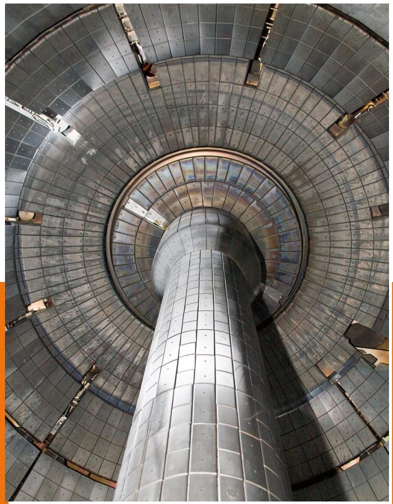
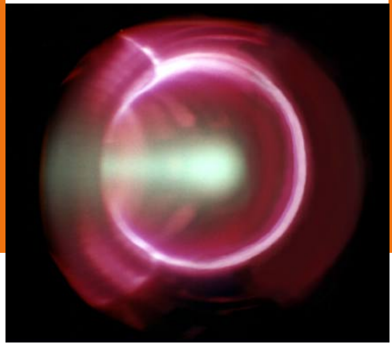
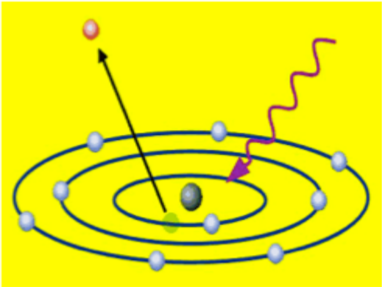
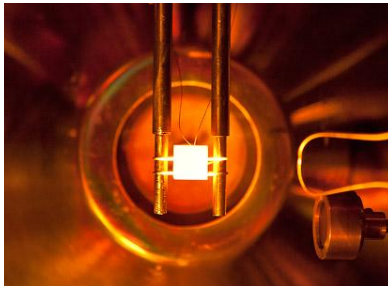





# Understanding the Plasma-Materials Interface in Fusion Devices


Angela M. Capece
Princeton Plasma Physics Laboratory


June 12, 2015

# Outline

I. Overview of plasma-materials interactions

II. Processes that occur at the materials interface

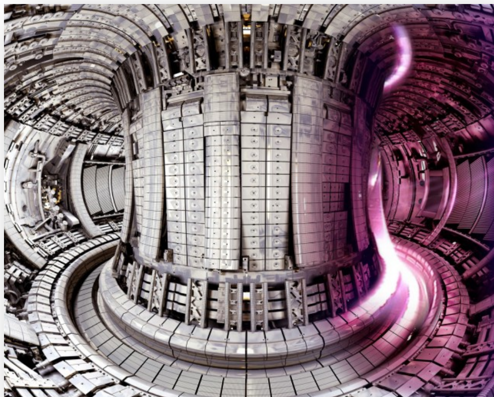
III. Key PMI issues in fusion devices

IV. Candidate materials for fusion reactors

V. How we study surfaces

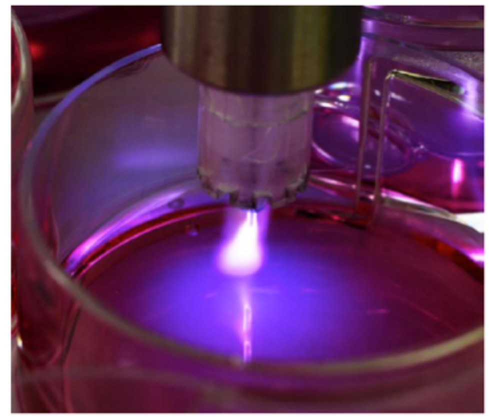
VI. Conclusions

# Plasmas are used for a variety of different applications



**Fusion plasmas**

- Clean energy source
- Hydrogen fuel extracted from seawater



**Electric thrusters**

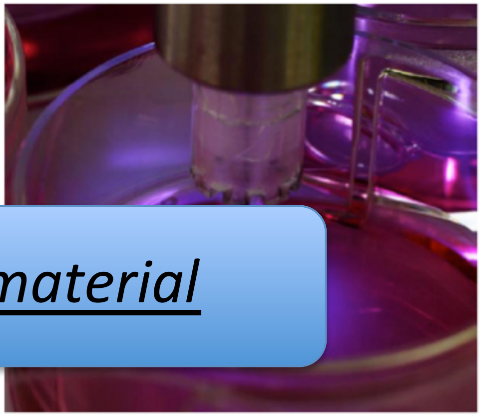
- Used on 100's of satellites orbiting the earth
- Currently used on the Dawn mission to explore Ceres & Vesta

**Plasma Medicine**

- Used for sterilization
- May be used to treat antibiotic-resistant bacteria, cancer tumors

# Plasmas are used for a variety of different applications

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

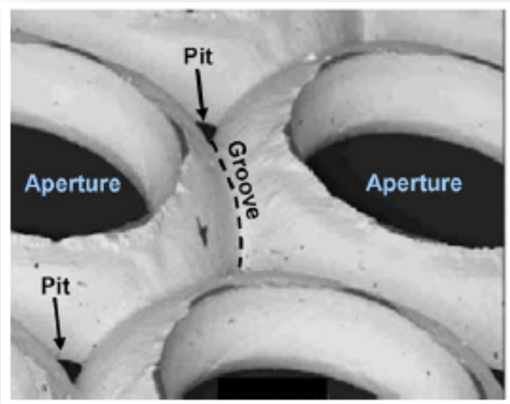


All involve *plasma in contact with a material*

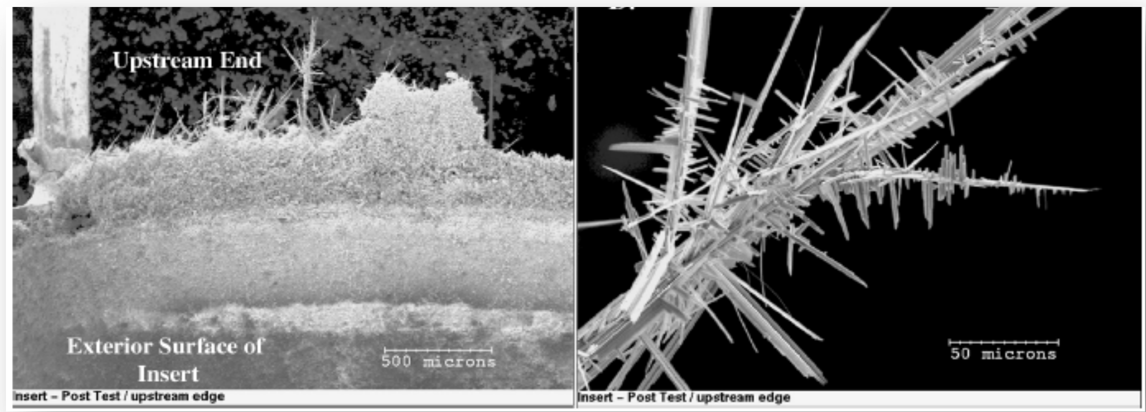
**Electric thrusters**
- Used on 100's of satellites orbiting the earth
- Currently used on the Dawn mission to explore Ceres & Vesta

**Plasma Medicine**
- Used for sterilization
- May be used to treat antibiotic-resistant bacteria, cancer tumors

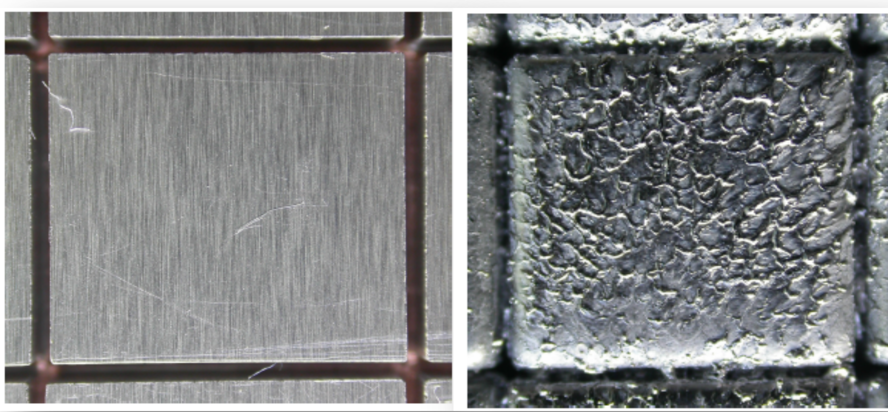
# Plasmas can be spectacularly destructive!




Erosion of molybdenum ion thruster grid
*R.E. Wirz, IEEE Trans. Plasma Sci. (2008)*



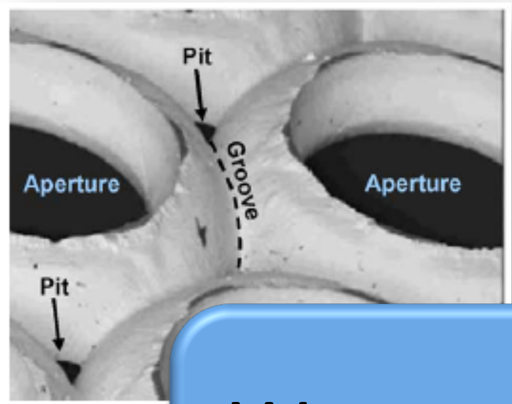

Plasma erosion of a tungsten cathode and tungsten crystal growth *J.E. Polk & A.M. Capece, Appl. Surf. Sci. (submitted)*



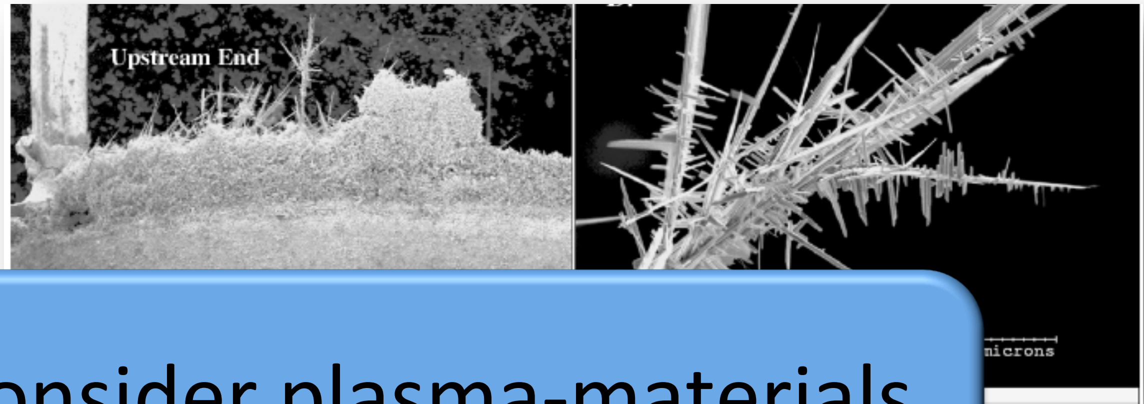
Tungsten tile in fusion device, before & after plasma exposure *Z. Hartwig, MIT*

Melted tungsten tile
*B. Lipschultz, Nucl. Fusion (2012)*

# Plasmas can be spectacularly destructive!

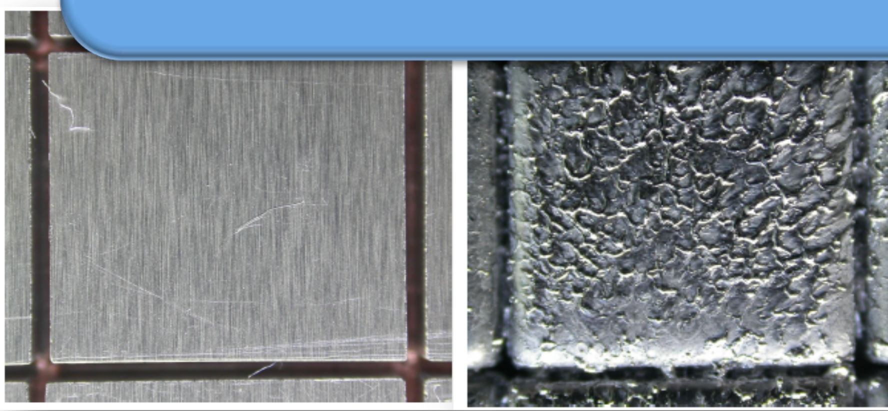



Erosion c
ion thrus
*R.E. Wirz, IE*




ngsten
*bmitted)*

**We must consider plasma-materials interactions in any plasma device!**



Tungsten tile in fusion device, before & after plasma exposure *Z. Hartwig, MIT*

Melted tungsten tile
*B. Lipschultz, Nucl. Fusion (2012)*

# 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

# 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

# Five main processes that occur at the plasma-materials interface

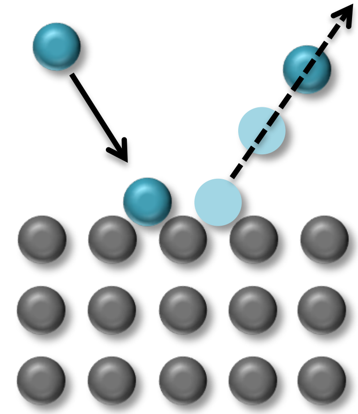
1. Positive Ion Neutralization (Recombination)
   - Ions that hit the surface are neutralized
     $e + A^{+} + S \rightarrow A + S$

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

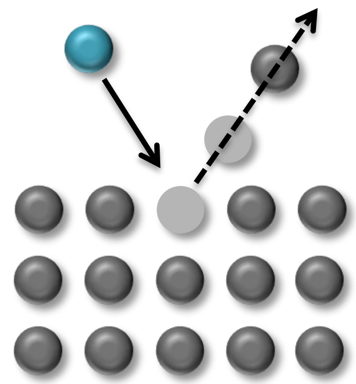
3. Physical Sputtering (10-100 eV)
   - Independent of surface temperature

4. Implantation (1000 eV)

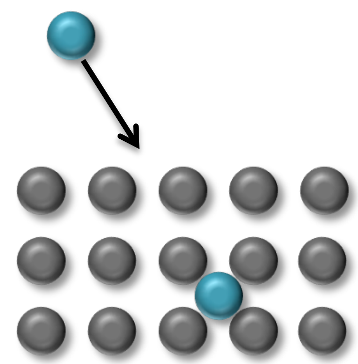
5. Reactions with/on a surface
   - Dependent on surface temperature



Absorption/Desorption



Sputtering



Implantation

# Reality is much more complex

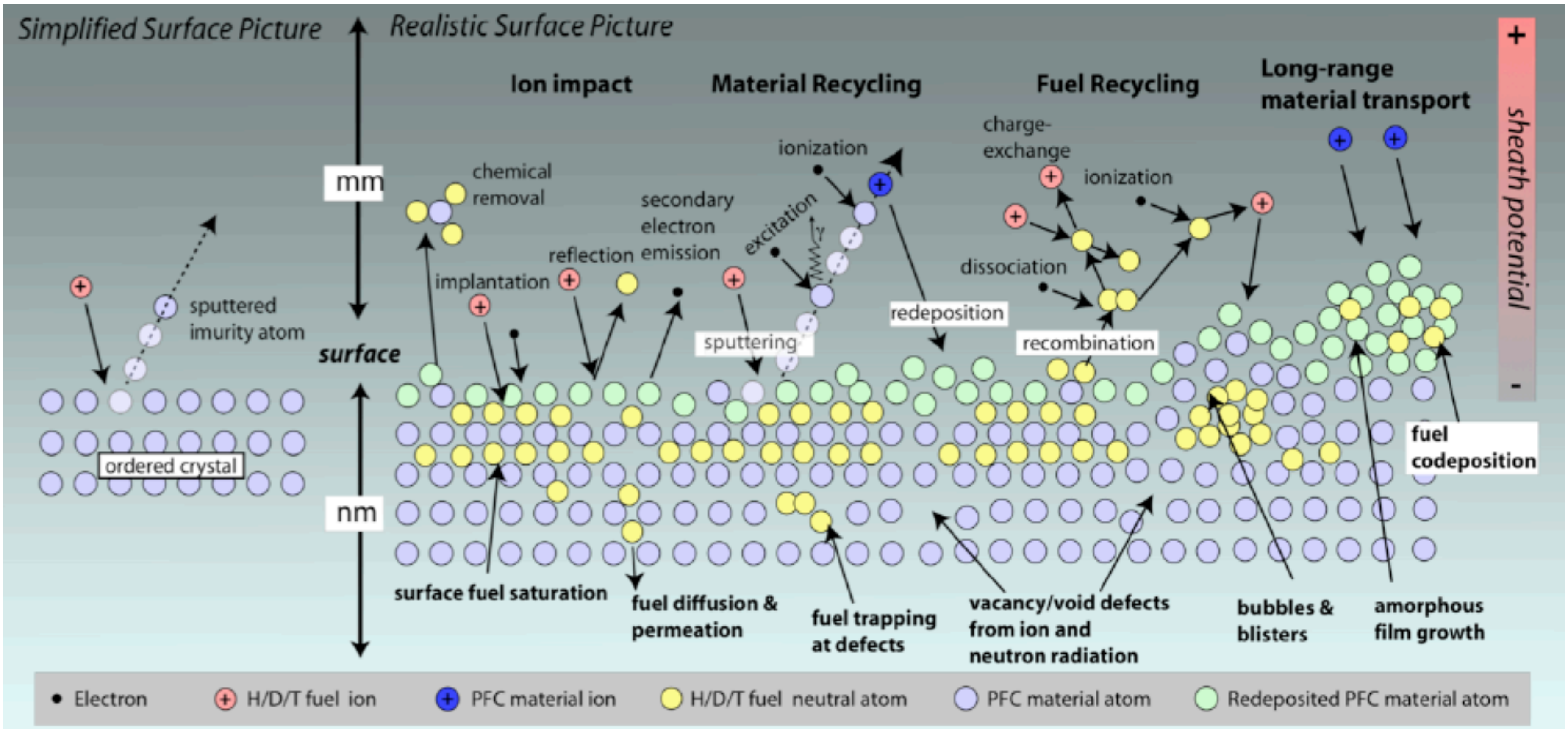
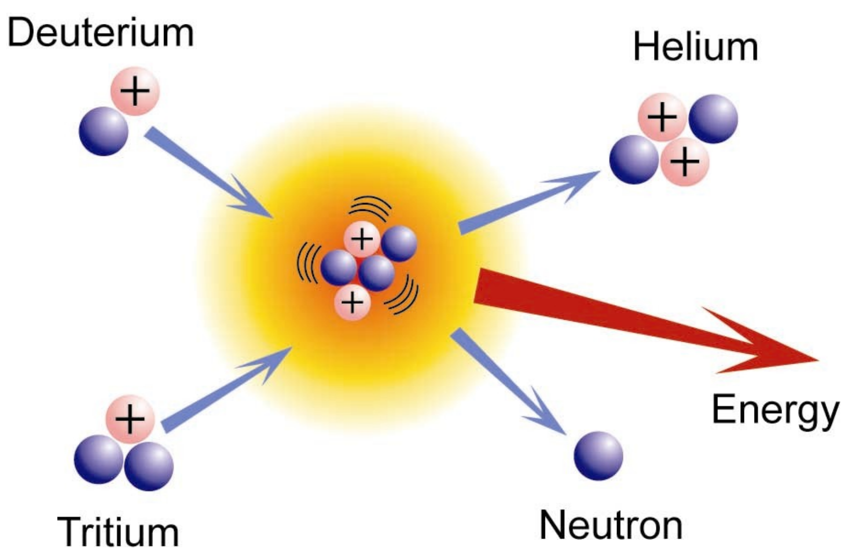



Image from D. Whyte, http://psisc.org/mission

# 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

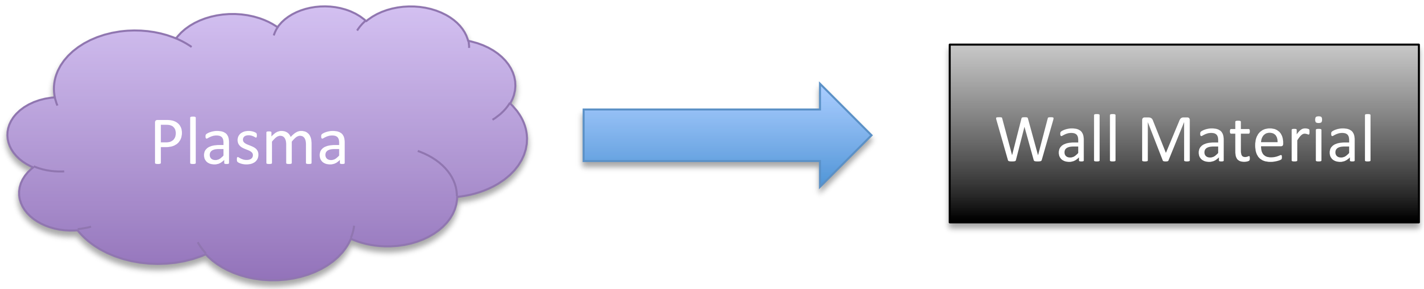
The trouble with fusion is…

- 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*

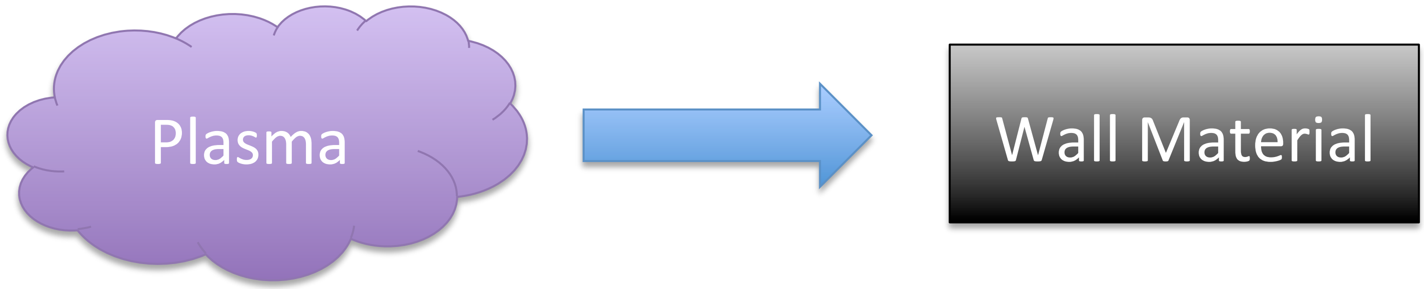



- Changes in the physical & chemical properties of the material can occur

# Key materials issues in fusion devices

**Two aspects:**

*1. How the plasma affects the material*



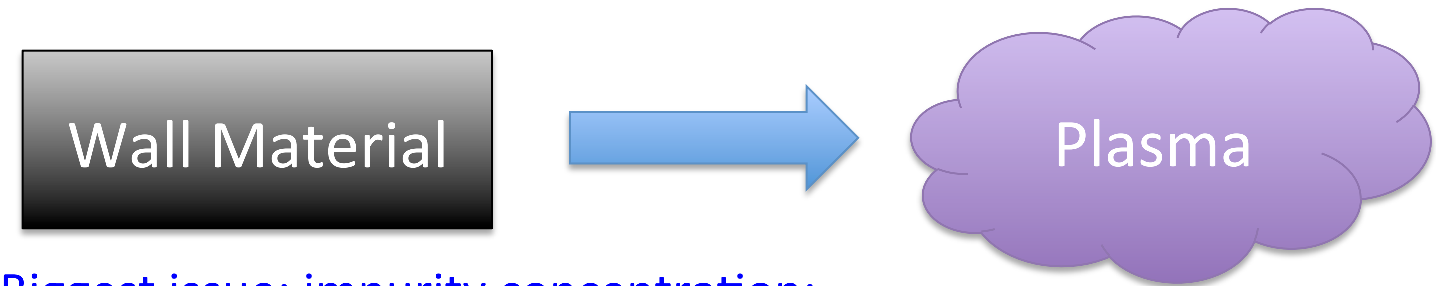

- Changes in the physical & chemical properties of the material can occur

- 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

# Key materials issues in fusion devices

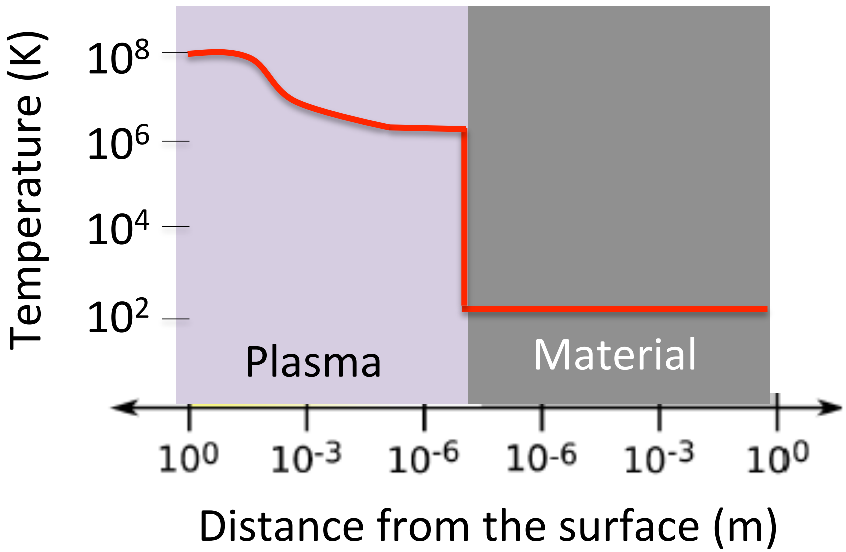
**Two aspects:**

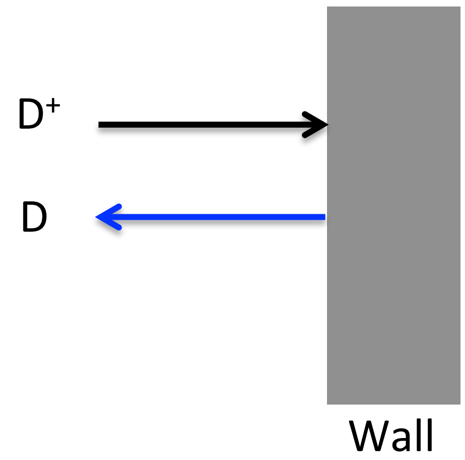
*2. How the material affects the plasma*


- Biggest issue: impurity concentration:
  - can result in fuel dilution, radiated power losses, deposition of material where it is not wanted

- 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



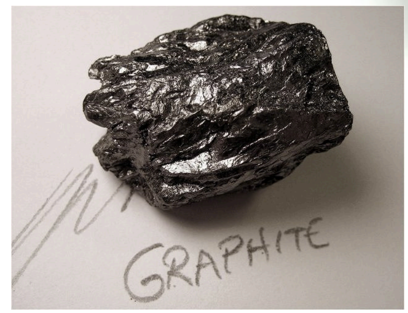




- $D^+$ neutralizes at the surface
- D atom is released into plasma at low temperature!
- This cools the plasma!
- Fusion reaction will extinguish

# 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

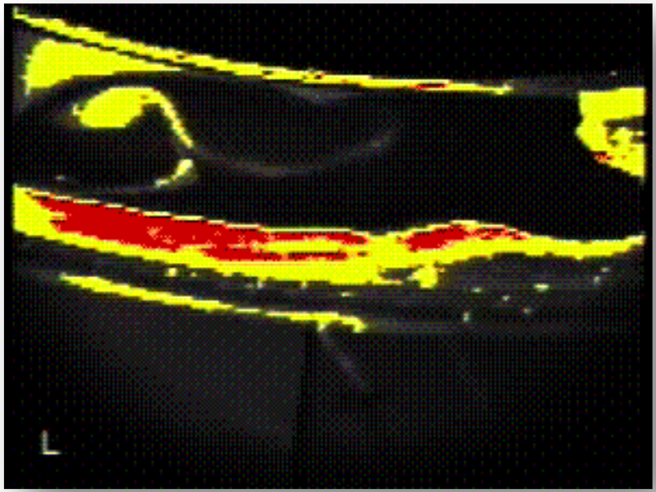
No thermal fatigue

No neutron damage

Resilient again high heat fluxes

Refreshes the surface

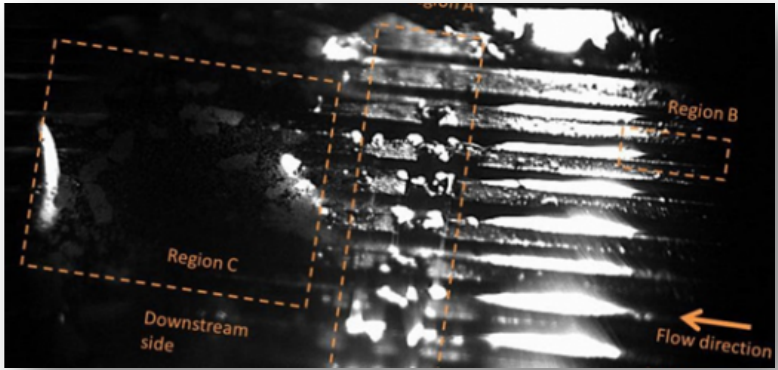
Li concentration in the plasma is low



*Infrared image of liquid lithium a fusion device at PPPL.*

**Li has shown to improve the plasma performance!**

**Improved confinement time → Very important for fusion!**



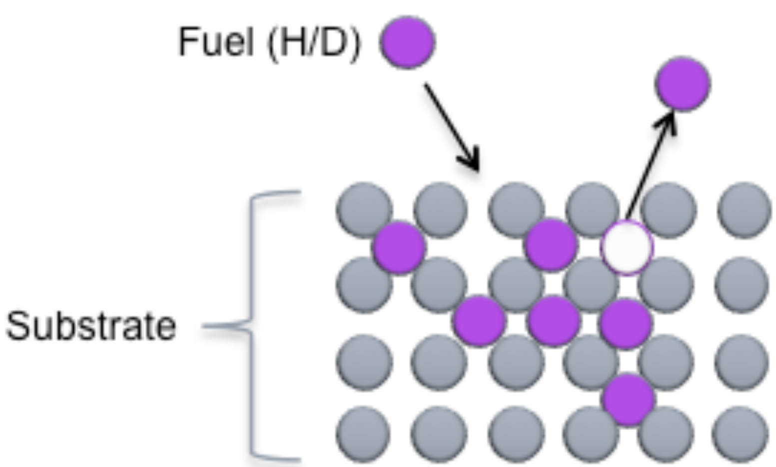

*Flowing liquid Li experiment at University of Illinois at Urbana-Champaign*

# But why does Li help?

**Working hypothesis: Deuterium retention**

High D retention → Low recycling → High edge temperature → Reduced temperature gradients

- Recycling Process:




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

But how is D retained in Li?

1. Through volumetric conversion of Li to LiD (Baldwin & Doerner)

2. Through complexes that involve oxygen (Krstic, Allain, Taylor)

# We need to understand the surface in order to find out!

# We need to understand the surface in order to find out!

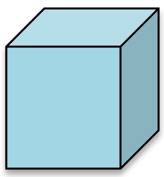
- Atoms at the surface behave differently than atoms in the bulk material.

- The surface provides an environment where unique chemistry can occur.

# We need to understand the surface in order to find out!

- Atoms at the surface behave differently than atoms in the bulk material.
- The surface provides an environment where unique chemistry can occur.

So, how do we study surfaces?



$$\rho = 10^{23} cm^{-3}$$

$$\rho_s \approx \rho^{\frac{2}{3}} \approx 10^{14} cm^{-2}$$

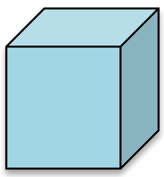
*Surfaces contain ~$10^{14}$ atoms/$cm^2$*

# We need to understand the surface in order to find out!

- Atoms at the surface behave differently than atoms in the bulk material.
- The surface provides an environment where unique chemistry can occur.

So, how do we study surfaces?

**Challenge:** Detect $10^{14}$ $cm^{-2}$ signal on a $10^{23}$ $cm^{-3}$ background



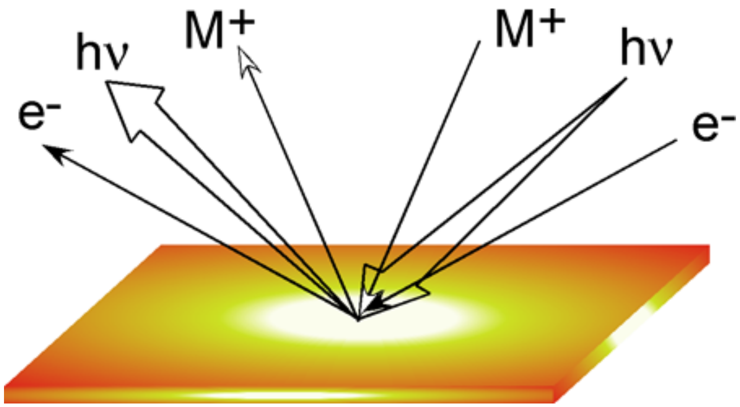
$$\rho = 10^{23} cm^{-3}$$

$$\rho_s \approx \rho^{\frac{2}{3}} \approx 10^{14} cm^{-2}$$

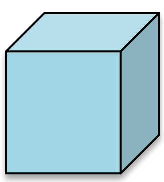
*Surfaces contain ~$10^{14}$ atoms/$cm^2$*

# We need to understand the surface in order to find out!

- Atoms at the surface behave differently than atoms in the bulk material.
- The surface provides an environment where unique chemistry can occur.




So, how do we study surfaces?



$$\rho = 10^{23} cm^{-3}$$

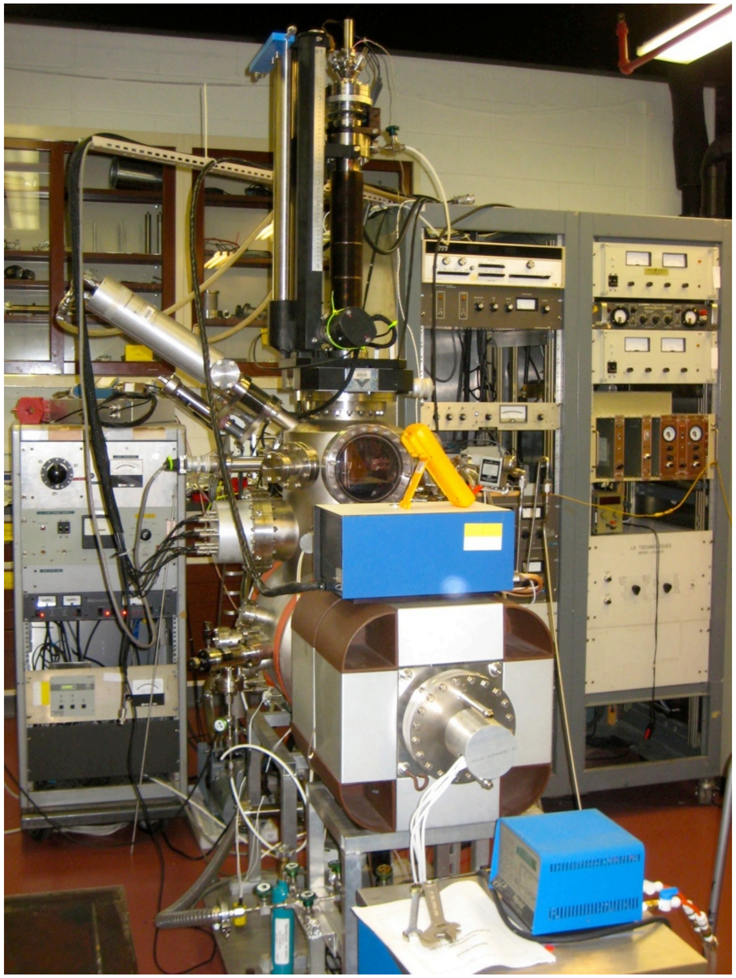
$$\rho_s \approx \rho^{\frac{2}{3}} \approx 10^{14} cm^{-2}$$

*Surfaces contain ~$10^{14}$ atoms/$cm^2$*

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

**Solution:** Use probes that strongly interact with matter, such as as electrons, ions, and photons (X-rays, UV light).

# Surface science provides fundamental information needed to understand PMI



*Test stand instrumentation in the Surface Science & Technology Lab*

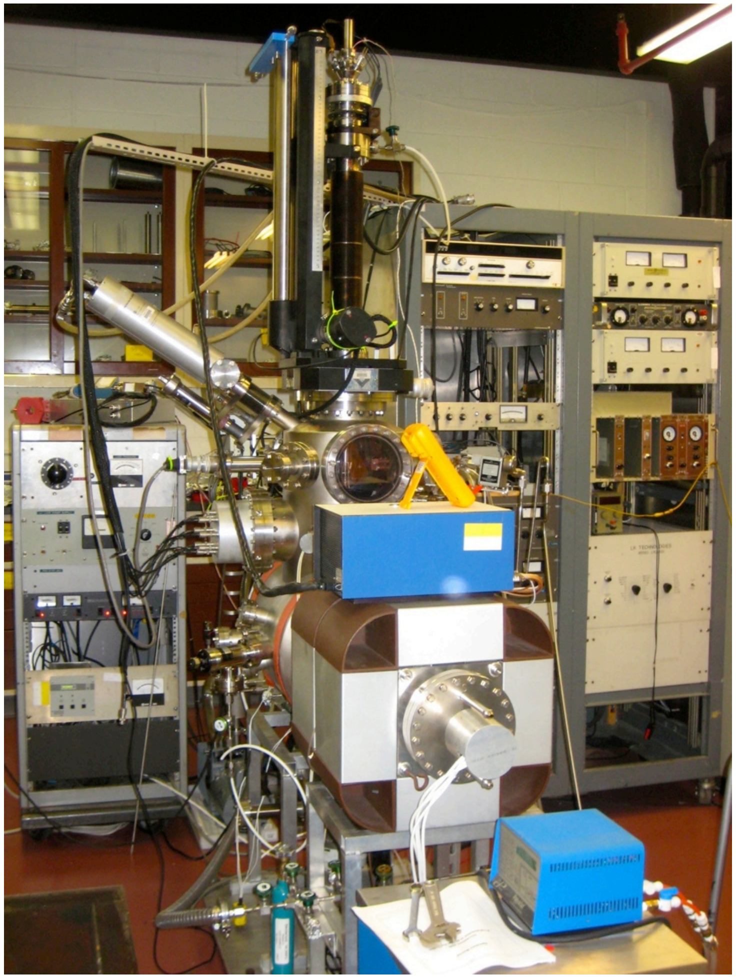
Key variables affecting chemistry at surface:

- 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!*

# Surface science provides fundamental information needed to understand PMI



*Test stand instrumentation in the Surface Science & Technology Lab*

Key variables affecting chemistry at surface:

- Pressure (residual gases)
- Temperature (plasma heating)
- Composition (Mo, Li, D, etc.)

Lab-based surface science experiments enable <u>independent control</u> of all variables

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

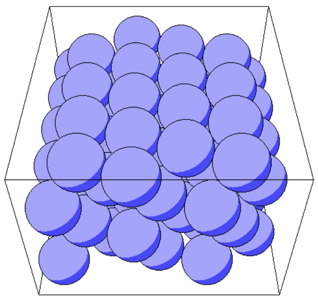
Isolate effects of:

- 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** → **More Complex Systems**

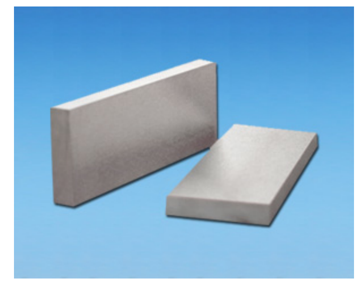


Mo(110) crystal

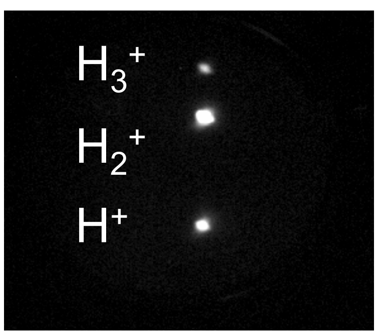
Grain boundaries

Alloying elements: Ti, Zr, C

Surface roughness



TZM Mo alloy




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

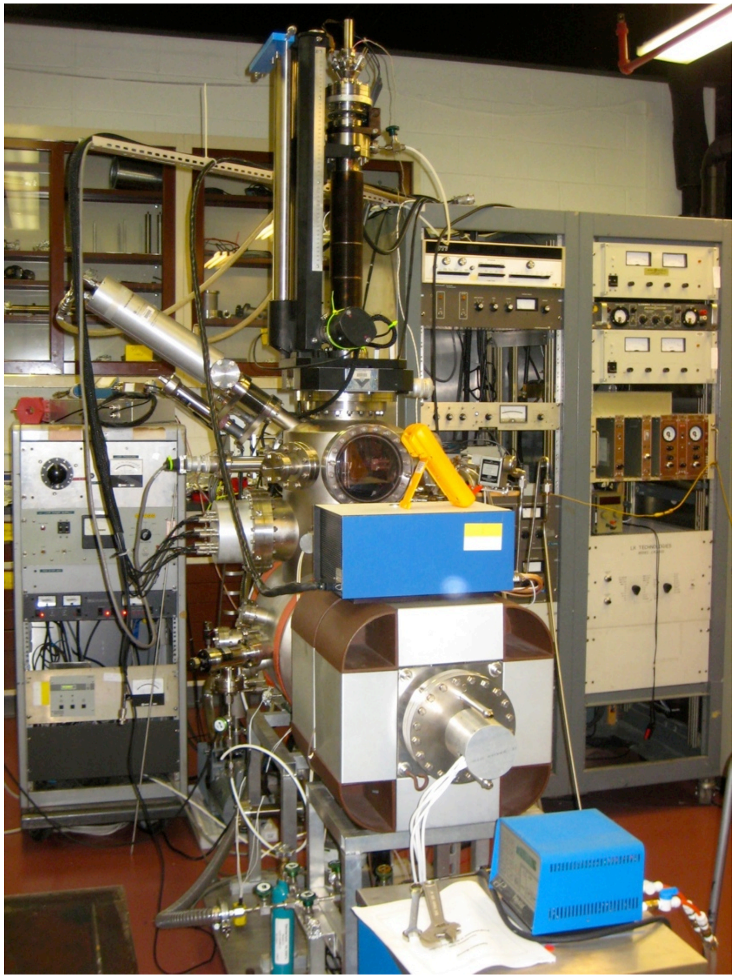
Multiple species: $H^+$, $H_2^+$, $H_3^+$

Increased flux: $10^{12} \rightarrow 10^{16}$ $cm^{-2}$ $s^{-1}$

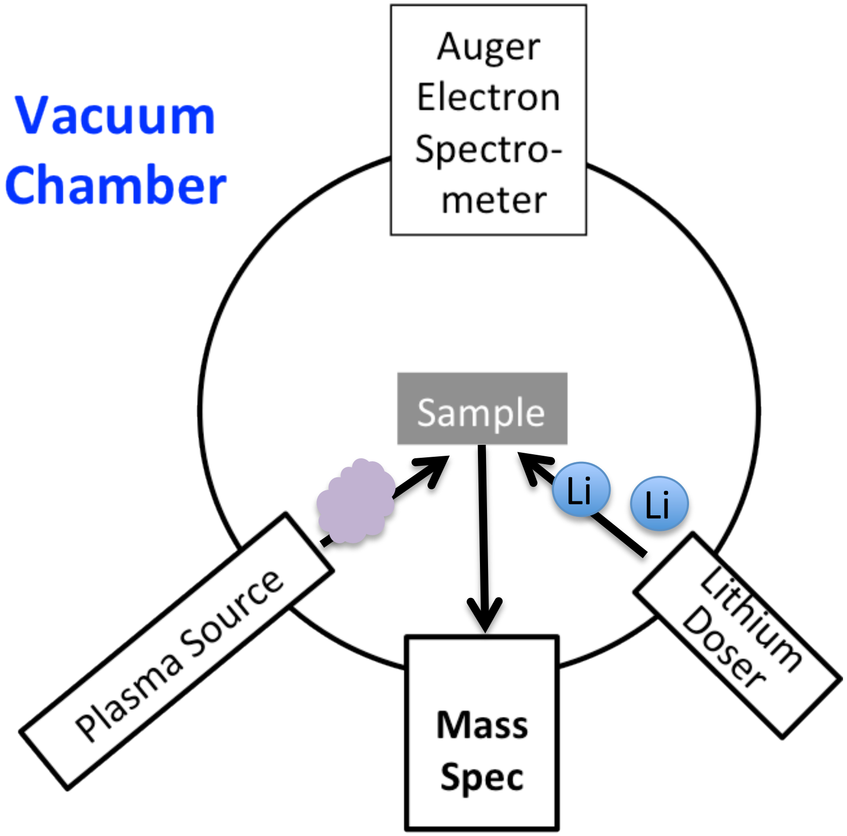
Atoms, ions, or atoms + ions

ECR plasma source

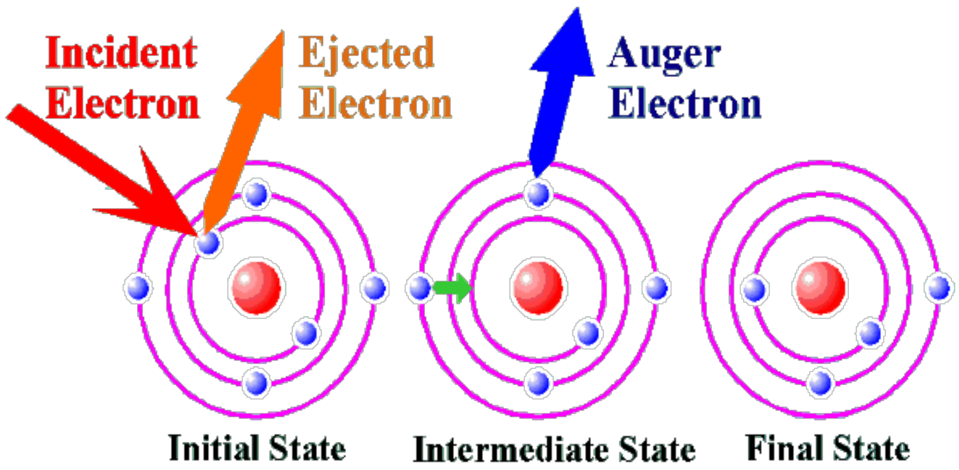
# Surface science provides fundamental information needed to understand PMI



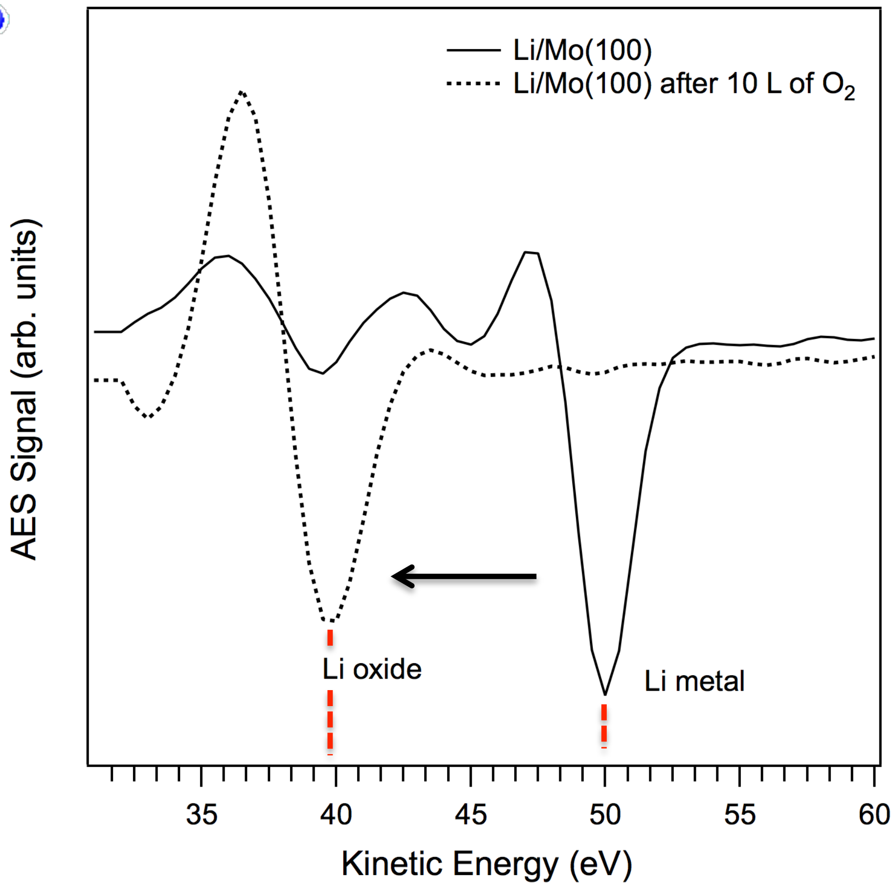
*Test stand instrumentation in the Surface Science & Technology Lab*



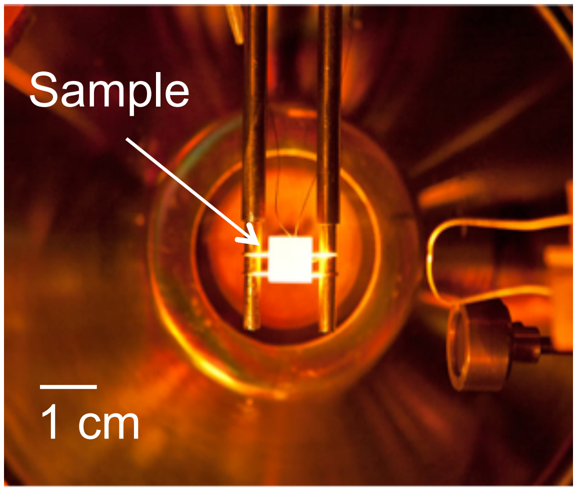
# Auger electron spectroscopy

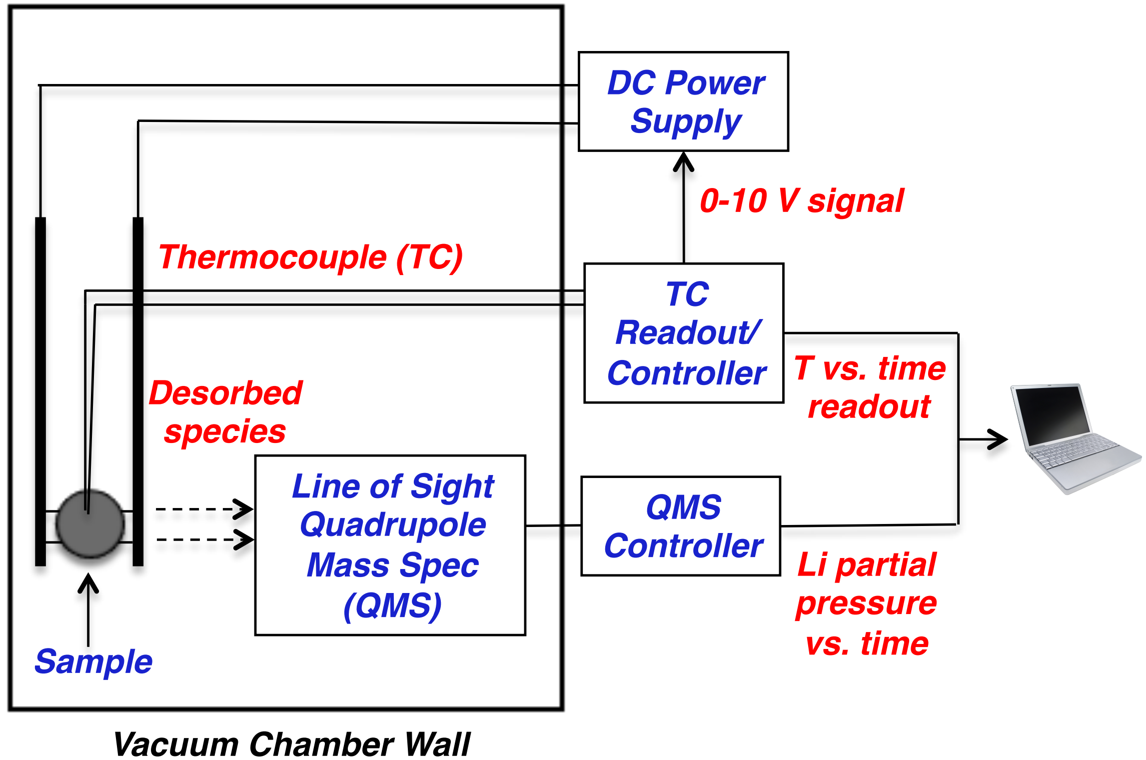



AAES gives elemental information (and also oxidation state) !



# Temperature programmed desorption

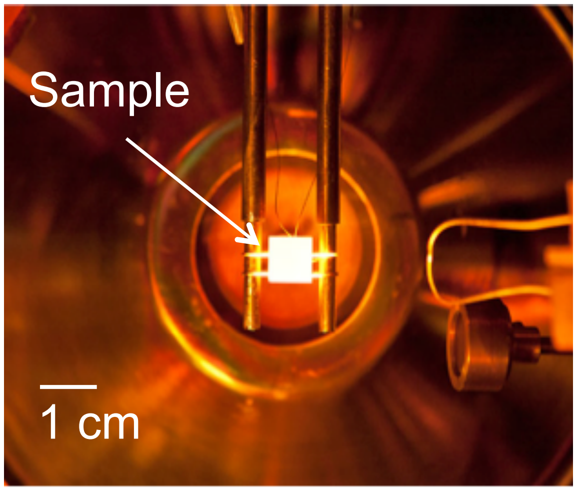


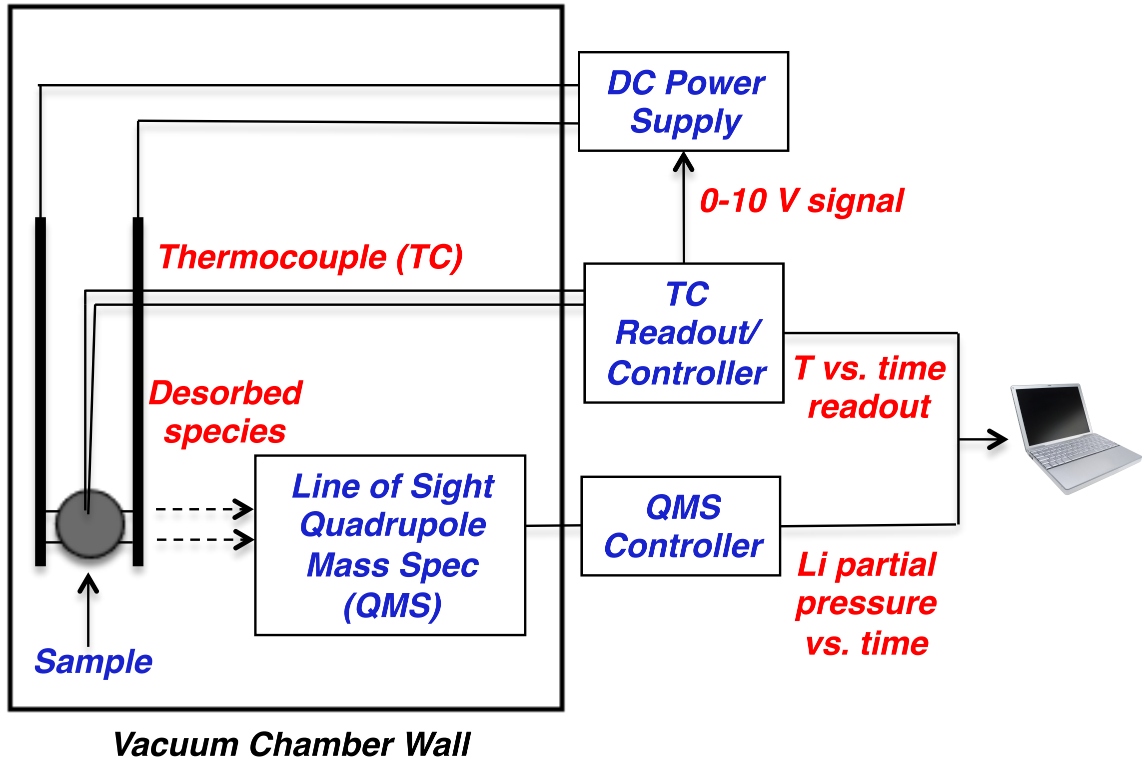




Temperature Programmed Desorption (TPD) Technique:

- 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

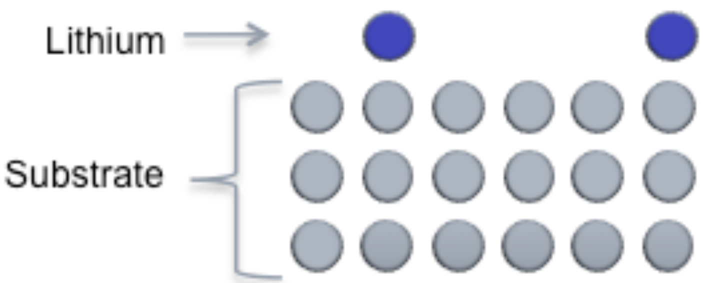


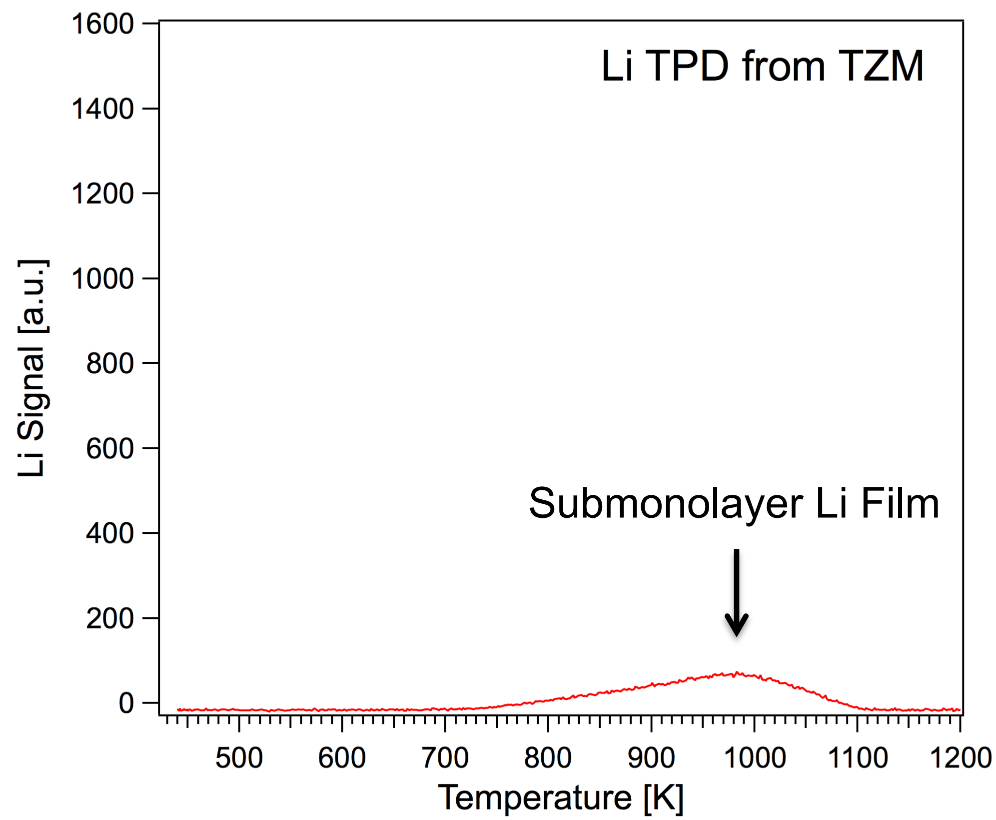

Area under pressure vs. time curve → # of atoms desorbed

TPD can be used to measure D retention!

# Example: Desorption of Li from Mo

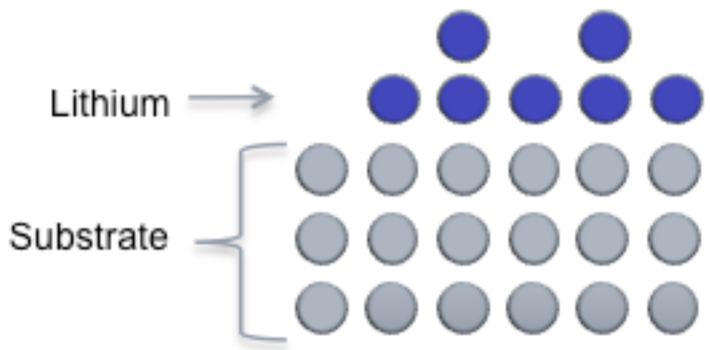



- Submonolayer Li film on TZM stable up to 1000 K
- Represents Li-Mo bonding
- Desorption energy ~2.7 eV

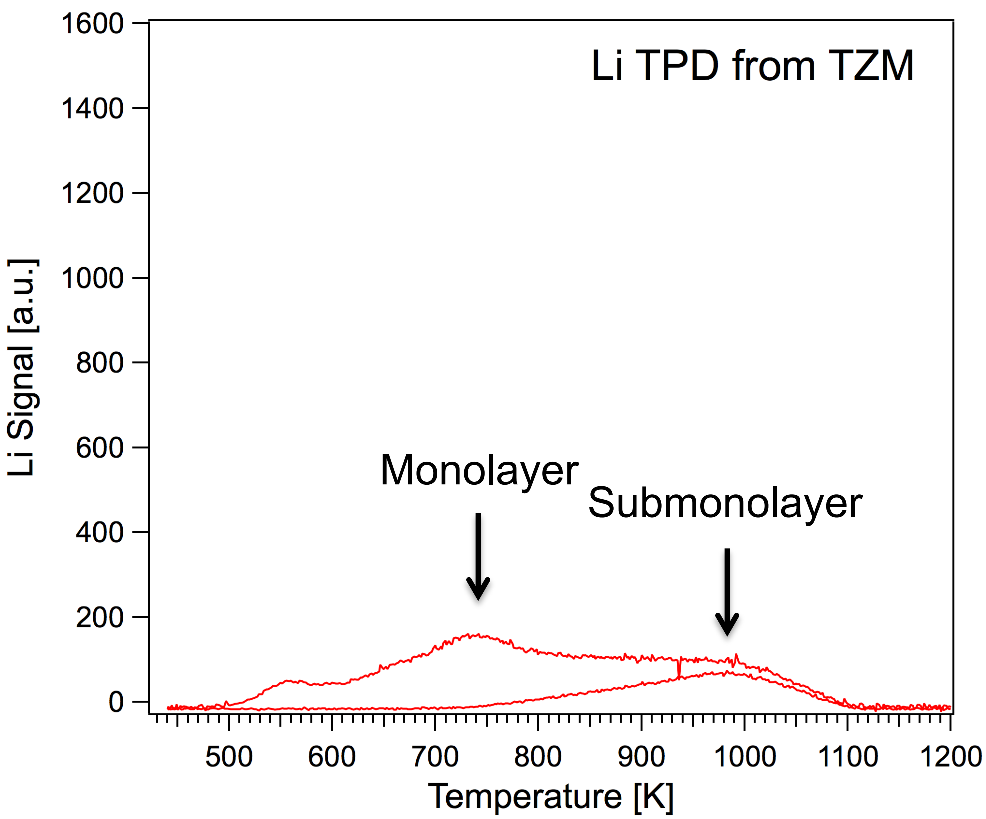



C.H. Skinner et al., JNM 438, S647 (2013)

# Example: Desorption of Li from Mo

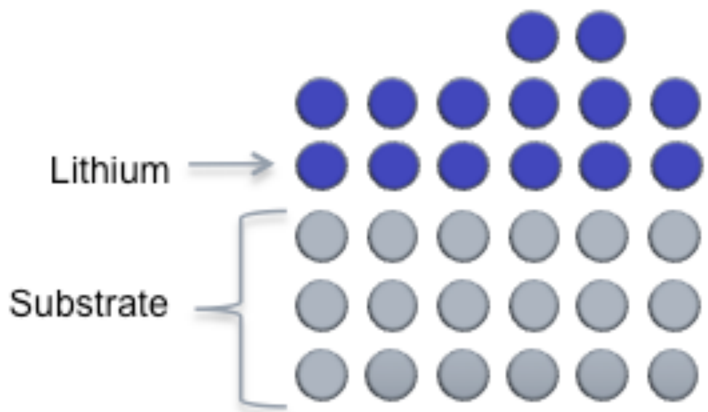



- Area under Li TPD curve increases with Li dose
- Dipole interactions lower the desorption energy (~2 eV)
- $E_d$ is a function of coverage

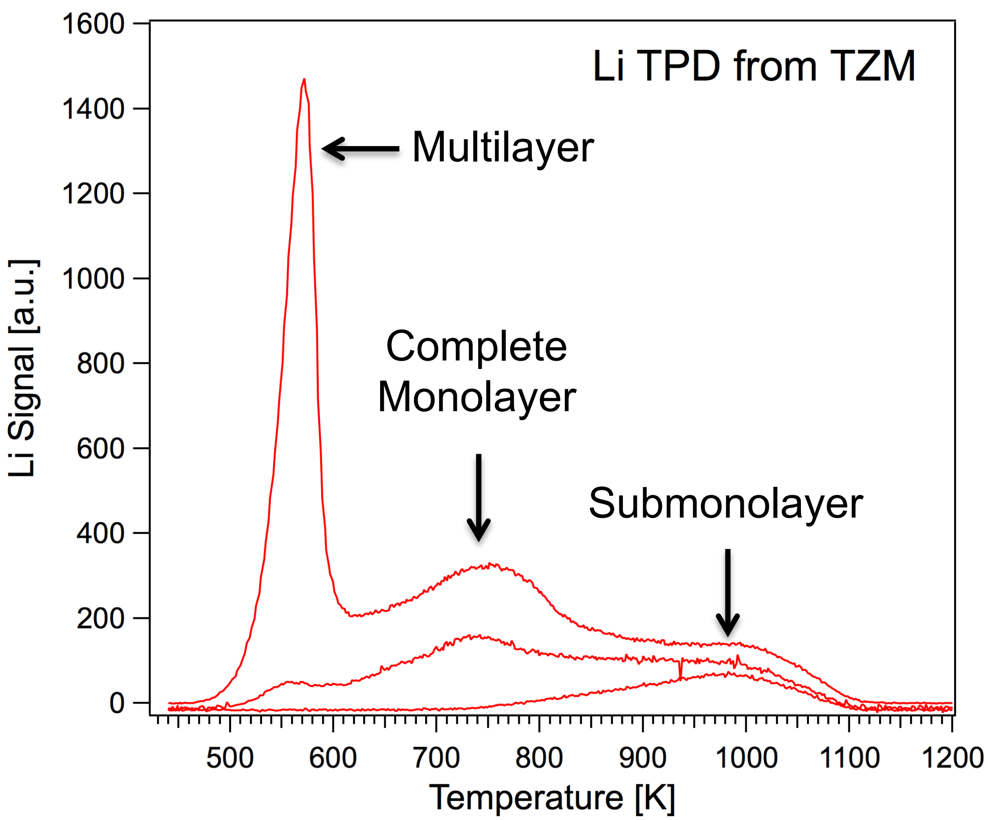



C.H. Skinner et al., JNM 438, S647 (2013)

# Example: Desorption of Li from Mo

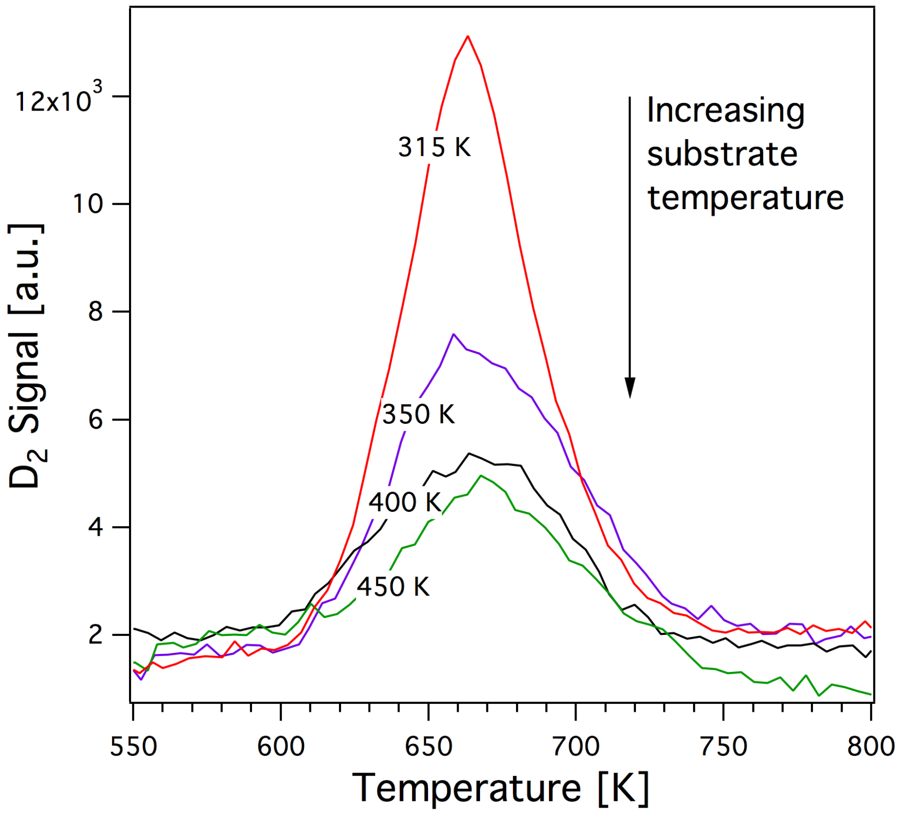


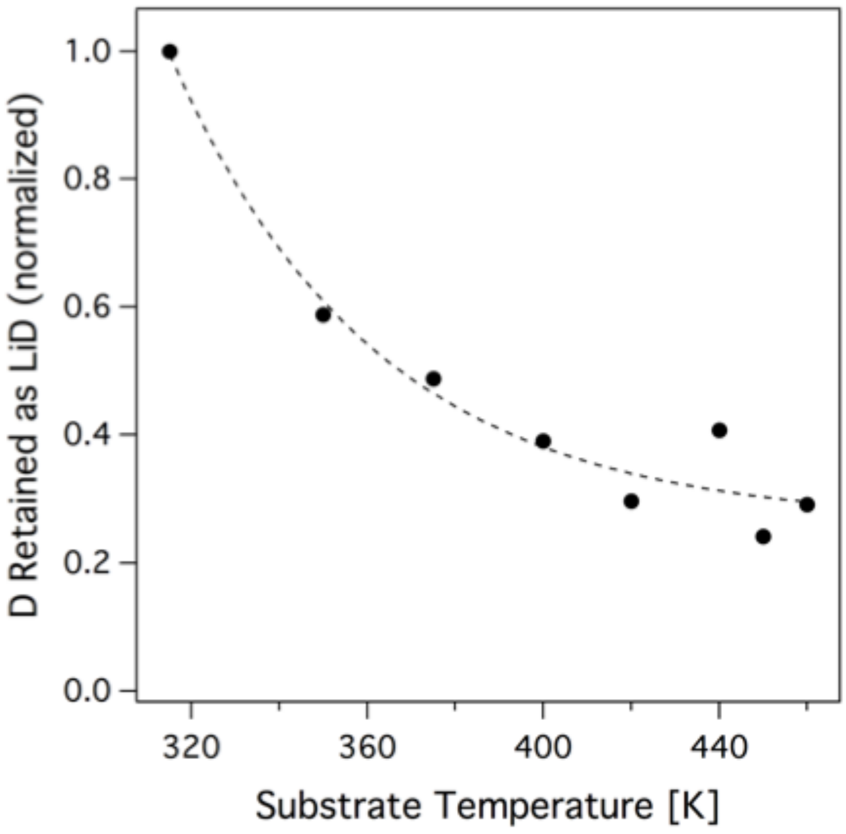

- Thick Li films (multilayer) evaporate at 500 K
- Multilayer film represents Li-Li bonding
- Cohesive energy of metallic Li ~1.7 eV



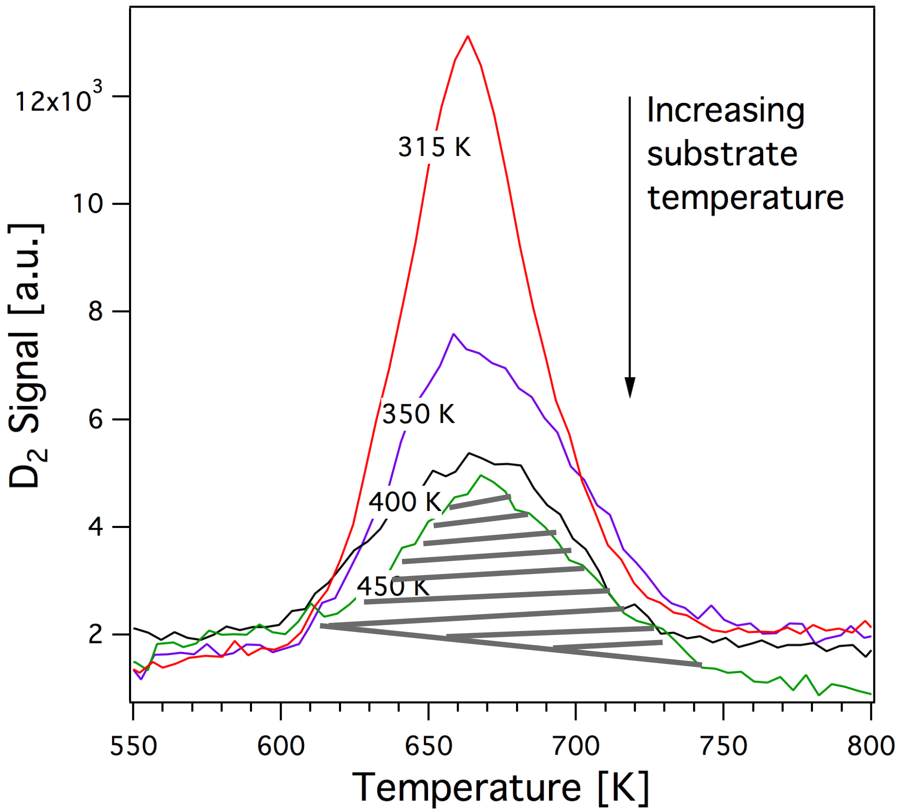

C.H. Skinner et al., JNM 438, S647 (2013)

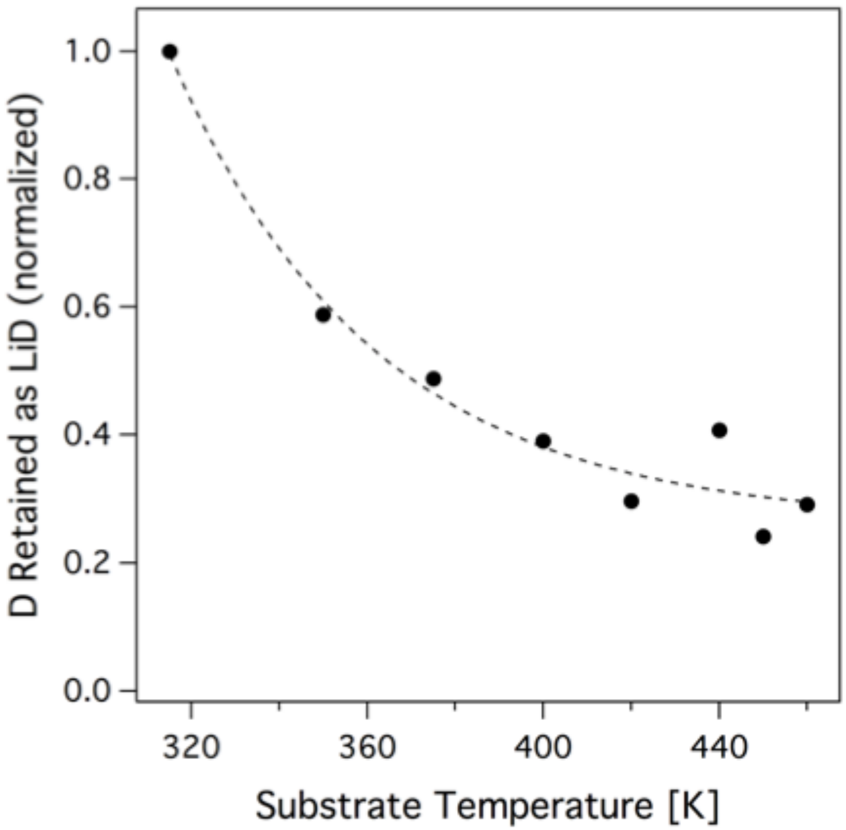
# TPD can be used to determine D retention



# 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