Challenges for Engineering Plasma Facing Components for Fusion in Steady-State

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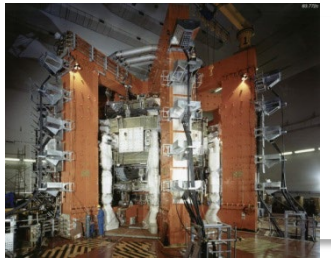
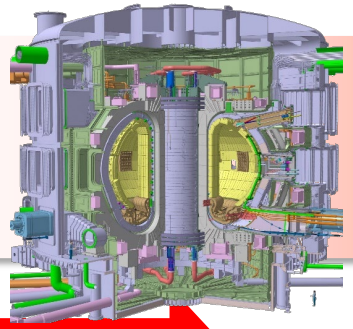
November 16, 2022

Plasma facing components – we have many orders of magnitude to go

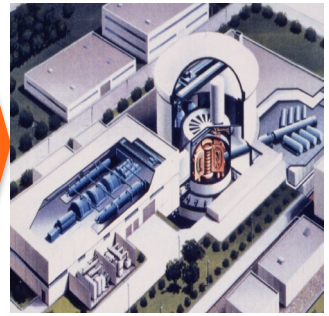
JET



ITER



Fusion DEMO



50 x divertor ion fluxes

5000 x divertor ion fluence

10^6 x neutron fluence (1dpa)

up to 5 x ion fluence

up to 100 x neutron fluence (150dpa)

Operates for seconds

Operates for an hour

Operates continuously

Materials need to be developed and tested under fusion prototypic conditions:

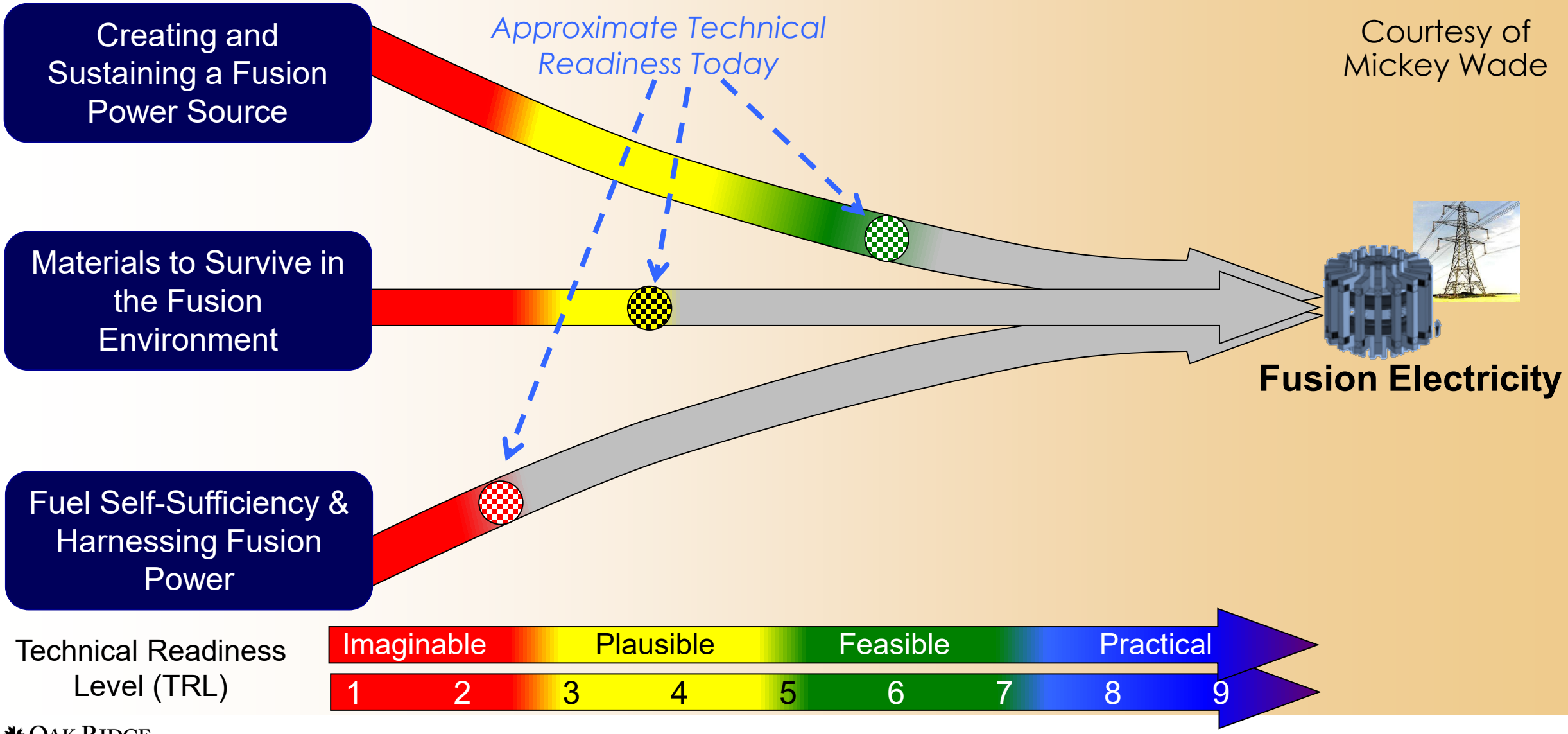
High fluxes, high ion fluence, high neutron fluence

Increasing duration and hazards

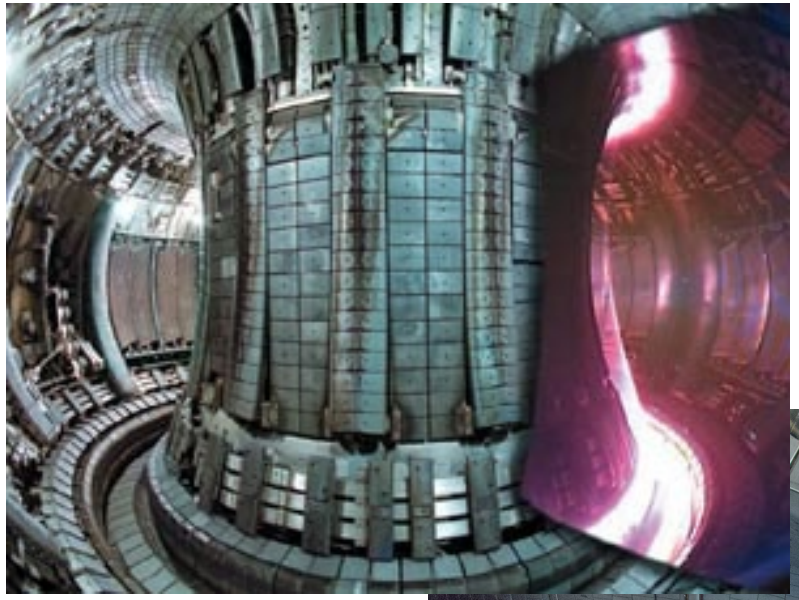
Short operation to long operation

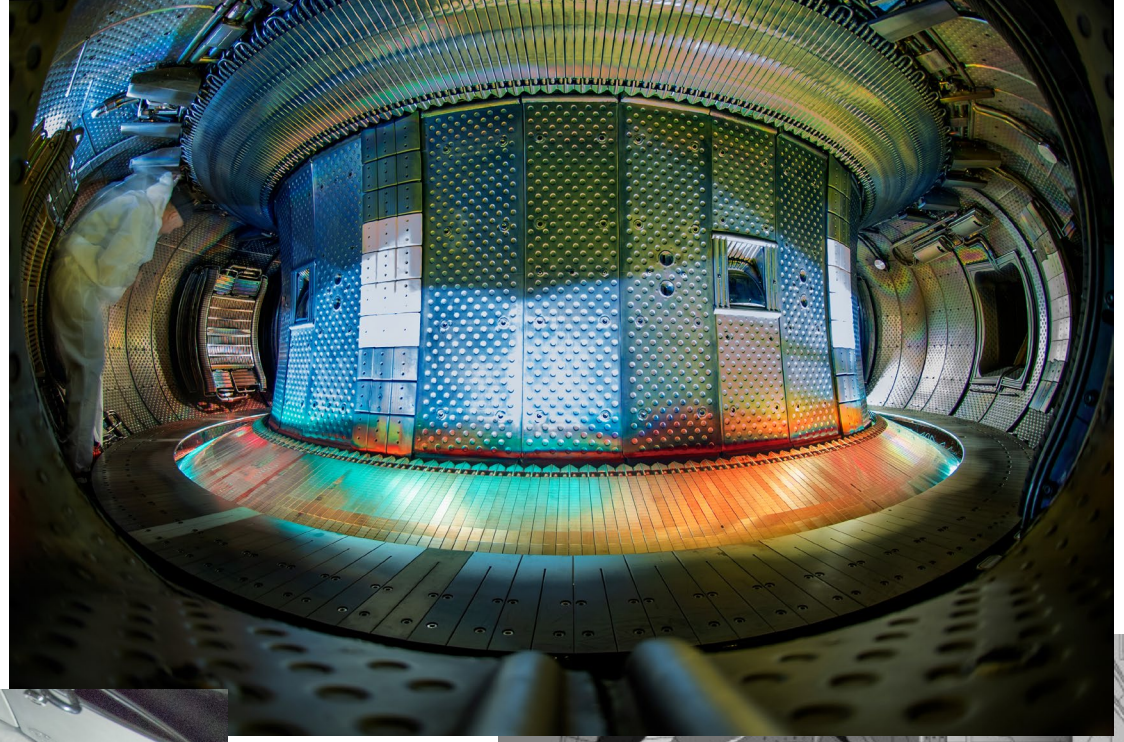
Long operation to extreme environment

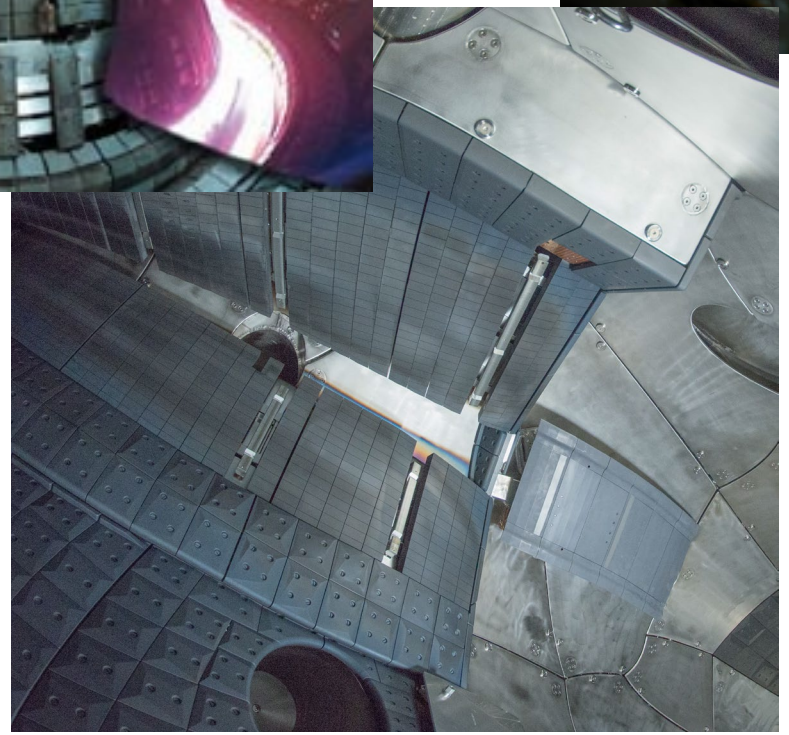
Generating Electricity from Fusion Energy Requires Resolution of Three Scientific/Technological Challenges

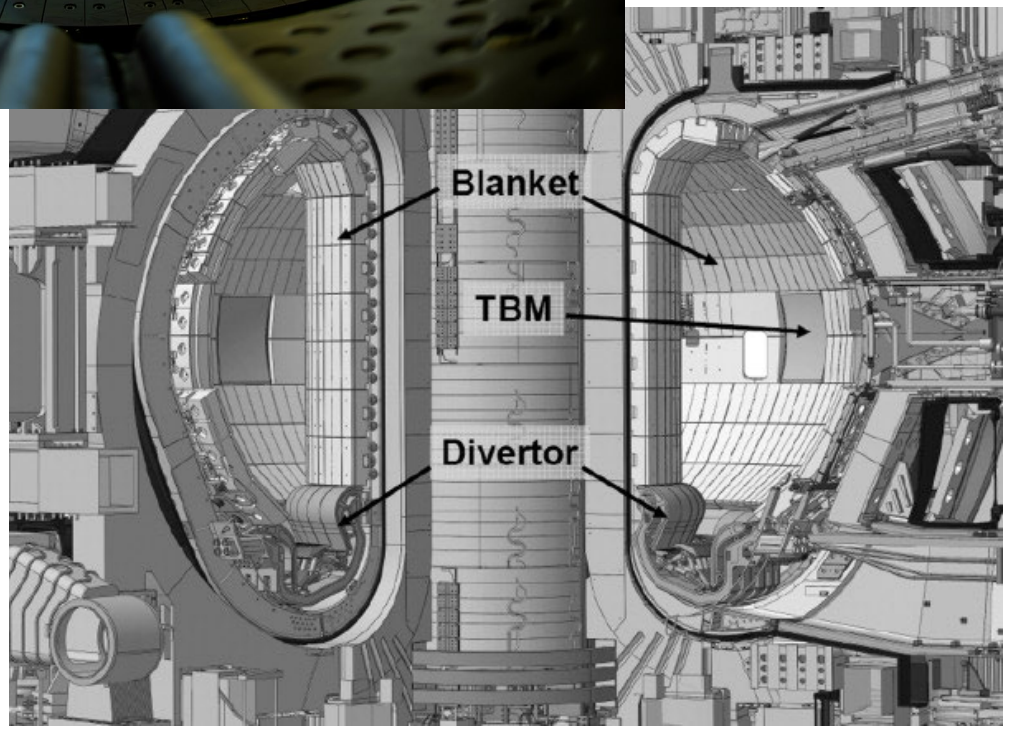


How do we design PFC's for a reactor?









"Components" of PFC's

- Plasma facing surface (tungsten? liquid lithium? RAFM steel?)
- Coolant (water, helium, liquid metal, molten salt)
- Intermediate thermal structure
  - Must transfer heat from the surface to the coolant
  - Must survive "just below the surface" requirements

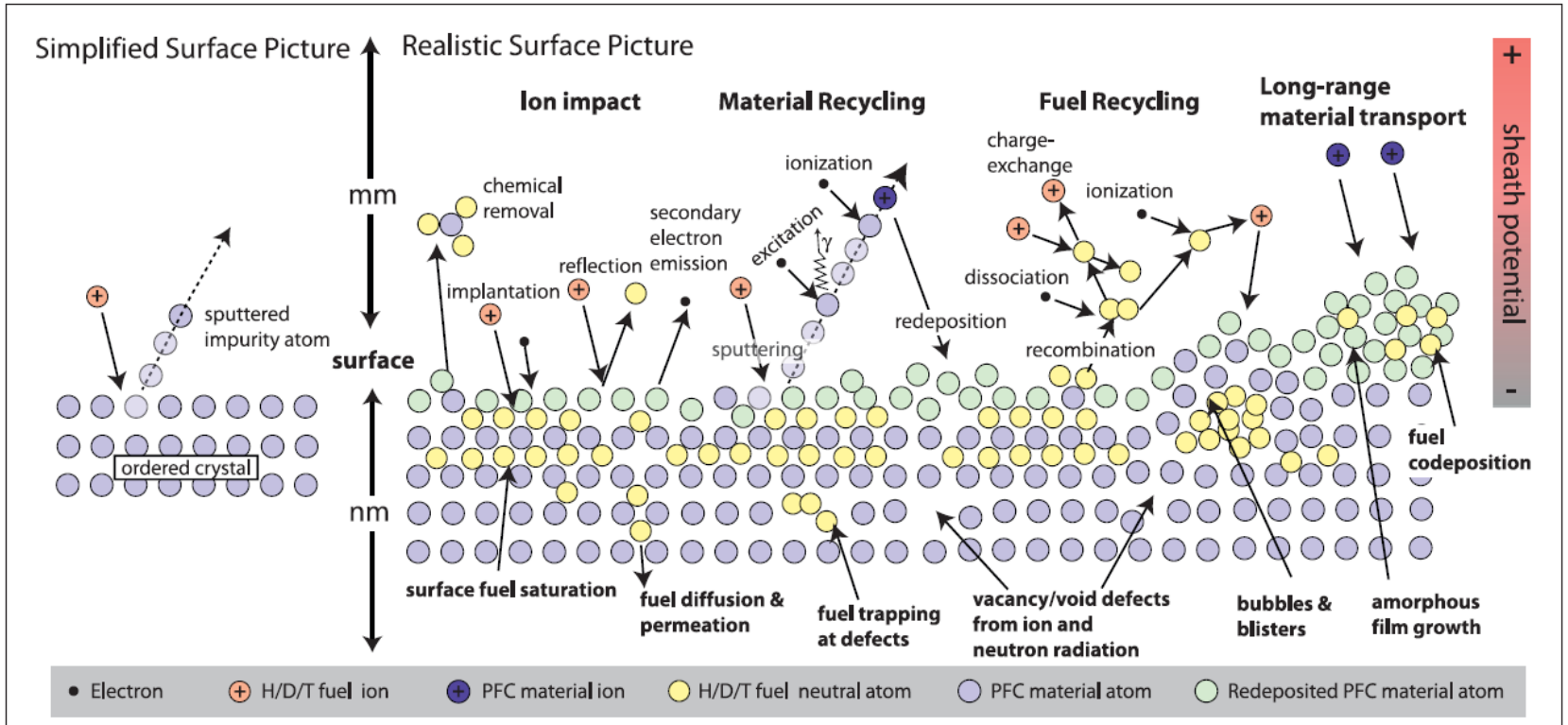


Figure from B.D Wirth, K. Nordlund, D.G. Whyte, and D. Xu, "Fusion materials modeling: challenges and opportunities," *MRS Bulletin*, Vol. 36, pp. 216-222, 2011.

Examples of intermediate structure (1)

- Water cooling
  - Monoblock with twisted tape
  - Hypervapotron

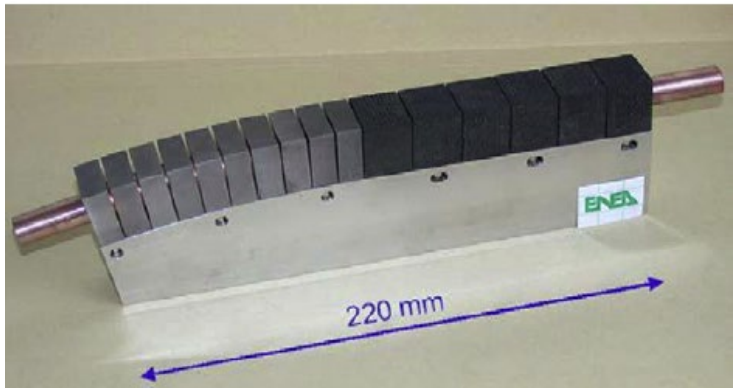


Figure from A.R. Raffray, et al, “High heat flux components—Readiness to proceed from near term fusion systems to power plants,” *Fusion Engineering and Design*, Vol. 85, pp. 93-108, 2010.

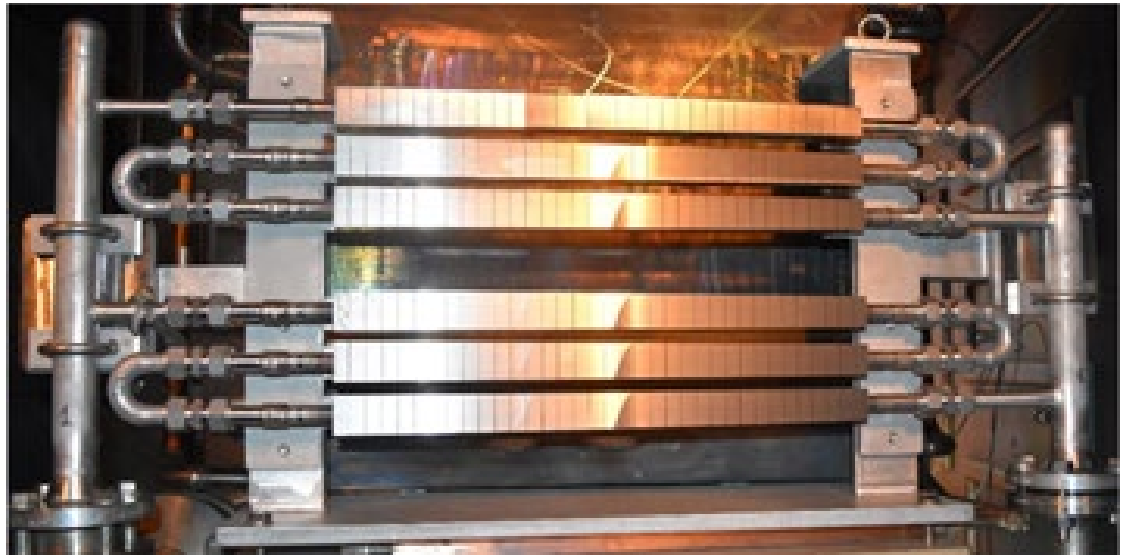


Figure from M. Richou, et al, “Acceptance tests of the industrial series manufacturing of WEST ITER-like tungsten actively cooled divertor,” *Physica Scripta*, Vol. 96, 2021.

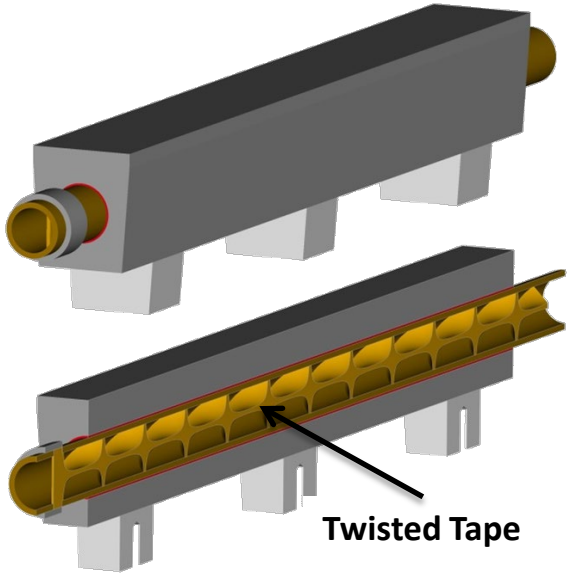


Figure from A. Lumsdaine, et al, “Modeling and Analysis of the W7-X Divertor Scraper Element,” *IEEE Transactions on Plasma Science*, Vol. 42, pp. 545-551, 2014.

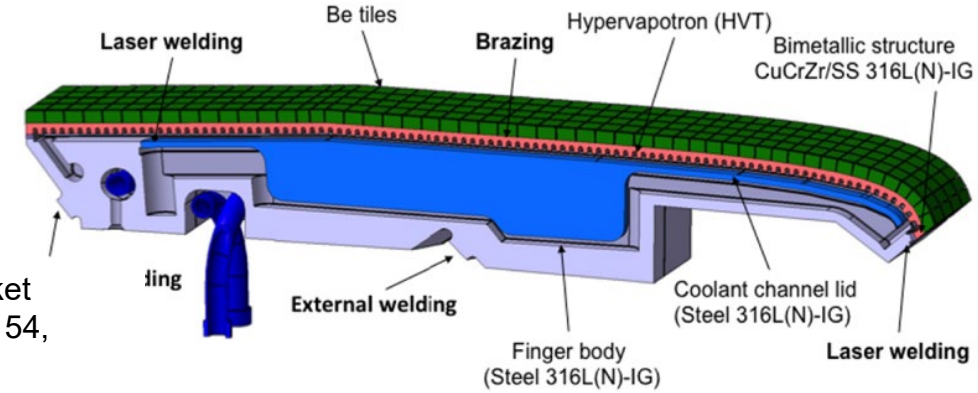


Figure from A.R. Raffray, et al, “The ITER blanket system design challenge,” *Nuclear Fusion*, Vol. 54, 2014.

Examples of intermediate structure (2)

- Helium cooling
  - Modular finger arrays (HEMS, HEMP, HEMJ)
  - T-tube
  - Refractory foam

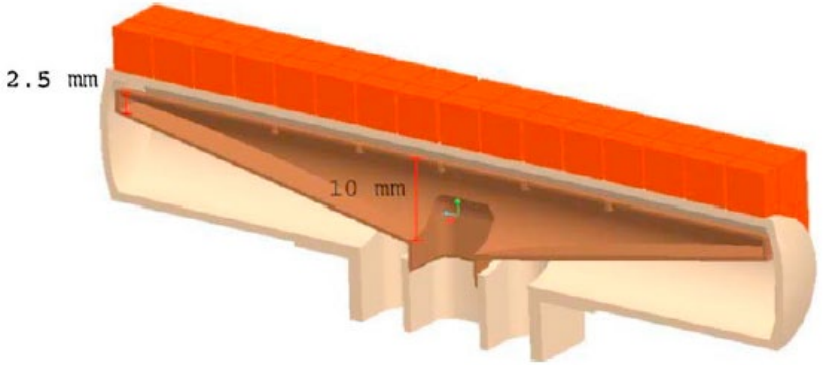


Figure from X.R. Wang, S. Malang, M.S. Tillack, J. Burke, "The ARIES team, recent improvements of the helium-cooled W-based divertor for fusion power plants," *Fusion Engineering and Design*, Vo. 87, pp. 732-736, August 2012.

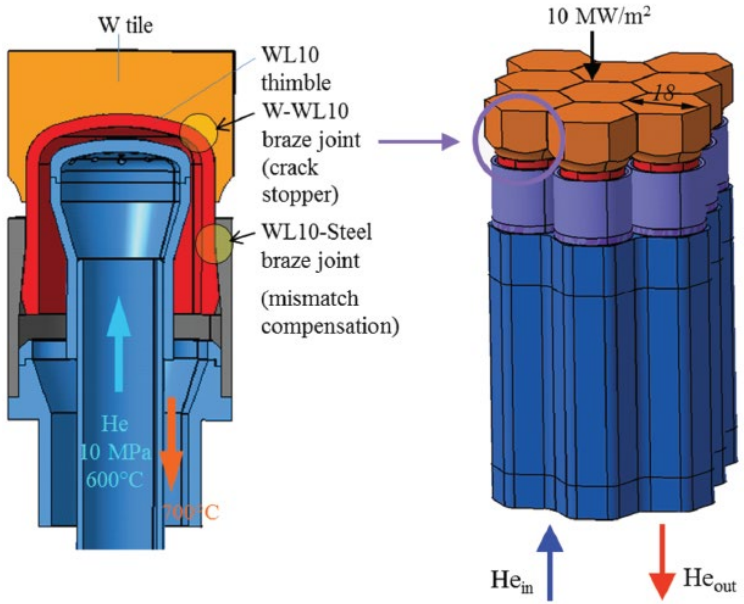


Figure from P. Norajitra, W.W. Basuki, R. Giniyatulin, C. Hernandez, V. Kuznetsov, I. V. Mazoul, M. Richou, L. Spatafora, "Recent progress in the development of helium-cooled divertor for demo," *Fusion Science and Technology*, in press, 2015.

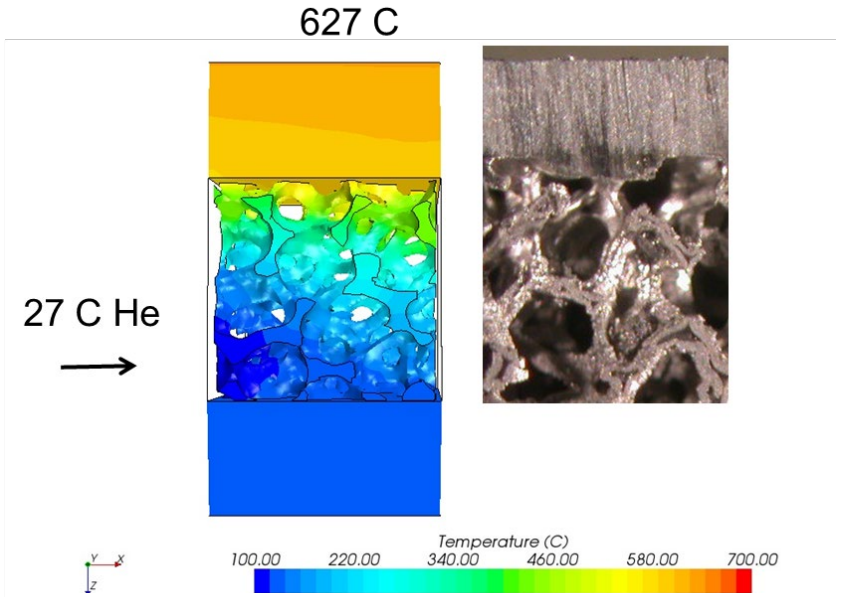
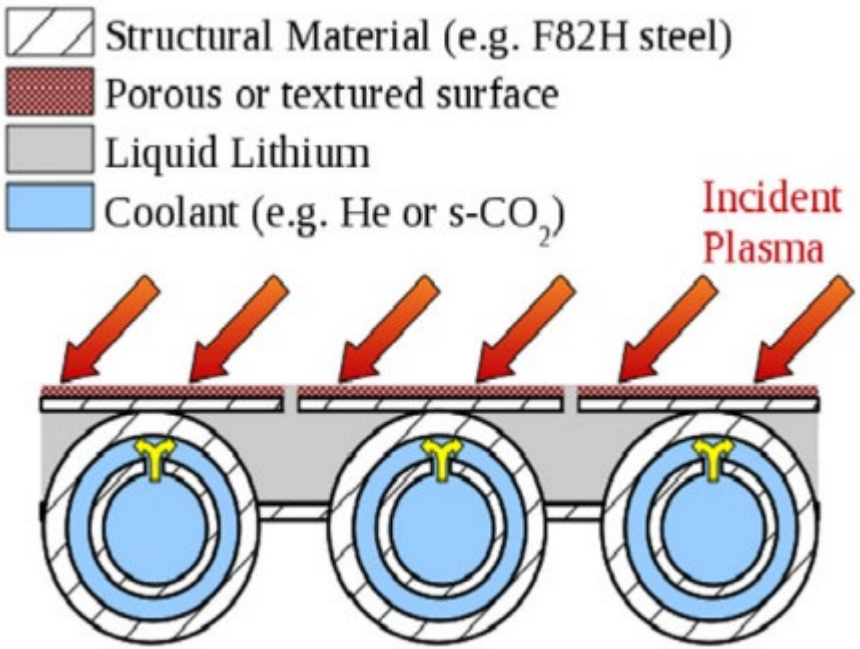


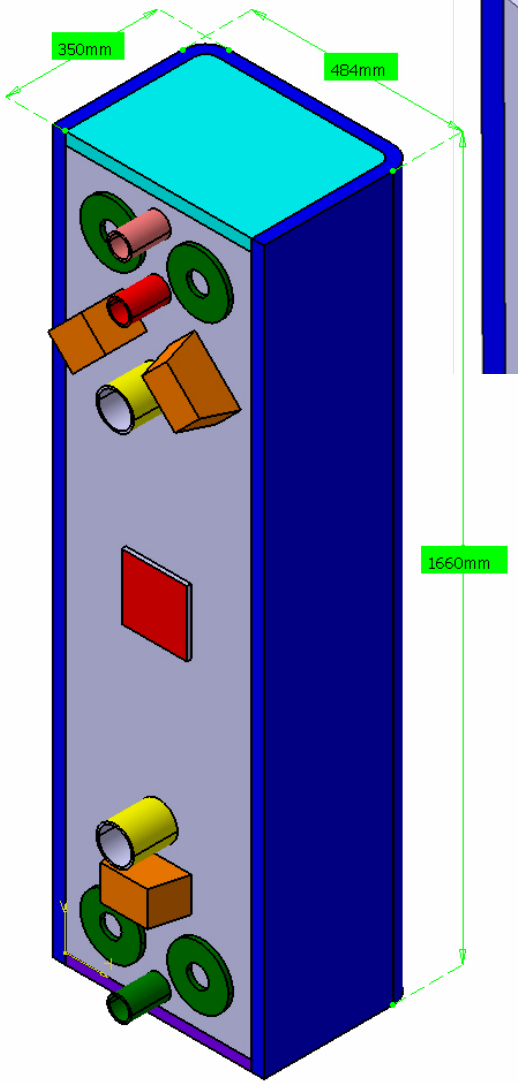
Figure from D. L. Youchison, J. M. Garde, "Thermo-mechanical evaluation of high-temperature refractory foams used in thermal management systems," *Fusion Science and Technology*, Vol. 61, No. 1T, pp. 322-328, January 2012.

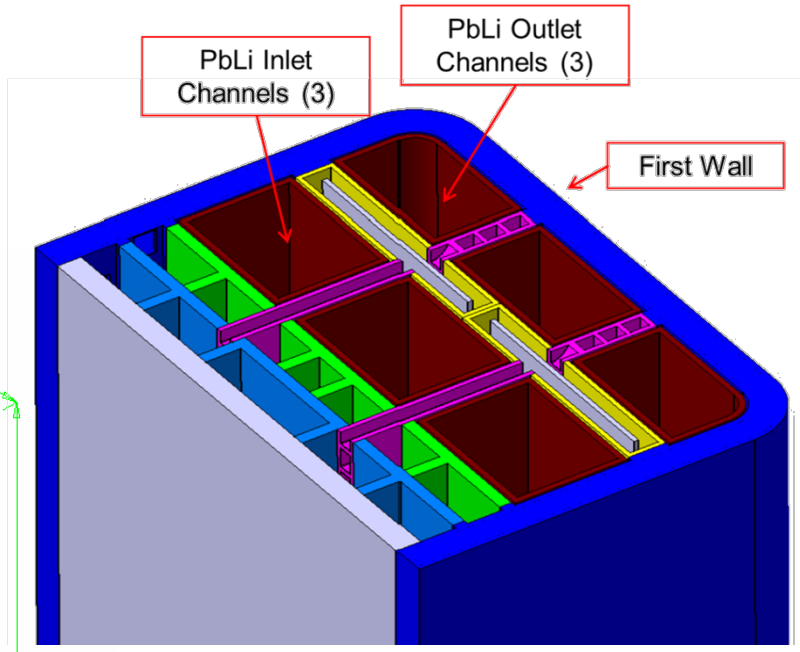
Examples of intermediate structure (3)

- Liquid metal cooling



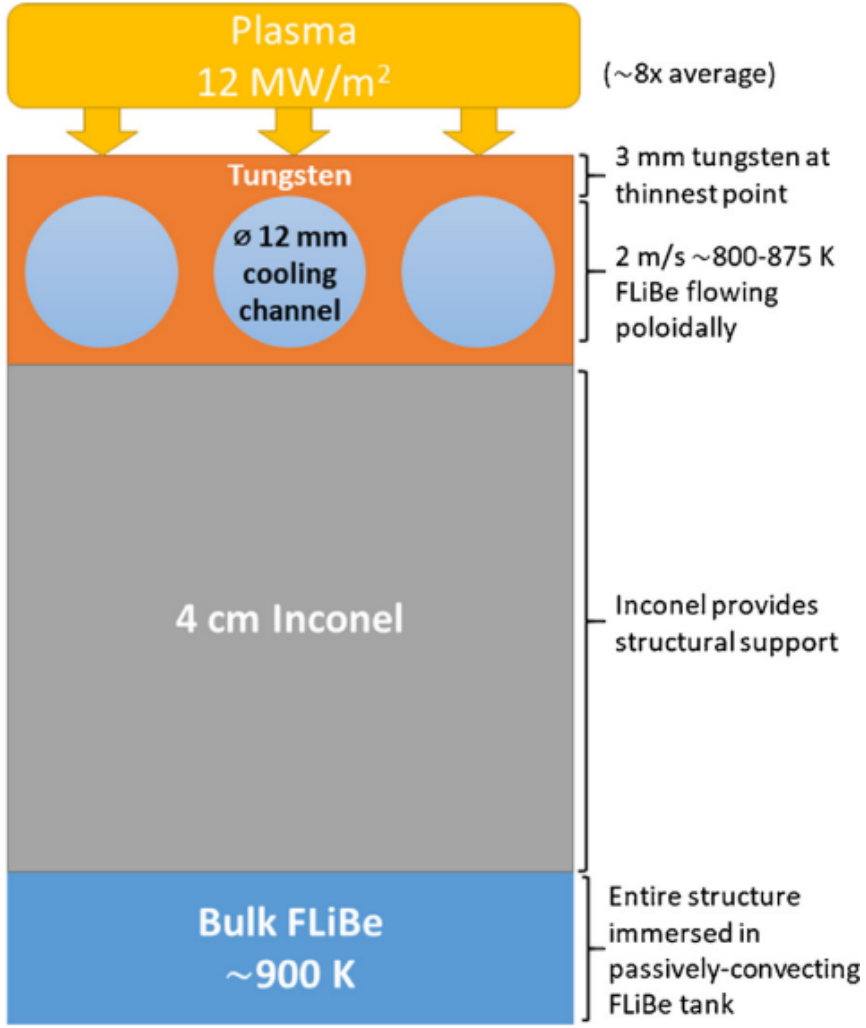
From M A Jaworski, A Khodak and R Kaita, “Liquid-metal plasma-facing component research on the National Spherical Torus Experiment,”, *Plasma Phys. Control. Fusion*, Vol. 55, 2013.



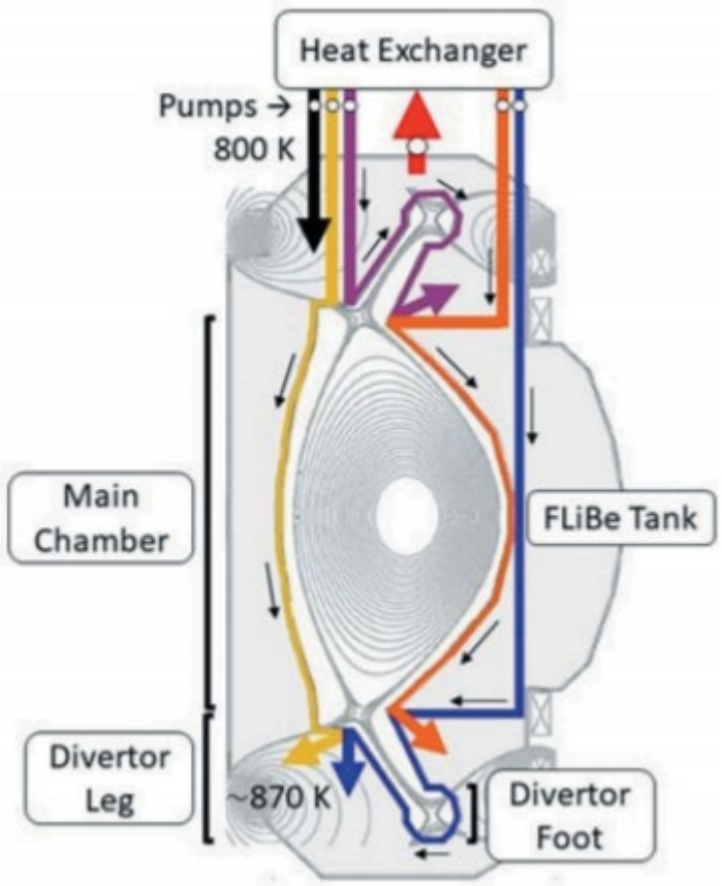


Examples of intermediate structure (4)

- Molten salt cooling



From A.Q. Kuang, et al, "Conceptual Design Study for Heat Exhaust Management in the ARC Fusion Pilot Plant," *Fusion Engineering and Design*, Vol. 137, pp. 221-242, 2018.



From C. Forsberg, G. Zheng, R. G. Ballinger, S. T. Lam, "Fusion Blankets and Fluoride-Salt-Cooled High-Temperature Reactors with Flibe Salt Coolant: Common Challenges, Tritium Control, and Opportunities for Synergistic Development Strategies Between Fission, Fusion, and Solar Salt Technologies," *Nuclear Technology*, Vol. 206, 2019.

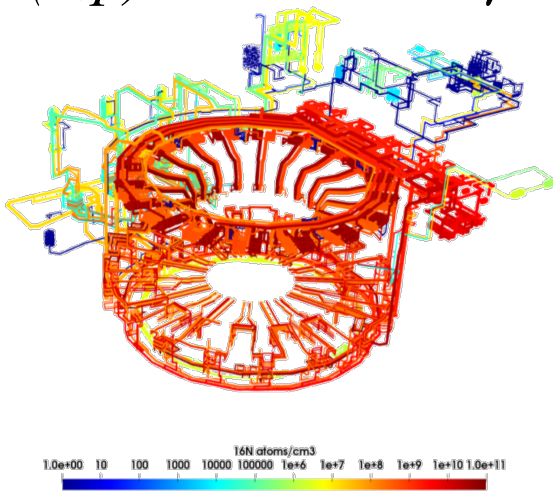
Considerations of operation time and conditions

- Short pulse operation
  - Plasma interacts “weakly” with plasma facing surface only
  - Anything behind first few microns is invisible to plasma
- Long pulse operation
  - Plasma interacts strongly with plasma facing surface
  - Plasma influenced by entire PFC
- Long pulse nuclear operation
  - Plasma interacts strongly with plasma facing surface
  - Full and continuous interaction with entire PFC

ITER Radiation Maps during operations at 500MW

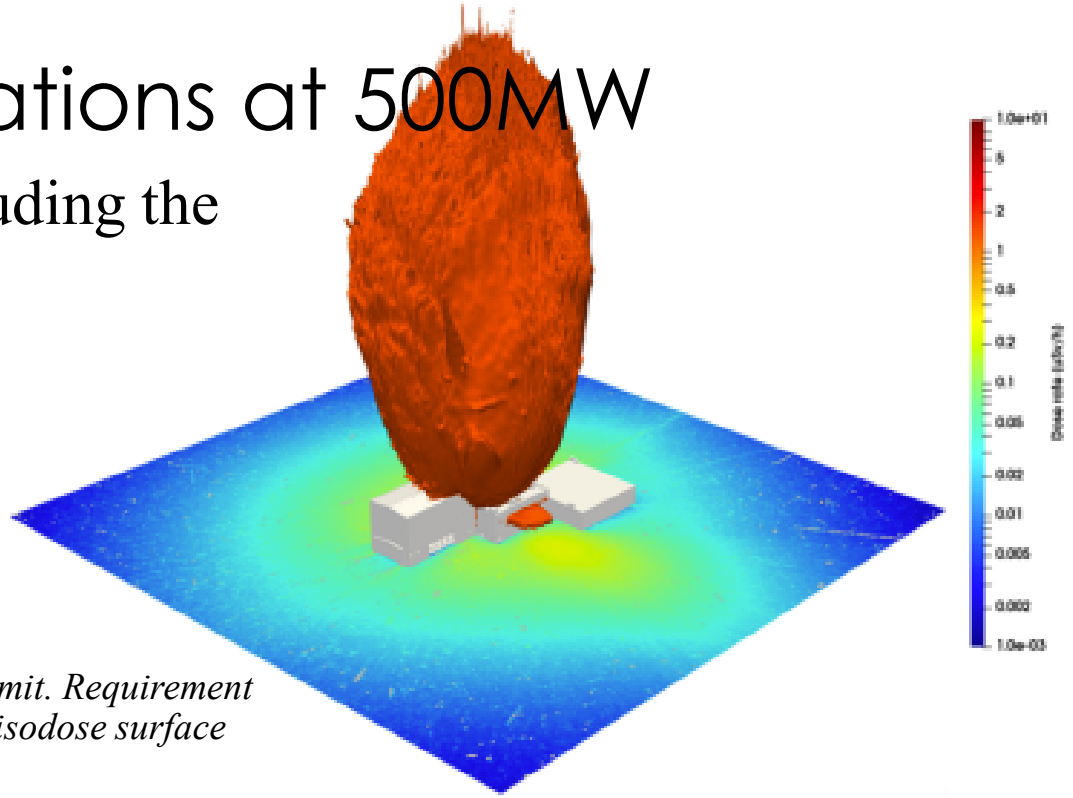
The plasma interacts with every part of the PFC (including the coolant). The water is activated.

$$^{16}O(n,p)^{16}N \rightarrow 6MeV\ \gamma\text{-}ray\ (T_{1/2}=7.13\ sec.)$$



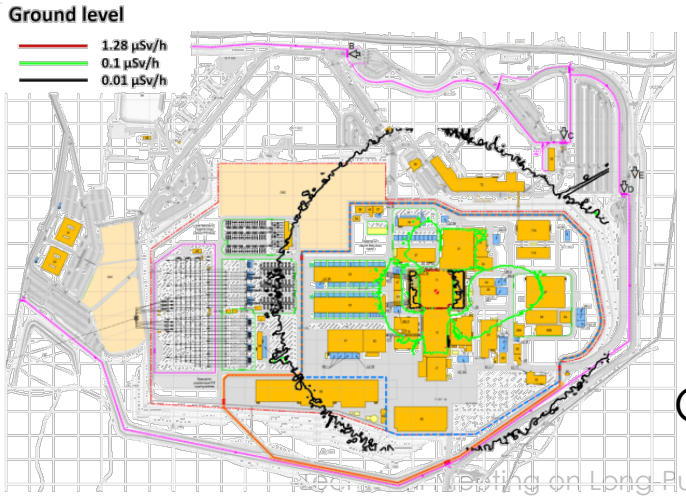
γ-ray source is distributed throughout the building.

Data produced by UNED, Spain under ITER contract 43-2108.



Isodose surface at limit. Requirement is met outside red isodose surface

Radiation field extends outside the building. Shielding is designed to ensure radiation protection requirements are met.



Dose at ground level

Courtesy of Michael Loughlin

Plasma Facing Surface Challenges

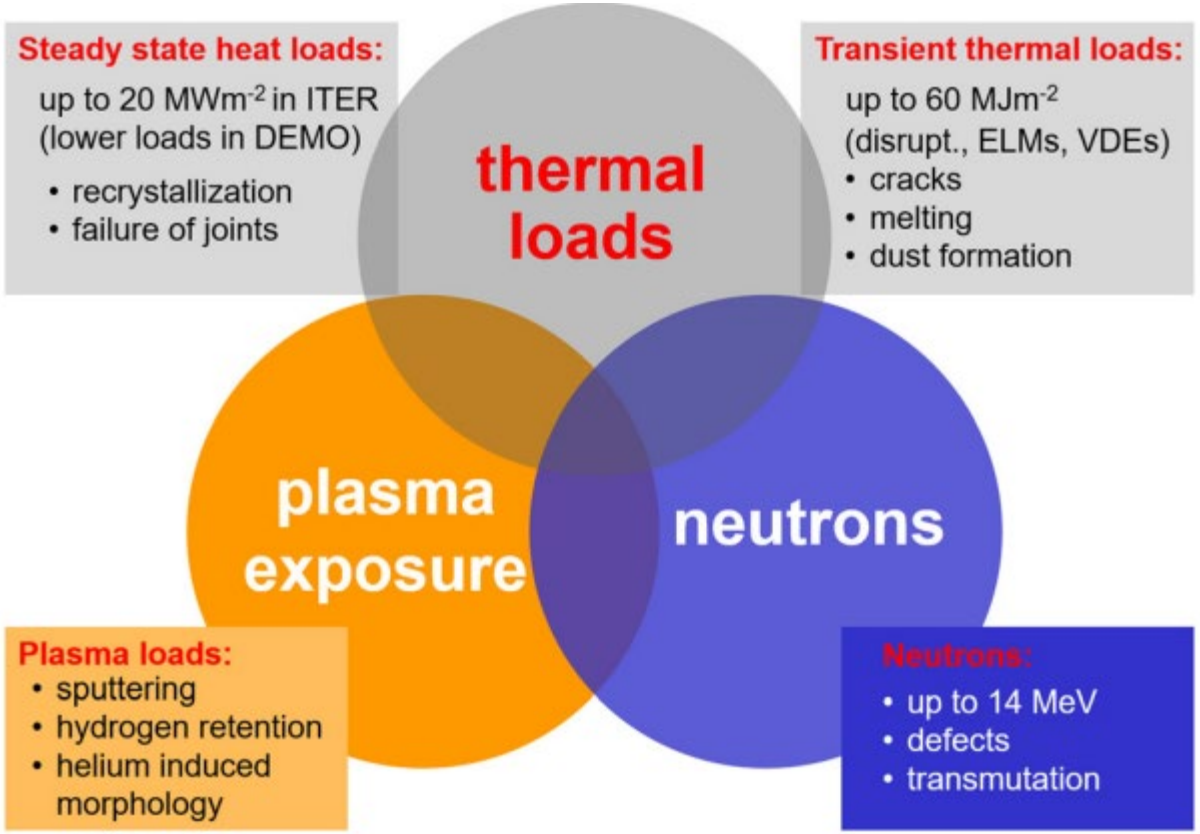
Inherent

- High temperature (property window)
- High heat-flux (thermal conductivity)
- Thermal shock (TS resistance)
- Tritium retention (inventory)
- Erosion / redeposition (property changes)
- Plasma contamination (sputtering, etc.)
- Neutron damage (property changes, swelling, transmutation)
- Helium implantation (property changes)

Interfaces (coolant & thermal structure)

- High pressure / high stress
- Corrosion
- Neutron transmission
- Joining (to heat sink, TE mismatch, thermal resistance, gas retention)
- Heat removal

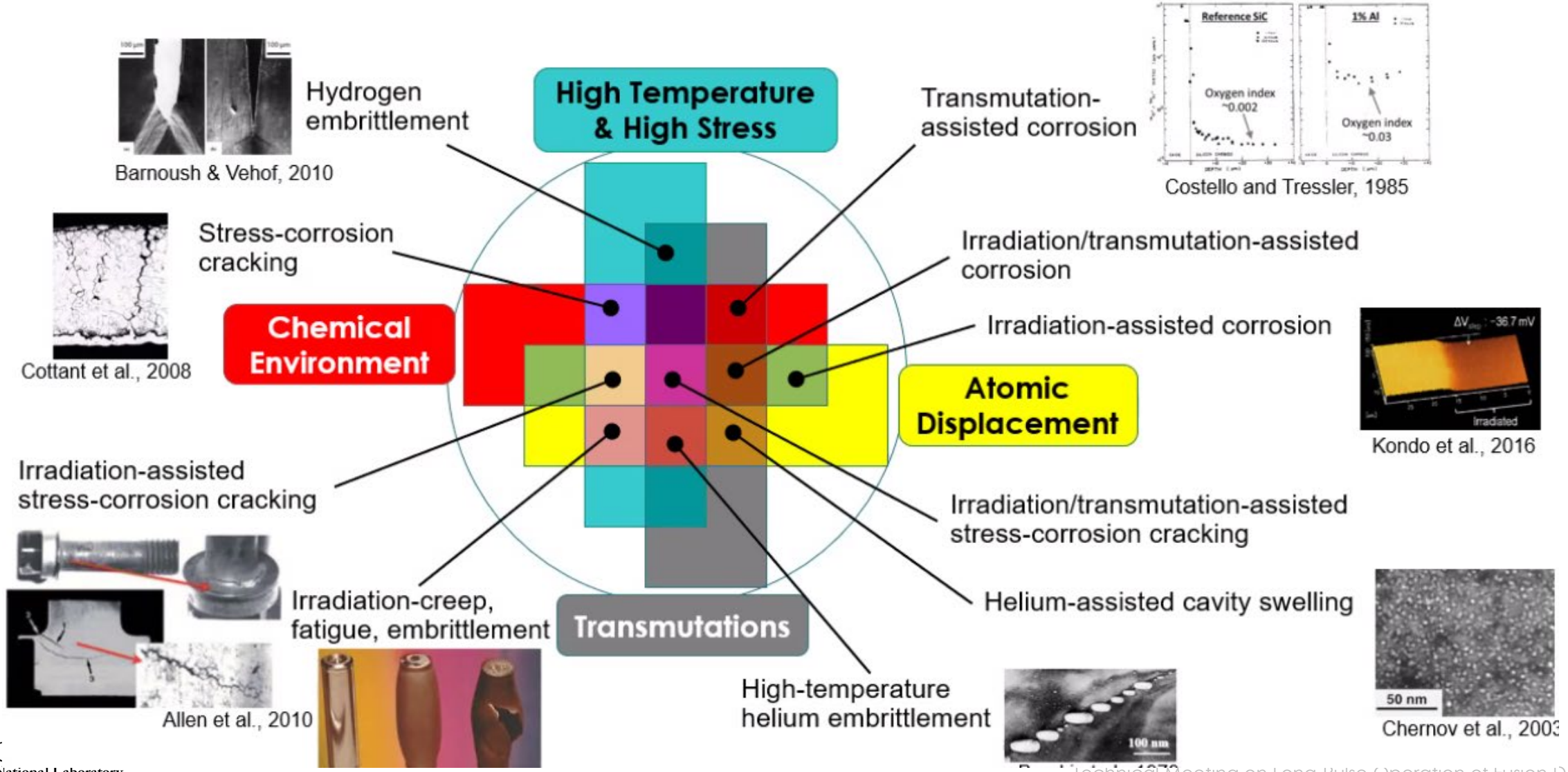
Plasma Facing Surface Considerations (from Linke)



From Linke, et al, *Matter and Radiation at Extremes* **4**, 056201, (2019); https://doi.org/10.1063/1.5090100

Plasma Facing Surface Considerations (from Katoh)

Our challenges are complex multiple-extremes



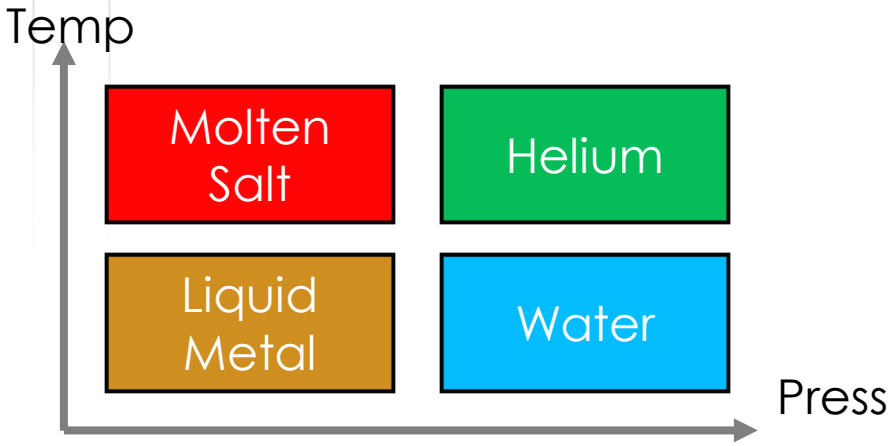
Coolant Challenges

Inherent

- High temperature
- Pressure / pumping power
- Tritium retention
- Neutron damage / transmutation
- EM interaction
- Heat removal (thermal conductivity, heat capacity)

Interfaces (PFM & thermal structure)

- High pressure / high stress
- Corrosion
- Neutron transmission
- Tritium breeding / extraction
- Power generation efficiency



Intermediate Thermal Structure Challenges

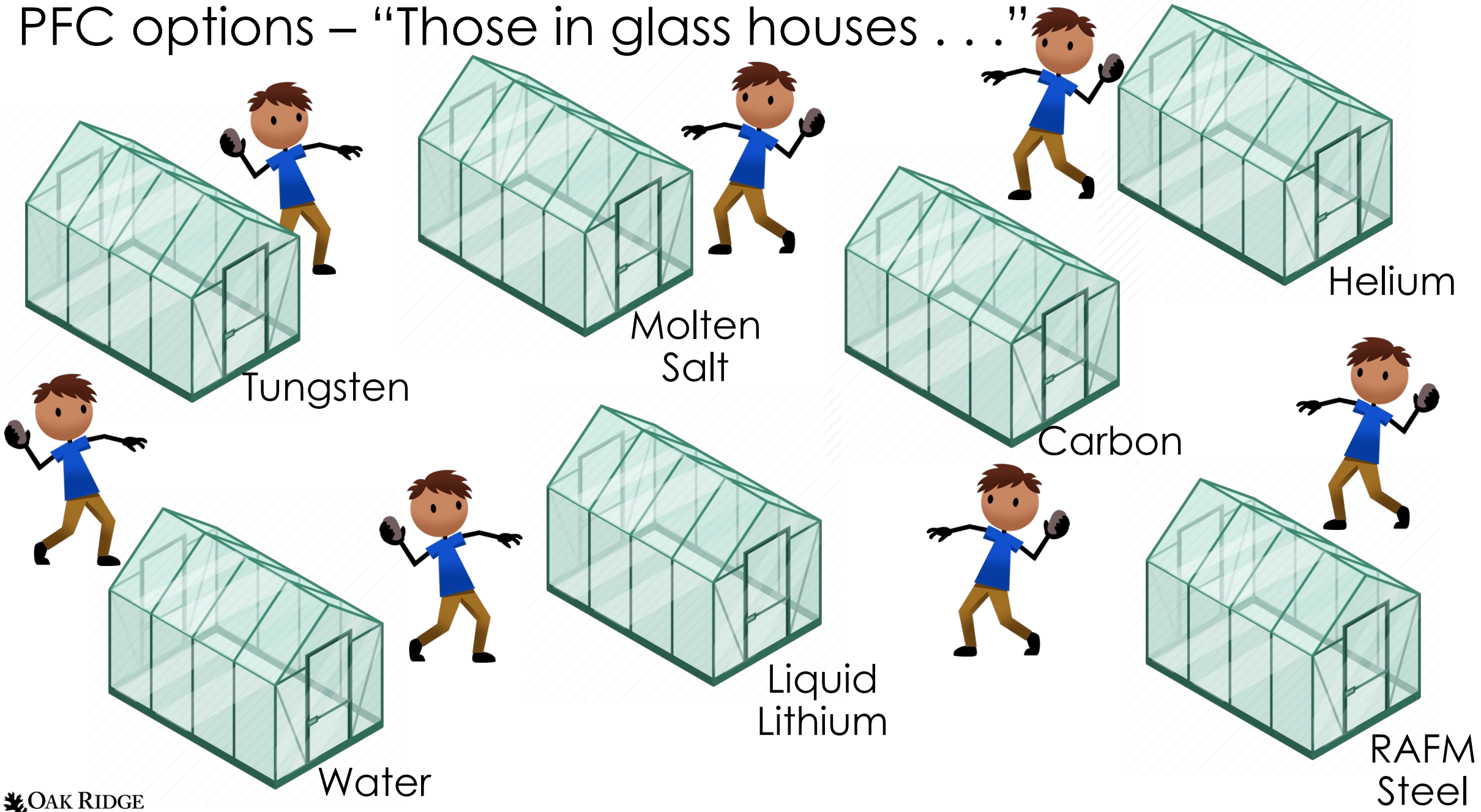
Inherent

- High temperature
- High thermal gradient
- Topology
- Neutron damage (property changes, swelling, transmutation)

Interfaces (PFM & coolant)

- High pressure / high stress
- Corrosion
- Joining (to plasma facing material)
- Neutron transmission
- Fluid interaction
- Heat removal

PFC options – "Those in glass houses . . ."



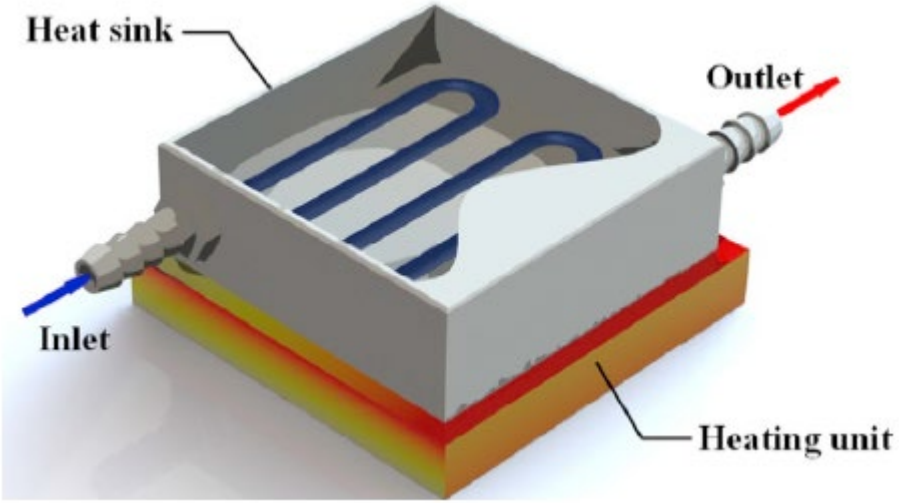
Some questions

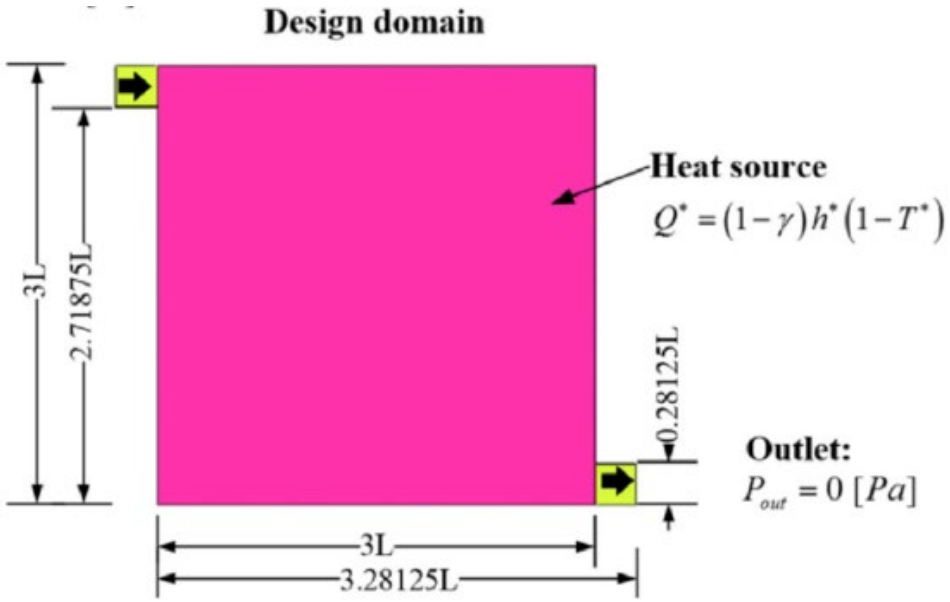
- What heat fluxes can we handle (how high can we go)?
  - Dependent on material options, coolant, joining tech, topology
  - R&D necessary – can we develop guidelines?
- How can we robustly join dissimilar materials?
- Can we examine these "components" individually, or is an integrated PFC program necessary?
- "Is there a viable divertor & first wall PFC solution for DEMO/FSNF?" (or FPP – show stopper)

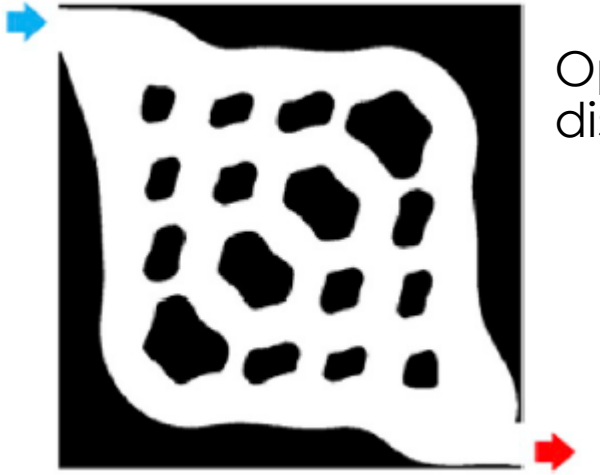
S.J. Zinkle, A. Möslang, T. Muroga and H. Tanigawa, Nucl. Fusion 53 (2013) 104024

- Are there tools for designing better PFC's?

Heat sink topology design





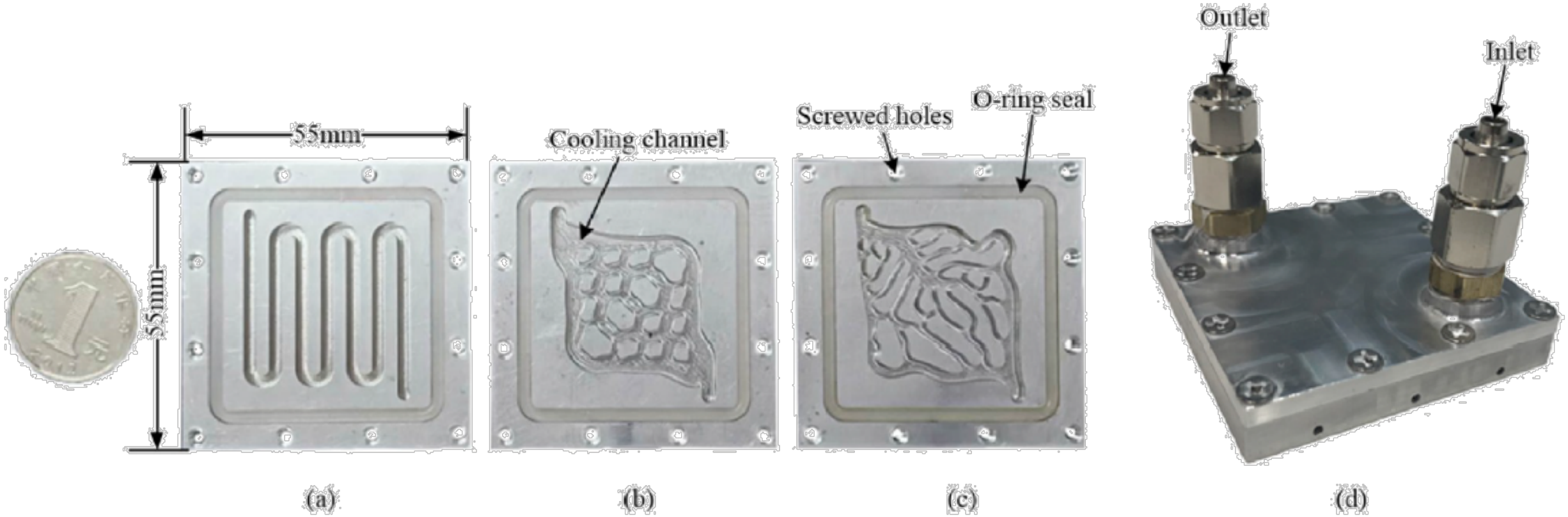


Optimal flow distribution

Maximum heat transfer

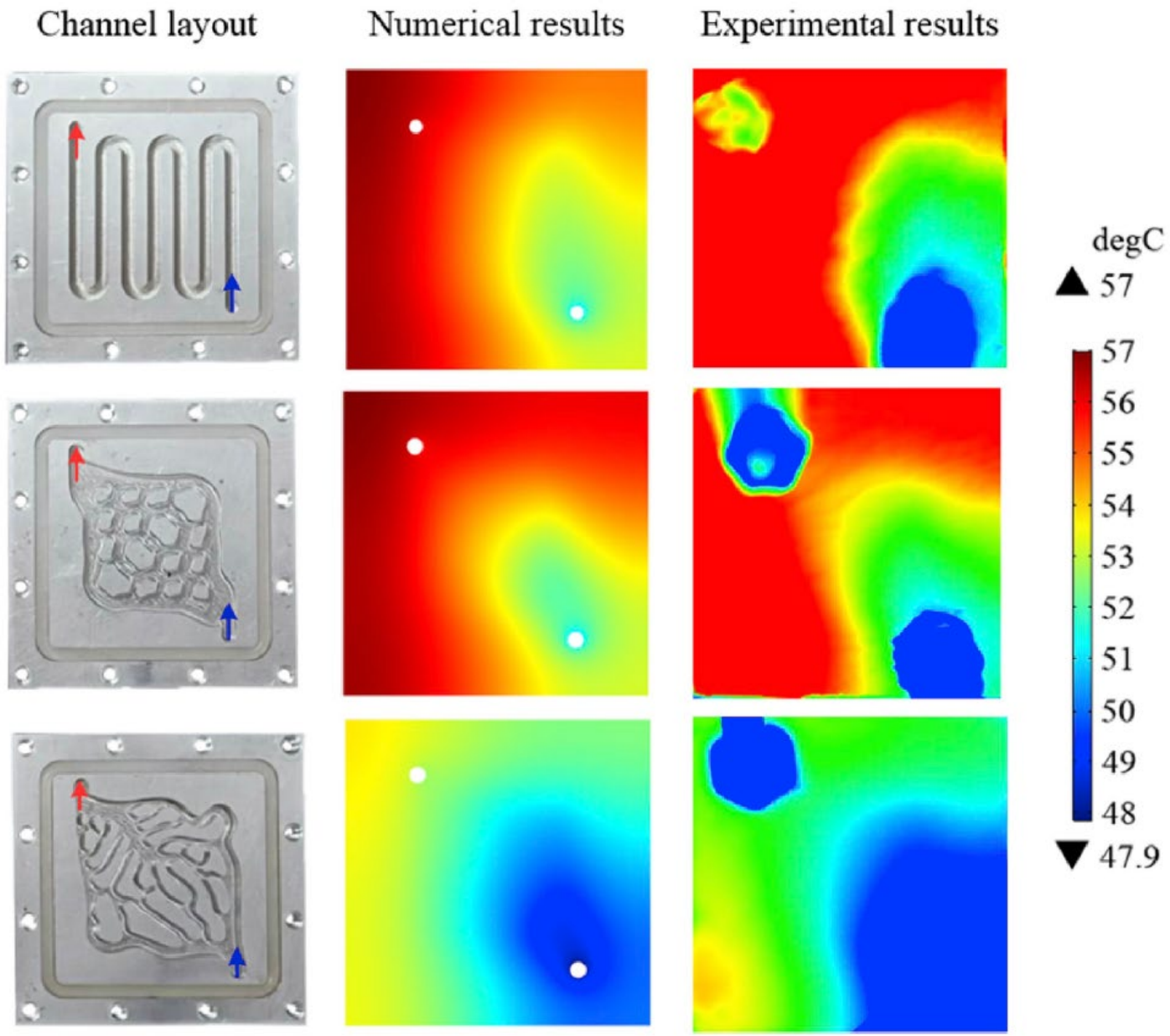
Figures from H. Li, X. Ding, D. Jing, M. Xiong, F. Meng, "Experimental and numerical investigation of liquid-cooled heat sinks designed by topology optimization," *International Journal Thermal Sciences*, Vol. 146, 2019.

Heat sink test

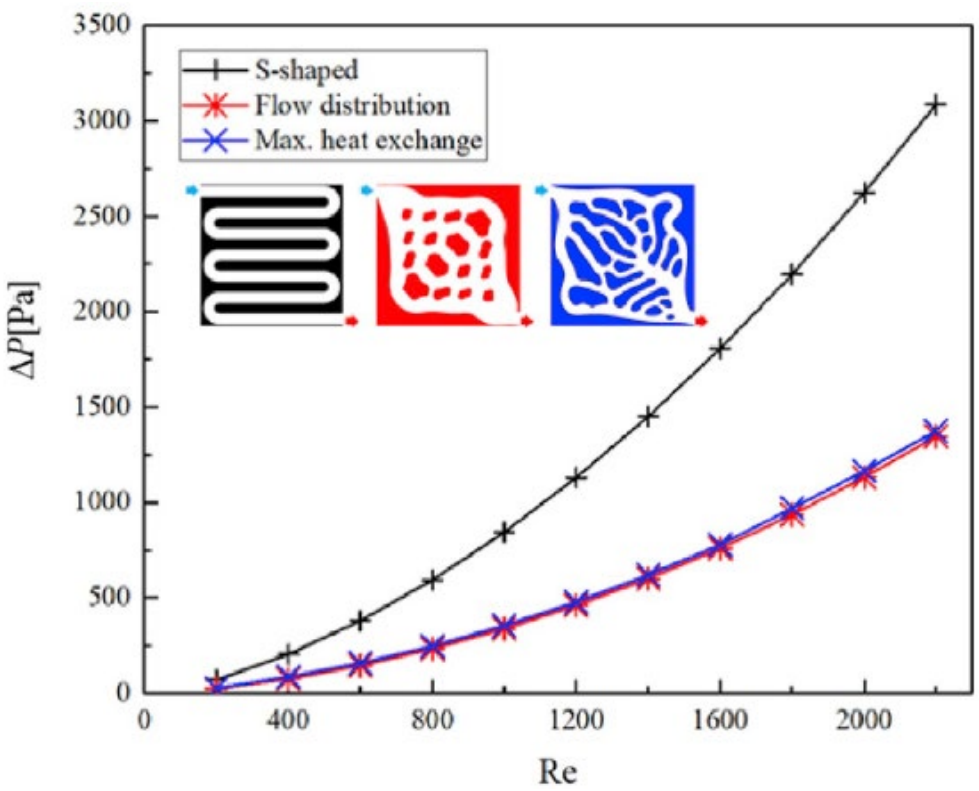


Figures from H. Li, X. Ding, D. Jing, M. Xiong, F. Meng, “Experimental and numerical investigation of liquid-cooled heat sinks designed by topology optimization,” *International Journal Thermal Sciences*, Vol. 146, 2019.

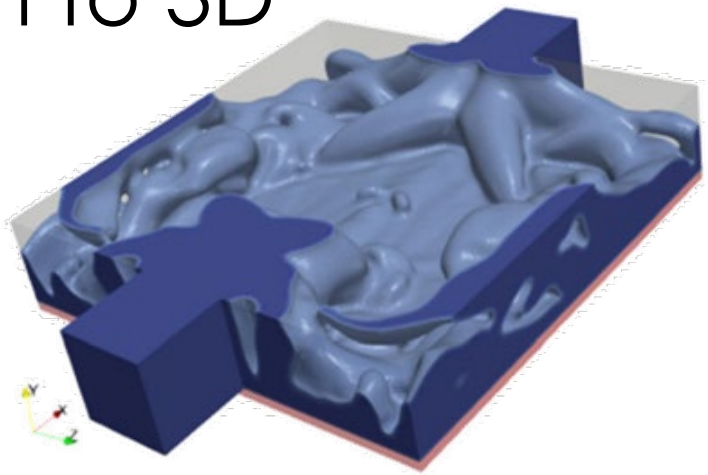
Comparison of results

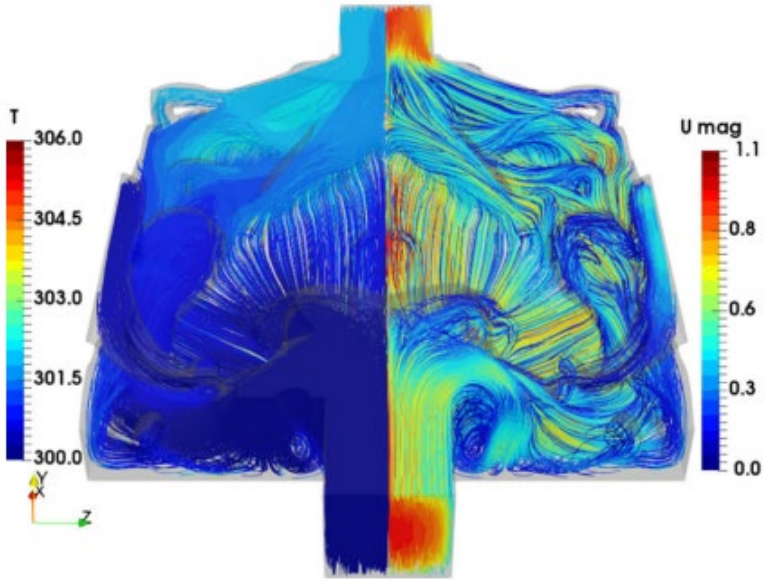


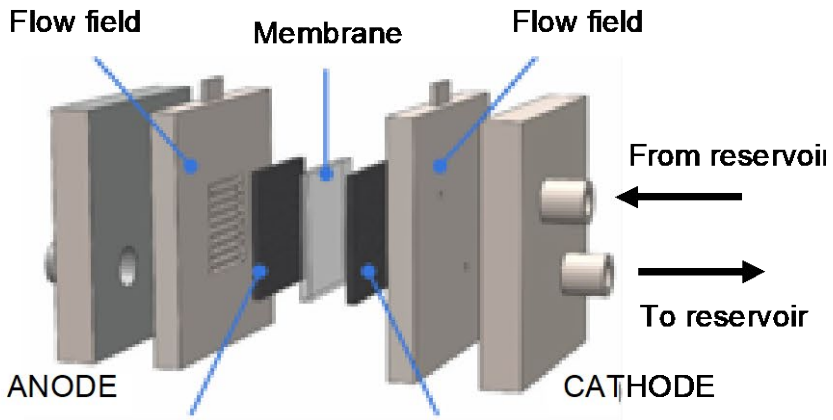
q" = 17 kW/m^2



Extension to 3D

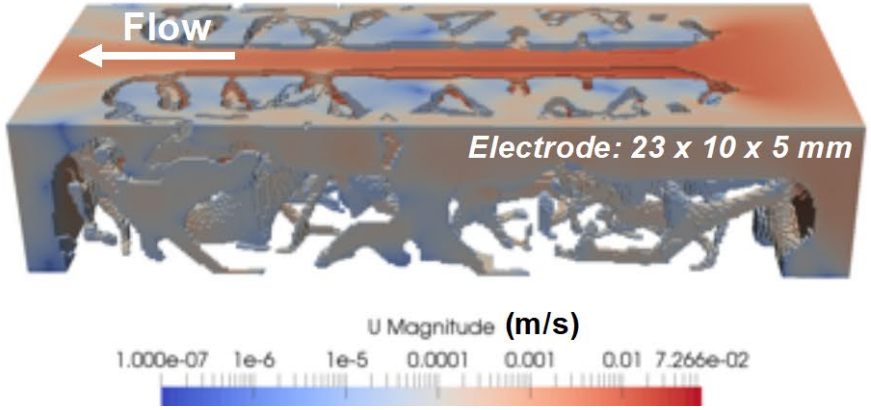






Porous electrode

Fluid region



Figures from S. B. Dilgen, C. B. Dilgen, D. R. Fuhrman, O. Sigmund, B. S. Lazarov, "Density based topology optimization of turbulent flow heat transfer systems," *Structural and Multidisciplinary Optimization*, Vol. 57, pp. 1905–1918, 2018.

Summary and Conclusions

- Functioning PFC solutions are essential for long pulse devices and any fusion pilot plant.
- We have very few validated solutions for long-pulse devices, and even these solutions cannot work for a fusion pilot plant.
  - Most first step fusion power devices do not plan to have reactor relevant PFCs
- Reactor relevant PFC will likely be multi-material, complex topology components.
- Integrated R&D and implementation on long pulse devices and test stands should be accelerated (proactively).
- All three aspects of PFCs – surface, coolant, intermediate thermal structure – need R&D, with integrated solutions.