DIII-D: A Public Facility's Role in Enabling Fusion Commercialization

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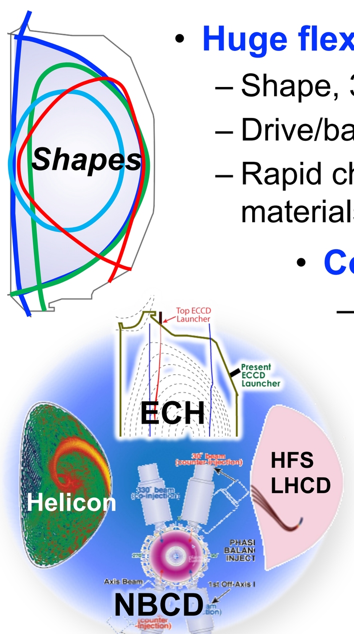
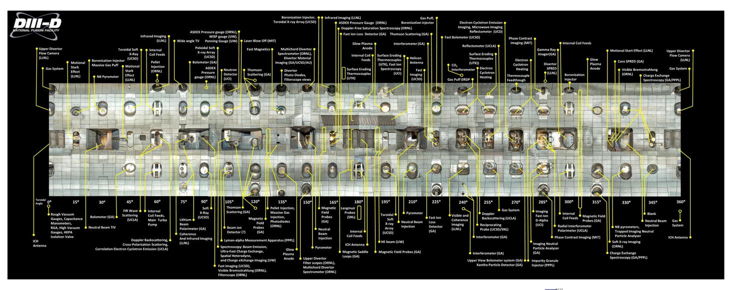
ABSTRACT

The DIII-D program has pivoted to support the private sector path to fusion energy, with an aggressive technology program that supports, derisks and speeds research of private fusion partners, and by opening its user model to directly engage private fusion companies in research at DIII-D, provided free at the point of delivery for research conducted openly in the public domain that yields insights to all. Come join us!

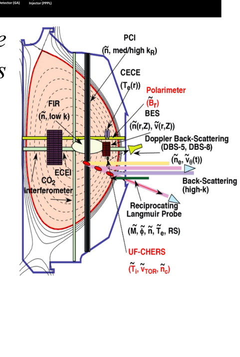
DIII-D CAPABILITIES TO ADDRESS COMMERCIALIZATION AGENDA



- **Huge 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 & systems in relevant regimes



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



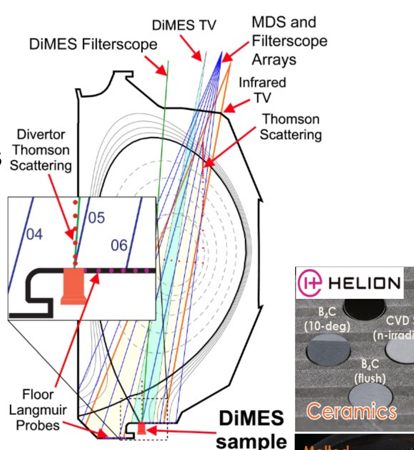
Comprehensive diagnostics

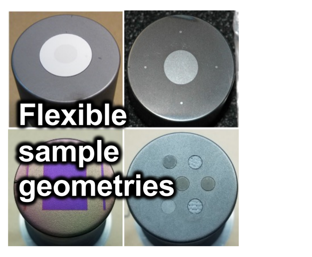
- **Collaboratively led with over 800 users**
  - Research areas led by universities, national labs private industry & international partners
  - Joint development of strategy with independent oversight by User Board & Advisory Committee
  - 20 Private industry partners

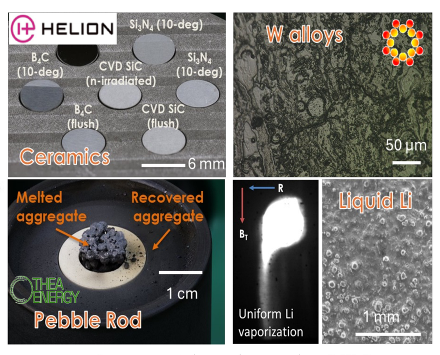
Key testbed to answer critical questions in fusion condition

FUSION MATERIALS

- **Needs:** Materials choice is critical for FPP design
- **DIII-D capabilities:** Rapidly change out samples from ~mm to tiles & rings
  - DiMES system changes out divertor samples every 15 minutes →
  - Understand plasma interaction at power plant heat fluxes to 15<MW/m²
  - Comprehensive measurement assesses materials degradation, influxes and impact on core plasma
- **Key insights:** 61 novel plasma-facing materials from more than 12 institutions were successfully tested over the last two years
  - Liquid lithium (Li) capillary porous structure (CPS) demonstrated uniform Li vapor emission and suppression of droplet ejection when pre-heated to 350 °C
  - Helion Energy: down-selection of ceramic materials → bulk SiC
  - Tokamak Energy: testing of k-doped W and W-Ta alloys under attached & detached plasmas
  - Avalanche Energy: preferential erosion of multi-principle element alloys MPEAs
  - Thea Energy: first demonstration of boron pebble rod divertor concept







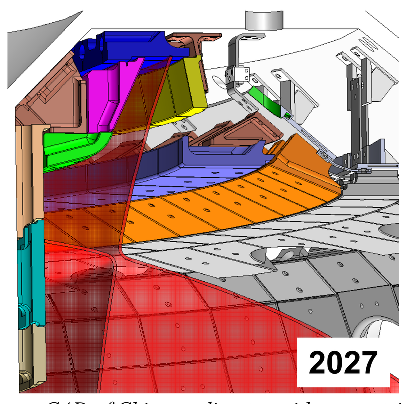
Some material samples tested on DIII-D.

Active contribution to fusion materials R&D and populating fusion materials database

POWER HANDLING

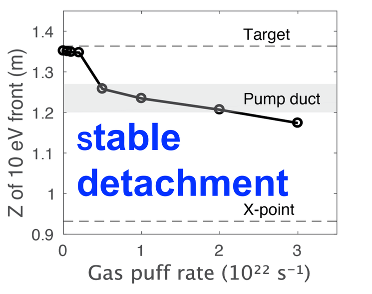
New 'Chimney' Divertor Concept

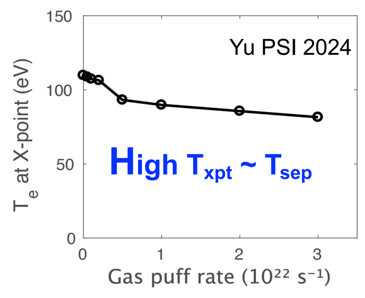
- **New divertor predicted to enable robust divertor detachment with a hot core:**
  - Pump duct positioned part way up leg in a tightly baffled divertor slot →
  - Recycled neutral particles from exhaust accumulate near the target
    - → contribute to dissipation processes, cooling plasma before it contacts the materials
    - → Neutrals removed upstream so neutral density is low approaching the core plasma
  - Simulations predict a passively stabilized detachment front and detachment access at lower $n_{e,sep}$ relative to a pump duct positioned closer to the target [7,8].

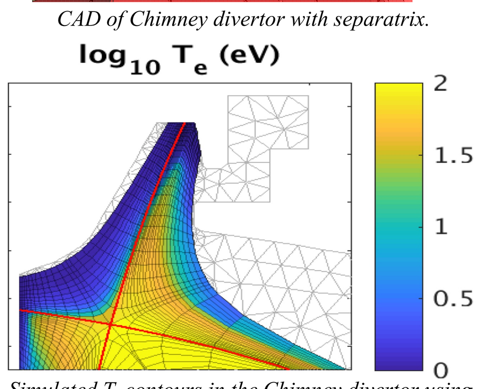


CAD of Chimney divertor with separatrix.

As gas puff rate is varied →





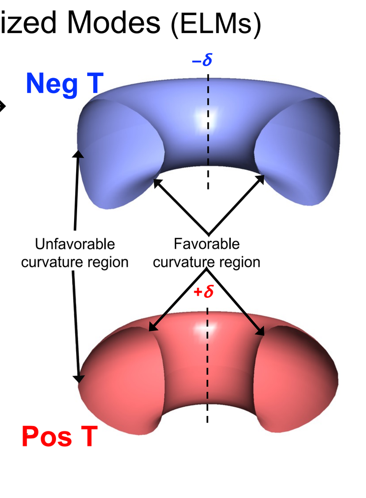


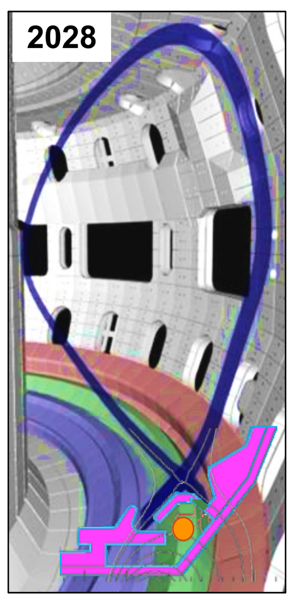
Simulated T_e contours in the Chimney divertor using SOLPS-ITER[7] demonstrating a cold divertor target and hot separatrix with 10eV detachment front stabilized near the pump duct.

- → *Potential to reduce requirements on the plasma-facing materials in a reactor.*
- A future upgrade including reactor-relevant materials in the divertor slot is being planned

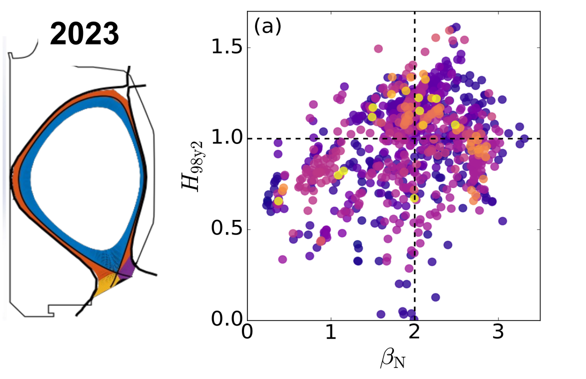
Negative Triangularity Closed Pumped Divertor

- **May solve two greatest challenges for tokamak:** Divertor & Edge Localized Modes (ELMs)
  - NT shape prevents access to H-mode transport barrier ('pedestal')
  - Favorable field curvature recovers confinement from lost pedestal in core →
    - → *No requirement for heat into scrape-off layer to maintain H mode.*
    - → *No ELMs*
- TCV showed favorable results in limited configurations
- DIII-D showed high performance in high power diverted plasma in 2023
  - *Key question: Compatibility with dissipative divertor?*





Negative Triangularity closed pumped divertor.

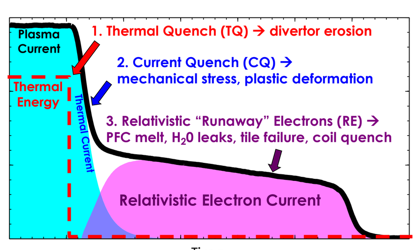


- **In 2027-8 DIII-D will install an NT closed pumped divertor**
  - Physics design by LLNL
  - Conceptual engineering design by General Atomics →
  - Full engineering by Kyoto Fusioneering
    - → *A true public – private partnership!*
- → *NT divertor will be available to all users on an equal basis, managed by DOE's "Tokamak Research" program*

DIII-D confronting the greatest plasma physics challenges with pioneering solution

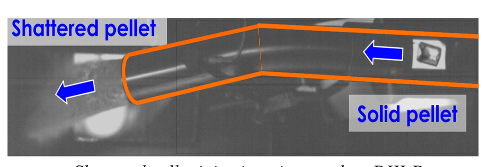
PELLET FUELING AND SAFE QUENCHING OF FUSION PLASMAS

- **Needs:**
  - **Fueling:** Burning plasmas will be highly opaque to neutrals, necessitating pellet injection as a core fueling source
  - **Disruptions:** Fusion plasmas need fast quenching mechanisms to dissipate → heat and free energy before it damages device integrity
  - **Fusion Performance, Q:** Explore spin polarized fusion as a way to increase Q



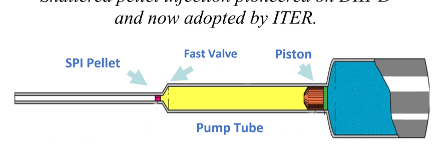
Disruption challenge for tokamaks.

- **Fueling: Real-time control of the pellet size and injection rates implemented on DIII-D**
  - Allows variation of particle source to meet control requirements based on plasma conditions.
  - Adaptive model-based control of the pellet and gas injection designed via simulation and tested in DIII-D
- **Disruption: New particle injection methods** for safely quenching fusion plasmas
  - Room-temperature solid pellets: payloads within a thin-walled "shell"
  - Lithium coatings to minimize perturbation of plasma edge prior to core delivery
  - Layering of conventional cryogenic pellets DIII-D



Shattered pellet injection pioneered on DIII-D and now adopted by ITER.

- **Q: Spin polarized fusion tests** being prepare for DIII-D
  - Develop diagnosis methodology and then assess how long polarization state maintained

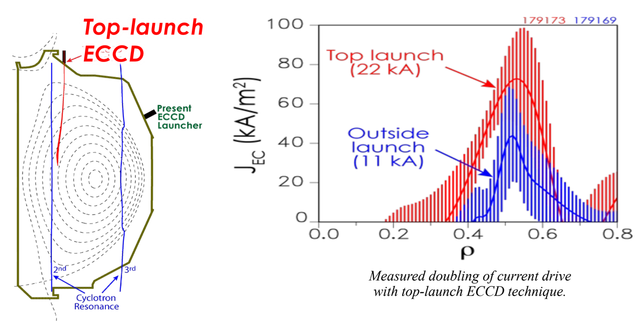


Two-stage light gas gun schematic showing the key elements of the second stage pump tube, piston, fast valve, and SPI pellet in the breech of the gun to deliver pellets at higher speed to reach core of the plasma.

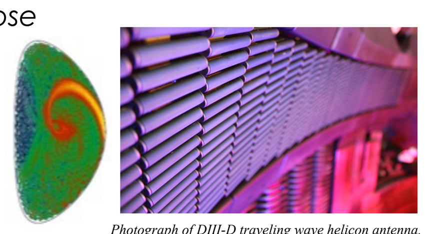
DIII-D testing critical pellet technology and interaction with core

RF SYSTEMS AND CURRENT DRIVE

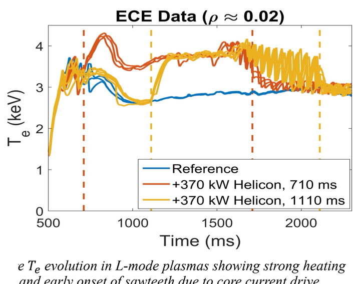
- **Need: Heating & current drive very challenging in power plant**
  - *Efficiency of heating and current drive*
  - *Coupling to plasmas*
  - *Survivability in reactor (heat, particles, neutrons)*
- **Capabilities:** DIII-D reaches relevant core regimes, and edge heat and particle flux, to provide critical tests
  - *Able to rapidly install new systems, compare to others & diagnose*
- **Approach:** DIII-D pioneering a range of techniques:
  - **Top-launching electron cyclotron current drive** (ECCD)
    - *Near-vertical ray increases resonant interaction, allowing absorption further out in tail of electron distribution, doubling current drive efficiency*
  - **Helicon ultrahigh harmonic fast wave**
    - *Potential for improved efficiency over ECCD at higher plasma density*
    - *Comb-line traveling wave antenna provides multiple launch points, leading to robust coupling at increase distances from the plasma*
    - *Experiments confirm coupling to correct wave and heating in line with theory*
  - **High field side Lower Hybrid Current Drive**
    - *Potentially even higher efficiency, for off-axis at high density*
    - *High field side predicted improved wave penetration & safer location for antenna*
    - *Deposition matches theory predictions without free parameters*
  - **DIII-D is further opening up RF infrastructure for other tests**
    - *e.g., high-power microwave drilling (Terrawave), and gyrotron conditioning*
  - **Training of private industry staff on operation**



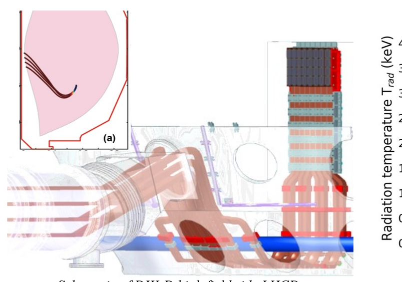
Measured doubling of current drive with top-launch ECCD technique.



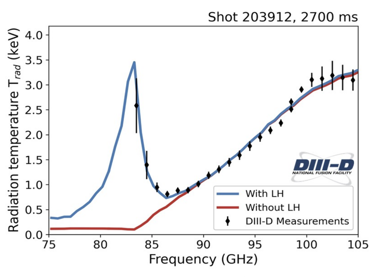
Photograph of DIII-D traveling wave helicon antenna.



T_e evolution in L-mode plasmas showing strong heating and early onset of sawteeth due to core current drive.



Schematic of DIII-D high field side LHCD system.



Predicted and measured response on the ECE diagnostic for HFS LHCD absorption.

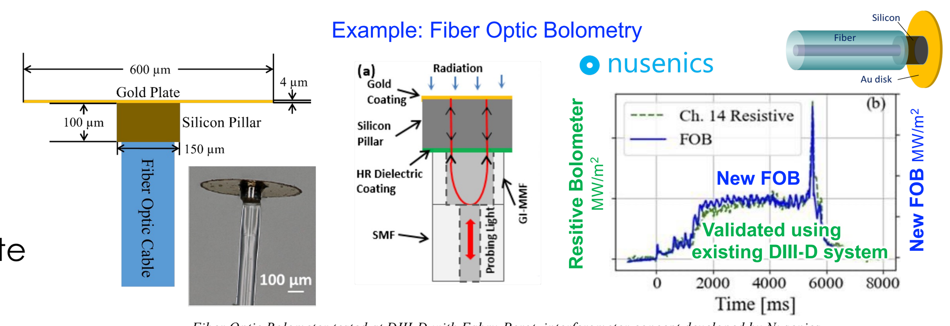
More efficient RF systems a crucial requirement for fusion power plants

POWER PLANT DIAGNOSTICS

- **Need: Power plants need new diagnostic types**
  - *Survival in plasma & neutron fluences*
  - *Miniaturization & modularization*
  - *Reduced diagnostic set*
- **Capabilities:** DIII-D ideal proving ground to validate reactor diagnostics against proven DIII-D systems
- **Approach:** Pursuing range of diagnostic technologies:
  - **Innovative radiation & radiation-hardened sensors**
    - *E.g: Fiber Optic Bolometer (FOB): Fabry-Perot interferometer measures phase shift induced by the thermal expansion of a silicon pillar, unaffected by darkening of the optical fibers.*
  - **Particle detectors (Xantho), stray EC (ITER), spin polarized fusion sensor (UCI)**
  - **Super-resolution synthetic diagnostics for real time control (P-U)**

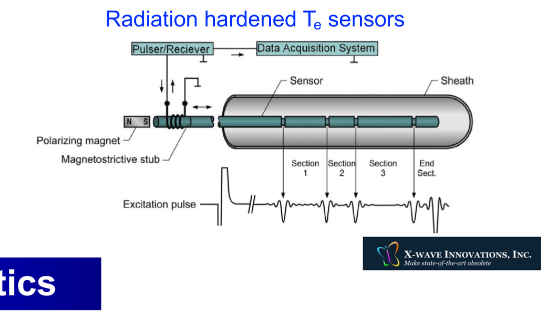
Plus techniques developed through DOE measurement innovation awards

Example: Fiber Optic Bolometry



Fiber Optic Bolometer tested at DIII-D with Fabry-Perot interferometer concept developed by Nusenics.

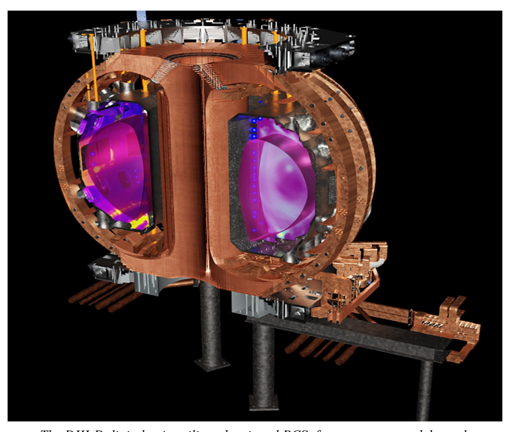
Radiation hardened T_e sensors



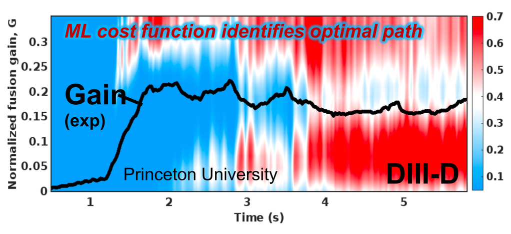
Unique testbed to validate reactor diagnostics

AI AND DIGITAL TWIN

- **Needs:** AI and Digital Twins (DTs) emerged as key ways (i) accelerate research, (ii) develop control solutions, (iii) assimilate information into whole system models.
- **DIII-D capabilities:** Uniquely broad range of measurements, and ability to integrate new AI systems to close loop on control, in fusion-relevant regimes.
- **Approach:** DIII-D DT [13] leverage DIII-D digital infrastructure, integrating advanced modeling, machine learning surrogate models, and real-time diagnostics.
  - Virtual PCS (vPCS) derived from PCS: possible to go back and forth between off-line and on-line in developing algorithms (test offline, prove online)
  - Fast neural net of a kinetic equilibrium reconstruction code calculates plasma evolution
  - Very fast surrogate model allows the DIII-D DT to be highly interactive
- **Implementation:**
  - Integration with NVIDIA Omniverse is a central component of the DT enabling detailed 3D visualization of tokamak plasma behavior and heat flux deposition to the first wall
  - Digital models of DIII-D components, such as the neutral beam system, ensure accurate representation of the physical device ← DT for infrastructure development
  - Couple predictive modeling directly to experiment, informing operations in real time
  - Assimilates information to provide visualization to aid interpretation



The DIII-D digital twin utilizes the virtual PCS, fast surrogate models, and NVIDIA Omniverse to achieve a rapid interactive capability to explore new plasma scenarios.



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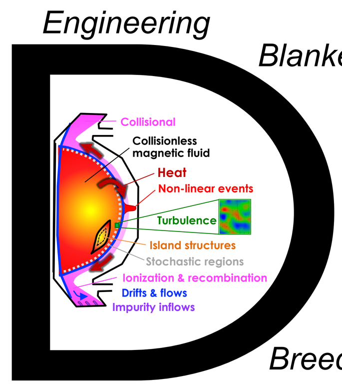


Why AI? Beyond supercomputer challenges!

- Plasma: vast ranges of scales – time & space – *10^{10} !*
  - *Non-linear interactions from macro to micro*
- Materials: *synthesize & predict, from atomic to bulk properties*
- Facility design: *connecting uncertainties in technology & science*

How to synthesize the intractable to predict solution?

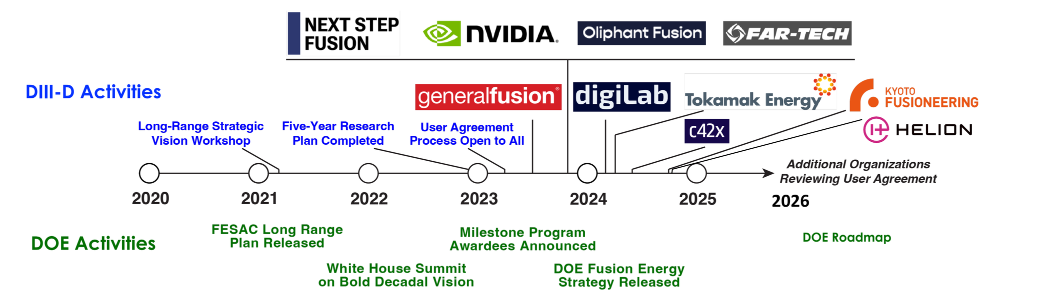
Fusion Data Platform making data accessible

Foundation for developments in tokamak modeling, while serving as backbone to integrate new workflows & models into unified infrastructure

ACCELERATING INDUSTRY ENGAGEMENT AT DIII-D

- **Non-proprietary User Agreement** provides free access to the DIII-D Research Program in a process that can be completed in a single day core:
  - Protects private IP while sharing public IP
  - Provides support, training, expertise & shared leadership
  - Partnership approach with workshops and six companies on our PAC
- **Strong uptake** leading to continued growth in industry participation

Proprietary engagement modes possible through cost recovery model
Please get in touch



DIII-D providing a key tool to validate techniques for commercial fusion

CONCLUSIONS

- **DIII-D is providing major support to the private fusion path, with 20 fusion companies now signed up and conducting non-proprietary research.**
- **An aggressive technology research and testing program is rapidly advancing key technologies and providing crucial tests.**
- **DIII-D is an open user facility provided to private, public and international partners free at the point of delivery, with support – join us!**

References

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GENERAL ATOMICS