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 solid wall components

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 2\textsuperscript{nd} week spending daily hours on zoom; it’s exhausting and I’ll try to present something \textbf{easy to follow}

- I want this lecture to be welcoming to a \textbf{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 \textbf{further resources} to dig deeper and where to read about the latest

\textit{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
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
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

Our most 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 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 exactly & always follow magnetic field lines (cross-field and other anomalous transport)
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
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 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...

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...

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

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...

chemical erosion

implantation

reflection

physical sputtering

clustering

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

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:**

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


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:
\[ W_{\text{plasma}} \times 10-50, \text{ deposition area } \times 2 \]

**ELMs:** expel \(~6\%\) of \( W_{\text{pl}} \) at 1-2 Hz
\[ \rightarrow \text{ peak } 5-10 \, \text{MJ/m}^2, \text{ 250-500 } \mu\text{s} \]
& increased particle fluxes

**Disruptions:** expel all of \( W_{\text{pl}} \)
\[ \rightarrow \text{ peak } 5-15 \, \text{MJ/m}^2, \text{ 1-3 } \text{ms} \]
(thermal quench)

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

Plasma ions may stay in the material

**Mainly studied in materials physics**

- **Surface saturation**
- **diffusion & permeation**
- **Trapping in defects**
- **Bubbles & blisters**

**This is a vacancy**

**This is an interstitial**

Fuel co-deposition

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)

Others (W) retention driven by implantation

T tends to diffuse; easier to recycle that in near-surface
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]:

\[ \text{ret}_T = \gamma_{\text{eros}} \times c_T \text{ in co-deposits} \]

Others (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

- 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)

- 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

David just explain this wonderfully an hour ago. ➔ focus on summary
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 $T_{\text{melt}}(\text{W-Be}) \approx T_{\text{melt}}(\text{W})/3$

- Impurities **dilute** the burning plasma + high-Z radiate → limit concentrations ($\rho_\text{W} < 10^{-5}$ for ITER)

- **Slag**: accumulation of material in specific areas

- **Formation of ‘dust’** (especially in machines w/ carbon)
E.g., the less-heard-of formation of dust

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
The substrate properties will be altered through:

- Vacancy/void defects from bubble bursting,
- And ion & neutron irradiation

Material mixing (alloying)

Vacancy/void defects from bubble bursting, and ion & neutron irradiation

Amorphous film growth

---

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 → higher T trapping
- Introduce impurity sites

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

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

Mixing of the target material / impurities:
- Alloying: W+Be → lower melting temperature
- Changes in morphology → higher T trapping
- Form carbides
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Damage by irradiation with neutrons*: dis/re-organization of the target material’s structure
- Increase T trapping
- Micro-cracking

M.J. Baldwin and R.P. Doerner
*Nuclear Fusion 48 (2008) 3
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/m²
- Transient events – need to be mitigated

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’)

*ITER: International Thermonuclear Experimental Reactor
In addition to ions, the plasma deposits heat

Heat fluxes affect the material & surface by changing its temperature

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

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

Fuel retention increases due to material degradation

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
- ....

The usual *trade-off* is Low vs high Z: easier to erode but less problematic (beneficial) VS harder to erode but higher consequence

*Image from: matmatch > blog > fusion-energy-materials*
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 heat flux**
The volumetric heat deposition has a typical maximum value of a few W/cm² 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 & vol heat deposition**

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.

**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/m² 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/m². 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/m². 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*...)

*temperature profile in PLT during W accumulation*
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 content, driven by source & impurity accumulation (e.g., P, C, O) →

Vacuum-grade graphite available → benign under thermal overload → almost all devices

Operation with high-current, high density and/or divertor has allowed using refractory (high-Z) metals, with low plasma temperature in contact with the high-Z metals →

All metal ITER: a tungsten divertor, beryllium first wall
Requirements change with the area

**Divertor:**
- high heat & particle fluxes
- Smaller area (than the 1\textsuperscript{st} wall)
- Further from the confined plasma (lower impurity penetration)

\begin{center}
\textit{Allows for use of high-Z materials}
\end{center}

**First wall:**
- Large area
- Close to the confined plasma
- Be is the choice of ITER

\begin{center}
\textit{Low-Z seem to suit best}
\end{center}

- 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\textsuperscript{st} wall)
Each PFM candidate has pro’s & con’s

<table>
<thead>
<tr>
<th>Carbon (Fiber Composites, CFC)</th>
<th>Beryllium</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Absence of melting</td>
<td>- High thermal conductivity</td>
</tr>
<tr>
<td>- Excellent thermal Shock resistance</td>
<td>- Oxygen gatherer</td>
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<tr>
<td>- High thermal conductivity</td>
<td>- Little T chemical affinity</td>
</tr>
<tr>
<td>- Low atomic number</td>
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<table>
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<tr>
<th>SiC (ceramics)</th>
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<tr>
<td>- Low atomic number</td>
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<tr>
<td>- Low activation</td>
</tr>
<tr>
<td>- n-damage resilience</td>
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<tr>
<td>- Medium T chemical affinity</td>
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<tr>
<td>- T permeation barrier</td>
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<table>
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<th>Tungsten (&amp; alloys)</th>
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<tr>
<td>- Highest melting point</td>
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<td>- High thermal conductivity</td>
</tr>
<tr>
<td>- Low sputtering yields</td>
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<tr>
<td>- No T chemical affinity / inventory</td>
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<tr>
<td>- Low activation</td>
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</tbody>
</table>
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 solids 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!*
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?

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<tr>
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<th>Measurement</th>
<th>Management</th>
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<td>• Scheduled replacement</td>
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<td>• Wall component lifetime</td>
<td>• Observation during operation</td>
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<td>• Local microbalance</td>
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<td>• Other methods</td>
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|                                 | • Other methods                |                               |
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In-situ: Spectrometers measure impurity influxes (WI, Bel...)

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

Based on: B.D. Wirth et. al, JNM 463 (2015)
How do we model this?

Based on: B.D. Wirth et. al, JNM 463 (2015)

Time scales

days-years

ms-s

us-ms

ns-ns

Particle-in-cell sheath

Plasma edge ion/neutrals

Reaction-diffusion kinetic rate theory

Reduced parameter continuum

“Top-down” approach: (continuum framework)

“Bottom-up” approach (atomistic based)

Plasma-surface interface

Acceleration scales

atomic-nm

nm-um

um-mm

mm-m
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, multi-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

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)
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 papers.