SAND2011-7736P

US Activity in Gas-cooled Refractory Divertors

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Albuquerque, New Mexico, USA

Divertors & He-cooling

- **Divertor design studies in ARIES**
- **He-cooled high heat flux targets in PMTF and a new approach in modeling He flow in porous media**

Tokamak Tiles

- **W tiles in Alcator C-MOD at MIT**

PSI & Materials covered elsewhere

- ***PSI investigations on W and new activities in the US materials program***

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NNSA National Nuclear Security Administration

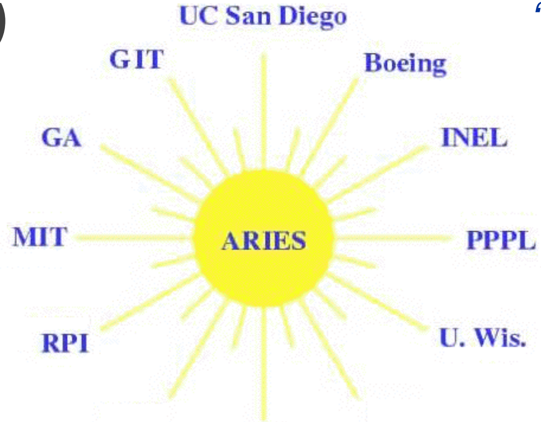
Sandia National Laboratories

ARIES Divertor Design Effort

"Pushing the limits of He-cooled high heat flux components"

(beyond 10 MW/m²)

Mark Tillack for the ARIES Team,
TOFE-19 Nov 2010



"W-Based Alloys for Advanced Divertor Designs: Options and Environmental Impact of State-of-the-Art Alloys," El-Guebaly, Kurtz, Rieth, Kurishita, Robinson *Also in TOFE:*

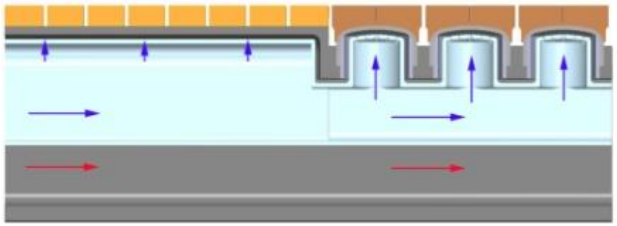
1. High <u>conductivity</u> and <u>strength</u> enable high heat flux capability
2. <u>High temperature</u> capability for high conversion efficiency
3. Good characteristics for <u>activation</u>, <u>radiation damage</u> and <u>safety</u>
4. Current … attention in the design and materials R&D communities.

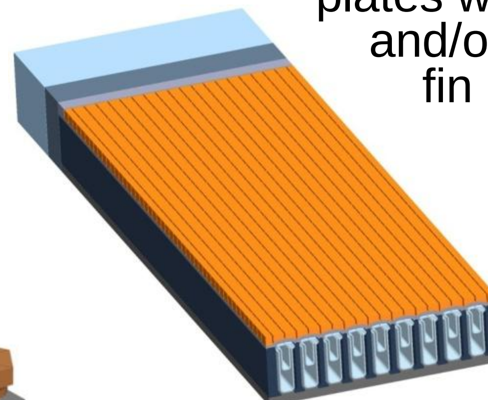
5. Alloy development needed; <u>issues</u> with all existing forms of W
   - *Low ductility, fracture toughness*
   - *Limited temperature window for operation (due to DBTT & recrystallization)*
   - *Difficult fabrication*

UC San Diego

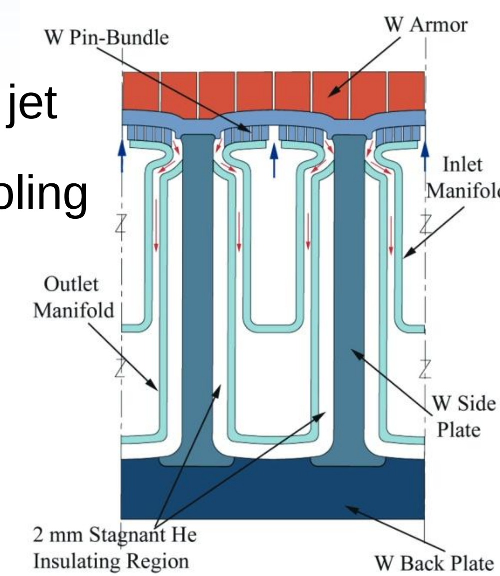
CER Center for Energy Research

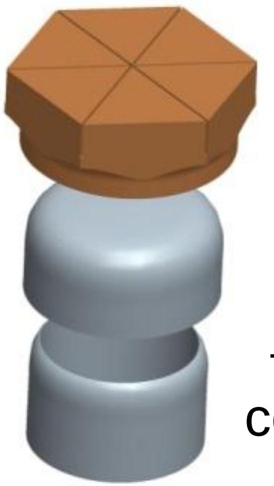
Several W-He divertor designs have been explored in ARIES recently



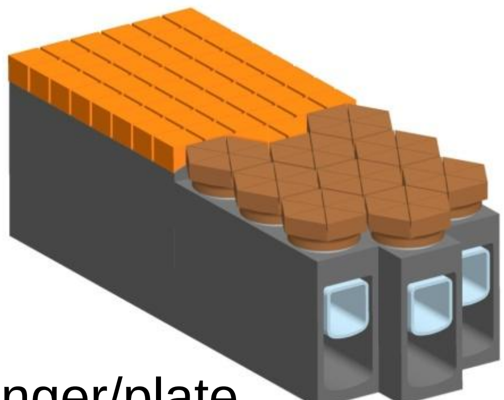


plates with jet and/or fin cooling

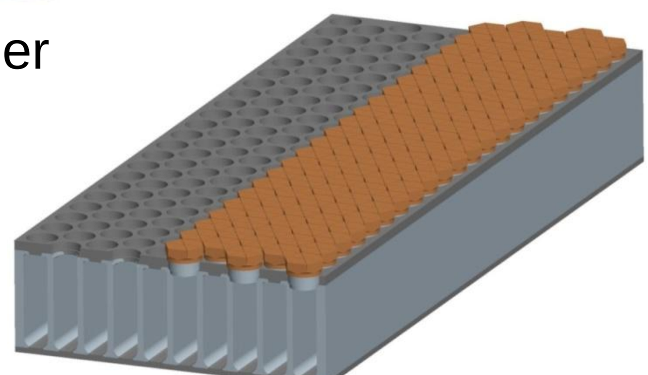


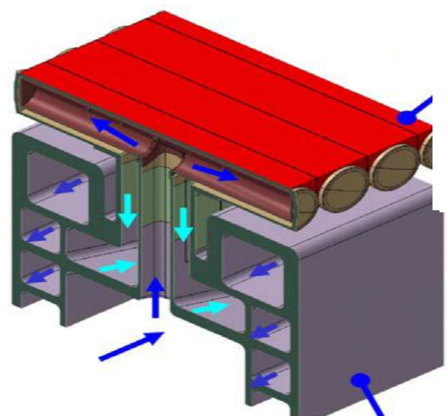


finger

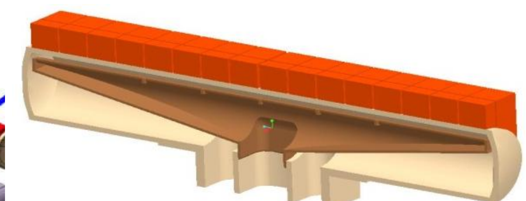


finger/plate combinations





module body steel



T-tube

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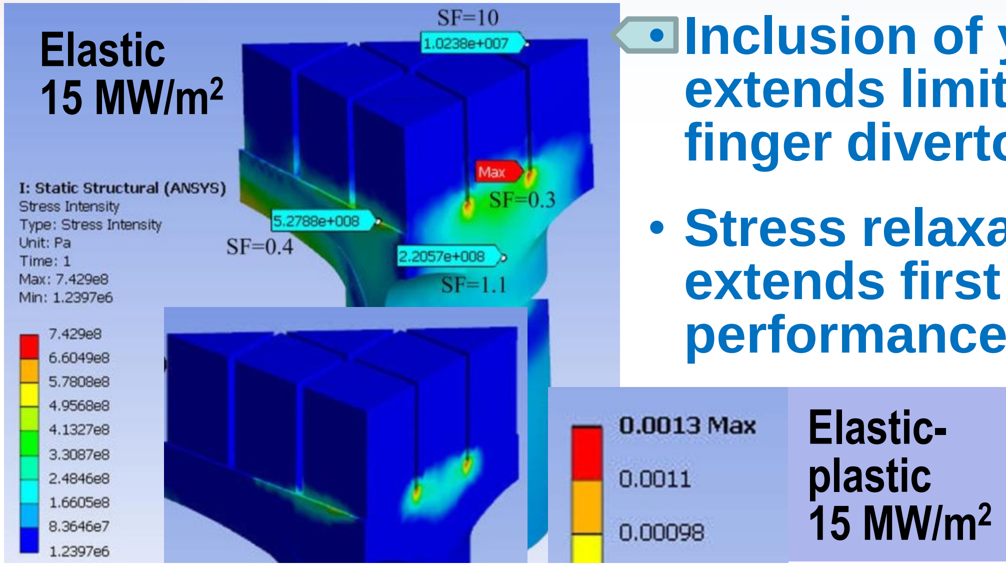
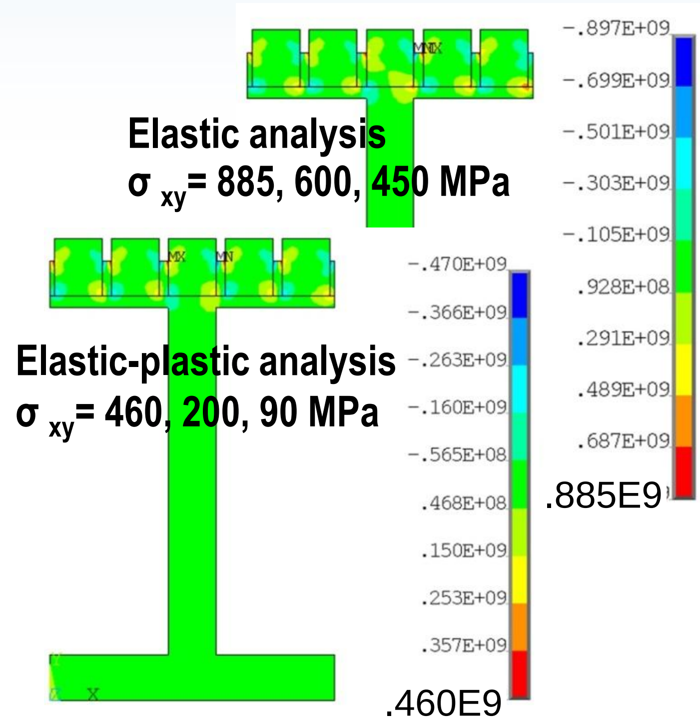
Pushing limits with more detailed analysis



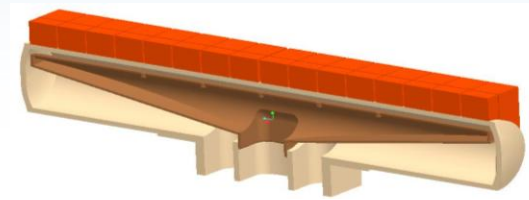
- Inclusion of yield extends limits for finger divertor
- Stress relaxation extends first wall performance

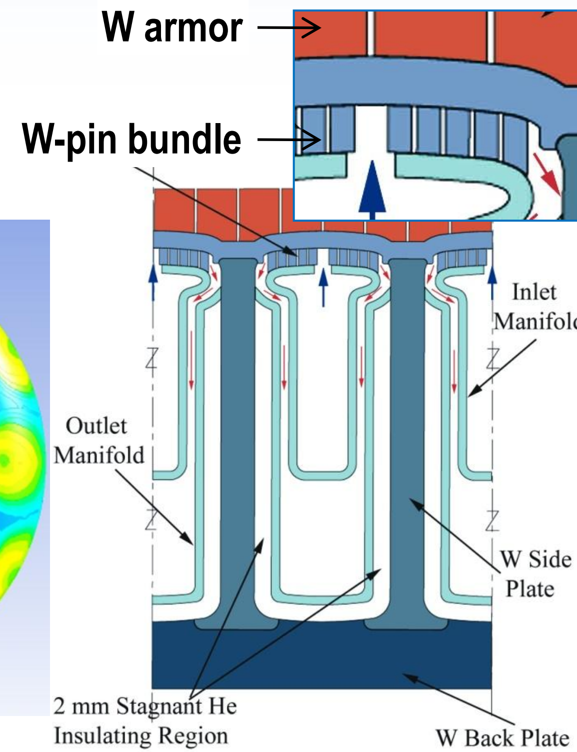


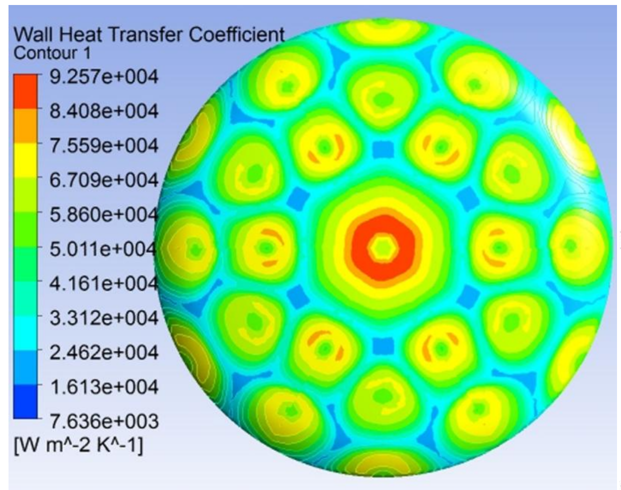
1. 3D elastic-plastic analysis with thermal stress relaxation (*yield*)
2. Application of accumulated strain limit (0.5 e_{ue} instead of $3S_m$)
3. **Birth-to-death** modeling
   - Fabrication steps, operating scenarios, off-normal events
4. *Future work*: Thermal and irradiation creep, crack growth and low-cycle fatigue, irradiation damage effects

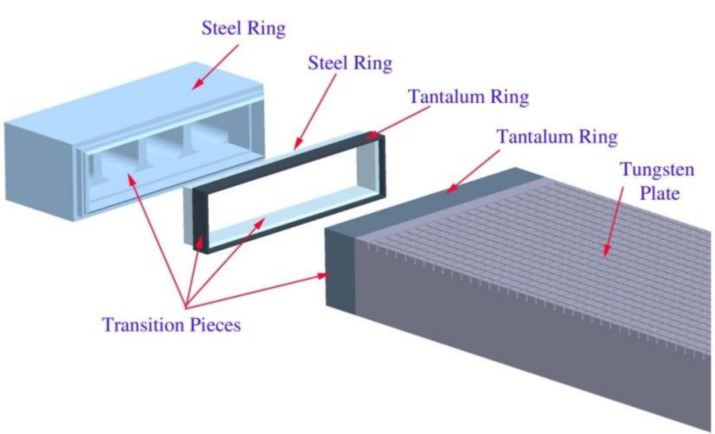
Pushing limits with design improvements

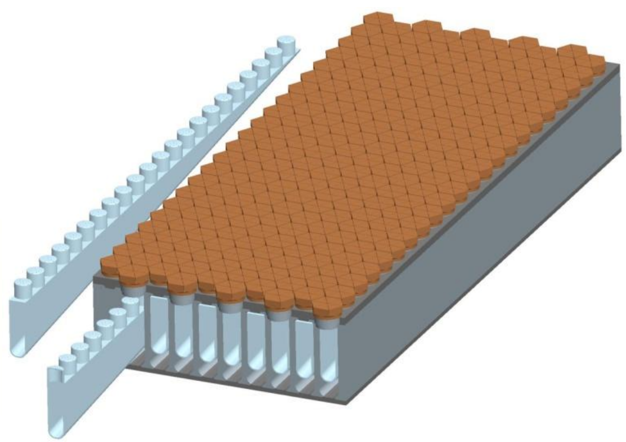
1. Tapered T-tube divertor
2. Modified divertor finger
3. W-pin first wall concept (not shown)
4. Heat transfer enhancement with jets + fins
5. External transition joints
6. Fingers-in-plate design
7. External transition joints

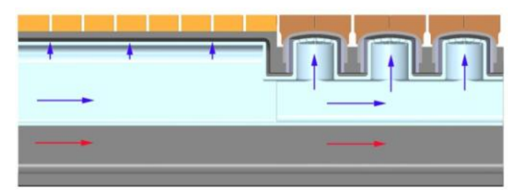












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O U T L I N E

- Divertor design studies in ARIES [ARIES Team]
  - *Pushing design limits*
- **Refractory PFC Development [Sandia]**
  - ***He-cooled high heat flux targets in PMTF***
  - ***New approach to model He flow in porous media***
- Refractory Divertor Tiles in Alcator C-MOD [MIT]
  - *New measurements of edge scrape-off length*
  - *Tungsten fuzz observed in a tokamak*

"Breakthrough analysis" of flow in porous media for fusion applications

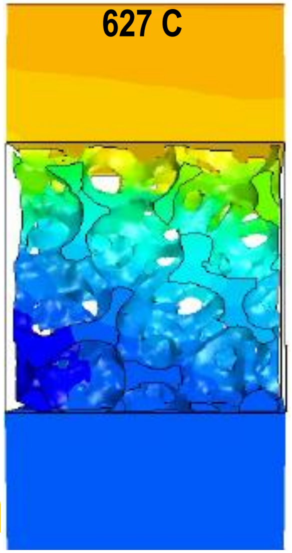
Dennis Youchison
DMTS at Sandia

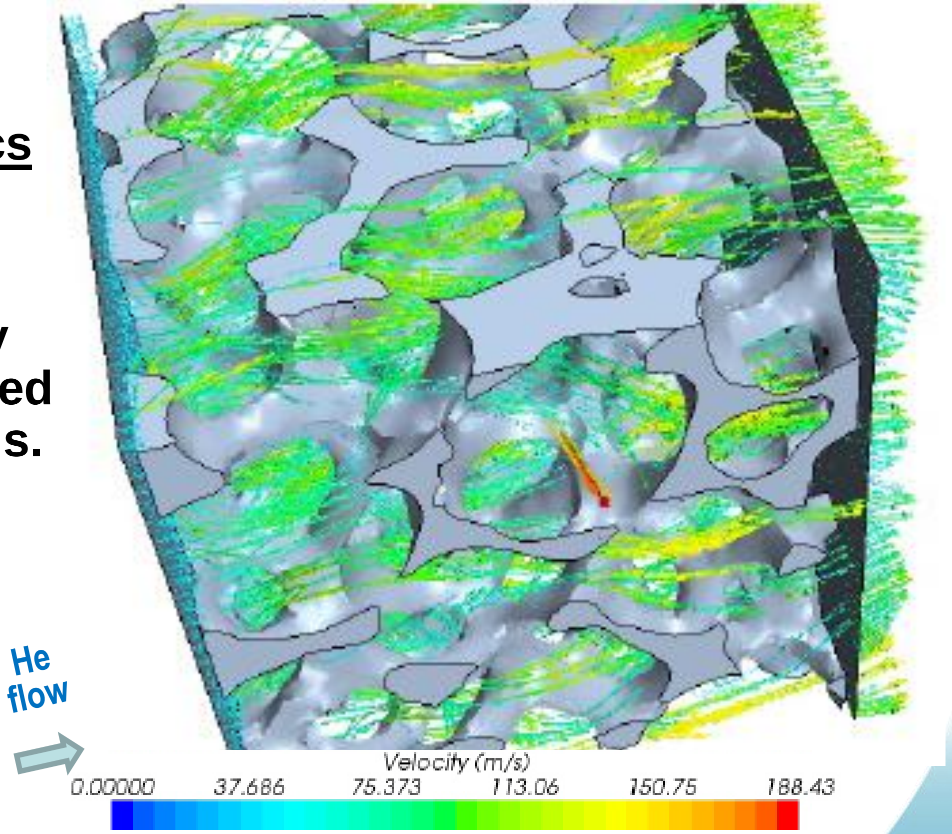
Early work for helium-cooled fusion heat sinks used correlations (Ergun equation) to predict heat transfer in porous media.

<u>New approach</u> combines accurate and <u>irregular geometry</u> and <u>full fluid physics</u> of boundary layers and turbulence to model fluid flow and heat transfer.

Computerized X-ray micro-tomography used to image foam. Software translated data to format for irregular solid models.

*carbon foam made by Ultramet, Inc. (Pacoima CA)



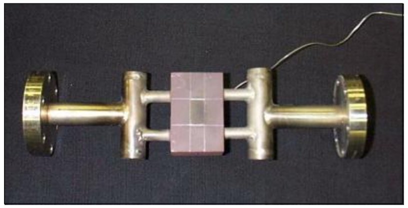


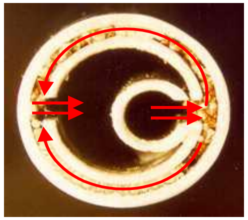
2x2 mm volume from model
65 ppi, 10% dense Mo foam

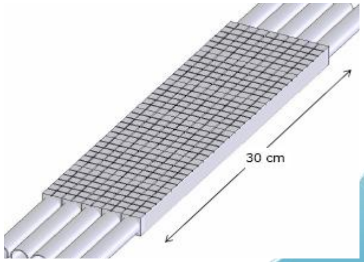
Analysis reveals turbulent mixing and fin effect created by foam.

Helium-cooled modules for PFCs

year	*Type of Test Article*	*fabricator*
1993	Cu Micro-channel HX (~100μ channel size)	Creare, Inc.
	Cu Divertor mockup A (0.46mm channels)	General Atomics
	Cu Porous (40%) metal HX (0.43mm dia.)	Thermacore, Inc.
1994	Cu Dual channel porous metal HX	Thermacore, Inc.
	Cu Div. mockup A retest, higher heat loads	General Atomics
1996	Cu Phase-II porous metal HX	Creare, Inc.
	Vanadium spiral-tube HX	General Atomic
1997	Cu Faraday shield A	Thermacore, Inc.
	Cu Divertor mockup B	Thermacore, Inc.
1998	Cu Faraday 2^{nd} shield B	Thermacore, Inc.
	Cu Divertor 2^{nd} mockup C	Thermacore, Inc.
	Tungsten heat sinks	
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







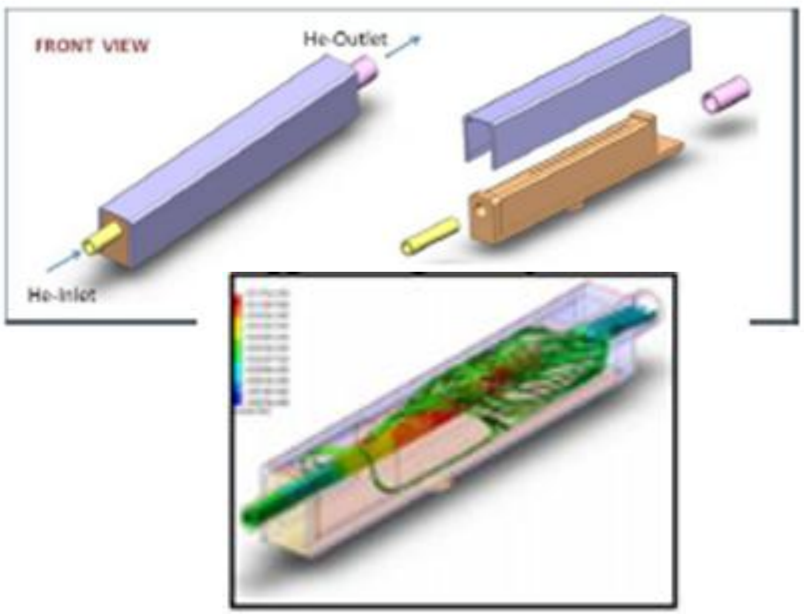
2011 He-Li HX test in EB1200

Refractory He-cooled Divertor Targets

We test these modules in PMTF. The US Dept. of Energy funds the development of the modules through grants to small businesses.

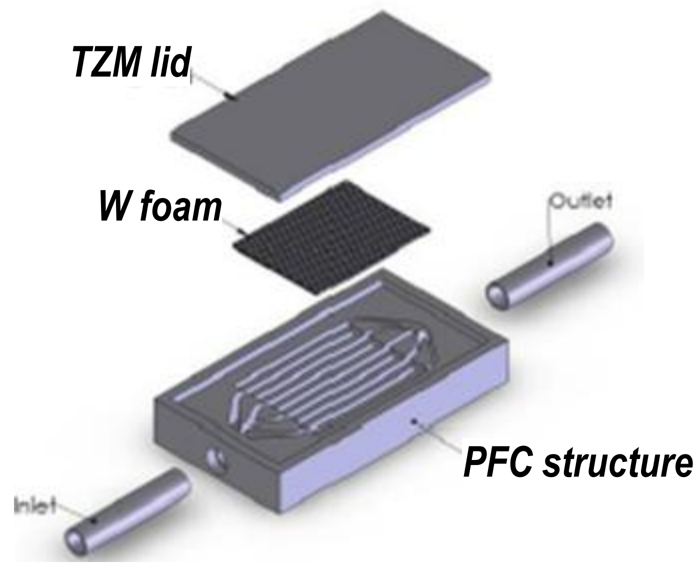
He cooled Moly heat sink tested in EB60

1. *No foam*
2. *45 ppi 75% porosity*
3. *65 ppi 75% porosity*
4. *100 ppi 75% porosity*



4 channel panel tested in EB60

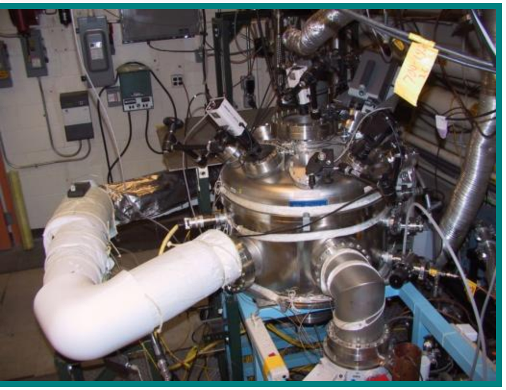
Panels failed due to poor design of joint at edge of top surface.

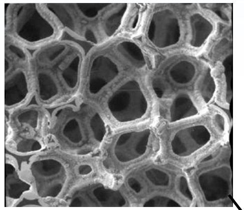


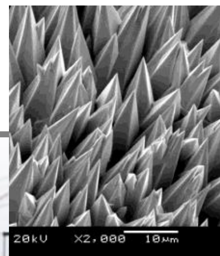
Tests with He starting in EB1200

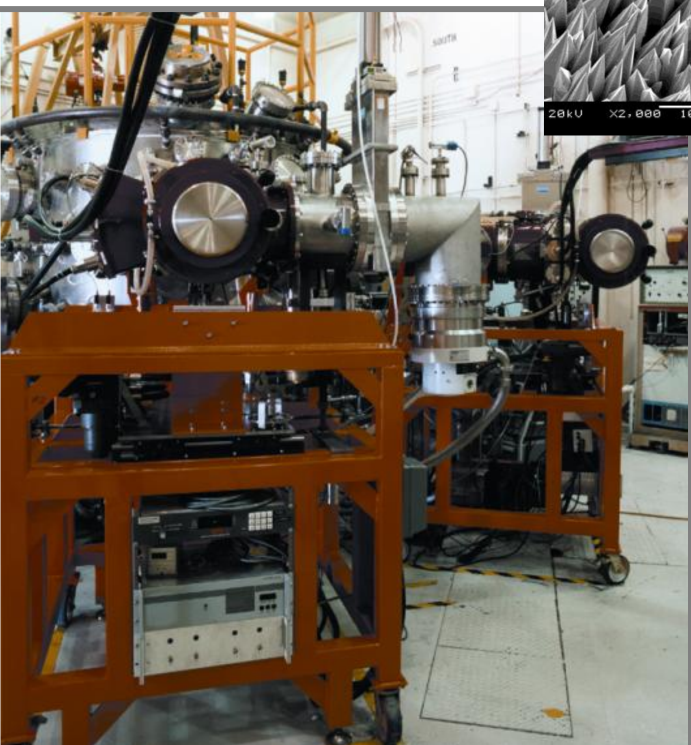
- 1.2 MW beam power
- Digital beam raster
- High T, High P water
- He loop upgrade
- Li-He HX

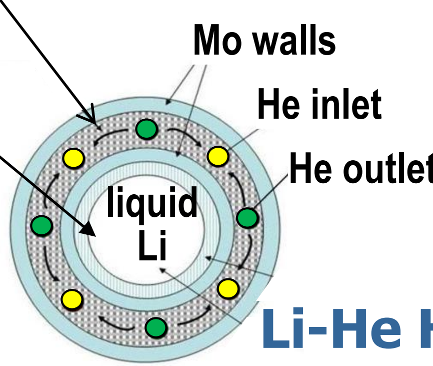
- Extensive diagnostics: *IR, pyrometers, RGA, water calorimetry, beam power, etc.*



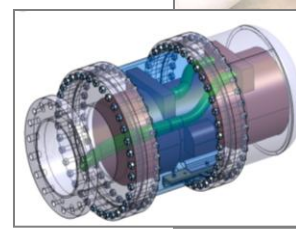


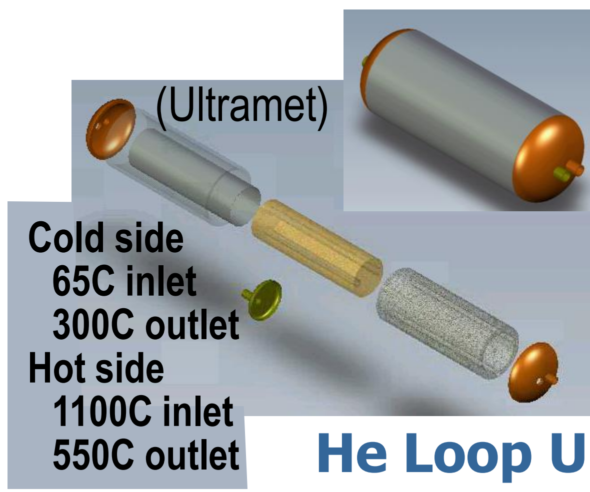






Li-He HX





He Loop Upgrade

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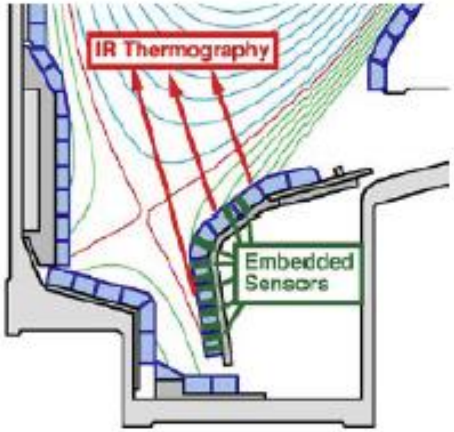
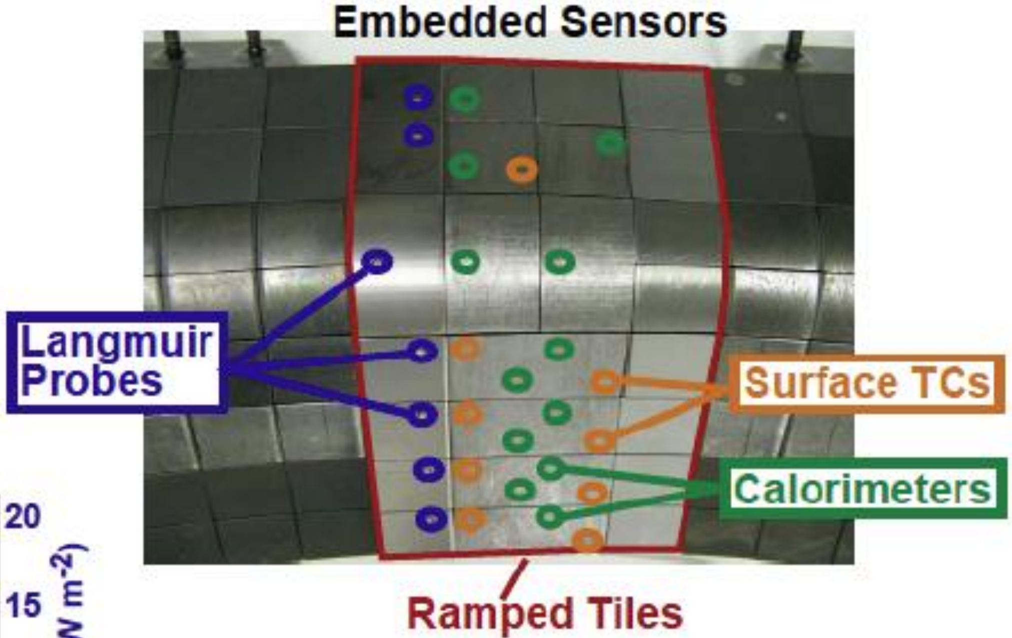
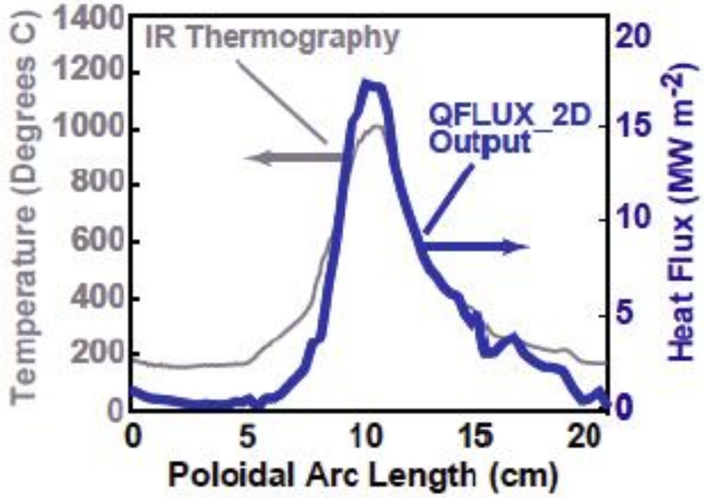
  - New approach to model He flow in porous media
- **Refractory Divertor Tiles in Alcator C-MOD [MIT]**
  The Team at the Plasma Fusion Science Center at MIT has installed tungsten tiles in the C-MOD divertor in the past. New results from work in progress are shown here.
  - New measurements of edge scrape-off length
  - Tungsten fuzz observed in a tokamak

New thermal/heat load diagnostics have allowed great progress to be made in terms of wall heat load research on C-Mod

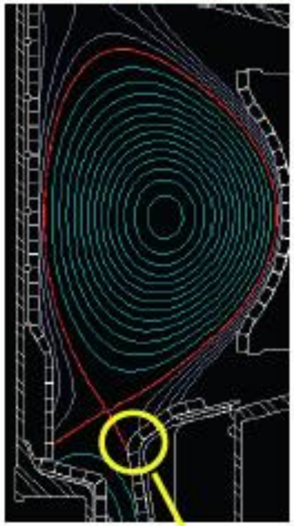






- Able to obtain surface temperature profiles.
- And heat flux/thermal footprint profile through modeling (QFLUX_2D)

C-Mod Helium plasmas produced necessary conditions for fuzz growth at the outer strikepoint

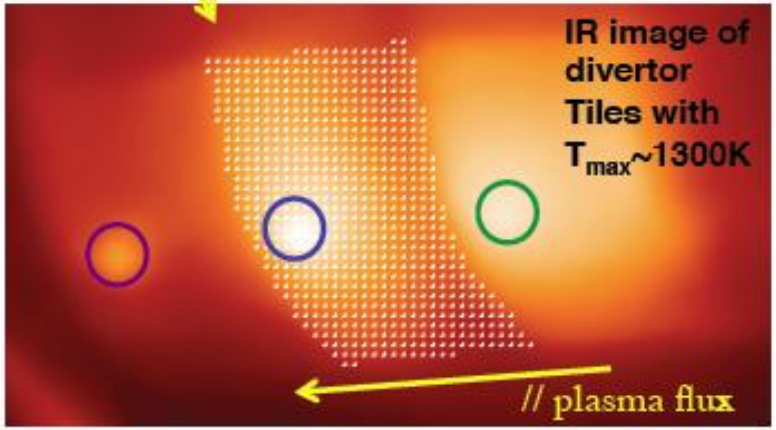


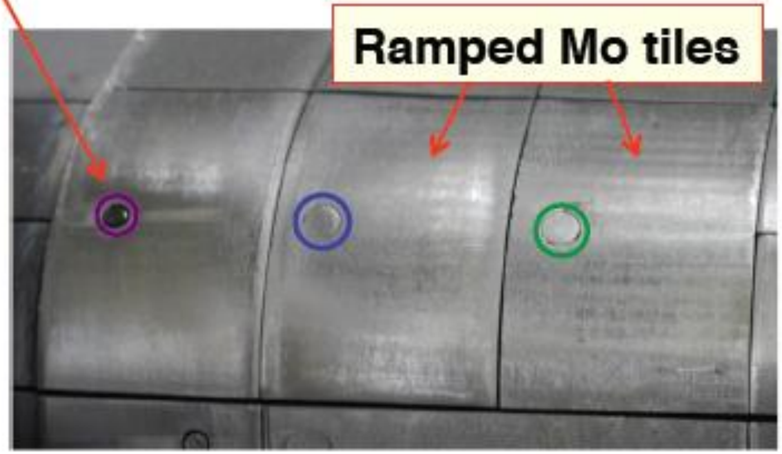
12 shots, ~ 3 MW ICRF, L-Mode

$T_{e,divertor}$ ~ 20 eV, $q_{//}$ > 0.2 GW/m^2

~ 12-15 seconds exposure

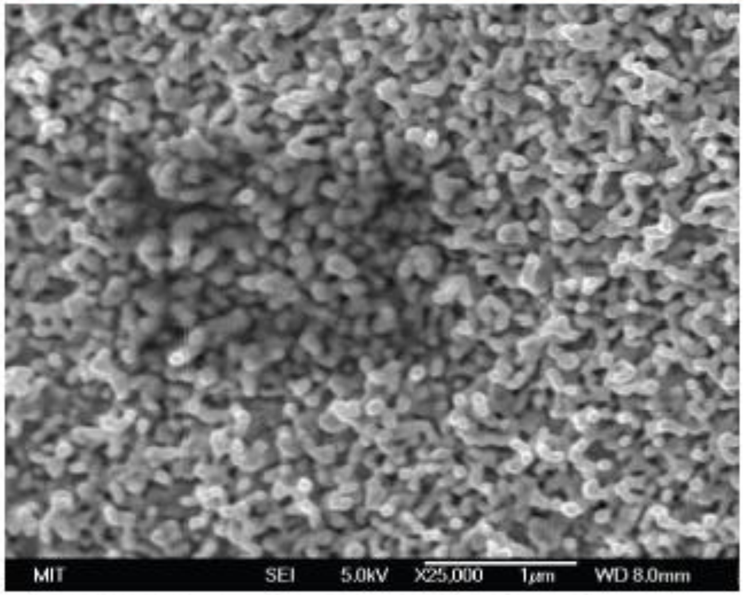
W langmuir probe and Mo calorimeters were hottest
Clearly reduced reflectivity of W probe indicative of fuzz





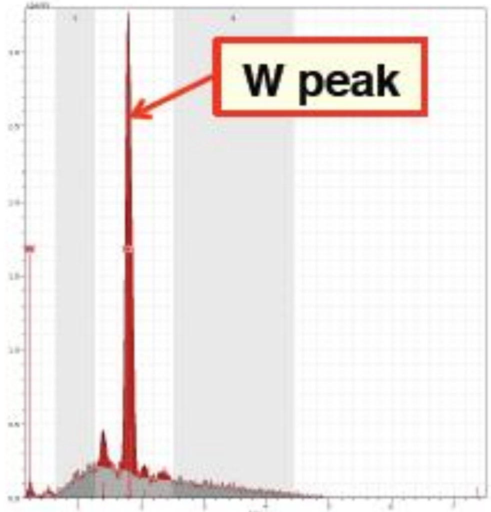
High resolution SEM images show fully formed nano-tendrils on the surface of the tungsten probe.

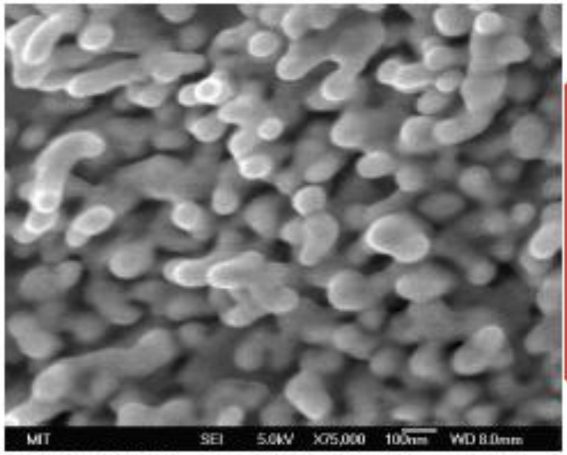
Interpretation of these observations is done in collaboration with UCSD.



Fully formed nano-tendrils have almost total surface coverage of the probe tip.

EDX measurements confirm that the fuzz is ~100 % tungsten.





Thickness of individual tendril is 50-100 nm, which is thicker than tendrils grown in linear devices (20-30 nm)

Considerations Raised in the
Fusion Nuclear Science Pathways Assessment

The FNSPA commenced in the summer of 2010, is an assessment of R&D and priorities in fusion nuclear science and includes study options for a Fusion Nuclear Science Facility. The report, now in preparation, is an internal planning document at this point.

Senior members of this FNS community have expressed the following opinions that relate to US-Japanese collaboration.

- Development of fusion nuclear science requires a cadre of researchers with specialized expertise that takes years to develop. We need expansion of the program and the ability to engage young researchers.
- Successful development of divertors and integrated first wall and blanket modules requires attention to design requirements and options at the level of subsystems (typically not done in, for example, a DEMO reactor design).

Divertor designs is one potential area of mutual interest for collaboration for the US and Japan.

Thank you

Arigatou gozaimashita