Song of summer'20:
Can you see my screen?

At the interface of the plasma and the walls

An overview of plasma-surface interactions with <u>solid</u> 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:

- After a strange-enough semester, this is your 2nd week spending daily hours on zoom; it's exhausting and I'll try to present something **easy to follow**

- 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

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

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

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

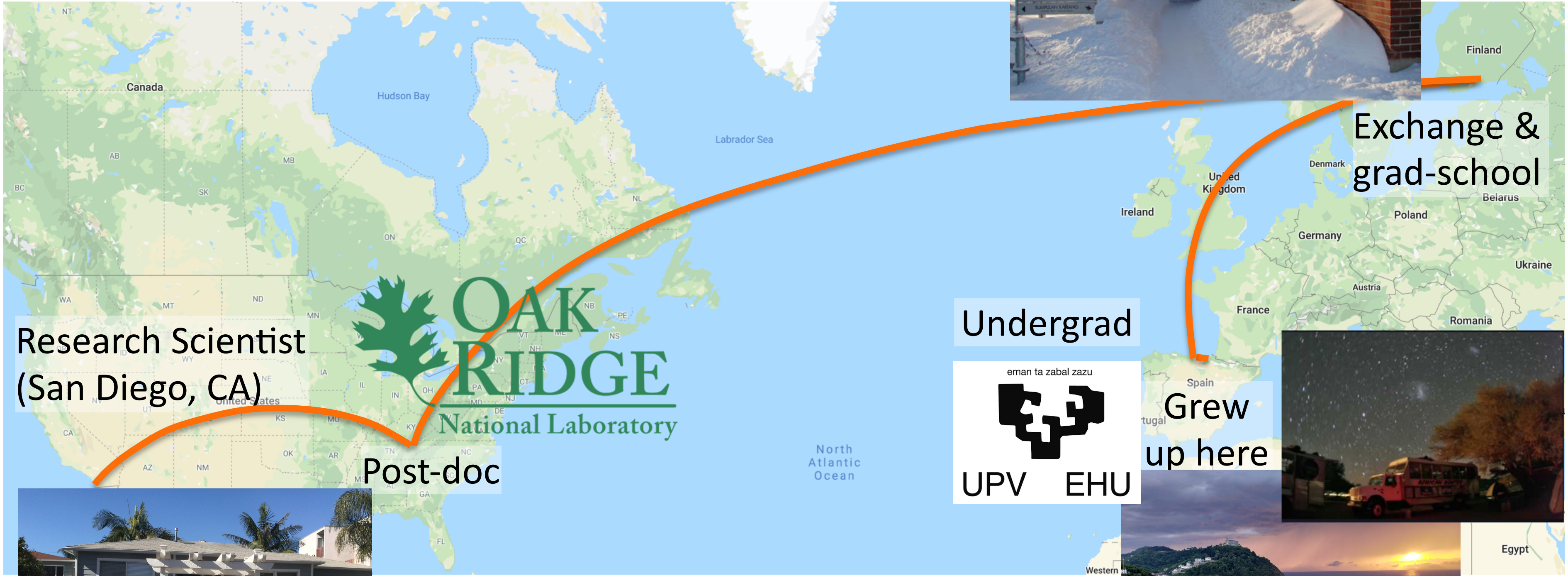
Much of the material shown here is inspired by the 2009 and 2019 ITER summer schools, which focused on Plasma-Surface Interactions and development of Plasma-Facing Components

- You may notice many examples use values of and predictions for ITER

Many of the figures are taken from the review articles that I highlight at the end, in further resources

Note: marked with a *(*)* the topics that are – or I expect to be – covered by other lectures.

Life is rarely a straight line…



…but it's (usually) worth it!

Being a scientist is very compatible with many other hobbies

Photo credit: D. Shiraki & A. Lasa

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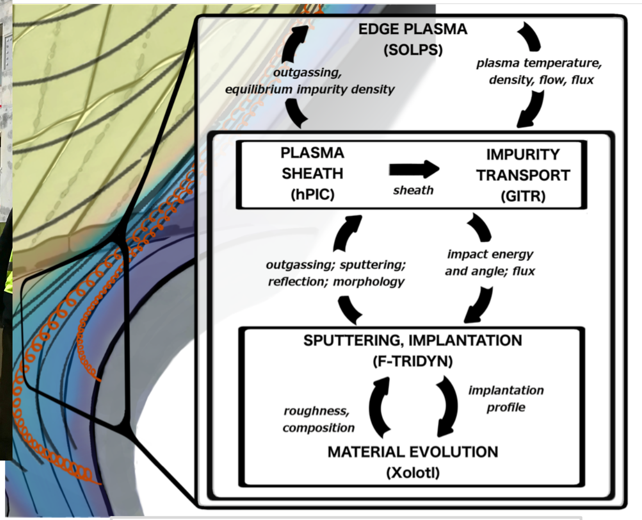
I am most interested in coupled PSI modeling

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)

Me, in a visit to ITER, Jan. 2019



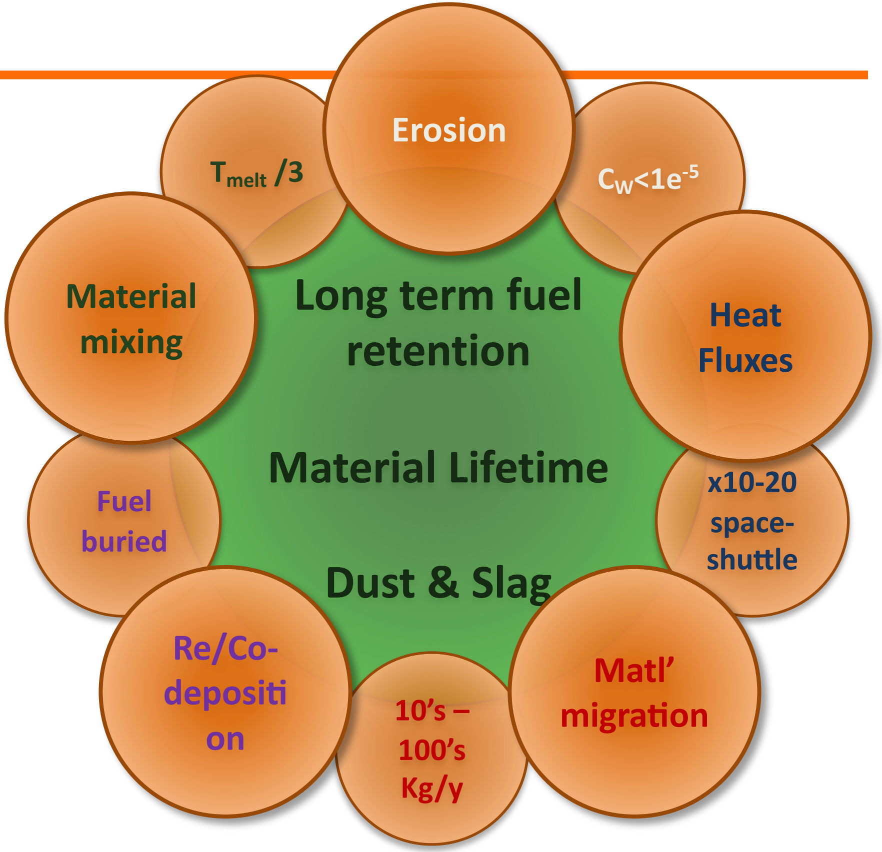
A. Lasa. PSI-SciDAC proposal

Outline

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

Our best contestants for facing the plasma

Our work tools: experimental and modeling approaches



Outline

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

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Our work tools: experimental and modeling approaches

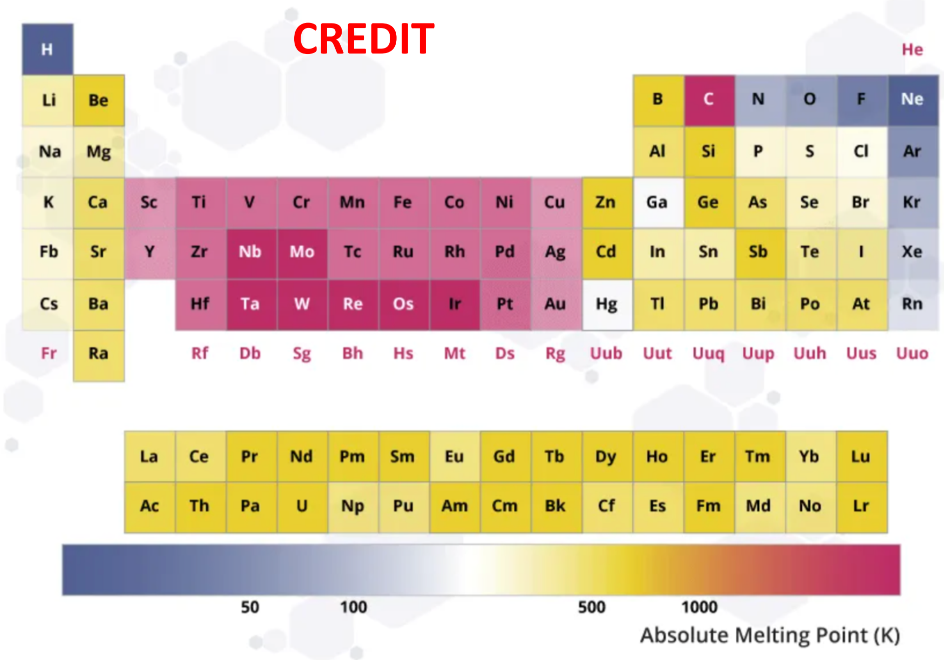

Image from : matmatch > blog > fusion-energy-materials

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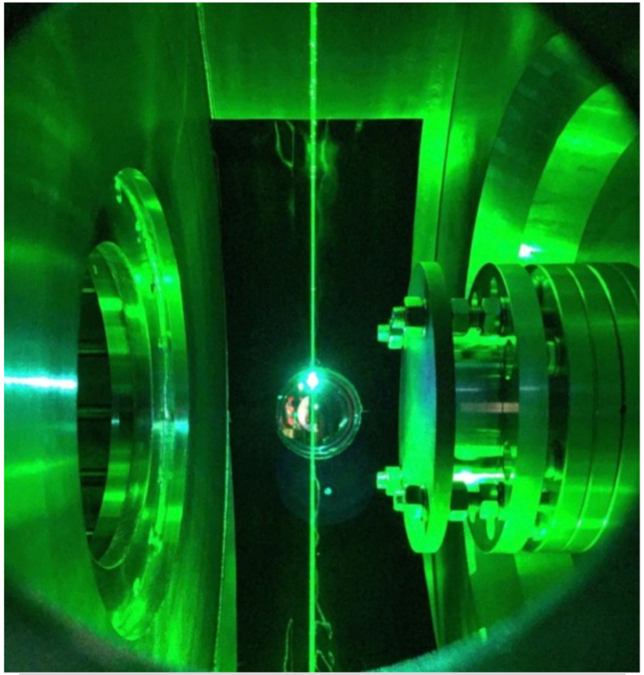
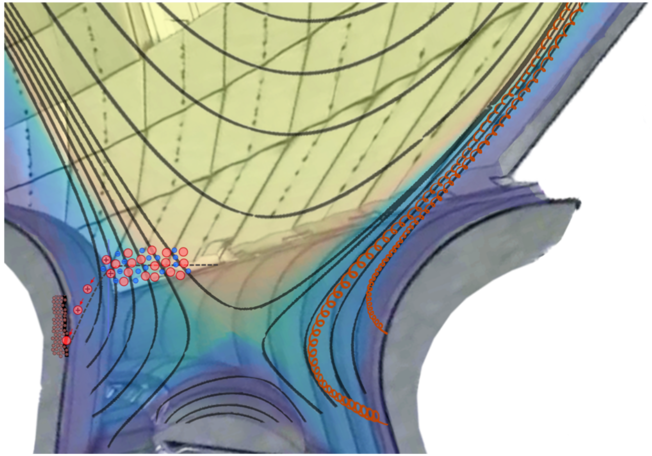


Alignment with lasers at Proto-MPEX
Photo credit: Ted Biewer/ORNL, DOE

Plasma-Surface Interactions

Why do plasmas and wall materials interact?

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



Why do plasmas and wall materials interact?

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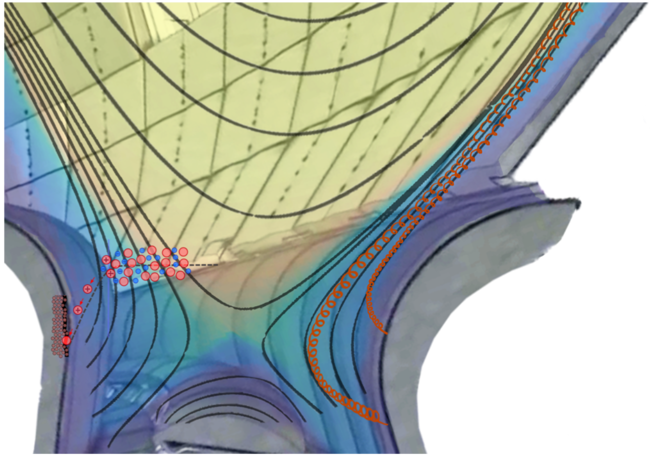
- Even if we could perfectly confine the plasma, it would not be beneficial: the exhausted fuel (i.e, helium ash) and other impurities need to leave the confined volume to avoid contamination of the core



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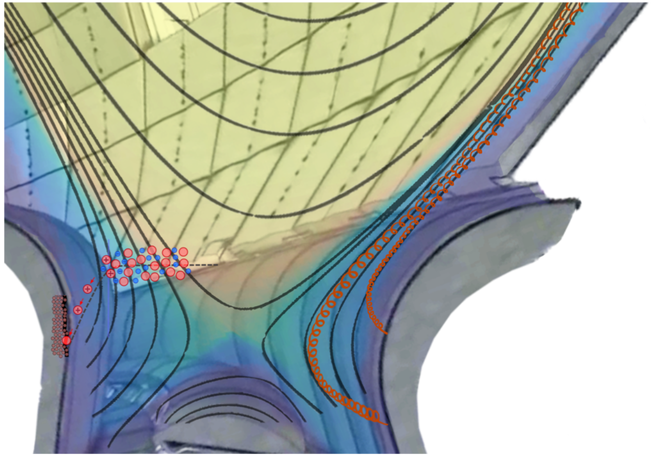
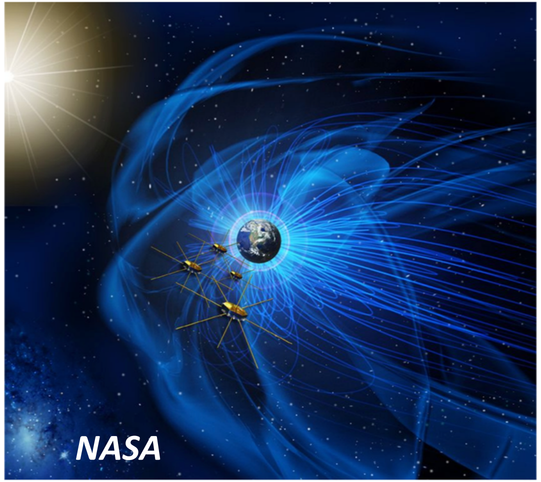


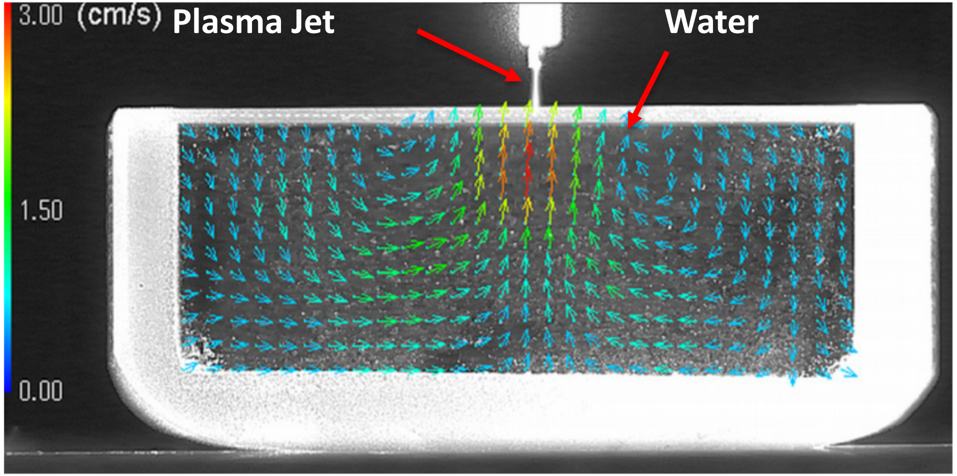
When leaving closed magnetic field for open ones, the plasma ions will interact with the surrounding walls

→ **that's plasma surface interactions!**

Plasma-surface interactions are nearly everywhere

Plasma-surface interactions take place in many systems, sometime purposely, sometime 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

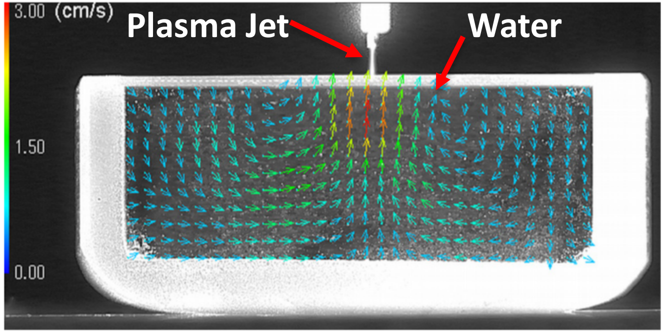
Plasma-surface interactions take place in many systems, sometime purposely, sometime unavoidably; plasma cleaning, spacecrafts, microchip fabrication…

In confinement devices, PSI 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



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, sometime purposely, sometime unavoidably; plasma cleaning, spacecrafts, microchip fabrication…

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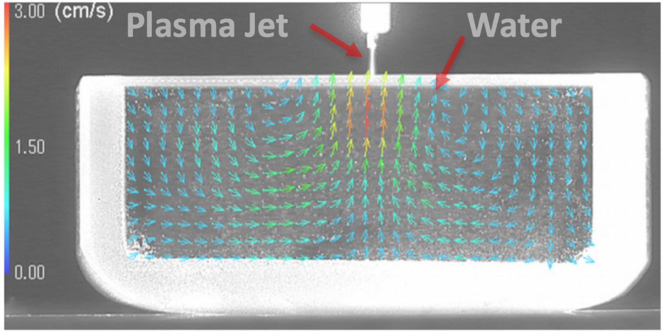


Plasma facing surfaces are the **first layer of protection** (i.e., ‘skin’) for all components that lay behind them: structural materials*, tritium breeding blankets*, magnets* …

→ 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 & reliability**

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

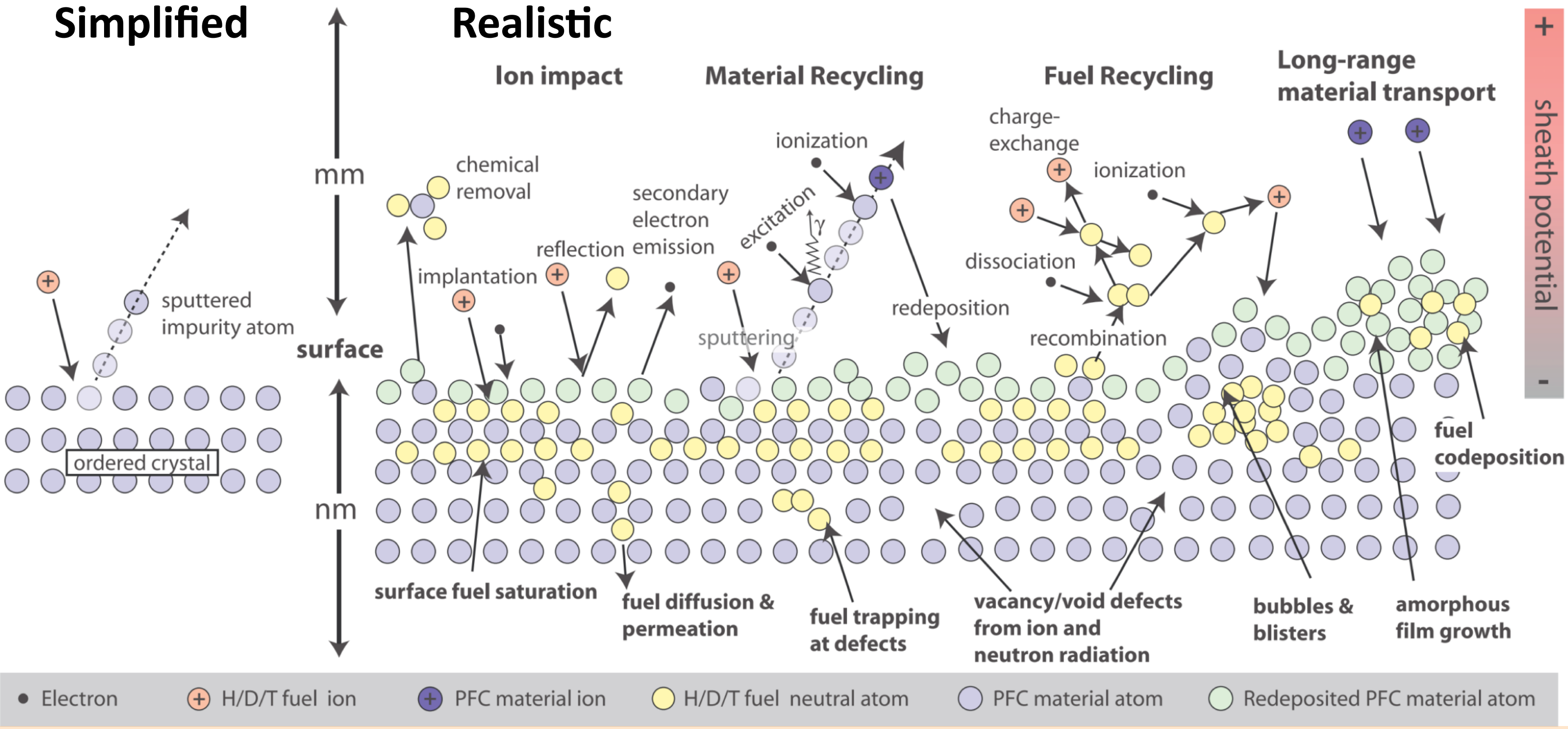
- Fuel trapped in walls is not available for burning; & tritium is a limited resource

→ **fusion reactions / energy production**

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

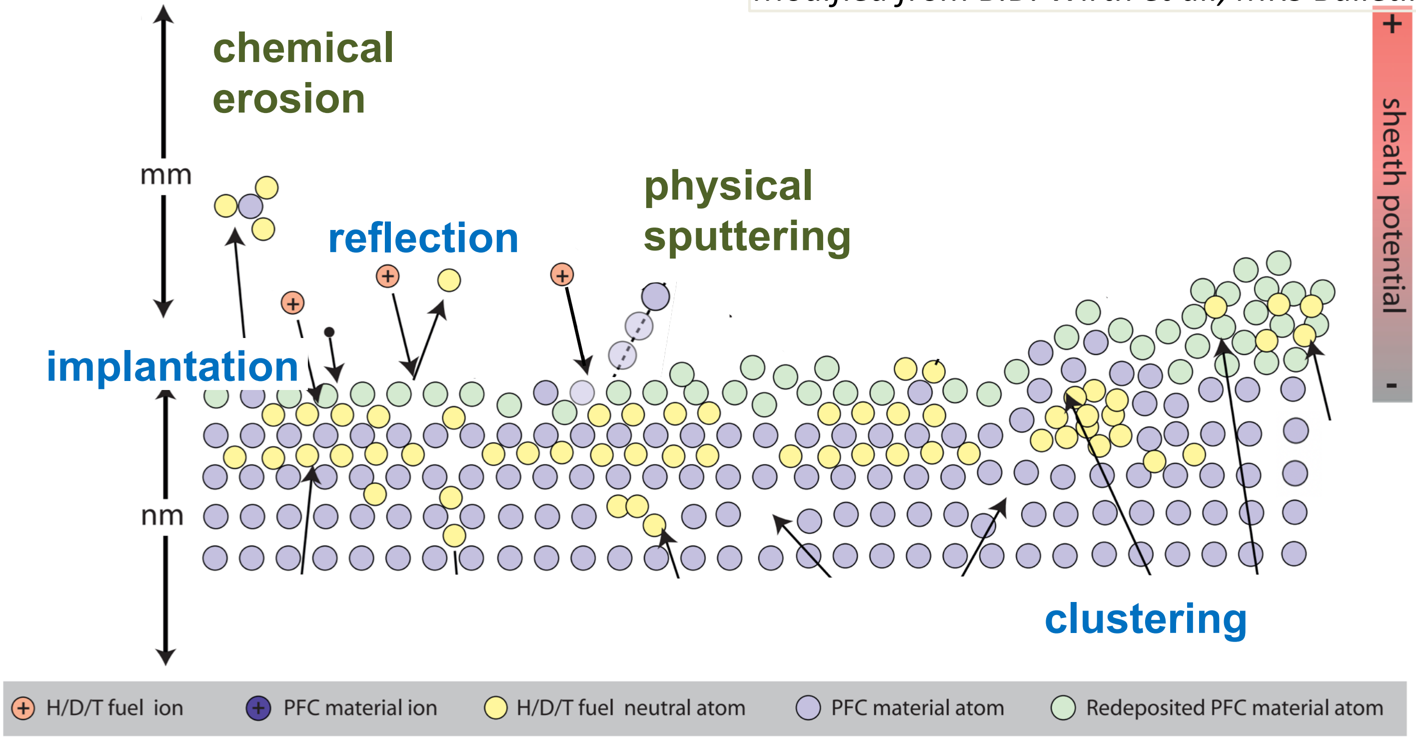
A lot can happen when the plasma touches a surface

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



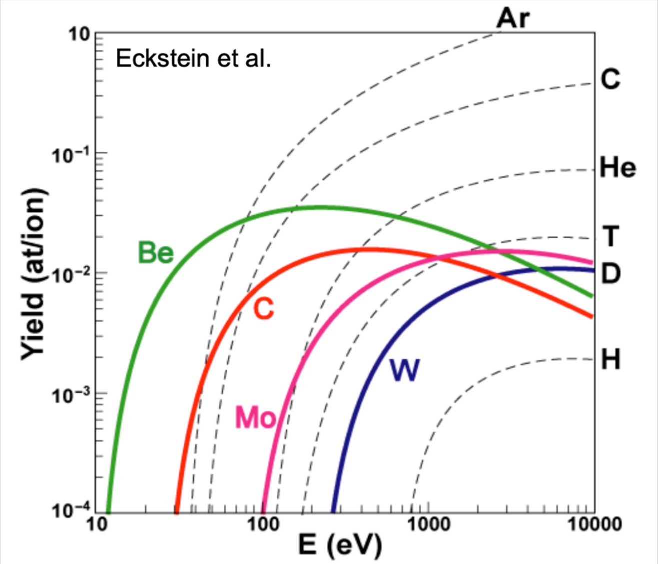
When an ion impacts…

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



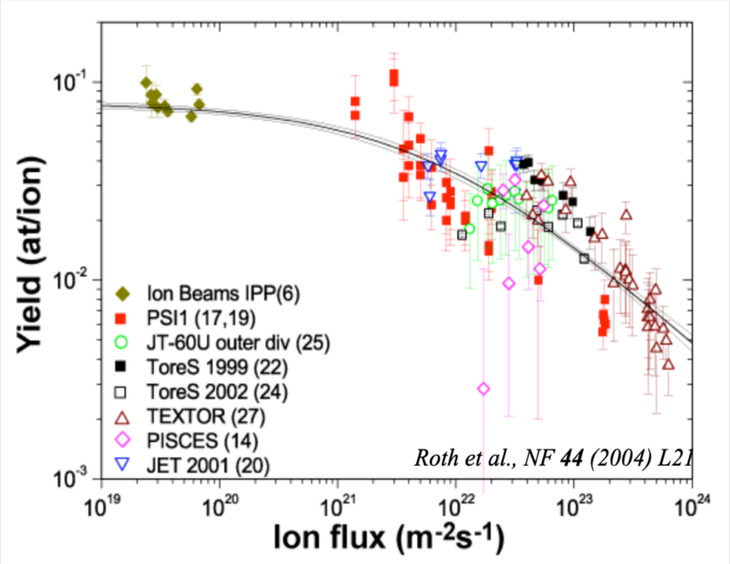
Erosion depends on target material and plasma characteristics

Physical sputtering:



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

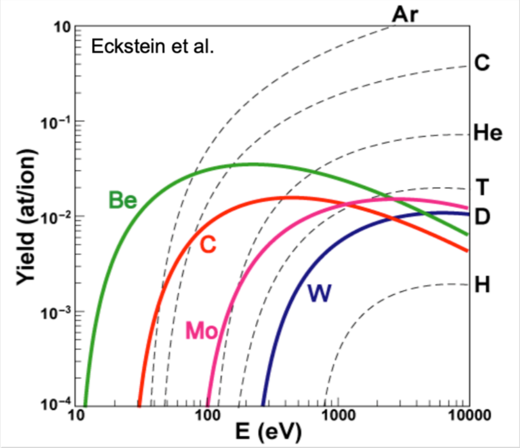
Chemical erosion:



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

Erosion depends on target material and plasma characteristics

Physical sputtering:



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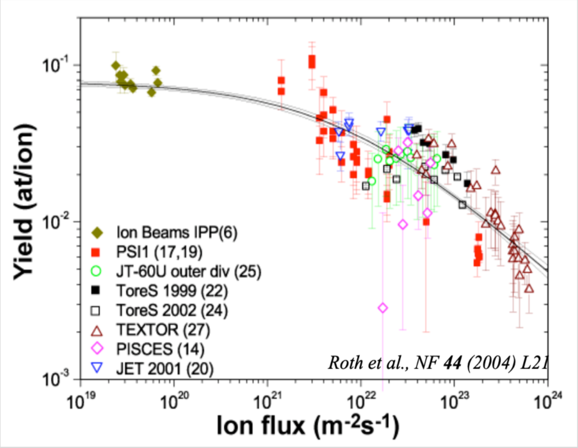
Chemical erosion:



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., enrichment)

Transients & other sources add to steady-state erosion

Transients:

Probably the biggest threat for large-scale erosion in future devices: W_{plasma} x10-50, deposition area x2

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)

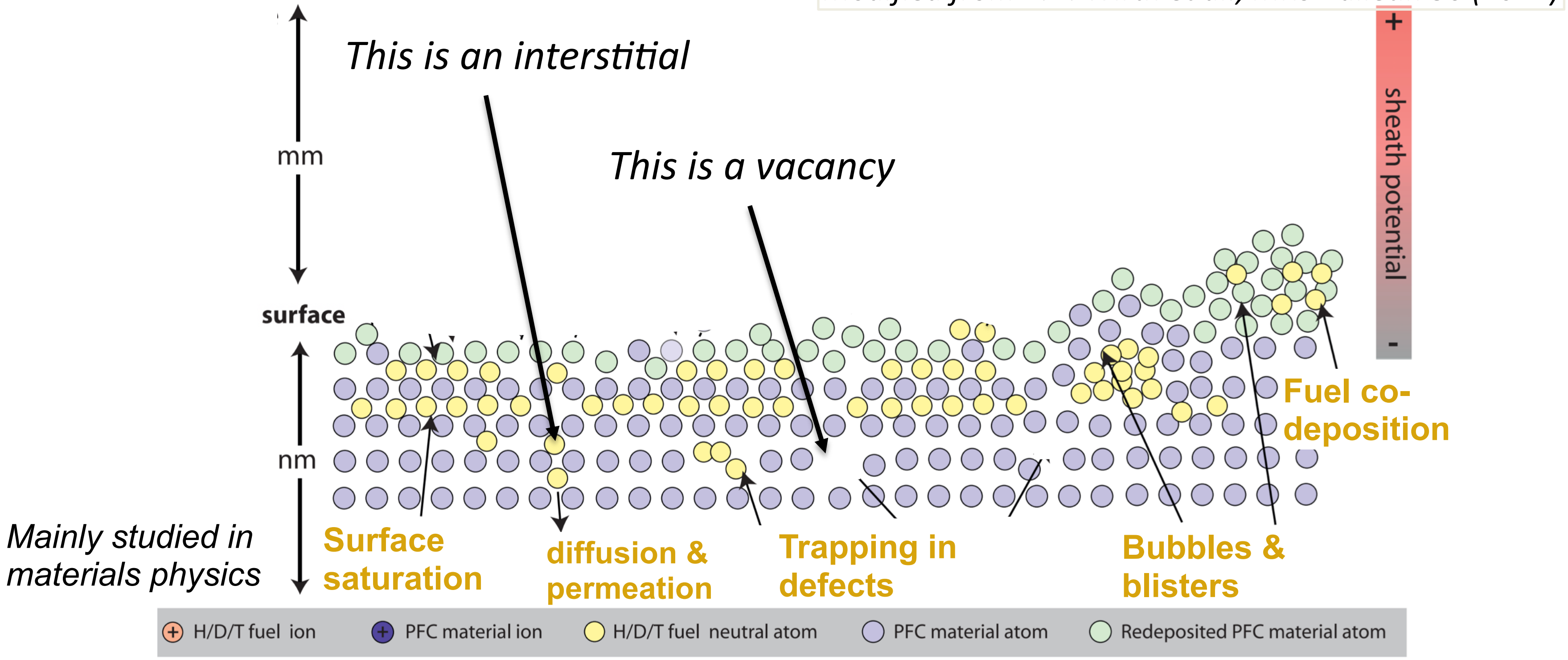
Additional sources:

- **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

Plasma ions may **stay** in the material

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



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**

*More on tritium safety & economics tomorrow
"Closing the fuel cycle", Xiao

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

Efforts to quantify and predict the retention expected with 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 implantation → T tends to diffuse; easier to recycle that in near-surface

Gas dynamics & fuel retention

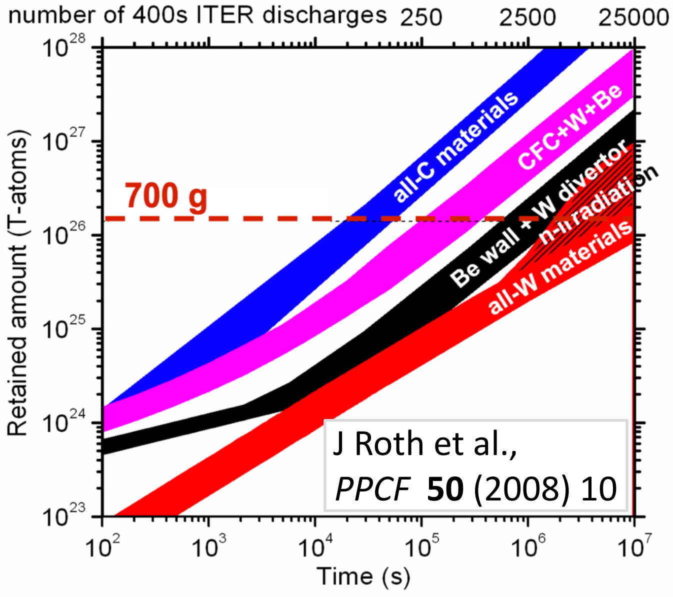
Fuel (tritium, T) retention is important mainly for Safety & Economics
→ Ensure T is burning and not on/in the walls

Efforts to quantify and predict the retention expected with different plasma-facing materials for ITER

For materials that form hydride mol's (C, Be):
retention driven by [erosion → co-deposition]:

$$ret_T = Y_{eros} \times c_T \text{ in co-deposits}$$

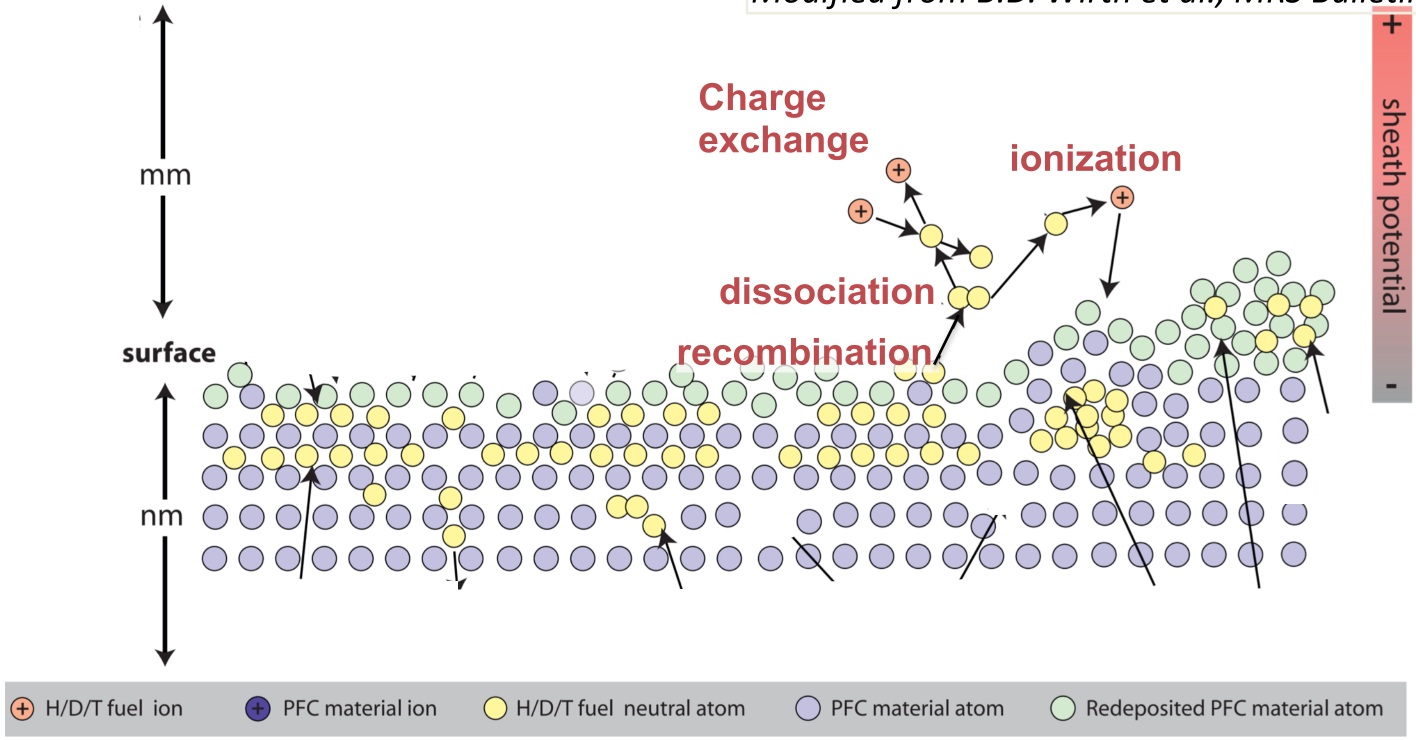
Ohers (W) retention driven by implantation
- Affected damage (n-irrad), fusion ash, impurities…



J Roth et al.,
PPCF **50** (2008) 10

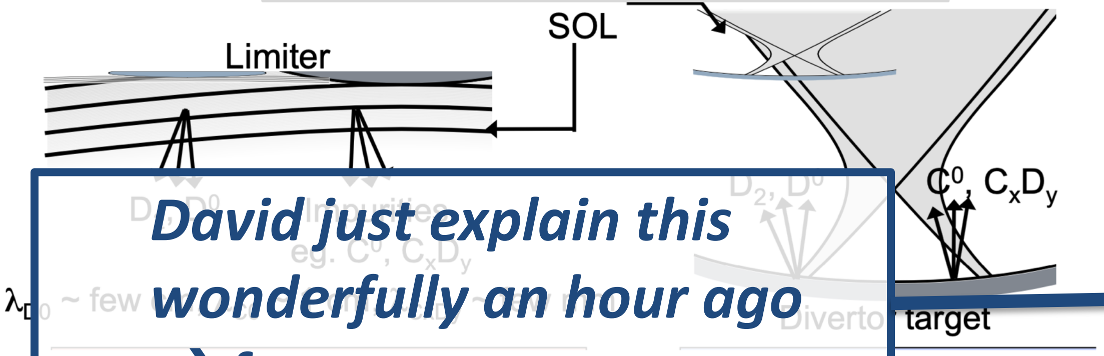
Plasma ions may stay in the material or recycle

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



David just explain this wonderfully an hour ago

→ focus on summary

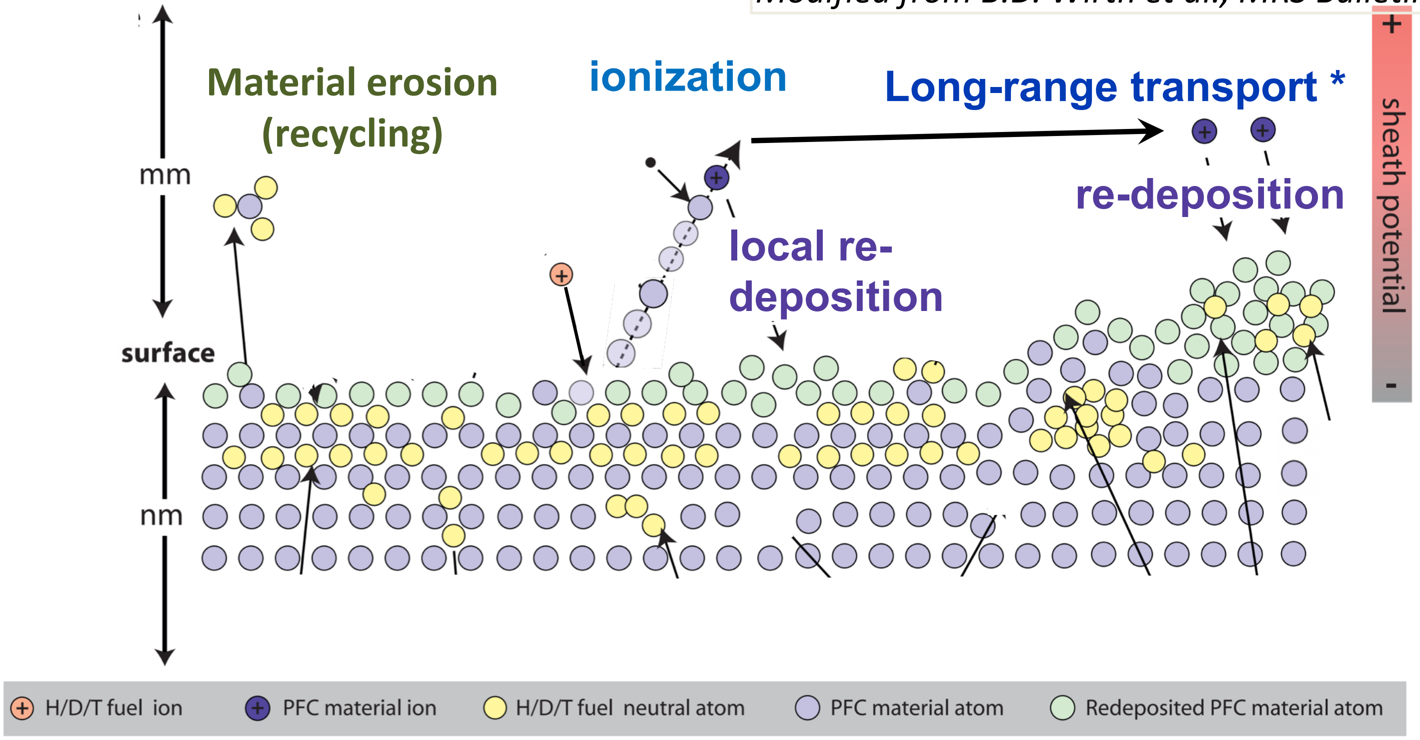
- Close contact with plasma
- Strong influx of fuel & impurity neutrals into the edge
- Little cooling in SOL → hot plasma

- 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)

Material can be eroded, transported & deposited

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



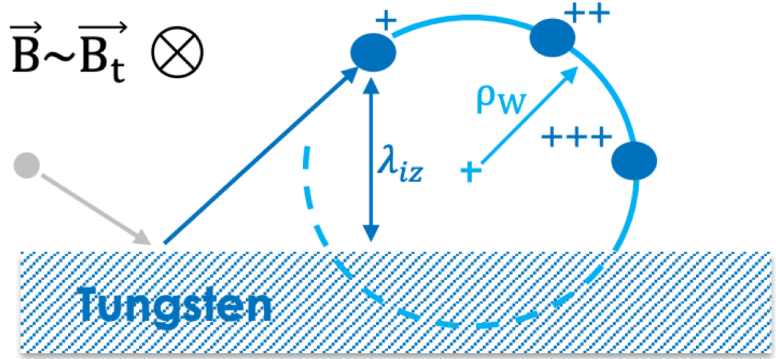
Impurity migration starts with ionization

Material eroded from the surface is quickly ionized → all single-ion motion rules apply

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

It's a balance between ionization (e-structure) & gyro-radius (charge / mass)

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



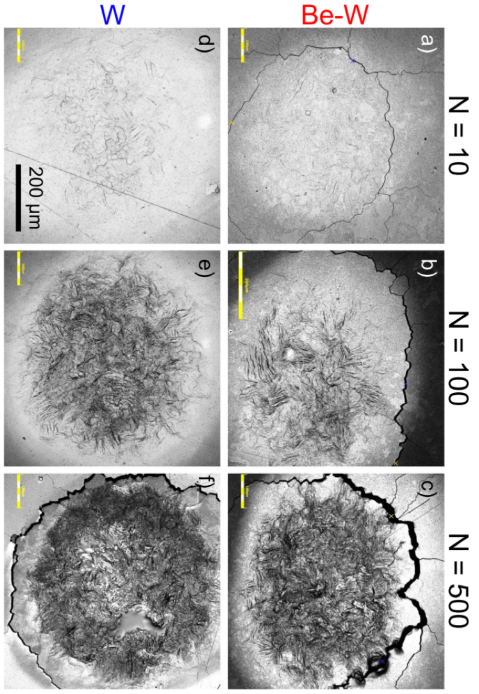
J. Guterl et al., APS-DPP 2019

Migration turns local challenges into global ones

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

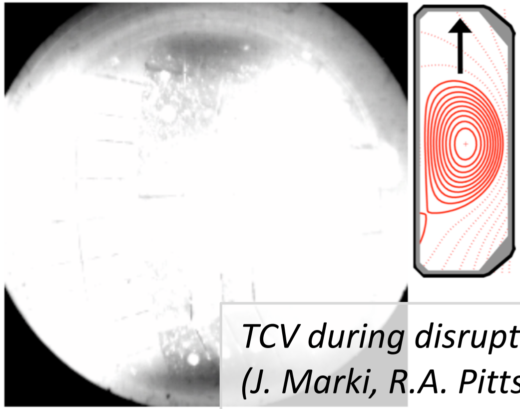
Also causes new challenges:

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



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

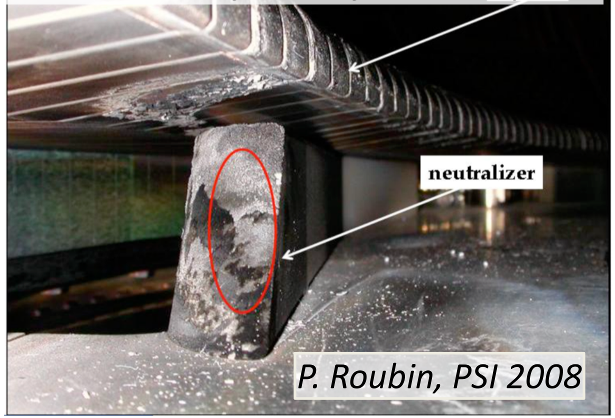
E.g., the less-heard-of formation of dust



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

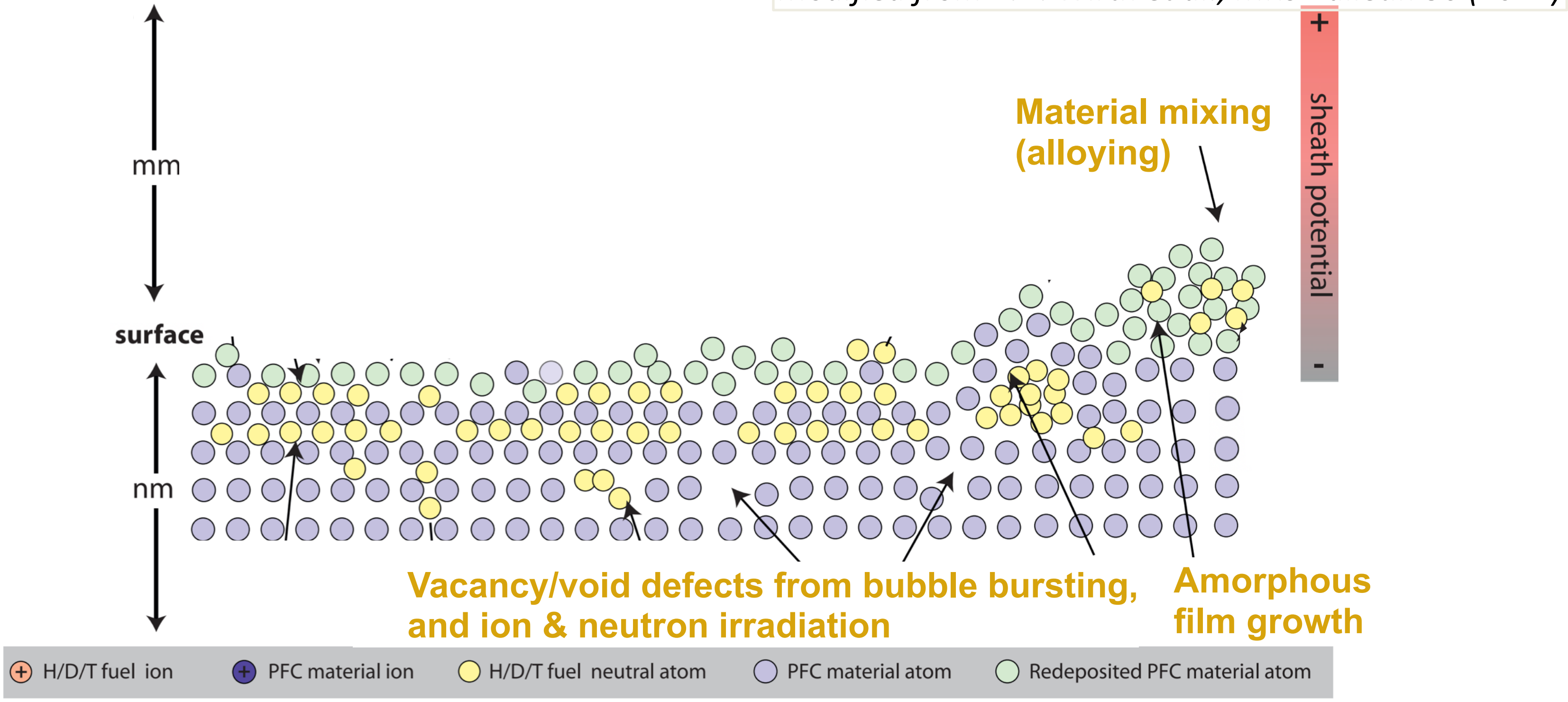
<u>formation of 'dust'</u>

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

The substrate properties will be altered

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



The substrate properties will be altered

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 impurity sites

→ 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

Story-time:

we exposed tungsten to He plasma, but that looks like carbon on the surface…

That’s the whole fuzz about W-fuzz!

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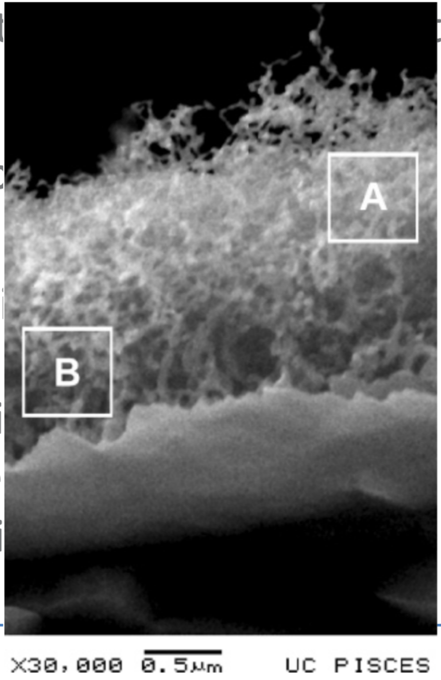


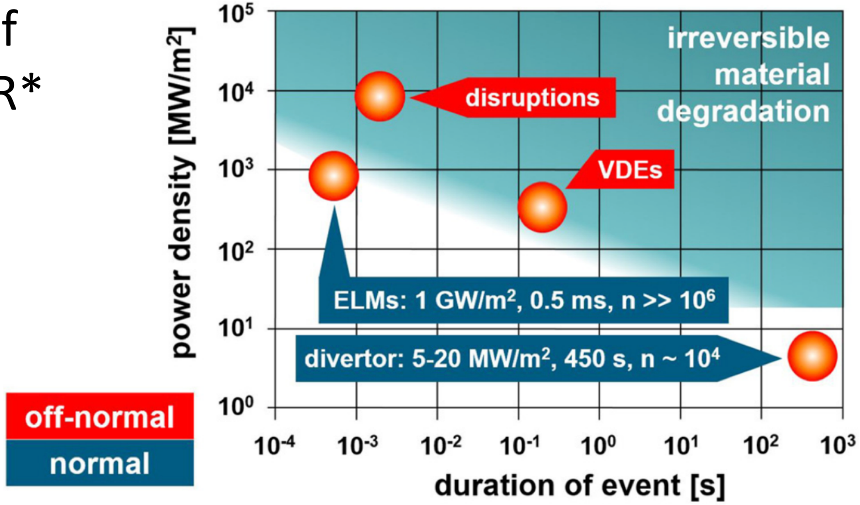
M.J. Baldwin and R.P. Doerner
Nuclear Fusion **48** (2008) 3

Story-time:
we exposed tungsten to He plasma, but that looks like carbon on the surface…

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

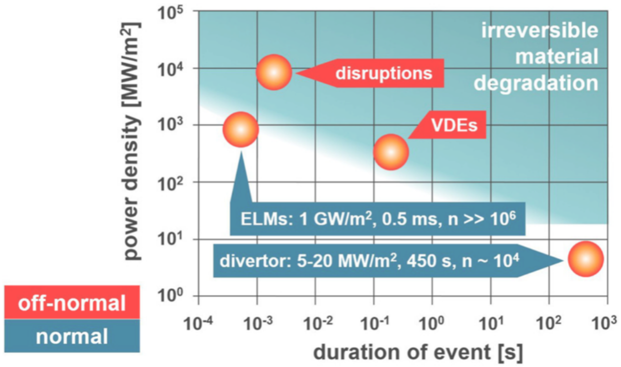


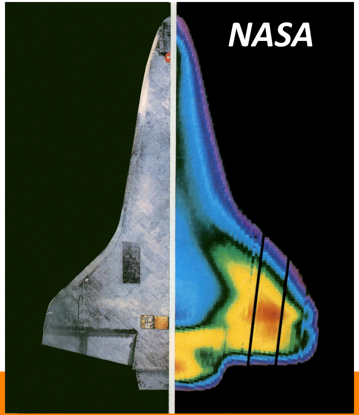
J. Linke et al., *Matter Radiat. Extremes* **4**, (2019) 056201

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

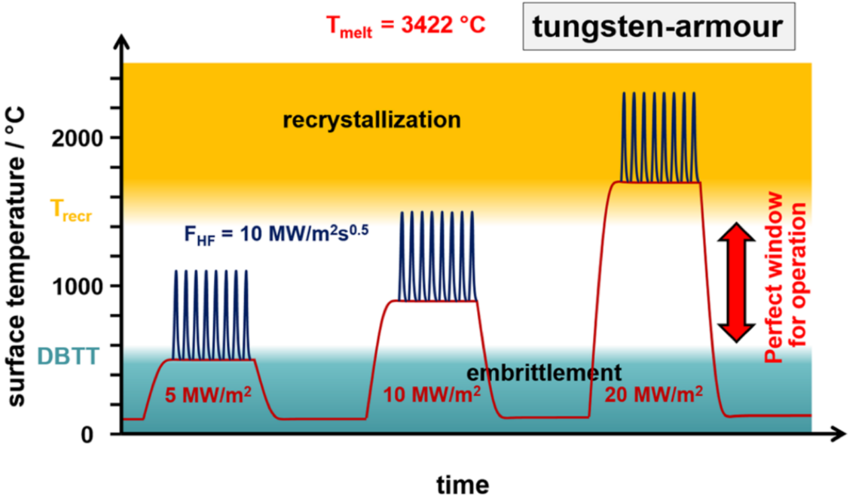
Space shuttle: 0.5 MW/m² (a little higher for Apollo)

→ 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')

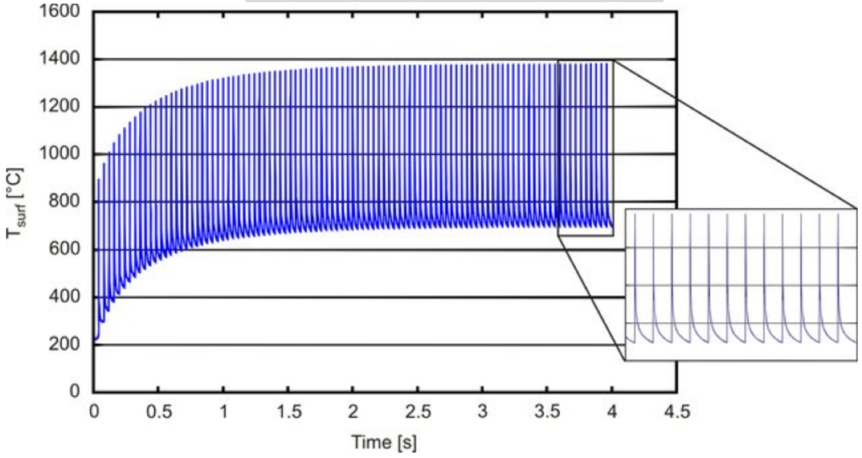
In addition to ions, the plasma deposits heat

Heat fluxes affect the material & surface by changing its temperature



Rieth et al., *J. Nucl. Mater*. **519**, 334-368 (2019)

Thesis of Th. Loewenhof



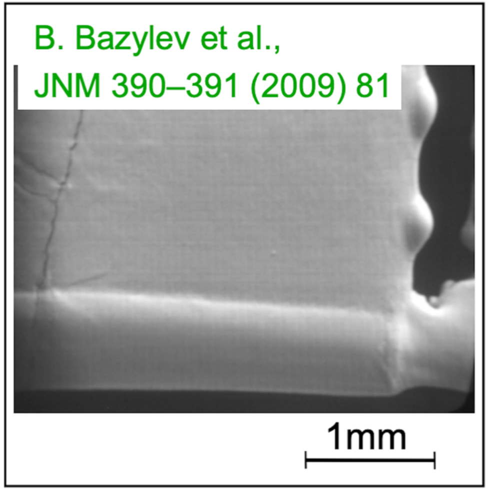
Heat fluxes affect the materials by changing their temperature

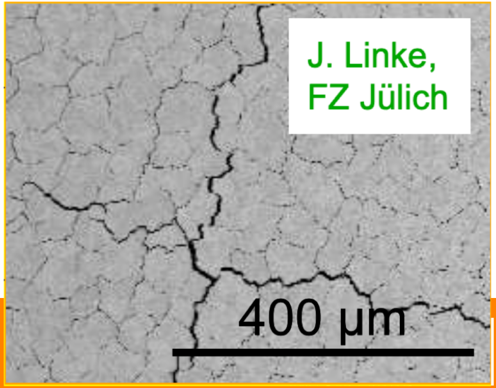
Surface atoms may evaporate or the surface might melt

Change in surface properties at lower than melting temperatures (e.g., recrystallization…)

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

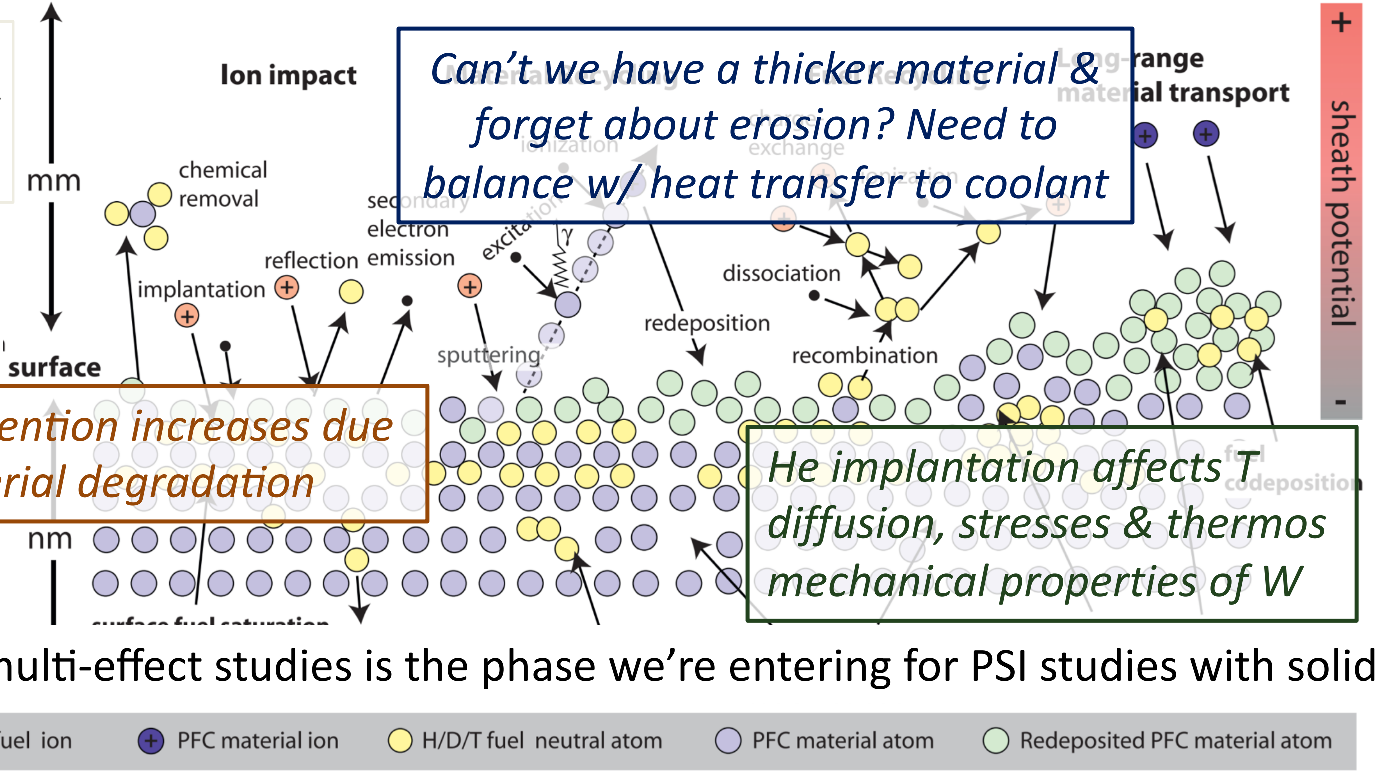
Control of temp. is important as some increase can be beneficial
- Better properties at mid-temps (Ductile to Brittle Transition)
- Enhanced diffusion of T
- Suppressed chemical erosion





In reality, there are all sorts of the synergies

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



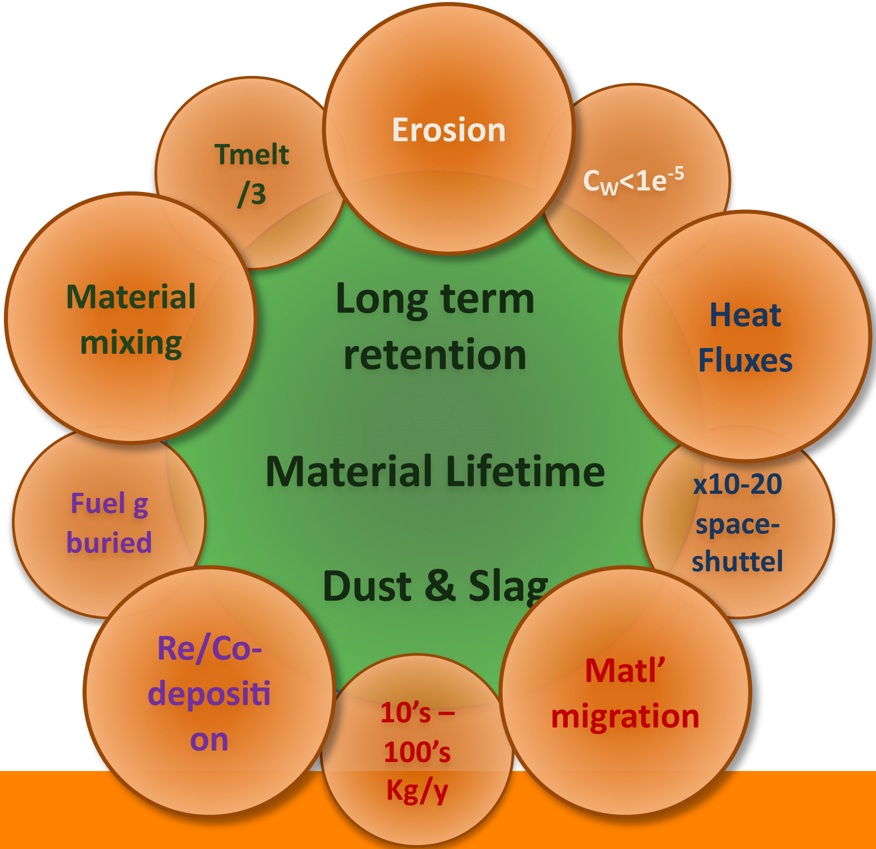
Can't we have a thicker material & forget about erosion? Need to balance w/ heat transfer to coolant

Fuel retention increases due to material degradation

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

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

Just to summarize all these effects



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 of the first are also the layer of 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
- ….

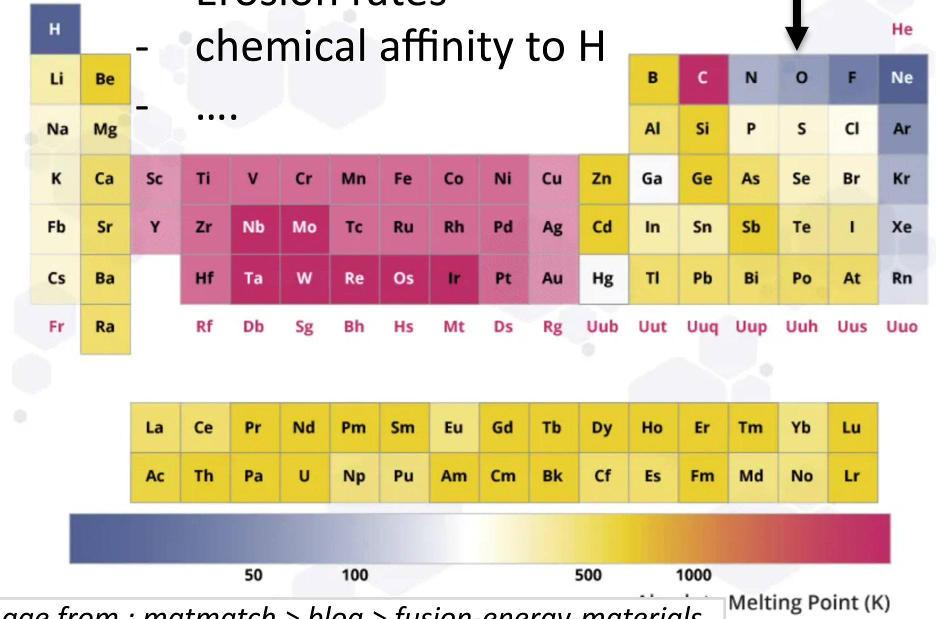


Image from : matmatch > blog > fusion-energy-materials

The usual trade-off is Low vs high Z:

easier to erode

but less problematic (beneficial)

VS

harder to erode

but higher consequence

There are additional inputs to design a component

In addition to plasma exposure, there are engineering inputs to consider:

EM loads

During a plasma instabilities eddy currents are induced in the PFCs. These currents interact with the toroidal magnetic field thus resulting in extremely high forces applied to the PFCs. These forces can generate mechanical stresses up to a few hundreds of MPa with a consequent strong impact in the design of the supporting structures.

Surface erosion

The particle flux impinging onto the PFCs causes surface erosion due to physical sputtering (and also chemical sputtering in the case of carbon). One effect of this phenomenon is that the thickness of the plasma facing material is progressively reduced. Furthermore the eroded particles can migrate into the plasma thus increasing the radiative energy loss by *bremsstrahlung* and diluting the deuterium and tritium concentration. Another consequence is that some eroded particle (like carbon or beryllium oxide) may trap tritium atoms when they redeposit onto the surface of the PFCs (the so-called "co-deposition"). This results in an increase of the tritium inventory in the plasma chamber with the associated safety concerns.

Surface heat flux & vol heat deposition

The **volumetric heat deposition** has a typical maximum value of a few W/cm^3 in the FW structures and then decreases radially in an exponential way. It has mainly an impact on the design of the supporting structures, which thus need to be actively cooled.

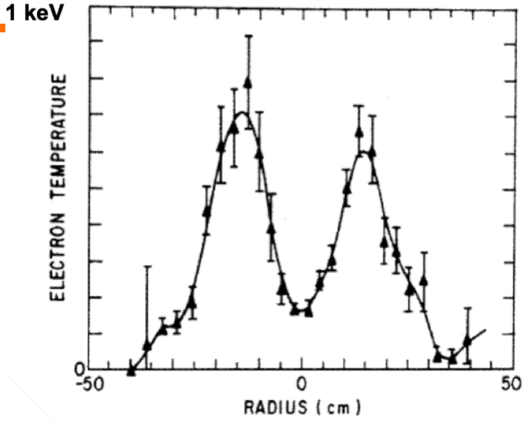
Surface heat flux due to the radiative and particle flux from the plasma. This is of particular concern for the next generation of fusion machines where, due to the high number of operating cycles, a thermal fatigue problem is anticipated. Particularly harmful are the off-normal heat loads, which are associated to plasma instabilities (such as a plasma disruption or vertical displacement). Up to some tens of MJ/m^2 can be deposited onto the PFCs in a fraction of a second resulting in melting and evaporation of the plasma facing material. About 10% of the discharges are anticipated to end with plasma instability in the next generation of fusion machines, whereas this figure should decrease to less than 1% in a commercial reactor.

Neutron damage

The **neutron damage** will be the main lifetime limiting phenomenon in a commercial reactor. It is measured in "displacements per atom" (dpa) that is the number of times an atom is displaced from its position in the lattice due to the action of an impinging particle. The dpa is proportional to the neutron fluence. As an example 1 MW-year/m^2 causes about 3 and 10 dpa in beryllium and copper or steel, respectively. The dpa value is a measure of the neutron damage. Typical effects of this damage are embrittlement and swelling.

Neutron flux from the plasma. The neutron flux is referred to as "wall loading" and measured in MW/m^2. This is the power density transported by the neutrons produced by the fusion reaction. The wall loading multiplied by the total plasma burn time gives the neutron fluence, which is measured in MW-year/m^2. The two main effects of the neutron flux are the volumetric heat deposition and the neutron damage.

A brief look into history



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

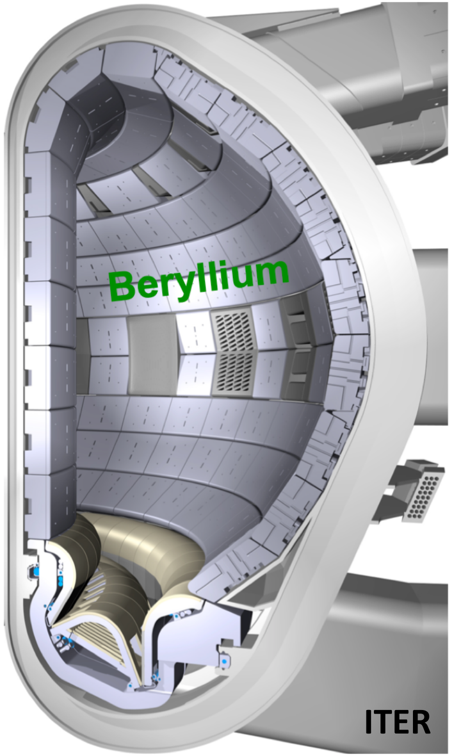
The priority of early devices was vacuum compatibility
→ gold-plated SS liners

Higher edge temperatures, core confinement & performance with low low-Z conte... source & impurity accumulation (e.g., P...

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

Vacuum-grade graphi... r thermal 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...



Requirements change with the area

Divertor:

- high heat & particle fluxes
- Smaller area (than the 1^{st} 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 & 1^{st} wall)

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?

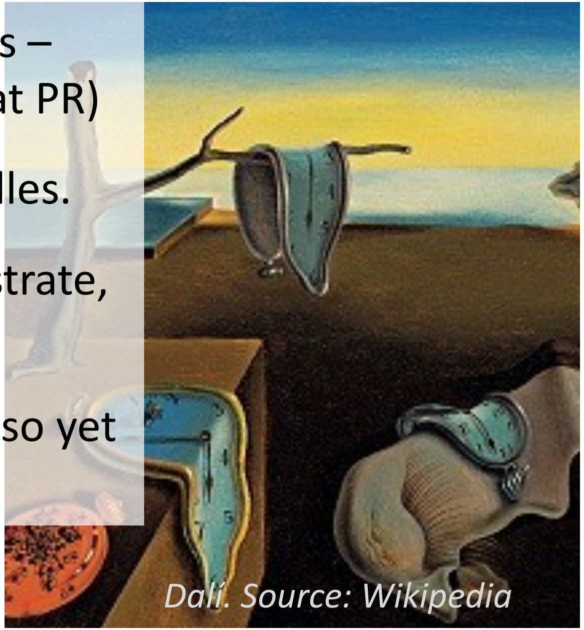
Solids and LMs solution-candidates exist for PFCs of future fusion reactors.

Often LMs are presented as “the solution” to all solid PFCs issues – and us working on solida highlight all of our challenges (not great PR)

- While technically that’s usually true, LMs face their own hurdles.
- Complex systems, fires, finding a corrosion & n-resistant substrate, fuel retention & separation, liquid flow stability, etc.

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

But that’s enough, there’s an entire lecture on LMs coming!



Dalí. Source: Wikipedia

How do we study this?

PSI can be studied directly in confinement devices

Confinement devices:

Removable tiles

- movable “PFC”, e.g. DIMES in DIII-D;
- post-mortem, e.g., the metal-ring campaign

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

- exceptional focus at JET in preparation for ITER

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 **…**

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

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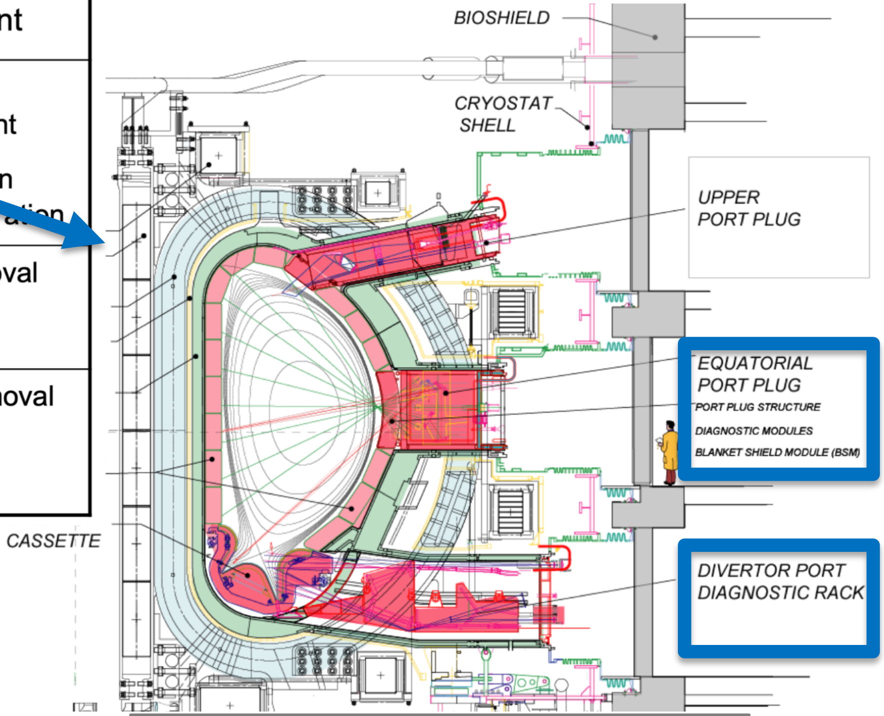

P. Andrews, ITER Summer School 2009

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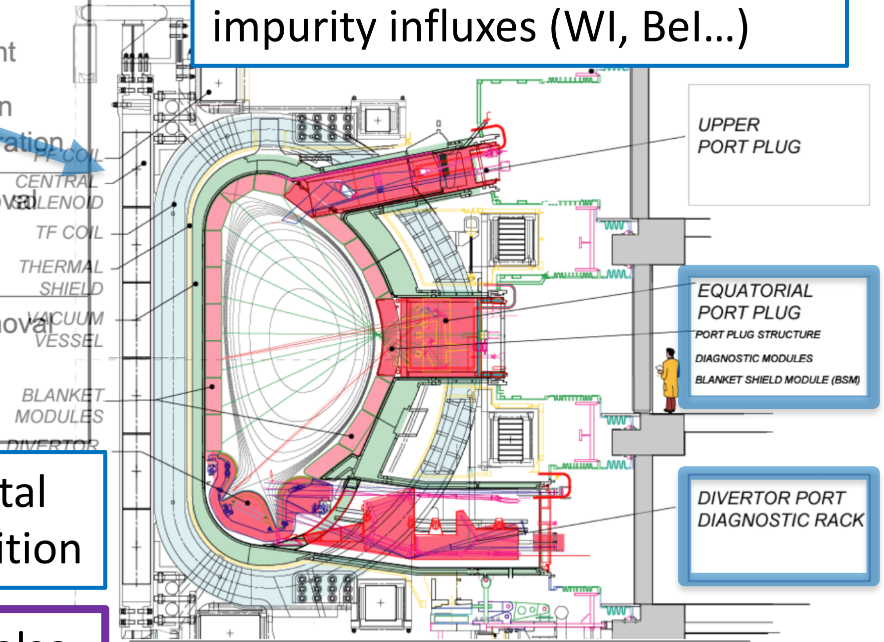
Tritium Retention	• Inventory limits	• Global measurement • Local measurement	• Tritium removal

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

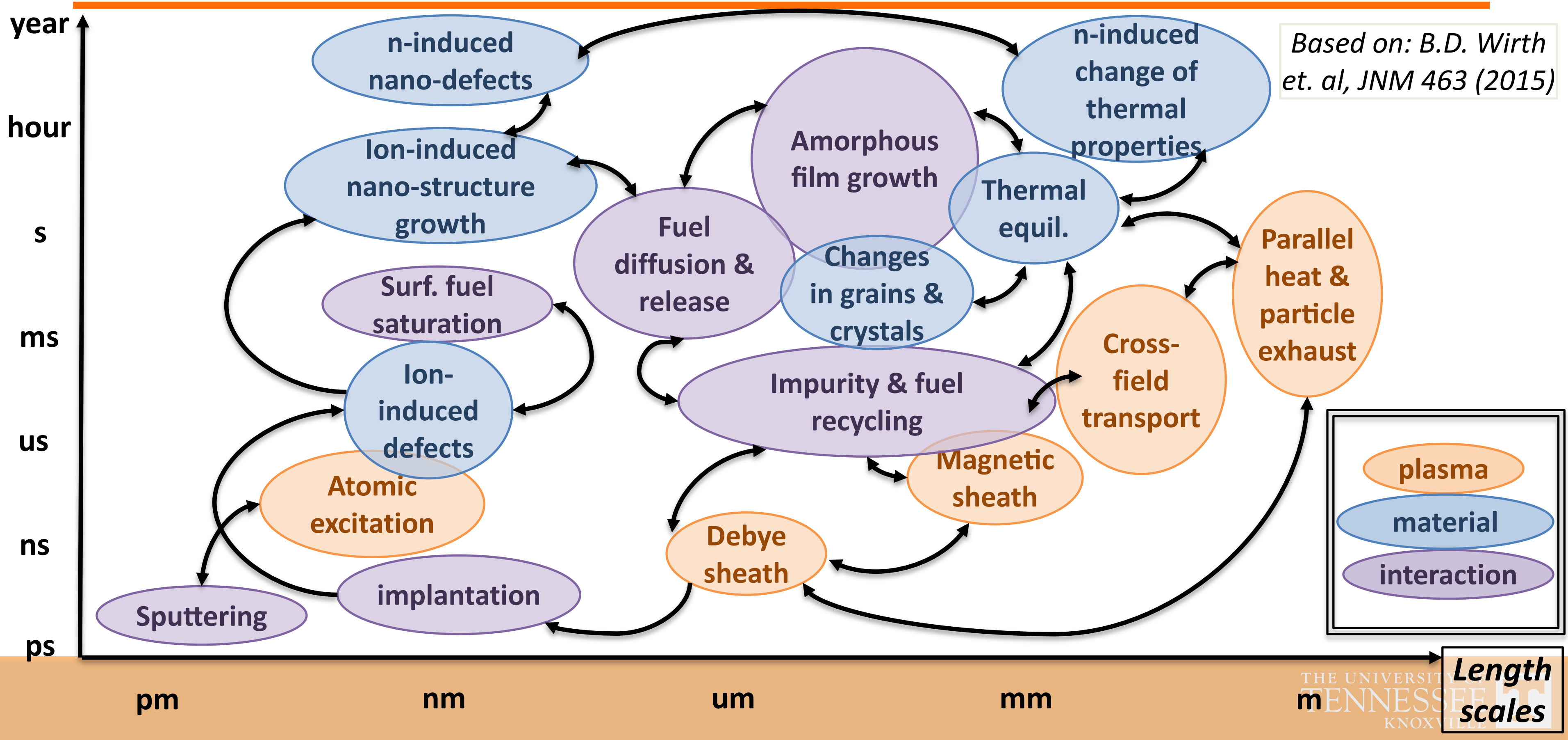


P. Andrews, ITER Summer School 2009

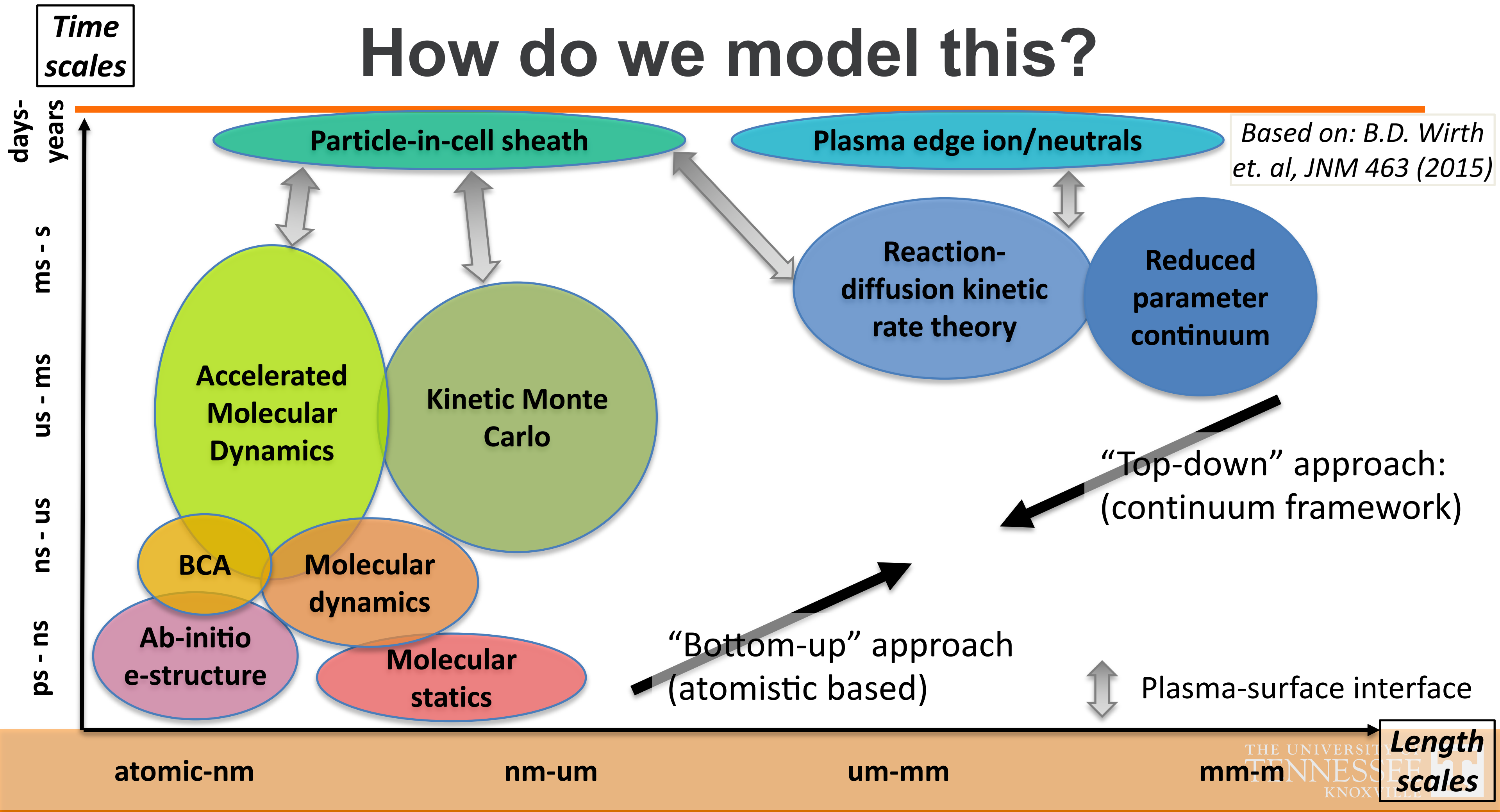
Post-mortem measurements: elemental analysis, mass loss/gains, layer deposition

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

PSI are multi-scale in nature



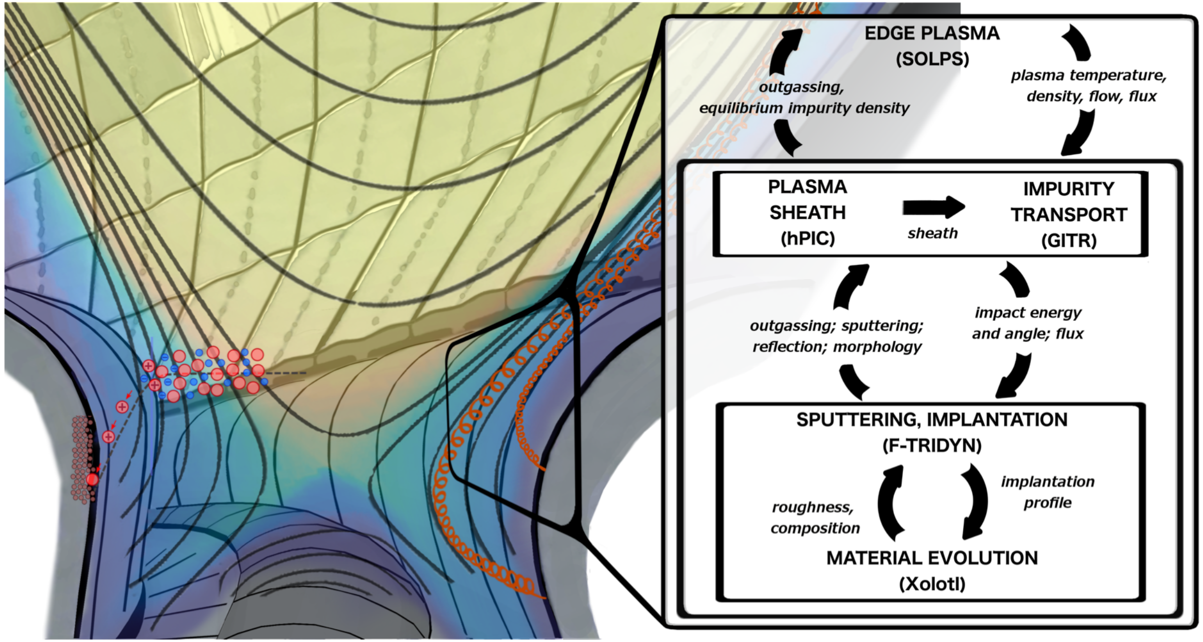
How do we model this?



Model coupling for a comprehensive description

Integrated modeling: to plasma, and to/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 lifetime of a fusion device;
- To this end, understanding and predicting PSI is essential

PSI lead to a wide-range of complex,mult-scale and closely interlinked 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 models is needed for their simulation and prediction;
- integrated models can often offer a more comprehensive description of the system

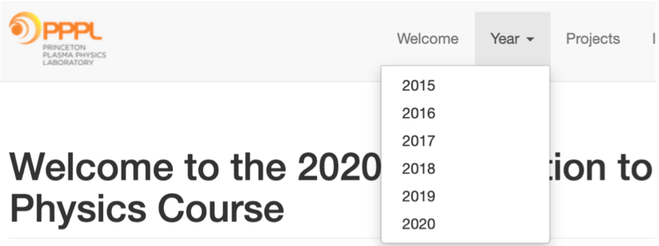
I really appreciate your time and attention.

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

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

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]

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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

Fusion materials modeling: Challenges and opportunities

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

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

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]

Institute of Physics Publishing Plasma Physics and Controlled
Plasma Phys. Control. Fusion 47 (2005) B303–B322 doi:10.1088/0741-3335/47/1

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]