Understanding the Plasma-Materials Interface in Fusion Devices

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Outline

I. Overview of plasma-materials interactions
II. Processes that occur at the materials interface
III. Key PMI issues in fusion devices
IV. Candidate materials for fusion reactors
V. How we study surfaces
VI. Conclusions
Plasmas are used for a variety of different applications

**Fusion plasmas**
- Clean energy source
- Hydrogen fuel extracted from seawater

**Electric thrusters**
- Used on 100’s of satellites orbiting the earth
- Currently used on the Dawn mission to explore Ceres & Vesta

**Plasma Medicine**
- Used for sterilization
- May be used to treat antibiotic-resistant bacteria, cancer tumors
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All involve *plasma in contact with a material*
Plasmas can be spectacularly destructive!

Erosion of molybdenum ion thruster grid


Plasma erosion of a tungsten cathode and tungsten crystal growth


Tungsten tile in fusion device, before & after plasma exposure

Z. Hartwig, MIT

Melted tungsten tile

B. Lipschultz, Nucl. Fusion (2012)
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We must consider plasma-materials interactions in any plasma device!

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What happens when you try to contain a plasma?

1. The plasma affects the surface
2. The surface affects the plasma
3. The plasma and the material work together to do something useful
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Five main processes that occur at the plasma-materials interface

1. Positive Ion Neutralization (Recombination)
   - Ions that hit the surface are neutralized
     \[ e + A^+ + S \rightarrow A + S \]

2. Absorption/Desorption (low energy, 1 eV)
   - Evaporation rate increases exponentially with temperature

3. Physical Sputtering (10-100 eV)
   - Independent of surface temperature

4. Implantation (1000 eV)

5. Reactions with/on a surface
   - Dependent on surface temperature
Reality is much more complex

Image from D. Whyte, http://psisc.org/mission
Quick review of fusion plasmas

To get hydrogen to fuse together, we need high temperature and pressure! → Plasma!

- Temperatures of 100 million K have been achieved!
- Use magnetic fields to keep the plasma together

The trouble with fusion is...
- Confining enough hydrogen
- For long enough times
- At sufficiently high temperatures
Key materials issues in fusion devices

Two aspects:

1. How the plasma affects the material

- Changes in the physical & chemical properties of the material can occur
Key materials issues in fusion devices

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1. How the plasma affects the material

   - Changes in the physical & chemical properties of the material can occur
   
   - Heat loads
     - Average heat loads (e.g., from alpha particle heating, 10 MW/m^2)
     - Transient heat loads (from ELMs; on order of milliseconds; wall temps must be below melting point)
   
   - Erosion of wall materials
     - Sputtering by ions and high energy neutrals, chemical reactions (erosion yield depends on material)
   
   - Tritium retention (max allowable value of mass in the machine; rate of T saturation depends on material)
   
   - Nuclear embrittlement, swelling, fuzz formation
Key materials issues in fusion devices

Two aspects:

2. How the material affects the plasma

- Biggest issue: impurity concentration:
  - can result in fuel dilution, radiated power losses, deposition of material where it is not wanted
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2. How the material affects the plasma

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- Fuel dilution from wall materials
  - impurities in the plasma can decrease fusion power; line radiation can change plasma temperature
  - pressure & temperature gradients near the wall can have negative effects on plasma stability and confinement
Large temperature gradients exist at the wall

- $D^+$ neutralizes at the surface
- $D$ atom is released into plasma at low temperature!
- This cools the plasma!
- Fusion reaction will extinguish
Some candidate materials and their properties

Graphite:
- Does not melt (sublimes)
- Erosion and transport occurs easily leading to C deposits
- Can trap large amounts of tritium

Beryllium:
- Low Z material
- Good thermal conductivity
- High sputter yields
- Low melting point

Tungsten:
- High Z material
- Low sputter yield
- High melting point

*High Z materials (e.g. W, Mo):*
- Poison the plasma
- Moderate uptake of tritium
- Good thermo-mechanical properties
- Low or negligible erosion at low plasma temperatures
Liquid metals

Advantages of liquid metals (lithium):
No erosion
No thermal fatigue
No neutron damage

Resilient again high heat fluxes
Refreshes the surface
Li concentration in the plasma is low

Li has shown to improve the plasma performance!
Improved confinement time ➔ Very important for fusion!

Infrared image of liquid lithium a fusion device at PPPL.

Flowing liquid Li experiment at University of Illinois at Urbana-Champaign
But why does Li help?

**Working hypothesis:** Deuterium retention

High D retention $\rightarrow$ Low recycling $\rightarrow$ High edge temperature $\rightarrow$ Reduced temperature gradients

- Recycling Process:

  1. Through volumetric conversion of Li to LiD (Baldwin & Doerner)
  2. Through complexes that involve oxygen (Krstic, Allain, Taylor)

Li absorbs $D^+$ ions and “retains” them better than other materials

But how is D retained in Li?
We need to understand the surface in order to find out!
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- Atoms at the surface behave differently than atoms in the bulk material.
- The surface provides an environment where unique chemistry can occur.
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So, how do we study surfaces?

\[ \rho = 10^{23} \text{ cm}^{-3} \]
\[ \rho_s \approx \rho^{\frac{2}{3}} \approx 10^{14} \text{ cm}^{-2} \]

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**Challenge:** Detect \( 10^{14} \) cm\(^{-2} \) signal on a \( 10^{23} \) cm\(^{-3} \) background.

**Solution:** Use probes that strongly interact with matter, such as electrons, ions, and photons (X-rays, UV light).
Surface science provides fundamental information needed to understand PMI

Key variables affecting chemistry at surface:
- Pressure (residual gases)
- Temperature (plasma heating)
- Composition (Mo, Li, D, etc.)

Lab-based surface science experiments enable independent control of all variables

...something we cannot achieve in a tokamak or linear plasma device!

Test stand instrumentation in the Surface Science & Technology Lab
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Isolate effects of:
- Chemistry
- Incident particle fluxes and energies
- Substrate temperature
- Surface composition
- Morphology

Start simple and add complexity to bridge gap between model systems and tokamak environment
From the simple to the complex

Simple Model Experiments

- Mo(110) crystal
- Grain boundaries
- Alloying elements: Ti, Zr, C
- Surface roughness

Monoenergetic ion beam
(Image of He ions on phosphor screen)

More Complex Systems

- TZM Mo alloy
- ECR plasma source

- Multiple species: H⁺, H₂⁺, H₃⁺
- Increased flux: 10¹² → 10¹⁶ cm⁻² s⁻¹
- Atoms, ions, or atoms + ions
Surface science provides fundamental information needed to understand PMI.

Test stand instrumentation in the Surface Science & Technology Lab.
Auger electron spectroscopy

AAES gives elemental information (and also oxidation state)!
Temperature Programmed Desorption (TPD) Technique:

- Linear temperature ramp applied to sample
- Partial pressure of desorbing species measured
- Temperature of desorption peak relates to binding energy
- Area under pressure vs. time curve proportional to number of atoms desorbed
Temperature programmed desorption

Area under pressure vs. time curve → # of atoms desorbed

TPD can be used to measure D retention!
Example: Desorption of Li from Mo

- Submonolayer Li film on TZM stable up to 1000 K
- Represents Li-Mo bonding
- Desorption energy ~2.7 eV

C.H. Skinner et al., JNM 438, S647 (2013)
Example: Desorption of Li from Mo

- Area under Li TPD curve increases with Li dose
- Dipole interactions lower the desorption energy (~2 eV)
- $E_d$ is a function of coverage

C.H. Skinner et al., JNM 438, S647 (2013)
Example: Desorption of Li from Mo

- Thick Li films (multilayer) evaporate at 500 K
- Multilayer film represents Li-Li bonding
- Cohesive energy of metallic Li ~1.7 eV

C.H. Skinner et al., JNM 438, S647 (2013)
TPD can be used to determine D retention

![Graph showing D retention vs. substrate temperature](image)

Increasing substrate temperature
TPD can be used to determine D retention.
Key takeaway messages

- Plasma-materials interactions have great implications for a variety of applications including energy, propulsion, medicine, and nanomaterials.

- The plasma and material are strongly coupled!

- Key PMI issues in fusion devices include: heat loading, erosion, fuel dilution, tritium retention, nuclear embrittlement.

- So far, no perfect fusion material exists. Candidates are graphite, tungsten, beryllium, lithium.

- Surface science can help to understand and diagnose the surface in model experiments that can help simulate the tokamak environment.