Plasma Materials Interactions II: Revenge of the PMI

Tyler Abrams

with special thanks to
G. Sinclair, J. Guterl

General Atomics

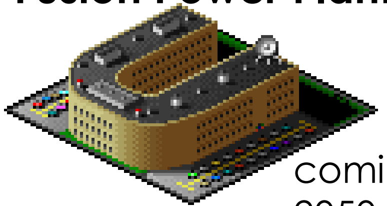
Presented to the

2021 SULI Lecture Series

June 22, 2021

My Career in Plasma Physics, So Far

Sim City 2000
Fusion Power Plant

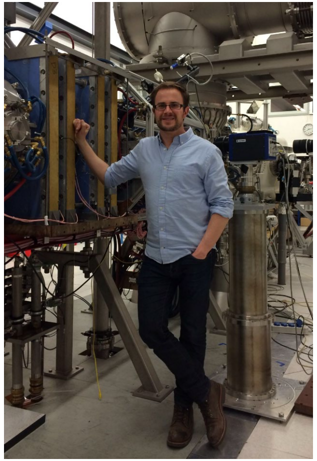


coming
2050

MIT PSFC (undergrad)

DIII-D (NUF internship)

PPPL / DIFFER (grad school)



DIII-D (Postdoc)

DIII-D (GA Staff Scientist)

Outline

- **How to Evaluate Plasma-Materials Interactions**
  - Characterize the Edge Plasma
  - Observe the Effect on the Wall Material (Spectroscopy)
  - Perform "Post-Mortem" Analysis of the Material
- **Promising Plasma-Facing Materials**
  - Tungsten
  - Silicon Carbide
  - Liquid Metals
- **Wrap-Up and Final Thoughts**

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Edge plasma conditions diagnosed via Langmuir probes and Thomson scattering

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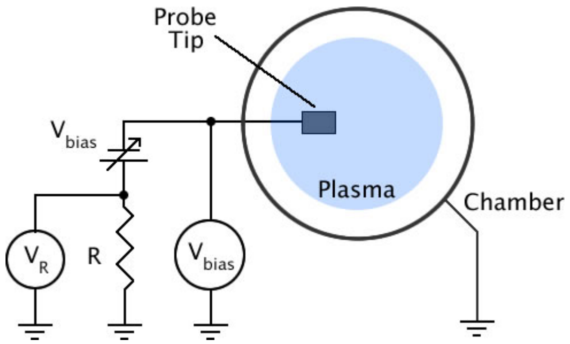
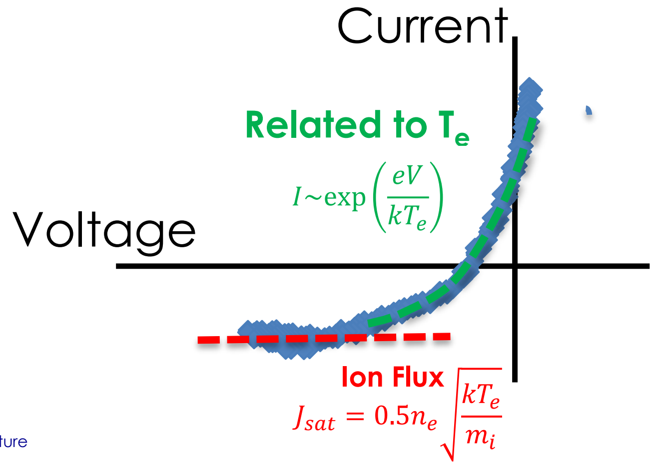
  - Conductive probe contacts plasma
  - Collected current varies with voltage due to sheath effects
  - Ion flux, n_e, T_e can be extracted
  - Fast (~1-10 kHz), but can only measure at the edge



Courtesy of D. Pace



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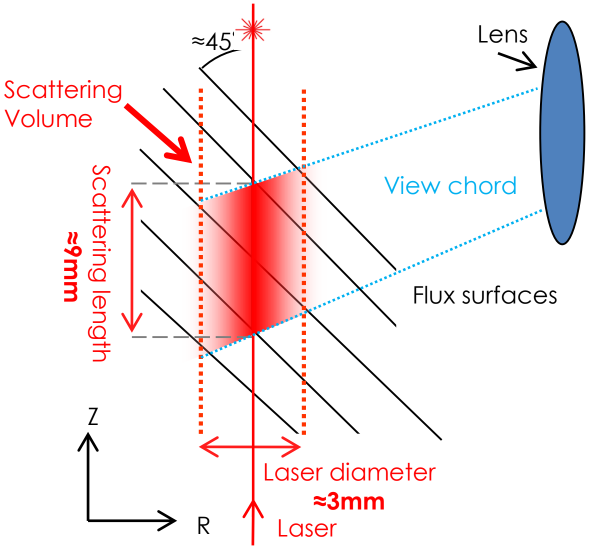
- **Thomson Scattering**
  - Spectroscopic measurement of photon-electron collision
  - Extract n_e,T_e from line height/width
  - Slow (50-100 Hz), but measure anywhere in the plasma



Courtesy of D. Eldon

Divertor Heat Flux characterized via IR thermography

- **Utilize Planck's Law to relate IR emission to temperature:**

$$B_\lambda(T) \sim \frac{2hc^2}{\lambda^5}\frac{1}{\exp(hc/\lambda kT) - 1}$$

"Gray-body" radiation

Wave-length

Surface temperature

- **Apply thermal model to relate temperature to heat flux*:**

Initial surf. temperature

Thermal diffusivity

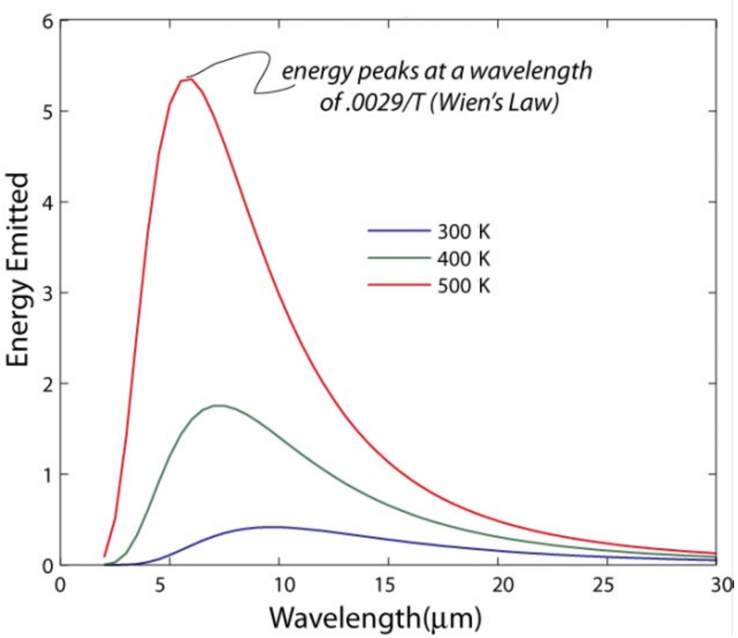
*1-D semi-infinite slab

$$T(t) = T_0 + q\left(\frac{4\alpha t}{\pi k_{th}}\right)^{1/2}$$

Heat flux (MW m^{-2})

Thermal conductivity

Planck's law Power spectrum vs. Temperature and Wavelength



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Heat flux (MW m^{-2})

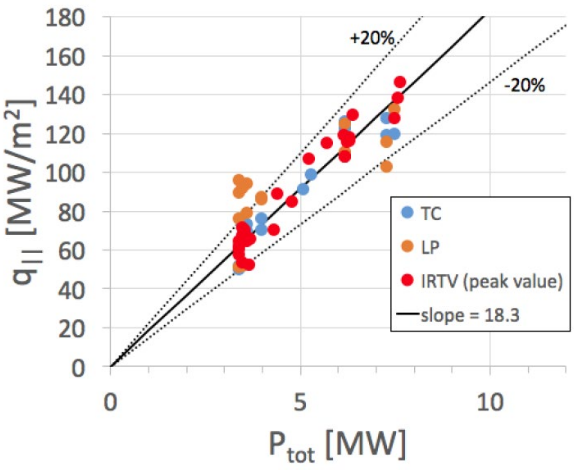
Thermal conductivity

HF measured by Langmuir probes generally agree reasonably well with IR

$$q_\parallel \approx \gamma T_e J_{sat}/\sin\theta$$

$\gamma \approx 7$ — Sheath heat flux factor

$\theta \approx 1.5°$ — Field line angle

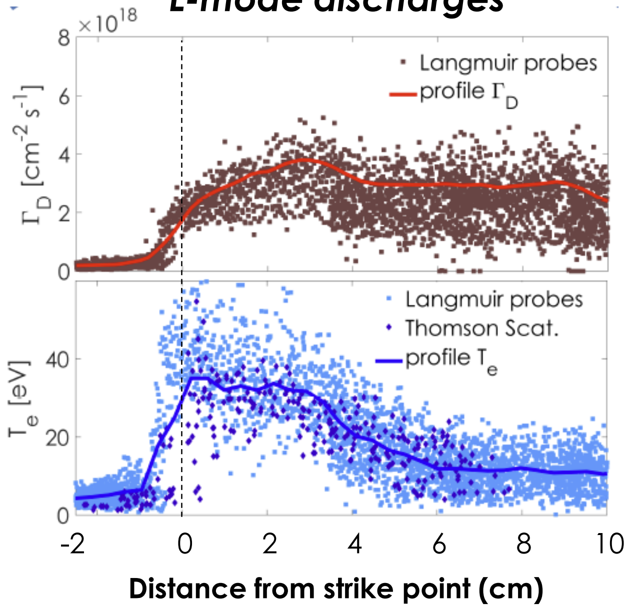


Barton Phys Scr 2017

Divertor plasma profiles look very different in L-mode and H-mode (ELM vs. inter-ELM)

- **L-mode: Poor confinement implies broad plasma profiles**
  - Scale lengths O(several cm)
  - No fast time constants -> fast time response not crucial
- **H-mode: Better confinement means narrower profiles**
  - Fast time constants (ELMs) implies need for fast time response
  - Typically average over end portion of ELM cycle
- **What if LP and TS are not consistent?**

Typical J_{sat} and T_e profiles in DIII-D L-mode discharges



Guterl PET 2017

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- **What if LP and TS are not consistent?**

J_{sat} is more "trusted" from LPs. Actual ion flux measurement at the target

T_e is more "trusted" from TS. Local measurement, not averaged over a flux tube

Density can be "backed out" based on Jsat and T_e

Plasma conditions in H-mode oscillate due to ELMs

- **Edge Localized Modes**
  - Periodic bursts of energetic plasma expelled from the core
  - "Spikes" observed on heat flux measurements
  - **Big problem for reactors!**
- **Current understanding of ELMs is still somewhat empirical**
  - "Free streaming model": detachment of a pedestal plasma filament into SOL

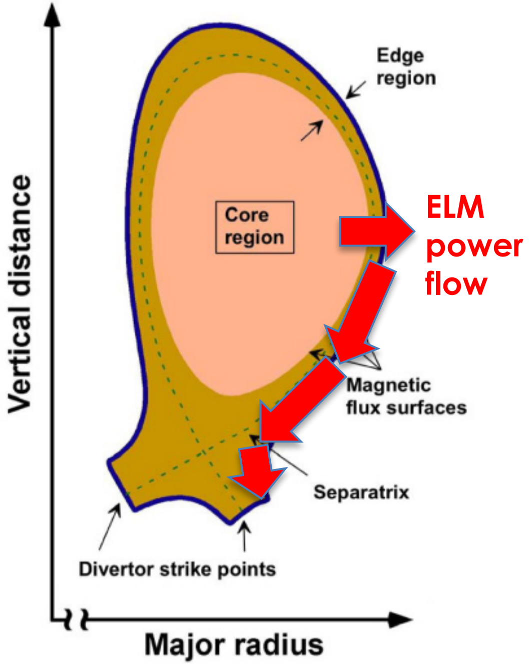
ELM energy

ELM power

$$p_{o,i}^{ELM}(t) = \frac{2}{3}\frac{E_o + E_i}{\sqrt{\pi}} \times \left(1 + \left(\frac{\tau_{FSP}^{o,i}}{t}\right)^2\right) \times \frac{\tau_{FSP}^{o,i}}{t^2}$$
$$\times \exp\left(-\left(\frac{\tau_{FSP}^{o,i}}{t} - H_{fl}^{o,i} M_{\parallel}\right)^2\right).$$

ELM decay time (fitting param.)

Mach number



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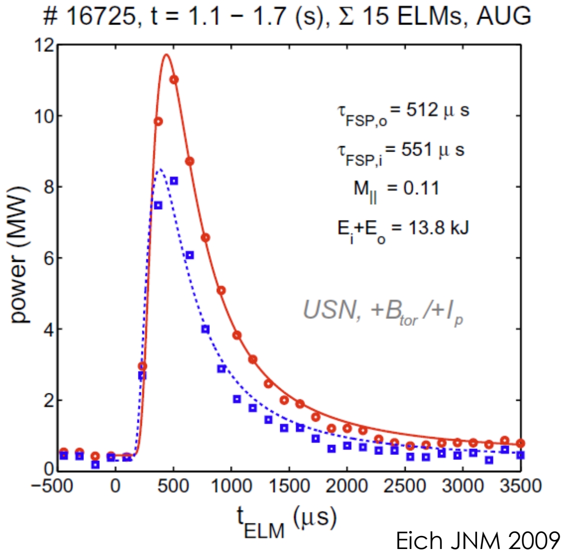
ELM power

ELM decay time (fitting param.)

Mach number

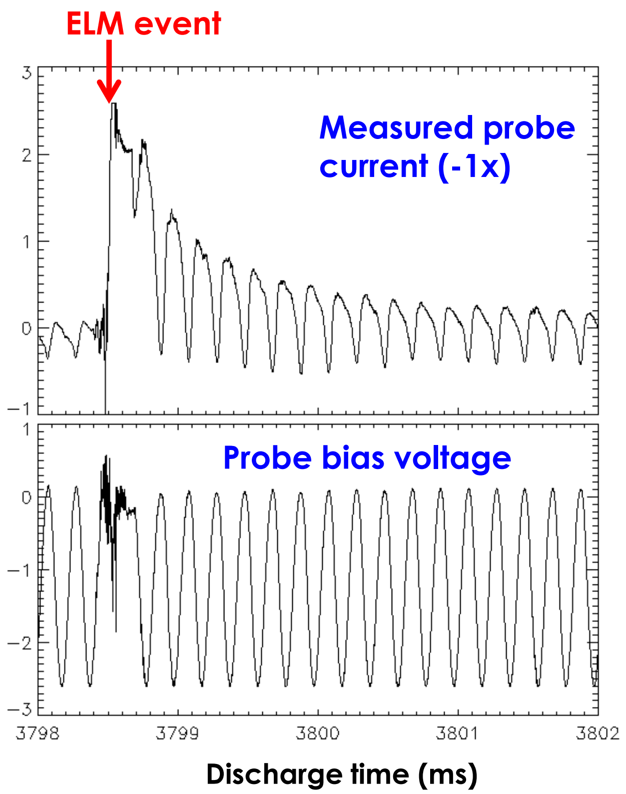
Empirical model for ELM power deposition agrees reasonably well with data



Eich JNM 2009

Intra-ELM plasma conditions are difficult to diagnose

- **Langmuir probes run into power supply current limits**
  - Results in "back off" on bias
  - Do not capture peak of J_{sat}
  - Cannot fit exponential to I-V curve to infer T_e



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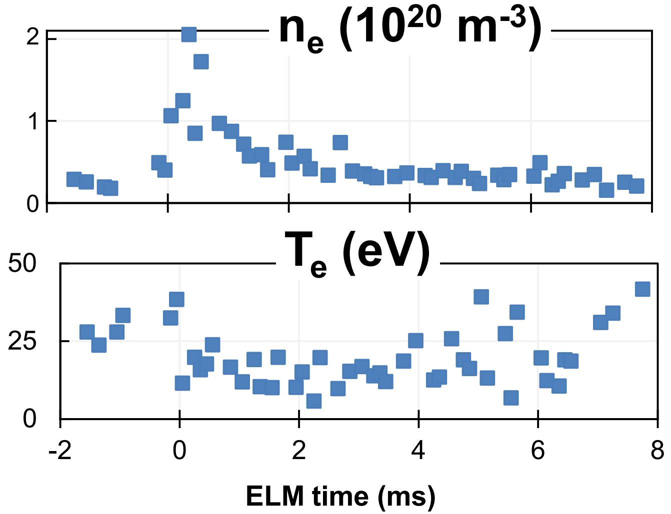
- **TS measurement frequency is comparable to ELM frequency**
  - No information on ELM evolution
  - Can use "coherent averaging" if a number of similar ELMs exist

DTS indicates strong n_e increase during ELMs, but similar (or decreased) T_e



Abrams APS 2016

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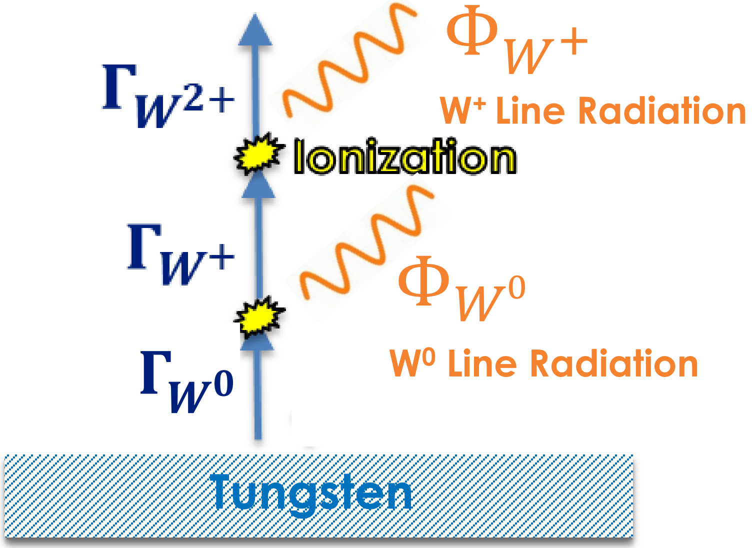
Measuring PMI Involves Using Spectroscopic Diagnosis of the Edge Plasma

- **Eroded wall material becomes an *impurity* in the plasma**
  - Impurities emit line radiation via electronic transitions



- **Impurities in the plasma measured with spectroscopy**

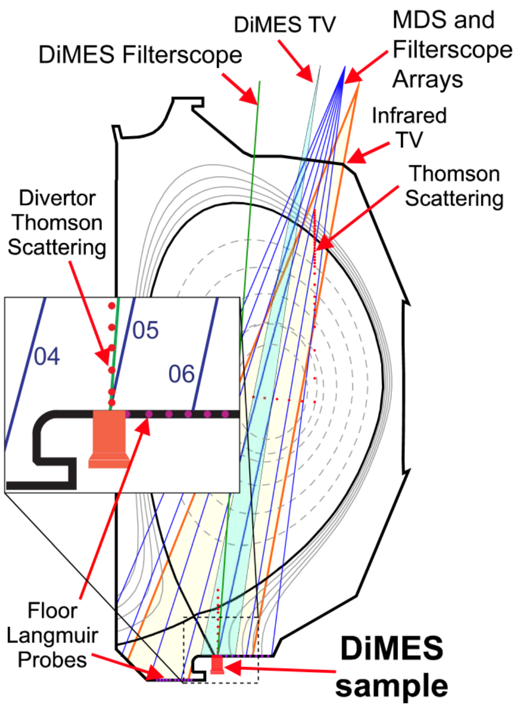
$$\Gamma_{W^0} = \frac{S}{XB} \int_0^\infty \Phi_{W^0} dz$$

$$\frac{S}{XB} \equiv$$ **"Ionizations per photon"** **"Inverse photon efficiency"**

- **S/XB coefficients typically obtained from databases**
  - e.g., ADAS: www.adas.ac.uk

What spectroscopy diagnostic you need depends on what you want to measure

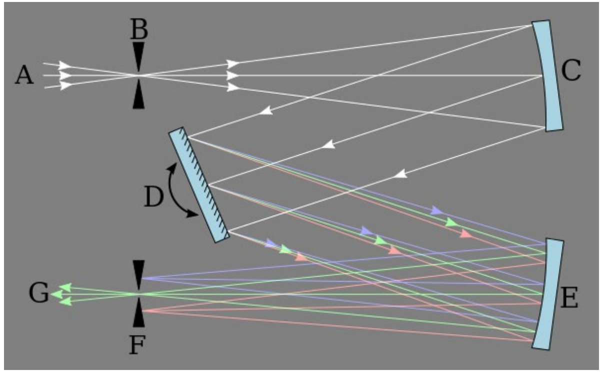
Diagnostic	Spectral resolution	Spatial resolution	Time resolution
Spectrometer	Can be very high (<0.1 nm)	Requires multiple chords. O(cm) spot sizes	Limited by read-out time, integration time. typically ms-s
Filterscopes	1-10 nm wavelength region (Bandpass filter)	Requires multiple chords. O(cm) spot sizes	Very fast, limited by digitizers, typically kHz-MHz
Filtered camera	1-10 nm wavelength region (Bandpass filter)	2D image, mm-cm, depends on lens	Slow cameras (30 Hz) are cheap, Fast cameras (kHz-MHz) are expensive



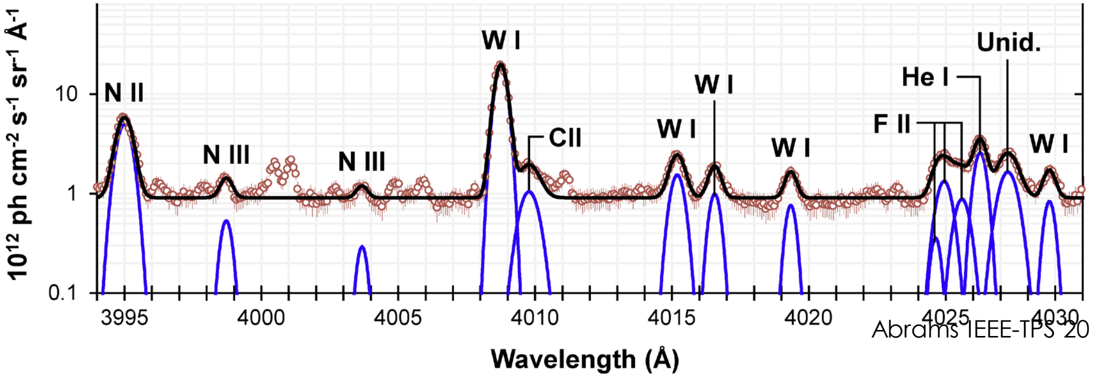
Abrams NF 2017

Grating-based spectrometers measure intensity vs. wavelength

- **Czerny-Turner design enables high spectral resolution**
  - Distinguish closely neighboring lines
  - Zeeman splitting -> B_T, LOS
  - Doppler shifts/broadening -> v_i, T_i
  - Careful line identification possible

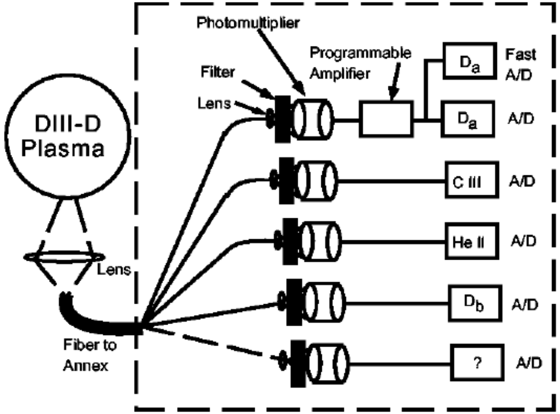


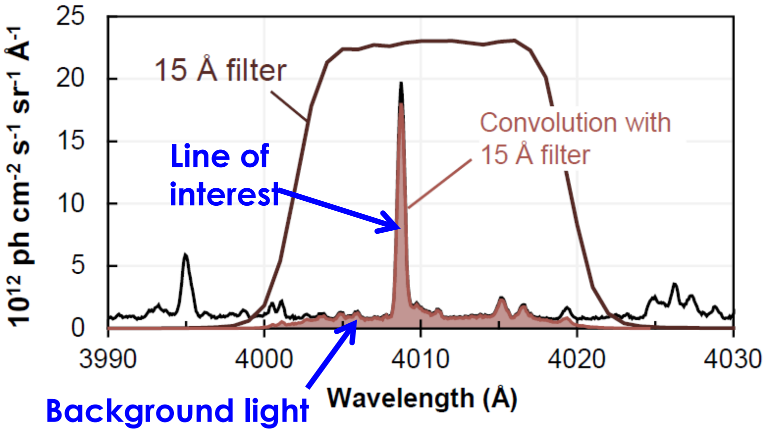
Typical Spectrum acquired with DIII-D High-Resolution Spectrometer



Abrams IEEE-TPS 2017

Filterscopes provide very high time resolution over an integrated spectral range





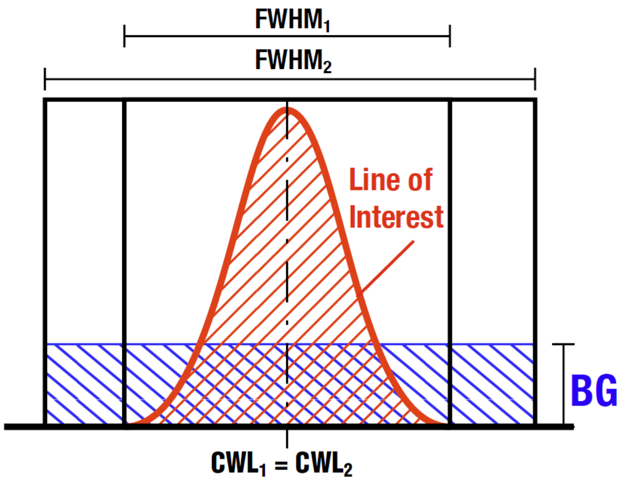
- **Light directly coupled to photo-multiplier tubes (PMTs)**
  - Bandpass filters only transmit a certain narrow wavelength range
  - ELM-resolved information!

- **Caveat: Signals includes both line of interest and background**

Abrams IEEE-TPS 2017

Filterscopes provide very high time resolution over an integrated spectral range

Two-filter method developed on DIII-D to separate signal from background



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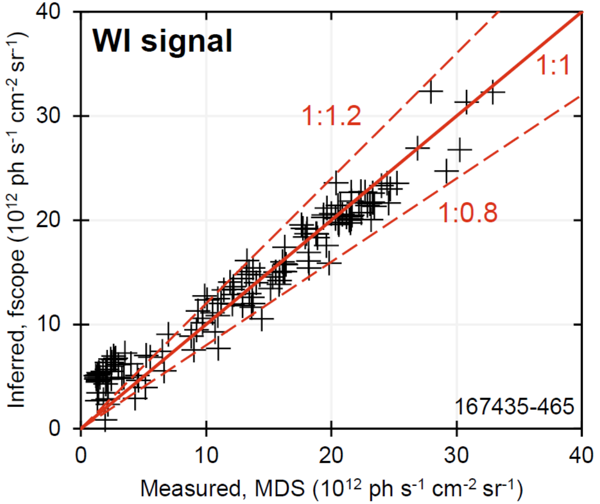
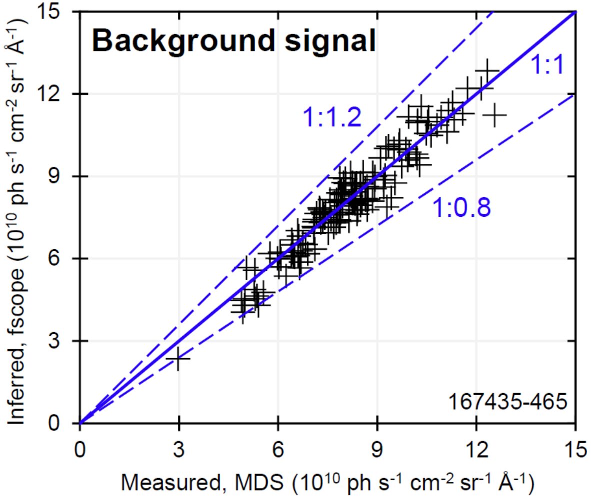
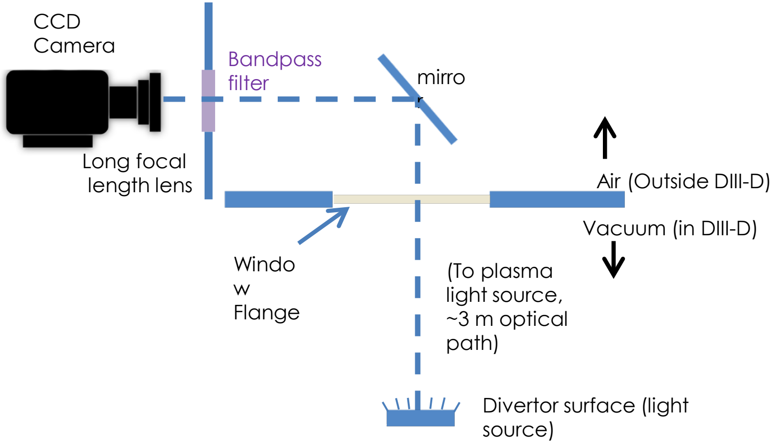


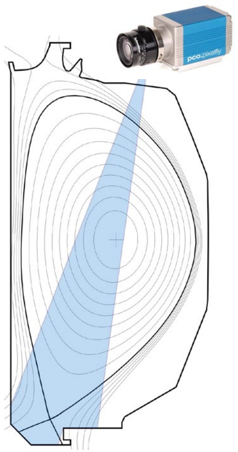


Abrams IEEE-TPS 2017

Filtered imaging provides spatially resolved light intensities

- **Camera images divertor surface through bandpass filter**





- **Background subtraction can be performed from a local source**
  - Assume toroidal symmetry
  - Subtract ROI toroidally offset as background

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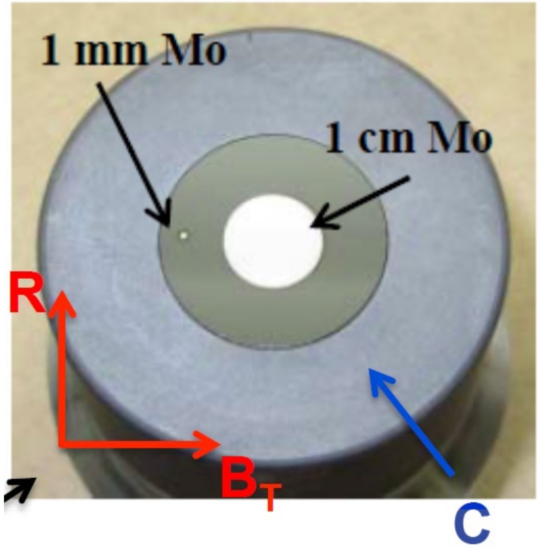
Measurements of W prompt re-deposition can be conducted via post-mortem analysis

- **W/Mo re-deposition inferred from post-mortem analysis on DIII-D**
  - DIII-D DiMES experiments
  - Small 1 mm spot (R~0) vs. large 1 cm spot (R~?)
  - Decent agreement with ERO code, assuming 1.8% C concentration

	Mo		W	
	EXP	ERO	EXP	ERO
Net erosion rate (nm/s)	0.42	0.43	0.18	0.14
Net/gross erosion ratio	0.56	0.61	0.29	0.33

R. Ding



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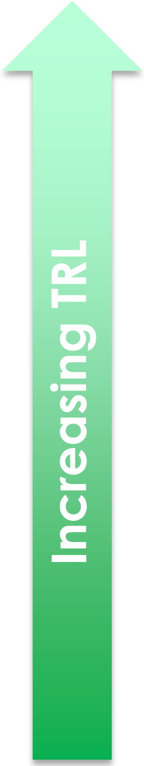
Three Classes of Materials are Envisioned to Have Potential as Plasma-Facing Materials for Fusion

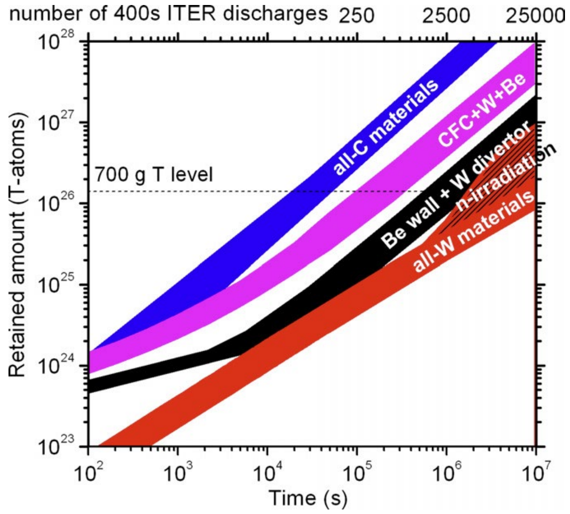


1. **Refractory Metals (W and W-alloys)**
   - Acceptable operational temperature window, >800 °C
   - Difficult/expensive to fabricate, machine
2. **Ultra High-Temperature Ceramics (UHTCs)**
   - Graphite, SiC, other carbides, diborides, MAX phase…
   - High temp. (> 1000 °C), maintain strength under high neutron fluence
   - Fiber composites generally at lowest TRL (joining, hermeticity)
3. **Liquid Metals**
   - Primarily Lithium, but also Sn, Sn-Li Eutectics
   - "Self-healing:" separates the material problem from PMI problem
   - Most difficult chemically and technologically

Bolt FED 1993
Snead JNM 2000

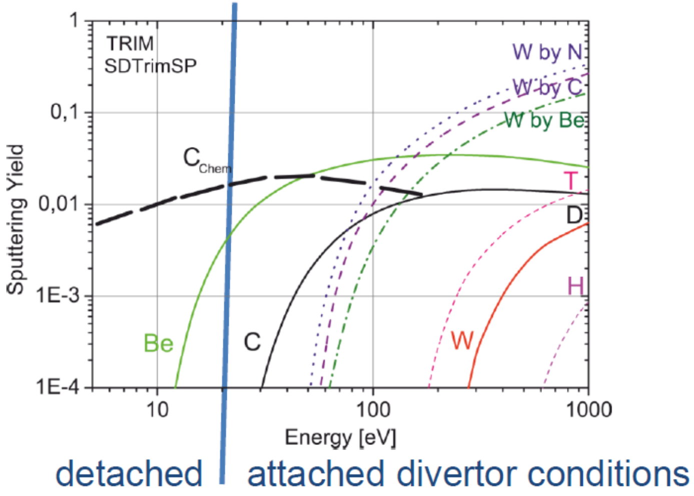
W was chosen as ITER divertor material due to low T retention, good thermal properties, & low sputter yield

- **CFC divertor in ITER eliminated due to concerns about cost + T retention via C co-deposition**
- **"Be wall + W divertor" planned for entire ITER lifetime**
  - Divertor replacement?



Roth PPCF 2008

Sputtering yields of plasma-facing materials

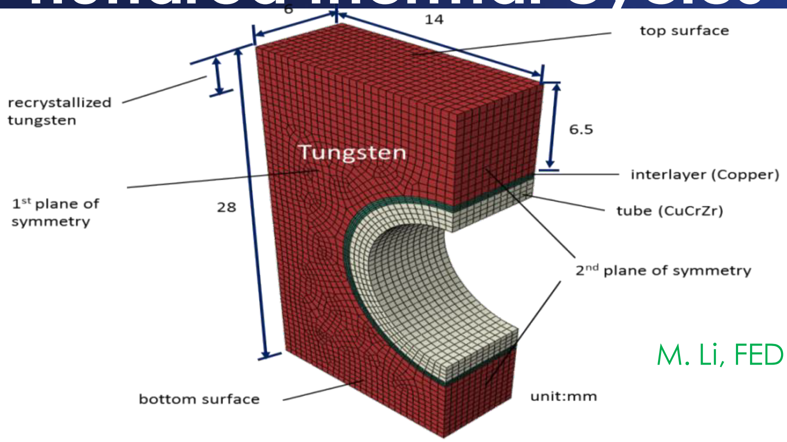


- **W sputters significantly less than low-Z materials like C or Be**

  …but one W atom in core is much worse than a C/Be atom

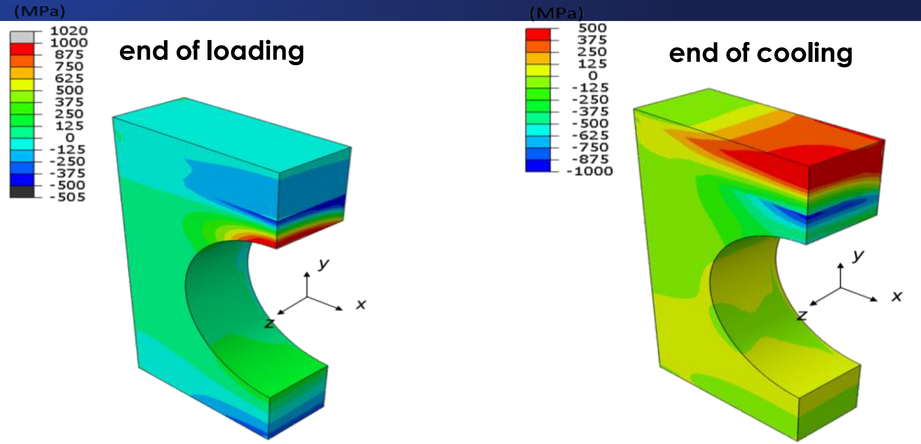
- **W has highest melting temp of any solid material (except C)**

ITER/DEMO W monoblock design tends to fail after several hundred thermal cycles

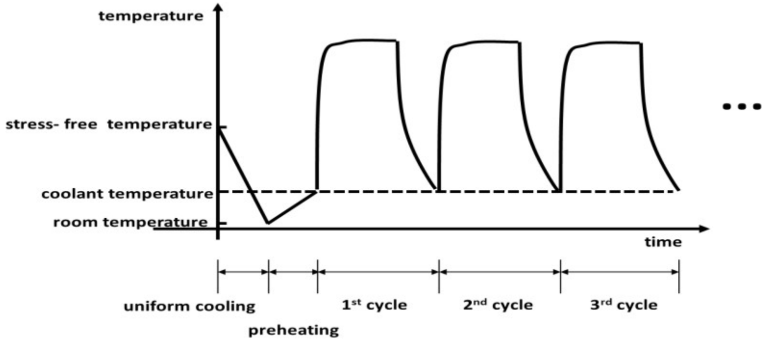


FE mesh of an ITER monoblock

M. Li, FED 101 (2015) 1



Stresses in x direction for a heat flux of 20 MW/m²



Thermal excursion of monoblock

FE analysis:
deep cracking

in ITER monoblock

G. Pintsuk et al. FED 88 (2013) 1861

due to **plastic deformation** and **recry-stallization** resulting in **brittle** failure during

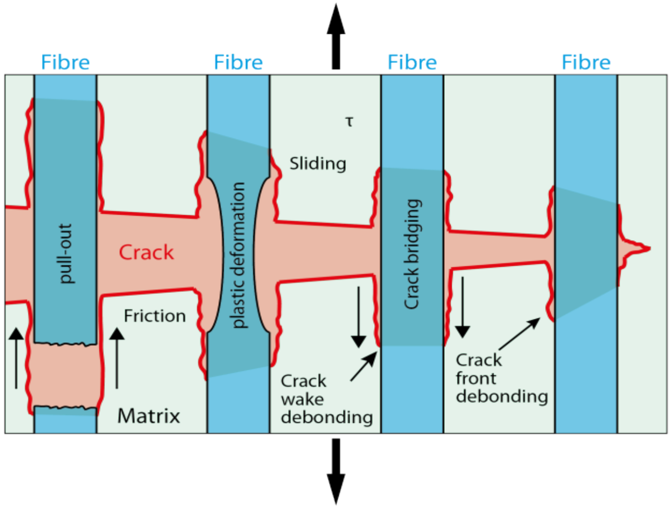
cool- down after only few hundreds of cycles

Toughening of Tungsten Fiber Composites (W_f/W)

Toughening by mechanism analogous to ceramic-fiber-reinforced ceramics

Stress redistribution by local energy dissipation acting behind cracks

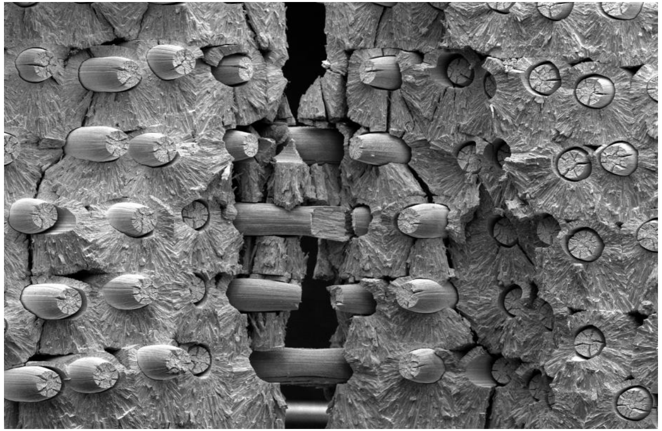
Pseudo-ductile Tungsten!



[based on Evans, J Am Ceram Soc 73, Nb. 2, 1990]

W_f/W fabricated at FZ Julich[1]

[1]Riesch Phys Scr 2014



Fracture surface of W_f/W after Charpy impact test

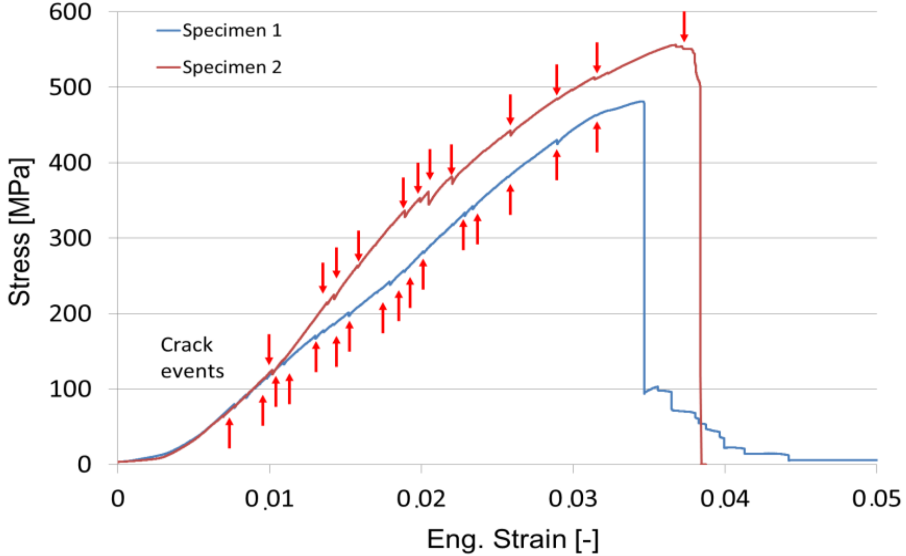
H. Gietl et al., Fus. Eng. Design 124 (2017) 396

Neu PPPL Seminar

W_f/W shows good performance in mechanical testing

Increasing the toughness of W:

- Production of dense W_f/W by CVD
- Development of optimized fabrics and continuous deposition



Stress-Strain diagramm of W_f/W tensile tests

W_f/W samples confirm:

- Charpy impact tests
  ->ductile behaviour of fibers

Monotonic tensile test -> no catastrophic failure

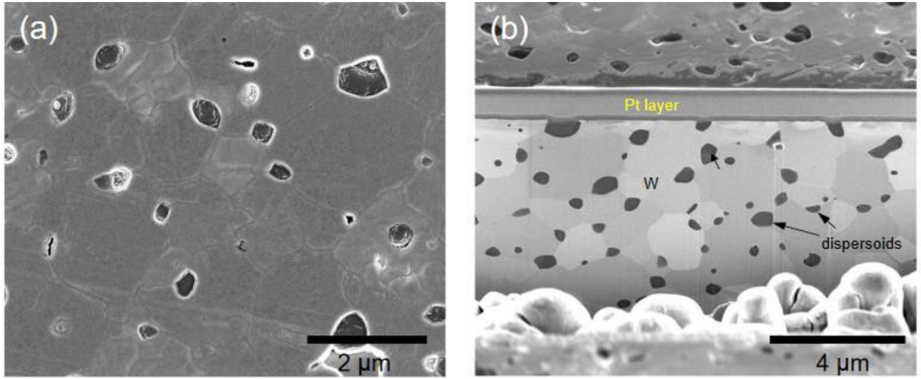
H. Gietl et al.,
Fus. Eng. Design 124 (2017) 396

- Low cycle fatique testing
  10000 cycles at 60/70/90/100% (each) of maximum stress without failure

Neu PPPL Seminar

Dispersoids can help to stabilize W microstructural features, improve resilience to neutron damage

- **Incorporation of dispersoids can improve resistance of W to n-damage, recrystallization at high temperatures.**
- **Ongoing material development at Penn State, University of Utah, Tohuku University [1-3].**



Above: SEM/FIB images showing microstructure of dispersoid strengthened W specimens [2]

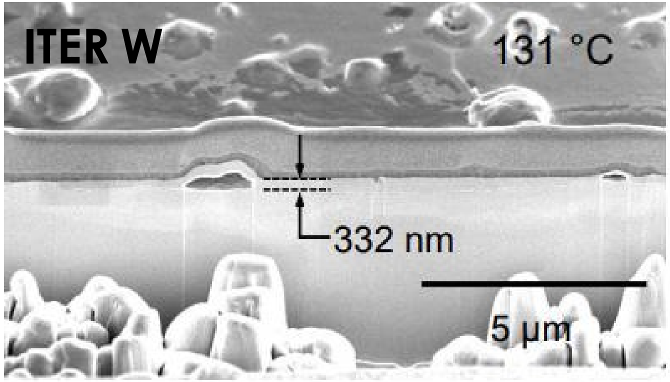
- **Most testing to date with "single effect" laboratory experiments**
- **Planned expts. will use DIII-D/DiMES to expose specimens to combined high heat and particle flux**

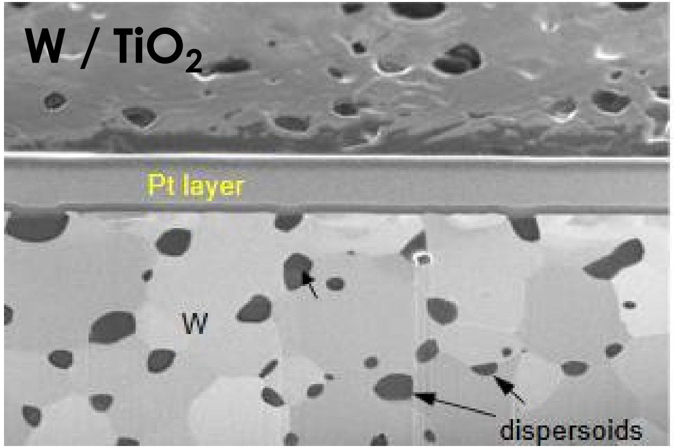
1 H. Kurishita, S. Matsuo, H. Arakawa, et al., *Phys. Scr.* **T159** (2014) 014032.
2 R. D. Kolasinski, D. A. Buchenauer, R. P. Doerner,et al., *Ing. J. Ref. Met. Hard Mat.* **60** (2016) 28.
3 E. Lang, H. Schamis, N. Madden, et al, *J. Nucl. Mater.* **545** (2021) 152613.

Laboratory testing of dispersoid-strengthened W shows promising results

Dispersoid strengthened W properties and experimental results:

- Near-surface blistering during H exposure nearly eliminated up to ~10^{25} D/m^2



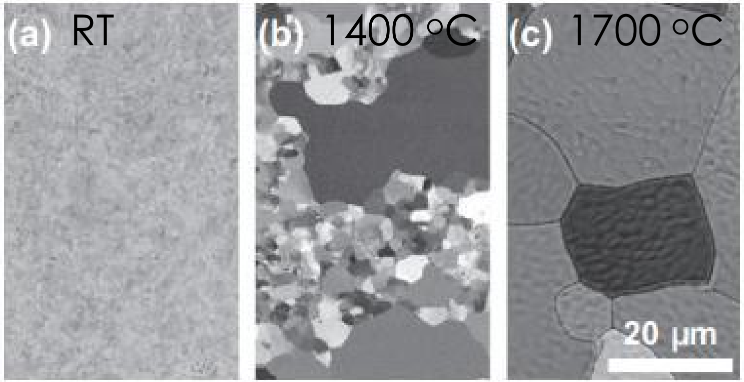


Laboratory testing of dispersoid-strengthened W shows promising results

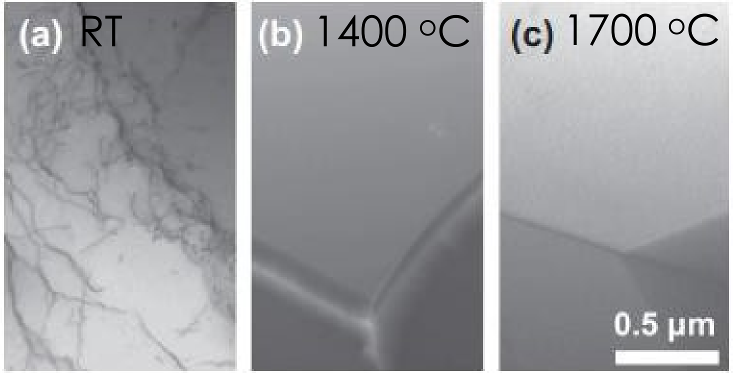
Dispersoid strengthened W properties and experimental results:

- Near-surface blistering during H exposure nearly eliminated up to ~10^{25} D/m^2
- Improved resistance to grain growth during high-temperature annealing up to 1800 °C

[1] A. Manhard, K. Schmid, et al., *J. Nucl. Mater.* **415** (2011) S632.



grain growth in ITER W



defect annealing in ITER W

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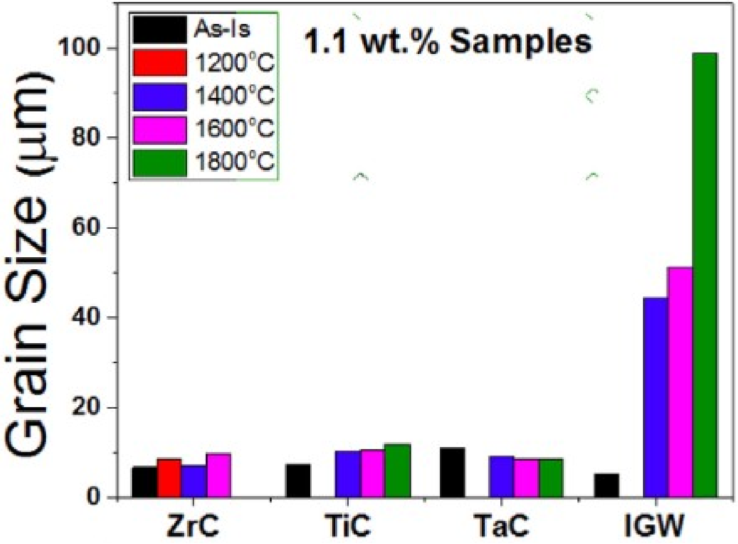


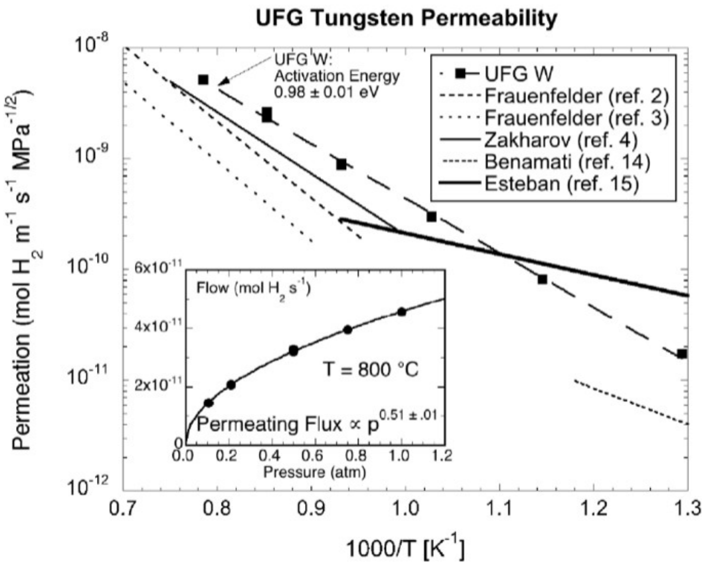
Above: Comparison of grain growth in IGW vs. different dispersoid strengthened W materials

E. Lang, H. Schamis, N. Madden, et al, *J. Nucl. Mater.* **545** (2021) 152613.

Laboratory testing of dispersoid-strengthened W shows promising results

Observations:

- Near-surface blistering during H exposure nearly eliminated up to ~10^{25} D/m^2
- Improved resistance to grain growth during high-temperature annealing up to 1800 °C
- Moderately higher (2-3 x) hydrogen isotope retention / permeation
  - However most trapped inventory can be liberated from the surface at low temperature (< 300 °C) [Barton et al., *Nucl. Mater. Energy* (2019)]



Above: Hydrogen permeability through different W materials, c.f. D. A. Buchenauer et al., *Fusion Eng. Design* (2016).

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  - Liquid Metals
- **Wrap-Up and Final Thoughts**

SiC Poses a Number of Potential Advantages as a Plasma-Facing Component (PFC) for Next-Step Devices

- **Graphite and Tungsten are the most studied, but are not ideal…**

PFC Property (not comprehensive)	Graphite	Tungsten	Silicon Carbide
Chemical Erosion*			?
Physical Erosion*			?
Melting/ Leading Edges			
Impurity Radiation			

Ultimate limit on T retention (via co-deposition)[1]

- **Graphite largely not considered reactor-relevant due to hydrogen retention and low neutron tolerance**

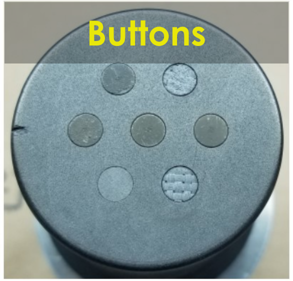
- **Silicon Carbide could reduce C erosion and co-deposition without the drawbacks of high-Z materials**
  - Next generation SiC/SiC composites[2] has stimulated renewed interest
  - Physical and chemical erosion properties need to be better understood -> ongoing research

[1]Doerner NME 2019
[2]Katoh JNM 2014

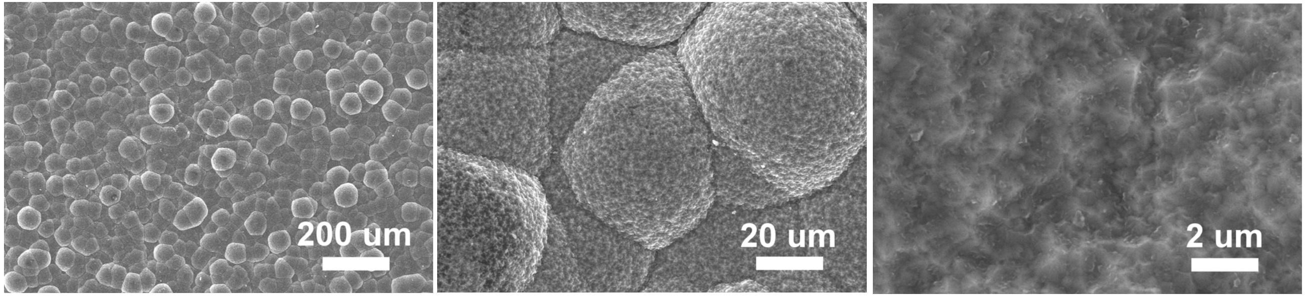
SiC coatings fabricated at General Atomics via chemical vapor deposition (CVD) were used for plasma bombardment testing

- **SiC samples were fabricated by General Atomics**
- **Chemical vapor deposition on ATJ graphite substrate**
  - crystalline β-SiC coating
  - layer thickness = 100-200 μm
- **Pristine composition: 50 ± 5 % Si/50 ± 5 % C**
- **Sample geometries: Buttons, DiMES caps, DIII-D tiles**

SiC-coated samples



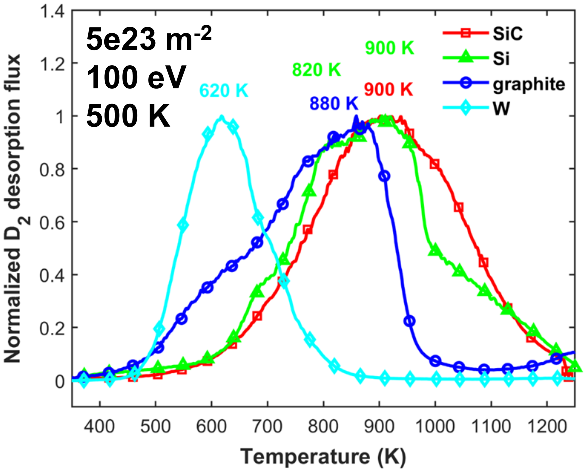
SEM micrographs of SiC surface



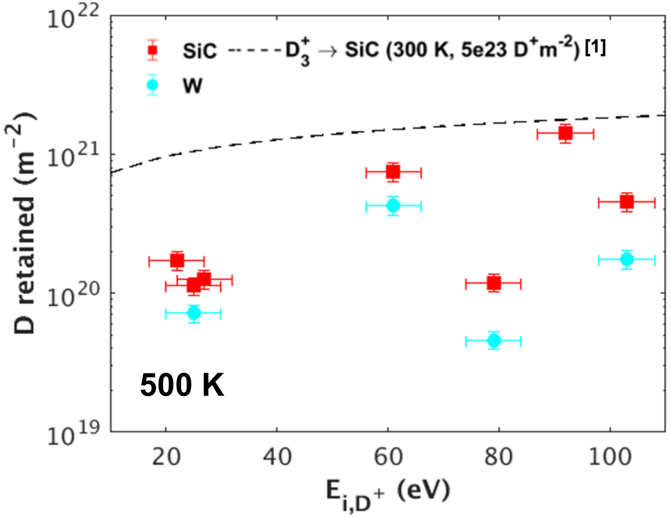
D retention via implantation in SiC measured in PISCES, found to be relatively similar to tungsten

- W and SiC samples exposed to same conditions in PISCES-E linear plasma device
- Total retention in SiC ~2x higher than W

Normalized desorption flux spectra



Total retention: SiC vs. W



- SiC samples exhibited one major desorption peak ~ 900 K
  - Somewhat higher than W (~600 K)
  - More similar to peaks in pure Si & graphite

Sinclair NME 2021

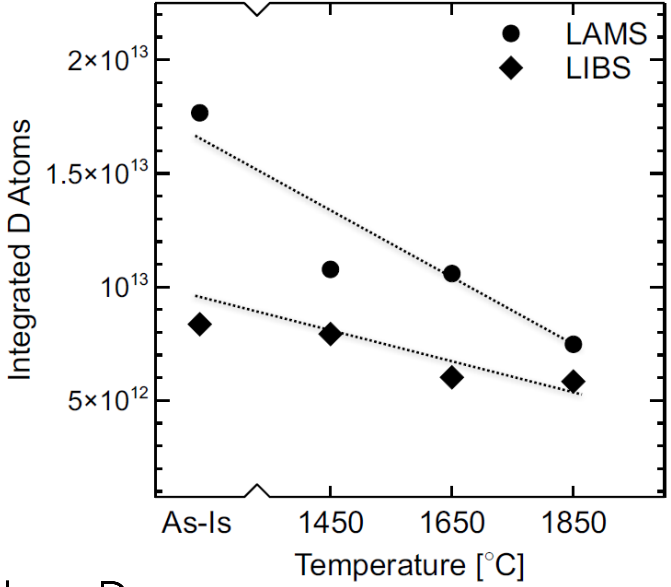
Heat-treated SiC samples exhibited slightly lower overall D retention due to annealing of intrinsic defects

- **DIII-D divertor (DiMES) exposure conditions**
  - L-mode, Fluence ~ 2.5×10^{24} m^{-2}
  - Average D^+ energy ~ 100 eV

- **D retention quantified via Laser-Induced Breakdown Spectroscopy/Laser Ablation Mass Spectrometry (LIBS/LAMS)**
  - Erosion/pulse (LAMS) ~ 0.3 μm

- **Higher heat treatment temperature lowers overall D retention**
  - adding heat anneals intrinsic defects that can trap D

Total retained D (LIBS/LAMS)

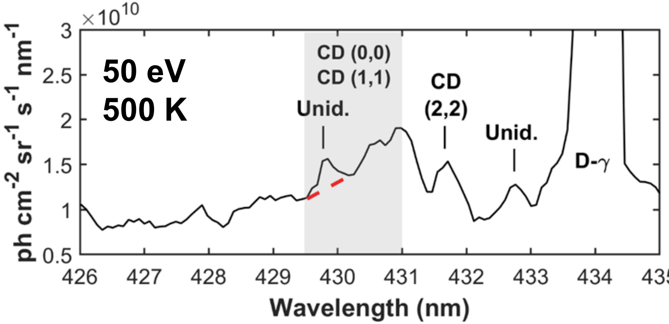


Bringuier, 2018

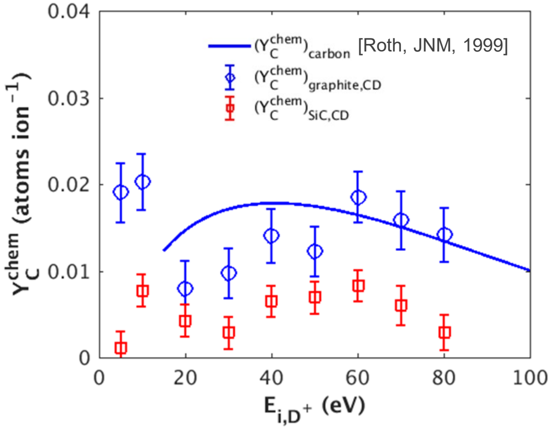
SiC samples exhibited 4× decrease in carbon chemical erosion compared to graphite samples; chemical erosion of Si not observed

- **CD emission band (430 nm) serves as proxy for chemical erosion of carbon**
  - D/XB method used to approximate Y_C^{chem} from CD band
- **Y_c^{chem} from SiC is 4× lower than that from graphite on average**
  - estimated Y_C^{chem} values from graphite are consistent with Roth formulation [1]
- **Si II, C II peaks not observed**
  - T_e in PISCES too low for significant ionization

Average emission intensity near CD band

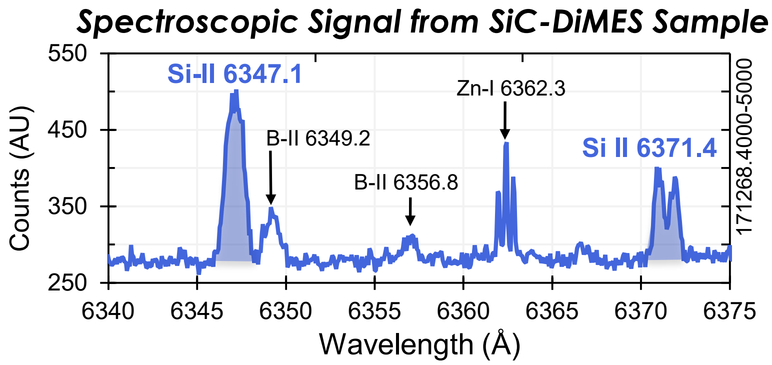


Y_c^{chem} vs. $E_{i,D+}$ for SiC & graphite

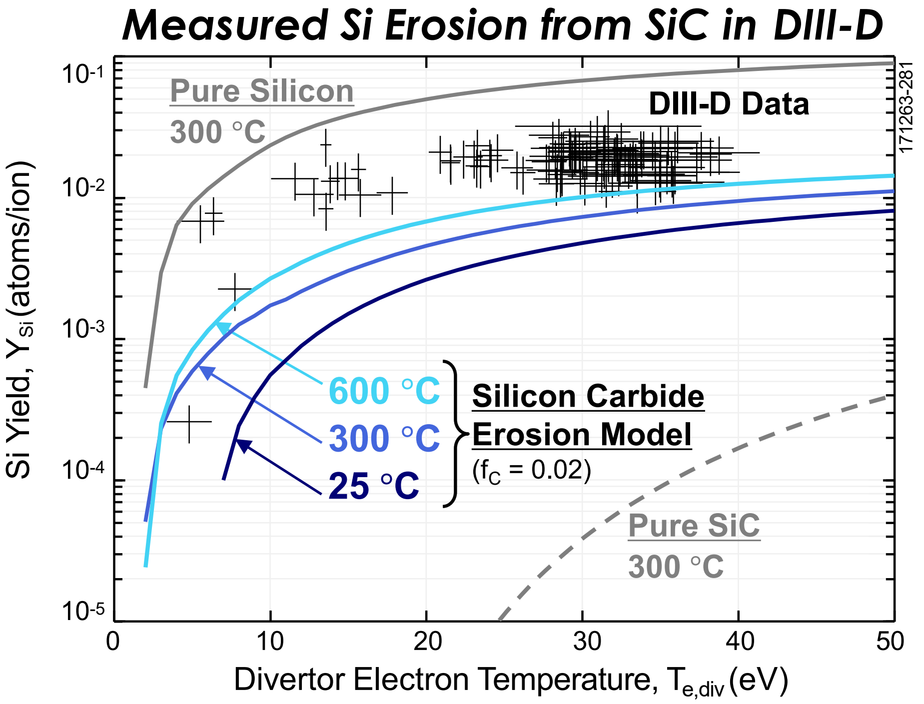


[1] Roth, 1999, JNM

Spectroscopically Inferred Si Erosion from SiC is Significantly Lower than for Pure Silicon in DIII-D

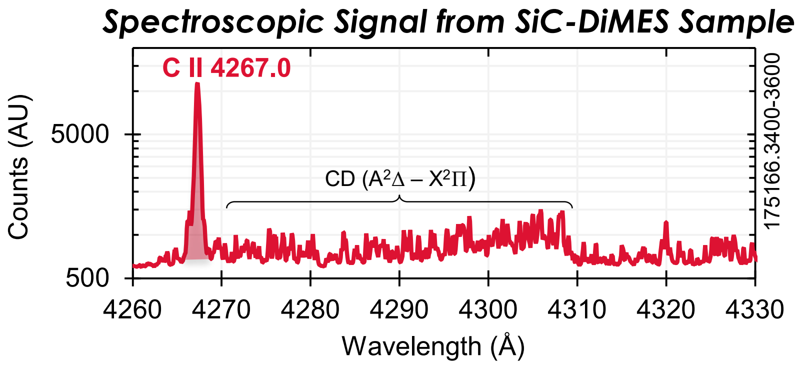


- **Atomic erosion flux inferred via ionizations/photon (S/XB) method[1]**
  - Emission intensity ~ erosion rate
  - Normalized to ion flux to measure Y_{Si}
- **Data closer to pure Si due to enrichment**
- **Model slightly under-estimates Si erosion, likely due to ELMs (not included in model)**

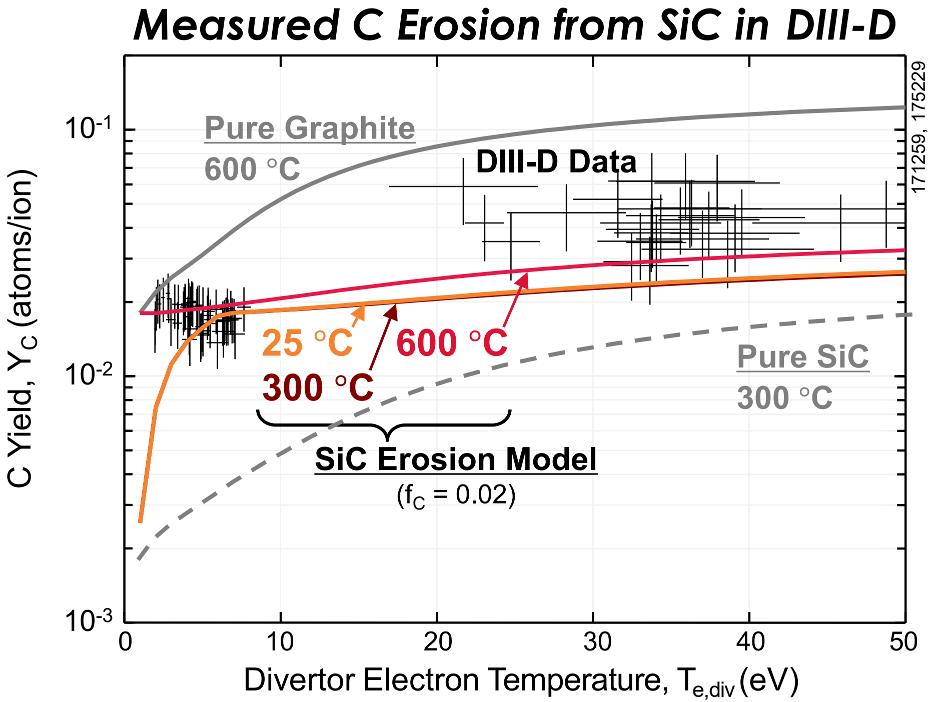


[1]ADAS, www.adas.ac.uk

Spectroscopically Inferred C Erosion from SiC is Significantly Lower than for Pure Graphite in DIII-D



- **Atomic erosion flux inferred via ionizations/photon (S/XB) method[1]**
  - Emission intensity ~ erosion rate
  - Normalized to ion flux to measure Y_C
- **Measurements of Y_C are close but slightly above model calculations**
  - Likely due to ELMs (not included in model)

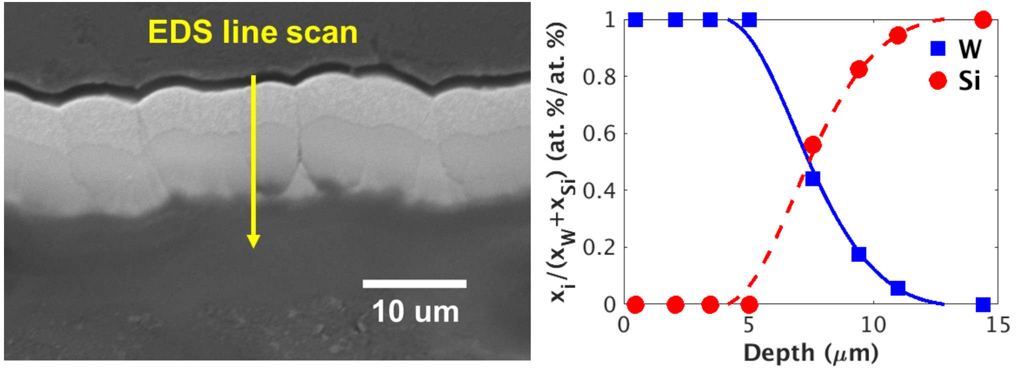


[1]ADAS, www.adas.ac.uk

Promising advanced SiC composite prototypes were also tested

- **W-SiC functionally-graded composite**
  - good compatibility between W & SiC
  - Goal: 100% W at surface → 100% SiC at coating interface
  - fabricated via physical vapor deposition
  - layer thickness ~ 10 µm
- **SiC_f-SiC composite**
  - improved toughness over monolithic SiC [1]
  - fabricated via chemical vapor infiltration over a fiber-reinforced matrix

EDS line scan of W-SiC cross-section



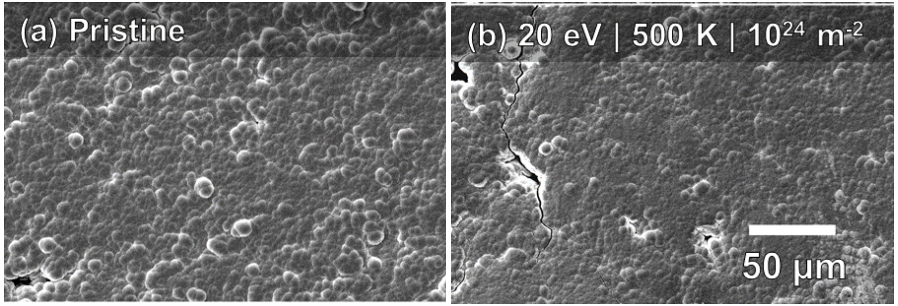
Property		W	SiC
CTE (@ 300 K)	[10^{-6} K^{-1}]	4.3	3.8
Structural operating temperatures	[K]	800-1300	550-1050

[1] Katoh, JNM, 2014

Significant increases in D retention in W-SiC compared to pristine tungsten likely caused by manufacturing-induced defects

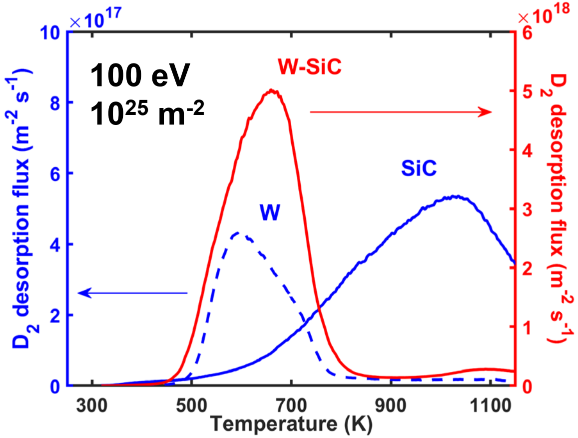
- **Exposure of W-SiC samples in PISCES resulted in minimal surface degradation**
- **Surface concentration remained > 70% W up to 10^{25} m^{-2} fluence**
- **Total D retention in W-SiC was ~ 10× higher than in W or SiC**
  - most D trapped at W-specific intrinsic defects
  - improvements in fabrication may reduce intrinsic trap density

SEM micrographs of surface (before vs. after)



Sample	Total D retained (m^{-2})
W-SiC	2.0×10^{21}
SiC	4.4×10^{20}
W	1.6×10^{20}

Desorption: W-SiC vs. W vs. SiC



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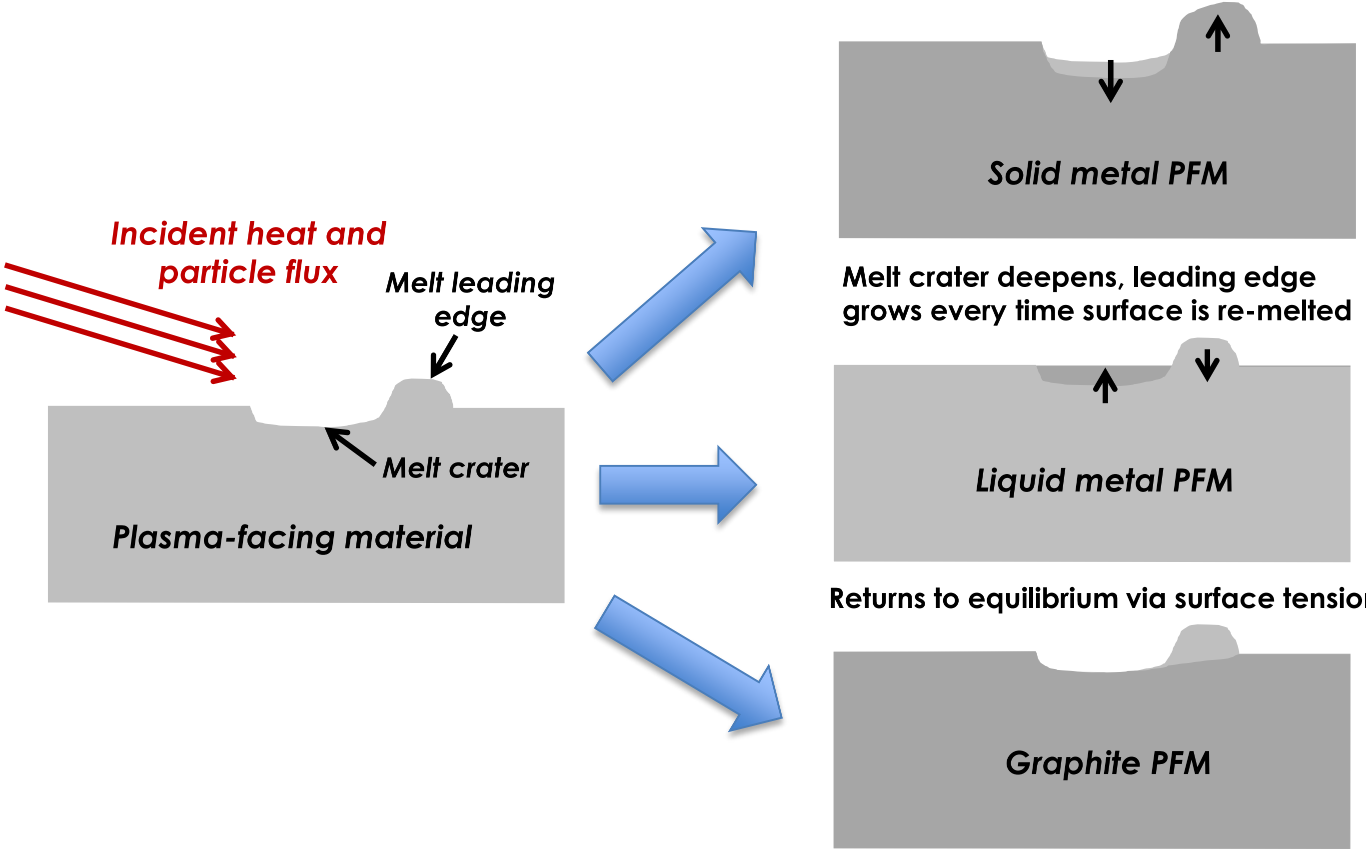
Solid metals suffer from the "reshaping problem" while liquid metals are "self healing"



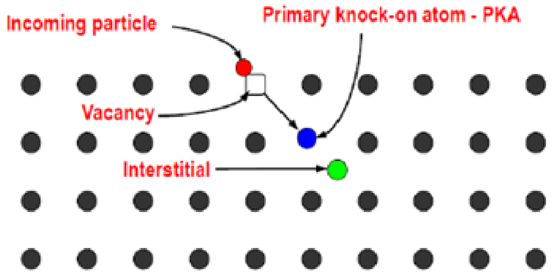
Melt crater deepens, leading edge grows every time surface is re-melted

Returns to equilibrium via surface tension

Leading edge is "machined away" by plasma flux

Neutron damage is problematic in solid materials

- **Damage characterized by dpa = "displacements per atom"**
  - ITER: ~0.7 dpa lifetime
  - Reactor: ~100 dpa lifetime

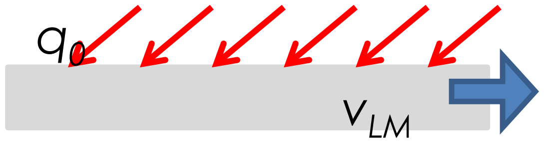


- **Problems cause by neutrons:**
  - Embrittlement
  - Increased T retention
  - Degrades thermal conductivity (lowers acceptable heat flux)
  - Activation

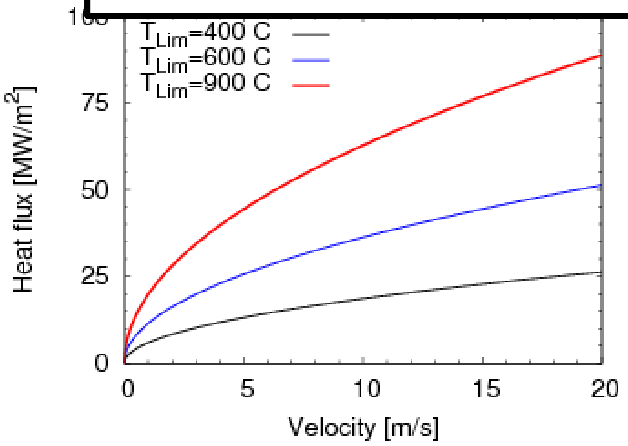
- **Liquid metals have no "structure" -> no neutron damage**
  - Note: the underlying solid material will still be damaged
  - LMs **separate** the heat flux problem from neutron damage effects!

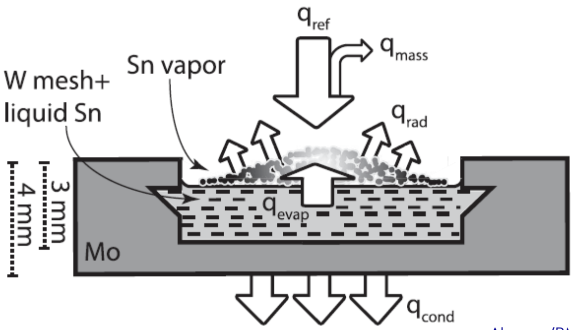
Liquid metals provide potential additional channels for heat dissipation

- **Flowing liquid dissipates heat via convection**
- **"Vapor shielding"**
  - LM evaporation produces neutral vapor cloud
  - Plasma-neutral interactions lead to heat dissipation
  - Recently demonstrated experimentally for liquid Sn[1]



Incident heat flux vs. velocity





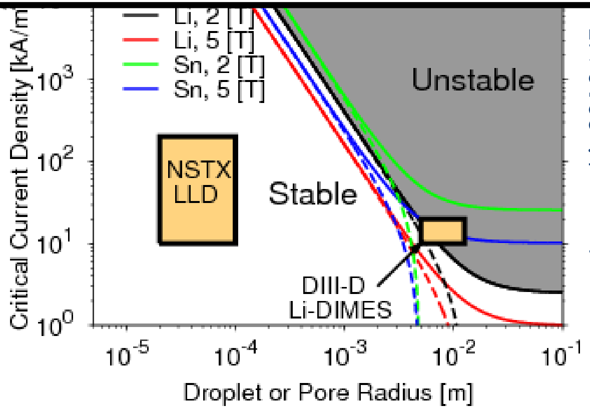
[1]van Eden PRL 2016

Issue 1: The liquid metal needs to stay on the wall (1/2)

- **Liquid metal surfaces can become MHD unstable (R-T or K-H)**
  - Leads to droplet ejection -> video
  - Macroscopic ejection events can dominate erosion
    - Seen on DIII-D, HT-7, EAST, Magnum-PSI

- **LM surface can be stabilized using porous targets**
  - Essentially a LM "sponge"
  - Capillary forces counter-act jxB ejection forces

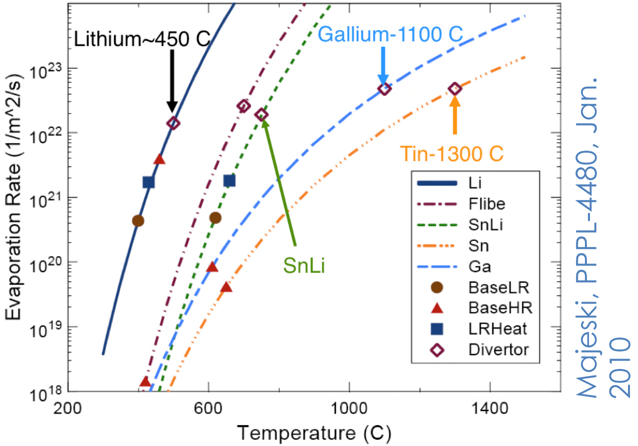
Rayleigh-Taylor stability analysis for liquid metal surfaces

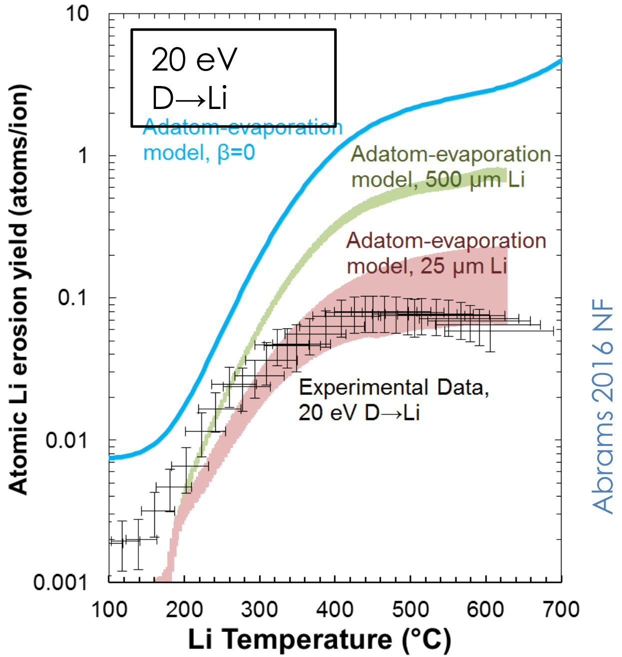


Jaworski, 2013 NF

Issue 1: The liquid metal needs to stay on the wall (2/2)

- **Very strong LM evaporation could lead to unacceptable core contamination levels**

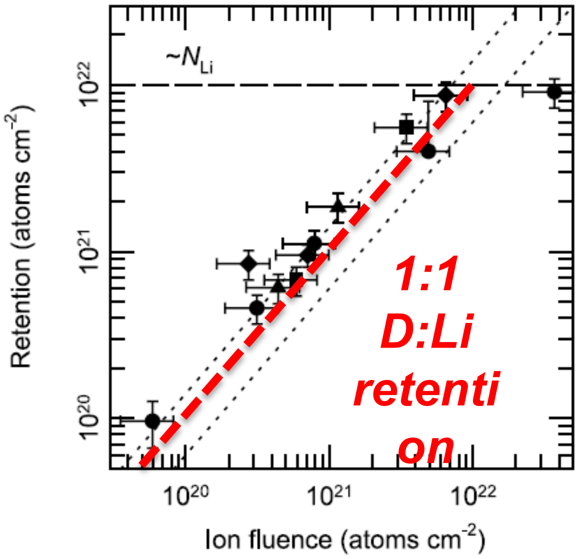




- **D uptake in liquid Li may help**
  - LiD formation appears to strongly suppress erosion
  - Could widen the temp. window for liquid Li divertor

Issue 2: Tritium Extraction

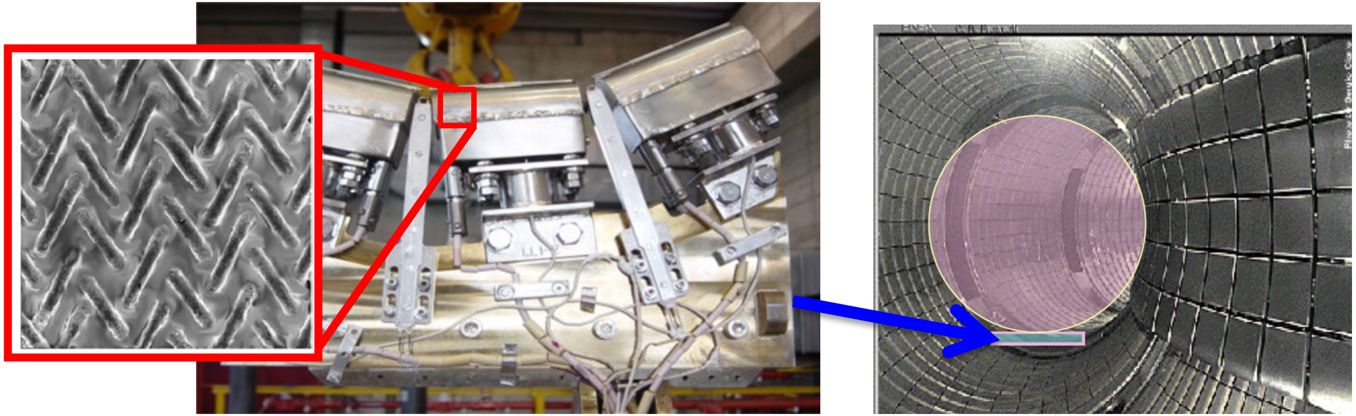
- **In the D-T fuel cycle, high tritium burn fraction required to maintain TBR > 1**
- **In ITER, safety concerns limit T inventory to 700 g**
- **Liquid Li retains H/D/T isotopes in up to a 1:1 ratio**
  - Some filtration systems must be developed
  - "Just an engineering issue"
- **Other liquid metals (Sn, Ga, etc.) only retain 1-2% hydrogenics**
  - Comparable to solid metals (W, Mo, etc.)



Baldwin 2002 JNM

Capillary-porous system (CPS) targets prevent droplet ejection

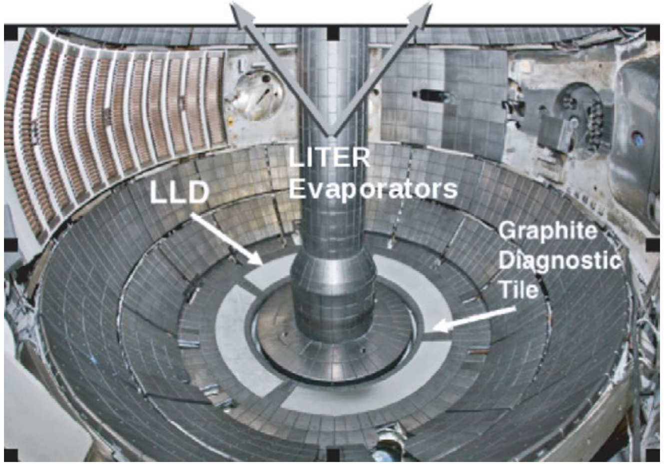
- Liquid Li CPS system installed on Frascati Tokamak Upgrade (FTU) in Frascati, Italy



- No droplet ejection or confinement degradation observed
- Demonstrates technological feasibility for liquid Li PFCs

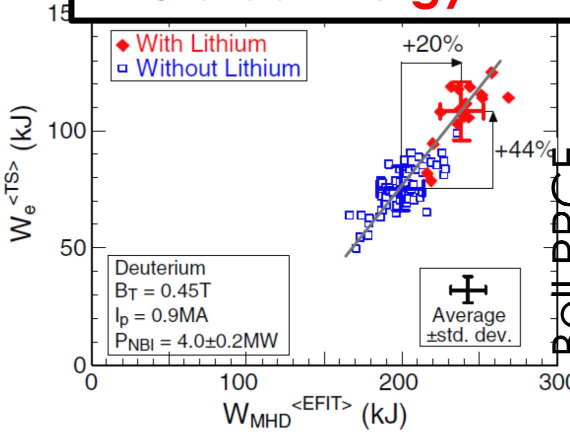
NSTX Evaporated Li experiments and Liquid Lithium Divertor (LLD)

- **Improved plasma performance with Li evaporative wall conditioning on graphite**
- **LLD experiment attempted in 2012 for full liquid Li divertor…**



Jaworski NF 2013

Stored Energy in NSTX



Bell PPCF 2009

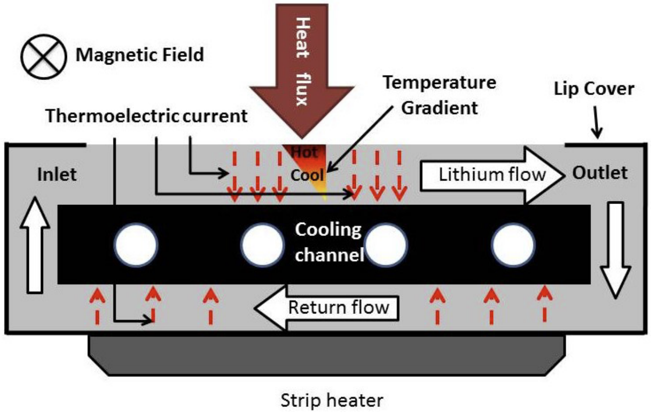
…had some problems

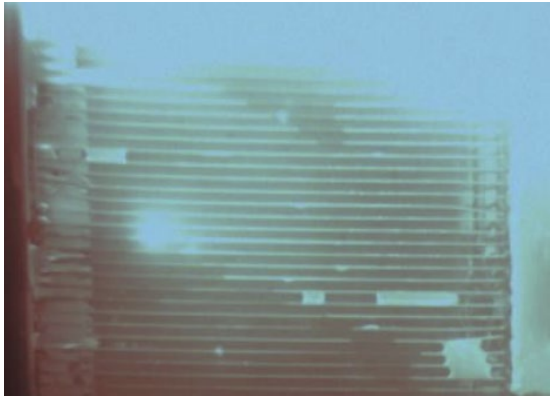
- 3/4 modules failed due to shorted heater leads
- Liquid Li could not be maintained w/o plamsa heating

- **Plus side: No droplet, macroscopic Li ejection**

Flowing liquid Li concepts tested in HT-7

- **SLiDE concept (U. Illinois)**
  - Thermal gradients drive currents at the junction between two materials (thermoelectric effect)
  - Liquid Li flows in ~1 mm wide trenches
  - Previously demonstrated in benchtop experiments -> video
  - No droplet ejection observed on HT-7





SLiDE during HT-7 plasma shot

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Final Thoughts

- **PMI is probably the 2nd most critical physics issue to be solved for fusion reactors (after disruptions)**

- **Tungsten remains the leading candidate PFC material but a suitable W alloy for reactors has yet to be developed**
  - We need a back-up plan: SiC or liquid metals

- **The U.S. Community must develop a cohesive road map to address outstanding PMI physics gaps for a fusion pilot plot!**