



ReNeW: Thrust #11

Innovations for Improved Power and Particle Handling

ReNeW

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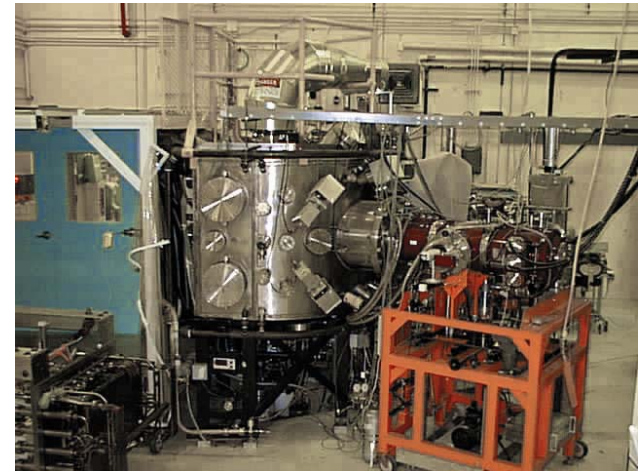
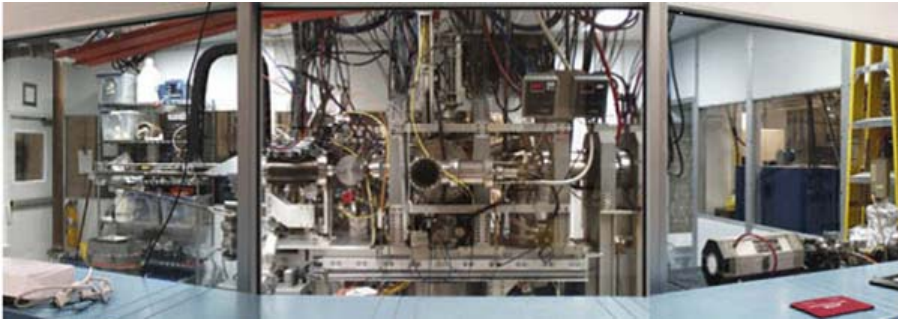
Dennis Youchison
Sandia National Laboratories

Bethesda, MD
June 9, 2009

Thrust #11 Outline

- **Improved Power and Particle Handling Activities**
 - **Advanced divertor concepts & clever PFC design**
 - Innovative divertor designs
 - Precision PFC alignment and shaping – engineering diagnostics
 - **Helium-cooling concepts for PFC heatsinks**
 - Thermal aerolics (porous media, jets) design, modeling, testing
 - Low-Z coatings
 - High temperature (High-Z) materials development (armor/joint/heatsinks)
 - **Liquid metal PFC development**
 - LM handling, transport, and impurity control
 - Driving flows and MHD effects
 - **Dedicated PFC materials development for refractories and joining concepts**
 - Innovative processing of alloys/composites (nanotechnology)
 - Materials testing including irradiation

Cross Cuts

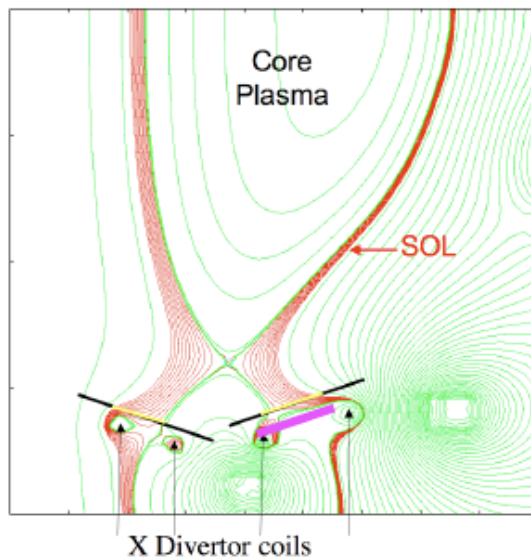


- **Strong cross cut with Thrust #10**
 - **New facilities needs**
 - Helium and liquid metal test loops (TR4 forever...)
 - Synergistic HHF and plasma response (ELMS, disruptions)
 - Irradiation facilities & material properties measurements
- **If thrust #10 does not move forward, then thrust #11 cannot proceed!**
- **Also strong cross cut with materials, MHD and thermo-mechanical modeling. (Thrusts #10,14)**

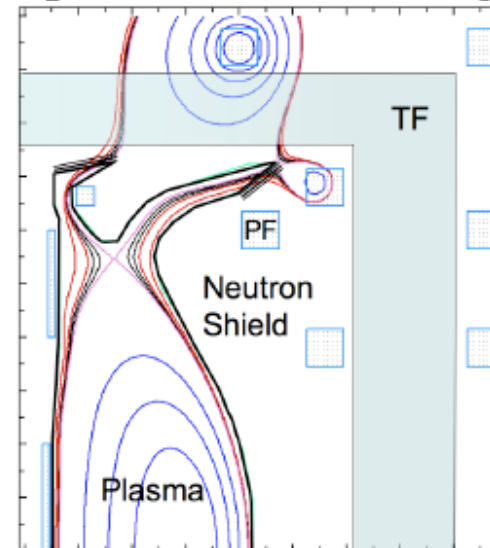
Advanced divertor concepts

- **Snowflake, Super-X**
 - Modeling and design (higher surface area, lower q'')
 - Testing on toroidal machines – NSTX, DIII-D
- **Vertical targets with $<1^\circ$ inclination, better alignment**
- **Extended chamber design**

XD/Snowflake: expand flux



Super X-Divertor (Large R_{div})



Why helium-cooling?

Advantages:

- inherently safe, inert chemical properties
- lack of corrosion
- single-phase heat transfer without the possibility of CHF->High Temps
- lack of neutron activation
- easy separation from tritium.
- fluid of choice for a highly efficient, high temperature Brayton cycle exhibiting minimal wear and corrosion of gas turbines.

Disadvantages:

- low thermal mass, ρC_p , that is less than 1% of water
- high pressure systems -> high stored energy
- compressible gas requiring higher pumping or blower power and larger supply and return piping compared to liquids
- higher cost and sophistication of the turbomachinery such as compressors, high temperature turbines, and recuperators



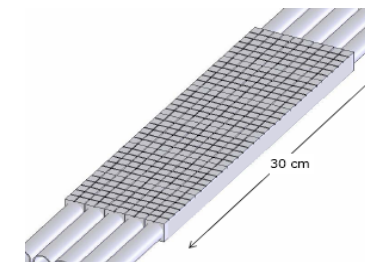
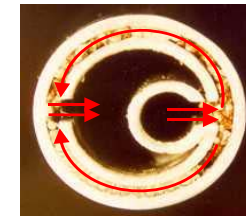
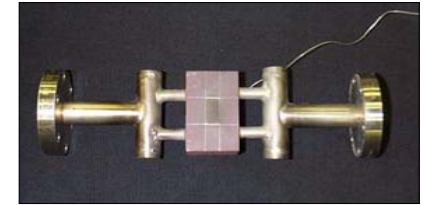
Gaps in helium-cooling

1. **Ductile W-alloy development, and other refractories: Mo, V, RAFS**
 - Divertor – W alloy
 - FW/BM – V, RAFS, ODS-RAFS, SiC
2. **Low-cost fabrication techniques w/ integrated manifolding**
3. **Joining development, refractory armor and RAFS**
4. **Innovative, low-pressure-drop thermal designs**
CFD/HX modeling of porous media, jets
5. **Flow instabilities in multi-channel devices**
6. **High temperature, high pressure testing capabilities**
7. **Tritium permeation into the coolant**
8. **Purity control and high temperature diagnostics**

Background: Helium-cooled modules developed for PFCs

TR3

<u>year</u>	<u>Type of Test Article</u>	<u>fabricator</u>
1993	Cu Micro-channel HX (~100 μ channel size) Cu Divertor mockup A (0.46mm channels) Cu Porous (40%) metal HX (0.43mm dia.)	Create, Inc. General Atomics Thermacore, Inc.
1994	Cu Dual channel porous metal HX Cu Div. mockup A retest, higher heat loads	Thermacore, Inc. General Atomics
1996	Cu Phase-II porous metal HX Vanadium spiral-tube HX	Create, Inc. General Atomic
1997	Cu Faraday shield A Cu Divertor mockup B	Thermacore, Inc. Thermacore, Inc.
1998	Cu Faraday 2 nd shield B Cu Divertor 2 nd mockup C	Thermacore, Inc. Thermacore, Inc.
1999	Div. mockup B retest, added diagnostics	Thermacore, Inc.
2000	W tubes with W foam	Ultramet, Inc.
2000	W FW module with W porous medium	Thermacore, Inc.
2001	VPS W tube with VPS porous medium	Plasma Processes
2006	W tube with W foam in axial flow	Ultramet, Inc.
2008	Sq. Mo w/ Mo foam, circumferential flow	Ultramet, Inc.
2009	4-Channel, Larger Area Mo panel	Ultramet, Inc
2009	W Tee-tube Jet impingement	Plasma Processes



TR4



Helium-cooling activities for DEMO

HHF He-Cooled PFC Development

- all refractory metal heat sink
- helium-cooled, high Delta-T heat sink, $\dot{m}C_p\Delta T$
- high efficiency gas turbine technology
- hydrogen production

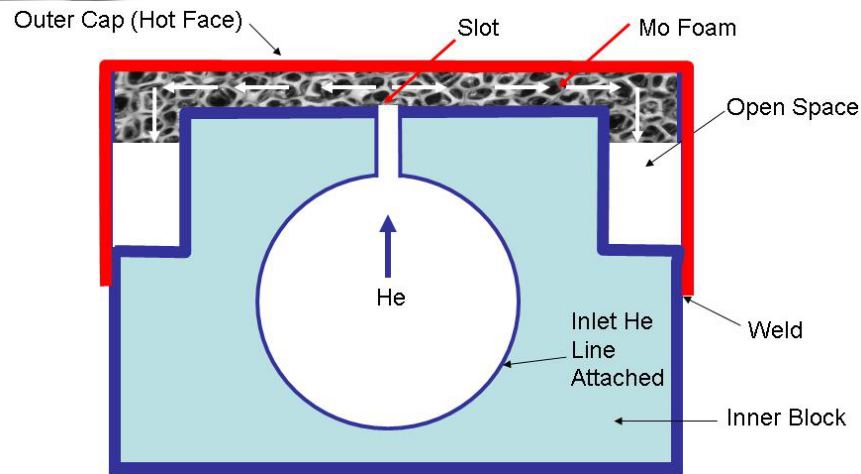
• goals:

- investigate heat transfer analyses for porous media and jet impingement - identify useful modeling approaches
- demonstrate performance in medium scale test (implies we have a test stand and a capable loop)
- deploy helium-cooled module in toroidal facility

• needed development:

- incorporate low-cost fabrication concepts for refractories including manifolding and connectors
- accommodate thermal stresses in face plates
- adequate heat transfer analyses for porous media and jets

Ultramet to deliver larger panels for phase-II.



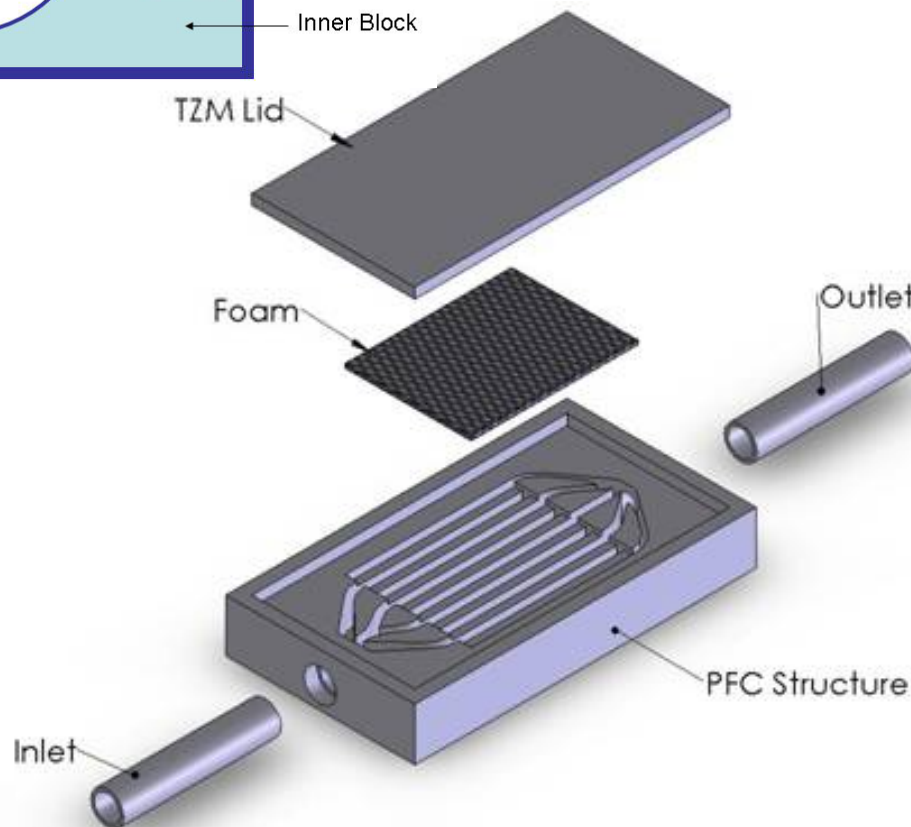
Testing in fall 2009

- Multiple channel (4)
- Flat surface
- All refractory
- Short flow paths
- 600 C inlet temps

concept

1

Porous media



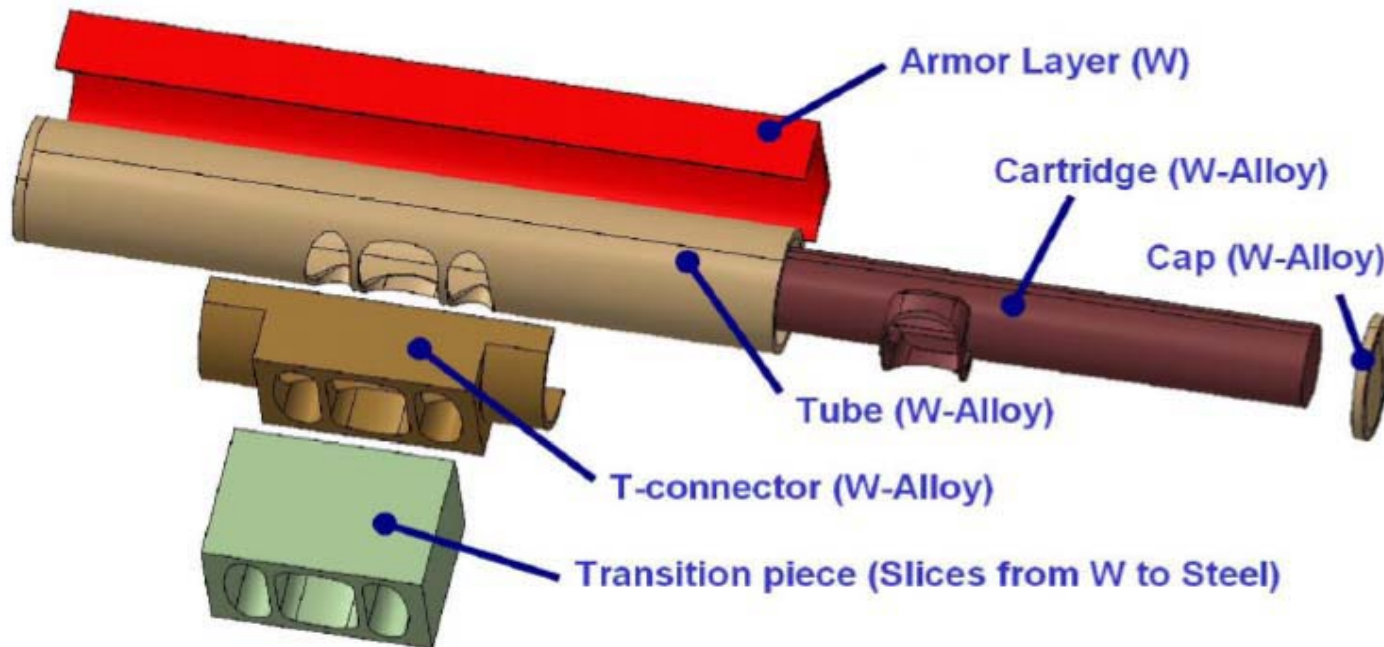
- Investigate:
- Larger heated areas
 - Flow instabilities

Plasma Processes Tee-Tube Concept

Testing in winter 2009

- **ARIES CS design**

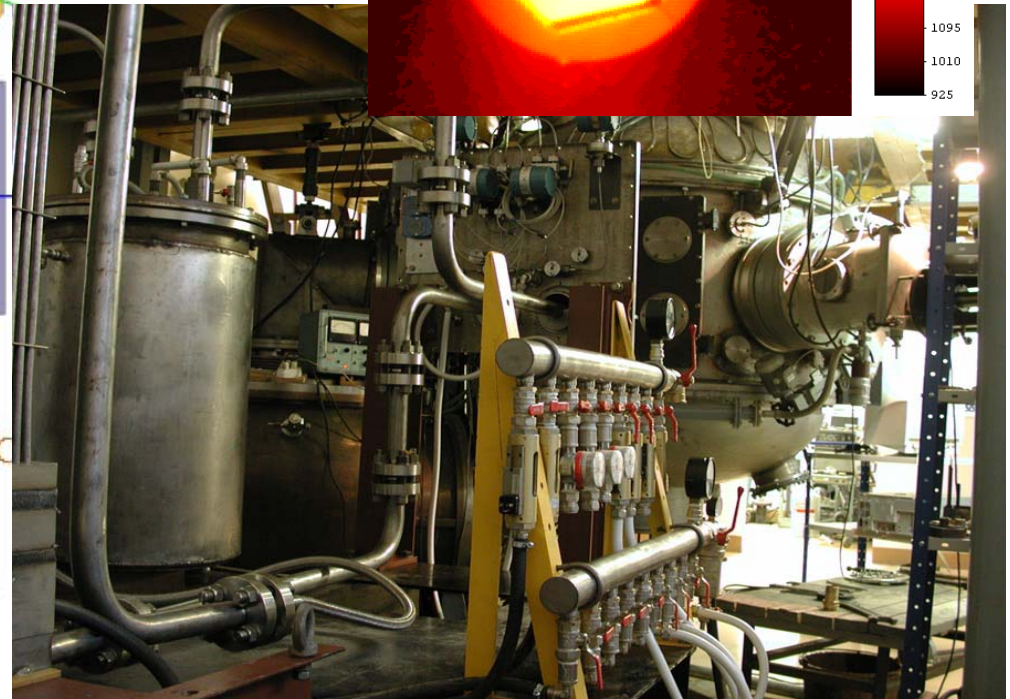
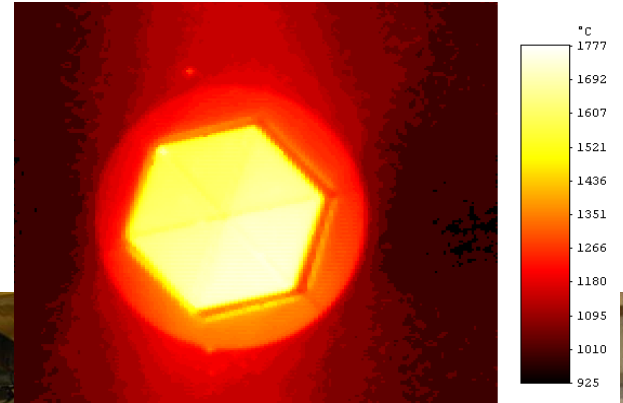
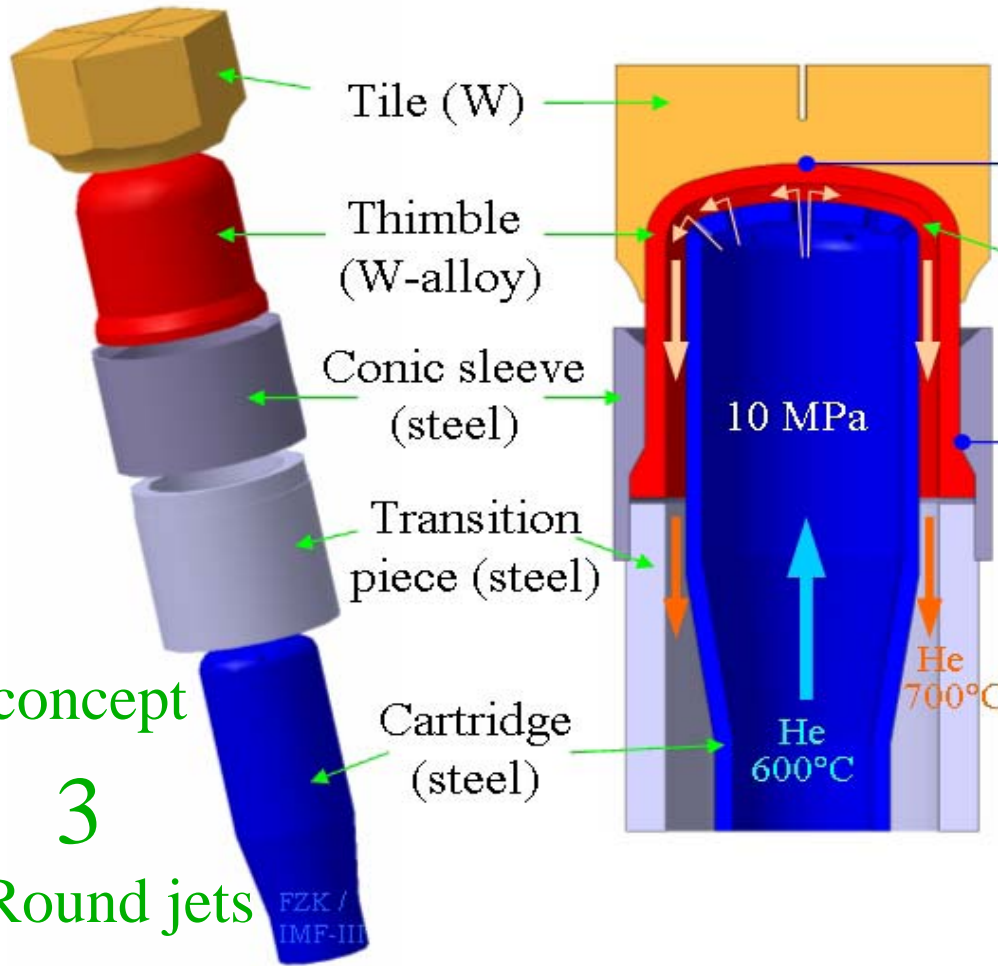
concept
2
Slot jet



HEMJ from FZK/Efremov (Norajitra)

US testing in early 2010 as IEA NTFR collaboration

Tsefey
2007



600C, 10 MPa, 25 g/s



concept
3
Round jets

FZK /
IMF-III



Innovations for improved power and particle handling

⇒ Liquid metal PFCs in burning-plasma reactors

- Develop renewable plasma-facing components (PFCs) for reactor applications, based on liquid metals**
- Investigate high power-density options for PFCs, based on liquid metals**

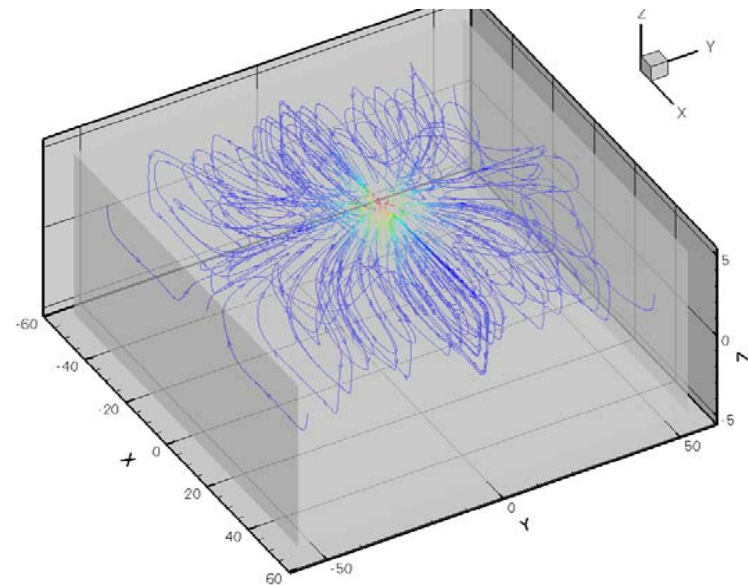
Innovations for improved power and particle handling

⇒ Liquid metal PFCs in burning-plasma reactors

Near-term tasks, each task requires modest cost, moderate development effort

- MHD modeling of liquid metal transport at high Hartmann and Reynolds numbers
 - Fusion-relevant magnetic fields configurations, and gradients
 - Effect of plasma MHD on the stability of LM
- Substrate optimization for slowly-flowing LM
 - Flow drive
 - Capillary flow
 - Fluid restraint
 - Chemistry, insulators, erosion, wetting
- Design, engineer devices and techniques to inject, control, remove liquid metals from an operating tokamak
- Design, engineer effective heat removal systems for liquid metal PFCs
 - Jet systems: heat is removed with fluid LM

Ha=2155 (B = 0.5 T)



Flow streamlines in beam-heated liquid lithium - UCLA, HyperComp Inc.

Development of liquid metal PFCs on test stands

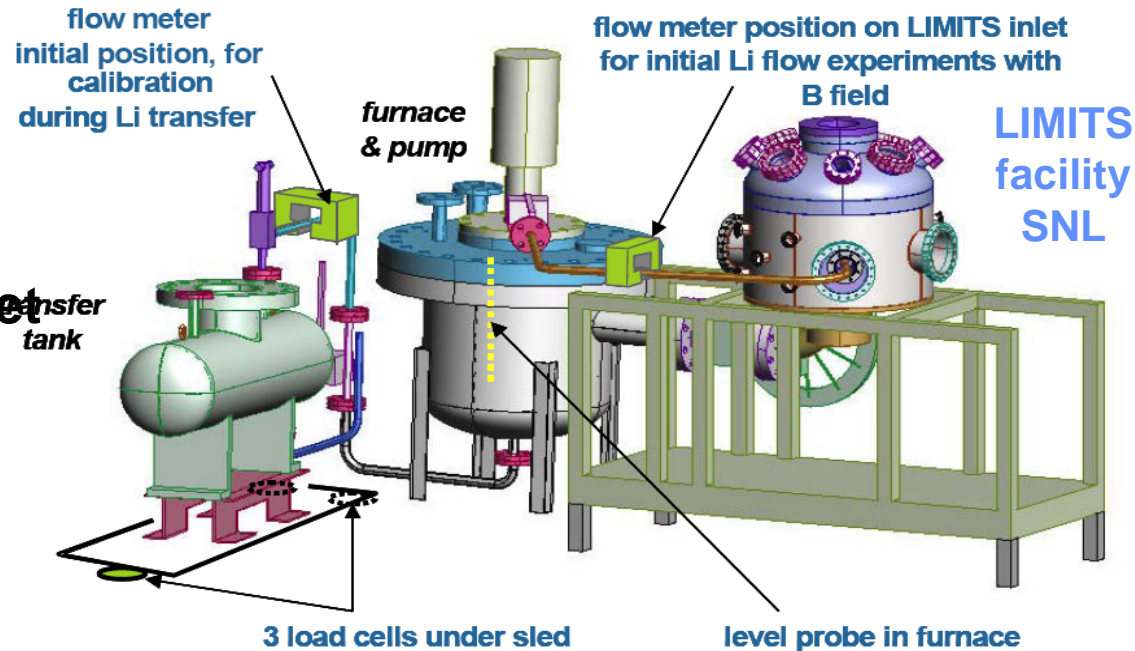
- **Medium scale task:**
Comprehensive liquid metal test stand capability

- Liquid metal flow loop feeding and draining a target surface

- Appropriate flow rates, fluid thickness over the surface
- Jet, capillary flow capability

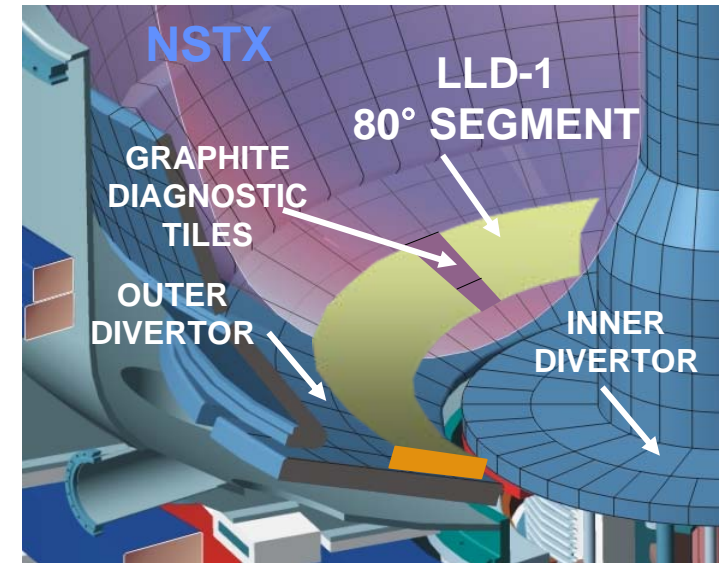
- Relevant magnetic field magnitude, field line angle, gradient capability, over a sufficient volume
- High heat flux capability, in combination with B field
- Ability to perform simultaneous PMI studies, preferably in-situ
- Comprehensive liquid metal flow, compositional, thermal diagnostics

- **Full test suite may require multiple facilities**

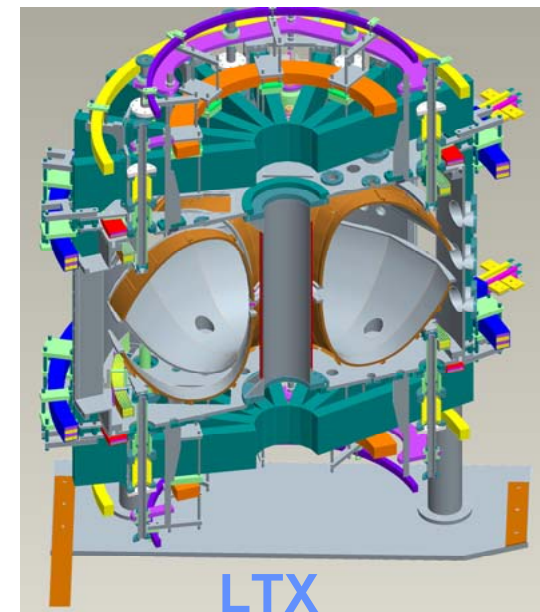


Development of liquid metal PFCs on confinement devices

- Testing with static liquid metals, in confinement devices, has already begun. In the U.S.:
 - LTX: full film liquid lithium wall on stainless steel this summer
 - Full (5 m²) molybdenum coated shell complete by FY09 end
 - NSTX: nearly full lower outer divertor: lithium on molybdenum/SS, FY10
- All work on lithium, due to observed/expected performance advantages for low recycling walls
 - Experience informs use of other liquid metals
- In order to advance the state of the art, test stands, modeling must move to:
 - Flowing liquid metals
 - Exploration of power handling limits
- Analysis, results from LTX and NSTX must be tightly coupled

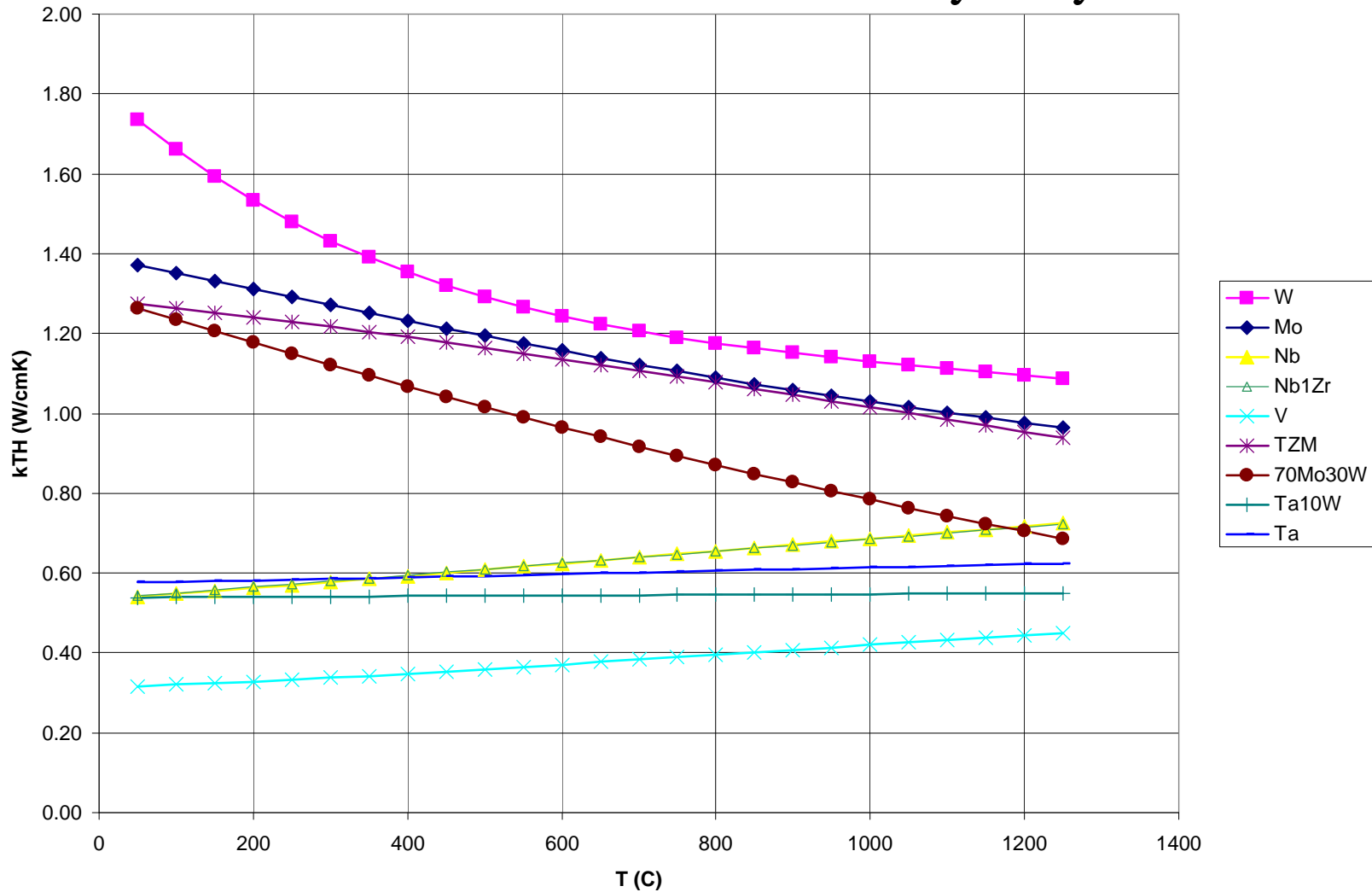


TRL-6



Is W the only game in town?

Thermal conductivities of refractory alloys

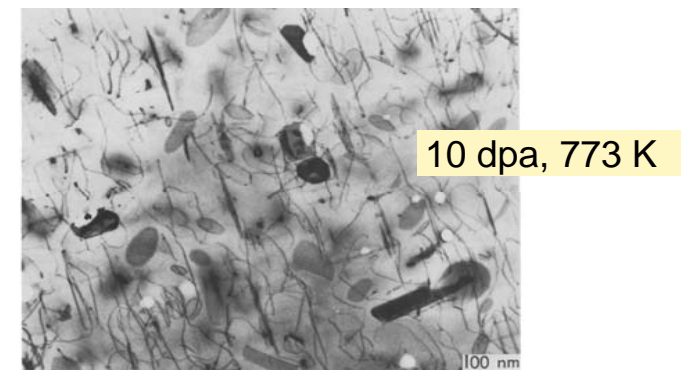
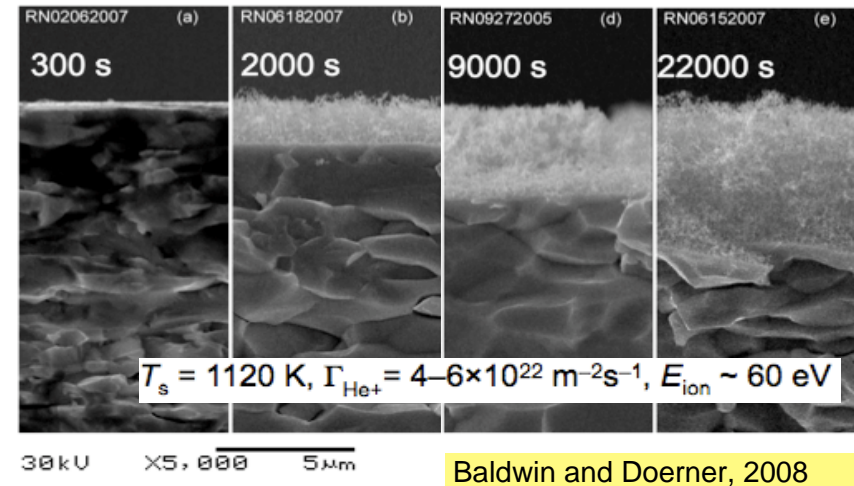


Refractory PFC Materials: Issues of Power and Particle Handling in Reactor Environments

PMI/PFC refractory materials have two primary design constraints:

1) Maintaining a viable plasma-surface interface compatible with burning plasma operation and 2) maintaining a viable structure in an aggressive nuclear environment

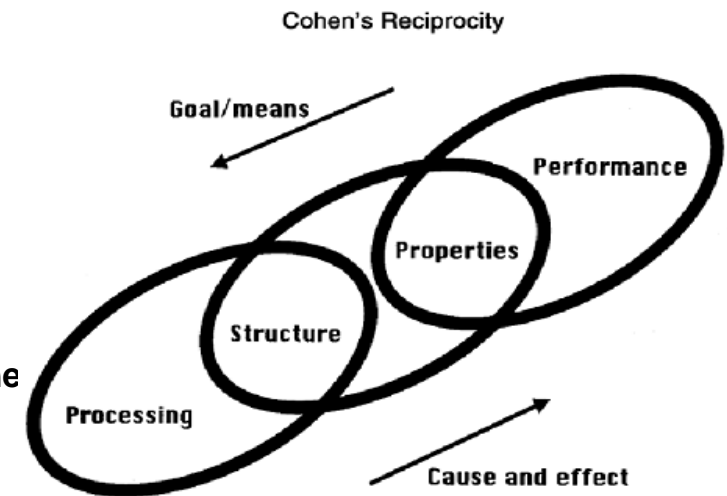
- Plasma-facing environment
 - Surface morphology (e.g. nano fuzz)
 - Tolerable erosion levels
 - Plasma transients (ELMs, disruptions)
 - Particle retention/recycling
- Radiation environment
 - Mechanical Properties
 - Irradiation creep, brittle fracture, hardening, swelling, transmutation, phase stability
 - Tritium retention/permeation
 - High temperature performance
 - Coupling armor with heatsink materials and cooling technologies (joint development)



L.K. Mansur 1994

Innovations in Plasma-Facing Component Materials

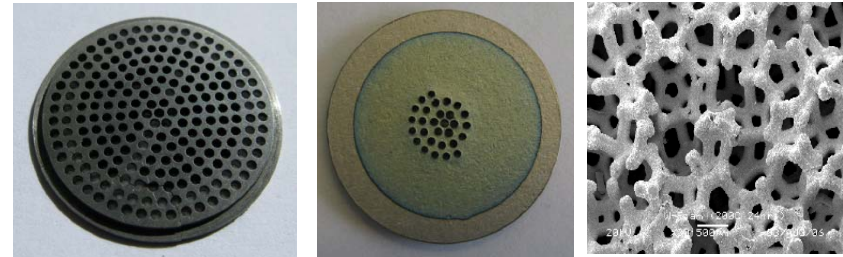
- Adaptive refractory alloys that are both compatible with plasma-coupling and extreme radiation environments controlling both power and particle inventory
- Exploit nano-, micro-, mesoscopic scale properties and performance of new materials
- He-cooled refractory alloys, porous systems
- UFG refractory alloys
 - Nano-crystalline solids, incl. dispersoids
- Innovations in processing
 - Fabrication of large/complex structures (near-net-shape)
 - Sintering-based techniques (e.g. spark plasma) for new ultra-fine grained systems
- Others: carbon-based materials
 - SiC composites
 - Flow-through Carbon concepts (Stangeby)



Materials design must be compatible with performance and processing techniques

Low-Z/ High-Z plasma-facing materials systems

- Edge alpha effects
 - He-induced nano-scale fuzz
 - Near-surface bubbles/cavities
- Mitigating edge alpha effects
 - Low-Z material coatings (need real-time deposition)
 - W-C layers inhibit He-induced morphology (Doerner and Baldwin)
 - B-W surface concept by Wong et al.
 - Low-Z/High-Z nano-composite coatings
 - Radiation-tolerant structures: nano-crystalline refractory materials
 - Enhancing trap sites for helium
- Candidate PFC material must be compatible with transient events

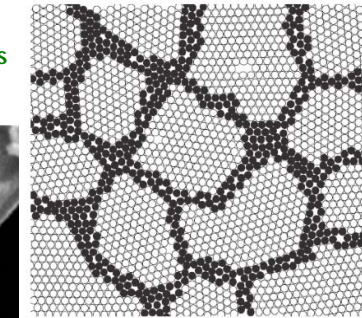
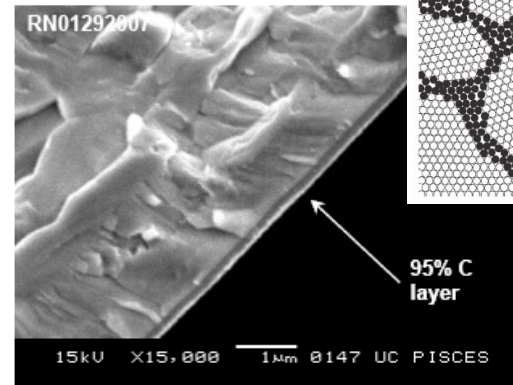


Drilled W-disc
2 cm diam. disc
1 mm diam. holes

Boronized coating on
middle of W disc, ultimately
on W foam

C.P.C. Wong et al.

nc-W with ~10-nm grains and
Low-Z (Lithium) grain boundaries
Allain et al.



10 nm

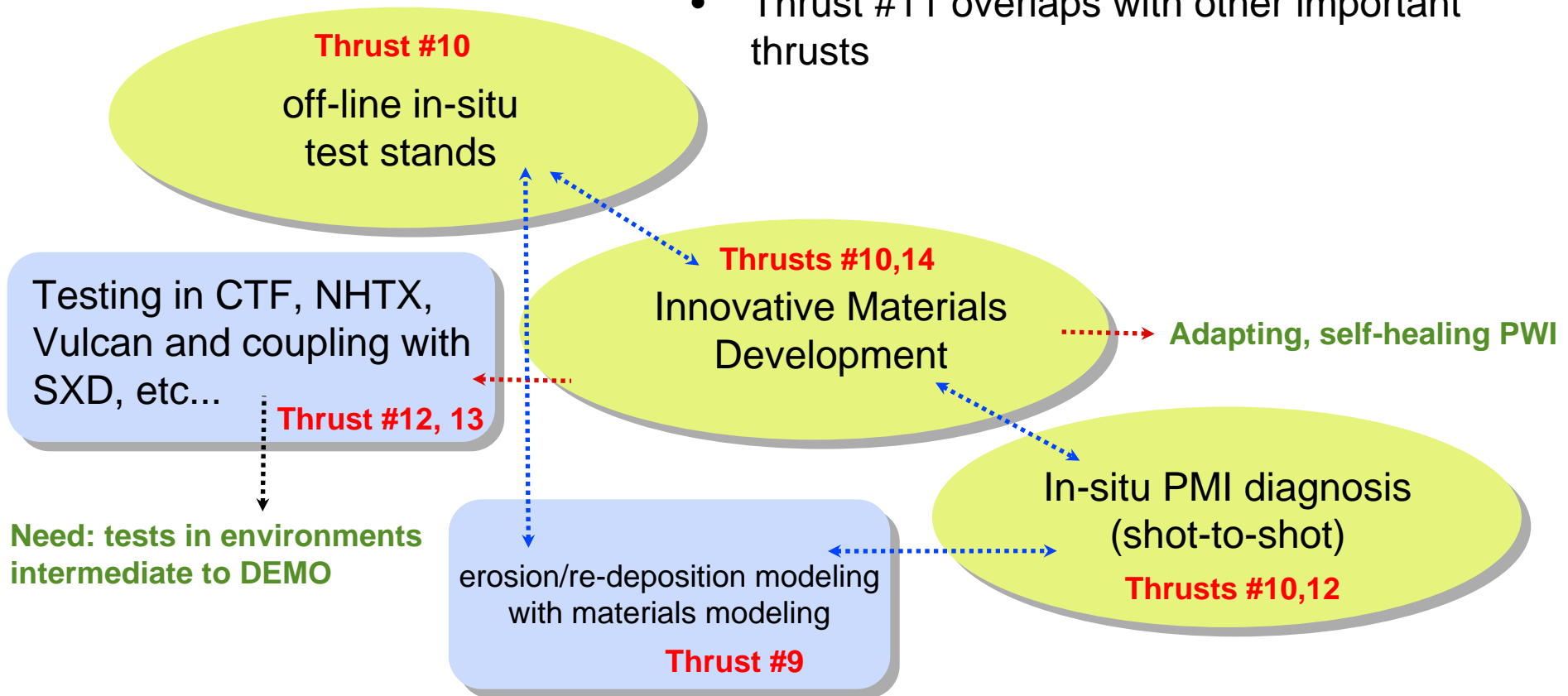
$E_i = 15 \text{ eV}$, $T_s = 1100 \text{ K}$, Fluence = $10^{25} \text{ He}^+/\text{m}^2$,
 $n_{\text{He}^+}/n_e \sim 10 \%$, $n_{\text{C}^+}/n_e < 0.1 \%$ $\Delta t = 3600 \text{ s}$

Qualification of innovative plasma-facing materials

- ***Experiments in upgraded current PMI/PFC facilities***
 - Upgrade existing PMI/PFC testing facilities with additional *in-situ* diagnostics to measure material surface properties
 - Probing techniques to measure hydrogen transport across relevant spatial scales in innovative candidate materials under realistic environment conditions
 - Upgrade to realistic radiation environment (i.e. high heat flux, long-pulse) and test impact on plasma-surface interface coating/heat-sink interface
- ***Experiments in new PMI/PFC facilities***
 - Development of refractory coatings and heat sinks using complementary *in-situ* material characterization techniques
 - Measurement of heat transfer properties coupled to surface/interface characterization (e.g. XPS, RBS, LEISS, DRS)
 - Measurement of particle transport in candidate materials and impact on coating/heat sink interface
 - “*Simulated experiments*” coupled to computational materials science code development to assess multi-scale (time, space) materials development

Summary: innovative materials must be developed in a coordinated strategy coupled to innovative testing environments

- Thrust #11 overlaps with other important thrusts



- Need for in-situ diagnosis of a dynamic environment that replicates coupling to plasma affecting materials properties *during* irradiation