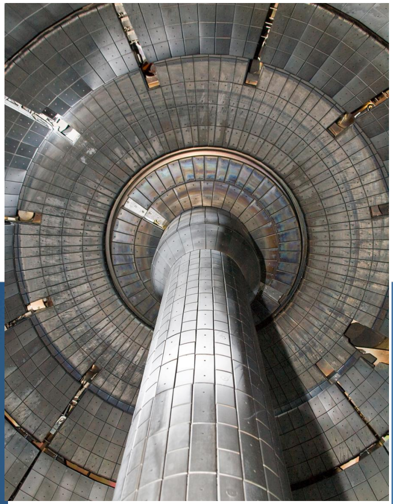
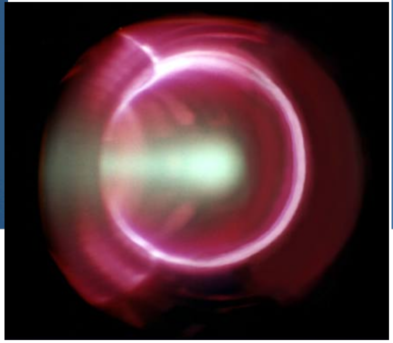
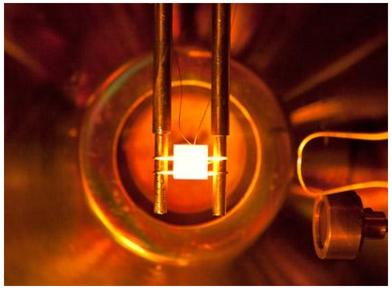




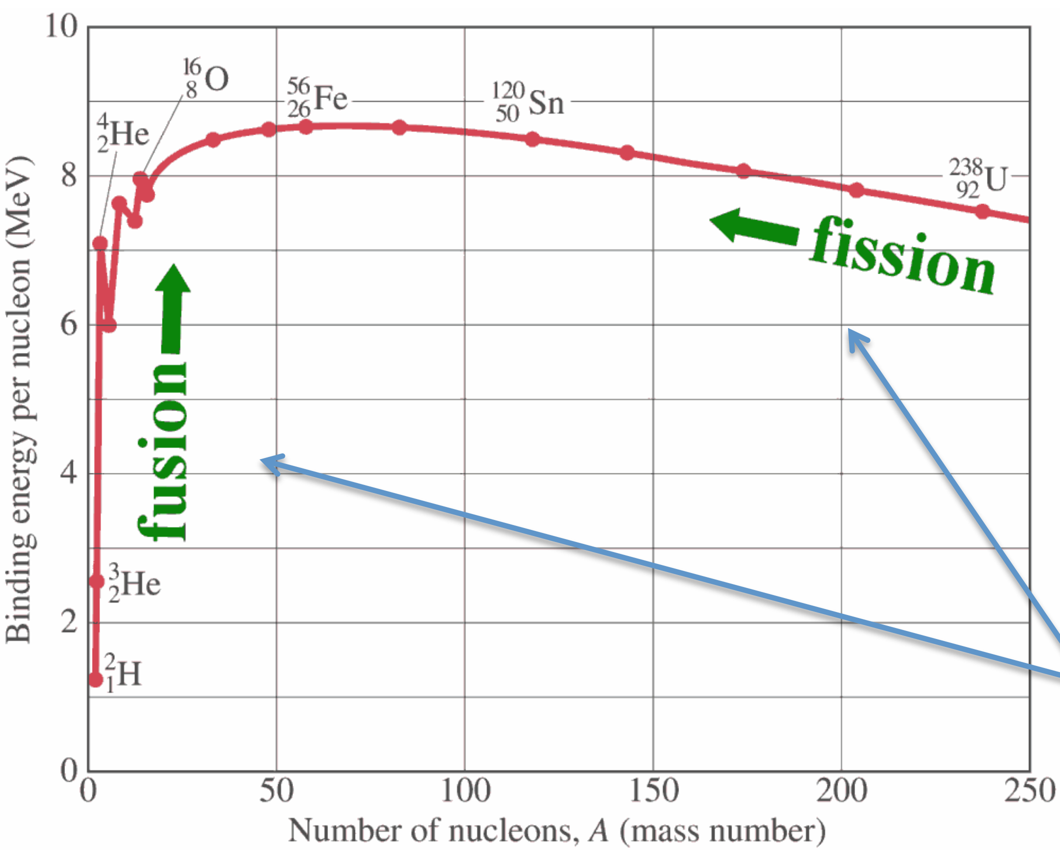

Materials Science in Fusion Devices

Angela M. Capece
Department of Physics
The College of New Jersey

SULI Introductory Course
in Plasma Physics, PPPL

June 12, 2018

Nuclear energy (fission & fusion) comes from the mass defect of the nucleus



Advantages of fusion energy:

- Clean
- Green
- Safe
- Abundant

MASS DEFECT:

The whole < the sum of the parts! (e.g., mass of He nucleus is less than mass of 2p + 2n)

Larger mass defect → greater BE

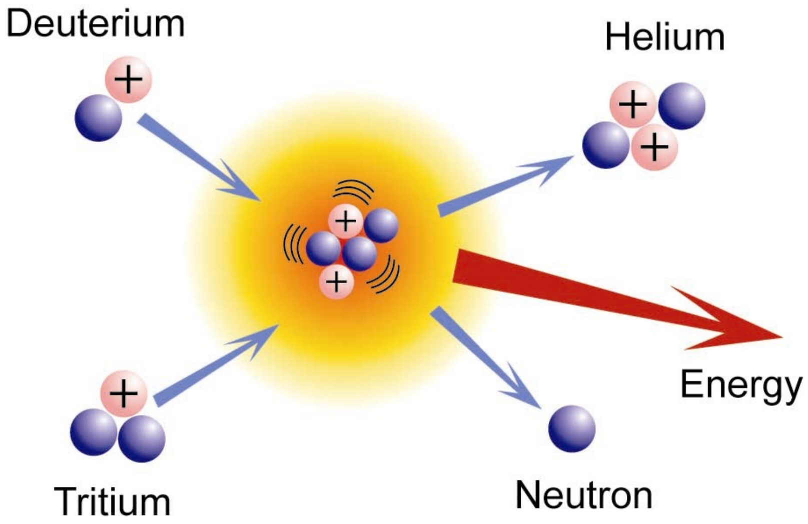
Going from low BE to higher binding energy releases energy

We need fusion to survive

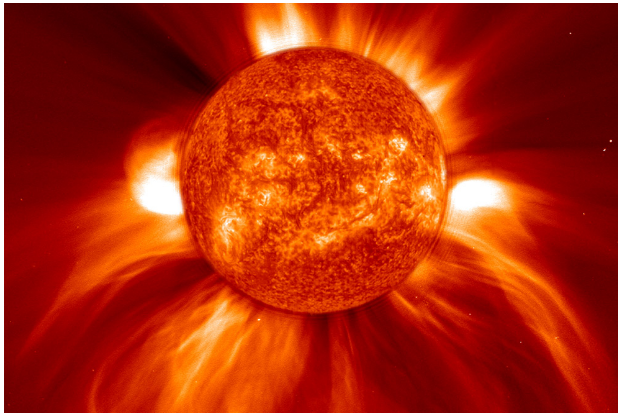
- H fuel extracted from seawater
- D-D fusion can power the world for 2×10^9 yr
  - Coal: 200 yr
  - Natural gas: 20 yr
  - U235/Th232 breeder reactors: 20,000 yr
- Fuel efficient
  - City of 1 million, need 60 kg of H_2

Advantages of fusion energy:

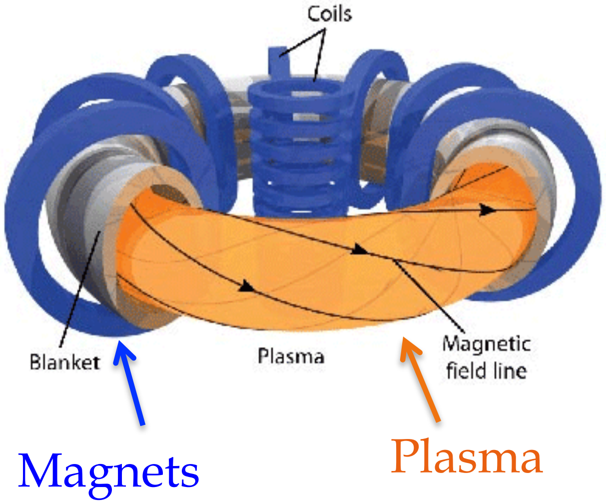
- Clean
- Green
- Safe
- Abundant



Hydrogen fusion requires high temperature & pressure → Plasma!

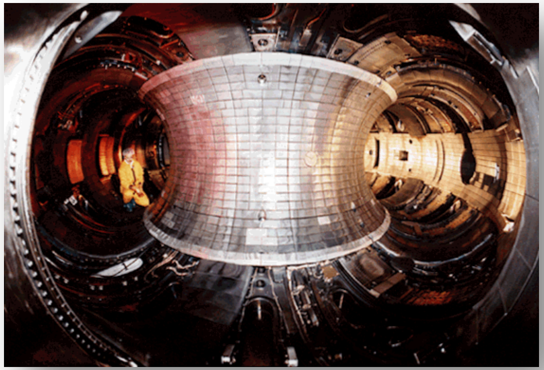


- Temperatures of 100 million K are required (and have been achieved!)
- The sun uses gravity to confine the plasma
- We use magnetic fields



Is it possible on Earth?

<u>**YES!**</u> We've done it before. In fact, we did it here.
(Nov 2, 1994 – 10 megawatts of fusion power)



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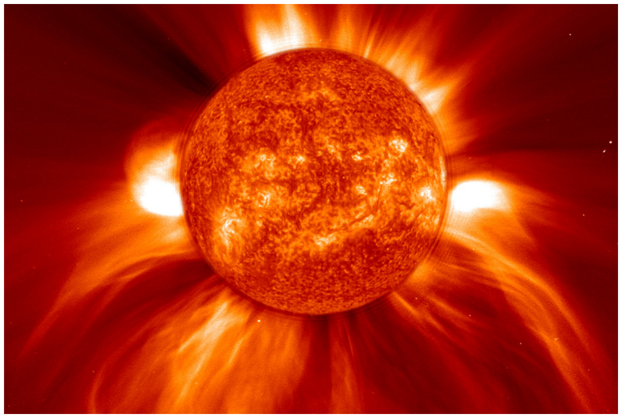
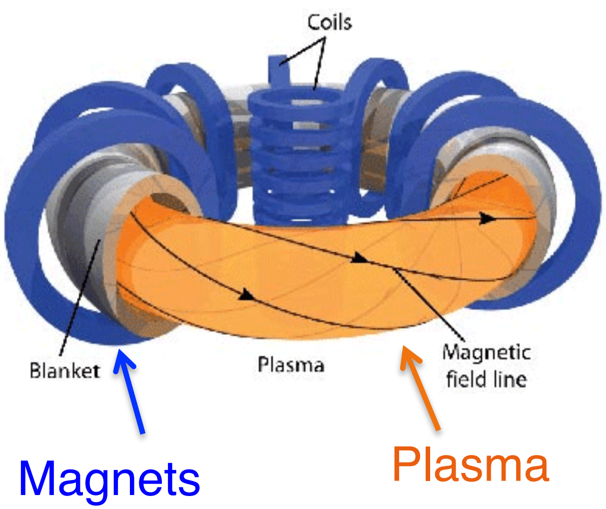


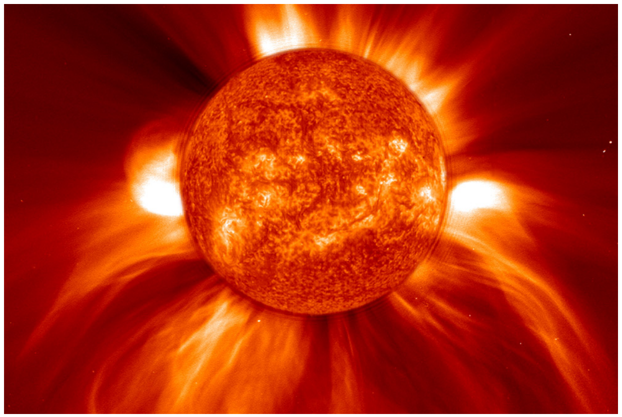
So why don't we have it yet?

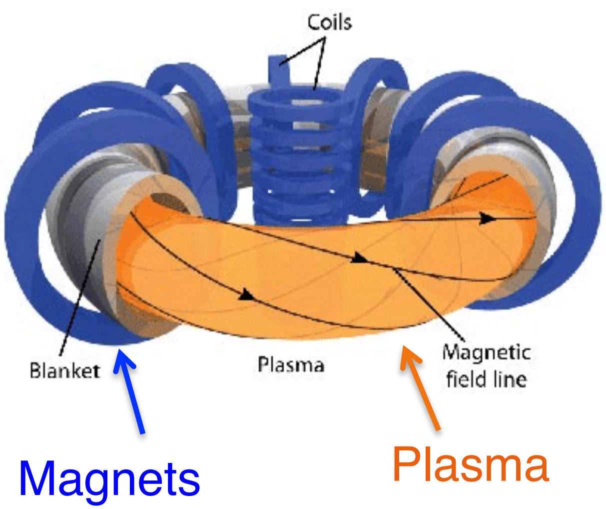
The trouble with fusion is…

- Confining enough hydrogen
- For long enough times
- At sufficiently high temperatures



Hydrogen fusion requires high temperature & pressure → Plasma!





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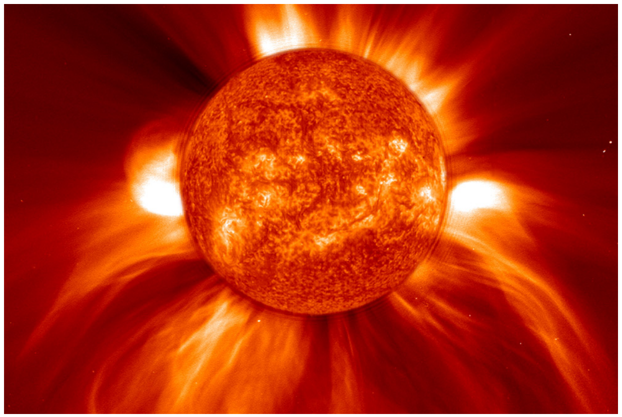
We need…

1. **Better magnets**
2. **Better materials**

Hydrogen fusion requires high temperature & pressure → Plasma!



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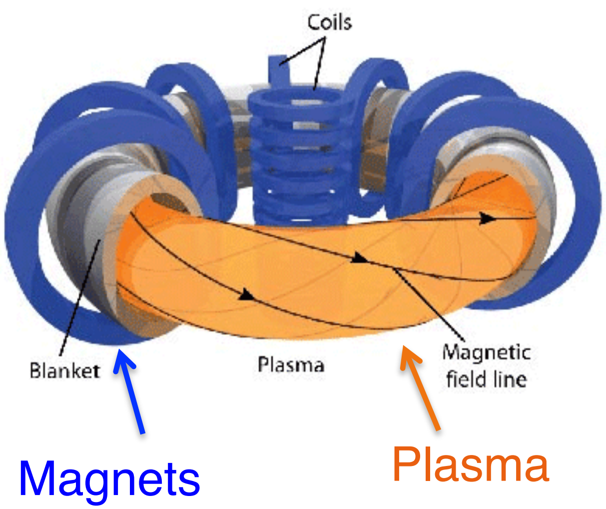
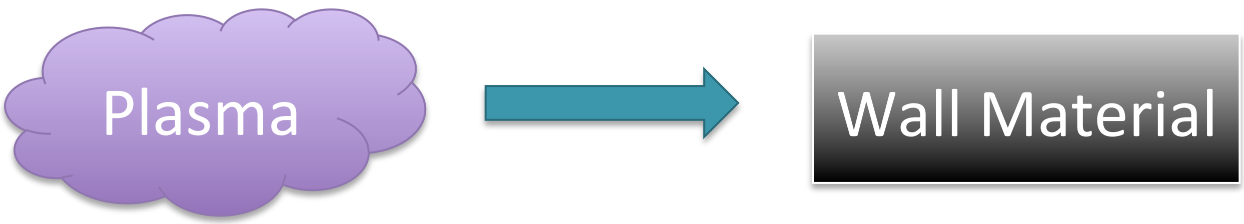


We need…

1. **Better magnets**
2. **Better materials**

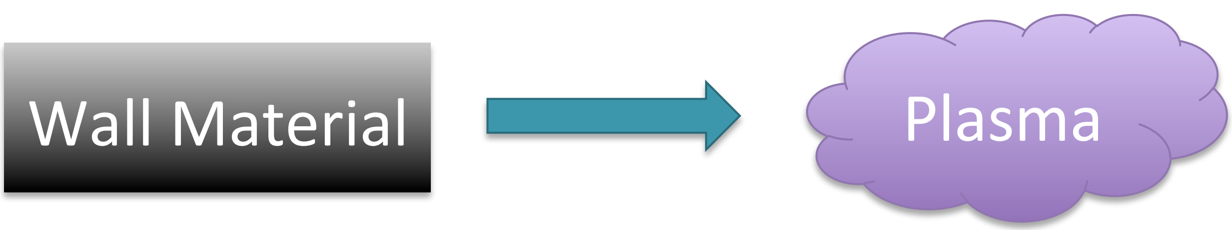
What happens when you try to contain a plasma?

1. The plasma affects the surface



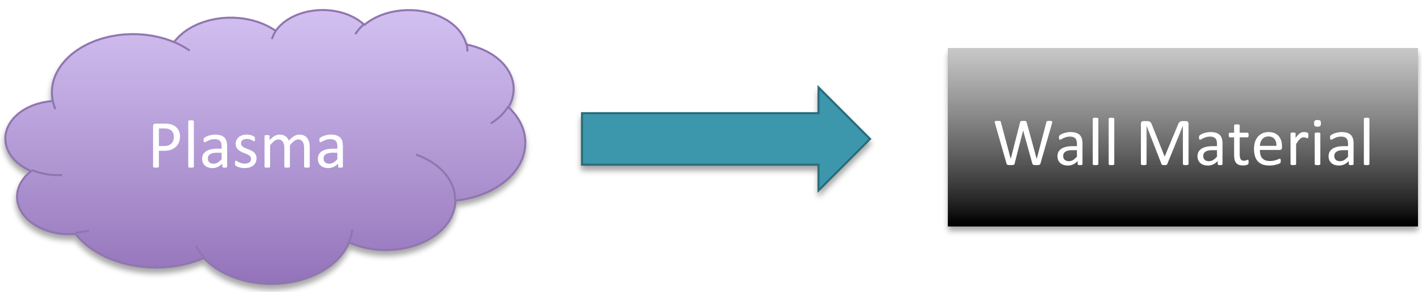
Physical & chemical properties of the material can change

2. The surface affects the plasma



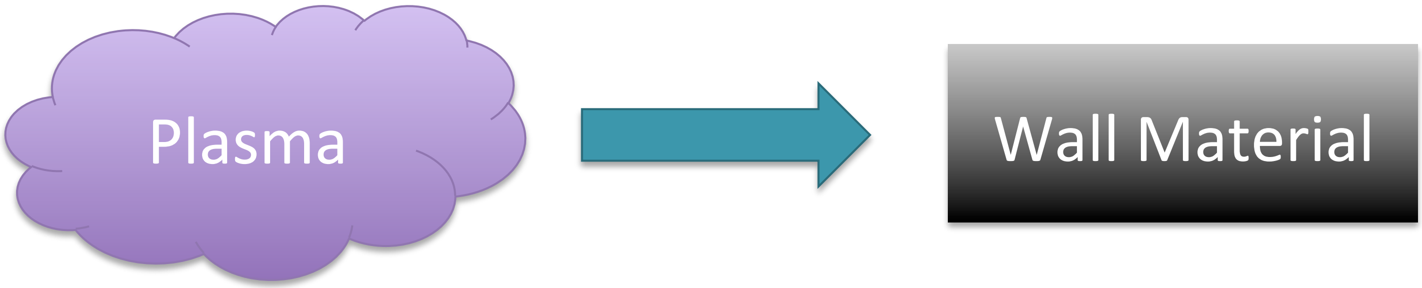
Chemical composition of the plasma can change

How plasma affects the surface:



What do we have in the plasma?

How plasma affects the surface:

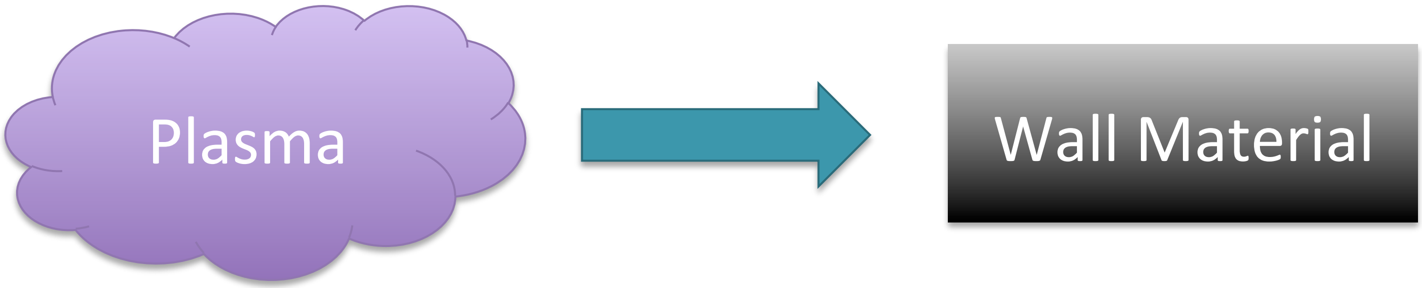


What do we have in the plasma?

- High energy electrons
- H_2, H, H_2^+, H^+, He, He^+
- neutrons

We have high energy particles & reactive species

How plasma affects the surface:



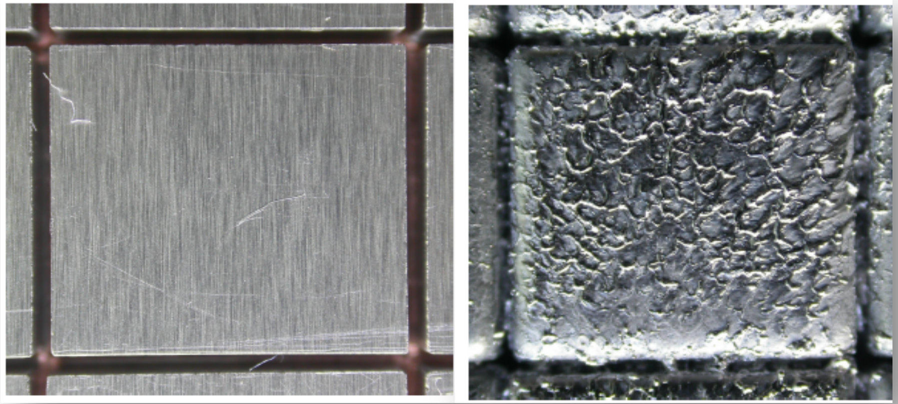
What do we have in the plasma?

- High energy electrons, H_2, H, H_2^+, H^+, He, He^+, neutrons

What do these species do?

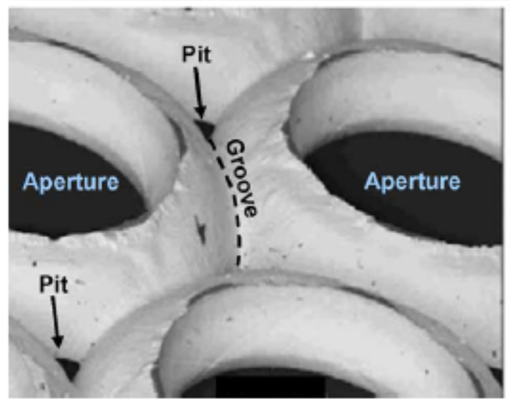
- Impart energy to the wall (heating): ave loads are 10 MW/m^2
- Erode the wall material
- Implant themselves in the wall – Limit on tritium retention!
- Do chemistry on the wall – form different compounds
- Can weaken the material – material swelling / embrittlement from neutrons, fuzz formation

Plasmas can be spectacularly destructive!

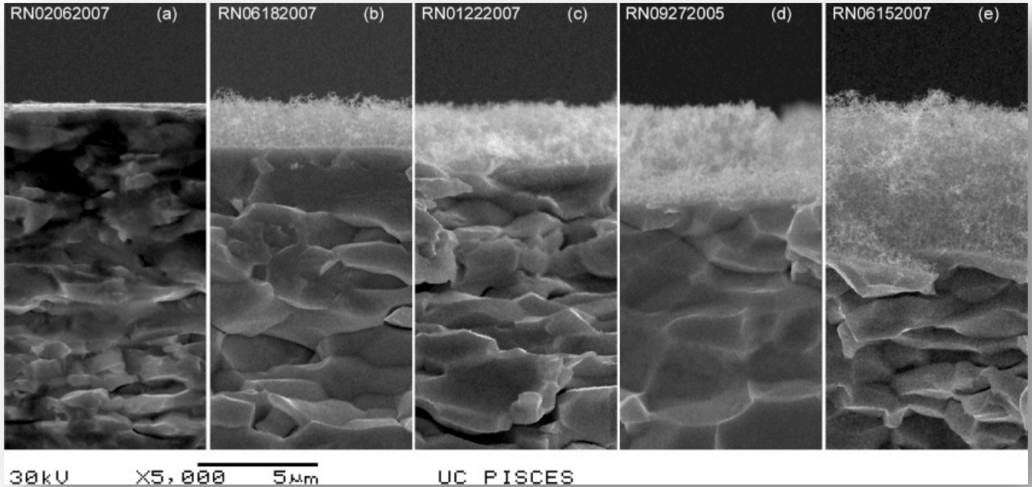


Tungsten tile in fusion device, before & after plasma exposure *Z. Hartwig, MIT*

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

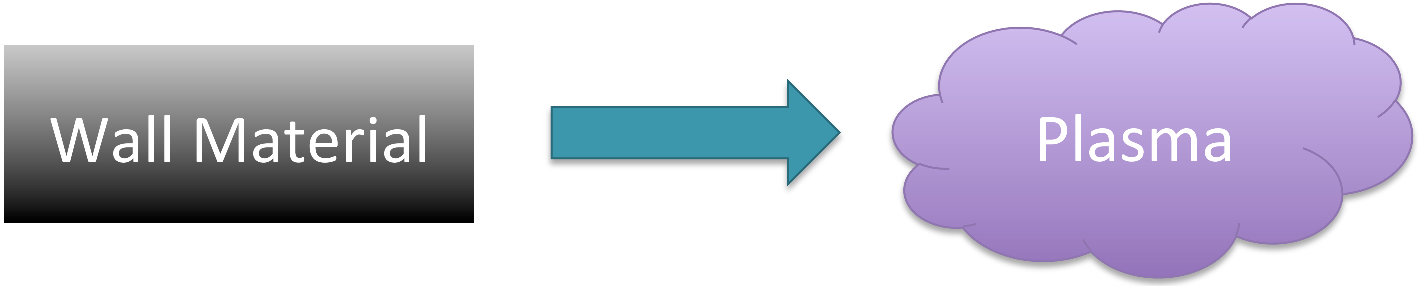


Erosion of molybdenum ion thruster grid
R.E. Wirz, IEEE Trans. Plasma Sci. (2008)



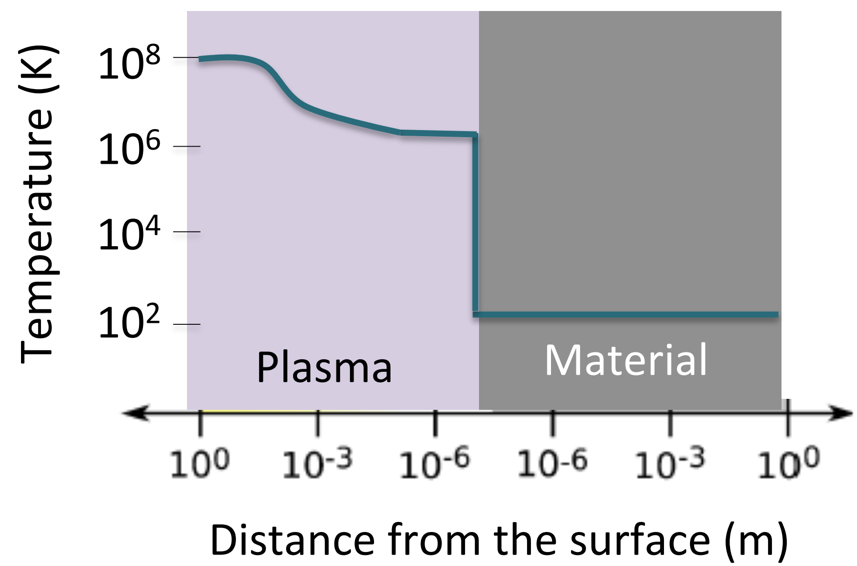
Tungsten fuzz
M.J. Baldwin & R.P. Doerner, Nucl. Fusion (2008)

How the surface affects the plasma:

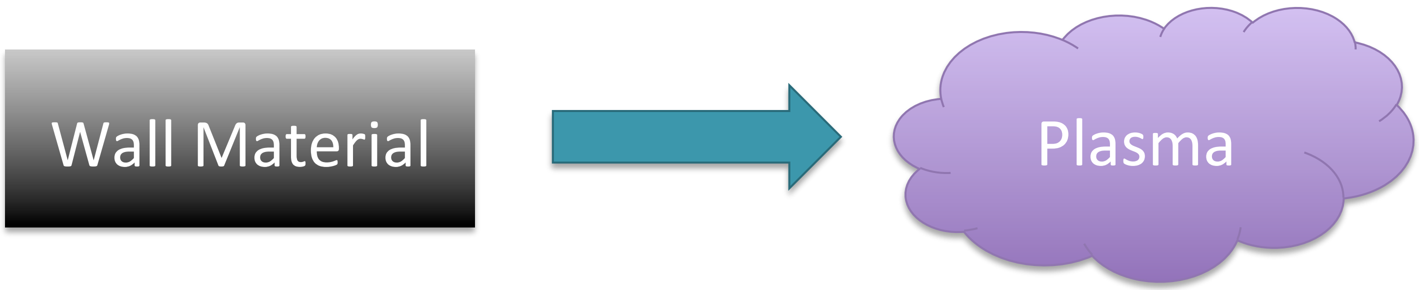


What do we have at the surface?

- A thermal sink (results in temperature gradients near the wall)



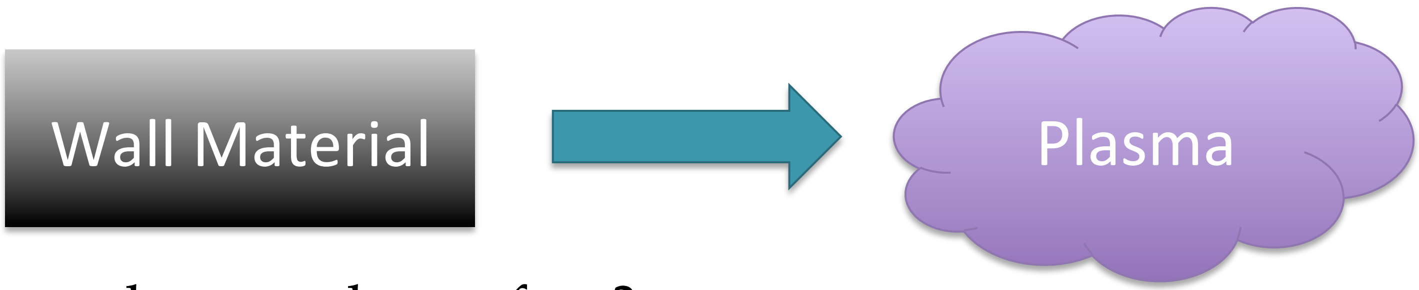
How the surface affects the plasma:



What else do we have at the surface?

- A thermal sink (results in temperature gradients near the wall)
- A nearly infinite source of impurities
- A source of electrons (from the atoms in the surface)

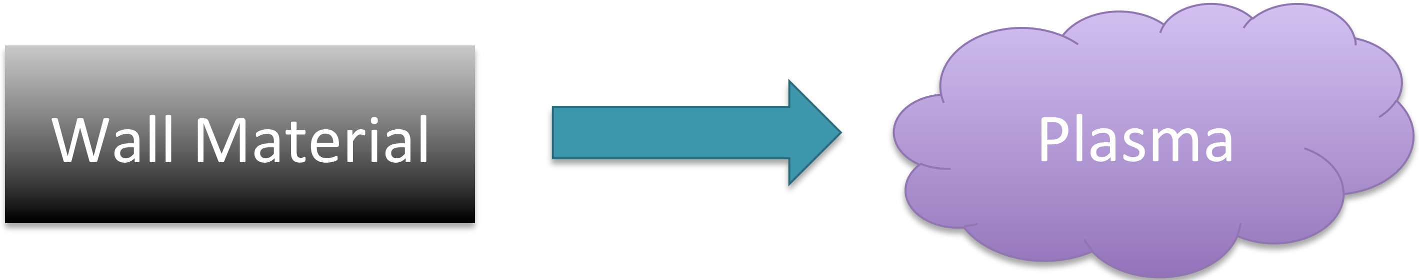
How the surface affects the plasma:



What do we have at the surface?

- A thermal sink (results in temperature gradients near the wall)
- A nearly infinite source of impurities
  - Impurities enter at low temps → reduction in plasma temperature!
  - Dilute the fuel → leads to reduction in fusion power!
  - Material deposited where it is not wanted (e.g., on an expensive diagnostic)

How the surface affects the plasma:



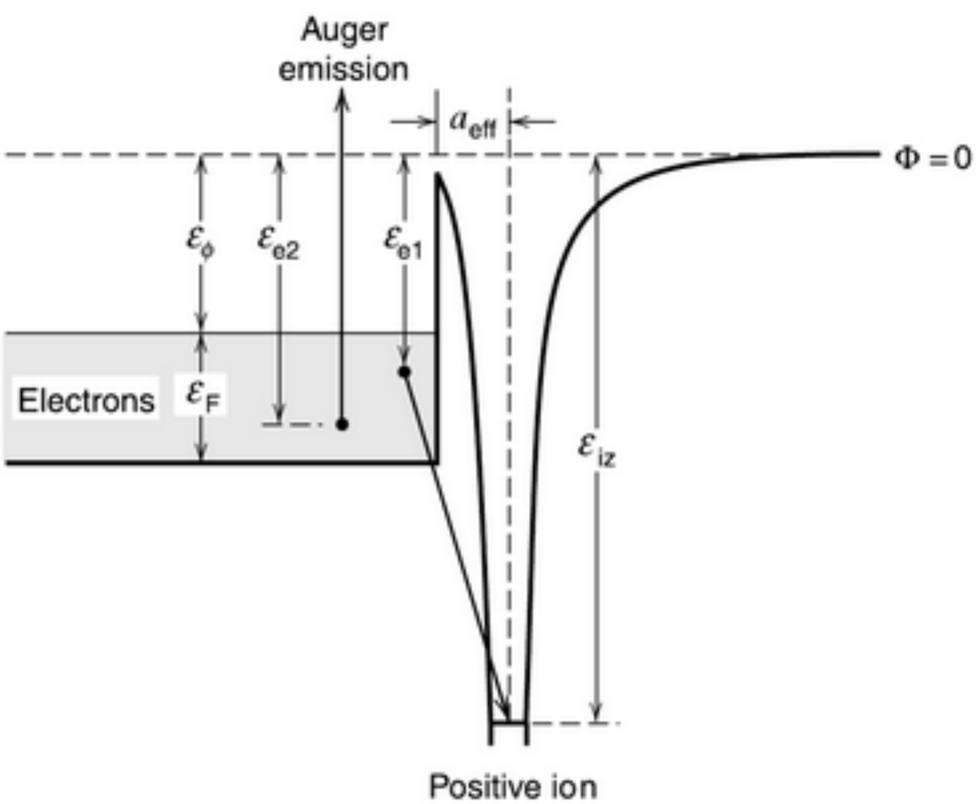
What do we have at the surface?

- A thermal sink (results in temperature gradients near the wall)
- A nearly infinite source of impurities
- A source of electrons (from the atoms in the surface)
  - Electron emission from the wall: cools the edge plasma & changes electric potential
  - Results in gradients in temperature and potential → drives instabilities & reduced confinement

Five main processes that occur at the plasma-materials interface

Five main processes that occur at the plasma-materials interface

1. Positive Ion Neutralization (Recombination)



Occurs for all energies (10-1000 eV, typical)

All ions immediately neutralized

2 options:
-Electron enters excited state (radiates a photon as it transitions to lower state)

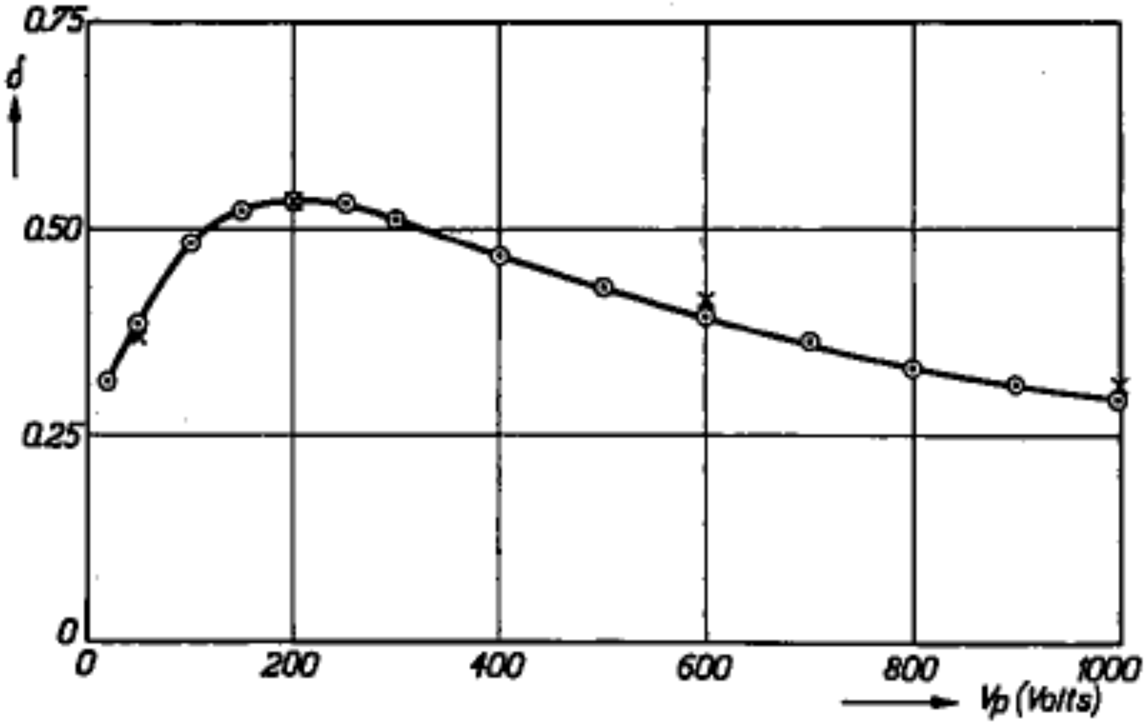
-Electron enters ground state & 2nd electron absorbs excess energy – Auger Neutralization also called secondary electron emission (SEE)

M.A. Lieberman, Principles of Plasma Discharges & Materials Processing

Five main processes that occur at the plasma-materials interface

1. Positive Ion Neutralization (Recombination)

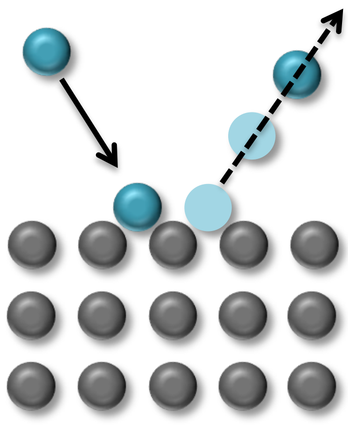
SEE yield of Be



Bruining, Physica 5 (1938) 17.

SEE depends on the ion species and the composition of the solid

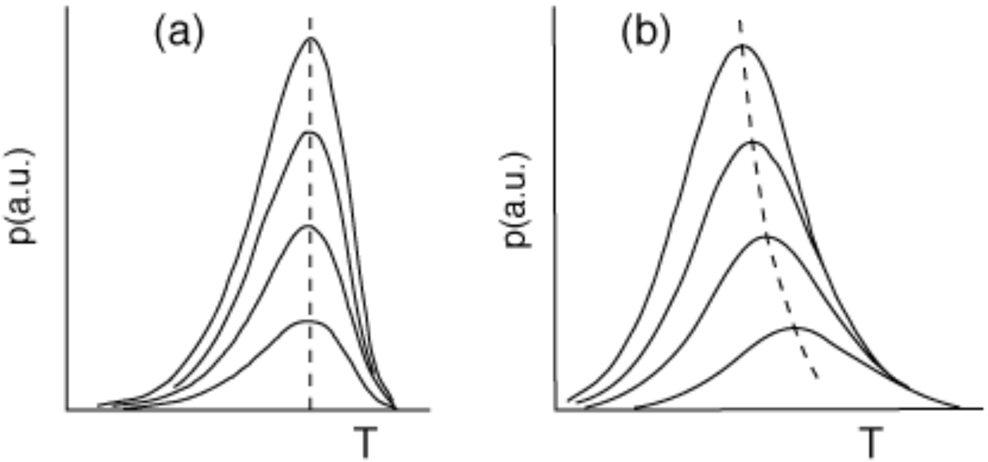
Five main processes that occur at the plasma-materials interface



2. Adsorption/Desorption **(low energy, 1 eV)**

Rate equation for desorption:
(dependent on binding energy & temperature)

$$R = \frac{dN}{dt} = -\nu N^a e^{-\frac{E}{RT}}$$

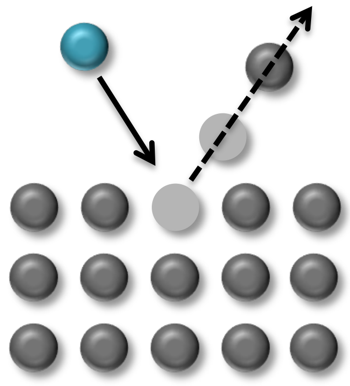


Desorption of 1st order (a) & second order process (b)

http://users-phys.au.dk/philip/pictures/physicsfigures/node18.html

Five main processes that occur at the plasma-materials interface

3. Physical Sputtering **(10-1000 eV)**



Higher energy transfer when masses are similar:

$$E = E_i \frac{4m_i m_t}{(m_i + m_t)^2}$$

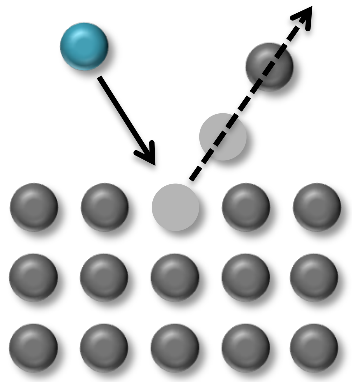
Rate equation:

$$R = \frac{dN}{dt} = -\frac{N}{N_0} Y \Gamma_i$$

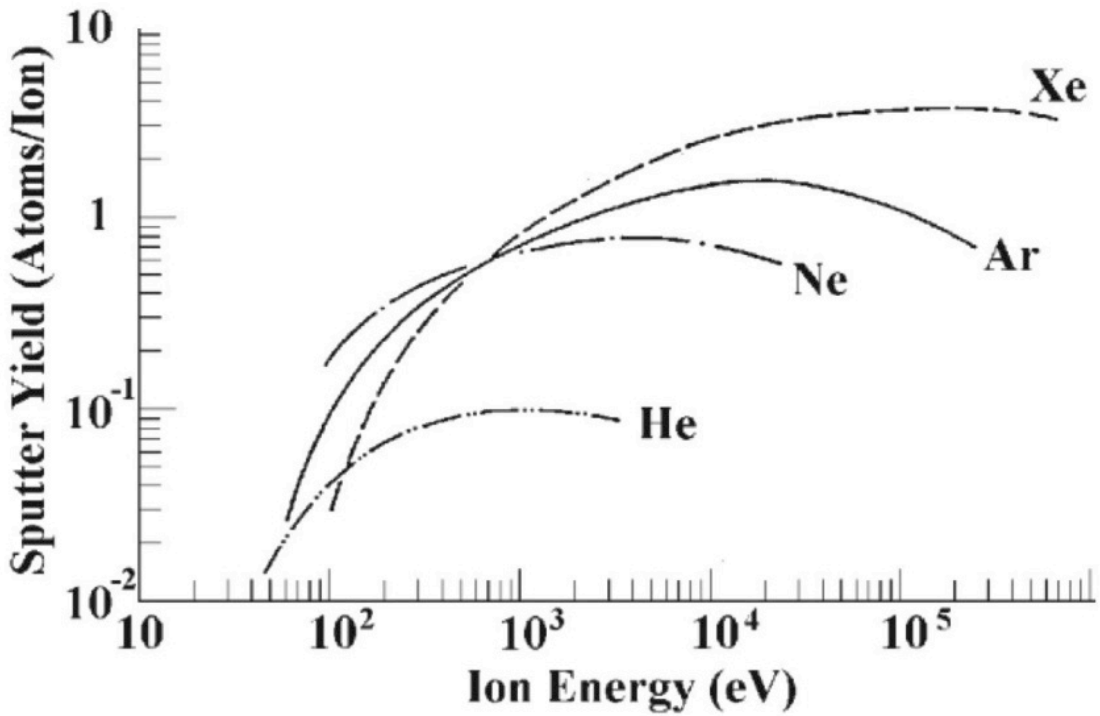
Yield (empirical) = number sputtered per incident ion

Five main processes that occur at the plasma-materials interface

3. Physical Sputtering **(10-1000 eV)**



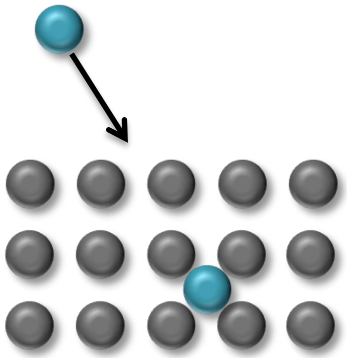
Sputter yields of silicon as a function of ion energy for noble gas ions:



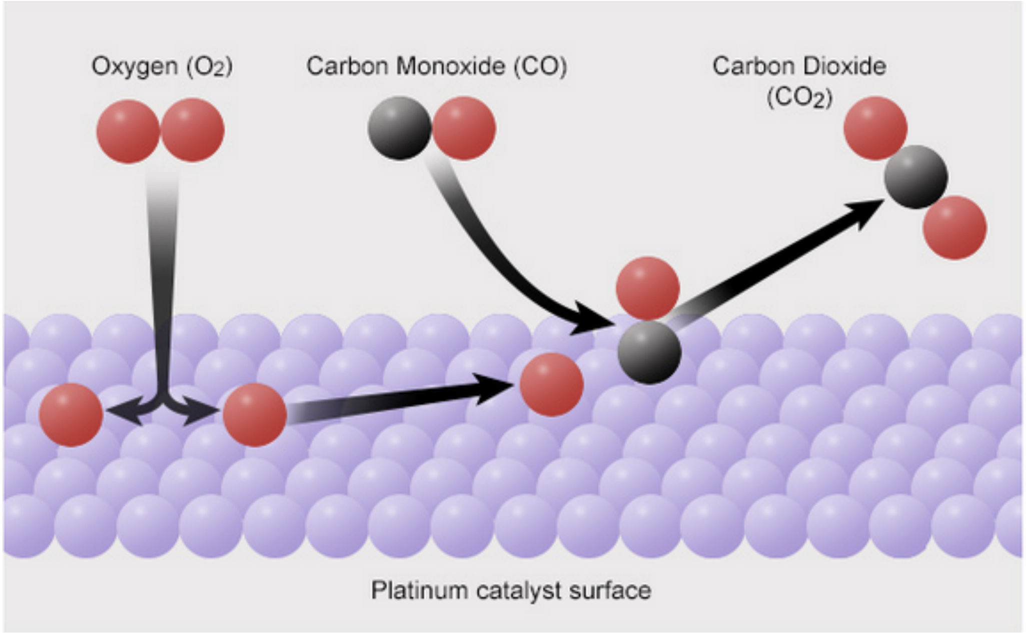
http://xpssimplified.com/depth_profiling.php

Five main processes that occur at the plasma-materials interface

4. Implantation **(1000 eV)**



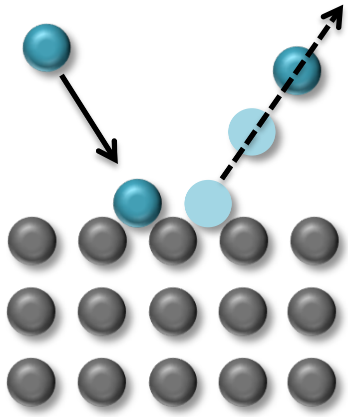
5. Reactions with/on a surface



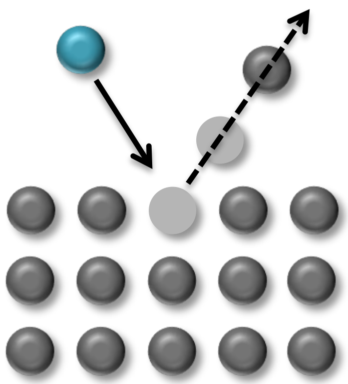
http://www.abc.net.au/science/articles/2015/05/25/4229949.htm

Five main processes that occur at the plasma-materials interface

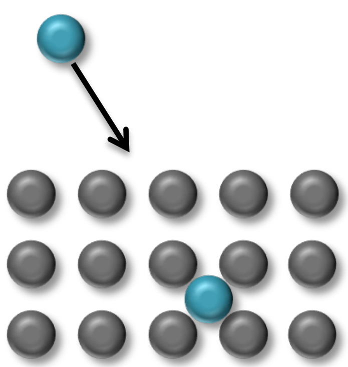
1. Positive Ion Neutralization (Recombination)
   - Ions that hit the surface are neutralized
     $e + A^+ + S \rightarrow A + S$
2. Absorption/Desorption **(low energy, 1 eV)**
   - Evaporation rate increases exponentially with temperature
3. Physical Sputtering **(10-1000 eV)**
   - Independent of surface temperature
4. Implantation **(1000 eV)**
5. Reactions with/on a surface
   - Dependent on surface temperature



Absorption/Desorption

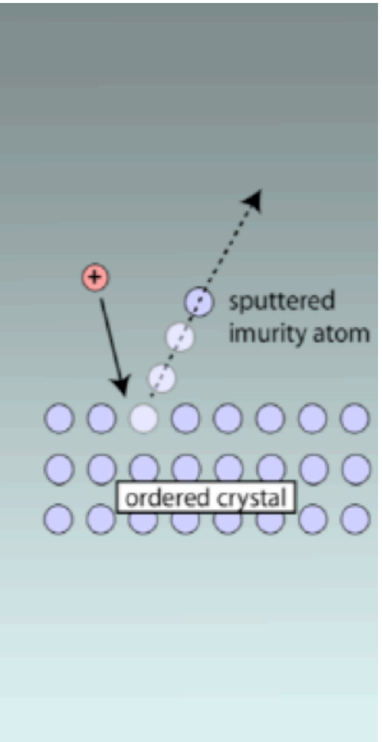


Sputtering



Implantation

Simplified Picture



Reality is much more complex!

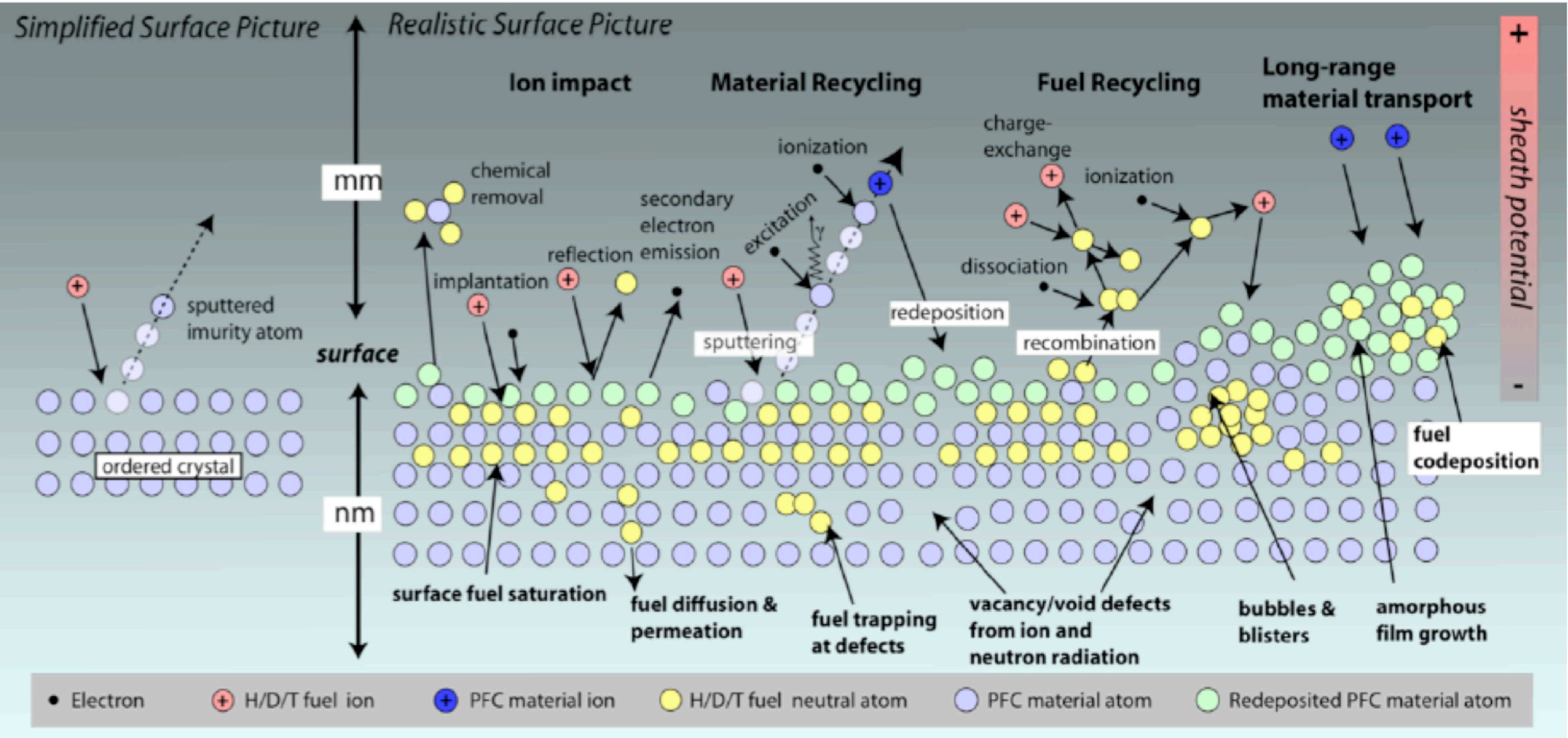


Image from D. Whyte, http://psisc.org/mission

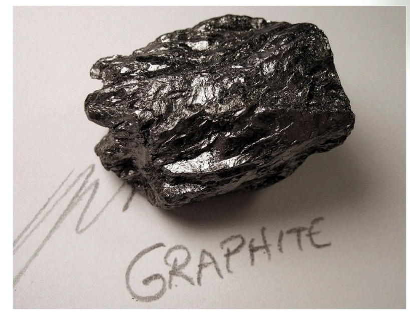
Requirements for fusion plasma materials

The material must:

- withstand the neutron flux
- not retain too much radioactive waste (tritium)
- withstand large heat fluxes / conduct heat
- minimize contamination of the plasma

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

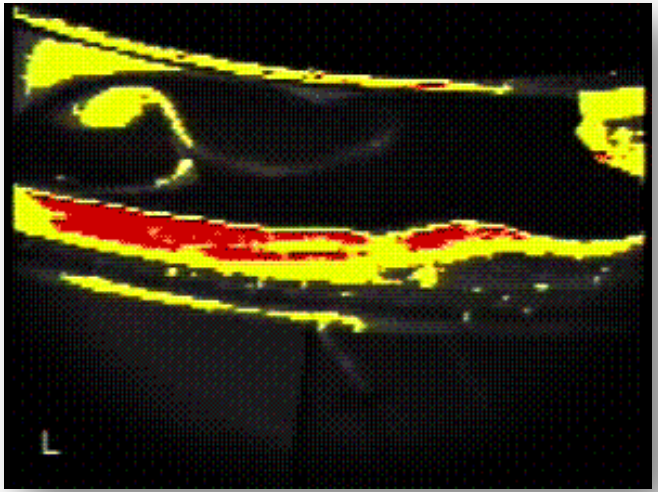
High Z materials (e.g. W, Mo):
- Poison the plasma
- Moderate uptake of tritium
- Good thermo-mechanical properties
- Low or negligible erosion at low plasma temperatures

Liquid metals

Advantages of liquid metals (lithium):

No erosion
No thermal fatigue
No neutron damage

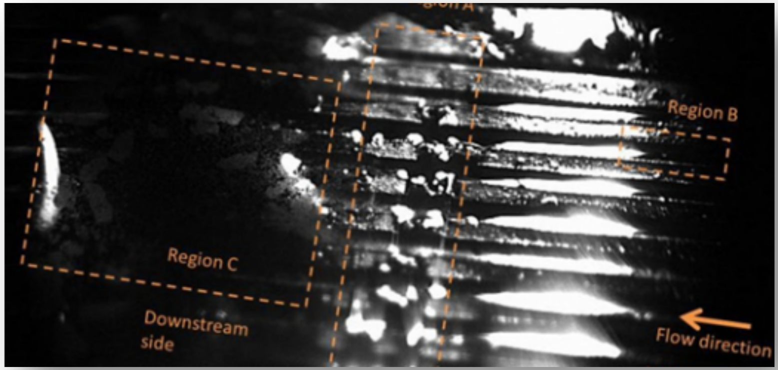
Resilient again high heat fluxes
Refreshes the surface
Li concentration in the plasma is low



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!



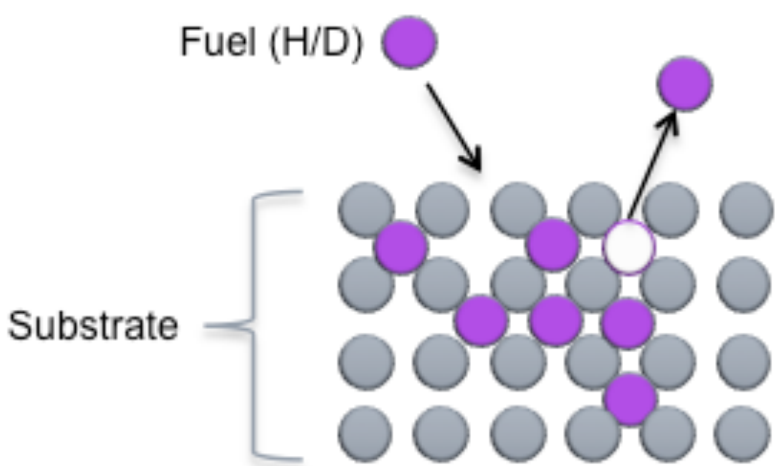
Flowing liquid Li experiment at University of Illinois at Urbana-Champaign

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)

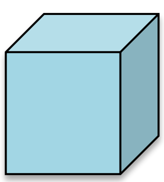
2. Through complexes that involve oxygen (Krstic, Allain, Taylor)

Which material is best? We need to understand what happens at the surface!

- 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

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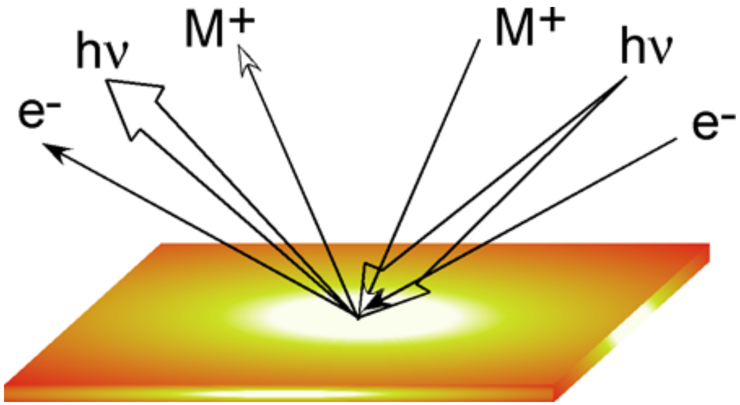

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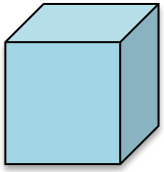

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Surfaces contain ~10^{14} atoms/cm^2

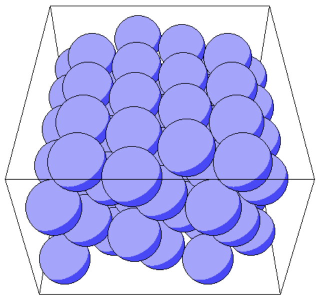
Challenge: Detect 10^{14} cm^{-2} signal on a 10^{23} cm^{-3} background.

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

From the simple to the complex

Simple Model Experiments

More Complex Systems

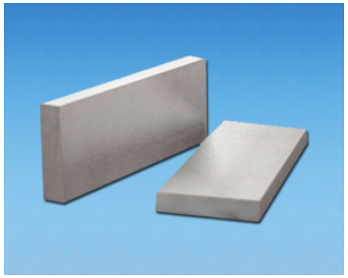


Single crystal

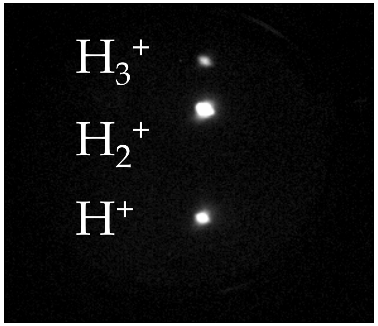
Grain boundaries

Alloying elements: Ti, Zr, C

Surface roughness



TZM (Engineering materials)



Monoenergetic ion beam

(Image of He ions on phosphor screen)

Multiple species, increased fluxes, atoms/ions/electrons/radicals

Plasma sources / fusion devices

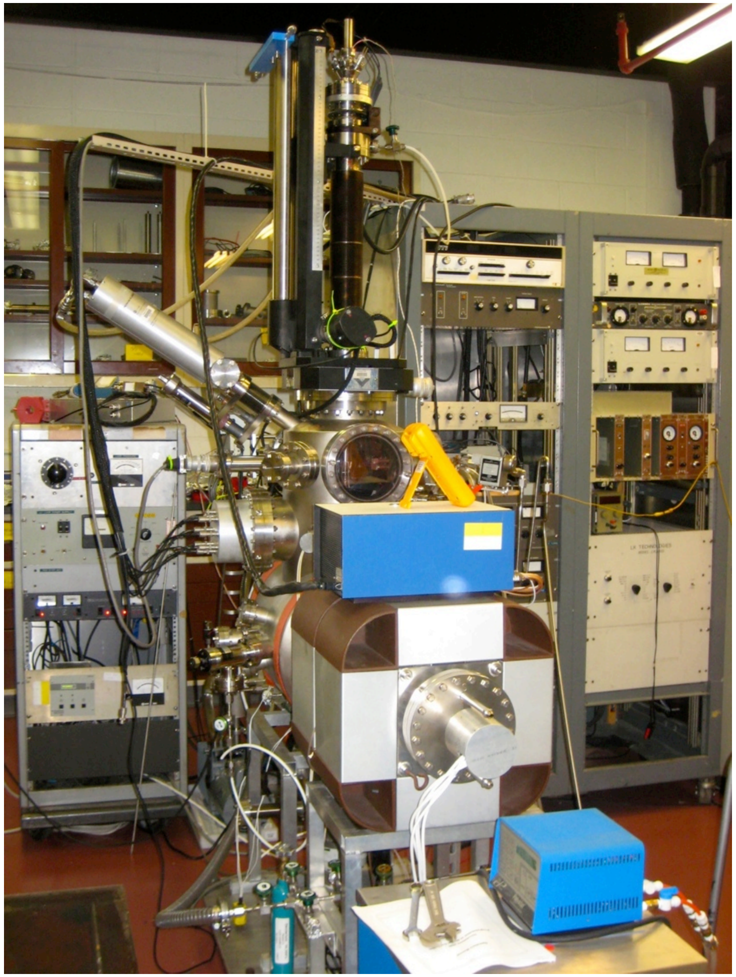
From the simple to the complex

Simple Model Experiments → **More Complex Systems**

Laboratory surface science experiments → Linear plasma devices → Fusion devices

Laboratory surface science experiments

simple → complex



Test stand instrumentation in the Surface Science & Technology Lab

Key variables affecting chemistry at surface:

- Pressure
- Temperature
- Composition

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

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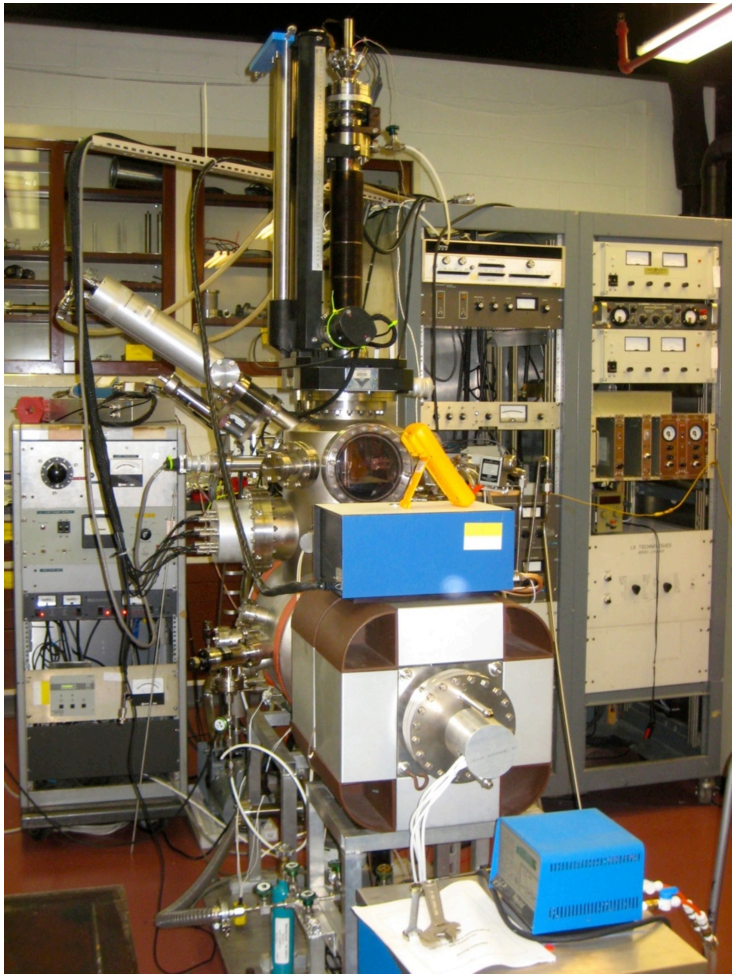
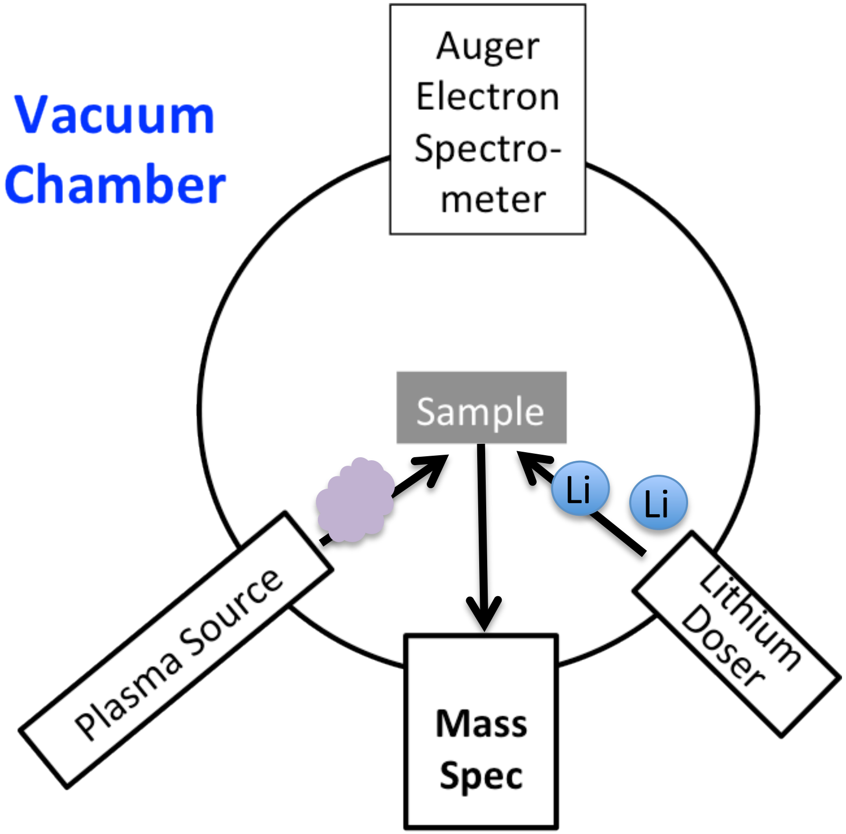
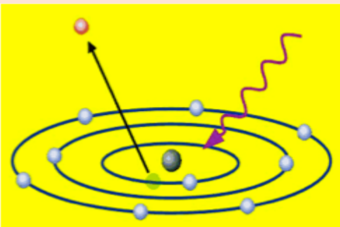
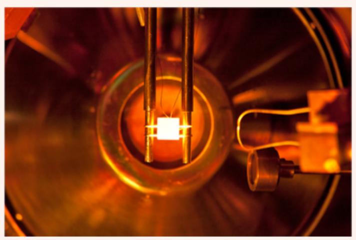
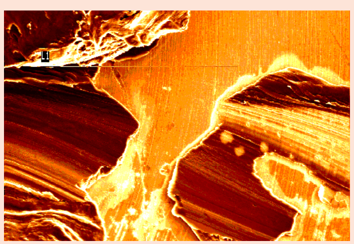


Test stand instrumentation in the Surface Science & Technology Lab

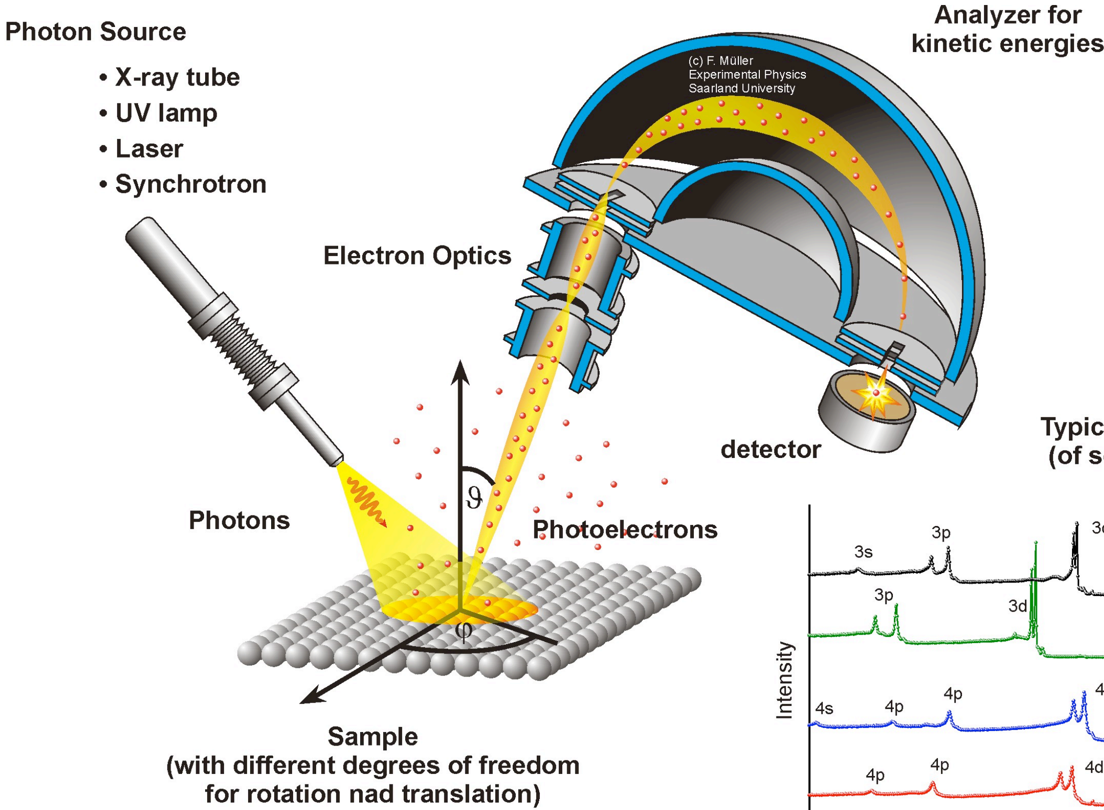


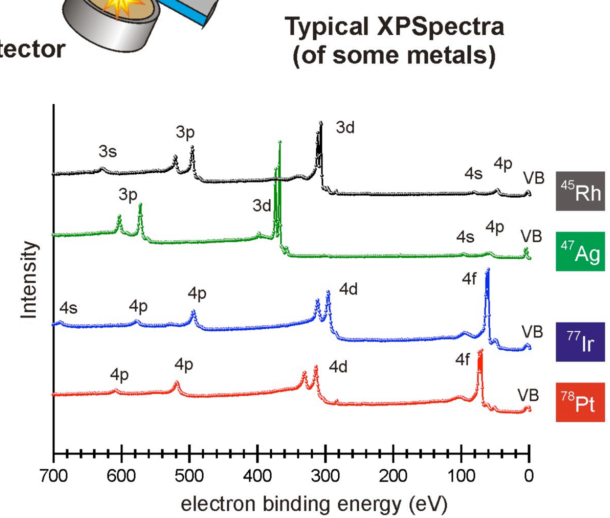
Atomic-Level Diagnostics

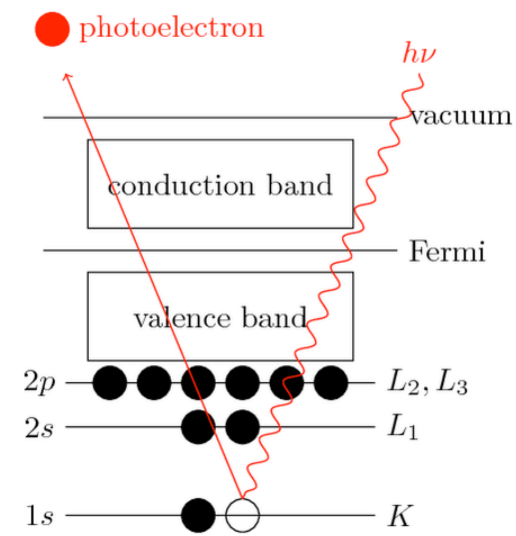
	Technique	Info Obtained	Additional Notes
	X-ray Photoelectron Spectroscopy (XPS) / Auger Electron Spectroscopy (AES)	• Chemical composition • Oxidation state	• Cannot detect H/D or He • Probe depth ~10 nm
	Temperature Programmed Desorption (TPD)	• Desorption energy • Rate constants	• Detects H • Can determine the total amount of an adsorbed species on the surface
	Scanning Auger Microscopy (SAM)	• 2D elemental map of surface • Ion etching • SEM images	• Cannot detect H/D or He • Can use ion etching to probe into deeper layers
	Ion Scattering Spectroscopy (ISS)	• Atoms/ molecules in top 1-3 layers	• Can use direct recoil spectroscopy to detect H/D

X-ray Photoelectron Spectroscopy (XPS)

Gives composition of top 5-10 nm

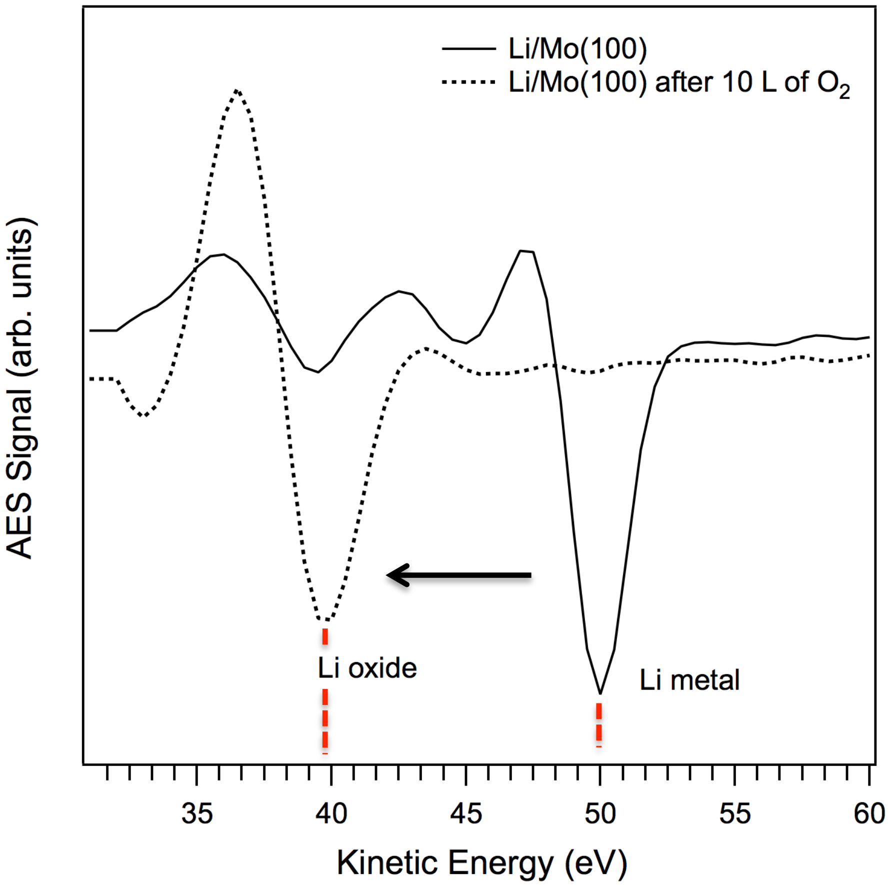


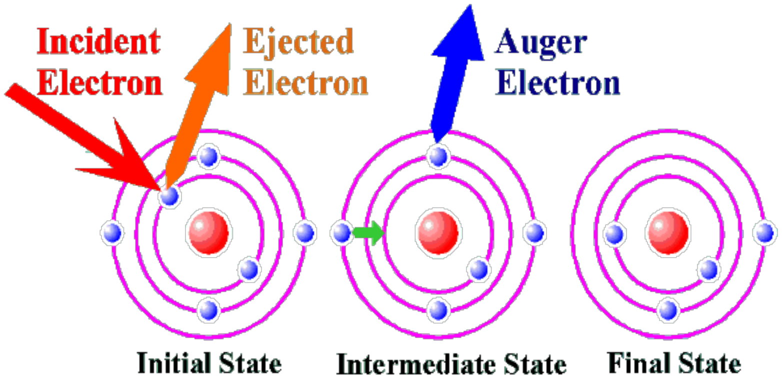


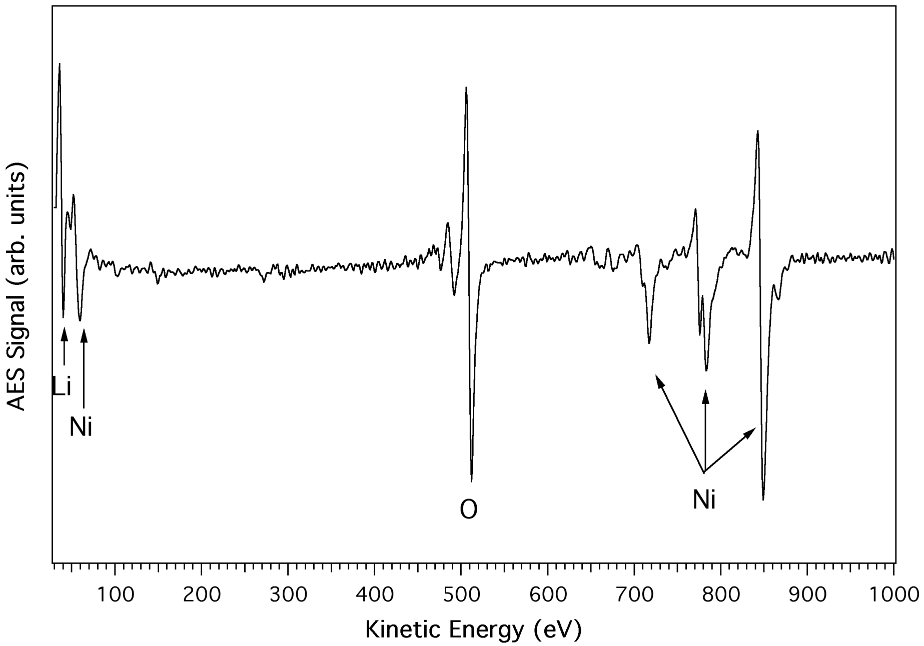


http://jacobs.physik.uni-saarland.de/english/instrumentation/uhvl.htm

Auger Electron Spectroscopy

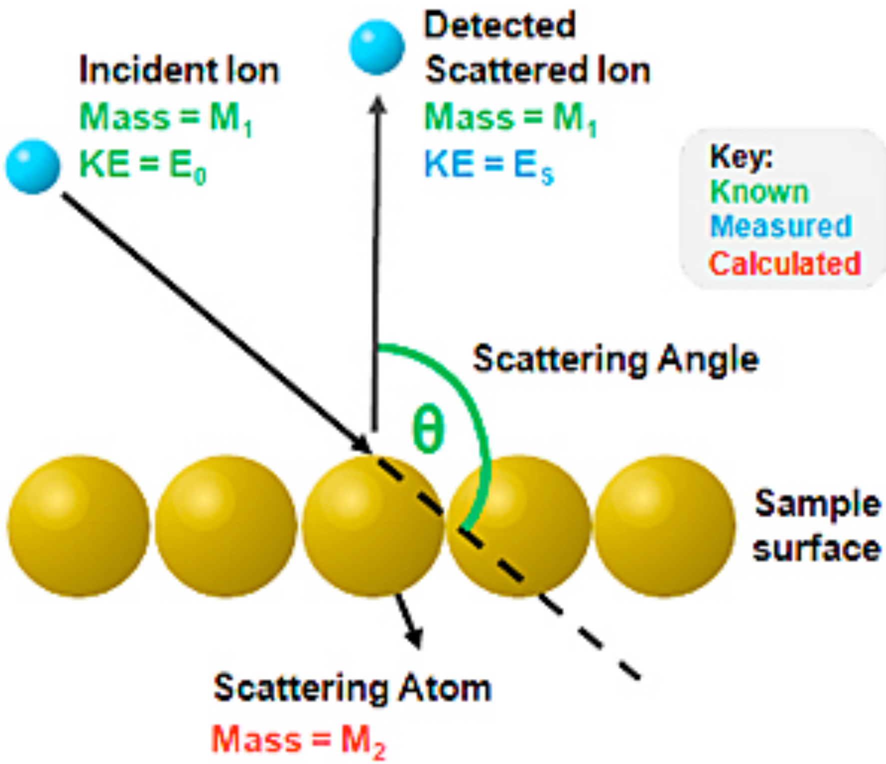






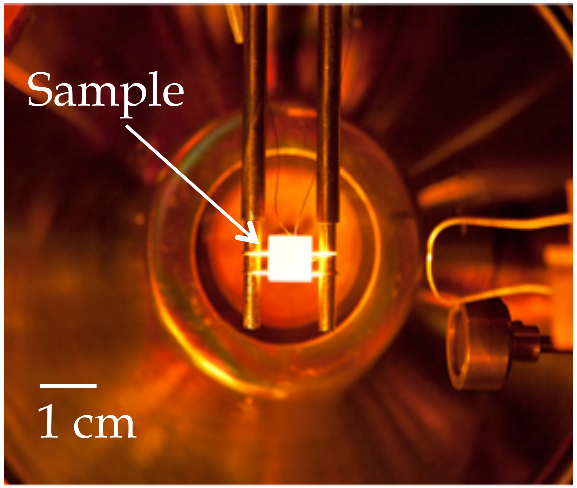
Low-energy Ion Scattering Spectroscopy (LEISS)

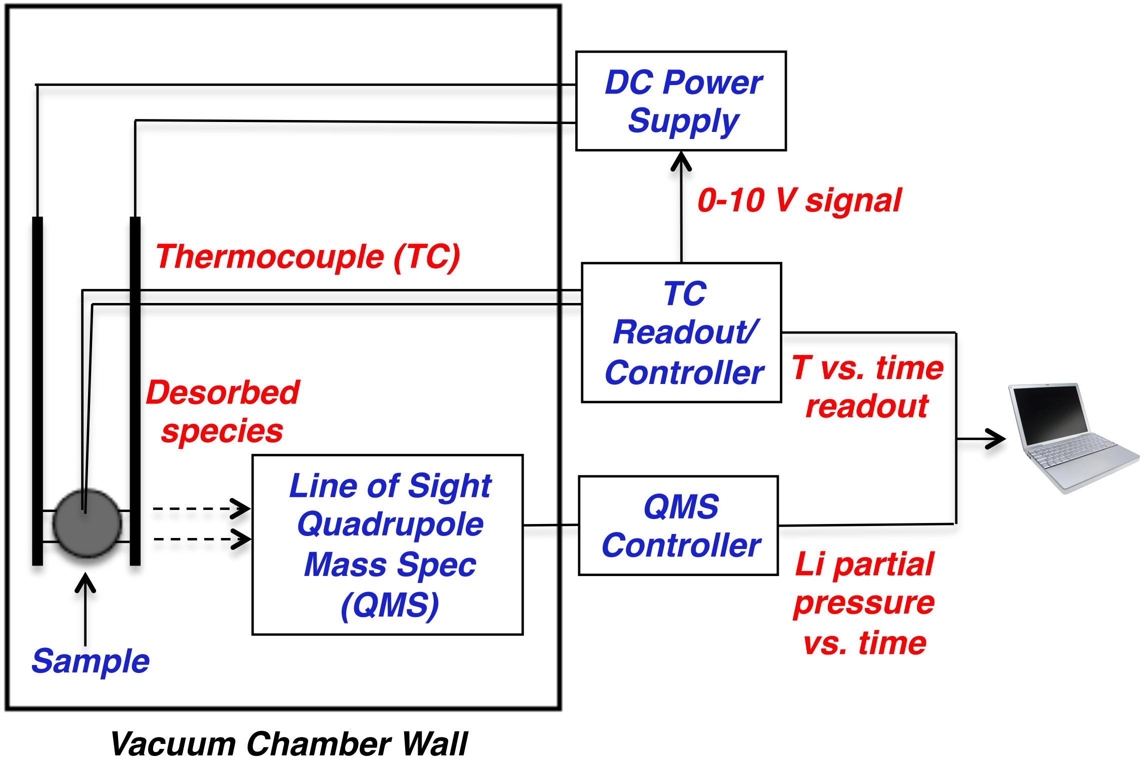
Very surface sensitive
(probes top 1-3 layers)
He usually used for incident ion



$$\frac{E_s}{E_0} = \left[\frac{\cos\theta \pm \left[\left(\frac{M_2}{M_1} \right)^2 - \sin^2\theta \right]^2}{1 + \frac{M_2}{M_1}} \right]^2$$

Temperature programmed desorption

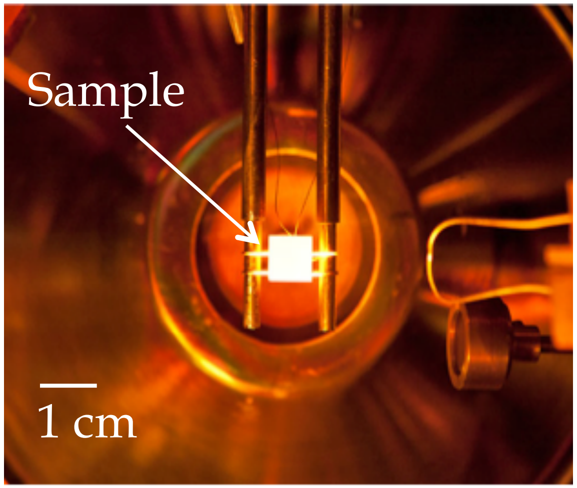


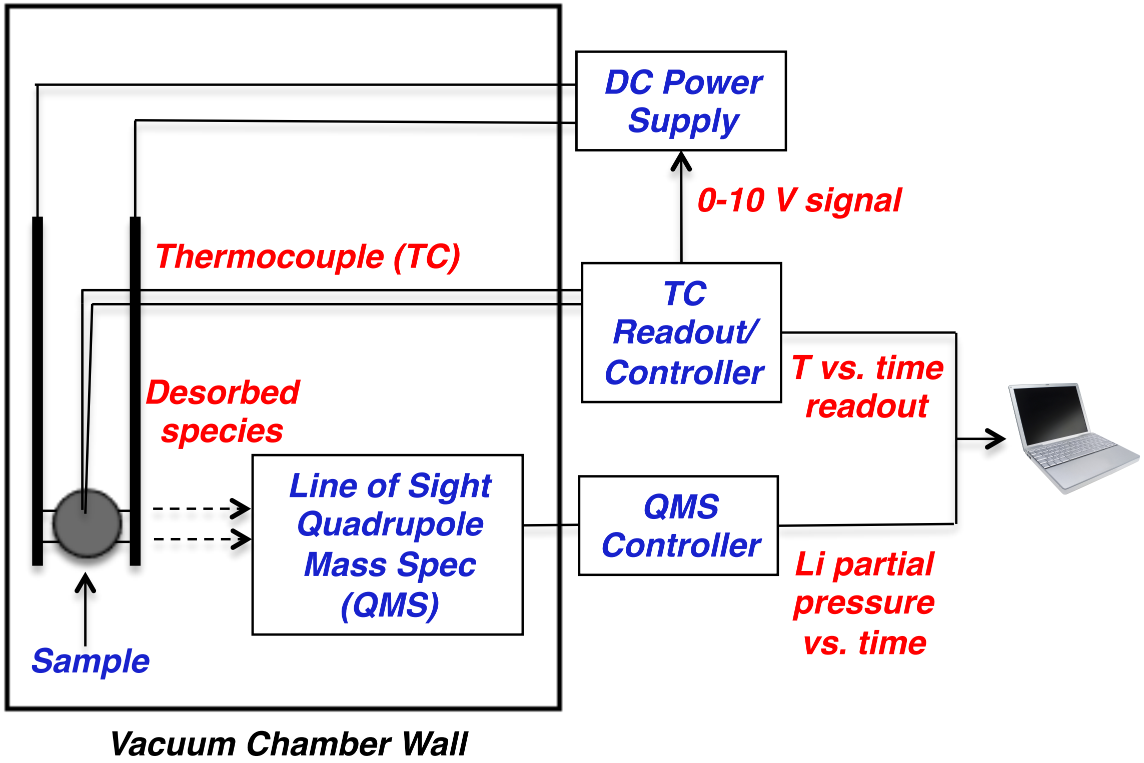


Temperature Programmed Desorption (TPD) Technique:

- 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



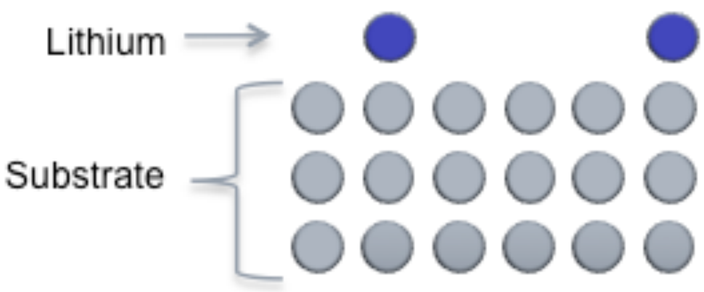


Area under pressure vs. time curve → # of atoms desorbed

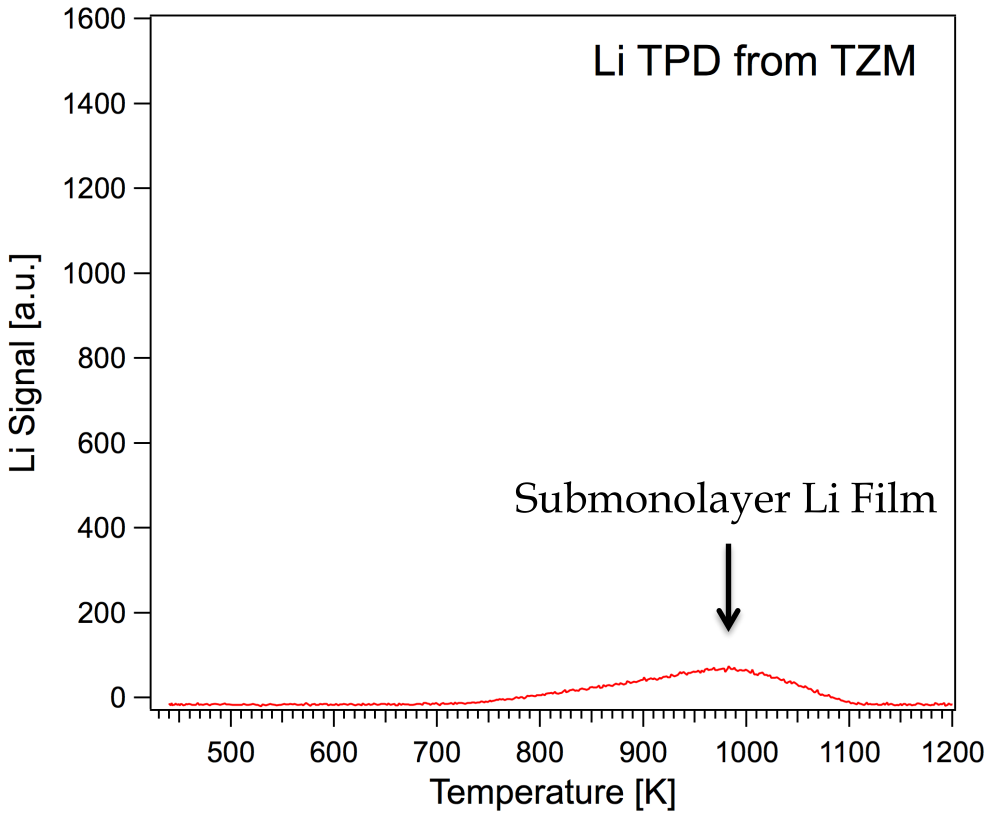
TPD can be used to measure D retention!

Example: Desorption of Li from Mo

simple → complex



- 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

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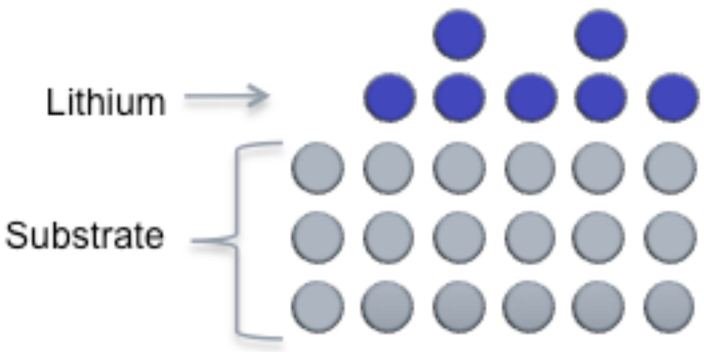
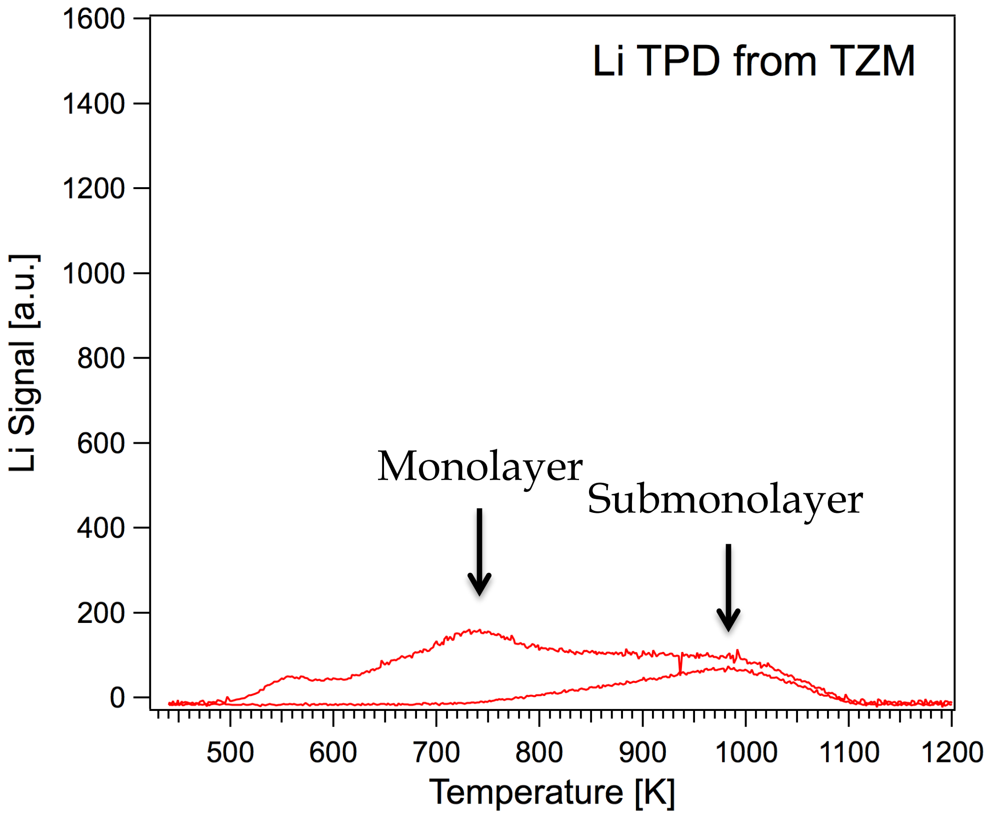


- Area under Li TPD curve increases with Li dose
- Dipole interactions lower the desorption energy (~2 eV)
- E_d is a function of coverage



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Example: Desorption of Li from Mo

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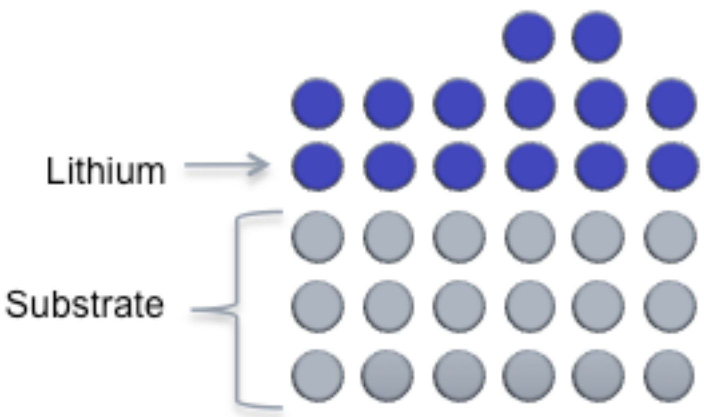
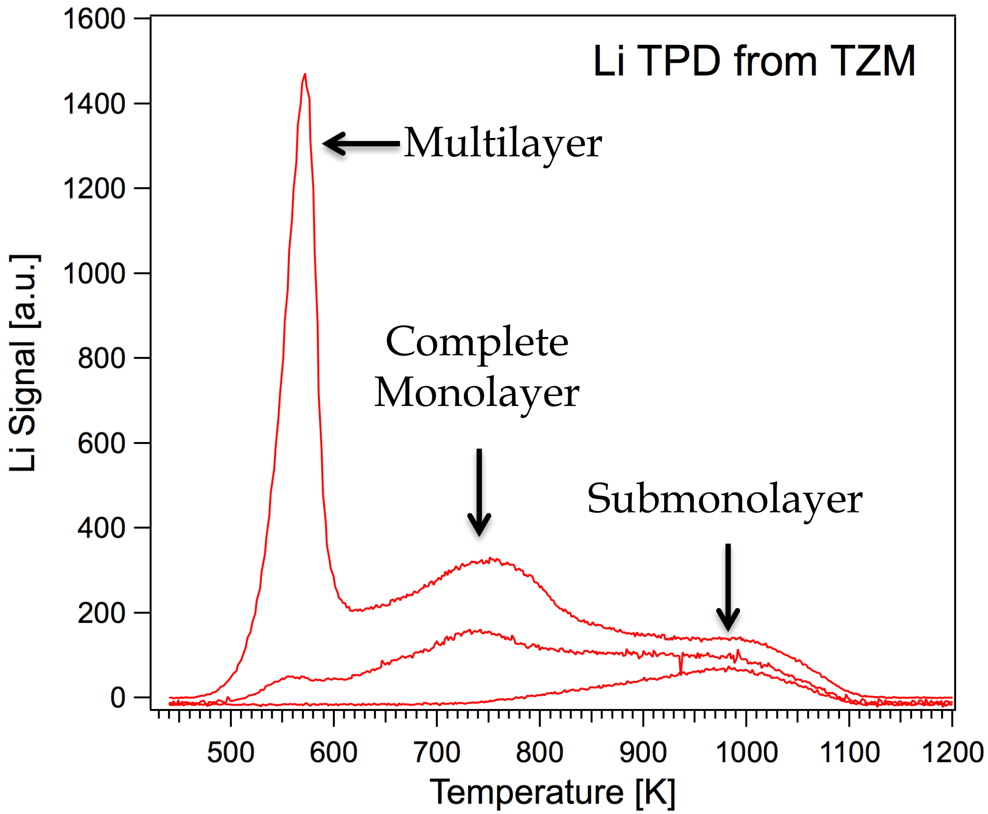


- Thick Li films (multilayer) evaporate at 500 K
- Multilayer film represents Li-Li bonding
- Cohesive energy of metallic Li ~1.7 eV

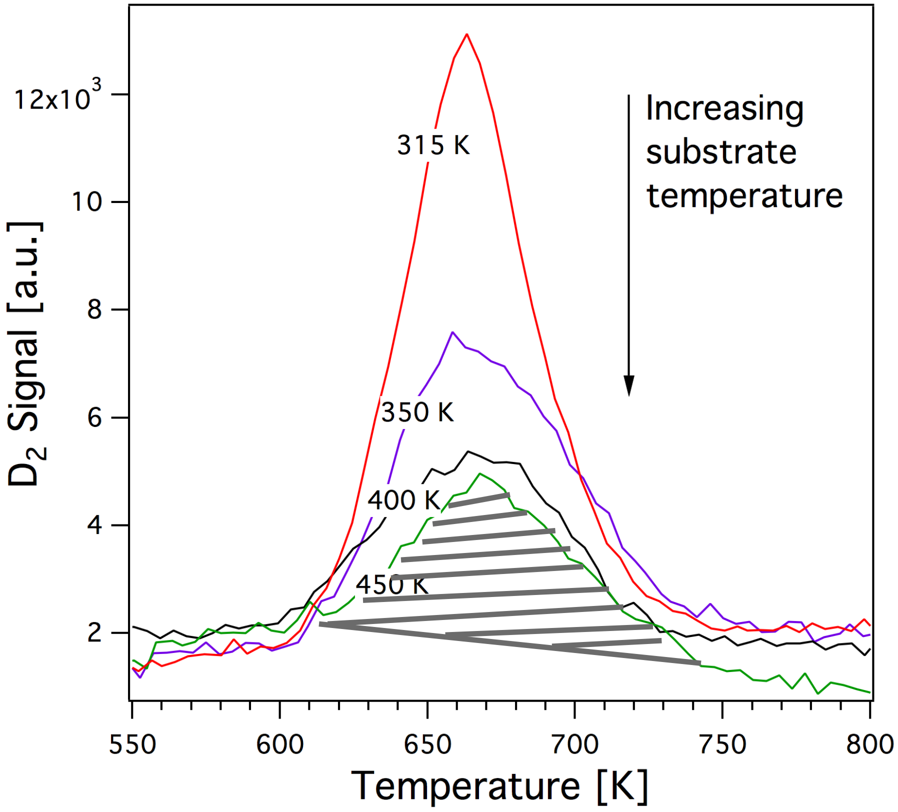


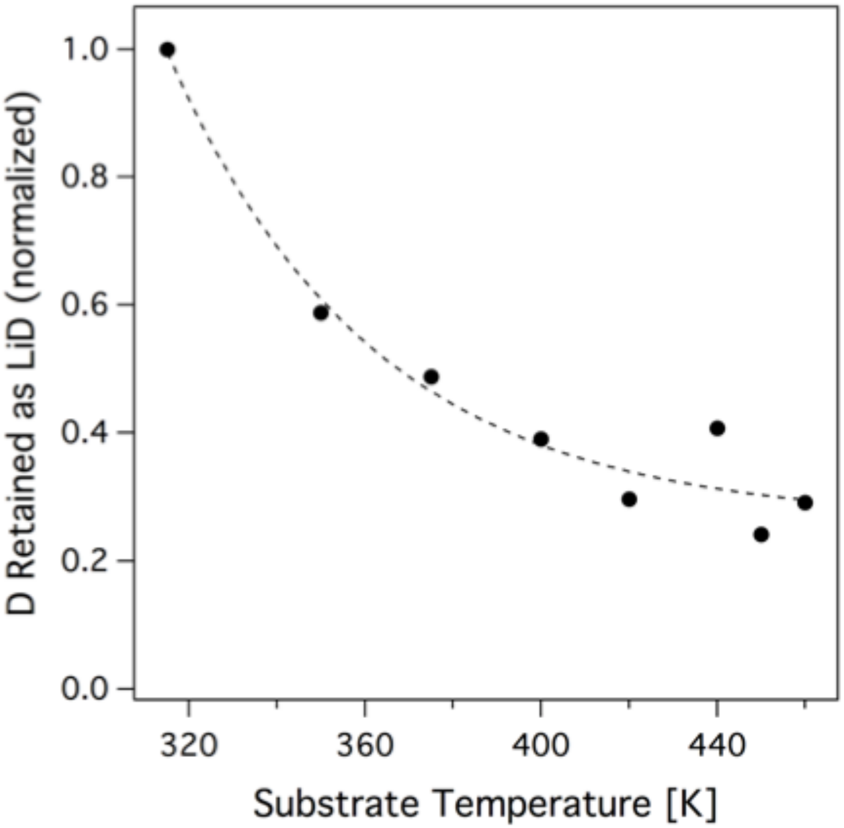
C.H. Skinner et al., JNM 438, S647 (2013)

TPD can be used to determine D retention

simple ○——→ complex

In lithium films as function of temperature:



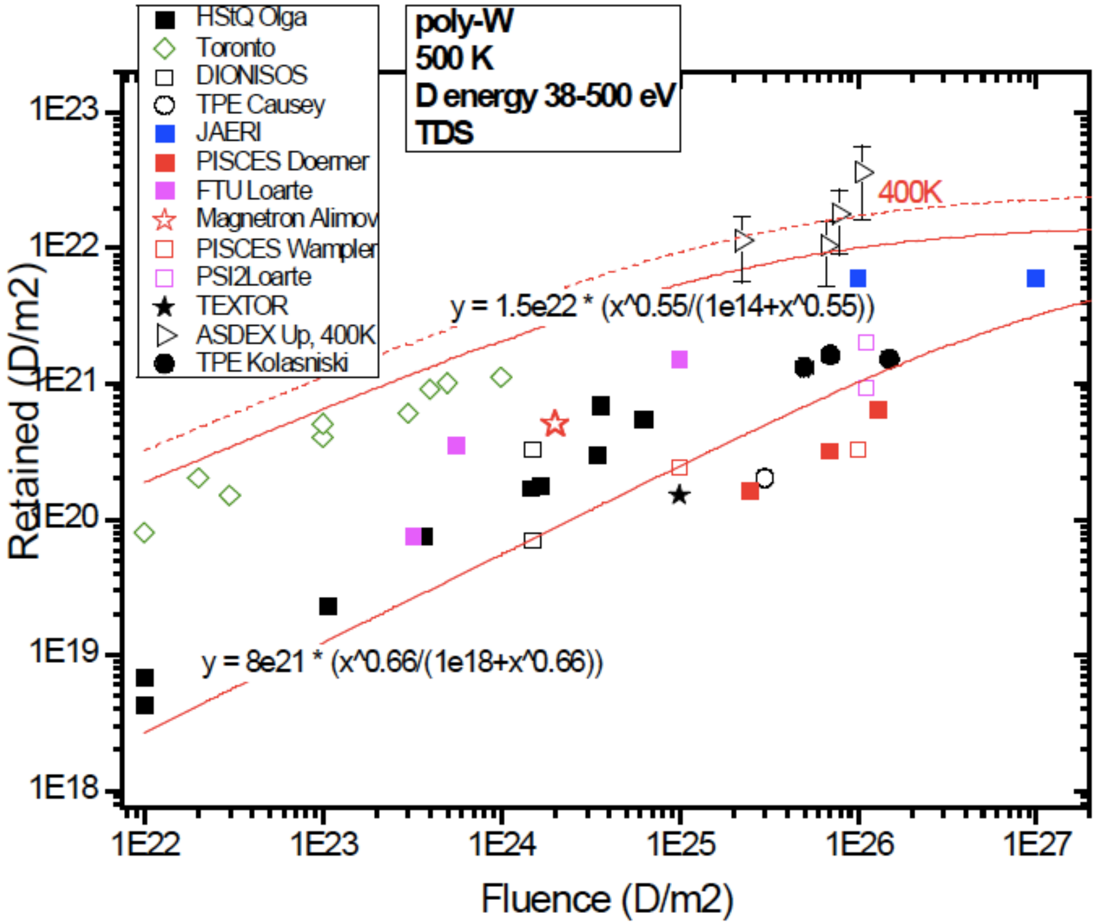


A.M. Capece, et al., JNM (2015)

TPD can be used to determine D retention

simple ⟶ complex

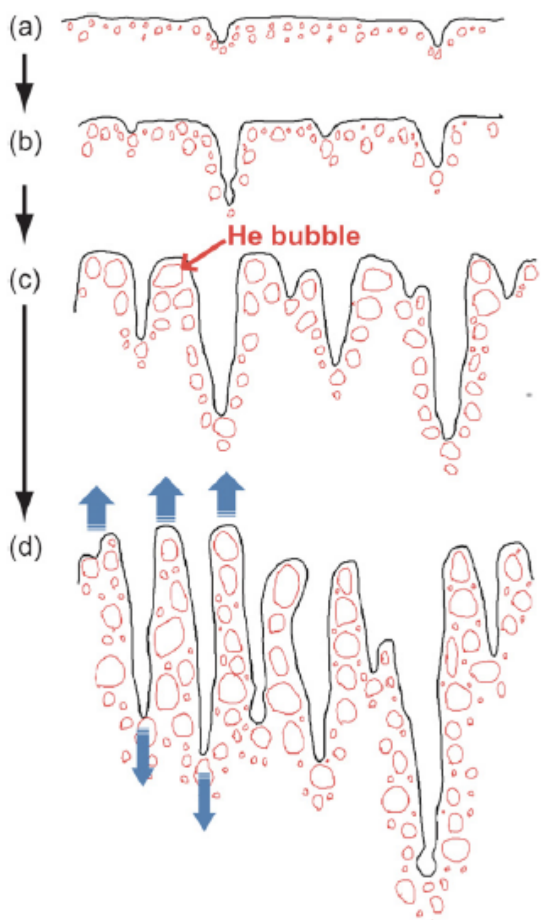
In tungsten as function of fluence:



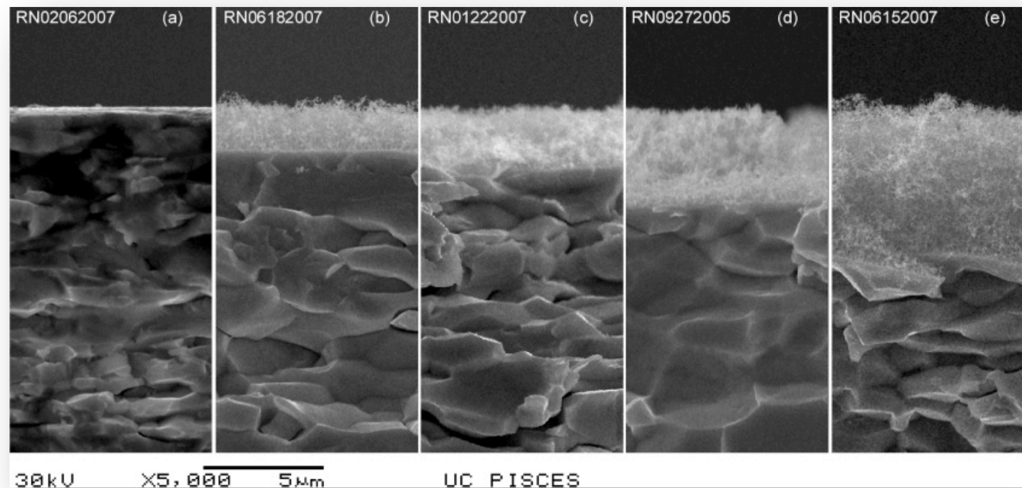
Lipschultz et al., (2010) MIT Report PSFC/RR-10-4

SEM used to understand fuzz & bubble formation in W

simple → complex



S. Kajita, Nucl. Fusion 49 (2009) 095005

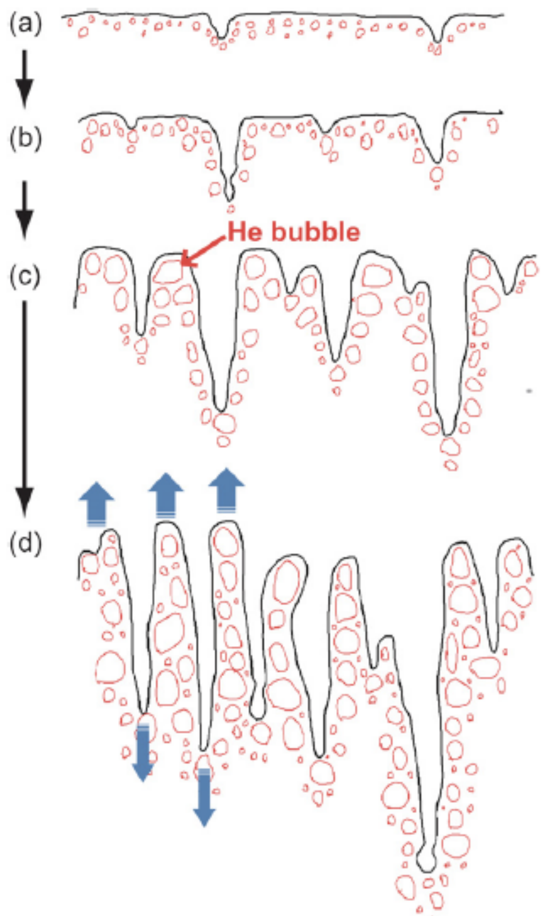


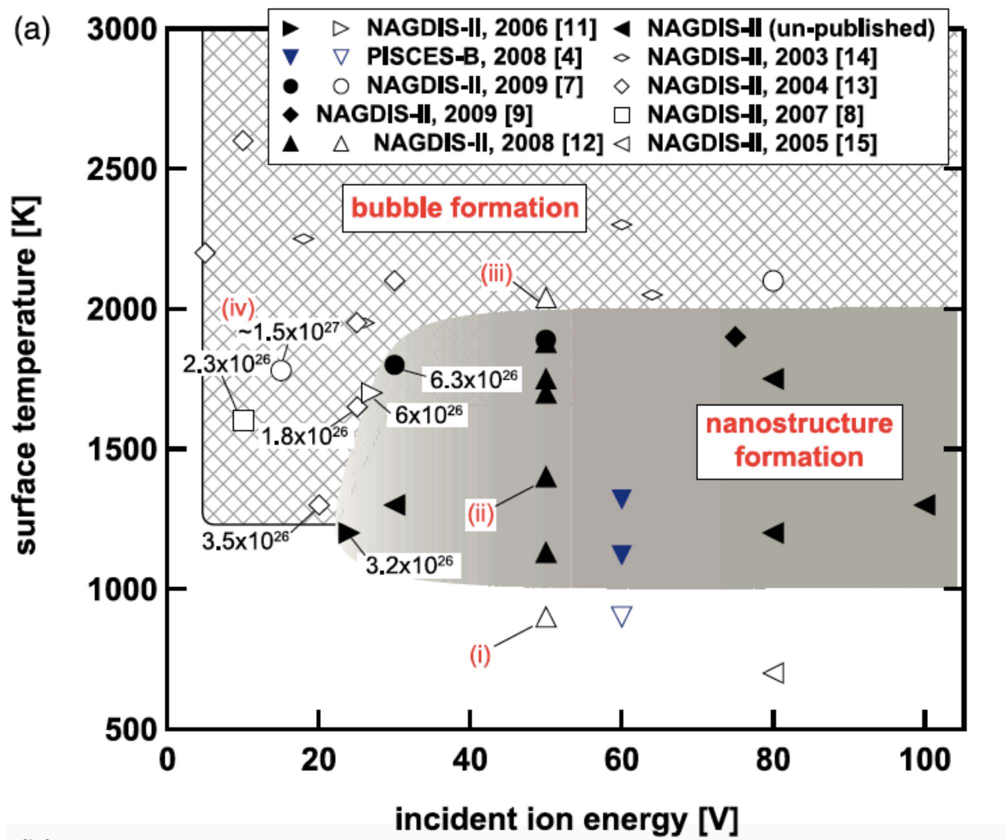
Tungsten fuzz

M.J. Baldwin & R.P. Doerner, Nucl. Fusion (2008)

SEM used to understand fuzz & bubble formation in W

simple → complex





S. Kajita, Nucl. Fusion 49 (2009) 095005

Materials Analysis Particle Probe (MAPP)

simple ——————————○→ complex

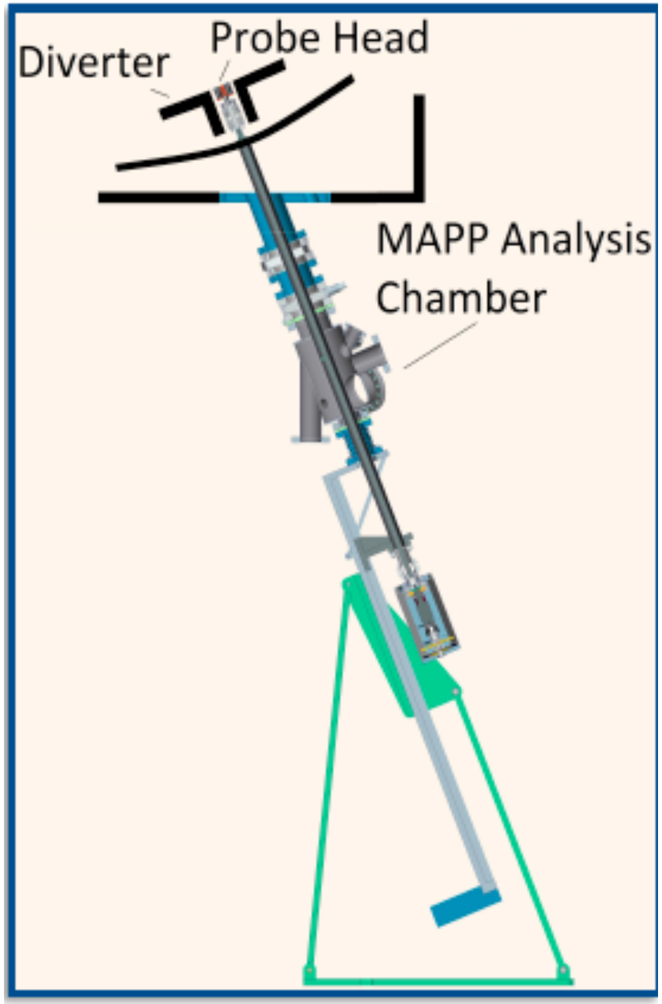
- Provides in-vacuo analysis of surface exposed to fusion plasma
- Correlates plasma performance with the surface state
- Provides immediate analysis

XPS: Elemental/ chemical composition

TPD: Gives binding energies, desorption products

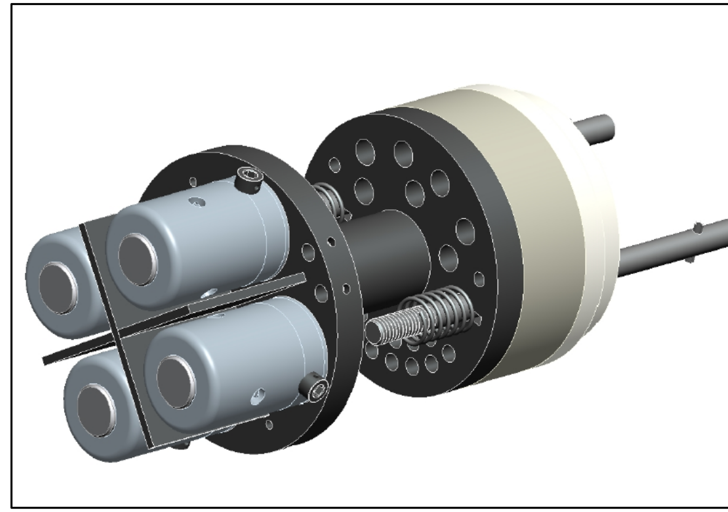
Ion Scattering Spectroscopy: IDs surface species

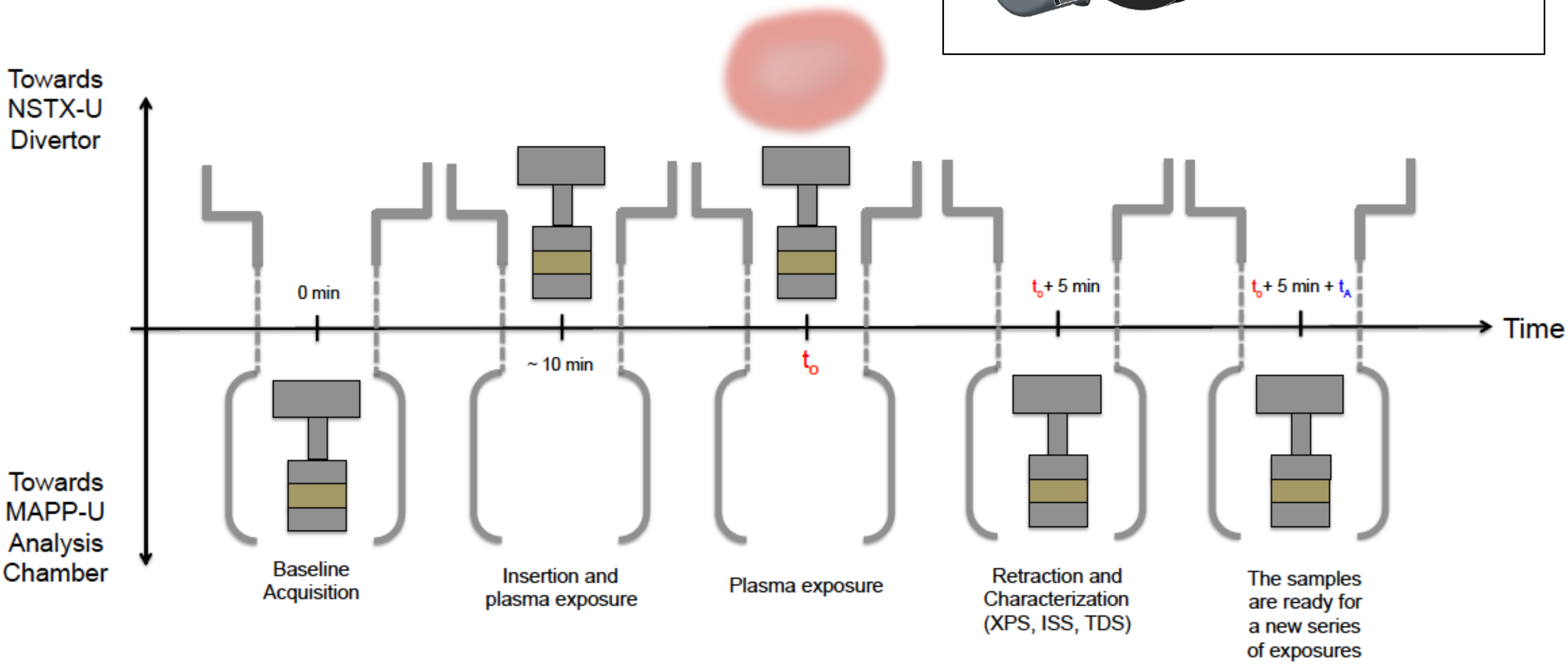
Direct Recoil Spectroscopy: Can detect H



Courtesy of F. Bedoya

Materials Analysis Particle Probe (MAPP)





Key takeaway messages

- 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
- A variety of experiments of differing complexity are needed