PMI Breakout Group Debrief

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DIII-D New Wall Community Workshop June 12-13 2024

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Outline

- **Breakout Group Talks**
    - Adam Vaughan (Dauntless.io)
    - Aritra De (ORAU)
    - Daniel Andruczyk (UIUC)
    - Peter Stangeby (U. Toronto)

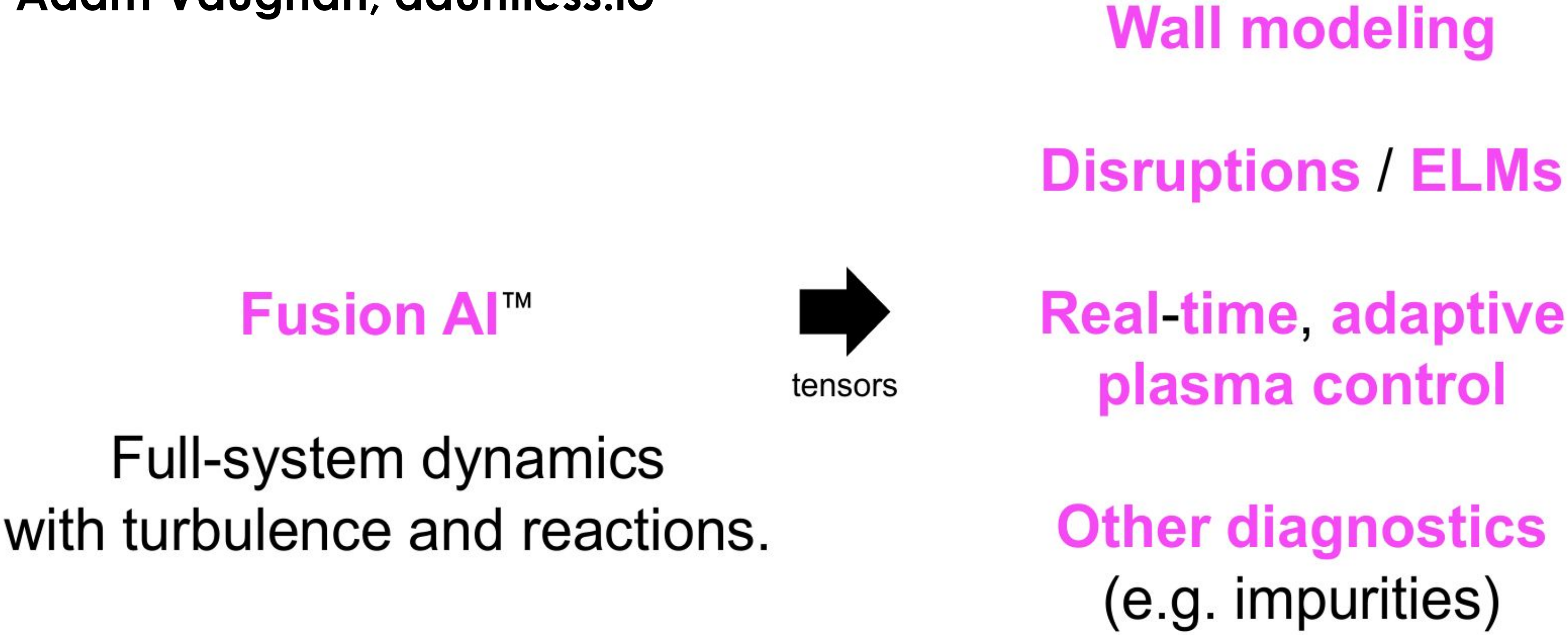
- **Capability Gaps**

- **Alignment**

- **Approaches and Resources**

Use predictive AI to study the plasma and PMI in new wall material environment

Adam Vaughan, dauntless.io



Fusion AI™

Full-system dynamics
with turbulence and reactions.

tensors

Wall modeling

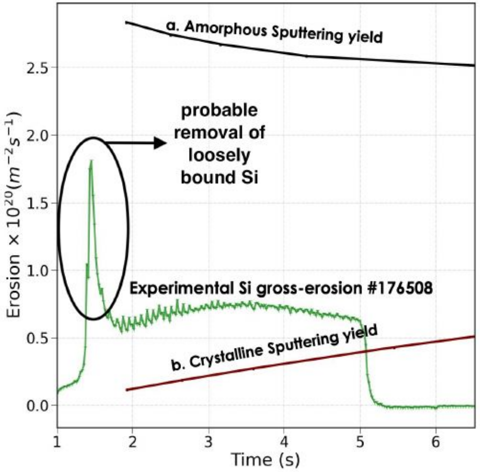
Disruptions / ELMs

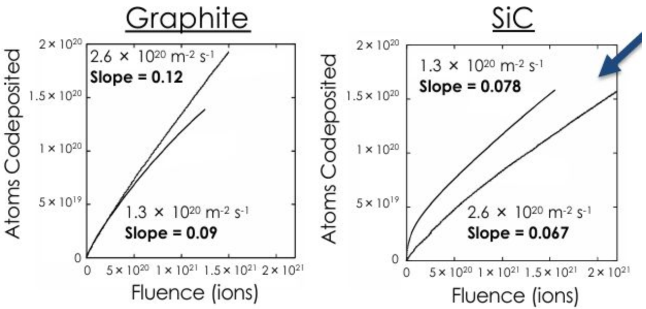
Real-time, adaptive
plasma control

Other diagnostics
(e.g. impurities)

SiC can reduce C and O impurity sources, but increased Si erosion due to amorphization, T retention needs further study

- SiC walls reduce C erosion substantially (Abrams et al NF 2021)
- But irradiation-induced amorphization of SiC leads to an increase of Si gross erosion by x1.5 (De et al 2024 In Preparation)
- Preferential sputtering of C from SiC may lead to effective siliconization, i.e. O gettering (Samm JNM 1995)
- Uncertainty regarding T retention in SiC, desorption possible at >800 C (Causey JNM 2003, Lantaigne NME 2022)
- Research is required on SiC's mechanical strength and thermal compatibility with heat sink materials

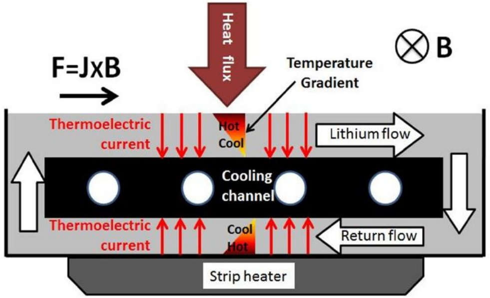


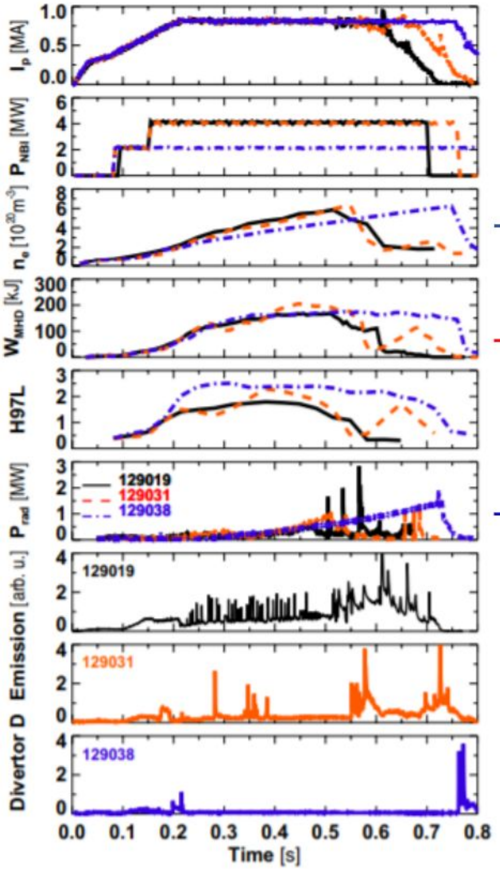


Lithium facilitates ELM-free H-mode access with improved confinement, new plasma regimes with broad Te profiles

Lithium surfaces substantially changes the plasma and PMI scenarios

- Low D recycling
- Reduction in instabilities
- Reduces H-mode power threshold
- Flattening of the temperature gradient
- Impurity reduction and removal
- Helium retention and removal
- Heat flux handling
    - 3-D structured mesh
    - Vapor Shielding





– No Li

– Medium Li coating

– Thick Li coating

= ELM-free

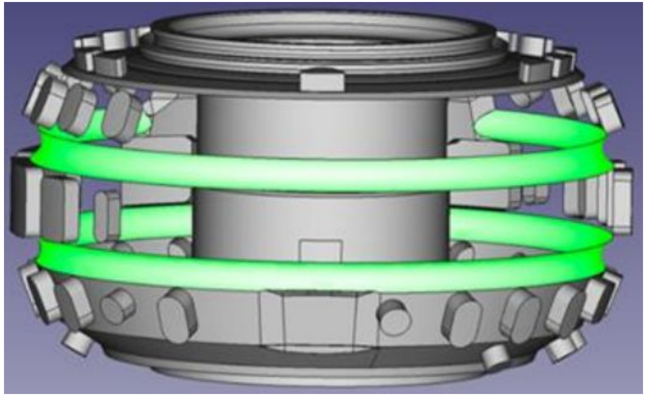
ut G

DIII-D NATIONAL FUSION FACILITY

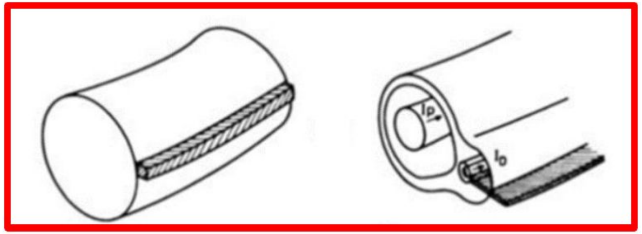
DIII-D wall material research requires toroidal limiters

Toroidal limiters provide the ideal means for assessing main-wall materials

- Facilitate studys of main chamber psi and material impact
- 3D->2D far SOL
- Enable better diagnostic characterization of far SOL
- Enables far SOL model validation with 2D codes



toroidal limiter = poloidal divertor



create 2D SOLs

Capability gaps

- FPP developers need data on how new wall materials impact the plasma behavior (-> core-edge integration), especially high-Z materials like W, which can exacerbate disruptions. This involves understanding material erosion, impurity influx, and their effects on plasma confinement and stability.

- Private sector has to move fast (~5 year time scale) would like to see rapid change of walls in DIII-D, generate new data urgently needed (preferably for W, LM based materials) to advance TRLs for new materials. AI can help to assess and qualify new materials faster.

- New material environments provide opportunity to enhance capabilities for predicting and mitigating disruptions, particularly by integrating AI-driven technologies to improve the speed and accuracy of disruption detection.

Capability gaps

- New materials need to be assessed wrt durability, performance, fuel retention, sputtering rates, slag, dust build up and UFO disruptions

- Explore new operational regimes with new wall materials that were previously inaccessible, such as higher temperature, flat temperature profiles, reduced instabilities, ELM-fee H-mode (intrinsic w Li walls);

- FPP and ITER relevant fuel retention and recycling studies in metals, Li, and B require carbon-free environments

Key physics parameters for material choice

Parameter	Current state	Desired state	Relevance
Sputtering	high	low	Longevity of materials, Impurity influxes affect plasma performance
Power handling	low	high	Crucial for integrity and safety
Disruption frequency	high	low	Impacts plasma stability and safety
Neutron tolerance	low	high	Essential for integrity, safety
Tritium retention	high	low	crucial for safety and efficiency in fuel use
Thermal conductivity	low	high	Needed for heat exhaust

Additional considerations and alternatives

- Symmetric far SOL important for wall PMI studies and 2D codes
- Using different materials for the 1) divertor 2) plasma wetted wall and 3) rest of the wall to determine the main culprits for slag formation, core impurity
- Carefully consider mixing of certain materials due to concerns regarding complex chemistry, incompatibilities (Li vs Si), challenges for model validation wrt multi-impurity species sputtering, migration and fuel retention
- Consider small-scale LM studies w single LiLi wall element as alternative to full LM divertor
- Low-Z layers on high-Z surfaces possible due to erosion from low-Z wall or active conditioning (boronization, siliconization, IPD etc.)
- Consider heated carbon divertor to demonstrate its FPP relevance (proposal by Abrams et al 2015)
- Wall material studies should be supported by new diagnostics capabilities (wall CX fluxes & AI)

Alignment

- Better communication between public and private sector is desirable. DIII-D should collaborate with private fusion companies and upgrade its AI capabilities to adjust to industry's fast timescales.

- Private public partnerships for new materials: DIII-D should do rapid generation of new data on wall material testing and integration

- Support ITER success and address urgent issues (W integration, disruptions, fuel retention, boronization with dropper)

- Collaborative opportunities with NSTX-U on liquid metals, and KSTAR, AUG, WEST on W integration

Alignment

Material considerations/priorities:

Tungsten and Liquid Metals

- Has customers: highly relevant, with strong industry interest for testing and potential use in future FPPs and ITER. Aligns well with DIII-D's role in advancing technology readiness levels (TRLs) in FM&T

Silicon Carbide

- Presently lack of interest from FPPs and ITER. Unique opportunity to demonstrate relevance because there is no other machine with SiC wall components.

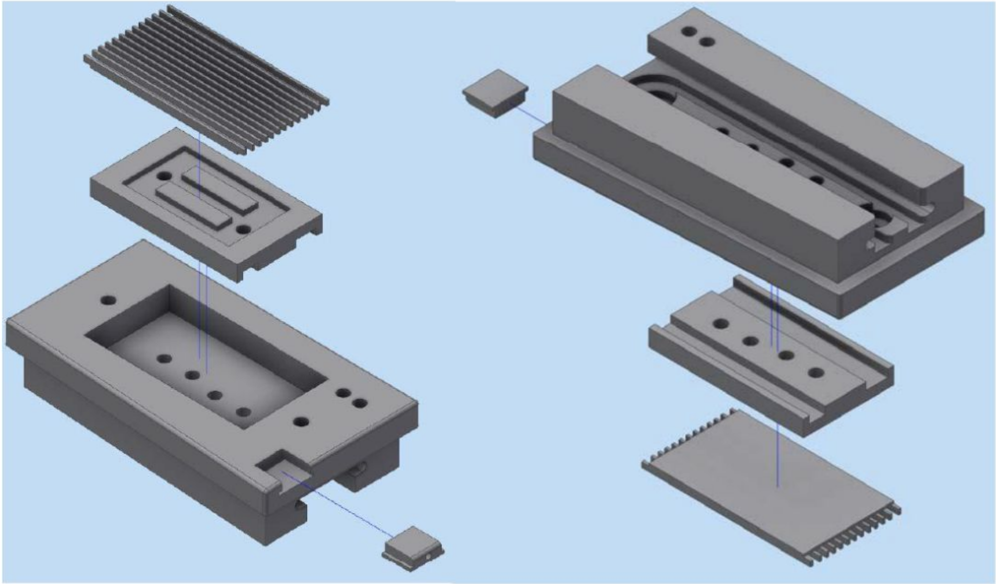
Approaches and Resources

Alternative	**Cost, Scope**	**Key Risks**	**Key Rewards**	**Limitations**
Nothing=C	No change	C sputtering, T retention via co-deposition	Core-edge compatible, more C material studies	Material not FPP/ITER relevant
W	High initial investment	slag, untested at high temp, high radiative losses - limited scenarios, make disruptions worse	Low erosion, ITER/FPP relevance, C free for retention studies, LM compatible, low-Z layer studies possible w IPD	Requires diagnostic upgrades
SiC	Moderate, easy to return to C	Premature for divertor (conductivity degradation); complex impurity mix, T retention prospects unclear	Unique (no other machine is doing it); presumably easy for core plasma	Not suitable for HHF divertor, incompatible w liquid metal studies for FPPs
Liquid Metal	Expensive, complex	Operational risks, plasma property changes	New plasma regimes, ELM suppression, FPP relevant	Affects diagnostics, incompatible w SiC

Appendix

Instrumented Tile Experimental Manifold (ITEM)

- The idea behind the ITEM diagnostic is to substitute one of the outer divertor tiles in DIII-D with a variety of advanced concepts.
- Have diagnostic attachments, heater attachments, and cooling attachments, but would otherwise be identical to the tile in terms of total shape, size and support structure.
- Liquid lithium concepts could be mounted and tested, once the local parameters have been determined. For example a LiMIT tile could be mounted (see figure)
- In an ideal world this substitute tile would be on a retractable arm similar to the DiMES probe and fit into the rest of the divertor structure.
- However, if cost of such a mechanism would be prohibitive, instead this diagnostic tile would be installed and removed during a vacuum opening by a technician.
- If a new experimental tile was not desired, a standard tile could be attached in its place. This simplifies the introduction mechanism and greatly reduces the cost.

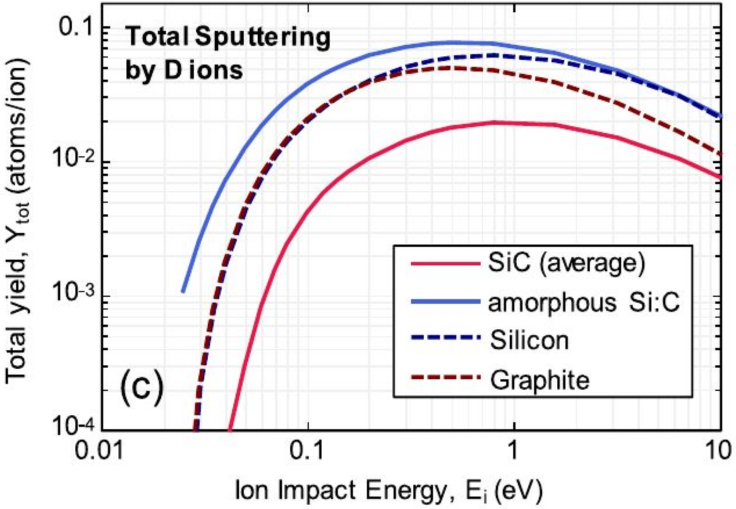


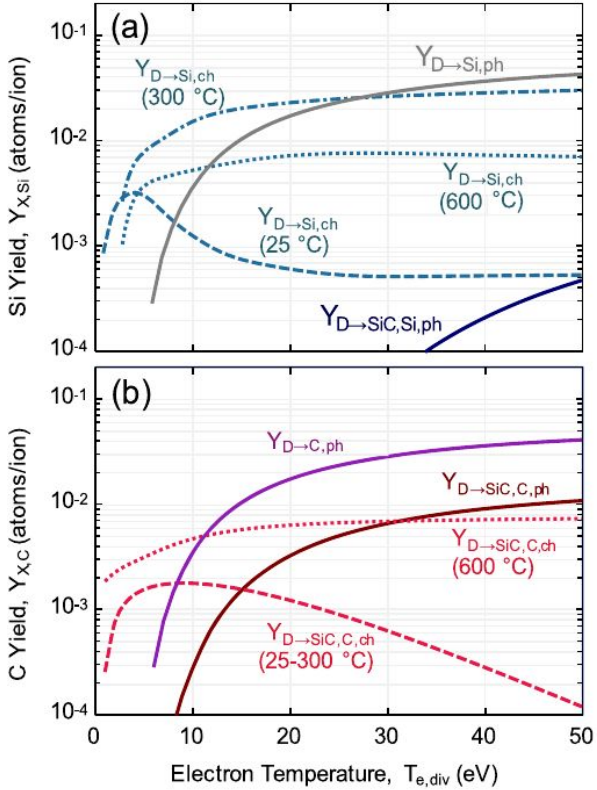
Exploded top and bottom views of a LiMIT tile configured as an experiment to be placed in ITEM. The small tab which slides into the plasma-facing side of the tile will be have embedded markers in it and is easily removable for post-exposure analysis.

SiC physical sputtering is lower than graphite by 2-10x, chemical sputtering by 10x

- SiC physical sputtering is lower than graphite (2-10X) Abrams et al 2021
- Westerhout et al 2009, Balden et al 2000
- C from SiC chemical sputtering is 10x lower than graphite(Abrams et al 2021)
- No observed Si chemical erosion from SiC (Sinclair NME 2021, Balden JNM 2001) although there is chemical erosion of Si from pure silicon.

Abrams et al 2021

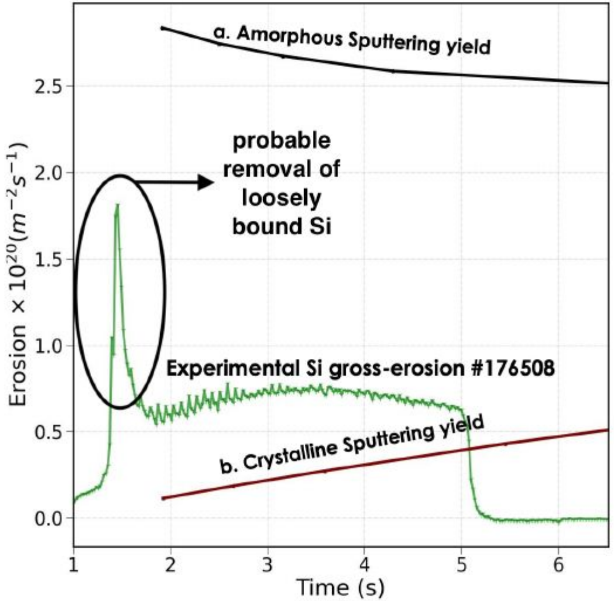




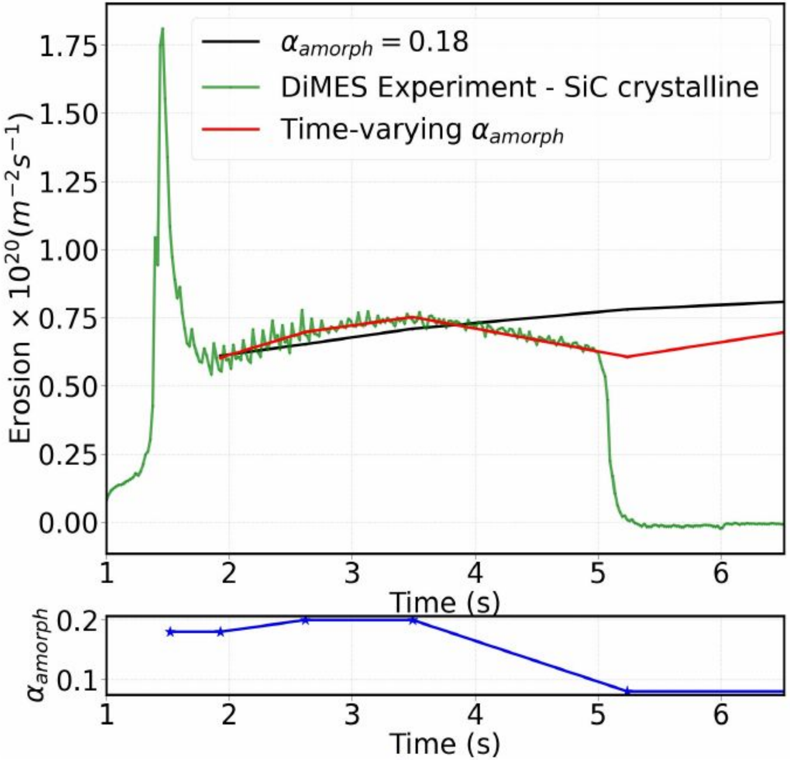
Amorphization of SiC due to accumulation of displacement damages under ion, neutron irradiation

- **A time-varying amorphization ratio of around 0.2 is needed to explain experimental Si gross erosion rates.**
- **Effect of amorphization on the Si gross erosion rates ~ 1.5 x the gross erosion from pure crystalline SiC.**
- **Implies a shorter lifetime than a pure SiC wall.**

De et al 2024 In Preparation

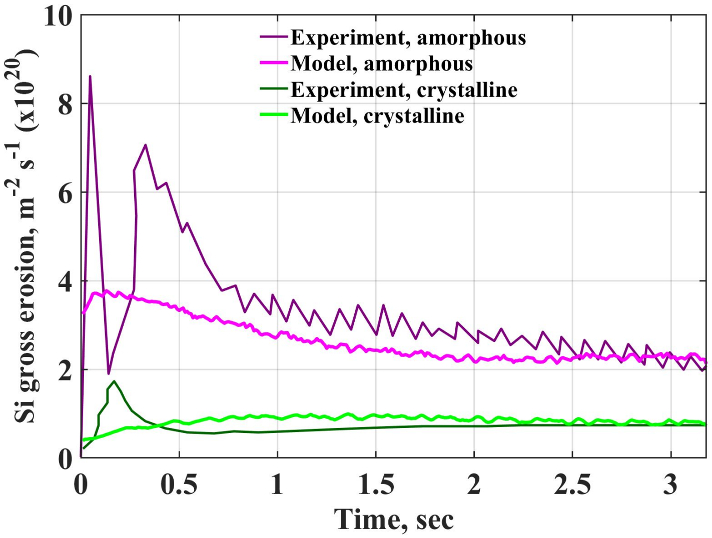


$$\bar{Y} = \alpha_{amorph}\bar{Y}_{amorph} + (1-\alpha_{amorph})\bar{Y}_{crystal}$$



Assessment of SiC surface amorphization and impact on erosion

Modeling of single L-mode discharge showed only deposition/redeposition effect on surface amorphization



single L-mode discharge

Modeling [3, 4]:

- Only deposited and redeposited C and Si form amorphous material.

- ✔ ~3 times lower Si erosion from crystalline material in single discharge
- ✔ However, Si erosion similar to amorphous in multi-discharge experiments [2]
- ✔ Displacement damage by D ions during long operation or/and ELMs can lead to surface amorphization

Experiments at DIII-D [1]:

- Measurements during the first shot on the samples
- First high peaks in measurements were explained by loosely bound Si, possibly in form of micro-particles

[1] D. L. Rudakov, et al., Phys. Scr. T171 (2020) 014064

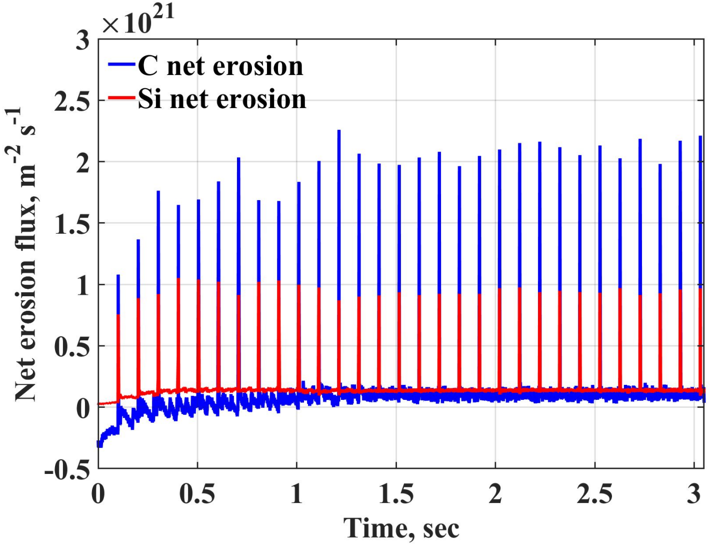
[2] T. Abrams, et al., Nucl. Fusion 61 (2021) 066005

[3] T. Sizyuk, J. Brooks, A. Hassanein, T. Abrams, APS DPP 2023

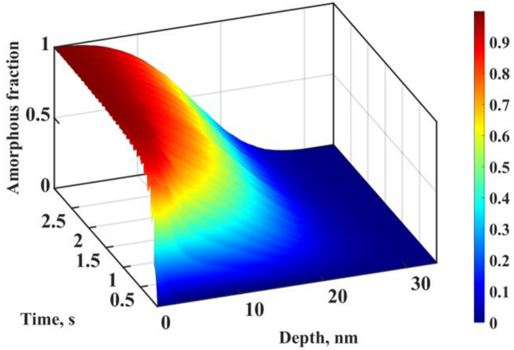
[4] T. Sizyuk, J. Brooks, T. Abrams, A. Hassanein, PSI 2024

Modeling of H-mode discharge in DIII-D experiments showed effect of displacement damage on surface amorphization during ELMs

Plasma: T_e ~30 eV; n_e ~ 3×10^{19} m^{-3}



Evolution of net erosion during and between ELMs with surface amorphization



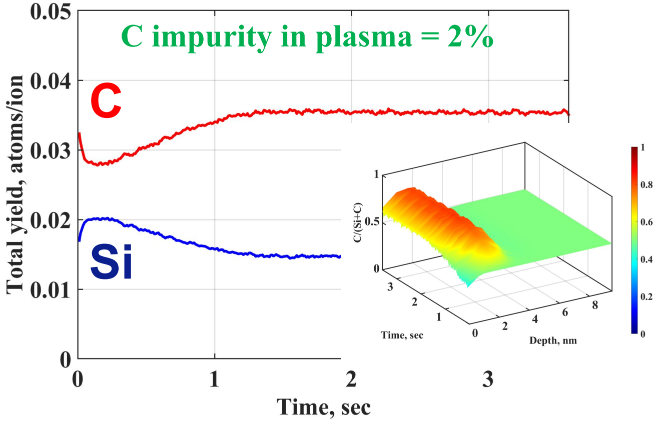
Modeling results:

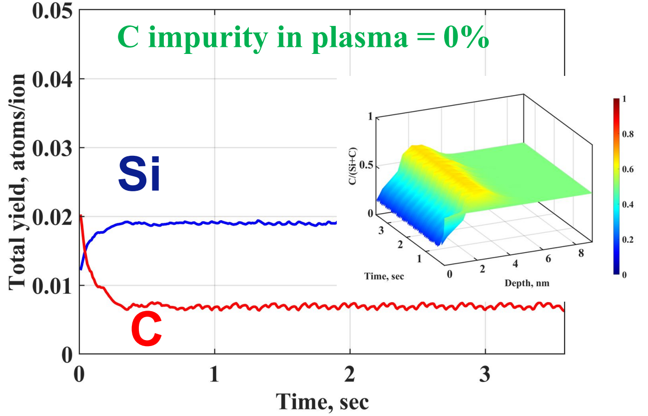
- ✔ **~10 nm of surface can be fully amorphized due to displacement damage by D during several ELMs.**
- ✔ **Large difference in the redeposition of Si and C.**
- ✔ **Slight difference in the redeposition for amorphous and crystalline surfaces.**

[1] T. Sizyuk, J. Brooks, A. Hassanein, T. Abrams, APS DPP 2023

[2] T. Sizyuk, J. Brooks, T. Abrams, A. Hassanein, PSI 2024

Significant change of C erosion with slight variation of C impurity in plasma





Modeling results [1, 2]:

- ✔ Sputtering yields of Si and C from amorphized surface are the same as in multi-discharge DIII-D experiments [3] – for 2% C impurity
- ✔ Surface enrichment in Si in the case of graphite-free chamber → 7 times lower C sputtering yield than from graphite surface
- ✔ 100% local redeposition of chemically sputtered C (at the attached plasma conditions)

- ✔ In addition, preferential chemical bonding in Si-C-D compound further reduces C chemical erosion and prevents Si chemical erosion (from thermodynamic calculations [4])

[1] T. Sizyuk, J. Brooks, A. Hassanein, T. Abrams, APS DPP 2023

[2] T. Sizyuk, J. Brooks, T. Abrams, A. Hassanein, PSI 2024

[3] T. Abrams, et al., Nucl. Fusion 61 (2021) 066005

[4] H. Efstathiadis, et al., Phys. Rev. B 46, 13119 (1992)