Research Thrust to Address PMI Knowledge Gaps for DEMO

PMI Working Group:

Presentation at:
PMI Research Needs Workshop at UCLA
4-Mar-2009
A Near-term Research Thrust is Needed to Address the PMI Knowledge Gaps

• Review of the knowledge gaps
• Scientific issues to be addressed by research thrust
• A multi-faceted approach
  — Additional emphasis on modeling (Krstic, Brooks)
  — Additional emphasis on existing test stands
  — New facility

• An Advanced Linear PMI Facility coupled with an enhanced modeling effort can cost effectively address many of the PMI knowledge gaps
  — Contributions in all PMI areas: PWI, PFC, IC

• Possible facility features and concluding remarks
The Divertor Requirements in DEMO Go Well Beyond ITER

ITER conditions: Pulsed, Low T, C, Be, W

Plasma Interaction in Divertor
- \( n_e = 10^{21} \text{ m}^{-3} \)
- \( T_e = 1-10 \text{ eV} \)
- \( \Gamma_{D,T} = 10^{24} \text{ m}^{-2} \text{ s}^{-1} \)
- \( q_{\text{div}} = 10 \text{ MW/m}^2 \)

DEMO conditions:

Similar to ITER with:
- Steady-state
- elevated temperature (600 C cooling)
- Refractory metals
- Neutron irradiation (up to 100 dpa)

Parameter range is inaccessible in present tokamaks and PMI experiments
Proposed Research Thrust Will Address PMI Knowledge Gaps

• Erosion/redeposition – fundamental understanding of the complexity of multi-species plasma and mixed materials (PWI)
• Tritium retention and permeation – processes leading to surface retention and bulk permeation (PWI, PFC)
• Radiation transport - high density optically thick plasmas expected in a DEMO environment (PWI)
• Periodic off-normal heat-flux and energetic particle bombardment (PWI, PFC, IC)
• PFC component lifetime and heat transfer – unprecedented exposures to high heat flux and durations will challenge PFC design (PFC)
• Neutron irradiated materials – effect of high neutron fluence on PFC and internal component properties (PWI, PFC, IC)
• Development of new materials and concepts (PWI, PFC, IC)
Plasma Wall Interactions

Example: hydrogen plasma and carbon target

Material surface is changed by plasma contact:

- Deposition of thin films, thick films
- Material mixing at the surface (in case of metals: alloys)
- Morphology of surface changes (in case of refract. metals: cracking of surface)
- Re-deposited layers flake off and become dust
- Eroded and flaked off material itself has impact on plasma (radiation losses etc.)
## PWI Gaps vs. Tools to Develop Understanding and Control; Version 2.3

### General Requirements on the Tools

<table>
<thead>
<tr>
<th>SOL and Divertor Plasma</th>
<th>Theory &amp; Modeling</th>
<th>Existing/Upgraded/New Test Stands</th>
<th>Existing/Upgraded Confinement Facilities</th>
<th>New Confinement Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impurity transport Radiation transport He pumping</td>
<td>ELMs &amp; Disruptions Off-normal heat flux Energetic electrons Dust production Impurity injection</td>
<td>3-D MHD, two-fluid, &amp; kinetic models including runaways. Control techniques such as edge ergodicity, stimulated edge transport and small ELMs.</td>
<td>Tests of impacts of Demo-relevant off-normal events. Tests on neutron-irradiated materials.</td>
<td>Tests of advanced models and control techniques. Scenario development with focus on stability.</td>
</tr>
</tbody>
</table>

### Research Thrust

Hillis PMI Renew - 6
Fundamental Science is the basis for a long-term PMI research program:

Understanding and control of PMI processes

Efficient energy conversion

Urgent, critical issues

Machine and mission specifics:

**ITER**
- Dynamic surface, C+Be+W?
- \(\langle T_{\text{wall}} \rangle \sim 100 \, ^\circ\text{C}, \text{cycling}\)
- Pulse \sim 400 \, \text{seconds}
- Tritium uptake & removal

**DEMO**
- Refractory metal surface (W?)
- \(\langle T_{\text{wall}} \rangle > 600 \, ^\circ\text{C}\)
- Steady-state operation
- Blistering, nanostructure
- Tritium permeation & retention
- High neutron fluence
“Atomistic” Molecular Dynamics (MD) Successfully Models Chemical Sputtering in Basic Beam-surface Experiments

Selected projectiles
- Ion, atom, molecular beams
- External control of mass, kinetic & internal energy, angle

Prepared target
- Composition, morphology, band structure, hydrogenation
- Known history, temperature

Products
- Erosion & implantation
- Particle reflection & sputtering

Thursday PMI Presentations
P. Krstic, J. Brooks, et al.
- Need for theory validation
Modelling of High Flux Plasma-wall Interaction is Complicated by Surface Response to Plasma Bombardment

**Incident plasma**
- Multi-species, multi-state plasma
- Multi-component, multi-directional distribution function

**Evolving target**
- History of irradiation, heating
- Surface deposition & damage

**Products**
- Particle reflection, implantation, sputtering
- Synergetic surface chemistry

*No retention model available*
*No data for Be, W for T > 300 °C*

Retained deuterium concentration in C, Be and W co-deposition conditions (J. Roth et al., PPCF 50 (2008)103001)

Hillis PMI Renew - 9
Comprehensive PMI diagnostics needed!

Impinging plasma

- plasma constituent energy
- species distributions

\[ T_e, T_i, n_e \]

LP’s, Thomson Scattering

- impurity content,
- hydrogenic constituents,
- \( v_{\text{vib}}, v_{\text{rot}}, T_i \)

RFA

Interaction products

- mass velocity distributions
- erosion products,
- internal state distrib’s,
- velocity & angular distrib’s

TOF, QMS

Visible Spect.

IR

LIF

UV and visible Raman,
AFM, XPS, SEM, AES

- hydrogen retention
- hydrocarbon precursor concn’s

TDS or TPD

- surface temperature profile
  multi-frequency pyrometry

Target

- surface morphology,
- carbon hybridization, \( \text{sp}^3/\text{sp}^2 \)
- content, chemical composition
- bonding

RFA – retarding field analyzer
LP – Langmuir probe
AFM – atomic force microscopy
XPS – X-ray induced photon spectroscopy
TDS – thermal desorption spectroscopy
TPD – thermal programmed desorption
SEM – scanning electron microscopy
AES – Auger electron microscopy
DEMO Makes It Necessary to Study PWI and PFCs in a Nuclear Environment

- Production of radiation-induced defects (vacancies, interstitials, traps, …)
- Changes of microstructure – including surface
- Change of chemical composition (transmutation, He production)
- Degradation of PFC material properties:
  - ductility (hardening)
  - He embrittlement
  - Thermal conductivity
  - Swelling

See Theme IV talks by Kurtz, Stoller, …

W after $^4$He impact and plasma erosion (Koidon)
Neutron Irradiation Alters Bulk PFC Properties

• Need to test *neutron irradiated and toxic* plasma facing and internal components under high heat loads and plasma exposure to prepare for DEMO
  – PMI processes (Erosion, fuel retention and dust formation)
  – Thermo-mechanical properties of PFCs (fatigue, shock resistance)
  – Modification of bulk heat transfer properties
  – Testing of the integrity of coatings, brazes, welds for cooling lines, etc. for internal components

• Need to perform tests under simultaneous high heat loads
  ~ 10 MW/m² and high surface temperature ~ 600 °C
## Methods to Address the Gaps in PMI Knowledge

<table>
<thead>
<tr>
<th>PMI Gap</th>
<th>Non-plasma Experiments</th>
<th>Existing Linear Test Stands</th>
<th>Advanced Linear Test Facility</th>
<th>Dedicated Toroidal Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Interactions</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOL Transport</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Tritium Retention</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Erosion &amp; Redeposition</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Radiation Transport</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>New Materials</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>PFC Lifetime and Heat Transfer</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Neutron Damaged Materials</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Proposed Thrust to Address the PMI Gaps

- Fundamental PMI Physics
- Computation and model verification
- Hydrogen retention in plasma facing components
- Erosion and Redeposition
- Surface science
- Material transport and dust
- Advanced Linear Facility
- Plasma physics in strongly coupled regime
- Lifetime of plasma facing components
- Neutron irradiated material effects
- Contributions from Toroidal Facilities: DIII-D, C-Mod, NSTX, JET, …
Linear Test Facility Required R&D Capabilities

- Particle fluxes > $10^{23}/m^2/s$, parallel heat flux up to 40 MW/m²
- Large plasma area ~100 cm² applied to inclined surfaces at elevated T
- Powerful plasma source and RF heating for $n > 1-3 \times 10^{19} \text{ m}^{-3}$
- Ability to test hazardous materials and neutron irradiated samples
- Variable B > 1 T
- Heat pulses (~ few ms time scale for ELM simulation)
- Progressively longer plasma durations $10^3$ s, eventually to $10^6$ s.
- In-situ and ex-situ PMI diagnostics; plasma diagnostics
- Multi-scale Monte-Carlo computer modeling for data interpretation

Suggests

- Use Helicon plasma source without internal electrodes
- Plasma device placed inside a Hot Cell
Possible Features of a Linear PMI Test Facility

- Helicon antenna
- Cooled ceramic cylinder
- Ion cyclotron antenna
- EBW heating region
- Target

• Example shows $|B| \sim 2.8$ T at target with 10 cm perpendicular spot size, for $|B| < 1$ T in 20 cm diameter helicon source. High density plasma operation at lower $|B|$ is also possible

• Multiple coils provide flexibility in magnetic field profile and target parameters

Hillis PMI Renew - 16
Proposed Facility Will Use a Helicon Plasma Source

- Usually consists of a source tube with gas injected into it, surrounded by an antenna and a solenoid producing an axial magnetic field.

- At high plasma density, antenna couples power by launching circularly polarized electromagnetic wave along magnetic field which damps through electron collisions.
Why use a Helicon Plasma Source for a PMI Test Facility?

- Helicon plasma sources couple power through rf waves and have no internal electrodes
  - Results in low impurity generation
  - Allows for true cw operation with no need to replace internal components

- Large diameter plasmas can be produced – 10 cm is a typical diameter

- Plasma production is much more efficient than with other RF sources. Power is coupled through an electromagnetic wave that directly heats the core plasma

- Helicon axial magnetic field geometry is compatible with application of additional ion cyclotron heating (ICH) – high efficiency single pass ICH in a helicon produced plasma stream has been demonstrated experimentally

- High performance helicon operation with light ions including H, D, and He, with plasma density > $10^{19}$ m$^{-3}$ and gas utilization efficiency $\eta_g$ (= ions out/atoms in) approaching 100% has been achieved, making it worthwhile to develop this type of plasma source for use in a PMI linear test facility
Prototype Under Development: High Particle Flux at High Magnetic Field

- Maximum source diameter limited to 15 cm due to size of bore of existing magnets to be used in the project.

- 1 T magnetic field in a 15 cm diameter plasma production region maps to ~ 2.25 T in a 10 cm diameter target region. A slightly larger, 20 cm diameter source would map to 4 T.

- Achievable particle flux:
  - Best light-ion results to date are from VASIMR: $4 \times 10^{20}$ s$^{-1}$ total flux at ~ .15 T, 20 kW input power (deuterium). Have also achieved $> 10^{21}$ s$^{-1}$ with Ar, 30 kW input power
  - Goal for this project is $2 \times 10^{21}$ s$^{-1}$ with up to 100 kW input power
  - Corresponds to average flux of $2.5 \times 10^{23}$ m$^{-2}$ s$^{-1}$ over 10 cm diameter target
  - Requires ~4.8 sls (standard liters per second) input gas flow with 100% gas utilization

Currently being addressed at ORNL with internal funds
A Hydrogen Helicon-based Negative Ion Source is Presently Being Tested at ORNL for Possible Use on the SNS

High density hydrogen plasma operation

Rf antenna
A Near-term Research Thrust is Proposed to Address the PMI Knowledge Gaps

• A multi-faceted approach
  — Requires a strong theory and modeling effort
  — Supported by experimental validation on existing devices
  — An Advanced Linear PMI Facility will cost effectively address many of the PMI knowledge gaps
  — Contributes to all PMI areas: PWI, PFC, IC

• The envisioned New PMI facility would complement and extend the capabilities of current PMI facilities, such as PISCES

• Promotes US competitiveness in the PMI area

• The new PMI facility is foreseen to be a user facility, whose final design is developed through PMI community participation
## Facility Parameters

| Facility | $n_e^\text{sep}$ | $n_e^\text{div}$ | $T_e^\text{sep}$ | $T_e^\text{div}$ | $q_{\text{div}}^\text{max}$ | $L_{||}$ |
|----------|----------------|----------------|----------------|----------------|----------------|---------|
| C-Mod    | 1-3            | 0.5-20         | 40-80          | 0.5-25         | 10?            | 2-15    |
| DIII-D   | .01-0.2        | .1-10          | 30-80          | 0.5-40         | 6-7            | 5-50    |
| NSTX     | .03-1          | .1-2           | 20-50          | 0.5-30         | 12-15          | 1-20    |
| Linear   |                |                |                |                |                |         |

C-Mod: LaBombard PoP 1995, DIII-D & NSTX from various sources
From Greenwald panel report:

**The plasma material interface:**

*The state of knowledge must be sufficient to design and build, with high confidence, robust material components which interface to the hot plasma in the presence of high neutron fluences.*

…which can convert fusion products to useful forms of energy in a reactor environment, including a self-sufficient supply of tritium fuel.

**Plasma wall interactions:**

*Understanding and control of all processes which couple the high-performance plasma to its immediate surroundings*