PPPL PRINCETON PLASMA PHYSICS LABORATORY

Plasma-Material Interactions

Hanna Schamis (PPPL)

Introduction to Plasma and Fusion, June 09, 2026

Special thanks to Prof. Angela M. Capece (TCNJ)

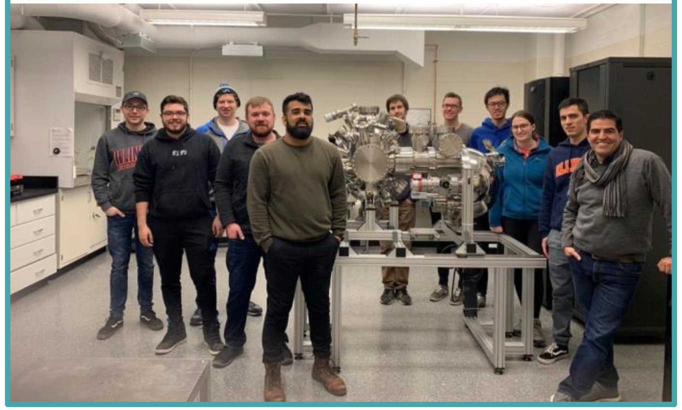
About me – how I got here

Grew up in Buenos Aires

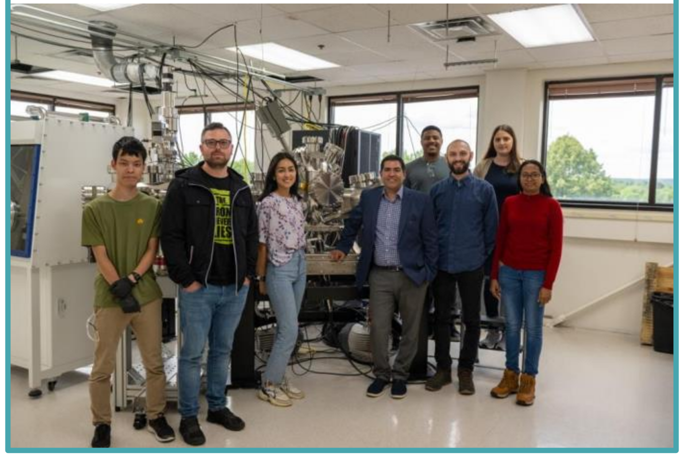
University of Michigan
(2016, BS Physics)

SULI at PPPL (x2!)

University of Illinois (2019, MS Nuclear, Plasma, and Radiological Engineering)

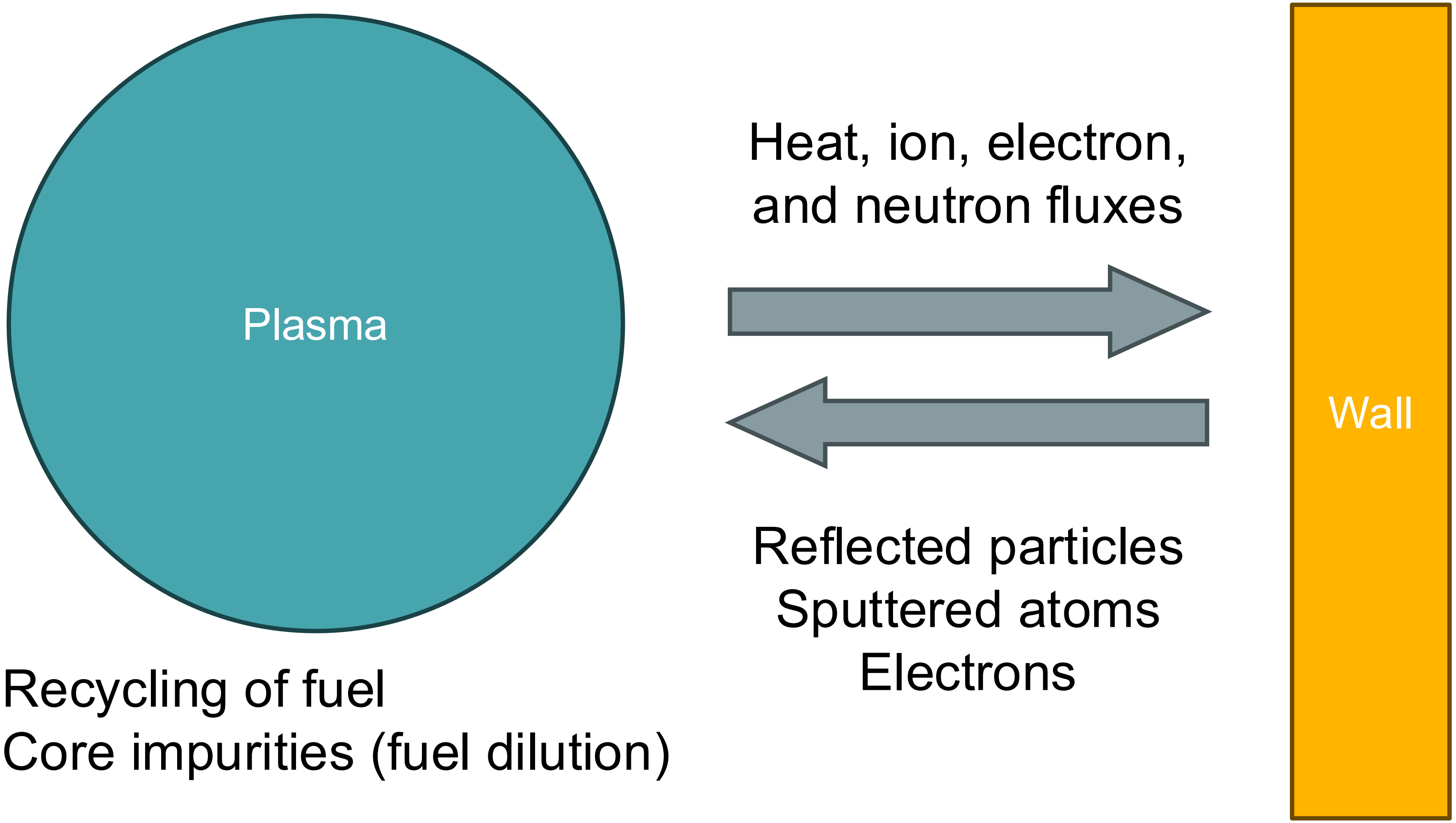


Penn State (PhD Nuclear Engineering)



PPPL (2023 -- ??)

Plasmas affect materials and materials affect plasmas



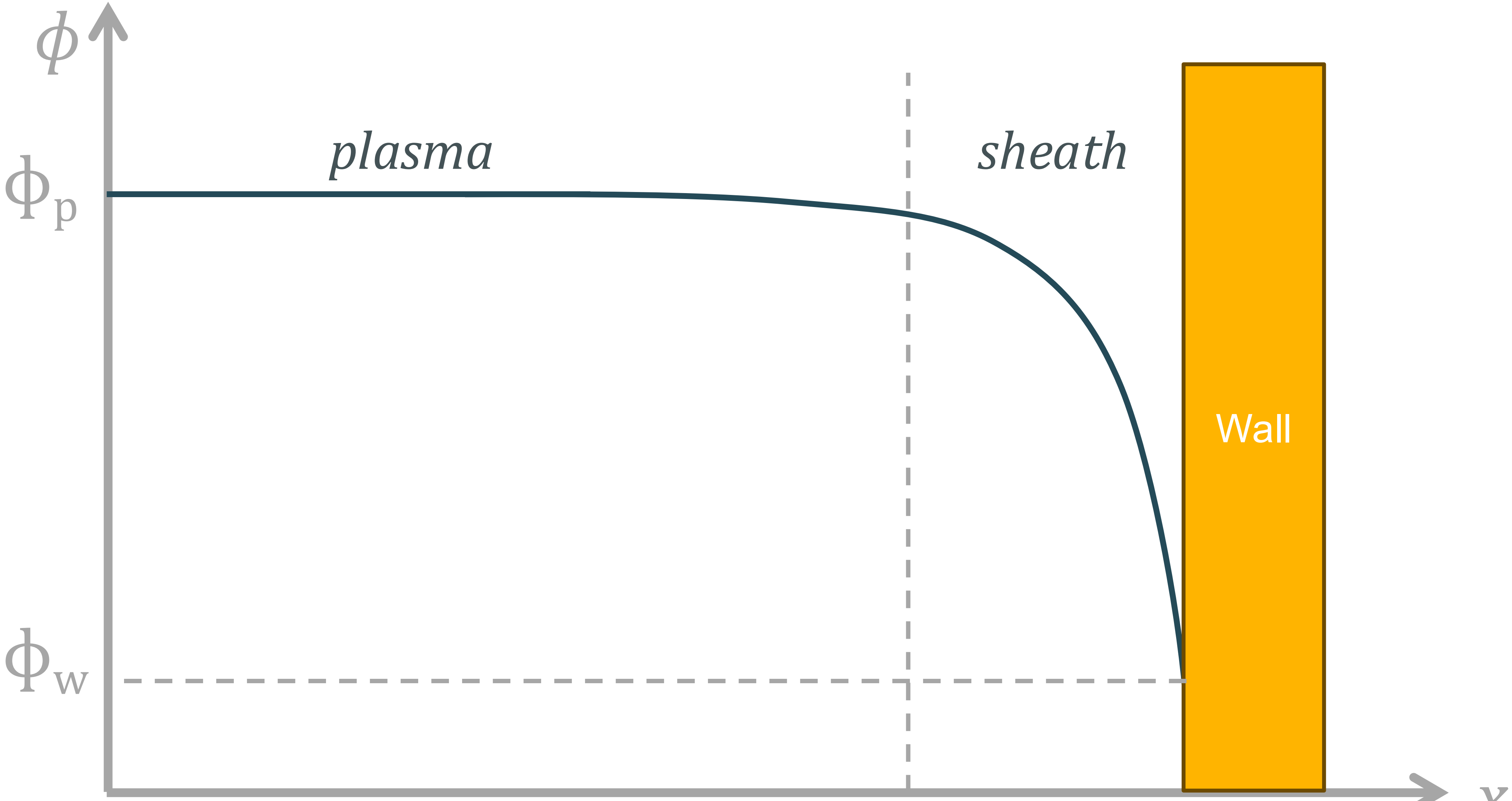
Heat, ion, electron,
and neutron fluxes

Reflected particles
Sputtered atoms
Electrons

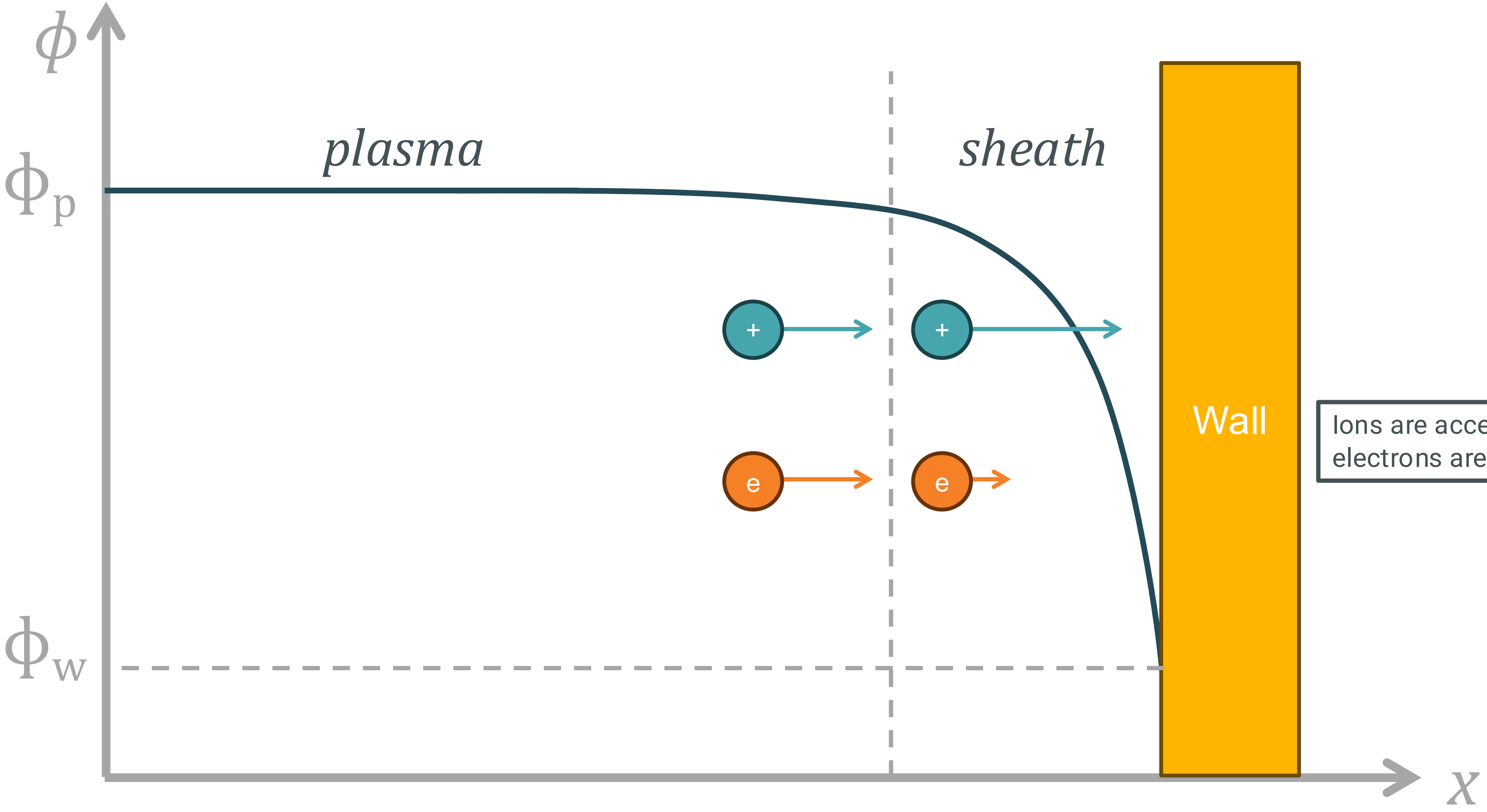
Melting
Cracking
Embrittlement
Transmutations
Erosion
Retention
Chemistry

Recycling of fuel
Core impurities (fuel dilution)

The sheath plays a dominant role in plasma-material interactions

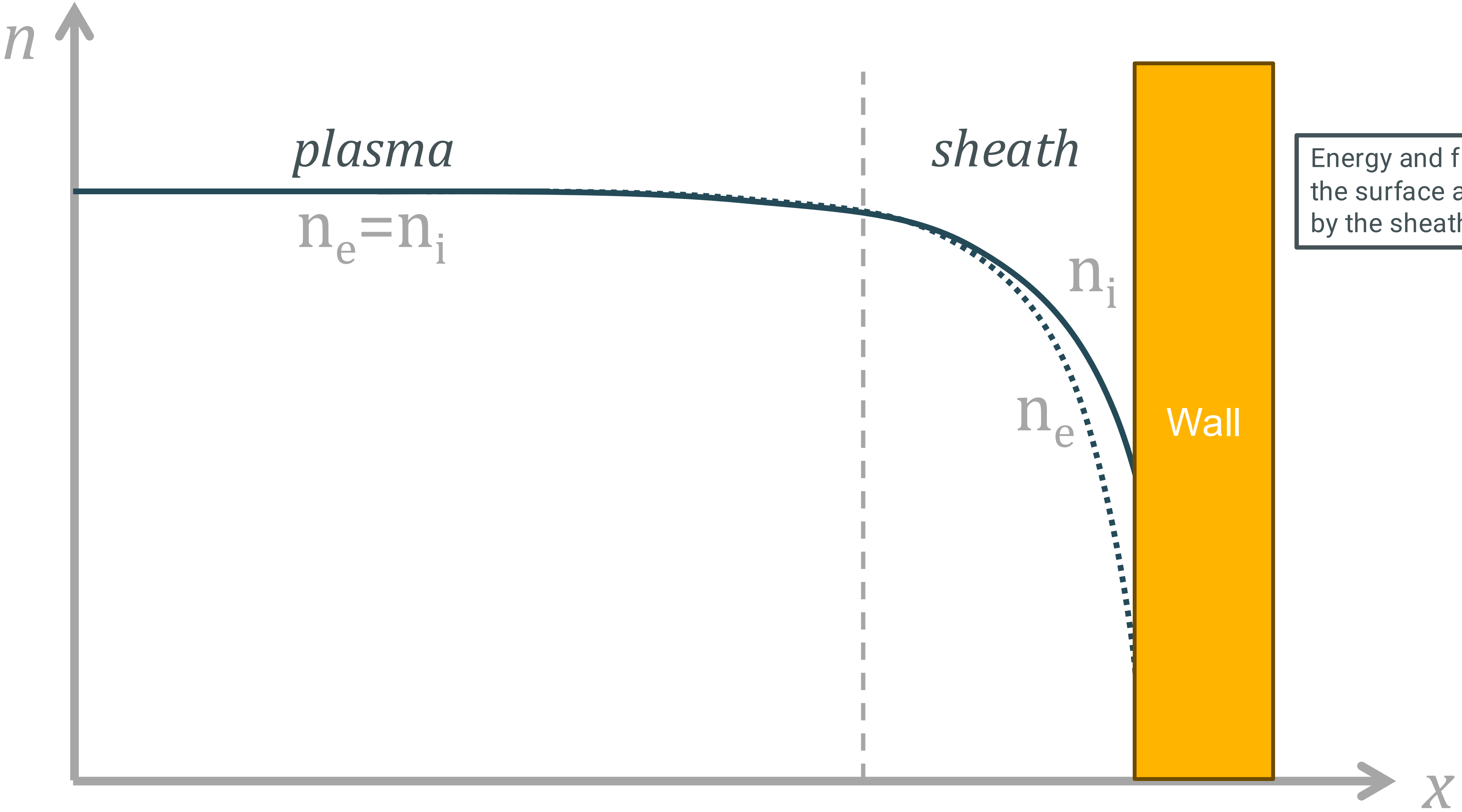


The sheath plays a dominant role in plasma-material interactions



Ions are accelerated, electrons are repelled

The sheath plays a dominant role in plasma-material interactions



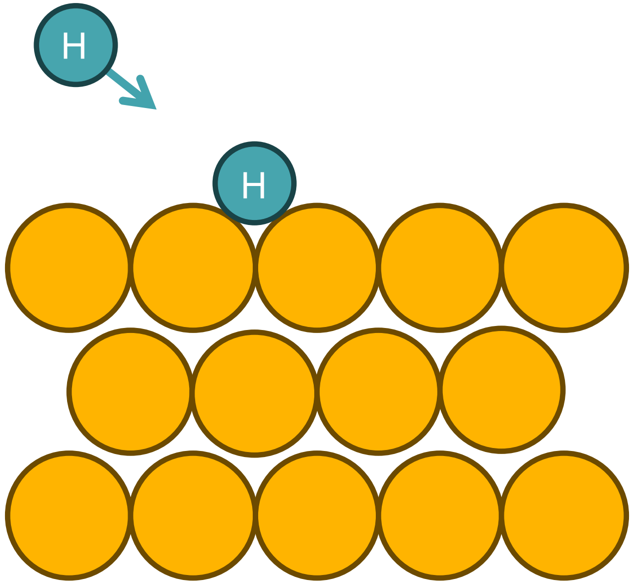
Energy and flux of ions to the surface are determined by the sheath

The basic mechanisms at the plasma-materials interface are largely determined by the ion energy

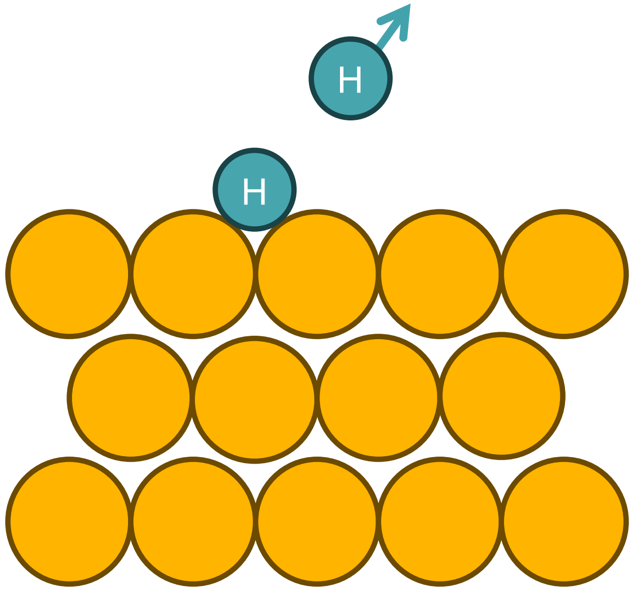
< 10 eV

Adsorption/Desorption

Adsorption



Desorption

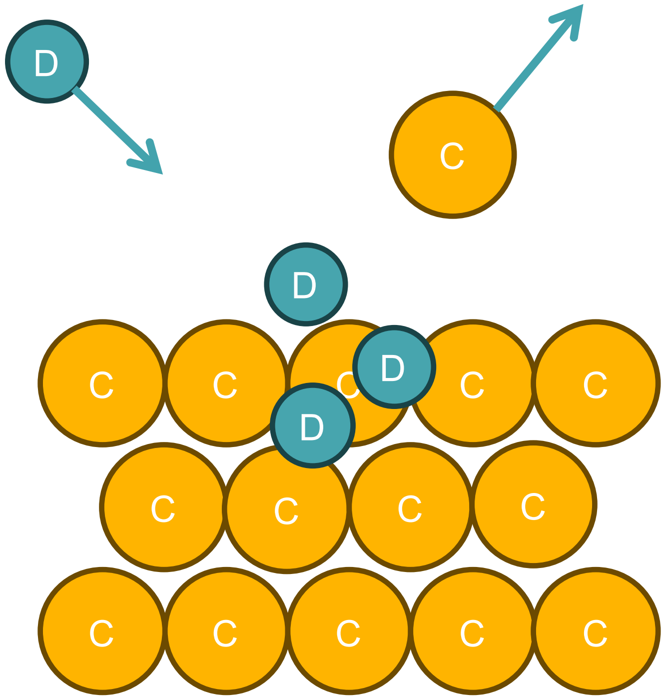


The basic mechanisms at the plasma-materials interface are largely determined by the ion energy

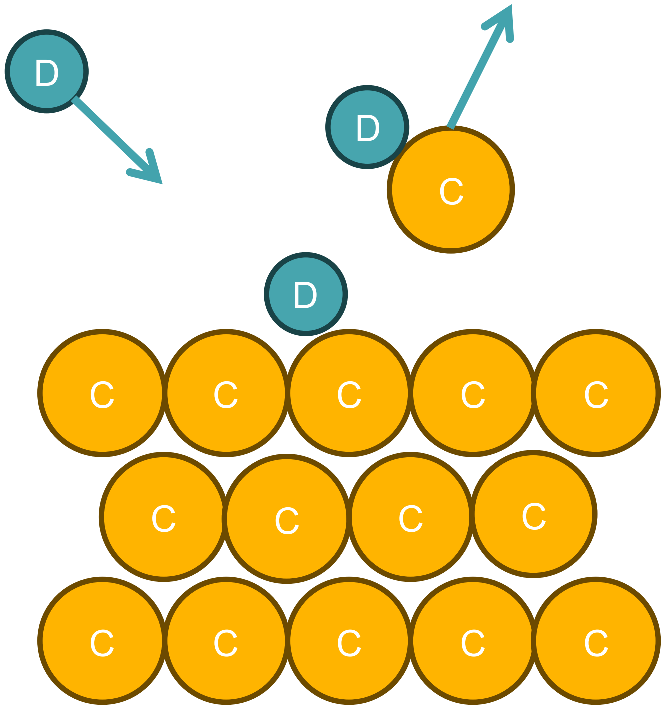
< 10 eV
Adsorption/Desorption

10s eV – 5 keV
Sputtering

Physical Sputtering



Chemical Sputtering



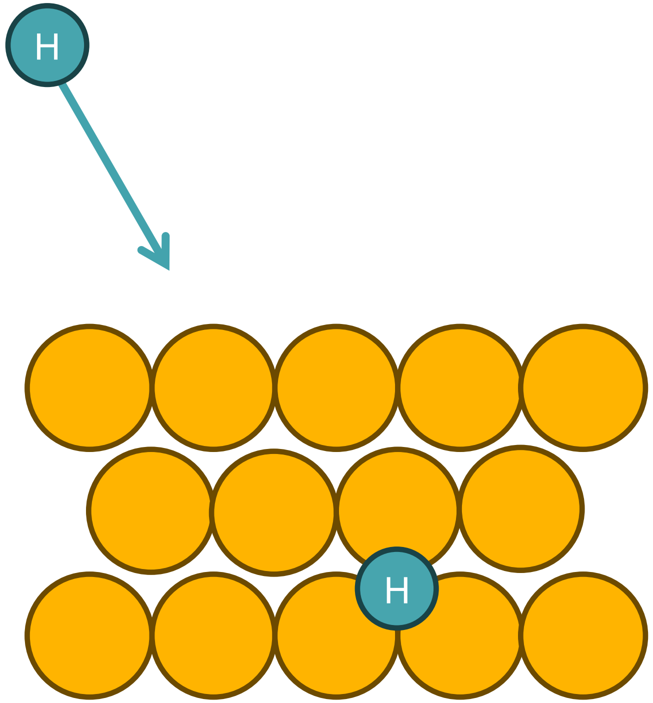
The basic mechanisms at the plasma-materials interface are largely determined by the ion energy

< 10 eV
Adsorption/Desorption

10s eV – 5 keV
Sputtering

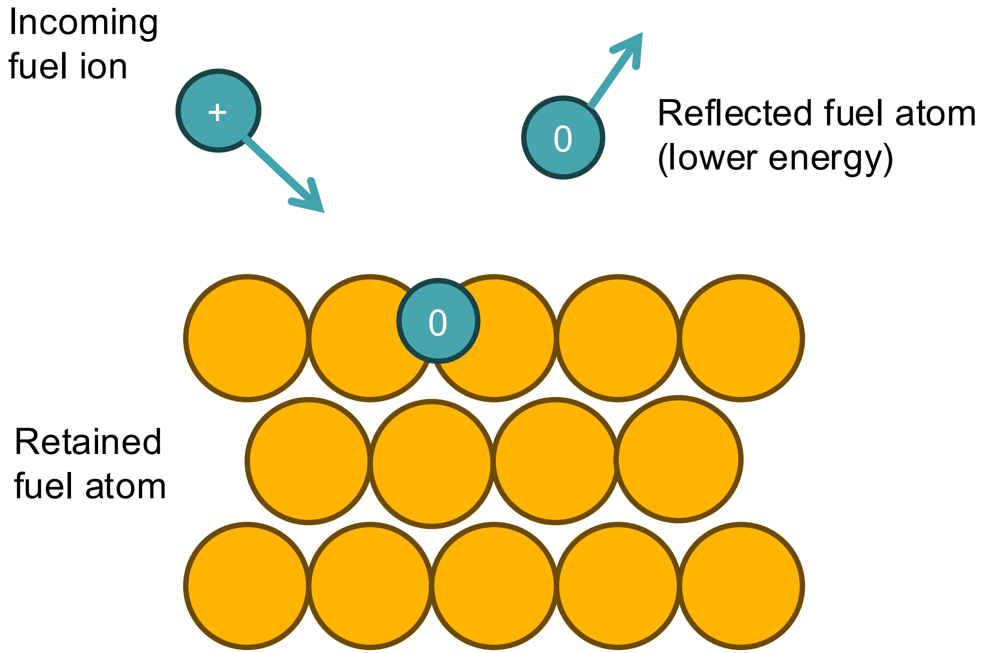
>10 keV
Implantation

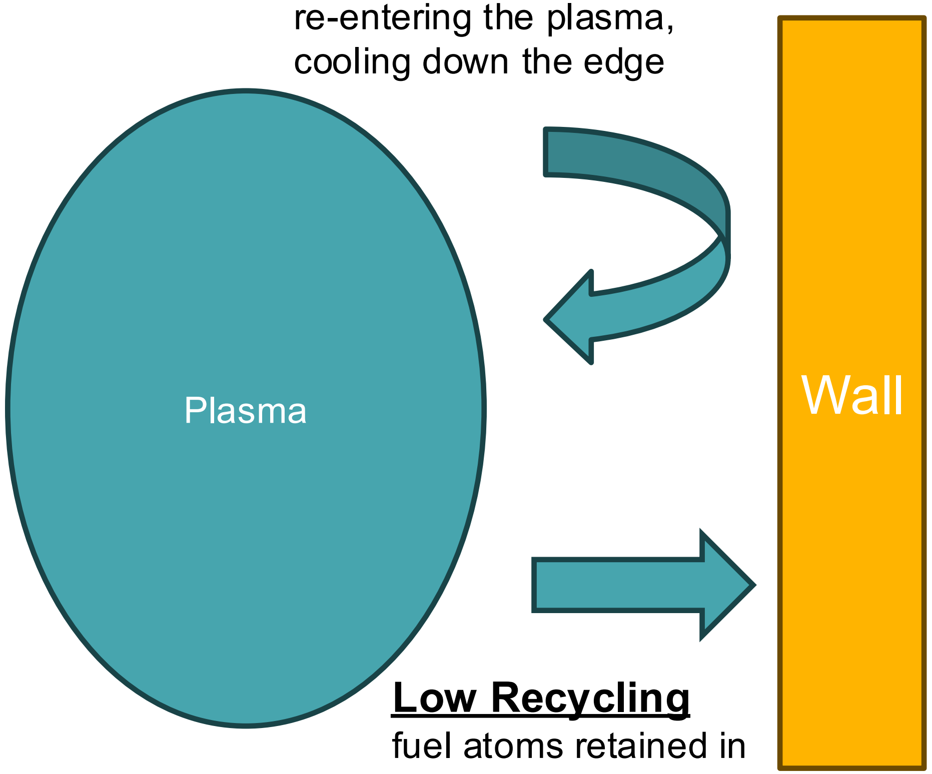
Implantation



The basic mechanisms at the plasma-materials interface are largely determined by the ion energy

Reflection/recycling



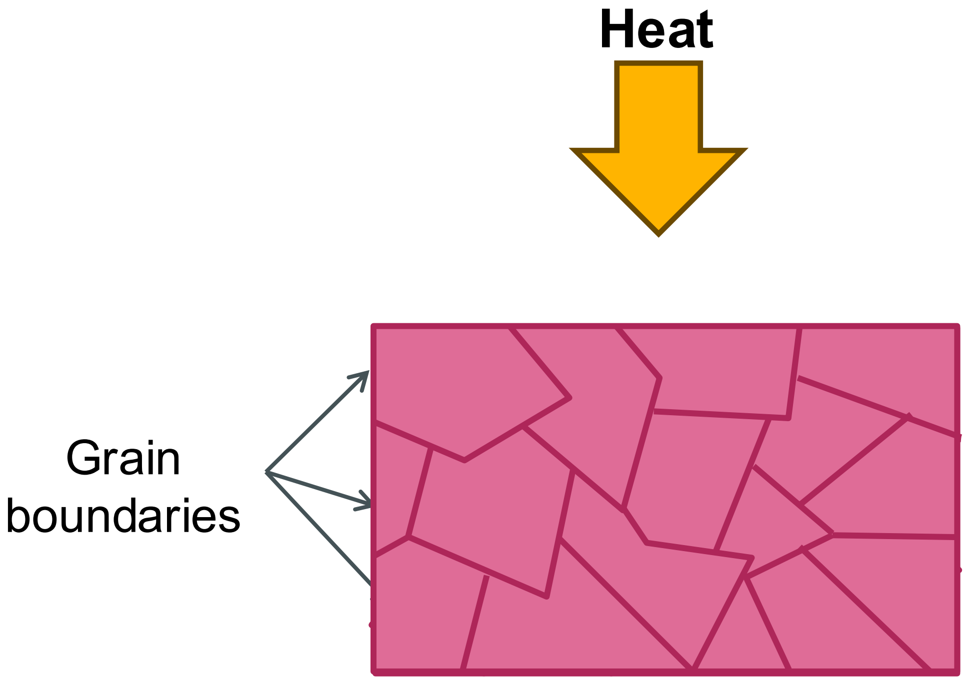


High Recycling
fuel atoms reflecting and
re-entering the plasma,
cooling down the edge

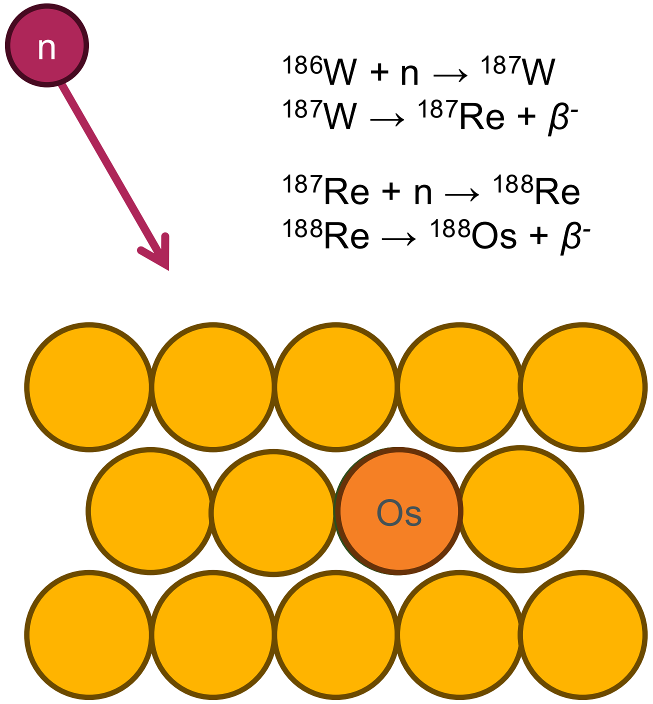
Low Recycling
fuel atoms retained in
wall, no cooling of edge

In fusion reactors, high heat fluxes and radiation also modify materials

Recrystallization



Transmutation

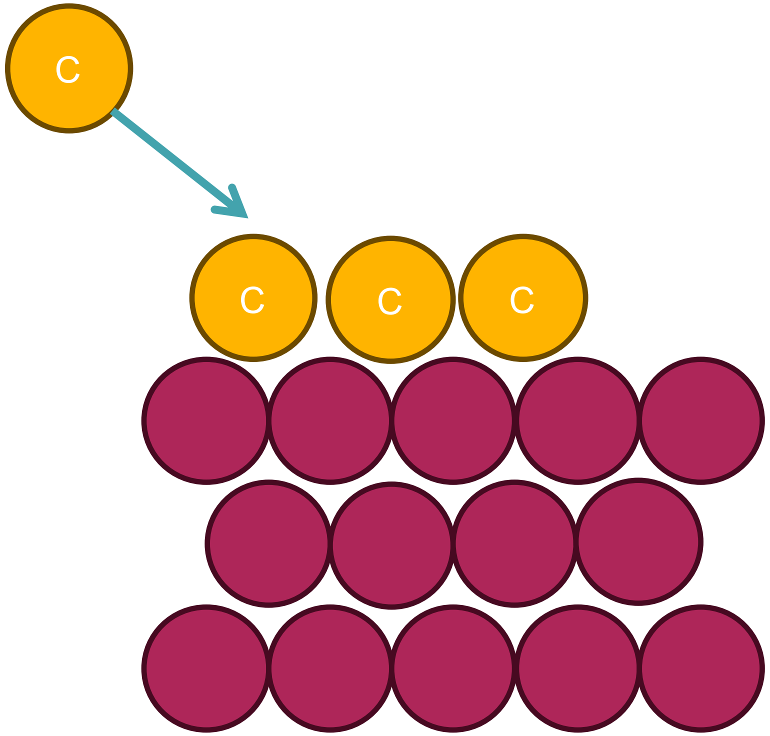


$^{186}W + n \rightarrow {}^{187}W$
$^{187}W \rightarrow {}^{187}Re + \beta^-$

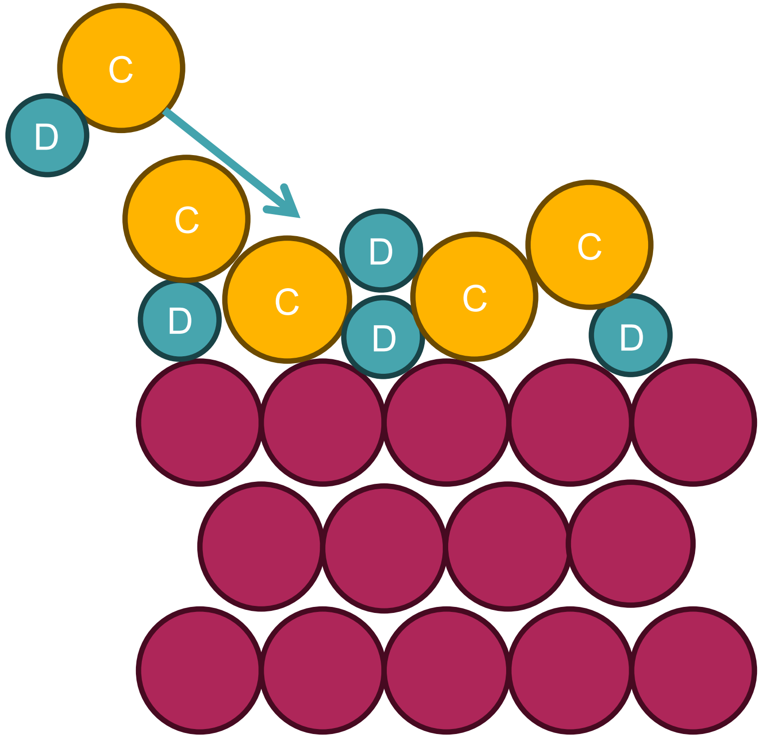
$^{187}Re + n \rightarrow {}^{188}Re$
$^{188}Re \rightarrow {}^{188}Os + \beta^-$

Long-term and long-range plasma-material interactions also play an important role in fusion reactor material performance

Redeposition



Co-Deposition

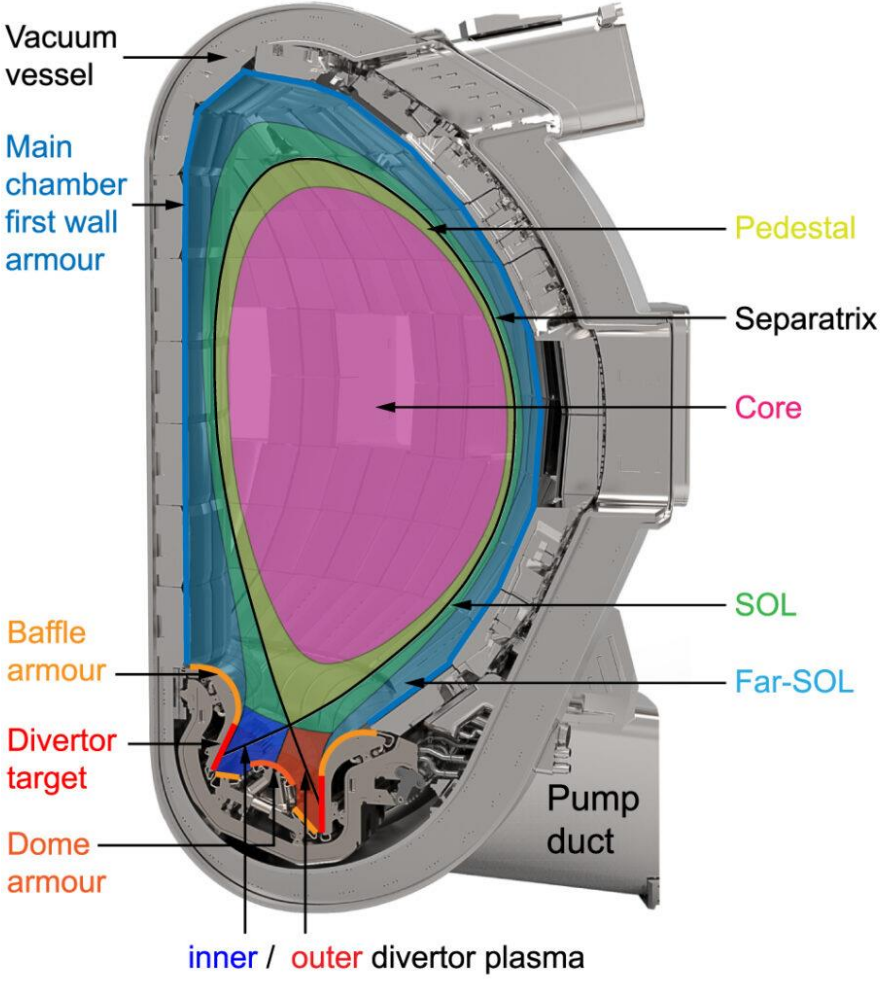


What material do we use to build plasma-facing components for a fusion reactor?

Two main regions of PMI:

- Divertor / target
  - High ion fluxes (10^{24} m^{-2} s^{-1})
  - Ion energies 10—150 eV
  - High steady state heat fluxes (20 MW m^{-2})
  - Transient heat fluxes (10 GW m^{-2})

- First wall / main chamber
  - High heat fluxes
  - Charge-exchange neutrals up to 200 eV

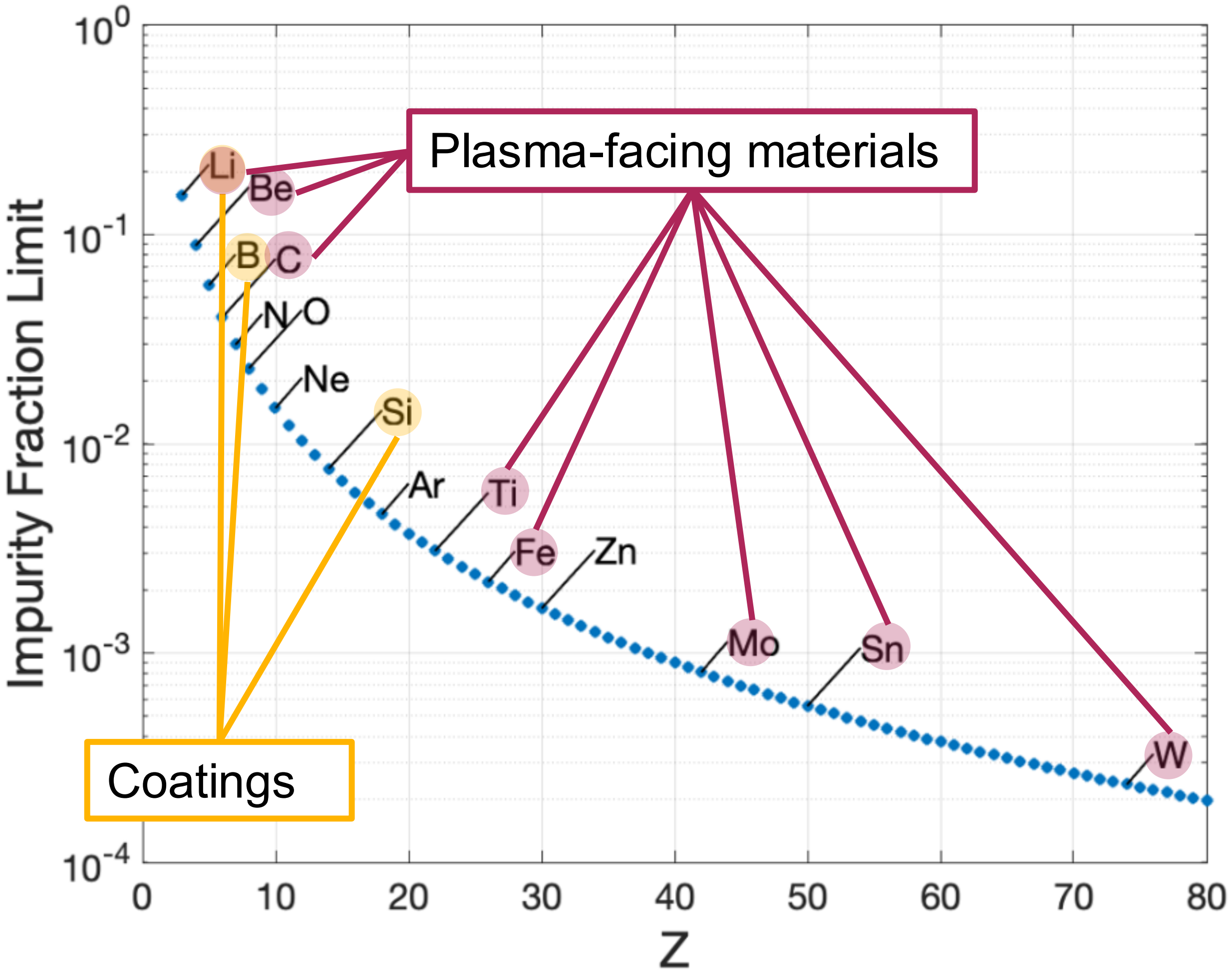


[Krieger Nucl. Fusion 2025]

What material do we use to build plasma-facing components for a fusion reactor?

Desired characteristics:

- Low Z and/or low sputter yield
  - Higher impurity fraction limit for low Z



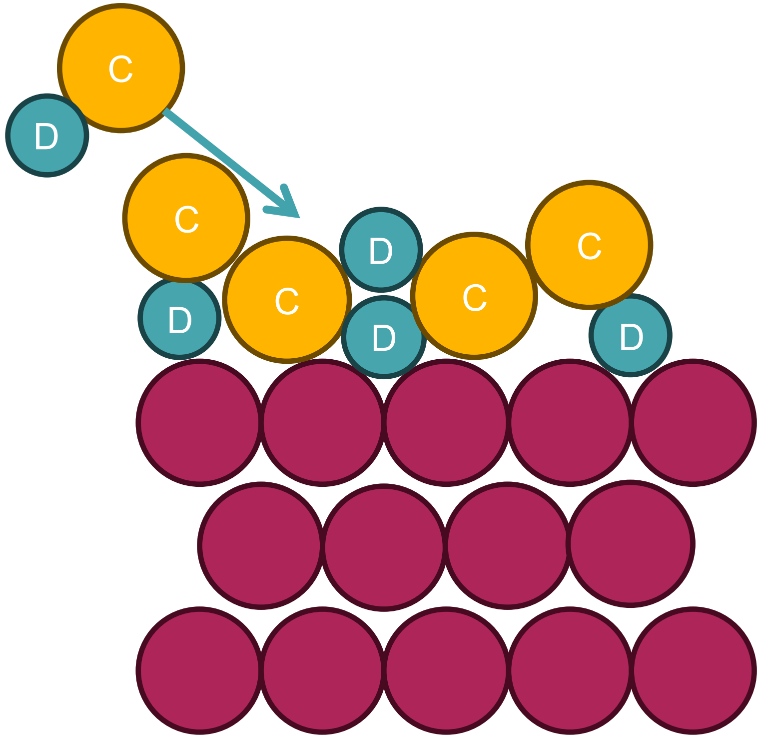
[M. S. Parsons (2023)]

What material do we use to build plasma-facing components for a fusion reactor?

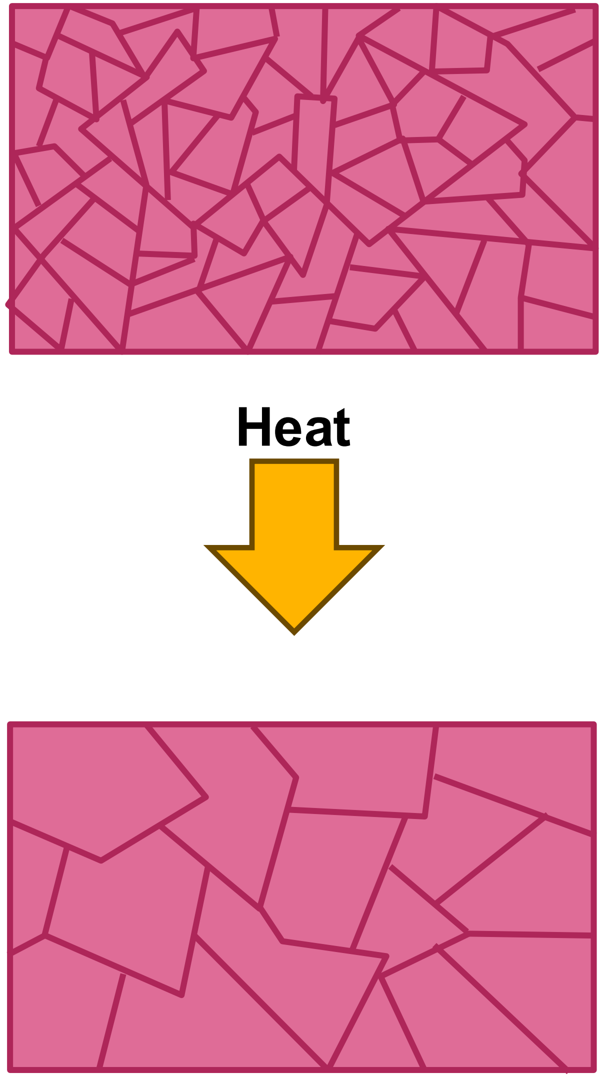
Desired characteristics:

- Low Z and/or low sputter yield
- Low hydrogen isotope retention and low co-deposition rate
  - Concerns about tritium inventory

Co-Deposition



What material do we use to build plasma-facing components for a fusion reactor?



Desired characteristics:

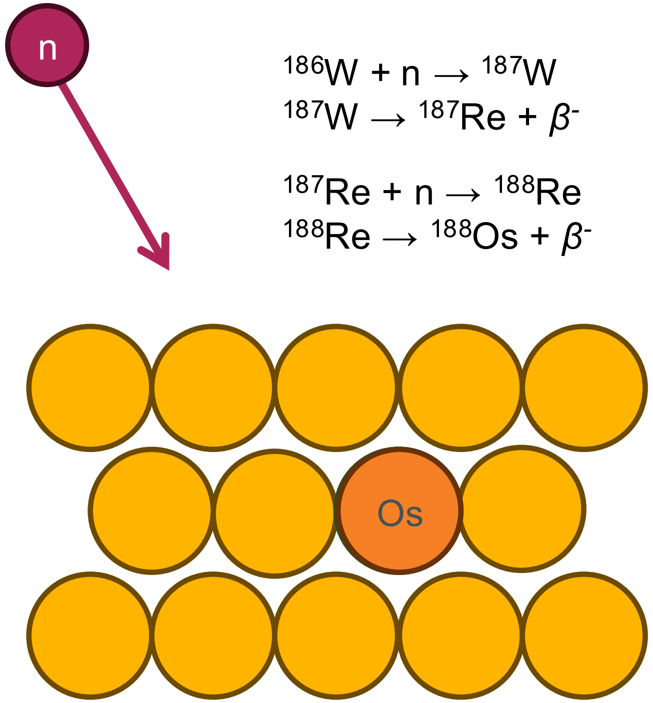
- Low Z and/or low sputter yield
- Low hydrogen isotope retention and low co-deposition rate
- High thermal conductivity, high melting temperature
  - Able to remove high thermal fluxes deposited on the surface

What material do we use to build plasma-facing components for a fusion reactor?

Desired characteristics:

- Low Z and/or low sputter yield
- Low hydrogen isotope retention and low co-deposition rate
- High thermal conductivity, high melting temperature
- Neutron resistance
  - Avoid activation that leads to long-lived byproducts
  - Avoid transmutations that lead to composition and property changes

Transmutation



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	Carbon
Z	6
Sputtering	High (high chemical yield)
H isotope retention	High (C-H bonding)
Thermal conductivity	~200 W m^{-1} K^{-1}
Melting temperature	None/Sublimation at 3642 C
Neutron resistance	Good
Other	

Widely used PFM
- DIII-D
- NSTX / NSTX-U
- ASDEX
- Tore Supra
- KSTAR (pre-2023)

Among many others

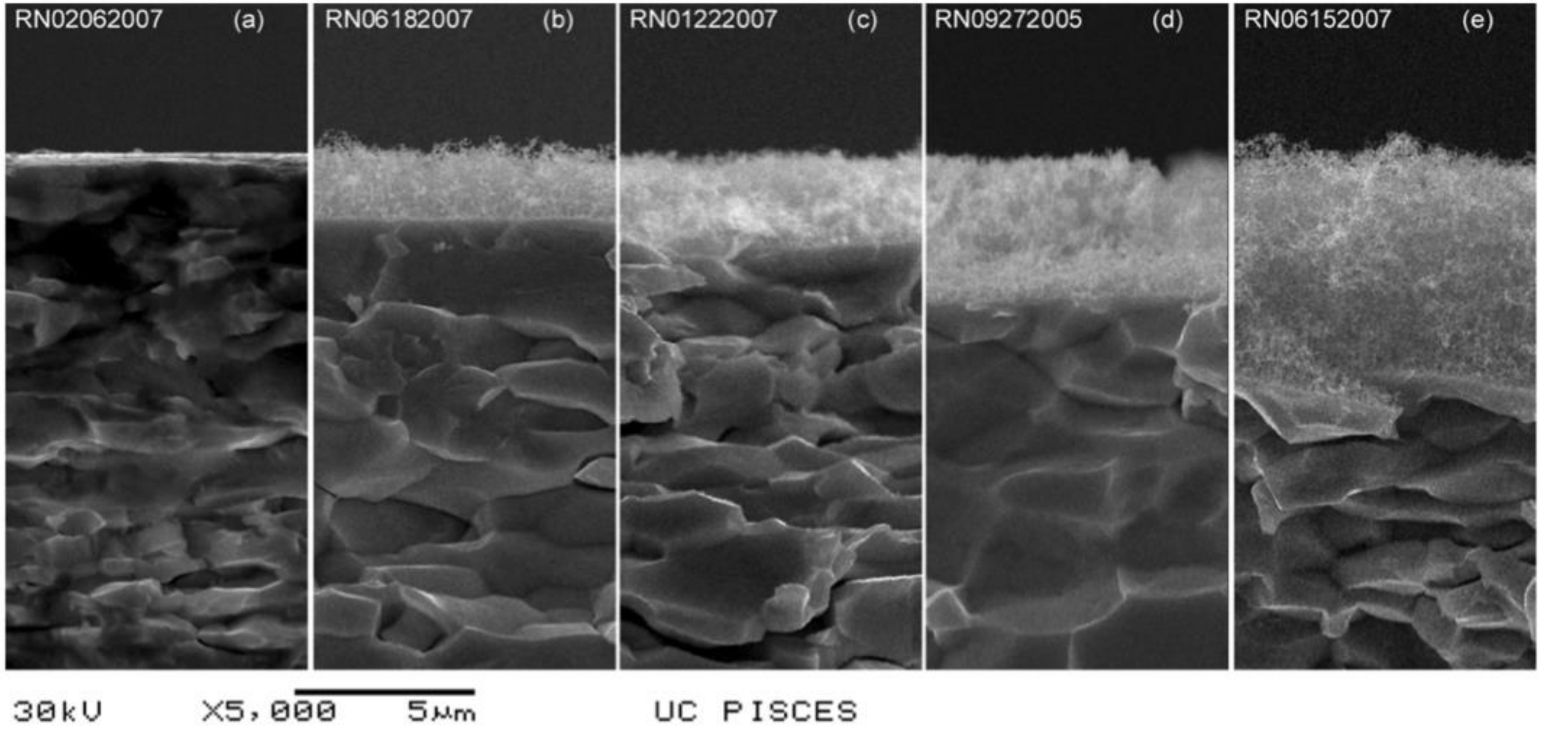
	Carbon	Tungsten
Z	6	74
Sputtering	High (high chemical yield)	Low (no chem. sput.)
H isotope retention	High (C-H bonding)	Low
Thermal conductivity	~200 W m^{-1} K^{-1}	173 W m^{-1} K^{-1}
Melting temperature	None/Sublimation at 3642 C	3422 C
Neutron resistance	Good	Good – transmutation and embrittlement are possible
Other		Hard to fabricate

Widely used PFM
- ASDEX Upgrade
- WEST (formerly Tore Supra)
- EAST (divertor)

Anticipated:
- KSTAR
- DIII-D
- ITER

W has many attractive properties, but it can degrade over time with ion exposure

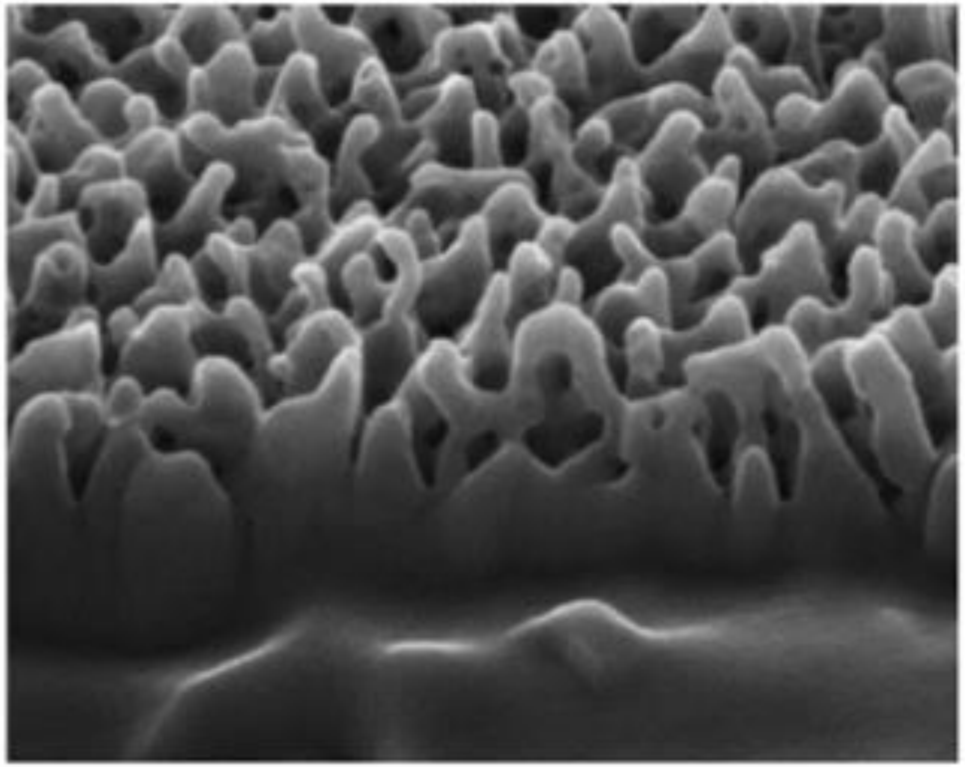
- For example, W fuzz formation with He ion exposure

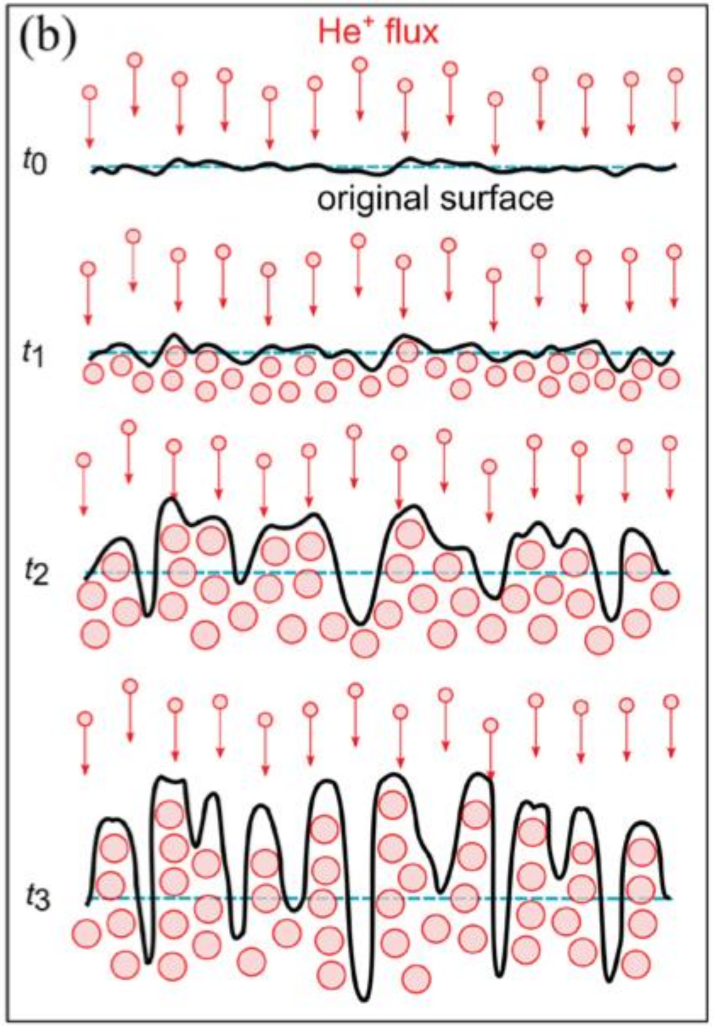


[M. J. Baldwin, et al., Nuclear Fusion 48 (2008)]

W has many attractive properties, but it can degrade over time with ion exposure

- For example, W fuzz formation with He ion exposure

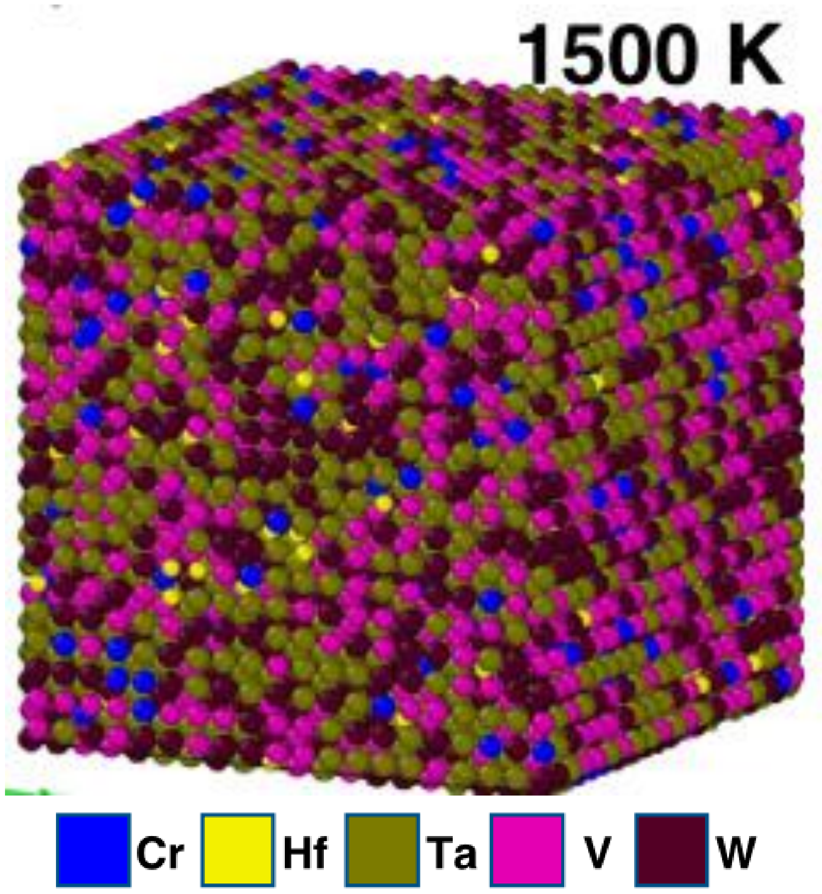




[D. Dasgupta, et al., Nuclear Fusion 59 (2019)]

Novel W-based alloys and composites have some additional resilience to ion and neutron-induced material degradation

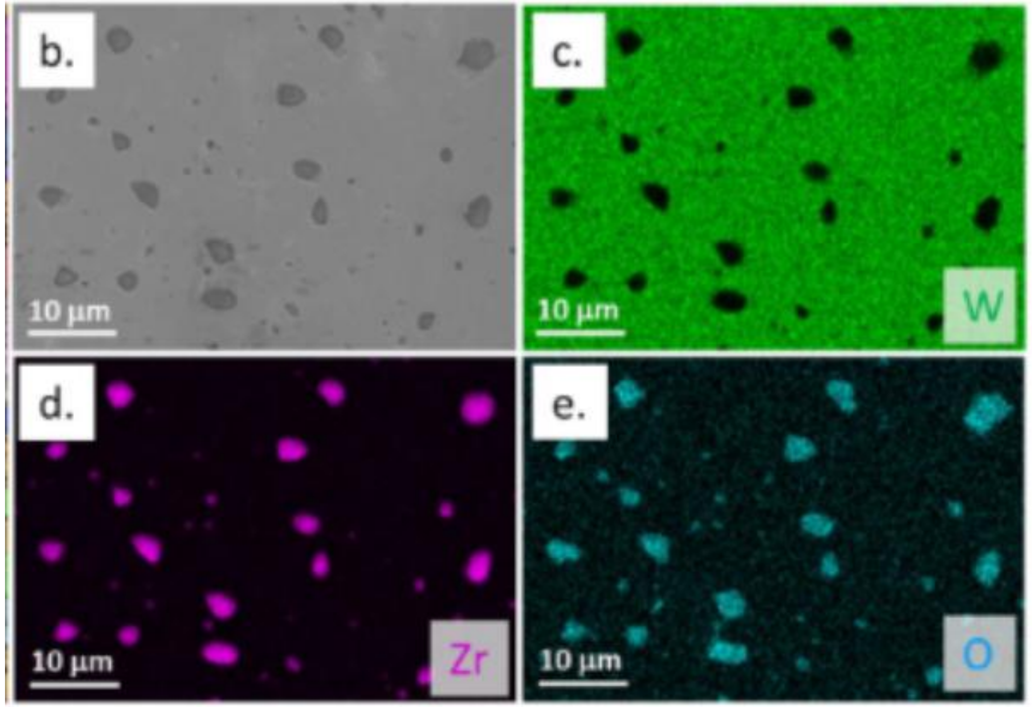
- High-entropy alloys (HEAs)
  - Example: $W_{31}\ Ta_{34}\ Cr_5\ V_{27}Hf_3$



[O. El Atwani *et al.* Nature 2023,

Novel W-based alloys and composites have some additional resilience to ion and neutron-induced material degradation

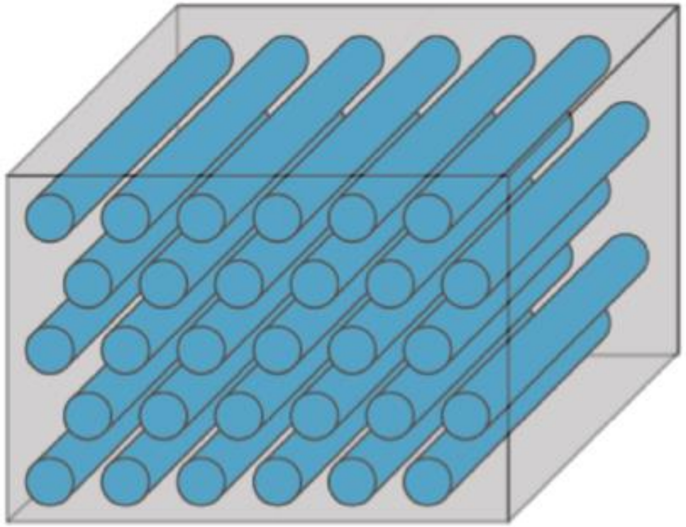
- High-entropy alloys (HEAs)
- Dispersion-strengthened tungsten composites
    - Transition metal carbide or oxide dispersoids

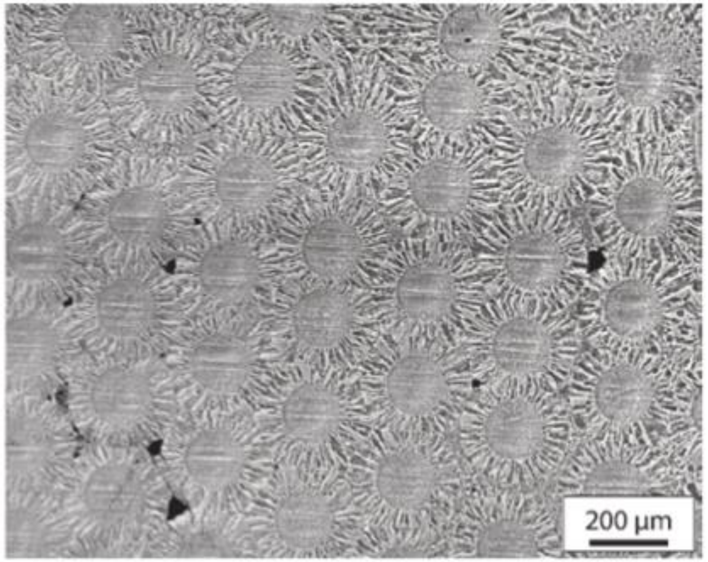


[T. Marchhart, *et al.*, Sci. Rep. 2024]

Novel W-based alloys and composites have some additional resilience to ion and neutron-induced material degradation

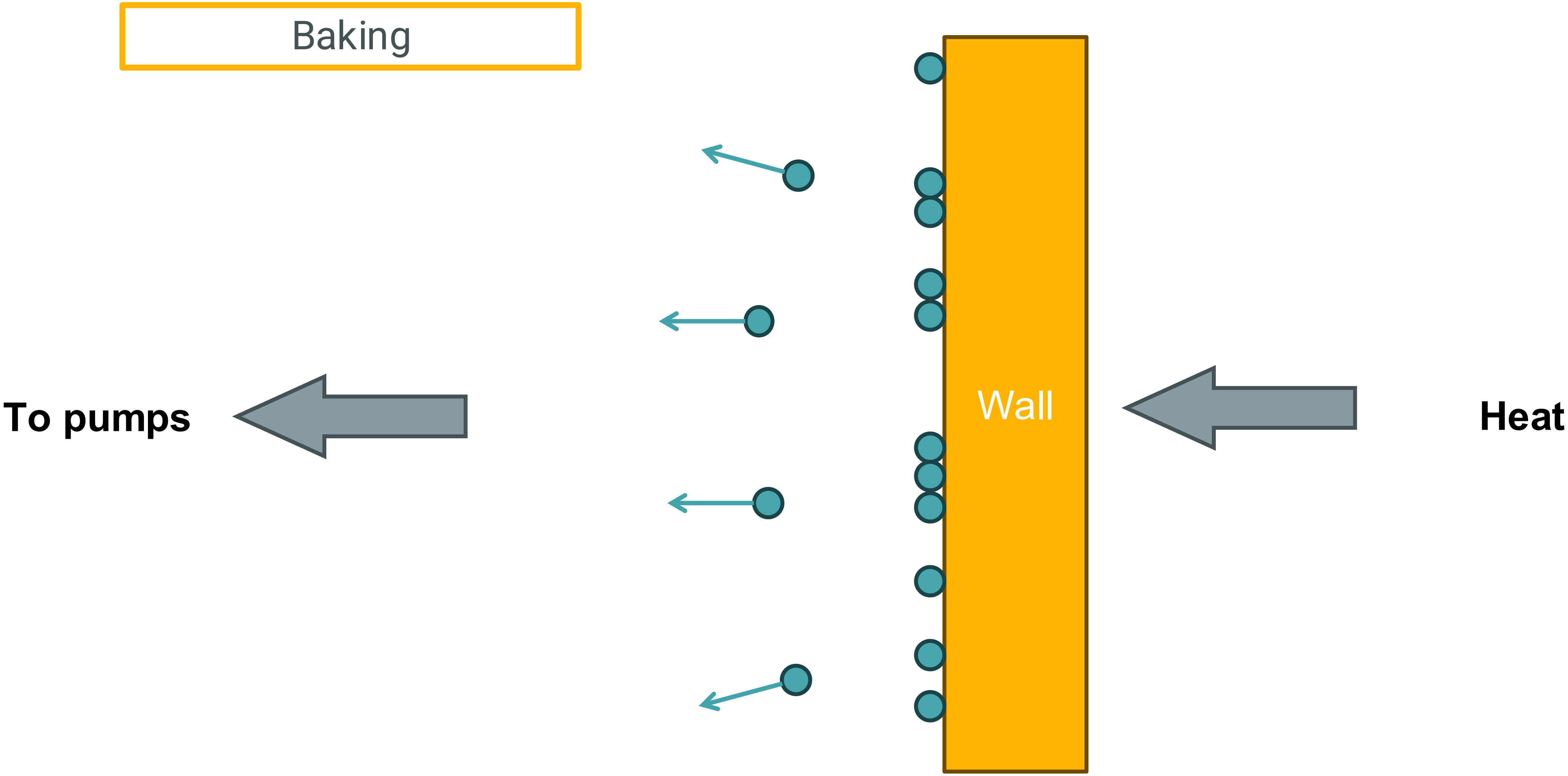
- High-entropy alloys (HEAs)
- Dispersion-strengthened tungsten composites
- Tungsten Fiber composites
  - Tungsten fiber embedded in a tungsten matrix





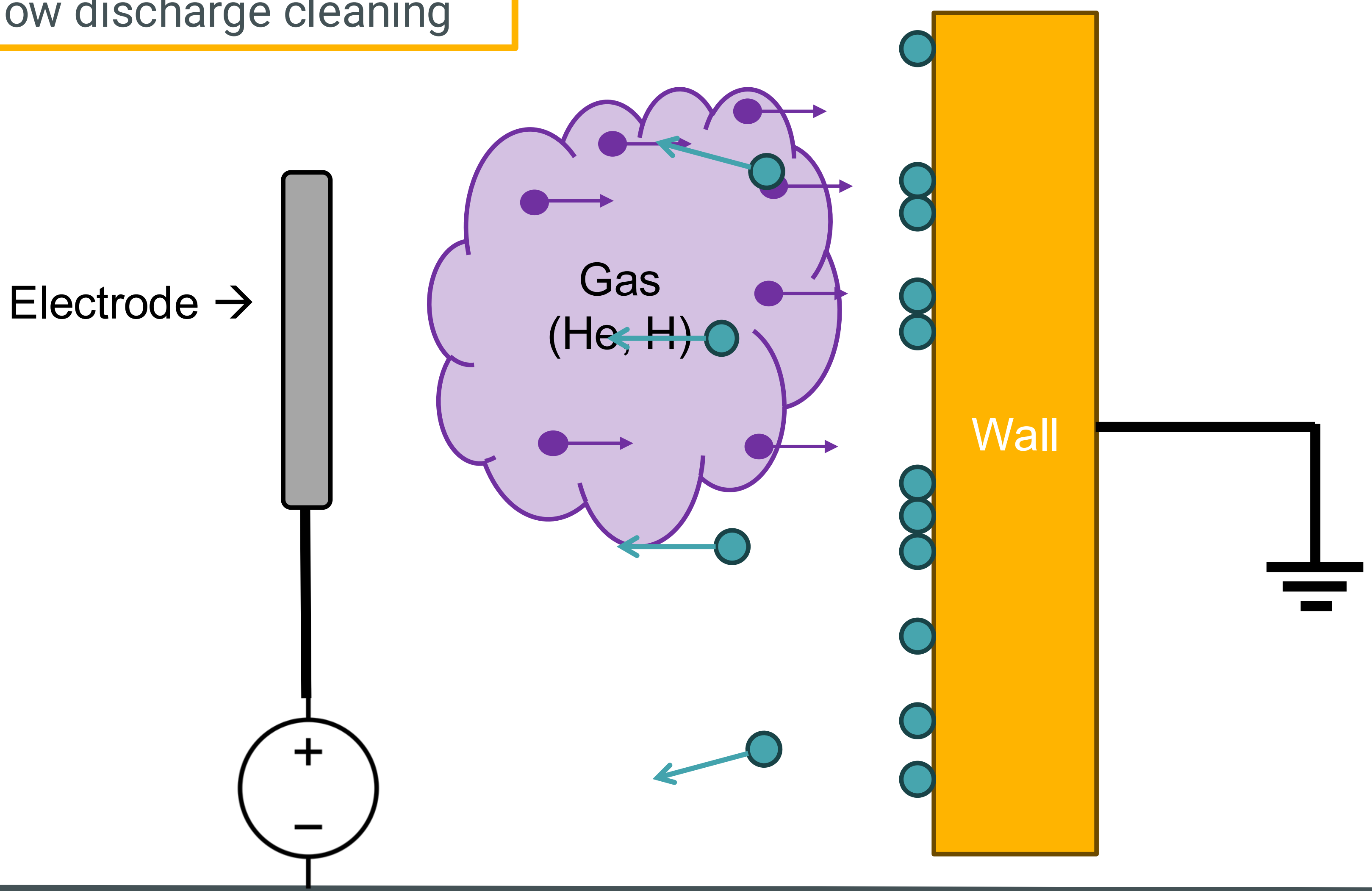
[A. Karcher, *et al.*, Nucl. Mater. Energy, 2021]

Wall conditioning techniques are needed with any plasma-facing material in order to reduce impurity content in the core

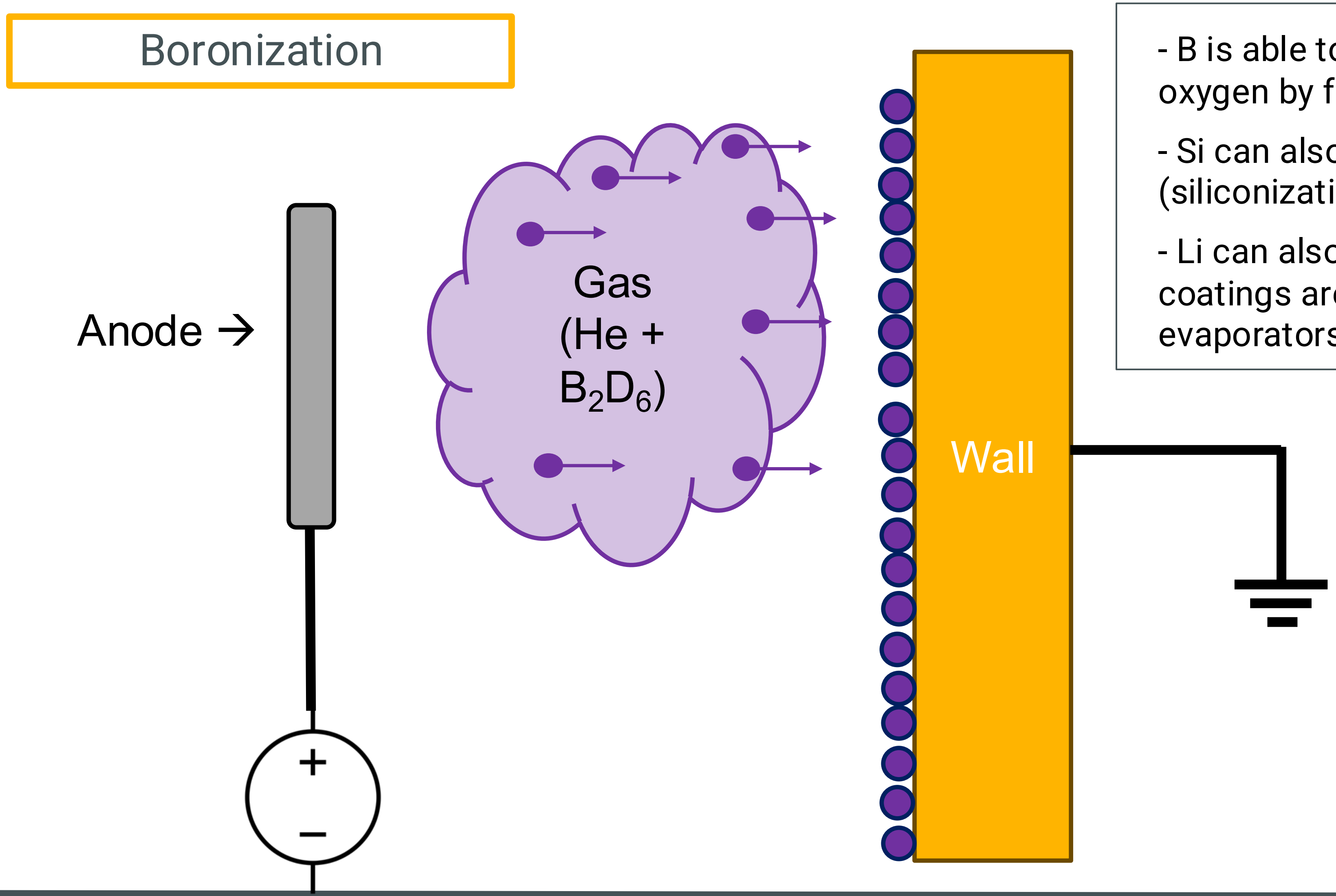


Wall conditioning techniques are needed with any plasma-facing material in order to reduce impurity content in the core

Glow discharge cleaning



Wall conditioning techniques are needed with any plasma-facing material in order to reduce impurity content in the core



- B is able to remove impurity oxygen by forming B2O3
- Si can also be used as a coating (siliconization)
- Li can also be used (lithiumization, coatings are applied via evaporators)

	Carbon	Tungsten	Beryllium
Z	6	74	4
Sputtering	High (high chemical yield)	Low (no chem. sput.)	High (low chem. sput.)
H isotope retention	High (C-H bonding)	Low	Low (no co-deposition)
Thermal conductivity	~200 W m^{-1} K^{-1}	173 W m^{-1} K^{-1}	200 W m^{-1} K^{-1}
Melting temperature	None/Sublimation at 3642 C	3422 C	1287 C
Neutron resistance	Good	Good – transmutation and embrittlement are possible	Good
Other		Hard to fabricate	Very expensive to fabricate due to health hazards

JET first wall
ITER design (pre-2023)

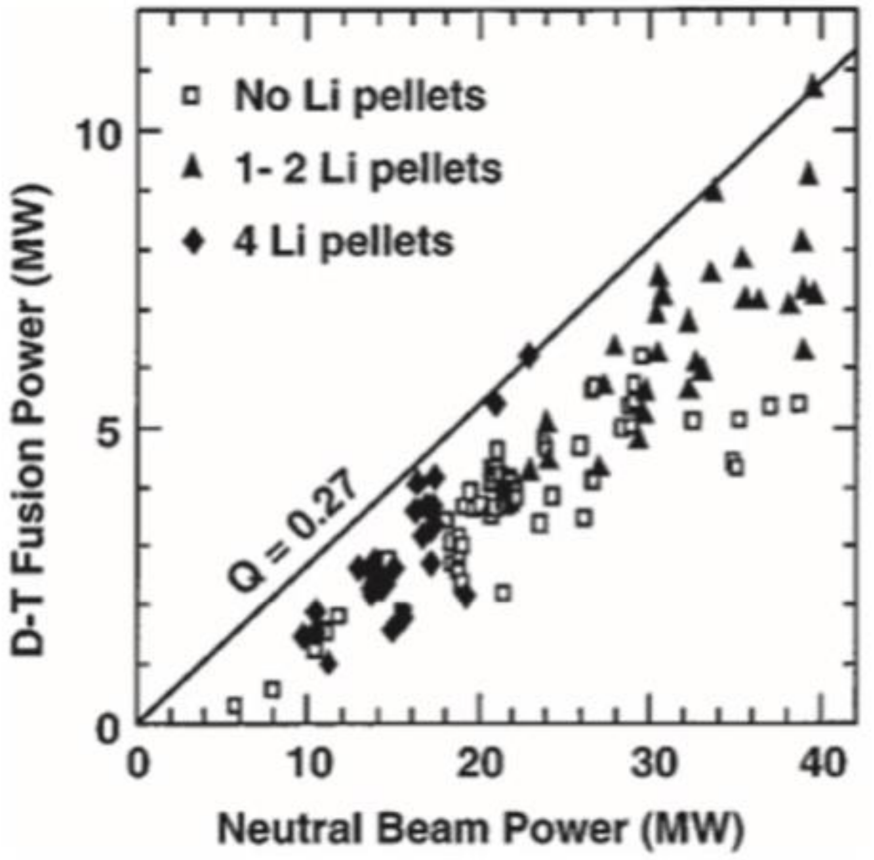
	Carbon	**Tungsten**	**Beryllium**	**Molybdenum**
Z	6	74	4	42
Sputtering	High (high chemical yield)	Low (no chem. sput.)	High (low chem. sput.)	Low (no chem. sput.)
H isotope retention	High (C-H bonding)	Low	Low (no co-deposition)	Low
Thermal conductivity	$\sim 200\ \mathrm{W\ m^{-1}\ K^{-1}}$	$173\ \mathrm{W\ m^{-1}\ K^{-1}}$	$200\ \mathrm{W\ m^{-1}\ K^{-1}}$	$138\ \mathrm{W\ m^{-1}\ K^{-1}}$
Melting temperature	None/Sublimation at 3642 C	3422 C	1287 C	2623 C
Neutron resistance	Good	Good – transmutation and embrittlement are possible	Good	Forms longer-lived radioactive byproducts
Other		Hard to fabricate	Very expensive to fabricate due to health hazards	

C-Mod (MIT)
EAST (first wall)

	Carbon	**Tungsten**	**Beryllium**	**Molybdenum**	**Lithium**
Z	6	74	4	42	3
Sputtering	High (high chemical yield)	Low (no chem. sput.)	High (low chem. sput.)	Low (no chem. sput.)	Low
H isotope retention	High (C-H bonding)	Low	Low (no co-deposition)	Low	Very High (LiOH / LiH)
Thermal conductivity	~200 W m^{-1} K^{-1}	173 W m^{-1} K^{-1}	200 W m^{-1} K^{-1}	138 W m^{-1} K^{-1}	85 W m^{-1} K^{-1}
Melting temperature	None/Sublimation at 3642 C	3422 C	1287 C	2623 C	180 C
Neutron resistance	Good	Good – transmutation and embrittlement are possible	Good	Forms longer-lived radioactive byproducts	Good
Other		Hard to fabricate	Very expensive to fabricate due to health hazards		

Lithium as the plasma-facing material

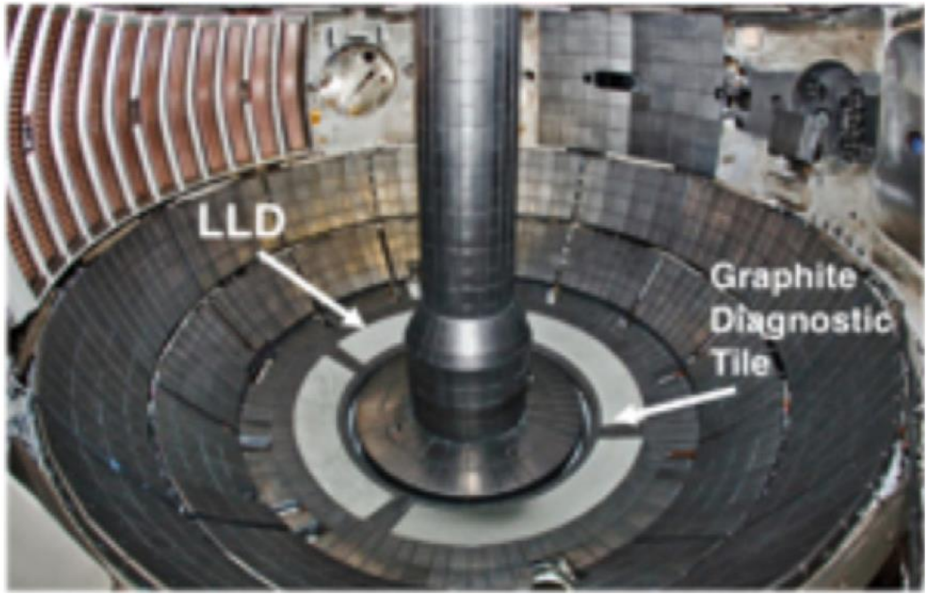
- TFTR ”Supershot”
  - Q = 0.27
  - Higher neutron rate
  - Higher stored energy
  - Higher energy confinement time
  - Higher ion temperature
  - Less carbon in core

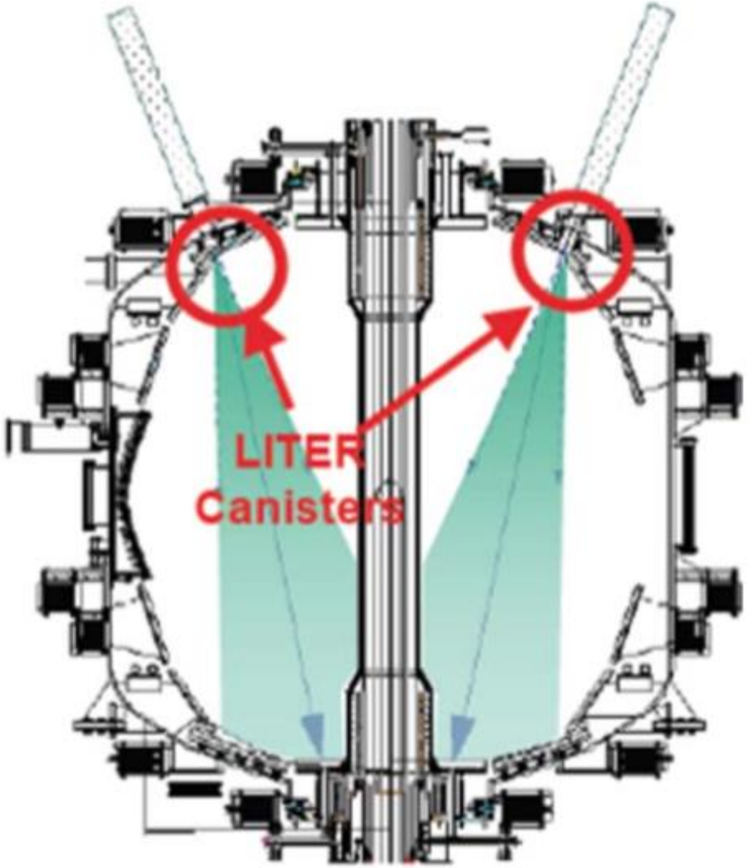


[J.A. Snipes *et al* JNM 1992]

Lithium as the plasma-facing material

- NSTX Liquid Lithium Divertor and Lithium Evaporators (LITER)

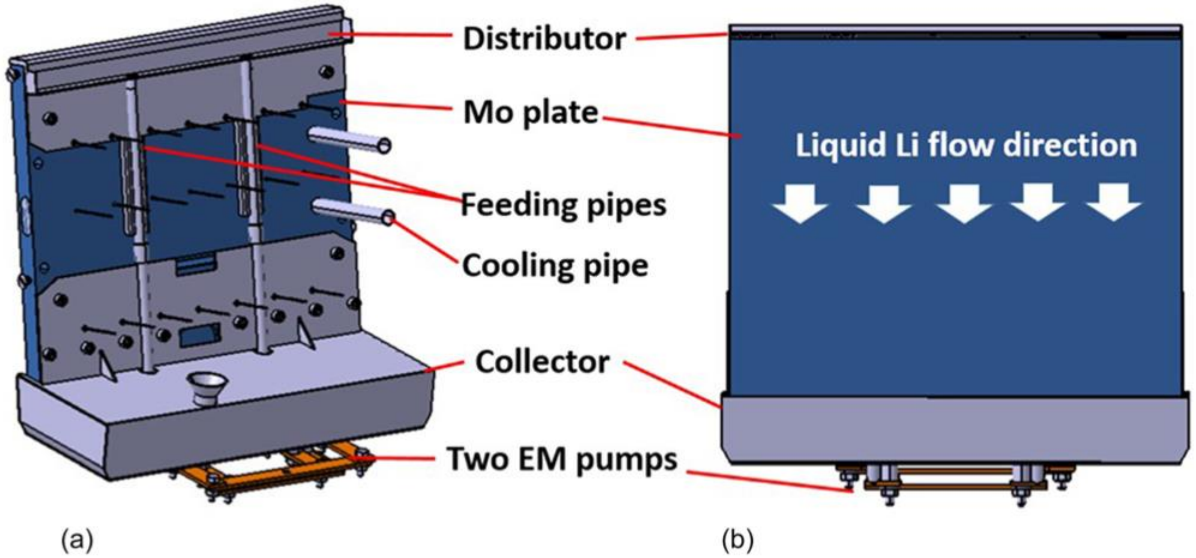


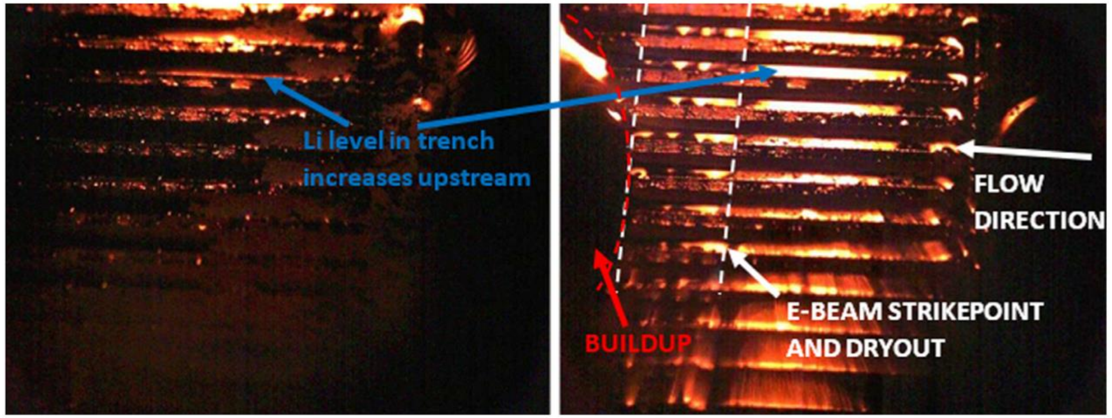


H. W. Kugel *et al.*, Fusion Engineering and Design, 2012

Lithium as the plasma-facing material

- NSTX Liquid Lithium Divertor and Lithium Evaporators (LITER)
- Flowing liquid lithium concepts:
    - Flowing liquid lithium (FLiLi) limiter
    - Lithium Metal Infused Trenches (LiMIT)

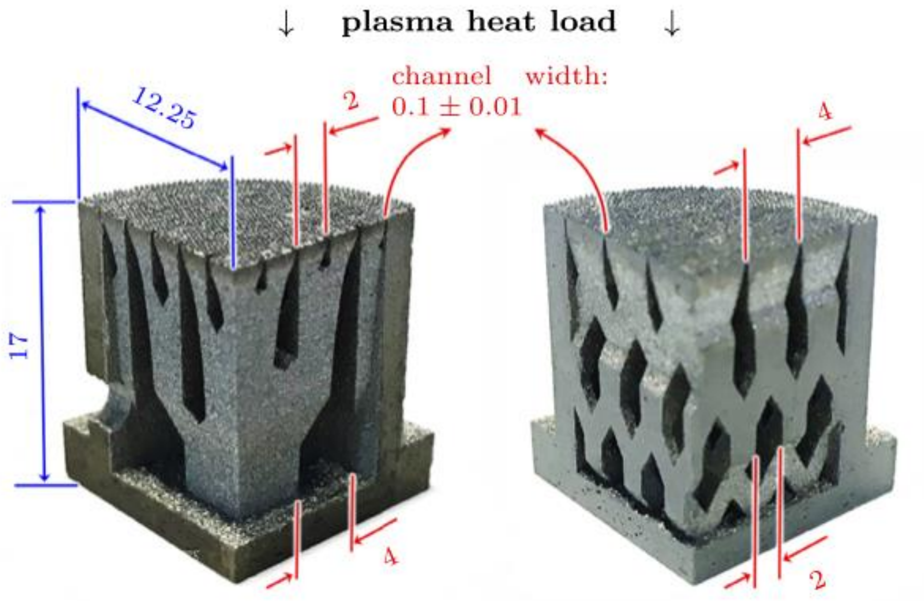


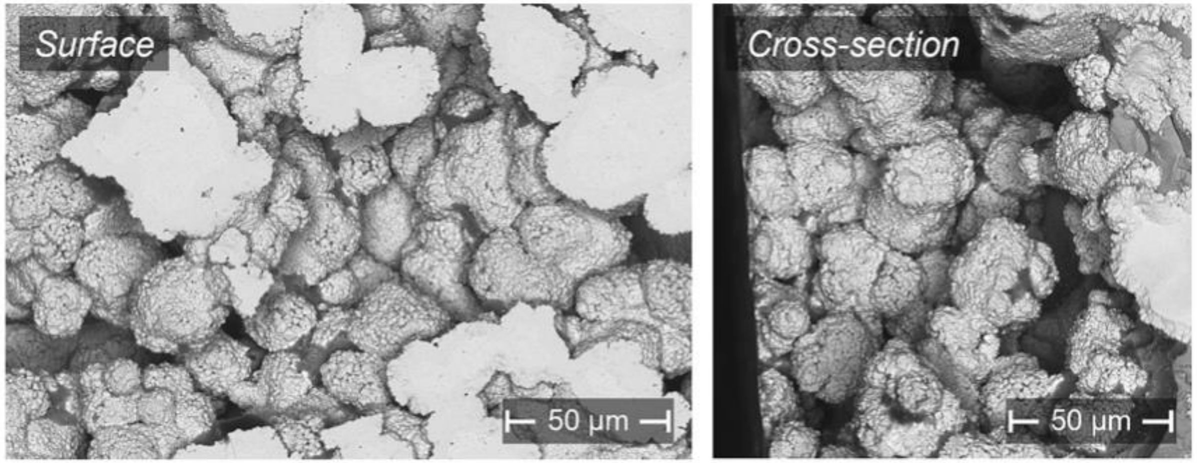


[G. Z. Zuo PoP 2020; D. N. Ruzic NME 2017]

Lithium as the plasma-facing material

- NSTX Liquid Lithium Divertor and Lithium Evaporators (LITER)
- Flowing liquid lithium concepts
- Capillary porous systems

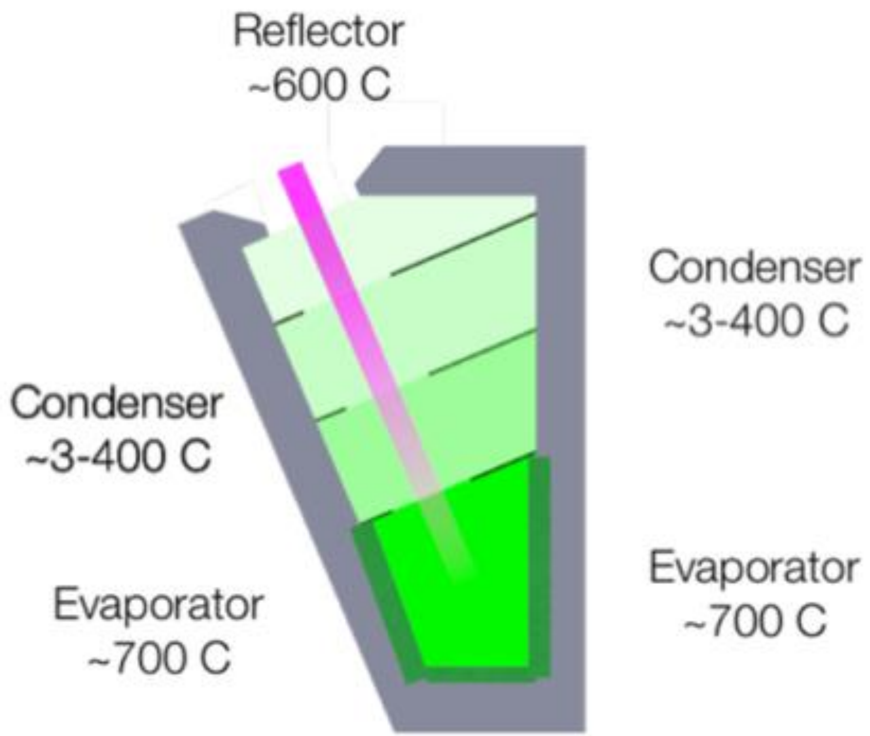




[P. Rindt, Nucl. Fusion 2019; C. López Pérez, Nucl. Mater. Energy 2023]

Lithium as the plasma-facing material

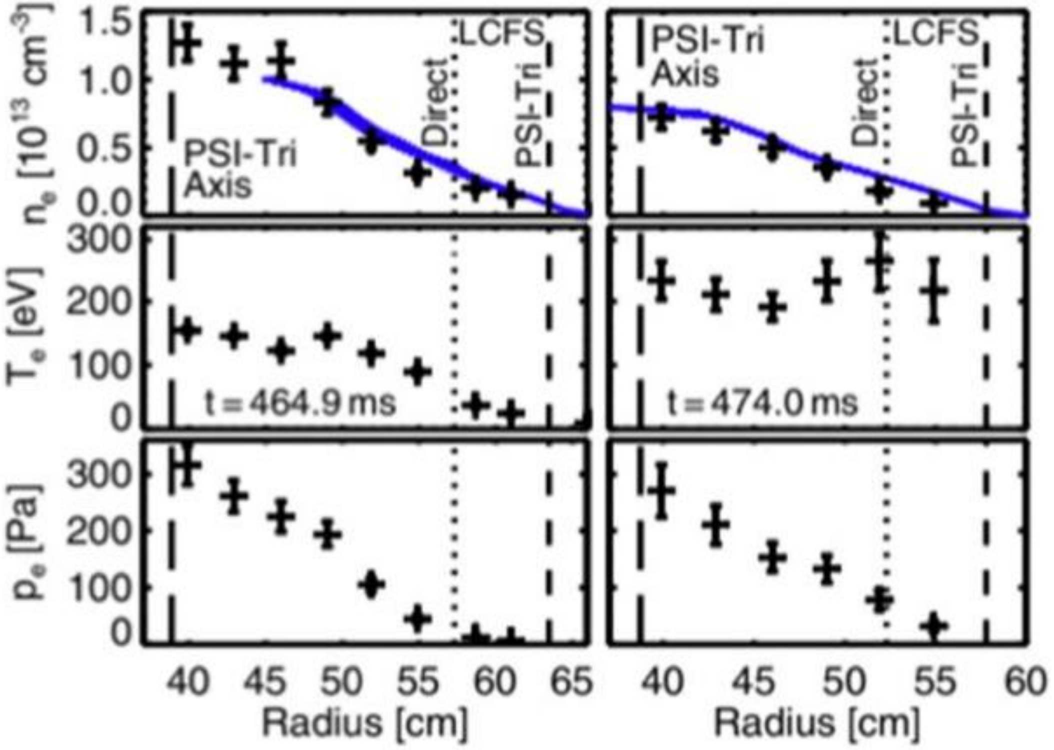
- NSTX Liquid Lithium Divertor and Lithium Evaporators (LITER)
- Flowing liquid lithium concepts
- Capillary porous systems
- Lithium vapor box



[E. D. Emdee NF 2019]

Lithium as the plasma-facing material

- NSTX Liquid Lithium Divertor and Lithium Evaporators (LITER)
- Flowing liquid lithium concepts
- Capillary porous systems
- Lithium vapor box
- All-lithium walls:
  Lithium Tokamak eXperiment (LTX)



[D. P. Boyle, *et al.*, PRL 2017]

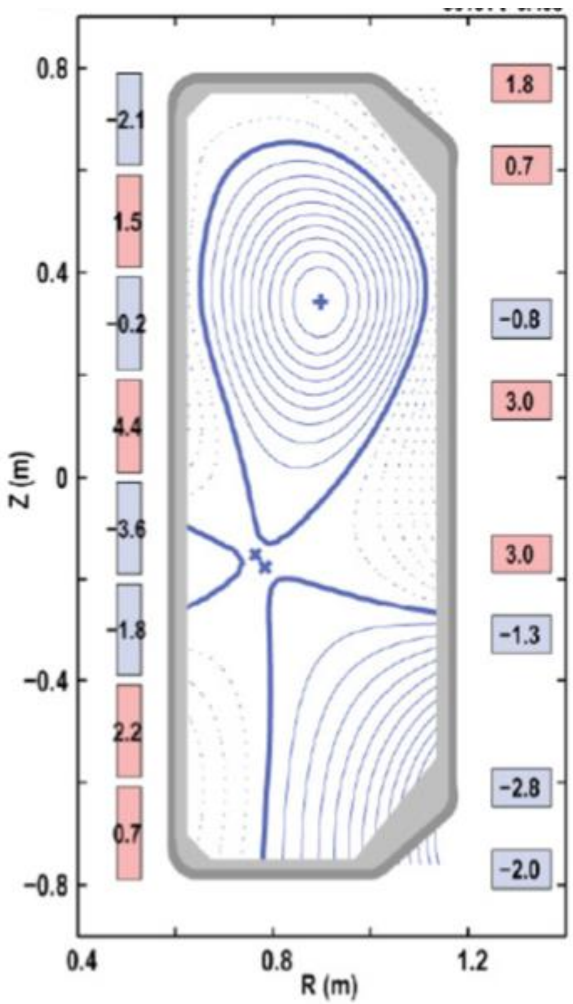
What material do we use to build plasma-facing components for a fusion reactor?

Desired characteristics:

- Low Z and/or low sputter yield
- Low hydrogen isotope retention and low co-deposition rate
- High thermal conductivity, high melting temperature
- Neutron resistance

Alternative divertor geometries can be used to mitigate heat fluxes to divertor targets

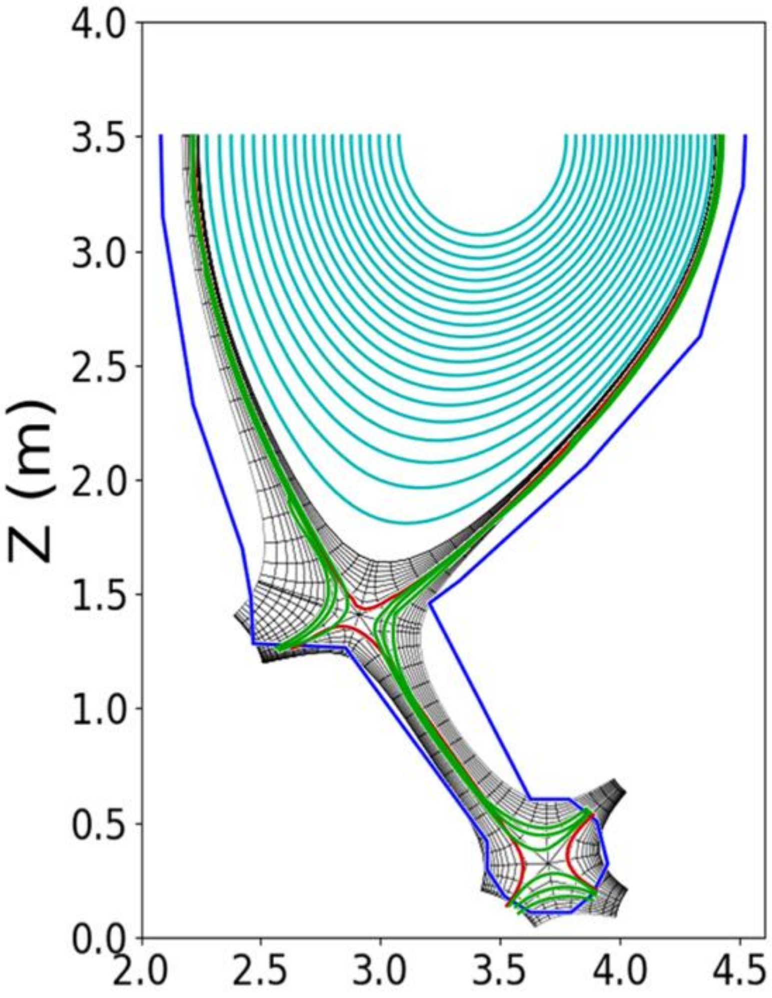
- Snowflake divertor
  - Additional null point
  - 4 strike points instead of 2



[D. D. Ryutov PoP 2015]

Alternative divertor geometries can be used to mitigate heat fluxes to divertor targets

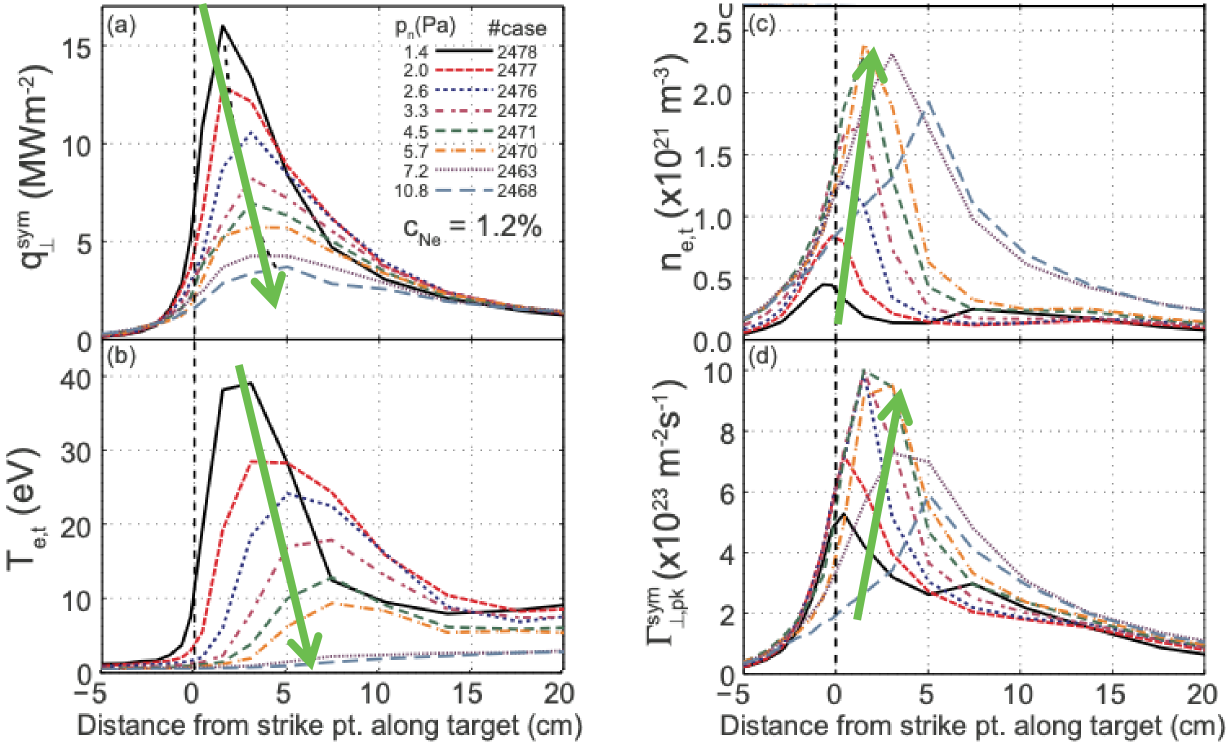
- Snowflake divertor
  - Additional null point
  - 4 strike points instead of 2
- Long legged divertor
  - Strike point further from X-point



[M.R.K. Wingram Nucl Fus 59 2019]

Divertor detachment is achieved through impurity seeding and can also mitigate heat fluxes

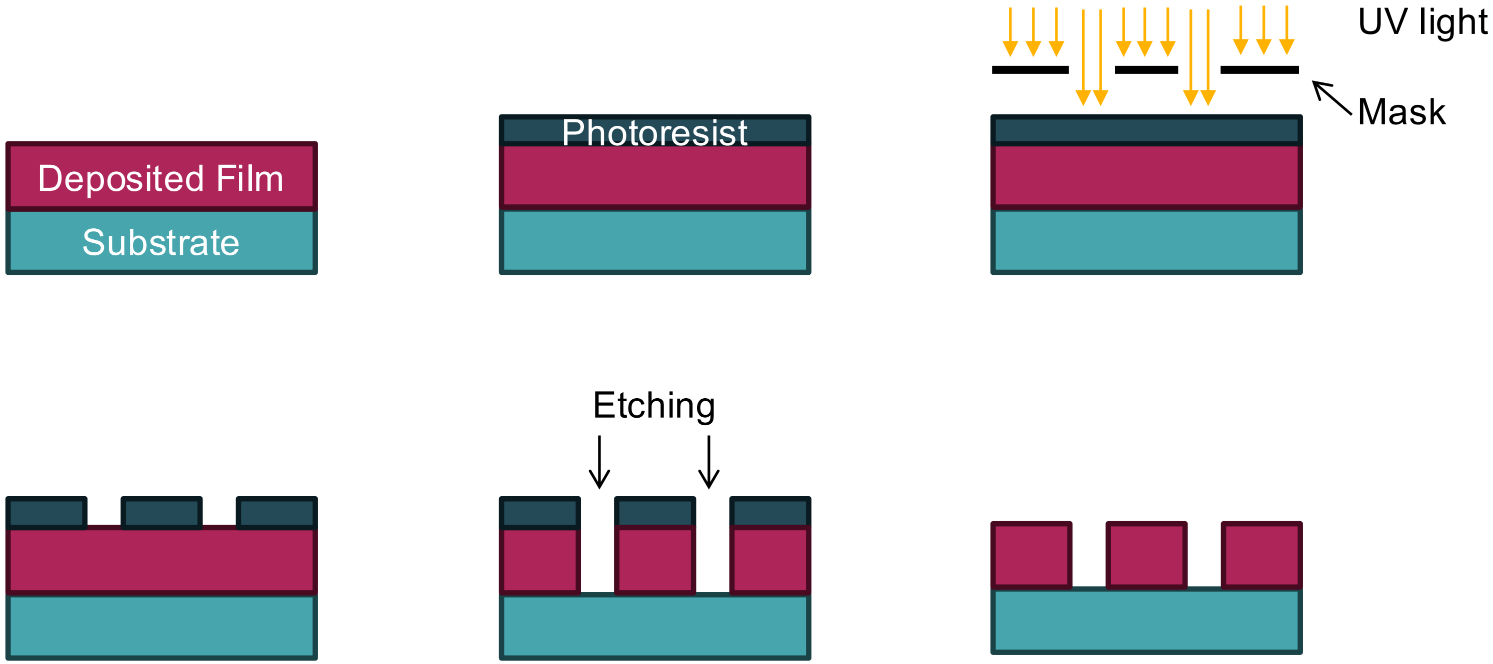
- Impurity seeding (e.g., Ne gas puffing) increases neutral pressure in SOL:
  - Increases collisions and radiative losses
  - Decreases heat flux
  - Decreases Te
  - Decreases ion impact energy
  - Increases flux to the divertor plates



[R. Pitts, *et al.*, Nuclear Materials and Energy 20 (2019)]

Semiconductors (aka the profitable plasma reactors)

- Fine-tuned PMI processes are used for semiconductor manufacturing
    - Film deposition (e.g., chemical or physical vapor deposition)
    - Etching (chemical etching, or chemical or physical ion sputtering)



Summary

- Plasma-material interactions is a two way street! It involves learning about plasma physics and materials science to really understand the dynamics
- PMI has applications to fusion reactors, semiconductor industry and electric propulsion.
- The principles of PMI are the same, but the conditions are varied
- Sheath plays an important role in driving PMI; ion energy is important in determining the physical processes that take place
- No magic solution for plasma-facing materials in fusion reactors
- Lots of out-of-the-box ideas!

What does PMI research look like? (or what it has looked like for me)

- Small-scale laboratory experiments
  - Hands-on work in a small (<0.5 m) vacuum chamber
  - Exposure and analysis of materials to understand fundamental surface processes

- Linear plasma devices *
  - Exposure of materials at much larger ion fluences and heat fluxes to understand effects of fusion-relevant conditions

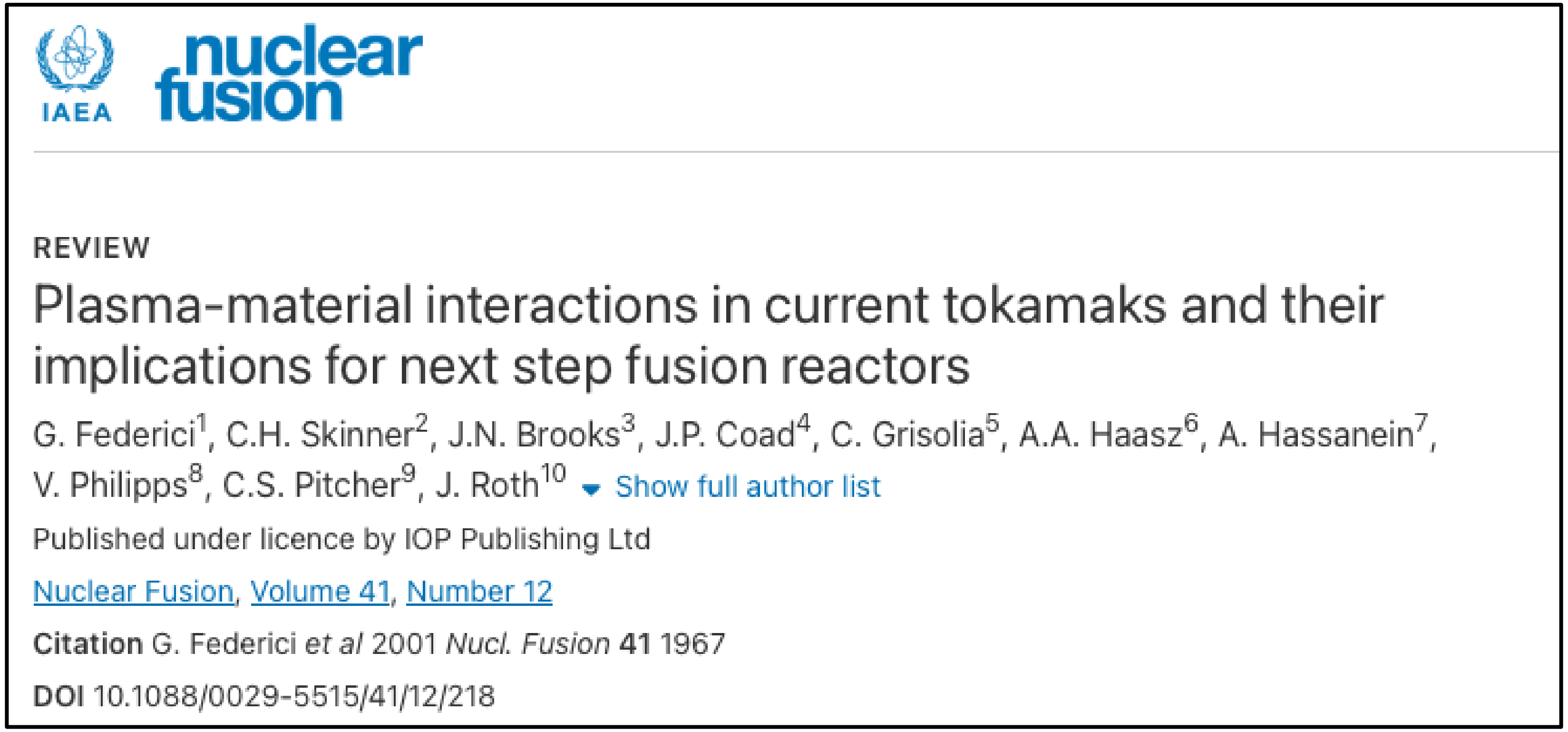
- Tokamak experiments
  - Impurity injection experiments at KSTAR
  - Analysis of post-mortem samples from NSTX-U and DIII-D

- Computational PMI
  - Atomic-scale modeling of surface processes
  - Large-scale (~reactor length scales) modeling of material erosion, migration, and redeposition

Useful References

General Overview of Fusion PMI

- G. Federici *et al* 2001 *Nucl. Fusion* **41** 1967 doi.org/10.1088/0029-5515/41/12/218



REVIEW

Plasma-material interactions in current tokamaks and their implications for next step fusion reactors

G. Federici[1], C.H. Skinner[2], J.N. Brooks[3], J.P. Coad[4], C. Grisolia[5], A.A. Haasz[6], A. Hassanein[7], V. Philipps[8], C.S. Pitcher[9], J. Roth[10] Show full author list

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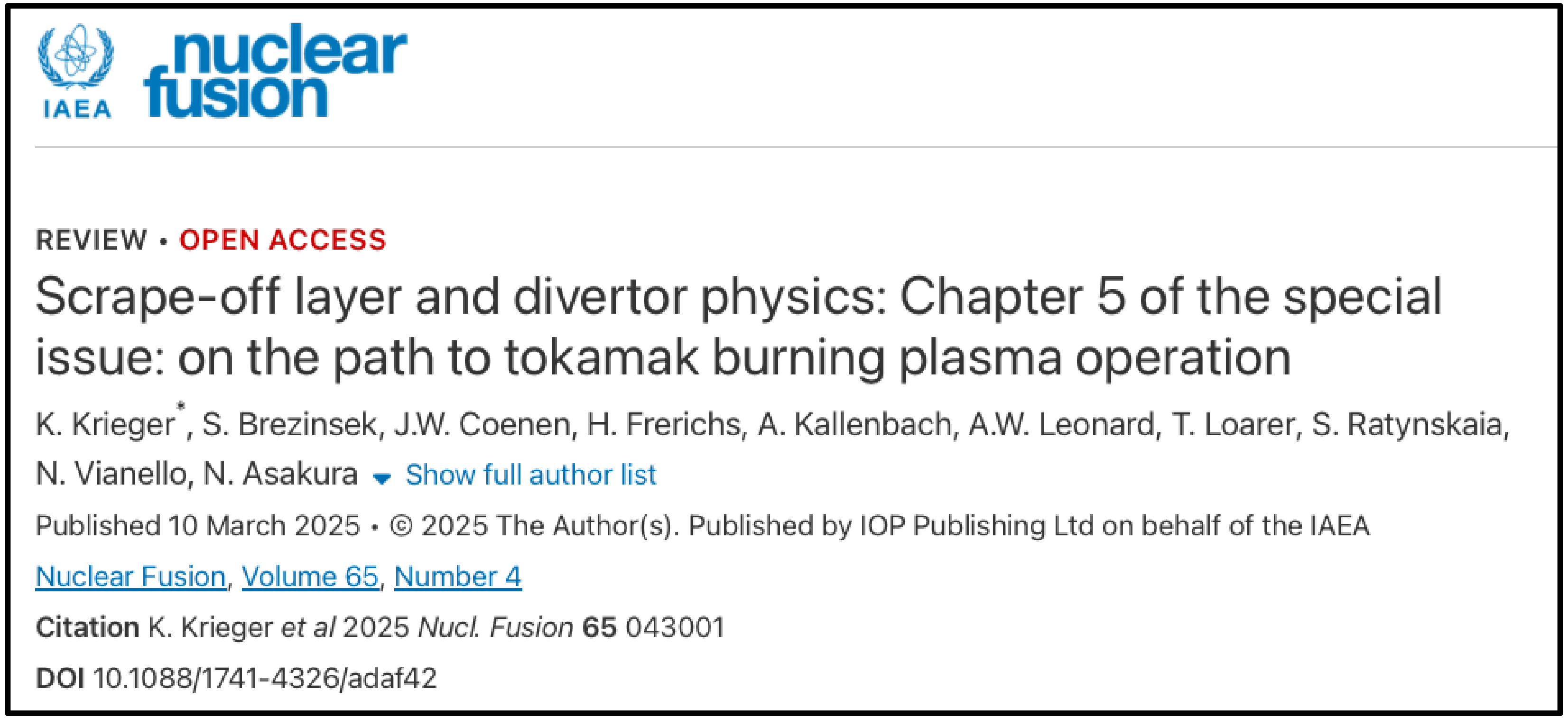
Citation G. Federici *et al* 2001 *Nucl. Fusion* **41** 1967

DOI 10.1088/0029-5515/41/12/218

Useful References

General Overview of Fusion PMI

- G. Federici *et al* 2001 *Nucl. Fusion* **41** 1967 doi.org/10.1088/0029-5515/41/12/218
- K. Krieger *et al* 2025 *Nucl. Fusion* **65** 043001 doi.org/10.1088/1741-4326/adaf42



REVIEW • OPEN ACCESS

Scrape-off layer and divertor physics: Chapter 5 of the special issue: on the path to tokamak burning plasma operation

K. Krieger*, S. Brezinsek, J.W. Coenen, H. Frerichs, A. Kallenbach, A.W. Leonard, T. Loarer, S. Ratynskaia, N. Vianello, N. Asakura Show full author list

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Nuclear Fusion, Volume 65, Number 4

Citation K. Krieger *et al* 2025 *Nucl. Fusion* **65** 043001

DOI 10.1088/1741-4326/adaf42

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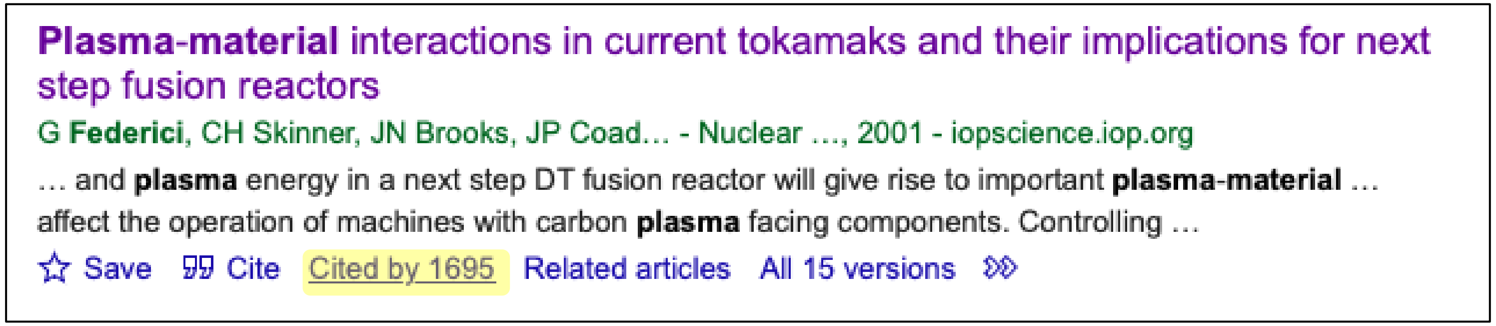
- K. Krieger *et al* 2025 *Nucl. Fusion* **65** 043001 doi.org/10.1088/1741-4326/adaf42
- → Cover almost every topic, look at the references within article

Tip: If article seems relevant, look at work citing it ("Cited by" on Google Scholar)



Plasma-material interactions in current tokamaks and their implications for next step fusion reactors

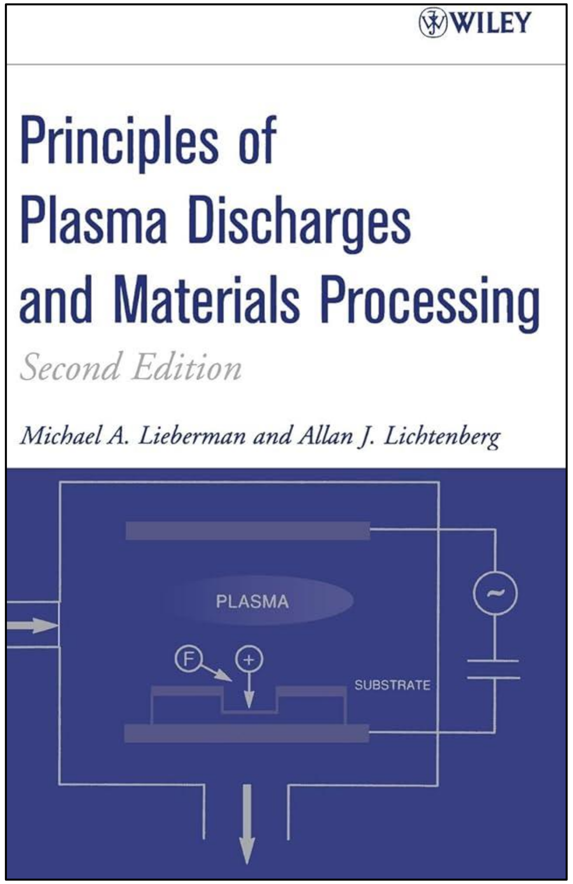
G **Federici**, CH Skinner, JN Brooks, JP Coad… - Nuclear …, 2001 - iopscience.iop.org

… and **plasma** energy in a next step DT fusion reactor will give rise to important **plasma-material** … affect the operation of machines with carbon **plasma** facing components. Controlling …

Useful References

General Overview of Fusion PMI

- G. Federici *et al* 2001 *Nucl. Fusion* **41** 1967 doi.org/10.1088/0029-5515/41/12/218
- K. Krieger *et al* 2025 *Nucl. Fusion* **65** 043001 doi.org/10.1088/1741-4326/adaf42
- M. A. Lieberman and A. J. Lichtenberg, “Principles of Plasma Discharges and Materials Processing” (2005)



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- K. Krieger *et al* 2025 *Nucl. Fusion* **65** 043001 doi.org/10.1088/1741-4326/adaf42
- M. A. Lieberman and A. J. Lichtenberg, “Principles of Plasma Discharges and Materials Processing” (2005)

Scrape off Layers

- P. Stangeby, “The Plasma Boundary of Magnetic Fusion Devices” (2000)

Wall Conditioning

- J. Winter 1996 Plasma Phys. Control. Fusion **38** 1503 doi.org/10.1088/0741-3335/38/9/001

Lithium:

- R. Kaita 2019 Plasma Phys. Control. Fusion **61** 113011 doi.org/10.1088/1361-6587/ab4156

Don’t overlook Theses and Dissertations! They often include long literature reviews on a topic