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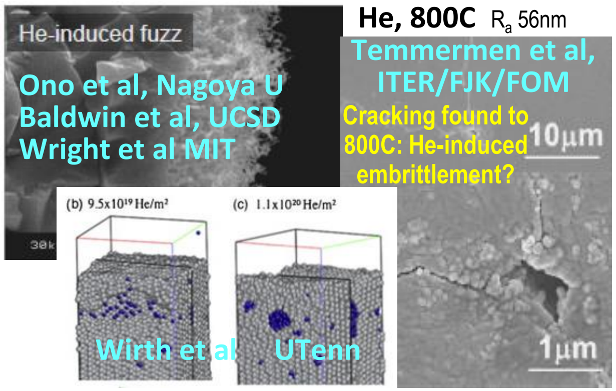

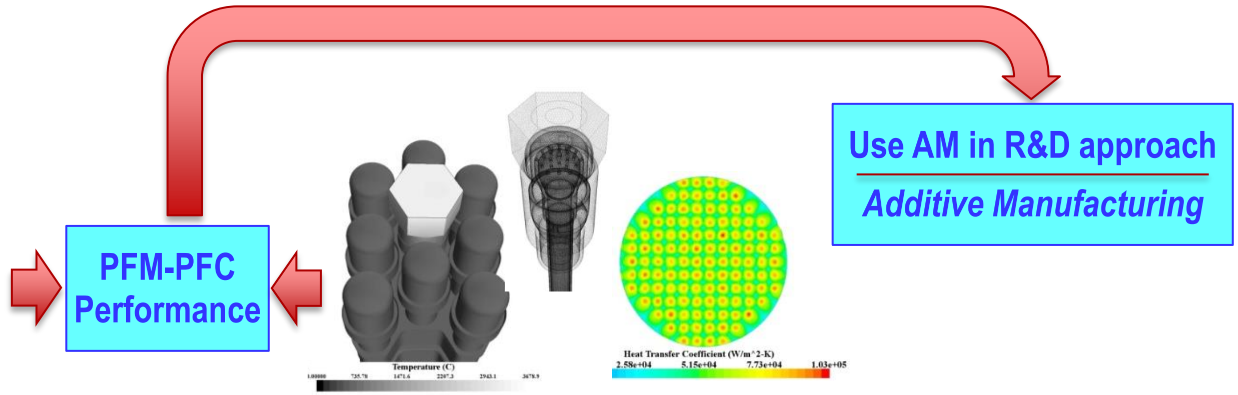

We see a growing understanding of materials issues with tungsten, greater computational capability in materials modeling and CFD and development of advanced manufacturing methods

A New Vision of Plasma Facing Components

Richard E. Nygren *Sandia National Laboratories*
Dennis L. Youchison *Sandia National Laboratories*
Brian D. Wirth *University of Tennessee - Knoxville*
Lance L. Snead *Massachusetts Institute of Technology*

JIAM JOINT INSTITUTE FOR ADVANCED MATERIALS
OAK RIDGE National Laboratory
THE UNIVERSITY of TENNESSEE KNOXVILLE

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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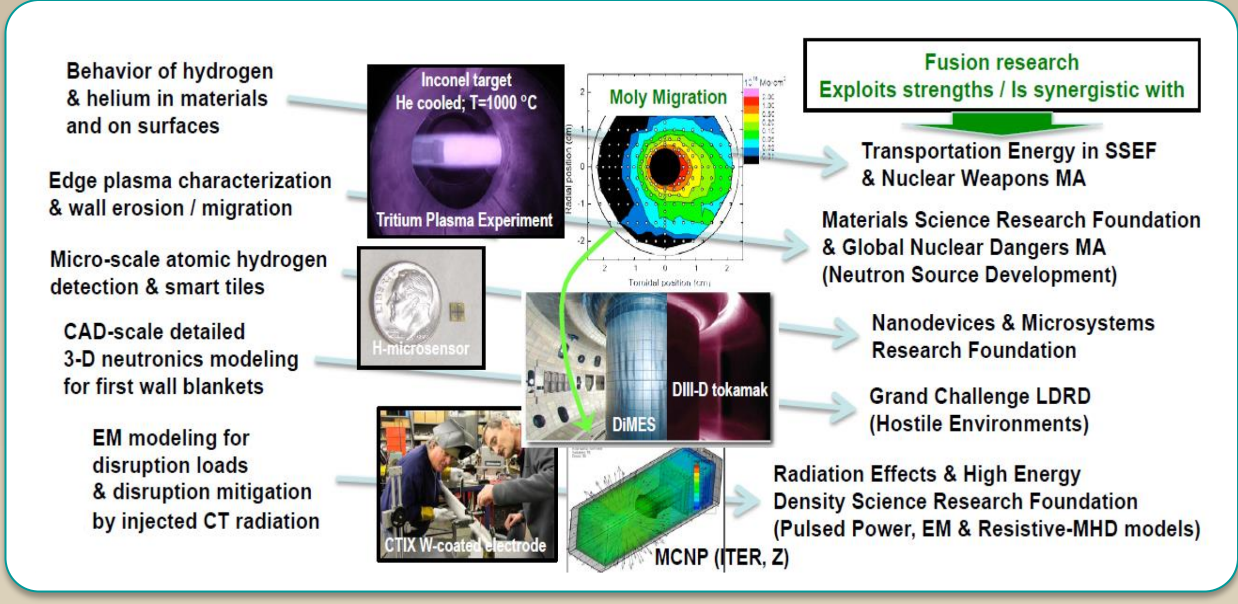
Outline

Introduction

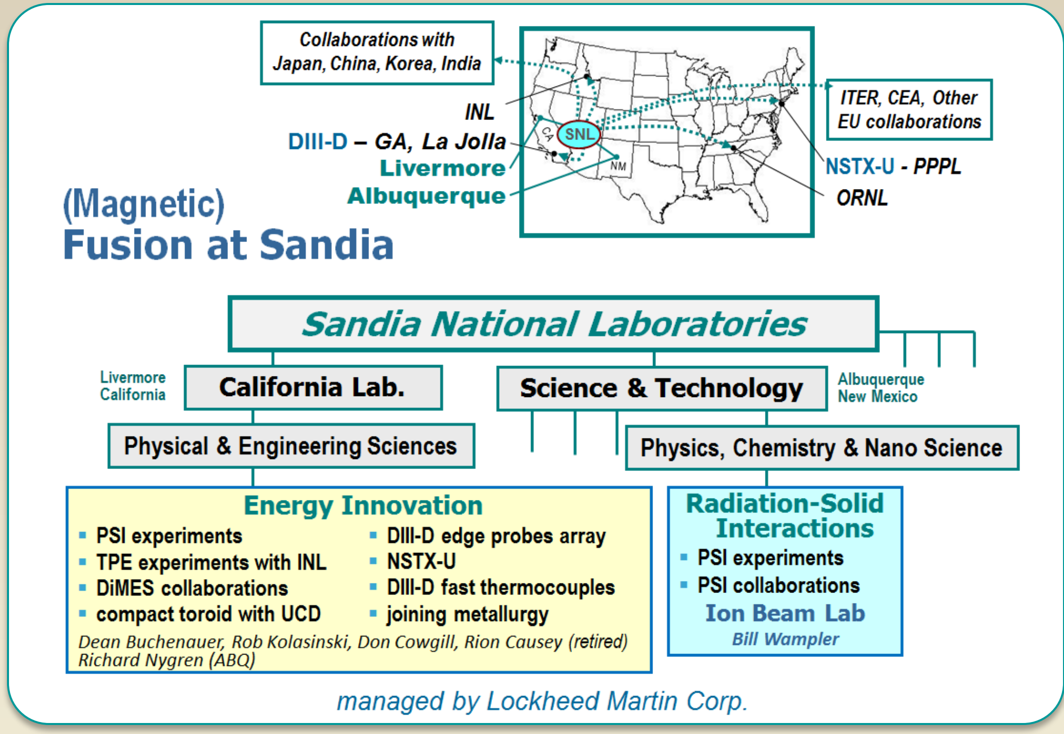
- **Sandia National Labs**
- **Magnetic fusion at Sandia**
  - alignment with US goals
  - leverage inside Sandia
  - strong collaborative efforts



Refractory (solid) PFCs

- Tungsten (W)
  - Damage and scale, He migration
  - Modeling and materials architecture
- Engineered PFCs
  - integrated structure
  - efficient gas cooling and scale
- Developing engineered PFCs
  - Advanced Manufacturing
  - Some examples in US

Closing Comments

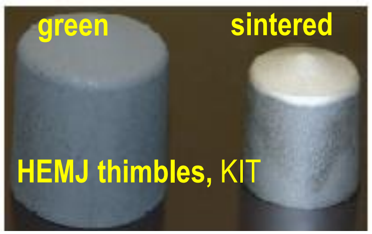


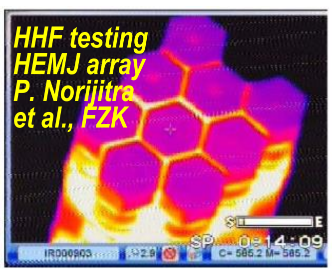
HEMJ is most developed He-cooled tungsten PFC

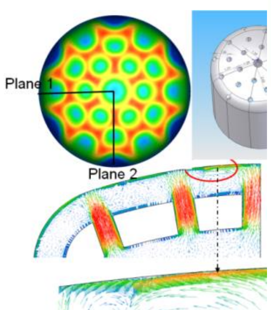
Coordinated materials development, fabrication and module testing

Praj 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 Sci. Tech., in press, 2015.

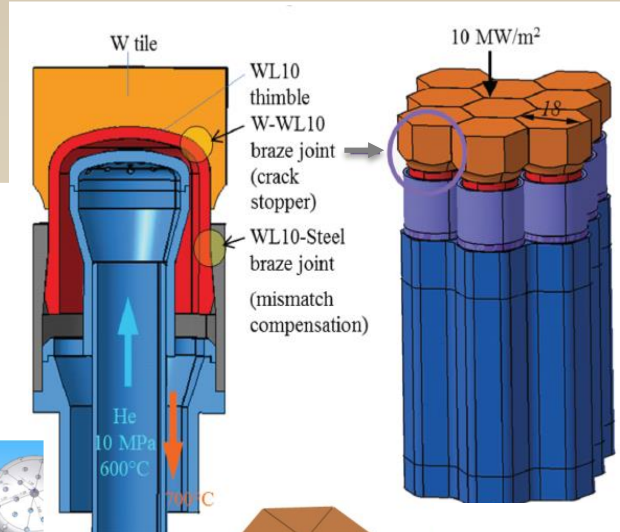
PIM application for mass production of He-cooled divertor parts, at ICFRM-14, S. Antuscha, P. Norajitraa, V. Piottera, H.-J. Ritzhaupt-Kleissla

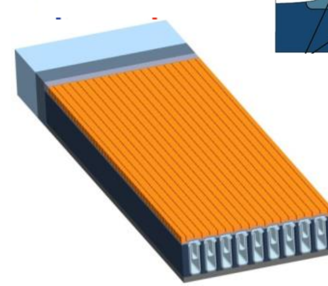




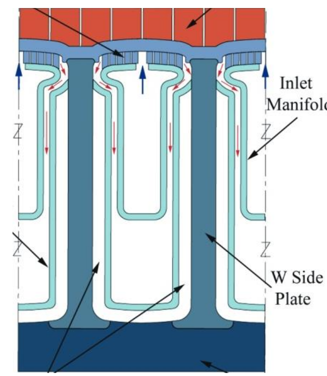


HEMJ CFD analysis
M. Narula, A. Ying, P. Norajitra, M. Abdou

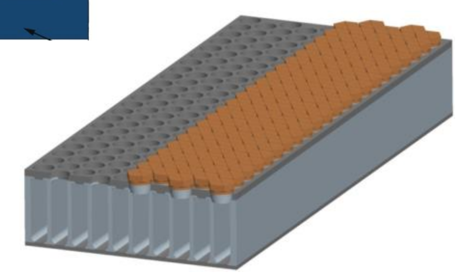




Optimizations of HEMJ ..., Wang 2015
M. Tillack, A. Raffray, X. Wang, S. Malang, S. Abdel-Khalik, M. Yoda, D. Youchison,.
... advanced He-cooled W-alloy divertor .. FED 2011



- large area arrays
- common manifolds
- easier assembly
- W/Ferritic for FW

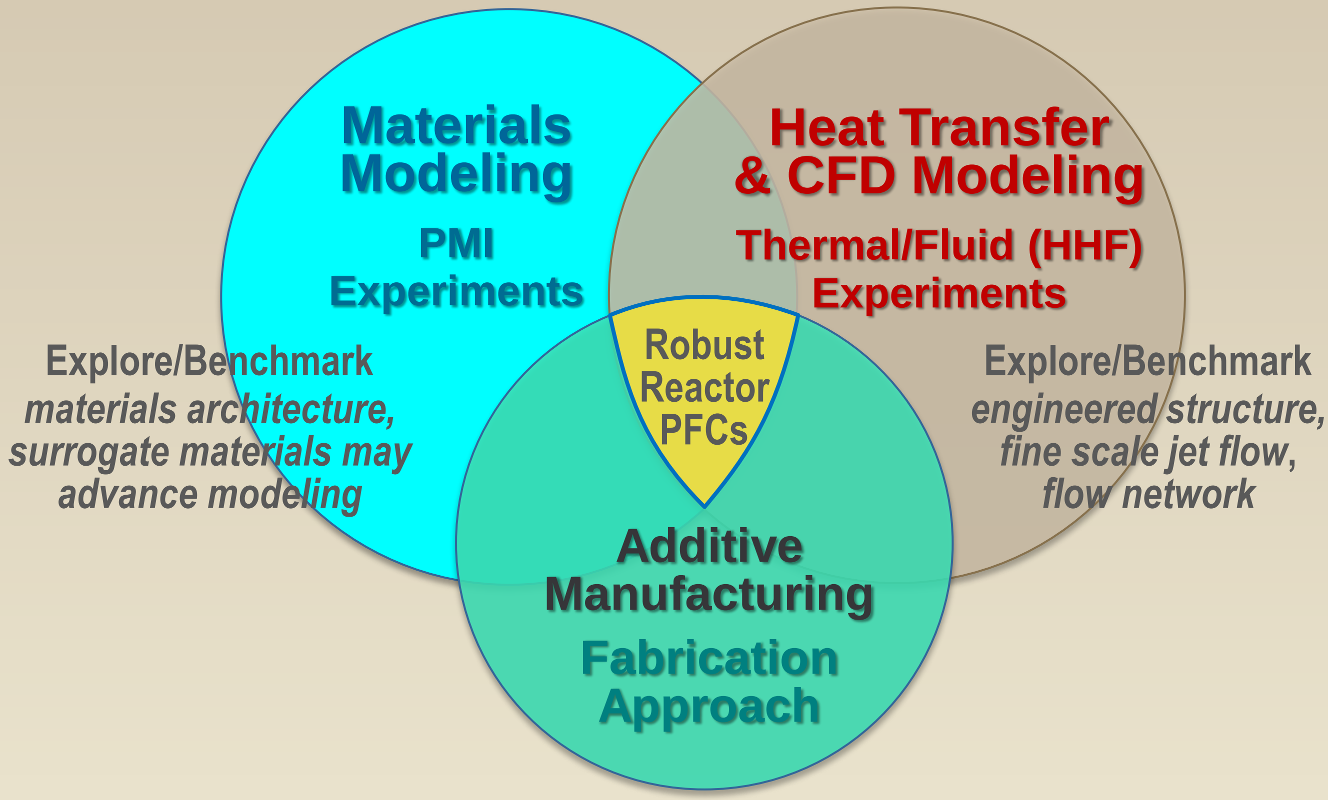


Jet flow cooling is effective, but we need a new approach to development.

A new vision for PFC development

PFM W solution:
overcome limitations of bulk W

PFC gas cooling solution:
change scale for optimal heat transfer



Explore/Benchmark
several advanced manufacturing processes may be helpful

A new vision for PFC development

PFM W solution: *overcome limitations of bulk W*

For Plasma Facing Materials (PFMs) for FNSF, *inherent limitations for bulk W and C are evident well before 30 dpa.*

- W transmutes to Re/Os. Re and radiation produced defect cluster embrittle W.
- **k_{rad}/k** (thermal conductivity) for W or C decreases.
- graphites swell and loose mechanical integrity.

Direction forward:

Develop materials architecture with insights from modeling coordinated with experiments on ion-damaged W-based engineered materials.

Enable migration of He and transmutation products to benign sites. Mitigate tritium permeation. Maintain adequate robustness for a satisfactory lifetime.

PFC gas cooling solution: *change scale for optimal heat transfer*

High efficiency heat transfer occurs and thermal stresses are minimized when the arrays of flow jets are small enough to defeat excessive turbulence where the flows from adjacent jets meet.

Develop engineered structures with complex flow distribution for divertors and integrated FW-blanket modules.

Direction forward:

Exploit available technology. Arrays of tiny (100-500 µm dia.) micro-jets are prevalent in electronics and typically use low pressure air to cool steel or copper.

Arrays with many hundreds of jets are fabricated using MEMS technology such as lithography combined with additive manufacturing.

Refractory Solid PFCS: PFM W solution
What does materials modeling tell us?

Sandia National Laboratories

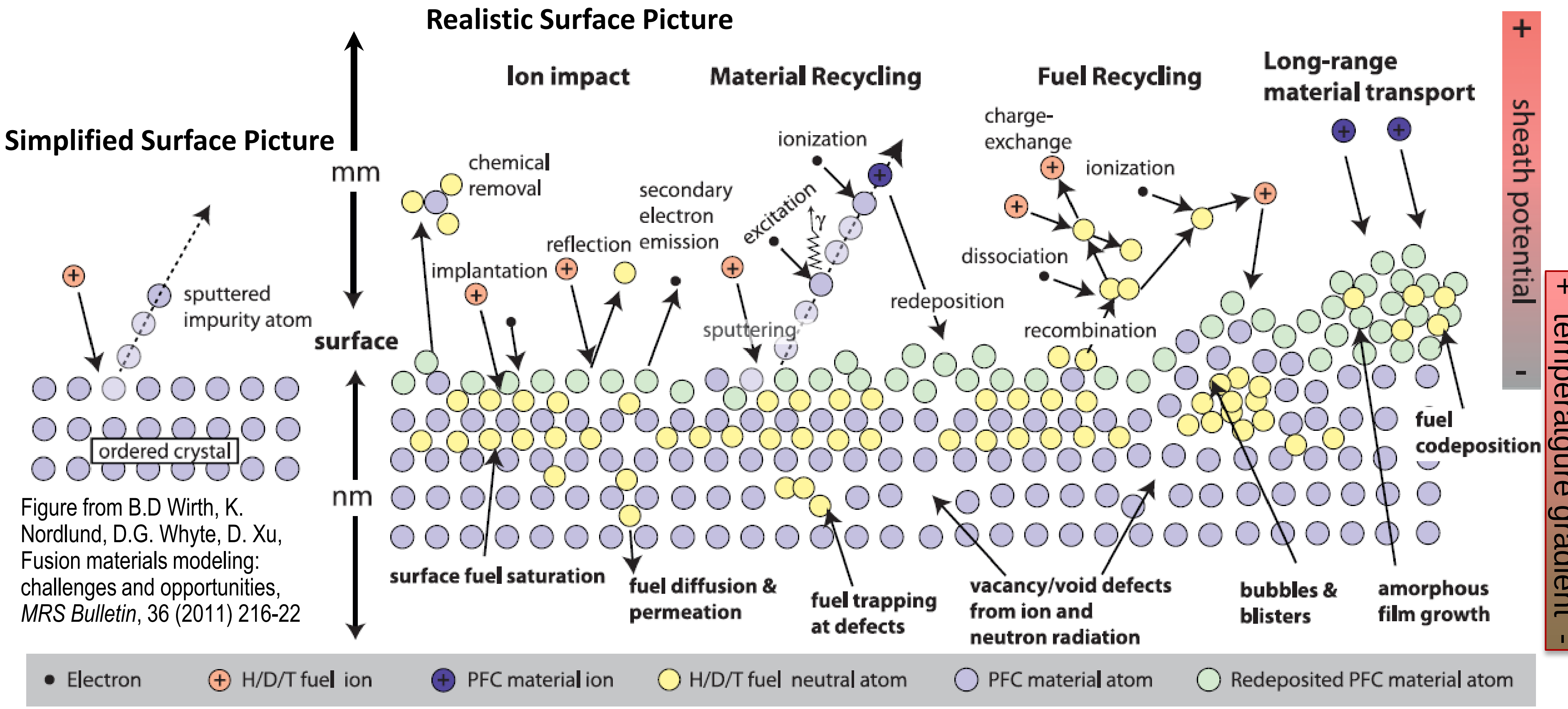


Figure from B.D Wirth, K. Nordlund, D.G. Whyte, D. Xu, Fusion materials modeling: challenges and opportunities, *MRS Bulletin*, 36 (2011) 216-22

The microstructure evolves. Many process are at work that add and subtract atoms and rearrange microstructure.

Refractory Solid PFCS: PFM W solution
What does materials modeling tell us?

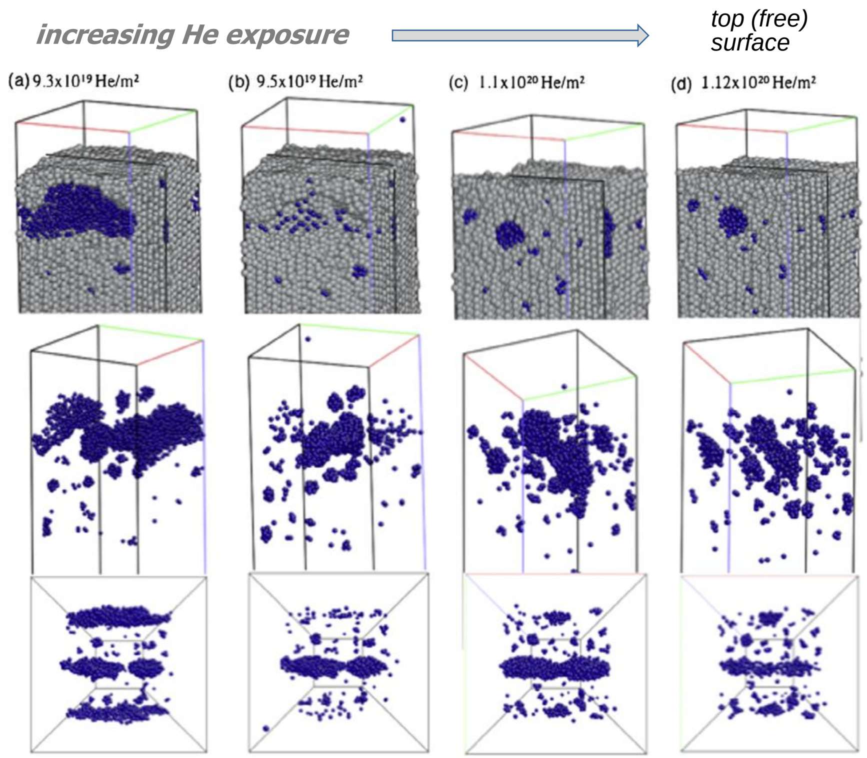


Figure from Brian D. Wirth, K.D. Hammond, S.I. Krasheninnikov, D. Maroudas, Challenges and opportunities of modeling plasma–surface interactions in tungsten using high-performance computing, JNM 463 (2015) 30–38

s

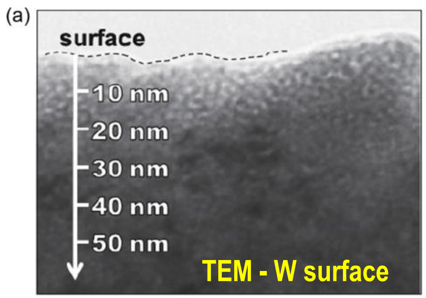
MD simulation, He in W (eft)

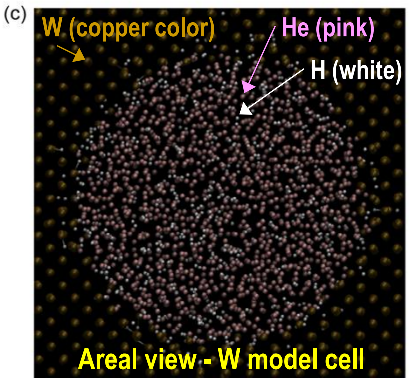
Cell is ~6.4 nm (x,y) by ~10 nm (z) along [100] with (100) top surface intersected by a Σ5 grain boundary and periodic boundary conditions.

Thermalized He (200K) implants randomly. Initial distribution uses the W N-body potential and W-He pair potential by Juslin/Wirth.

The depth distribution is consistent with measured values for exposure at 60 eV He to 10^{27} He/(m^2-s), e.g., 1.8 nm gas bubbles to ~20 nm depth, exposed at 200 C to 60 eV plasma 5%He–95%D to ~10^{25} m^2.

Model distribution at right shows He (pink) and H (white) atoms in a 2 nm radius gas bubble within W (copper color).



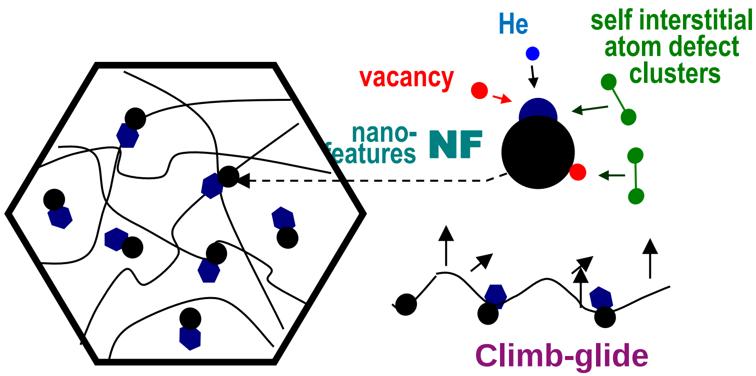


Modeling shows precursor for fuzz formation via He bubbles that push up the surface. Nano-features influence He migration (next slide).

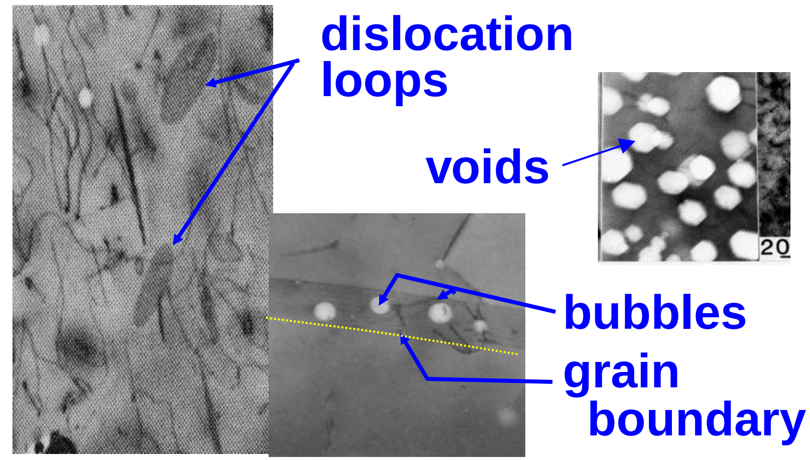
Refractory Solid PFCS: Ferritic R&D
What does materials modeling tell us?

Sandia National Laboratories

Let's look at R&D on radiation resistance in ferritics.



Odette, Alinger, Wirth, Recent Developments in Irradiation Resistant Steels, *Annual Reviews of Materials Research* V38 (2008) 371-403



Trapping at nano-features (NF) is a key strategy to manage He.

The microstructure evolves. Modifications affect the evolution. Can we ...

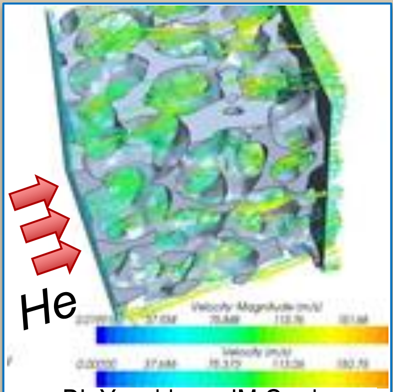
1. Enable migration of He and transmutation products to benign sites – *maybe use nanoparticles.*
2. Mitigate tritium permeation – maybe controlled porosity can provide escape.
3. Maintain adequate robustness – mitigate deleterious crack growth with graded composition, transition layers and designs to reduce stress.

Refractory Solid PFCS: PFC solution
What does heat transfer modeling tell us?

Our experience with the ITER first wall and He-cooled PFCs shows that fluid correlations are not useful for fusion PFCs.

CFD* models with full fluid physics are required, along with appropriate experiments to validate models.

*Computational Fluid Dynamics



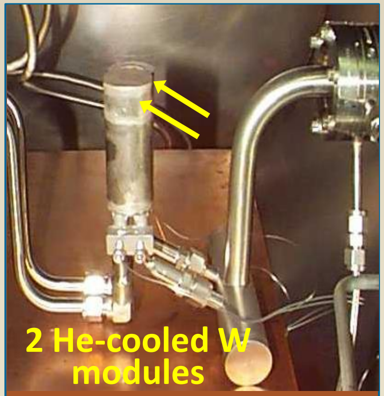
DL Youchison, JM Garde, Thermo-mechanical evaluation .. *Fusion Sci. Tech.*, 61/1T 2012

Flow in porous media

Youchison, who pioneered CFD* modeling of gas flow in porous media, found it to be less effective than jet flow for cooling fusion PFCs.

Parallel flow instability with He cooling

High heat flux tests at Sandia with high temperature He, high density and strong thermal gradients revealed this instability. It has huge implications for designing fusion systems, e.g., manifold design.



DL Youchison, MT North Thermal Performance ... *Fusion Tech.* **39**/2 2001

Modeling with well coordinated testing

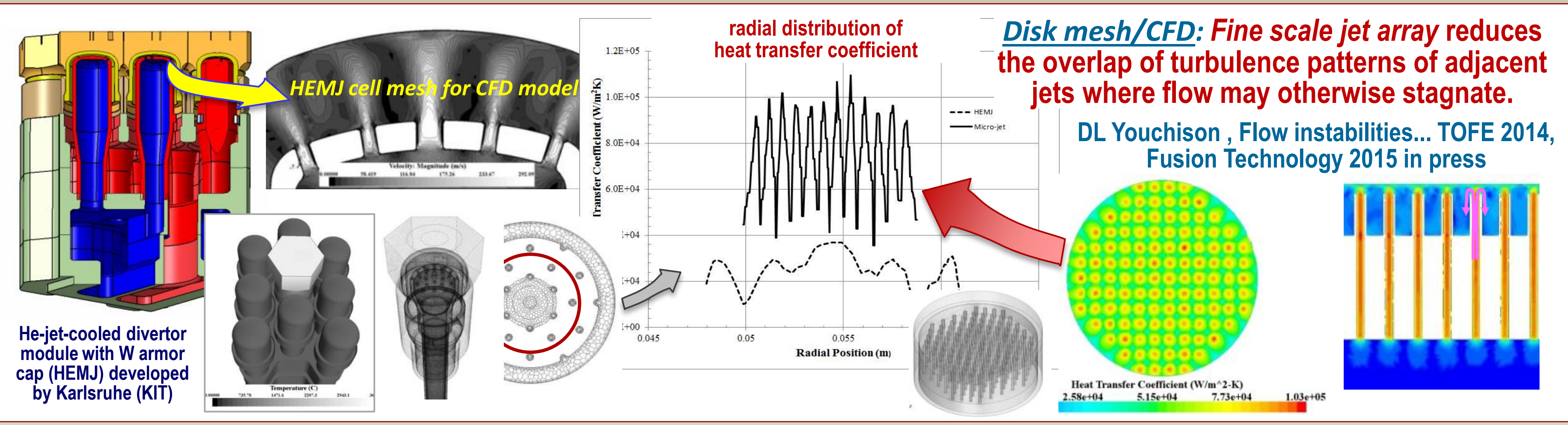
Experiments may lead modeling and show gaps. The initial CFD models did not reproduce the flow instability noted above. Later models did.

The roles of the experimental R&D are to explore and to validate.

A new vision for PFC development

Sandia National Laboratories

PFC gas cooling solution: *flow jets on fine scale for optimal heat transfer*



Comparing scale with HEMJ

Youchison compared heat removal and flow in the center 25 mm^2 of an HEMJ cell and disk with a micro-jet array at 10 MW/m^2 and like He conditions. The finer scale improved heat transfer and reduced stresses.

Micro-flow jet applications

Arrays of low pressure air micro-jets are prevalent in electronics in heat sinks for high power devices* Typically these are 100-500 µm dia. and cool steel or copper.

*insulated gate bipolar transistors, Si-controlled rectifiers and for solid state switching (MOSFETS, JFETS, RF power transistors)

Arrays with 100's of jets are made using lithographic MEMS technology and advanced additive manufacturing such as LENS, LIGA or SPS. *[Ref: Youchison]*

A new vision for PFC development

Sandia National Laboratories

Explore potential of Advanced Manufacturing

We are not experts in this area but see overlap between its potential and needs for a certain engineered fusion structures.

Additive manufacturing (AM) denotes ways for printing material layer by layer in 3-D directly from CAD models of a component.

Among AM’s advantages for PFCs are its ability to form intricate parts *(e.g., with micro-channels or controlled porosity),* transitions in composition and wide flexibility. Few or no joining steps and reduction of waste are also benefits.

This relatively new technology is being applied to high-value components.* But as yet structure-property relationships cannot be predicted.

*General Electric has announced 3-D printing of fuel nozzles for the Leap jet engine.
Several US organizations are exploring AM technology for turbine blades using Ti-Al powders.
ORNL and Penn State have state-of-the-art AM facilities developed for collaborations.

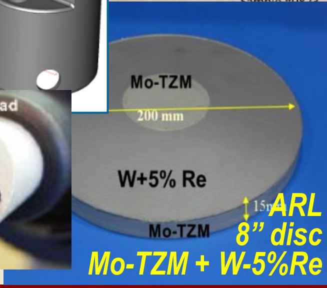
Let’s explore AM to make PFCs with micro-channels and a materials architecture to mitigate effects from neutron and ion damage.

Other advanced manufacturing processes *can be useful to make (smaller) parts that have complex materials architectures.*

The Applied Research Lab (ARL, Penn State) can make gas-cooled DIII-D tiles with micro-channels using field assisted sintering in an industry-scale press.

Woodruff Scientific (WSI, small business) will make parts for diagnostics.

WSI probe head model



Comments on PFM-PFC and AM

Other US supporters: *Steve Zinkle (U. Tenn.) TOFE 2013 FST 64 (2014)*
Dennis Whyte (MIT) SOFE 2015 in press

significant implications for models

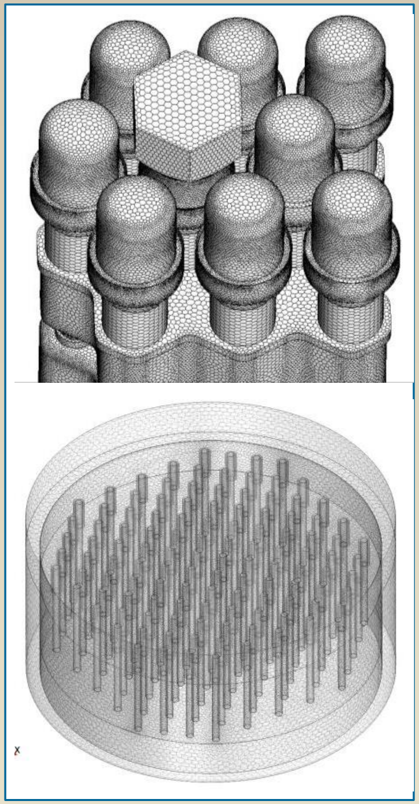
Long term neutron damage is a concern for the PFM solution. But this solution can differ from that for the substructure. For example, the basic requirement for the strength of the material may be drastically reduced. Nor is radiation damage now a feature of a "bulk material" in thick armor.

+ In near term R&D, we can separate the ion-damaged PFM (weak, ?porous) from the engineered substructure (strong, vacuum boundary). We can also use surrogate materials in modeling and testing that advance modeling even if these are not appropriate for end use in a PFC.

- Challenge: Develop predictive models of performance; converge on solutions; reasonable R&D cost. (many variables: nano-features, porosity, composition gradients, appropriate data on radiation effects, processing temps, ...)

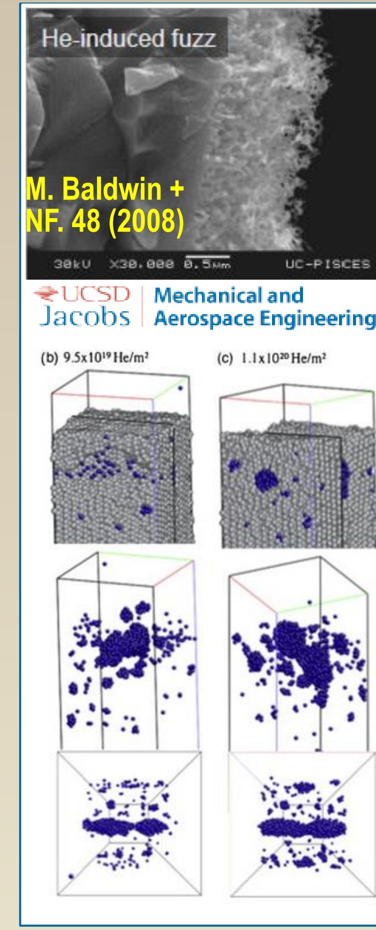
Close collaboration is required *between modelers and experimenters. This means not just that modelers use experimental data, but that modeling is a tool both for identifying needs for data and for designing experiments, e.g., what can and should be measured.*

Additive manufacturing is an essential element in the combined solution for a robust PFM-PFC solution.



To realize robust PFCs for FNSF, we need

- suitable **materials architecture** for PFMs,
- **engineered micro-features** (microjets for gas cooling),
- **advanced manufacturing methods**, and a
- new vision of the R&D path for materials and PFCs.



B. Wirth et al., Challenges and opportunities of modeling plasma–surface interactions in tungsten using high-performance computing, JNM 463 (2015) 30–38

PFM-PFC Performance

Conclusion: Recommendation for Action

The vision outlined here is not yet accepted.

For the US we have suggested two important objectives and related near-term tasks.

One important objective for PFMs is the capability for predictive modeling of performance and generation of data to benchmark the models.

An important corollary in this new approach is the utility of surrogate materials in both modeling and testing that will advance the modeling even if these are not appropriate for end use in a PFC. To this end we can identify some useful tasks.

- Use experts in materials and PSI and identify PFMs for DEMO or FNSF.
- Use materials experts and identify fab methods for FNSF and for DEMO.
- Identify materials (surrogates as needed) to validate models and for use testing in off-line facilities as well as exposures in DIII-D, NSTX-U and perhaps foreign devices.

THANK YOU