PRINCETON PLASMA PHYSICS LABORATORY

Plasma-Material Interactions

Hanna Schamis (PPPL)

Introduction to Plasma and Fusion, June 18, 2024

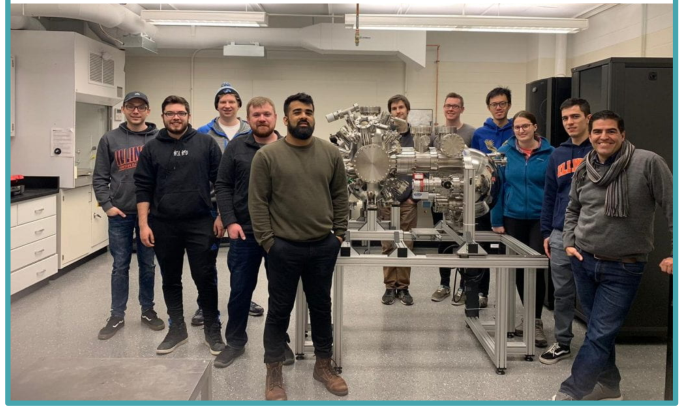
About me – how I got here

Grew up in Buenos Aires

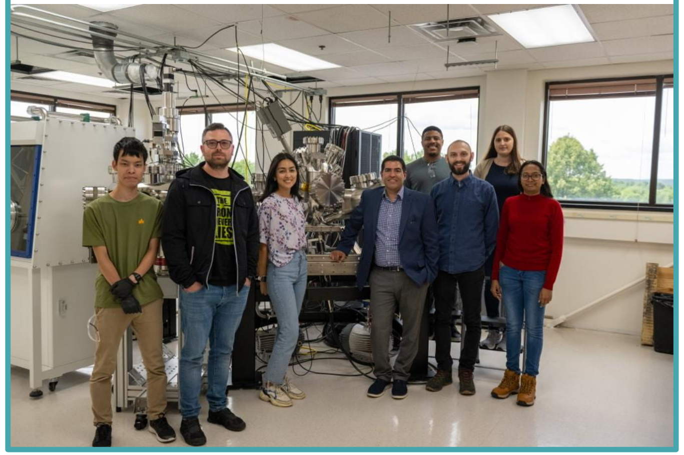
University of Michigan (2016, BS Physics)

SULI at PPPL (x2!)

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



Penn State (PhD Nuclear Engineering)



PPPL (2023 -- ??)

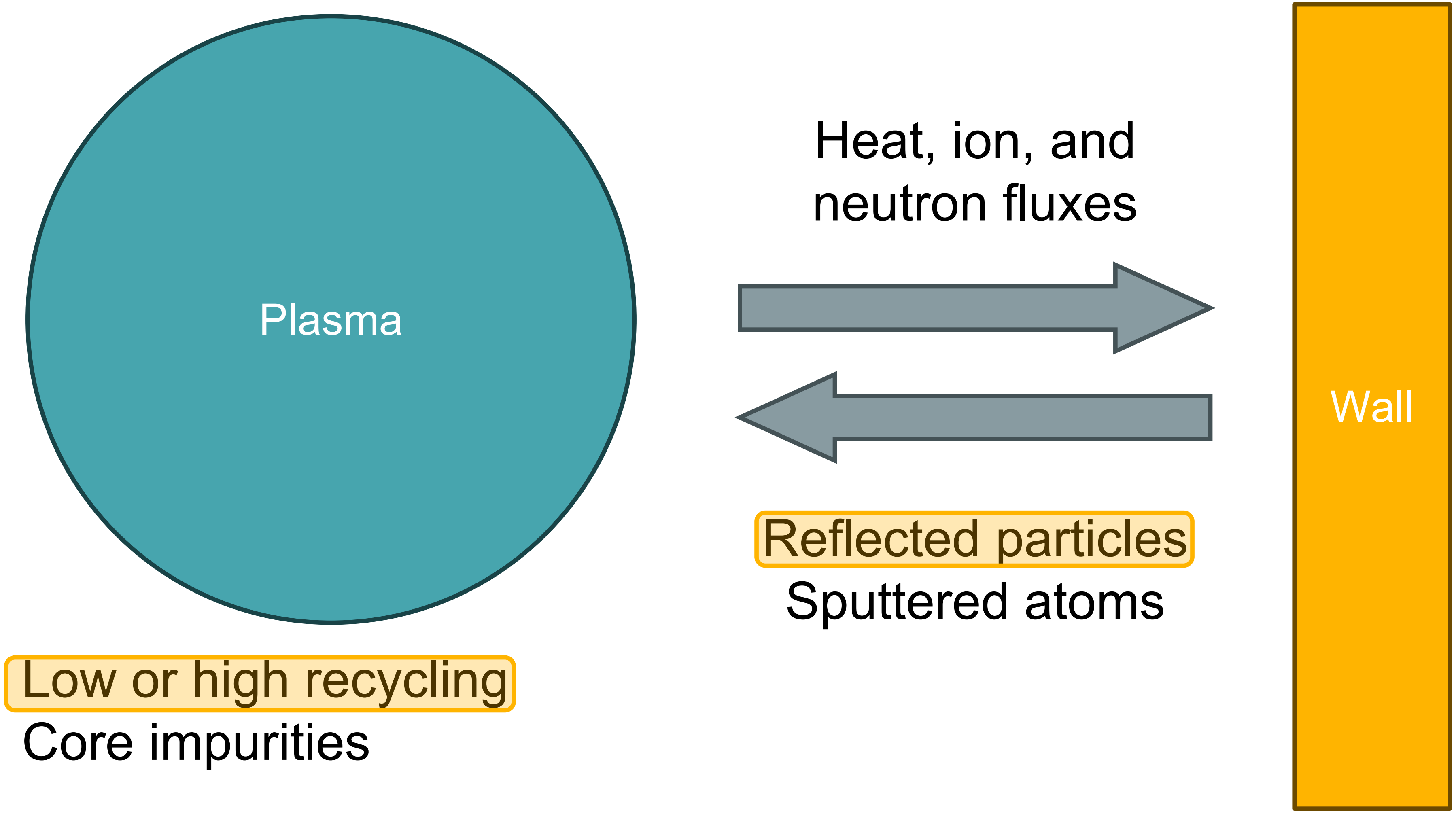
Disclaimer

- This talk focuses on plasma material interactions (PMI) for fusion applications

- Other areas where PMI is important:
  - Semiconductor manufacturing
  - Electric propulsion
  - Solar wind/space weathering of asteroids

- In this talk: “hydrogen” is short for “hydrogen isotopes” = H/D/T

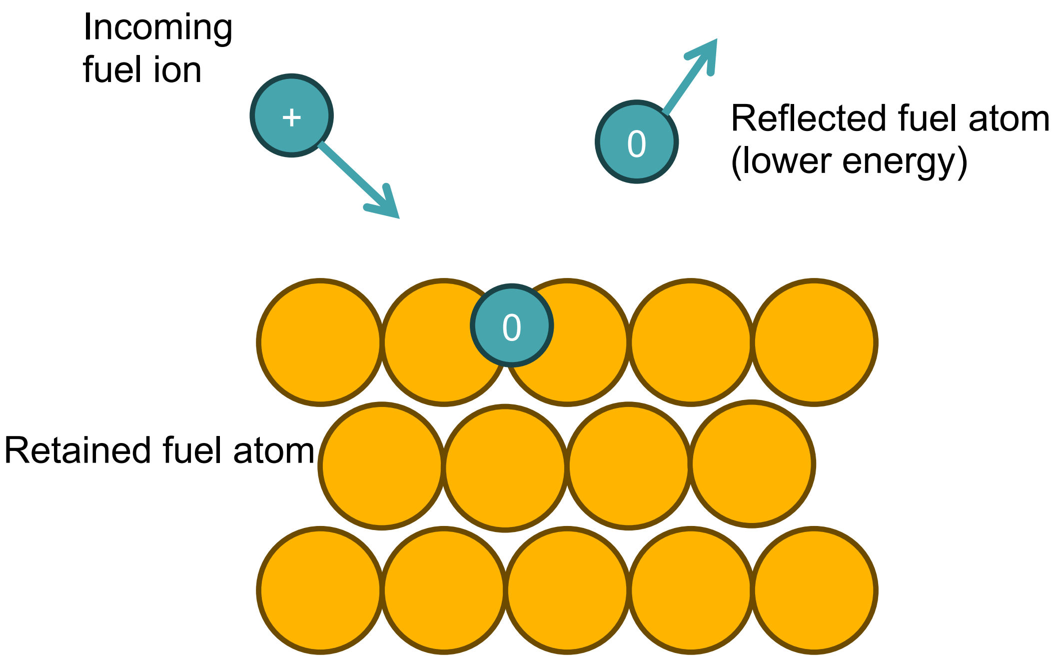
Plasmas affect materials and materials affect plasmas

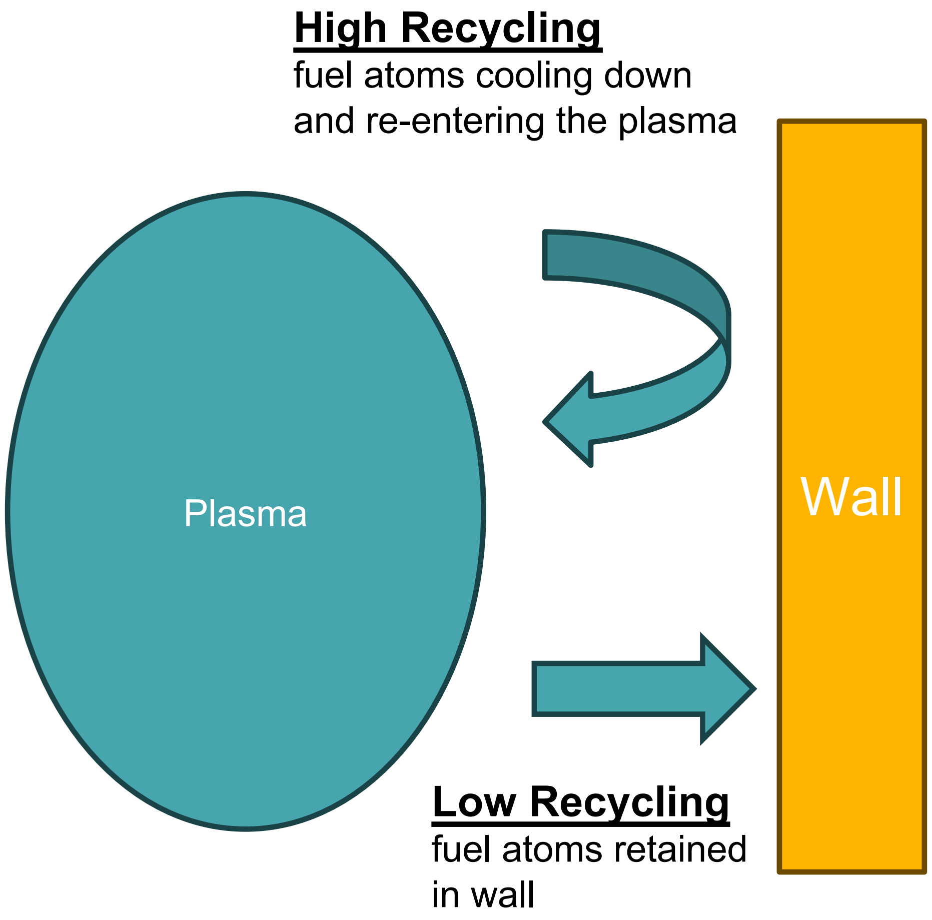


Melting
Cracking
Embrittlement
Transmutations
Erosion
Retention

Retention / Reflection / Recycling

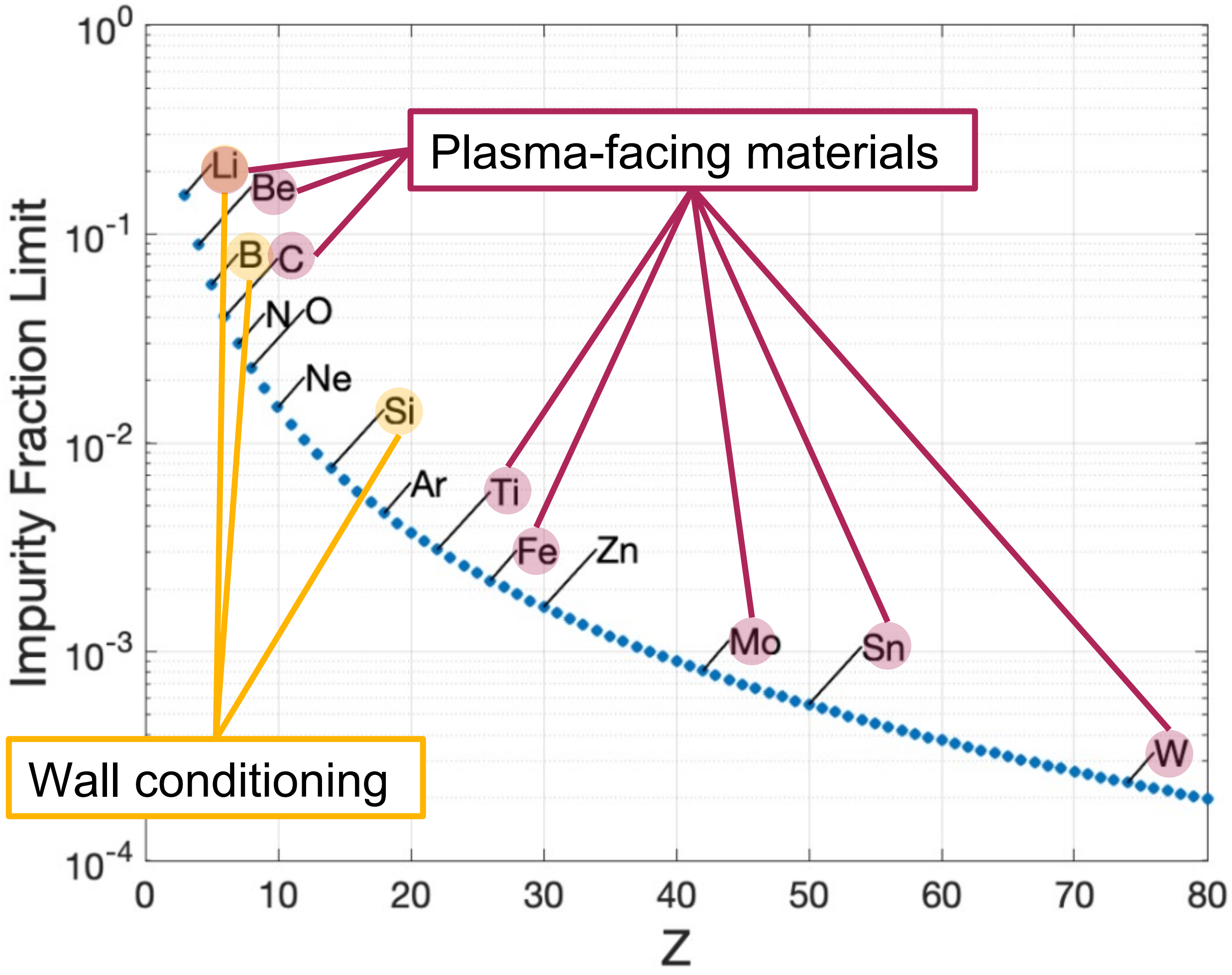
- describe different parts of the same process





1950 1960 1970 1980 1990 2000 2010 2020

- 1951: Spitzer recognized impurities from PMI could be a threat to plasma purity

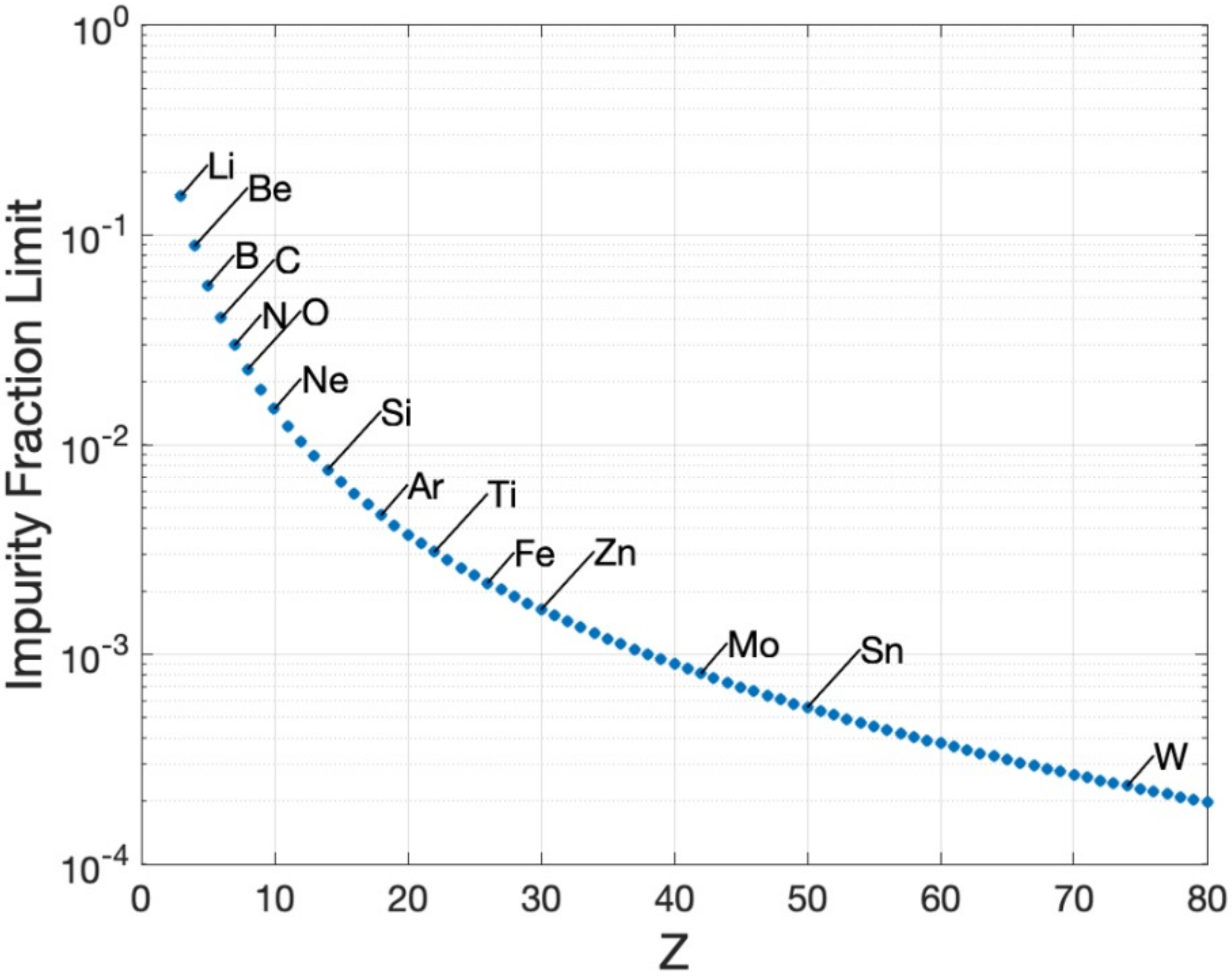


[G. Federici, Nucl. Fusion, 2001; M. S. Parsons, Dissertation, 2023]

1950 1960 1970 1980 1990 2000 2010 2020

- 1951: Spitzer recognized impurities from PMI could be a threat to plasma purity

- 1950s: early stellarators had severely contaminated plasmas due to vacuum conditions.



[G. Federici, Nucl. Fusion, 2001; M. S. Parsons, Dissertation, 2023]

1950 **1960** 1970 1980 1990 2000 2010 2020

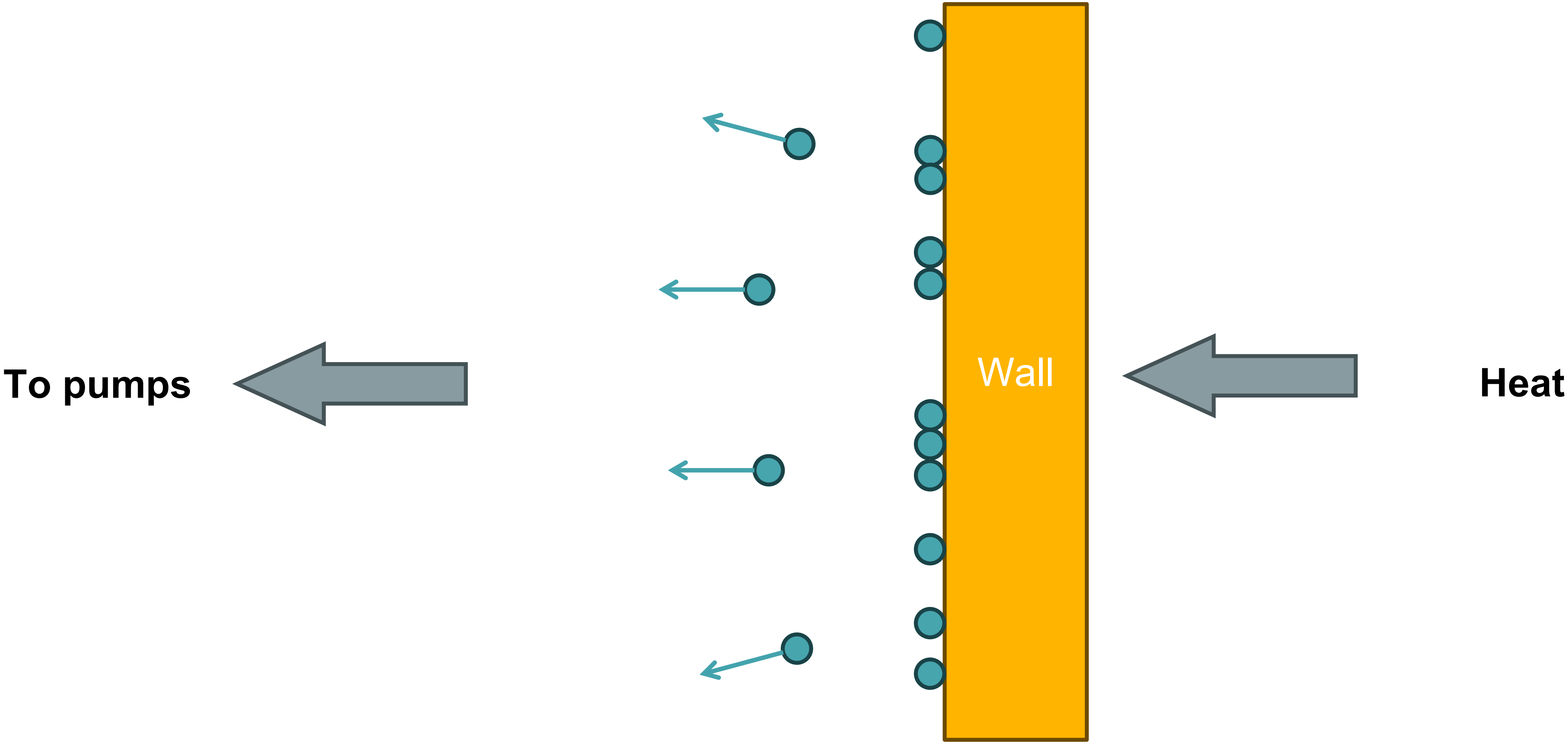
- 1960s: Early tokamaks contained large amounts of carbon, oxygen and metallic impurities, despite reduction efforts.
  - Stainless steel vacuum vessel
  - All-metal seals
  - Baking
  - Discharge cleaning

→ **Wall conditioning**

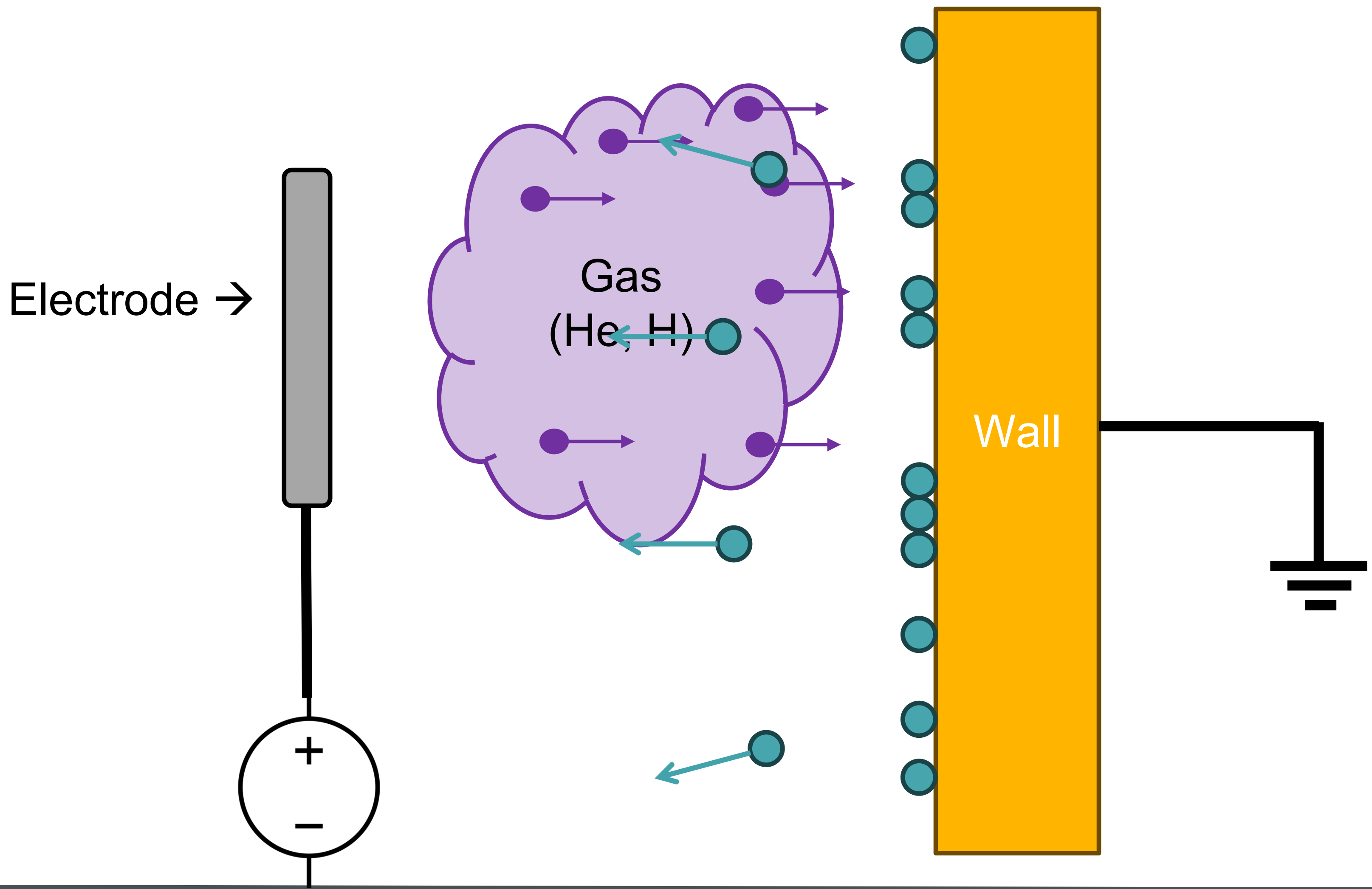
Removing impurities to improve plasma performance

[G. Federici, Nucl. Fusion, 2001]

Wall conditioning – Baking

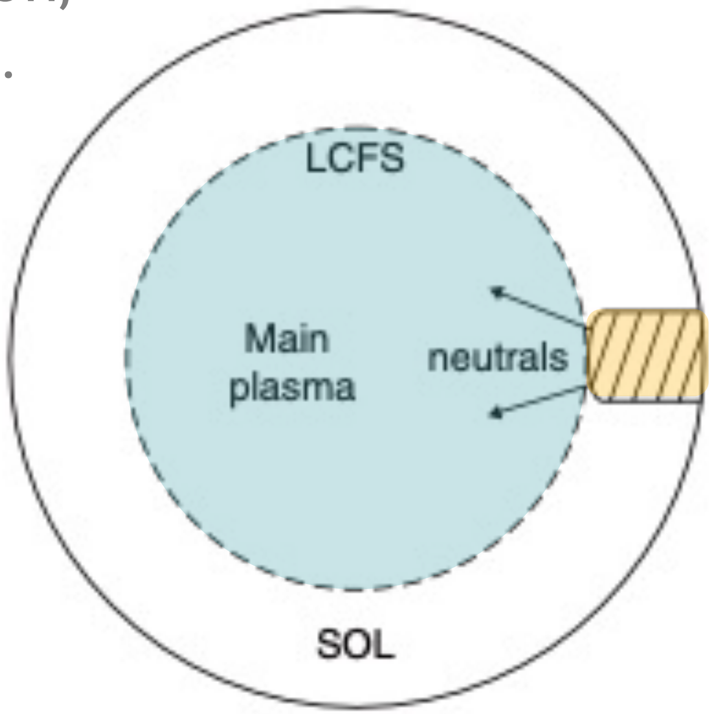


Wall conditioning – Discharge Cleaning



1950 **1960** 1970 1980 1990 2000 2010 2020

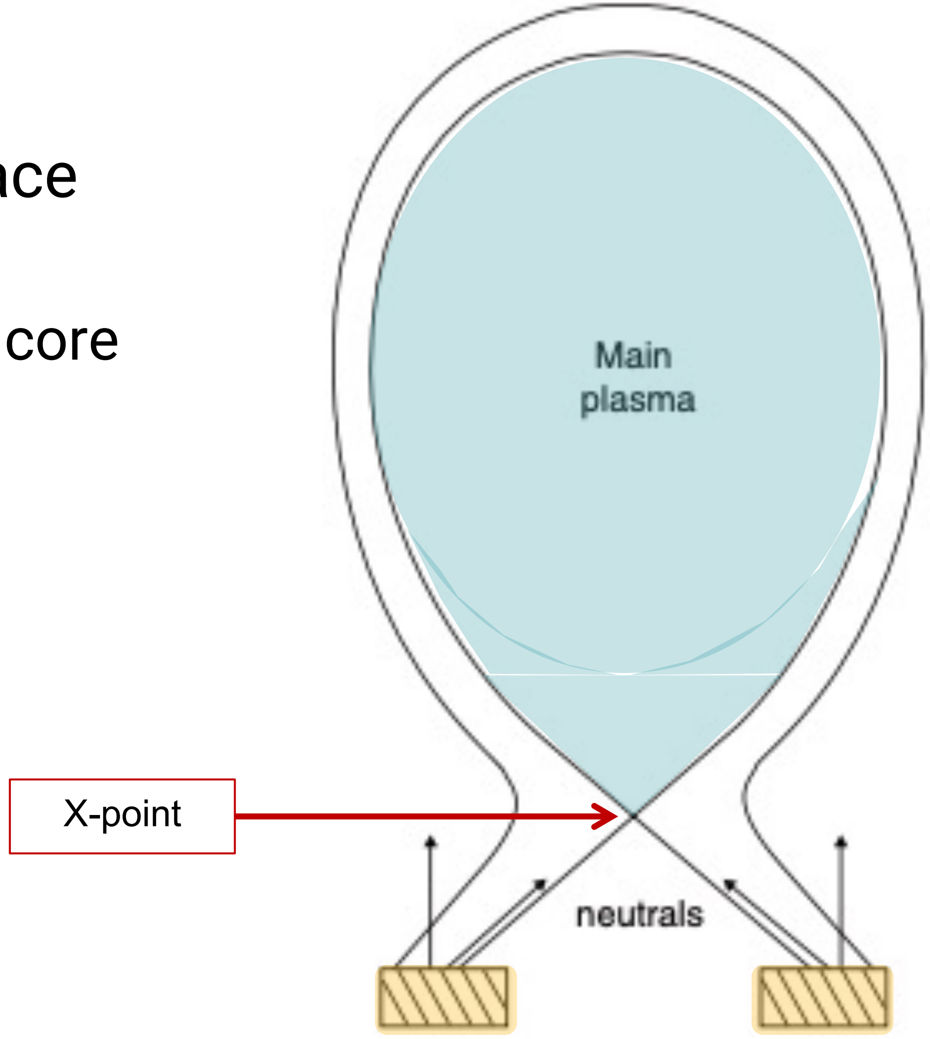
- 1960s: Early tokamaks contained large amounts of carbon, oxygen and metallic impurities, despite reduction efforts.
- Late 1960s, early 1970s: Limiters are introduced
  - Stainless steel
  - Refractory metals (molybdenum, tungsten, titanium)
  - Ceramics (boron carbide, alumina)



[G. Federici, Nucl. Fusion, 2001; P. Stangeby "The Plasma Boundary of Magnetic Fusion Devices," 2000]

1950 1960 **1970** 1980 1990 2000 2010 2020

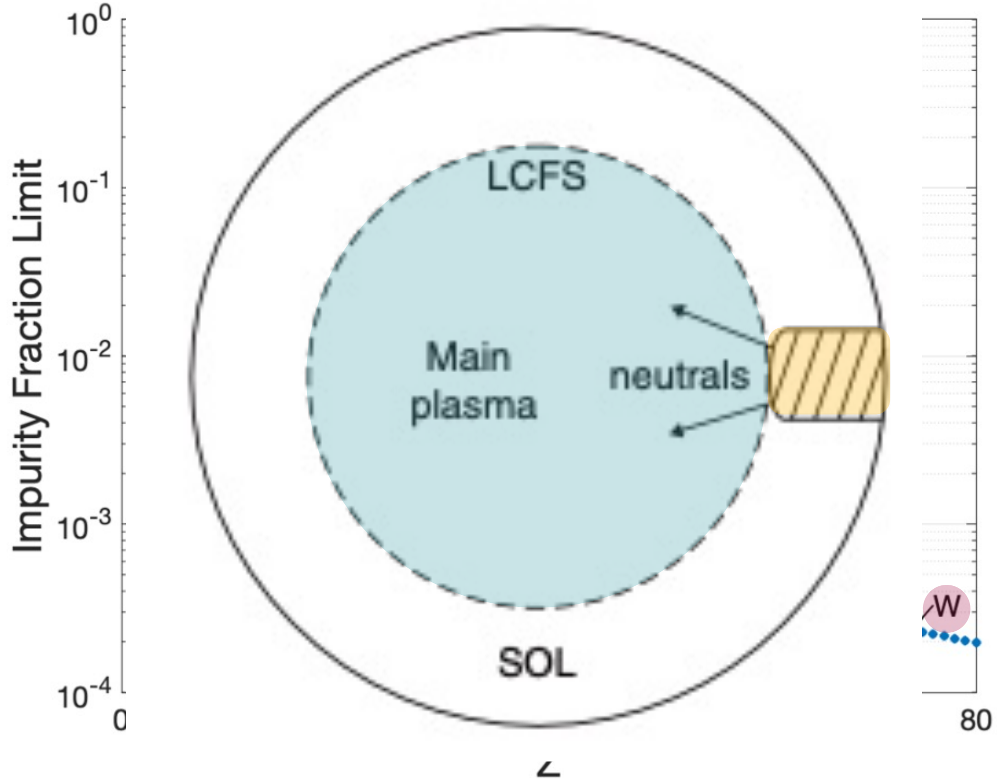
- Mid-1970s: new divertors move contact surface further away from the core
  - Scrape-off-layer (SOL): buffer zone between core and materials



[G. Federici, Nucl. Fusion, 2001; P. Stangeby “The Plasma Boundary of Magnetic Fusion Devices,” 2000]

1950 1960 **1970** 1980 1990 2000 2010 2020

- Mid-1970s: new divertors move contact surface further away from the core
- Late 1970s: Auxiliary heating (neutral beams) results in hotter plasmas
  - Higher heat fluxes at the limiter, higher edge Te
  - Princeton Large Torus had a tungsten limiter switched to graphite, reduced core radiation



[G. Federici, Nucl. Fusion, 2001; P. Stangeby "The Plasma Boundary of Magnetic Fusion Devices," 2000; M. S. Parsons, Dissertation, 2023]

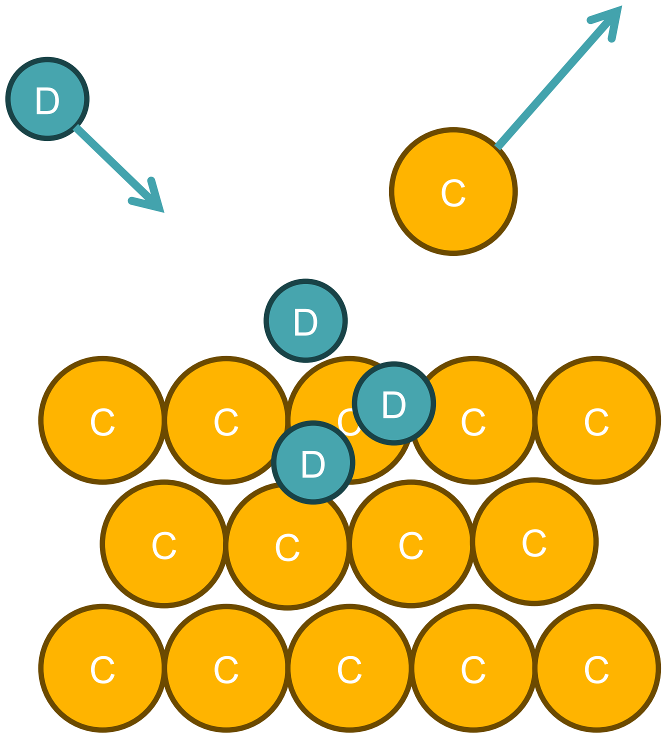
1950 1960 1970 **1980** 1990 2000 2010 2020

- Early laboratory experiments of D → C
  - High chemical sputtering
  - Trapping of hydrogen in co-deposited layers

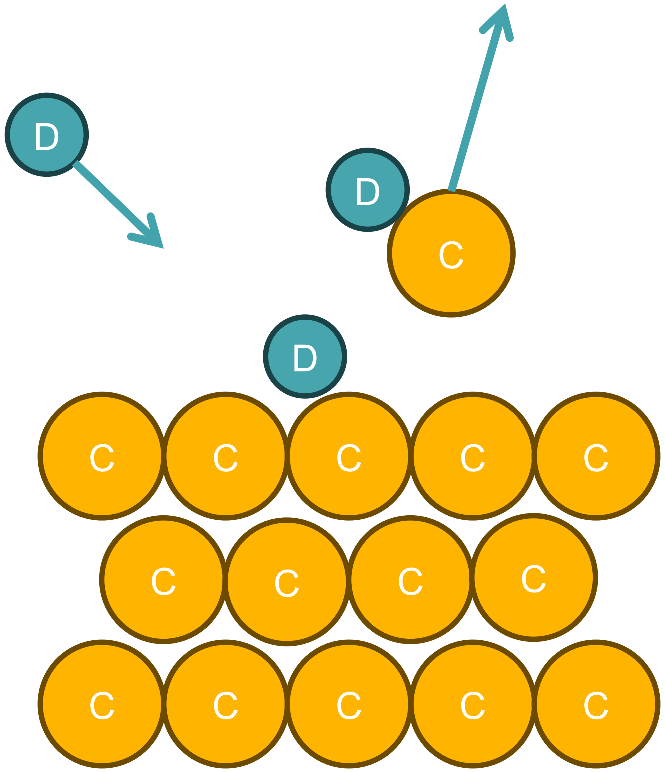
[G. Federici, Nucl. Fusion, 2001]

Sputtering processes

Physical Sputtering

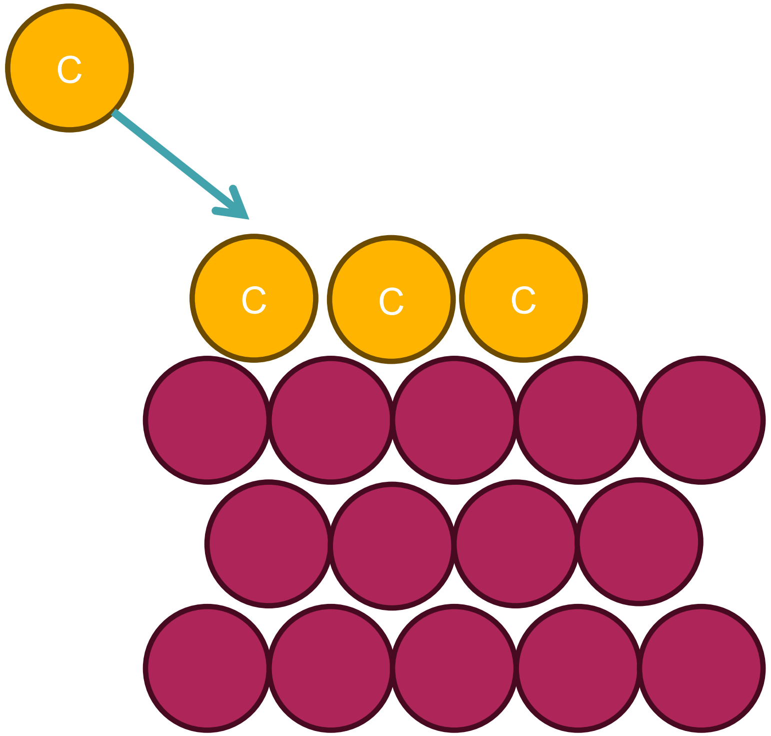


Chemical Sputtering

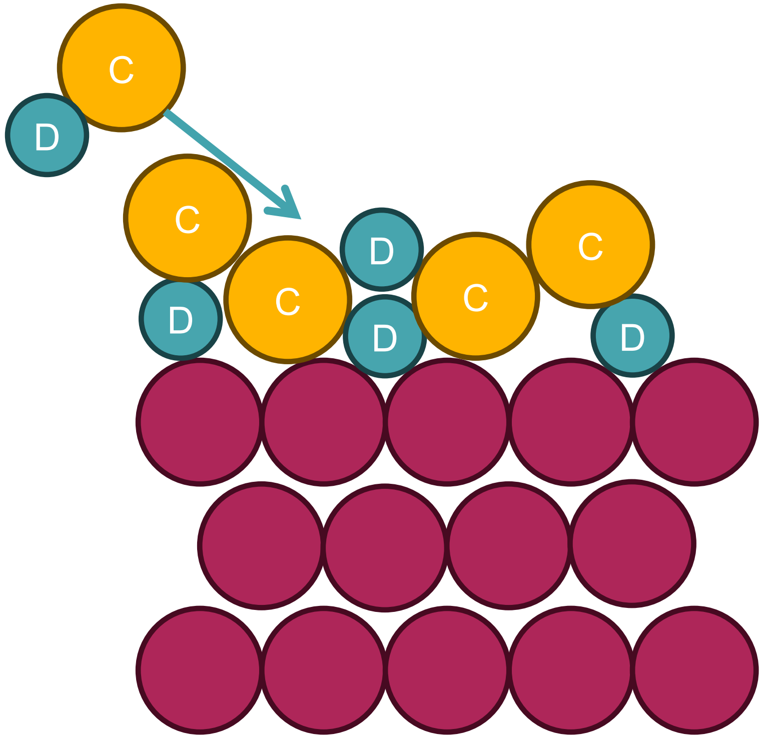


Material migration: re- and co-deposition

Redeposition

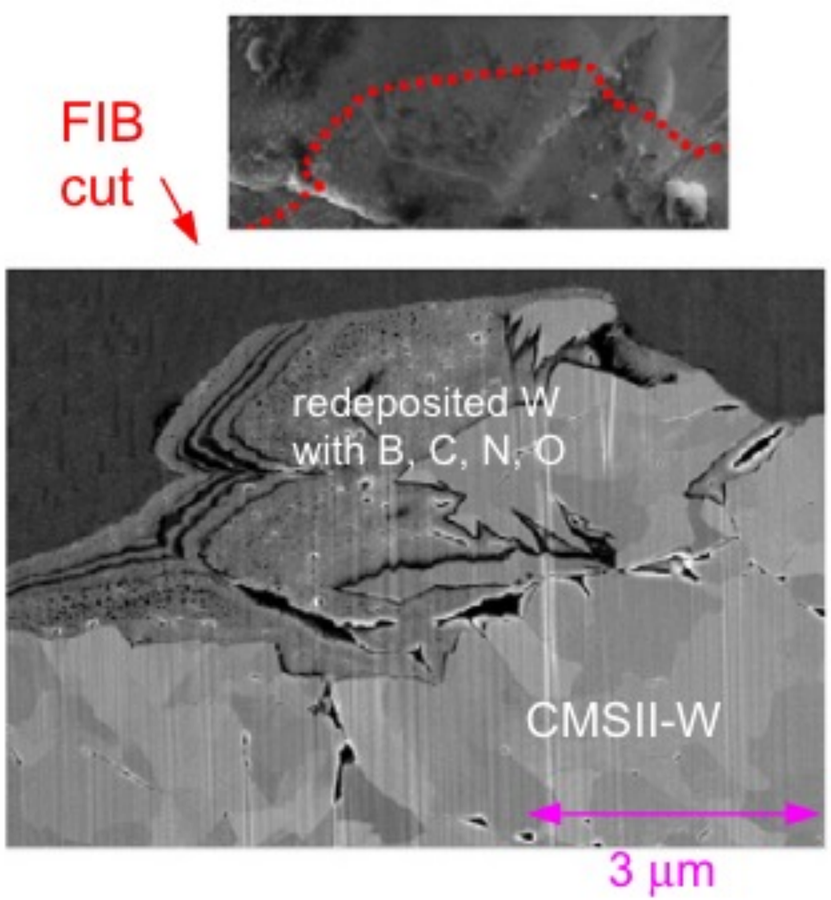


Co-Deposition



Co- and re-deposition happens constantly in tokamaks and leads to thick mixed-material layers

- From ASDEX upgrade:



Note: H/D/T can't be detected in most surface analysis techniques

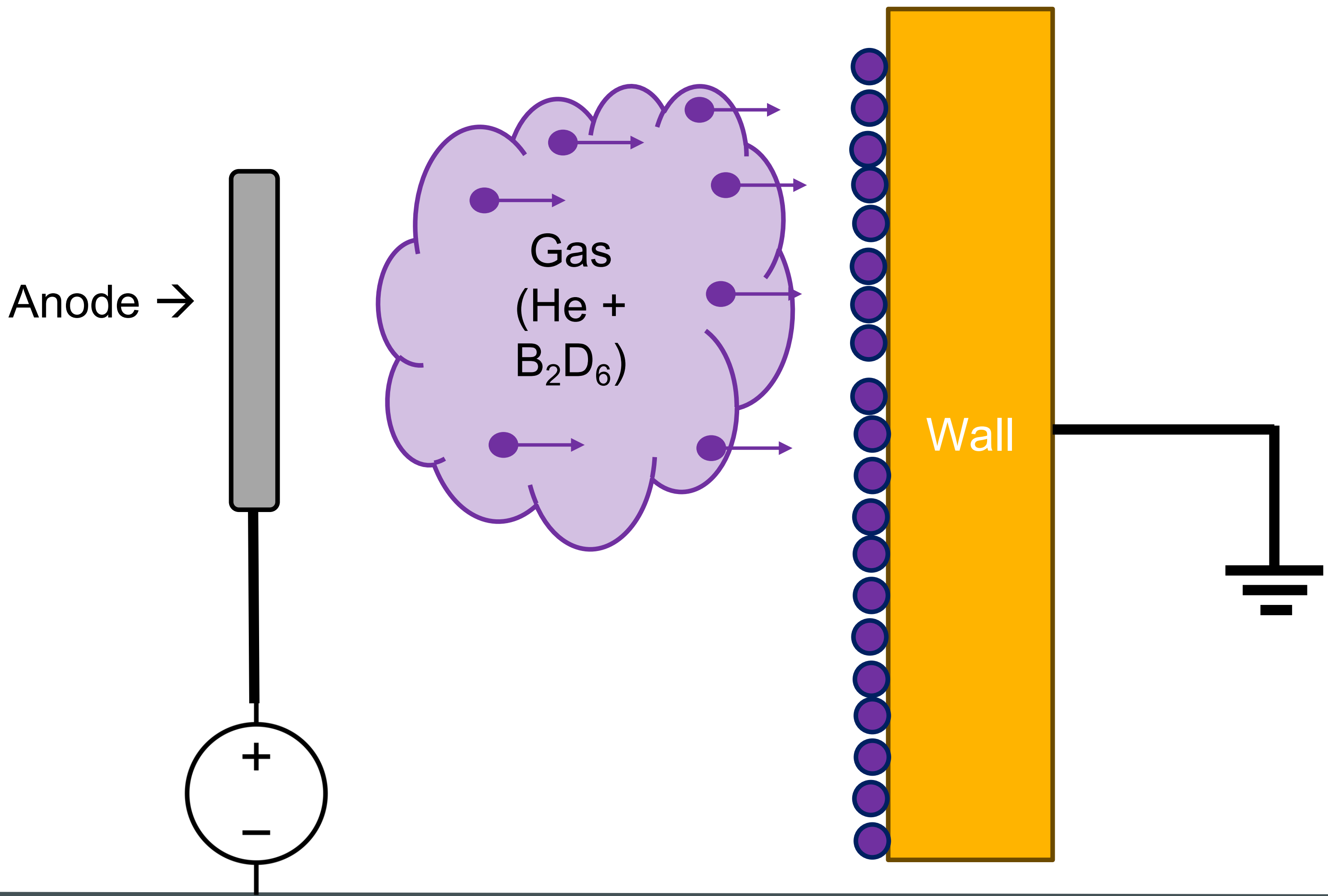
[A. Kallenbach J. of Nucl. Mater. 2011]

1950 1960 1970 **1980** 1990 2000 2010 2020

- Early laboratory experiments of D → C
- First plasma-deposited coatings:
  - Boronization
  - Siliconization
  - Carbonization

[G. Federici, Nucl. Fusion, 2001]

Wall conditioning – coatings



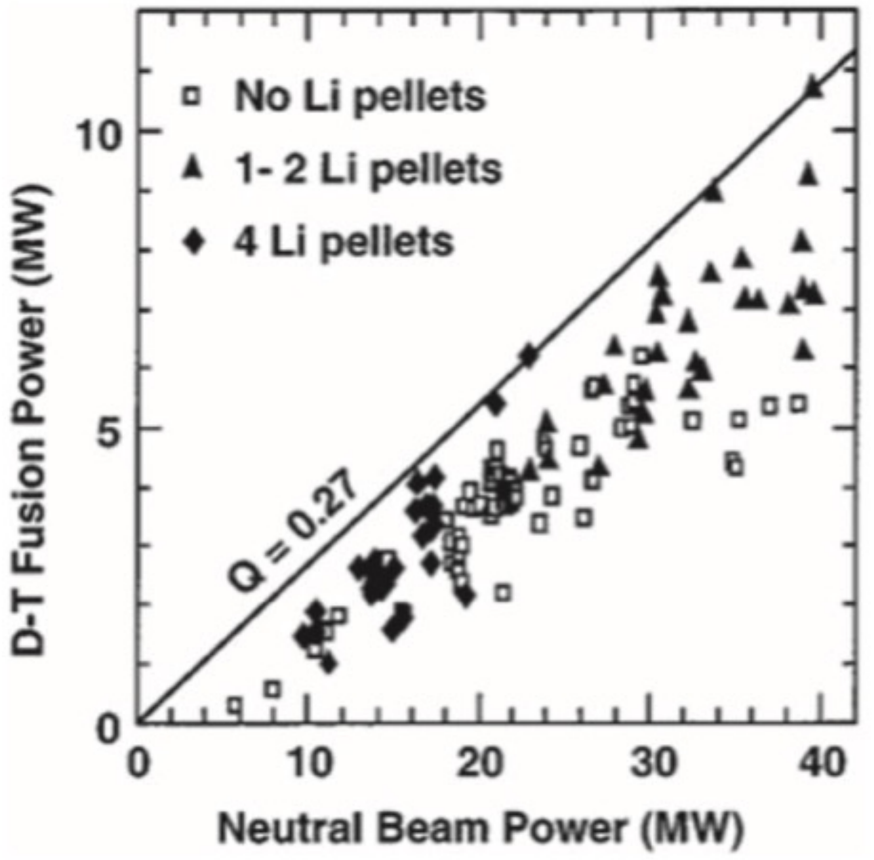
1950 1960 1970 **1980** 1990 2000 2010 2020

- Early laboratory experiments of D → C
- First plasma-deposited coatings
- Many tokamaks had graphite limiters/divertor plates
- New tokamaks
  - TEXTOR 1980 – 2013
  - TFTR 1982 – 1997
  - JET 1983 – 2023
  - **DIII-D 1986 – present**
  - Tore Supra 1988 – 2010 / **WEST 2016 – present**

[G. Federici, Nucl. Fusion, 2001]

1950 1960 1970 1980 **1990** 2000 2010 2020

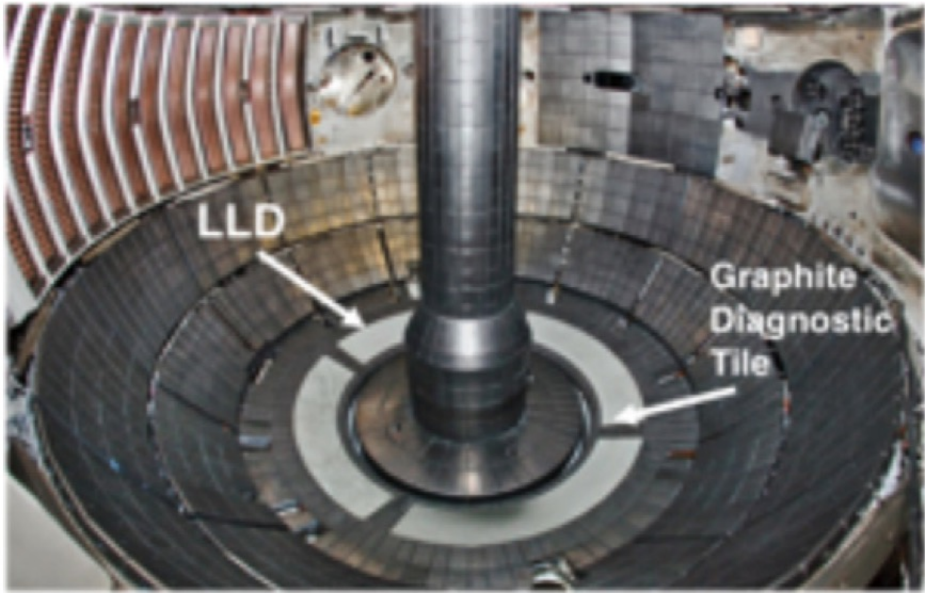
- TFTR ”Supershot”
  - Q = 0.27
  - Higher neutron rate
  - Higher stored energy
  - Higher energy confinement time
  - Higher ion temperature
  - Less carbon in core

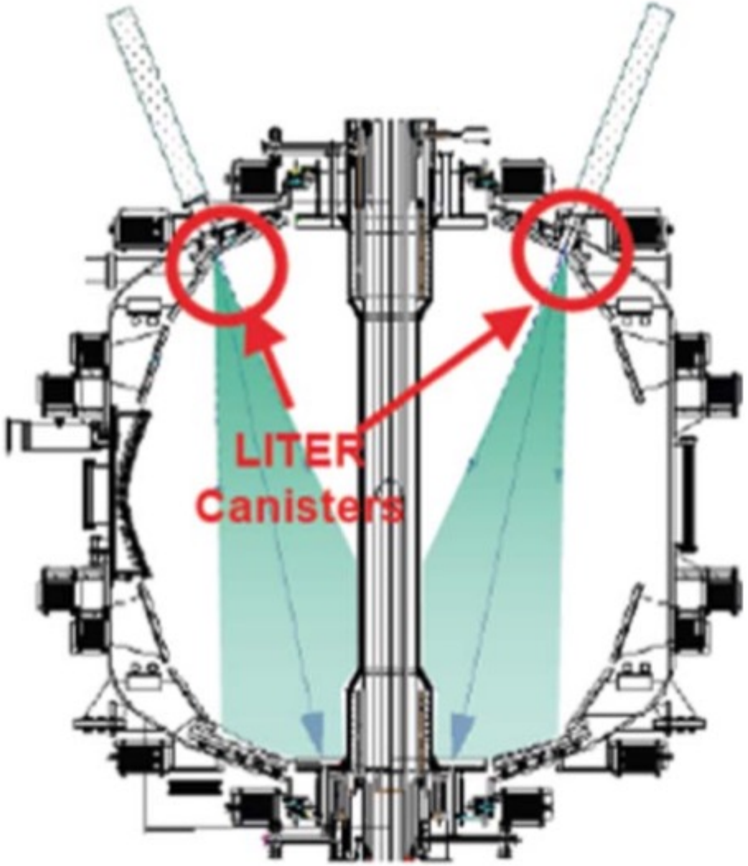


[J.A. Snipes *et al* JNM 1992

Lithium as the plasma-facing material

- NSTX Liquid Lithium Divertor and Lithium Evapora

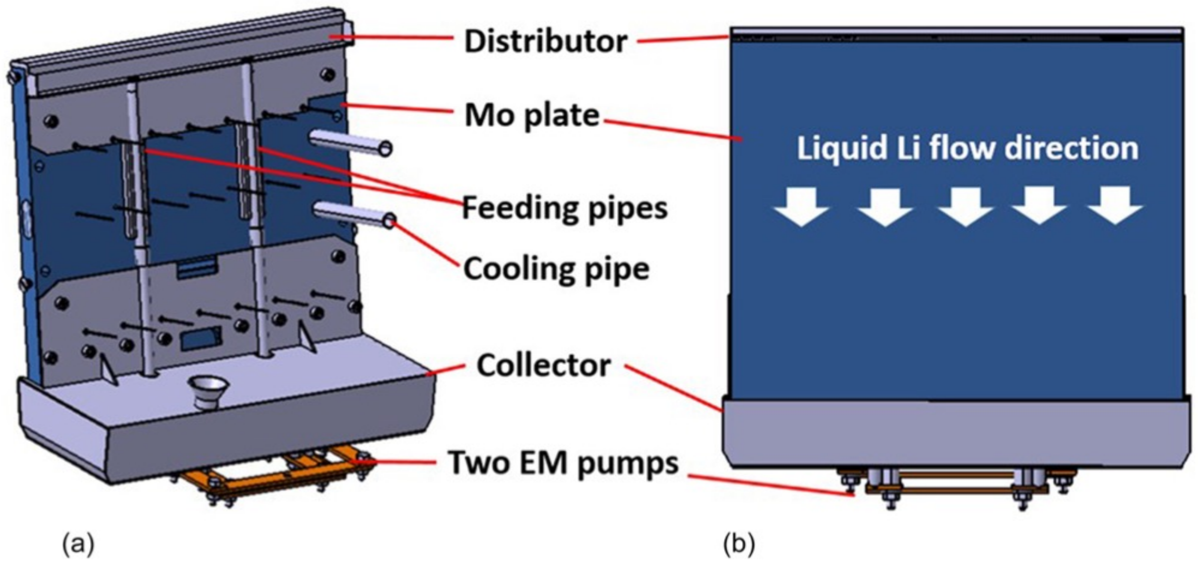


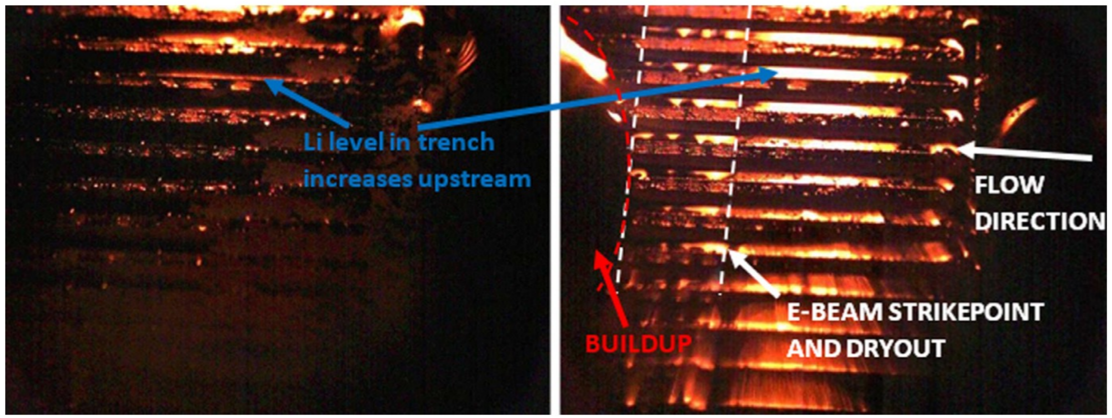


H. W. Kugel *et al.*, Fusion Engineering and Design, 2012

Lithium as the plasma-facing material

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

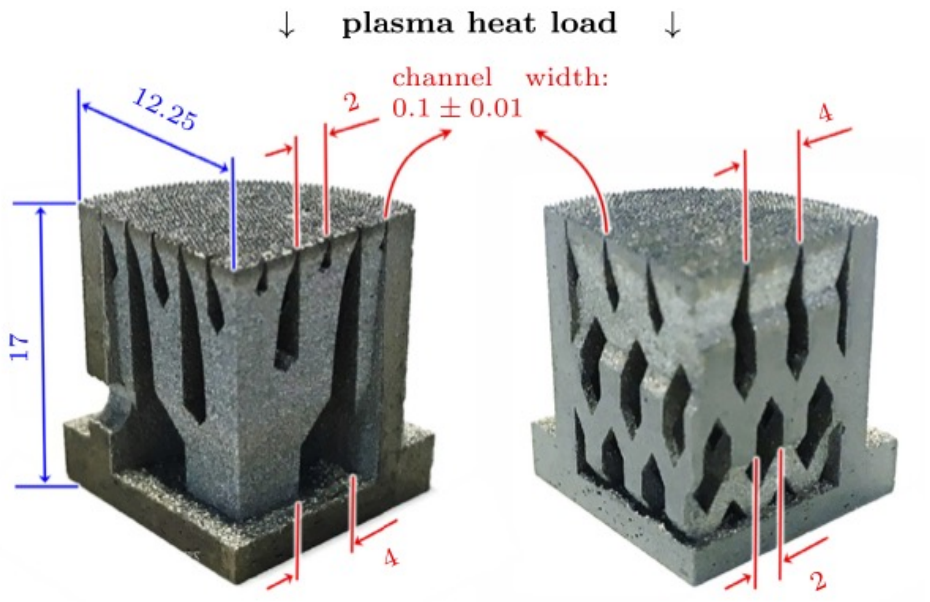


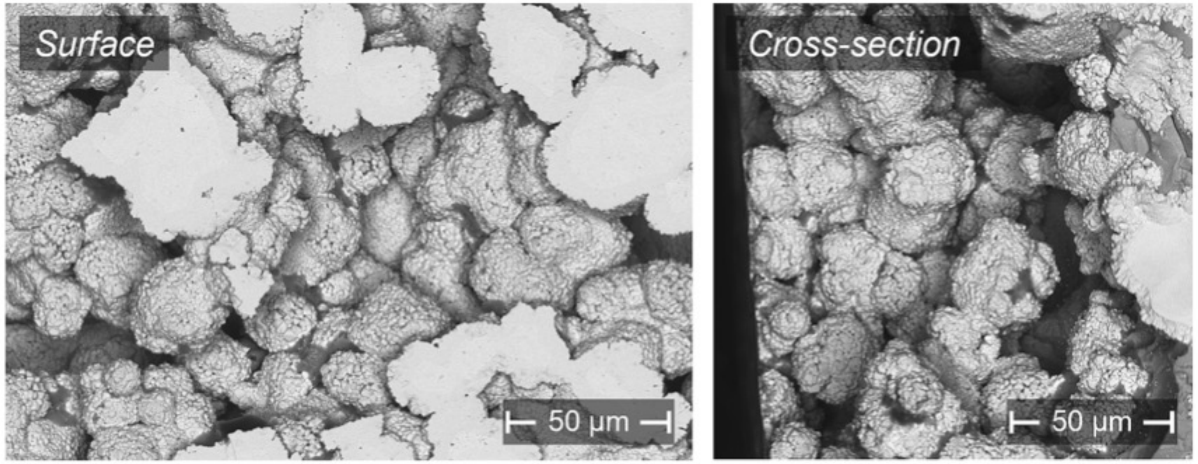


[G. Z. Zuo PoP 2020; D. N. Ruzic NME 2017]

Lithium as the plasma-facing material

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

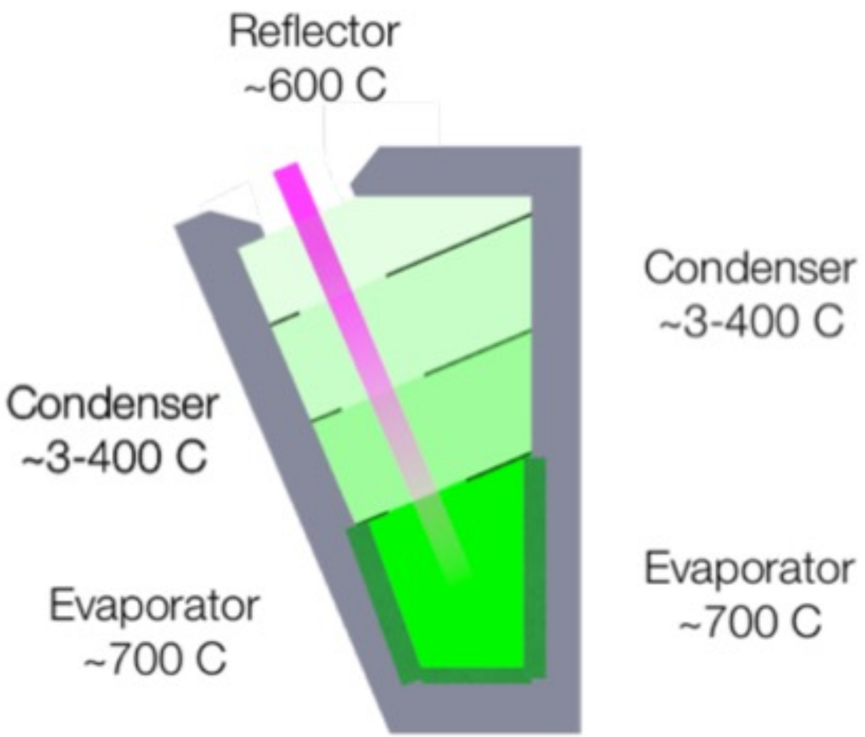




[P. Rindt, Nucl. Fusion 2019; C. López Pérez, Nucl. Mater. Energy 2023]

Lithium as the plasma-facing material

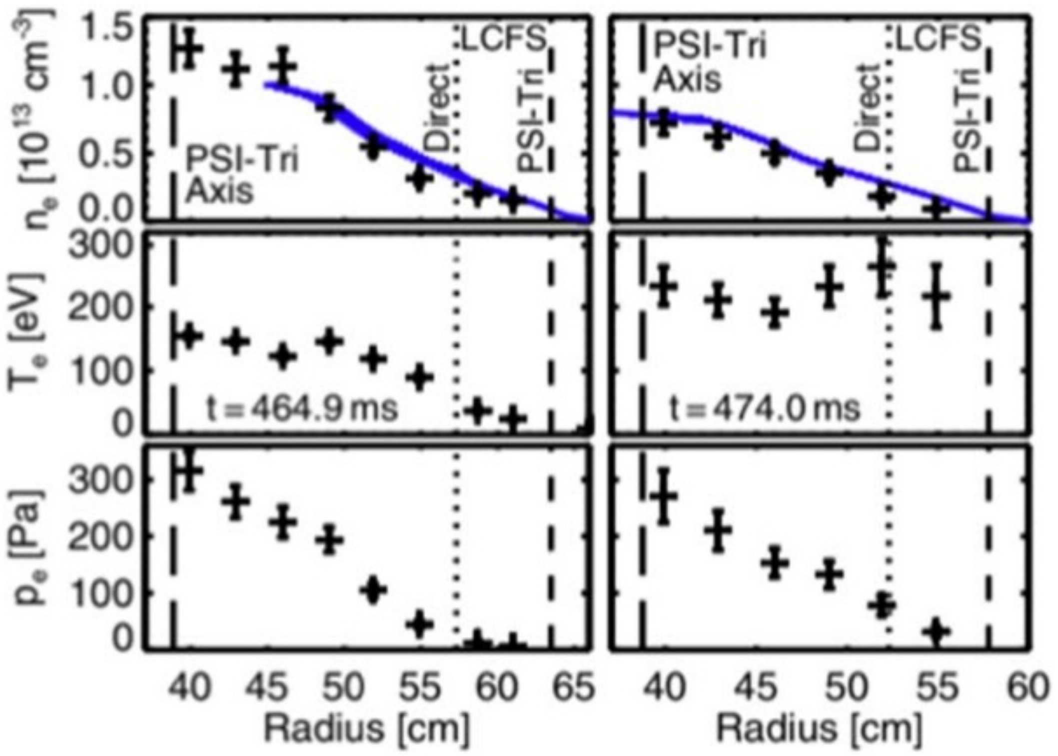
- NSTX-U Liquid Lithium Divertor and Lithium Evaporators (LITER)
- Flowing liquid lithium concepts
- Capillary porous systems
- Lithium vapor box



[E. D. Emdee NF 2019]

Lithium as the plasma-facing material

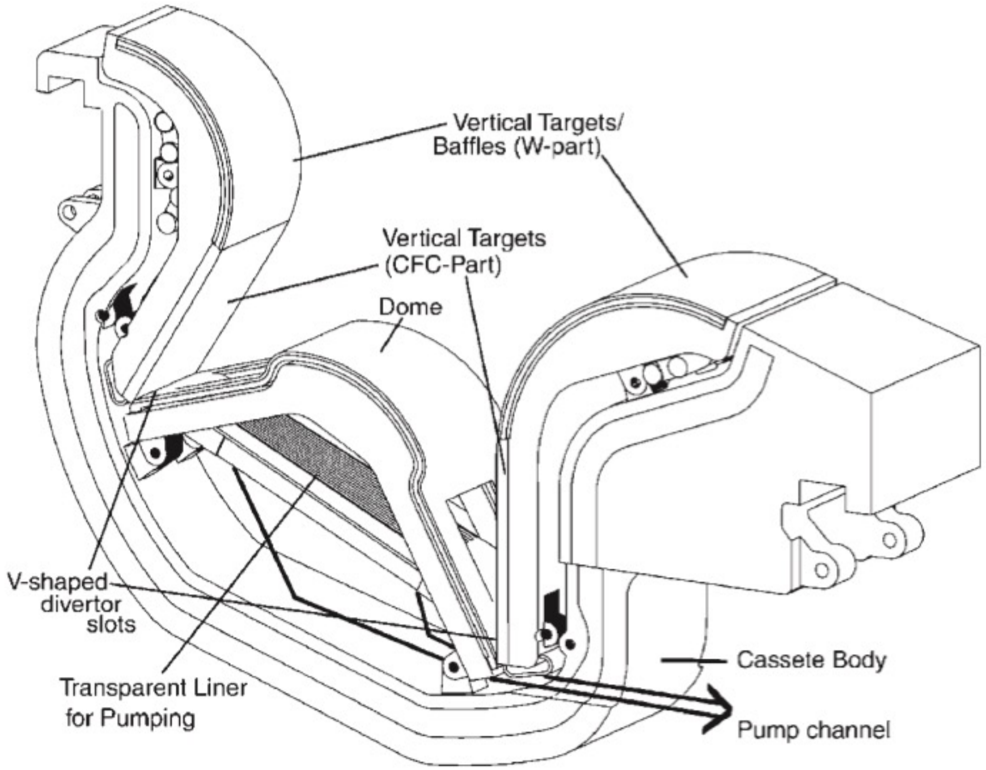
- NSTX-U Liquid Lithium Divertor and Lithium Evaporators (LITER)
- Flowing liquid lithium concepts
- Capillary porous systems
- Lithium vapor box
- All-lithium walls:
  Lithium Tokamak eXperiment (LTX)



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

1950 1960 1970 1980 **1990** 2000 2010 2020

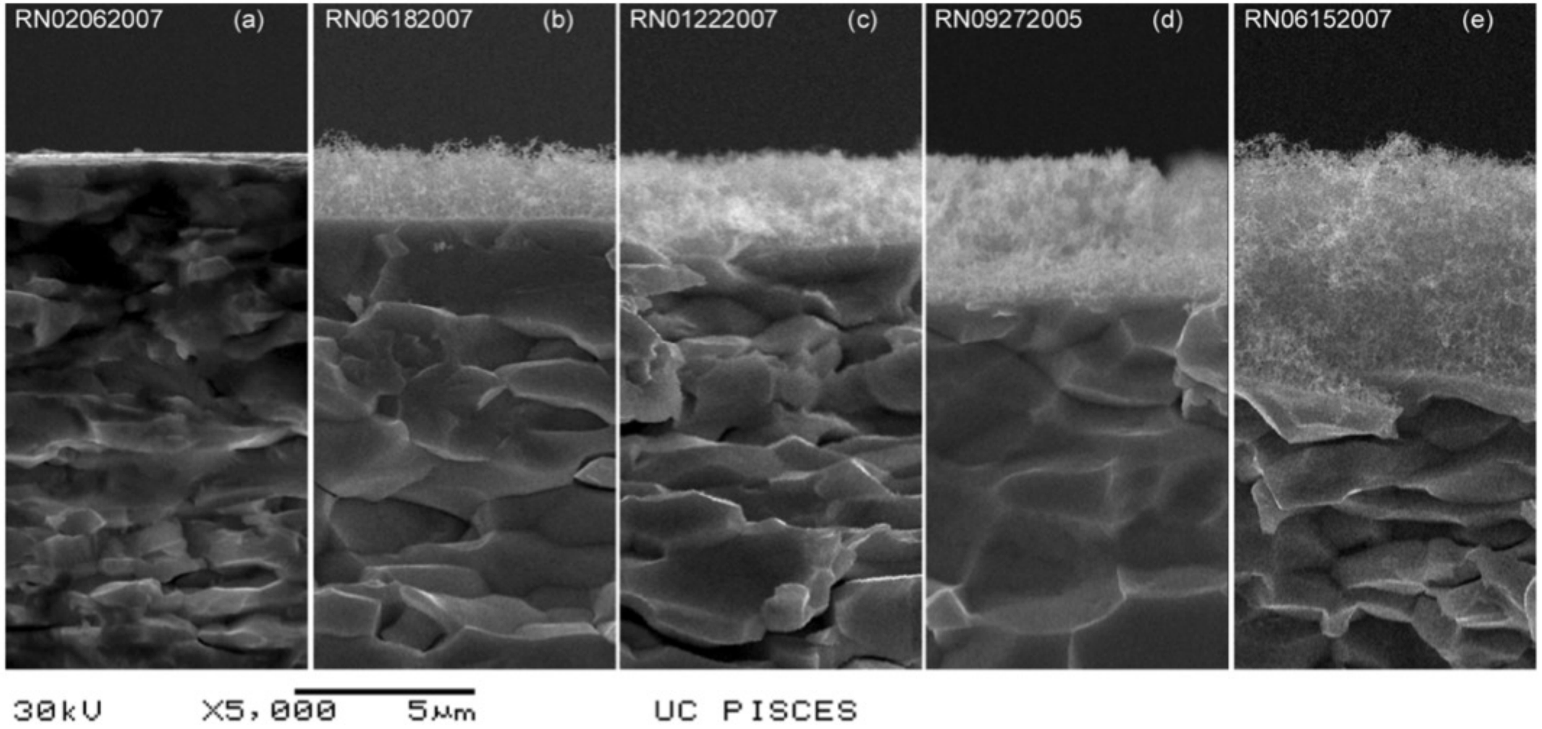
- TFTR "Supershot"
- First ITER design
  - Goal: Q > 10
  - Divertor: CFC + W (later: just W)
  - First wall: Be



[R. Aymar, *et al.* Plasma Phys. Control. Fusion **44** 2002]

1950 1960 1970 1980 1990 **2000** 2010 2020

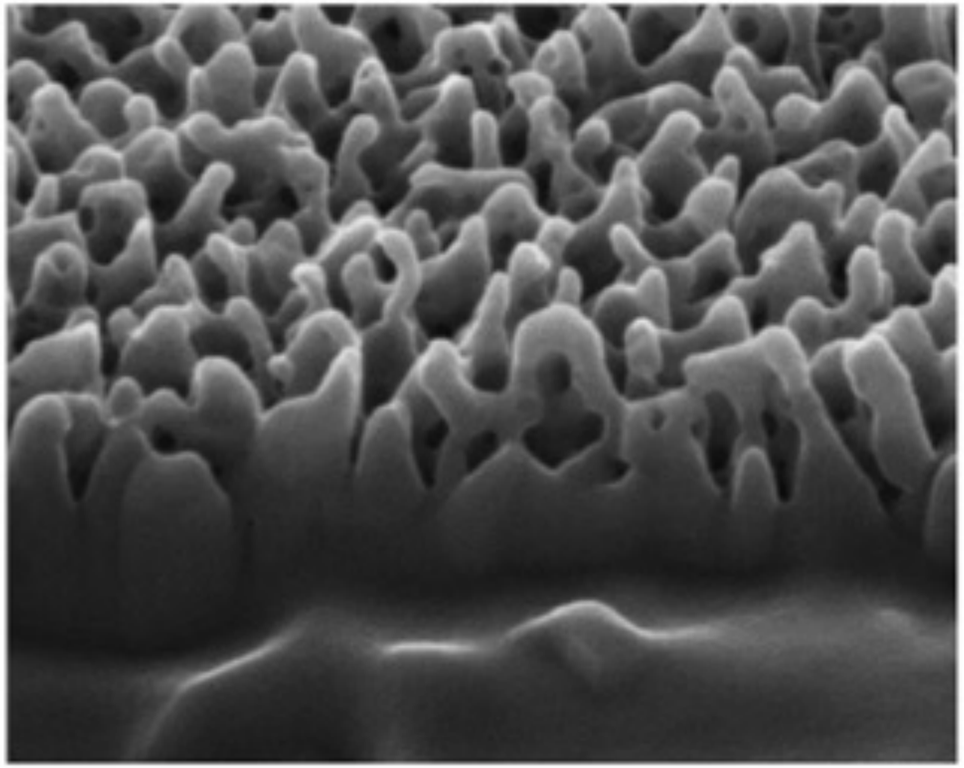
- 2008: tungsten fuzz

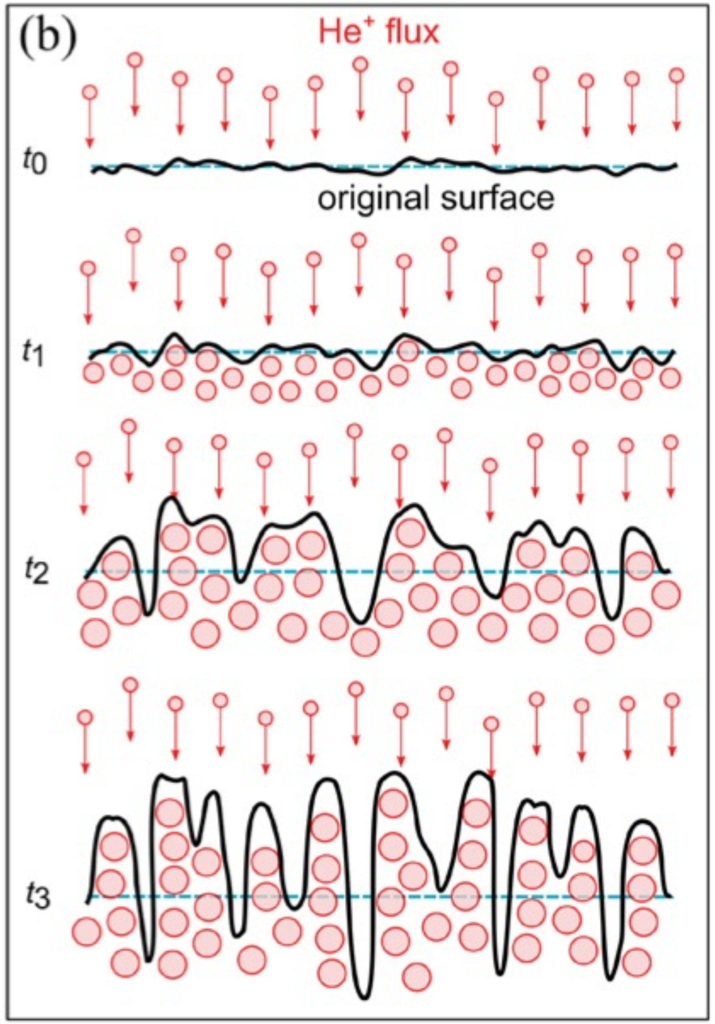


[M. J. Baldwin, et al., Nuclear Fusion 48 (2008)]

1950 1960 1970 1980 1990 **2000** 2010 2020

- 2008: tungsten fuzz

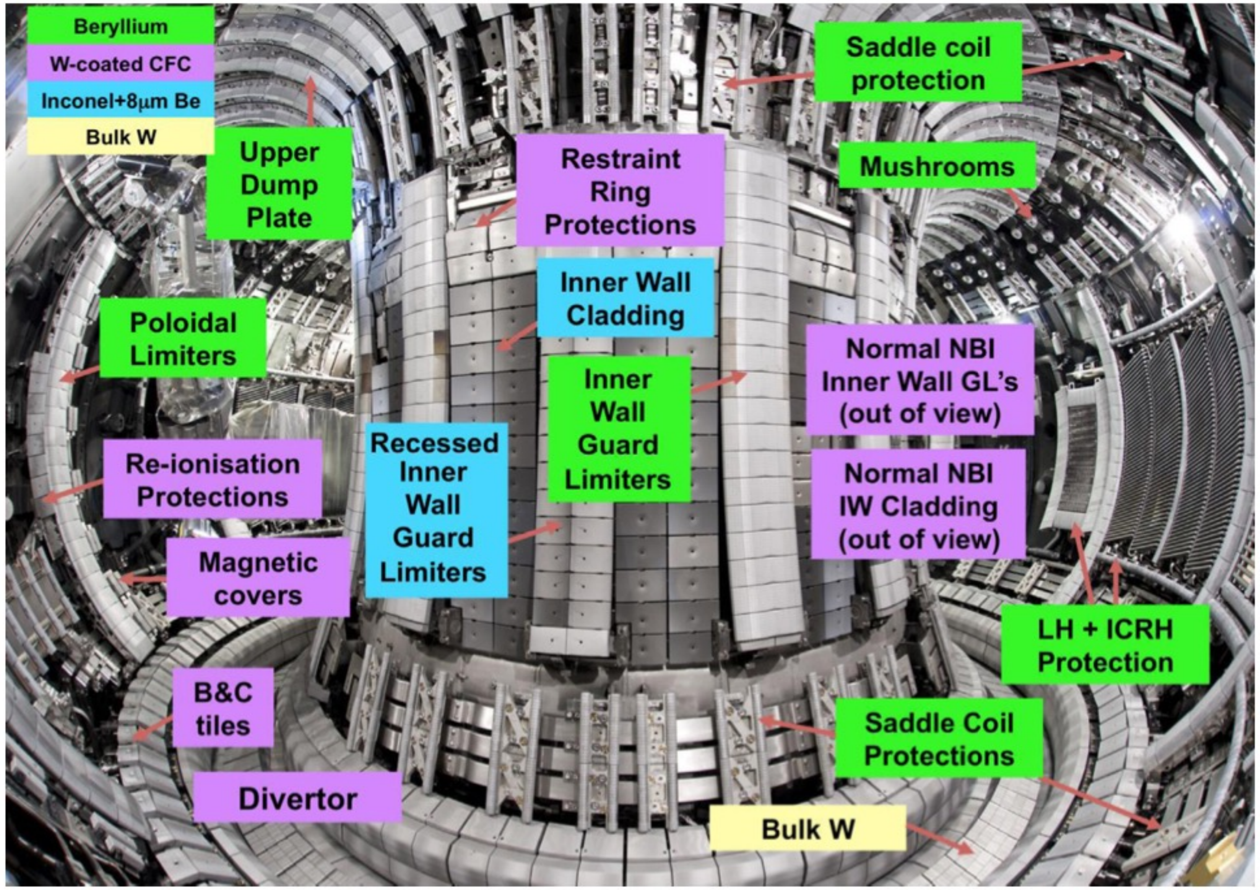




[D. Dasgupta, et al., Nuclear Fusion 59 (2019)]

1950 1960 1970 1980 1990 2000 2010 2020

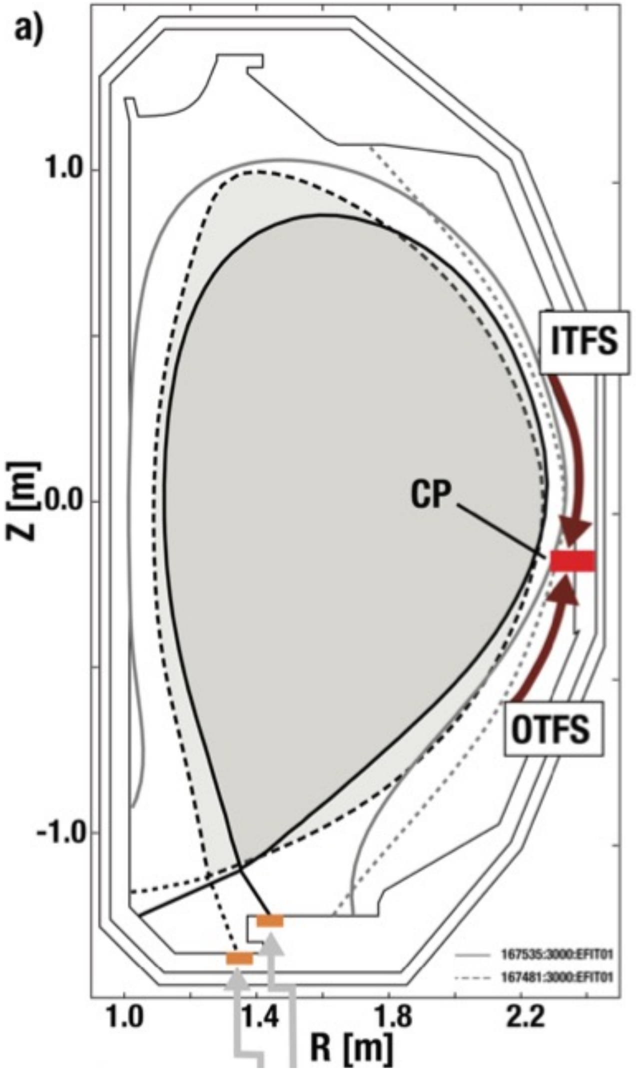
- 2011: JET ITER-like wall (ILW)

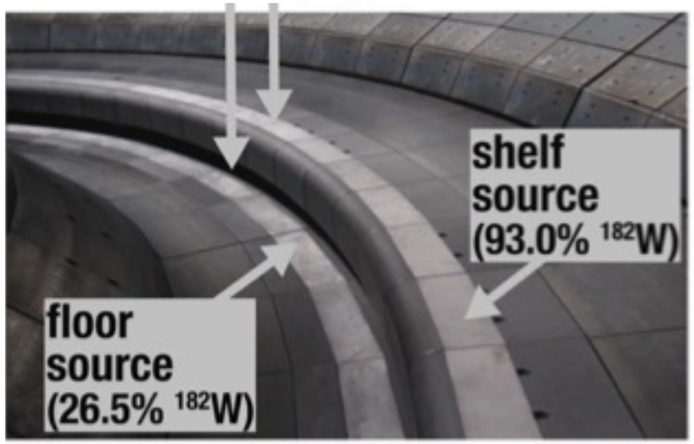


[L. Horton, *et al.*, Fusion Engineering and Design, 2013]

1950 1960 1970 1980 1990 2000 **2010** 2020

- 2011: JET ITER-like wall (ILW)
- 2015: DIII-D Metal Rings Campaign

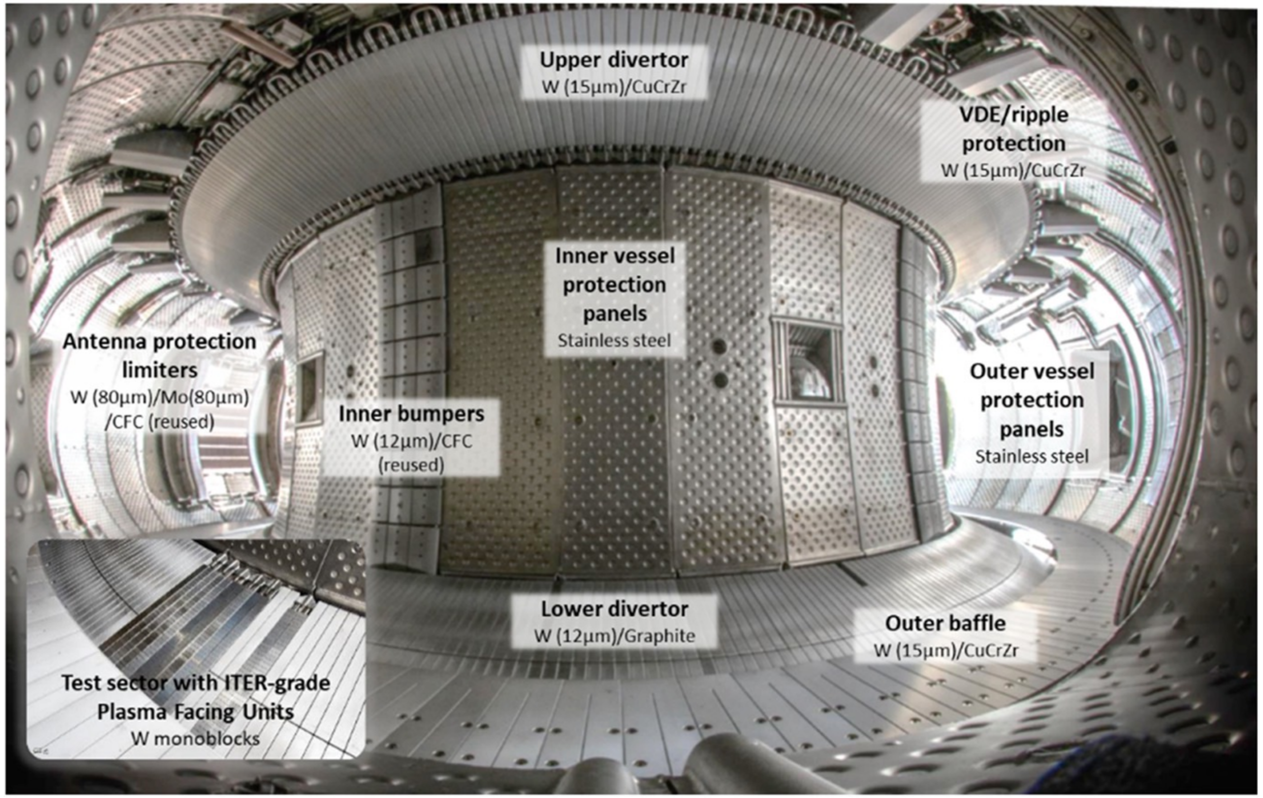




[E. A. Unterberg, *et al.*, Nuclear Materials and Energy, 2019]

1950 1960 1970 1980 1990 2000 **2010** 2020

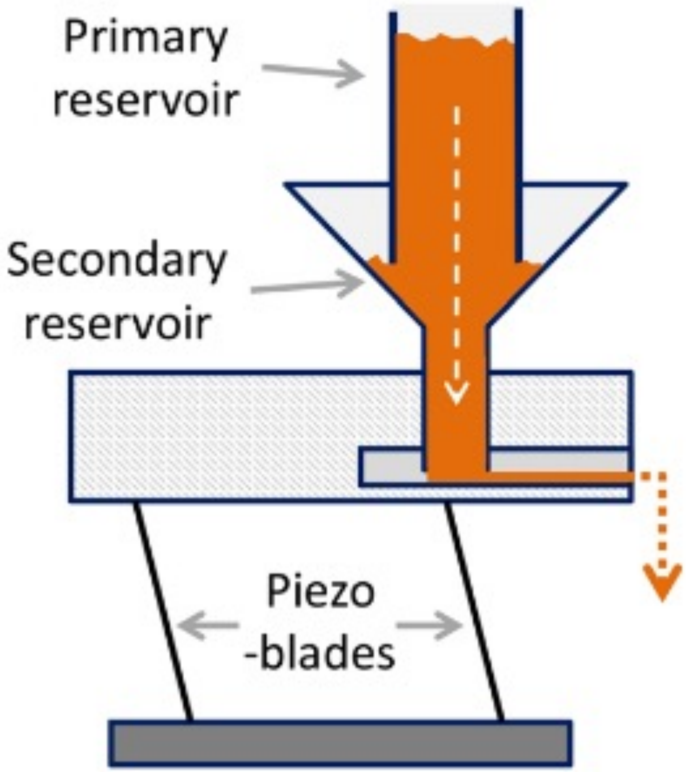
- 2011: JET ITER-like wall (ILW)
- 2015: DIII-D Metal Rings Campaign
- 2017: WEST operates with full W walls



[J. Bucalossi, *et al*., Nuclear Fusion, 2022]

1950 1960 1970 1980 1990 2000 **2010** 2020

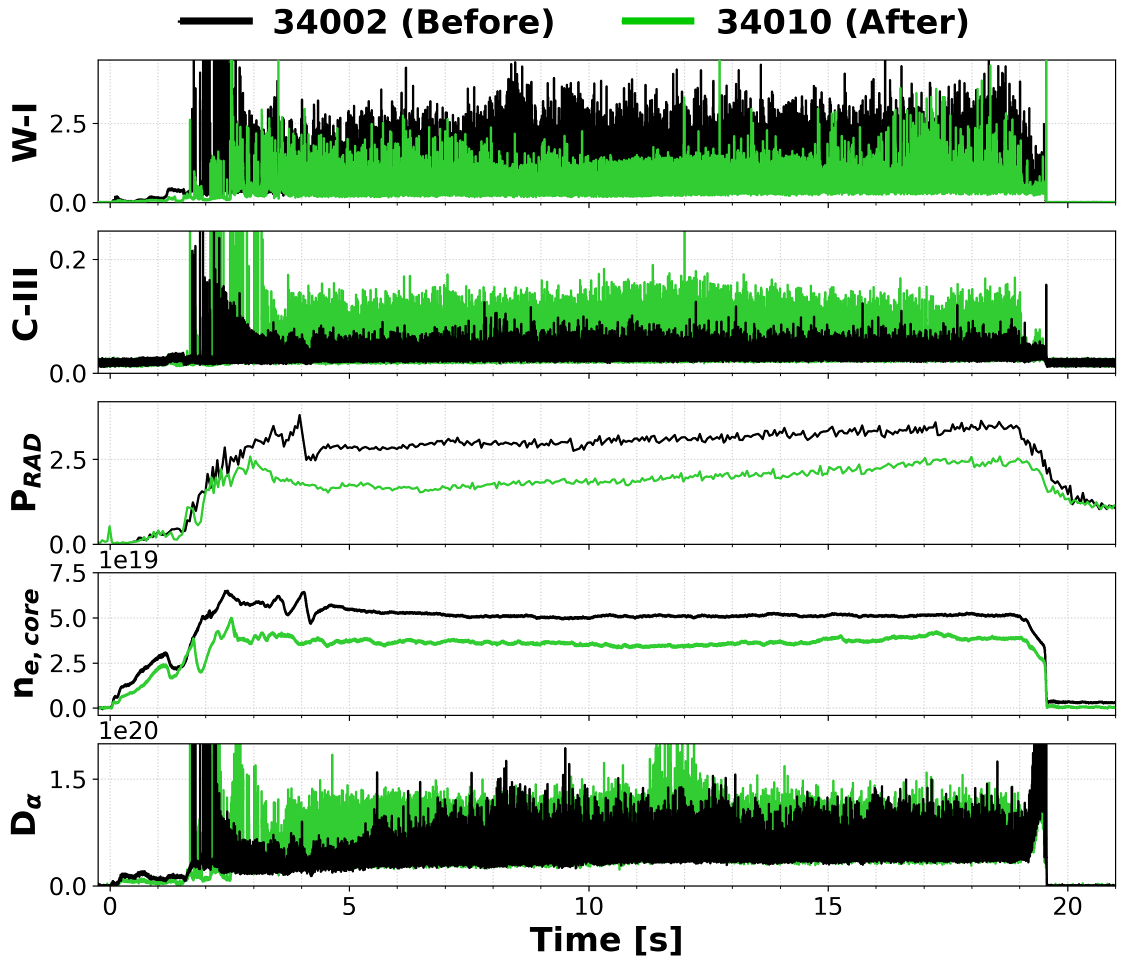
- 2011: JET ITER-like wall (ILW)
- 2015: DIII-D Metal Rings Campaign
- 2017: WEST operates with full W walls
- 2018: Impurity Powder Droppers
  - Insert powders into plasma *during* plasma discharges
  - Can be used with almost any powder (Li, Si, C)
  - Installed on DIII-D, ASDEX-Upgrade, WEST, W7X, LHD, KSTAR and EAST
  - Results: ELM suppression and mitigation, wall conditioning



[A. Nagy, et al., Rev. Sci. Instrum. 89 (2018)]

1950 1960 1970 1980 1990 2000 2010 **2020**

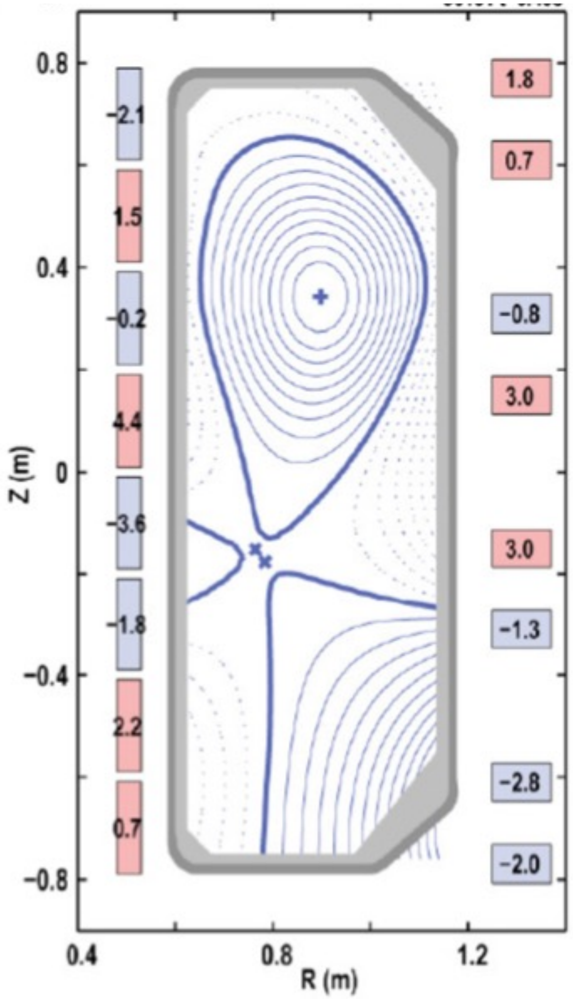
- 2023: ITER updates its baseline
  - Be first wall → W first wall
  - Needs boronization



[H. Schamis, *in preparation*]

Brief overview of other PMI topics: Divertor geometry

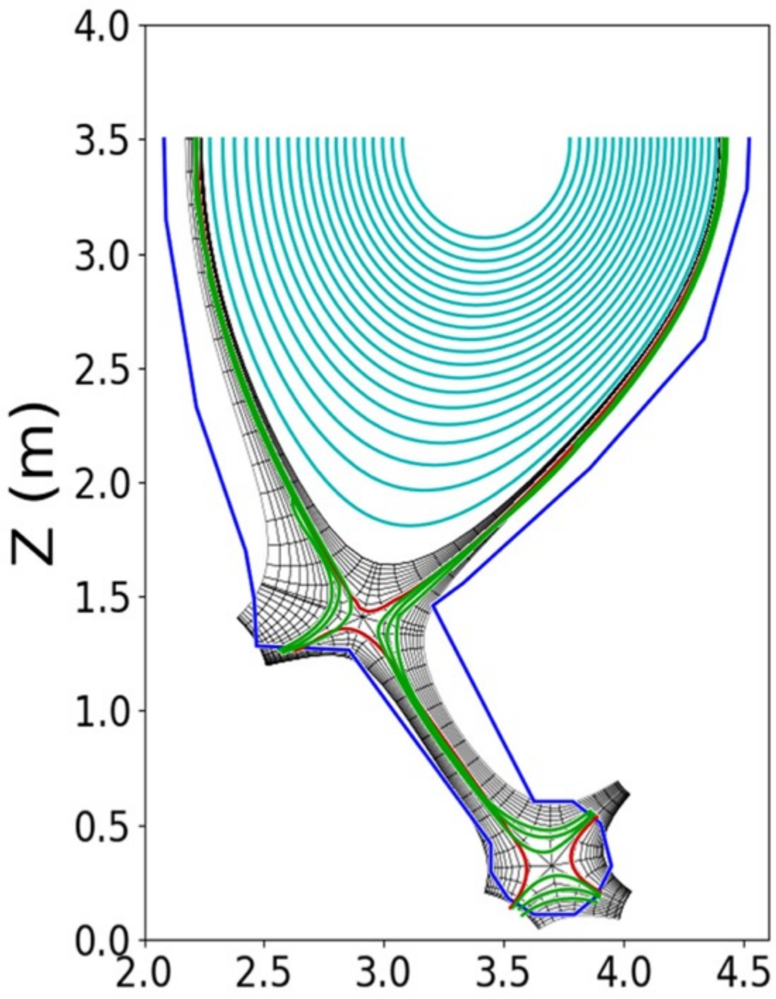
- Snowflake divertor
  - Additional null point
  - 4 strike points instead of 2



[D. D. Ryutov PoP 2015]

Brief overview of other PMI topics: Divertor geometry

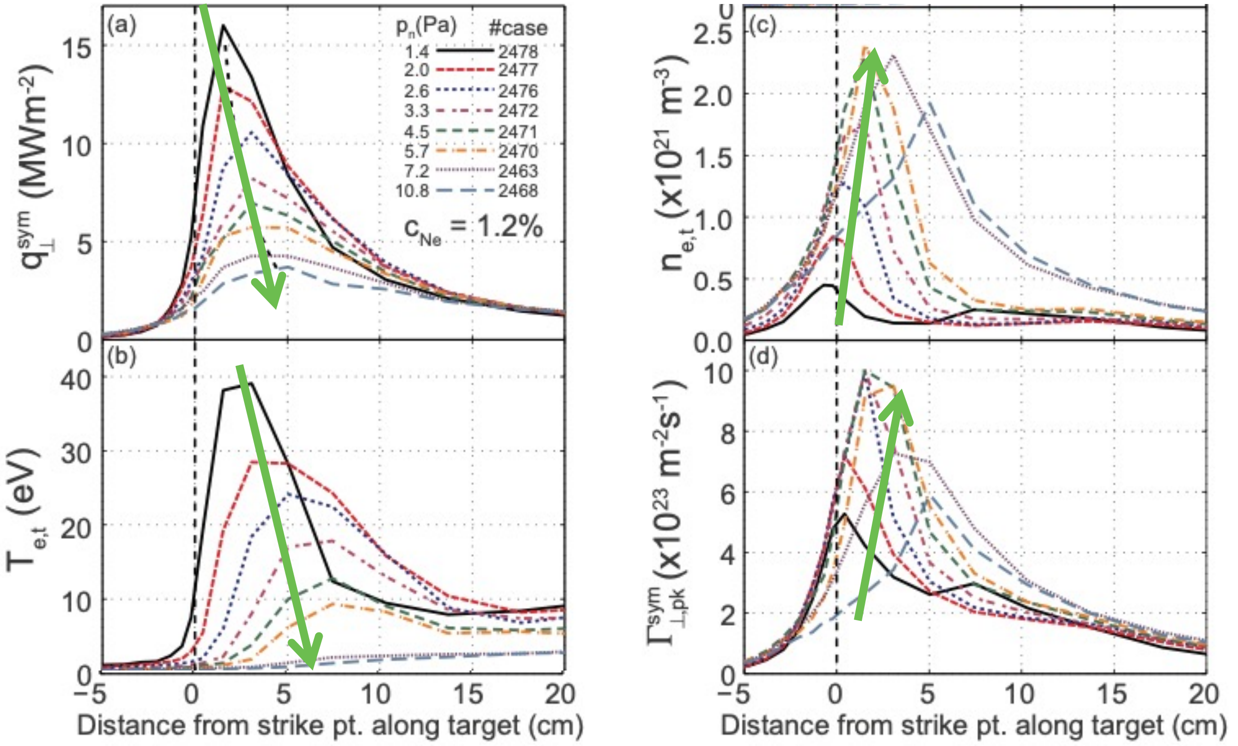
- Snowflake divertor
  - Additional null point
  - 4 strike points instead of 2
- Long legged divertor
  - Strike point further from X-point



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

Brief overview of other PMI topics: Detachment

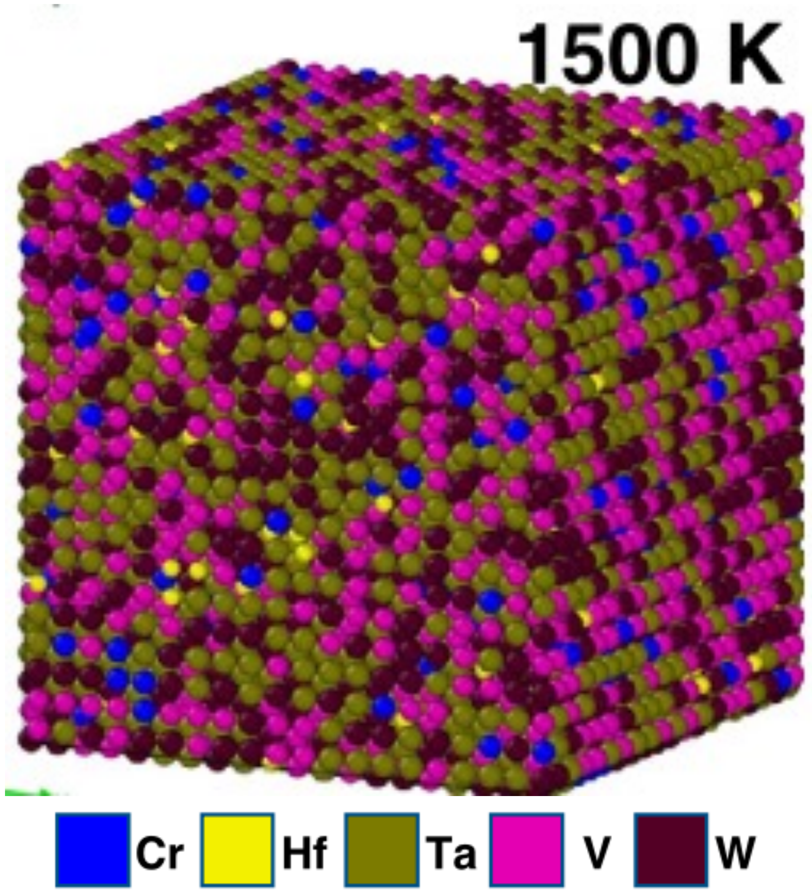
- Impurity seeding (e.g., Ne gas puffing) increases neutral pressure in SOL:
  - Increases collisions and radiative losses
  - Decreases heat flux
  - Decreases Te
  - Decreases ion impact energy
  - Increases flux to the divertor plates



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

Brief overview of other PMI topics: Novel materials

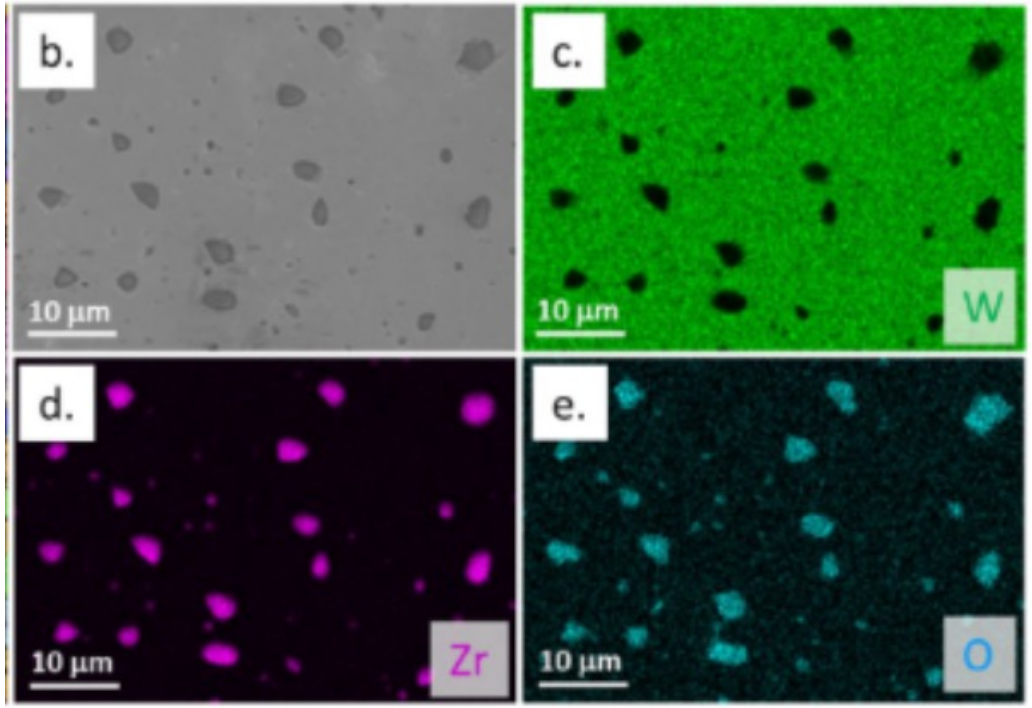
- High-entropy alloys (HEAs)
  - Example: W_{31} Ta_{34} Cr_5 $V_{27}Hf_3$



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

Brief overview of other PMI topics: Novel materials

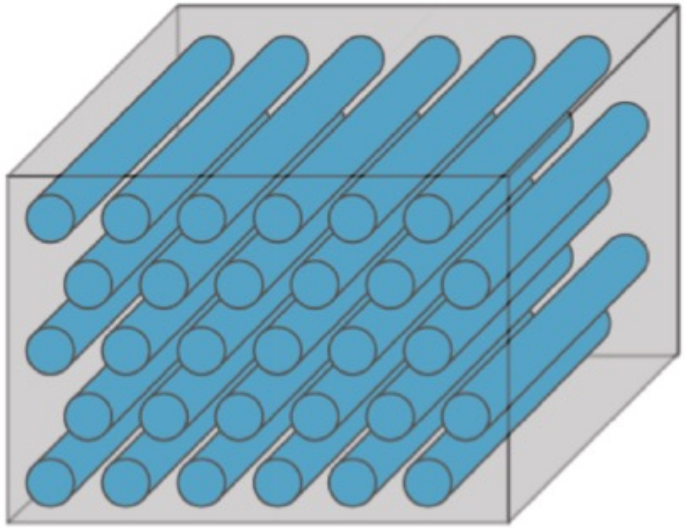
- High-entropy alloys (HEAs)
- Dispersion-strengthened tungsten composites
  - Transition metal carbide or oxide dispersoids

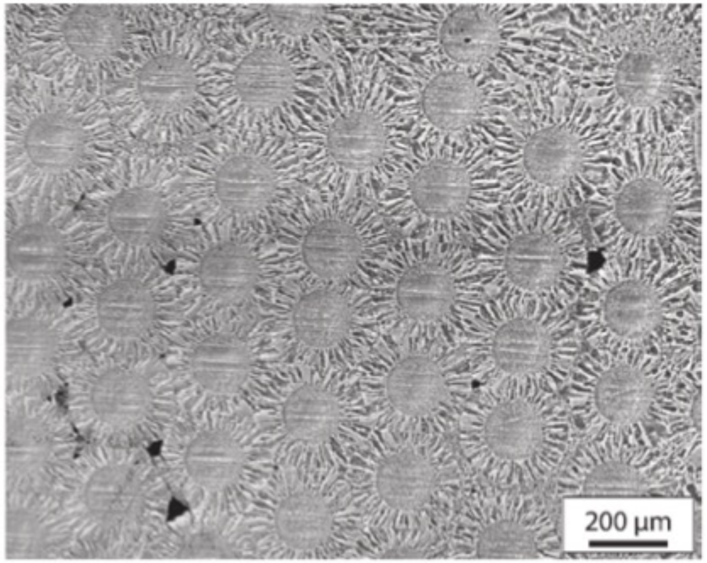


[T. Marchhart, *et al.*, Sci. Rep. 2024]

Brief overview of other PMI topics: Novel materials

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

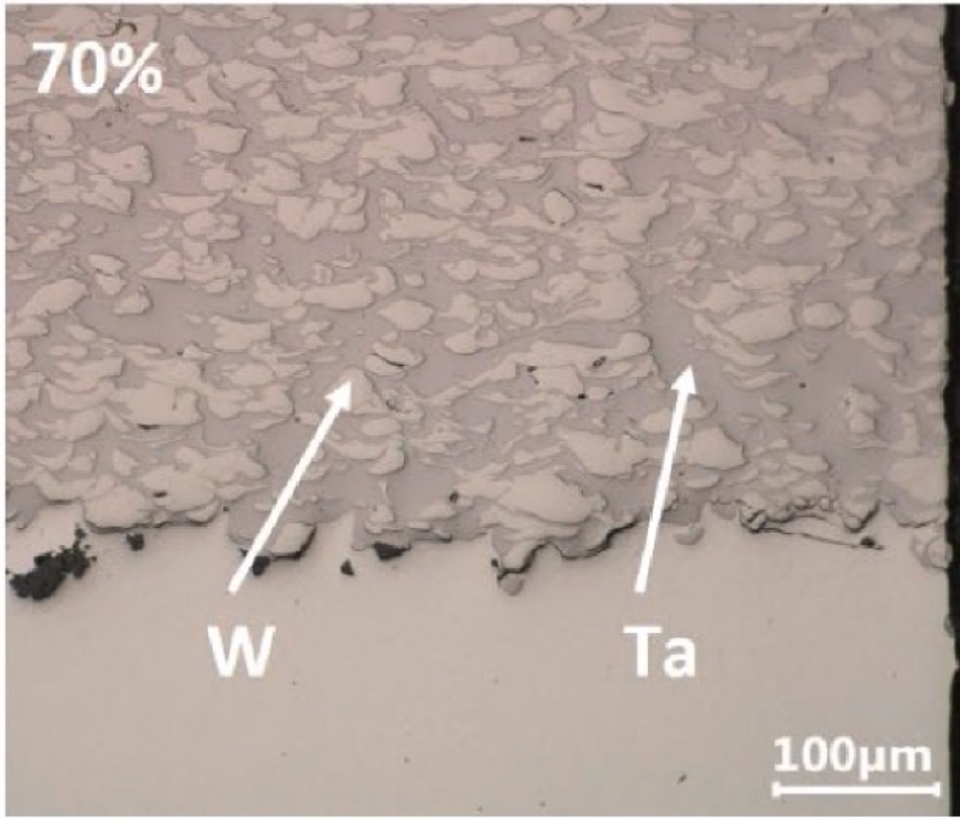




[A. Karcher, *et al.*, Nucl. Mater. Energy, 2021]

Brief overview of other PMI topics: Novel materials

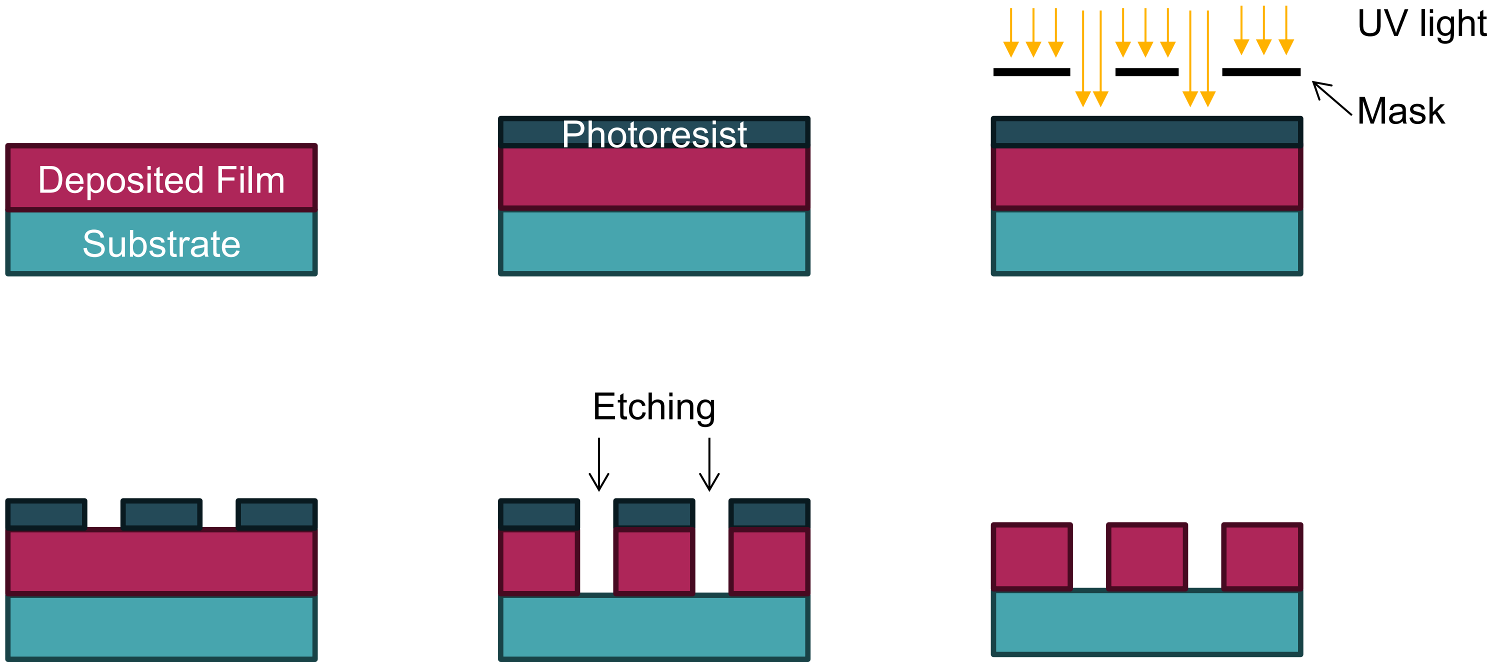
- High-entropy alloys (HEAs)
- Dispersion-strengthened tungsten composites
- Tungsten Fiber composites
- Tungsten and/or Tantalum cold spray



[R. Neu, *et al.*, Nucl. Mater. Energy, 2023

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

- PMI, like all research, builds upon decades of previous knowledge
- Some PMI has been "accidental" – lithium
- Themes recur – W limiters replaced with C in 1980s, and now many present-day devices use W divertors
- No magic solution for PMI 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
- Tokamak experiments
- Computational PMI

Useful References

General PMI

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

IAEA nuclear fusion

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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Nuclear Fusion, Volume 41, Number 12

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

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

Useful References

<u>General PMI</u>

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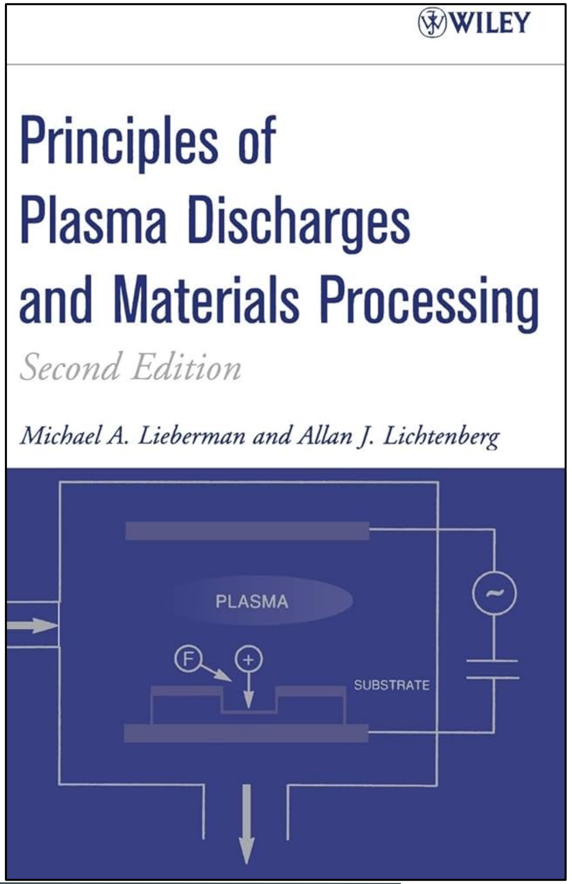

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- G. Federici *et al* 2001 *Nucl. Fusion* **41** 1967 doi.org/10.1088/0029-5515/41/12/218
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