Oak Ridge National Laboratory

Implications of Net Erosion & Redeposition of Solid-surface, Plasma-Facing Material on Long-pulse Operation*

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Presented at

2022 IAEA-TM on Long-pulse Operation (LPO) in Fusion Devices

at

IAEA Headquarters, Vienna

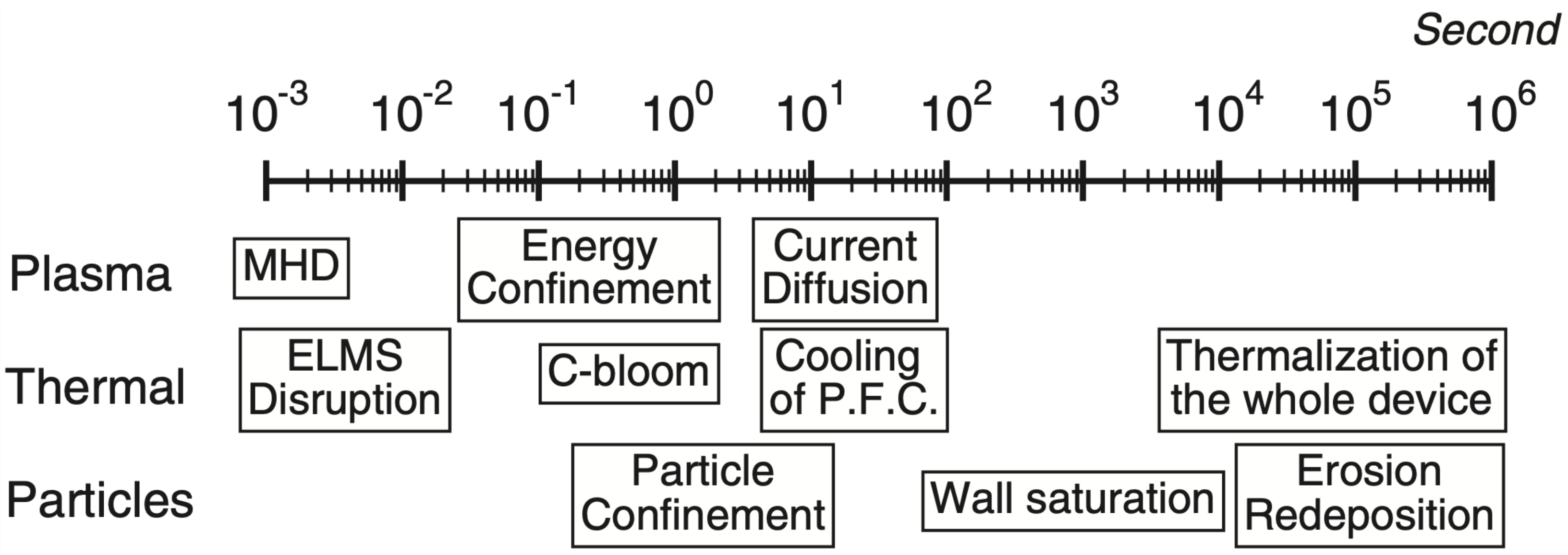
on

November 16, 2022

U.S. DEPARTMENT OF ENERGY

***Full co-author list:**
Stangeby et al. (2022) Plasma Phys. Control. Fusion
doi:10.1088/1361-6587/ac55f8

Outline: Device Walls & Plasma-wall Interactions (PWI) are More/Most Relevant at Long Time-scales/Pulse-length



Saoutic (2002) PPFC

Implications for/on:

- Global figure(s) of merit, e.g., n_i-T_i-$\boldsymbol{\tau}_E$, P/S, Wall FOM
- Thick redeposits (slag) in critical areas of tokamaks due to high fluences
- Present-day, open research topics → pathway to predictive capability for next-step devices

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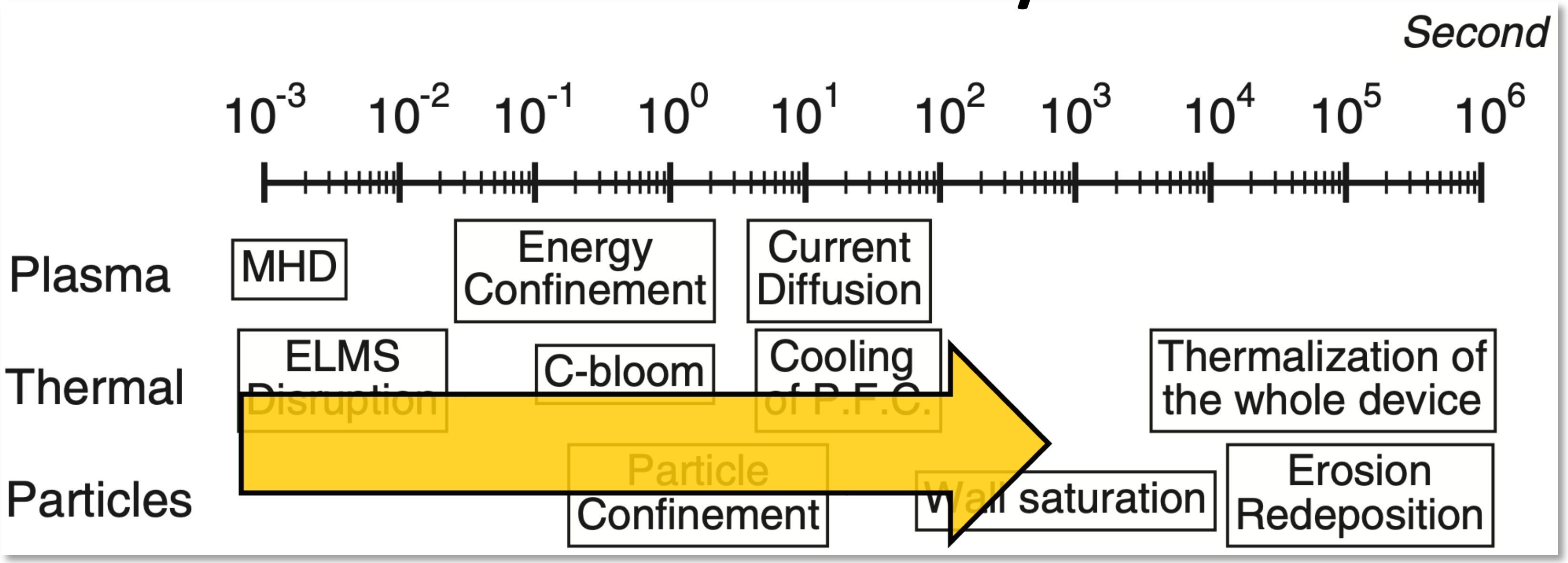

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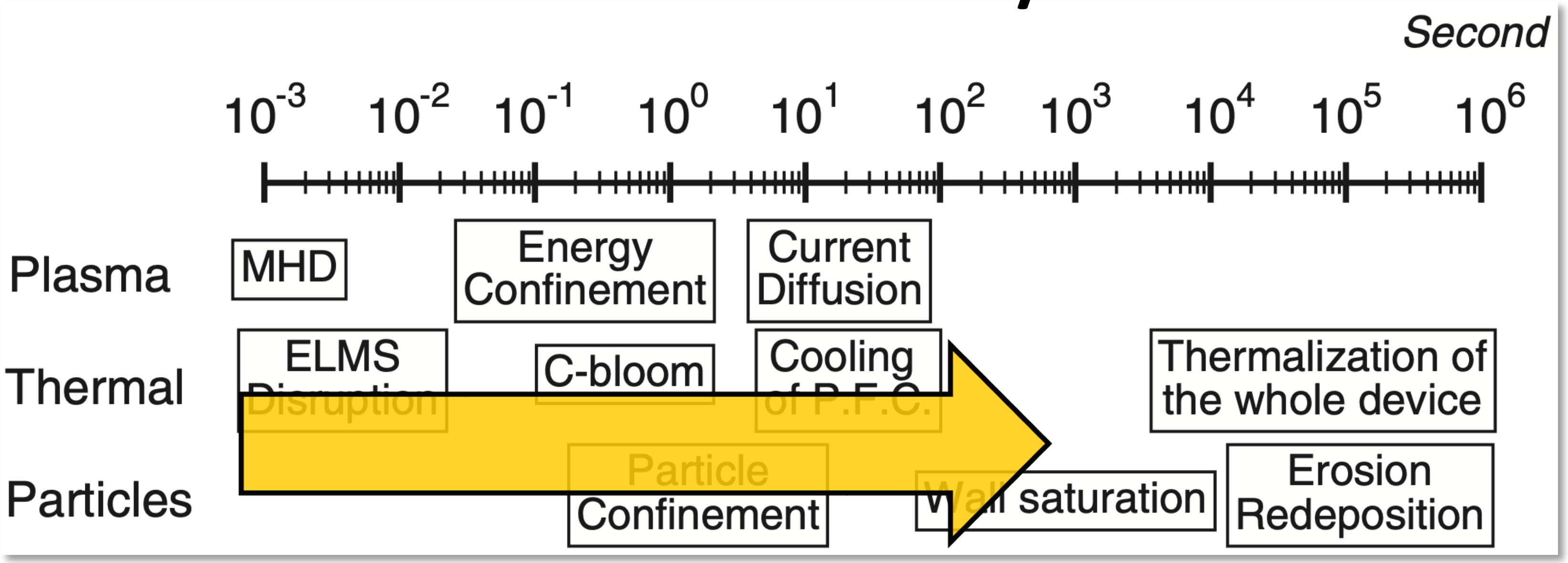

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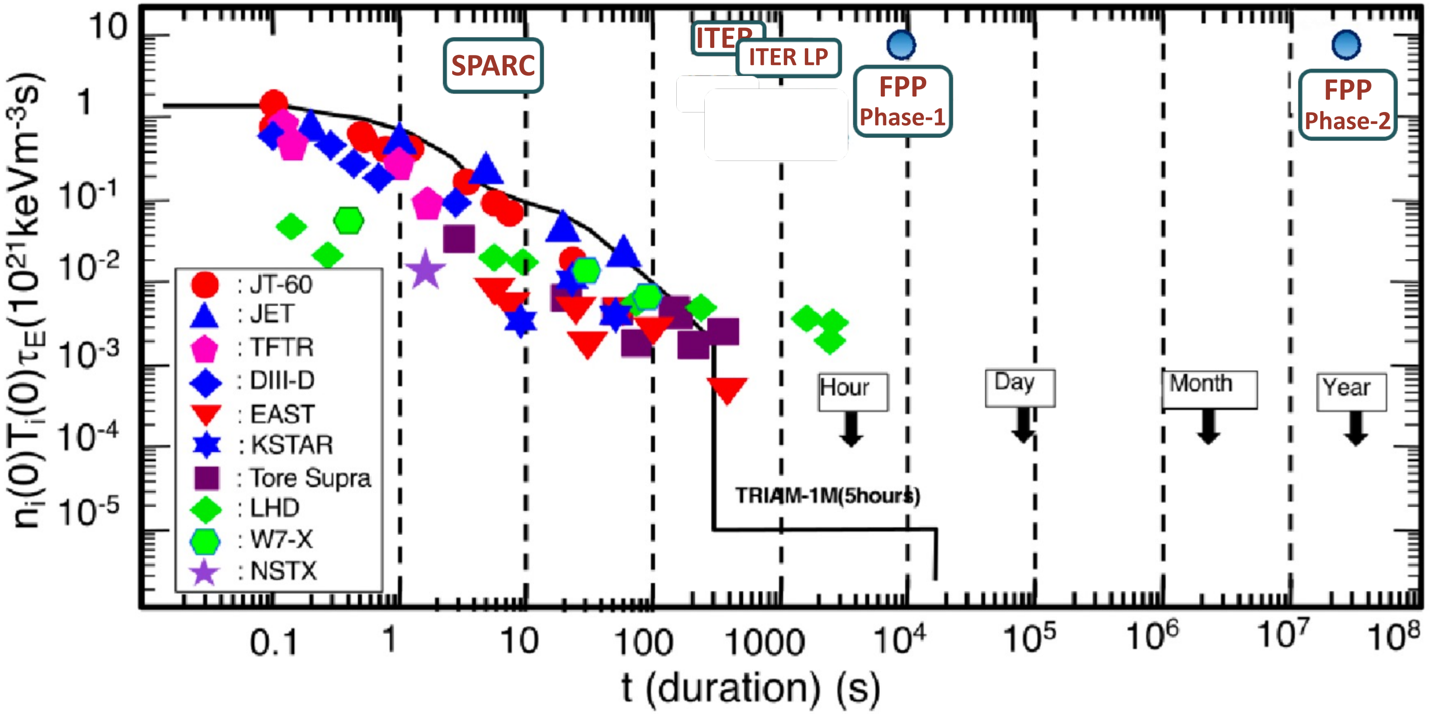
Global Fusion Figures of Merit (FoM) are Impacted as Pulse Duration & Performance Increases

- Multi-machine database of n_i-T_i-τ_E shows performance degradation
  - Attributed to combination of PWI issues and/or auxiliary power coupling

Reduction of n_i-T_i-τ_E with pulse duration does not project to future devices



Adapted from: NASEM Report (2021) "*Bringing Fusion to the U.S. Grid*" doi: 10.17226/25991

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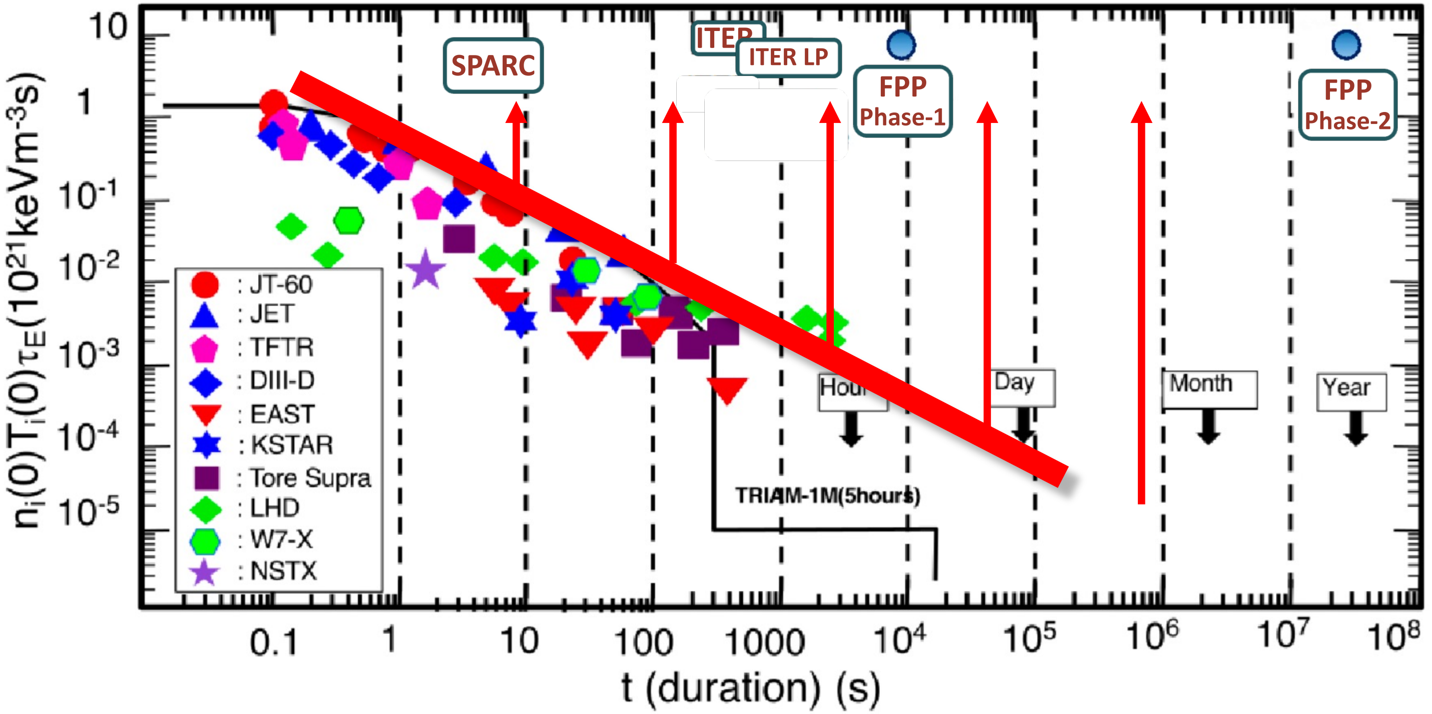

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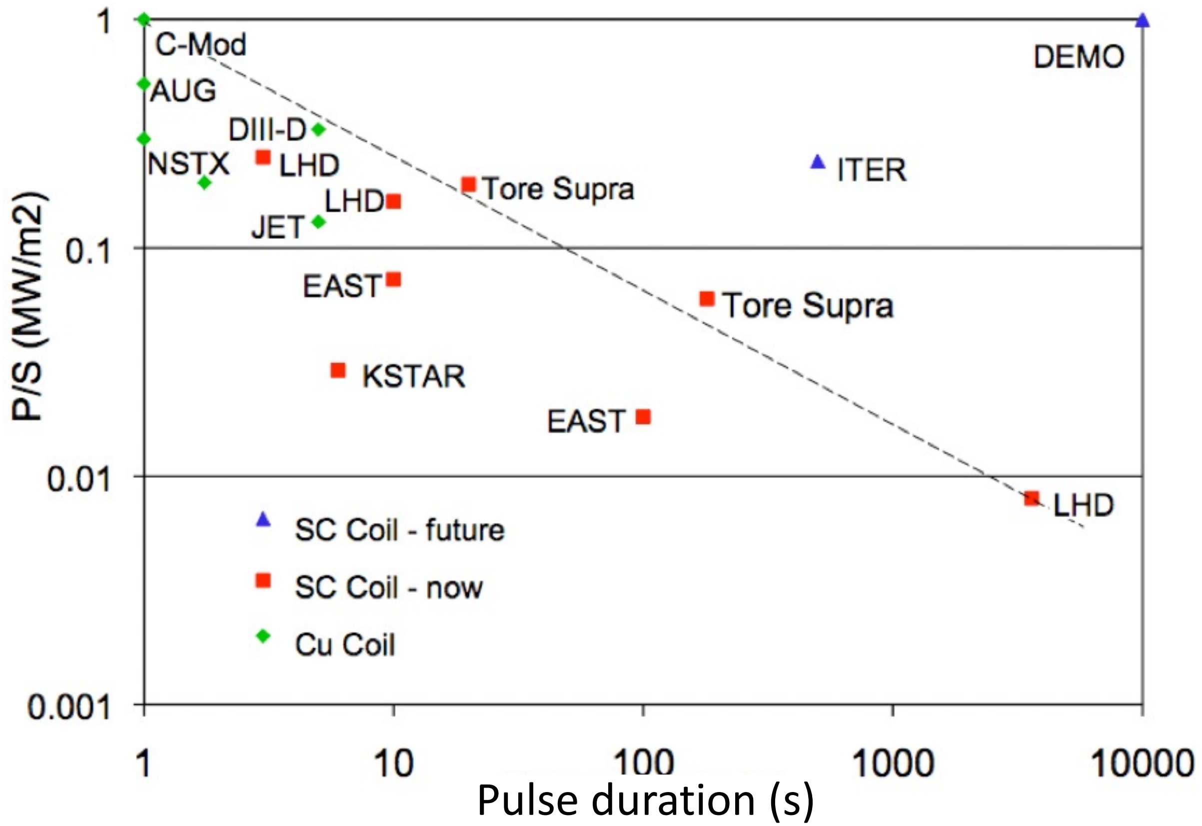
  - P/S proposed for reactor PMI similarity scaling (as opposed to P/R)*

"PMI-scaling" FoM also trends opposite that needed for next-step devices



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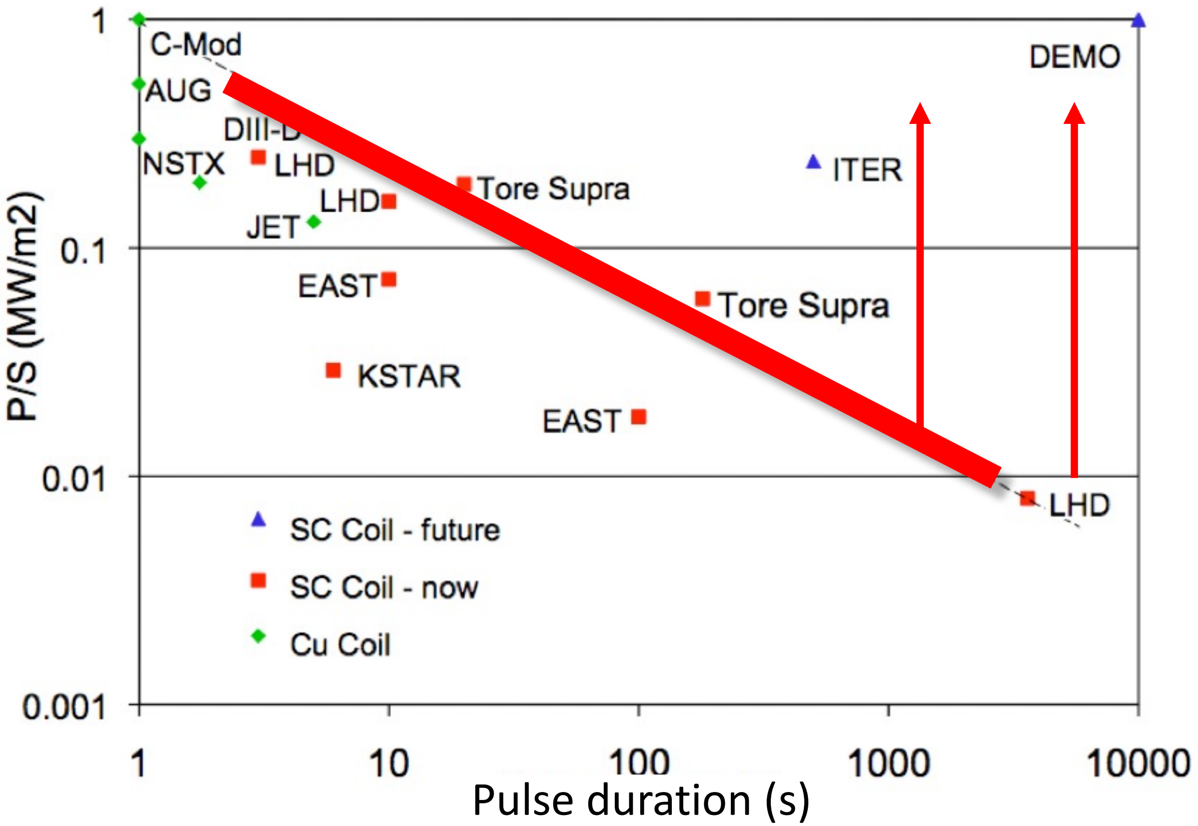

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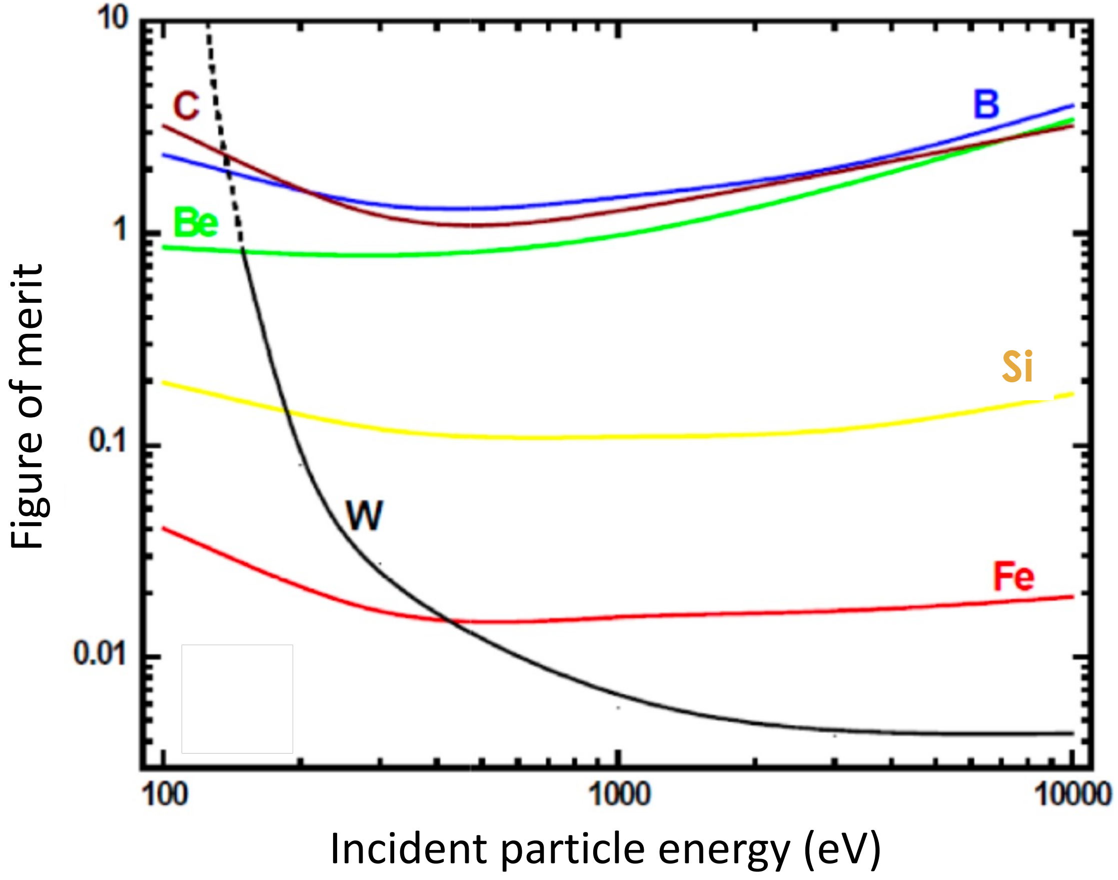
- Wall FoM estimates compatibility of PFM as SOL performance increases**
  - Wall FoM is maximal allowed core concentration over sputter yield

Main wall FoM estimates up to potential reactor charge exchange energies

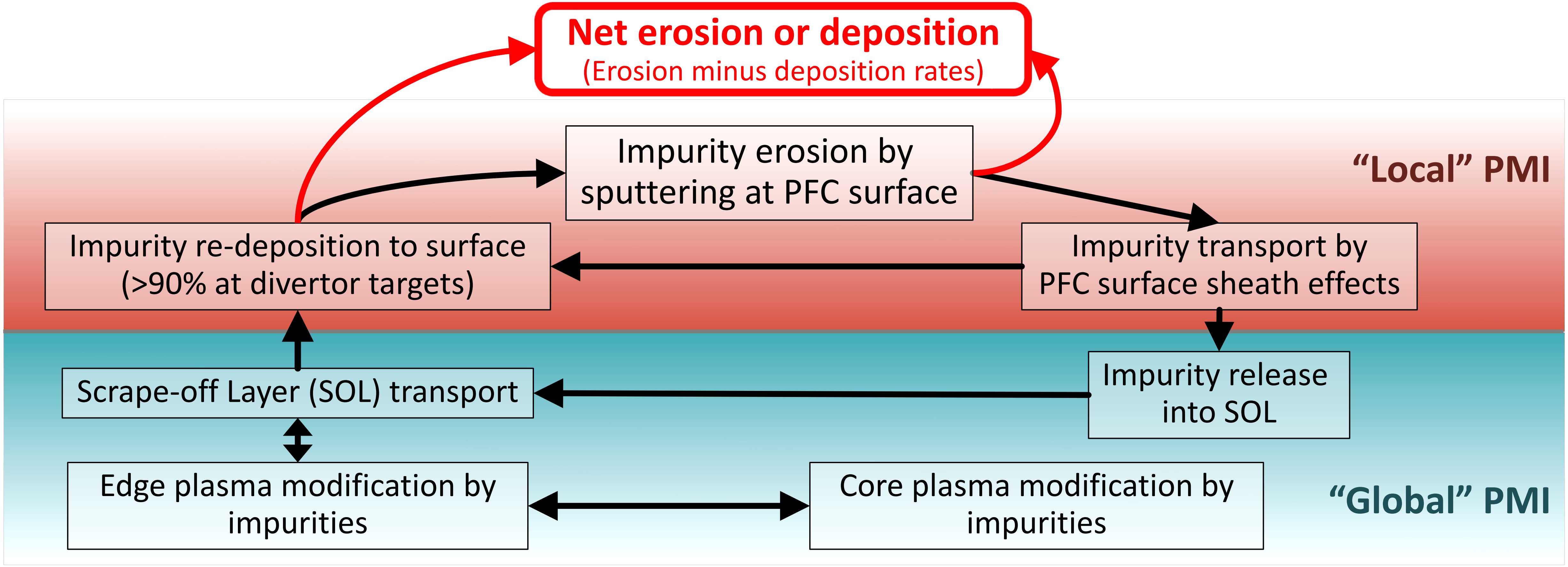


Stangeby et al. (2022) PPFC

*Whyte et al. (2012) FED; LaBombard et al. (2015) Nucl. Fusion **Roth et al. (1990) J. Nucl. Mater.

A Bit of Context: Net Erosion or Deposition Drives Overall PFC Integrity & Depends on Impurity Flux Balance

- Not only important for PFC performance → impacts whole system performance



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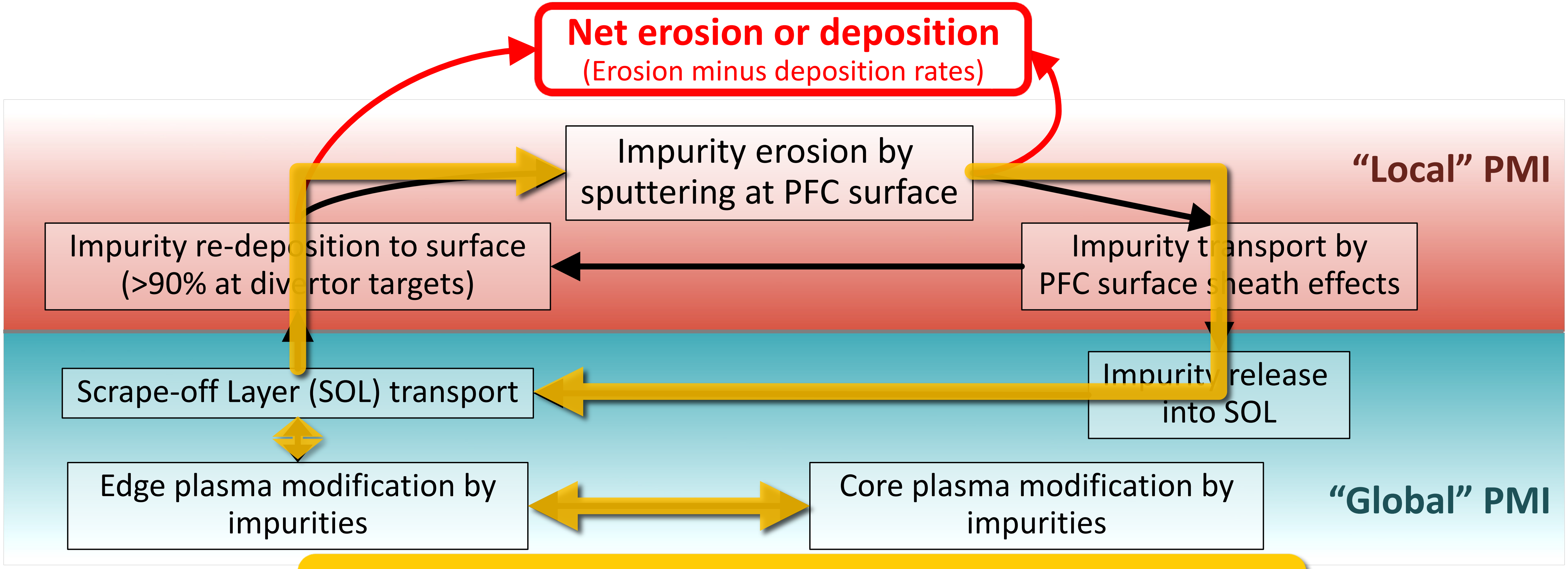
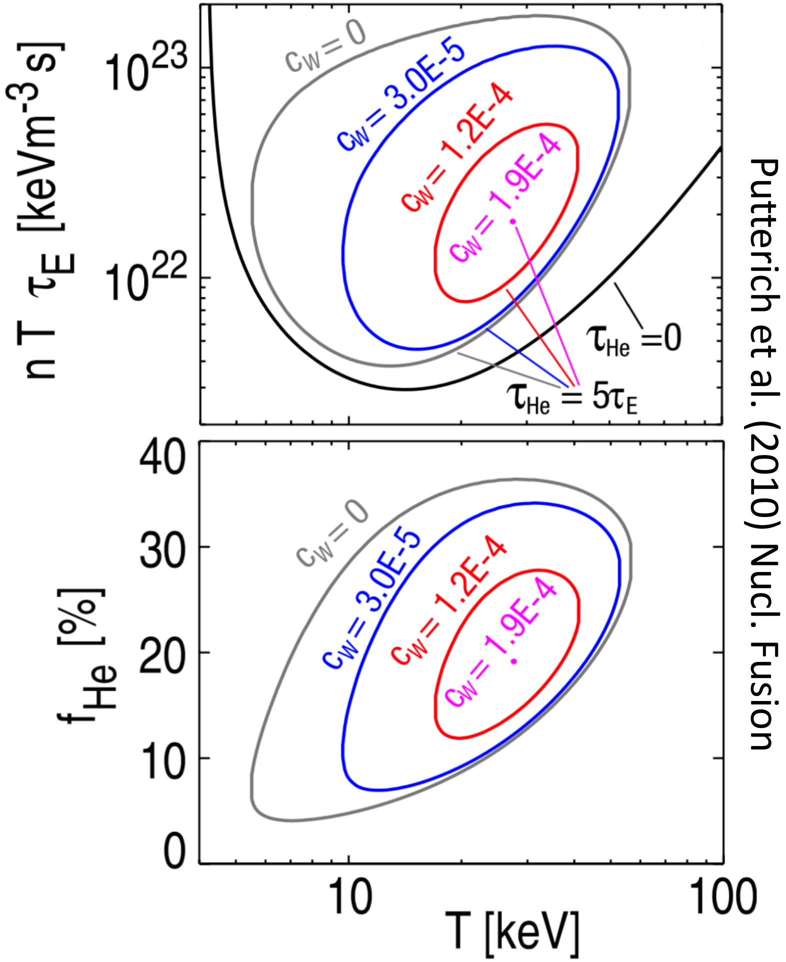


Rough mapping of main path for PWI impurity contamination through key links in "impurity chain"

CORE IMPURITIES WILL LIMIT IDEALIZED IGNITION CONDITIONS

- **Viable ignition operating space collapses quickly, e.g. from impurity-free (D-T only) when including He & W**
  - *Here, c_W (n_W/n_e) ~ low 10^{-5} (~0.001%) range impacts operation + increases minimum-T_i needed*

Ignition curves showing impact of W & He

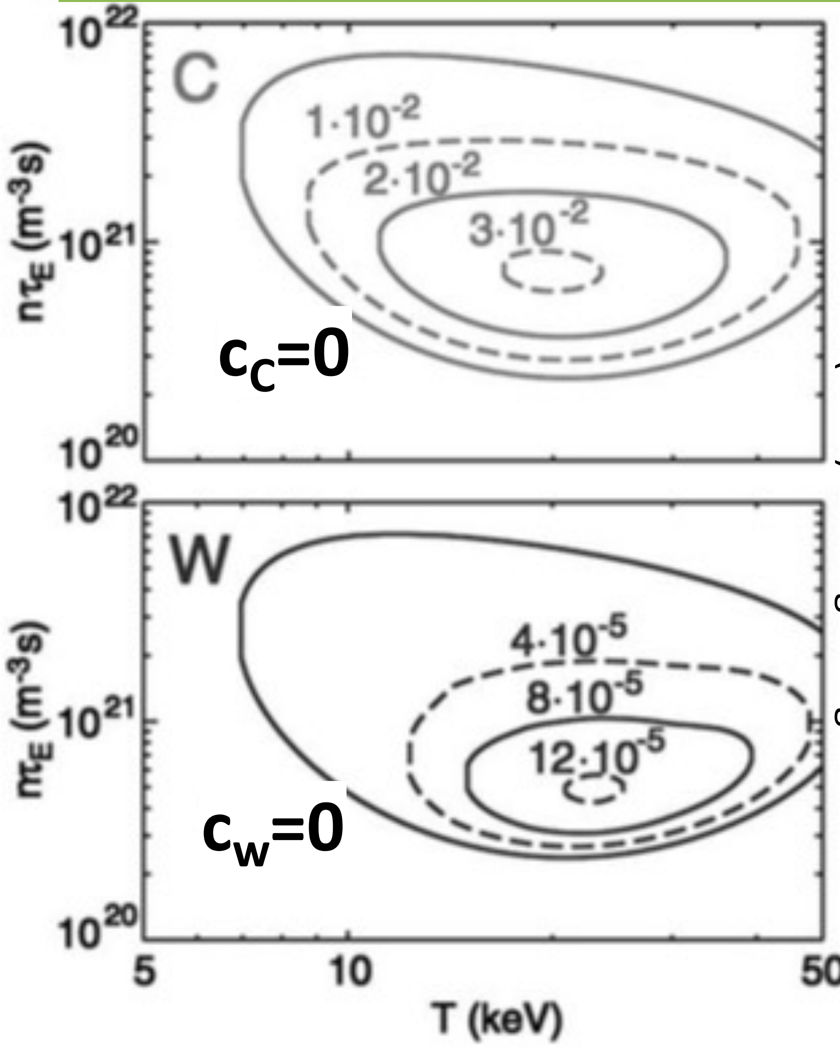


Putterich et al. (2010) Nucl. Fusion

CORE IMPURITIES WILL LIMIT IDEALIZED IGNITION CONDITIONS

Ignition contour differences with Low- vs Hi-Z

- **Viable ignition operating space collapses quickly, e.g. from impurity-free (D-T only) when including He & W**
  - *Here, c_W (n_W/n_e) ~ low 10^{-5} (~0.001%) range impacts operation + increases minimum-T_i needed*
- **Operating space is restricted with any additional impurity**
  - *Although orders of magnitude more can be tolerated with Low-Z (~1%) vs Hi-Z (~0.001%)*



Neu et al. (2003) Fus.Eng. Design

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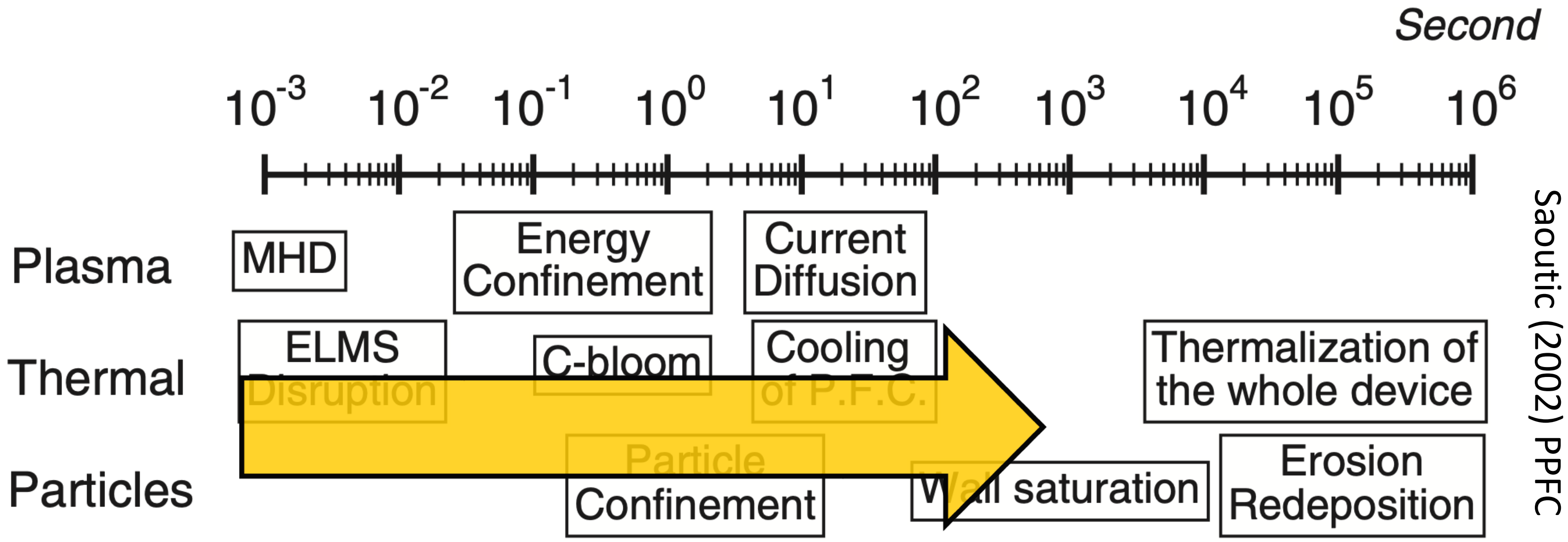

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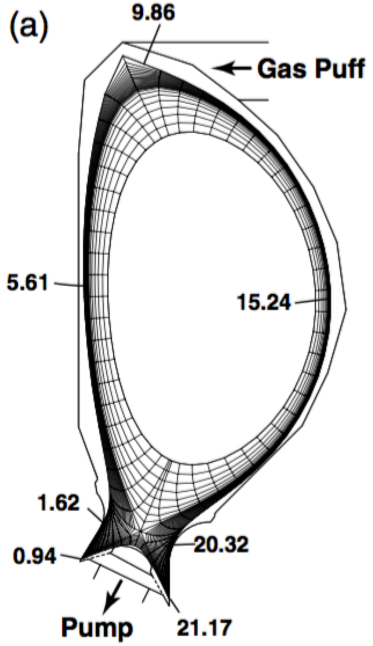
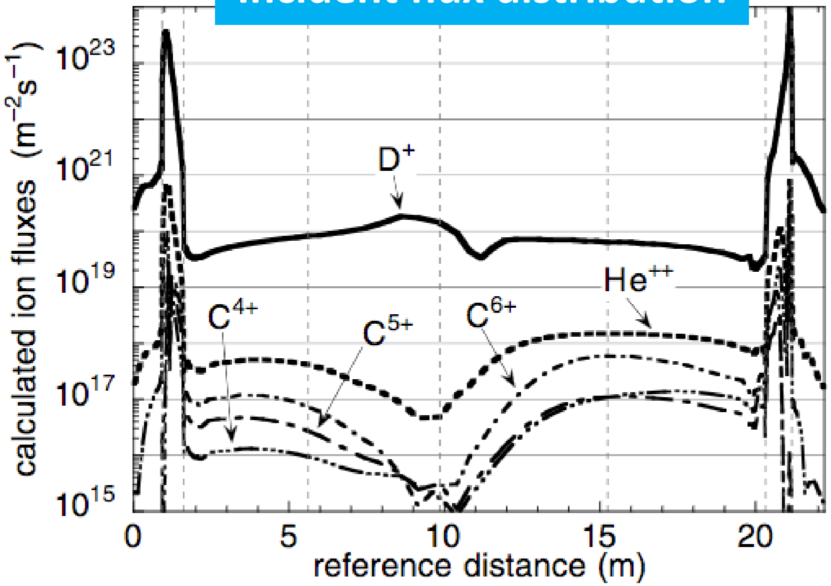
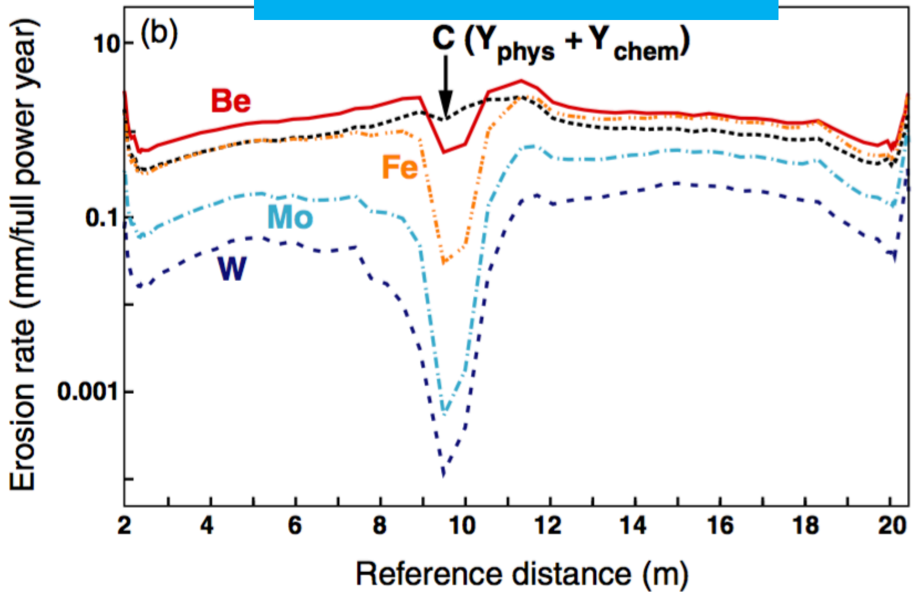
Erosion & Migration Depends on Fluxes to Surfaces That Vary Tremendously by Location

ITER erosion modeling by different incident species on a variety of material surfaces*





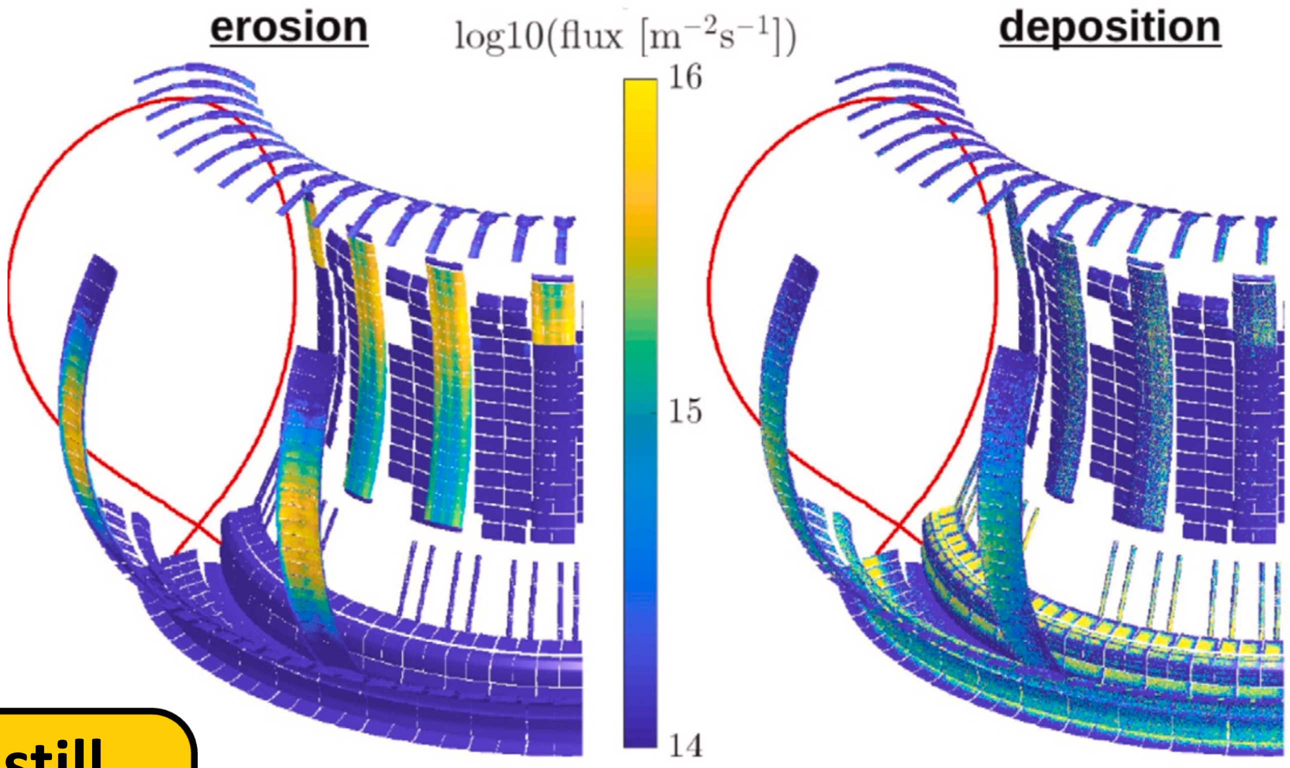


- **Erosion & Migration is:**
  - Multi-dimensional problem in space & time
  - Complicated by wide ranges of magnitudes/energies

*Pitts et al. (2005) PPCF; Behrisch et al. (2003) JNM

PWI 'State-of-the-Art' → Material Migrates from Main Chamber into Divertor Region

ERO2.0 modeling of JET-ILW erosion/migration



Romazanov et al. (2019) NME

- **Both high-Z & low-Z material eventually end up in divertor**
- **Exact nature of re-deposition depends on plasma conditions, divertor geometry, & elemental species**
- **Better diagnosis & model validation still required → quantitative predictive capability**

VOLUME OF MATERIAL ERODED + SLAG BUILD-UP IN NEXT-STEP DEVICES IS MASSIVE

Main Wall Net Erosion Rate Estimates*

(based on c-x neutrals only, no ions + 100% wall coverage)

Device	P_{SOL} [MW]	Yearly duty cycle [%]	Wall Load [TJ/yr]	Net Erosion Rate [kg/yr]		
				Be	C	W
DIII-D	20	3.2×10^{-2}	0.2	**0.13**	**0.08**	**0.16**
EAST	24	0.32	1.6	**1.60**	**0.82**	**1.80**
JT-60SA	34	3.2×10^{-2}	0.22	**0.22**	**0.15**	**0.27**
ITER	100	3.2	100	**29-286**	**44-54**	**17-80**
ST Pilot	50	~32	500	**330**	**190**	**400**
ARC	100	~32	1000	**650**	**370**	**790**
CPP	260	~32	2600	**1.7×10^{3}**	**1.0×10^{3}**	**2.0×10^{3}**
CFETR	1000	38	12000	**7.8×10^{3}**	**4.4×10^{3}**	**9.5×10^{3}**
Reactor	400	79	10000	**$6.5\text{-}21\times10^{3}$**	**3.7×10^{3}**	**$5\text{-}7.9\times10^{3}$**

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Current Device Estimates (DIII-D, EAST, JT-60SA)

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Volume of Material Eroded + Slag Build-up in Next-step Devices is Massive

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3+ decade increase from current levels!

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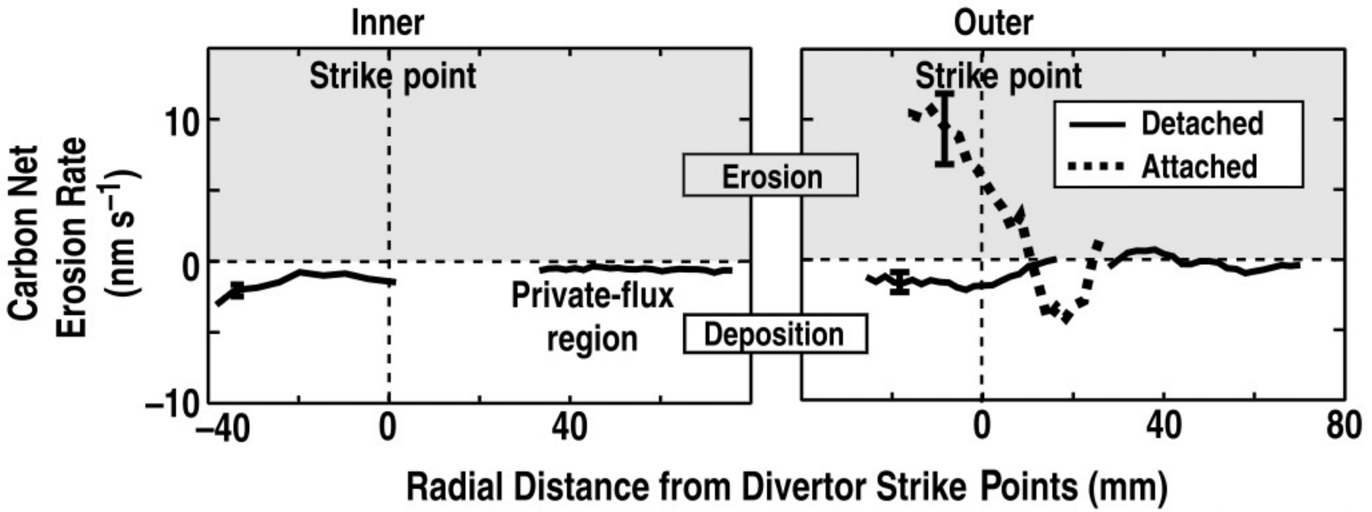
MATERIAL MIGRATION PATH LEADS TO LARGE DEPOSITS ON & NEAR DIVERTOR TARGETS

- **Detached divertor targets enhance material deposition build-up**

DIII-D divertor target net erosion rate changes to net deposition with detached conditions

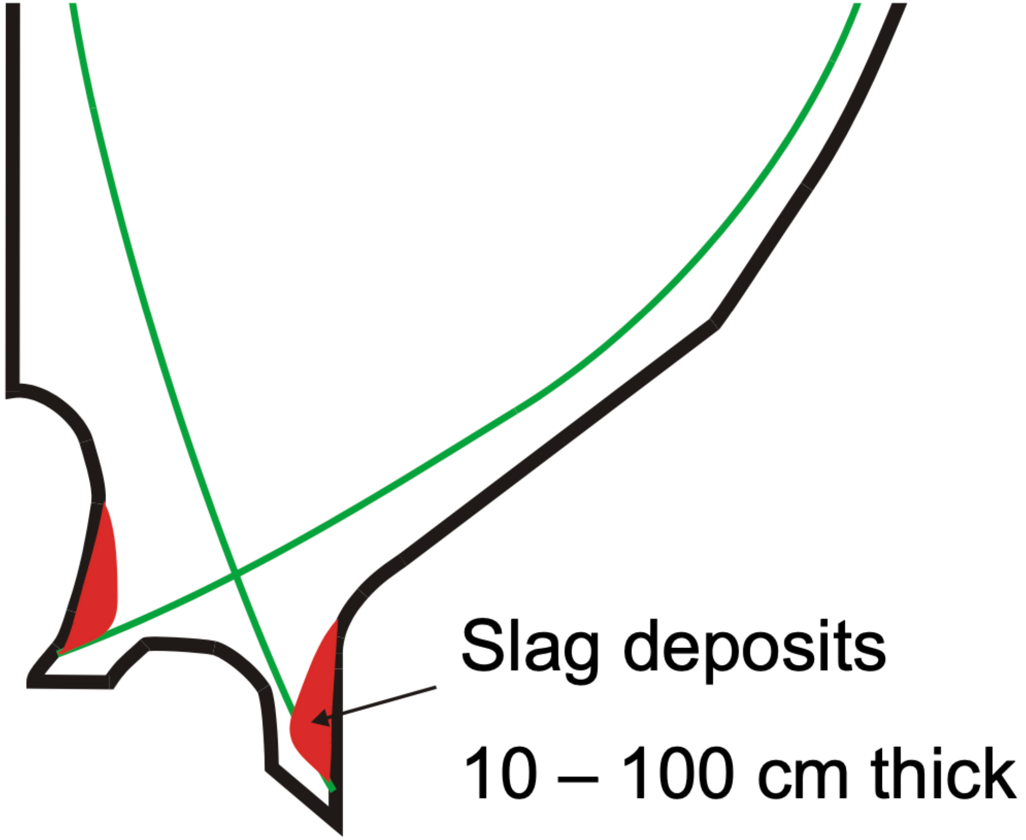


Whyte et al. (2005) Fus. Sci. Tech.

Material Migration Path Leads to Large Deposits On & Near Divertor Targets

If untreated, deposits could reach up to 10's cm thick for 1-year operation

- **Detached divertor targets enhance material deposition build-up**
- **Beginning with FPPs on to Reactors, volume of material depositing will be significant at critical target locations**
- **Large material deposition creates concern for:**
  - Tritium co-deposition
  - Delamination/UFO → disruptions
  - Dust production → explosive hazard



*Courtesy of J.W. Davis

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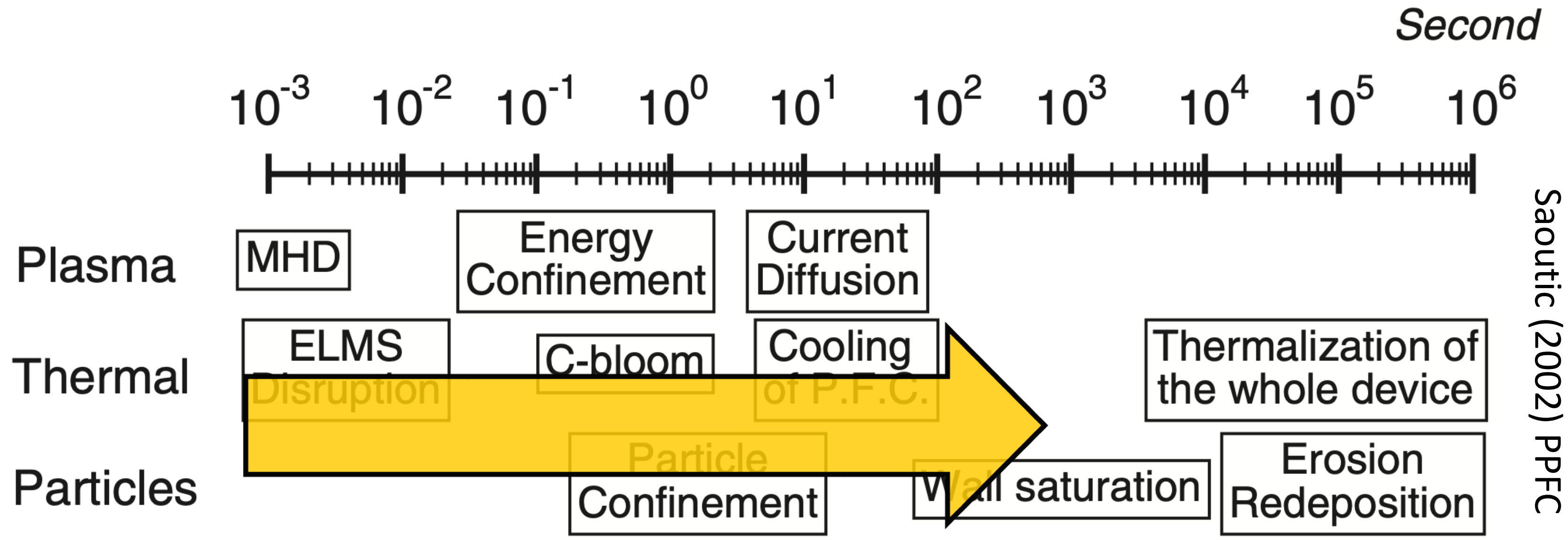

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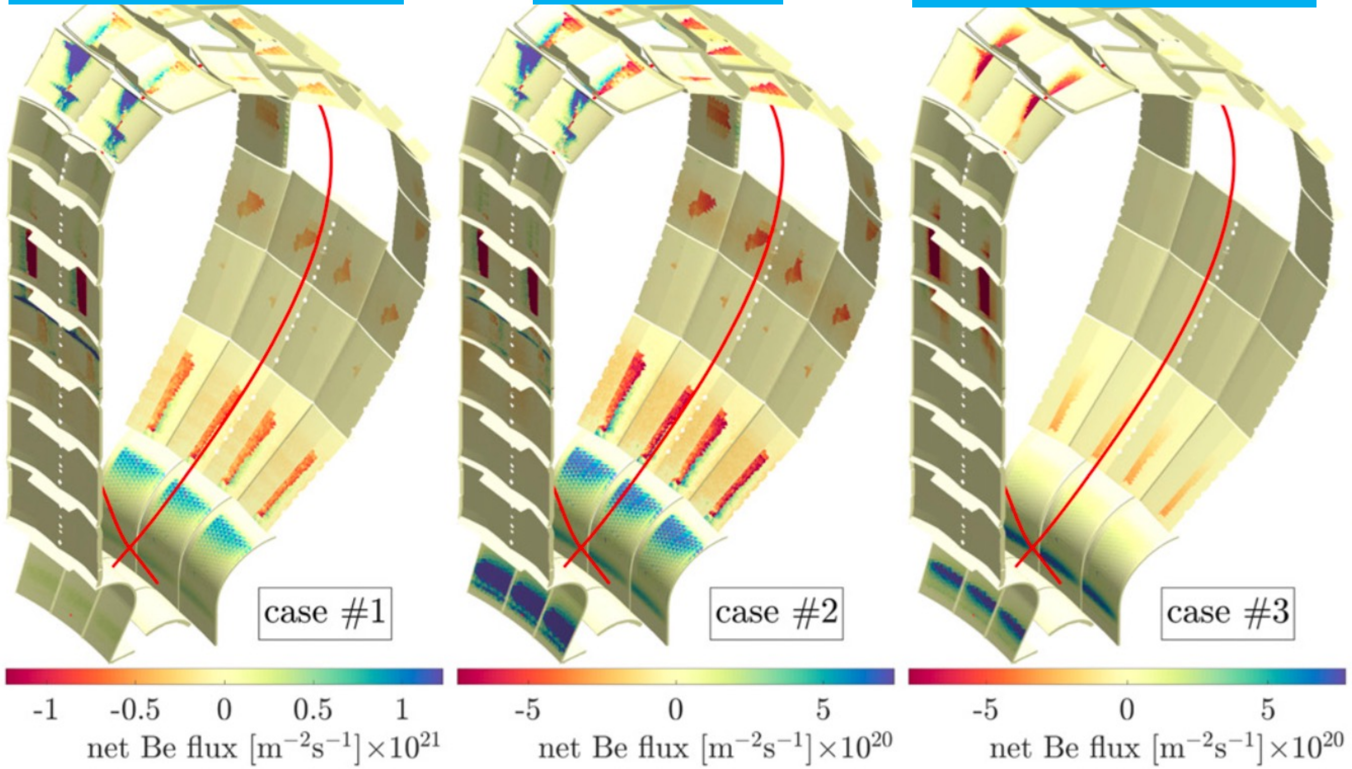
Uncertainty in Far-SOL Conditions Complicates Estimates of Deposition Amounts

- **Background plasma conditions are a key driver of main wall erosion**

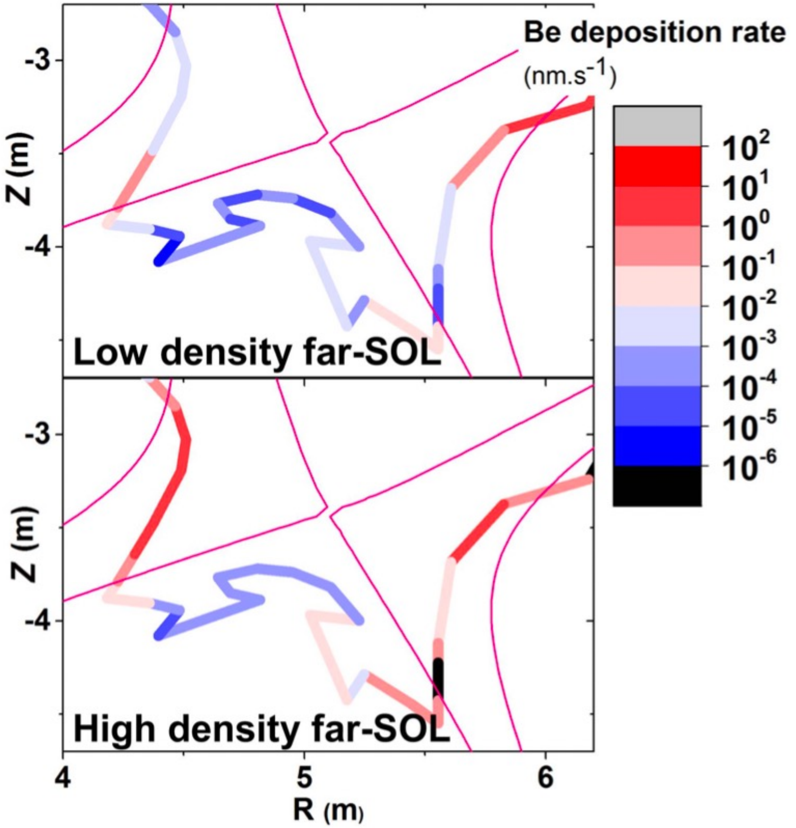
ITER ERO2.0 modeling of Be migration

Low-density far-SOL | + SOL Flows | High-density far-SOL



Romazanov et al. (2022) Nucl. Fusion

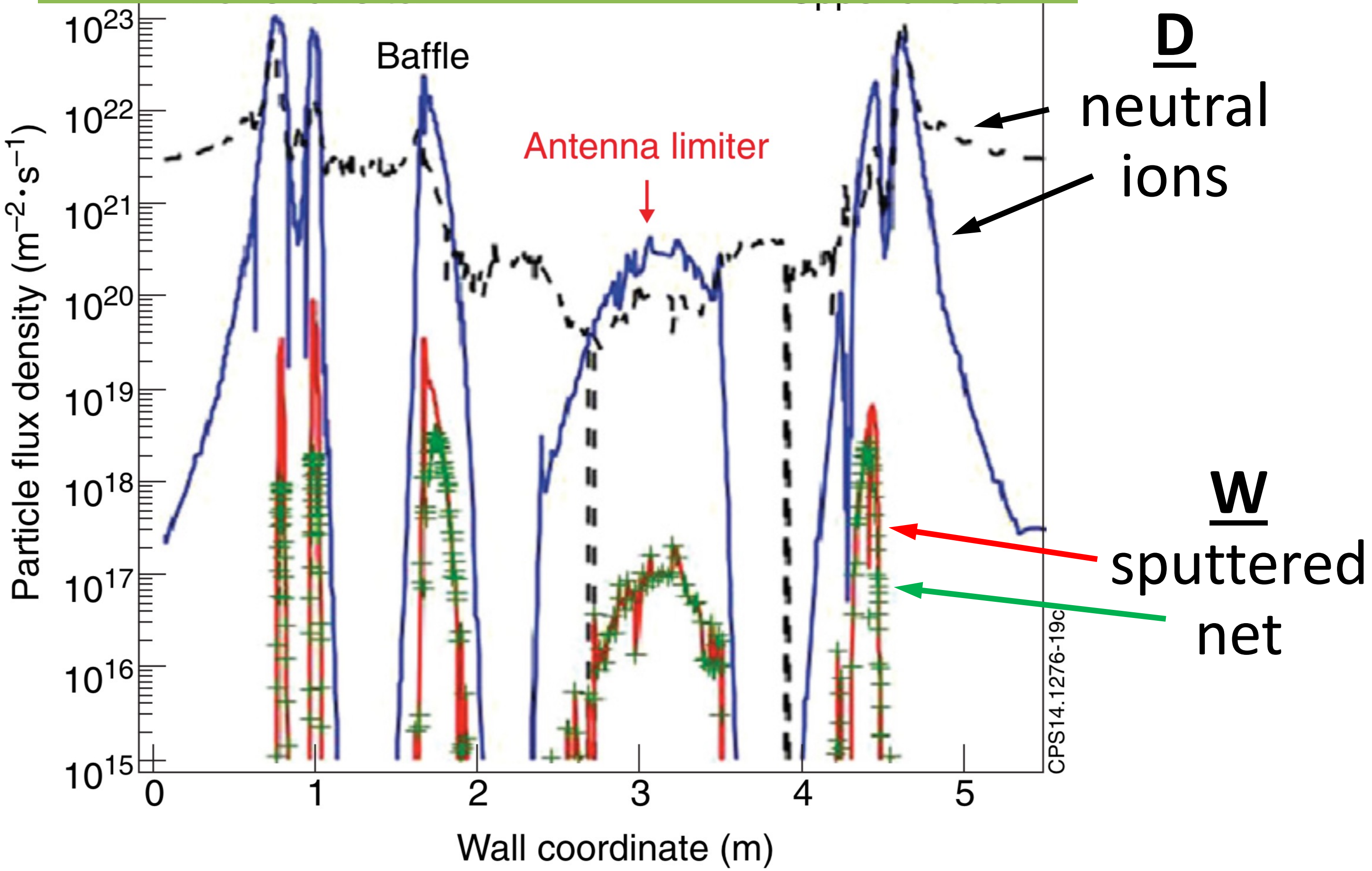
WallDYN deposition prediction



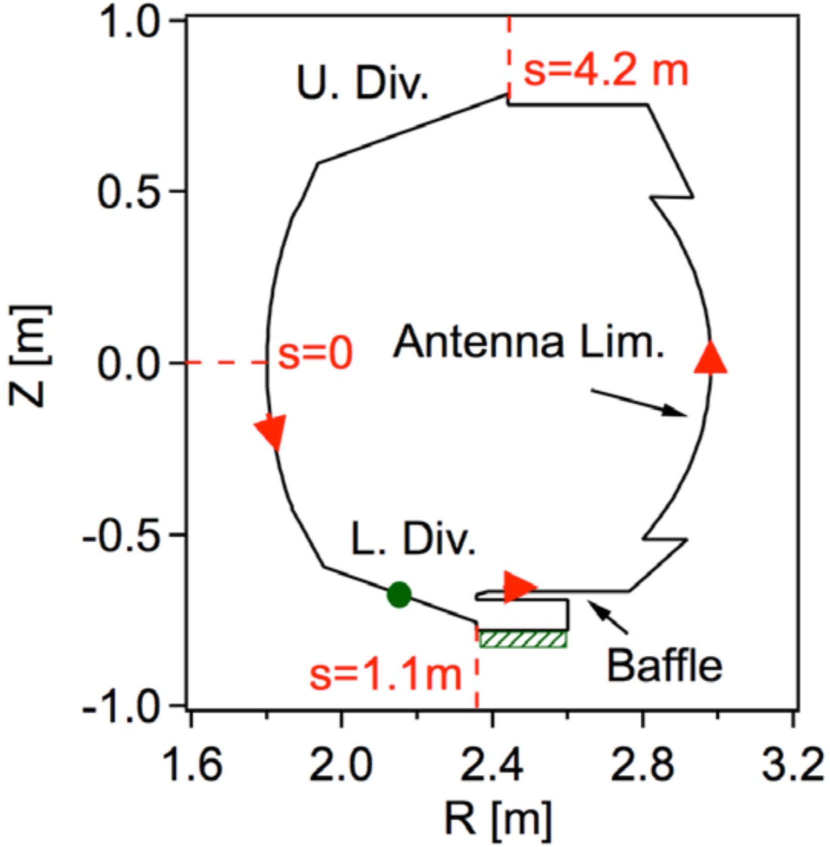
deTemmerman et al. (2018) PPCF

PFC Wear Predicted to be Highly Non-uniform &, Again, Dependent on Poloidally Varying Incident Fluxes (1/2)

Steady-state simulation of D & W fluxes to WEST PFCs*



Wall coordinate

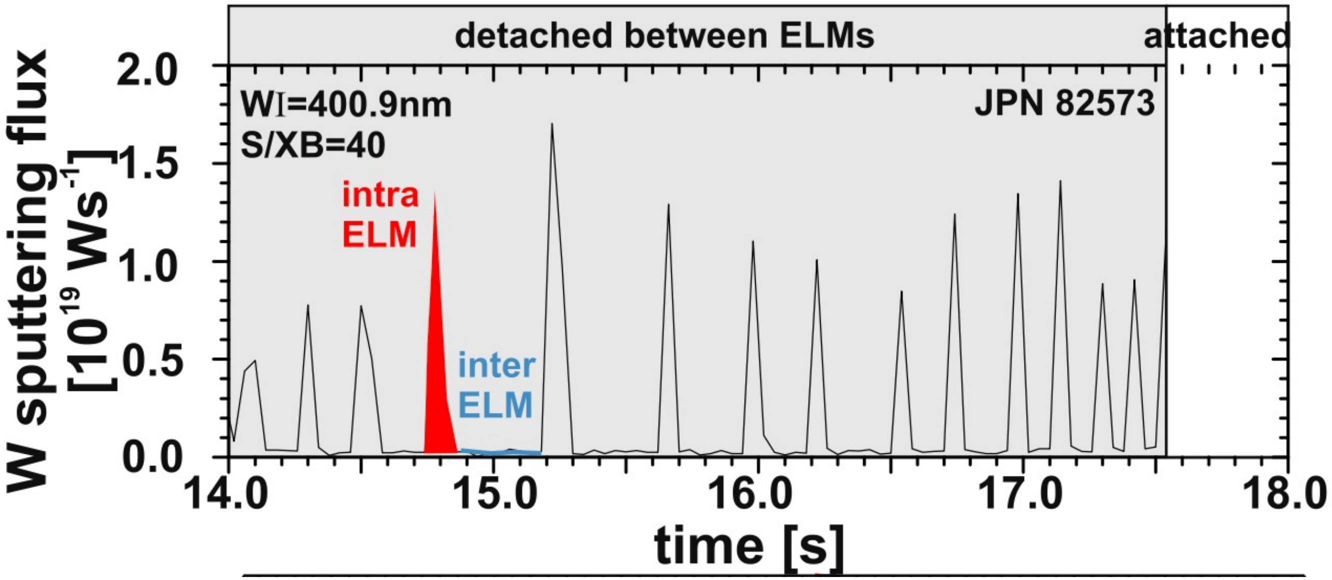


*Bourdelle et al. (2015) Nucl. Fusion

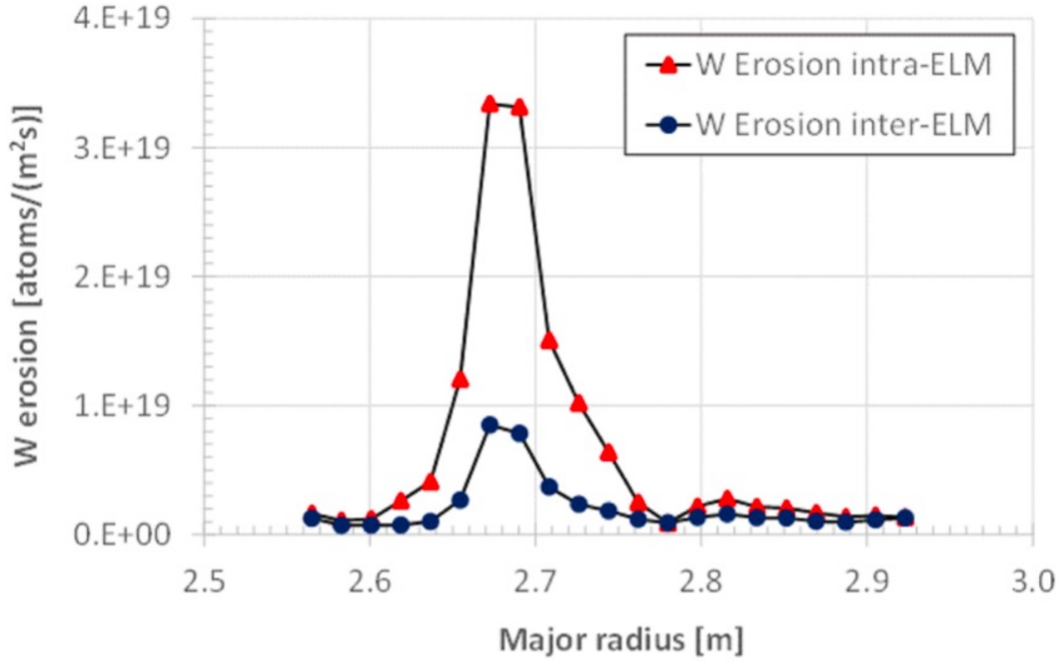
PFC Wear Predicted to be Highly Non-uniform &, Again, Dependent on Varying Incident Fluxes (2/2)

Transients (ELMs) complicate net erosion

JET-ILW outer divertor target W sputtering*



Simulated erosion profiles of JET-ILW outer divertor target**



*Brezinsek et al. (2015) J. Nucl. Mater. **Kirschner et al. (2019) NME

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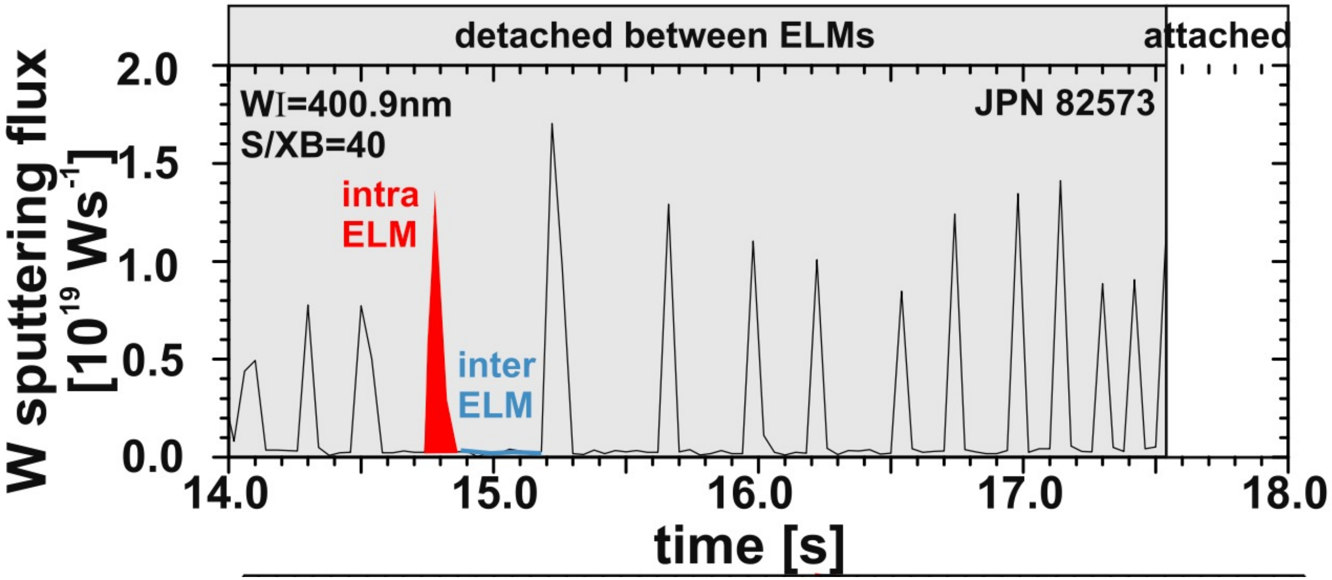

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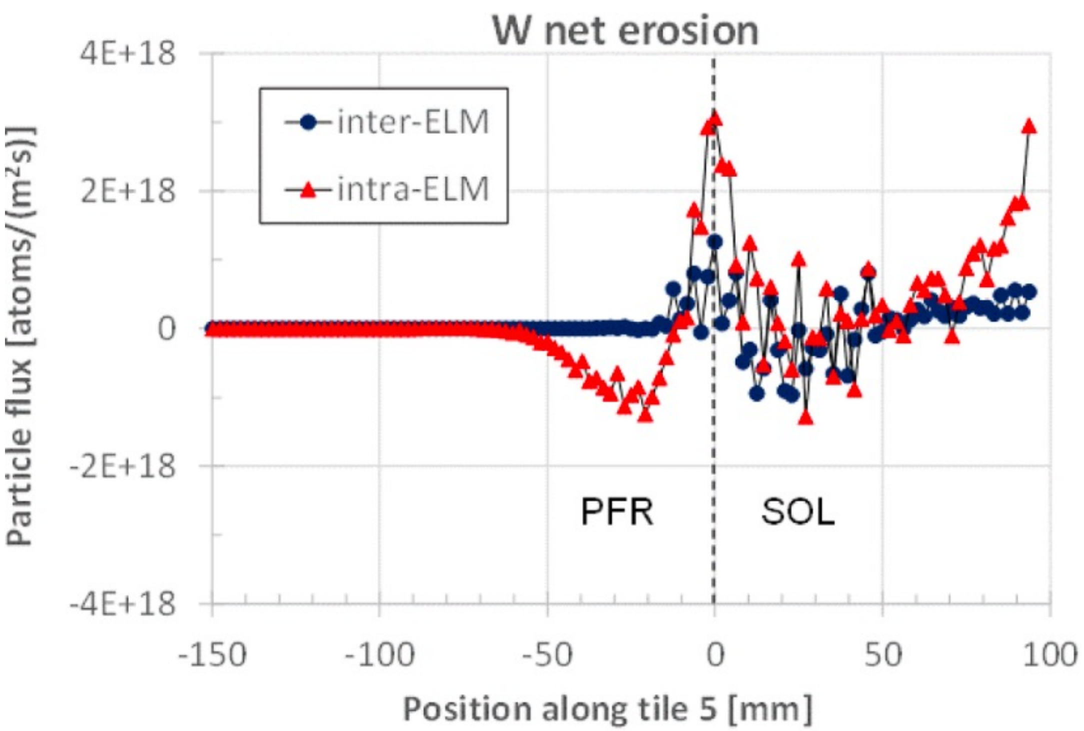
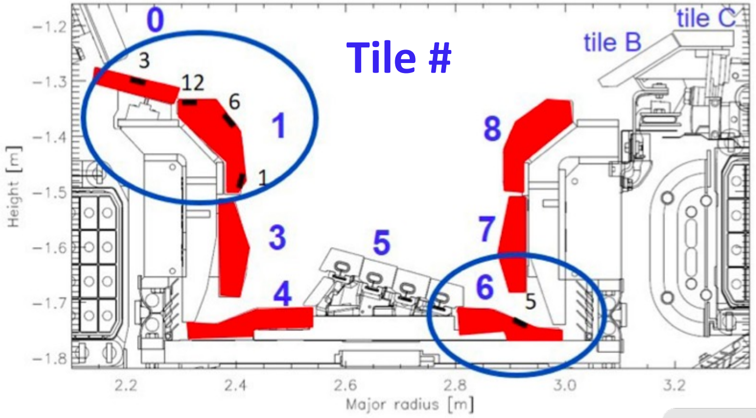


*Brezinsek et al. (2015) J. Nucl. Mater. **Kirschner et al. (2019) NME

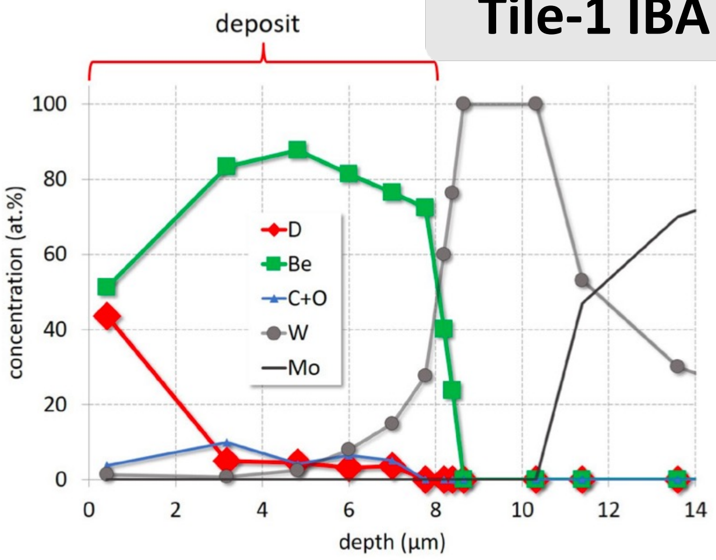
CURRENT DEVICES SHOW SIGNIFICANT REDEPOSITED LAYERS IN DIVERTOR (1/2) → SLAG IS REAL!

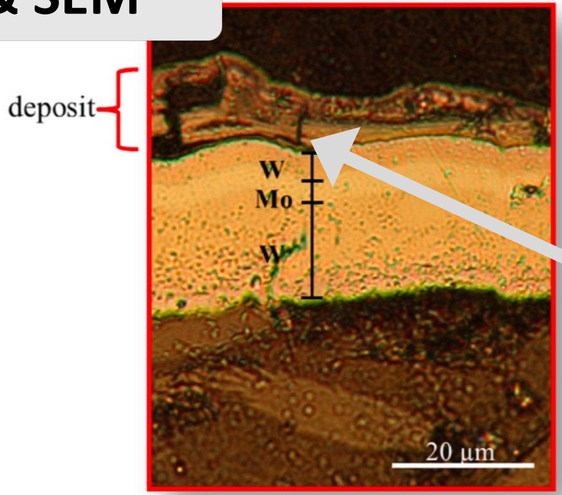
JET ITER-like Wall (ILW) has resulted in thick Be deposition layers



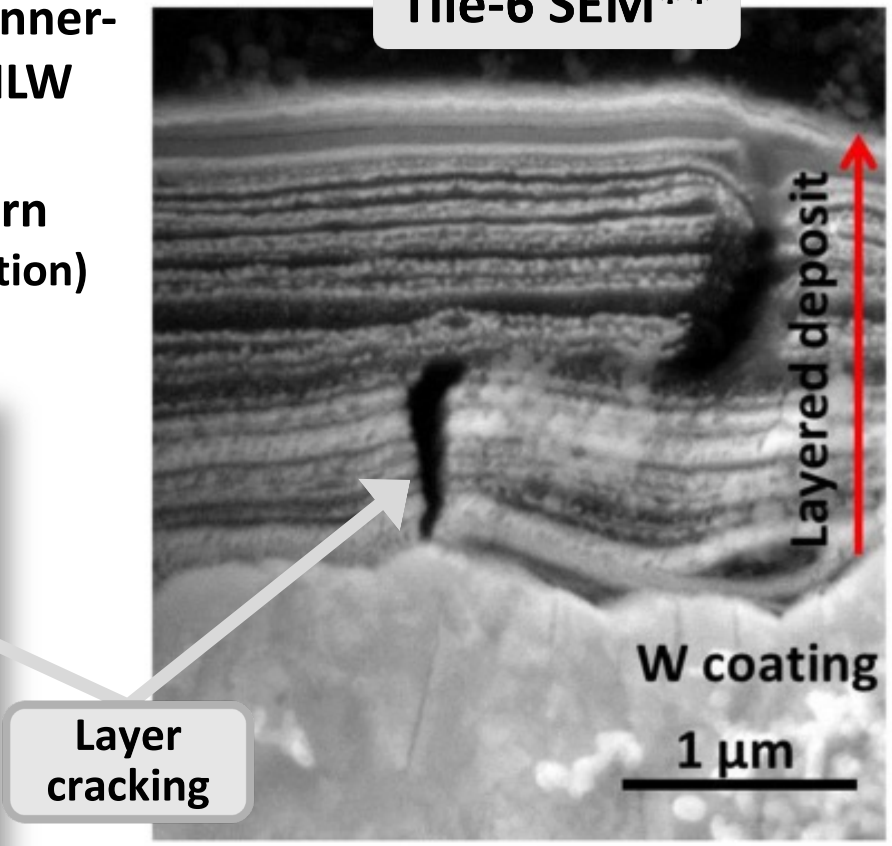
- **Similar to JET-C redeposits but inner-leg shelf more prominent with ILW**
- **Stability of these layers a concern (delamination + dust/UFOs production)**

Tile-1 IBA & SEM*





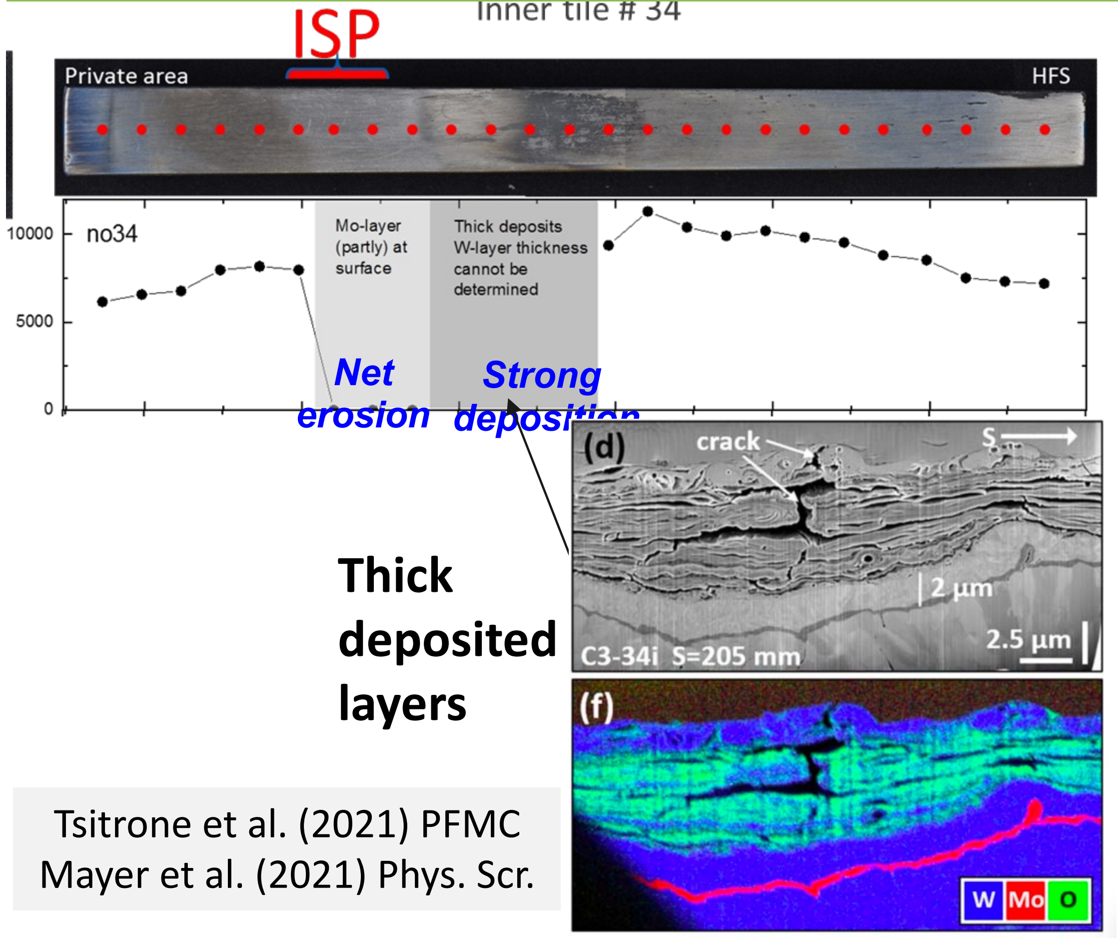
Tile-6 SEM**



*Heinola et al. (2017) Nucl. Fusion **Widdowson et al. (2017) Nucl. Fusion

CURRENT DEVICES SHOW SIGNIFICANT REDEPOSITED LAYERS IN DIVERTOR (2/2) → SURFACE MORPHOLOGY IMPLICATIONS FOR W PMI

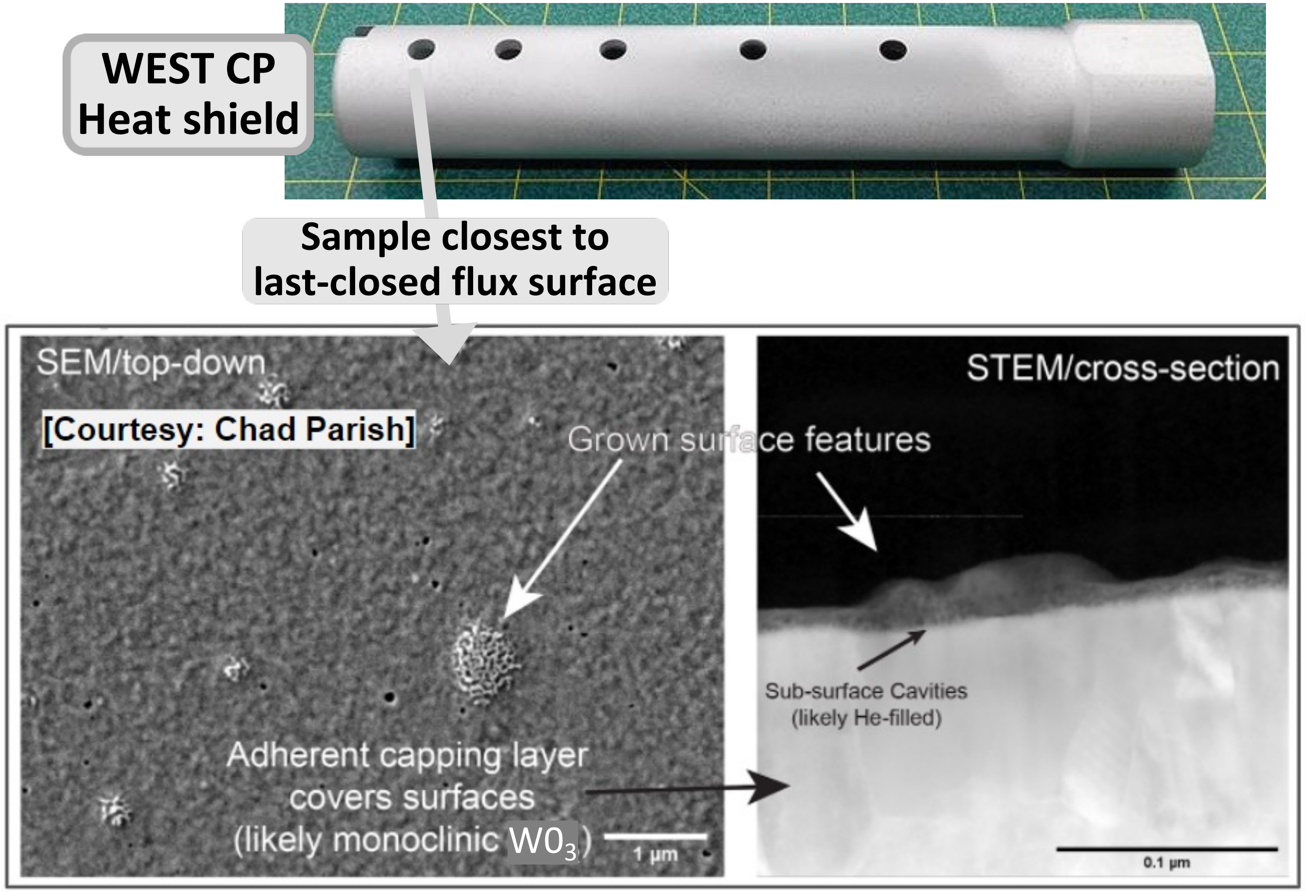
Formation of large/thick oxygen-rich deposition regions on WEST inner target PFCs



Thick deposited layers

Tsitrone et al. (2021) PFMC
Mayer et al. (2021) Phys. Scr.

Trapping of He between WO_3 surface layer & single-crystal W substrate



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Current Devices Show Significant Redeposited Layers in Divertor (2/2) → Surface Morphology Implications for W PMI

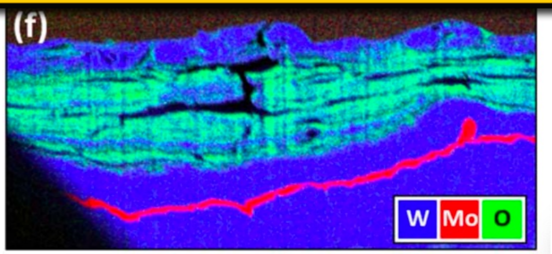
Formation of large/thick oxygen-rich deposition

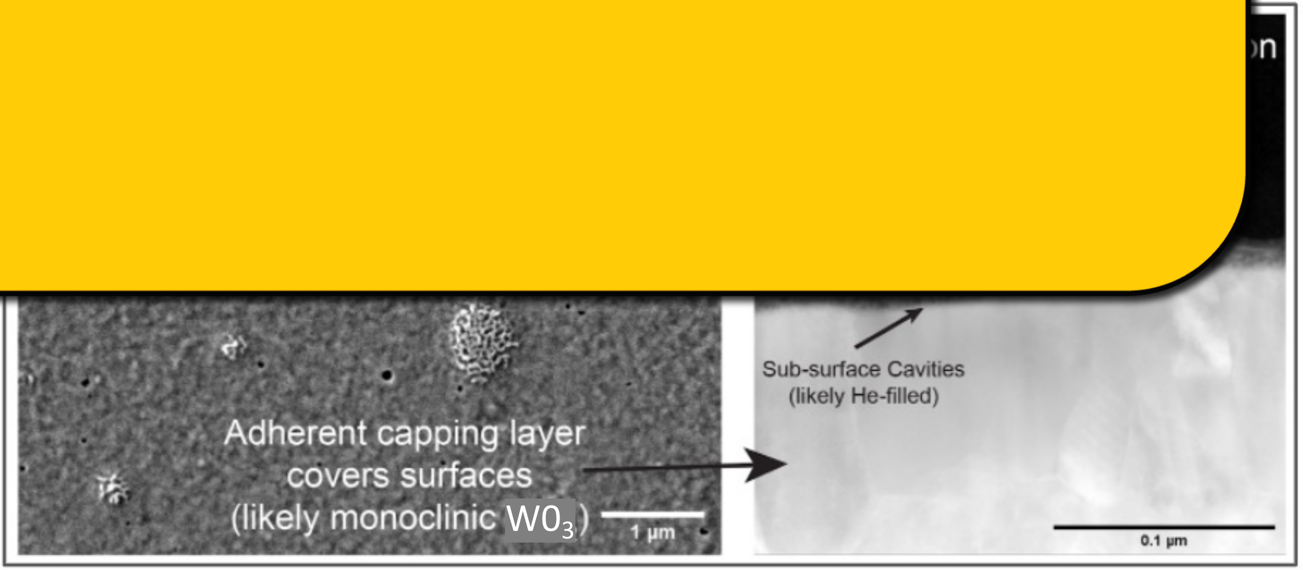
Trapping of He between WO_3 surface layer &

Such surface morphology issues are key mechanisms in T-retention and dust/UFO formation

layers

Tsitrone et al. PFMC (2021)
Mayer et al. Phys.Scri. (2021)





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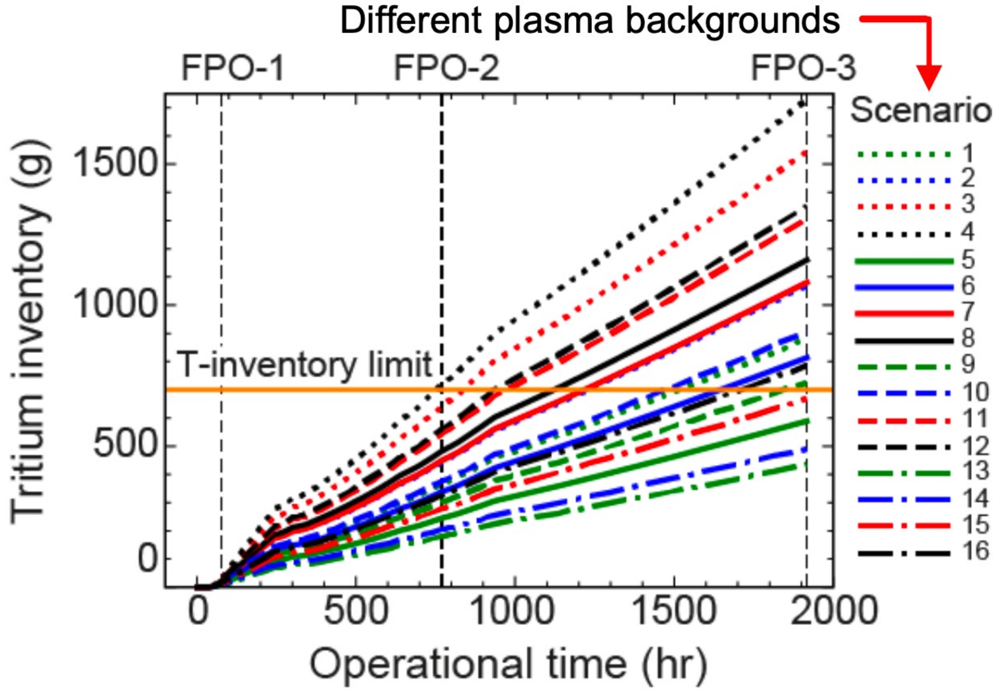
REDEPOSITED LAYERS IN DIVERTOR REGION → TRITIUM RETENTION CONTINUES TO BE A MAJOR CONCERN & UNCERTAINTY FOR NEXT-STEP DEVICES

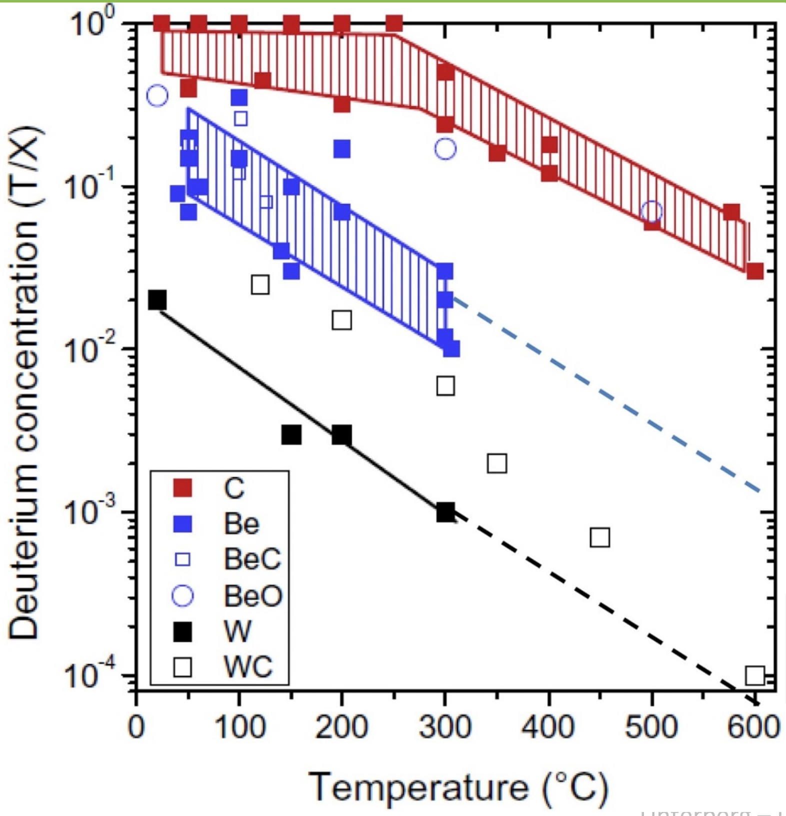
- **Multiple (highly uncertain) factors contribute to deposition & removal of T**

ITER modeling showing variability of T retention based on details of background plasma



Courtesy of R. Pitts et al., PSI (2022)

Removal of hydrogenic species in relevant slag layers is highly temperature dependent



Doerner et al. (2019) NME

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Summary: Device Walls & Plasma-wall Interactions (PWI) are More/Most Relevant at Long Time-scales/Pulse-length

Implications for/on:

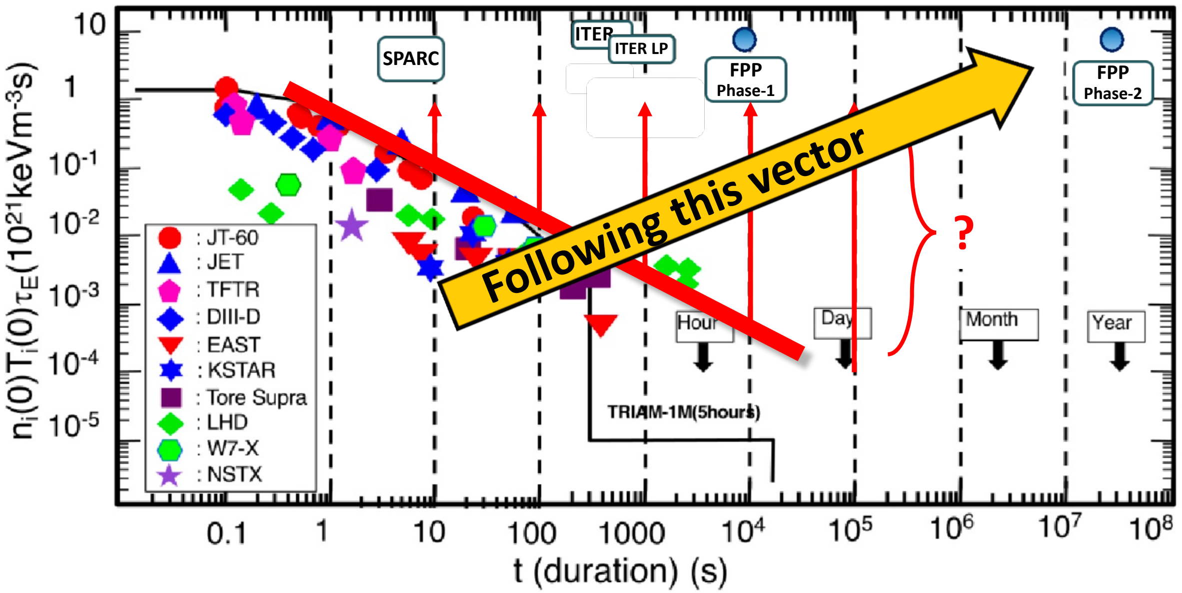
- Global figure(s) of merit, e.g., n_i-T_i-$\boldsymbol{\tau}_E$, P/S, Wall FOM
  - *Operating space is restricted with any additional impurity + PFC performance limited*
- Thick redeposits (slag) in critical areas of tokamaks due to high fluences
  - *Beginning with FPPs, deposited material at critical target locations will be significant*
- Present-day, open research topics → pathway to predictive capability for next-step devices
  - *Better diagnosis & model validation (predictive capability) still required*
  - *Slag creates concern for: T co-deposition; Delamination/UFOs → disruptions; Dust production → explosive hazard*

Backups

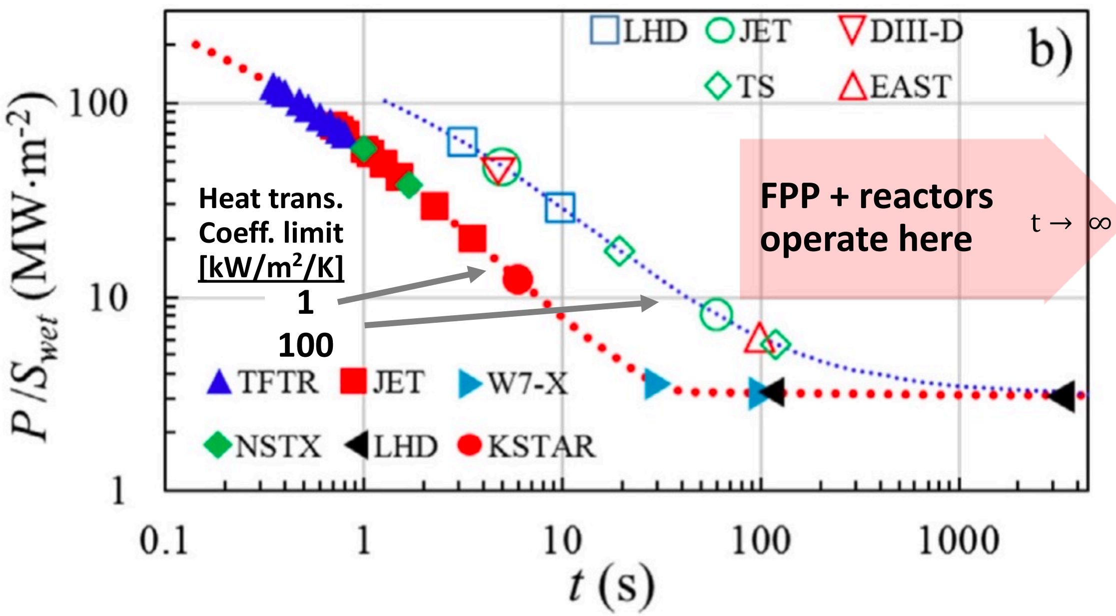
- .

SOME FINAL CONSIDERATIONS: MAJOR ROAD-BLOCK (SHOW-STOPPER!) IS CONTROLLING WALL HEAT FLUX HANDLING FOR LONG PERIODS

Progress toward fusion pilot plant (FPP) means extending pulse length



Limit to fusion devices to-date is critical heat flux in infinite slab & T_{crit} ~2300K

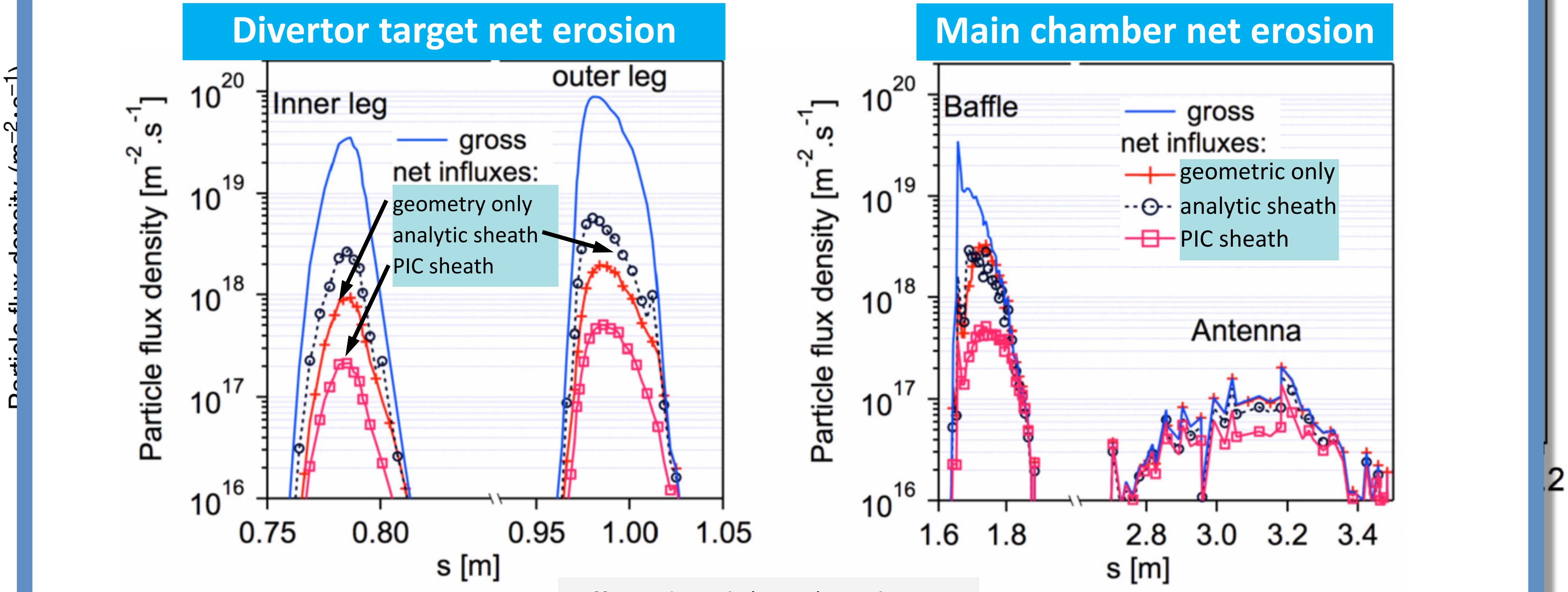


Kuteev & Sergeev (2020) Nucl. Fusion

- **Historically, tokamaks have been limited in area power flux density (P/S) → next step devices with need sustained high-P/S**
- **New paradigms for PFC design → give high TRL options**

PFC Wear Predicted to be Highly Non-uniform &, Again, Dependent on Poloidally Varying Incident Fluxes

Validation of W net erosion & migration models needed due to large uncertainties in calculations



Bufferand et al. (2015) Nucl. Fusion

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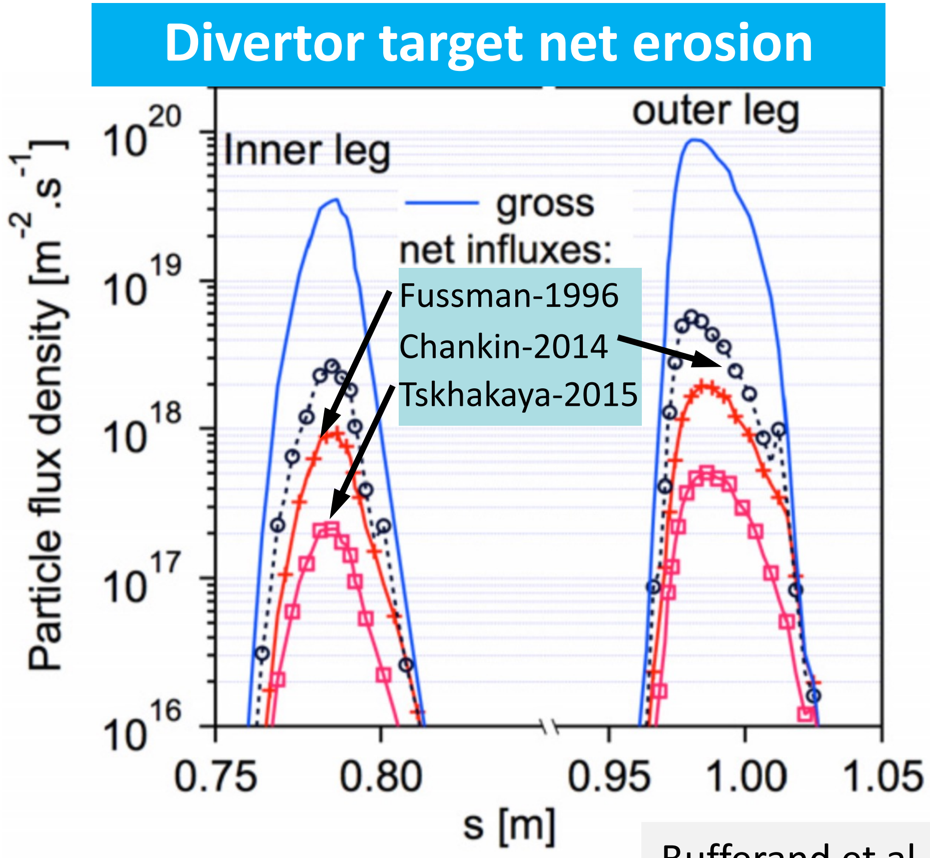

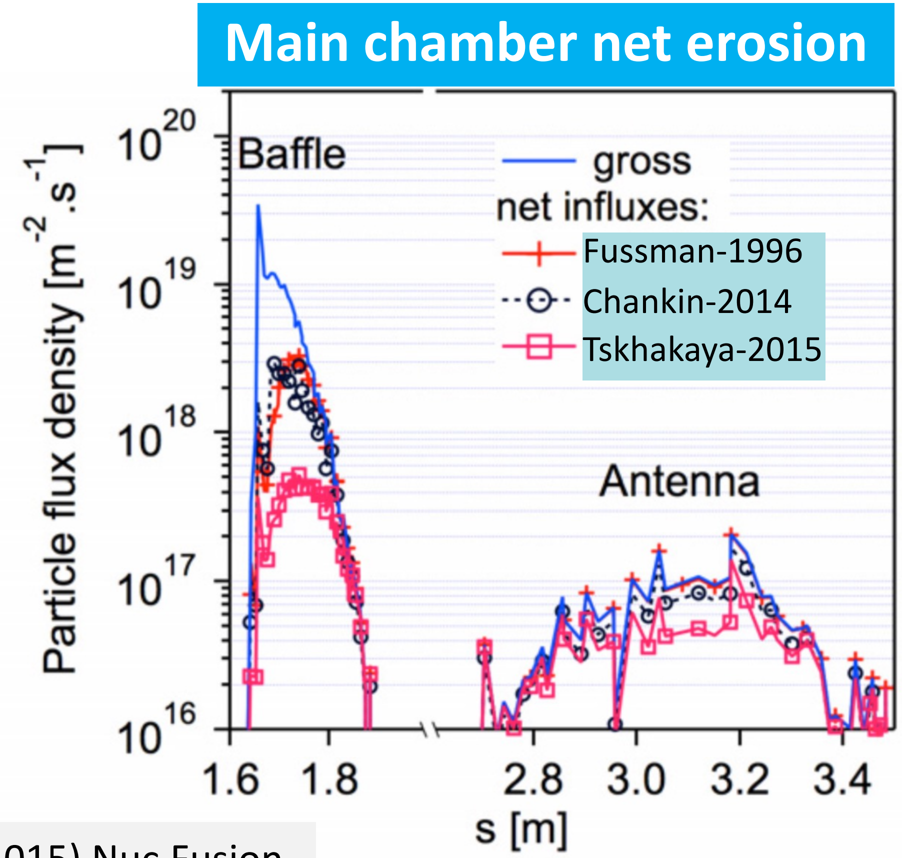

Bufferand et al. (2015) Nuc.Fusion

THIS MATERIAL MIGRATION PATH LEADS TO LARGE DEPOSITS AROUND DIVERTOR TARGETS

- **Detached conditions at targets compound material deposition condition**

DIII-D divertor target material migration summary