Technology Development Opportunities at DIII-D

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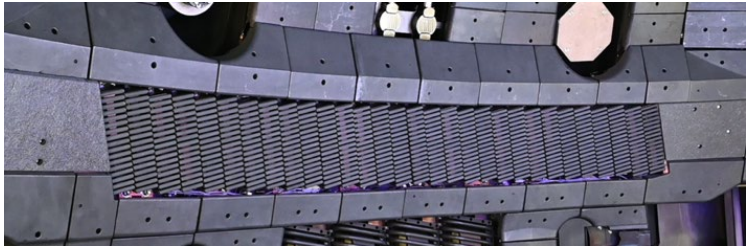
Summary:

This presentation details DIII-D's evolving role to becoming a technological test bed for Fusion Material and Technology development. The purpose is to communicate how to utilize DIII-D to close technology gaps.

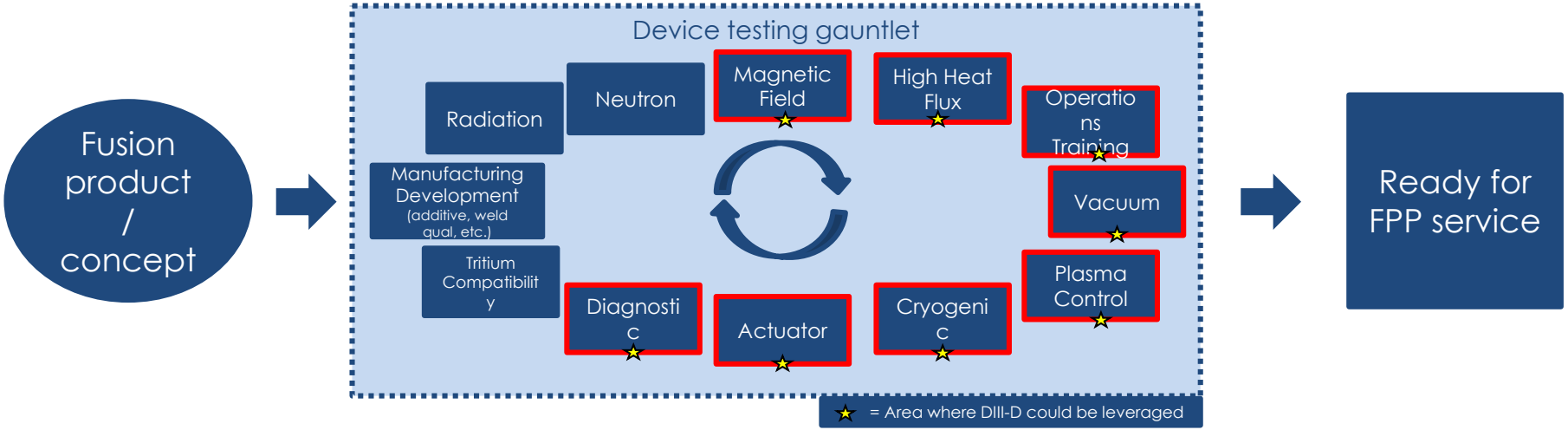
DIII-D enable development of Fusion Technology hurdle

- **Development of fusion technology is costly and difficult because of Fusion's extreme environmental conditions.**
  - Radiation, Neutron fluence, Particle Fluence, Magnetic fields, Extreme temperatures, etc.
  - All these environmental factors have an impact on technology performance; need to be vetted
- **DIII-D's technological mission is to enable rapid, economical testing**
- **We are defining a technology development workflow that can be easily understood and utilized by Fusion Ecosystem to iterate and mature product.**



DIII-D is a platform to enable rapid testing

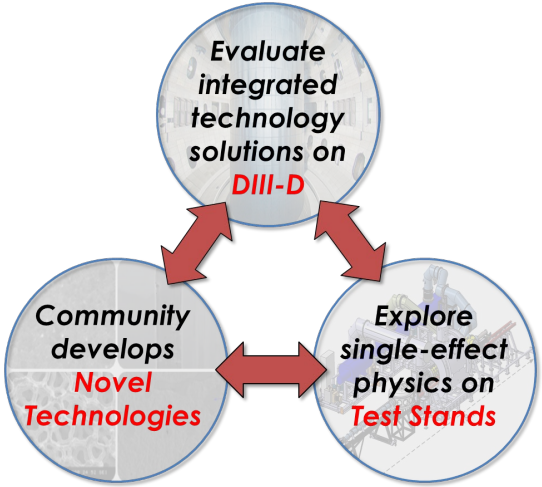
- **Below is a common example of environmental testing typically required to release a FPP ready diagnostic, actuator, or device.**



- **Development workflow is costly, difficult to source, and can provide inconsistent results**
- **DIII-D community is developing a fusion workflow that leverages DIII-D as an economical test bed, where novel products can be benchmarked and compared to existing techniques.**

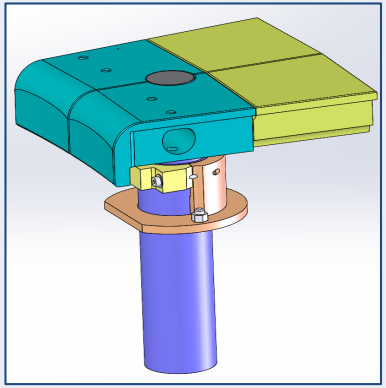
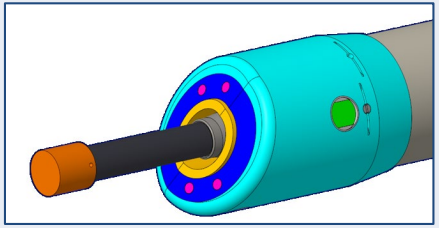
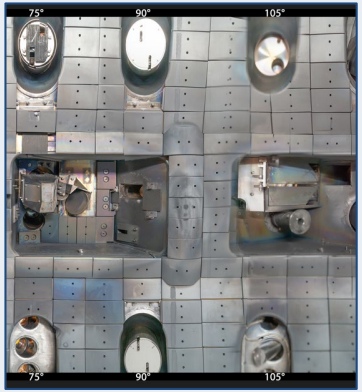
DIII-D focus is technology iteration until FPP maturity

- **This presentation provide a glimpse into DIII-D technology opportunities and to communicates specifics of how to utilize DIII-D.**
  - There are many aspects that are not explicitly mentioned (simulation software, divertor physics, various plasma scenarios, etc.).



Material Test Bed – Tools available

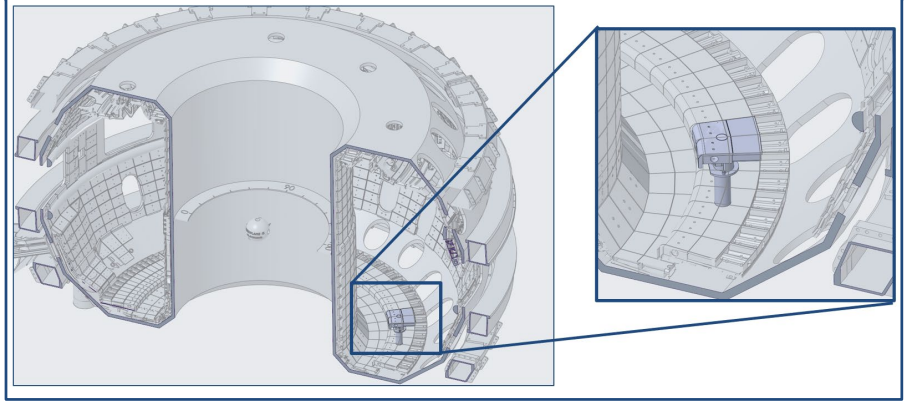
- **DIII-D has several tools for exposing samples to plasma conditions. Listed below are devices readily available. These devices have several diagnostics that are focused near the areas.**

DiMES, small coupons	DiMES, large coupon	Midplane Reciprocating Probe, MiMES	Fixed Tiles
Angled coupons or flat coupons of Ø7mm (up to seven unique samples)	Large flat Ø50mm heads and liquid	Main chamber, mid plane device that pierces ~4inch into plasma.	Long term testing of tiles in DIII-D
			

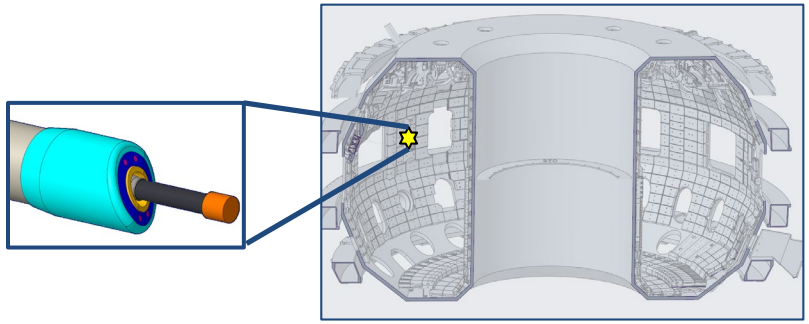
Material Test Bed – DiMES and MiMES locations in tokamak

- **What can DIII-D offer the Fusion Ecosystem?**
  - Rapid sample exposure (every shot)
  - Plasma environment
    - Heat flux at divertor of **20 MW/m^2, angled (for ~6 sec duration)**
    - Heat flux at divertor of 3 MW/m^2, flat (for ~6 sec duration)
    - **Magnetic field strength of 2.1 T**
    - **Neutron fluence of 4e14 neutron/sec**
    - Total 1 MJ of thermal energy
  - ELM environment
    - Heat spikes of **100 MW/m^2 (~1-10 msec duration)**
    - Particle flux at divertor of 1A/cm2
  - Diagnostics
    - Calibrated spectroscopy
    - IR imaging (to study ELM impacts on DiMES samples)
    - **Thermocouples**, Langmuir probes, RFEA probes on DiMES samples

DiMES location; 150deg on divertor

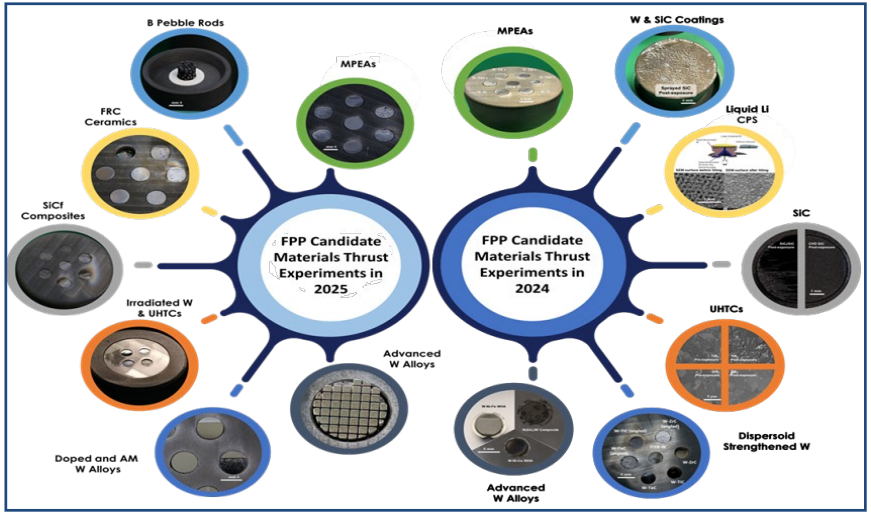


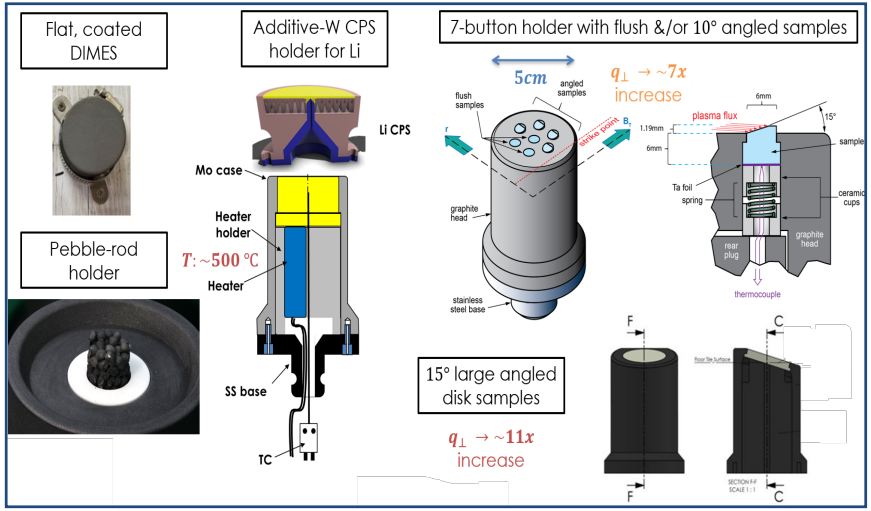
MiMES location; 240degrees at midplane port (R0)



Success Story: 61 plasma facing materials tested

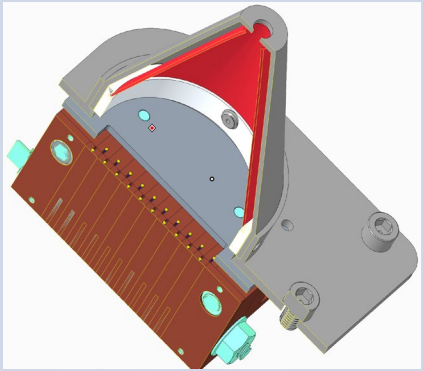
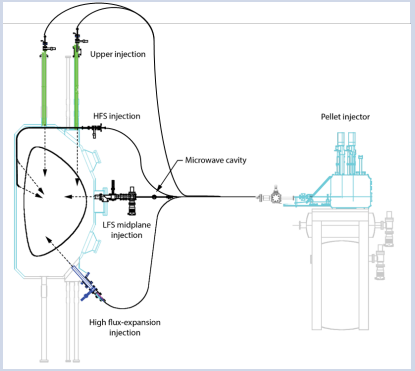
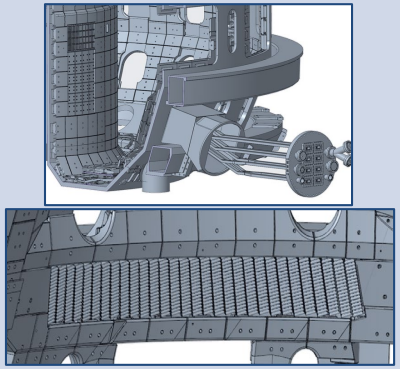
- **Various novel materials successfully tested from twenty institutions, including four private companies. Rapid and economic testing, bolstered by the DIII-D community expertise, will lead to breakthrough.**
- **DIII-D, working with Clear Air Task Force, is building a material database of exposed samples**





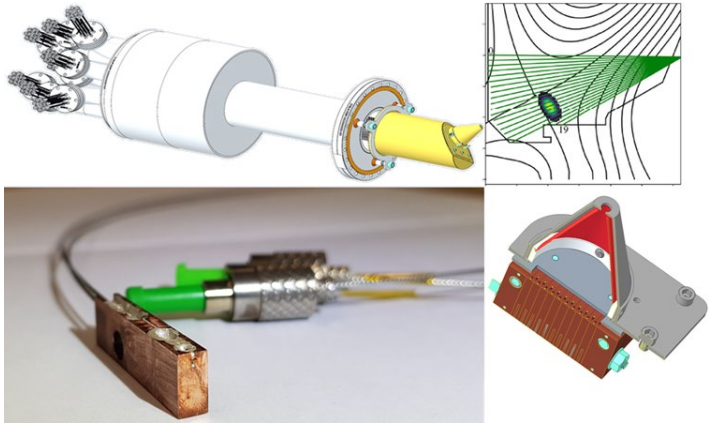
Diagnostic and Actuator Test Bed – Tools Available

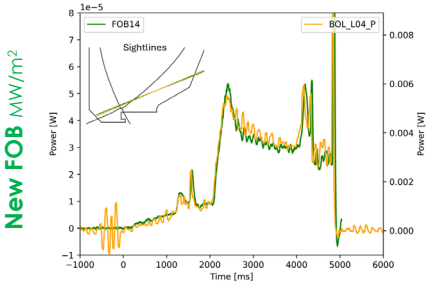
- **The large collection of diagnostics, the maturity of pellet injection, and the availability of heating and current drive sources, position DIII-D for rapid testing and learning**

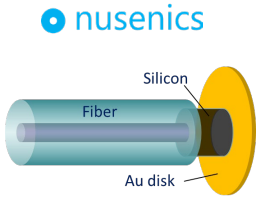
Diagnostic Comparison Test bed	Pellet Injectors Test Bed	Heating and Current Drive methods	
Diagnostics	Pellet development; disruption mitigation and fueling	HFS LHCD, Helicon, NBI	Electron Cyclotron Heating
FPP relevant diagnostics can be baselined against non FPP diagnostics and optimized	Novel pellet injector, like Spin Polarized Fusion, technology can be baselined. Supportive infrastructure can used for new ideas	Novel H&CD systems can be tested in relevant plasma conditions and characterized with several diagnostics	Leveraging DIII-D's diagnostics novel ECH gyrotron designs (specifically from Kyoto Fusioneering) are being validated.
			

Success Story: Fiberoptic Bolometer/creation of Nusenics LLC

- **DIII-D enabled fiberoptic bolometry development.**
  - This novel, FPP relevant sensor was commission on DIII-D utilizing the facilities expertise to test, fail, iterate, and optimize.
  - Results were compared to present bolometry data for functionality verification
- **Led to creation of diagnostic start up → Nusenics LLC**



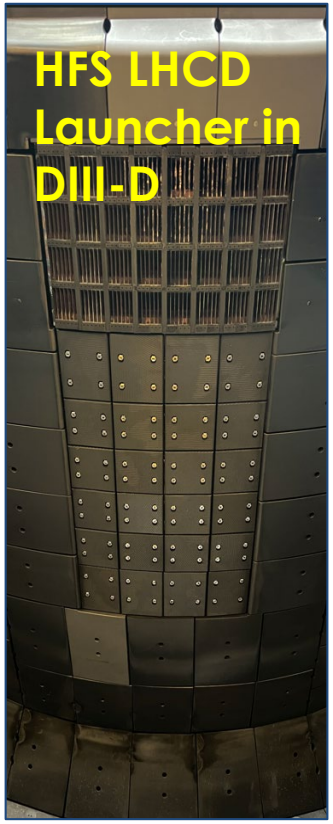


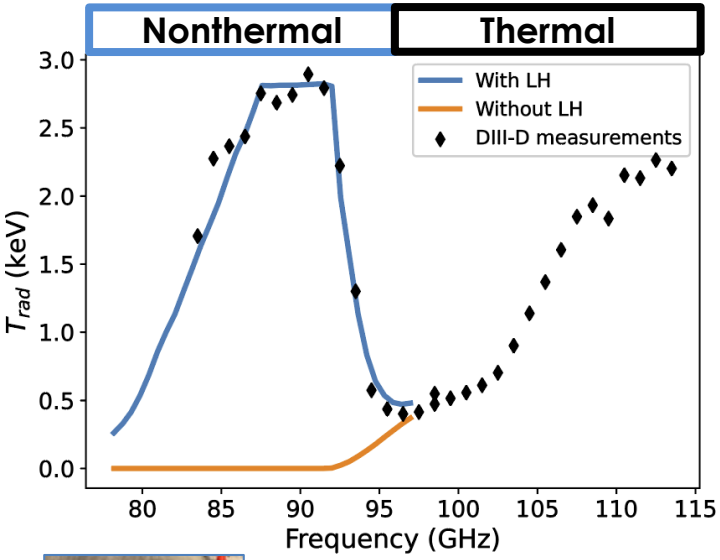


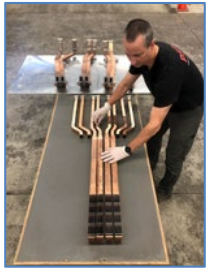
S. Lee, et al., Rev. Sci. Instrum., under review

First Results from Novel HFS LHCD Experiment has Validated HFS Wave Physics

- **Additively manufactured RF launcher enable critical first test of high field side lower hybrid current drive (HFS LHCD) physics.**
  - AM enabled compact RF design and use of high strength, high conductivity copper alloy minimizing power loss.
- **Results confirms HFS LHCD physics are largely correct.**
  - Ray trajectory shows ~25% of injected power is absorbed on first pass.
- **For the first time ever, simulated ECE response closely matches experiment.**
  - Predicts 36 kA for 83 kW coupled power (430 kA/MW)
- **Existing codes can reasonably be used to inform future experiments and devices**

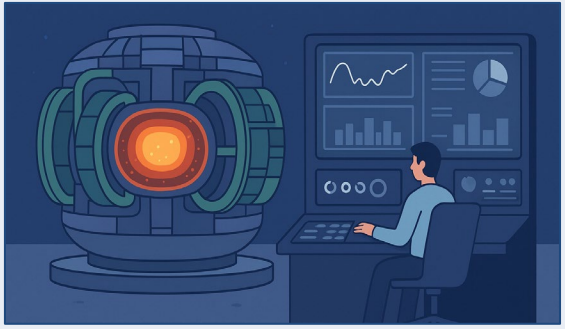


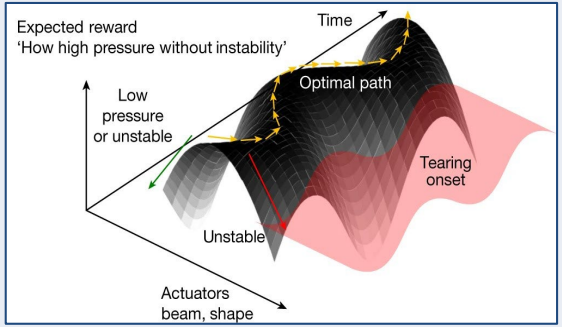




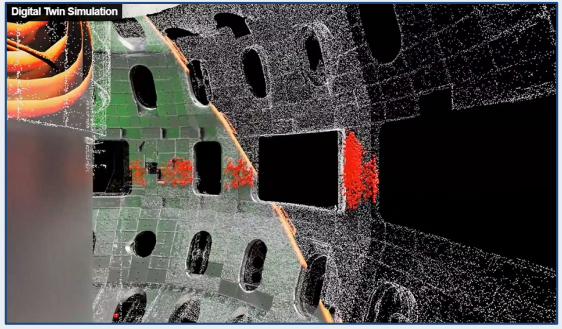
Plasma Control System Test Bed– Tools Available

Control System Test Bed	Historical Data	Simulation Validation Test Bed
Integration into the PCS is an option at DIII-D. This will enable verification and optimization of plasma control algorithms. Additionally, subcomponent controllers (ECH) can be verified	DIII-D historical data leveraged for machine learning with the goal of predicting disruptions with a minimal set of FPP relevant diagnostics. Specifics could include tearing mode identification	Utilizing advanced digital engineering, AI, ML, and high-performance computing to fast-track fusion development



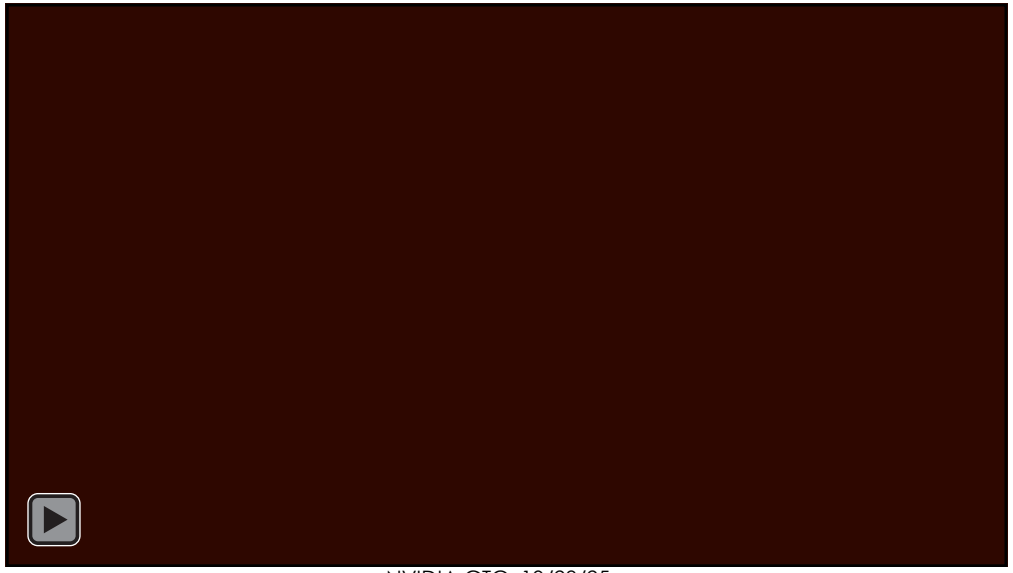


(Seo, J., Kim, S., Jalalvand, A. et al. Avoiding fusion plasma tearing instability with deep reinforcement learning. Nature 626, 746–751 (2024)



Success Story: Advanced AI/ML Driven Digital Twin

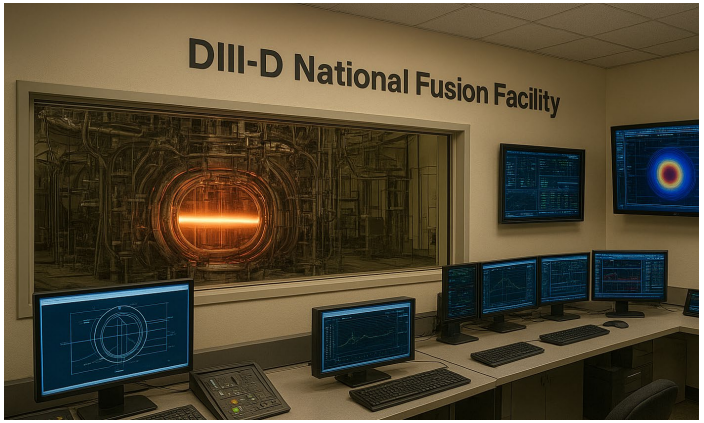
- **NVIDIA created a digital twin that fuses sensor data, physics simulations, engineering designs, and AI surrogates into a unified environment**
- **Useful for DIII-D to advance precise simulation, for rapid design iteration, and for real-time optimization of fusion reactor systems.**
  - NVIDIA's digital twin approach executed on DIII-D can be model for other fusion experiments



NVIDIA GTC, 10/28/25

Active Training Facility & Work Force Development Center

- **Specific pieces of hardware, including:**
  - ECH Gyrotrons
  - Neutral Beams
  - Physics Operators
  - Other potential diagnostics
- **Staff have unique expertise in many fusion technologies**
- **Mechanisms in place for joining the team in a mutually beneficial interaction.**
  - Cost, support role definitions, and other details are determined on a case-to-case basis.
- **MPEX came here to see how to operate a facility**
- **DIII-D trained people are active in most fusion companies**



Joining and utilizing DIII-D

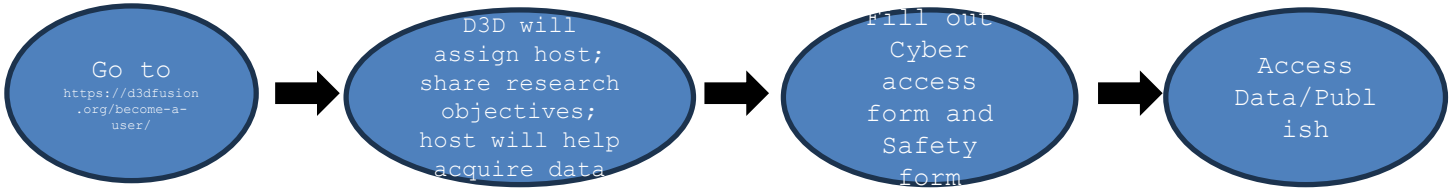
- **There are four use cases most often pursued in utilization of DIII-D:**
  - Access DIII-D data
  - Utilize DIII-D as a test bed
    - Without dedicated experimental runtime (i.e. piggyback)
  - Execute an experiment
    - Dedicated experimental runtime to test diagnostic, device, controller, etc.
  - Train how to operate a portion of the reactor
- **More information is available at d3dfusion.org**

- **Utilizing the facility is free with publishing; implementation resources required by DIII-D**

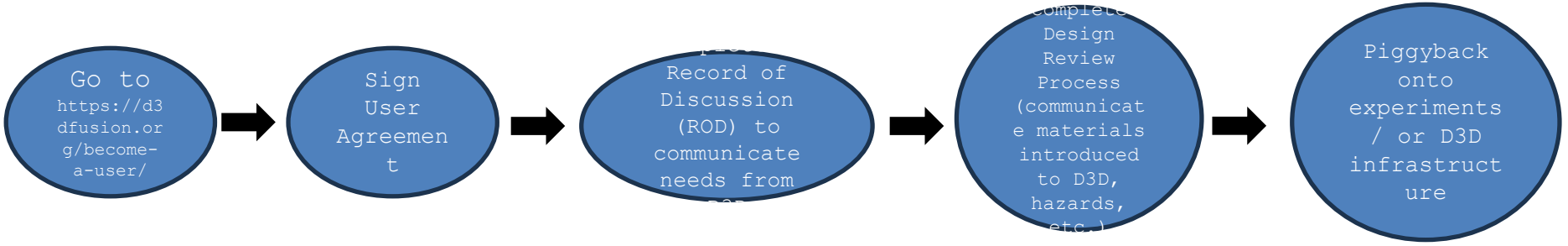
- **All use cases require a dissemination of learnings (but not necessarily IP utilized to create product). The reasoning is that DIII-D is a public funded entity; thus, the public must ultimately benefit from use.**

Joining and utilizing is a streamlined process

- **The steps to <u>access DIII-D data</u> include:**

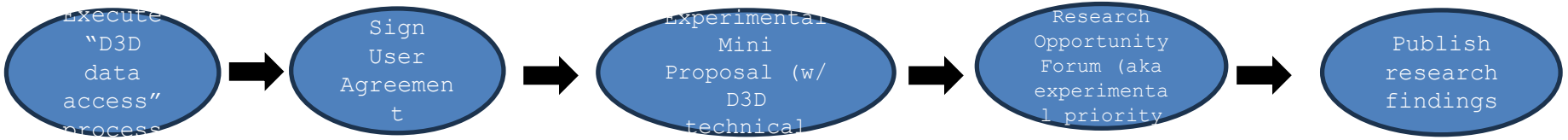


- **The steps to <u>utilize DIII-D as a test bed</u> include:**



Joining and utilizing is a streamlined process

- **The steps to <u>execute an experiment</u> include:**



- **The steps to <u>train how to operate</u> include:**

Fusion will be deployed by private sector; DIII-D is helping bolster impact

- **DIII-D has onboarded 18 private companies with 88 private users**

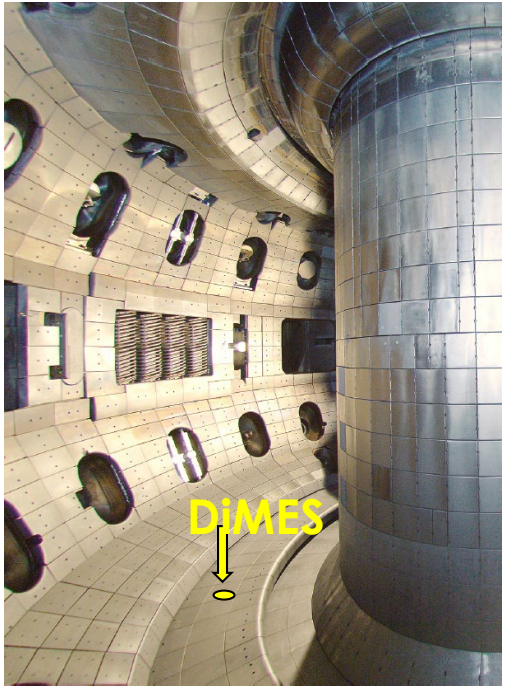
DIII-D actively advancing fusion technology

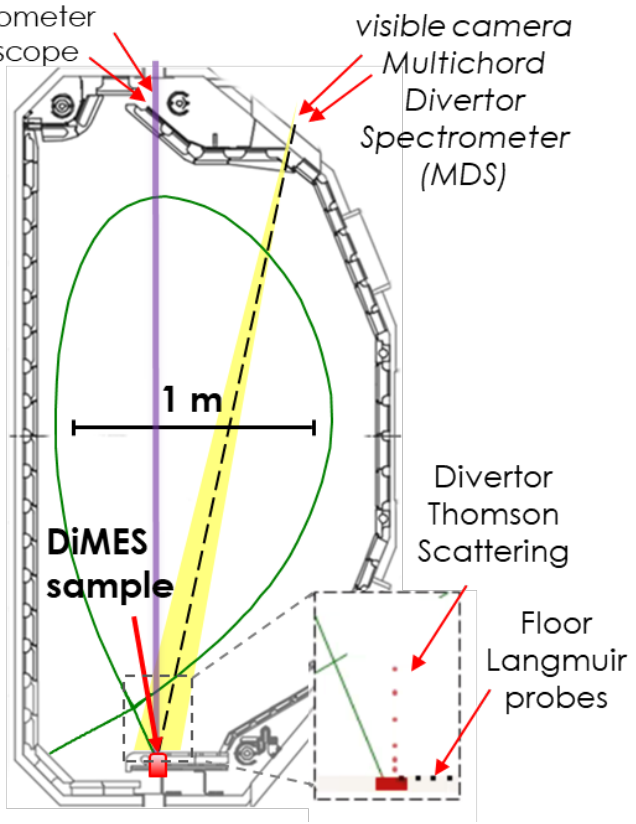
- **DIII-D's mission is to provide support to the Fusion Ecosystem through rapid, cost effective, and baselined testing.**
- **DIII-D has existing**
  - Diagnostic and actuator test beds,
  - Material testing test bed, and
  - Control systems test beds
- **DIII-D has experience professionals willing to educate about the nuances of operating a tokamak.**
- **Onboarding is rapid and quick, can be done in less than a week**
- **The DIII-D team looks forward to continuing accelerating Fusion with the private and public sectors**

Thank you for your attention

Divertor Materials Evaluation System (DiMES) at DIII-D

- All Thrust experiments utilized DiMES
- DiMES allows exposure of pre-characterized samples to well-controlled plasmas with world-leading diagnostic coverage
- Usually lower Single Null (LSN) plasmas with the outer Strike Point (OSP) placed on DiMES
- Samples images by filtered visible cameras and spectroscopy → erosion rates
- Heat flux data is reconstructed from IRTV and LP data





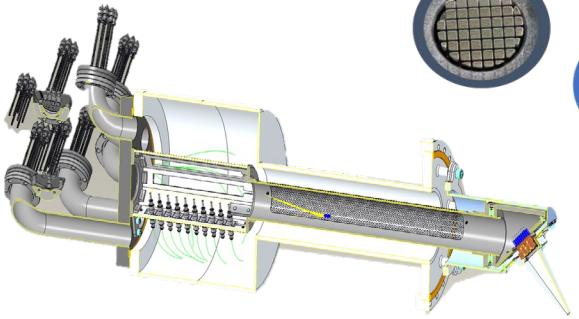
DIII-D NATIONAL FUSION FACILITY

Next Step Fusion

Users that are a part of current DIII-D community

- **DIII-D has had over 17 organizations join.**
- **Some of the recent progress include material testing campaigns, digital twin modeling, and diagnostic development**
- ***Add graphic of organizations that have joined D3D**

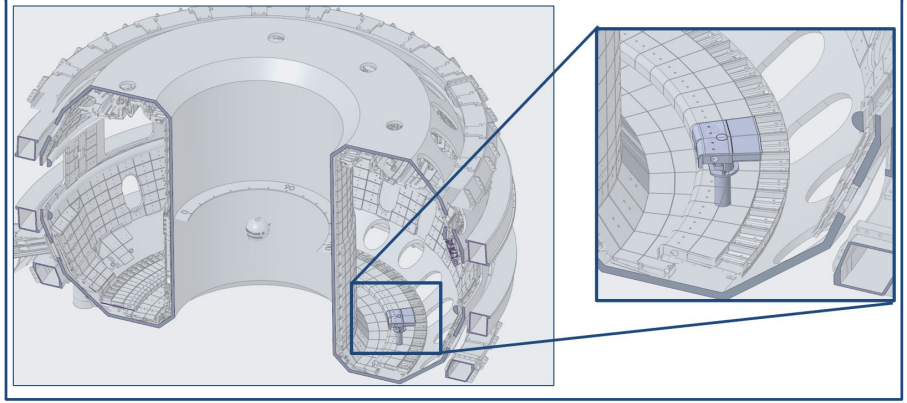
Digital twin image (NVIDIA)



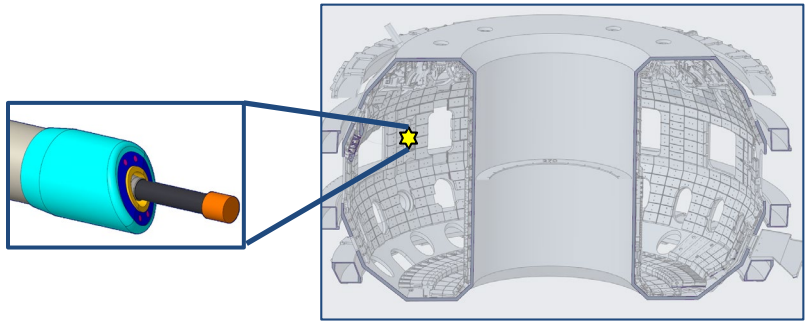
Material Test Bed – location of probed

- **What can DIII-D offer the Fusion Ecosystem?**
  - Rapid sample exposure (every shot)
  - Plasma environment
    - Heat flux at divertor of 20 MW/m^2, angled (for ~6 sec duration)
    - Heat flux at divertor of 3 MW/m^2, flat (for ~6 sec duration)
    - Magnetic field strength of 2.1 T
    - Neutron fluence of 4e14 neutron/sec
    - Total 1 MJ of thermal energy
  - ELM environment
    - Heat spikes of 100 MW/m^2 (~1-10 msec duration)
    - Particle flux at divertor of 1A/cm2
  - Diagnostics
    - Calibrated spectroscopy
    - IR imaging (to study ELM impacts on DiMES samples)
    - Thermocouples, Langmuir probes, RFEA probes on DiMES samples

DiMES location; 150deg on divertor



MiMES location; 240degrees at midplane port (R0)



Material Test Bed

- **What can DIII-D offer the Fusion Ecosystem?**
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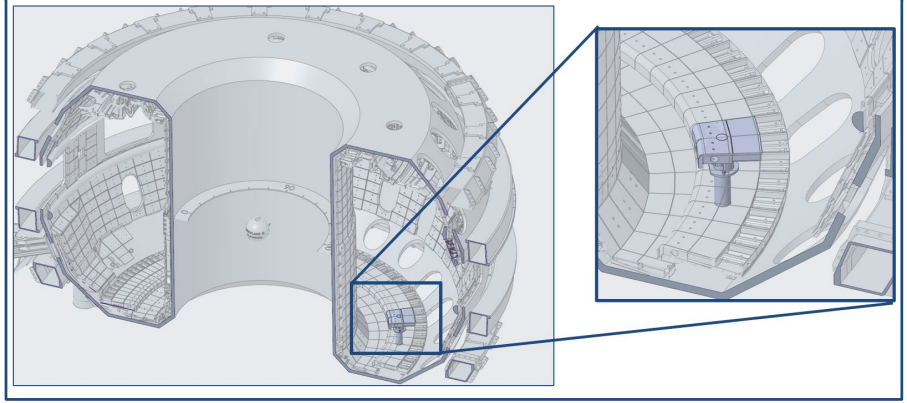
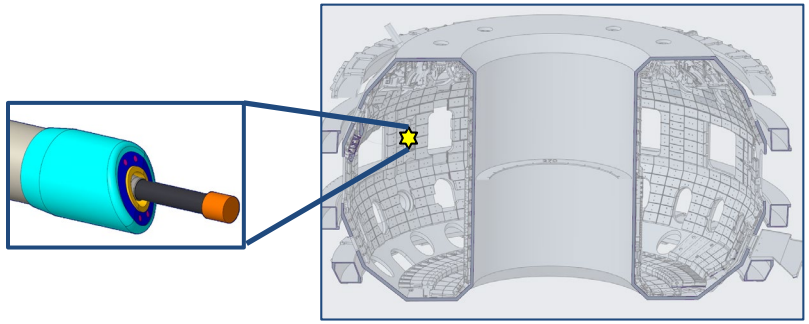
  - Diagnostics
    - Calibrated spectroscopy
    - IR imaging (to study ELM impacts on DiMES samples)
    - Thermocouples, Langmuir probes, RFEA probes on DiMES samples
- **Example of DIII-D utilization**
  - Company "X" want to research novel divertor alloys on DiMES.
  - Company "X" wants to research coatings that can be applied to the main wall on MiMES

DiMES location; 150deg on divertor

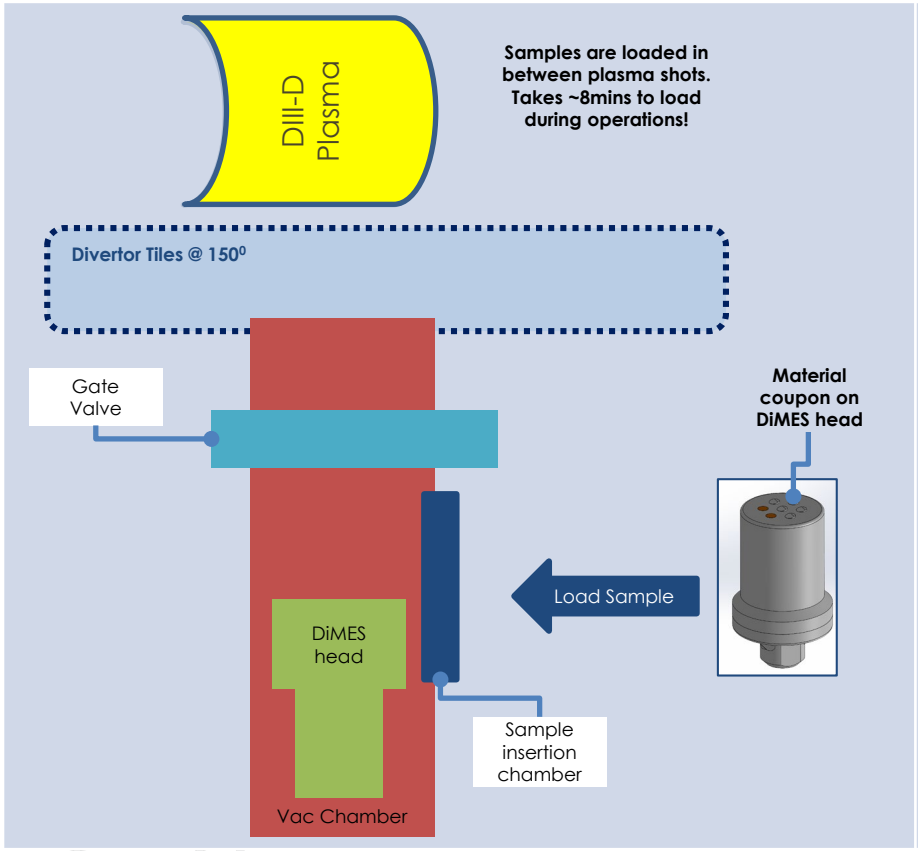


MiMES location; 240degrees at midplane port (R0)

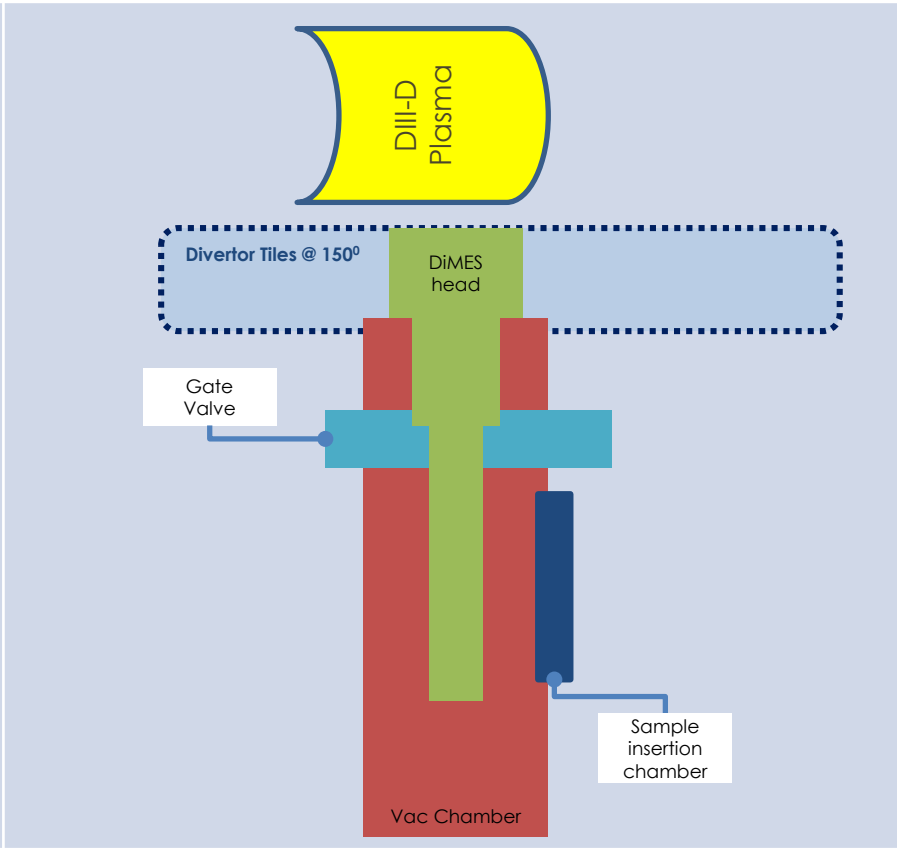


How does DiMES work; a cartoon rendition

DiMES as sample is loaded during plasma operations



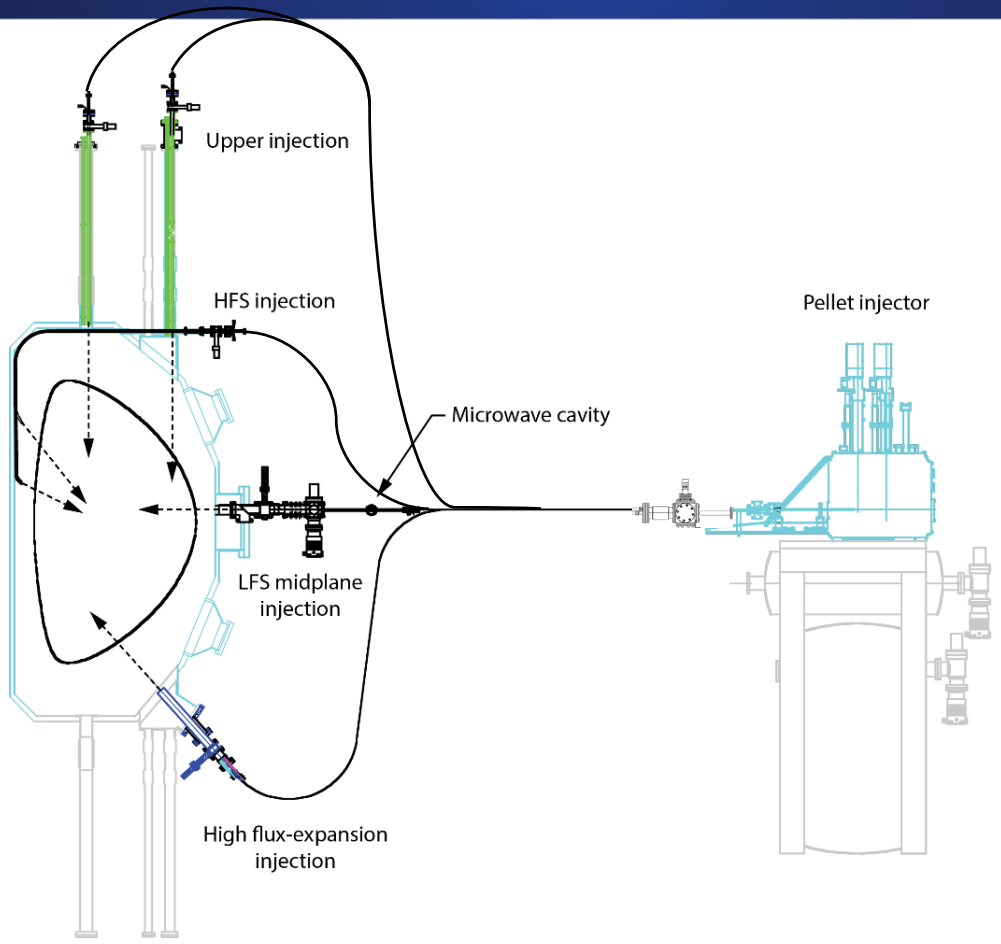
DiMES in DIII-D Tokamak at 150degrees



Historical Data for ML/AI Training

- DIII-D has a trove of data from historical shots; there have been over 200,000 plasma shots
- The data wasn't initially organized to be fed into AI/ML models (that technology didn't exist in 1986!)
- Approved users can obtain access to this data but will require a DIII-D guide.

- Add an image of Aza and Nik or add image of D3D data


Upper injection
HFS injection
Pellet injector
Microwave cavity
LFS midplane injection
High flux-expansion injection

Content

- **Purpose of talk**
- **Fusion technology development pipeline**
- **Areas that DIII-D can help develop:**
  - Materials test bed
  - Heating and Current Drive test bed
  - Plasma Control System test bed
  - Training facility
  - Historical data for AI/ML training
- **Joining/utilizing DIII-D**
- **Conclusion**