NSTX

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Overview of Current and Future Materials Needs for High Power Fusion Devices:

- from DOE 2009 ReNeW Assessment and Current PPPL Research

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Henry W. Kugel, et al.

Rutgers PPPL Fusion Materials Discussion

Director's Conference Room

June 03, 2009

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Outline

- PPPL is Collaborative National Center for Plasma and Fusion Science
- Material Issues Increasing Pace Fusion Progress
- Central Issue: Interfacing Plasma to Room Temperature Surroundings
- Summary of Candidate Plasma Facing Component (PFC) Materials
- Radiation Damage
- Candidate Fusion Blanket Structural Materials
- Examples of Current PSI Issues Observed in Recent Experiments
- Conclusions

PPPL is Collaborative National Center for Plasma and Fusion Science

- Princeton University manages PPPL under contract with the US DOE, Office of Fusion Energy Sciences (OFES) to advance fusion energy and plasma physics.
- We are conducting research along the broad frontier of plasma science and technology. This contributes to the database and innovations needed to achieve fusion as an energy source for the world.
- We also support the national research enterprise in these fields, and we educate the next generation of plasma and fusion scientists (~34 grad students from Departments of Astrophysical Sciences and Engineering).

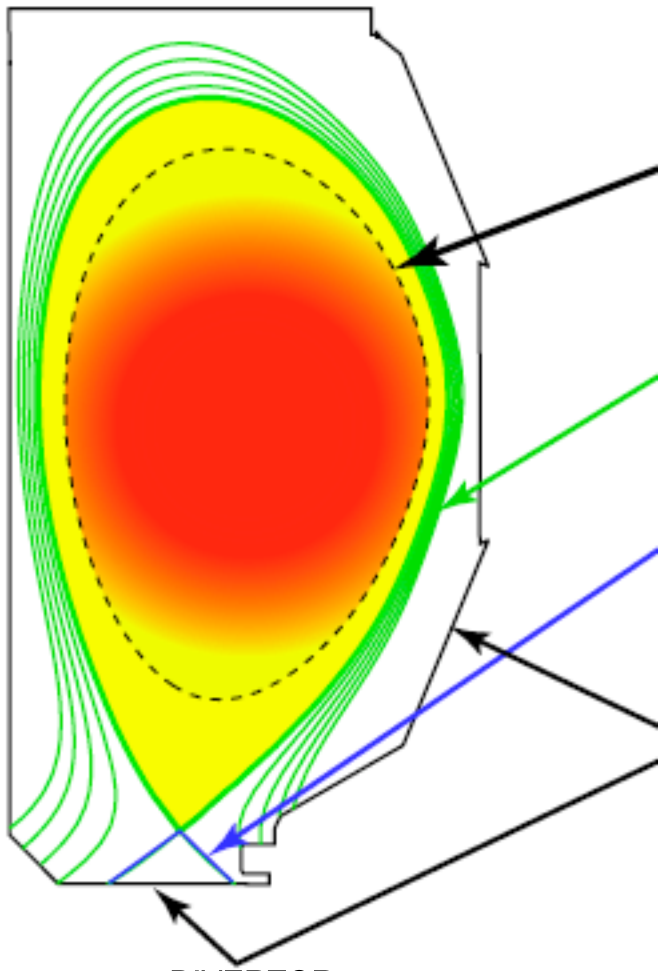
Extensive National and International Collaborations on NSTX

- National Spherical Torus Experiment (NSTX) at PPPL is a major element of the US Fusion Energy Sciences Magnetic Confinement Program. About 1/3 of the NSTX researchers are collaborators who submitted proposals to DOE for work on NSTX.
- Material and technology R&D supported by NSTX must be related to its mission.
- NSTX benefits from fusion material research and technology development from the OFES, Development & Technology Division's Virtual Laboratory for Technology (VLT), and other OFES funded research.

Material Issues Increasing Pace Fusion Progress

- PPPL researchers increasingly encounter fusion material issues:
  - PPPL experimental projects perform mission related material research
  - fusion materials issues in the research and design for ITER, and next-step, higher power devices, e.g.,
    - power handling surfaces (C, Be, W, liquid Li)
    - neutron absorption effects, ,e.g.,
      - Structural strength of internal hardware
      - PFC erosion and dust generation
      - Insulation integrity (magnetic coils, instrumentation, and cabling)
      - First mirror and window deterioration
    - co-deposition of incident tritium fuel and ablated PFC materials
    - H and He fuel gas dilution from (n,p), and (n,α) reaction products

The Central Issue: How to interface a 100 Million Degree Burning Plasma to its Room Temperature Surroundings?



- **Physics of the formation, structure and stability of the edge plasma.**
- **Plasma and impurity transport in the Scrape-of-Layer (open field lines).**
- **Tritium retention and plasma material interactions.**
- **Erosion and decomposition of plasma facing materials and components.**

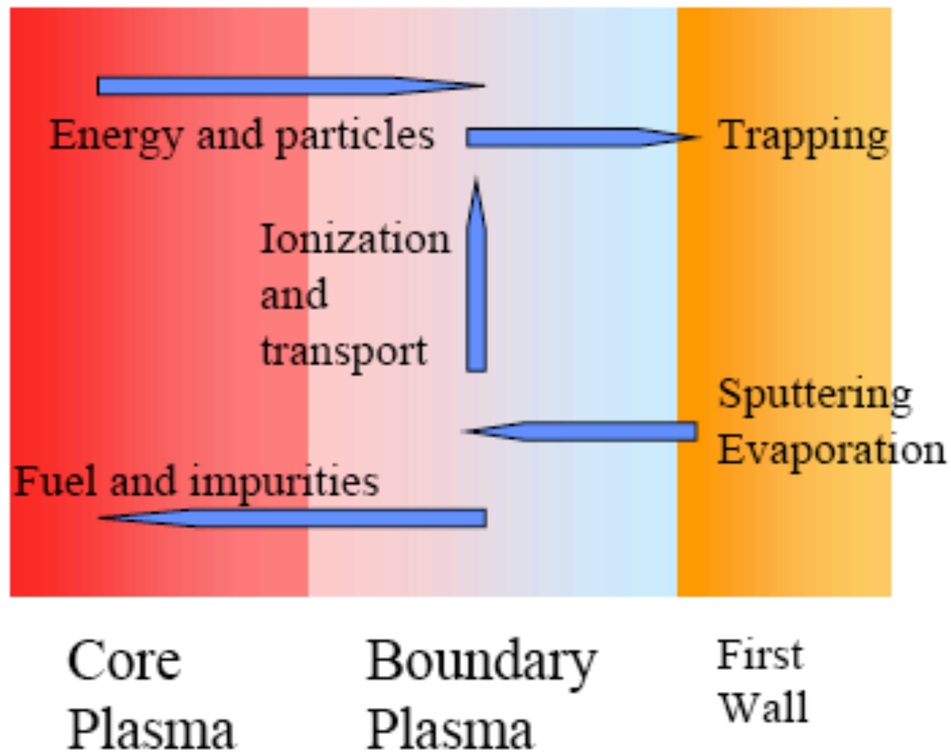
M. Ulrickson

Sandia National Laboratories

First Wall Plasma Materials Interactions

• **The core plasma must be kept clean of impurities and Helium ash**

- The first wall surface sees plasma heat and particle flux due to radial transport
- Key issues are hydrogen trapping, wall erosion, and redeposition
- Conflicting requirements for low Z facing plasma and low erosion (favors high Z)



- Current PFC Materials of most interest: solid Be, C, Mo, W, and liquid Li (and Ga, Sn, Pb, and their compounds)

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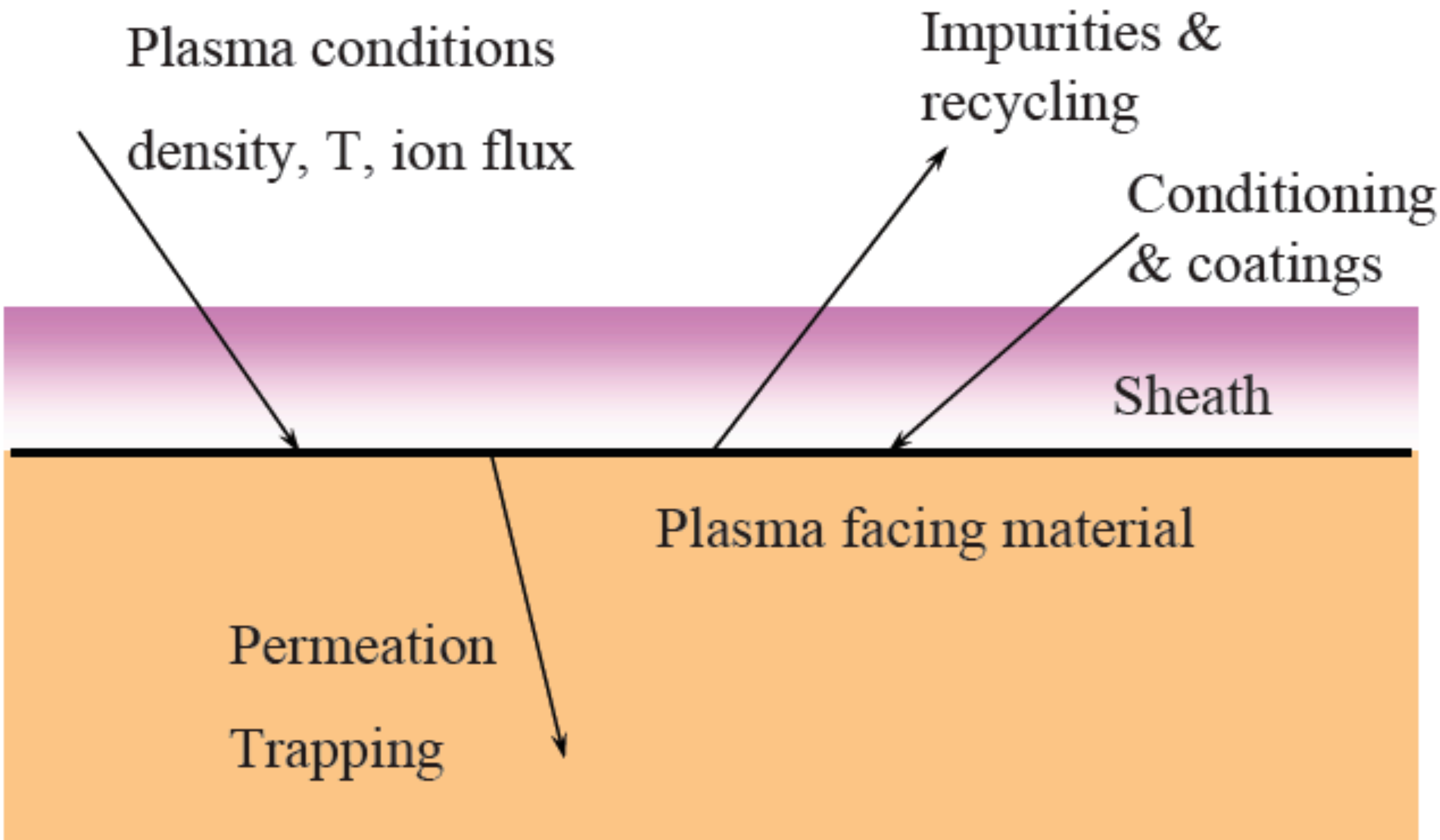
Intense Plasma Material Interactions at the Divertor Plate



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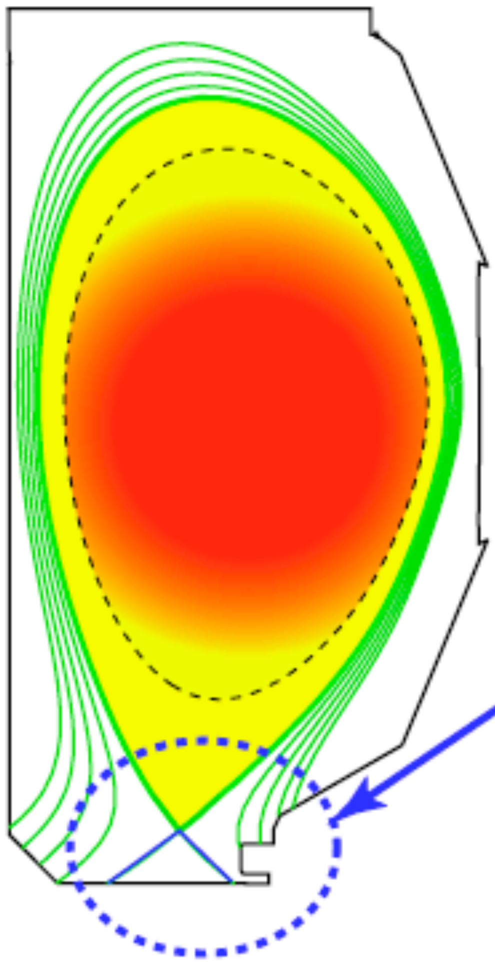
Divertor Material and Geometry Are Currently the Most Challenging High Power, Next-step Design Issues

Tritium retention and plasma material interactions



- Plasma materials interactions include:
  - Collisions of ions with the wall (sputtering) causing erosion
  - Chemical processes (chemical sputtering) causing erosion
  - Deposition of impurities and particles in the wall
  - Erosion takes place at divertor and main chamber wall, impurities enters SOL and can influence core plasma performance
- Tritium can be retained in the walls, particularly with carbon
  - Important for in-vessel inventory, a safety and operations issue
- Understand & control large plasma heat and particle loads -- divertor and main walls
  - Steady-state loads
  - Pulsed loads from ELMs - difficult to predict in burning plasma experiment
- New diagnostics needed for flows, heat, and particle flux profiles, and impurity generation - also need experiments and modeling of tritium (carbon) transport
- Improved theory and modeling to integrate PMI and SOL modeling

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Significant Gaps Exist in Plasma Materials Interactions (PMI) Theory, Modeling and Experimental Validation

- Effects of turbulent energy transport to PFCs (divertor and walls)
- Mixed materials effects (Be,C,W) on plasma vapor formation and response
- Melt layer formation and splashing
- Liquid metal surface (Li, Ga, Sn) response to transient energy transport
- Droplet and dust formation

A. Hassanein

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Summary of Present Candidate PFC Materials

Plasma facing materials and components

- Low-Z solid wall materials (C, Be)
  - Low radiation if leak into core
  - Large database developed on tokamaks and other devices - high particle and heat loads have been handled
  - Database developed of fundamental properties
  - Reliable engineering solutions have been found for steady-state high heat flux (absence of neutrons)
  - Tritium retention (in re-deposited material) problem must be addressed

- Medium and High-Z solid wall materials (Molybdenum, Tungsten)
  - Used successfully on several machines
  - Database developed of fundamental properties
  - Some concern on off-normal events (ELMs and disruptions)
  - Reliable engineering solutions have been found for steady-state high heat flux (absence of neutrons)

- Liquid walls
  - Developing database, earlier stage of development
    - **Self-healing from erosion and neutrons damage**
    - **Sweeps out tritium and impurities**
    - **Yields hotter edge, significant discharge improvement**

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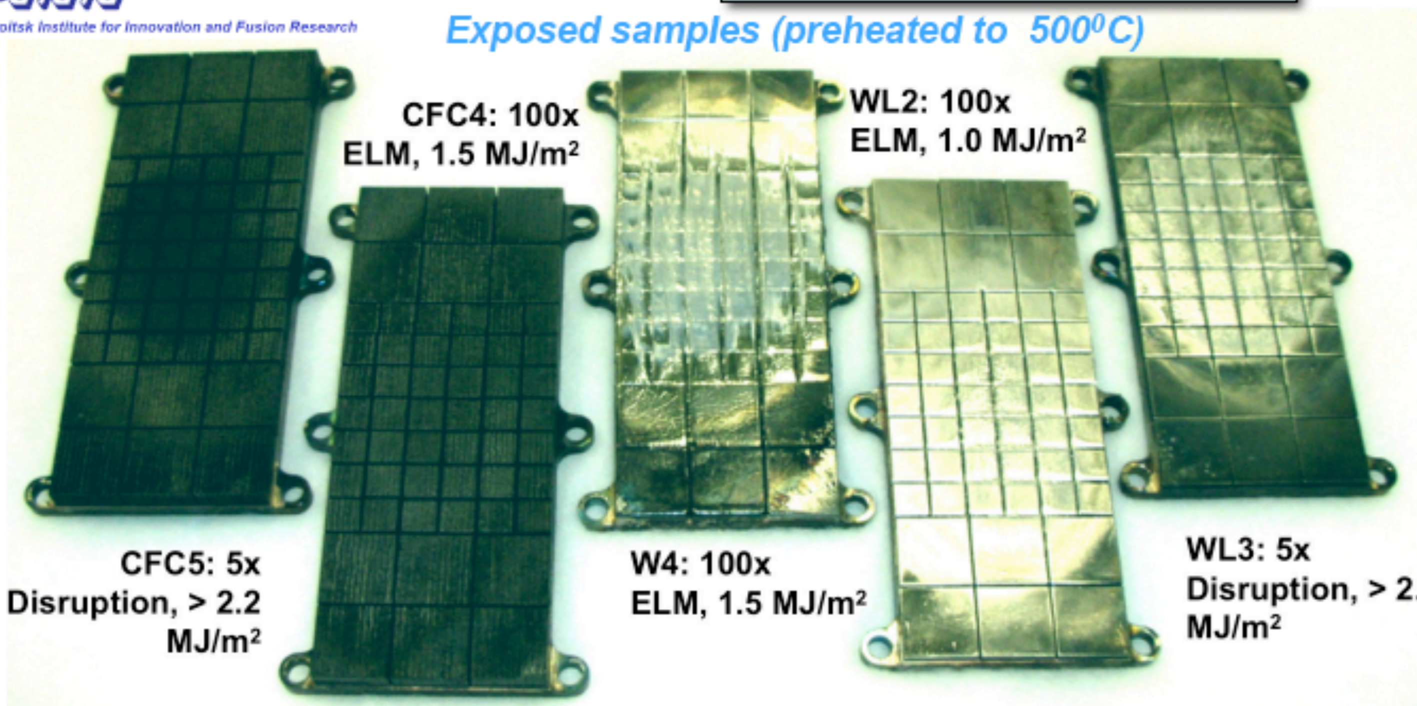
Presently Solid Divertor Target Materials Are Operating at Their Limits for Heat Removal

ELM simulation results from QSPA facility in Troitsk[1]

Troitsk Institute for Innovation and Fusion Research

ELM duration ~ 0.5 ms
ELM size ~ 1/10th ITER!

Exposed samples (preheated to 500^0C)



[1]Klimov, N., et al., "Experimental study of PFCs erosion under ITER-like transient loads at plasma gun facility QSPA," 18th PSI Conference, Toledo, Spain, 2008.

B. Labombard, MIT

Comparison of fission and fusion structural materials requirements

	Fission (Gen. I)	Fission (Gen. IV)	Fusion (Demo)	JIMO space react.
Structural alloy maximum temperature	<300°C	500-1000°C	550-1000°C	~1000°C
Max dose for core internal structures	~1 dpa	~30-100 dpa	~150 dpa	~10 dpa
Max transmutation helium concentration	~0.1 appm	~3-10 appm	~1500 appm (~10000 appm for SiC)	~1 appm
Coolants	H_2O	He, H_2O, Pb-Bi, Na	He, Pb-Li, Li	Li, Na, or He-Xe
Structural Materials	Zircaloy, stainless steel	Ferritic steel, SS, superalloys, C- composite	Ferritic/ martensitic steel, V alloy, SiC composite	Nb-1Zr, Ta alloy, Mo alloy

- Common theme for fusion,Gen IV fission and space reactors is the need to develop higher temperature materials with adequate radiation resistance

S. Zinkel

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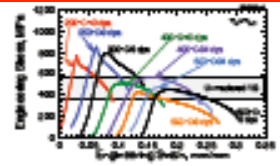
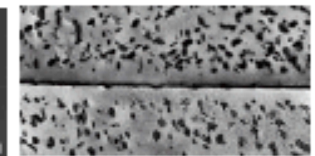
Radiation Damage can Produce Large Changes in Structural Materials

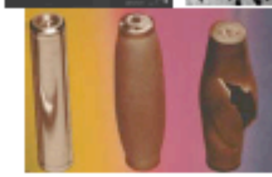
- Radiation hardening and embrittlement ($<0.4\ T_M$, >0.1 dpa)



- Phase instabilities from radiation-induced precipitation ($0.3\text{-}0.6\ T_M$, >10 dpa)

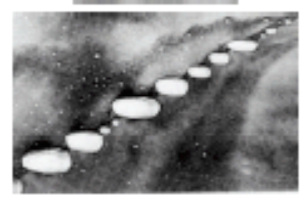


- Irradiation creep ($<0.45\ T_M$, >10 dpa)



- Volumetric swelling from void formation ($0.3\text{-}0.6\ T_M$, >10 dpa)

- High temperature He embrittlement ($>0.5\ T_M$, >10 dpa)



In addition…

- The irradiation environment associated with a D-T fusion reactor is more severe than in existing fission reactors
  - Higher lifetime dose requirements for structure
  - Higher He generation rates (promotes He embrittlement of grain boundaries, void swelling)

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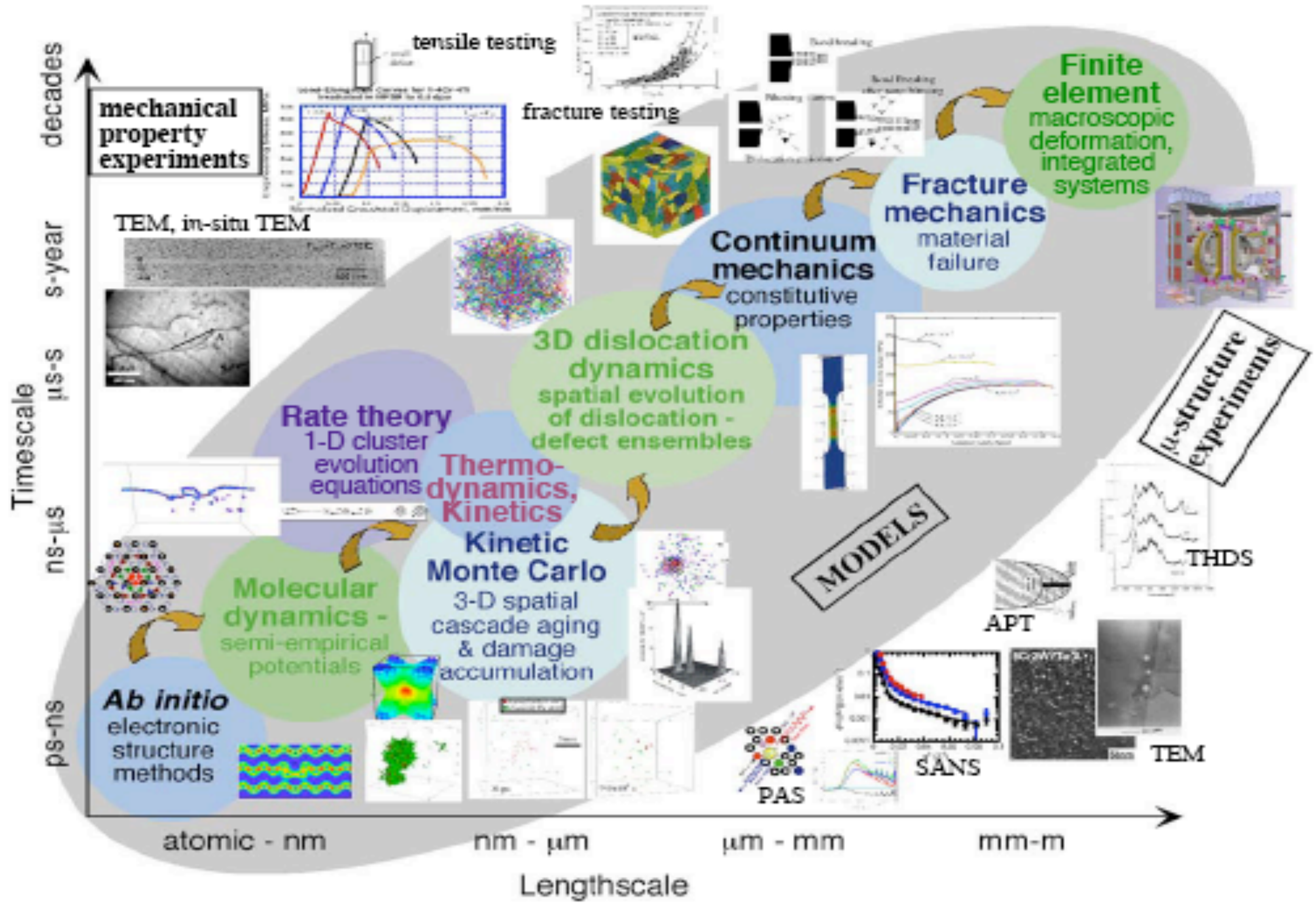
Radiation damage is inherently multiscale with interacting phenomena ranging from ps to decades and nm to m



B.D. Wirth, UC-Berkeley

Materials Issues Are Also Encountered in Achieving Robust and Efficient Power Extraction Designs

- Joining technology for low activation solid and liquid materials
  - joining without introducing weakening link
- Understanding the elements of the complete fuel cycle
  - Tritium breeding and tritium retention in vessel components
- Understanding how the properties of low activation materials used for structures and walls evolve during reactor conditions
- Sufficient database to guarantee safety over the plant life cycle

N. Morley, UCLA

Leading candidate fusion blanket structural materials

- Of all blanket materials, structural materials most strongly impact economic and environmental attractiveness potential of fusion power
- Key issues include thermal stress capacity, coolant compatibility, safety, waste disposal, radiation damage effects, and safe lifetime limits
- Ti alloys, Ni base superalloys, and most refractory alloys have been shown to be unacceptable for various technical reasons
- Based on safety, waste disposal, and performance considerations, the 3 leading candidate blanket structural materials are:

  - Ferritic/martensitic steels
  - Vanadium alloys
  - SiC/SiC composites

None of the current reduced activation fusion materials existed 15 years ago

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Examples of Current Plasma-Surface Interactions Materials Issues as Observed in Recent Experiments

- D retention in refractory metals (Mo, W, etc...)
  - work by: G. Wright, D. Whyte, B. Lipschultz
- Mixed-metal nanoscale morphology (Be, W) at high temperatures (phase transformations)
  - work by: M. Baldwin, R. Doerner
- Helium irradiation of W and nanoscale morphology evolution
  - work by: M. Baldwin, R. Doerner
- Lithiated graphite surface chemistry
  - work by: C. Taylor, J.P. Allain, C. Skinner, H. Kugel, and R. Kaita
- TPD experiments on D/T retention
- UIUC experiments on lithiated graphite physical and chemical sputtering and sublimation

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J.P.Allain

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Conclusions

- Material issues are increasingly pacing fusion progress.
- Current material issues include erosion, tritium retention, permeation, trapping, impurities, dust, power handling, and radiation effects (hardening, embrittlement, phase instabilities, creep, and volumetric swelling).
- In present fusion devices, solid PFC and divertor target materials are operating at their limits for heat removal.
- PFC and structural materials development is widely-acknowledged to require focused experiments and coordinated modeling.
- Materials synergies might be found in the area of alloy development once the underlying mechanisms for property degradation in the fusion environment are understood.