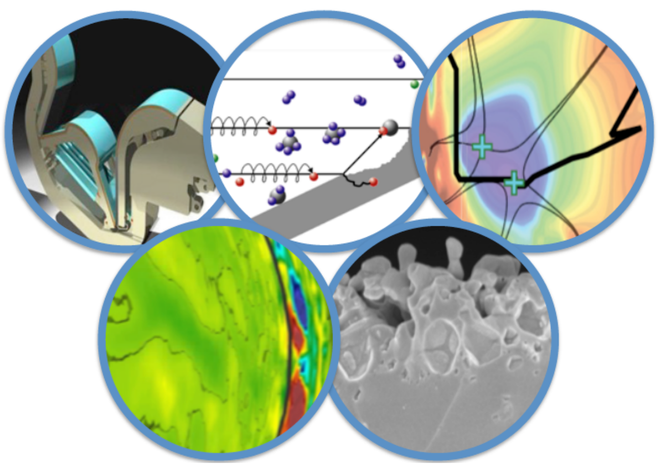
PMI Community Workshop Summary

Workshop Leaders: R. Maingi, S. Zinkle

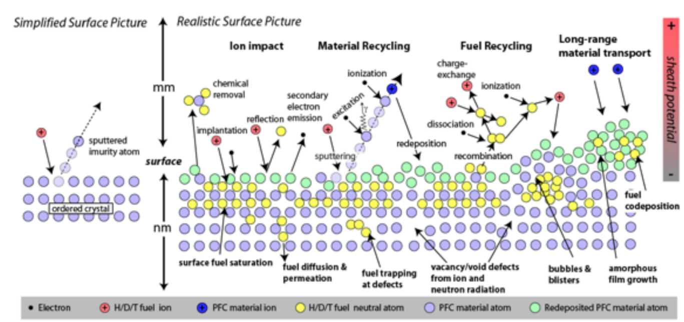
Topical group leaders: J.P. Allain, R. Doerner, H.Y. Guo, A. Hubbard, C. Kessel, B. LaBombard, A. Leonard, D. Youchison

Cross-cutting advisors: D. Hill, D. Hillis, J. Menard, H. Neilson, D. Whyte

FES contact: M. Foster



FESAC meeting
Bethesda, MD
Jan. 13-14, 2016



Outline

- Process and broad leadership team

- Priority Research Directions - 5
  - These overlap the existing domestic research in PMI, but suggestions are made to extend the research in certain areas

- Cross-cutting research opportunities - 4
  - Elements that cut across the Priority Research Directions, offering the opportunity to leverage particular areas

Goal: evaluate leading scientific challenges and options in area of plasma-materials interactions (10 year outlook)

- ReNeW community activity (2009) as a starting point, and examined reports from follow-on FESAC studies
  - 4 thrusts in PMI theme at ReNeW, used to organize a sub-panel of ~ 10 experts per thrust for this activity
- Guidance: consider enhancements in
  - Existing facility capabilities
  - Theory, computation and validation
  - International collaborations
  - New starts
- Challenges are forward-looking: PMI harder for reactors
- ITER important element, but no ITER data expected in next ten years

Process modeled after Basic Research Needs Workshops used in Basic Energy Sciences

- Call for white papers: 77 submissions
- Face-to-face workshop: May 4-7, 2015 @ PPPL – 55 talks
  - Many sub-group and executive committee conference calls before and after the workshop
- Community feedback webinar 6/30/15
- Final report submitted 8/21/15
  - Identified 5 (separable) Priority Research Directions (PRDs)
  - Identified 4 Cross-Cutting Research Opportunities across PRDs
  - **No prioritization** across PRDs and cross-cutting research opportunities

Multi-institutional team from Industry, *ITER*, National Labs, & Universities

SOL & divertor physics (ReNeW Thrust #9):

- Leader/Deputy: H.Y. Guo (GA), B. LaBombard (MIT)
- Panelists: R. Goldston (PPPL), I. Hutchinson (MIT), S. Krashenninikov (UCSD), J. Myra (Lodestar), V. Soukhanovskii (LLNL), P. Stangeby (U. Toronto), P. Valanju (U. Texas), X. Xu (LLNL)

Advancing PMI science and innovation (ReNeW Thrust #10 and part of #14):

- Leader/Deputy: J.P. Allain (UIUC), R. Doerner (UCSD)
- Panelists: M. Jaworski (PPPL), R. Kolasinski (SNLL), R. Kurtz (PNNL), J. Rapp (ORNL), *G. de Temmerman (ITER Organization),* B. Wirth (UT-K), G. Wright (MIT)

Engineering innovations for plasma exhaust challenges (ReNeW Thrust #11)

- Leader/Deputy: C. Kessel (PPPL), D. Youchison (SNLA)
- Panelists: J. Blanchard (UW-M), R. Callis (GA), R. Ellis (PPPL), R. Majeski (PPPL), N. Morley (UCLA), D. Ruzic (UI-UC), M. Tillack (UCSD), S. Wukitch (MIT), M. Yoda (GIT)

Compatibility of boundary solutions with attractive core scenarios (ReNeW Thrust #12)

- Leader/Deputy: A. Hubbard (MIT), T. Leonard (GA)
- Panelists: J. Canik (ORNL), M. Kotschenreuther (UT-A), R. Majeski (PPPL), P. Snyder (GA), J. Terry (MIT), Z. Unterberg (ORNL), R. Wilson (PPPL)

Cross-cutting group to facilitate discussions, identify high leverage opportunities

- S. Zinkle (UT-K), D. Hill (LLNL), D. Hillis (ORNL), R. Maingi (PPPL), J. Menard (PPPL), H. Neilson (PPPL), D. Whyte (MIT)

Five Priority Research Directions were identified

1. Understand, develop and demonstrate innovative dissipative/detached **divertor solutions for power exhaust & particle control**
2. Understand, develop and demonstrate innovative boundary plasma solutions for **main chamber wall components**
3. Understand the **science of evolving materials** at reactor-relevant plasma conditions and how **novel materials and manufacturing methods** enable improved plasma performance
4. Identify the **present limits on power and particle handling, and tritium control**, for solid and liquid **PFCs**
5. Understand how boundary solutions and plasma-facing materials influence **pedestal and core performance**

PRD #1: Main Scientific Questions

- What are the physics mechanisms of divertor dissipation, detachment, stability and control?
- What are the effects of divertor magnetic topology, geometry and materials, including solid & liquid?
- What are the physics mechanisms underlying near SOL heat flux width and its scaling?
- How can we extrapolate to reactor regimes?

PRD #1: Action plans

- **Validation: Make high resolution 2-D measurements of plasma & turbulence properties, and dissipation processes in divertor and near SOL**
  - Develop fully predictive models of dissipation/detachment
- **Enhancements to existing facilities: Explore current power handling/performance limits & upgrade divertor configurations and materials (solid & liquid)**
- **International collaborations, including ITPA :**
  - Advanced divertors & materials: MAST, TCV, HL-2M
  - Long pulse material migration: EAST, KSTAR, JT60-SA
  - High-Z PMI: JET, AUG, WEST, EAST
- **New starts: develop a Divertor Test Tokamak**
  - Flexible magnetic configuration, chamber geometry, and target materials
  - Dissipative divertor solutions at reactor-level parameters

Five Priority Research Directions were identified

1. Understand, develop and demonstrate innovative dissipative/detached **divertor solutions for power exhaust & particle control**
2. Understand, develop and demonstrate innovative boundary plasma solutions for **main chamber wall components**
3. Understand the **science of evolving materials** at reactor-relevant plasma conditions and how **novel materials and manufacturing methods** enable improved plasma performance
4. Identify the **present limits on power and particle handling, and tritium control**, for solid and liquid **PFCs**
5. Understand how boundary solutions and plasma-facing materials influence **pedestal and core performance**

PRD #2: Main Scientific Questions

What governs the processes below, and can we predict these quantitatively:

- **Far SOL transport, including blobs and transients, and main chamber recycling**?
- **SOL interactions with RF and other active components**? What techniques can be applied to optimize active component effectiveness while mitigating PMI?
- **Impurity erosion, transport into core plasma and long-range migration**? What are mitigation/control schemes?

A reactor environment introduces new challenges not experienced in current experiments:

- Do our understandings and 'solutions' **extrapolate to reactor regimes**?

PRD #2: Action plans

- **Validation: Make high resolution 2-D measurements of plasma & turbulence properties in far SOL**
  - Develop divertor/SOL/RF theory and computational tools
- **Enhancements to existing facilities: enhanced diagnostics and runtime, more people**
  - PMI with inner wall launchers (C-Mod), RF compatibility with a range of wall materials (NSTX-U), PFCs/single tiles at high temperature and testing advanced materials (DIII-D)
- **International collaborations:**
  - Long pulse: EAST, KSTAR, JT60-SA, W7-X
  - Mix of first-wall materials: JET, ITER, EAST
- **New starts: develop a Divertor Test Tokamak**
  - Explore innovative RF heating and current drive techniques compatible with power density and SOL conditions prototypical of a reactor

Five Priority Research Directions were identified

1. Understand, develop and demonstrate innovative dissipative/detached **divertor solutions for power exhaust & particle control**
2. Understand, develop and demonstrate innovative boundary plasma solutions for **main chamber wall components**
3. Understand the **science of evolving materials** at reactor-relevant plasma conditions and how **novel materials and manufacturing methods** enable improved plasma performance
4. Identify the **present limits on power and particle handling, and tritium control**, for solid and liquid **PFCs**
5. Understand how boundary solutions and plasma-facing materials influence **pedestal and core performance**

PRD #3: Main Scientific Questions and Action Plans

- What are the processes that dominate the spatial formation and destruction of reconstituted surfaces over time?
  - US devices: Measure charge exchange fluxes to wall, and diagnostics for migration during or between discharges
  - International: material migration in long pulse devices
  - New starts: for droplet emission, coupled to linear device
- How can we simulate the complex experimental conditions and measure the in-situ evolution of reactor relevant reconstituted surfaces?
  - Increased portfolio of in-situ and in-vacuo diagnostics, including sample transfer stations
  - Upgrade existing accelerator capability, e.g. SNS, MTS
  - Collaborate on long pulse international devices with refractory walls, and on MAGNUM-PSI linear device
  - Develop new domestic linear device with high particle and parallel heat flux, inclined targets, steady-state

PRD #3: Main Scientific Questions and Action Plans

- How can we characterize and predict surface composition, morphology, and microstructure evolution of the reconstituted surfaces under reactor-relevant conditions?
  - Existing facilities: advanced surface analysis tools, laser-based techniques, microscopy for bubble formation
  - JET: collaborate on Be codeposit science
  - New start: combine high energy ion beam or X-ray analysis with high power plasma device
- What are the key neutron irradiation synergies with PMI and can advanced materials address these?
  - Expand irradiation effects program and develop ductile phase reinforced composite tungsten
- How can we accelerate development of multi-scale models to predict the evolution of reconstituted surfaces during plasma exposure?
  - Closely coordinate fundamental modeling, e.g. via SciDAC, to measurements for in-depth validation

Five Priority Research Directions were identified

1. Understand, develop and demonstrate innovative dissipative/detached **divertor solutions for power exhaust & particle control**
2. Understand, develop and demonstrate innovative boundary plasma solutions for **main chamber wall components**
3. Understand the **science of evolving materials** at reactor-relevant plasma conditions and how **novel materials and manufacturing methods** enable improved plasma performance
4. Identify the **present limits on power and particle handling, and tritium control**, for solid and liquid **PFCs**
5. Understand how boundary solutions and plasma-facing materials influence **pedestal and core performance**

PRD #4: Main Scientific Questions and Action Plans

- What are the maximum steady state heat fluxes and operating temperatures for actively cooled solid and liquid PFCs?
- What are the tolerable peak heat and particle loads, and transient durations for solid and liquid actively cooled PFCs?
  - New high heat flux facility, high duty cycle & availability, coupled with theory and validation for solid and free surface liquid PFCs
  - Capability for pulsed loads to simulate plasma transients
- What are the effects of tritium implantation and permeation, and tritium retention in liquid and solid PFCs?
  - Linear, likely new plasma facilities for implantation and permeation assessments
  - Dedicated test stand and toroidal facilities for liquid PFCs

PRD #4: Main Scientific Questions and Action Plans

- How will the neutron induced transmutation and He production affect the PFC's function, bulk and surface?
  - Fusion-like neutron damage of PFCs via SNS, IFMIF, MTS, and then evaluate those materials in linear devices
- What processes will limit the lifetime of PFCs, including fusion neutrons, erosion, thermo-mechanical cycling, or surface modification?
  - Erosion and morphology evolution in linear plasma and toroidal confinement facilities
  - Thermo-mechanical and fluid accessed in high heat flux facilities
  - Liquid metal interactions with substrate in MHD flow loops
- How can advanced manufacturing be utilized to extend PFC performance and lifetime limits?
  - Develop new alloys and structural materials, incorporating state-of-the-art multi-scale, multi-physics modeling

Five Priority Research Directions were identified

1. Understand, develop and demonstrate innovative dissipative/detached **divertor solutions for power exhaust & particle control**
2. Understand, develop and demonstrate innovative boundary plasma solutions for **main chamber wall components**
3. Understand the **science of evolving materials** at reactor-relevant plasma conditions and how **novel materials and manufacturing methods** enable improved plasma performance
4. Identify the **present limits on power and particle handling, and tritium control**, for solid and liquid **PFCs**
5. Understand how boundary solutions and plasma-facing materials influence **pedestal and core performance**

PRD #5: Main Scientific Questions

1. What physics sets the **profiles of plasma temperature and density** in the edge transport barrier or 'pedestal'?
   - How do **low vs high recycling and retention** of fuel influence the pedestal region?
   - How are **impurities** transported in the pedestal and what is their effect?
2. How is pedestal transport modified by **edge transient (ELM) control techniques and in regimes without large transients**?
3. What are the **limits to robust pedestal operation**, and how do they constrain divertor solutions?
4. **How can the pedestal and divertor be integrated to optimize performance of burning plasmas?**

PRD #5: Action plans

- **Validation: new diagnostics and coordinated experiments**
  - E.g. 2-D ionization profiles, main ion temperature, and fluctuations in pedestal region for model validation
  - Coordinated density, collisionality, impurity seeding scans
- **Enhancements to existing facilities: enhanced diagnostics and runtime, more people**
  - PFC material options including solid and liquid, high-Z and low-Z, and advanced designs of RF launchers
  - Explore innovative RF heating and current drive techniques compatible with the SOL
- **International collaborations:**
  - Emphasize near term JET, ASDEX-U, MAST-U, longer term EAST, KSTAR, JT-60SA (once edge diagnostics improve)
- **New starts: develop a Divertor Test Tokamak**
  - Low fueling within pedestal, high heat flux, high radiated power fraction, high confinement without large ELMs
  - Improved actuators for sustainment and optimization

Four crosscutting research opportunities identified

- **Enhanced exploitation of existing machines for PMI issues**
  - Leverage existing investments with new PMI diagnostics, targeted upgrades, enhanced PMI dedicated run time; new staff expertise, enhanced modeling and simulation (SOL, etc.)
  - Opportunity to integrate boundary plasma and plasma materials R&D
- **Examine long pulse PMI science issues under reactor-relevant conditions of high accumulated plasma and neutron fluxes**
  - Long pulse toroidal (international collaboration) and linear plasma devices (upgrades/new build)
- **Understand the science of liquid surfaces at reactor-relevant plasma conditions and examine the feasibility of liquid PFC solutions**
- **Develop integrated plasma-material solutions in a purpose-built Divertor Test Tokamak**
  - Provide experimental test bed to develop and test models and divertor + PFC solutions for reactor-relevant conditions

Relation between Cross-Cutting Opportunities and PRDs (assessment of cross-cutting group)

Cross-Cutting Initiative Impact

- Strong
- Moderate

Cross-Cutting Initiatives	Priority Research Directions: Advanced Divertor Science & Solutions	Main-Chamber Science & Solutions	Plasma-Materials Interactions Science & Solutions	Power & Particle Exhaust Science & Technologies	Divertor/PMI/ Pedestal/Core Integration Science
Enhance exploitation of existing machines	Moderate	Moderate	Moderate	Moderate	Strong
Examine long pulse PMI science issues	Moderate	Moderate	Strong	Strong	Moderate
Understand the science of liquid surfaces	Strong	Moderate	Strong	Strong	Moderate
Integrated PMI on Divertor Test Tokamak	Strong	Strong	Moderate	Moderate	Strong

Summary

- **Community-led panel identified leading challenges and options to address those challenges**
  - Five Priority Research Directions identified
  - Four Cross-Cutting Research Opportunities identified, which contribute to multiple PRDs
  - Considerable enthusiasm amongst participants to follow up on these research lines
- **Follow-on activities: specific action plans for each PRD; possible cross-cutting steps suggested below**
  - Existing experiments: identify high value actions with facility leaders
  - Long-pulse science: (i) use coming international re-competition to target specific science and technology areas in PRDs, and (ii) hold national workshop or form working group on US-led linear divertor simulator
  - Liquid surfaces: conduct national workshop to identify most important questions to be tackled first
  - Divertor test tokamak: initiate community-wide working group, assessing model extrapolation issues and evaluating the European DTT proposal(s)