Plasma – surface interactions

interplay between the plasma and solid wall components

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Ane Lasa | she/her | Dept. Nucl. Engineering

Thank you for making it to week 2!

This is just a brief intro to PSI

To those familiar with the field, this might fall short:

I want this lecture to be welcoming to a **diverse audience**: students interested in plasma physics, applied physics, electrical engineering, material science, etc.

In-depth discussion of specific research is not under the scope of this lecture. I will, however, provide **further resources** to dig deeper and where to read about the latest

Sorry if it feels a little superficial

Goal of this hour is to familiarize with PSI

Plasma-Surface Interactions are common to nearly all areas of plasma physics; I'll focus on their effect on confinement devices

Familiarize with the **scope and field of plasma-surface interactions** (PSI), and learn about the different plasma-facing materials

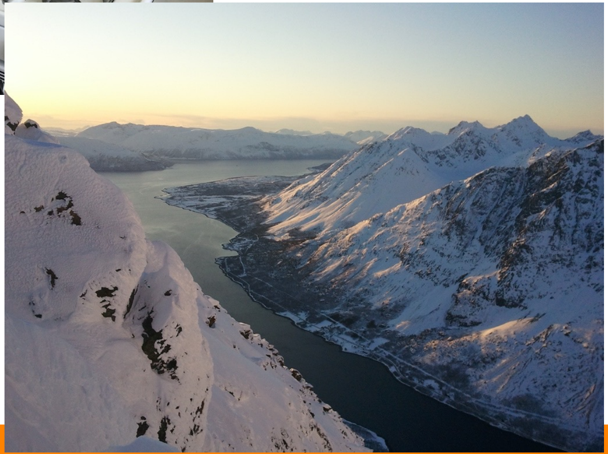
Present some of the most pressing challenges associated with **finding appropriate materials** for the first wall of future confinement devices

Credit where it's due

Much of the material shown here was prepared for the 2020 SULI summer course, inspired by the 2009 and 2019 ITER summer schools, which focused on Plasma-Surface Interactions and development of Plasma-Facing Components

- You may notice many examples use values and predictions for ITER
- Many of the figures are taken from the review articles that I highlight at the end, in further resources
- marked with a *(*)* the topics that are – or I expect to be – covered by other lectures

Being a scientist is very compatible with many other joys in life

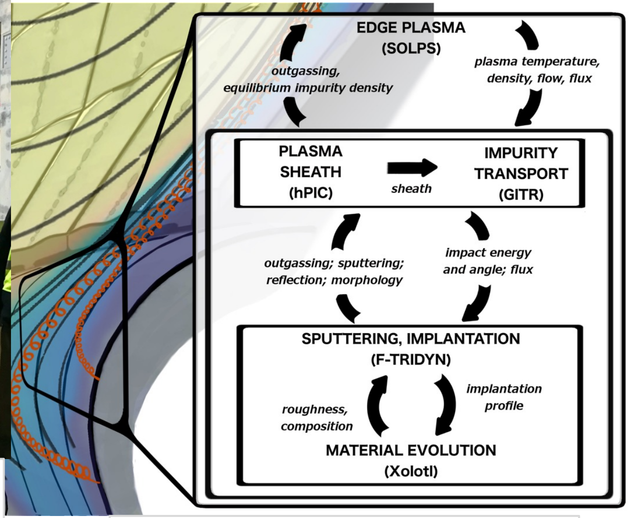


I am most interested in coupled PSI modeling

That is, in integrating plasma and material models for a more complete description of plasma-surface interactions

This draw from previous experience in modeling
- plasma-facing materials (PhD)
- boundary plasmas (post-doc)

Visiting ITER, Jan'19



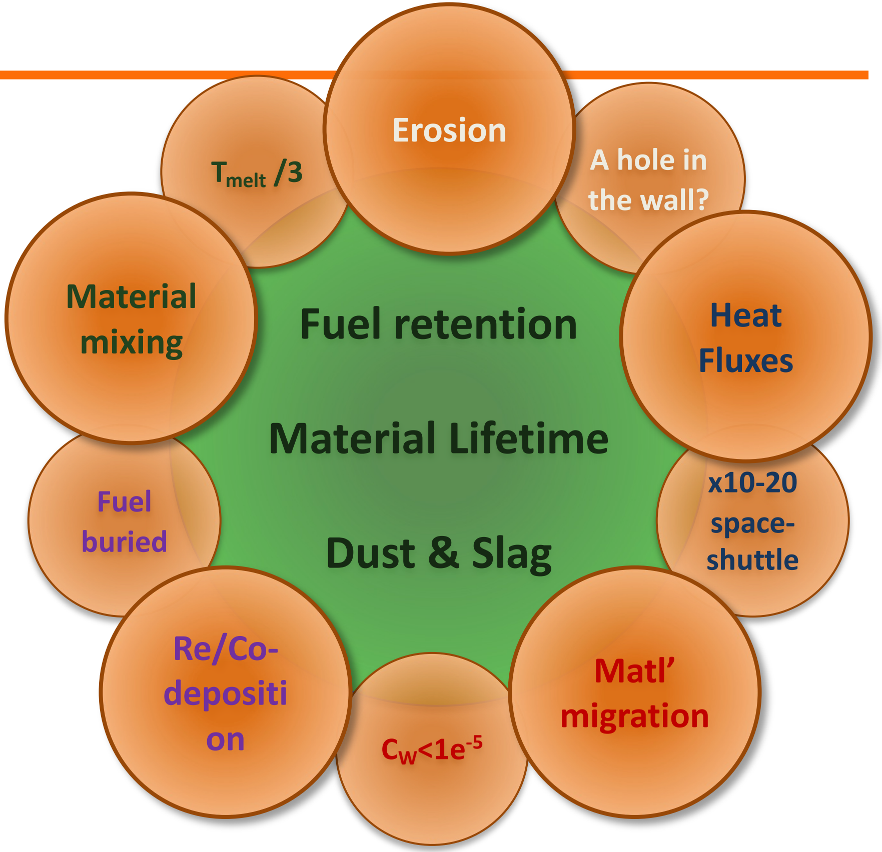
A. Lasa. PSI-SciDAC proposal

Outline

The why's and what's of plasma & solid-surface interactions

Our best solid contestants for facing the plasma

Our work tools: experimental and modeling approaches



Outline

The why's and what's of plasma-surface interactions

Our best solid contestants for facing the plasma

Our work tools: experimental and modeling approaches

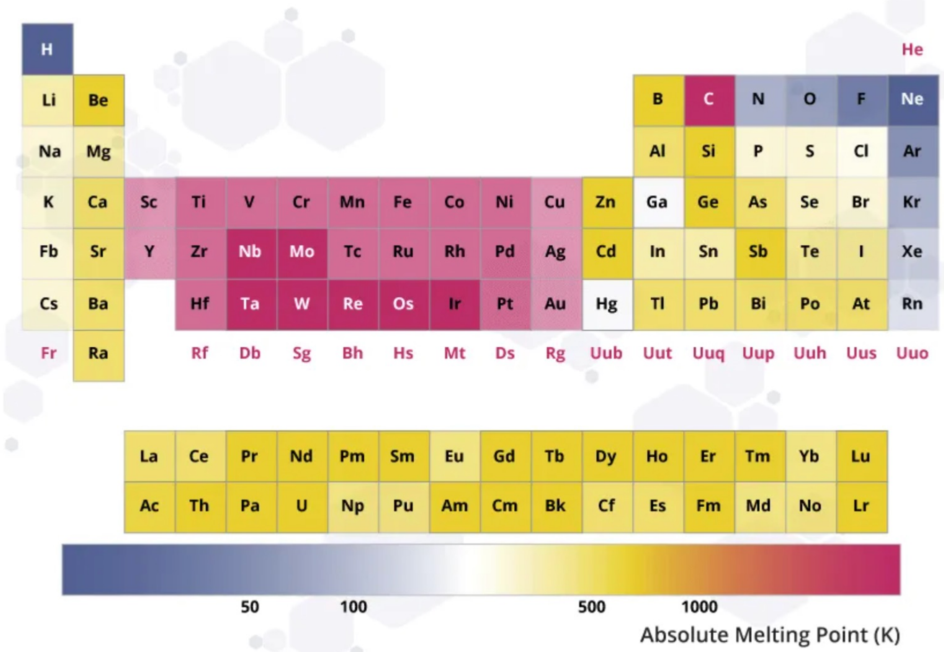


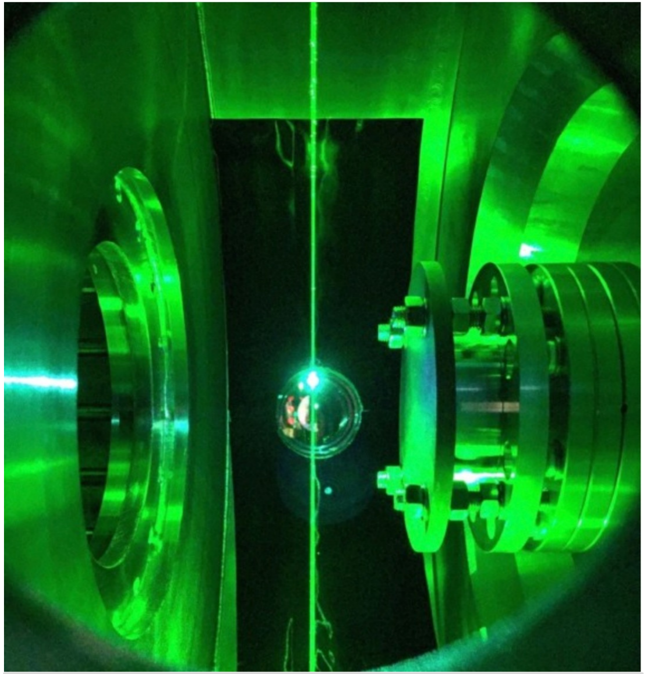
Image from : matmatch > blog > fusion-energy-materials

Outline

The why's and what's of plasma-surface interactions

Our best solid contestants for facing the plasma

Our work tools: experimental and modeling approaches

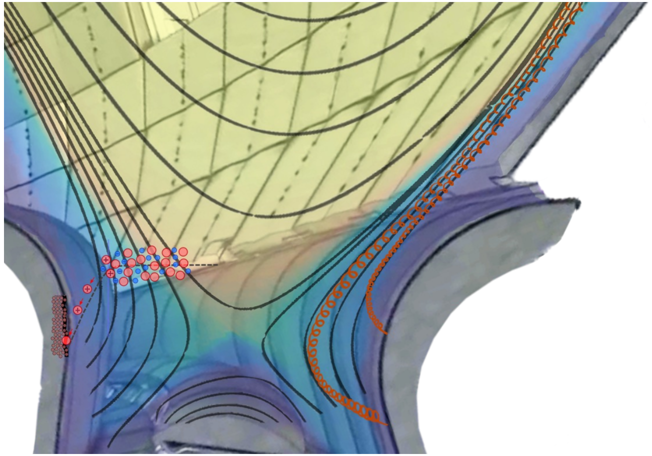


Alignment with lasers at Proto-MPEX
Photo credit: Ted Biewer/ORNL, DOE

Plasma-Surface Interactions

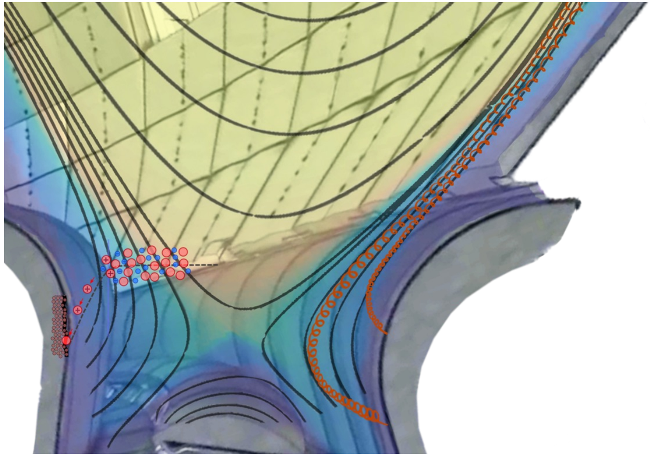
Why do plasmas and wall materials interact?

- Plasma ions don't perfectly & always follow magnetic field lines (cross-field and other anomalous transport)



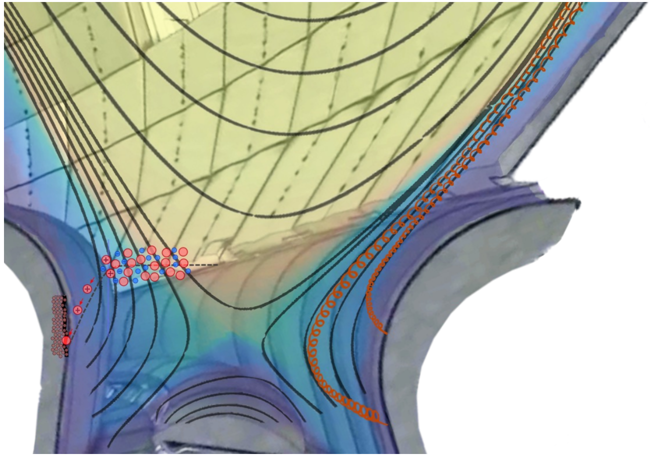
Why do plasmas and wall materials interact?

- Plasma ions don't perfectly & always follow magnetic field lines (cross-field and other anomalous transport)
- Even if we could perfectly confine the plasma, it would not be beneficial: the exhausted fuel (i.e, helium ash) and other impurities need to leave the confined volume to avoid contamination of the core



Why do plasmas and wall materials interact?

- Plasma ions don’t exactly & always follow magnetic field lines (cross-field and other anomalous transport)
- Even if we could perfectly confine the plasma, it would not be beneficial: the exhausted fuel (i.e, helium ash) and other impurities need to leave the confined volume to avoid contamination of the core

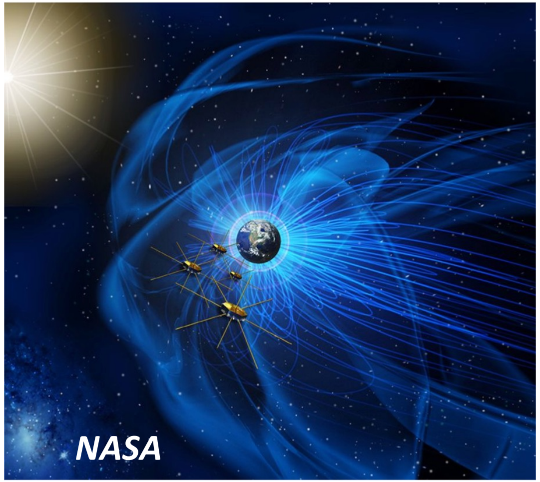


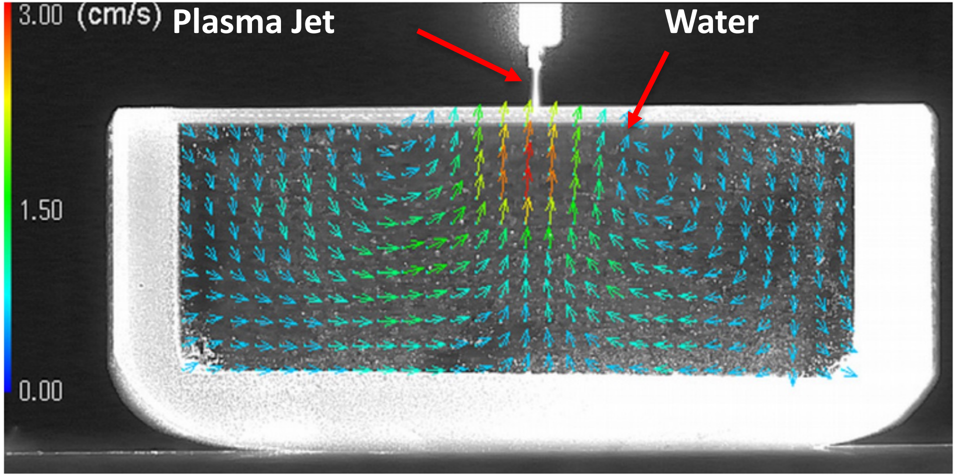
When leaving closed magnetic field for open ones, the plasma ions will interact with the surrounding walls

→ **that’s (e.g.) plasma surface interactions!**

Plasma-surface interactions are nearly everywhere

Plasma-surface interactions take place in many systems, sometimes purposely, sometimes unavoidably; plasma cleaning, spacecrafts, microchip fabrication…





Shimizu et al., New J. Phys. 13, 053025 (2011).
John E. Foster, Phys. Plasmas 24, 055501 (2017)

Plasma-surface interactions go by many names

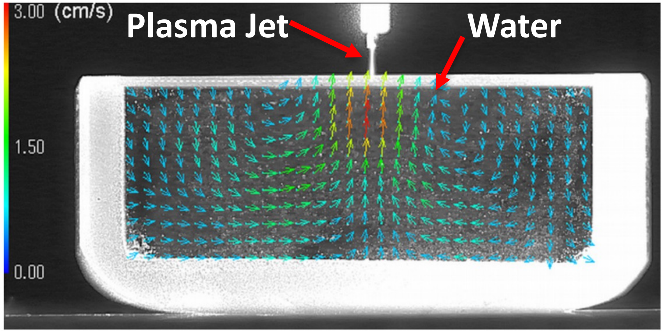
Plasma-surface interactions take place in many systems, sometimes purposely, sometimes unavoidably; plasma cleaning, spacecrafts, microchip fabrication…

We'll focus on PSI in confinement devices, which can be referred to as:

plasma-material interactions (PMI),

plasma-wall interactions (PWI)…

with small difference in their definitions; mainly in terms of how much of the material we account for



Shimizu et al., New J. Phys. 13, 053025 (2011).
John E. Foster, Phys. Plasmas 24, 055501 (2017)

Plasma-facing surfaces are like a skin for PFCs

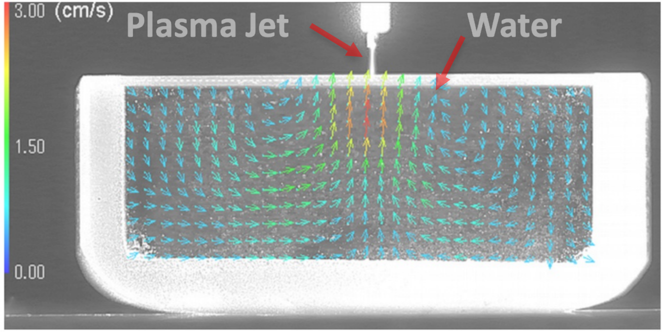
Plasma-surface interactions take place in many systems, sometimes purposely, sometimes unavoidably; plasma cleaning, spacecrafts, microchip fabrication…

We'll focus on PSI in confinement devices, which can be referred to as:

plasma-material interactions (PMI),

plasma-wall interactions (PWI)…

With small difference in their definitions; mainly in how much of the material we account for



Plasma facing surfaces are the **first layer of protection** (i.e., 'skin') for all components that lay behind them: structural materials*, tritium breeding blankets*, magnets* …

→ these are the **plasma-facing materials** (PFM) and components (PFCs)

Why do we care about PSI

The **material** erodes, its properties degrade, which impacts:

- Lifetime; i.e., how long we can run & how often we need to replace
  → **economic viability & sustainability**
- Due to presence of tritium & activated material
  → **Safety, economic viability & reliability**

Material impurities, especially if transported to the plasma core, can **degrade the burning plasma**; due to dilution and energy losses through radiation

- Fuel trapped in walls is not available for burning; & tritium is a limited resource
  → **fusion reactions / energy production**

Why do we care about PSI

The **material** erodes, its properties degrade, which impacts:

- Lifetime; i.e., how long we can run & how often we need to replace

  → **economic viability & sustainability**
- Due to presence of tritium & activated material

  → **Safety & reliability**

Material impurities, especially if transported to the plasma core, can **degrade the burning plasma**; due to dilution and energy losses through radiation

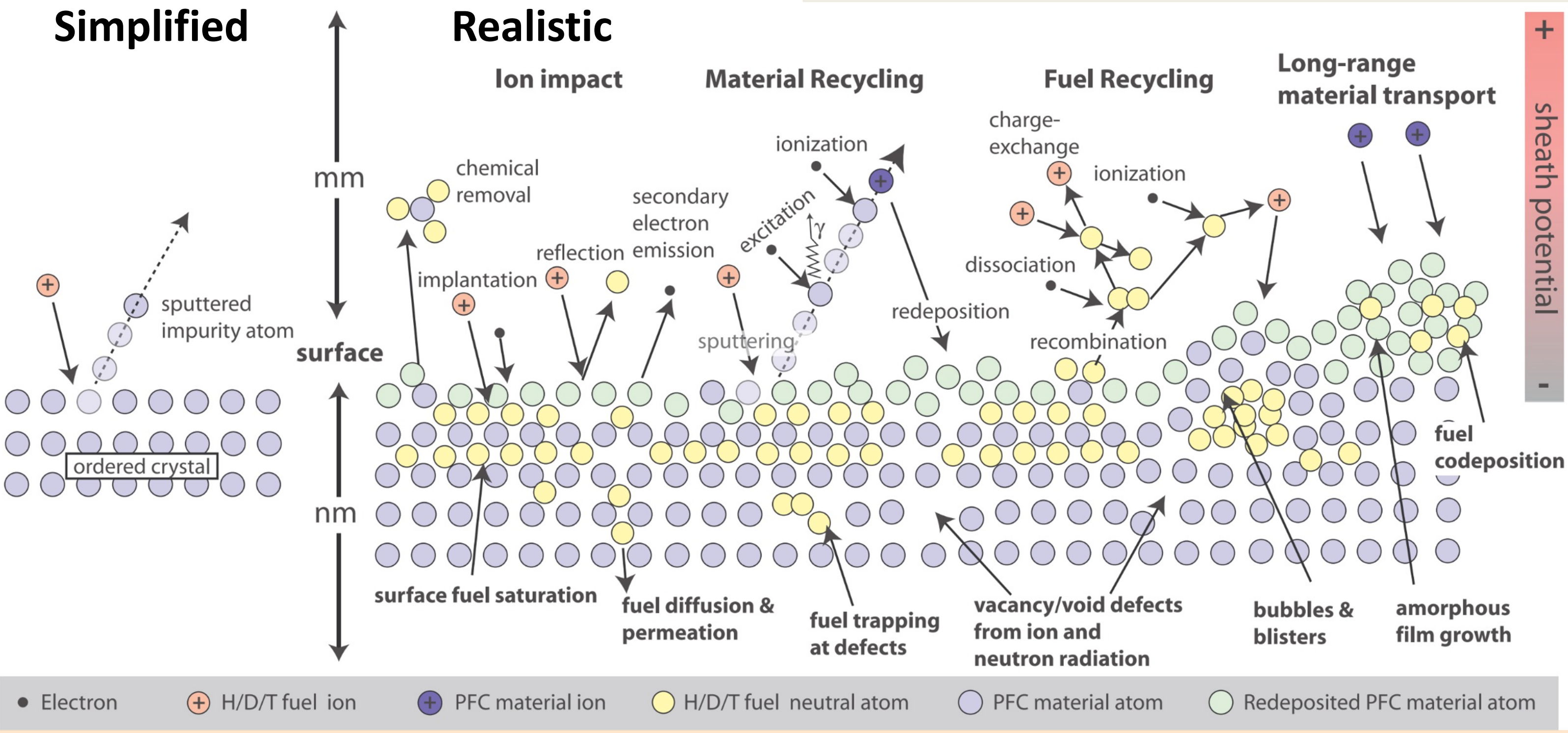
- Fuel trapped in walls is not available for burning; & tritium is a limited resource

  → **fusion reactions / energy production**

The study of plasma-surface interactions is essential to choose, design & engineer plasma-facing materials wisely, in order to maximize advantages and minimize drawbacks

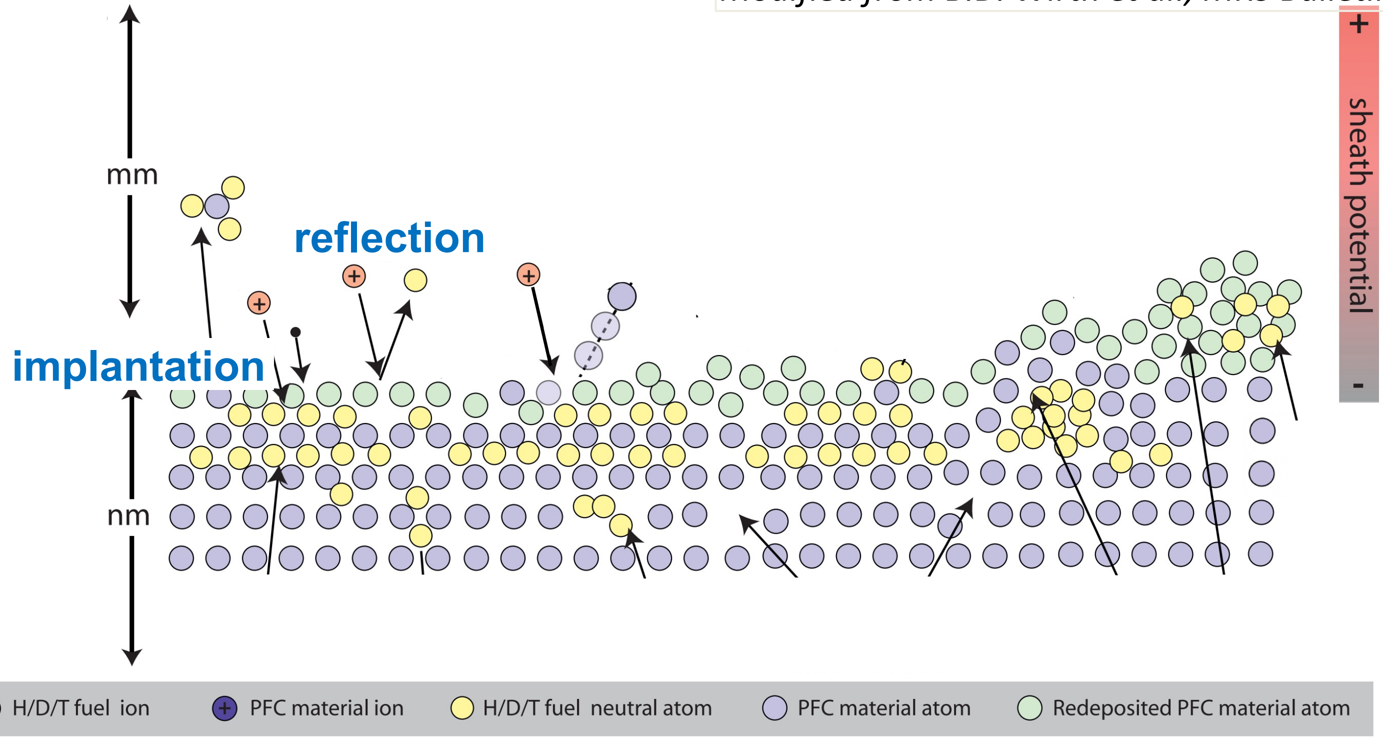
A lot can happen when the plasma touches a surface

Modified from B.D. Wirth et al., MRS Bulletin 36 (2011)



When an ion impacts…

Modified from B.D. Wirth et al., MRS Bulletin 36 (2011)



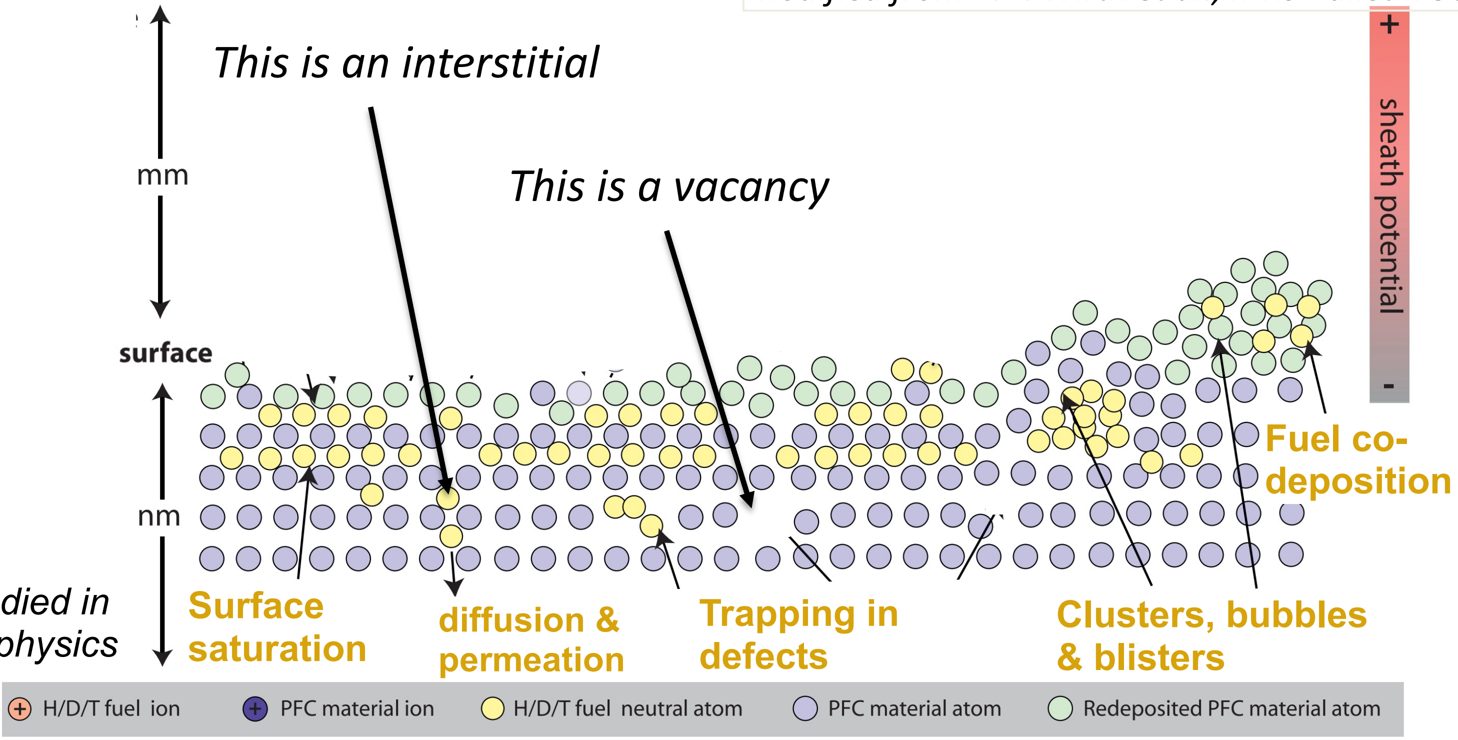
Plasma ions may **stay** in the material

Modified from B.D. Wirth et al., MRS Bulletin 36 (2011)

This is an interstitial

This is a vacancy

Mainly studied in materials physics



Tritium is expensive and radioactive

Fuel (tritium, T) retention is important mainly for:

- **Safety**: T is radioactive → limits on max allowed on-site
- **Economics**: Costs \$30,000 /g of **Tritium** (\$15 M/lb)

→ **Ensure T is burning and not on/in the walls**

T is retained by co-deposition or by implantation

Fuel (tritium, T) retention is important mainly for Safety & Economics
→ Ensure T is burning and not on/in the walls

Extensive efforts to quantify and predict the retention expected in different plasma-facing materials for ITER

For materials that form hydride mol's (C, Be) → T stays in the near-surface, but more strongly bound (can get buried)

Ohers (W) retention driven by trapping in defects → T tends to diffuse; easier to recycle that in near-surface

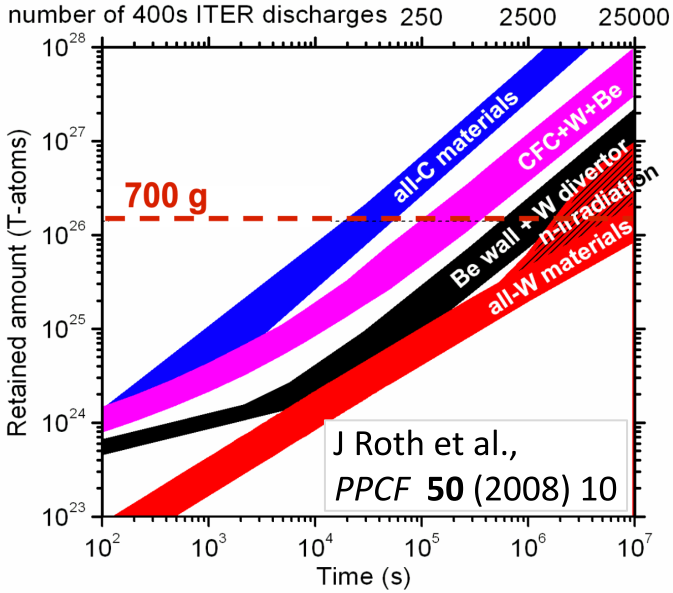
T is retained by co-deposition or by implantation

Fuel (tritium, T) retention is important mainly for Safety & Economics
→ Ensure T is burning and not on/in the walls

Extensive efforts to quantify and predict the retention expected in different plasma-facing materials for ITER

For materials that form hydride mol's (C, Be)

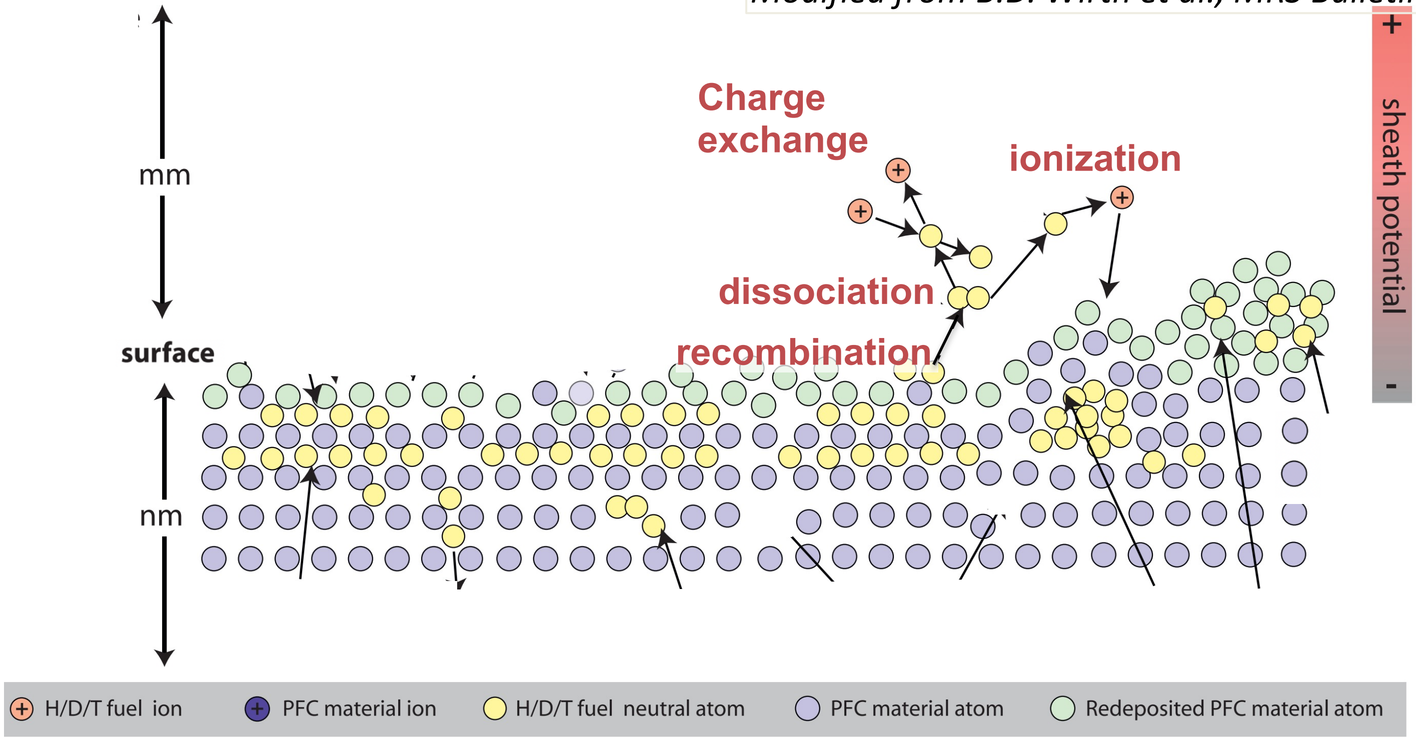
Ohers (W) retention driven by trapping in defects



THE UNIVERSITY OF TENNESSEE KNOXVILLE

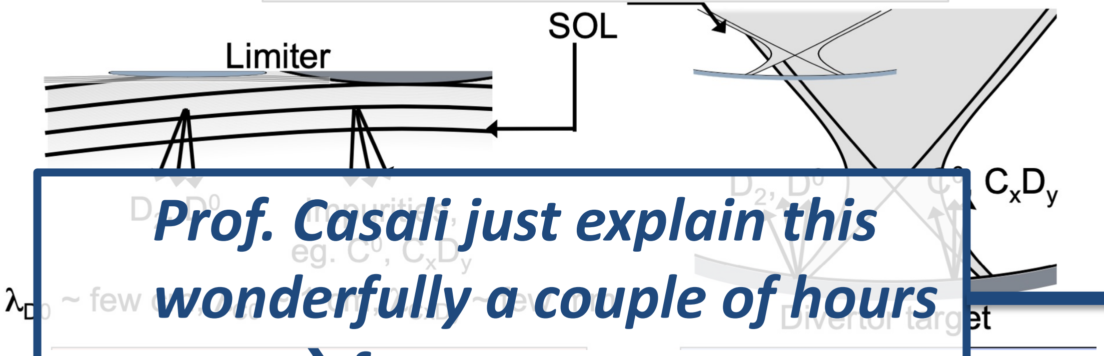
Or plasma ions may recycle

Modified from B.D. Wirth et al., MRS Bulletin 36 (2011)



Gas recycling is important for the local plasma parameters

W. Fundamenski, ITER summer school 2009



Prof. Casali just explain this wonderfully a couple of hours ago → focus on summary

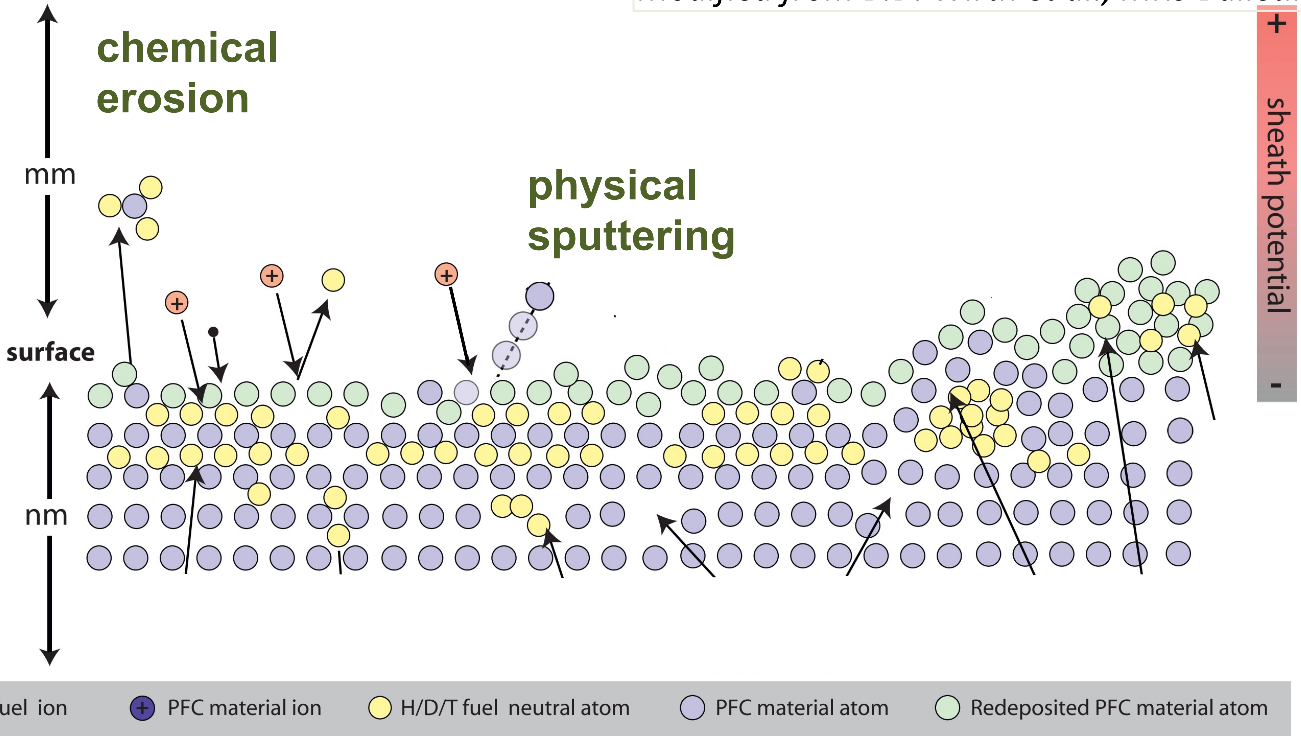
- Close contact with plasma
- Strong influx of fuel & impurity neutrals into the edge
- Little cooling in SOL → hot plasma

- PFCs removed from edge plasma
- Colder denser plasma due to higher recycling

- Recycling is important to determine the local plasma characteristics (e.g., detachment, impurity migration…)
- It can strongly vary even for the same material and device (e.g., during ELMs)

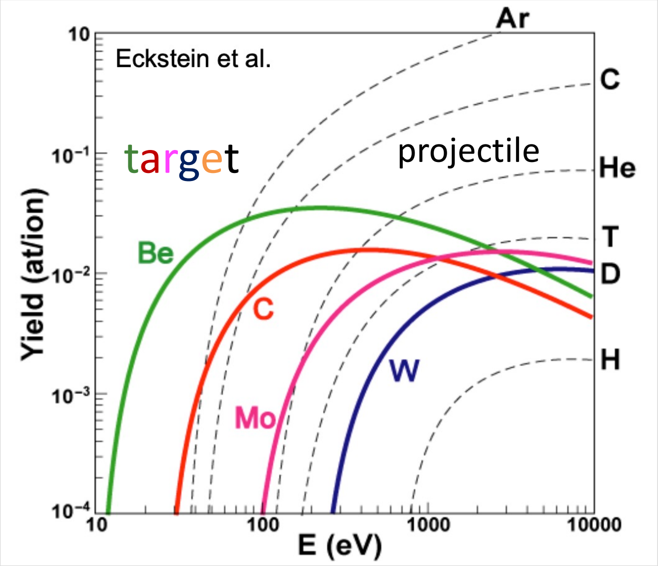
Substrate material may erode

Modified from B.D. Wirth et al., MRS Bulletin 36 (2011)



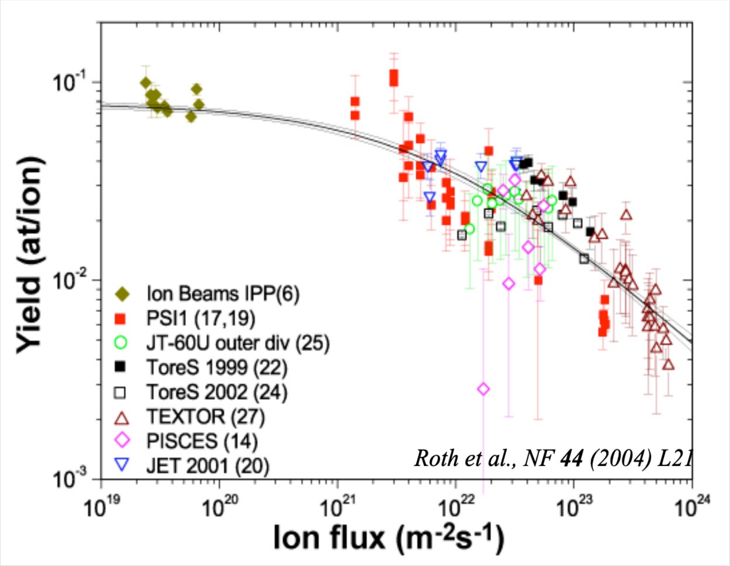
Erosion depends on target / projectile material and plasma characteristics

Physical sputtering:



Increases with projectile E & mass; decreases with atomic mass of target

Chemical erosion:

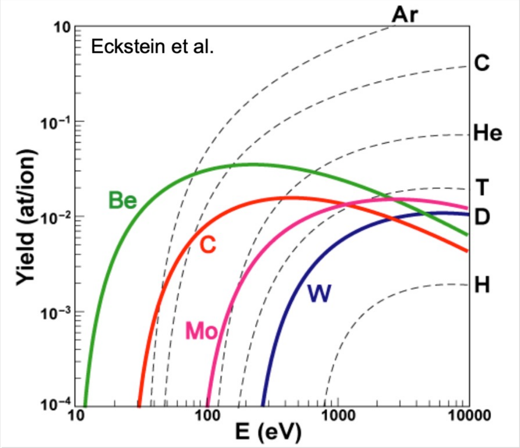


Mainly affects C. Decreases with D flux & strongly depends on target temperature

THE UNIVERSITY OF TENNESSEE KNOXVILLE

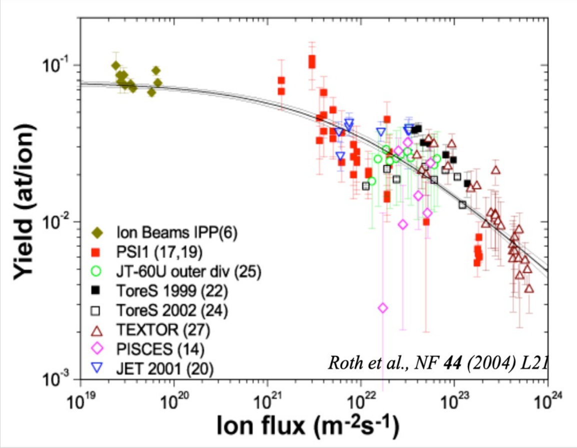
Erosion depends on target / projectile material and plasma characteristics

Physical sputtering:



Increases with projectile E & mass; decreases with atomic mass of target

Chemical erosion:



Mainly affects C. Decreases with D flux & strongly depends on target temperature

"Hybrid" sputtering (SCS) also affects some plasma-facing materials

K. Nordlund et al, *NIMB* **269** (2011) 11

In addition to thinning walls, erosion can change the **composition & morphology** (e.g., preferential sputtering)

Transients & other sources add to steady-state erosion

Transients:

Probably the biggest threat for large-scale erosion in future devices:

plasma energy (W_p) x 10-50

deposition area x 2

ELMs: expel ~6% of W_{pl} at 1-2 Hz
→ peak 5-10 MJ/m^2 , 250-500 us
& increased particle fluxes

Disruptions: expel all of W_{pl}
→ peak 5-15 MJ/m^2, 1-3 ms
(thermal quench)

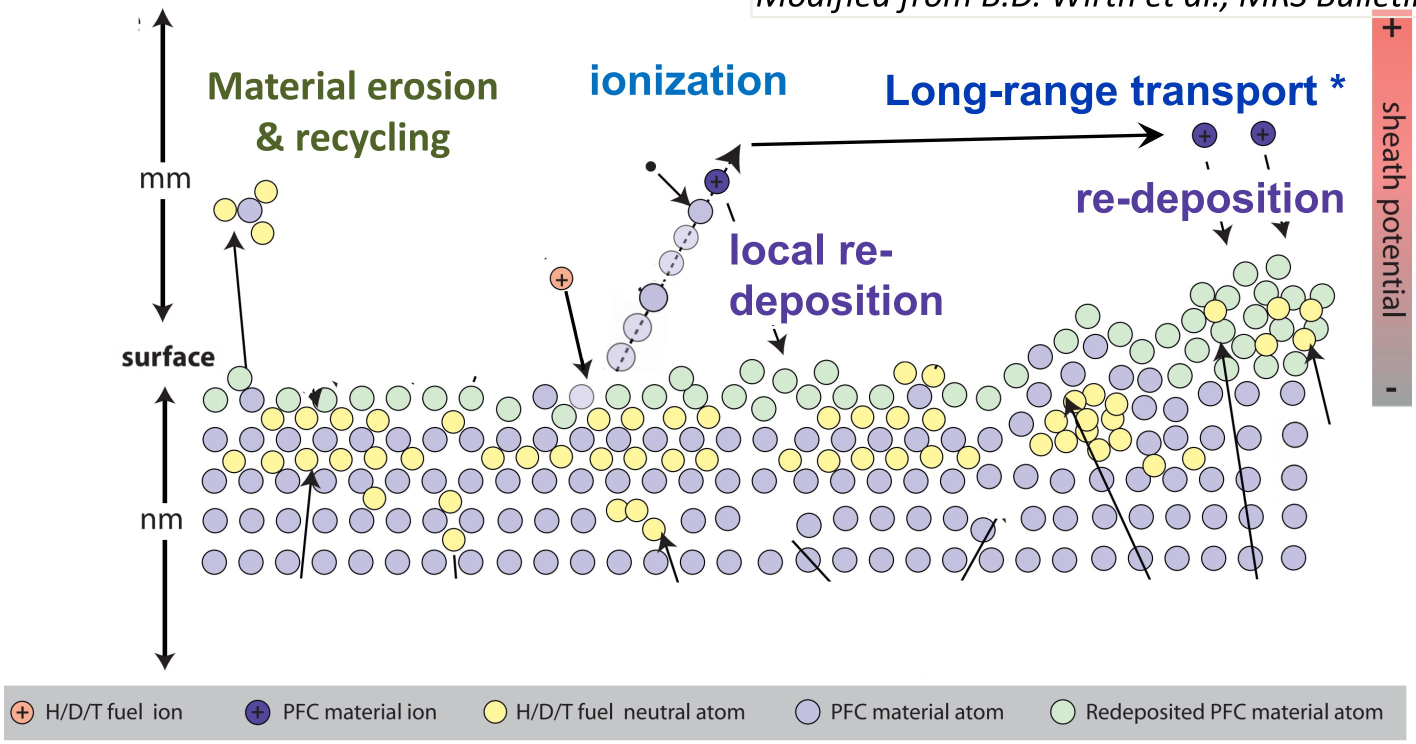
Additional sources:

- **CX fluxes**: highly energetic neutrals (not confined)
- **Plasma heating systems** (e.g., RF) can increase the sheath voltage drop

C.C. Klepper et al, *Physica Scripta* **T167** (2016) 014035

Material can be eroded, transported & deposited

Modified from B.D. Wirth et al., MRS Bulletin 36 (2011)



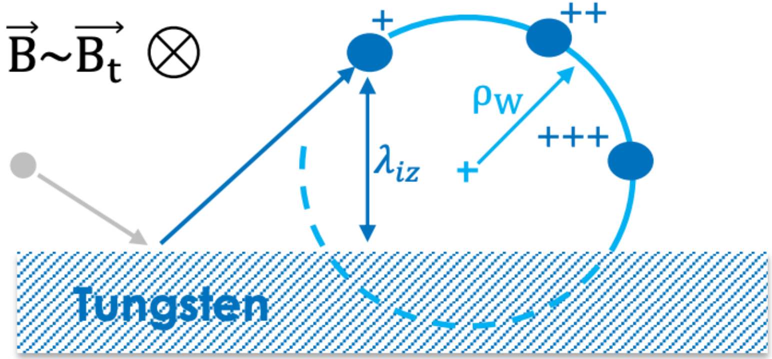
Impurity migration starts with ionization

Material eroded from the surface can get ionized → all single-ion motion rules apply

The ion may redeposit locally, be transported far from the source or enter the confined plasma.

Migration is a balance between ionization (e-structure) & gyro-radius (charge / mass)

high-Z ↔ local re-deposition ; low-Z ↔ long-range transport



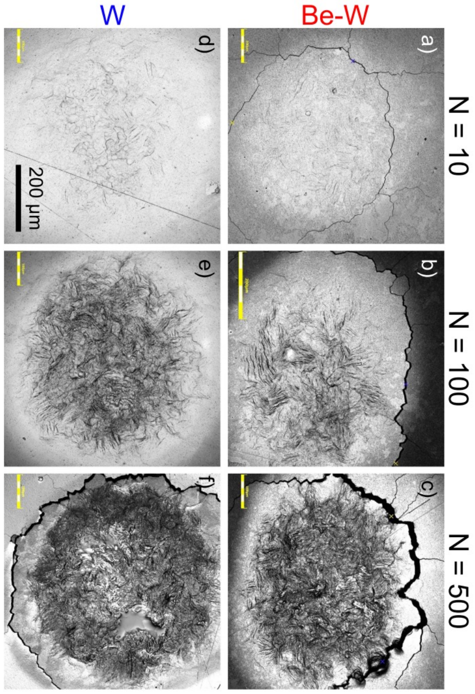
J. Guterl et al., APS-DPP 2019

Migration turns local challenges into global ones

This material migration turns local phenomena into global ones: e.g., T co-deposition

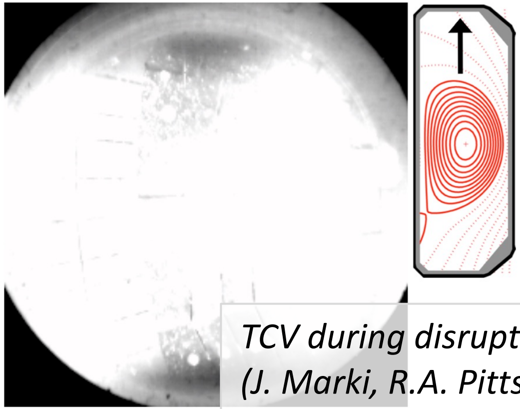
Also causes new challenges:

- <u>material mixing</u>: can result in less desirable properties
  → Melting temp T_{melt} (W-Be) ~ T_{melt} (W)/3
- Impurities <u>dilute</u> the burning plasma + high-Z <u>radiate</u>
  → limit concentrations ($\rho_W < 10^{-5}$ for ITER)
- <u>Slag</u>: accumulation of material in specific areas
- <u>formation of 'dust'</u> (especially in machines w/ carbon)



J H Yu *et al*
Phys. Scr. **T170** (2017) 014009

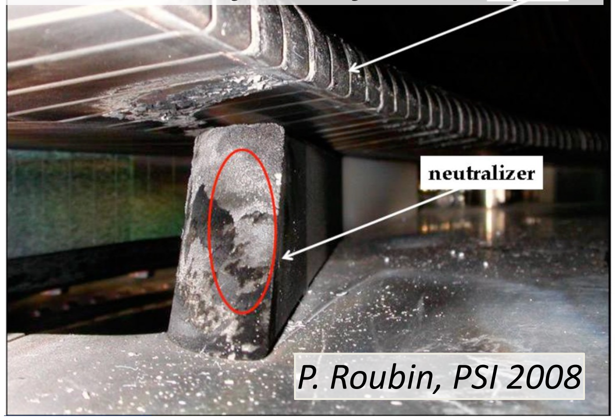
E.g., the less-heard-of formation of dust



TCV during disruption (J. Marki, R.A. Pitts)

DIII-D DIMES after a vent (D.L. Rudakov & W.P. West)

Dust on the floor of Tore Supra



P. Roubin, PSI 2008

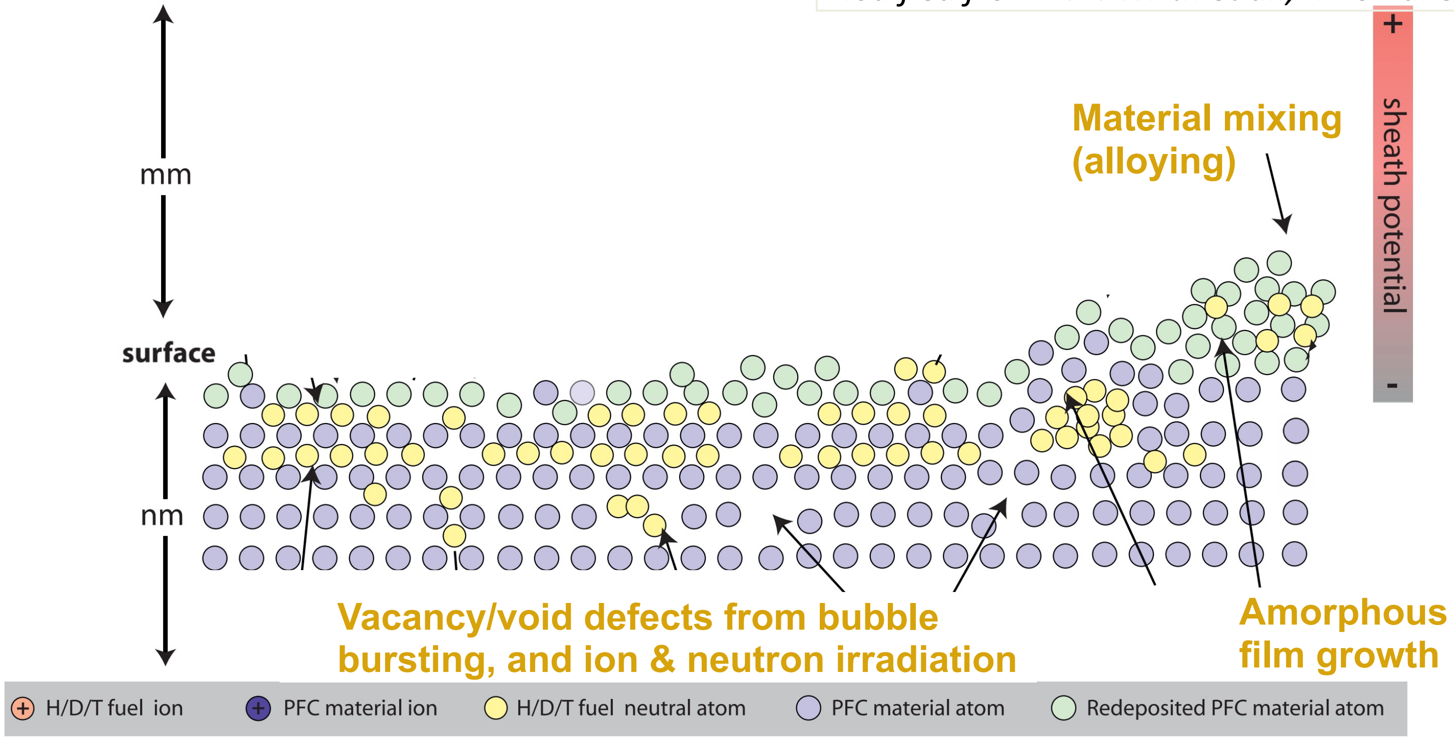
formation of 'dust'

Usually not an operational issue; often noticed when plasma touches surfaces after a while: 1st plasmas or due to disruption

However, it can be hazardous if there's a loss of vacuum (explosions, radioactive) → limits

These processes can alter substrate properties

Modified from B.D. Wirth et al., MRS Bulletin 36 (2011)



These processes can alter substrate properties

Mixing of the target and re-deposited material / impurities:

- Alloying: W+Be → lower melting temperature
- Changes in morphology (He fuzz) → Change in thermo-mech. properties
- Form carbides
- Introduce impurities / defects

] → higher T trapping

Damage by irradiation of plasma ions and neutrons*: dis/re-organization of the target material's structure → Create defects

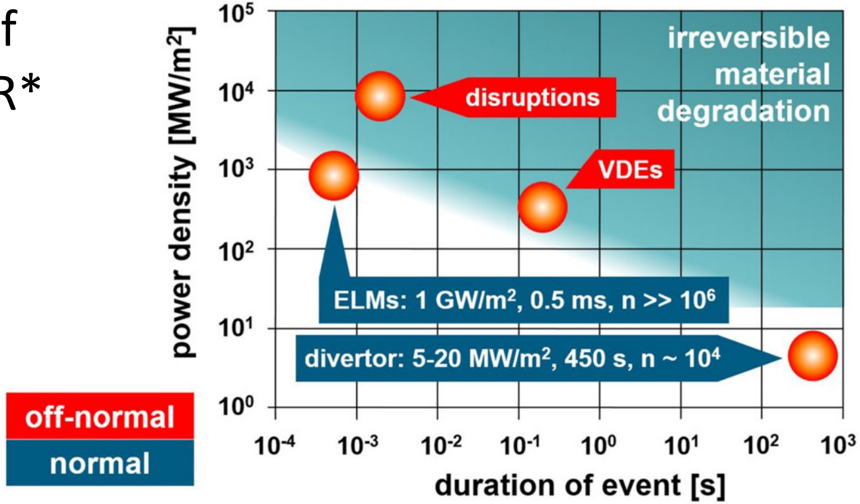
- Increate T trapping
- Micro-cracking

*Nieto-Perez, Thursday

In addition to ions, the plasma deposits heat

Current plasma facing surfaces are routinely exposed to high heat fluxes; 1-2 orders of magnitude higher in future reactors (ITER* & beyond).

- Steady state ~ 10 MW/m^2
- Transient events –need to be mitigated

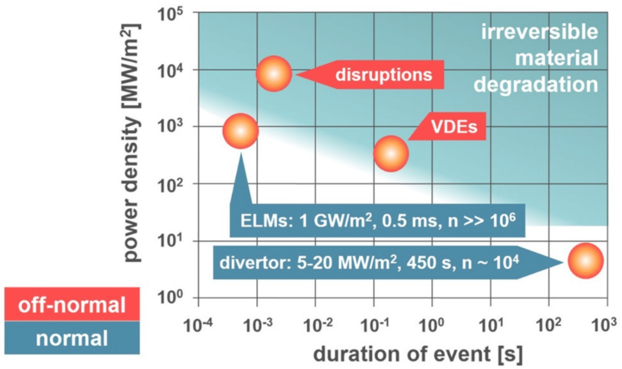


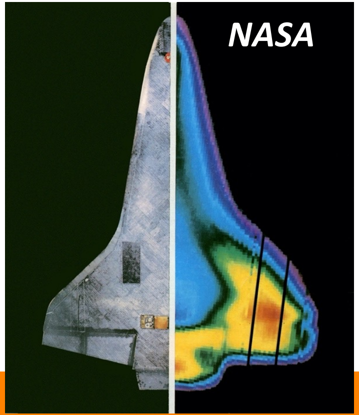
J. Linke et al., *Matter Radiat. Extremes* **4**, (2019) 056201

In addition to ions, the plasma deposits heat

Current plasma facing surfaces are routinely exposed to high heat fluxes; these values will be extreme in future reactors (ITER* and beyond).

- Steady state ~ 10 MW/m²
- Transient events, which need to be mitigated





Let's put these numbers into context: space craft reentry

Space shuttle: 0.5 MW/m² (a little higher for Apollo)

→ plasma facing materials will be exposed to x10-20 that in steady-state; plus transients!

→ good that these PFC tiles will have coolant running in the back (i.e., 'actively cooled PFCs')

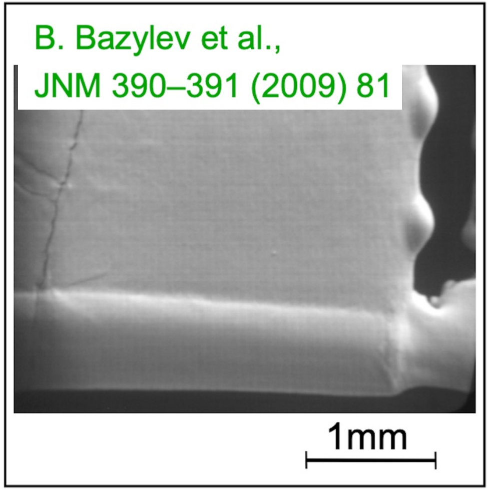
THE UNIVERSITY OF TENNESSEE KNOXVILLE

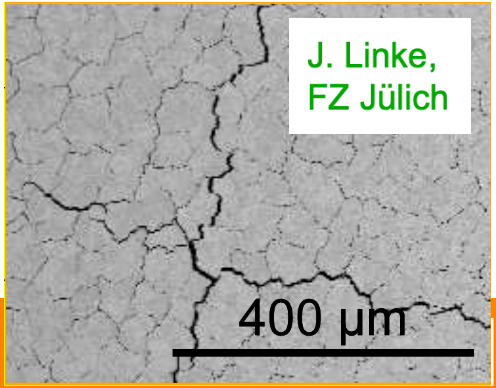
Heat fluxes change materials' surface temperature

Surface atoms may evaporate (carbides) or the surface might melt (metals)

Material properties can change at lower than melting temperatures (e.g., recrystallization…)

Materials expand with heat; if heat is deposited in cycles → stress the material, fatigue → eventual cracking



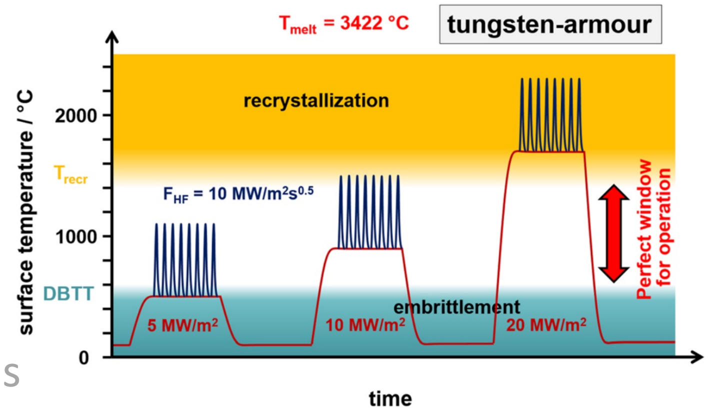


Heat fluxes change materials’ surface temperature

Surface atoms may evaporate (carbides) or the surface might melt (metals)

Material properties can change at lower than melting temperatures (e.g., recrystallization…)

Materials expand with heat; if heat is deposited in cycles → stress the material, fatigue → eventual cracking



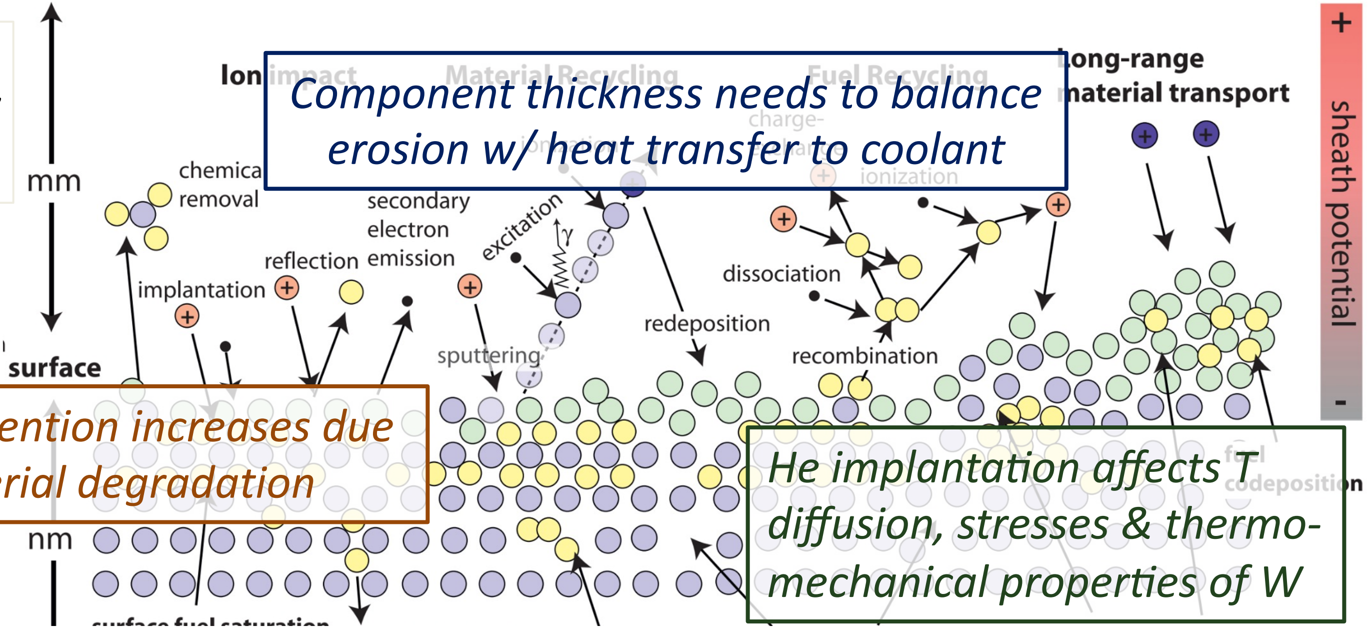
Rieth et al., *J. Nucl. Mater*. **519** (2019)

The goal is to control the temperature, as some increase are beneficial

- Better properties at mid-temps (Ductile to Brittle Transition)
- Enhanced diffusion of T
- Suppressed chemical erosion

In reality, there are all sorts of the synergies

Modified from B.D. Wirth et al., MRS Bulletin 36 (2011)



Component thickness needs to balance erosion w/ heat transfer to coolant

Fuel retention increases due to material degradation

He implantation affects T diffusion, stresses & thermo-mechanical properties of W

These multi-effect studies is the phase we're entering for PSI studies with solid walls

H/D/T fuel ion | PFC material ion | H/D/T fuel neutral atom | PFC material atom | Redeposited PFC material atom

Plasma-Facing Materials

Purpose of Plasma-facing components

Plasma facing surfaces are the **first layer of contact** between all the structures & components that lay behind them, and the plasma

→ these are the **plasma-facing materials** (PFM) and components (PFCs)

Plasma-facing materials are also the first contact between the plasma and blankets* (components where neutrons are slowed down to produce energy and tritium); i.e., closely related to **harnessing the power and the fuel** generated by fusion

Plasma heating systems* (e.g., RF antennas), diagnostics*, etc. are also often plasma-facing components; designs of these structures and of the device's geometry must be done to **protect** these components accordingly

How do you choose plasma-facing materials?

Down select based on:
- melting point
- heat conductivity
- Erosion rates
- chemical affinity to H
- ….

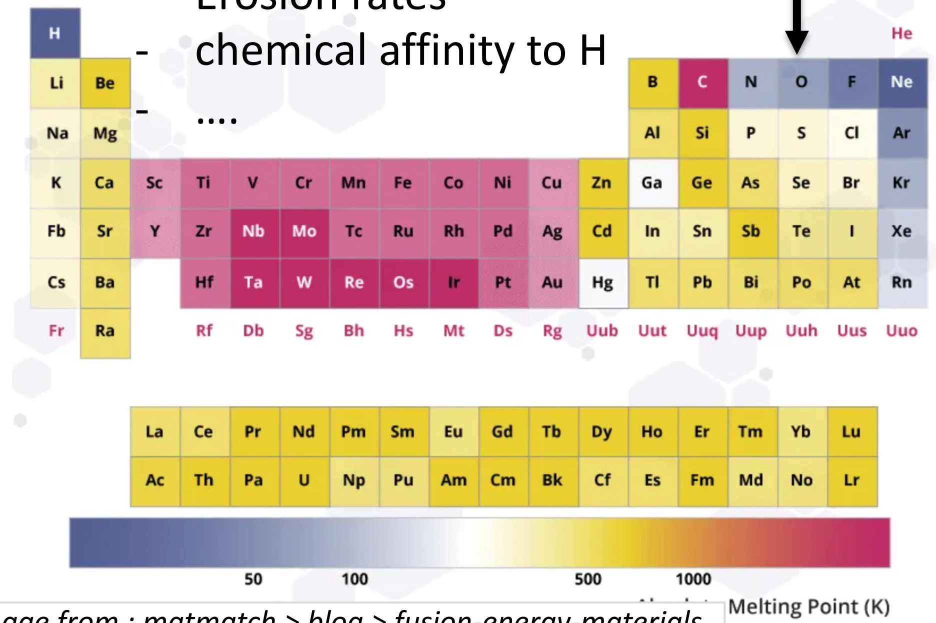


Image from : matmatch > blog > fusion-energy-materials

The usual trade-off is (e.g., for erosion) low vs high Z :

easier to erode

but less problematic (beneficial)

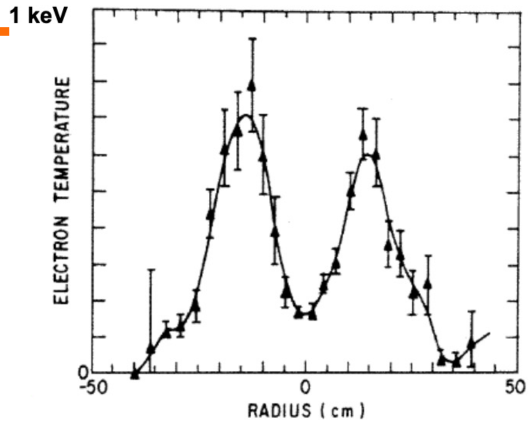
VS

harder to erode

but higher consequence

A brief look into history

temperature profile in **PLT** during W accumulation



The priority of early devices was **vacuum compatibility**
→ gold-plated SS liners (*ORMAK*)

Higher edge temperatures, core confinement & **performance** with low low-Z content, but higher sputtering source & impurity accumulation (e.g., *PLT* w/ W limiters)

Vacuum-grade graphite available; benign under thermal overload → adoption of C in almost all devices (*JET, DIII-D, ASDEX*…)

Operation with high-current, high density and/or divertor has allowed using **refractory (high-Z) metals**, with low plasma temperature in contact with the PFCs (*ASDEX-U, JET ILW*…)

A brief look into history

The priority of early devices was vacuum compatibility
→ gold-plated SS liners

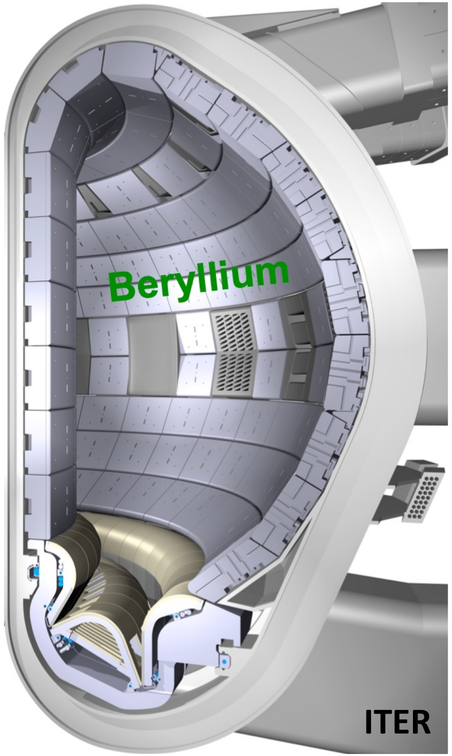
Higher edge tempera … rformance
with low low-Z conte … ce & impurity
accumulation (e.g., P

Vacuum-grade graph … ermal overlo
almost all devices

Operation with high-current, high density and/or divertor has a
(high-Z) metals, with low plasma temperature in contact with th

→ All metal ITER:
a tungsten divertor,
beryllium first wall

Unlikely Be will continue
to be used beyond ITER
(hard to handle)



Requirements change with the area

Divertor:

- high heat & particle fluxes
- Smaller area (than the 1st wall)
- Further from the confined plasma (lower impurity penetration)

Allows for use of high-Z materials

First wall:

- Large area
- Close to the confined plasma
- Be is the choice of ITER

Low-Z seem to suit best

- You may often see research with Al → just a non-toxic proxy for Beryllium
- Other materials being explored in the US: SiC at General Atomics (div & 1st wall)
- W doping / alloys are being developed to improve its fatigue tolerance, etc.

Each PFM candidate has pro's & con's

These are the pro's; absence of a property often hints at a con.

Carbon (Fiber Composites, CFC)
- Absence of melting
- Excellent thermal Shock resistance
- High thermal conductivity
- Low atomic number

Beryllium
- High thermal conductivity
- Oxygen gatherer
- Little T chemical affinity
- Low atomic number

SiC (ceramics)
- Low atomic number
- Low activation
- n-damage resilience
- Medium T chemical affinity
- T permeation barrier

Tungsten (& alloys)
- Highest melting point
- High thermal conductivity
- Low sputtering yields
- No T chemical affinity / inventory
- Low activation

If my surface could melt, why not roll with it?

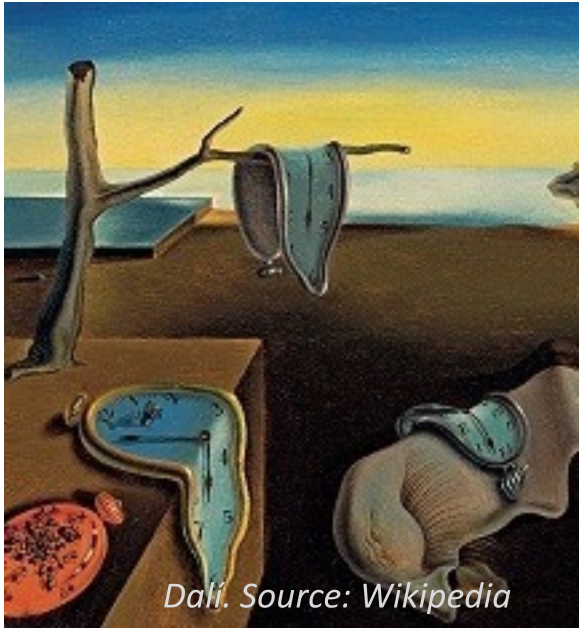
LMs solution-candidates also exist for PFCs of future fusion reactors.

Often LMs are presented as “the solution” to all solid PFCs issues – often that’s true, but they present their own set of challenges

- Complex systems, fires, finding a corrosion & n-resistant substrate, fuel retention & separation, liquid flow stability, etc.

The technologies are less advanced (lower TRL), and so yet to be seen how big these challenges might turn into.

Lecture on LM at SULI 2020, by J.P. Allain



Dalí. Source: Wikipedia

How do we study PSI and PFM?

PSI can be studied directly in confinement devices

Confinement devices:

Removable tiles

- (re)movable "PFC", e.g. DIMES & WITS in DIII-D;
- post-mortem, e.g., the metal-ring campaign

post-mortem global balance: fuel inventory, dust production, migration of wall material…

Dedicated PSI facilities exist as well

Non-confinement plasma exposures (US)

PISCES (UCSD)

- A: divertor-like conditions
- ~~B: Beryllium; 1st wall-like & high fluence~~
- upgrade plans for source & ion beam

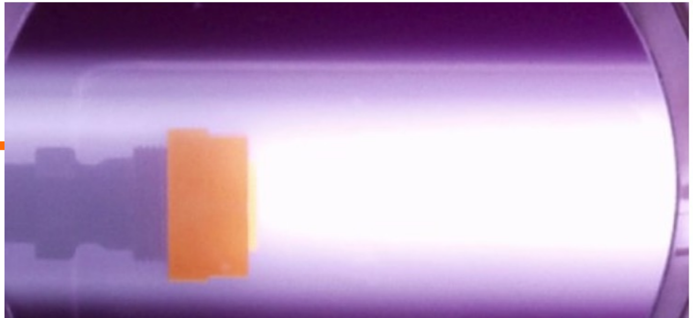
TPE (INL)

- Tritium exposures
- Permeation studies

MPEX (ORNL): ‘next-gen’

- Divertor like conditions
- Handle irradiated samples
- Hot ions, tilted target …

Study coupled effects



R. P. Doerner and the PISCES Team, UCSD

PFC development also requires **non-plasma testing**

- High-heat exposures
- Thermo-mechanical properties
- Coolants
- Stresses analysis
- n-irradiation*
- Joining
- …

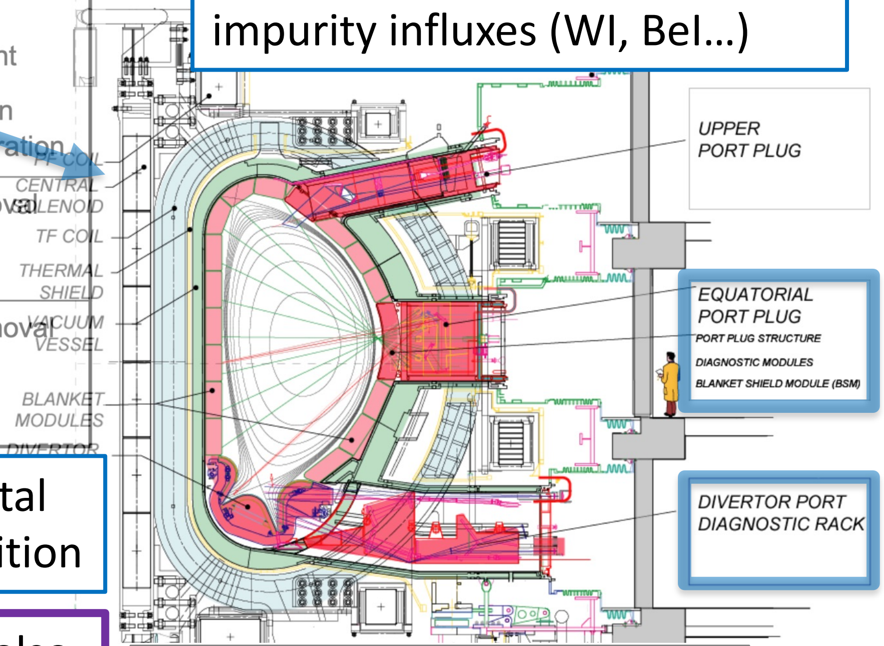
How do we diagnose* PSI & PFCs?

	Source	Measurement	Management
Erosion	• Plasma heat and particle source • Wall component lifetime	• LASER ranging techniques • Impurity flux measurement	• Scheduled replacement • Observation during operation
Dust Accumulation	• Inventory limits • Hot and cold dust	• Local microbalance • Other methods	• Dust Removal
Tritium Retention	• Inventory limits	• Global measurement • Local measurement	• Tritium removal

How do we diagnose* PSI & PFCs?

	Source	Measurement	Management
Erosion	• Plasma heat and particle source • Wall component lifetime	• LASER ranging techniques • Impurity flux measurement	• Scheduled replacement • Observation during operation
Dust Accumulation	• Inventory limits • Hot and cold dust	• Local microbalance • Other methods	• Dust Removal
Tritium Retention	• Inventory limits	• Global measurement • Local measurement	• Tritium removal

In-situ: Spectrometers measure impurity influxes (WI, BeI…)



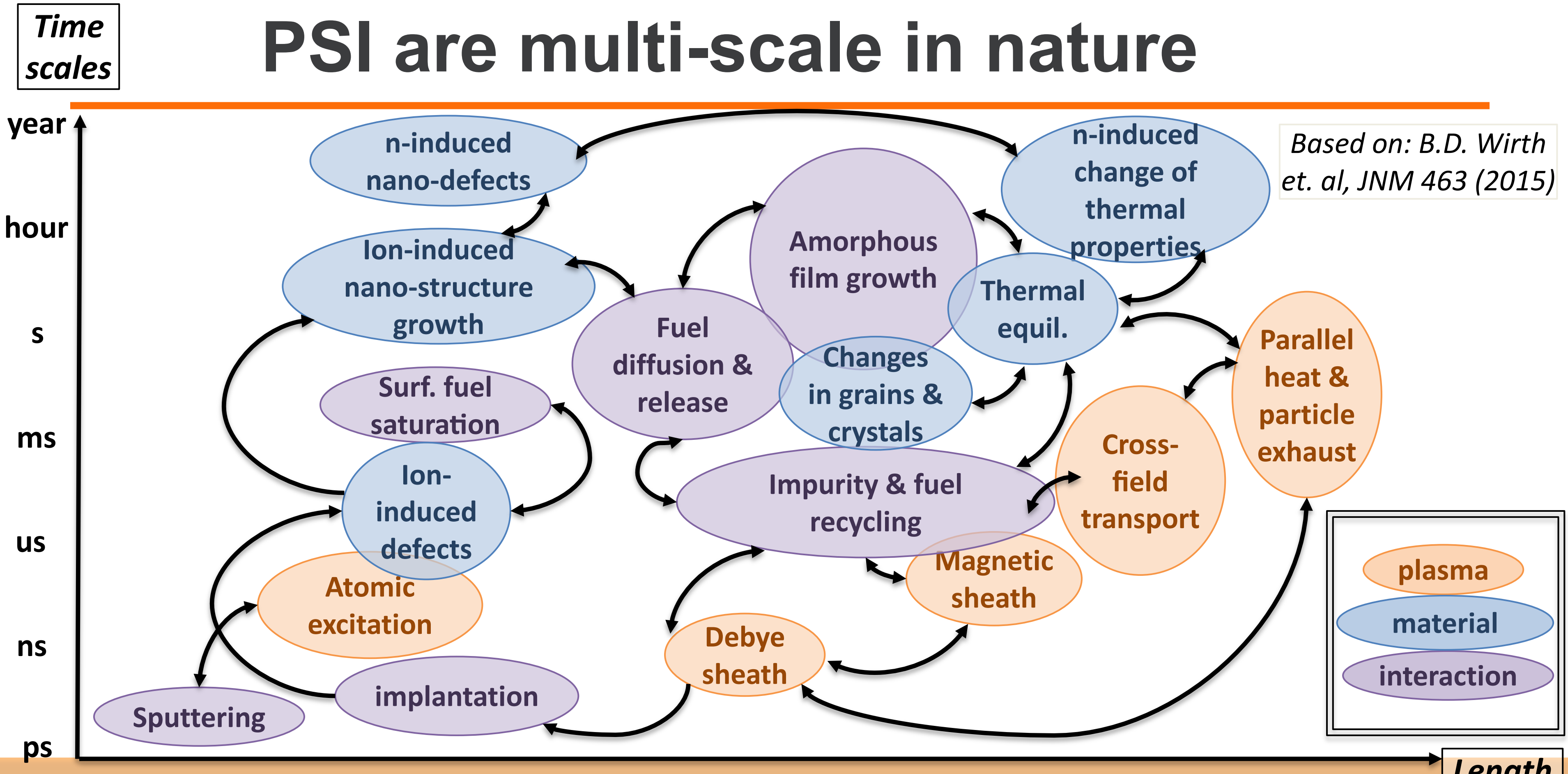
P. Andrews, ITER Summer School 2009

Post-mortem measurements: elemental analysis, mass loss/gains, layer deposition

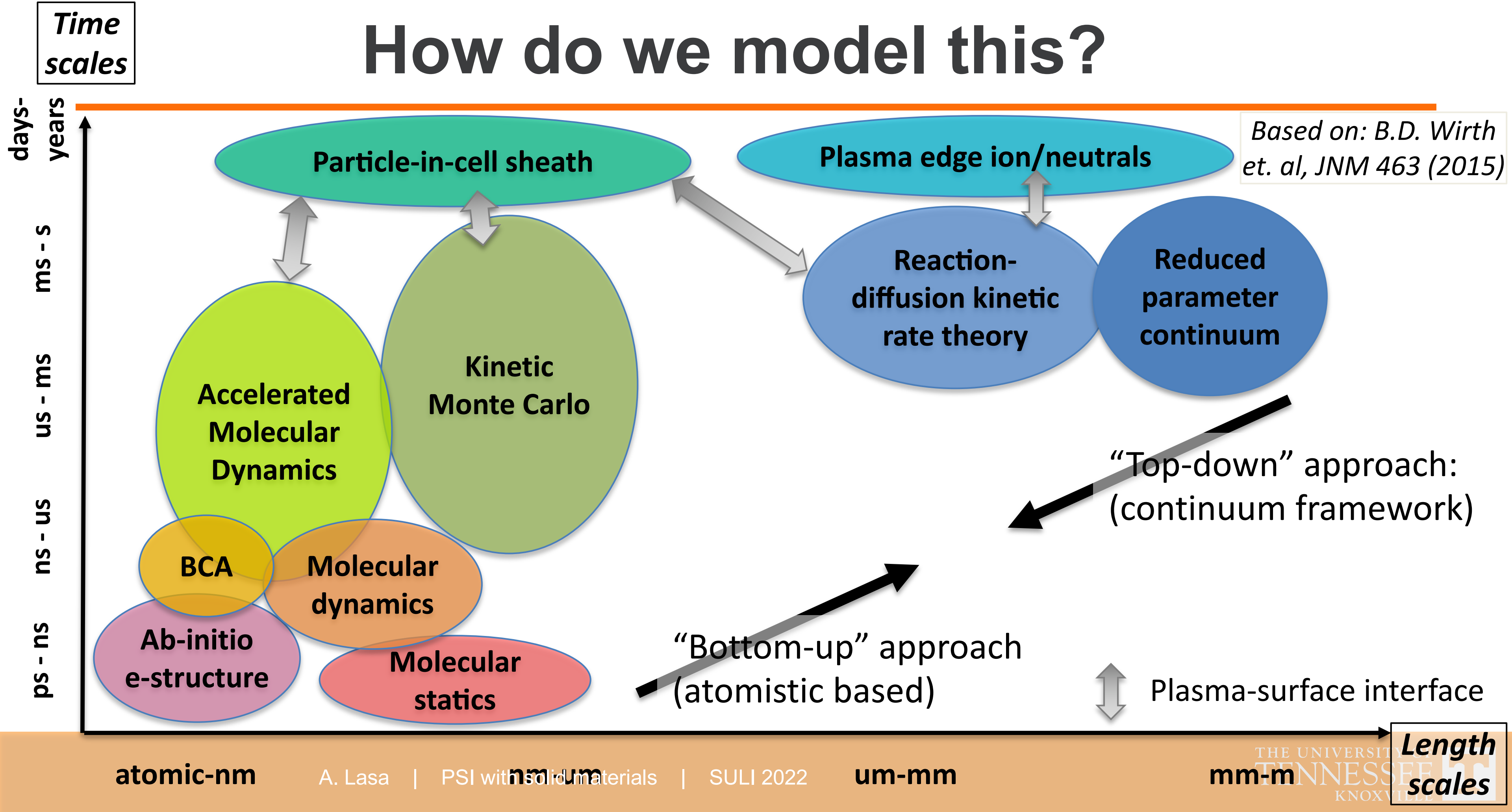
Good characterization of the boundary plasma is also essential to reducing uncertainties in PSI studies

THE UNIVERSITY OF TENNESSEE KNOXVILLE

PSI are multi-scale in nature



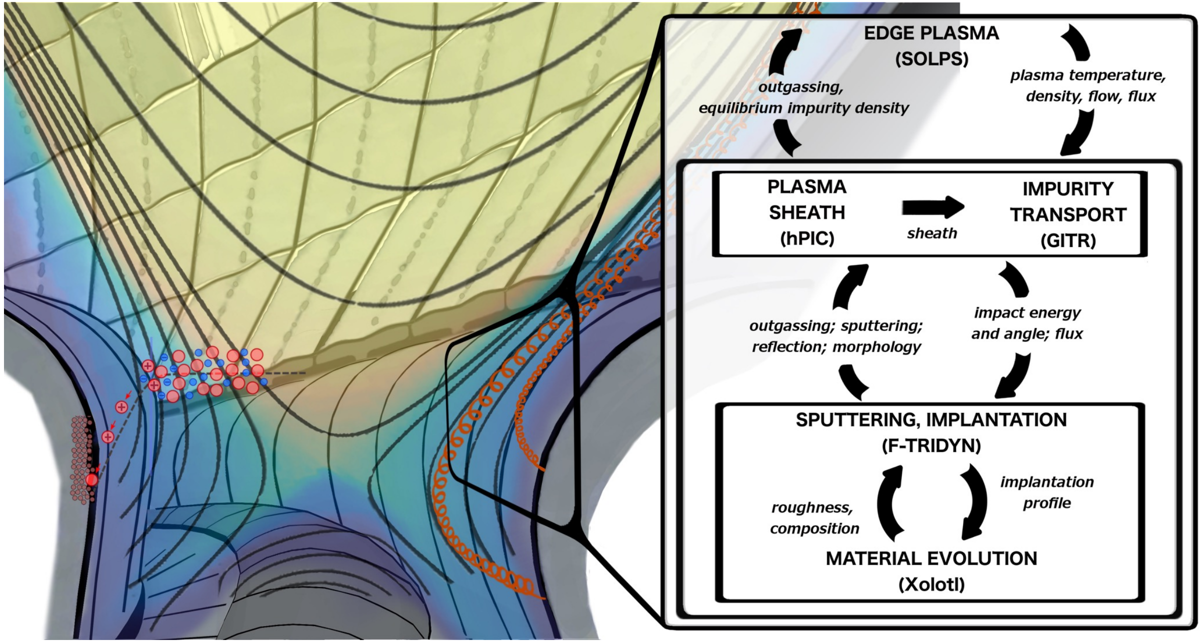
How do we model this?



Model coupling for a comprehensive description

Integrated modeling: plasma and across material – in line with stepping to the study of multi-effect

This is just an example; other integrated models include WallDYN (2D → 3D), ERO (to some degree)…



The takeaway

The development of PFCs is important for the safety and econ. viability of a fusion device

→ understanding and predicting PSI is essential

PSI lead to a wide-range of complex, multi-scale and closely interlinked plasma and material processes

PSI and development of PFCs are studied in confinement and linear plasma devices, as well as through testing of nuclear, thermomechanical, stress… properties

Given the multi-scale, multi-physics nature of PSIs, a wide range of diagnostics and models is needed for their characterization, simulation and performance prediction

→ integrated models can often offer a more comprehensive description

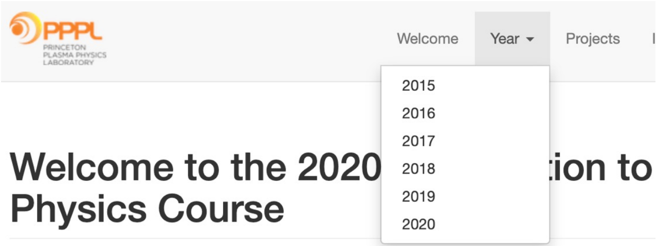
I really appreciate your time and attention.

You can find further resources below

Want to know more? Check out summer schools

Previous years of the SULI lectures

- many of them included a lecture in plasma-material interactions and/or fusion materials



2019	The Physics and Technology of Power Flux Handling in Tokamaks
2017	Physics of Disruptions and Control
2015	Transport and Pedestal Physics in Tokamaks
2014	High-Performance Computing in Fusion Science
2012	Radio-Frequency Heating
2011	Energetic Particles
2010	Magneto-Hydro Dynamics and Plasma Control
2009	Plasma-Surface Interactions
2008	Magnetic Confinement
2007	Turbulent Transport in Fusion Plasmas

If interested in PSI or any other fusion-related topics, and especially how it projects to ITER, spend a bit of time browsing through:

- https://www.iter.org/education/iis

Further resources: conferences & proceedings

Some of the most relevant conferences are:

- International Conference in Plasma Surface Interactions (PSI)
- International Conference on Plasma Facing Materials and Components (PFMC)
- International Conference on Fusion Reactor Materials (ICFRM)

- Sometimes the tutorial, invited and plenary talks are available online.
- I'd suggest to also look at the proceedings, starting from the plenary and invited talks, given the broader scope of these presentations (usually)

Review papers (used to prepare this lecture)

A great exercise for under/grad students (and anyone entering a new field, really) is searching for articles cited in these papers, and articles that have cited these paper

Download PDF Share Export

Journal of Nuclear Materials
Volume 463, August 2015, Pages 30-38

ELSEVIER

Challenges and opportunities of modeling plasma–surface interactions in tungsten using high-performance computing

Brian D. Wirth [a, b], K.D. Hammond [a], S.I. Krasheninnikov [c], D. Maroudas [d]

Show more

https://doi.org/

Fusion materials modeling: Challenges and opportunities

B.D. Wirth, K. Nordlund, D.G. Whyte, and D. Xu

Challenges for plasma-facing components in nuclear fusion

Cite as: Matter Radiat. Extremes **4**, 056201 (2019); https://doi.org/10.1063/1.5090100
Submitted: 24 January 2019 . Accepted: 06 June 2019 . Published Online: 21 August 2019

Jochen Linke, Juan Du, Thorsten Loewenhoff, Gerald Pintsuk, Benjamin Spilker, Isabel Steudel, and Marius Wirtz

COLLECTIONS

ished as part of the special topic on Special Issue on ICMRE 2018

INSTITUTE OF PHYSICS PUBLISHING PLASMA PHYSICS AND CONTROLLED

Plasma Phys. Control. Fusion **47** (2005) B303–B322 doi:10.1088/0741-3335/47/12

Material erosion and migration in tokamaks

R A Pitts[1], J P Coad[2], D P Coster[3], G Federici[4], W Fundamenski[2], J Horacek, K Krieger[3], A Kukushkin[4], J Likonen[5], G F Matthews[2], M Rubel[6], J D Strachan[7] and JET-EFDA contributors[8]

Journal of Nuclear Materials
Volume 463, August 2015, Pages 11-21

ELSEVIER

Plasma-surface interaction in the Be/W environment: Conclusions drawn from the JET-ILW for ITER

S. Brezinsek [a, b, 1], JET-EFDA contributors [2]