FPP Candidate Materials Thrust and the 2025 Fusion Materials Industry Day at DIII-D

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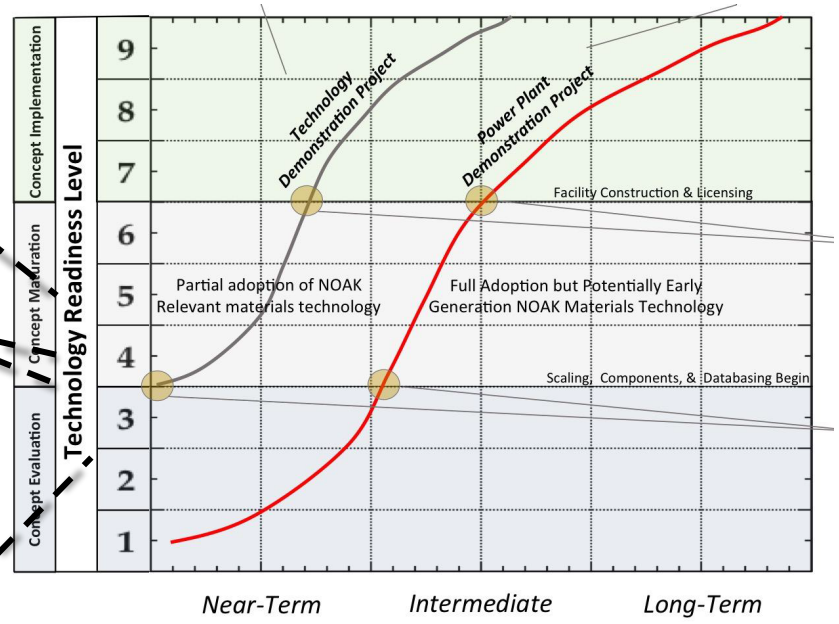
The evolving U.S. fusion landscape and PMI research

- **Research landscape is rapidly evolving in the US: private sector growth, growing interest in PMI at Department of Energy, federal programs to match**
- **Materials are recognized as a key technology gap for achieving commercial fusion energy**
  - Requires shift from physics studies to technology qualification
- **DIII-D is uniquely equipped to qualify low Technology Readiness Level (TRL) materials in an integrated fusion environment**
  - DIII-D research helps define the US Fusion Pilot Plant (FPP)

TRL Examples

4	• Alloy grade set; databasing underway • Non-nuclear environmental corrosion tests complete • Begin informing design codes with experimental data	• Combined effects (neutron, corrosive environment, complex stress, HHF) and subcomponent testing begins
3	• Optimized material design for application • Environmental tests covering design window • Preliminary pathway for demonstrating joining has been developed • Large "heats" procured and tested[7]	• Develop predictive materials models • Obtain model validation data from coupon level experiments • Develop pathway to scaled fabrication • Preliminary demonstrations of component fabrication



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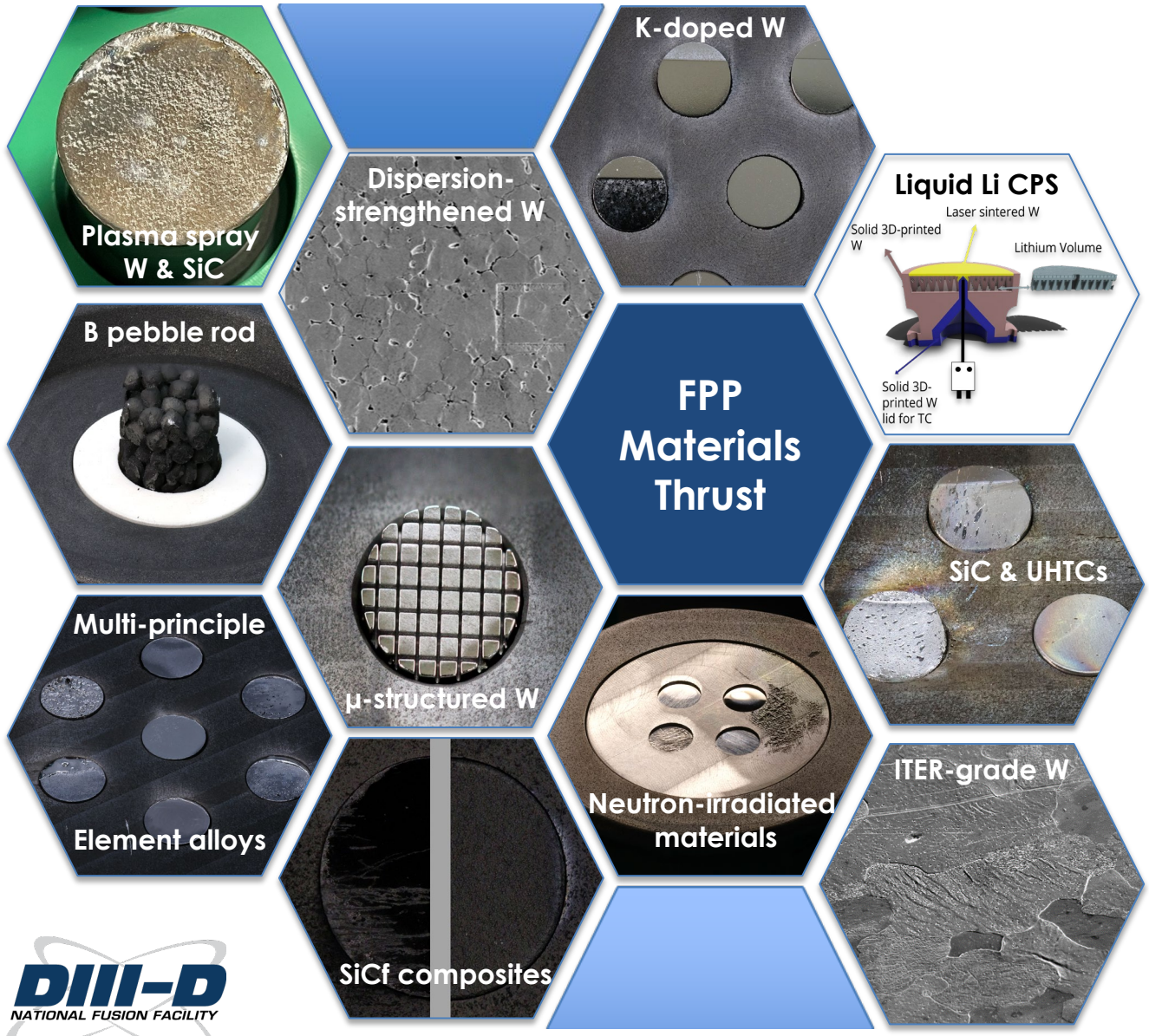
The FPP Candidate Materials Thrust at DIII-D



- **From 2024-2025, DIII-D conducted the FPP Candidate Materials Thrust**
- **Main goal: testing multiple classifications of materials under plasma conditions relevant to Fusion Power Plants (FPP)**
  - Divertor materials: **10-12 MW/m²**, H-mode plasmas
  - Wall materials: **2-3 MW/m²**, L/H-mode
- **Advance material TRLs through integrated testing and down-selection**

Lead: Jonathan Coburn (SNL)
Deputy: Florian Effenberg (PPPL)

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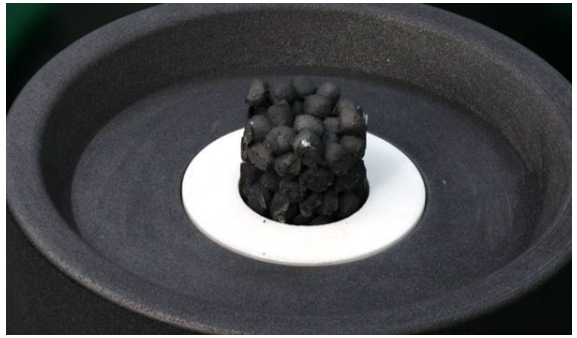
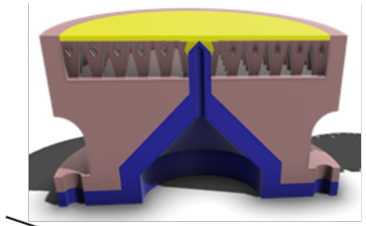
Various DiMES and sample designs were used to expose samples and achieve FPP-relevant conditions

Flat, coated DIMES

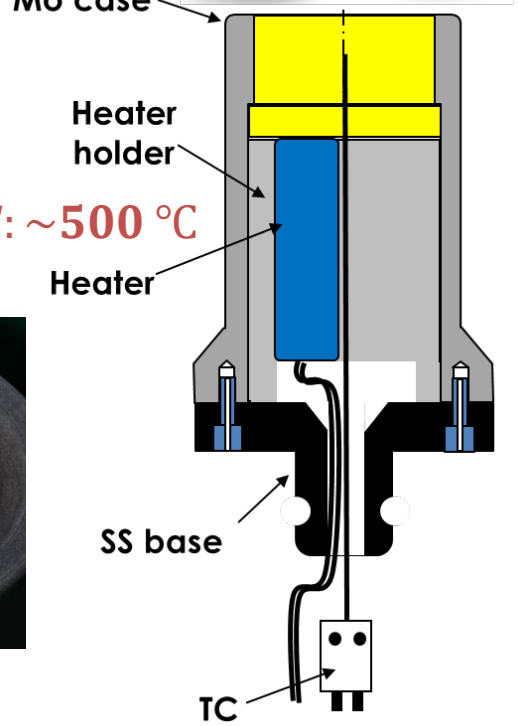
Pebble-rod holder



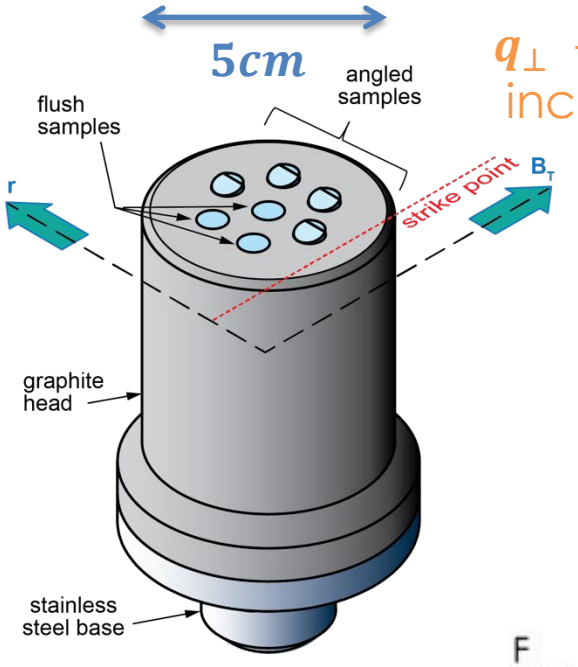
Additive-W CPS holder for Li

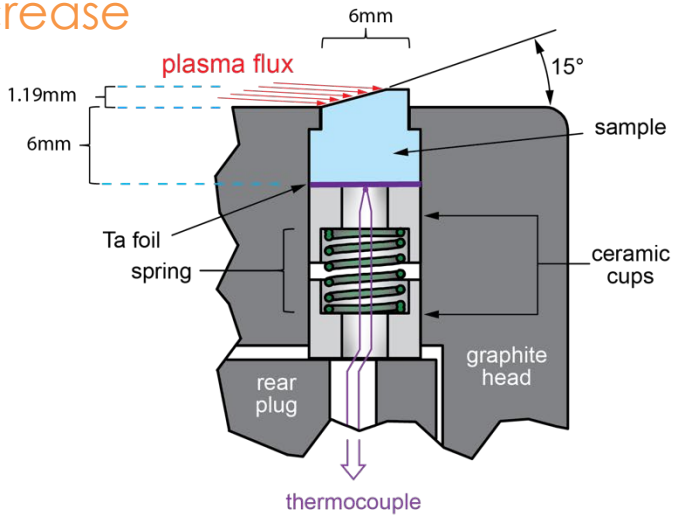


Li CPS



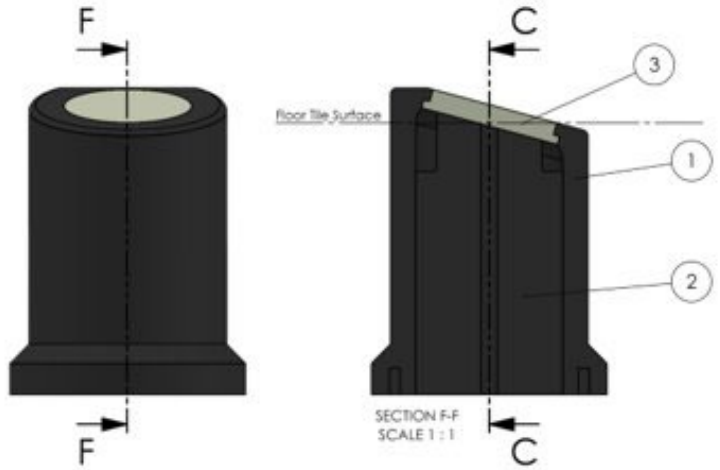
7-button holder with flush &/or 10° angled samples





15° large angled disk samples

$q_\perp$ → ~11x increase



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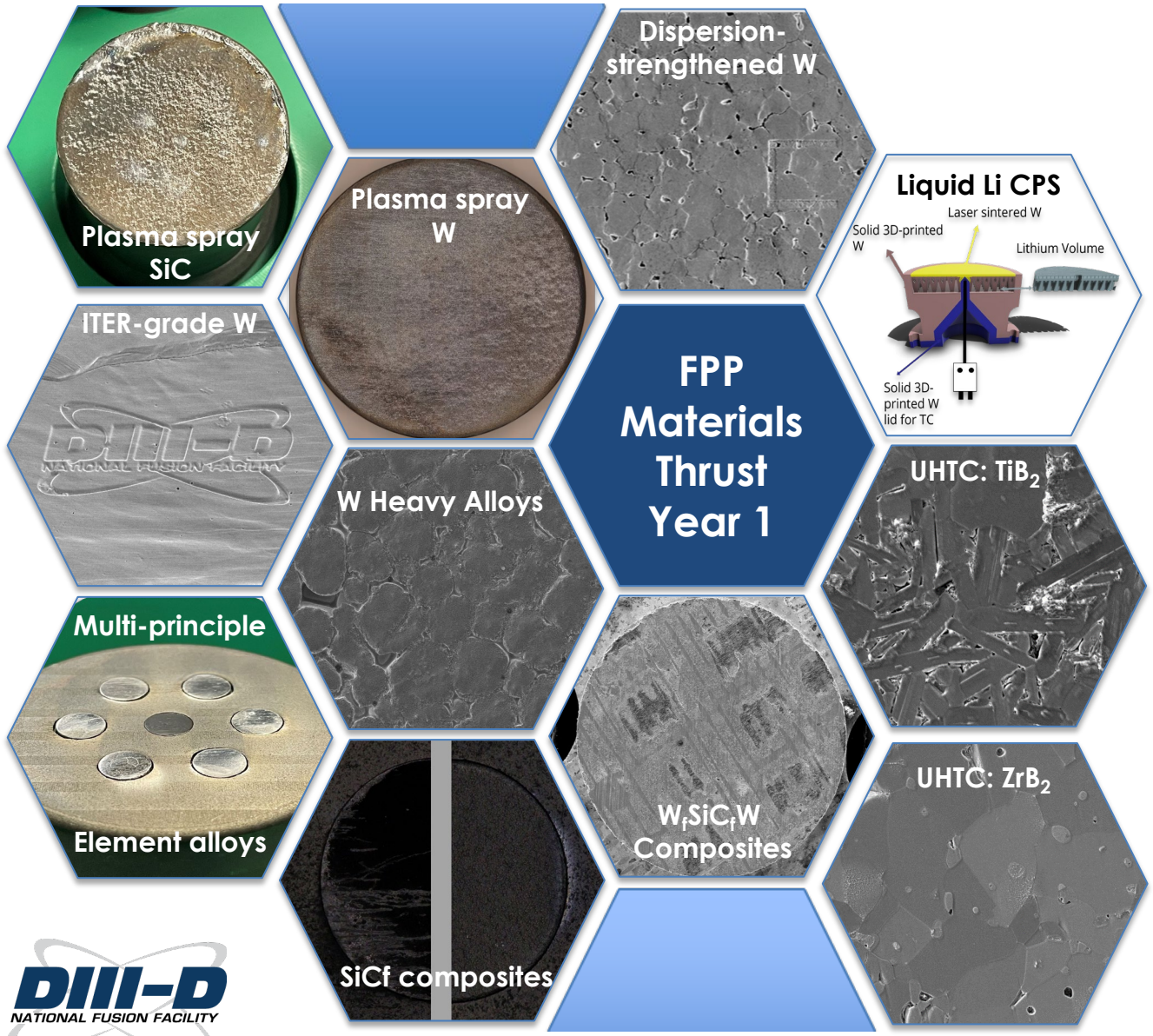
The FPP Candidate Materials Thrust – FY24 stats



- **In 2024, the Thrust conducted 3.5 days of experiments**
  - Includes 0.5 day of PhD time
- **A total of 17 novel plasma-facing materials (PFMs) from 8 institutions were successfully tested using the DiMES system**
  - Total # of DiMES holders: **15**
  - Total # of material samples: **75**
- **1st demonstration of many of these materials in DIII-D**

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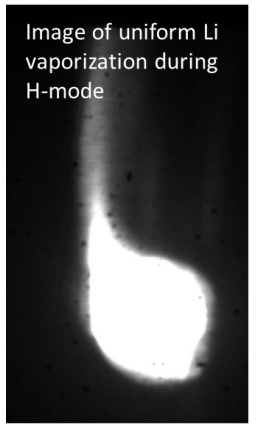
The FPP Candidate Materials Thrust – Highlights

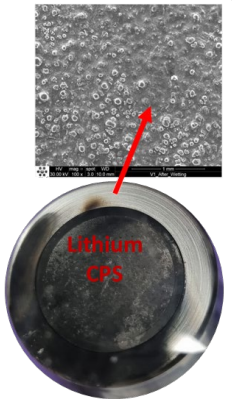
2024 Results Highlights

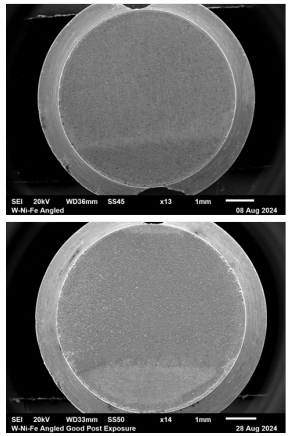
- First demonstration of liquid Li CPS system on a tokamak → uniform vapor cloud emission
- Dispersion-strengthened W down-selected to TiC variant
- Successful stress tests of W & SiC coatings:
- Down-selected functionally-graded W/SiC variants
- W Heavy Alloys: redeposition, arcing, surface morphology change
- Good fiber integrity for SiCf/SiC and Wf/SiCf/W
- Retention and preferential erosion of ultra-high temperature ceramics (UHTCs) and multi-principle element alloys (MPEAs)

DIFFER PPPL GENERAL ATOMICS

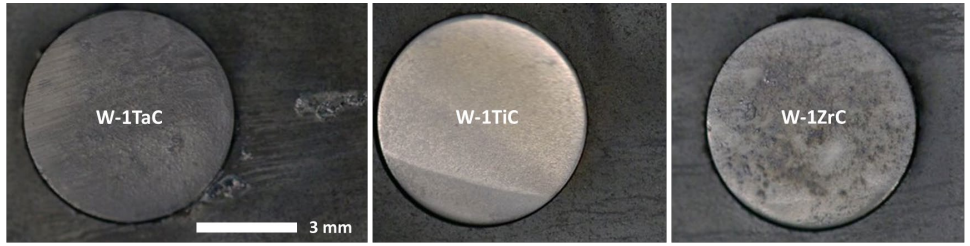


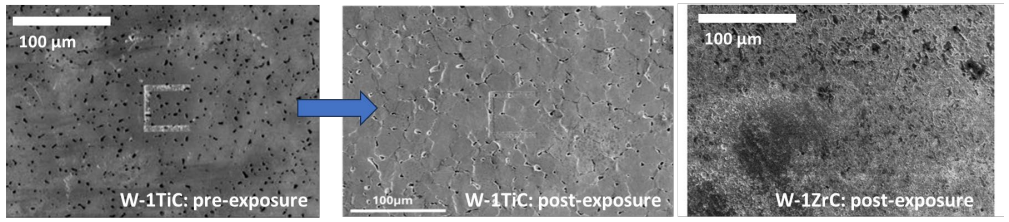
SEM surface after filling





PennState





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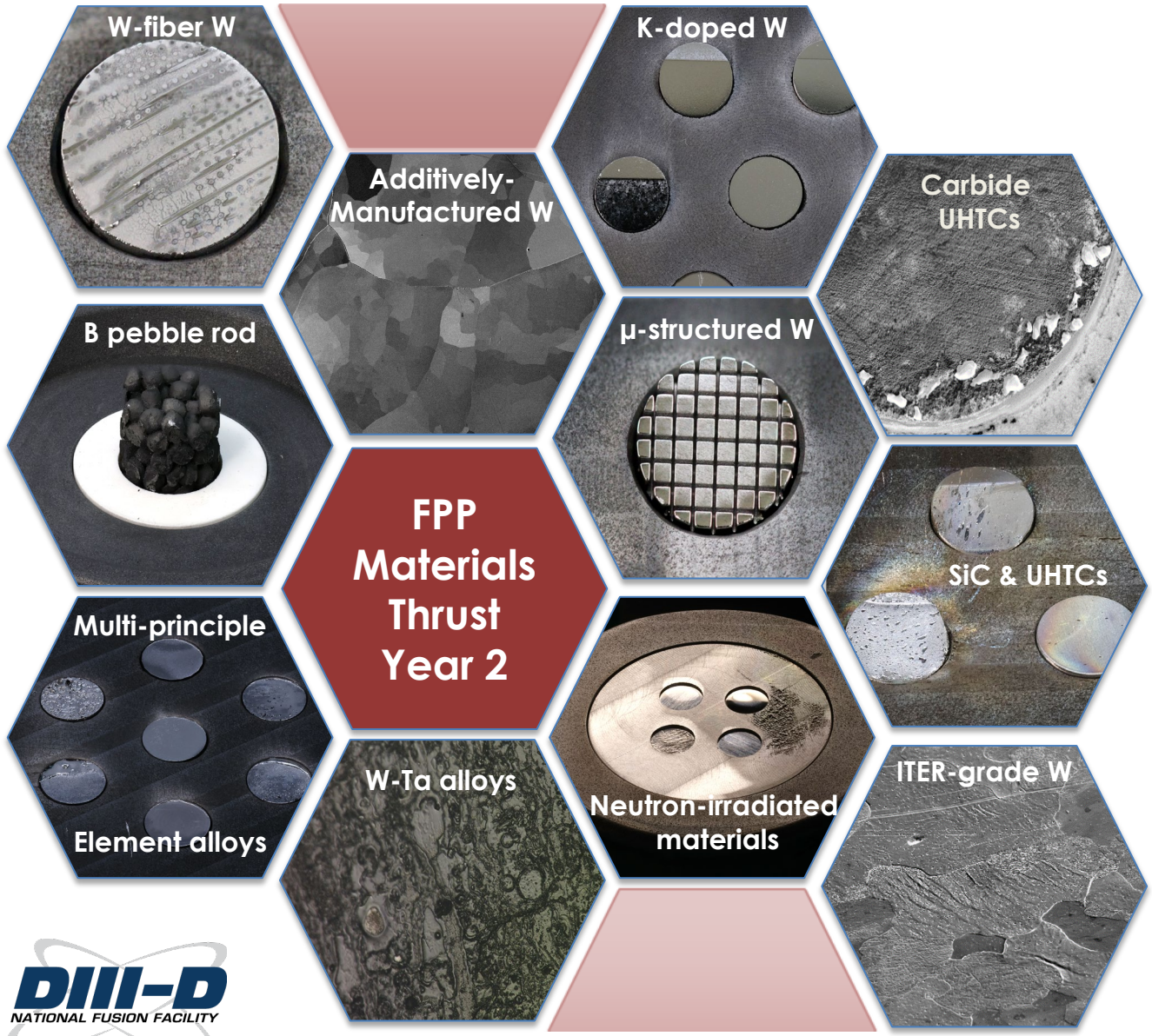
The FPP Candidate Materials Thrust – FY25 stats



- **In 2025, the Thrust conducted 3.5 days of experiments**
  - Includes 0.5 day of PhD
- **A total of 44 novel plasma-facing materials (PFMs) from 12 institutions were successfully tested at DIII-D using the DiMES system**
  - Total # of DiMES holders: **18**
  - Total # of material samples: **105**
- **Includes experiments from 4 private industry users, allocated through Director's Reserve "Fusion Materials Industry Day"**
  - 1.0 run day

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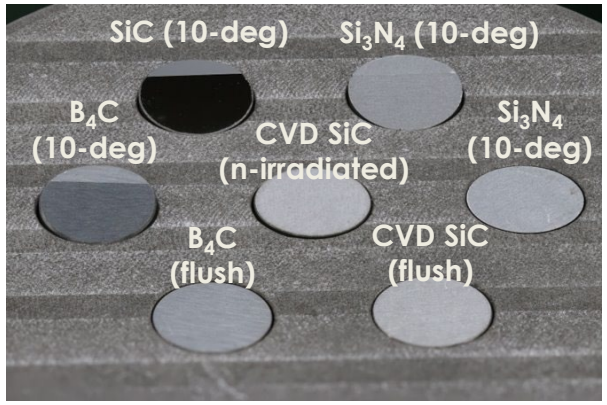
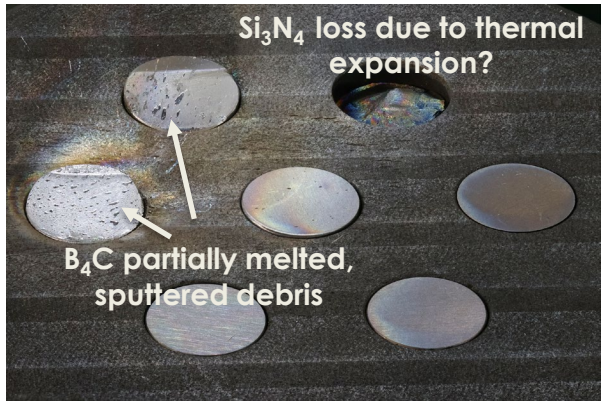
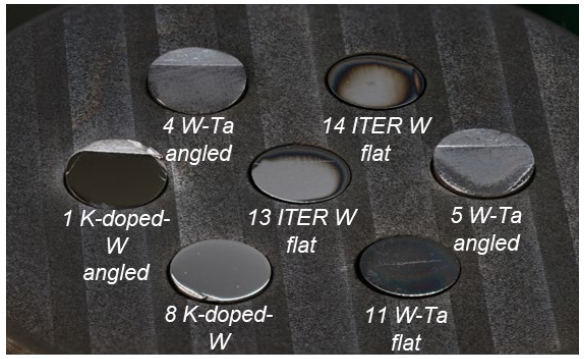
The FPP Candidate Materials Thrust – Highlights

HELION

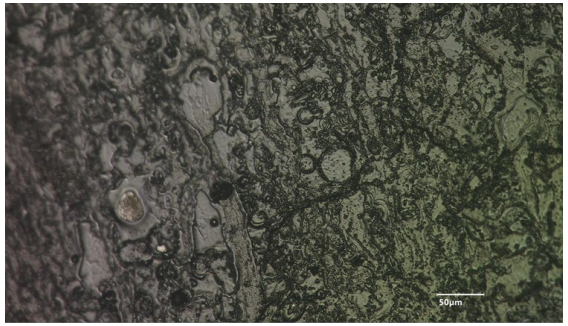




Tokamak Energy



Post-exposure DiMES head



4 W-Ta angled plasma exposed surface with melt spots

2025 Experiment Results Highlights

- Helion Energy: down-selection of ceramic materials → bulk SiC
- Tokamak Energy: testing of k-doped W and W-Ta alloys under attached & detached plasmas

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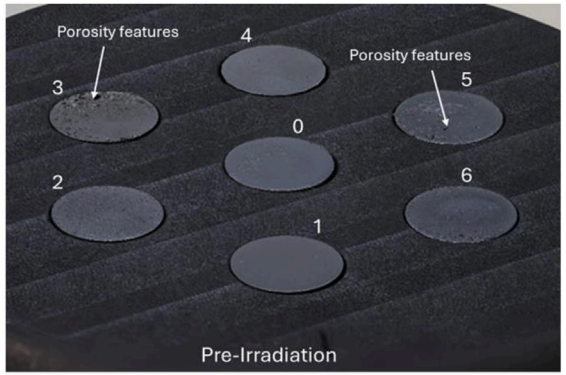
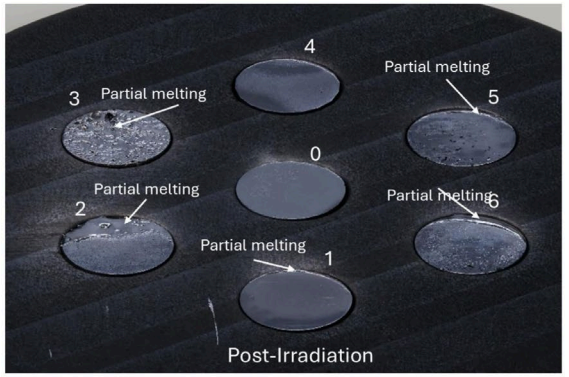
The FPP Candidate Materials Thrust – Highlights

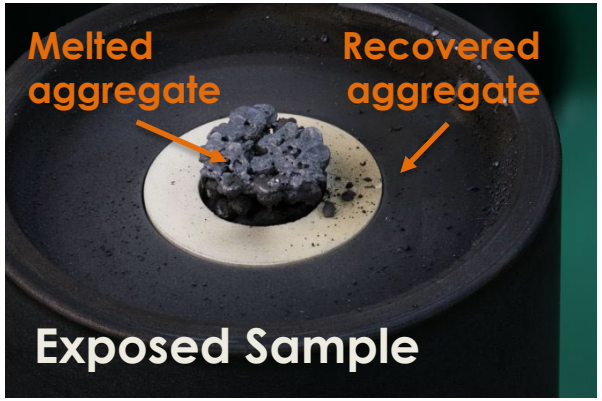
AVALANCHE





#0 - V28Ta45Hf25Mo2
#2 - Zr34Ti61Cr5
#4 - Zr35Ti55Hf10
#6 - Zr35Ti60Ta5

#1 - HfZrTiTa (equimolar)
#3 - Zr35Ti60V5
#5 - Zr35Ti60W5



THEA ENERGY

2025 Experiment Results Highlights

- 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 MPEAs
- Thea Energy: first demonstration of boron pebble rod concept
- First testing of neutron-irradiated samples (W, SiC) in DIII-D (one from Helion)
- Enhanced heat flux testing of industrial W alloys (K, Re doped) WfW composites, SiCf/SiC, AM-W, μ-structured W, Cr

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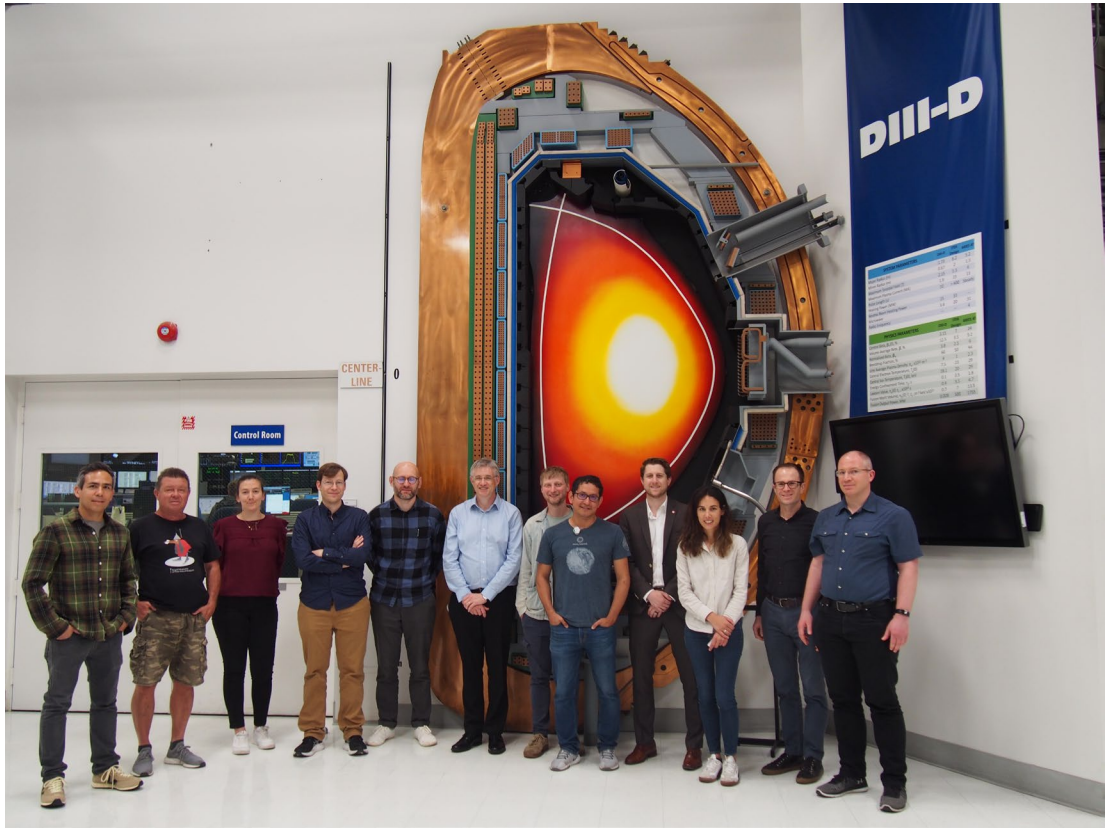
The 2-year FPP Candidate Materials Thrust successfully exposed multiple candidate PFMs in DIII-D

- **Record number of DiMES holders and samples**
- **Incorporation of private and public PFMs and concepts**
  - Everyone left the control room satisfied!
- **Cross-experiment PFM comparison is underway**
- **Interested? Contact us!**



Demand for materials testing at DIII-D is increasing. The PMI program is growing to meet it!

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Acknowledgements

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Supplemental Material

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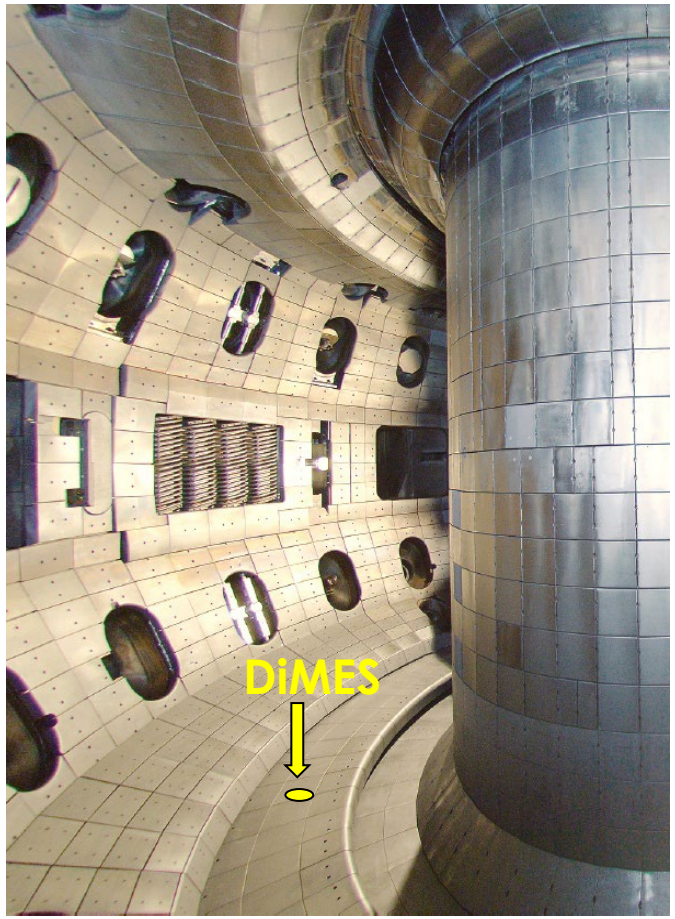
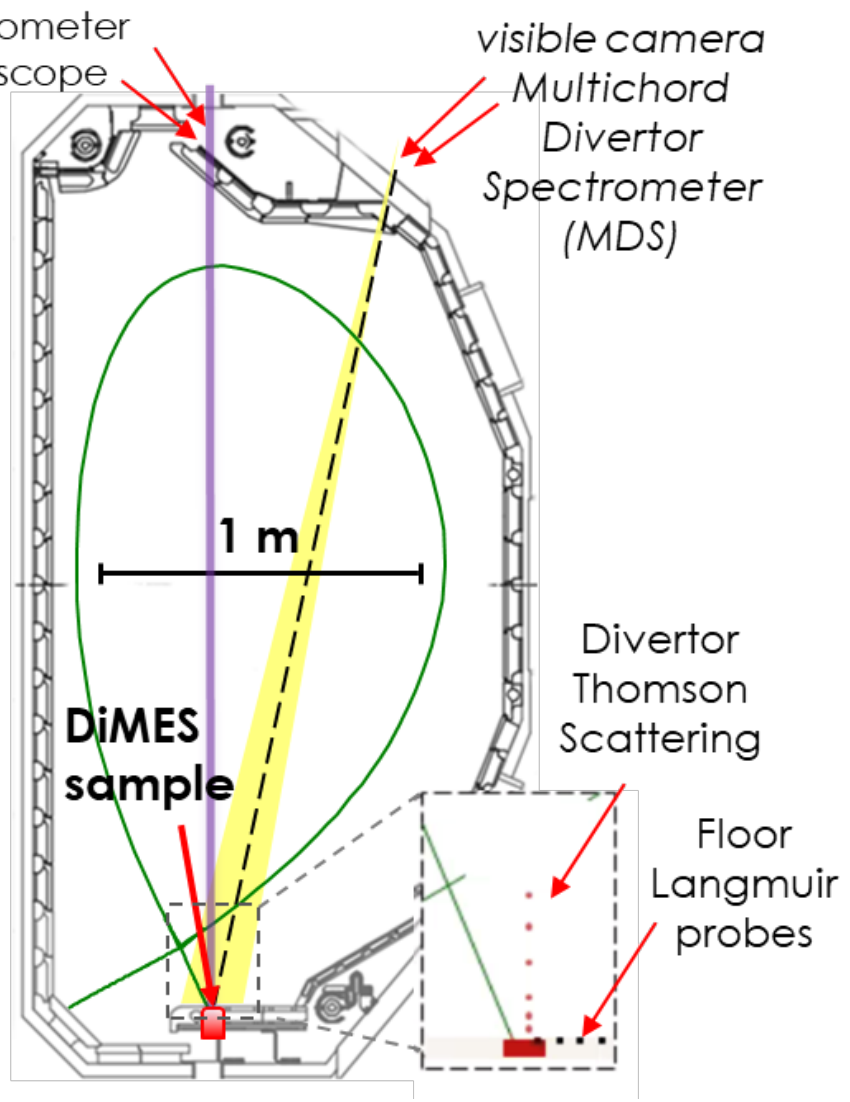
Divertor Materials Evaluation System (DiMES) at DIII-D

- 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





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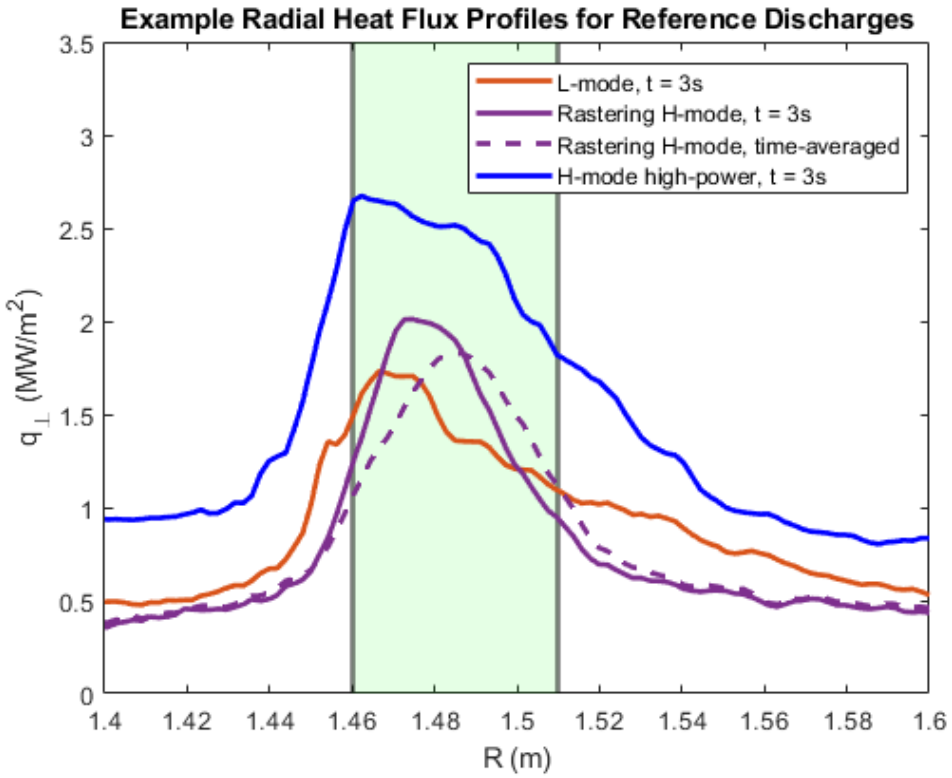
Thrust experiments used consistent reference exposures

- **Specific reference discharges were established through dedicated Controls Development time and repeated for most exposures**
  - Maintains compatibility and comparability across experiments
  - Developed rastering H-mode for more uniform exposure conditions
  - Essential for streamlined exposures of many DiMES!

Scenario	Sample Type	$q_\perp \left[\frac{MW}{m^2}\right]$	n_e	Time per shot $[s]$
L-mode	Flush	1.7	3.5e19	3-4
H-mode, rastering	Flush	1.6 – 2	3.0e19	2
	10° angled	12 – 15		2
H-mode, high power	Flush	2 – 3	8.5e19	3-4



The FPP Candidate Materials Thrust – FY24 stats

FY24 Experiment List:

MP #	Title	Session Leader	Institutions
2024-25-01	Investigate performance of 3D printed capillary porous structures carrying liquid lithium under H-mode plasma exposure	M. Morbey	DIFFER, PPPL
2024-25-02	Evaluating innovative materials based on multi-element tungsten alloys and advanced manufacturing processes	F. Effenberg	PPPL, PSU, GA, SNL, Kyoto U., IPP, UNM
2024-25-03	Exposure and characterization of novel ceramic materials in DiMES	S. Zamperini	GA, ORNL
2024-25-04	Examination of surface stability of dispersion-strengthened tungsten divertor plasma exposure in DIII-D	C. Hargrove	Penn State University (PSU)
2024-12-05	Scenario and shape development for consistent sample exposures in the wall materials thrust	J. Coburn	SNL, PPPL, PSU, GA, ORNL

The FPP Candidate Materials Thrust – FY25 stats

FY25 Experiment List:

MP #	Title	Session Leader	Institutions
2025-25-01	Tungsten DiMES Experiment	R. Kolasinski	SNL, UW Madison, SBU
2025-25-02	Plasma Exposure of Ceramic Materials in DiMES	L. Nuckols	ORNL, GA, Helion Energy
2025-25-03	Qualification of grain oriented, additively manufactured tungsten	A. Zuniga	NCSU
2025-25-04	Testing of private industry plasma-facing materials	J. Coburn	Tokamak Energy, Avalanche Energy, Thea Energy
2025-25-05	Plasma Exposure of Pre-Irradiated Materials in DiMES	L. Nuckols	ORNL
2024-12-03	Shape and scenario development for materials thrust	J. Coburn	SNL, PPPL, GA, Kyoto U. IPP, UW Madison