Materials Science & Technology Research Opportunities Now and in the ITER Era: A Focused Vision on Compelling Fusion Nuclear Science Challenges

Presented by Steve Zinkle

FESAC meeting

Bethesda, MD

Feb. 29, 2012

FESAC Materials sciences & technology subcommittee

Materials Degradation

Name	Institution
Steve Zinkle*(chair)	Oak Ridge National Lab
Rick Kurtz	Pacific Northwest National Lab
Brian Wirth	Univ. Tennessee-Knoxville
Jake Blanchard	University of Wisconsin
Peter Lee	Florida State Univ.

Plasma-Materials Interactions

Name	Institution
Chuck Kessel	Princeton Plasma Physics Lab
Rich Callis*	General Atomics
Dennis Whyte	Massachusetts Inst. of Technology
Richard Nygren	Sandia National Labs-Albuquerque
George Tynan	Univ. California-San Diego

Harnessing Fusion Power

Name	Institution
Neil Morley	Univ. California-Los Angeles
Farrokh Najmabadi*	Univ. California-San Diego
Scott Willms	Los Alamos National Lab /ITER
Kathy McCarthy*	Idaho National Lab

*FESAC member

Outline

- Overview of Charge
- Approach to Address the Charge
- Science Grand Challenges
  - Harnessing Fusion Power
  - Conquering Degradation of Materials and Structures
  - Taming the Plasma-Materials Interface
- Findings and R&D Options
  - Role of Technology Readiness Levels as a tool to focus R&D
  - Evaluation of Roles of Key Facilities
- Recommendations and Evaluation of Compelling Research Opportunities
- Summary Response to the Charge

FESAC charge on Materials science & technology

- "What areas of research in materials sciences and technology provide compelling opportunities for US researchers in the near term and in the ITER era? Please focus on research needed to fill gaps in order to create the basis for a Demo and specify technical requirements in greater detail than provided in the MFE ReNeW (Research Needs Workshop) report. Also, your assessment of the risks associated with research paths with different degrees of experimental study vs. computation as a proxy to experiment will be of value."
  - Consider near- and long-term (~0 to 5, 5-15, and 15+ years); what can be done with existing facilities, new facilities, and emergent international facilities
  - Experiment & the role of computation: Identify 2-3 paths with varying emphases on massively parallel computing–what are the risks associated with each path?
  - Materials defined to encompass nuclear (dpa's); non-nuclear (pmi); differential (single-effects) and integrated (multiple-effects) phenomena; harnessing fusion power

High level goal #2: Materials in a fusion environment

- Plasma/surface interactions: establishing boundary of a fusion plasma. Plasma facing surface survival, renewal: cracking, annealing. Fuel retention. Important for industrial, non-energy applications as well
- Nuclear effects on materials and structures, including the effects of > 100 dpa on structure integrity, helium creation in situ, and time evolving properties
- Harnessing fusion power depends on the nuclear material science above and is extended to tritium breeding and extracting fusion power

This requires the launching of a vigorous materials and nuclear science program that will be part of defining and constructing a fusion nuclear science facility, and will fill gaps en route to a DEMO.

The panel focused on three major science themes

- Harnessing Fusion Power
- Conquering Degradation of Materials and Structures
- Taming the Plasma-Materials Interface

https://aries.ucsd.edu/FESAC_MAT/

FESAC Material Panel

Home	Members	Charge	Community Input	Private

Annoucements

FESAC materials sciences subcommittee seeks community input

In response to a charge from the Office of Science to assess "what areas of materials sciences and technology provide compelling opportunities for US researchers in the near term and in the ITER era", a FESAC subcommittee consisting of 14 scientists is evaluating research needs to bridge current knowledge gaps in order to establish the scientific basis for a Demonstration power plant. The subcommittee evaluation is scheduled to be completed by January 31, 2012.

Research community input is solicited on key scientific challenges that need to be resolved, particularly in the following topical areas: Plasma-materials interactions, nuclear degradation of materials and structures, and fusion power conversion and tritium fuel cycle technologies. The contributions should focus on the scientific issue(s) to be resolved, rather than technical specifications of facility(ies) that might be important for resolving current engineering science barriers.

Short white papers or suggested scientific questions or issues to be considered by the subcommittee can be submitted to the FESAC materials sciences web site (http://aries.ucsd.edu/fesac_mat/) by sending the contribution to Farrokh Najmabadi (fnajmabadi@ucsd.edu). Questions regarding the scope of issues to be evaluated can be submitted to the subcommittee chair, Steve Zinkle (zinklesj@ornl.gov).

21 white papers and 5 emails received and discussed
15 teleconference (3 invited talks) and two 2-day face-to-face meetings

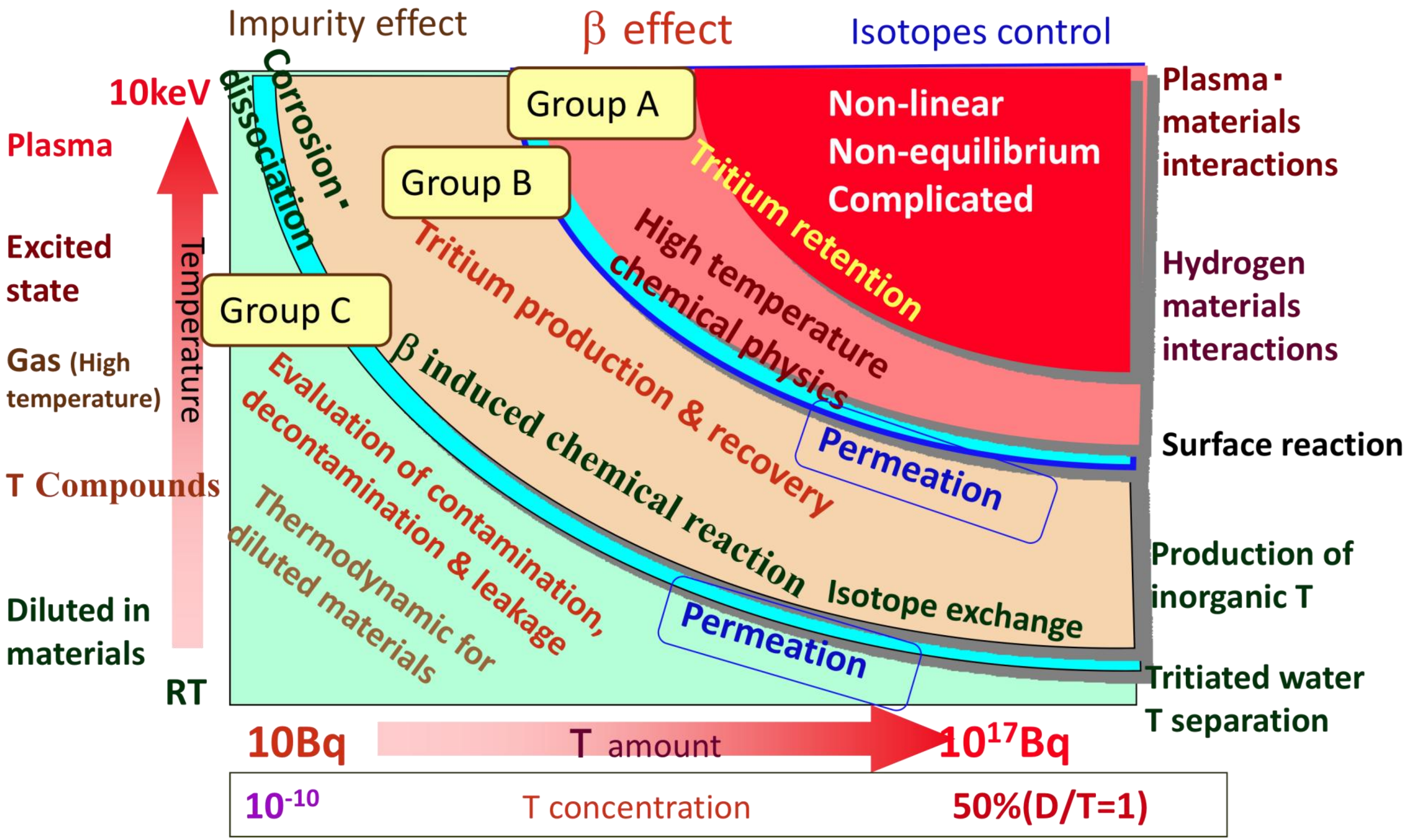
Identification of Grand Science Challenges Provided the Scientific Foundation for the Evaluation

Examples for Harness Fusion Energy

- **H1. Develop a predictive capability for the highly non-linear thermo-fluid physics and the transport of tritium and corrosion products in tritium breeding and power extraction systems.**
  - **Can tritium be extracted from hot PbLi with the required high efficiency to limit tritium permeation below an acceptable level?**
  - **Can we simulate the 3-D MHD effects in flowing liquid breeders to the degree necessary to fully predict the temperature, temperature gradients and stress states of blanket components and materials?**

Tritium Science & Technology for Fusion Reactor

Scientific Research in Priority Areas
Tritium for Fusion
2007 - 2011



T. Tanabe, ISFNT, Portland, 2011

MHD forces in flowing liquid metal coolants in MFE blankets can exceed normal viscous and inertial forces by >5 orders of magnitude

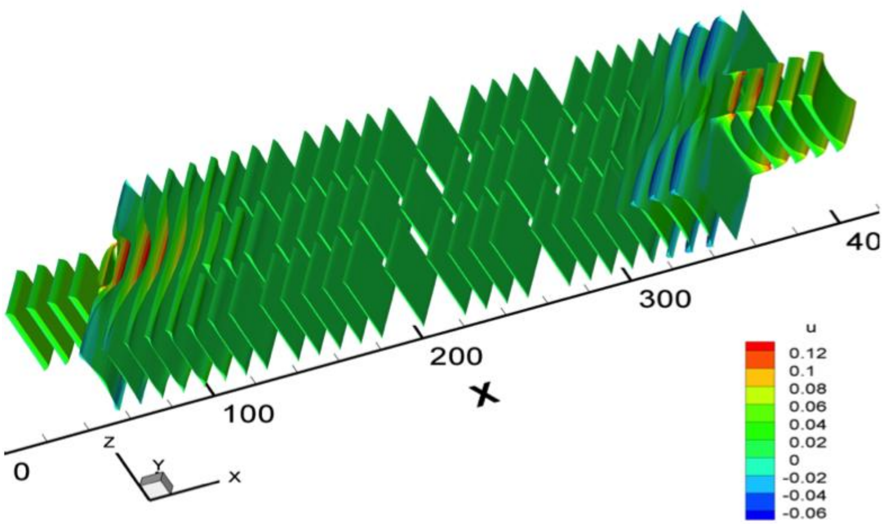
3D MHD simulation of flow distribution to 3 blanket channels from a common manifold

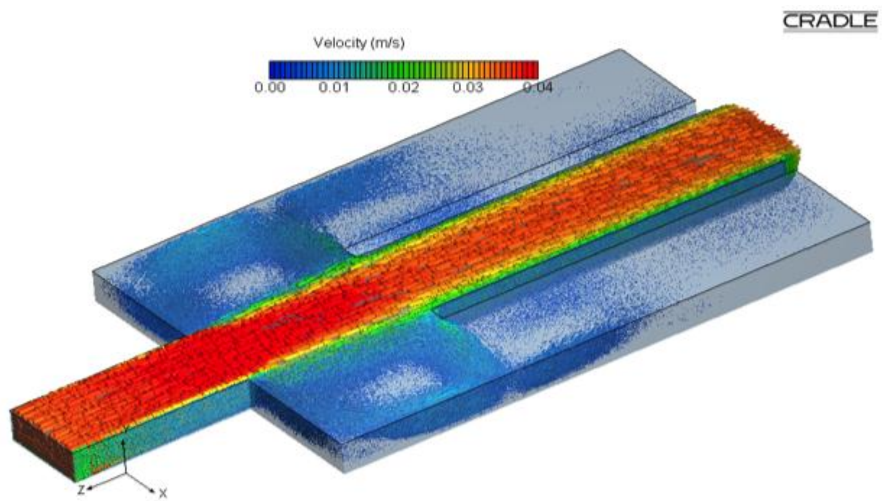
With B field

- **Coolant flow is uniform within three channels**

No B field

- **Coolant flow is concentrated in center channel**





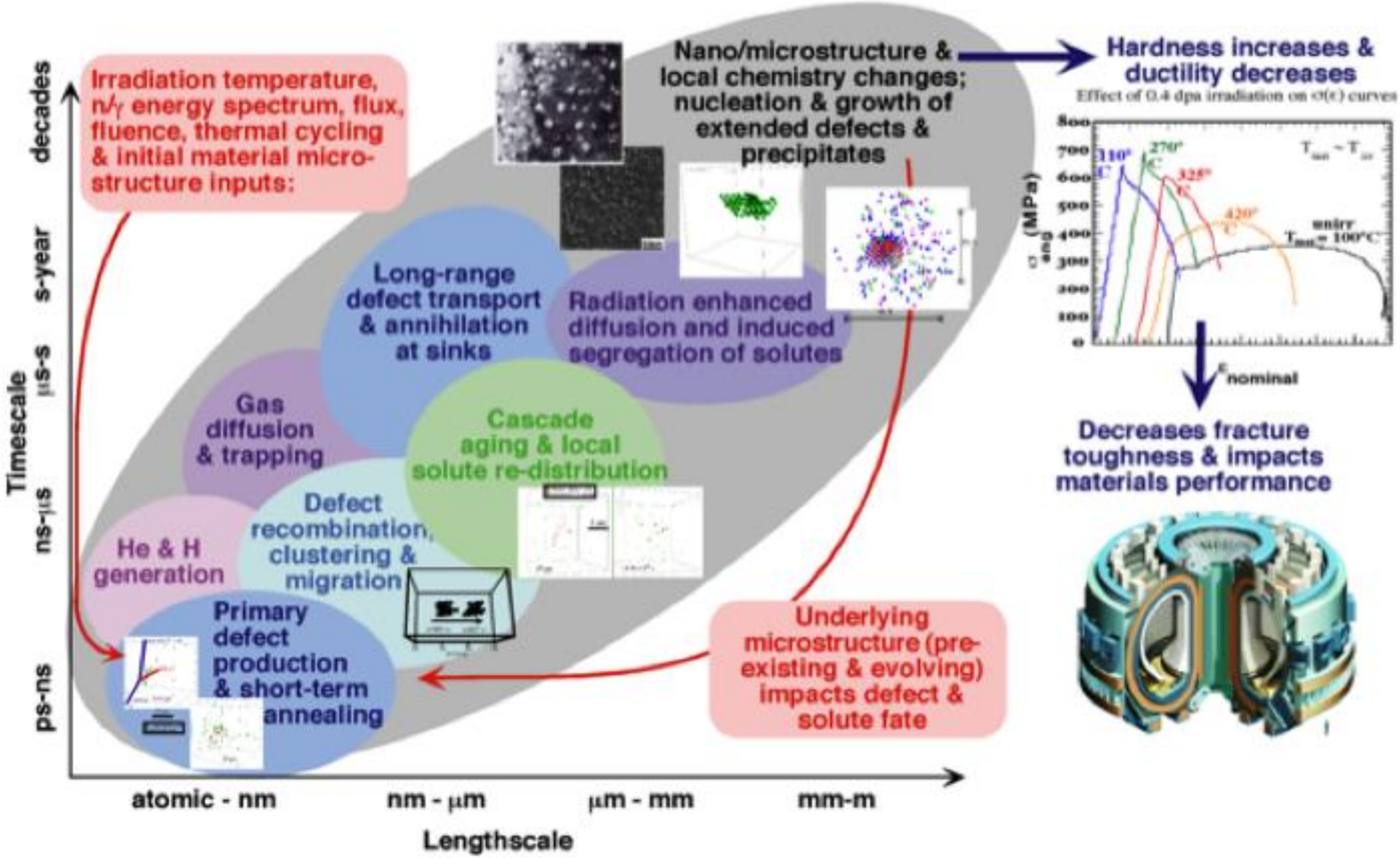
Identification of Grand Science Challenges Provided the Scientific Foundation for the Evaluation

Examples for Conquering Degradation to Materials and Structures

- **D1. Understand and devise mitigation strategies for deleterious microstructural evolution and property changes that occurs to materials exposed to high fusion-neutron fluence (dpa and H, He transmutations)**
- **D3. Comprehend and control tritium permeation, trapping, and retention in neutron radiation-damaged materials**
  - **Are materials development strategies for fusion neutron radiation resistance incompatible with minimizing tritium trapping?**
- **D4. Understand the fundamental mechanisms controlling chemical compatibility of materials exposed to coolants and/or breeders in strong temperature and electro-magnetic fields.**
  - **How do MHD and ionization effects impact corrosion**

Identification of Grand Science Challenges Provided the Scientific Foundation for the Evaluation

Examples for Conquering Degradation to Materials and Structures



Materials science strategies to improve radiation resistance may lead to enhanced tritium retention

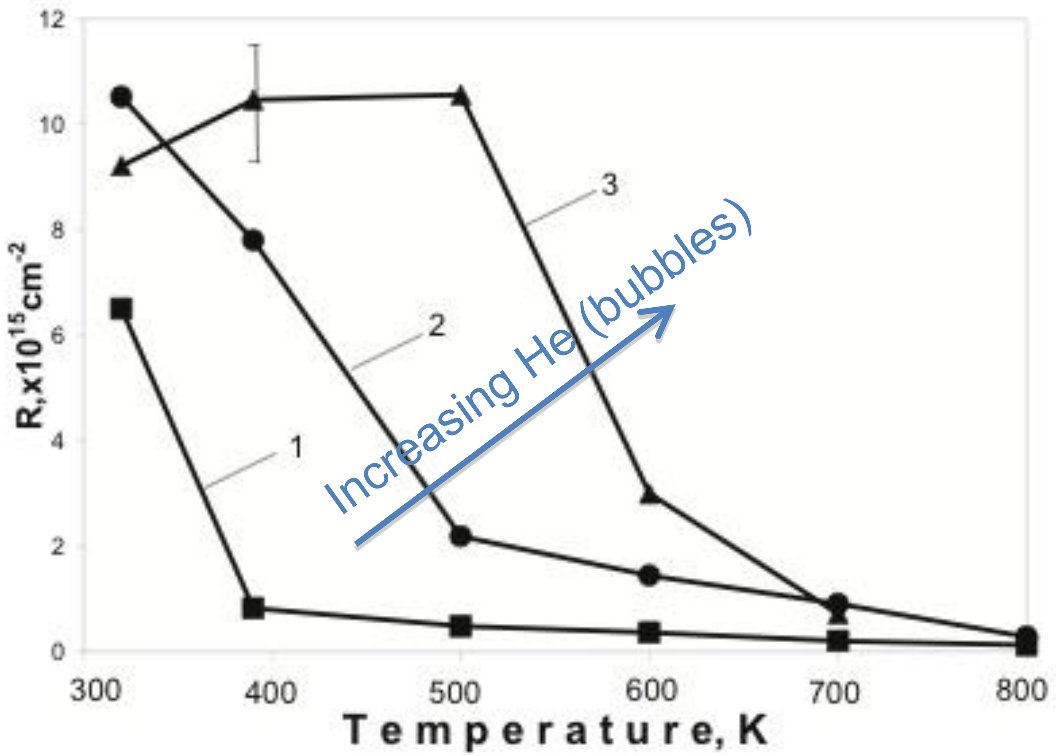


Fig. 8 Deuterium retention in 18Cr10NiTi steel implanted to $1x10^{16}$ cm^{-2} without helium (1) and with helium to $5x10^{15}$ (2) and to $5x10^{16}$ cm^{-2} (3).

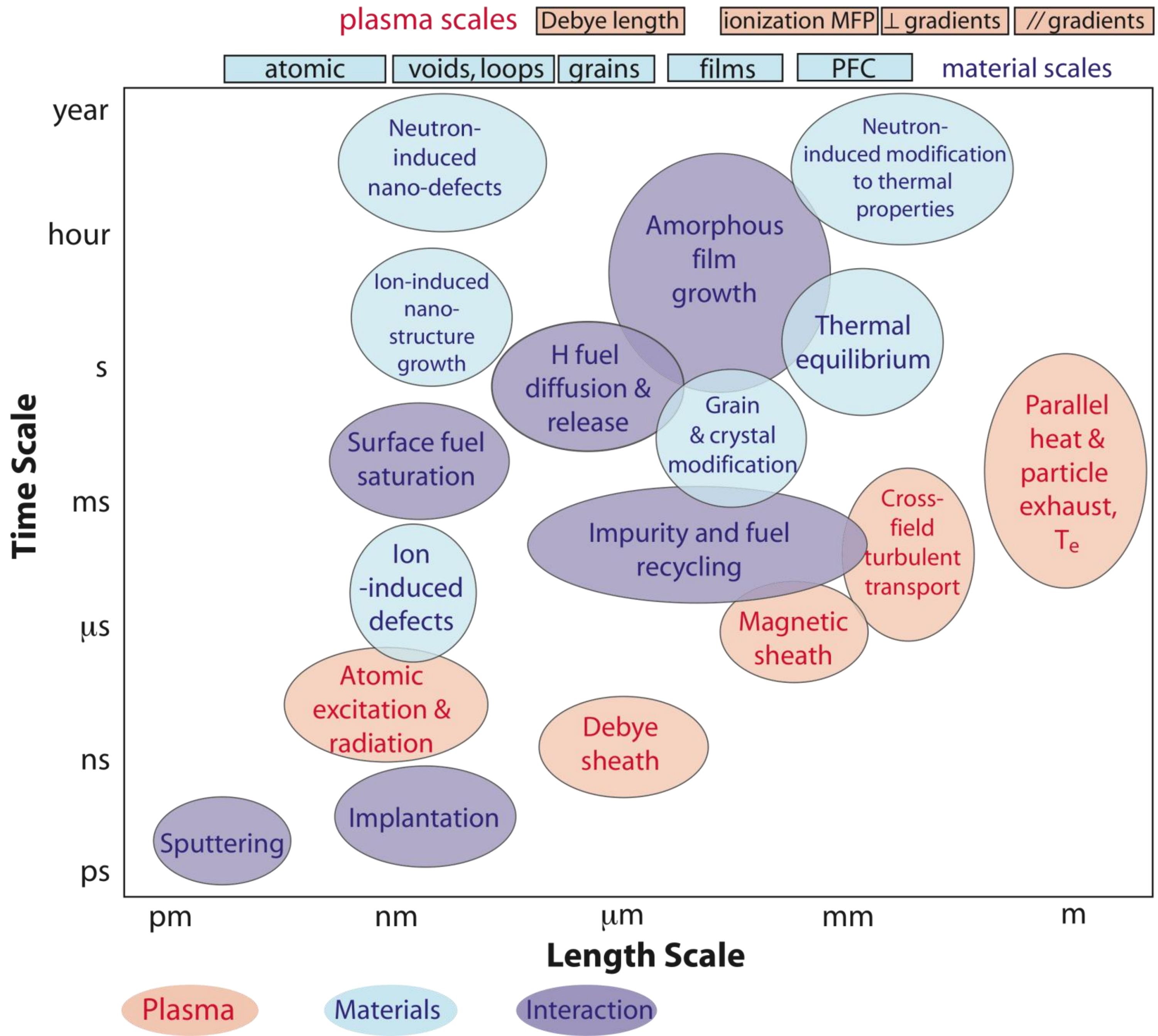
G.D. Tolstolutskaya et al., 12th Int. Conf. on Environmental Degradation of Materials in Nucl. Power System (TMS, 2005), p. 411

Identification of Grand Science Challenges Provided the Scientific Foundation for the Evaluation

Examples for Taming the Plasma-Materials Interface

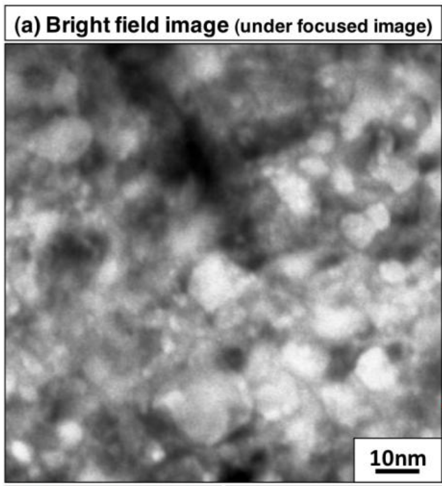
- **P1. Understand and mitigate synergistic damage from intense fusion neutron and plasma exposure.**
  - How does the coupling of intense heat flux, high temperature, and associated thermal gradients provide failure modes for plasma facing components?
- **P2. Understand, predict and manage the material erosion and migration that will occur in the month-to-year-long plasma durations required in FNSF/DEMO devices, due to plasma-material interactions and scrape-off layer plasma processes.**
  - Can the boundary plasma and plasma-material interface be sufficiently manipulated to ensure that year-long erosion does not exceed the material thickness ~5-10 mm anywhere in the device?

Plasma-material interactions are multiscale and interactive



W Temperature & PMI are coupled

~ 600 - 700 K | ~ 900 – 1900 K | > 2000 K



PISCES-A: D_2-He plasma

M. Miyamoto et al. NF (2009) 065035

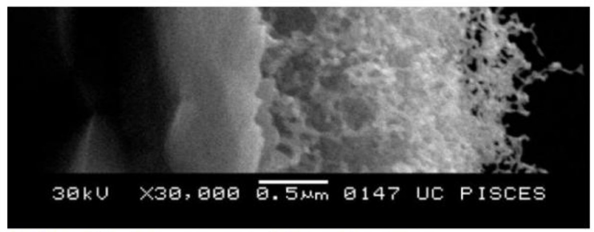
600 K, 1000 s, 2.0×10^{24} He^+/m^2, 55 eV He^+

- Little morphology
- He nanobubbles form
- Occasional blisters

PISCES-B: mixed D-He plasma

M.J. Baldwin et al, NF 48 (2008) 035001

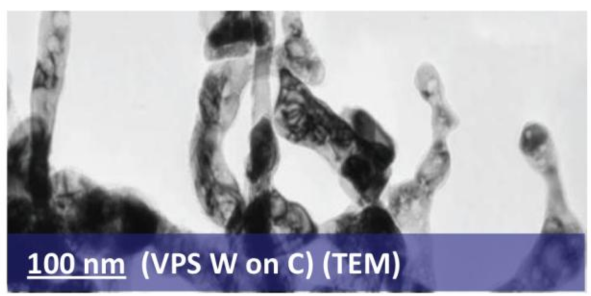
1200 K, 4290 s, 2×10^{26} He^+/m^2, 25 eV He^+



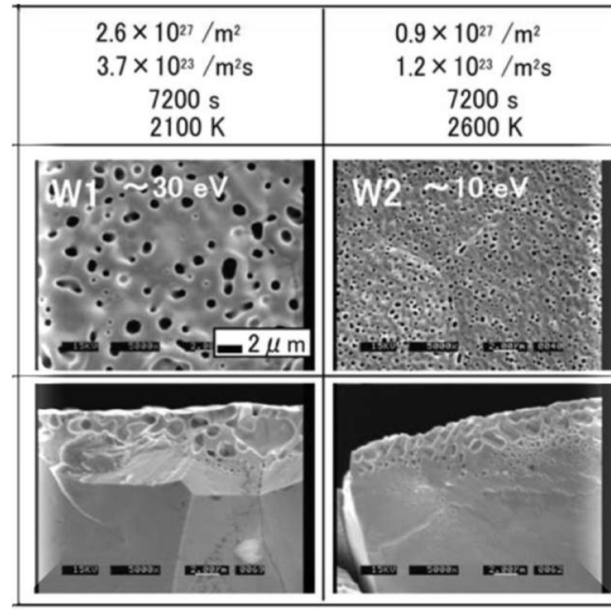
NAGDIS-II: pure He plasma

N. Ohno et al., in IAEA-TM, Vienna, 2006

1250 K, 36000 s, 3.5×10^{27} He^+/m^2, 11 eV He^+



- Surface morphology
- Evolving surface
- Nano-scale 'fuzz'



NAGDIS-II: He plasma

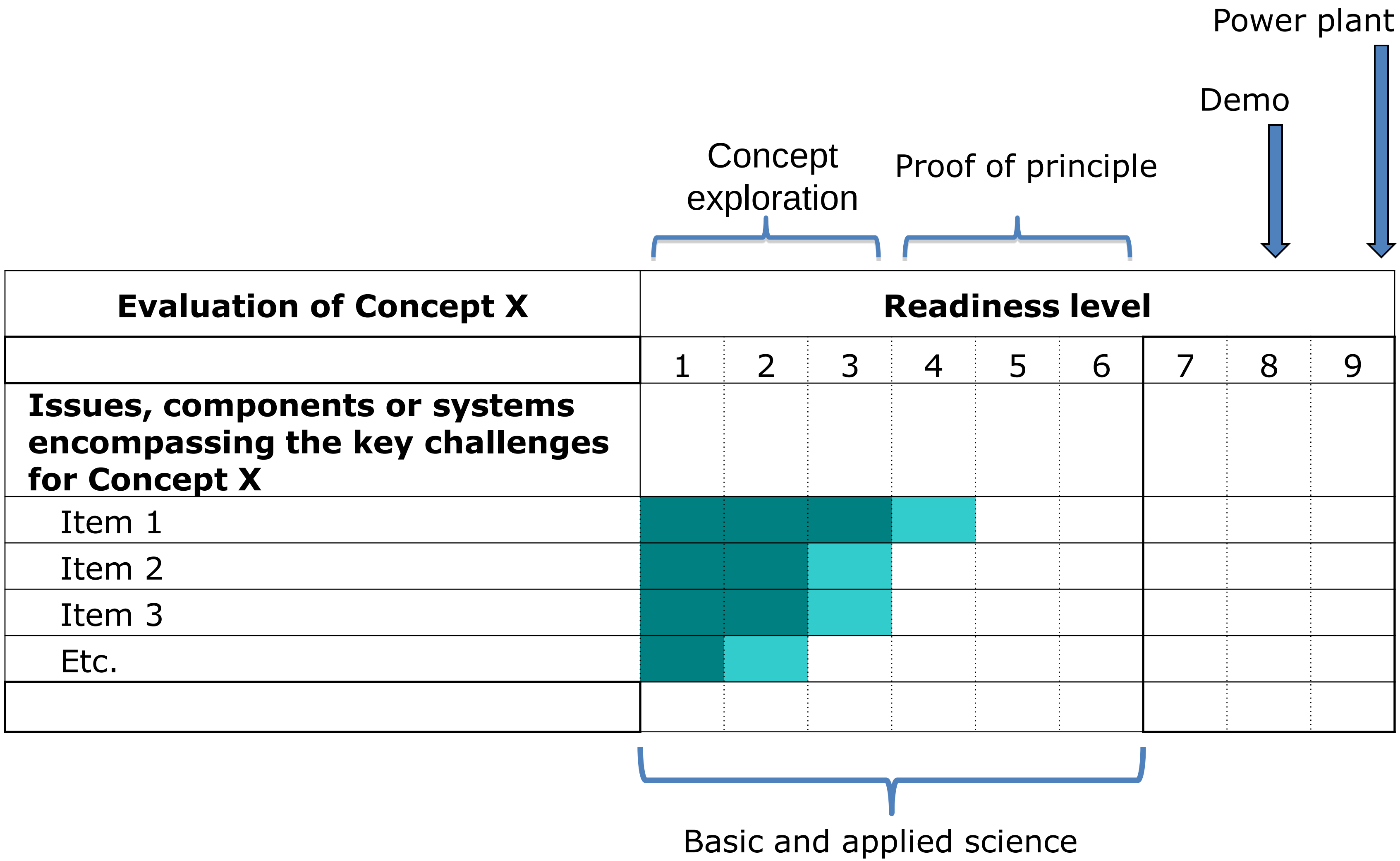
D. Nishijima et al. JNM (2004) 329-333 1029

- Surface morphology
- Shallow depth
- Micro-scale

Evaluation of Research Options involved examination of Technology Maturity and Facility Capabilities

- **Technology maturity evaluated using Technology Readiness Level (TRL) quantitative scale**
  - **Most fusion nuclear science is at a relatively immature TRL~3 (concept exploration stage)**
  - **The panel concluded optimal progress toward higher TRLs (proof of principle) is best achieved by focusing on front-runner candidates**
- **Facility capabilities to address knowledge gaps were examined for a broad range of scientific phenomena**
  - **A series of charts were constructed to quantify the contribution of different facilities to resolving knowledge gaps**

Readiness levels identify R&D gaps between the present status and any level of achievement, for a particular concept. They help to identify which steps are needed next.



TRL's can be applied to components

	Generic Definition	Blanket Subsystem-Specific Definition
1	Basic principles observed and formulated.	System studies define tradeoffs &requirements: heat loads, tritium breeding, magnetic effects (MHD, loads under off-normal operation scenarios), material constraints (temperature, stress, tritium inventory, radiation effects).
2	Technology concepts and/or applications formulated.	Blanket concepts including breeding material, structural material and cooling configuration explored. Critical parameters characterized.
3	Analytical and experimental demonstration of critical function and/or proof of concept.	Coupon-scale experiments on heat loads (and thermal-hydraulic), tritium generation and mass transfer; modeling of governing heat transfer, thermal-hydraulic (including MHD) and mass transfer processes (tritium behavior and possibly corrosion) as demonstration of function of blanket concept. Maintenance methods explored.
4	Component and/or bench-scale validation in a laboratory environment.	Bench-scale validation through submodule testing in lab environment simulating heat fluxes or magnetic field over long times, and of mockups under neutron irradiation at representative levels and durations. Maintenance methods tested at lab-scale.
5	Component and/or breadboard validation in a relevant environment.	Integrated module in: (1) an environment simulating the integration of heat loads and magnetic fields (if important for concept) at prototypical levels over long times; and (2) an environment simulating the integration of heat loads and neutron irradiation at prototypical levels over long times. Coupon irradiation testing of structural materials to end-of-life fluence. Lab-scale demo of selected maintenance scheme for blanket unit.
6	System/subsystem model or prototype demonstration in relevant environment.	Integrated subsystem testing in an environment simulating the integration of heat loads and neutron irradiation (and magnetic fields if important for concept) at prototypical levels over long times. Full-scale demonstration of maintenance scheme.
7	System prototype demonstration in an operational environment.	Prototypic blanket system demonstration in a fusion machine (for chosen confinement), including demonstration of maintenance scheme in an operational environment.
8	Actual system completed and qualified through test and demonstration	Actual blanket system demonstration and qualification in a fusion machine (for chosen confinement) over long operating times. Maintenance scheme demonstrated and qualified.
9	Actual system proven through successful mission operations	Actual blanket system operation to end-of-life in fusion power plant (DEMO) with operational conditions and all interfacing subsystems.

M. Tillack

Contribution of major facilities to PMI science and technology issues

Red: TRL 1-3 issues
Yellow: TRL 4-6 issues
Green: TRL 7-9 issues

ITER FNSF Demo

Major Science & technology issues: Plasma-Material Interactions

Facility	Plasma test stands	Non-DT confinement: inductive, low T	Non-DT confinement: non-inductive, low T	Non-DT confinement: non-inductive, high T	ITER: DT, inductive, low T	FNSF: DT, non-inductive, high T	DEMO
Divertor + Wall PMI							
Quiescent plasma heat/energy exhaust	1.-3. Sheath heat transmission, basica parallel plasma physics	3.-5. Non-stationary T, but possible high parallel power loading at small size	3.-5. Varying P/S ~ 0.2 - 1 MW/m2, activley cooled water	3.-6. Varying P/S ~ 0.5 - 1 MW/m2, activley cooled with gas, constant T	4.-5. Power density P/S~0.2 MW/m2,at reactor size, water cooled	7 - 8. Power density P/S~1 MW/m2, peak <10 MW/m2 one year /w neutron damage	
Transient plasma heat exhaust	1.-3. Surface response > 0.1 MJ/m2	4.-5. Disruption/ELM dynamics, too low W/S<0.02 MJ/m2			5.-7. Enery density W/S ~0.5 MJ/m2 in ~ms, pulsed	6.-7. Energy density W/S~0.5 MJ/m2 for one year	7.-8. Energy density W/S~1.5 MJ/m2 for one year
Erosion control	1.-3. Sputter yield + morphology evolution	4.-5. Cumulative erosion < 10 microns/year, local measurement rates + plasma Te reduction for control	4.-6. Cumulative erosion per shot > micron --> cumulative yearly erosion ~ mm		4.-5. Erosion at reactor size, W/C divertor, pulsed	7.-8. Peak divertor erosion < 5-10 mm/year, main-wall erosion < mm /year	
Dust and redeposit control	1.-3. Response of redeposits to plasma load, dust transport	3.-4. Basics of dust production and transport, redeposit properties	4.-5. Basics of dust production and transport, redeposits at cumulative depths > 0.1-1 mm	4.-6. Basics of dust production... > 0.1-1 mm with T > 500 C	4.-5. Deposits at reactor size, T<200 C	7.-8. <10-100 kg mobile dust, no disrupting UFOs from deposits after one year (~1e4 kg eroded)	
Tritium fuel retention	1.-4. Implantation & permeation from RT to > 500 C	3. High recycling but low and varying T	3.-4. High recycling with constant low T	4.-6. High recycling with constant high T	4.-5. Beryllium or carbon at low T, reactor-level inventory	7.-8. < 1 kg retained tritium per year, T>500 C	
Fueling, burn fraction & ash control		3.-4. Helium confinement, transport, de-enrichment		4.-5. Helium recycling control with hot W + surface morphology (fuzz)	4.-6. Fueling at reactor size, divertor He ash exhaust required	7.-8. <10% density variation, burn fraction > 1%, core He < 10% for one year	
Integrated viability of PMI with core plasma		3.-5. Core contamination, Zeff	3.-6. Erosion and power control at non-inductive densities towards P/S ~ 1 MW/m2		4.-5. Inductive scenario with low T walls	6.-7. Robust non-inductive low-Q scenario near density limit & heat removal limit	7.-8. Robust non-inductive high-Q scenario near density limit & heat removal limit
Integrated viability of PMI + nuclear damage effects	4. Irradiated sample testing					6.-7. <10 dpa radiation damage, ~30 TJ/m2 convected energy	7.-8. >10 dpa radiation damage, > 30 TJ/m2 convected energy

The numbers in the table cells refer to estimated TRLs

Contribution of major facilities to PFC development

ITER FNSF Demo

Facility	test stands and design studies	Short pulse toroidal devices; upgraded test stands	Non-nuclear SS Toroidal Devices	ITER and ITER TBM	PFC test device and/or Blanket Test Stand	FNSF	DEMO
Device Requirements for PFC Development							
Understand power flow, predict heat loads	2 edge modeling, development of new diagnostics	3 edge modeling, deployment of new diagnostics	5 better models, new diagnostics, more power	4 improved edge modeling, ITER H and D plasmas	*materials for diagnostics in IFMIF*	7 predictive models, right plasma edge (need rad-hard diag.)	8 confirm peformance for DEMO size & power
Relevant divertor size (area ratio to FW)	3 design studies	?4 MAST Super-X divertor experiment	5 EAST or other	3 ITER plasmas, wrong divertor	?6 PFC Test Device	7 right configuration, based on modeling	8 confirm peformance for DEMO size & power
DEMO relevant disruption mitigation	3 modeling, design studies	4 improved models, DIII-D experiments	5 improved techniques, experiments	6 ITER plasmas, system information, wrong edge plasma	?6 PFC Test Device	7 solution with right plasma	8 confirm peformance for DEMO size & power
Representative edge (density; parallel power flux)	3 modeling, design studies	4 improved models, experiments	5 better models, higher power	4 ITER plasmas, system information, wrong edge plasma	?6 PFC Test Device	7 solution with right plasma	8 confirm peformance for DEMO size & power
Solid PFC Configuration			develop poloidal limiters				
Relevant high temp operation	3 design studies, HHF Tests 400-600C, small mockups	4 design studies; HHF Tests 600-800C; hot wall tiles	5 400-600C PFCs	*some experience with recessed FW*	*NA*	8 relevant operation, confirm performance	8 preferred, optimized mat. & tempertures
DEMO relevant launchers, mirrors, etc.	2 modeling, design studies	3 better models & designs, HHF experiments	5 mature designs, deployed units, confirm performance	4 ITER plasmas, system information, wrong edge plasma	?6 PFC Test Device	7 relevant operation, confirm performance	8 preferred, optimized mat. & tempertures
W-based divertor	2-3 design studies, HHF experiments	4 HHF mockups; W tiles, hot wall (C-MOD); W div EAST	5 W div East-U (higher power) & Satellites	4 W div in ITER H & D plasmas	*divertor materials in IFMIF*	7 relevant operation, confirm performance	8 preferred, optimized mat. & tempertures
W-based limiters, recessed or highly-shaped high temp FW	2-3 design studies, HHF experiments	4 improved models, HHF experiments	?5 deployed W lim & recessed FW	*data from port plugs, FW modules*	*FW materialsin IFMIF*	7 relevant operation, confirm performance	8 preferred, optimized mat. &
Understand PFC failure modes, predict lifetime	2-3 design studies, HHF experiments	4 improved models, HHF experiments	4 models + HHF tests, anecdotal data	*anectdotal data, new failure modes*	?6 PFC Test Device	6-7 real data, predictive models, benchmarks	8 mature models, optimized mat.
Demonstrate acceptable div. life	2 design studies, HHF tests 400-600C	3 improved models; HHF tests, He-600C; He-cooled div., EAST	4 hot He-cooled W div East-U (more power) & Satellites	*anectdotal data*	*test samples with n-damage*	7 real data, confirm performance, models, data 20 dpa; He-600C	8 opt. mat., confirm performance, data 50-100 dpa; He-600C
Demonstrate acceptable life, integrated FW	2 design studies, HHF tests 400-600C	3 improved models; HHF tests, He-600C and blanket coolant	*NA*	*anectdotal data, shaped FW*	4-5 Blanket Test Stand	7 real data, confirm performance, models, data 20 dpa; He-600C	8 opt. mat., confirm performance, data 50-100 dpa; He-600C
Liquid Divertor (with solid FW)							
Demonstrated heat removal	2 modeling, design studies	3 improved models, HHF tests small area	4-5 HHF mockups; deployed liq. divertor	*NA*	?5 liquid divetor test in blanket test stand	6-7design based on models, confirm performance	8 opt. mat., confirm performance
Integrated op., acceptable life	2 modeling, design studies	3 improved models, improved designs and materials data	4 improved design models, mat. irradiations and PIE	*NA*	?5 data on failures from liq. div.tests in blanket test stand	5-6 design based on models, progressive phases to confirm performance, 20 dpa	7-8 opt. mat., matue life model, 50-100 dpa
Qualified PFC Supply							
Develop/qualify divertor fabrication process	2-3 design studies;	4-6 HHF and mat tests, irrad. data, improved mat., ITER experience & processes, off-line work with vendors				7 opt. process, large material lot., good QA	8 near commercial material and QA
Develop/qualify limiter fab process	2-3 design studies;	4-6 HHF and mat tests, irrad. data, improved mat., ITER experience & processes, off-line work with vendors				7 opt. process, large material lot., good QA	8 near commercial material and QA

The numbers in the table cells refer to estimated TRLs

Contribution of major facilities to Diagnostics science and technology issues

DEMO Relavent Diagnostics R&D						ITER	FNSF	Demo
Key facilities/Hardware	Computer simulation / integrated modeling	Non-nuclear test stands (mechanical, fabrication) (HHF, PSI, LM PFC, etc)	Ion beams & fission reactors	Short pulse Toroidal devices (DIII-D, CMOD, NSTX, etc.)	Non-nuclear SS Toroidal Devices (EAST, KSTAR, JT60-SA)	ITER	FNSF	DEMO
Define Minimum Set of Measurement Requirements for DEMO Control								
DEMO relevant diagnostics		2. Can computer simulation be used to compensate for lack of spacial resolution?		3. Explore if "detuned" diagnostics can safely control the plasma				
DEMO relevant FW & divertor instrumentation		2. Prototype robust instrumentation "smart tiles,"		3. Deploy "smart tiles," on short pulse toroidal devices.				
Sensor proximity viability				2-3.Explore sensor proximity effectiveness				
Diagnostic robustness		2.Test prototypes of new diagnostic sub-elements on single-effect test stands		3.Test prototypes of new diagnostics on existing devices	4-6.. Develop prototypes of new diagnostics using reactor relevant material and test on non-nuclear devices and/or ITER		7.Test new diagnostics using reactor relevant material on FNSF	8. Validatef new diagnostics at full parameters
Material Selection of FW Components								
Material qualification: mirrors, front end effectors	2. Modeling , design studies	2.Better models & designs, HHF experiments	3. Rad. stability of joints & fabrication approaches, up to 70 dpa/no He	3.Test mirrors fabricated from reactor relevant material and test onDIII-D	4-5. Develop prototypes of mirrors fabricated from reactor relevant material and test on non-nuclear SS toroidal devices and/or ITER confirm peformance		7. Relevant operation, confim performance	8. Validatef mirror performance at full parameters
Material qualification: insulators		2. Identify candidate materials, prioritizes into primary and secondary candidates	3. Fabricate, and test samples for irradiation affects, up to 150 dpa/With He, stress.	3. Develop prototypes of ceramic insualtor material and test on existing devices	4. Develop prototypes of mirrors fabricated from reactor relevant material and test on non-nuclear SS toroidal devices and/or ITER for long pulse PMI effects			
Develop Real-Time Interpretation and Analysis of Diagnostic Measurements								
Explore real-time measurement and analysis capability	2. Evaluate enhanced modeling of diagnostic measurements			3. Demonstrate the effectiveness of modeling on DIII-D, CMOD diagnostic	4.Use detuned diag. & modeling to show effective plama control			
DEMO relevant disruption mitigation	3.Develop control tools for mitigation and recovery from "off-normal" events			3-4 Improved models, DIII-D experiments	4-5. Improved techniques, experiments	5-6. ITER Plasmas, systm information, (wrong edge plasma)	7. Validate with right plasma edge	8.Confirm performance for DEMO size & Power
Calibration, Reliability and Robustness								
In-situ Claibration		2-3. Explore real time in-situ calibration systems on single-effect test stands		4. Demonstrate techniques for in-situ diagnostic calibration	5-6. Demonstrate in-situ diagnostic calibrate on SS toroidal devices			
Integrated remote maintenance strategy		2-3. Develop large scale, radiation-hard robotic devices				6-7. Demonstrate large scale, radiation-hard robotic devices.		8.Confirm performance for DEMO size

The numbers in the table cells refer to estimated TRLs

Contribution of major facilities to Plasma Heating science and technology issues

Red: TRL 1-3 issues
Yellow: TRL 4-6 issues
Green: TRL 7-9 issues

ITER FNSF Demo

DEMO Relavent Ion Cyclotron, Lower Hybrid, and Electron Cyclotron Launcher R&D

Key Facilities/Hardware	Computer simulation / integrated modeling	Non-nuclear test stands (mechanical, fabrication) (HHF, MPRF, MWTS, etc)	Ion beams & fission reactors	Short pulse Toroidal devices (DIII-D, CMOD, NSTX, etc.)	Non-nuclear SS Toroidal Devices (EAST, KSTAR, JT60-SA)	ITER	FNSF	DEMO
Advancement of IC/LH/EC Antenna/Launcher Technology								
Improve RF Sheath & near field modeling	2-3. Improve models for sheath physics							
Measure the SOL near and in front of the IC/ LH/EC antennas/launchers		3. Validate diagnosic perfomance on plasma-wall interaction test stands.		4. Perform diagnostic perfomance validation on DIII-D, CMOD & NSTX	5-6. Perfom diagnostic perfomance validation on SS toroidal devices			
Effects of heat load, neutrons & T retention on antenna/launcher materials	2. Model heat and particle fluxes to high-power, energized components.	2-3. Qualify structural, shield and coating material for antennas/launchers	3. Test coating techniques a advanced refractory alloys a doping	3.-4. Develop and test designs that incorporate active cooling	5-6. Validate antenna/ launcher performance on SS toroidal devices.	6.-7.Evaluate the anticipated contribution to dust formation from the materials selected for IC/LH/EC antenna/launcher front ends		8. Validate IC/LH/ EC antennas/launchers at full parameters
Increase Antenna/Launcher Power Density								
Validate new IC/LH/EC antenna/launcher concepts	2. Develop improved models of the properties that cause arcing.	3. Validate antenna/launcher concepts on long pulse MPRF, MWTS test stands		3. Test advanced IC/LH/EC antennas/launchers on non-nuclear facilities	4-5. Test IC/LH/EC antenna/ launcher concepts using nuclear grade materials	6. Test advanced IC/LH/EC Antennas/launchers in a nuclear environmen	7.Perform engineering validation (RAMI) on a FNSF device	8. Validate advanced IC/LH/EC antennas/ launchers at full parameters

The numbers in the table cells refer to estimated TRLs

Contribution of major facilities to Materials degradation science and technology issues

Red: TRL 1-3 issues
Yellow: TRL 4-6 issues
Green: TRL 7-9 issues

				ITER-TBM	Non-nuclear test stands	Fusion-relevant neutron source	FNSF	Demo
Facility	Non-nuclear Test Stands (thermo-mechanical)	Non-nuclear Test Stands (corrosion)	Ion beams and Fission Reactors	ITER TBM	Non-nuclear Test Stands (partially integrated)	Fusion Relevant Intense Neutron Source	Fusion Nuclear Science Facility	DEMO
First-Wall/Blanket Structural & Vacuum Vessel Materials								
Science-based design criteria (thermo-mechanical strength)	2. Develop high temperature creep-fatigue design rules for nuclear components				4. Validate high temperature creep-fatigue design rules w/o irradiation	5. Validate irradiated high temp structural design criteria (50-150 dpa with He, stress)	7. Code qualified designs	7-8. Code qualified designs
Explore fabrication & joining tradeoffs	2. Conventional & advanced manufacturing technologies	2. Loop tests of joints & novel fabrication approaches	2. Rad. stability of joints & novel fabrication approaches		5. Validate near prototypic fabrication and joining technology w/o irradiation	6. Validate near-prototypic fabrication & joining technology (50-150 dpa with He, stress)	7. Demo-relevant fab processes	8. Prototypic advanced fabrication
Resolve compatibility & corrosion issues		3. Basic and complex flow loops			5. Validate corrosion models w/o irradiation		7. Near prototypic operating environment	8. Prototypic extended operating environment
Scientific exploration of fundamental radiation effects in a fusion relevant environment			3. Up to 150 dpa/With He, stress (ion beams, fission reactors)			6. 50 - 150 dpa/With He and stress		
Material qualification: Structural stability in fusion environment (e.g., void swelling, irradiation creep)			3. Up to 70 dpa/no He (fission reactors)	2. Materials behavior in a low-dose, low-temp. env. (not Demo-relevant matl, <2 dpa, low temperature)		6. 50 - 150 dpa/With He and stress	7. 10 - 50 dpa, Demo prototypic environment	7-8. Prototypic operation, 50 - 150 dpa/With He/Fully Integrated
Material qualification: Mechanical integrity in fusion environment (e.g., strength, rad resistance, lifetime)	2. Unirrad. mech. prop. data (tensile, creep, fatigue, fract. toughness, da/dN, etc)		3. Up to 70 dpa/no He (fission reactors)	2. Materials behavior in a low-dose, low-temp. env. (not Demo-relevant matl, <2 dpa, low temperature)	5. Qualify components w/o irradiation	6. 50 - 150 dpa/With He and stress	7. 10 - 50 dpa, Demo prototypic environment	7-8. Prototypic operation, 50 - 150 dpa/With He/Fully Integrated
Fusion environment effects on tritium retention & permeation		2. Unirradiated diffusion and permeation data	3. Effect of radiation damage at Demo-relevant temperatures			6. Demo-relevant materials (up to 50-150 dpa with He at correct temp.)	7. System-scale tritium permeation and loss mechanisms	7-8. Prototypic permeation & losses

Contribution of major facilities to DCLL chamber blanket science and technology issues

Red: TRL 1-3 issues
Yellow: TRL 4-6 issues
Green: TRL 7-9 issues

			Tritium science facilities	ITER-TBM	FNSF	Demo
Tritium Breeding Blanket Systems						
Key Experiments	**Basic Experiments**	**Development Experiments (e.g. PMTF, MTOR, others)**	**Partially-Integrated (e.g. BT3F, TBEF)**	**ITER-TBM**	**FNSF**	**DEMO**
Performance Requirement						
Helium Temp/Flow Rate/Pressure per blanket module	gas bottle discharge or air simulant	600C, 0.1 kg/s, 4 Mpa	500C, 1.5 kg/s, 8 MPa	500C, 1.5 kg/s, 8 MPa	500C, 3 kg/s, 8 MPa	500C, 3 kg/s, 8 MPa
PbLi Temp/Flow Rate/Pressure per blanket module	PbLi properities, static testing, MHD	400C, 5 kg/s, 0.2 MPa	700C, 30 kg/s, 1 MPa	700C, 30 kg/s, 1 MPa	700C, 50 kg/s, 2 MPa	700C, 50 kg/s, 2 MPa
Surface Heating, module area	Contact heaters on small samples	1 MW/m2, 1 m2	0.5 MW/m2, 2 m2	0.3 MW/m2, 1.5 m2	0.5 MW/m2, 4 m2	0.5 MW/m2, 4 m2
Tritium extraction rate	Property measurements	Concept tests	~0.002 g/hr	~0.002 g/hr	2 g/hr	13 g/hr
Fraction tritium recovered	Property measurements	30% (7)	99.9%	90%	99.99%	99.99%
Magnetic Field	NA	2 T	2 T	4 T + poloidal field	5 T + poloidal field	8 T + poloidal field
Volumentric heated (as NWL), volume	NA	simulated w/ heaters, 0.01 m3	sim. w/ heaters, 2 m3	0.7 MW/m2 wall load, 0.5 m3	1-2 MW/m2, 2 m3	2-3 MW/m2, 2 m3
Max Operating time to replacement	NA	months	months to years	2 years	2-10 years	5 years
Tritium production per module, TBR	Cross-sections	NA	Coupling to fission or accelerator source	0.002 g/hr, 0.5	0.04 g/hr, >1 .0	0.07 g/hr, > 1.05
Tritium containment	NA	NA	Concept tests	Collect data	Fully Integrated	Fully integrated
No. Modules	NA	NA	1	6	50	200
Availability (on demand)	NA	NA	0.7	0.85	0.9	0.95
Duty factor (annual)	NA	NA	0.5	0.05	0.3	0.5
Pulse length w/ integrated conditions	NA	NA	weeks	1 hr	weeks	months
Fusion Fluence per component	NA	NA	NA	0.1 MW.yr/m2	1-6 MW.yr/m2	7.5 MW.yr/m2

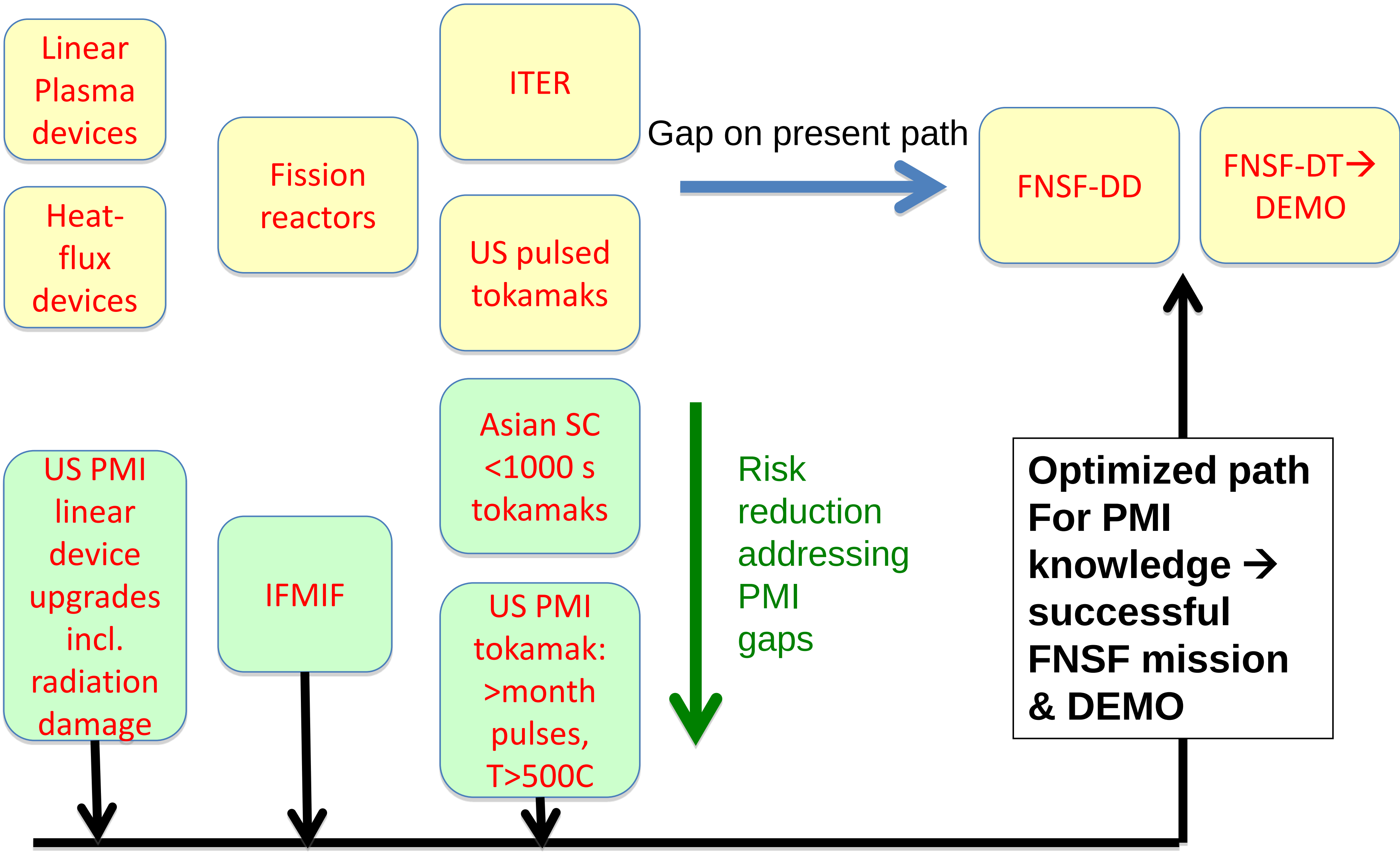
Contribution of major facilities to Tritium science and technology issues

Red: TRL 1-3 issues
Yellow: TRL 4-6 issues
Green: TRL 7-9 issues

ITER, FCDF FNSF Demo

Tritium Processing Systems						
Key Experiments	**Basic experiments**	**Development experiments**	**Partially-Integrated (e.g. TSTA/TFTR/JET)**	**ITER, FCDF**	**FNSF, FCDF**	**DEMO**
Performance Requirement						
Supplied T Conc	Few%	10's of %	50%	50%	50%	50%
DT Flowrate	Low sccm	high sccm	6 SLPM	120 SLPM	80 SLPM	120 SLPM
Tritium inventory	~1 gm	~10 gm	100 gm	4000 gm	4000 gm	6000 gm
Tritium containment	Hoods	Standalone confinement and detritiation	Partially integrated confinment and accident response	Fully integrated confinment and accident response	Fully integrated confinment and accident response	Fully integrated confinment and accident response
Recycle time requirement	NA	NA	24 hr	1 hr	1 hr	1 hr
Degree of integration	NA	NA	70%	85%	100%	100%
Overall Facility Size	NA	NA	3000 m3	40000 m3	35000 m3	30000 m3
DEMO relevance	NA	NA	0.3	0.6	0.85	1
Availability (on demand) (%)	NA	NA	70	85	90	95
Duty factor (annual)	NA	NA	5	5	30	50

Example of PMI-PFC Facilities Options Assessment



Panel Findings regarding R&D options

Overarching findings

- **Time to focus:** Research to explore the scientific proof of principle for fusion energy (TRL>3) is most expediently accomplished by focusing research activities on the most technologically advanced option.
- **Time to make selective reinvestments:** Most existing US fusion technology test stands are no longer unique or world-leading. However, numerous compelling opportunities for high-impact fusion research may be achievable by making modifications to existing facilities and/or moderate investment in new medium-scale facilities.

Panel Findings regarding R&D options

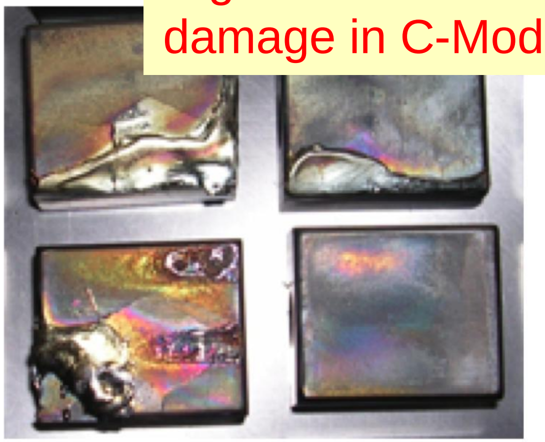
Plasma-material interactions findings

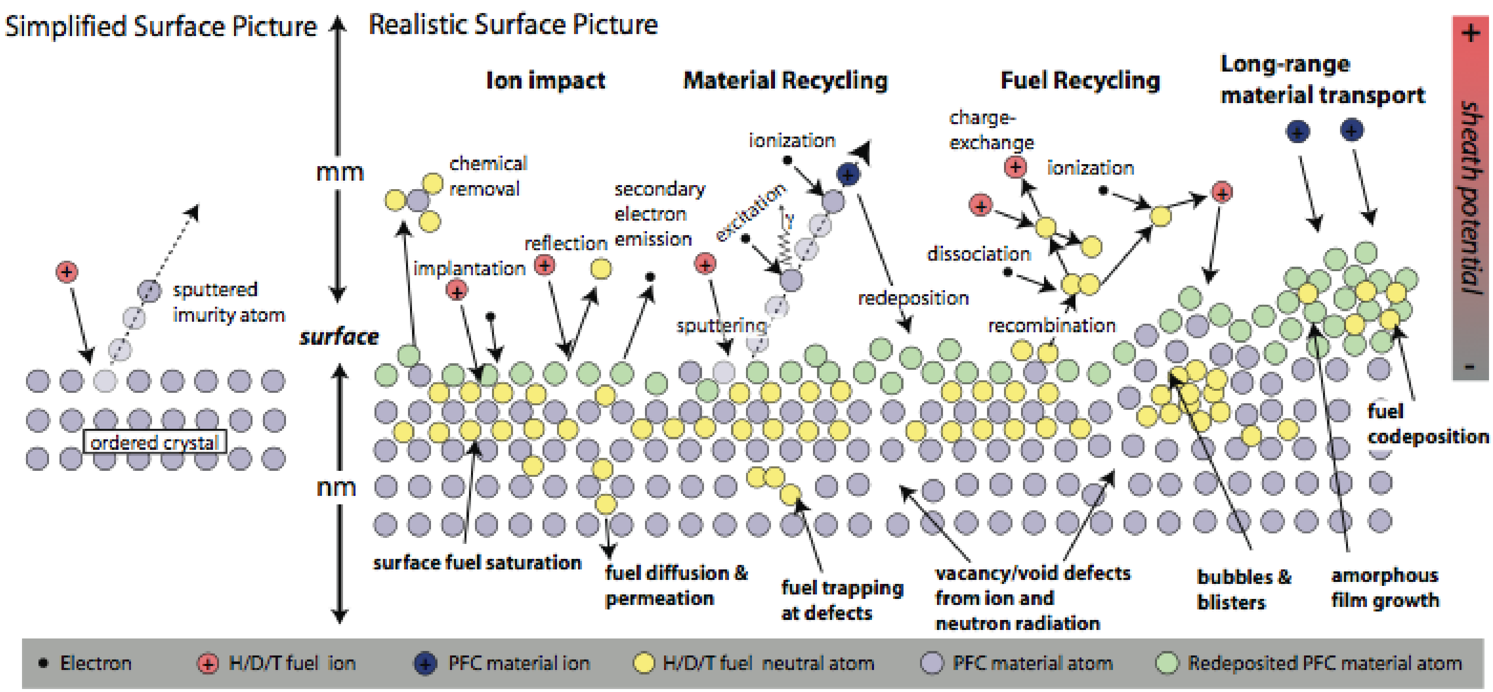
- **P1. Power handling on the first wall, divertor, and special plasma facing components is challenging in steady state, and is severely aggravated by non-steady loading.**
  - Efforts to mitigate transient and off-normal loads are critical, requiring compromises between loading conditions, plasma operating modes, material properties optimization, design solutions, and component lifetimes.
- **P2. Materials suitable for plasma facing components (PFCs) are limited and their performance in the fusion environment is highly uncertain.**
  - Establishing material and design candidates will require significant efforts in experimentation and multi-scale simulation, and the coupling of plasma science, materials science, and advanced engineering and manufacturing technology.

Plasma-material interactions

- **P1. Power handling on the first wall, divertor, and special plasma facing components is challenging in steady state, and is severely aggravated by non-steady loading.**
- **P3. Observing behavior at the plasma material interface during integrated <u>month-long plasma operation</u> AND at <u>relevant high temperatures</u> requires capabilities beyond present day and planned facilities.**

High-Z metal melt damage in C-Mod





Panel Findings regarding R&D options

Plasma-material interactions findings (continued)

- **P3. Observing behavior at the plasma material interface during integrated month-long plasma operation requires capabilities beyond present day and planned facilities.**
  - Predicting the long-term system behavior in light of this response requires some combination of non-nuclear month-long plasma PFC/PMI linear and confinement facilities and an extensive non-nuclear (or DD) phase of FNSF in order to alleviate risk to the nuclear (DT) phase of the FNSF.
- **P4. Developing measurement systems and the launching structures for plasma heating, that can survive the fusion environment, is a significant challenge.**
  - A significant effort is required to establish viable materials, configurations, operating modes, and overall feasibility in the combined plasma and nuclear loading conditions expected in a FNSF.

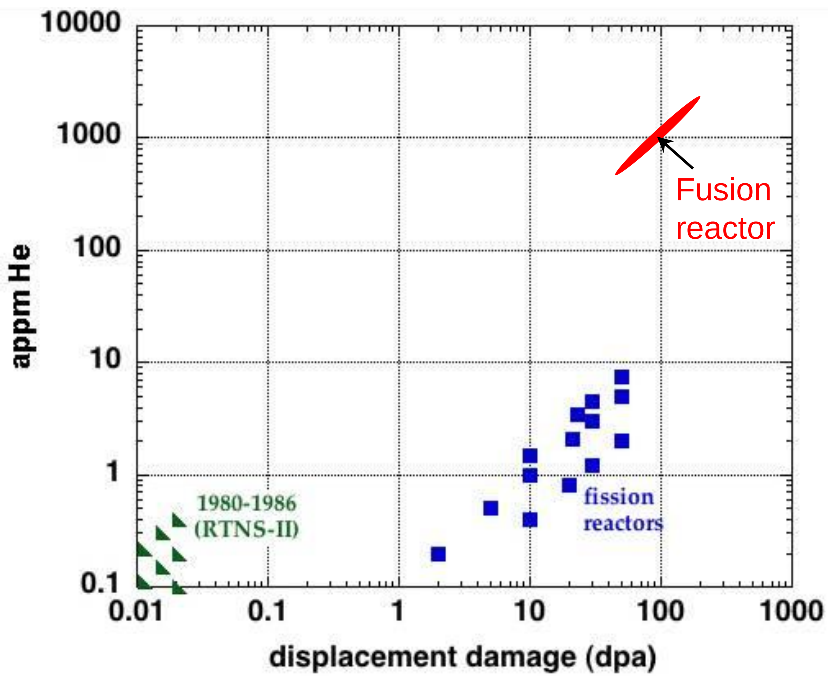
Panel Findings regarding R&D options

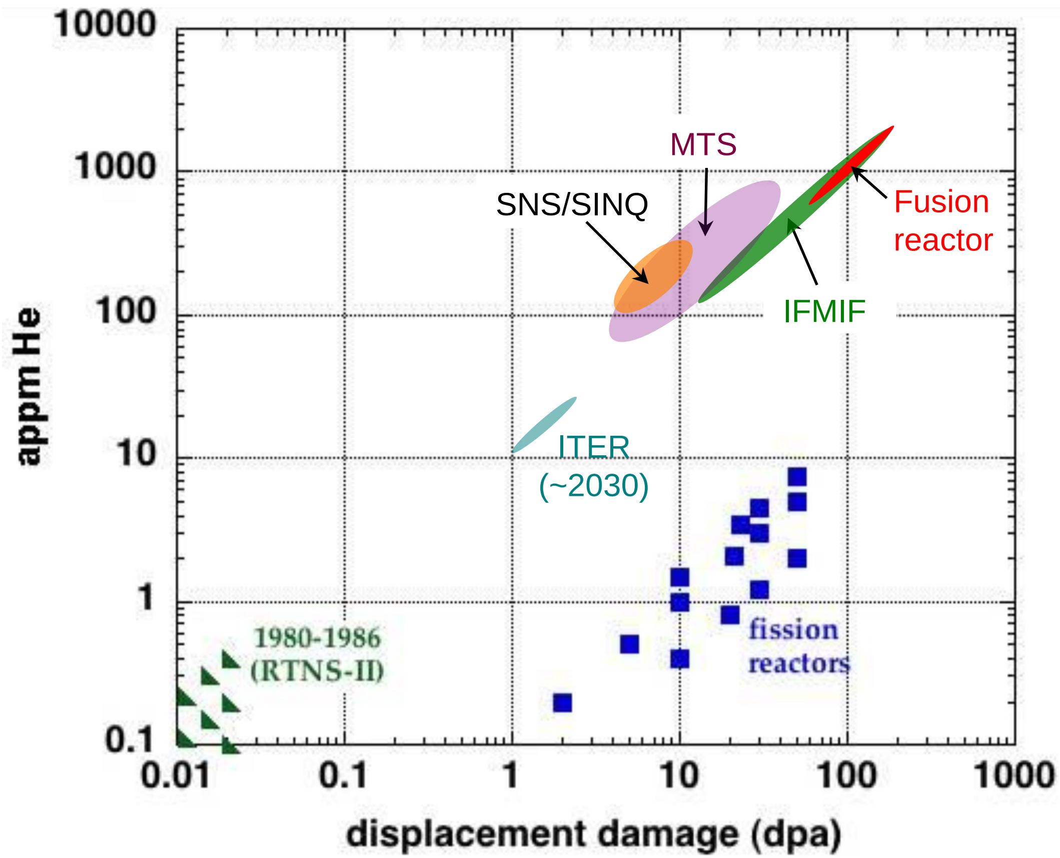
Degradation of materials & structures findings

- **D1. The lack of an intense fusion relevant neutron source for conducting accelerated single-variable experiments is the largest obstacle to achieving a rigorous scientific understanding and developing effective strategies for mitigating neutron-induced material degradation.**
- **D3. Knowledge of the processes controlling tritium permeation and trapping in advanced nanostructured alloys designed to manage high levels of helium is inadequate to ensure safe operation of next-step plasma devices.**

There are several options to close the current knowledge gap in fusion-relevant radiation effects in materials

Current knowledge base





Option A: IFMIF + fission reactors +ion beams + modeling
Option B: robust spallation (MTS) + fission reactors + ion beams + modeling
Option C: modest spallation (SNS/SINQ) + fission reactors + ion beams + modeling

Panel Findings regarding R&D options

Degradation of materials & structures findings (cont’d)

- **D4. Current understanding of the thermo-mechanical behavior and chemical compatibility of structural materials in the fusion environment is insufficient to enable successful design and construction of blankets for next-step plasma devices.**
- **D5. Disruptive advances in fabrication and joining technologies may offer new routes to high-performance materials with properties that enable construction of fusion power systems that fulfill safety, economic and environmental attractiveness goals.**
- **D6. The performance and economics of Magnetic Fusion Energy is significantly influenced by magnet technology.**
  - There is value in continuously exploring improvements in superconducting magnet capability

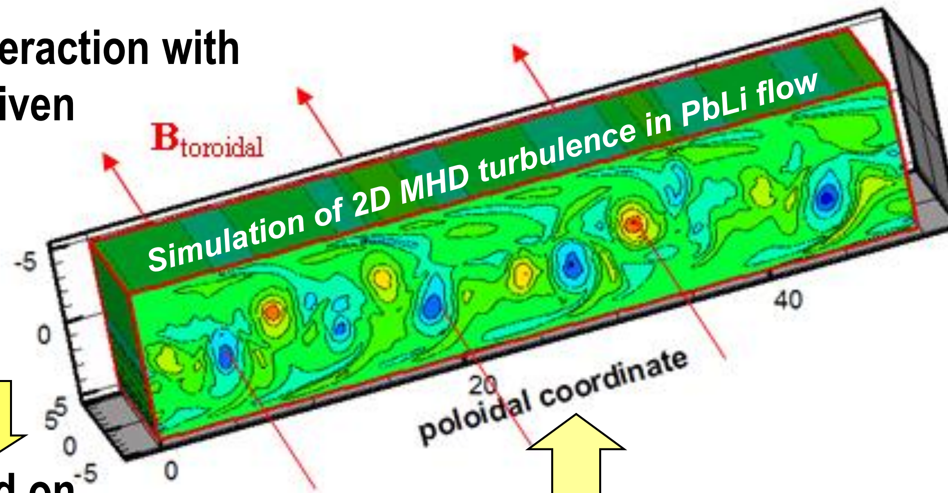
Panel Findings regarding R&D options

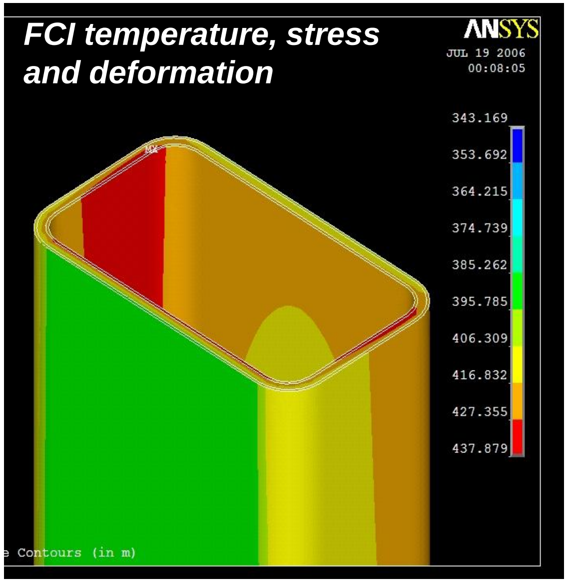
Harnessing Fusion Power findings

- **H1, H2. The ultimate attractiveness of a fusion system depends on the performance of power extraction and tritium breeding systems that surround the plasma.**
  - But, at present these systems are at a low TRL with high uncertainty as to the performance of envisioned solutions and material systems.
  - Efforts to improve current knowledge are hampered due to a lack of resources and test facilities.
- **H3. The US has developed a potentially attractive family of first wall / blanket concepts**
  - based on the use of Pb-Li as a breeder/coolant, separate gas cooling of reduced activation ferritic steel first wall and structure, and the use of thermal / electrical insulating inserts based on silicon carbide.

Harnessing fusion power

- PbLi flow is strongly influenced by MHD interaction with plasma confinement field and buoyancy-driven convection driven by spatially non-uniform volumetric nuclear heating
- Temperature and thermal stress of SiC FCI are determined by this MHD flow and convective heat transport processes
- Deformation and cracking of the FCI depend on FCI temperature and thermal stress coupled with early-life radiation damage effects in ceramics
- Cracking and movement of the FCIs will strongly influence MHD flow behavior by opening up new conduction paths that change electric current profiles





- **PbLi / DCLL is a potentially attractive blanket concept developed in the US**
- **But, higher TRL level multi-effect and integrated interactions must be explored**

Panel Findings regarding R&D options

Harnessing Fusion Power findings (continued)

- **H4. Public acceptance and safety of fusion energy is strongly dependent upon the ability to reliably control the chemistry and permeation of tritium**
  - (compared to fission reactors, fusion requires five orders of magnitude better control of tritium losses per unit of production).
  - ITER represents a large step forward in the handling of DEMO scale tritium flow rate, but ITER tritium systems will not be available to serve as test facilities to develop improvements still needed in processing time and system availability.
  - The ITER device does not address removal and processing of tritium from candidate breeder blanket systems.
- **H5. A fully integrated and coherent US strategy to develop and utilize non-nuclear test facilities, irradiation facilities, and fusion devices to understand the engineering feasibility in-vessel materials and components is needed.**

Panel overarching recommendations

- **Now is an appropriate time to focus:** As fusion nuclear science matures from concept exploration studies (TRL 1-3) to more complex proof of principle studies (TRL 4-6), it is appropriate to focus R&D on front-runner concepts.
- **Moderate facility investments should be considered:** Numerous fusion nuclear science feasibility issues can be effectively investigated during the next 5 to 10 years by efficient use of medium-scale facilities.
  - Several facilities, e.g. Fast neutron source, Blanket Thermofluid / Thermomechanics, Linear Plasma Device, etc. are explored in the report
- **The key mission of the next step device beyond ITER should be to explore the integrated response of tritium fuel, materials and components in the extreme fusion environment in order to provide the knowledge bases to contain, conquer, harness and sustain a burning DT plasma at high temperatures.**

Panel recommendations on Plasma-material interactions

- **P1. Significant confinement plasma science initiatives are required to provide any confidence in the extrapolated steady and transient power loadings of material surfaces for a FNSF/DEMO.**
- **P2. The leading FNSF/DEMO candidate solid material to meet the variety of PFC material requirements is tungsten.**
  - Several new initiatives should be started in the near term to resolve major feasibility questions
- **P3. Opportunities to access plasma pulse lengths in relevant exposure environments must be pursued in order to bridge the large gap in pulse lengths between present experiments and FNSF/DEMO.**
  - Linear plasma devices and a non-nuclear PMI facility
- **P4. Substantial effort in the areas of measurements (and their diagnostics) and heating/current drive systems that can survive the harsh FNSF environment should be maintained.**

Panel recommendations on Material degradation

- D1. Re-engagement in the IFMIF Broader Approach Engineering Validation and Engineering Design Activity (EVEDA) should be initiated, in parallel with limited-scope neutron irradiation studies in upgraded existing spallation sources such as SINQ or SNS.
- D2. A detailed engineering design activity should begin that is closely integrated with materials research activities including ~20 dpa data from SINQ or SNS to permit selection of a prime candidate reduced activation steel for FNSF.
- D3. A robust experimental and theoretical effort should be initiated to resolve scientific questions associated with the permeation and trapping of hydrogen isotopes in neutron-irradiated materials with microstructures designed to mitigate transmutation produced helium.
- D4. Science-based high-temperature design criteria and fundamental studies of chemical compatibility in the fusion environment should be significantly enhanced.

Panel recommendations on Harnessing fusion power

- **H1. Develop a fully integrated strategy to advance the scientific and engineering basis for power extraction and tritium breeding systems.**
- **H2. Examine key feasibility issues for Pb-Li blanket concepts as soon as possible**
  - T_2 extraction from hot Pb-Li, MHD flow effects, chemical compatibility, etc.
- **H3. Predictive capabilities that can simulate time-varying temperature, mass transport, and mechanical response of blanket components and systems should be emphasized.**
- **H4. Near-term research should be initiated on blanket and tritium extraction systems performance and reliability with prototypic geometry and loads**
  - Explore possibility of unanticipated synergistic effects

Panel statement on role of computational modeling

- **Computational modeling is viewed as an essential, integral component to fusion nuclear science R&D**
  - Particularly for multiple-effects phenomena associated with proof of principle research (TRL4-6), computational modeling is essential to guide and interpret experimental studies
- For the same reasons that experimental research without robust modeling is sub-optimal, computational research in isolation as a proxy to experiment is not recommended
  - The most expedient and cost-effective approach to fusion research involves careful integration of modeling, computational studies, and experimental research

Conclusions

- A careful focusing of breeding blanket and T_2 transport/recovery options to front-runner candidates is recommended to accelerate the development of fusion energy
- Utilization of a systems approach is important for prioritizing scope and schedule of R&D activities
- Considering the large gap in technology readiness between what will be obtained from ITER and medium-scale fusion facilities, an FNSF that focuses on the integrated response of tritium fuel, materials and components in the extreme fusion environment is recommended
    - Specific aspects of the potential vision of this facility need further analysis and research community input