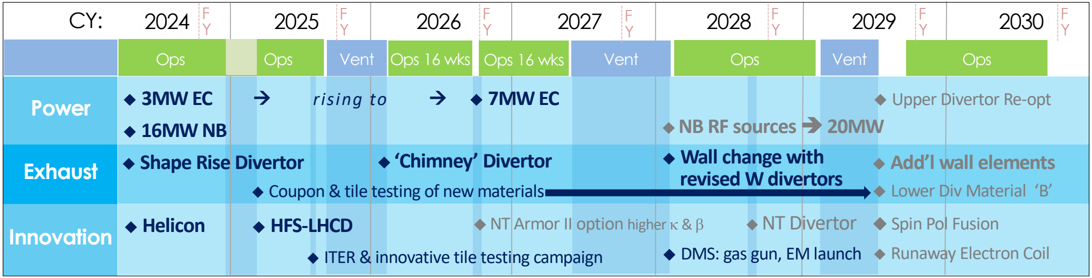
GENERAL ATOMICS

Context of DIII-D Planning

- **DIII-D research team drafted a five year plan for 2024-29**
  - From this plan DOE identified a number of projects to cost, also adding new wall
- **Several of these have been authorized & started/completed funding:**
  - ECH to 10 lines – Chimney divertor – Tungsten wall – LHCD completion
  - Plus various parallel project that may come to DIII-D: pellets, SPF, NB RF sources
- **Other projects have not been authorized yet, so are speculative**
  - The attached chart shows where they might land if they are funded
  - It is too early to speculate whether FES would be motivated to fund them
- **The detailed timeline does evolve as year to year budget decisions, and project designs and execution plans are developed**
  - The attached chart shows a realistic integrated plan that includes started projects and options under consideration with FES

Dynamic program environment, responding to need & developments

Indicative Timeline of DIII-D Facility Development to 2030



Grey=funding tbd

- **Projects in black are underway and receiving funding**
- ***Projects in grey are subject to later decisions in DOE's annual funding process for DIII-D***
  - *Actual funding commitments are not usually received until close to project start*
- **For detailed research plans, see the DIII-D Five Year Plan and the DIII-D Wall Proposal**
  - TRL approach implemented to direct and assess progress

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Heating, wall & divertor transform DIII-D capabilities to close gaps on FPP

Other Notes

- **Note timing of wall vent depends on an engineering plan under development, and will be commenced at the earliest opportunity**
  - Possibly a little earlier or later than shown
- **DOE call instructs proposers to not propose experiments beyond FY28 on DIII-D**
  - This does not preclude ongoing analysis to reach key deliverables and insights
- **A separate memo is released on "Essential Service Roles"**
  - See link: https://d3dfusion.org/wp-content/uploads/Essential-Service-Roles-at-DIII-D-250408.pdf
  - This covers activities that are essential to facility operation and provision of basic data to characterize plasma for most users.

For more details of the DIII-D mission

- **See:**
  - **Physics of Plasmas paper**: "DIII-D's role as a national user facility in enabling the commercialization of fusion energy"
    - *Phys. Plasmas 30, 120603 (2023), https://doi.org/10.1063/5.0176729*
  - **DIII-D Five Year Plan** (for users with internal access):
    - *https://fusionga.sharepoint.com/:b:/r/sites/DIII-DHub/Shared%20Documents/Program%20Plans/Five-Year%20Research%20Plans/D3D-FYRP-2024-2029.pdf?csf=1&web=1&e=vP4cfE*
  - **DIII-D Mission for new wall:** "Gaps and Alternatives for the First Wall Material in DIII-D" (for users with internal access)
    - *https://fusionga.sharepoint.com/:b:/r/sites/FullWallChangeOut/Shared%20Documents/4.%20Physics%20Evaluation%20(Gaps,%20PVR,%20etc.)/DIII-D%20Report%20of%20Gaps%20and%20Alternatives%20for%20Wall%20Change%20-%20release%202410116.pdf?csf=1&web=1&e=ljvBKk*
- **Or contact and discuss with DIII-D team members through the usual Record of Discussion process**
  - Contact form and instructions here: https://d3dfusion.org/become-a-user/#rod
- **Following slides summarize key capabilities and mission**

Additional Slides on DIII-D's Research Mission & Capabilities Enabled by Planned Enhancements

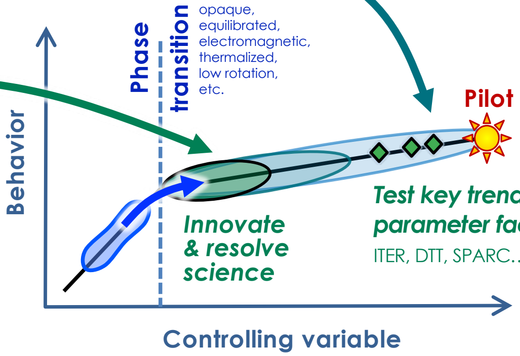
To Resolve Approach Must Access Right Regime, Innovate & Project

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

Need flexibility to find solutions

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

(3) Add the tools needed to address key issues & integration



Test key trends in high parameter facilities
ITER, DTT, SPARC…

Through this approach, DIII-D continues to play a critical & needed role in defining future facilities

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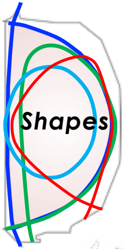
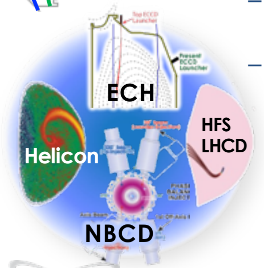
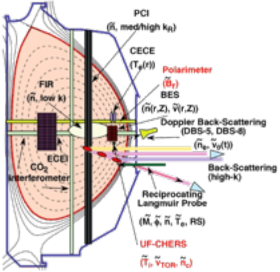
DIII-D is a Uniquely Flexible Tool to Resolve Required Solutions



- **High flexibility to discover new solutions**
  - Shape, 3D fields, fueling, impurities, density control
  - Drive/balance rotation, current & heat to e^-'s or ions
  - Rapid change outs to test new technologies, materials and systems in relevant regimes



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

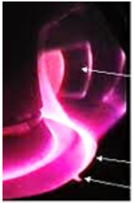


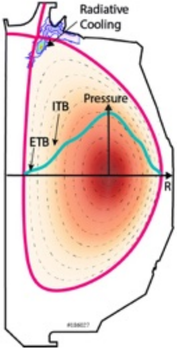
- **Collaboratively led with 700 users**
  - 21 fields led by uni's, Nat Labs, intl & GA
  - Joint development of strategy
  - Oversite by independent User Board & PAC

Supporting ~100 institutions to pursue their priorities with an effective user model

Fusion Requires an Integrated Core-Edge-Technology Solution

- **Performance 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





Our goal is to explore these challenges and discover new & better solutions

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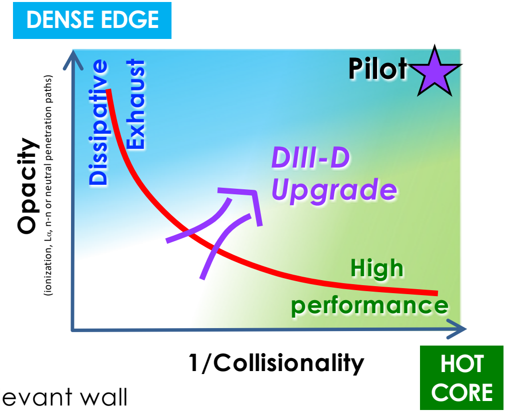
Address 'Integrated Tokamak Exhaust & Performance' (ITEP) Gap

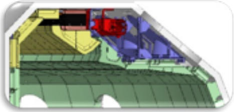
- **Tension between:**
  - High density radiative divertor solution
  - High temperature high performance core
- **Present devices tend to work between these regions**
  - To overcome must do both
- **DIII-D pursuing by**
  - Shape, volume and current rise } *high pressure*
  - Heating & current drive rises } *high pressure*
  - Advanced divertor & core configurations with relevant wall
    - ➢ ***Relevant physics regime for core-edge resolution & better solutions***

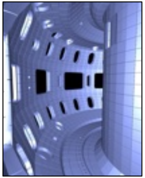


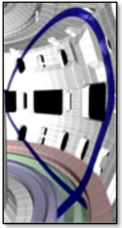
Basis to develop integrated solution

DIII-D Enhancement in Next 5 Years will Confront the ITEP Gap and Resolve Integration with Key Fusion Technologies

- **Increased shaping, volume & current**
  - Raise pressure & density → close gap on reactor regimes
- **Increase heating and current drive**
  - Support high performance dissipative regimes
- **Chimney divertor**
  - Isolate key physics & test better concept
- **Tungsten wall**
  - Carbon free to explore new materials & qualify solutions
- **Negative triangularity divertor** ***(funding not yet determined***
  - Potentially transformational path





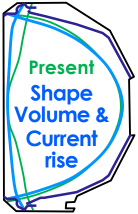


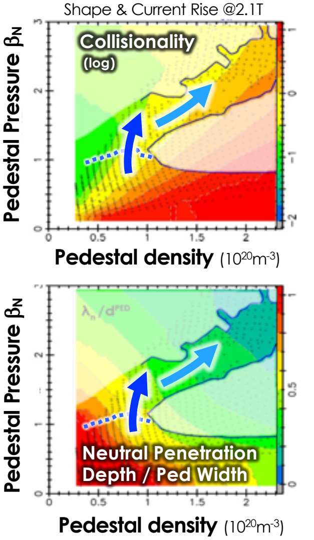
Enables program of advanced plasma scenario & technology testing, and their integration

New Shape Volume & Current Rise Divertor Raises Pressure, Density and Opacity to Confront Core-Edge Challenge

ITEP

- **Increased shaping opens large expanse in operational space**
  - Raises **pressure** and **density** access
  - Increases **opacity** & lowers **neutral penetration**
    - *Gradients become transport-defined, like FPP, rather than by neutral deposition*





- **Increases scope of pedestal exploration**
  - **Conventional pedestals: Low collisionality & high opacity** with high energy, pressure & density
  - **More advanced pedestals: Scope limits of performance & dissipation** through shaping & control techniques

Unique basis for core-edge integration & resolving reactor pedestal science

EPED, EIRENE, SOLPS

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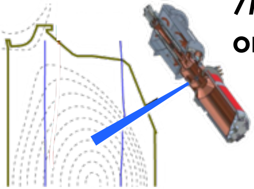
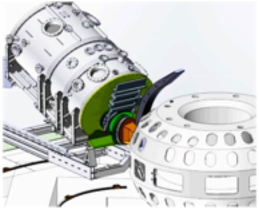
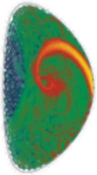
Increased Heating & Current Drive Supports High Density and Temperature for Core-Edge-Wall Integration



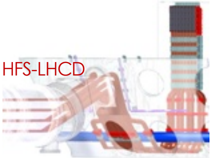
7MW ECH ordered: directable electron heating or current drive, without fueling or torque

20MW NBI with RF sources being developed by NC State: bulk heating, on/off axis current drive & co/ctr for rotation control





New helicon current drive: installed & testing



New HFS LHCD installed: testing in 2025

Provides high flexibility & developing new technology

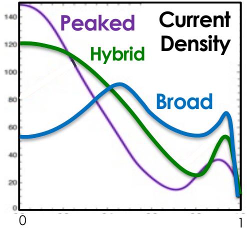
New Heating and Current Drive Enables DIII-D to Explore Candidate Power Plant Core Solutions

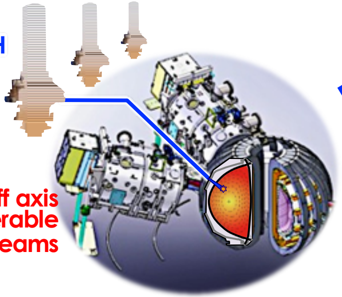
Spectrum of plasma regimes

– From broad → peaked currents, high bootstrap → driven currents

Heating upgrades provide scope to explore solutions & address physics

Regime	Strength	Challenge
Broad	β_N=5 potential; Low disruptivity	Fast ion transport wall modes
Hybrid	Efficient CD, Robustness	Current evolution β_N limit
Peaked	Good confine't no RWM	Sustainment; Tearing. Disrupts



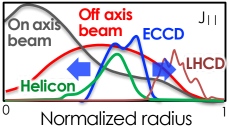


Performance (β)
Wall mode kinetic damping and fast ion instabilities vs. current profile

Burning Plasma Conditions (Ω T_e/T_i P_{ei})
Turbulent transport & kinetic effects in thermalized plasmas at low rotation

Core-Edge Integration (n, $q_{||}$)
High density and power to understand impurity and core-edge optimization

H&CD tools:

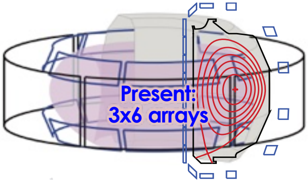


Unique flexibility to develop scenarios & resolve predictive science for FPP core

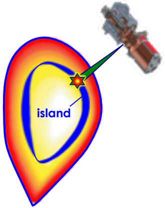
Electron Heating Rise Provides Crucial Capability to Resolve Transient Control in Relevant Regimes

Transients

- **ELM control:** *Unique access to relevant **low rotation & collisionality 'peeling limited' pedestals** to resolve integrated scenarios*
  - **Resonant 3D field ELM suppression** with flexible coil arrays
  - **QH and other benign ELM regimes:** resolve controlling edge physics & ExB rotation requirements with flexible profile control
  - **Pellet pacing:** sufficient triggering and heat reduction



- **Plasma control:** *Unique headroom through α-like electron heating, with precise deposition & profile control*
  - **Burn simulation & control** with FPP-like actuator and measurement constraints
  - **Tearing mode control** via direct island deposition or profile control
  - **Disruption avoidance:** Machine learning, faster-than-RT simulation, sensing
    - *Digital twin develops robust schemes offline for testing online*



DIII-D the key proving ground to resolve tokamak control & non-linear multiscale physics of MHD phenomena

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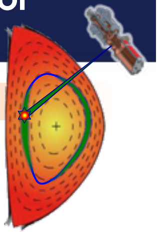
These Capabilities Enable DIII-D to Address Plasma Behavior and Interaction Questions Across the Board for FPP



EC

Lines	Power
6	3-4 MW
8	5.6 MW
10	7 MW

+ additional NBI, helicon & LHCD

Possibly more needed for some missions

← KEY TECHNIQUES →

Disruption mitigators

Entry point for high q_{min} AT

Divertor science & geometry tests

Novel RF technologies

FPP Diagnostics

Perturbative transport in H-mode

Shape rise & pedestal density & pressure limits

Radiative techniques

Peeling limited pedestals for ELMs

Materials erosion & transport

Sample & component testing

LIMITS

ITER dual NTM/sawtooth control, Q=10

AT stability limits

Pulsed FPP scenarios

ELM mitigation at low rotation & ν^*

Control impurity accumulation with ECH

Thermalized FPP-like fast ions

Alternate ITER scenarios

Burn simulation

Divertor science in opaque conditions

Components & materials at high T_e, density, $q_{||}$

ITER ramp up & steady state

Transport at low rotation, T_e~T_i, high β

Opaque collisionless pedestals

High performance & high dissipation core-divertor solutions with high SOL ν^*

Materials integration with core

CORE – EDGE INTEGRATION

Close plasma research and FM&T gaps for FPP

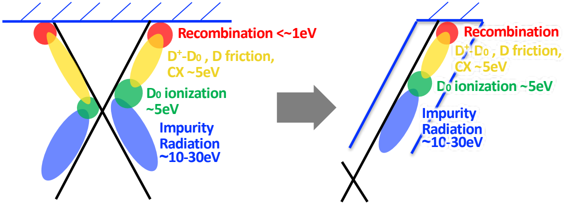
New "Chimney" Divertor Concept will Resolve Key Physics & May Offer Improved Divertor Solution

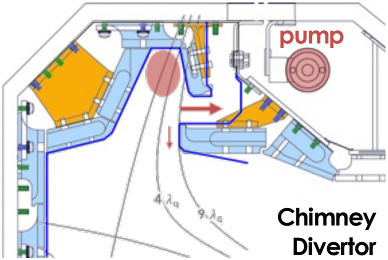
Longer leg

- Isolates physics for model validation
- Avoids X point degradation

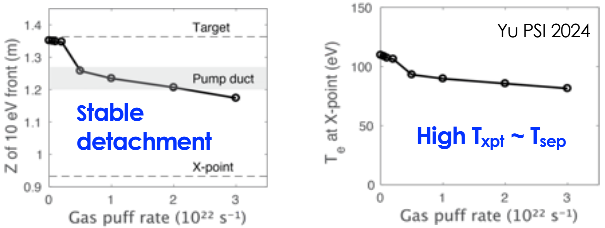
"Chimney" design improves detachment

- **Mid-leg pump** stabilizes radiation front at duct





SOLPS predicts cold dense target & hot X with good stability



Test key principles behind divertor design

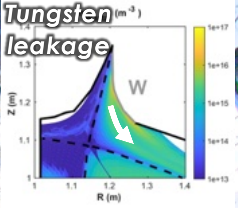
New Tungsten Wall to Resolve Fusion Solutions in Reactor Relevant Conditions

Wall & Tech

- **Wall a key constraint on the plasma solution**
  - Must tolerate core scenario
  - Influence detachment, pedestal, core performance & stability

DIII-D carbon wall influences core radiation, outgassing & erosion
  - ***Time to confront this ➔ DIII-D moving to W wall in 2027***

- **Adapt DIII-D developed scenarios for W environment,**
  - Benefiting from key mitigations in core, pedestal & divertor
- **Test innovative new materials without carbon**
  - Better solutions needed than tungsten
- **Resolve integrated core-edge-wall-technology solutions**



Tungsten wall transforms the context of much of DIII-D's research

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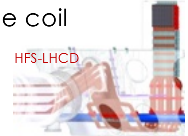
FPP Technology Development Program Pioneers New Solutions

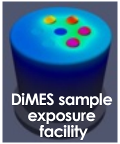
- **DIII-D brings key characteristics necessary**
  - **Flexibility**, diagnosis, relevant regimes, integration
  - **Swap out components rapidly & often**
    - Difficult → impossible in activated or tritiated devices
  - **Assess with relevant solutions** for wall divertor & core

Technology Group spans 1/3rd of DIII-D program

- **Platform approach with rapid facilitated access**
  - Materials, control, diagnostics, components
- **Pursue key innovative techniques**
  - Disruption mitigation: pellets & passive coil
  - Helicon & HFS-LHCD RF
  - Reactor fueling
  - Spin polarized fusion



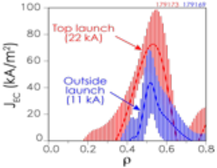
Proven track record



Materials interactions
- Explore degradation
- Understand transport
- Assess divertor leakage

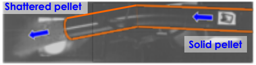
Studies of W & ELM behavior, and new materials

Top launch ECH
Doubled current drive efficiency



Shattered Pellet Disruption Mitigation
- Quench heat & current

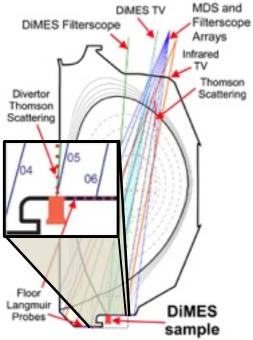
Adopted by ITER



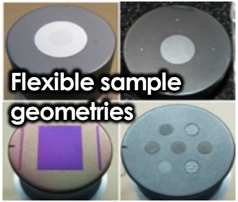
Key capabilities that will qualify critical fusion technologies

DIII-D Providing Key Testing Ground for Innovative Materials

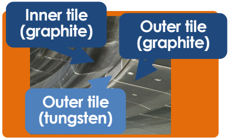
- **Divertor Materials Evaluation Station ➡**
  - well-diagnosed
  - varying geometries
  - shot-to-shot replacement
  - relevant plasma loads



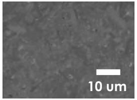
Diagnostic	Interest
IR imaging	Heat flux
Spectrometer	Erosion
Langmuir Thomson	Plasma parameters
Thermocouples	Temperature



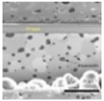
- **Tiles & rings to assess materials on bulk scale**

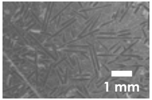


- **Exploring new alloys, ceramics & liquid metals**

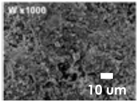


Ultra-High Temp Ceramics (UHTCs)

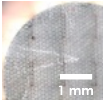

Dispersoids



Fiber-reinforced



Plasma spray



Microstructured W/Cu


Liquid Metals

Unique insights and tests possible

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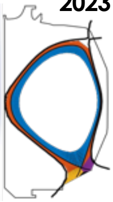
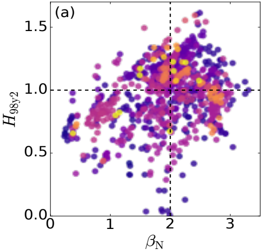
Negative Triangularity Provides Transformational Potential for Fusion (not yet funded)

- **Negative Triangularity gave high confinement with low power to divertor and no ELMs**
  - DIII-D changed hardware to test diverted 'NT'
    - ***in just two weeks!***
  - Exciting results with great confinement & stability ➡

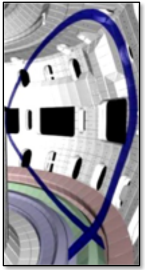
2023





- **New closed pumped NT divertor will combine with ECH upgrade to close remaining gaps**
  - Core-edge integration:
    - ***Detachment with high performance core***
  - Assess Advanced Tokamak & wall compatibility

Negative Triangularity could upend the tokamak concept !



Cryo-pumped full closed NT divertor

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DIII-D Supporting Engagement with Private Industry to Accelerate Commercialization

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

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

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

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

- **New user framework enables private sector to join**
  - **Protects private IP** while sharing public IP
  - **Provides support**, training, expertise & shared leadership
  - **Partnership approach** with workshops and six companies on our PAC

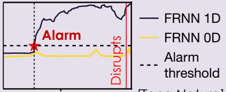
Industry examples

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]

20 companies joined or in process including non-tokamak & non-fusion

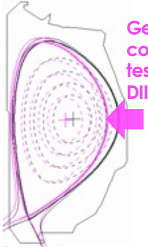
Rapid, free, flexible-scope access in as little as a day

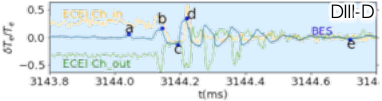
**Survey of 22 fusion companies, D.C. Pace, MBA thesis*

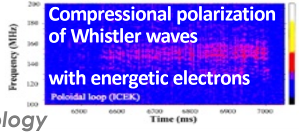
DIII-D Tests Common Research Needs of Novel Fusion Concepts, Fundamental Science and Technology

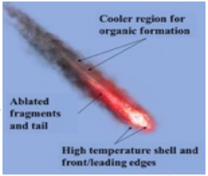
- **Many common fundamental processes behind fusion & wider plasma physics**
  - Different configurations: **common physics and technology questions**
- **Examples:**
  - **Compression-heating physics being tested for General Fusion in 2024**
  - **Advanced materials models for spacecraft heat shields**
  - **Wide range of fundamental plasma physics with DPS community**
  - **Organic molecule formation in meteor tails**

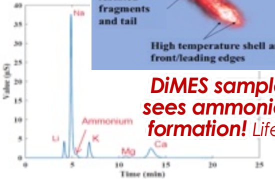
Tested SPARC error field correction & tile technology











DiMES sample sees ammonia formation! *Life!*

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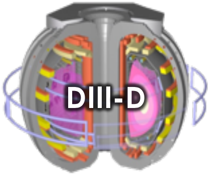
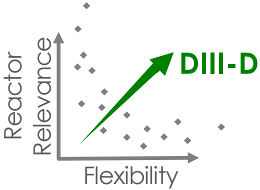
Incredible flexibility to answer key questions

DIII-D Provides Distinctive Capabilities Internationally and Basis to Lever US Collaborations



Develop techniques at high power density

- Flexibility to resolve & integrated innovative exhaust, core and wall solutions
- High opacity, low ν*, high performance, burning plasma relevant conditions
- Physics basis to project



Long pulses test evolution & wall

- Material & PFC evolution
- Long pulse control

Larger devices test scaling

- Projection to reactor
- Operational techniques

Key physics & novel techniques

- Aspect ratio & Shape
- Extreme divertor geometry
- Super Alfvénic ions & high β
- Liquid metals

Higher field: nuclear & burn

- HTS integration
- Core-edge demonstration
- Nuclear testing

Important to focus on insights that lever international progress

DIII-D Providing Critical Roles in Preparation for ITER

Distinctive Contributions:

- **Develop & accelerate early phase ITER research plan**
  - H mode access, ELM control, EC ramp up, DMS tests
- **Resolution of transients & development of ITER control**
  - Stability, ELMs, disruptions, runaway electrons
  - Control development & burn simulation
- **Validated physics models to project and interpret behavior <u>in relevant low rotation conditions</u> in ITER**
  - Turbulent transport in coupled, opaque, low ν^* & Ω regimes
  - Wall to core Tungsten transport, MHD turbulence and AEs
- **Development of robust, controlled scenarios to reach or exceed Q=10 & determine path to Q=5 steady state**
  - Baseline, reduced current & high β paths with radiative solutions

Key Capabilities:

- Carbon → Tungsten wall
- EC: torque-free electron heating with precise deposition control
- Balanced torque NBI
- New quench systems
- Integrated control
- Pellets for high density
- 3D coils
- Advanced measurements

US success and benefit in ITER – key for wider fusion path – *<u>requires</u>* DIII-D to prepare techniques, tools & team

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DIII-D Provides a Critical and Cost-Effective Tool to Make Rapid Progress on the Bold Decadal Vision

- **Highly flexible user facility able to pioneer the tokamak path to FPP**
  - Tokamak serves as 'first integrator' to resolve fusion technologies more broadly
- **Critical enabler of the wider vision & the private sector through technology testing, its flexibility & measurement systems, and sharing its expertise**
- **Serves entire fusion community well & productive now on all these goals**
  - Developing people, sharing knowhow, enabling success in private sector & ITER

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Get in touch if you want to participate!