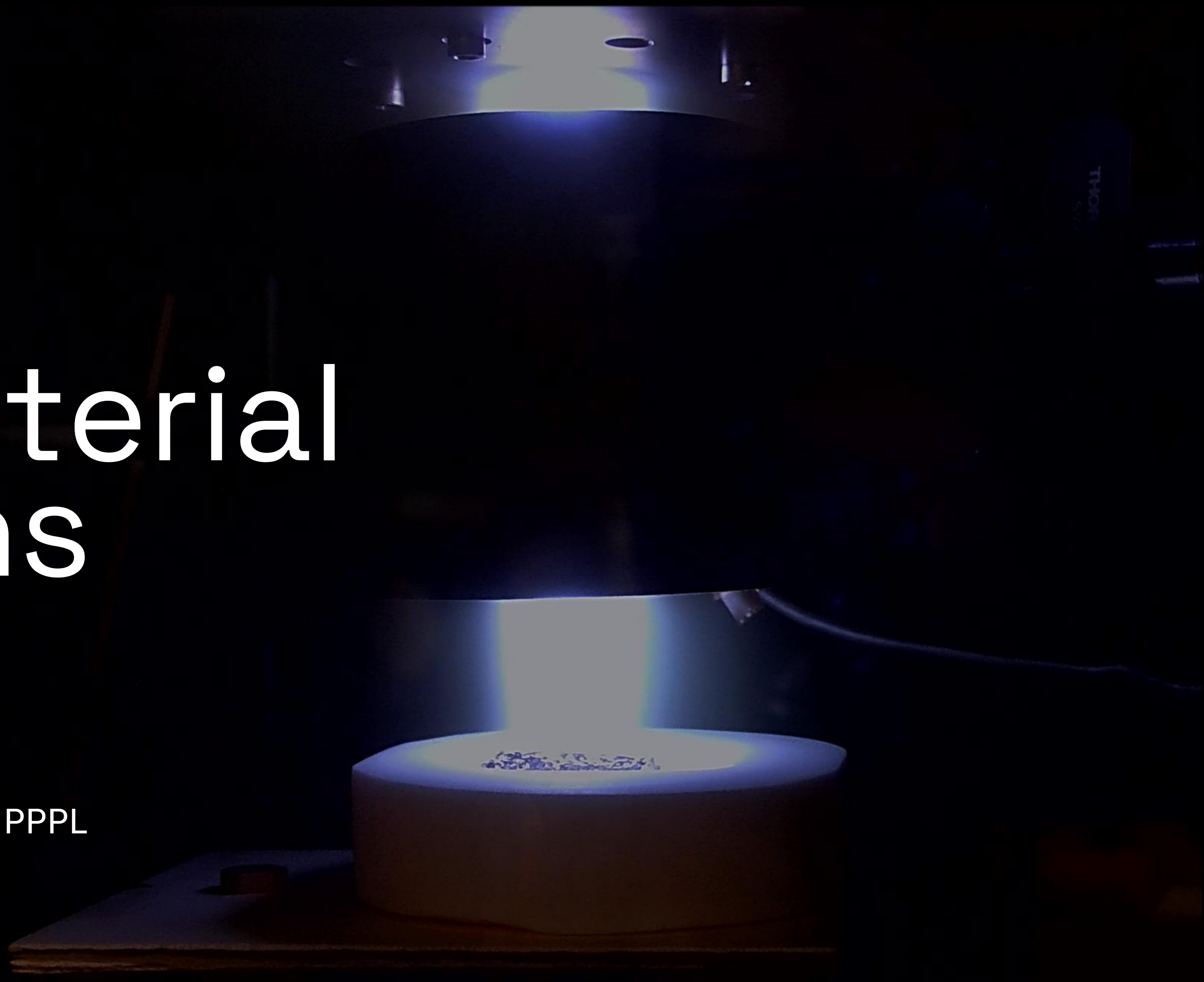
Plasma-Material Interactions



Angelica Ottaviano
Thea Energy, Inc.
SULI Introductory Course in Plasma Physics, PPPL
June 6th, 2025

Background and journey

Rome, Italy

Los Angeles
BS in physics at CSU Northridge

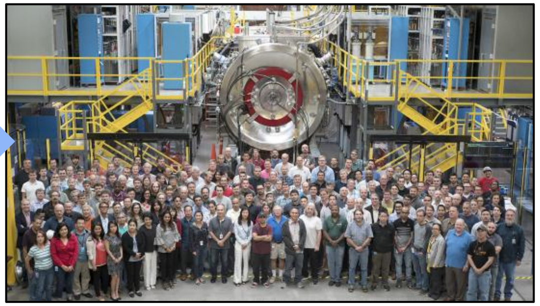
PRINCETON Chemical and Biological Engineering

DESY (Hamburg)

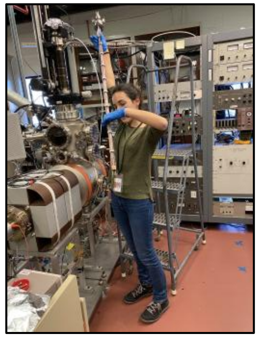
SULI Intern

Swiss Plasma Center, EPFL

TAE Technologies
Diagnostic Specialist



UCLA Mechanical and Aerospace PhD student



PPPL PCRF

Visiting grad student at PPPL

The Aerospace Corporation
Propulsion and Plasma Research Scientist

Today!

Thea Energy
Manager for Plasma-Material Interactions

Talk Outline

PMI: plasma-material interactions
PFC: plasma-facing component
PFM: plasma-facing material
MCF: magnetic confinement fusion

- Introduction
- Fundamental processes in PMI
- PMI tools and diagnostics
- PMI in magnetic confinement fusion
- PMI in space propulsion
- PMI at Thea Energy

**PMI can also be referred to as PSI: plasma-surface interactions*

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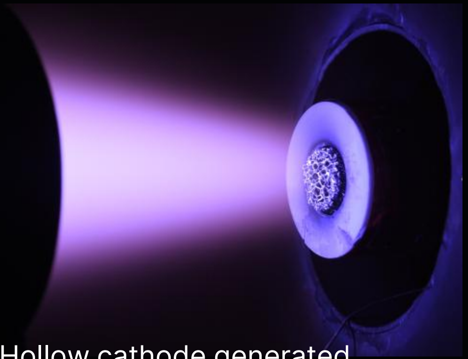
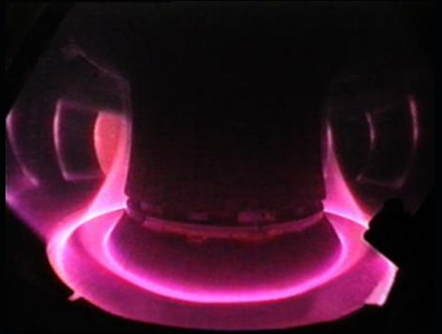
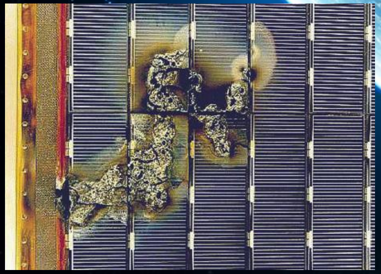
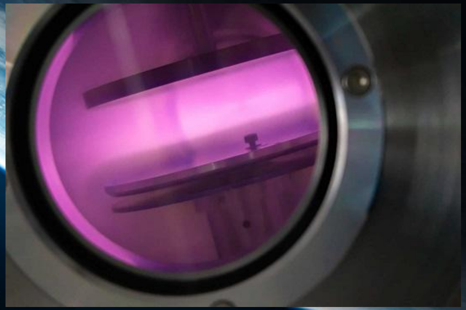
What are Plasma-Material Interactions?


Hollow cathode generated linear plasma device at UCLA


ASDEX-U tokamak divertor plasma


Tungsten damage from TEXTOR tokamak edge plasma (Julich)

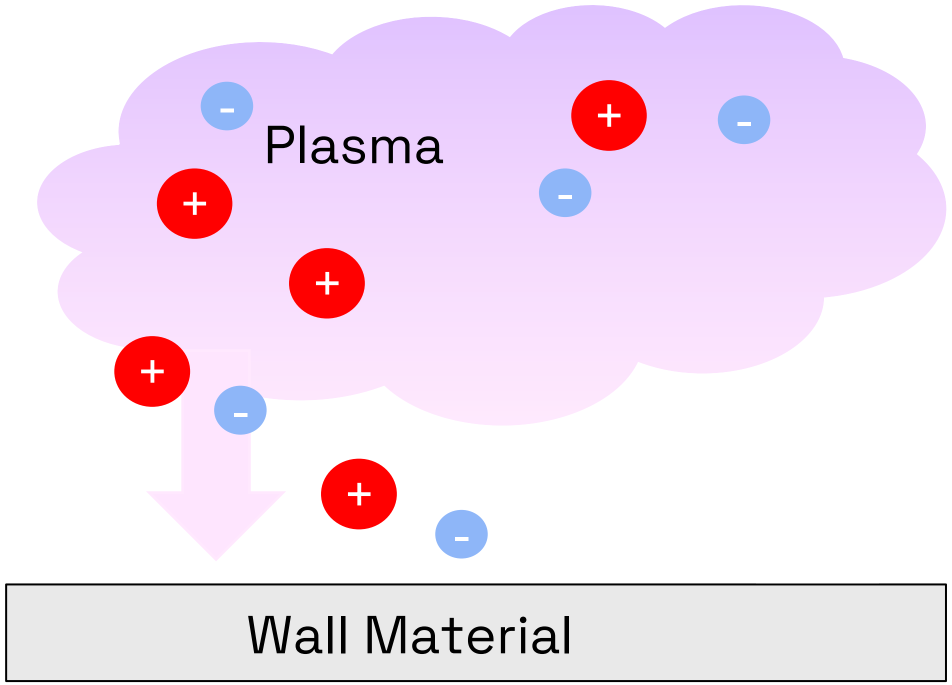

Solar array arc damage caused by electrostatic discharging in space plasmas (ESA)


Plasma etching of a water (AEM deposition)

Plasma-Material Interactions: a **dual** phenomenon

Materials in a plasma are modified by receiving energetic plasma *particles*, *heat*, and *momentum* flux

Simplified, conceptual picture



Plasma-Material Interactions: a **dual** phenomenon

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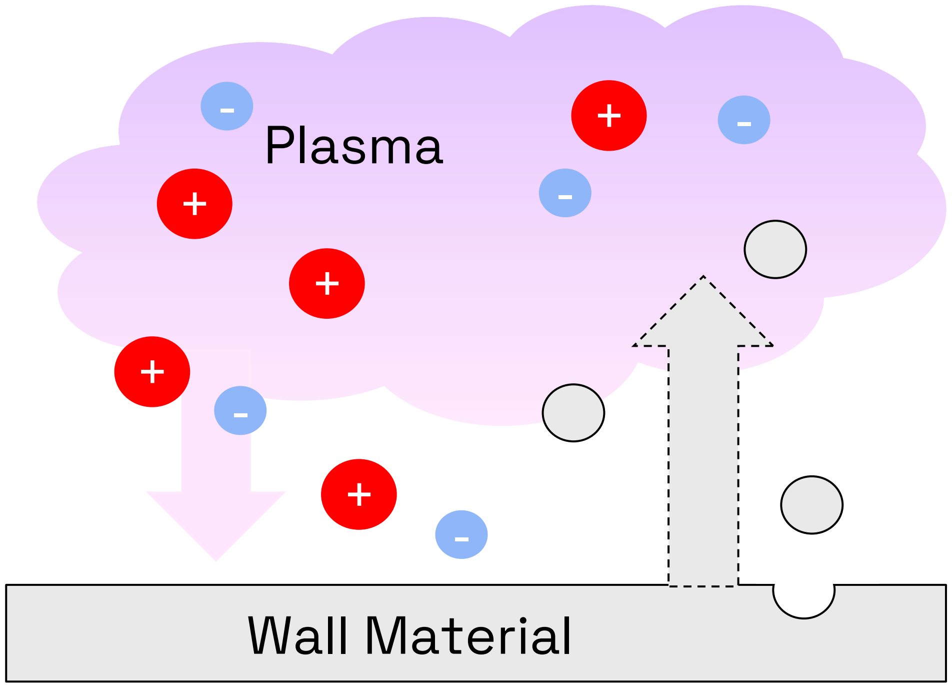
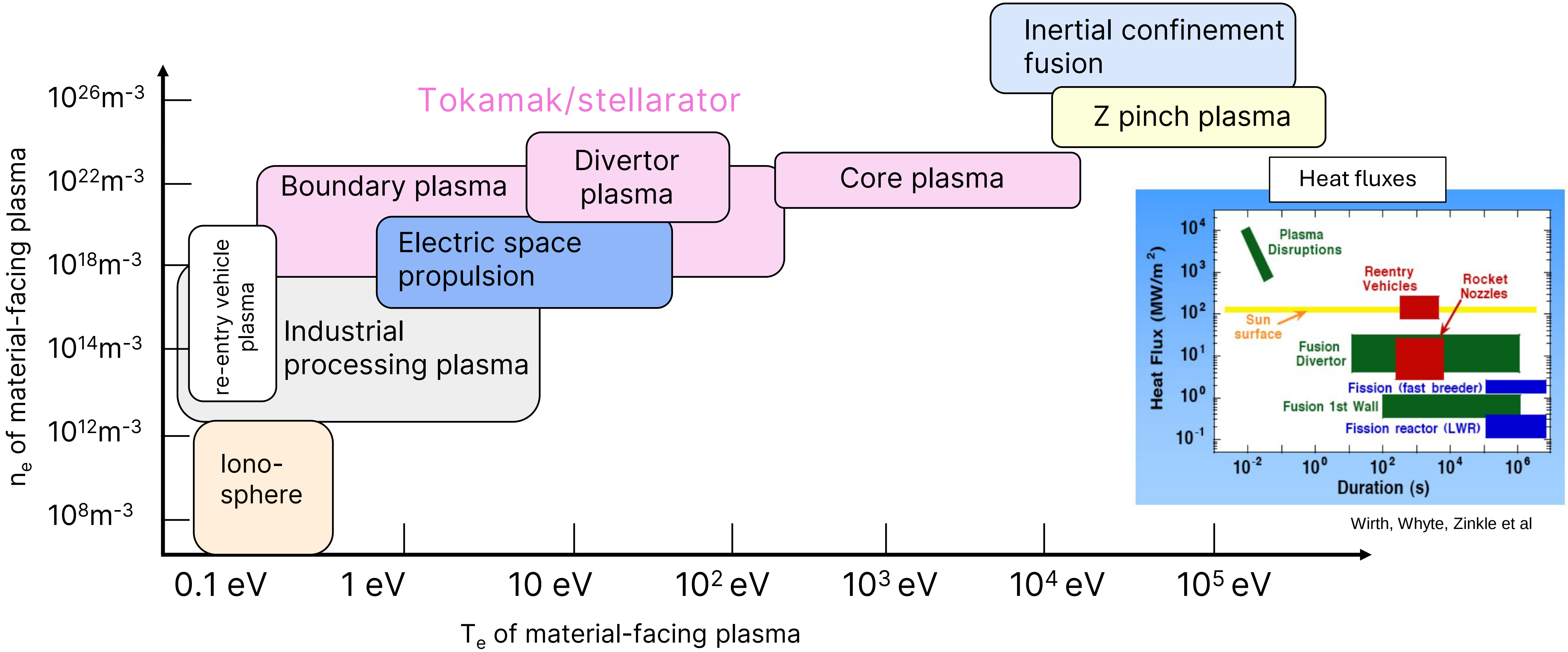
Simplified, conceptual picture



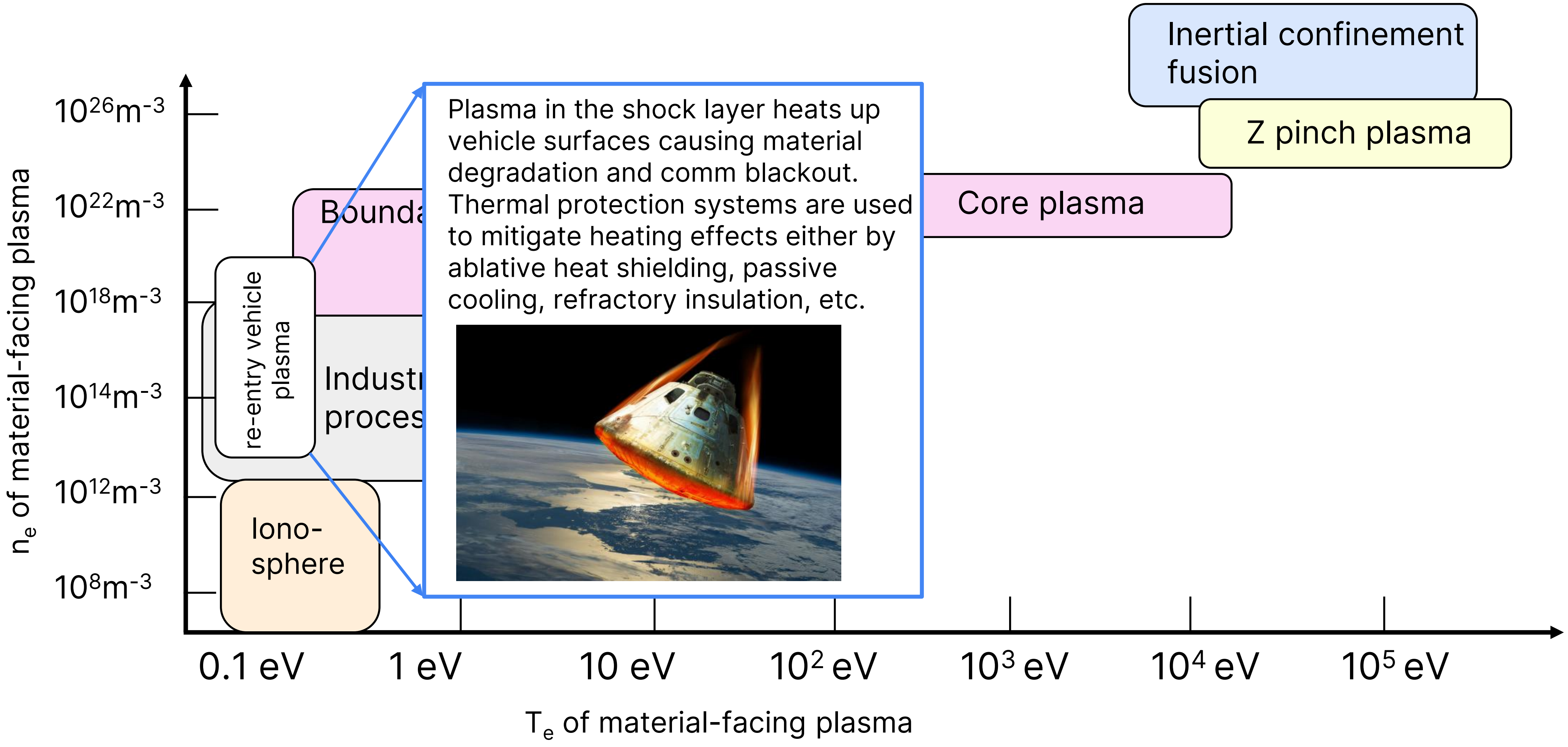
Plasmas are modified by receiving *charged and neutral particles* originating from the material

Variety of plasma-material interactions

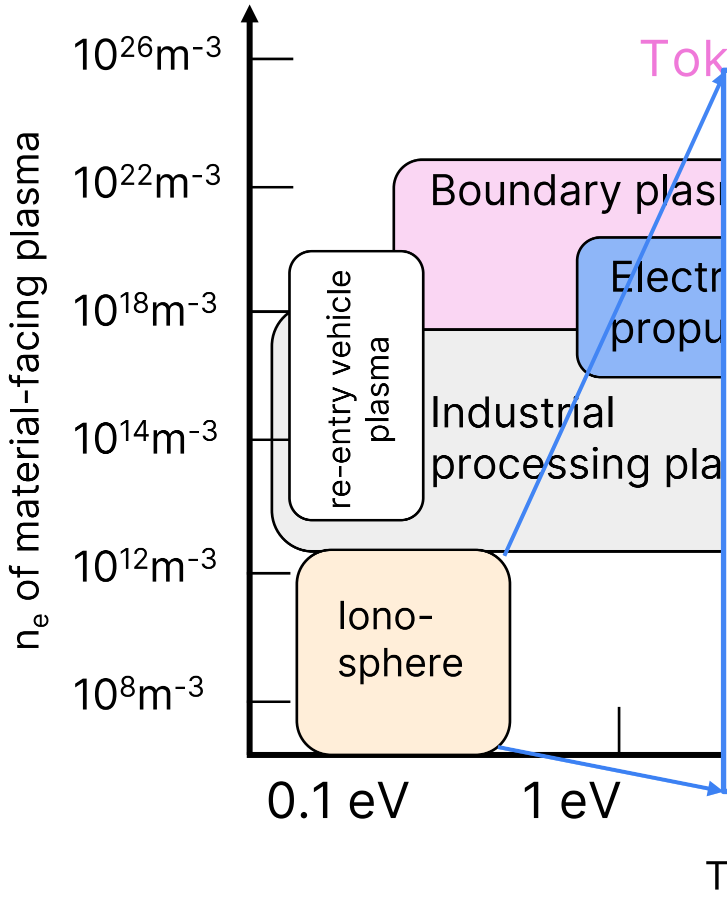


Wirth, Whyte, Zinkle et al

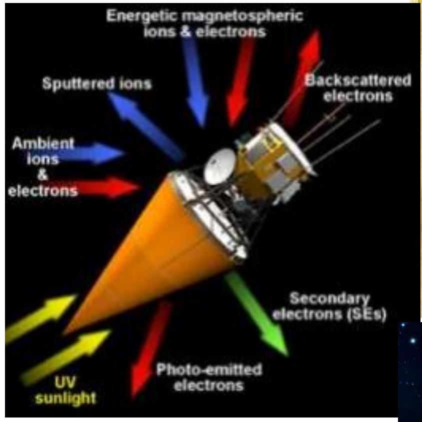
Variety of plasma-material interactions

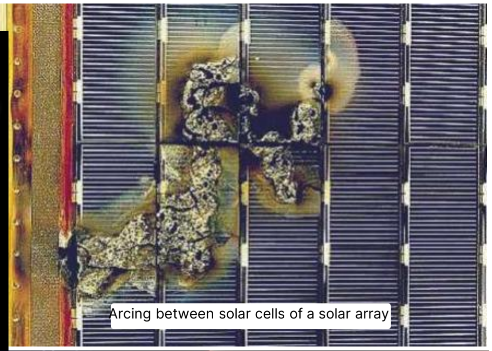


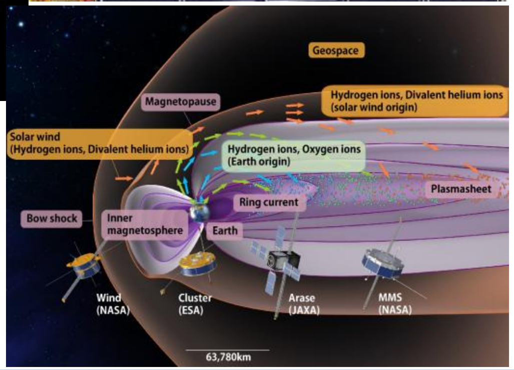
Variety of plasma-material interactions



Space plasma particles interact with spacecraft surfaces and cause surface charging, arcing, RF breakdown effects, erosion, sensor failure but can *also* be used for direct energy harvesting, attitude control/passive station keeping, and powered electrodes for plasma sensors.

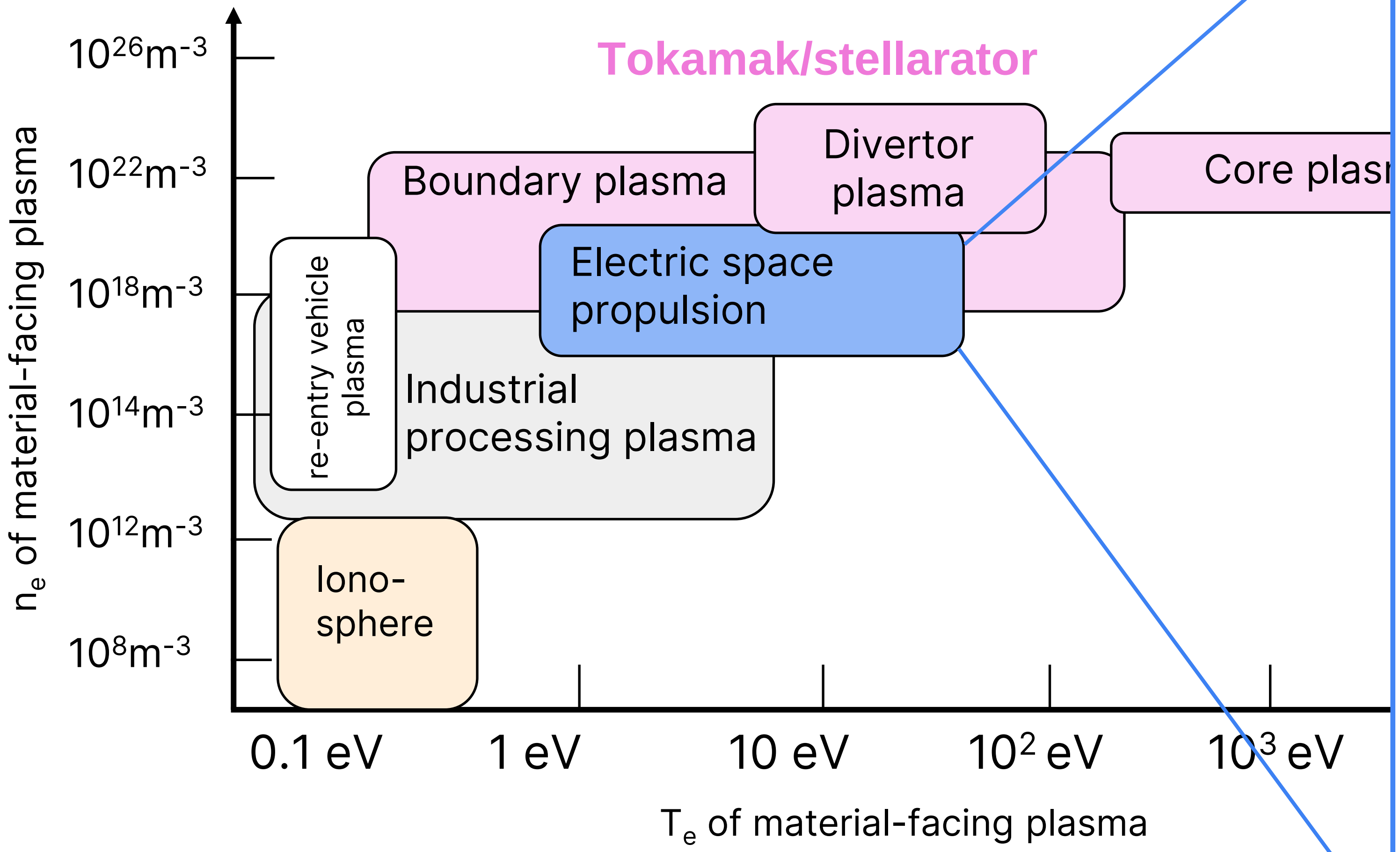




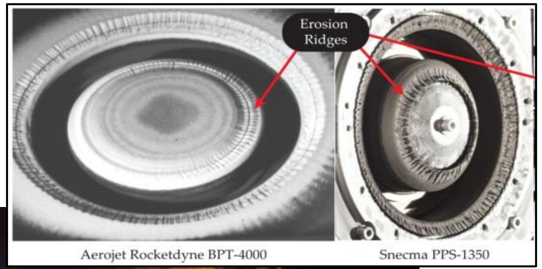


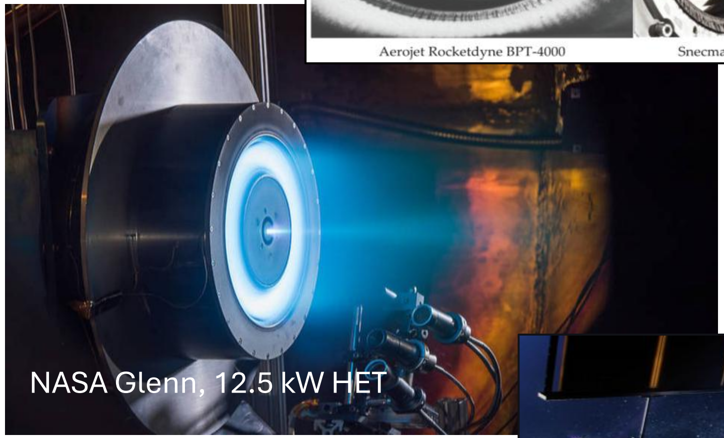
NASA, JAXA

Variety of plasma-material interactions



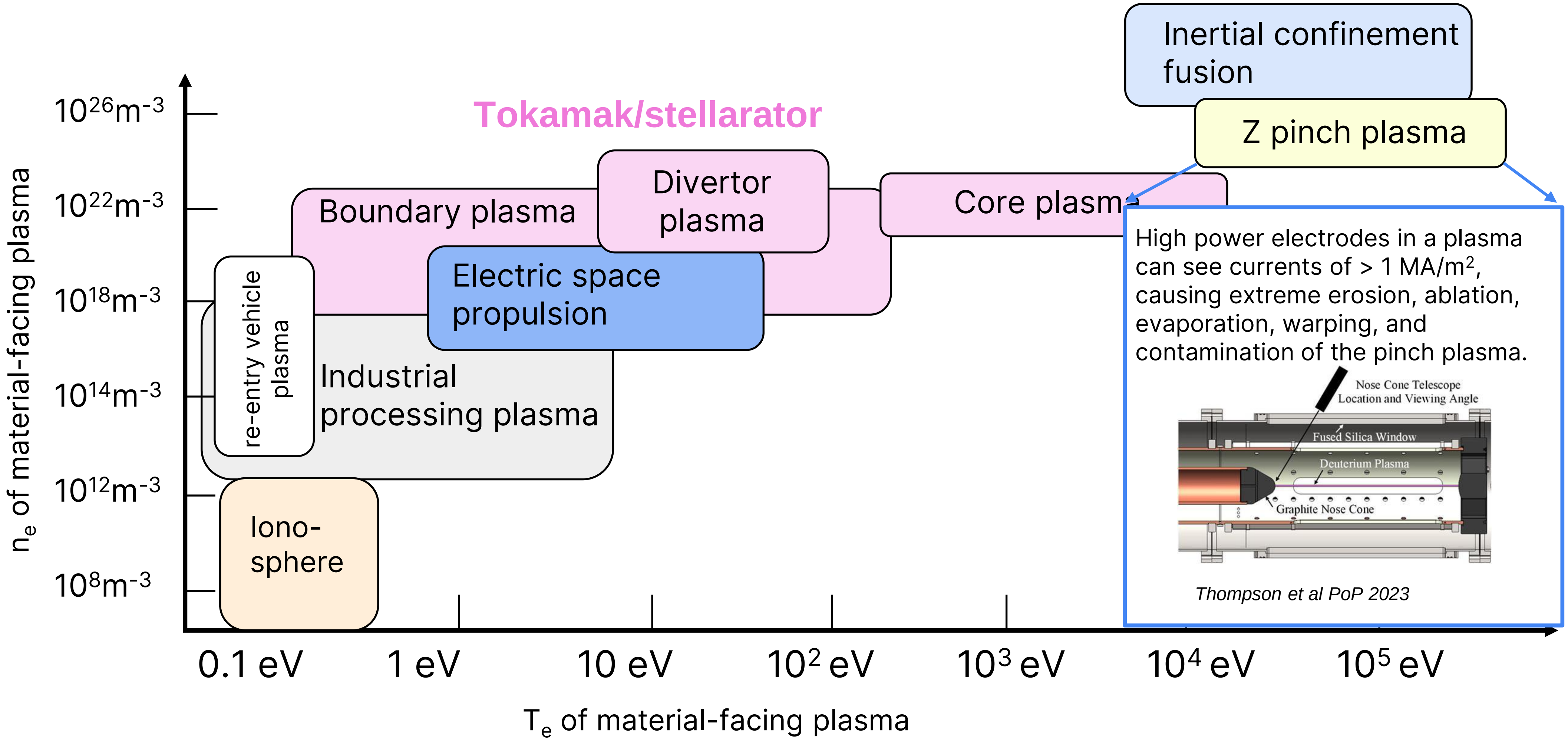
Channel erosion, sputtering, electron emission, plasma cooling, decreased thrust, increased plasma instabilities, plume diverging, component lifetime limiting, sheath modifications.



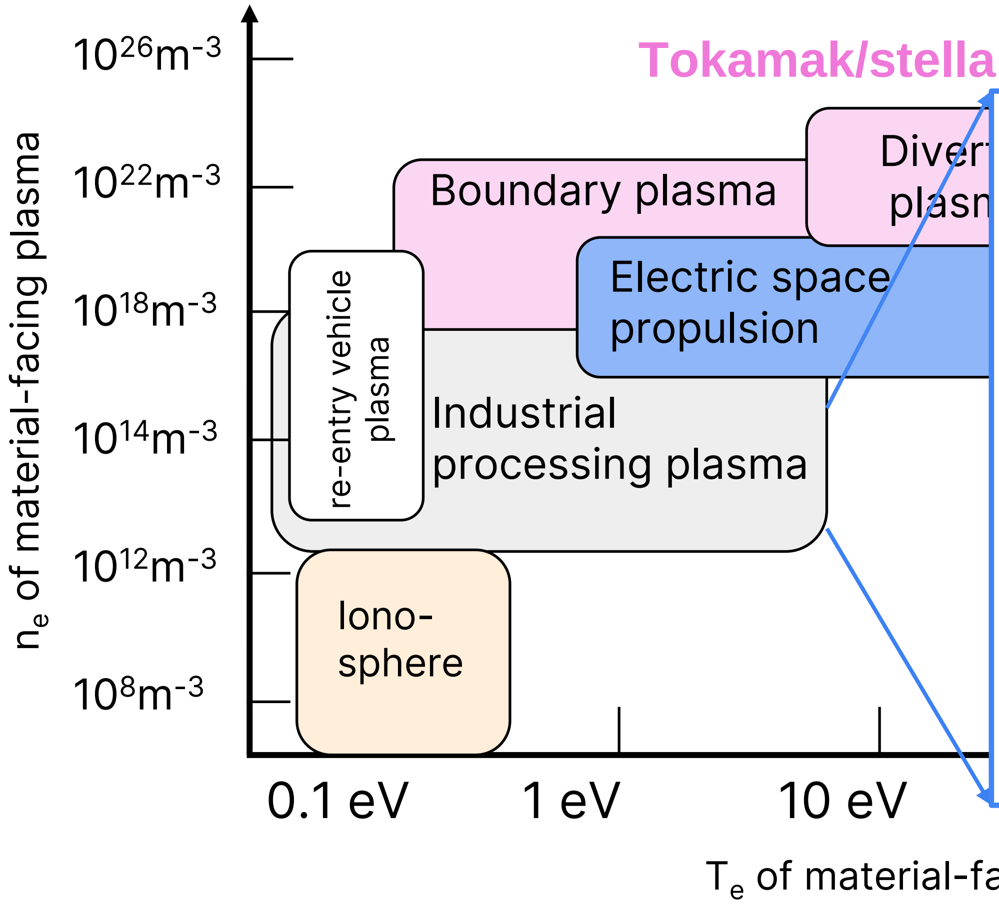


NASA/Maxar Gateway rendering

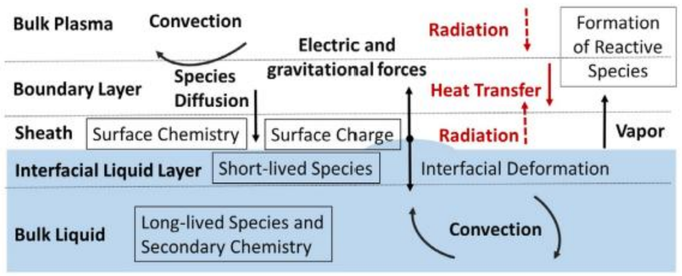
Variety of plasma-material interactions



Variety of plasma-material interactions

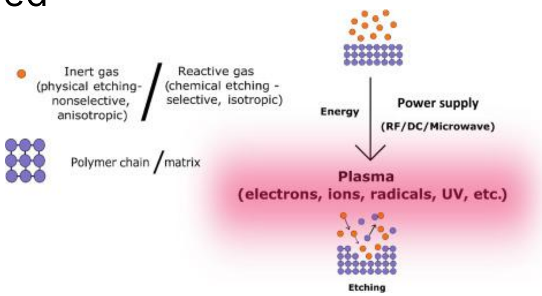


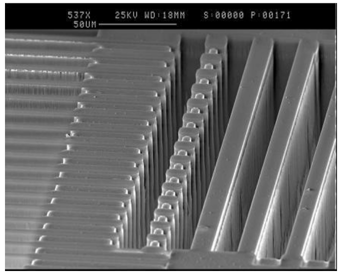
Low temperature plasmas (LTPs) have a rich chemical environment, are comprised of neutral atoms, molecules, radicals as well as ions and electrons, and are far from thermal equilibrium.



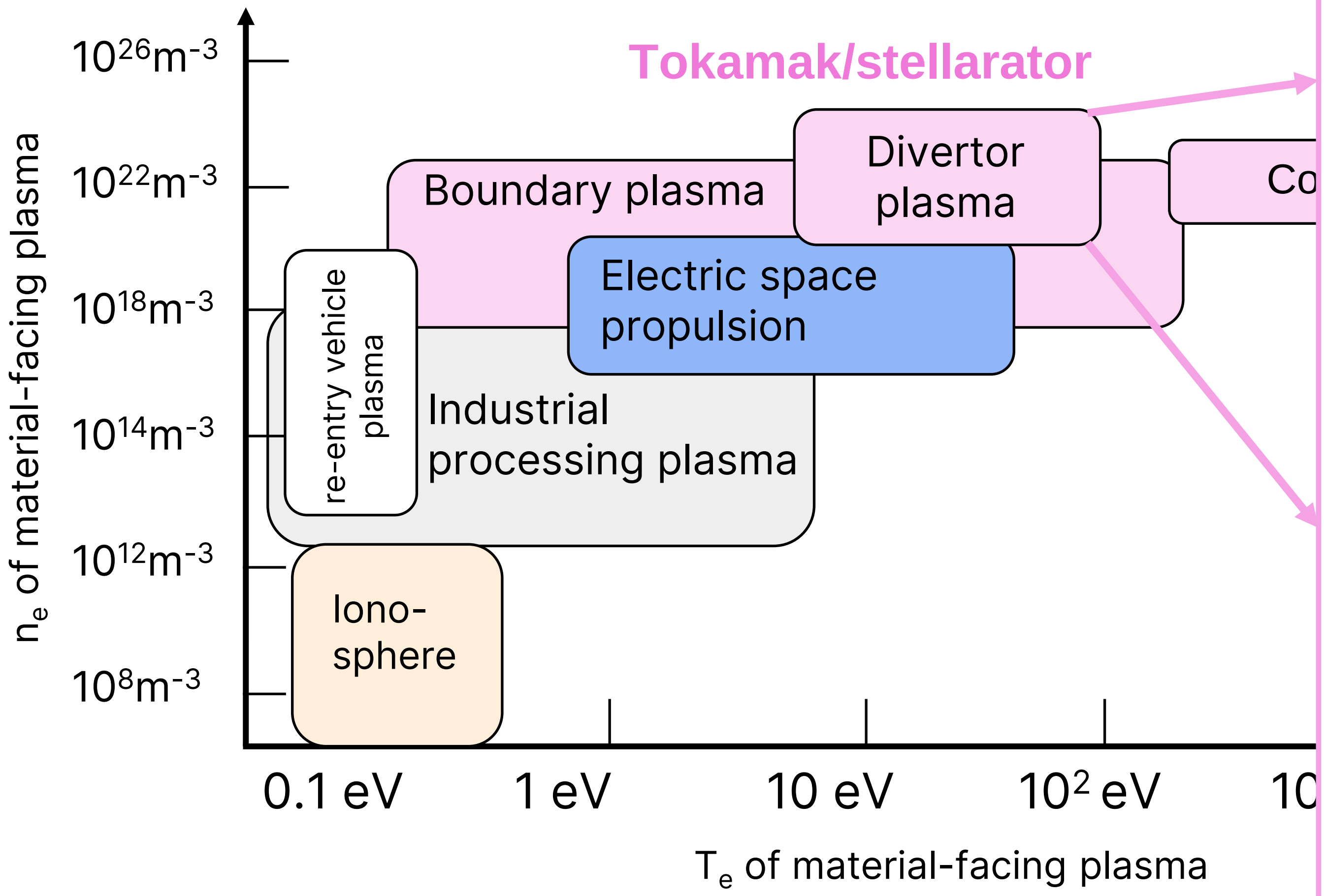
Adamovich et al 2017 J. Phys. D: Appl

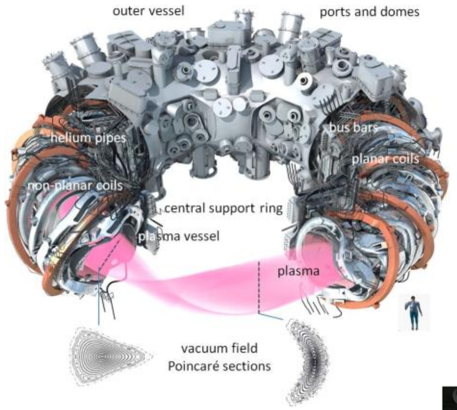
PMI of LTP is routinely used for the microelectronics industry, plasma etching, plasma deposition, and medical/biological applications.

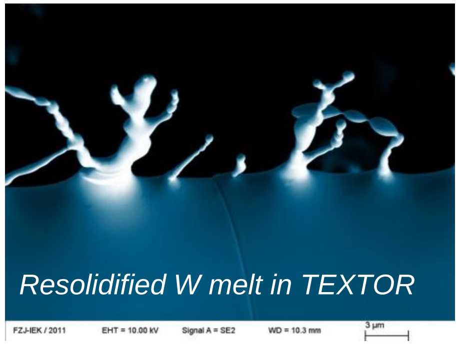




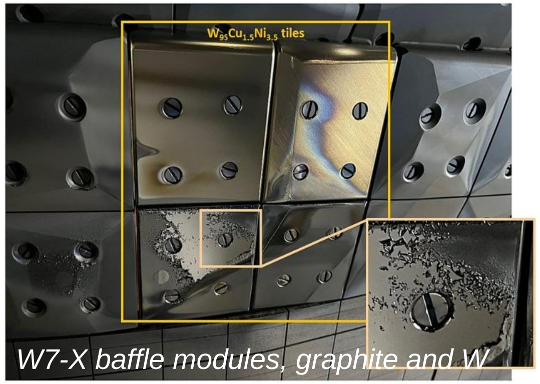
Variety of plasma-material interactions





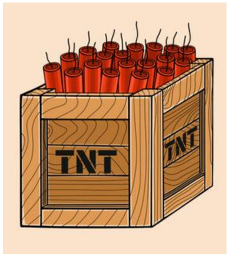

Resolidified W melt in TEXTOR

Magnetic Confinement Fusion: power plant conditions yet untested


W7-X baffle modules, graphite and W

Divertors in TNT

10 MW ~ 2.4 kg of TNT
A divertor has to withstand a small box of TNT exploding every second over every m^2



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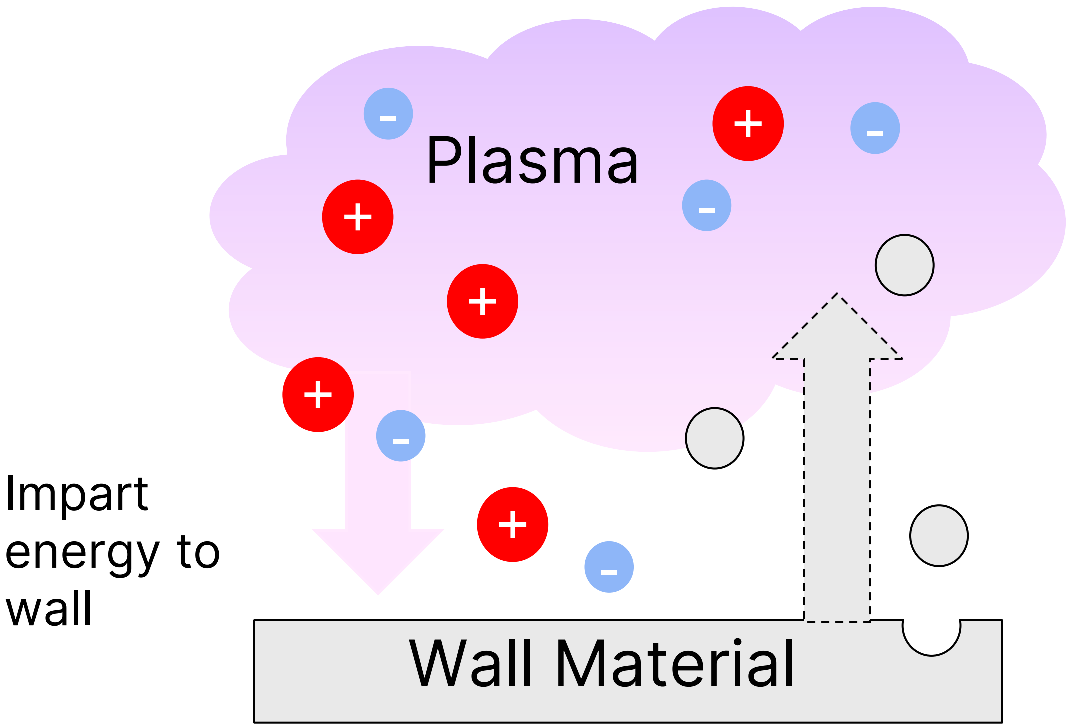
Fundamental PMI Processes

Plasma ↔ Surface effects

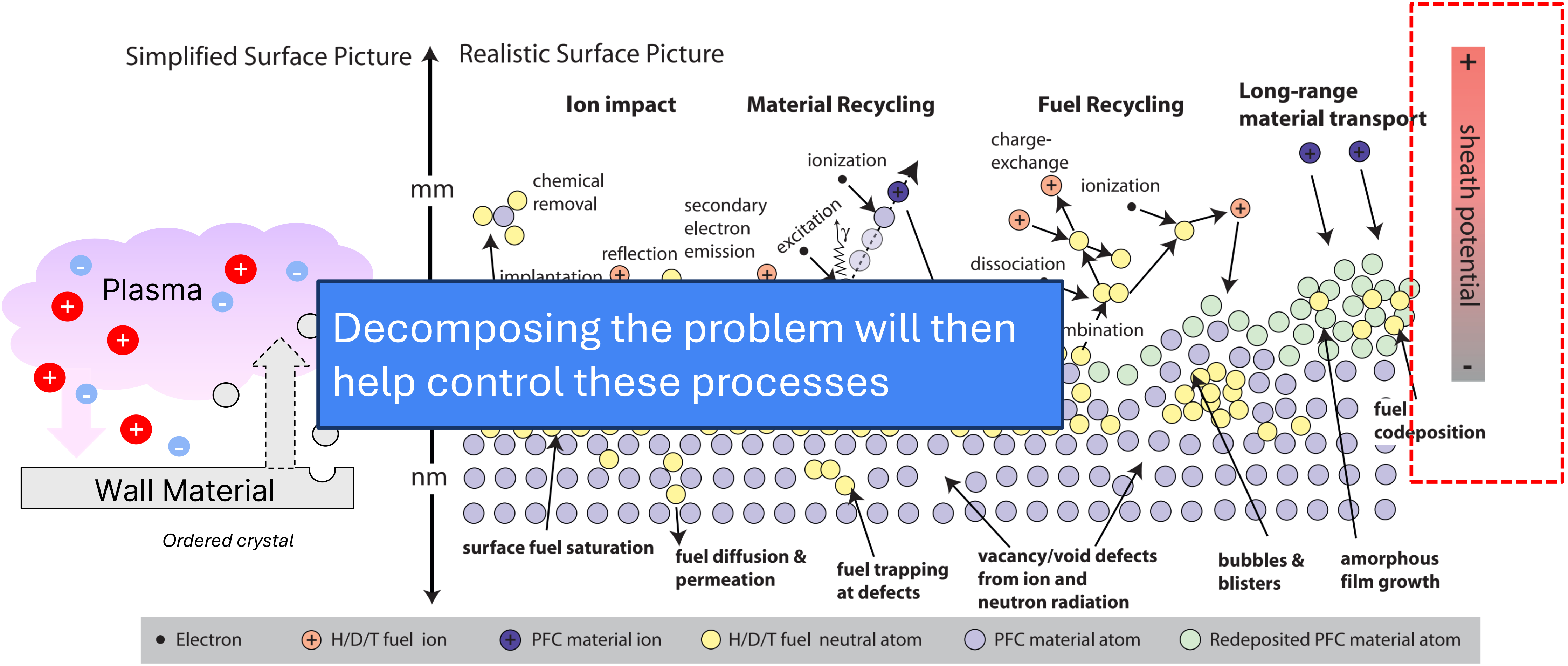


Wall Properties:
- Thermal sink
- Source of cold impurities → can drive instabilities leading to disruptions
- Source of surface atom electrons

(Fusion) Plasma species:
- Electrons (1eV – keV)
- D^+, D, H^+, H, He, He^+
- (Neutrons)

Wall effects
- Erosion
- Implantation of plasma particles (fuel)
- Chemistry, compound formation
- Bulk and structural material damage: cracking, bubbling, swelling, micro-structure formation, embrittlement

Comprehensive picture of PMI



Decomposing the problem will then help control these processes

Modified from: Wirth, B.D. et al. "Fusion materials modeling: Challenges and opportunities." MRS Bulletin 36 (2011): 216-222. © 2011 Materials Research Society

The electrostatic **sheath**

A region of strong electric field separating a quasi-neutral plasma from a material boundary

Debye Length: the potential at a distance r from a test charge q in a quasi-neutral plasma

$$\phi = \frac{q}{4\pi\epsilon_0 r}\exp\left(-\frac{\sqrt{2}r}{\lambda_D}\right)$$

Plasma "response" term

The characteristic shielding length is the Debye length:

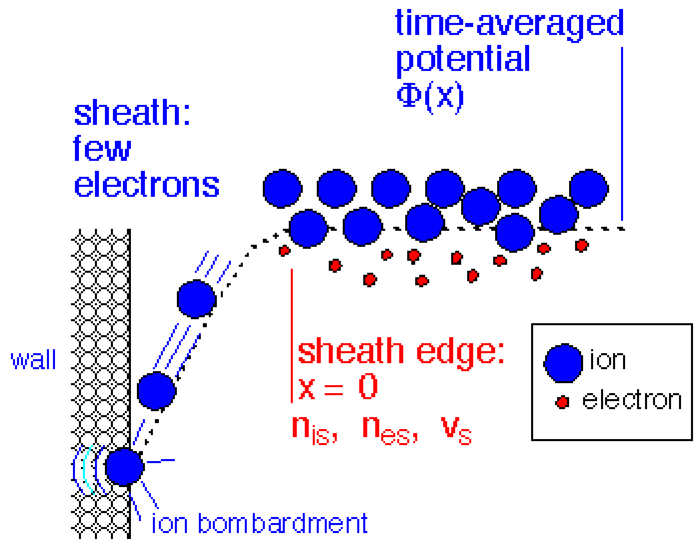
$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}$$

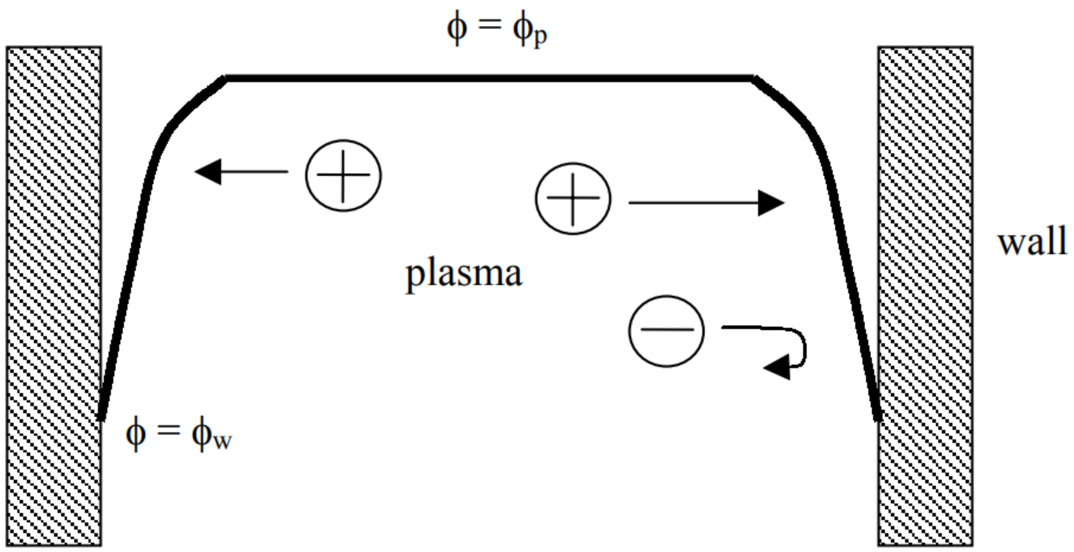
Sheath derivation uses conservation of energy, ion continuity and Poisson's equation to find:

$$n_e = n_0 \exp\left(-\frac{e\phi}{kT_e}\right) \qquad u_B = \sqrt{\frac{kT_e}{m_i}}$$

Boltzmann's relation for electrons

Bohm sheath velocity (ion sound speed)





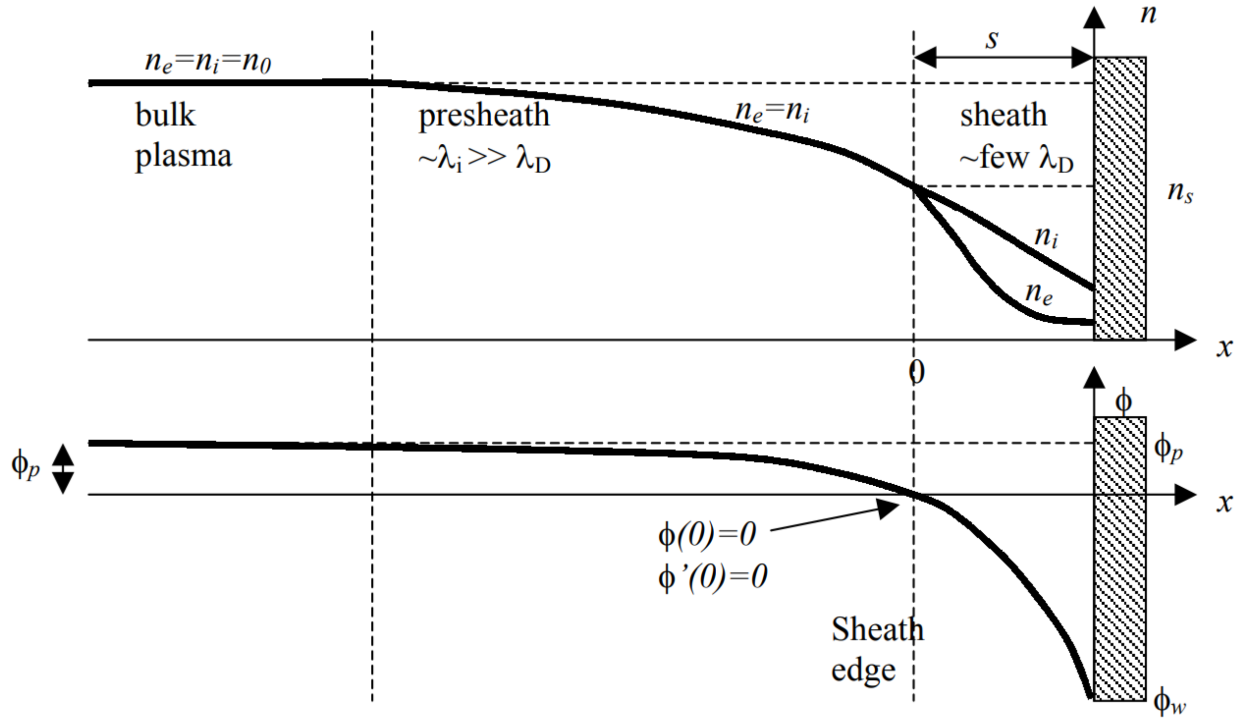
Lieberman, Michael A., and Alan J. Lichtenberg. *Principles of plasma discharges and materials processing.* John Wiley & Sons, 2005.
https://www.enigmatic-consulting.com/semiconductor_processing/CVD_Fundamentals/plasmas/ion_flux.html

Sheath of a floating wall

m_e and m_i mass difference will cause initial net negative wall current, raise bulk potential wrt walls and create an "ion" layer. Net current must be zero.

$$\phi_w(x=0) = -\frac{kT_e}{e} ln \sqrt{\frac{m_i}{2\pi m_e}}$$

Sheath thickness $\approx \mathbf{3\lambda_D}$



Presheath: a region in front of the sheath with the potential drop required to accelerate ions to enter the sheath

- Unmagnetized 'collisionless' plasma: $L_{ps} \approx L/2$ where L is the size of the confinement device
- Weakly collisional plasmas: $L_{ps} \approx \lambda_{mfp}$
-
- If $\lambda_D \ll \lambda_{mfp} \ll L$, then $L_{ps} = u_B/\nu$ (where ν is collision frequency)

The biased Sheath

Strong negative bias electrode
The electron density $n_e \to 0$ since $eV_0 \gg kT_e$. The ion current must remain constant through the sheath, and Poisson equation yields:

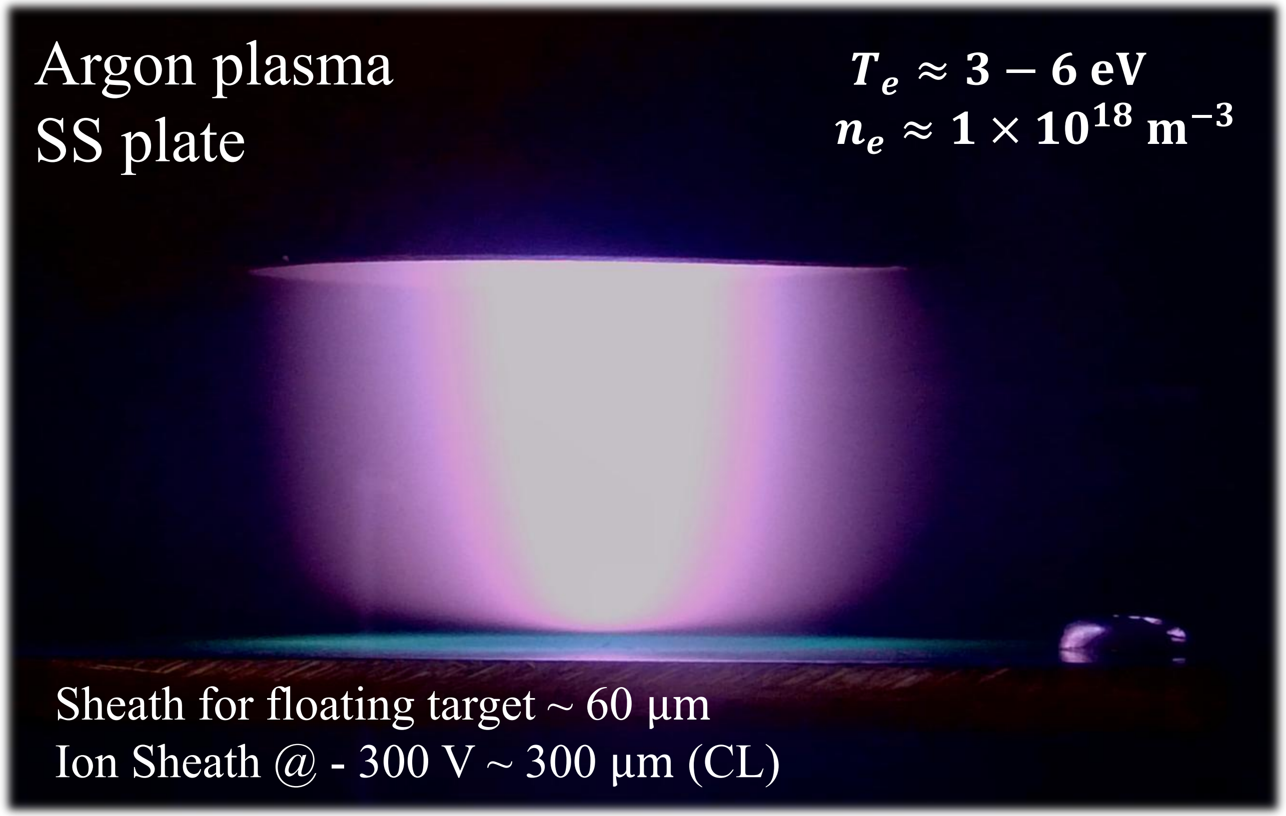
$$-\phi^{\frac{3}{2}} = \frac{3}{2}\left(\frac{J_0}{\epsilon_0}\right)^{\frac{1}{2}}\left(\frac{2e}{m_i}\right)^{-\frac{1}{2}} x$$

Integrating with $V_0 = -\phi$ and solving for x gives sheath thickness

$$s = \frac{\sqrt{2}}{3}\lambda_D\left(\frac{2eV_0}{kT_e}\right)^{\frac{3}{2}}$$ Child Law Sheath

The Child-Law sheath width adjusts to satisfy the Child law of space-charge-limited current as the *ion current from the plasma is fixed*

Visualization Demo: from floating to – 300 V

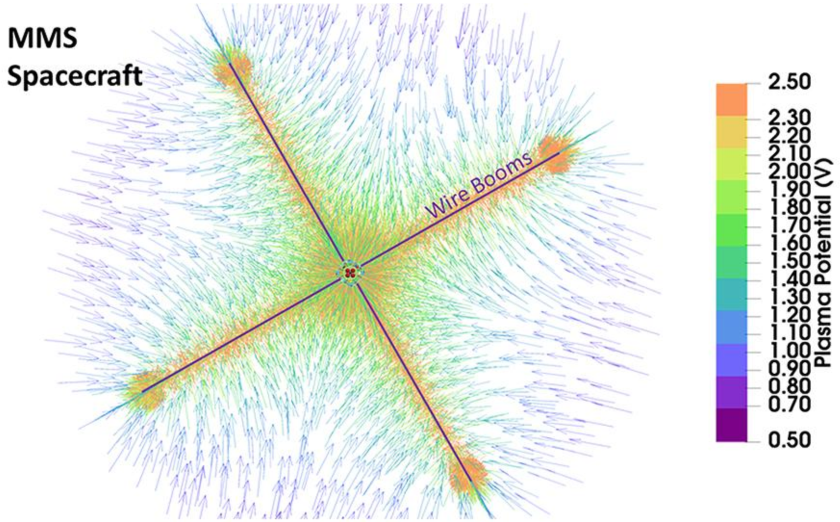


Baalrud, Scott D., et al. "Interaction of biased electrodes and plasmas: sheaths, double layers, and fireballs." *Plasma Sources Science and Technology* 29.5 (2020): 053001

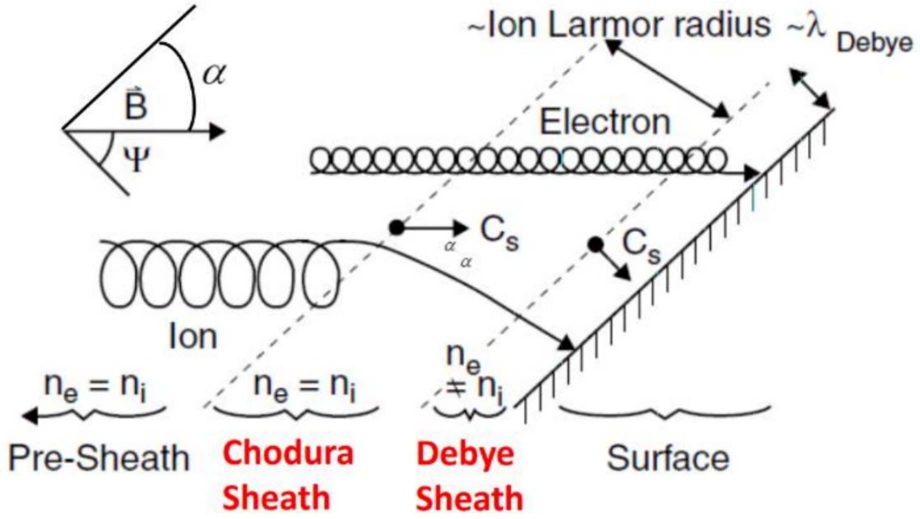
- https://mms.gsfc.nasa.gov/Mention Shota's work
- Chrobak, Christopher Peter. *Characterizing Erosion and Redeposition of Aluminum in DIII-D Divertor Plasmas*. University of California, San Diego, 2018.

Importance of sheaths

Near-Earth space plasma is *very rarefied.*
Sheath thicknesses meters to km's!



Tokamak plasma is *dense and magnetized*.
Sheath thicknesses microns to mm's!



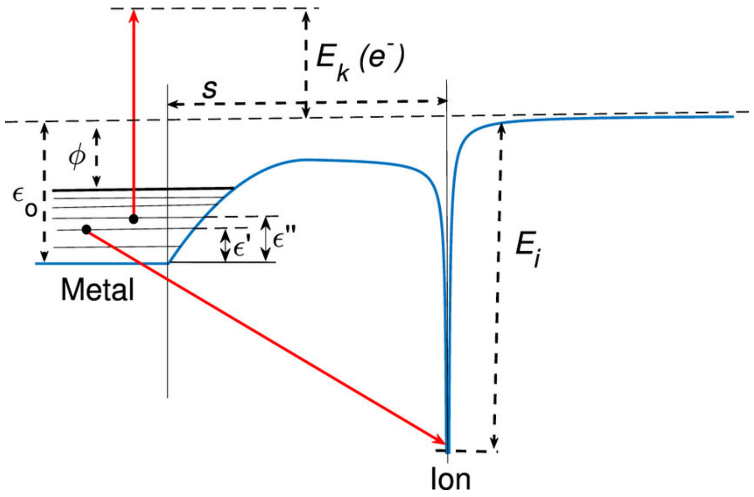
Knowledge of plasma sheath is critical for:
- Measuring plasma properties in devices with electrostatic probes
- Interpreting s/c data
- Understanding ion trajectory and energy at surface
    - Industrial processing/etching relevant
    - Predicting plasma device wall erosion (lifetime) and modification
    - Shields walls from high electron fluxes

Daksha, Manaswi, et al. "Material dependent modeling of secondary electron emission coefficients and its effects on PIC/MCC simulation results of capacitive RF plasmas." *Plasma Sources Science and Technology* 28.3 (2019): 034002

Particle emission: electron emission

Consider a wall/target an infinite source of electrons:

1. Auger electron emission via ion-neutralization

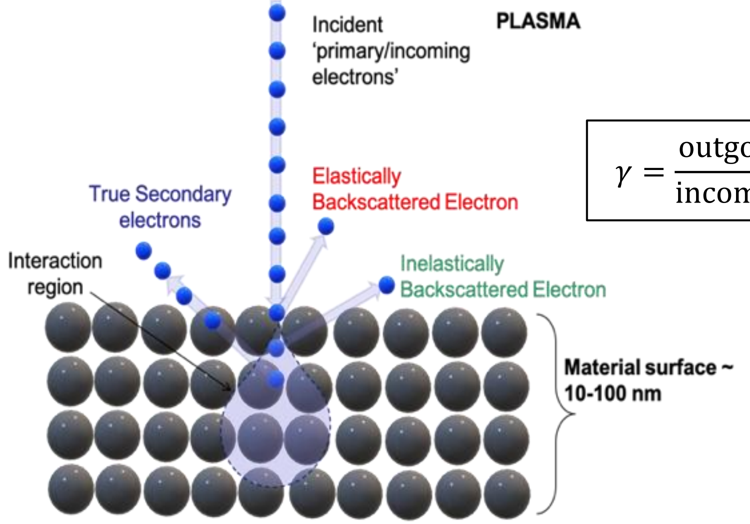


A positive ion approaching a wall can capture a conduction band surface electron, causing it to:

- Enter an excited state and emit a photon
- Enter ground state and emit an electron (Auger)

Results in cold, neutral particles re-entering the plasma

2. Electron or ion-induced electron emission

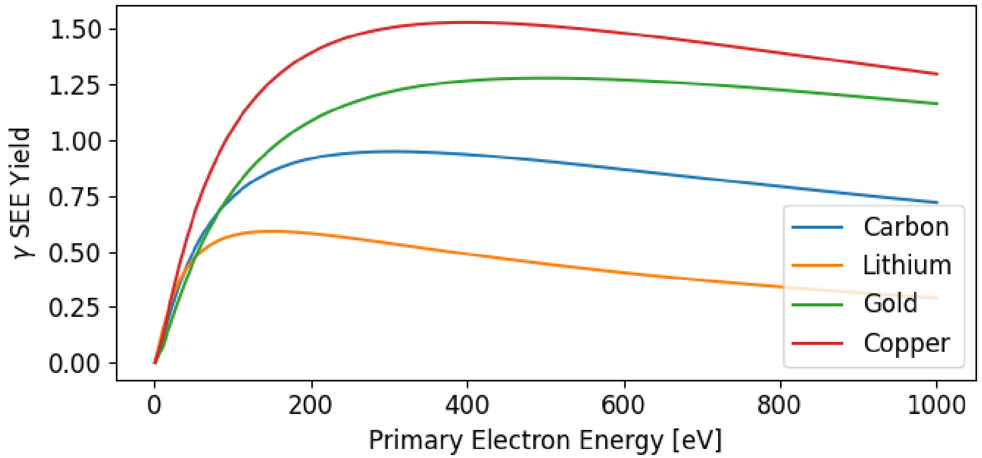


$$\gamma = \frac{\text{outgoing electrons}}{\text{incoming electrons}}$$

An ion or electron impacts a surface and transfers enough kinetic energy to electrons in the solid for them to escape the surface.

Results in cold electrons re-entering the plasma and an excess negative flux from the surface

Particle emission: electron emission



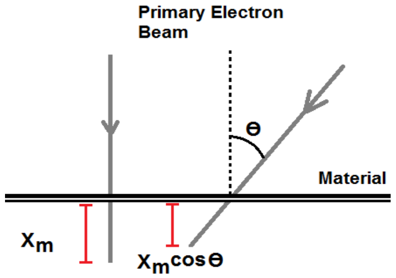
$$\gamma(E_p) = \gamma_{max}\exp\left[-\left(\frac{\ln\left[\frac{E_p}{E_{max}}\right]}{\sqrt{2}\sigma}\right)^2\right]$$

E_p= Primary Electron Energy
σ = 1.6 (variance)

- Normal Incidence
- Empirical model

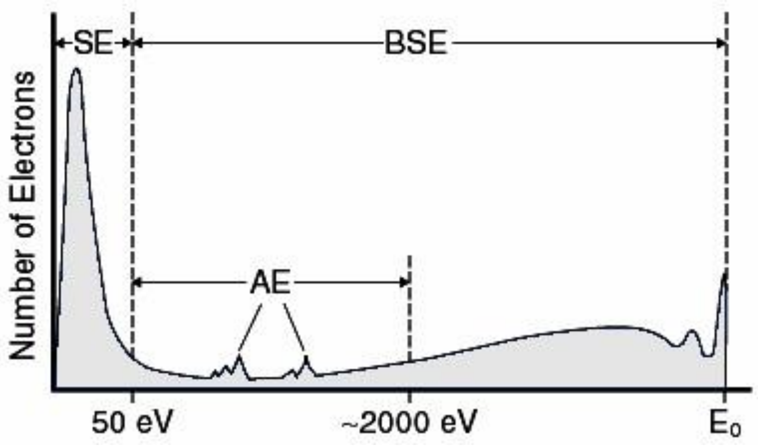
- Bruining, Hajo. *Physics and Applications of Secondary Electron Emission: Pergamon Science Series: Electronics and Waves—a Series of Monographs*. Elsevier, 2016
- G.D.HobbsandJ.A.Wesson,"HeatflowthroughaLangmuirsheath in thepresenceofelectronemission,"PlasmaPhys.9,85(1967).
- M.D.Campanell,A.V.Khrabrov, andI.D.Kaganovich, "Absenceof Debyesheathsduetosecondaryelectronemission,"Phys.Rev.Lett.108, 255001(2012)
- Baalrud, Scott D., et al. "Interaction of biased electrodes and plasmas: sheaths, double layers, and fireballs." *Plasma Sources Science and Technology* 29.5 (2020): 053001
- Langendorf, S., and M. Walker. "Effect of secondary electron emission on the plasma sheath." *Physics of Plasmas* 22.3 (2015): 033515

SEE Yield Dependence on Primary Angle of Incidence θ



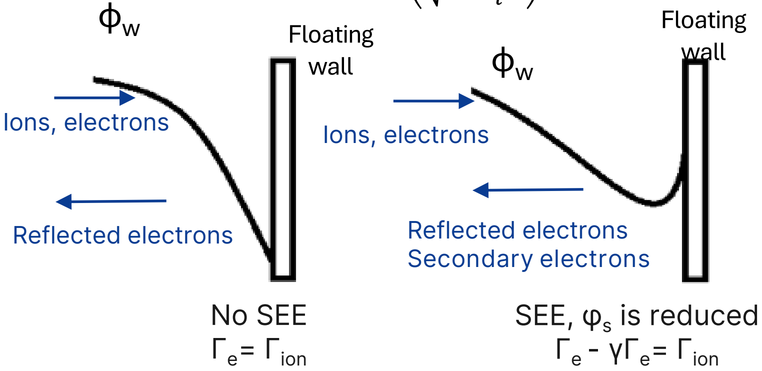
In general, as Θ increases SE escape path decreases by ~*cosθ,* increasing SEE Yield

Energy Distribution of SEs



Modification to Plasma Sheath

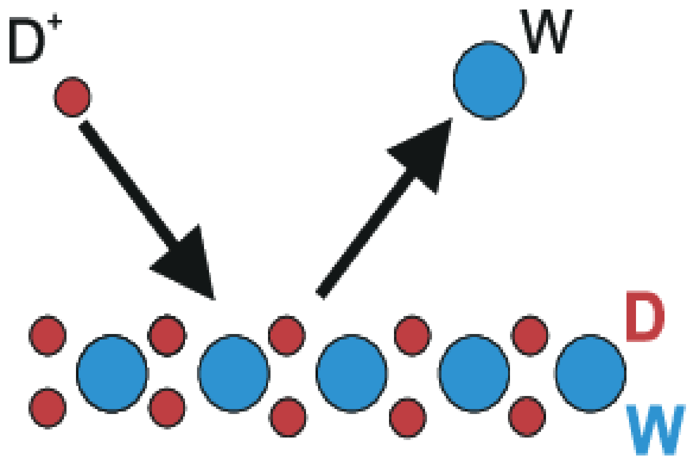
$$\phi_s = -\frac{T_e}{e}\ln\left(\frac{1-\gamma}{\sqrt{\frac{2\pi m_e}{m_i}}}\right)$$



Particle emission: sputtering

Causes plasma contamination and main contributor to surface erosion in PMI

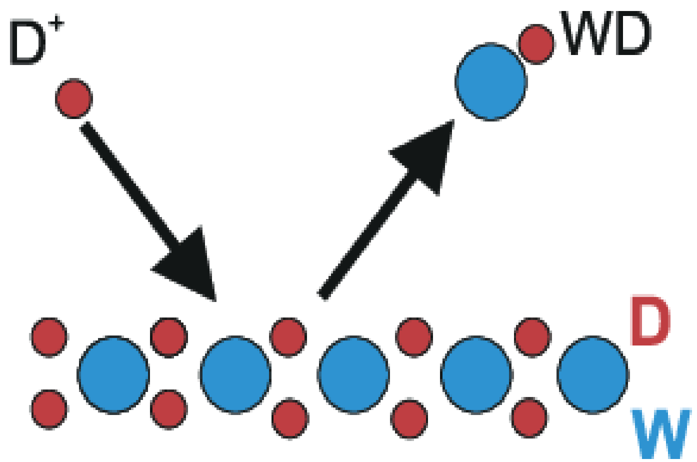
Physical



- D ions collide with tungsten, transfer energy to tungsten atoms, tungsten ejected from surface.
- Energy momentum transfer process.

$$E = E_i 4 \frac{m_i m_t}{(m_i + m_t)^2}$$

Chemical



- D reacts chemically with tungsten, forms volatile WxDx compounds, they desorb from surface.
- Temperature dependent, chemical process.

Total sputtering erosion is physical + chemical

(carbon is the worst offender of chemical sputtering, while in W it's negligible)

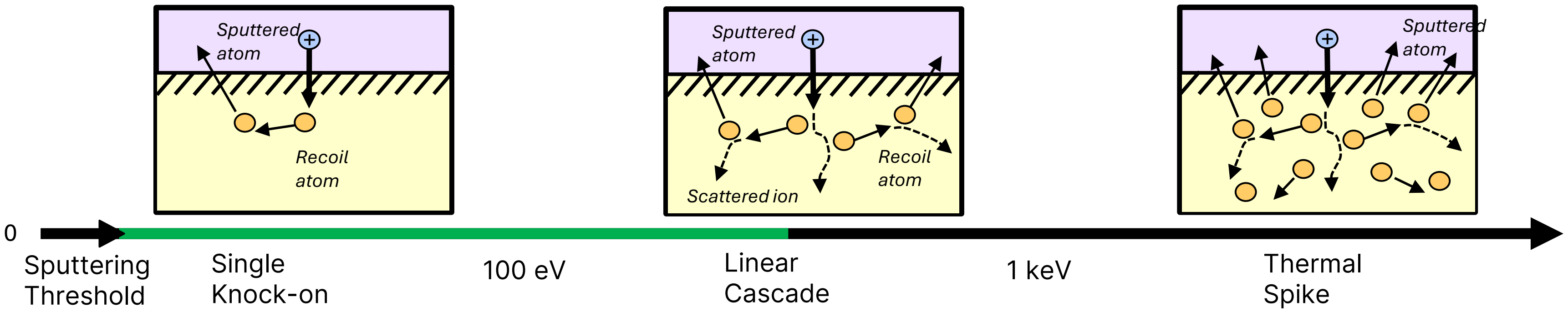
Brezinsek et al, Nuclear Materials and Energy, Vol 18 (2019)

Yamamura (1982) Rad Eff, Zhang and Zhang (2004) Raf Eff
Huerta, Matlock, Wirz (2016) JAP
Li, Gary Zhi. Plasma sputtering behavior of structured materials. University of California, Los Angeles, 2020

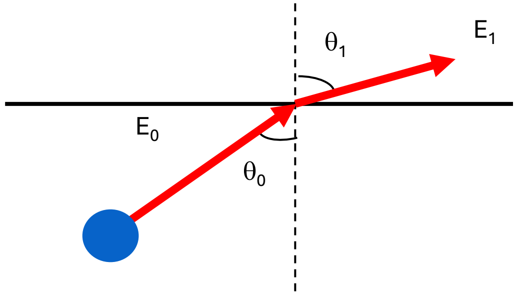
Physical sputtering < 1 keV incident energy

$$Y(E) = 0.42 \frac{\alpha Q K s_n(\epsilon)}{U_s[1 + 0.35\, U_s s_e(\epsilon)]}\left[1 - \left(\frac{E_{th}}{E}\right)^{\frac{1}{2}}\right]^{2.8}$$

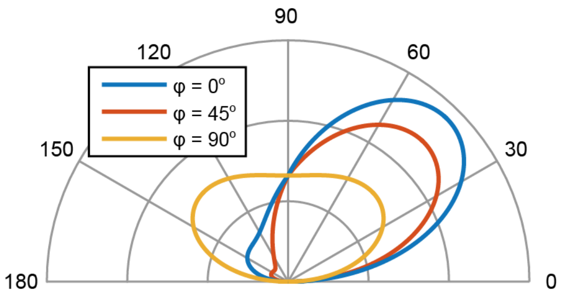
- α, Q, E_{th} empirical parameters: energy transfer proportionality constants, threshold energy minimum req'd to displace an atom
- s_n, s_e, U_s, are Lindhard's inelastic and elastic stopping energies and sublimation energy
- ϵ reduced energy



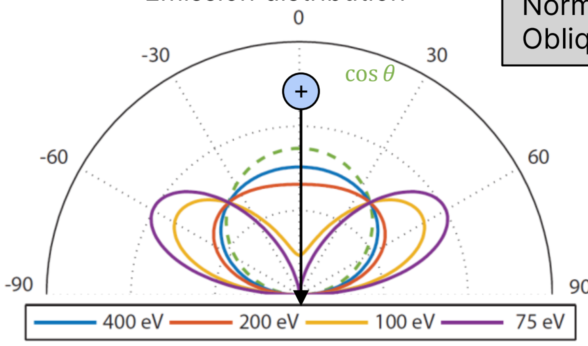
Angular Equations



Incident angle dependence

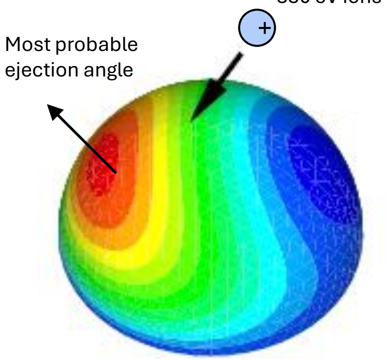


Emission distribution



Normal incidence → "Butterfly" distribution at low energy
Oblique incidence → Forward-biased profile

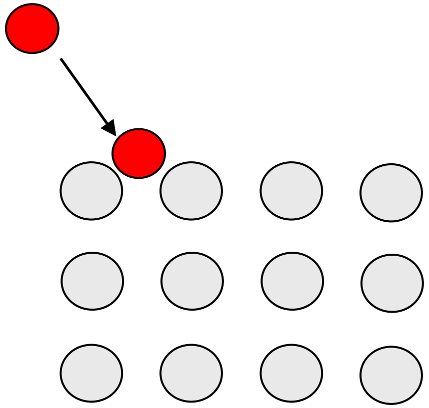
Oblique Incidence



$$S(E,\theta,\alpha) \propto \cos\alpha \times \left[1 - \frac{1}{4}\sqrt{\frac{E_{th}}{E}}\left\{\cos\theta\,\gamma(\alpha) + \frac{3}{2}\pi\sin\theta\sin\alpha\cos\phi\right\}\right]$$

$$\gamma(\alpha) = \frac{3\sin^2\alpha - 1}{\sin^2\alpha} + \frac{\cos^2\alpha(\sin^2\alpha + 1)}{2\sin^3\alpha} \times \ln\left(\frac{1+\sin\alpha}{1-\sin\alpha}\right)$$

Adsorption (1 eV)

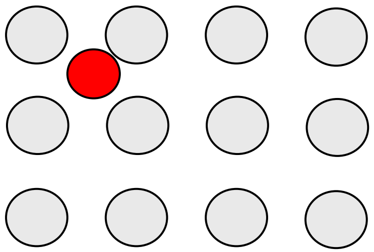


- Occurs are low energies (~ 1 eV)
- Depends on binding energy and temperature

$$R = -\nu N^{\alpha} e^{-\frac{E}{RT}}$$

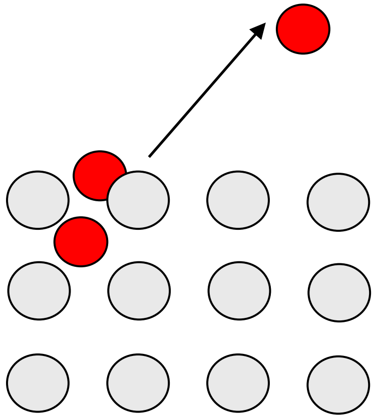
- Neutral species 'stick' to a surface via weak or strong surface atom bonds
- ν = escape frequency, N = absorbed density per area, E = activation energy, R = change in adsorbed species per area

Absorption (1 eV)



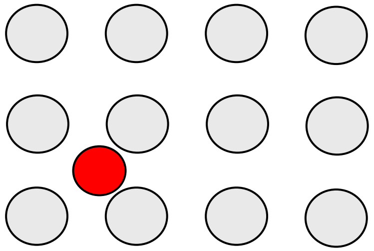
- Neutral species penetrate the bulk moving from the surface to the lattice.
- Diffusion-driven process.

Desorption (1 eV)

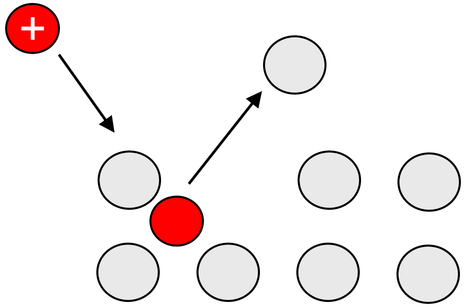


- Neutral species previously ad or absorbed release from the surface or bulk and return to plasma.
- Thermally or particle driven

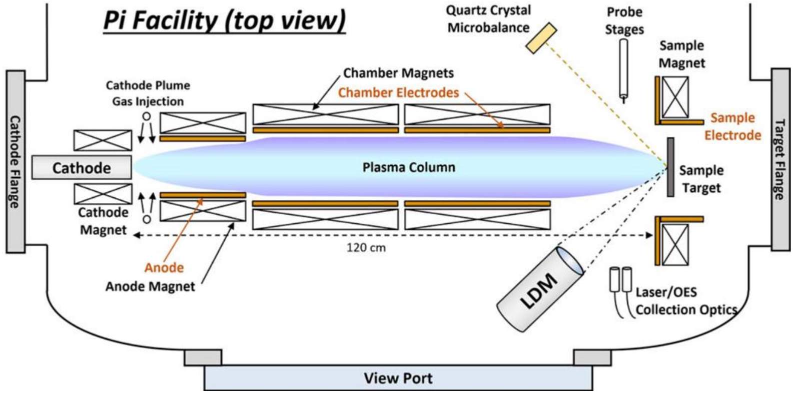
Implantation (1 keV)



Sputtering (1 – 1000 eV)

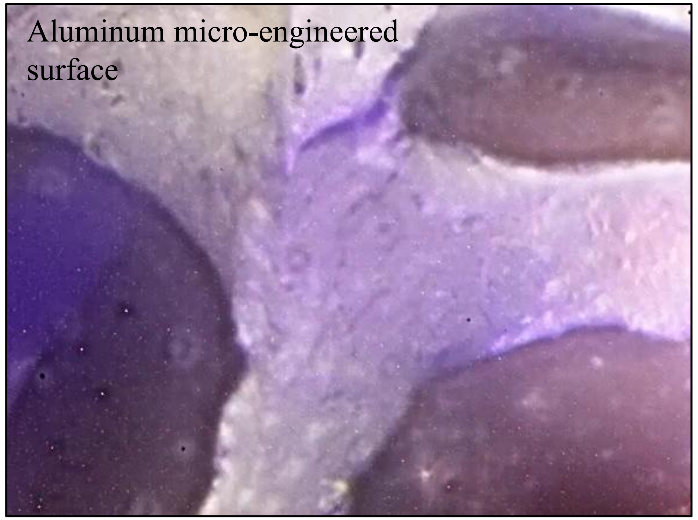


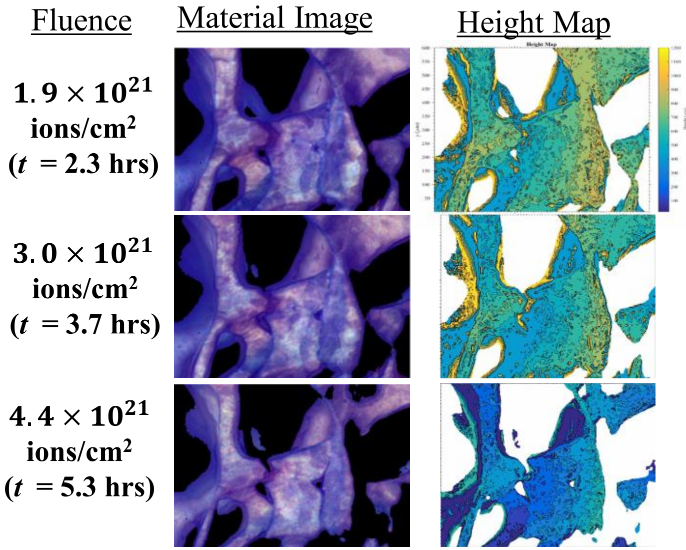
Visualization of sputtering in an argon plasma



Parameter	Typical values
Plasma density	10^{18} m^{-3}
Electron temperature	7 eV
Ion energy to target	40–300 eV
Ion flux to target	10^{17} cm^{-2} s^{-1}
Exposure diameter/area	1.5 cm/1.8 cm^2

Long-distance microscope with Focus-Variation Algorithm





Sputtering of Ar → Al causing surface to recede, flake, erode

Ottaviano, A., Thuppul, A., Hayes, J., Dodson, C., Li, G. Z., Chen, Z., & Wirz, R. E. (2021). In situ microscopy for plasma erosion of complex surfaces. *Review of Scientific Instruments*, *92*(7), 073701

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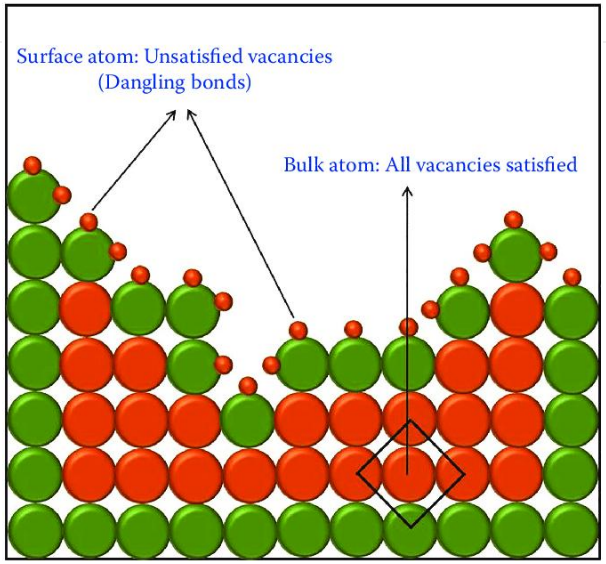
PMI Diagnostics and Surface Analysis Tools

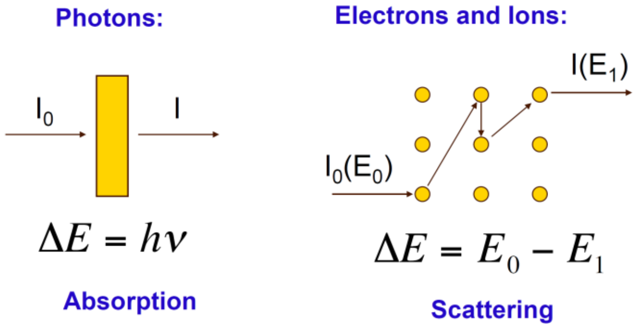
Surface vs bulk

Surface
- First 1 – 10 atomic layers of a material
- Atoms have altered electronic structures
- Unique binding sites
- Site for active chemistry
- Dictates work function, and in turn SEE, ion neutralization, and adsorption, diffusion, etc.
- $\rho_s \approx 10^{14} \frac{atoms}{cm^{-2}}$

Bulk
- Interior of the material
- Uniform, 3D periodic lattice structure
- Can participate in surface dynamics via implantation
- $\rho_v \approx 10^{22} \frac{atoms}{cm^{-2}}$



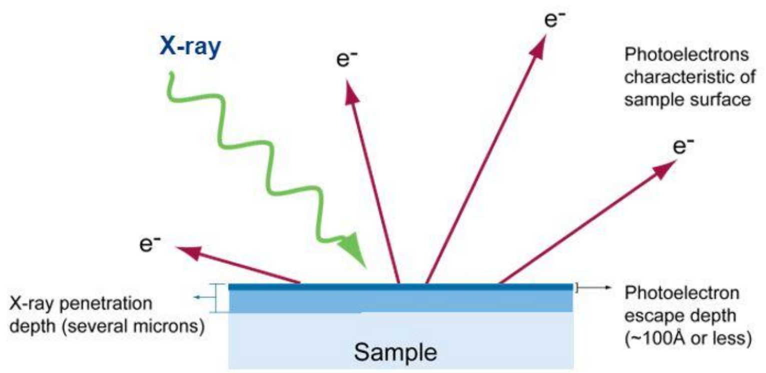
3 categories of material diagnostics using electron, X-rays, or ions to probe the material:
- Surface sensitive (angstroms – nm)
- Near-surface (1 – 10s of nm)
- Bulk (100s of nm to microns)



Baron-Wiechec, Aleksandra, et al. "Thermal desorption spectrometry of beryllium plasma facing tiles exposed in the JET tokamak." *Fusion engineering and design* 133 (2018): 135-141

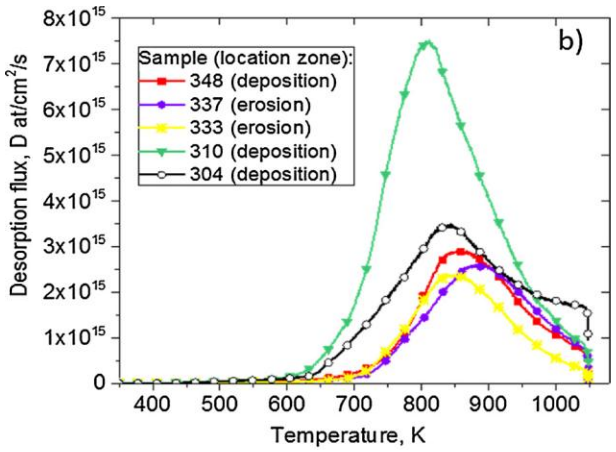
X-Ray Photoelectron Spectroscopy (XPS)

- Used to determine atomic composition and chemistry
- Depth: of 50 – 1000 A
- How: Irradiate surface with X-rays and induce photoelectron emission
  - Energy of emitted electrons show elements present, chemical bonding, and oxidation state
- Useful for: quantifying key impurities deposited or accumulated from plasma
  - Can determine chemical form of deposited or eroded surfaces
  - Identification of plasma fuel trapping sites

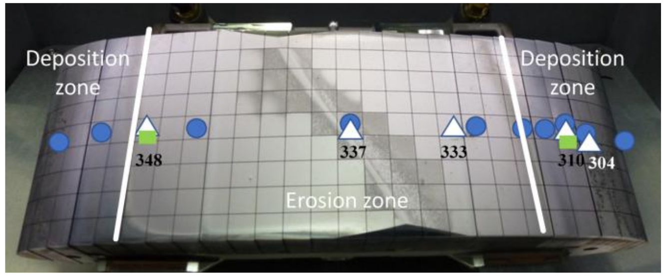


Thermal Desorption Spectroscopy (TDS)

- Used to determine amount of gas trapped in a material post plasma exposure
- Depth: surface and bulk
- How: A sample is placed in UHV and heated with a precisely controlled temperature ramp
  - Mass spectrometry is used to monitor partial gas pressures
- Useful for: total retained inventory of elements
  - Binding energies and trapping sites correspond with desorption peaks indicating lattice detects, impurities, co-deposited layers



Desorbed hydrogen deuteride from beryllium tiles exposed in JET



Goldstein, Joseph I., et al. *Scanning electron microscopy and X-ray microanalysis*. springer, 2017

Scanning Electron Microscopy (SEM) and X-ray Energy Dispersive Spectroscopy (EDX)

- SEM generates a visualization of the surface morphology of a material
- Depth: of 10 nm to a few microns
- How: rastering electron gun bombards surface with energetic electrons causing SEE
    - Secondary electrons are collected and translated into an image by their intensities
- Useful for: high field of view imaging with down to sub nm resolution

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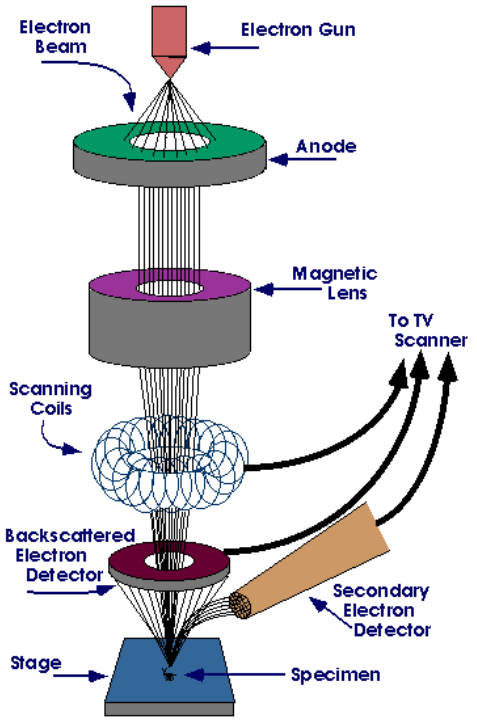
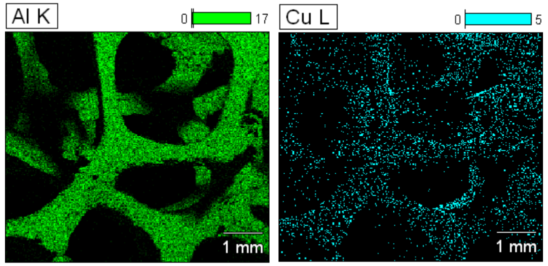
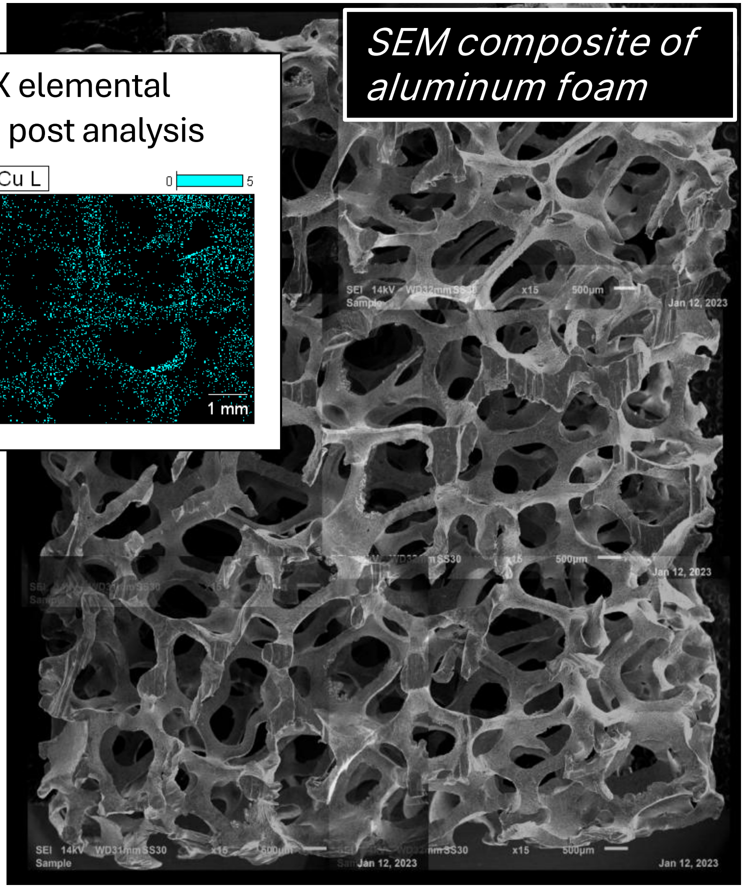
- In EDX, the same electron beam excites core-shell electrons which emit characteristic X-rays when outer-shell electrons fill the vacancies.
    - X-ray photons are measured and peaks associated with chemical composition
- Depth: 100 nm to a few microns



Quantitative EDX elemental mapping used in post analysis





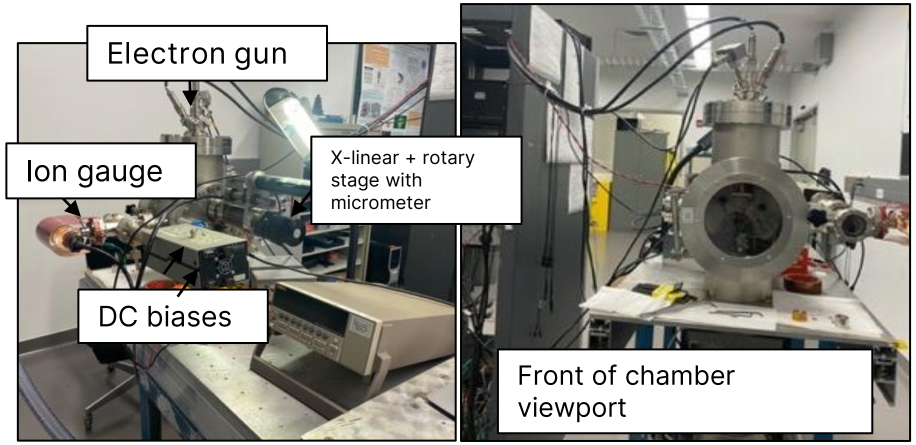
Brighter regions → higher SEE
Darker regions → lower SEE

Direct electron emission measurements

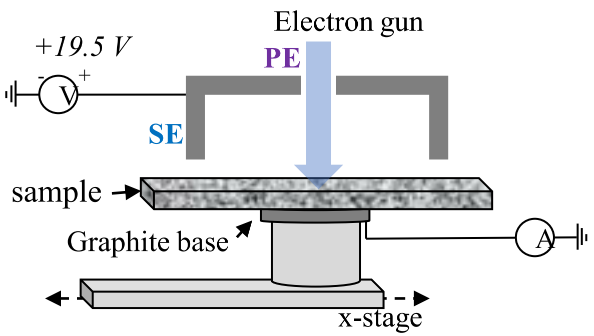
- In PPPL Nano Lab
- Electron beam used to generate secondary electrons from target
- All secondary electrons collected and measured
- Measure sample current to infer electron emission yield of materials

$$I_S = I_{PE} - I_{SE}$$
$$\gamma_{SEE} = I_{SE}/I_{PE}$$

$$\boldsymbol{\gamma_{SEE} = 1 - I_S/I_{PE}}$$

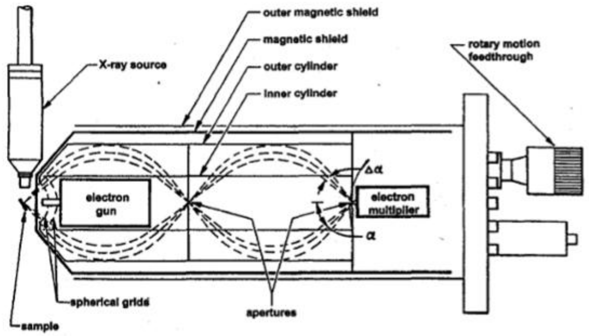


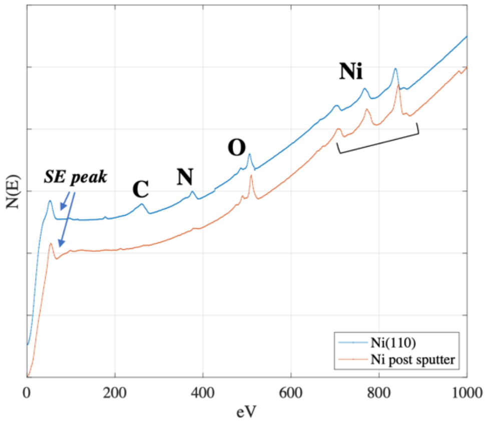
Sample current $I_S = I_{PE} - I_{SE}$

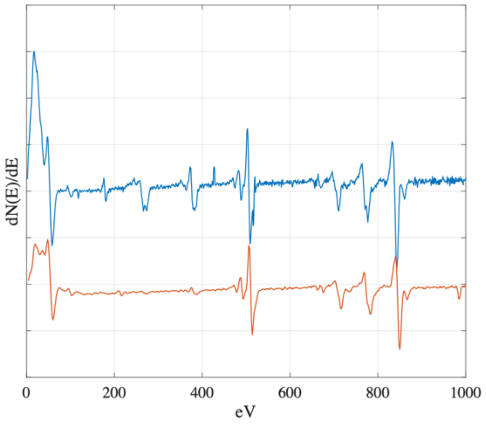


Auger spectroscopy

- In PPPL Surface Science and Technology Lab
- Electron beam excites atoms to emit secondary electrons
- Energy analyzer discerns Auger electrons to identify near-surface chemical composition







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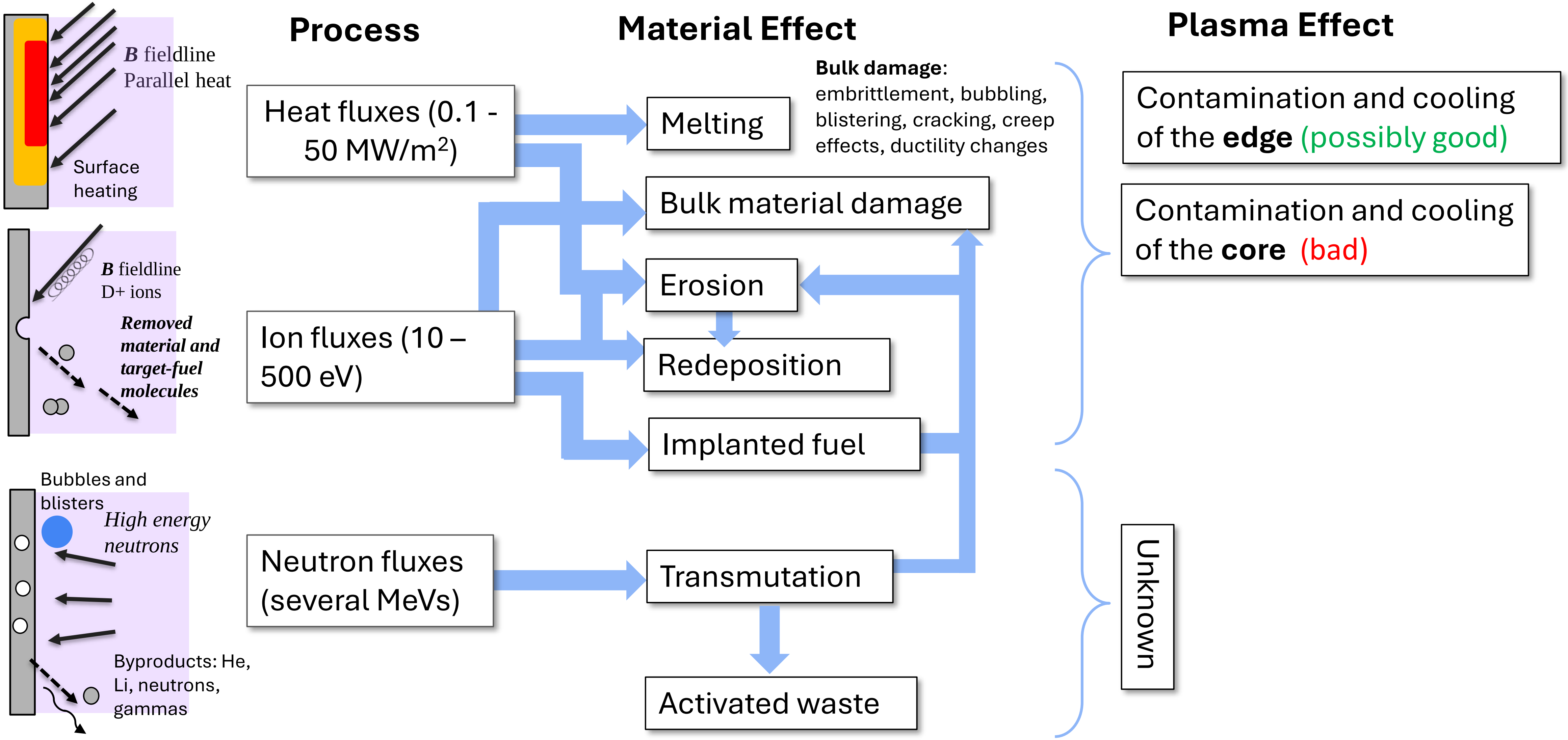
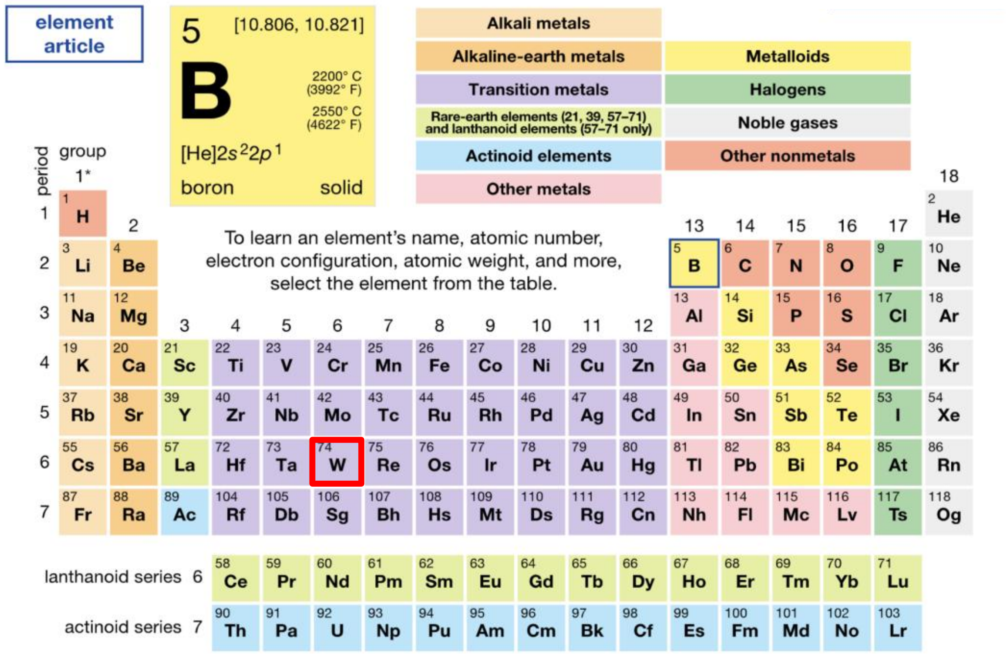
PMI In Magnetic Confinement Fusion

PMI in magnetic confinement fusion



Fusion material requirements

- Low material erosion: low chemical and physical sputtering properties at relevant ion energies and fluxes
- Low core plasma contamination (low-Z)
- Low fuel retention (D+T)
- Available and cost-effective material
- High melting point (> 2000 K)
- High thermal conductivity > 50 MW/mK
- Low/medium neutron activation
- High recrystallization temperatures
- Widely used choice: tungsten and tungsten alloys



Novel materials are being developed.

High entropy alloys

- Dispersion strengthened W composites
- Carbon Fiber Composites

Lithium is a commonly studied PFC element

- <u>Benefits</u>: low recycling (binds with H isotopes), self-healing properties, impurity trapping, efficient heat absorber and dissipator
- <u>Downsides</u>: highly reactive with air and water (safety risk), high T retention limiting recovery, poor material compatibility with structural elements, neutron activation

<u>Some PFC materials in research devices</u>

JET
- Be for main chamber, W divertors
- Regular boronization

W7-X
- Graphite tiles
- Boronization: glow discharge with diborane and boron powder (B4C) injection

HSX
- Graphite and stainless steel

ITER
- W PFCs (formerly Be first wall)

DEMO
- W and SiC composites

DIIID
- Graphite tiles, some W coatings

WEST
- W

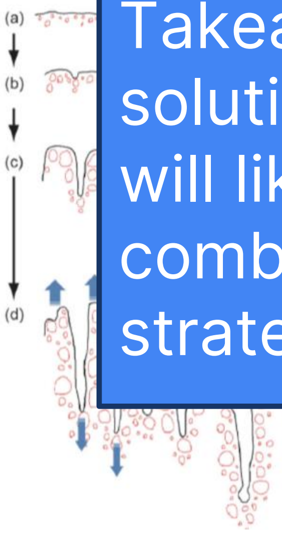
ASDEX
- W first wall and W divertor

- Kajita, Shin, Naoaki Yoshida, and Noriyasu Ohno. "Tungsten fuzz: Deposition effects and influence to fusion devices." *Nuclear Materials and Energy* 25 (2020): 100828.
- Patino, M. I., et al. "Temperature dependent study of helium retention in tungsten fuzz surfaces." *Nuclear Materials and Energy* 34 (2023): 101331.

Pros and cons of common PFCs

Takeaway: no "magic" solution exists. Fusion PFCs will likely employ combinations of mitigation strategies

Tungsten
- High melting point (3500 C)
- High thermal conductivity
- Low sputter yield and erosion rates
- Brittle at low temps (cracking, stress effects)
- Machining is hard
- Expensive
- W carbide formation
- W fuzz formation



energetic He ion bombardment. Image taken with SEM

Tungsten alloys
- Reduced brittleness at low temps
- Higher thermal conductivity for better heat removal systems
- Alloying elements can compromise melting point
- Low TRL
- More expensive
- Not all equally neutron resistant
- High Z, disrupts core performance

Beryllium
- Low Z minimizes impurities
- Good thermal properties
- Low sputter yield
- Toxic
- Brittle at low temps
- Radiation degradation

Boron coating
- Impurity capturing
- Neutron tolerant
- Low sputter yield
- Boron carbide formation
- High sputtering

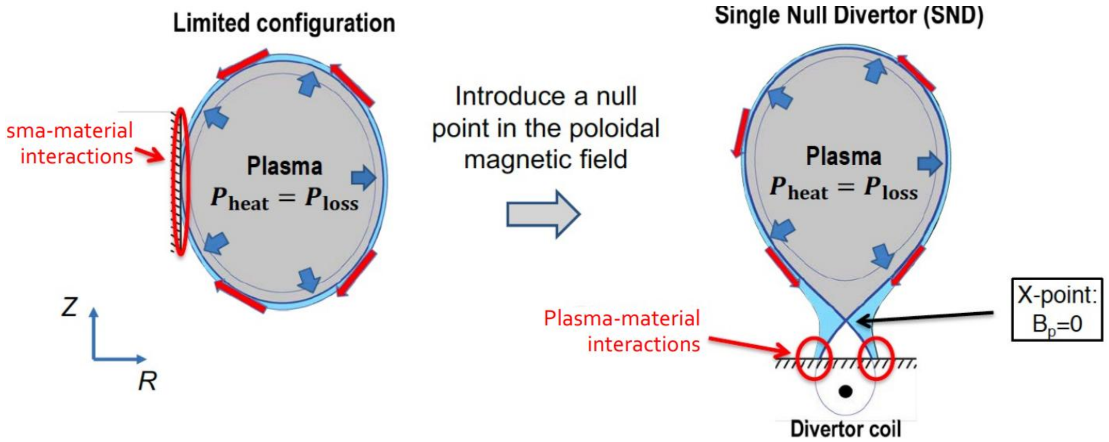
Carbon fiber composites
- Lightweight
- High thermal conductivity
- High melting point (3650 C)
- Sputtering yield can be high
- Graphitic forms
- Not neutron resistant

Steel and steel alloys
- High strength and ductility
- Good mechanical properties at all temperature
- Resistant to corrosion
- Low melting point (1370C)
- Not radiation resistant
- Can be ferromagnetic

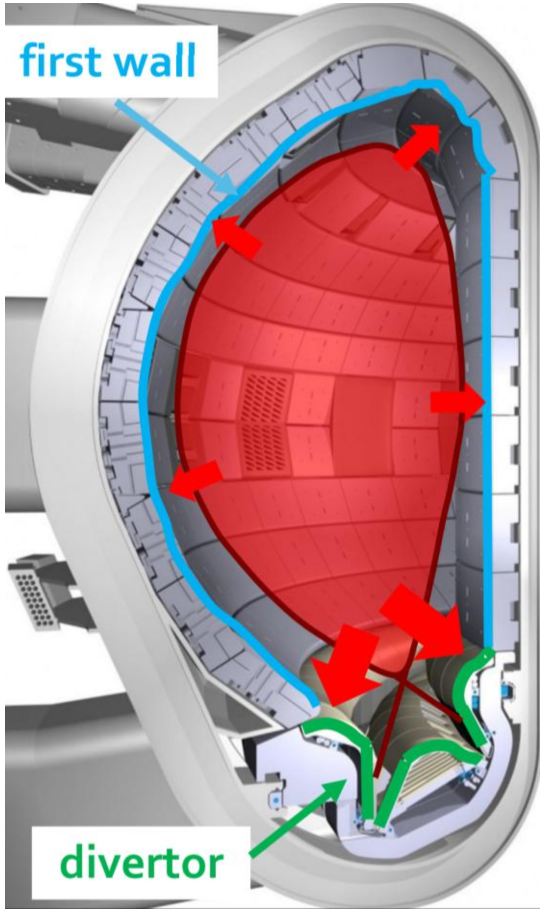
Plasma-Facing Components (PFCs) in fusion

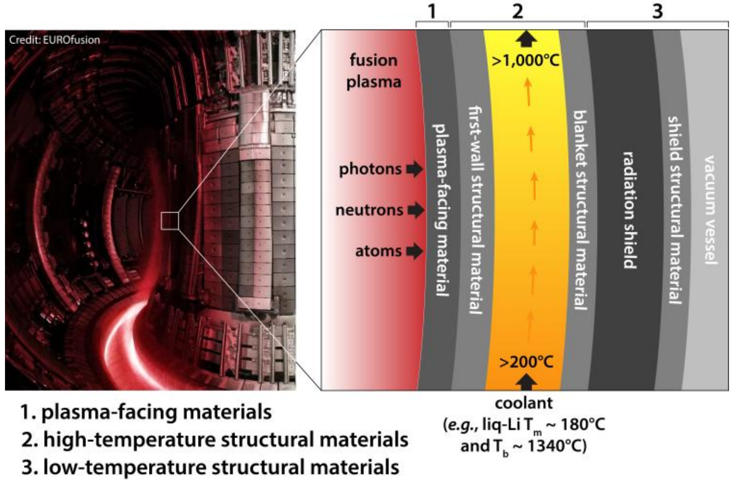
Diverting particles and heat fluxes with a… Divertor

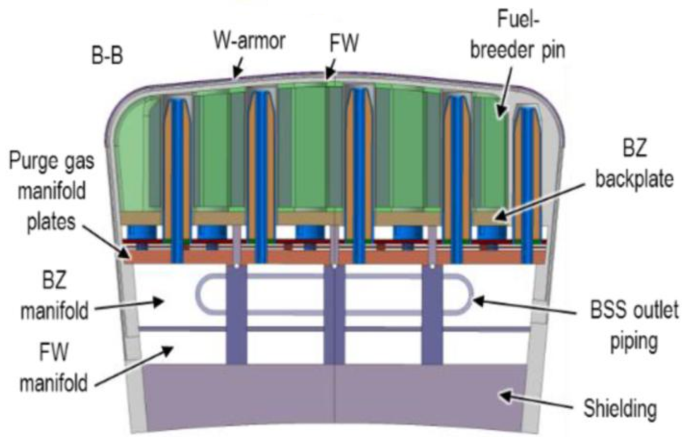
- Up to 40 MW/M² (!!)
- Reduce sputtering of other plasma facing component (PFC)
- Better control of plasma density and removal of He ashes via pumping (plasma density is higher in divertor)
- Particle flux ~10^{24} $m^{-2}s^{-1}$



10s of eV ion and electron energies

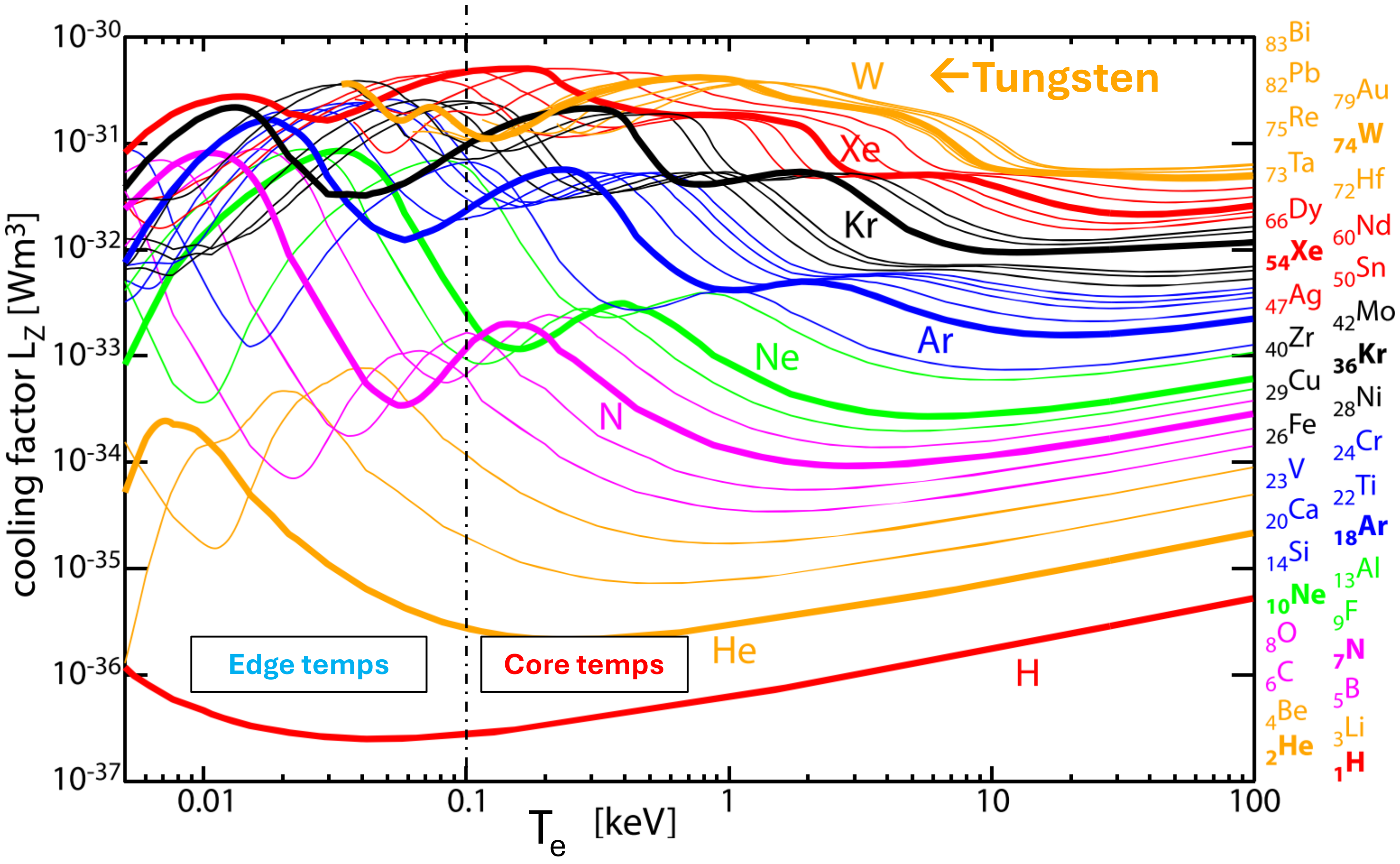






Low-Z vs high-Z impurities and materials

W radiates a lot of power in the core temperature regime when emitted into the plasma

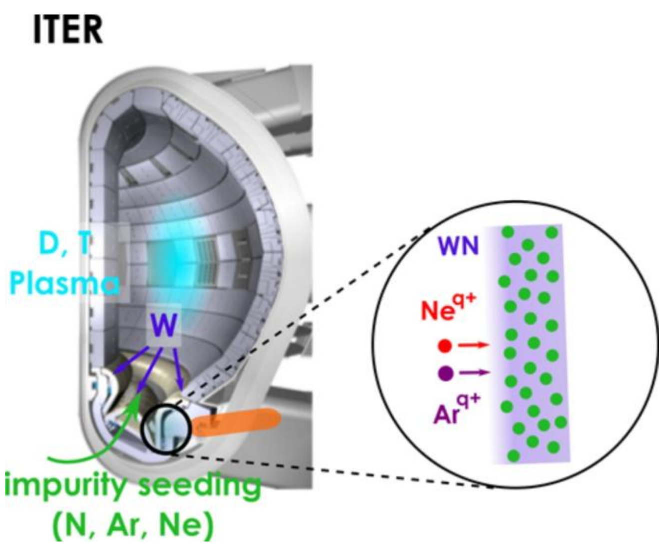


Higher-Z materials have higher radiation potential due to large number of bound electrons → numerous excitation/de-excitation (line radiation) transitions possible.

Power radiated is: $P_{rad} = n_e n_Z L_Z(T_e)$

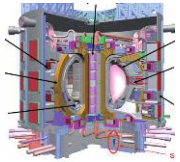
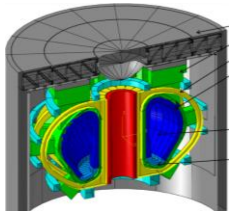
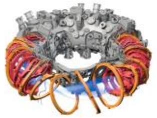
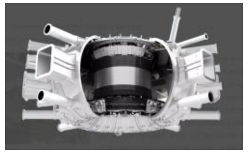
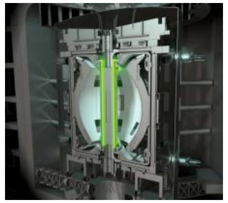
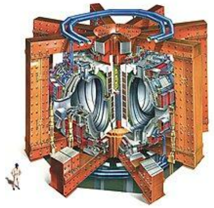
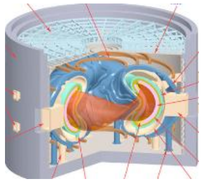
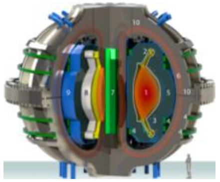
Impurity seeding used to mitigated heat loading to PFCs

Used for Divertor detachment



- Dobes, Katharina, et al. "Interaction between seeding gas ions and nitrogen saturated tungsten surfaces." *International Journal of Mass Spectrometry* 365 (2014): 64-67.
- Pütterich, Thomas, et al. "Determination of the tolerable impurity concentrations in a fusion reactor using a consistent set of cooling factors." *Nuclear Fusion* 59.5 (2019): 056013.

Summary of PFCs in select MFC Devices

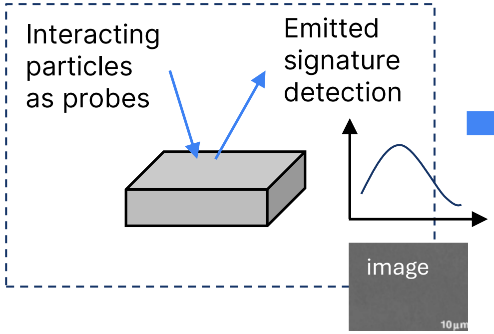
	ITER	DEMO	W7-X	ASDEX-U	STEP	JET	ARIES	CFS SPARC
Machine	Tokamak	Tokamak	Stellarator	Tokamak	Tokamak	Tokamak	Stellarator	Tokamak
Power	1180 MW	1998 MW	(Heating) 14 MW	(Heating) 27 MW	Up to 1800 MW	16 MW	2355 MW	525 MW
Radius	7.75 m	8.94 m	5.5 m	1.65 m	3.6 m	2.96 m	7.75 m	3.3 m
PFC Materials	Beryllium, tungsten	Advanced W alloys	CFC, graphite, tungsten	Tungsten	Tungsten, beryllium, ferritic steel	Carbon-based, Beryllium, W	Ferritic steel (surface of blanket module), W alloy	Tungsten
Divertor heat load	10 – 20 MW/m^2	5-10 MW/m^2	5-10 MW/m^2	5 – 10 MW/m^2	< 20 MW/m^2	5-10 MW/m^2	10 MW/m^2	10 MW/m^2
First wall heat load	up to 5 MW/m^2	< 0.5 MW/m^2	< 0.5 MW/m^2	0.2 MW/m^2	Not specified	<5 MW/m^2	0.6 – 0.8 MW/m^2	Not specified
Neutron flux	10^{14}-10^{21} n/s	10^{12} n/s	< 10^{14} n/s (2.45 MeV)	< 10^{16} n/s (2.45 MeV)	1-5 x 10^{20} n/s	~5 x 10^{18} n/s	8 x 10^{20} n/s	10^{19} n/s
Fusion fuel	Deuterium, Tritium	Helium, hydrogen, deutrium	Helium, hydrogen, deutrium	deuterium	Deuterium, tritium	Deuterium, tritium	Deuterium, tritium	Deuterium, tritium

Note: CuCrZr commonly used as a heat sink directly behind plasma-facing material

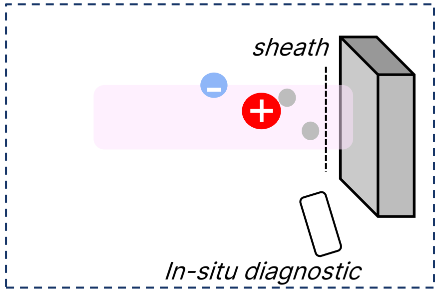
Common PMI workflow for fusion material development

Candidate sample

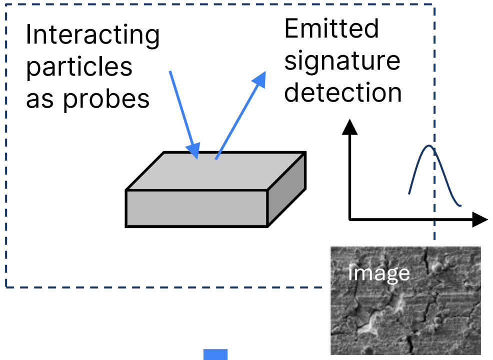
Surface analysis
Buk analysis



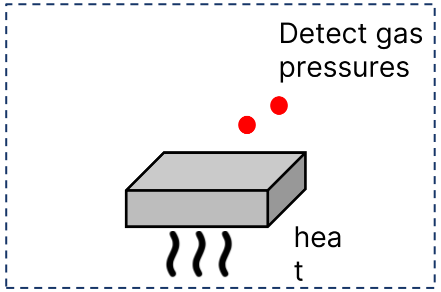
Exposure to plasma conditions



Surface analysis
Buk analysis:
assess damage and changes



Desorbed species



Adjust candidate sample

Knobs: composition, morphology, chemistry, purity, etc.

Qualify in a high heat flux, ion flux, neutron (or surrogate) experiment

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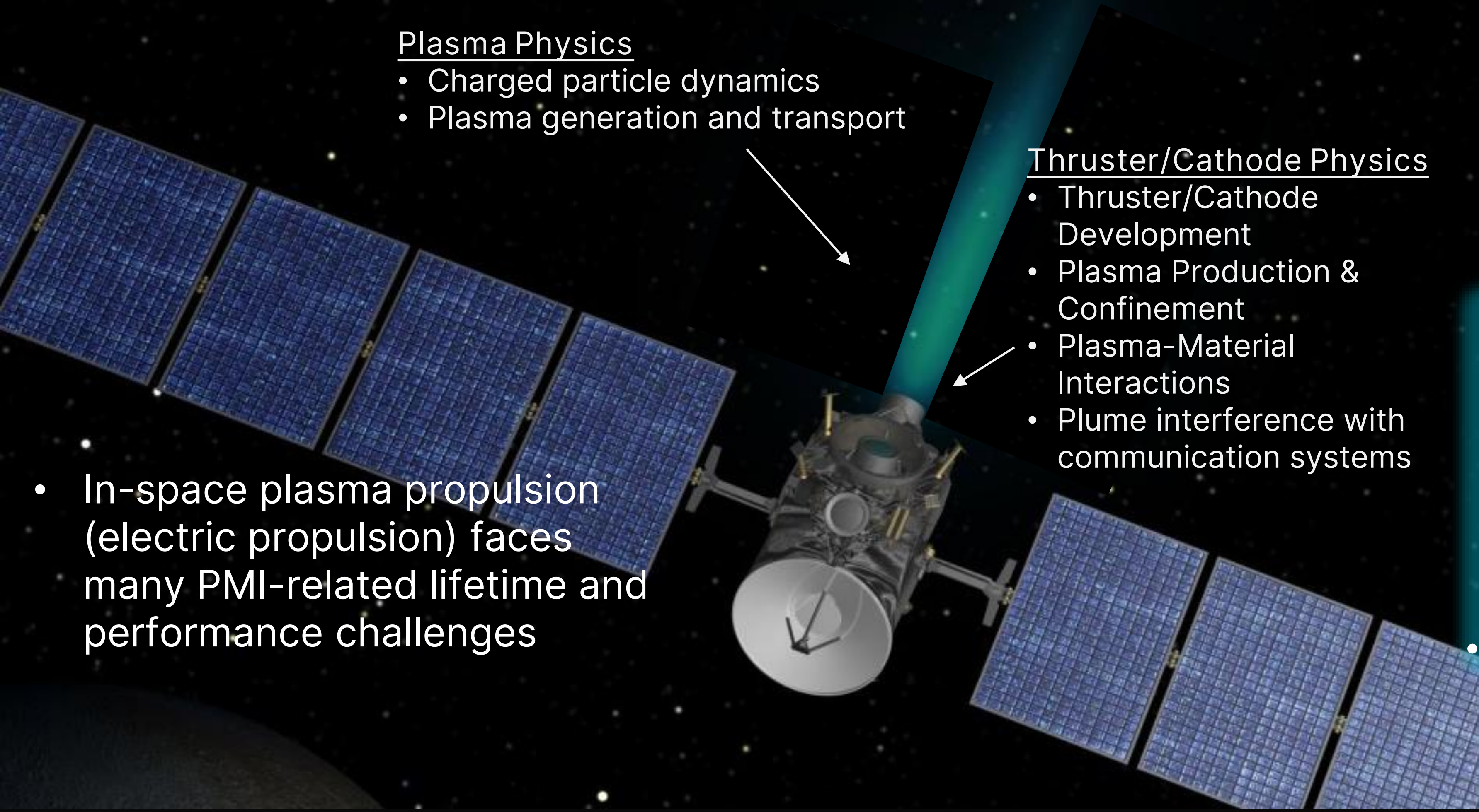
PMI in Space Propulsion

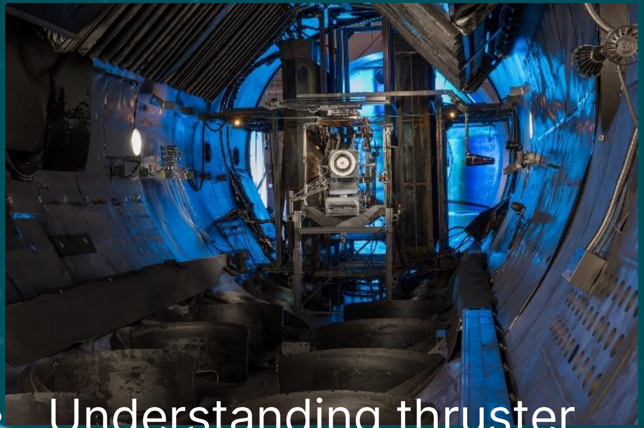
Plasma-materials in electric propulsion



Plasma Physics
- Charged particle dynamics
- Plasma generation and transport

Thruster/Cathode Physics
- Thruster/Cathode Development
- Plasma Production & Confinement
- Plasma-Material Interactions
- Plume interference with communication systems

Spacecraft Interactions and Facility Effects
- Plasma-Material Interactions
- Electron induced SEE and ion induced SEE
- Plasma transport



- In-space plasma propulsion (electric propulsion) faces many PMI-related lifetime and performance challenges
- Understanding thruster PMI is also critical for lab-based testing

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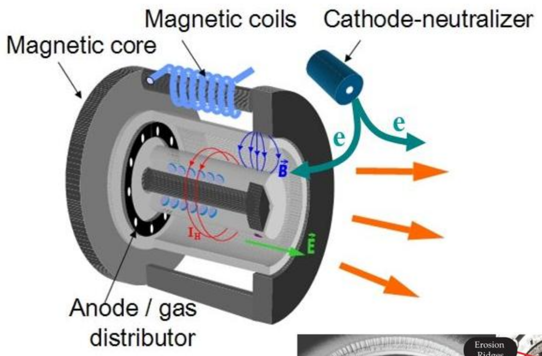
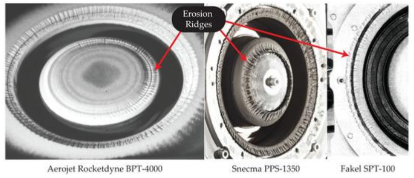
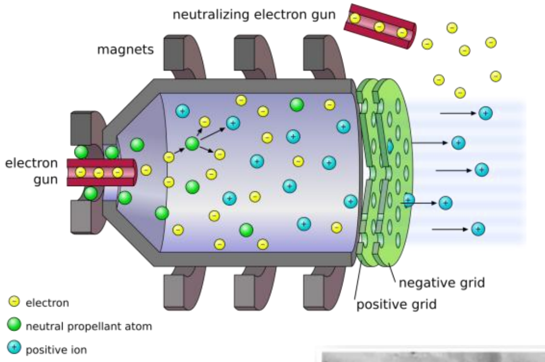
Plasma-Materials in Electric Propulsion

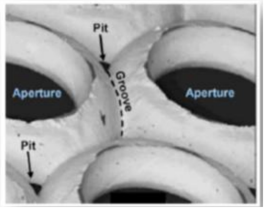
Hall thruster
- Accelerates ions to generate thrust by using an E x B field to trap electrons
- Channel wall erosion increased by sheath-reduction caused by high SEE from ceramic materials
- Cathode erosion from ion bombardment



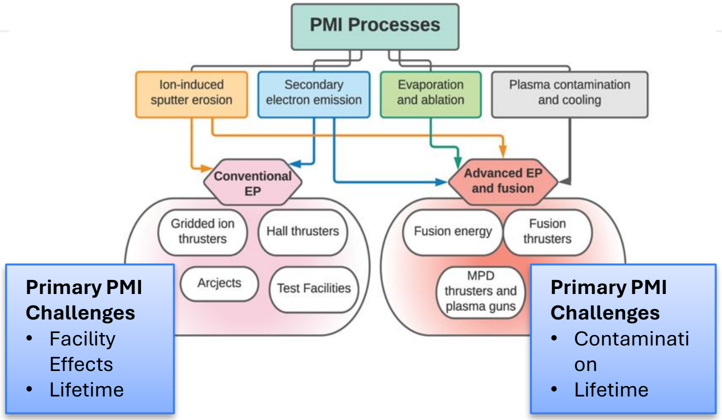


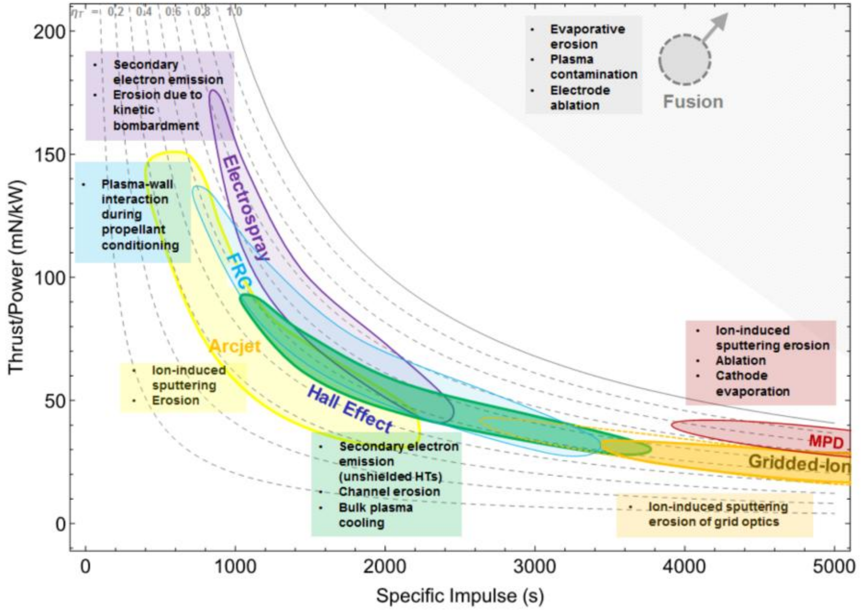
Ion thruster
- Accelerates ions with electrostatic grids to generate thrust
- Accelerator grid sputtering by up to 3 keV ions and charge-exchange neutrals
- Cathode erosion from ion bombardment





Common parameters:
- Heavy, inert propellant gas (Xe, Ar) have high sputtering yield
- Contamination from sputtering will degrade plasma properties and performance





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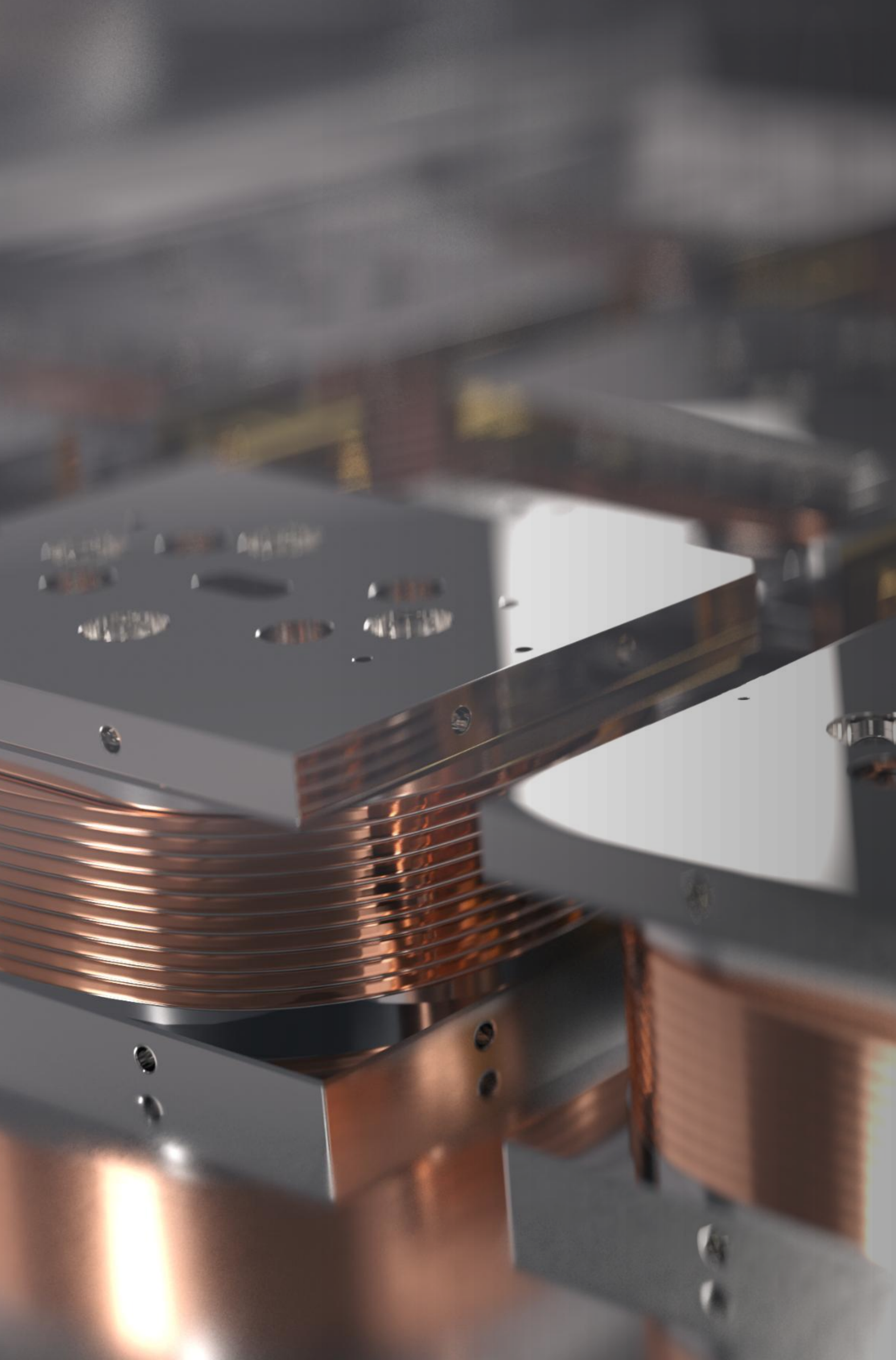

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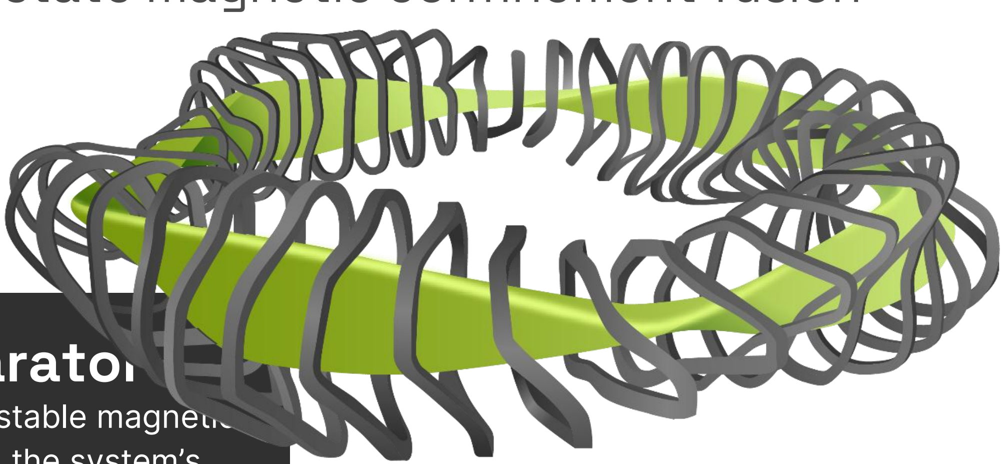
INFUSE

UNIVERSITY OF CALIFORNIA SAN DIEGO

PMI at Thea Energy: boron pebble rod study case with UC San Diego

Thea Energy is the first fusion spin-out of Princeton University / PPPL, the birthplace of the stellarator

Stable, steady-state magnetic confinement fusion



The Stellarator

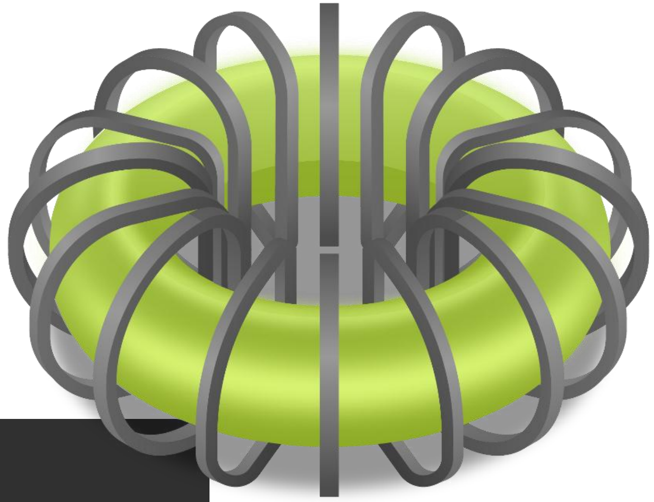
In a stellarator, a stable magnetic field is inherent in the system's coils, not due to an additional external transformer.

Steady-state

Inherently stable magnetic confinement with no risk of disruptions.

Highly efficient

No requirement for current drive systems, with low recirculating power.



The Tokamak

In a tokamak, the magnetic field is formed by putting a significant amount of energy into the system through current drive transformers.

The stellarator is a scientifically mature, optimal plant architecture

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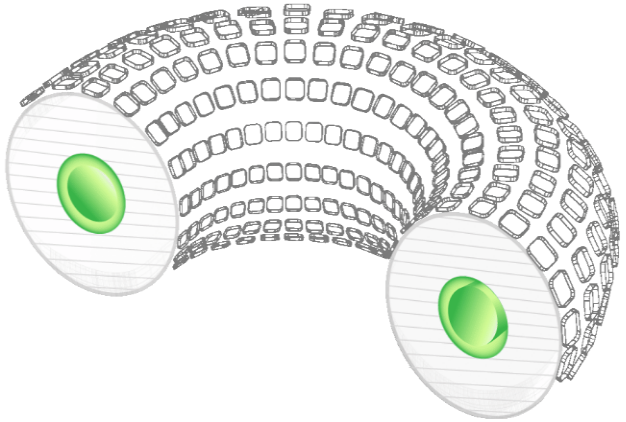
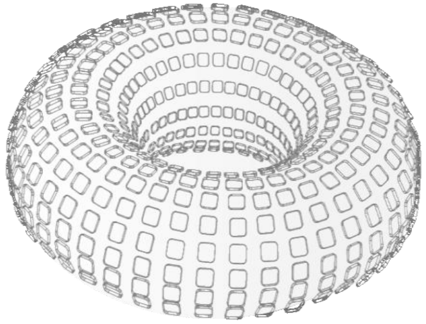
The planar coil stellarator

Dynamic System Control

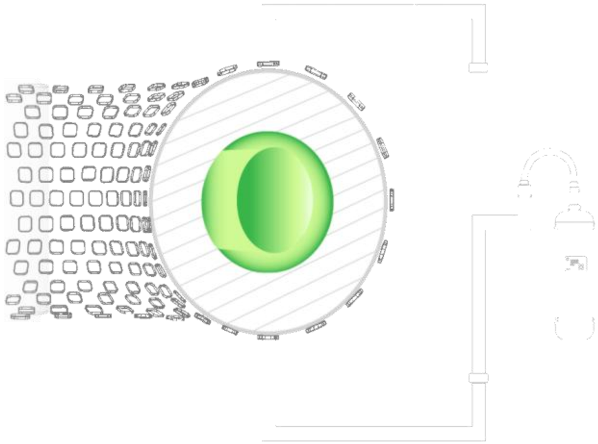
We can optimize machine parameters and dynamically change operating points in real-time



Simplified Commercial System Maintenance and Operation
Geometry enables sector maintenance with better access and large sector removal than even tokamak design

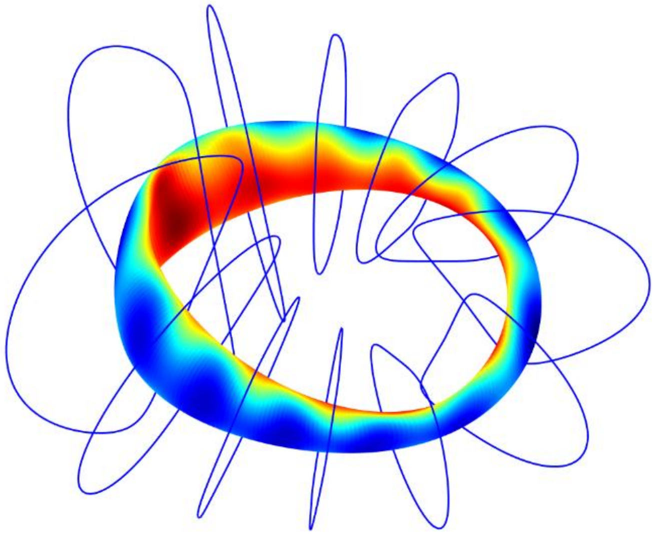


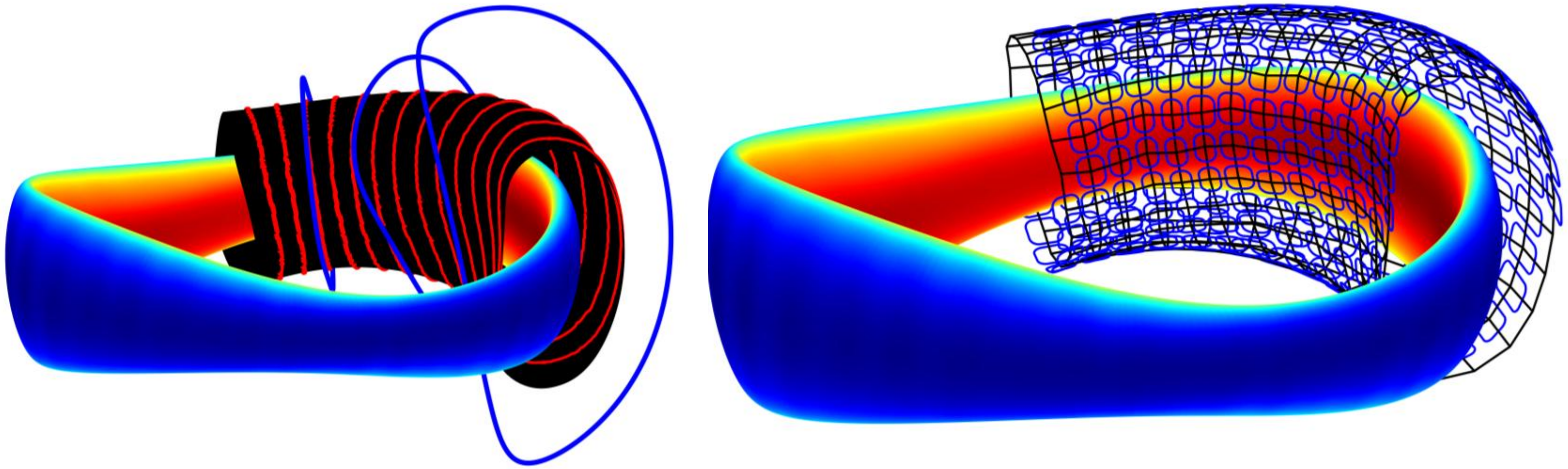
Capable of Near-Term Commercial Operation
D-D fusion for the production of tritium and other radioisotopes with steady-state operation



Planar stellarator coils designed for sector maintenance

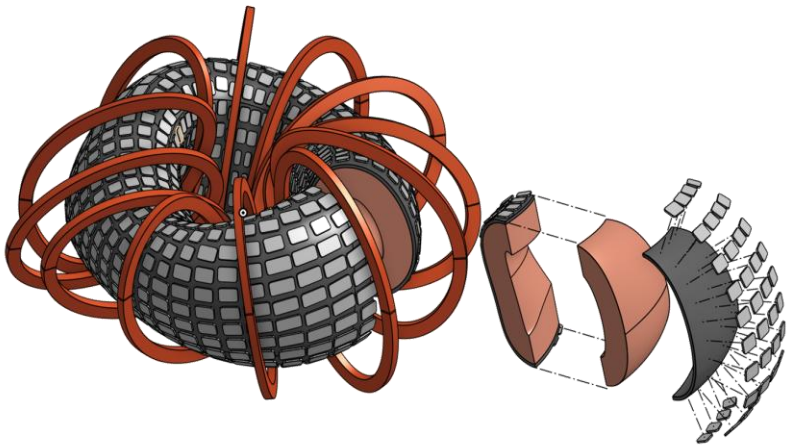
- Planar encircling coils (TF) provide most of the confining magnetic field
- A “winding surface” is used to locate the smaller planar coils within a coil array
- Coil columns (poloidal rings) are defined by the encircling coils
- Large toroidal sectors of the stellarator’s radial assembly can be extracted between the encircling coils





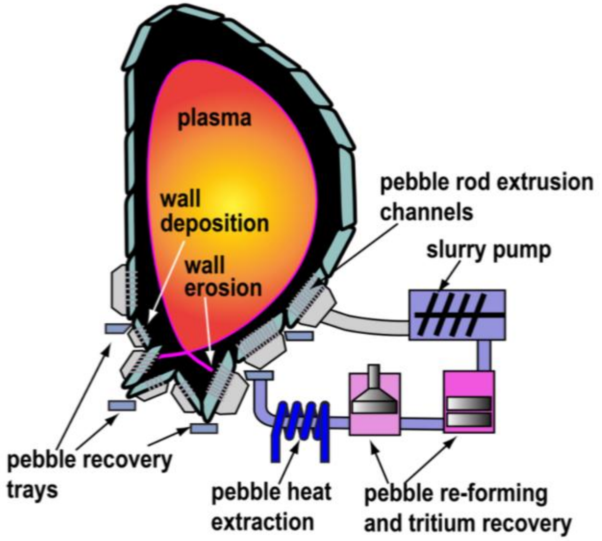
A winding surface is segmented by interpolating encircling coil planes

SECTOR MAINTENANCE CAPABILITY

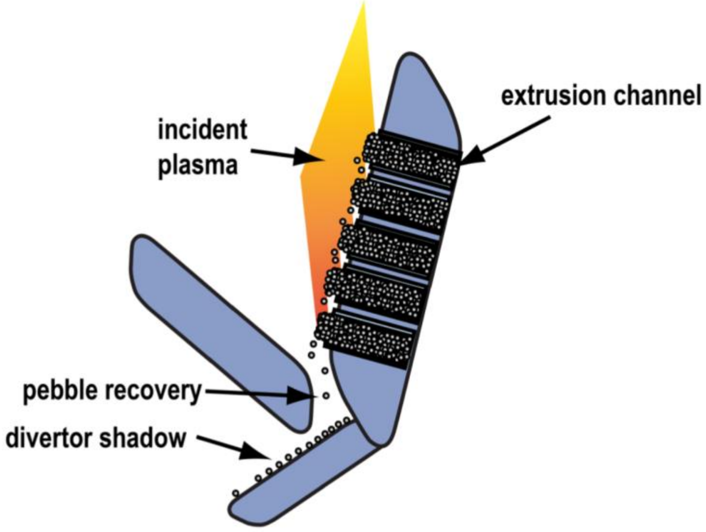


Renewable pebble wall: UCSD Collab

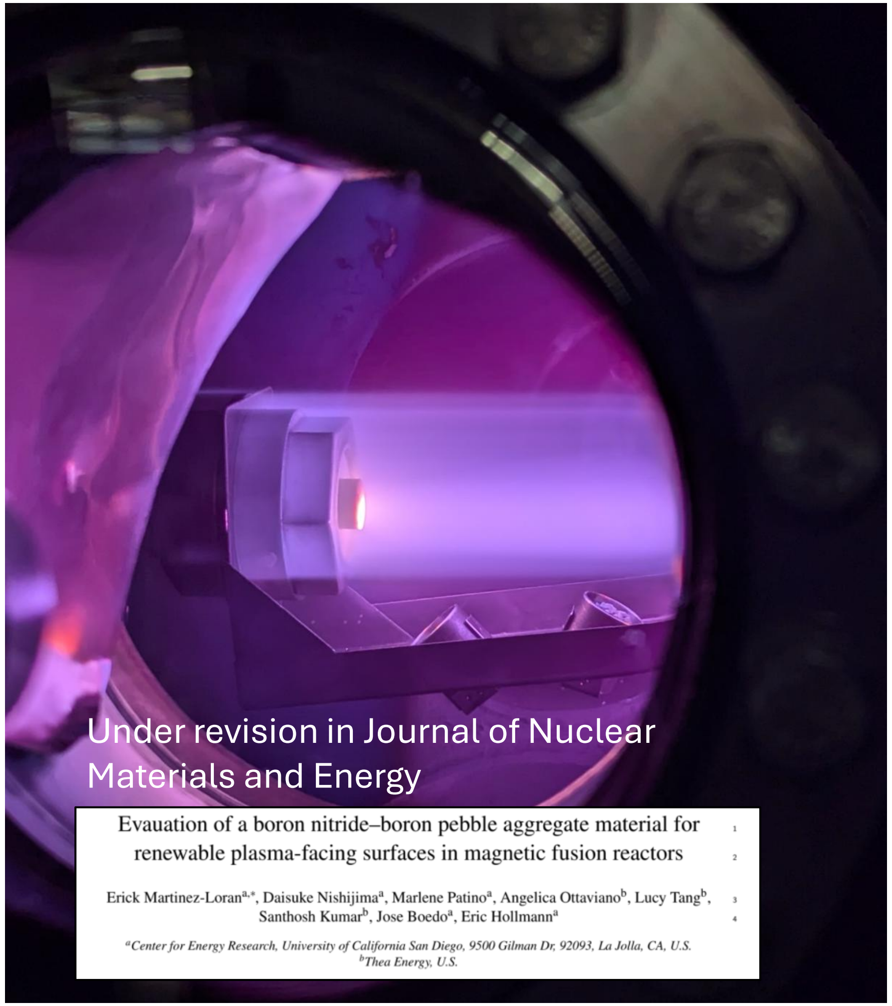
- Current FPP designs use high-Z materials: tungsten mono-blocks
- Tungsten significantly reduces core performance: impurity concentration tolerance is very low (ITER < 10^{-5}).
- Low-Z materials: improved core plasma performance but have high erosion rates.
- No material known solution for > 10s of MW/m^2 steady state heat flux Investigated concept: handling high heat fluxes and erosion products with flowing solid pebbles held together by a matrix into a rod.



Closed loop concept

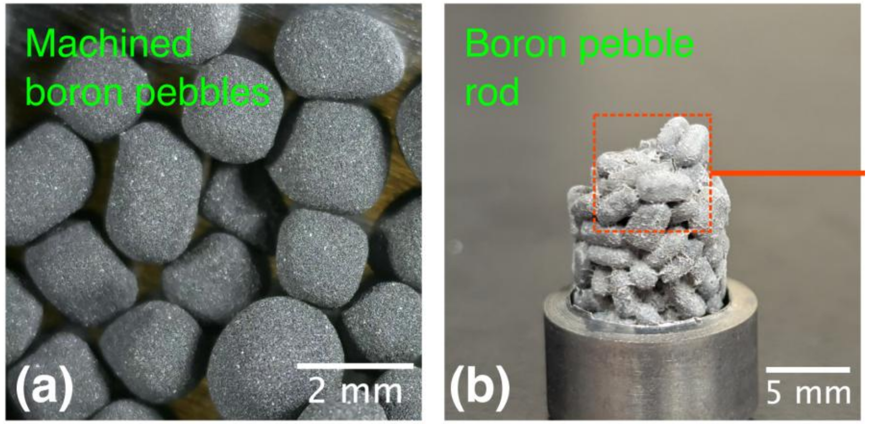


Rod extrusion at divertor

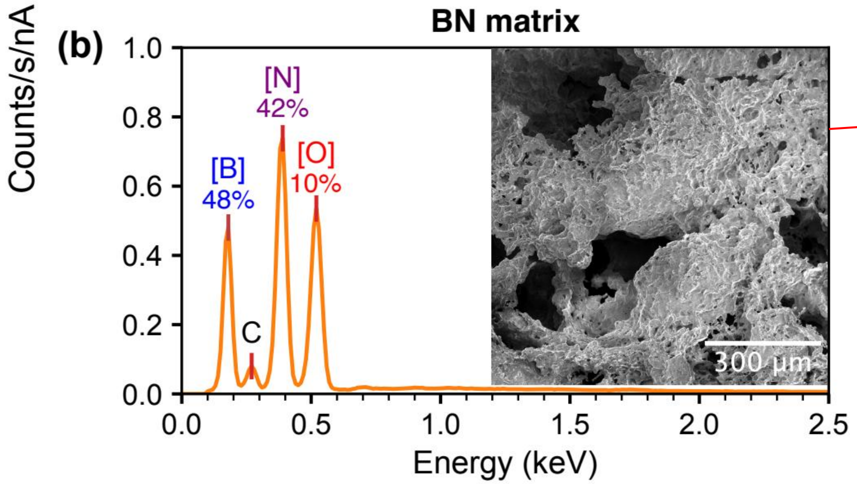


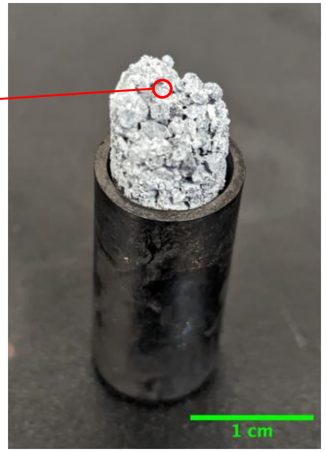
Boron pebble rod development

1. Manufacturing with pure boron and polymeric BN precursor binder



2. Measuring chemical composition with EDX and looking at morphology with SEM





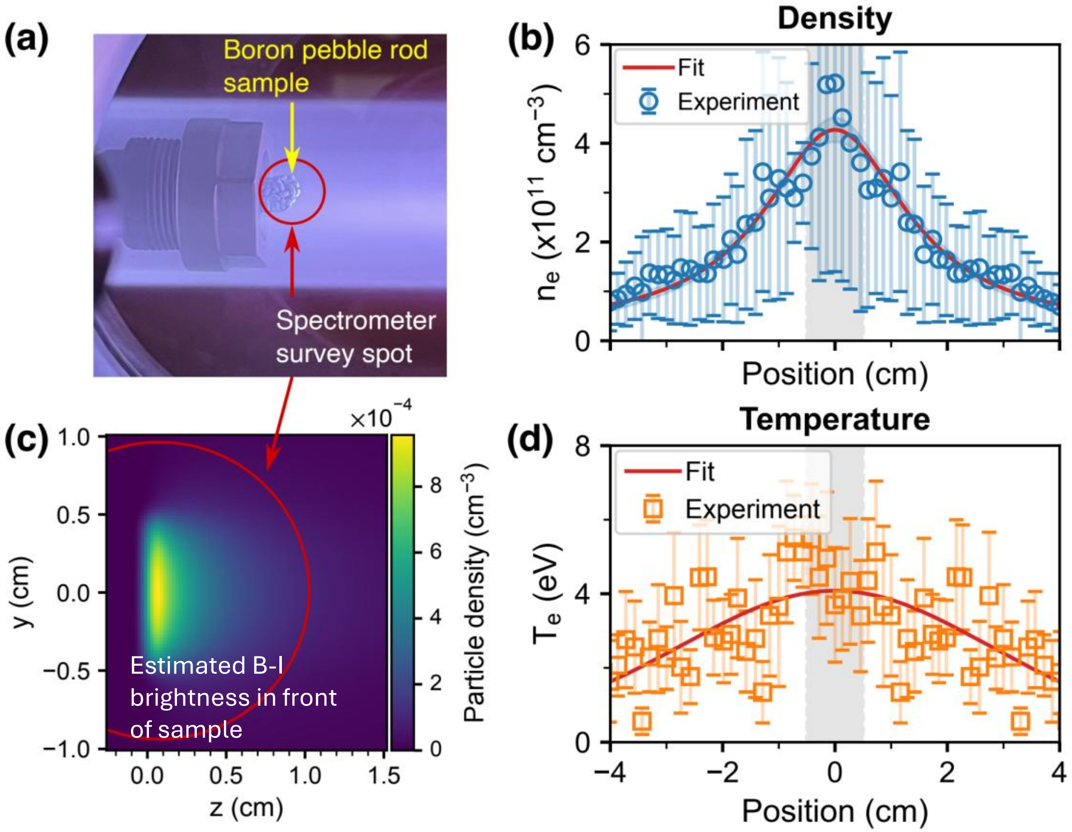
Pebble rod:

- Polycrystalline boron particles
- K_α transition X-ray emission line used for boron @ 183 eV
- % composition quantified from B_{K_α}, N_{K_α}, O_{K_α} of BN and H_2BO_3

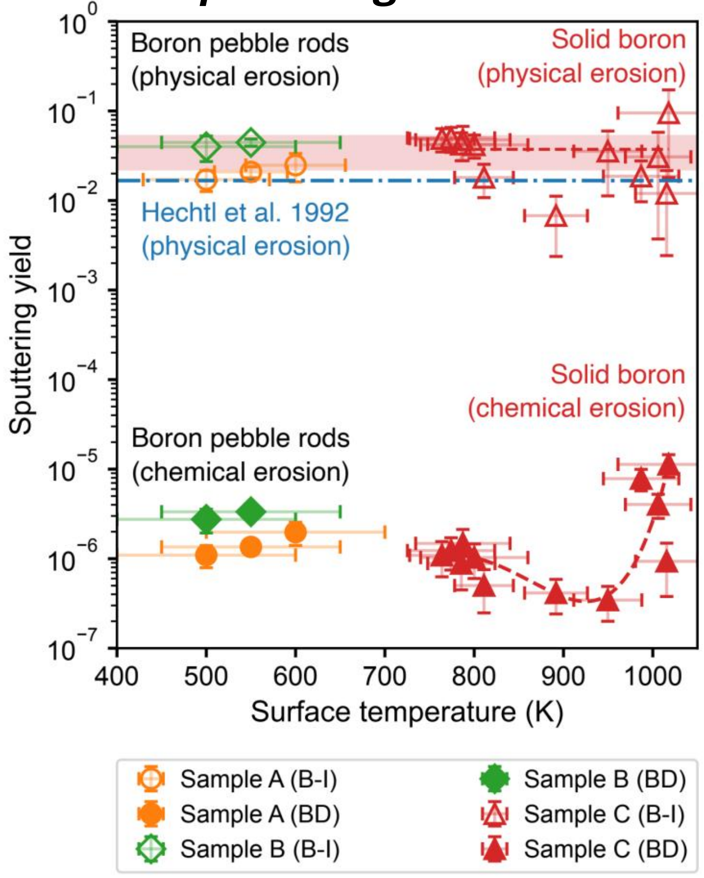
Boron pebble rod exposure

3. Exposure of a boron pebble rod in a linear deuterium plasma (PISCES-A)

- 1.5 hour exposure in D+ plasma (~$10^{25} m^{-2}$ fluence)
- Visible spectroscopy survey area covers 2 cm spot at end of sample

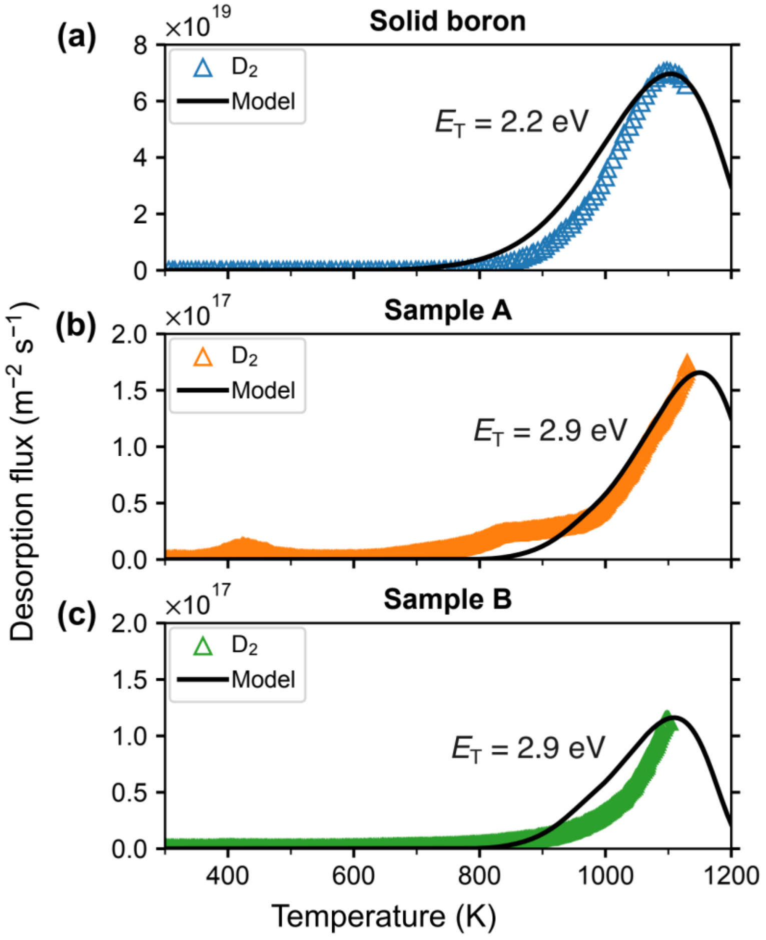


Sputtering measured

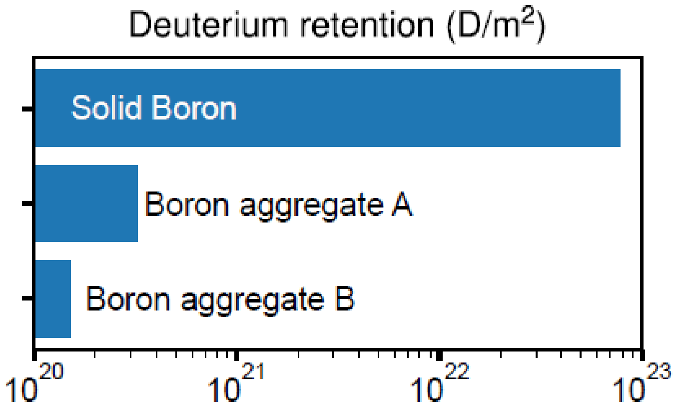


Boron pebble rod deuterium retention

4. Deuterium retention assessment



- Tool: Temperature Desorption Spectroscopy (TDS)
- Measure of how much deuterium is retained in boron and at what temperature it desorbs.
- Apparatus consists of a heater and a mass spectrometer
- Sample is heated at 0.3 K/s from ~300 K to 1200 K
- Total desorption flux estimated from partial pressure of each species: $\Phi_D = 2\Phi_{D_2} + \Phi_{D-H}$



Pebble rod testing in a tokamak divertor

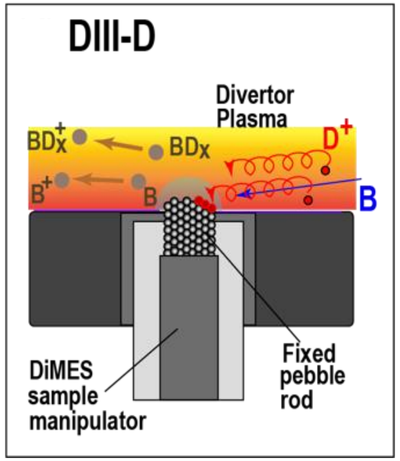
5. Hot and dense plasma test

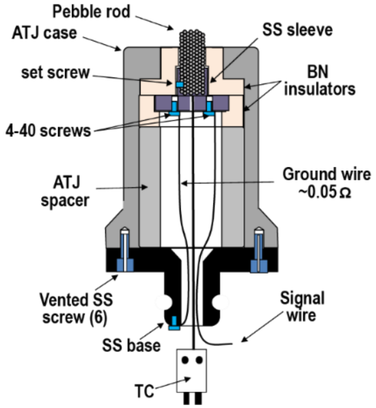
Technical Priorities:

- Evaluate recession rate of pebble release into collection sample holder region.
- Measure physical and chemical sputtering of boron pebbles in divertor conditions.
- Assess viability of pebble rods to handle heat fluxes ~5 (perpendicular) – 40 (parallel) MW/m^2 using up to 1s dwell times.
- Observe eroded boron trajectory in a grazing incidence, high strength B field.
- Assess post-mortem damage as a function of particle fluence including deuterium retention, microstructural damage, co-deposition, and binder melting effects.

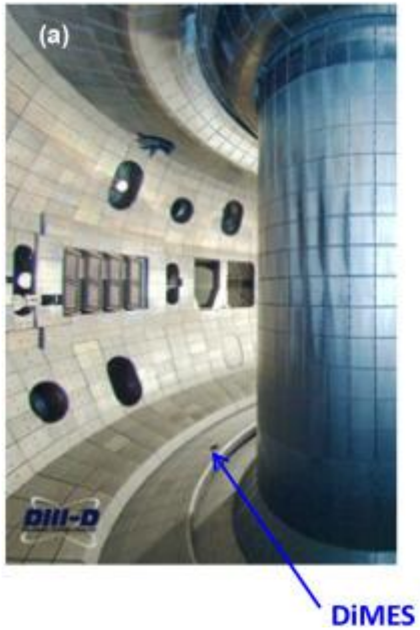
Diagnostics

- Visible filtered imaging (DiMES TV for B-I, B-II and BD)
- IR Imaging
- Bolometry (core and edge)





DiMES: Divertor Material Experiment in DIII-D



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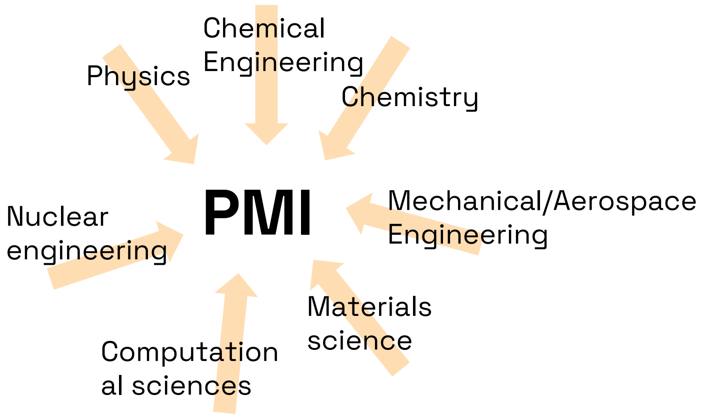
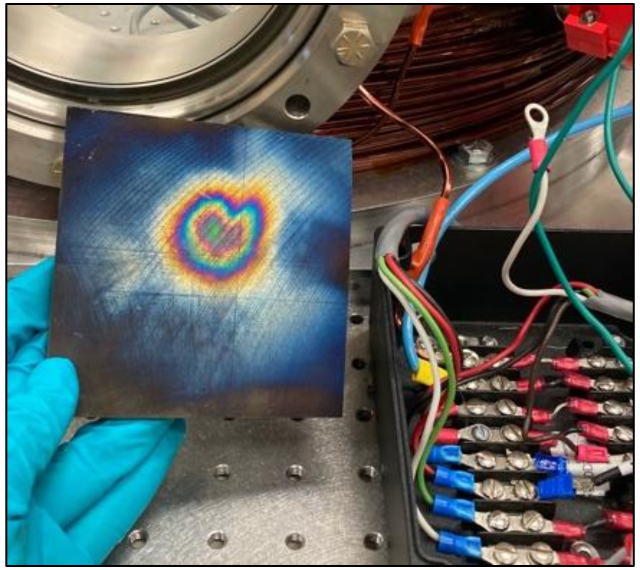
Key Takeaways

Summary

- Plasmas and materials are strongly coupled
- PMI is a potential go/no-go area for fusion energy development
    - Creative, interdisciplinary skills are required to find suitable fusion PMI solutions
- The plasma environment can be decomposed into simplified experiments
- Surface analysis tools help characterize and optimize plasma-facing materials
- The sheath is the electrostatic interface between a plasma and a surface





Thank you! Questions?

Internship opportunities at Thea Energy

We're working to solve one of the biggest problems that the world has ever faced.

Our team of changemakers is key to achieving this goal. Join us on our mission to create a limitless source of zero-emission energy for a sustainable future.

- Open full-time positions based in Kearny, NJ
  - HR & recruiting generalist
  - Control systems engineer – LabView developer
  - HTS magnet engineer
  - Test engineer
  - Mechanical engineer

https://jobs.lever.co/thea.energy

If you're interested in launching your career in fusion, Thea Energy offers year-round internship opportunities.

Interns are paired directly with a mentor and contribute across all company projects as well as their own personal areas of interest.

Internships for summer 2025 are filled! Please check back on LinkedIn and job.lever for fall 2025 postings.