SAND2018-7190C

DIII-D NATIONAL FUSION FACILITY

Attractive retention properties in displacement damaged ultra-fine grain tungsten exposed to divertor plasma

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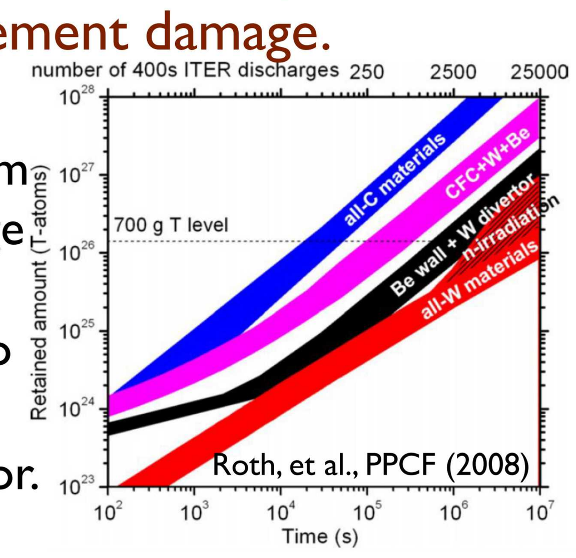
Motivation

➡ Hypothesis: Grain boundaries (GB) can provide a sink for mobile in-grain vacancies, so increasing the GB density can mitigate displacement damage.

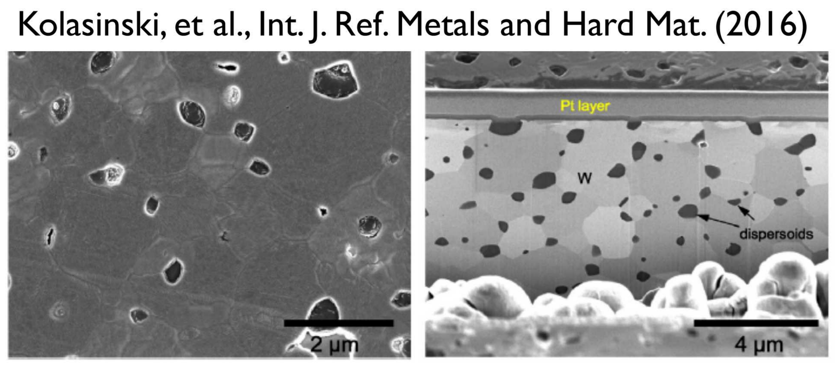
- Prescribed tritium inventory levels limit DT operation
- n-irradiated materials have more lattice defects that can trap tritium
- Trapped hydrogen isotopes in in-grain lattice vacancies require large (>700°C) heating temperatures to remove (*Shimada, NF, 2015*)
- Thus, we are concerned with displacement damage as it pertains to hydrogenic retention



We conduct the first retention tests of UFG W in a tokamak divertor. UFG and ITER grade W samples are pre-damaged with Si ions and retention is measured *post-mortem*.

Ultra-fine grain (UFG) W

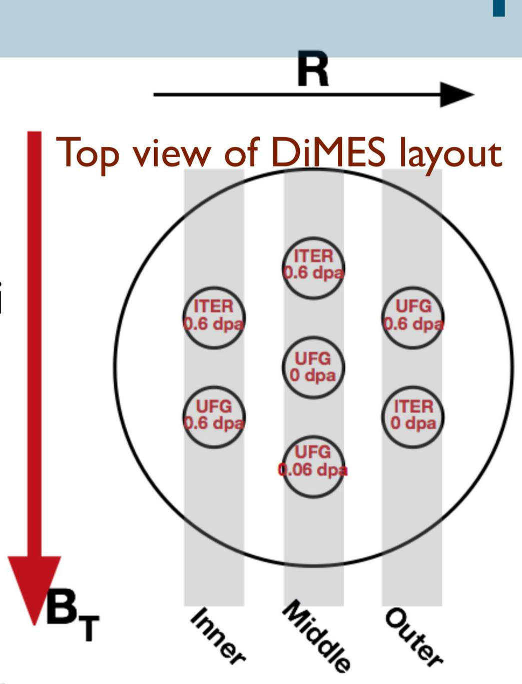
Kolasinski, et al., Int. J. Ref. Metals and Hard Mat. (2016)

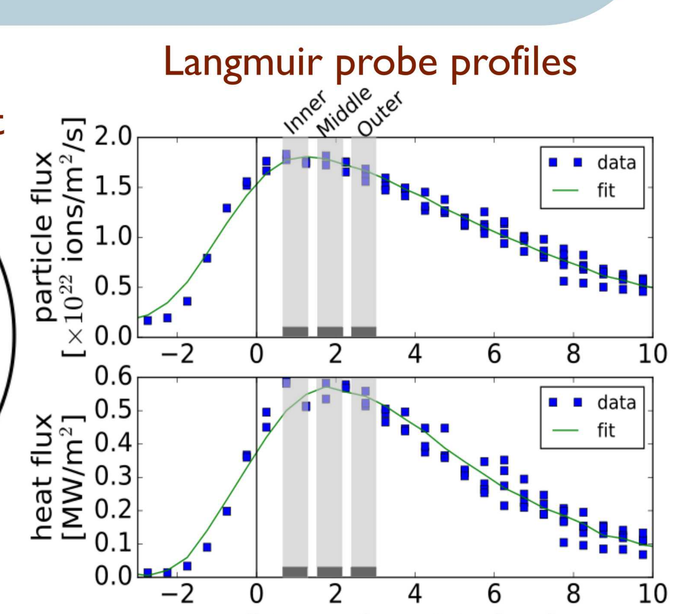


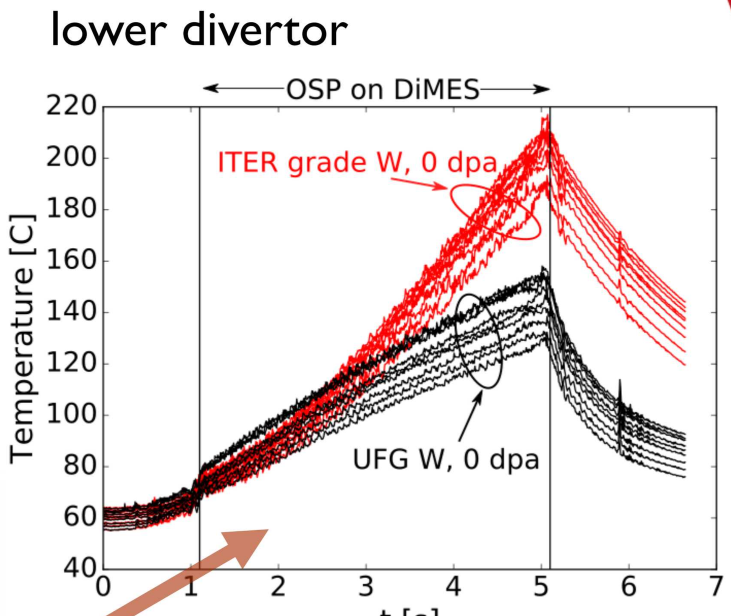
- Unique powder metallurgy process that uses Ti particles to act as grain growth inhibitors
  - Average grain size = 1 μm
  - Bulk samples: 2 mm thick & 6 mm ⌀
  - Choice of Ti for dispersoid additive was for convenience in these initial tests
- Properties and past experimental results
  - Ductile at room temperature
  - No measureable formation of surface bubbles/blisters in PISCES (with ~10^{25} D/m^2)
  - Resistant to recrystallization/grain growth
  - Resistant to damage from transient heat loading in e-beam experiments

DIII-D plasma exposure

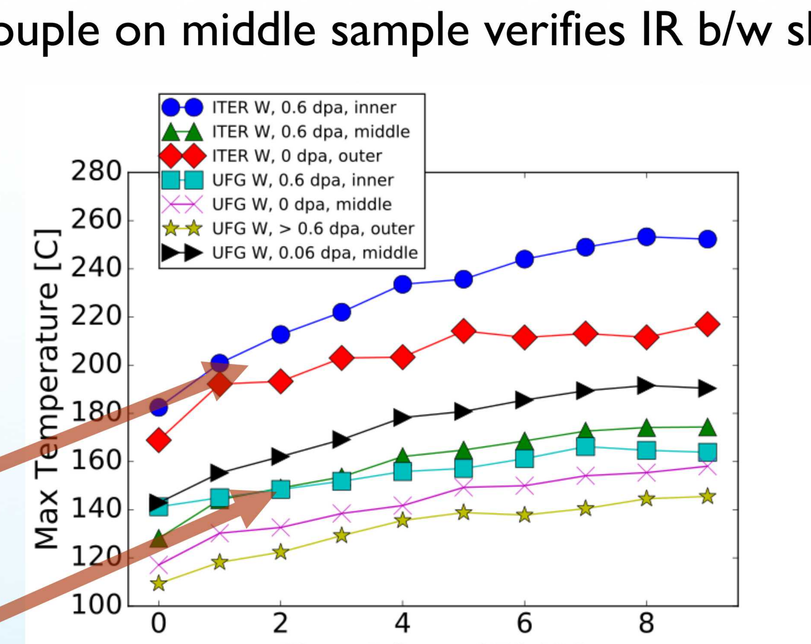
- UFG & ITER W samples
  - UFG W (ZZ Fang)
  - ITER grade W (Sumitomo)
  - Pre-damaged with 12 MeV Si ions to 0.06 & 0.6 dpa
- Exposure to plasma using Divertor Materials Evaluation Station (DiMES) in the DIII-D lower divertor





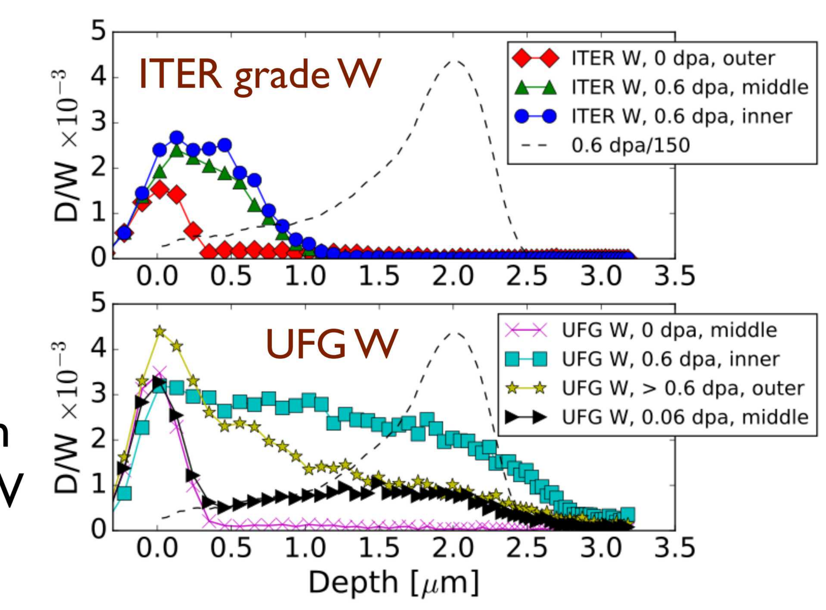


- Ten identical deuterium LSN L-mode discharges
  - 1.75 x 10^{22} D/m^2/s flux ➡ 7 x 10^{23} D/m^2 fluence
- Langmuir probe profiles show nearly uniform particle and heat fluxes across all samples
- IR camera views DiMES from top
  - Calibrated on W to 335°C before experiment
  - Thermocouple on middle sample verifies IR b/w shots
- Surface temperatures varied due to loss of thermal contact during discharge
  - Temperature uniformity is essential for retention comparisons among samples
- Peak temperatures at the end of each shot
  - Two ITER W samples significantly hotter
  - Fortunately, there is one set of 0.6 dpa UFG and ITER samples with identical temperature histories



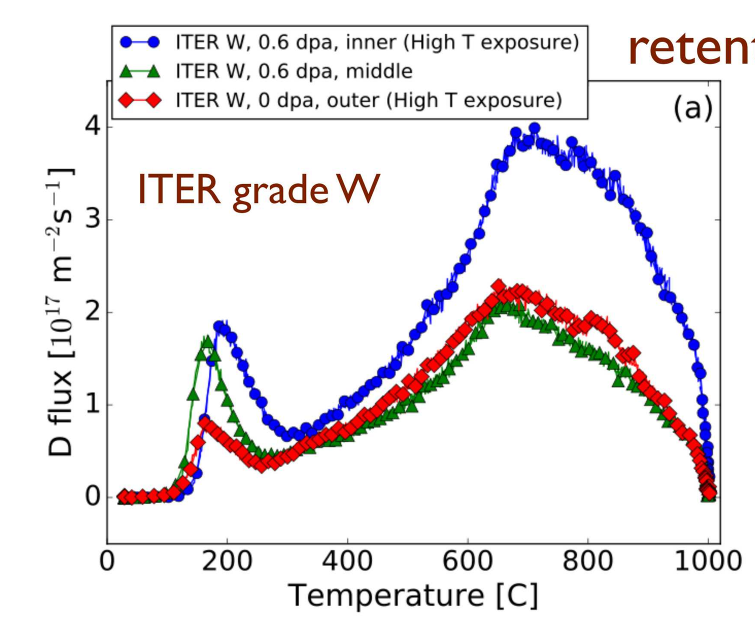
Retention analysis

Depth profiles measured with D(^{3}He,p)α nuclear reaction analysis (NRA) and TRIM simulation of damage profile (dashed line)

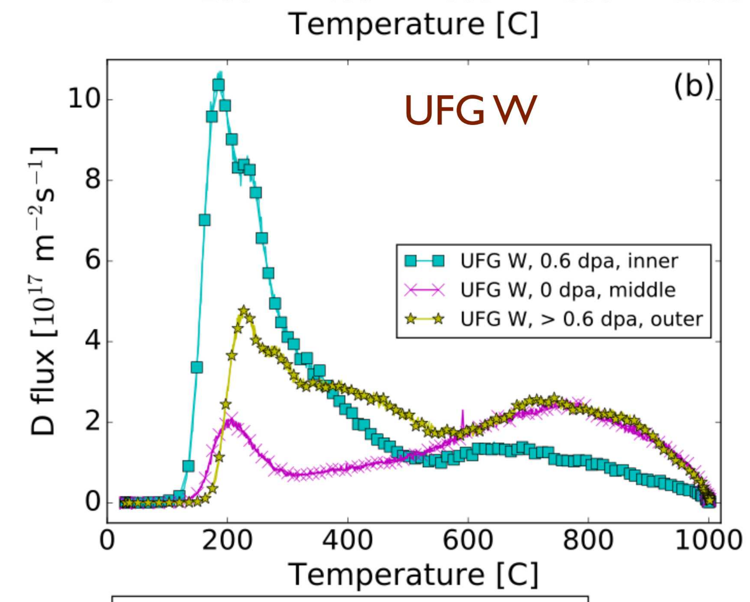


- Undamaged UFG has 2.3x higher inventory than ITER grade W
- Retention increase in damaged ITER W in < 1μm
- Entire damage region populated with D in UFG W for all damage levels (0.06, 0.6, and >0.6 dpa)

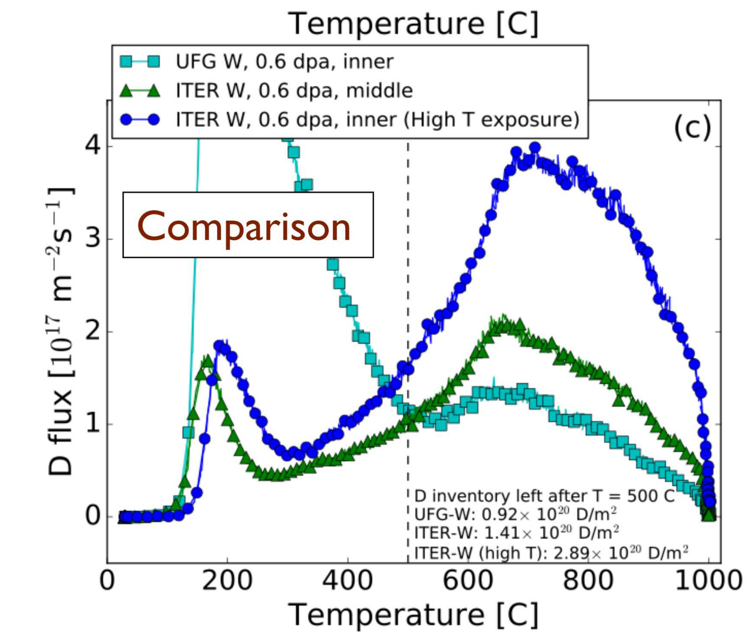
Thermal desorption spectroscopy (TDS) measures total retention and qualitatively describes trapping energies



ITER grade W
- Two clear flux peaks at low (200°C) and high (700°C) temperatures in all cases
  - Associated with low and high energy traps
- High temperature plasma exposure increases diffusivity and results in higher high-temp peaks
- Damage increases both low and high temp peaks (also see *Barton, NF, 2016 and Simmonds, JNM, 2017*)



UFG W
- Low and high temperature peaks similar to ITER grade W, but additional peaks in-between as well
- Damaged samples have increased low-temp peaks, but NO high-temp peak increase (>500°C)
  - Damage increases density of low energy traps (like grain boundary traps: *Zhou, NF, 2010*)
  - ➡ Displacement damage created vacancies assimilate into grain boundaries with a higher probability in UFG W



Comparison of samples with similar damage level and temperature history
- After heating to 500°C, the ITER grade W samples have significantly more D inventory retained
- Most of the trapped D in UFG W is released at low temperatures
- ➡ A high density of of low energy traps near the surface can dominate trapping and inhibit diffusion

Summary

Sample, location	dpa	Total retention [$\times10^{20} D/m^2$]	% within 3 μm (damage region)	Inventory left after heating to 500 °C [$\times10^{20} D/m^2$]
ITER, outer (high Temp)	0	2.04	25	1.59
UFG, middle	0	2.44	40	1.74
ITER, middle	**0.6**	**1.96**	**61**	**1.41**
UFG, inner	**0.6**	**3.98**	**100**	**0.92**
ITER, inner (high Temp)	0.6	3.63	39	2.89
UFG, outer	> 0.6	3.75	86	1.87
UFG, middle	0.06	1.89* only NRA available		–

- Most of the trapped D is released from damaged UFG W by low temp heating
  - Routine low-temp baking of UFG W can mitigate tritium retention in fusion reactors
- The increase of low energy traps suggests the in-grain vacancies created by displacement damage assimilate into the grain boundaries in UFG W

Future work
- Temperature & dpa scans to study the temperature & damage variations we observe here

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