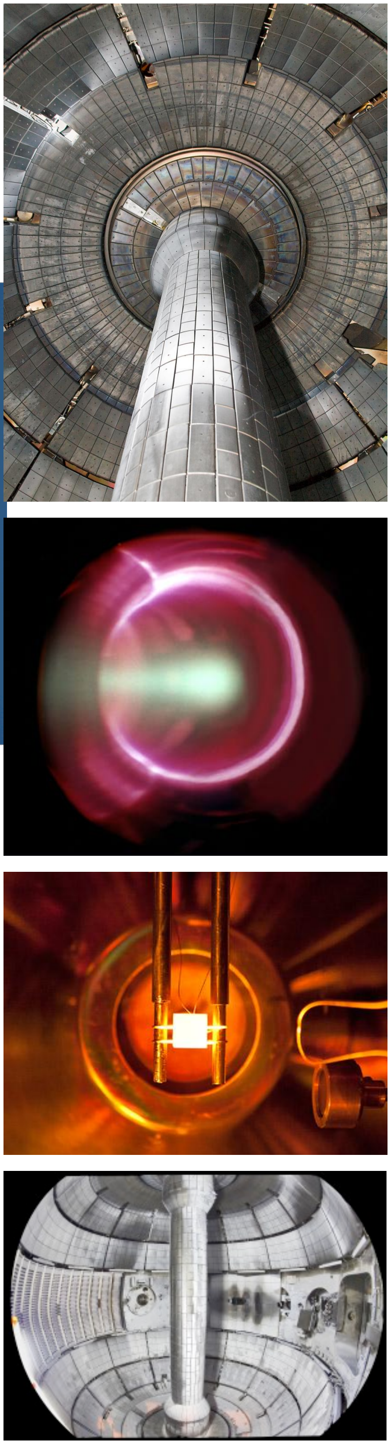


Materials Science in Fusion Devices

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

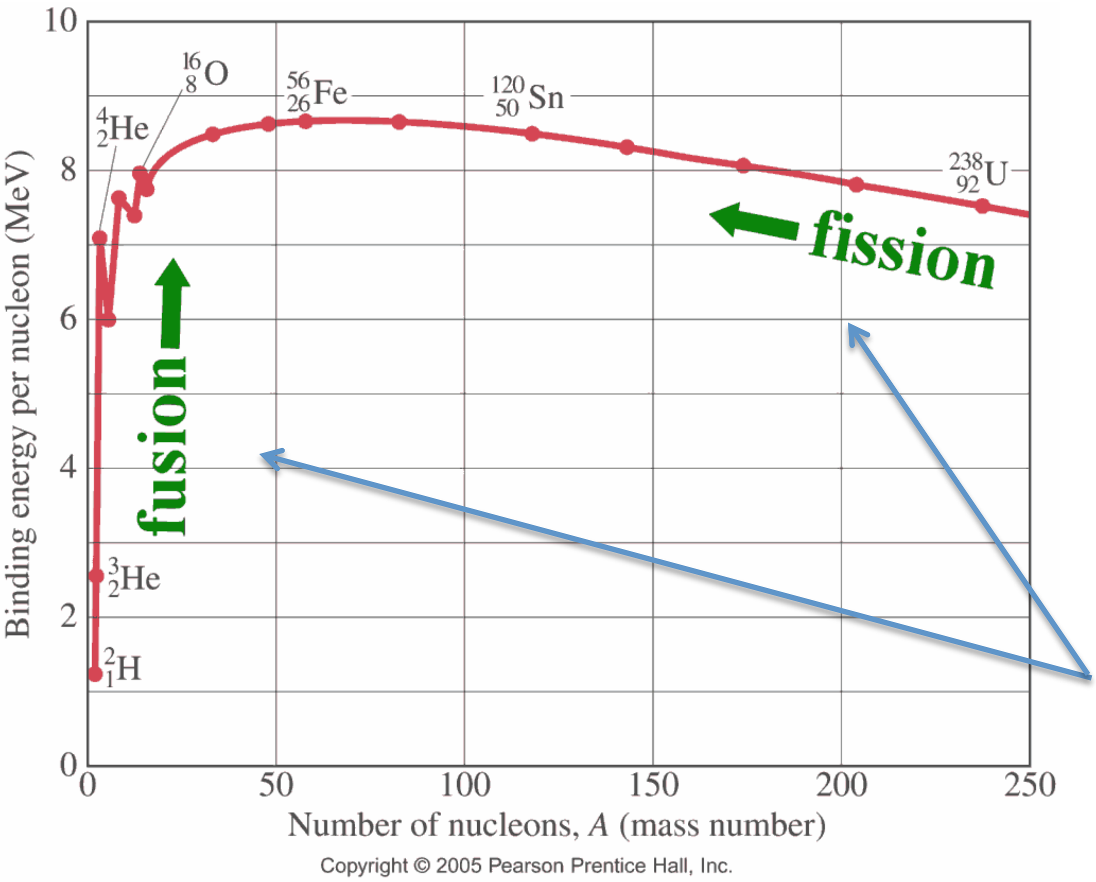
SULI Introductory Course
in Plasma Physics, PPPL

June 10, 2016

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

Advantages of fusion energy:

- Clean
- Green
- Safe
- Abundant



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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

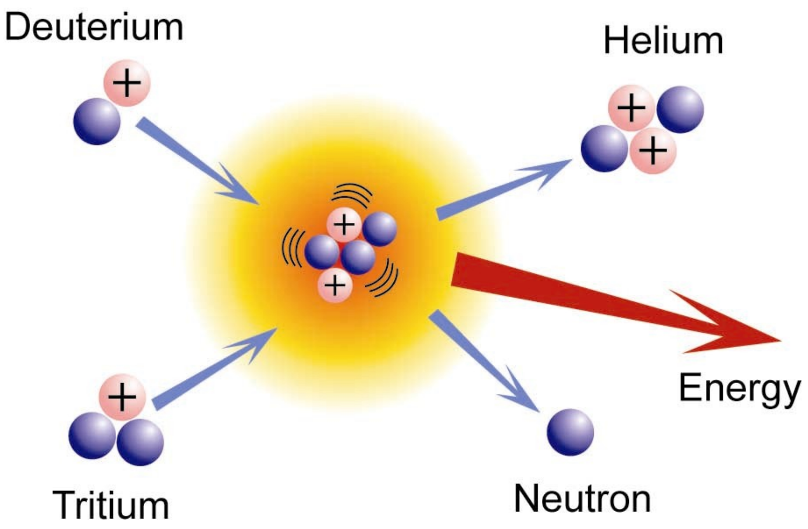
Going from low BE to higher binding energy releases energy

We need fusion to survive

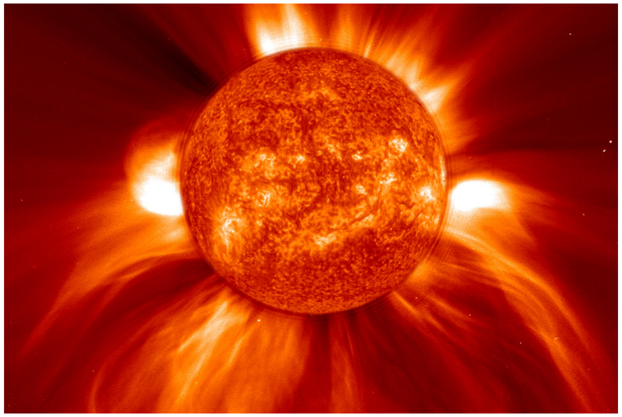
- H fuel extracted from seawater
- D-D fusion can power the world for 2×10^9 yr
  - Coal: 200 yr
  - Natural gas: 20 yr
  - U235/Th232 breeder reactors: 20,000 yr
- Fuel efficient
  - City of 1 million, need 60 kg of H_2

Advantages of fusion energy:

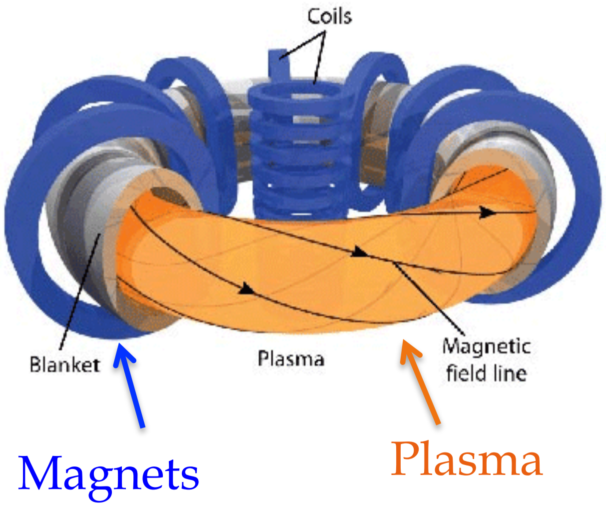
- Clean
- Green
- Safe
- Abundant



Hydrogen fusion requires high temperature & pressure → Plasma!

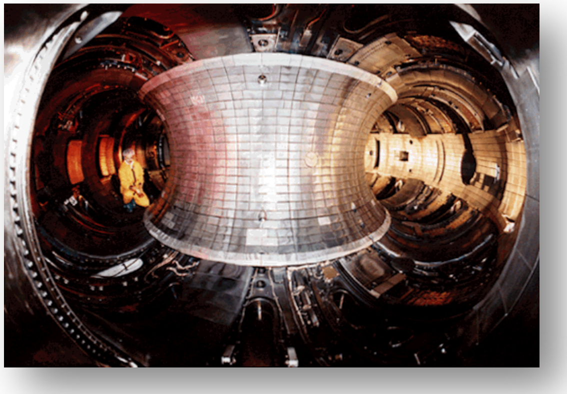


- Temperatures of 100 million K are required (and have been achieved!)
- The sun uses gravity to confine the plasma
- We use magnetic fields



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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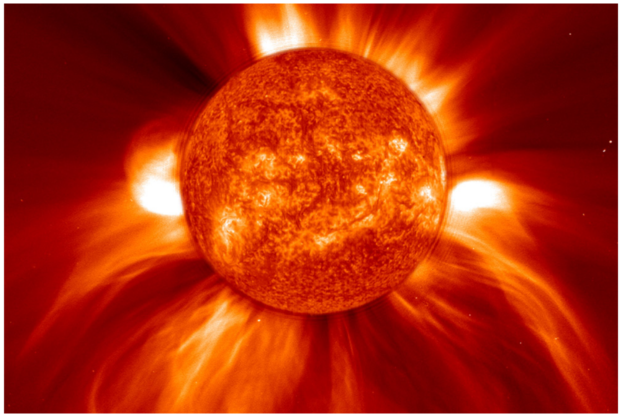
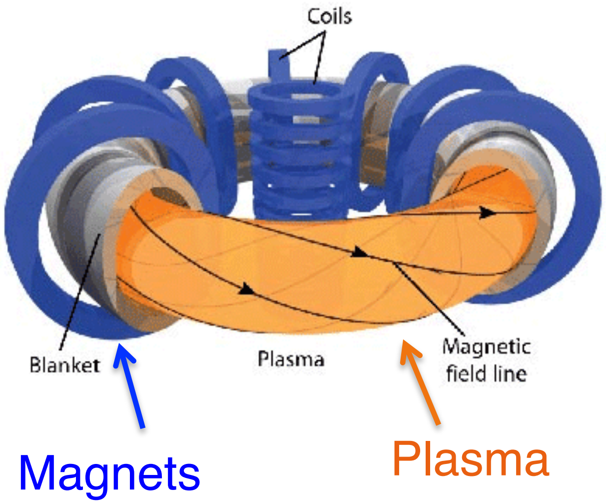


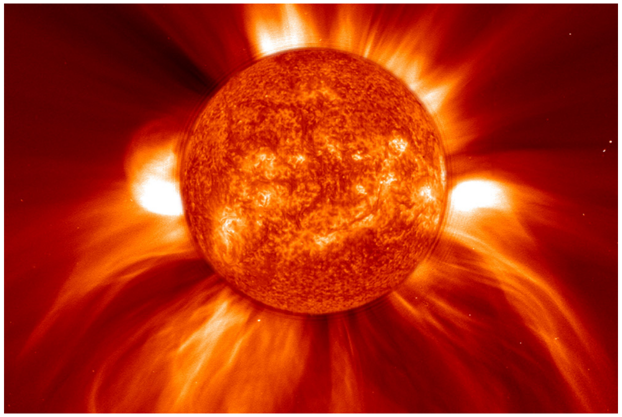


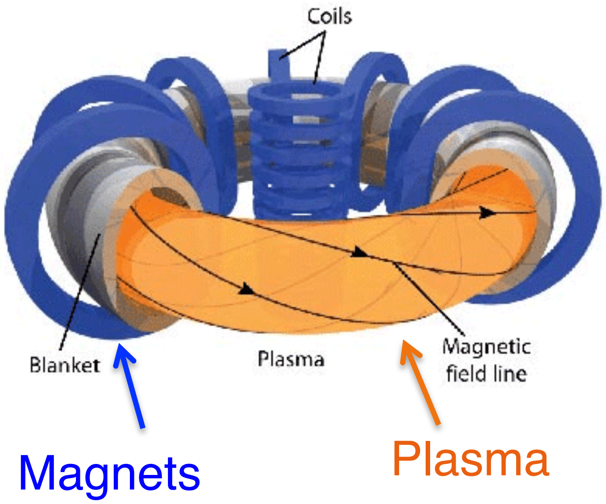
So why don't we have it yet?

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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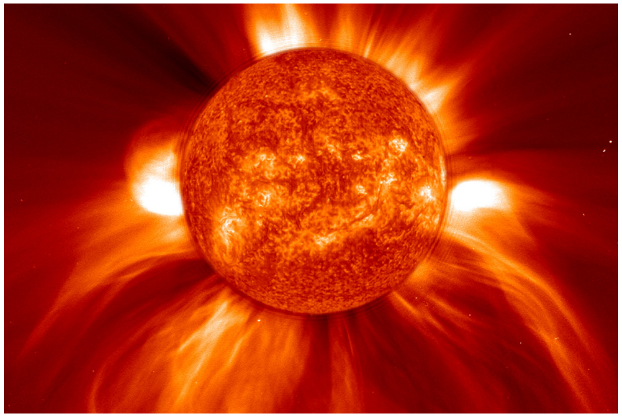
We need…

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

Hydrogen fusion requires high temperature & pressure → Plasma!



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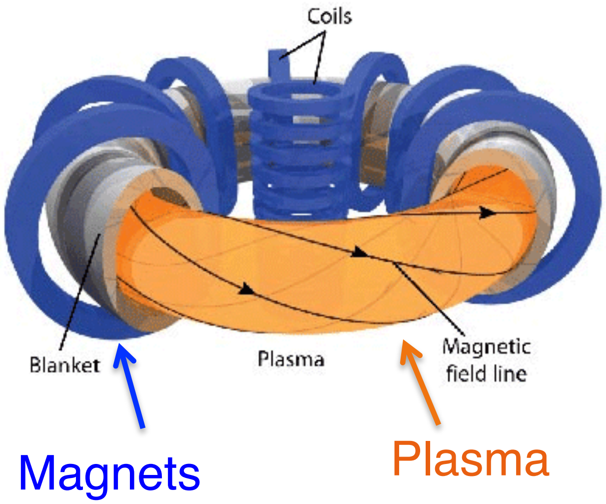
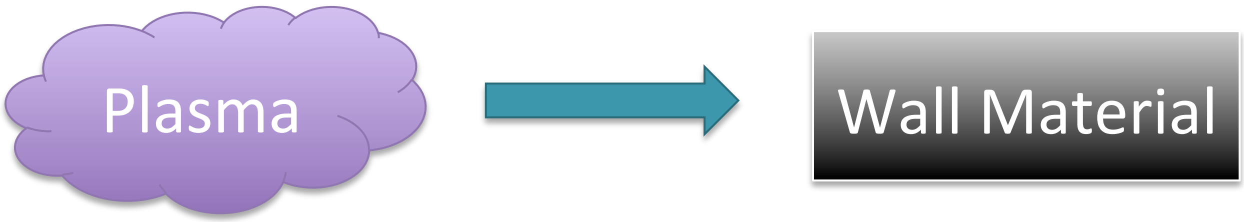


We need…

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

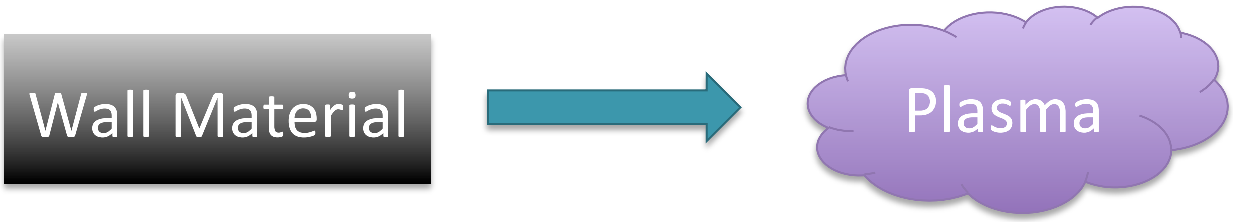
What happens when you try to contain a plasma?

1. The plasma affects the surface



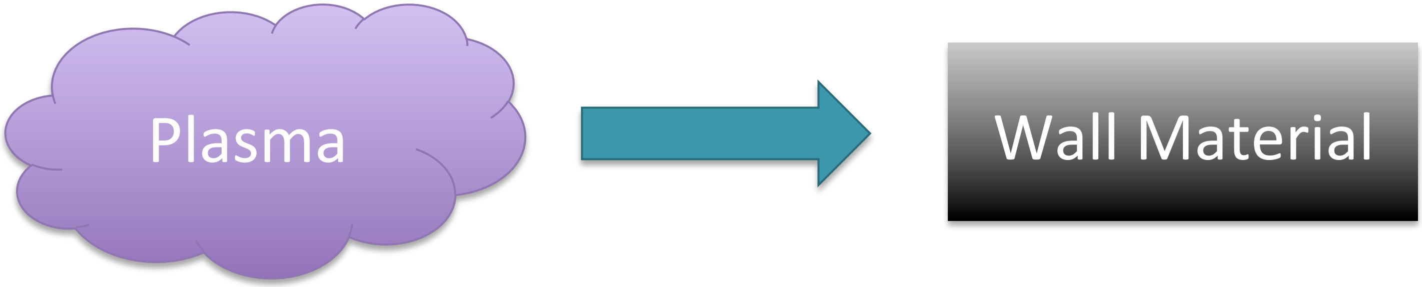
Physical & chemical properties of the material can change

2. The surface affects the plasma



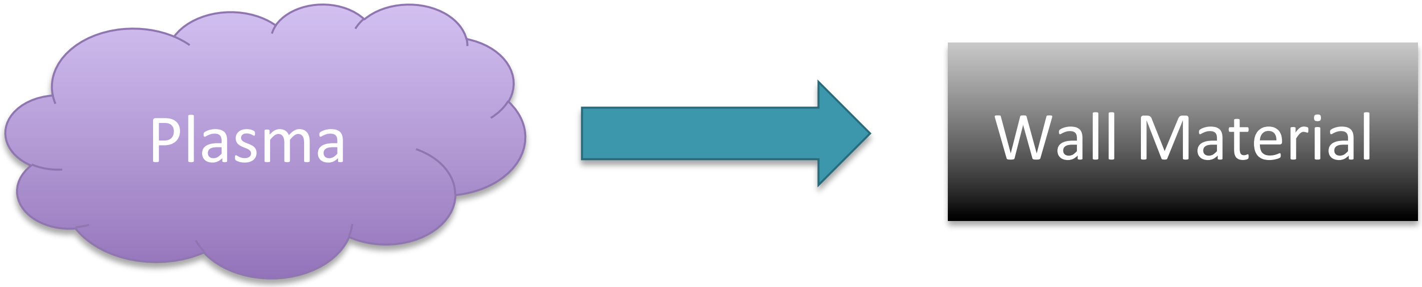
Chemical composition of the plasma can change

How plasma affects the surface:



What do we have in the plasma?

How plasma affects the surface:

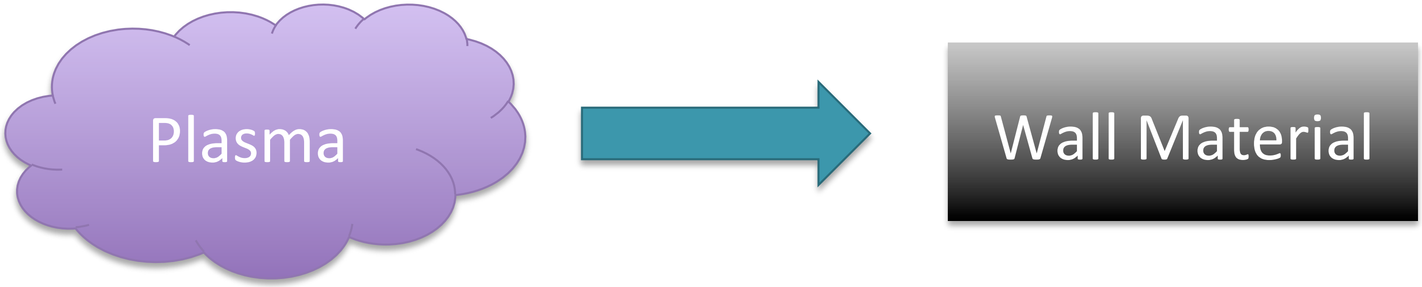


What do we have in the plasma?

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

We have high energy particles & reactive species

How plasma affects the surface:



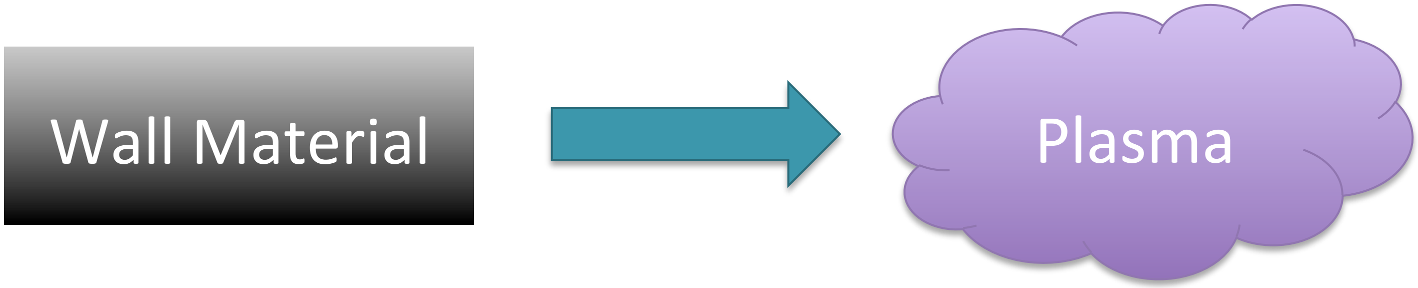
What do we have in the plasma?

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

What do these species do?

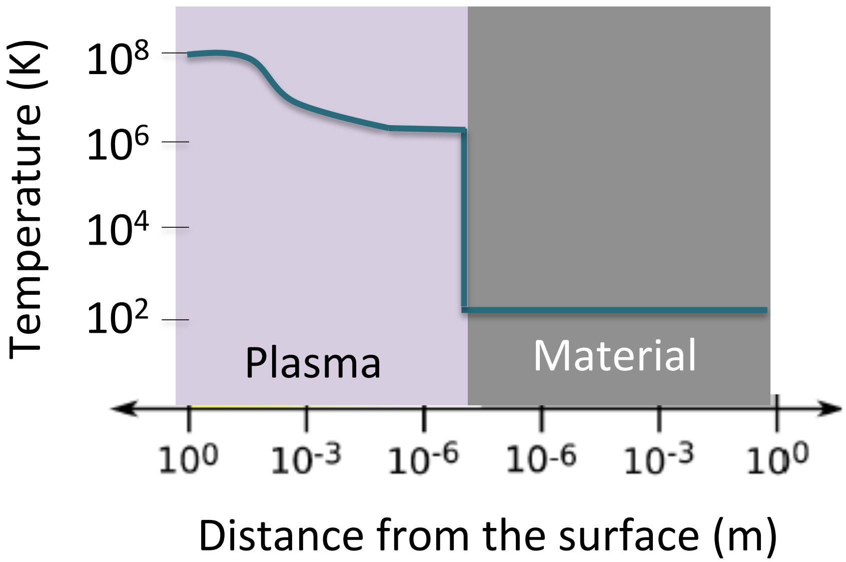
- Impart energy to the wall (heating): ave loads are 10 MW/m^2
- Erode the wall material
- Implant themselves in the wall – Limit on tritium retention!
- Do chemistry on the wall – form different compounds
- Can weaken the material – material swelling / embrittlement from neutrons, fuzz formation

How the surface affects the plasma:



What do we have at the surface?

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



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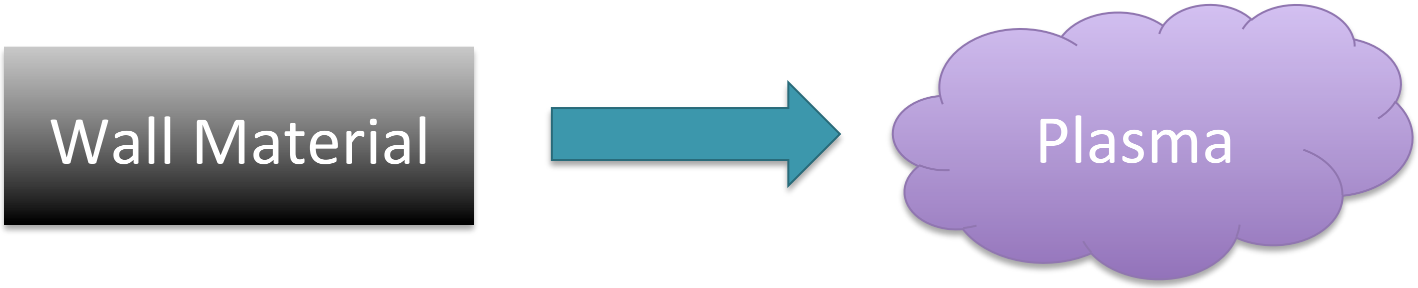


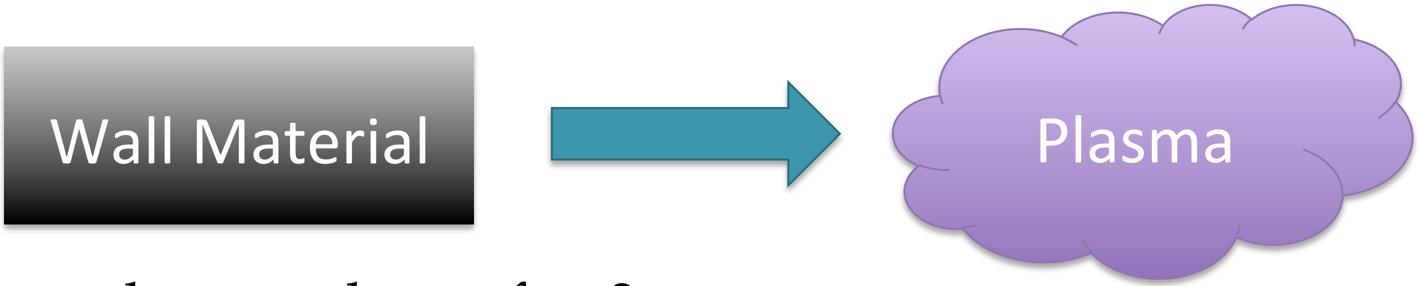
Wall Material

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:

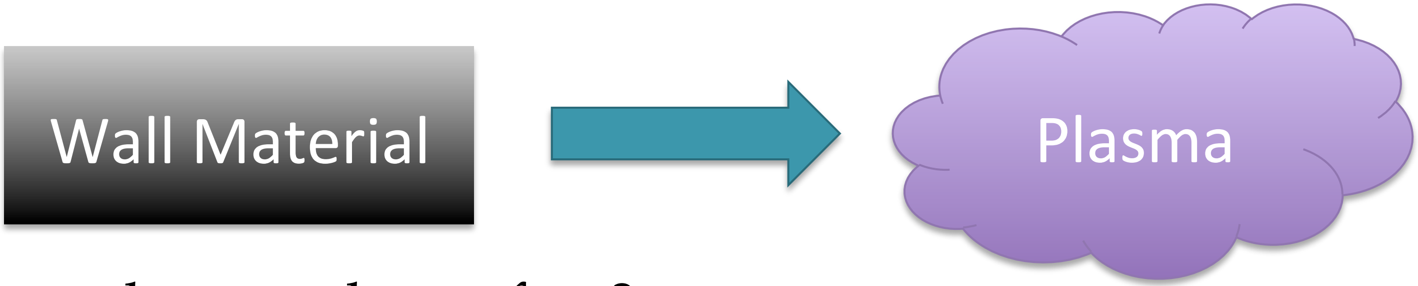


Wall Material → Plasma

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:

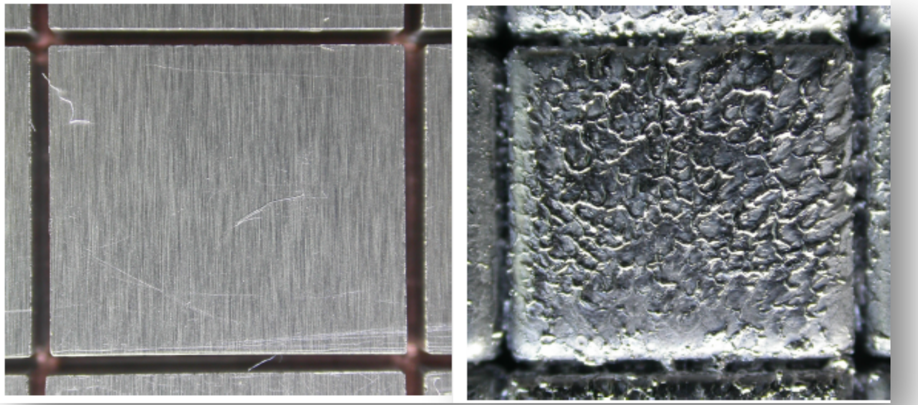


Wall Material → Plasma

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

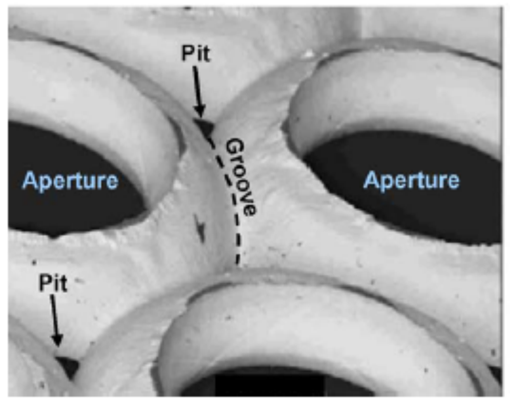
Plasmas can be spectacularly destructive!



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

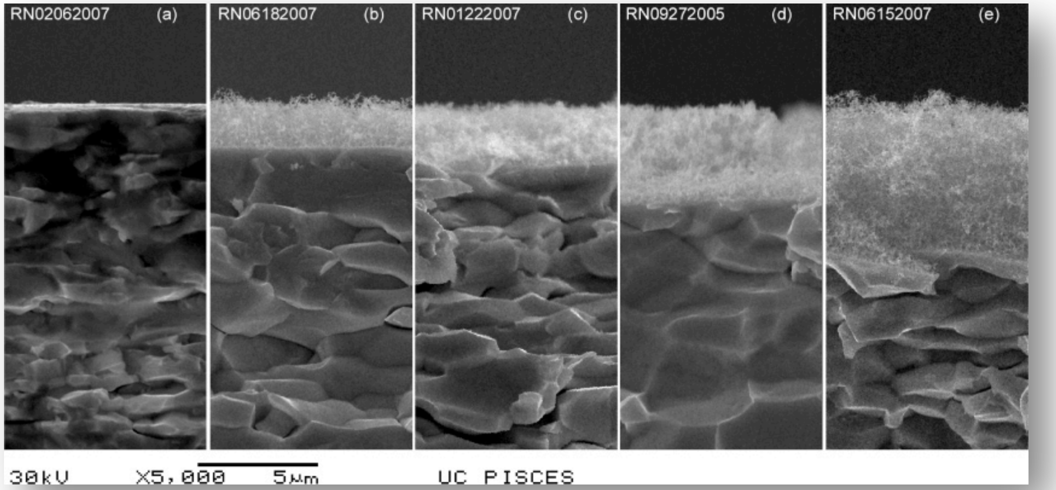
Melted tungsten tile

B. Lipschultz, Nucl. Fusion (2012)



Erosion of molybdenum ion thruster grid

R.E. Wirz, IEEE Trans. Plasma Sci. (2008)



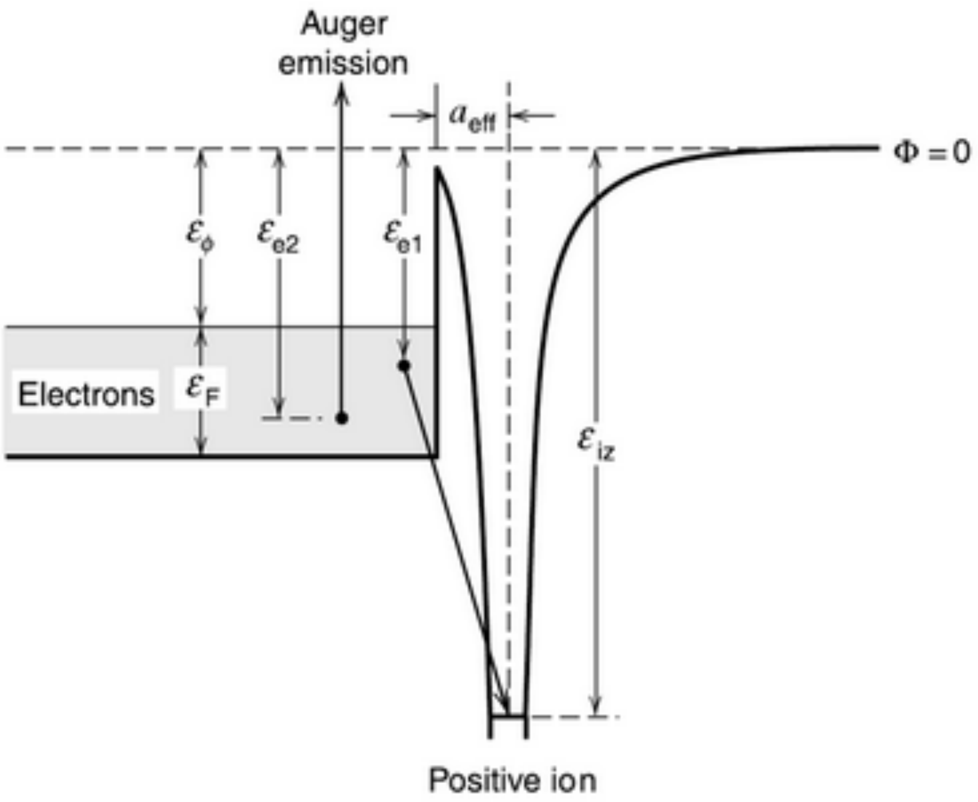
Tungsten fuzz

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

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)



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

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

All ions immediately neutralized

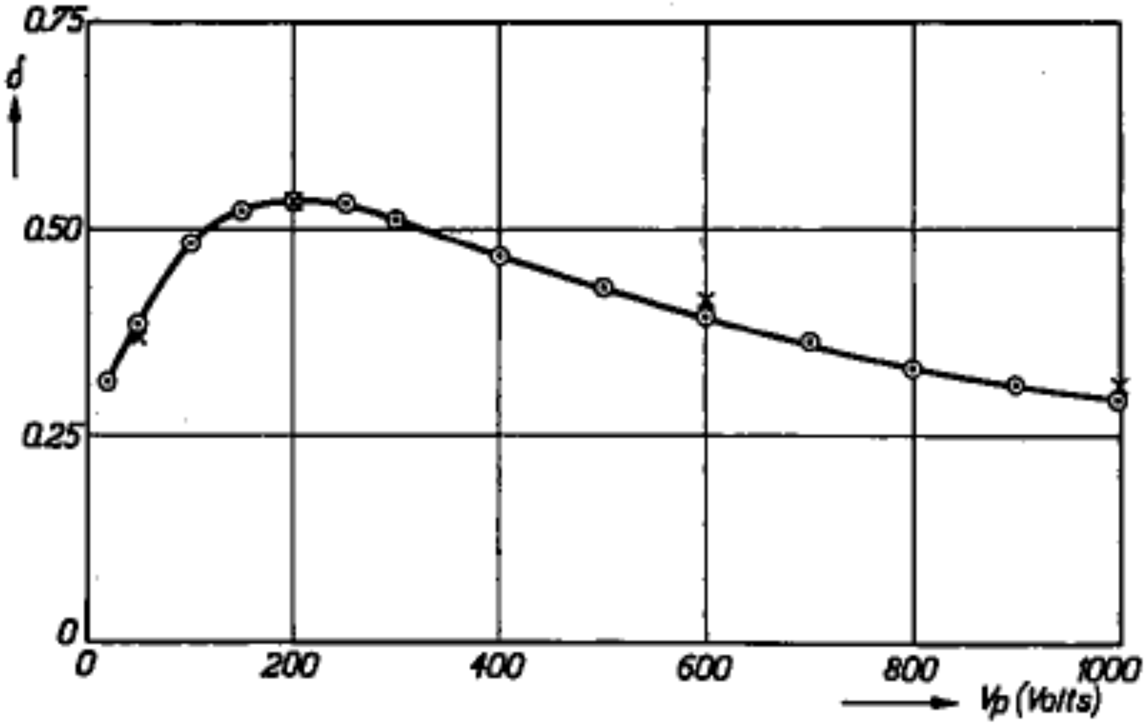
2 options:
-Electron enters excited state (radiates a photon as it transitions to lower state)

-Electron enters ground state & 2$^{\text{nd}}$ electron absorbs excess energy – Auger Neutralization also secondary electron emission (SEE)

Five main processes that occur at the plasma-materials interface

1. Positive Ion Neutralization (Recombination)

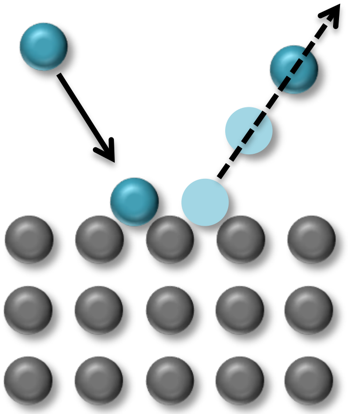
SEE yield of Be



Bruining, Physica 5 (1938) 17.

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

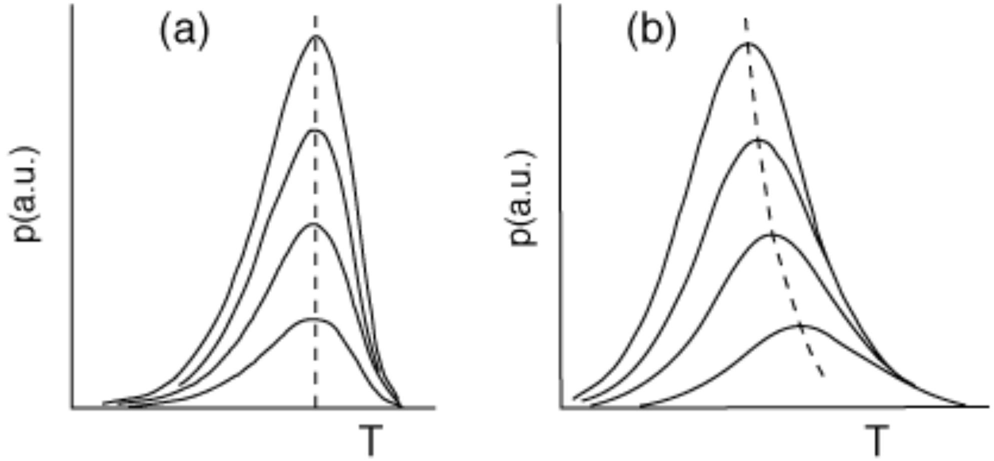
Five main processes that occur at the plasma-materials interface



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

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

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

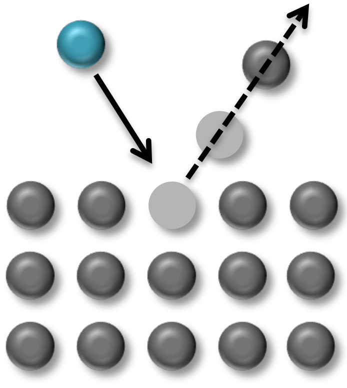


Desorption of 1st order (a) & second order process (b)

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

Five main processes that occur at the plasma-materials interface

3. Physical Sputtering **(10-100 eV)**



Sputtering

Higher energy transfer when masses are similar:

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

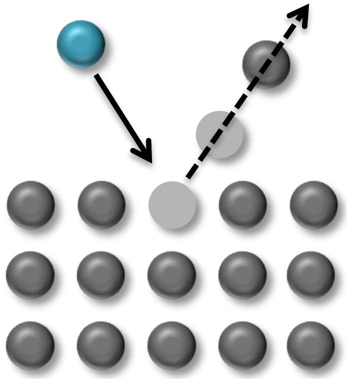
Rate equation:

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

Yield (empirical) = number sputters per incident ion

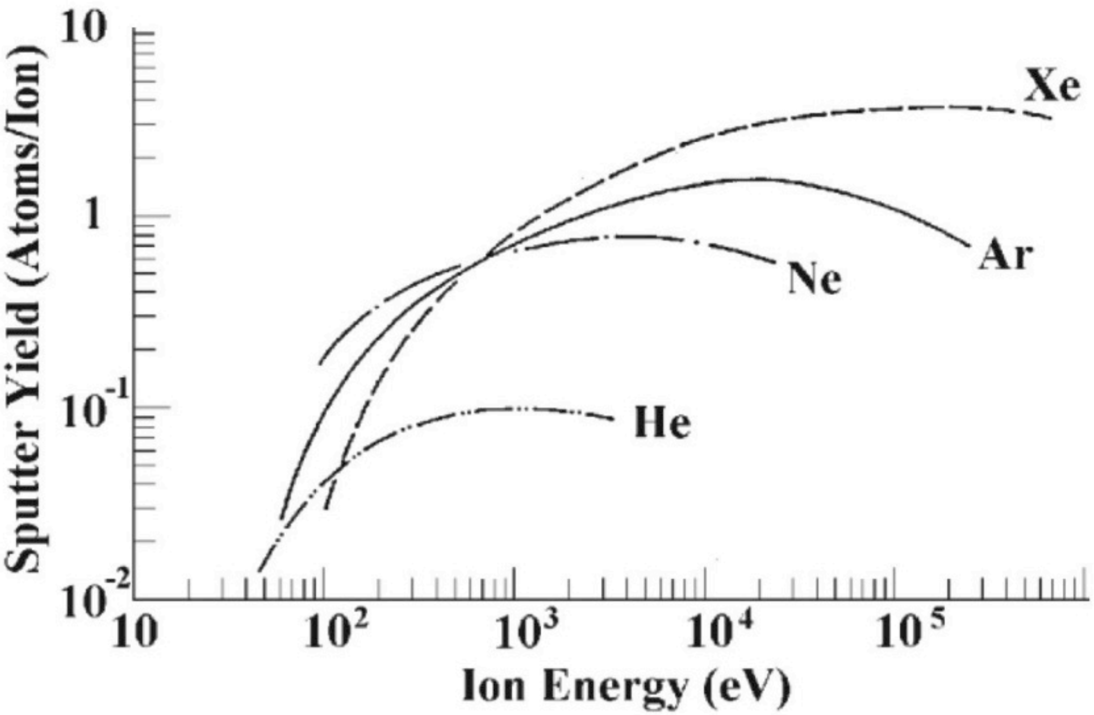
Five main processes that occur at the plasma-materials interface

3. Physical Sputtering **(10-100 eV)**



Sputtering

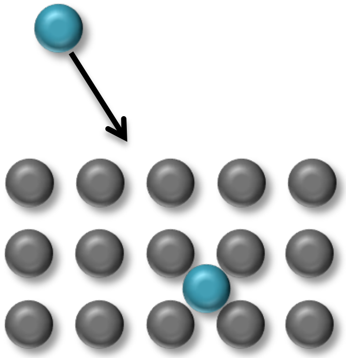
Sputter yields of silicon as a function of ion energy for noble gas ions:



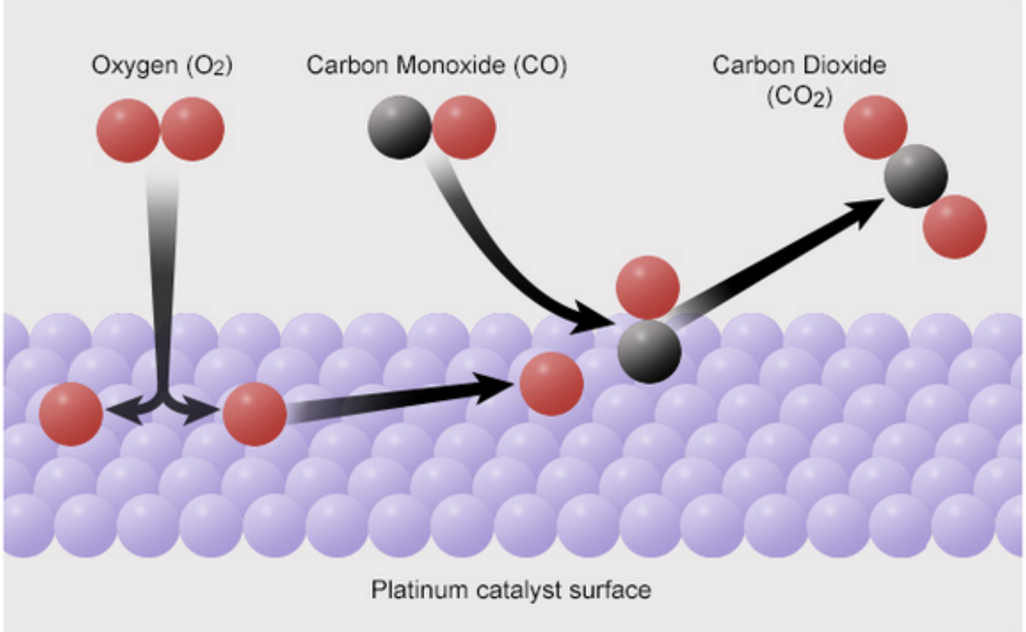
http://xpssimplified.com/depth_profiling.php

Five main processes that occur at the plasma-materials interface

4. Implantation **(1000 eV)**



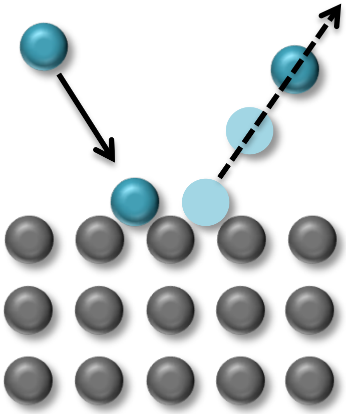
5. Reactions with/on a surface



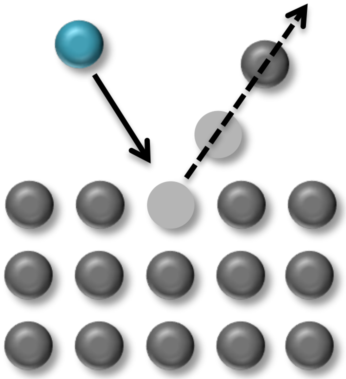
http://www.abc.net.au/science/articles/2015/05/25/4229949.htm

Five main processes that occur at the plasma-materials interface

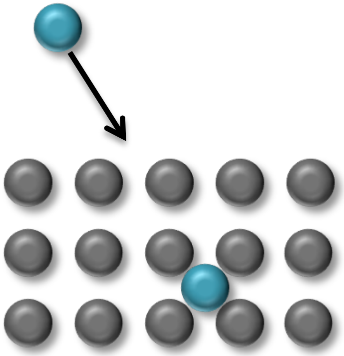
1. Positive Ion Neutralization (Recombination)
   - Ions that hit the surface are neutralized
     $e + A^{+} + S \rightarrow A + S$
2. Absorption/Desorption **(low energy, 1 eV)**
   - Evaporation rate increases exponentially with temperature
3. Physical Sputtering **(10-100 eV)**
   - Independent of 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!

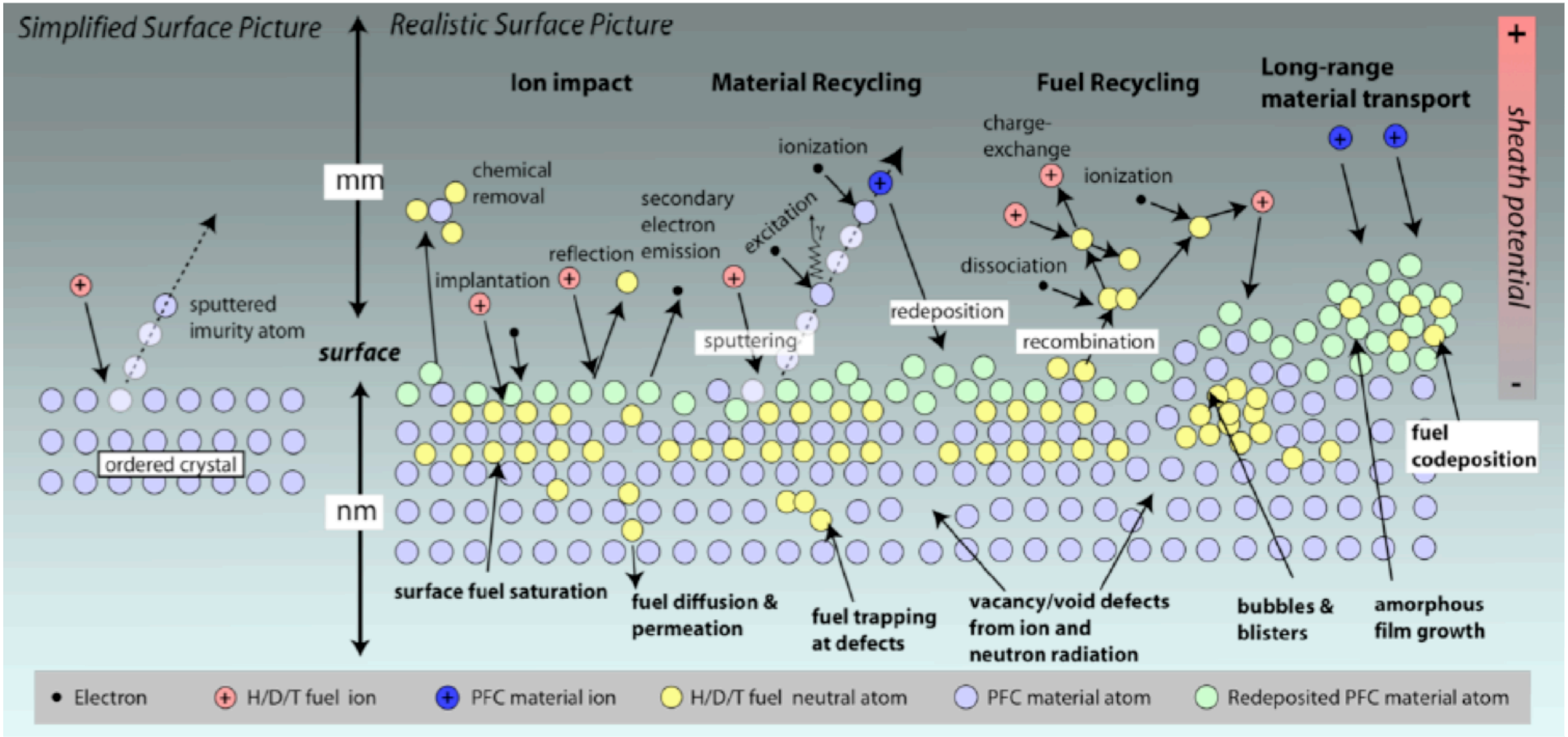


Image from D. Whyte, http://psisc.org/mission

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

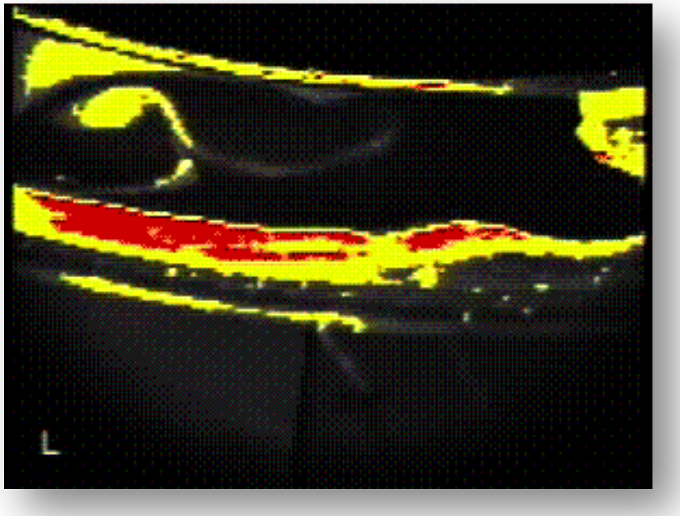
Advantages of liquid metals (lithium):

No erosion
No thermal fatigue
No neutron damage

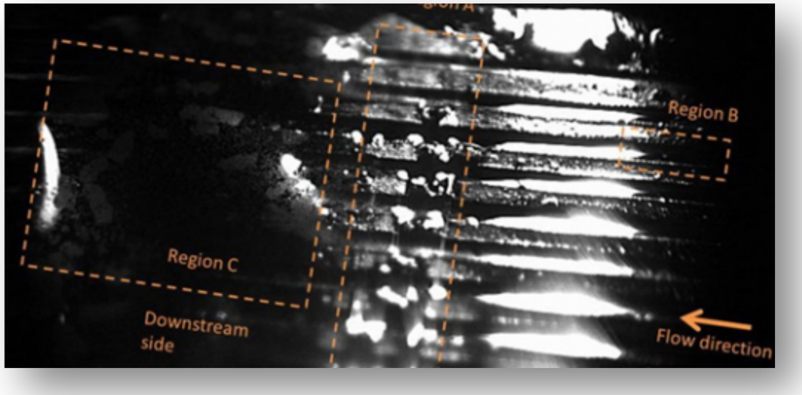
Resilient again high heat fluxes
Refreshes the surface
Li concentration in the plasma is low

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.



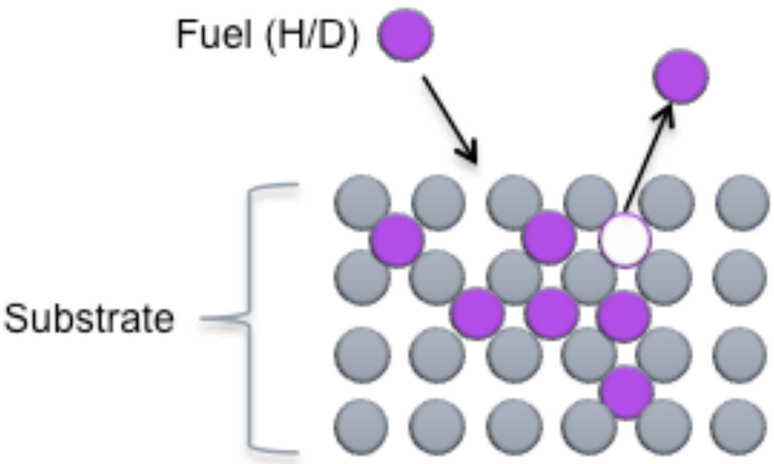
Flowing liquid Li experiment at University of Illinois at Urbana-Champaign

But why does Li help?

Working hypothesis: Deuterium retention

High D retention → 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)

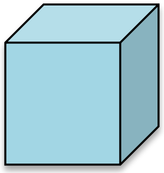
2. Through complexes that involve oxygen (Krstic, Allain, Taylor)

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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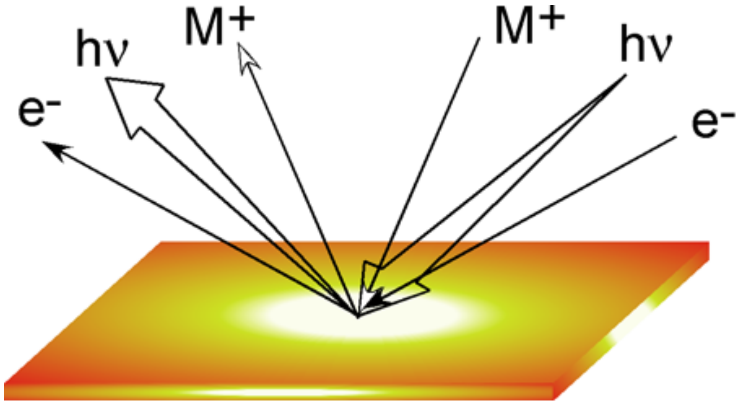

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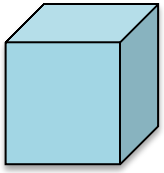

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Surfaces contain ~10^{14} atoms/cm^2

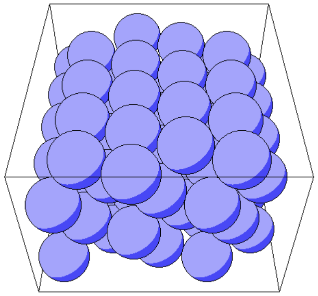
Challenge: Detect 10^{14} cm^{-2} signal on a 10^{23} cm^{-3} background.

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

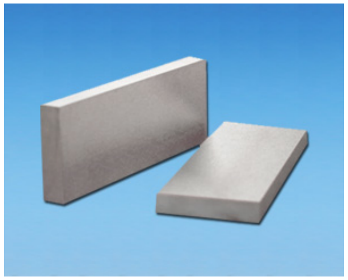


Single crystal

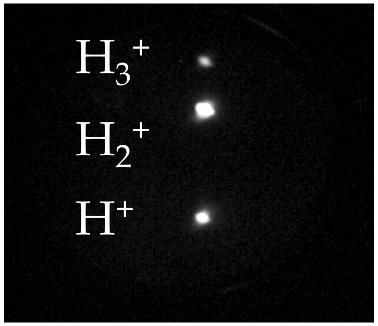
Grain boundaries

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

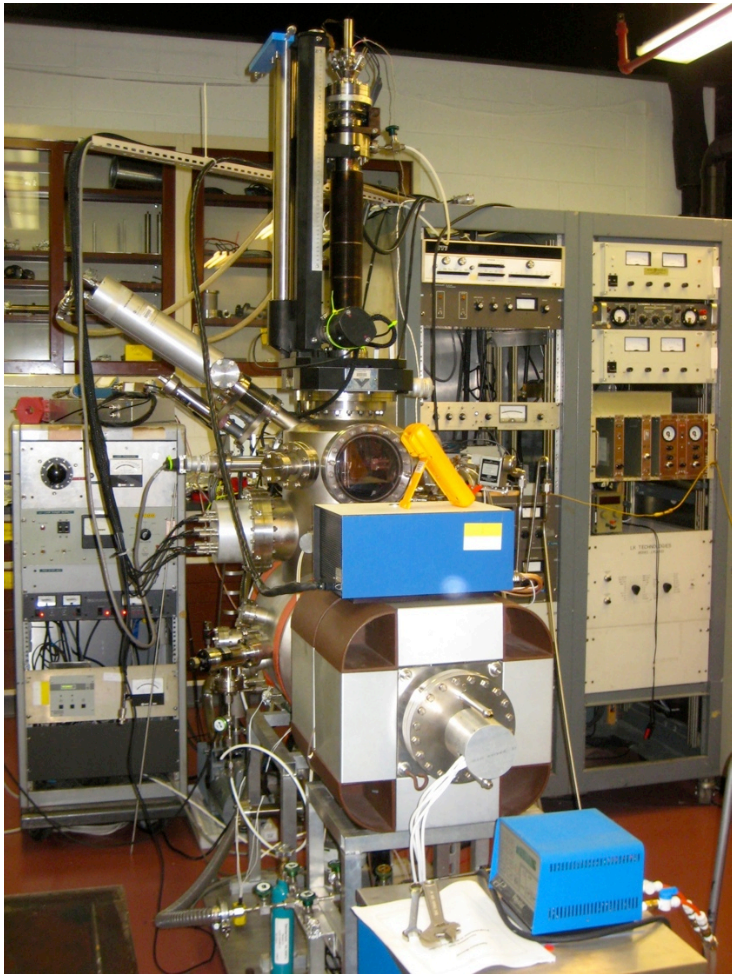
More Complex Systems

Laboratory surface science experiments

Linear plasma devices

Fusion devices

Laboratory surface science experiments



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

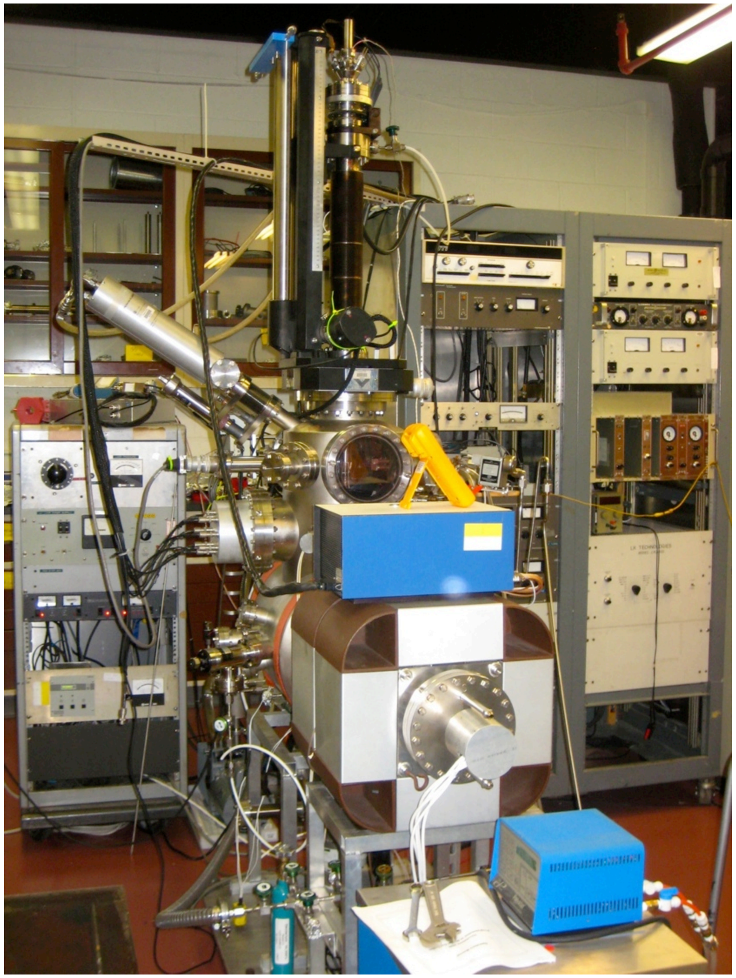
…something we cannot achieve in a tokamak or linear plasma device!

Isolate effects of:

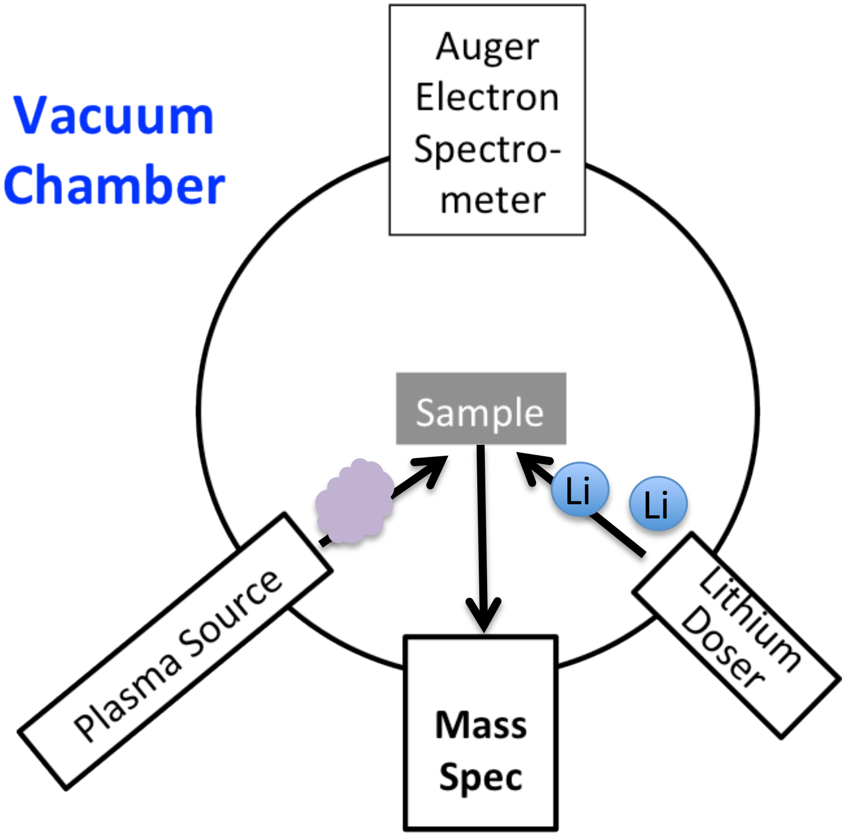
- Chemistry
- Incident particle fluxes and energies
- Substrate temperature
- Surface composition
- Morphology

Laboratory surface science experiments

simple ○————→ complex



Test stand instrumentation in the Surface Science & Technology Lab


Vacuum Chamber

Auger Electron Spectro-meter

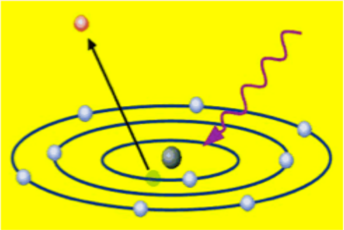
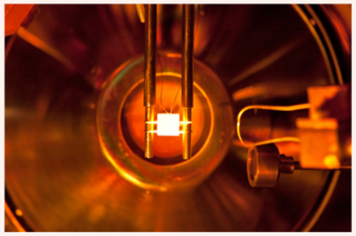
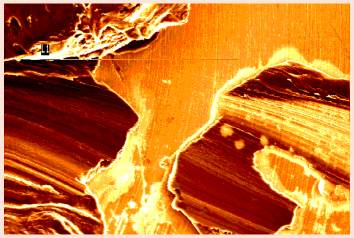
Sample

Plasma Source

Mass Spec

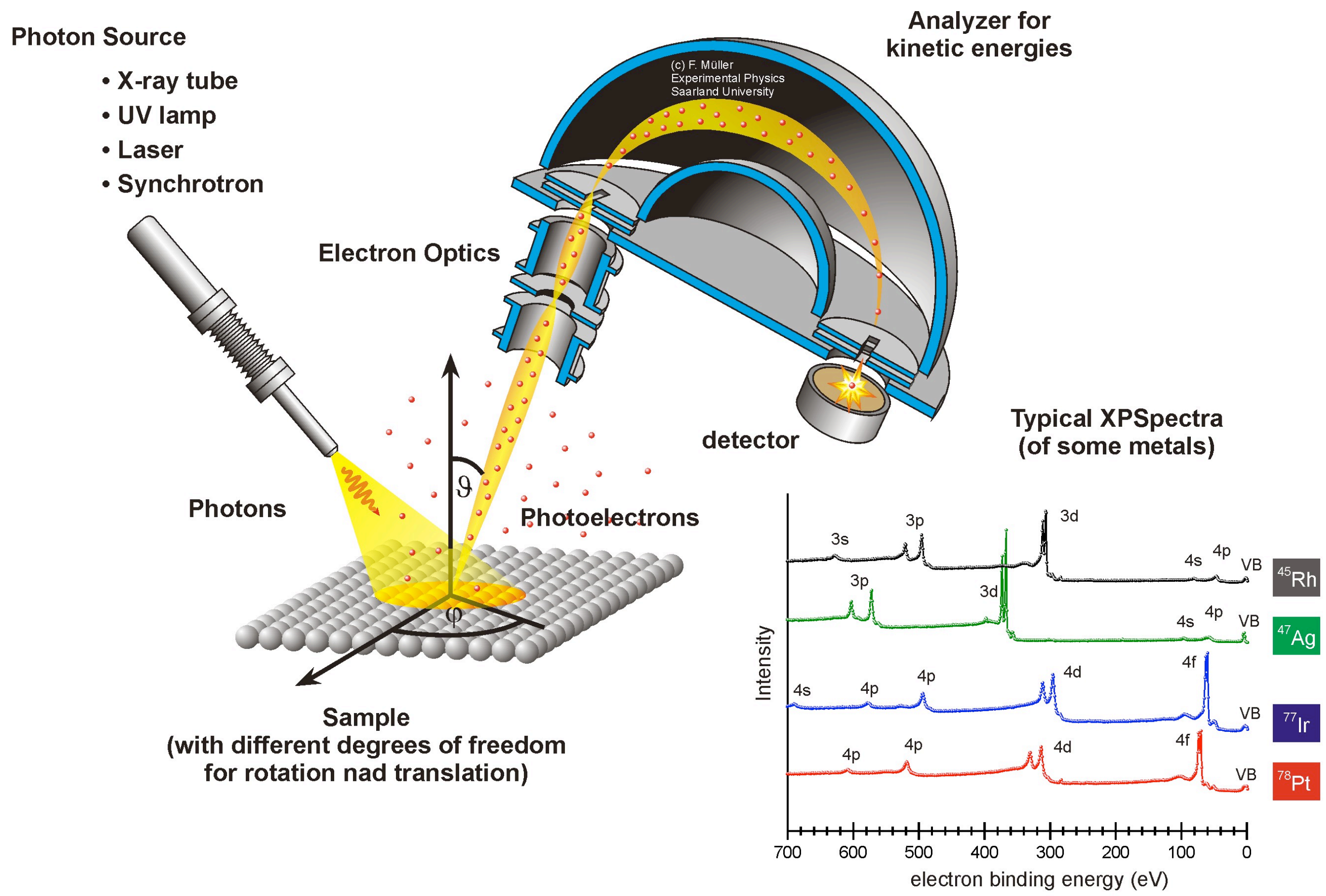
Lithium Doser

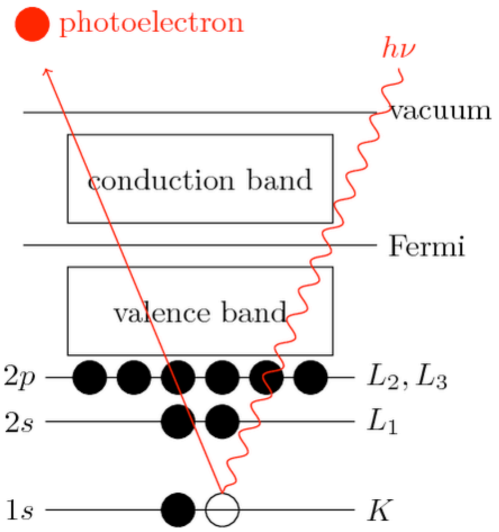
Atomic-Level Diagnostics

	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)

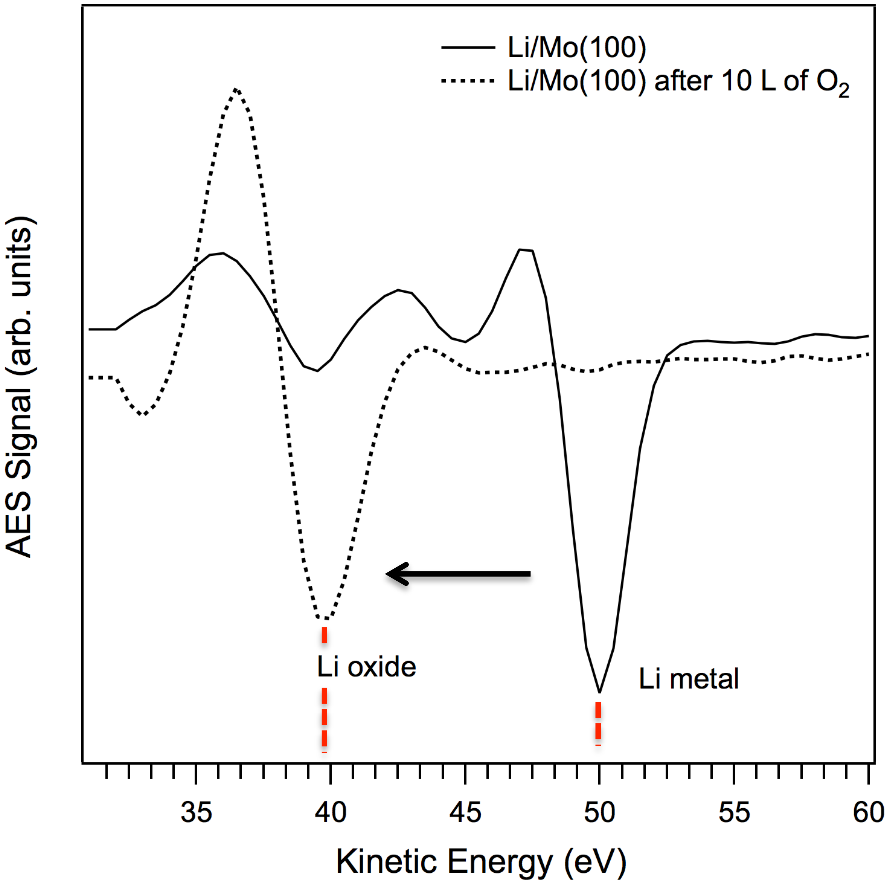
Gives composition of top 5-10 nm

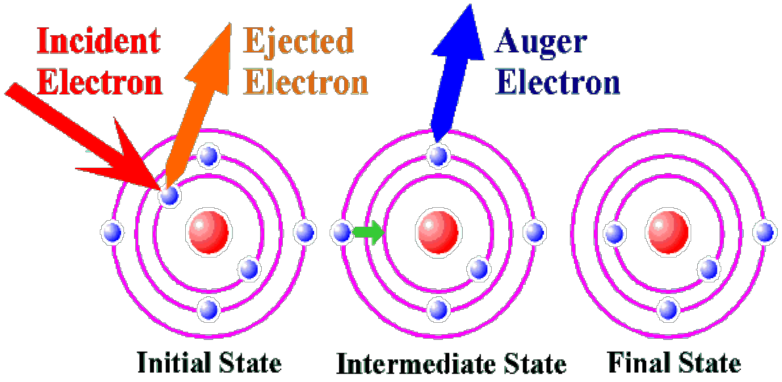


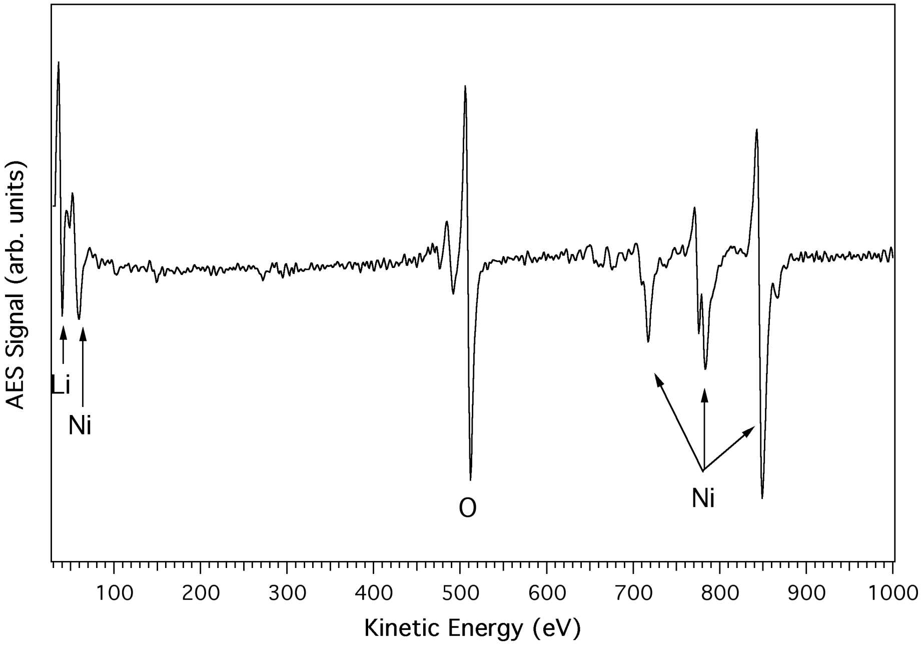


http://jacobs.physik.uni-saarland.de/english/instrumentation/uhvl.htm

Auger Electron Spectroscopy





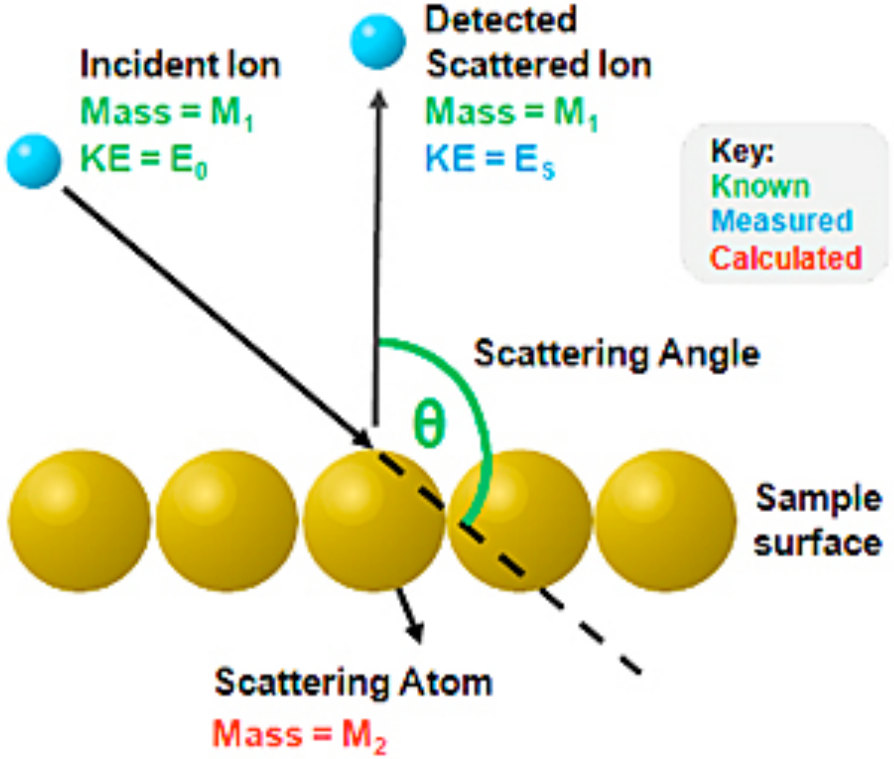


Low-energy Ion Scattering Spectroscopy (LEISS)

Very surface sensitive

(probes top 1-3 layers)

He usually used for incident ion



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

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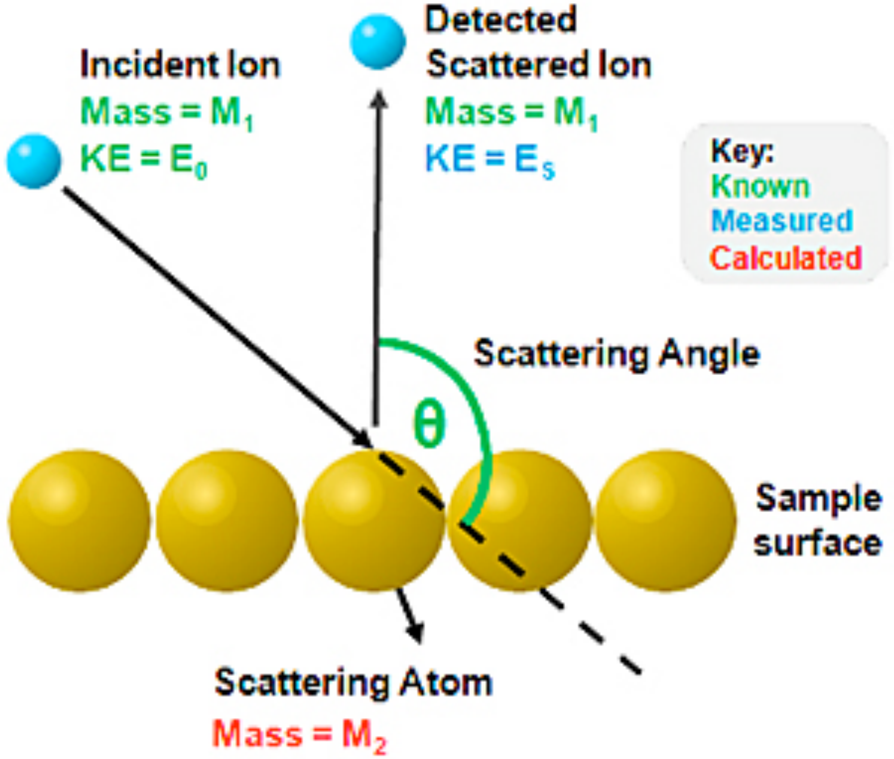

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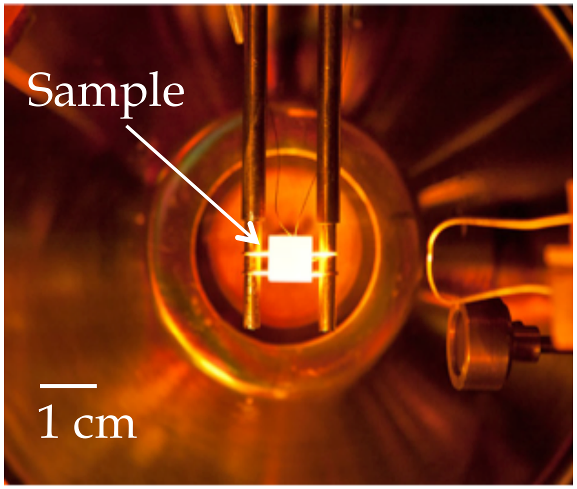
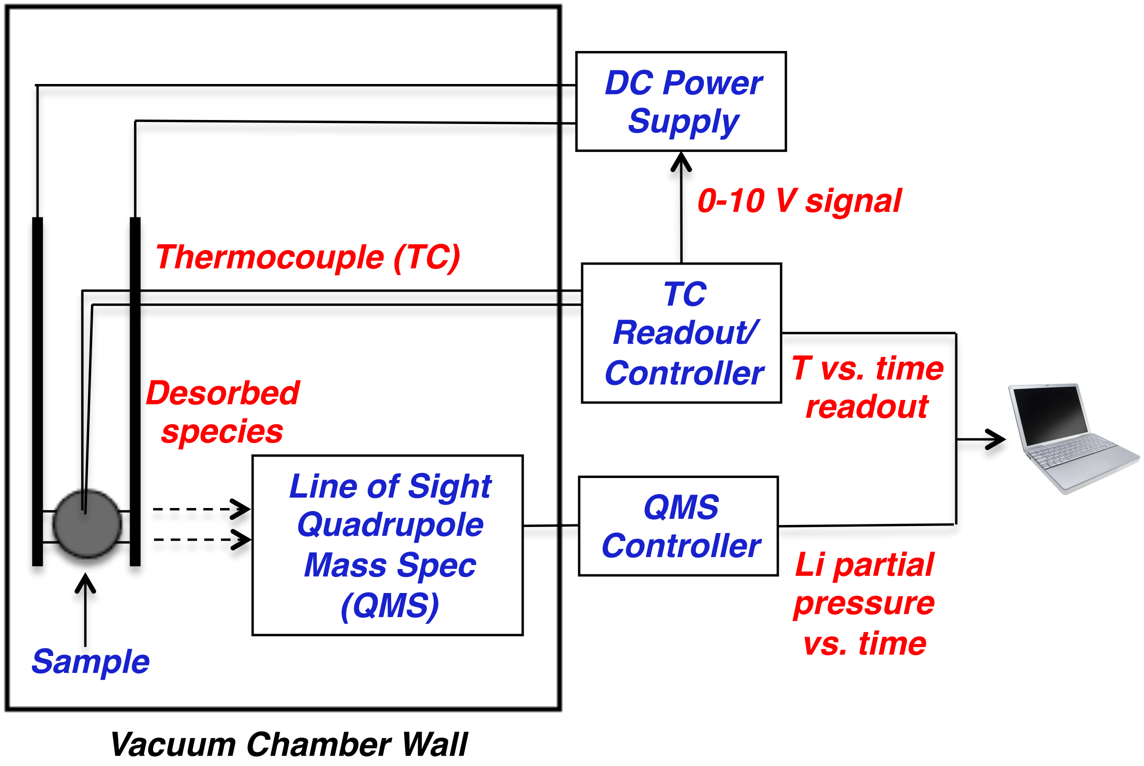
Temperature programmed desorption

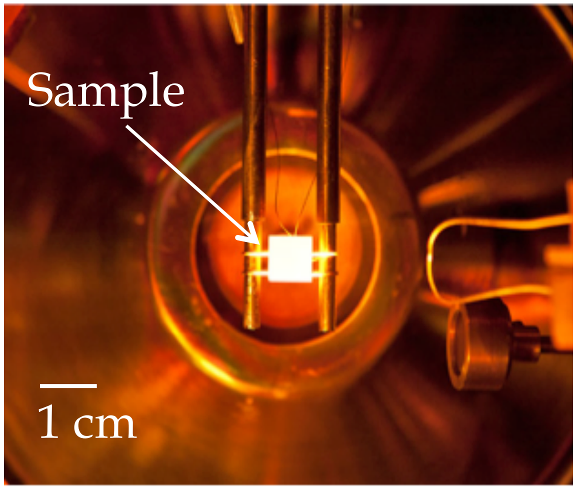


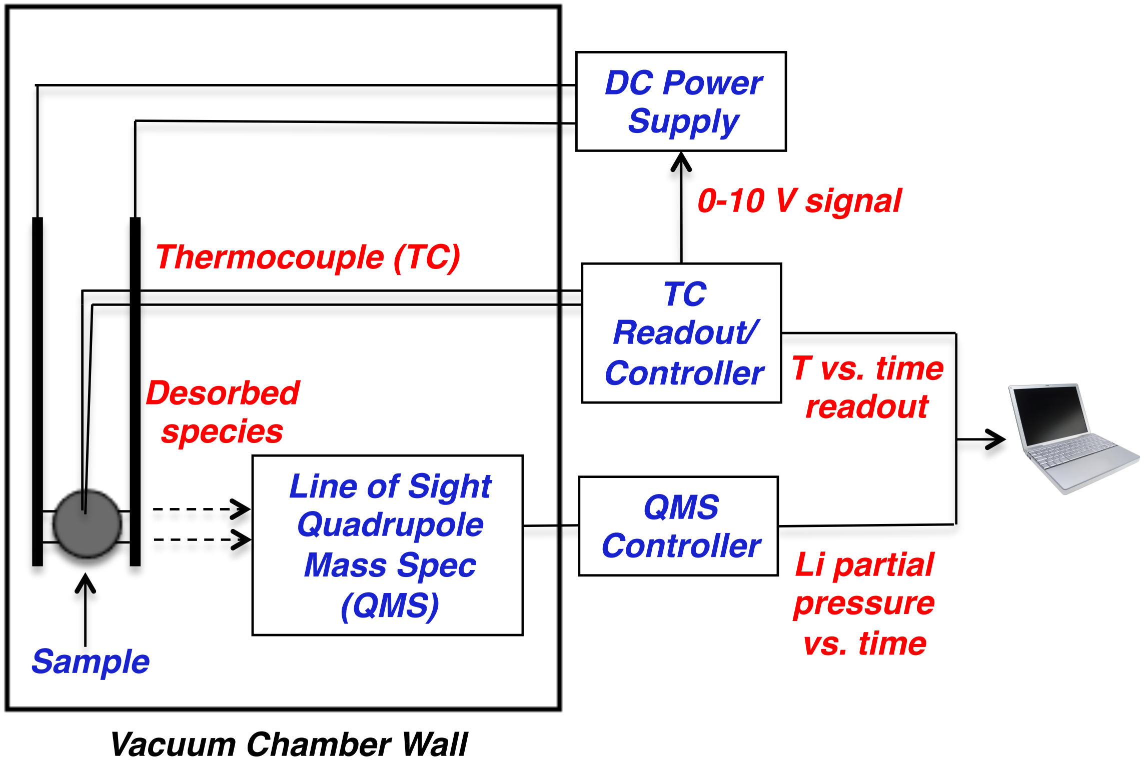


Temperature Programmed Desorption (TPD) Technique:

- 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




DC Power Supply

0-10 V signal

Thermocouple (TC)

TC Readout/ Controller

T vs. time readout

Desorbed species

Line of Sight Quadrupole Mass Spec (QMS)

QMS Controller

Li partial pressure vs. time

Sample

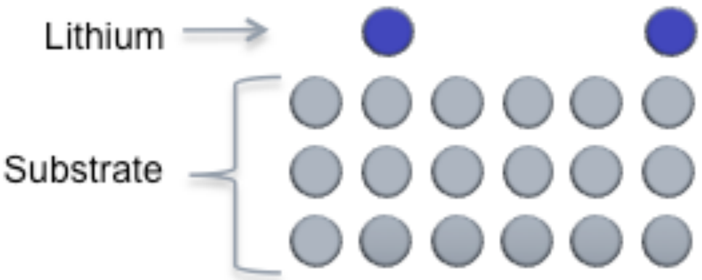
Vacuum Chamber Wall

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

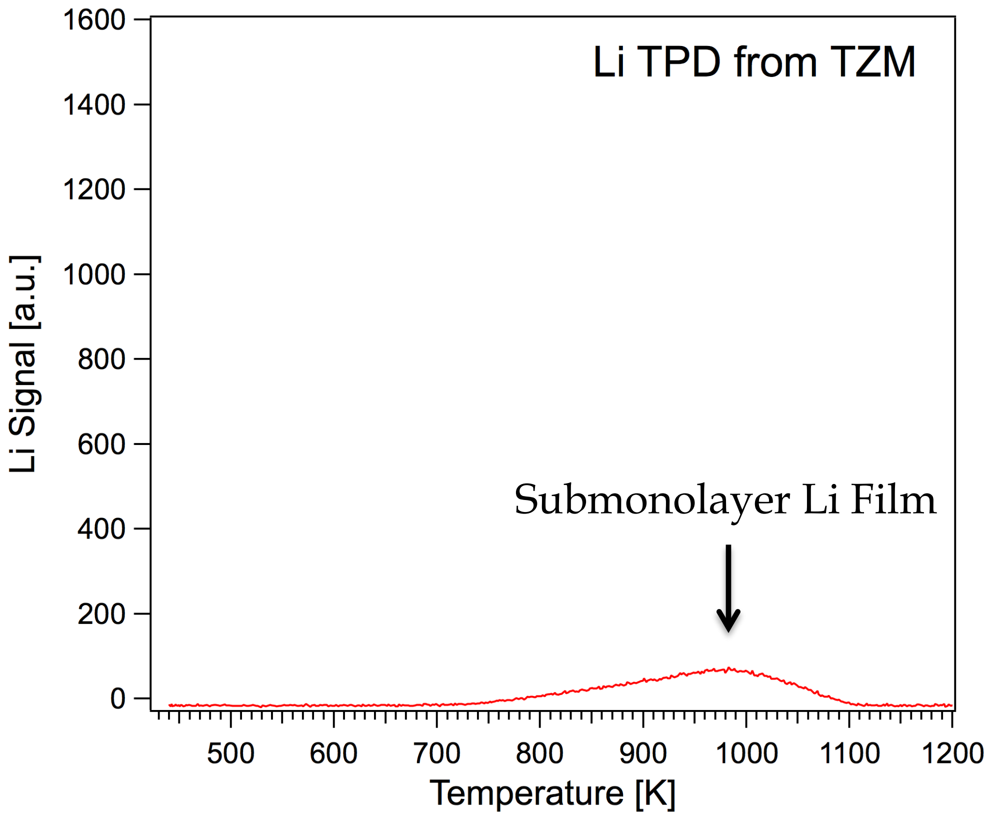
TPD can be used to measure D retention!

Example: Desorption of Li from Mo

simple → complex



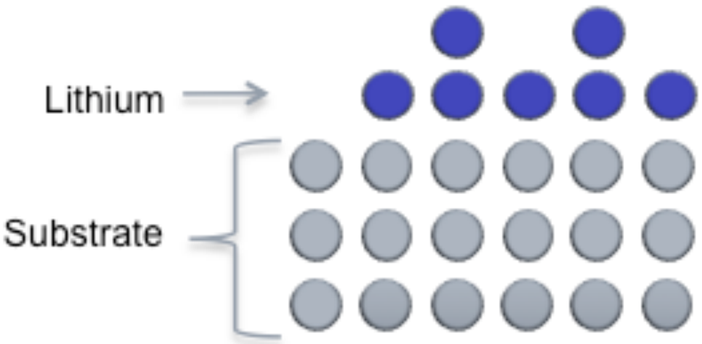
- Submonolayer Li film on TZM stable up to 1000 K
- Represents Li-Mo bonding
- Desorption energy ~2.7 eV



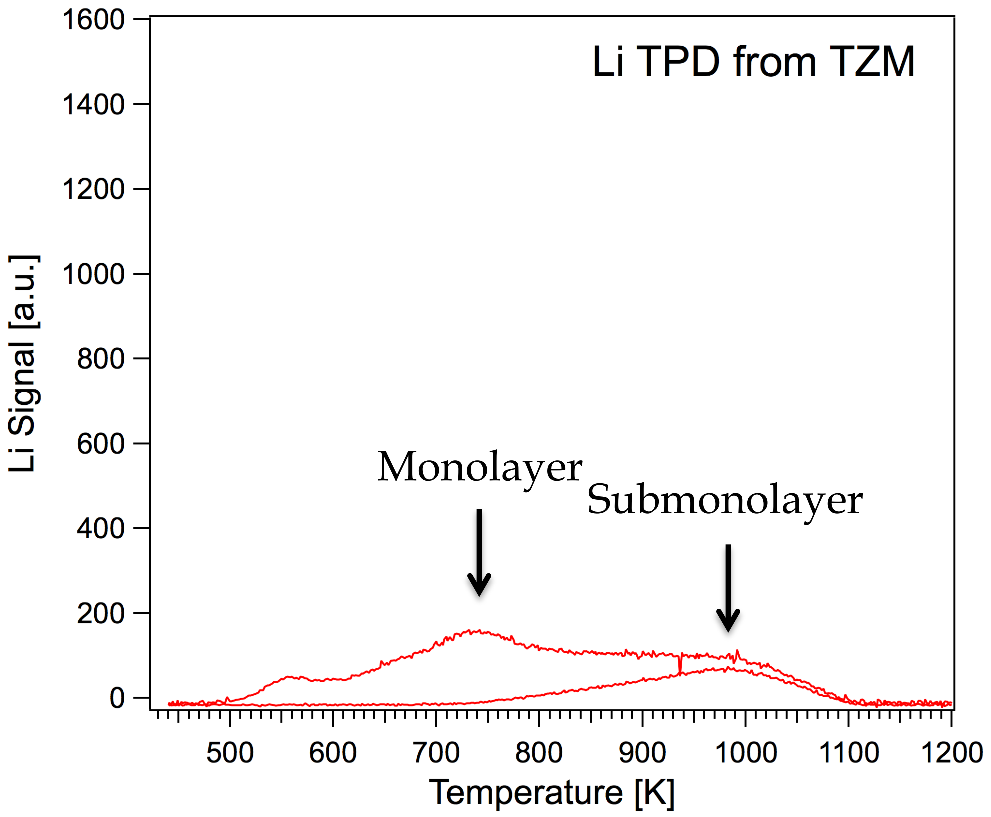
C.H. Skinner et al., JNM 438, S647 (2013)

Example: Desorption of Li from Mo

simple → complex



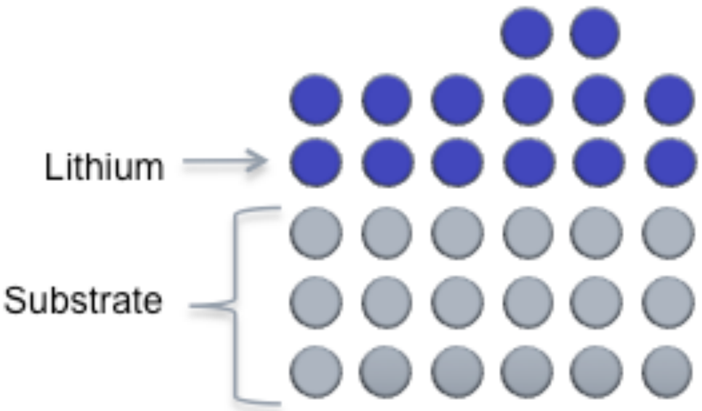
- Area under Li TPD curve increases with Li dose
- Dipole interactions lower the desorption energy (~2 eV)
- E_d is a function of coverage



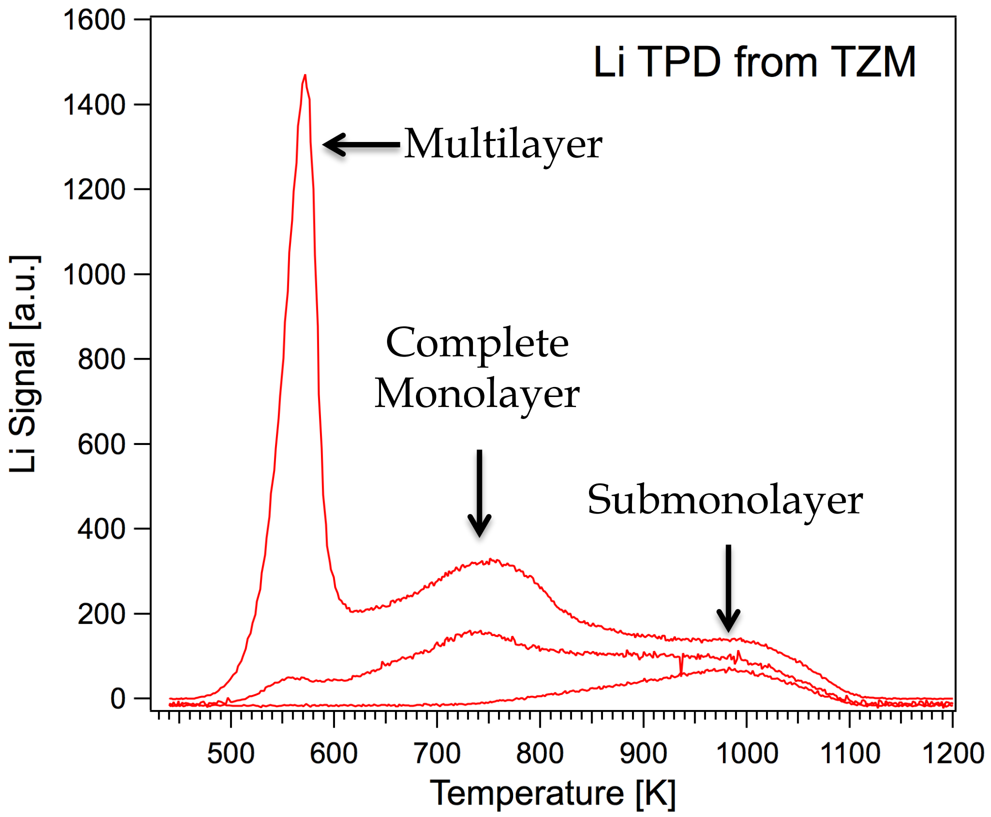
C.H. Skinner et al., JNM 438, S647 (2013)

Example: Desorption of Li from Mo

simple ○→ complex



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

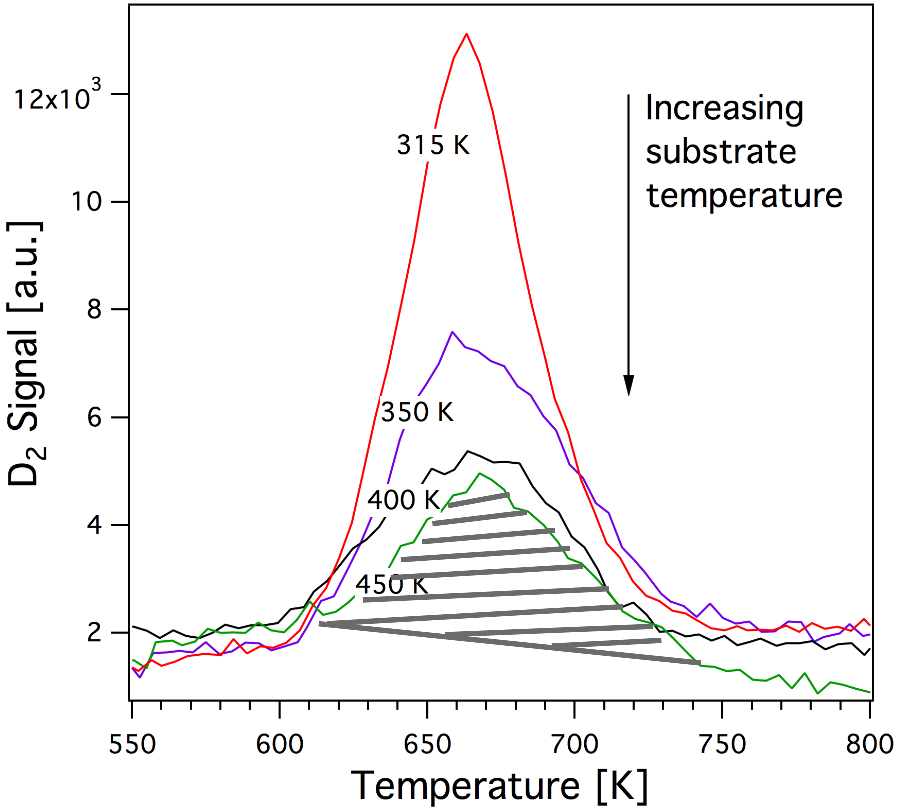


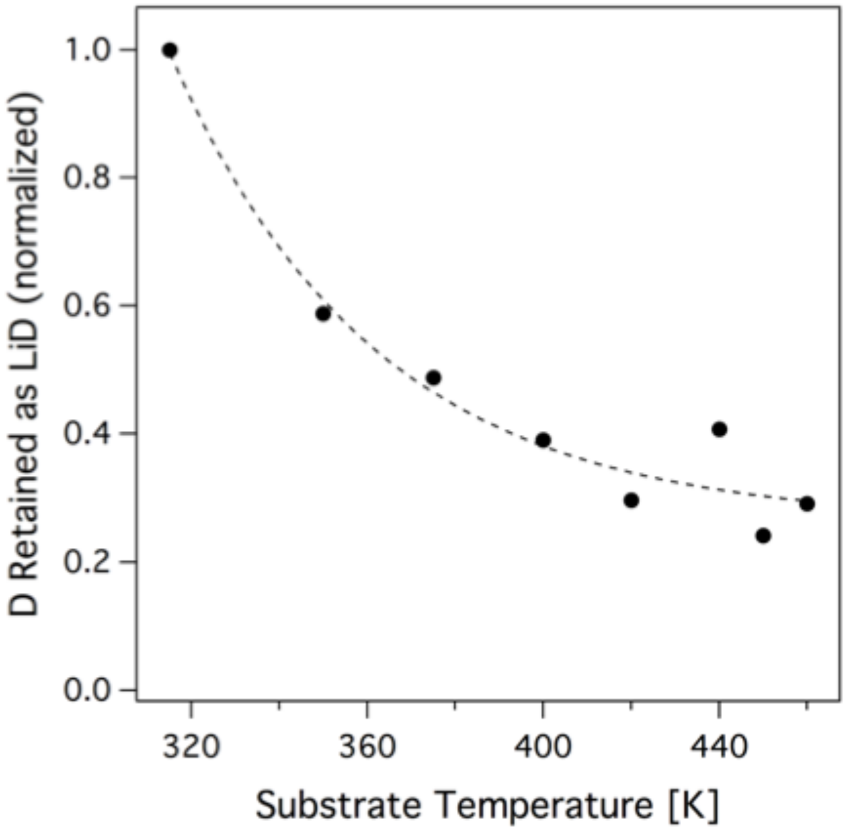
C.H. Skinner et al., JNM 438, S647 (2013)

TPD can be used to determine D retention

simple → complex

In lithium films as function of temperature:



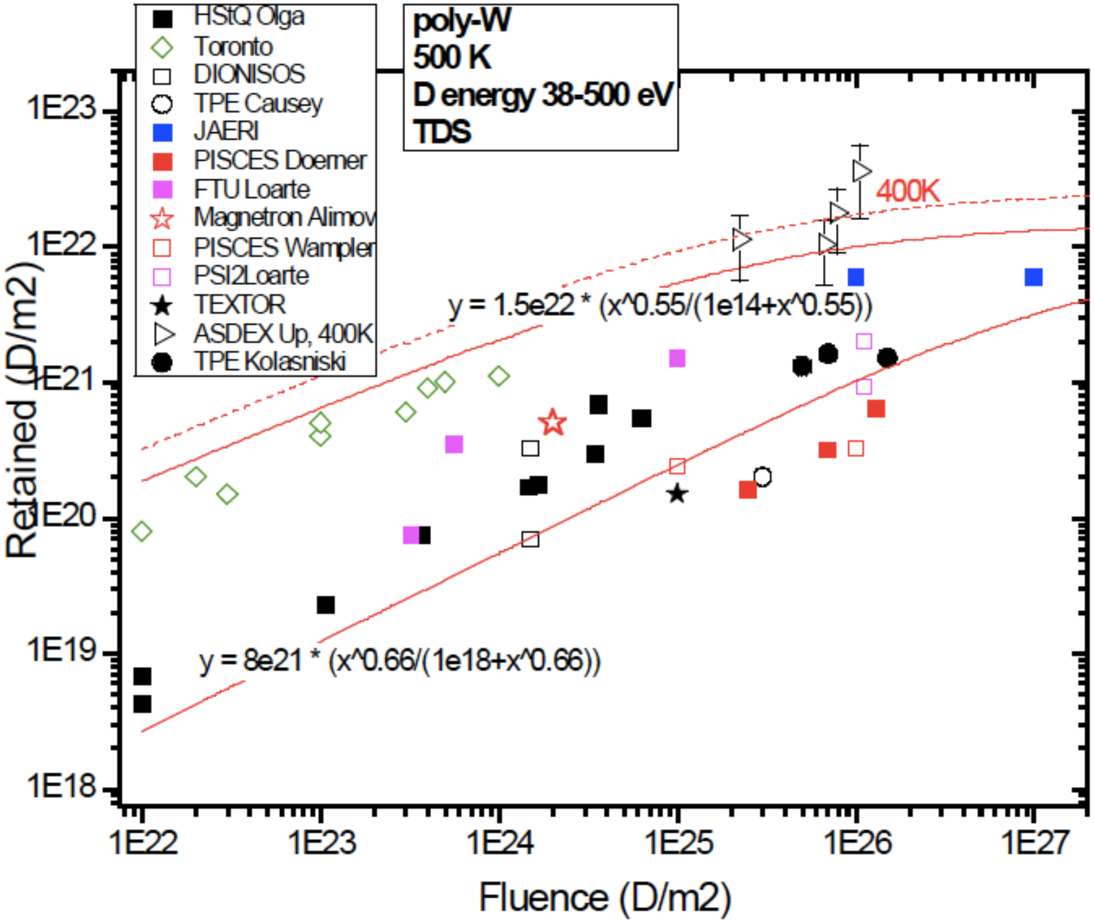


A.M. Capece, et al., JNM (2015)

TPD can be used to determine D retention

simple ———○——→ complex

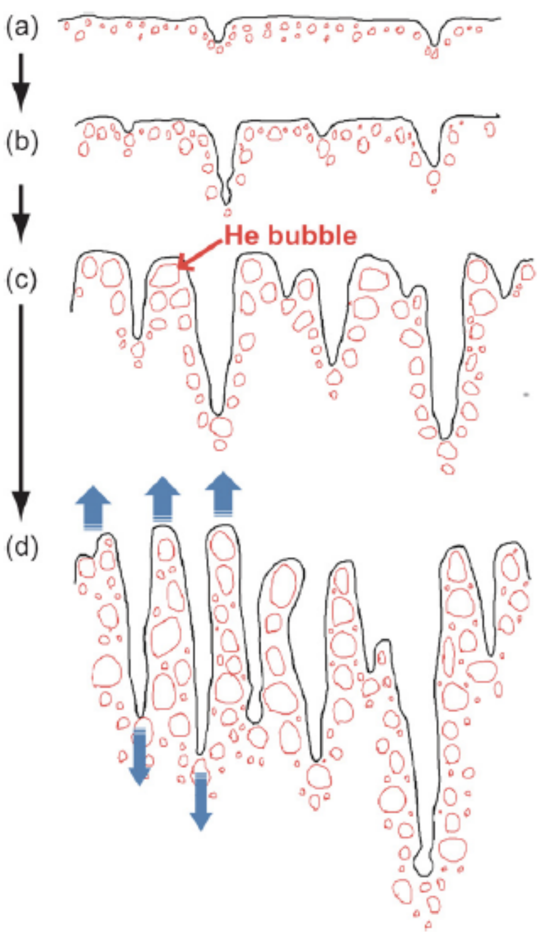
In tungsten as function of fluence:



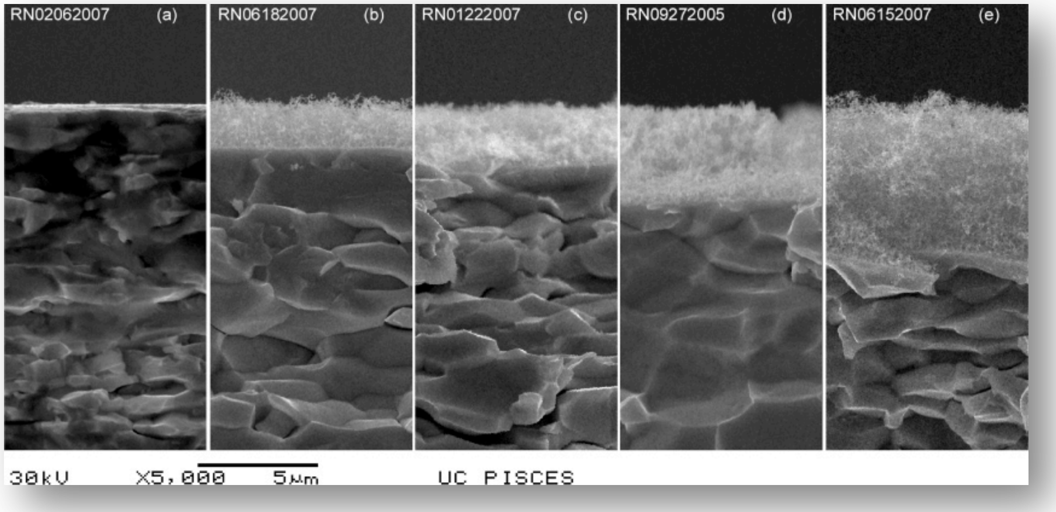
Lipschultz et al., (2010) MIT Report PSFC/RR-10-4

SEM used to understand fuzz & bubble formation in W

simple → complex



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

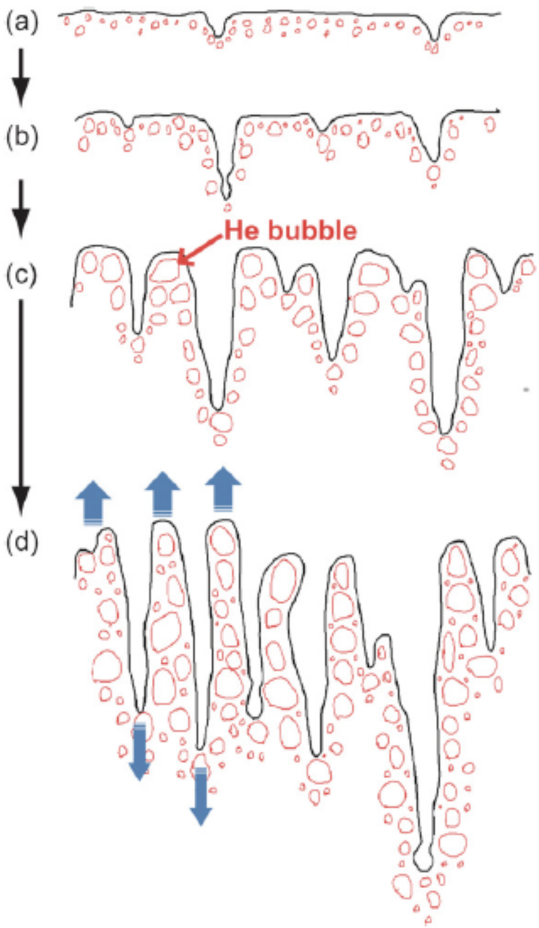


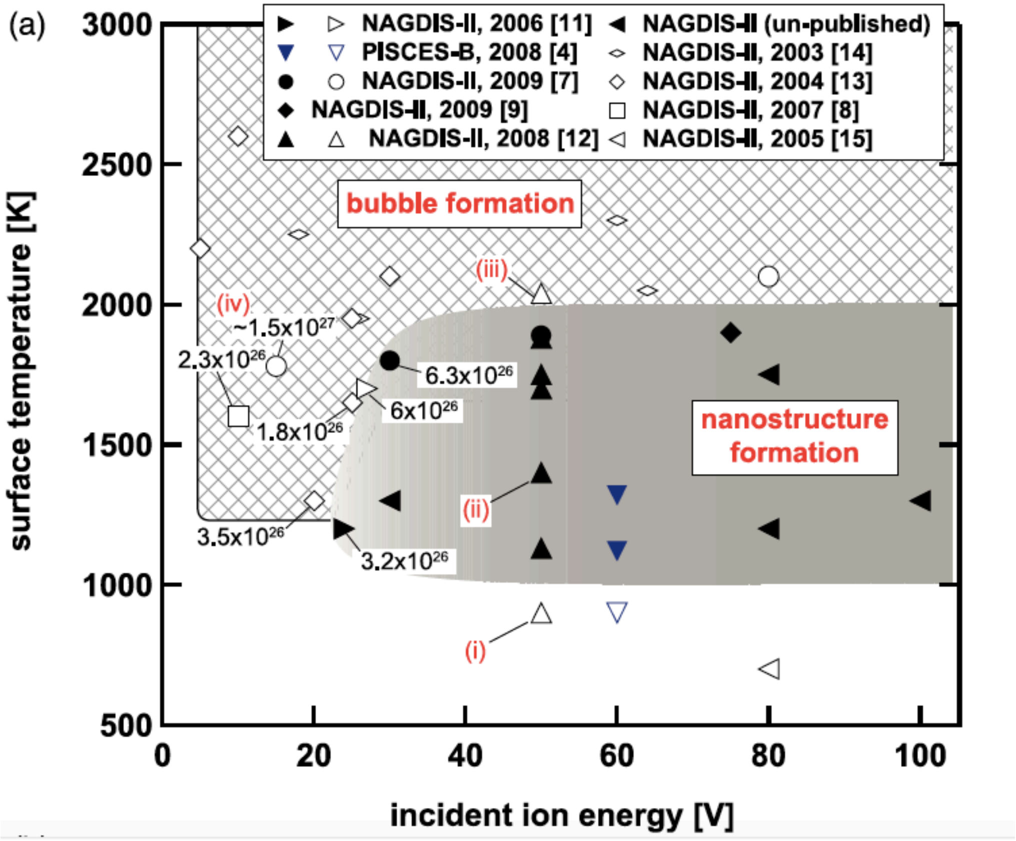
Tungsten fuzz

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

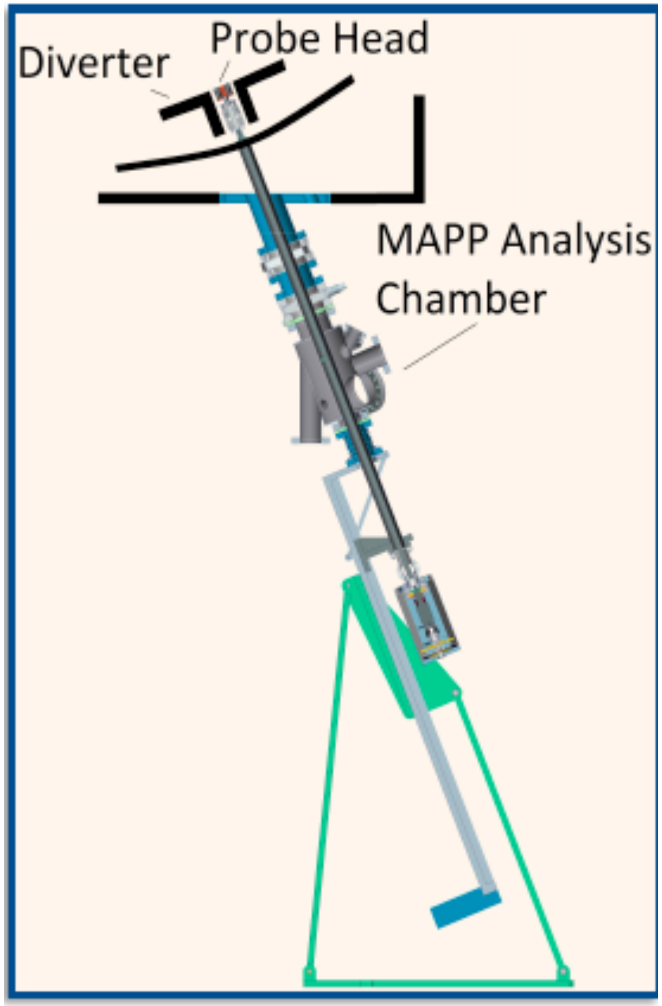
XPS: Elemental/ chemical composition

TPD: Gives binding energies, desorption products

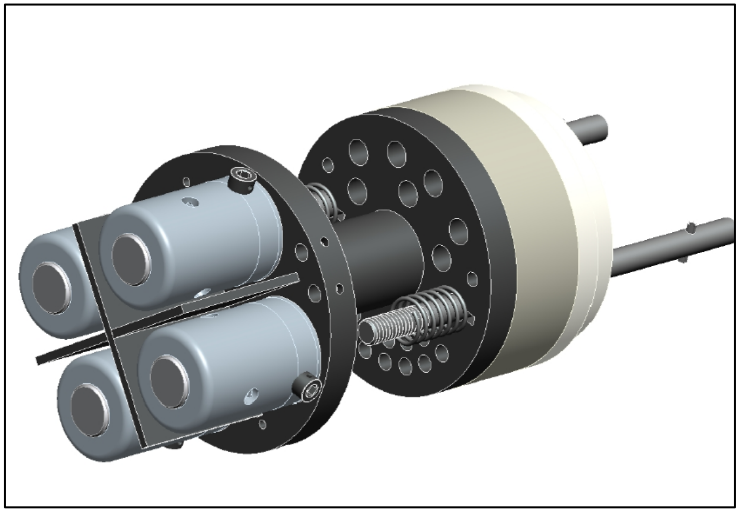
Ion Scattering Spectroscopy: IDs surface species

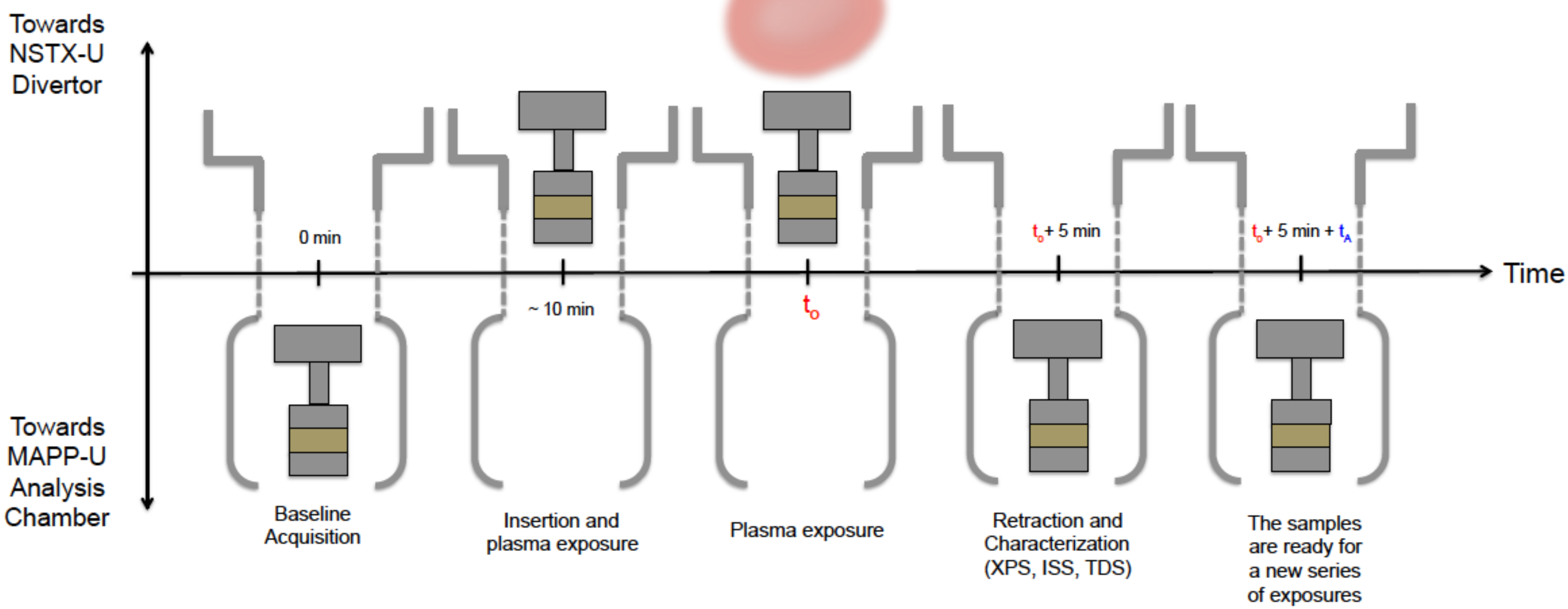
Direct Recoil Spectroscopy: Can detect H

Courtesy of F. Bedoya



Materials Analysis Particle Probe (MAPP)





Towards NSTX-U Divertor

Towards MAPP-U Analysis Chamber

Time

0 min

~ 10 min

t_o

t_o + 5 min

t_o + 5 min + t_A

Baseline Acquisition

Insertion and plasma exposure

Plasma exposure

Retraction and Characterization (XPS, ISS, TDS)

The samples are ready for a new series of exposures

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