Plasma Materials Interactions

Sept 27, 2004

M. Ulrickson
Presented at ECC Meeting
San Diego, CA

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Session Outline

- PMI Summary – Mike Ulrickson
- PMI Effects of Dust - Sergei Krasheninnikov

Sandia National Laboratories

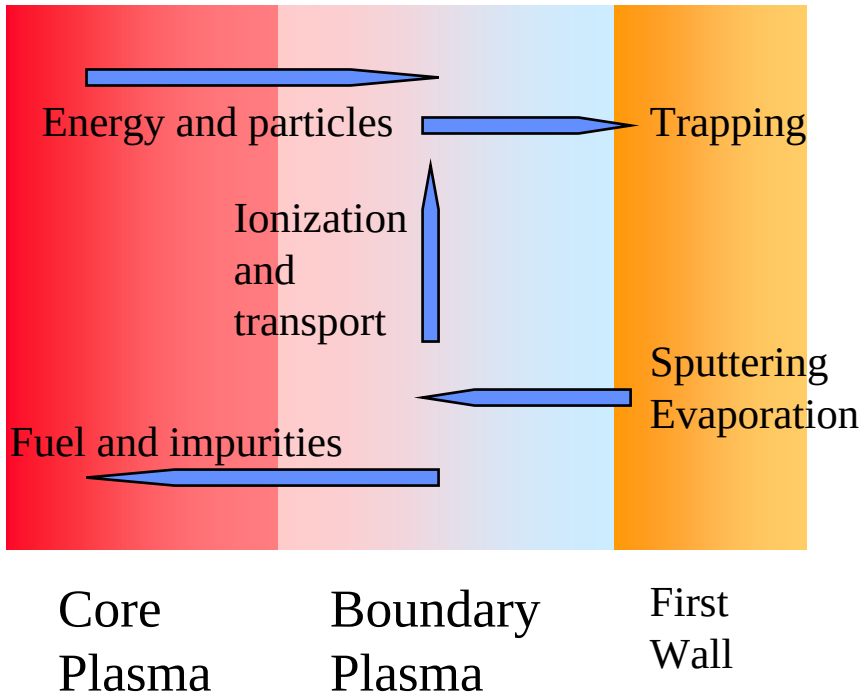
Outline

- Introduction to Key Issues
- Status of PMI Experiments and Modeling
- Primary Goals in the 5 Year Time Frame
- Additional Accomplishments With More Budget

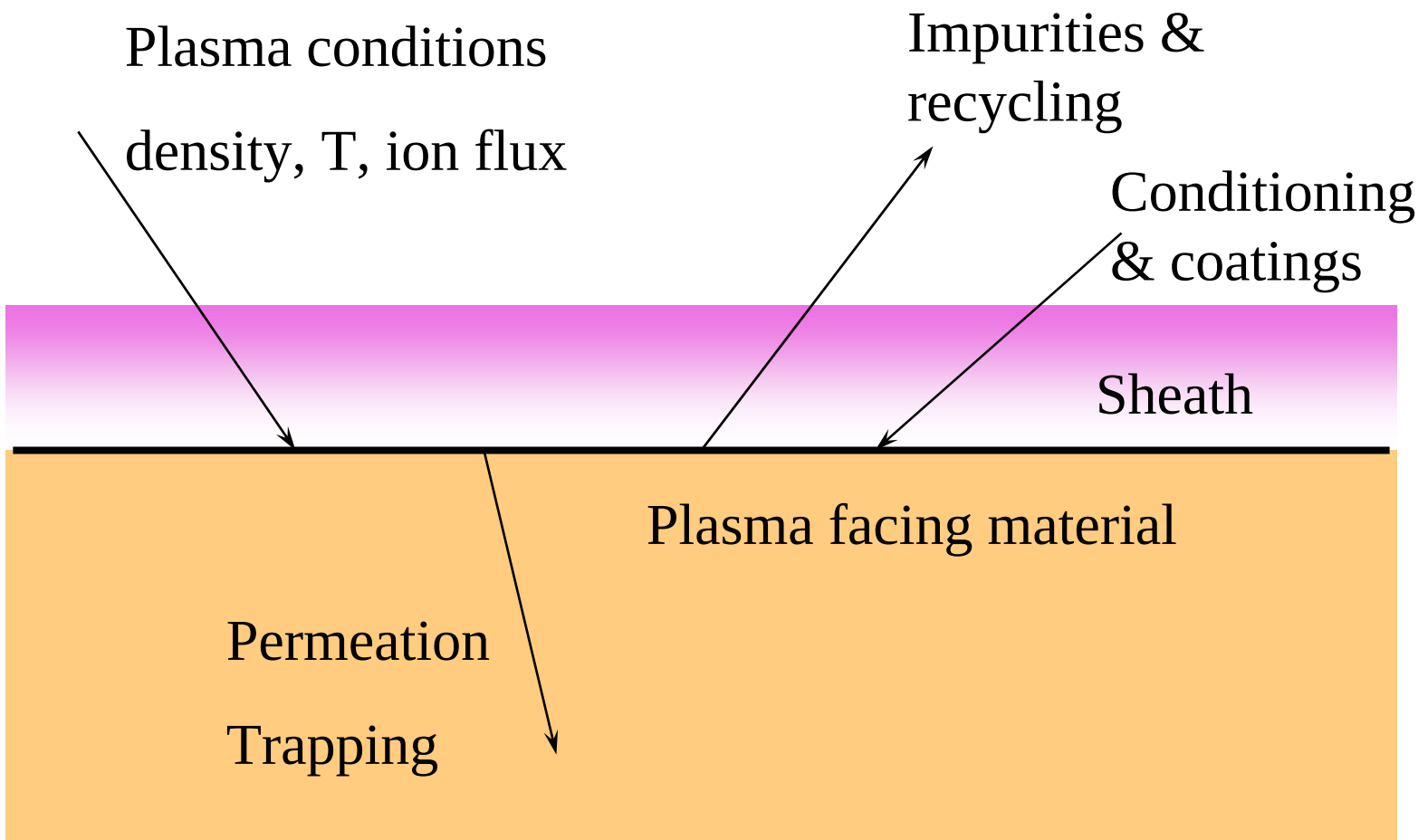
Sandia National Laboratories

First Wall Plasma Materials Interactions

- **The core plasma must be kept clean of impurities and He 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)**



PMI at the Divertor Plate



PMI Issues for the Future

- **Two PMI issues are potential serious issues for ITER:**
  - **T-retention related to C PFCs (erosion and redeposition process) is a safety and operating expense issue**
  - **Melting of metallic PFCs due to ELMs and disruptions (loss of armor thickness and reduced lifetime) decreases availability due to maintenance requirements**

PMI Impact on Fusion Device Operation

- "Blob" (convective) particle/energy transport to 1st wall is incompatible with beryllium wall surface (due to high sputtering, T/Be codeposition). Therefore, we need plasma edge/SOL regimes that minimize blob transport, or we should use a tungsten FW surface.
- Detached or semi-detached regime is the worst for carbon chemical sputtering at divertor and resulting tritium codeposition.

(J.N. Brooks)

Sandia National Laboratories

PMI Impact on Fusion Device Operation

- For all divertor surface materials, need to control the size of ELM's to minimize erosion of PFM.
- Need greater community recognition of the potential role of liquid metal divertor surfaces (these are not significantly more speculative than the current carbon divertor plan for ITER).

(J.N. Brooks)

Sandia National Laboratories

Status of PMI Experiments

Status of PMI Database

- Single material and incident Ion conditions
  - Measurement of physical sputtering yields is nearly complete and highly accurate.
  - Chemical erosion is understood except for the energy threshold
  - Ion radiation damage enhancement of erosion is measured for most interesting combinations
- Mixed material and incident Ion conditions
  - Data gathering is in early stages (PISCES experiments on Be/C and Be/W)

Sandia National Laboratories

PMI with Carbon PFCs

- **Carbon is one of the most valuable PFC materials. One of its chief deficiencies is chemical sputtering.**
- **Chemical sputtering may be only a transient effect (prominent in the relatively low duty cycle tokamaks), but may be only a brief feature of devices like ITER.**
- **Is there an ion energy threshold for chemical sputtering?**
- **Chemical sputtering is particularly important for detached divertor operation (baseline for ITER).**

PMI with Carbon PFCs

- **In single null divertor tokamaks, there is a broadly consistent deposition feature: C deposits almost entirely in the inner divertor, somewhere.**
- **The location is sometimes in regions where it could be easily removed and sometimes in areas that are very inaccessible to cleaning.**
- **What controls the location of co-deposition and can we learn how to manipulate the process?**

PMI with Carbon PFCs

- **We do not understand the source of carbon radiation and net erosion in detached divertors.**
- **Detachment initiated by noble gas injection (neon) produces extremely large net carbon erosion rates in the divertor, without any identifiable sputtering mechanism.**
- **Since detached divertor is the ITER baseline, and since impurity radiation is dissipating the power entering the ITER divertor, resolution of this matter is very important.**

FESAC Boundary WG

Sandia National Laboratories

Mixed Material PMI

- **We have weak ability to interpret – let alone predict – impurity production and edge transport, even for the simplest case of a single material PFC.**
- **Multiple-element PFC systems, such as the present ITER C/Be/W design, are unpredictable.**
- **Modeling the physical sputtering of high-Z elements such as W is particularly challenging since the principal mechanism is the impact of light impurity ions, such as C and Be, which themselves must be reliably modeled in detail.**

FESAC Boundary WG

Sandia National Laboratories

Tritium Inventory

- At locations where the impurities build up deposition layers, the radioactive tritium hydrogen fuel is effectively trapped and accumulates at a high rate; tritium inventory in deposit layers is a major issue for burning plasmas.
- Effective methods for tritium inventory control and understanding of impurity transport are essential for long pulse burning plasma operation.

FESAC Boundary WG

Sandia National Laboratories

Tritium Trapping

- Tritium trapping in redeposited carbon layers has been observed on JET and TFTR. (Net about 40% of injected T)
- In JT60-U, however, the carbon deposits were found to contain very little D (because of high tile temperature?).
- The amount of tritium retention is a key issue for ITER.
- Effective methods have been found for removing T from surface layers, but removal from hidden surfaces is still a problem.
- Additional recovery methods such as oxygen baking and mitigated disruption radiative heating release have been proposed (untested yet).

Specialized PMI Issues

- **The controlling physics of erosion of surfaces near RF launchers must be addressed.**
- **RF heating is an important plasma heating and current control method.**
- **The localized PMI near the RF launchers can cause impurity production and may limit RF hardware lifetime in long-pulse devices.**

Status of PMI Database

- Wall Conditioning
  - Effective methods are known for low duty factor operation (conditioning time is much longer than operating time)
  - Most devices use low Z coatings (B, some Li)
  - Some experience with medium Z (Si, Ti)
- Particle control
  - Active pumping of the divertor region is relatively new
  - Modeling is empirical (little predictive capability)

Sandia National Laboratories

Wall Conditioning for Long Pulses

- Conditioning of the plasma facing surface is often accomplished by glow discharge cleaning between pulses or by coating the wall.
- Long pulse operation is virtually unexplored with regard to changes in wall conditions or material damage due to bombardment.

Particle Control and Recycling

- **For long-pulse devices, uncontrolled density rises occur after a period ~minutes, requiring further development of wall-conditioning methods.**

Plasma Sheath at the Divertor

- **A basic aspect of plasma contact with a solid surface is the formation of a sheath**
- **The ratio of power to particle flux densities and the sheath heat transmission coefficient are not understood**
  - **Experimental values can differ greatly from the Langmuir-Bohm value of ~7**
  - **Often only ~1 near the outer strike point (the region of most intense plasma heat conduction).**
- **B-PHI Code models this region**

Experiments Needed in 5 Years

PMI Experiments Needed

- Long plasma exposure studies need to be carried out on tokamaks and on plasma simulators (both CFCs and graphite) to determine if chemical sputtering is a transient phenomenon.
- Detailed spectroscopy needs to be carried out in tokamaks (with carbon PFCs) with in-situ hydrocarbon injection and accurate T_e, T_i and incident ion energy measurements to determined if there is an ion energy threshold for chemical sputtering.

FESAC Boundary WG

Sandia National Laboratories

PMI Experiments Needed

- **Low temperature laboratory hydrogenic plasmas may provide data.**
- **Chemical erosion of boron coatings may provide an informative contrast to the carbon experiments.**

Carbon PMI Experiments

- **Experiments with a range of temperatures of the inner divertor structure to determine the retention of hydrogen.**
- **Experiments with various inner divertor geometries, with hot and cold surfaces, both for exposed surfaces and the hidden surfaces will establish how the location of co-deposition is influenced by surface temperature and geometry.**
- **A vigorous campaign is required on a number of tokamaks to test the most promising methods of tritium recovery.**

FESAC Boundary WG

Sandia National Laboratories

PMI Diagnostic Needs

- **In order to resolve sheath issues, the ability to make independent measurements of T_e, Γ_{dep}, q_{dep} needs to be available on several machines; methods for measuring T_i near targets need to be developed.**

Modeling Needs in 5 Years

5-Yr Vision for PMI Modeling

- **Integrated, predictive, plasma/material interaction 'Super-Code' computations.**
- **Super-code = Plasma SOL/Edge codes + Surface response codes + Impurity erosion/redeposition code. Real-time fully coupled. Run time < 24 hrs/problem.**
- **Plasma codes: Fluid (UEDGE*) + Kinetic (as needed) + Neutral (DEGAS) + Sheath (B-PHI).**

*** for all codes, code shown or equivalent**

(J.N. Brooks)

Sandia National Laboratories

5-Yr Vision for PMI Modeling

- **Example problems: Erosion/tritium-codeposition performance of a carbon divertor with complete carbon and hydrocarbon self-consistent transport. Lithium divertor performance with induced low-recycle plasma edge regime.**

(J.N. Brooks)

Sandia National Laboratories

5-Yr Vision for PMI Modeling

- **Surface response codes: sputtering, reflection, etc. via binary collision (TRIM/ITMC) and molecular dynamics code.**
- **Erosion/redeposition code: REDEP/WBC full kinetic, sub-gyro orbit.**
- **Desirable for super-code runs on PC, however, within 5-yrs would probably need supercomputer implementation.**

*** for all codes, code shown or equivalent**

(J.N. Brooks)

Sandia National Laboratories

PMI Research Needs

- **2D fluid codes (e.g., B2, UEDGE, EDGE2D, OEDGE, etc.) with Monte Carlo impurity codes (e.g., WBC, ERO, DIVIMP, …) should be used to study erosion under detached divertor conditions.**
- **A research effort is required on multiple-element PFC devices, such as AUG (C+W), C-MOD (Mo+B), JET (C+Be), to improve our interpretive and predictive capability for erosion.**
- **More experimental work, on devices that rely solely on RF heating schemes like C-Mod, is required to study enhanced erosion with RF heating.**

PMI 5 and 10 Year Goal

- **Within 5 years it should be possible to achieve *extrapolation* capability for many PMI issues, particularly for relatively small steps, e.g. from H-phase ITER to DT-phase ITER.**
- **Within 10 years, a genuine *predictive* capability will start to emerge.**

FESAC Boundary WG

Additional Progress With More Budget

Improved Theory and Modeling

- The amount of progress beyond extrapolation capability toward truly predictive modeling will be greatly enhanced by budget increases. (progress is limited by the effort available not fundamental physics issues; the available data exceeds the ability to model the data)
- Computer capacity/capability is a limiting factor (increased funding might increase capability, access or priority)

Sandia National Laboratories

Improved Experimental Understanding

- **Funding for fundamental PMI experiments could be adversely effected by ITER construction**
- **Mixed materials studies are making good progress and a clear path forward is identified (PISCES, TPE, JET, …)**
- **Increased funding is needed to settle the issue of T retention/removal from carbon and use of W in ITER (must be coordinated internationally)**

Sandia National Laboratories