Possible defect stabilization due to simultaneous deuterium exposure during annealing in self-ion damaged W

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Motivation

- Synergistic effects are known to affect defect creation/recovery and have a strong effect on hydrogen isotope retention.

- There is a strong need for simultaneous experiments (hydrogen isotope exposure during defect creation/annealing).

- These synergistic effects need to be included in the models in order to accurately predict hydrogen isotope retention and permeation.
Studying annealing of heavy-ion damaged W

Vacuum annealing (W-A-D)

W self-damaging → Annealing (vacuum) → D plasma exposure → NRA & TDS
Effect of D filled defects on annealing

Vacuum annealing (W-A-D)

W self-damaging → Annealing (vacuum) → D plasma exposure → NRA & TDS

Vacuum annealing after plasma exposure (W-D-A-D)

W self-damaging → D plasma exposure → Annealing (vacuum) → D plasma exposure → NRA & TDS

M. Pečovnik et al. 2020 Nucl. Fusion 60 106028
D presence during annealing clearly different

- monotonic decrease in LT peak
- monotonic decrease in HT peak

- large change in LT peak at 600 K anneal
- little change in HT peak until 800 K anneal
Next step: study simultaneous annealing+plasma

Vacuum annealing (W-A-D)

W self-damaging → Annealing (vacuum) → D plasma exposure → NRA & TDS

Vacuum annealing after plasma exposure (W-D-A-D)

W self-damaging → D plasma exposure → Annealing (vacuum) → D plasma exposure → NRA & TDS

Annealing during plasma exposure (W-D-AD-D)

W self-damaging → D plasma exposure → Annealing + D plasma → D plasma exposure → NRA & TDS
W-D (no annealing fiducial)

- strong D retention in damaged zone (< 2.2 µm)
Retention diverges for 473 K anneal

- strong D retention in damaged zone (< 2.2 µm)
- D retention change after vacuum anneal or plasma anneal

<table>
<thead>
<tr>
<th>A (K)</th>
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<tr>
<td>473</td>
<td>small decrease</td>
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Retention continues to diverge at 573 K

- strong D retention in damaged zone (< 2.2 µm)
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![Graphs showing D concentration vs depth for W-A-D and W-D-AD-D at different temperatures](image-url)
Retention ~constant up to 673 K plasma anneal

- strong D retention in damaged zone (< 2.2 µm)
- D retention change after vacuum anneal or plasma anneal

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- NRA shows nearly constant D retention in damage zone up to 673 K for plasma anneal, defect stabilization
Significant D depopulation and recovery at 773 K

- strong D retention in damaged zone (< 2.2 µm)
- D retention change after vacuum anneal or plasma anneal

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- NRA shows nearly constant D retention in damage zone up to 673 K for plasma anneal defect stabilization
W-D (fiducial for comparison)

- two desorption peaks
  - low-temperature (LT) mono-vacancies/dislocations?
  - high-temperature (HT) vacancy clusters?

E. Markina et al. 2015 J. Nucl. Mater. 463 329–32
Primarily LT grows (beyond damage zone)

- two desorption peaks
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- NRA shows nearly constant D retention in damage zone up to 673 K for plasma anneal \( \square \) defect stabilization
LT & HT grow (beyond damage zone)

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- NRA shows nearly constant D retention in damage zone up to 673 K for plasma anneal □ defect stabilization
Significant growth of HT (beyond damage zone)

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- NRA shows nearly constant D retention in damage zone
  - up to 673 K for plasma anneal □ defect stabilization
Significant shift to higher T for HT

- two desorption peaks
  - low-temperature (LT) □ mono-vacancies/dislocations?
  - high-temperature (HT) □ vacancy clusters?

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- NRA shows nearly constant D retention in damage zone up to 673 K for plasma anneal □ defect stabilization
Total D Retention (TDS)

- Initial increase probably due to higher D fluence in the case of W-D-AD-D
- Clearly very different behavior of defect recovery when D is present
- Modeling can give some insight into defect stabilization in the presence of D
Vacuum anneal well fit by 3 traps

- typically 3 trap types used to model TDS spectra
  - LT peak, HT peak, & HT tail
Plasma anneal needs additional trap

- typically 3 trap types used to model TDS spectra
  - LT peak, HT peak, & HT tail
- this work revealed the existence of the 4th trap type (small vacancy clusters?)
Vacuum anneal trap conc. monotonic decrease

• typically 3 trap types used to model TDS spectra
  ○ LT peak, HT peak, & HT tail
• this work revealed the existence of the 4th trap type (small vacancy clusters?)
• W-A-D monotonically decreasing trap densities
Plasma anneal exhibits complex trap evolution

- Typically 3 trap types used to model TDS spectra
  - LT peak, HT peak, & HT tail
- This work revealed the existence of the 4th trap type (small vacancy clusters?)
- W-A-D $\square$ monotonically decreasing trap densities
- W-D-AD-D $\square$ complex evolution of trap densities
Total D retention (including W-D-A-D)

- open = NRA (damage zone)
- filled = TDS

[1] M. Pečovnik et al. 2020 Nucl. Fusion 60 106028
D presence during annealing clearly different

- W-A-D
  - all traps empty during anneal
- W-D-A-D
  - traps partially D filled □ reduced recovery
  - D continuously desorbed while held-at-temperature

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D presence during annealing clearly different

- **W-A-D**
  - all traps empty during anneal
- **W-D-A-D**
  - traps partially D filled \(\Rightarrow\) reduced recovery
  - D continuously desorbed while held-at-temperature
- **W-D-AD-D**
  - traps partially D filled \(\Rightarrow\) reduced recovery
  - D continuously repopulated with D plasma exposure held-at-temperature
  - mobile defects annihilate at surface/GB but defects migrating further into bulk slowed/stabilized by D?

\[\text{Retention [10^2 D/m}^2\]\]

- open = NRA (damage zone)
- filled = TDS

[1] M. Pečovnik et al. 2020 Nucl. Fusion 60 106028
Thank you!

- Annealing of W simultaneously exposed to D plasma:
  - obvious synergistic effects
  - reduced defect recovery → D induced stabilization of defects
  - Further experimental details
    - M.J. Simmonds et al. 2022 Nucl. Fusion 62 036012

- Future:
  - ending Be work (Be box is gone!) and focusing on synergistic effects in W
  - finalizing plans for heavy ion accelerator (NEC) installation/coupling to PISCES-RF
  - improving modeling capabilities, including synergistic effects in the codes
Experimental Details
Sample Prep

- PCW samples:
  - 1.5 mm thick and 6 mm dia
  - polished and recrystallized
Heavy-ion induced defects

- **W-A-D**
  - W self-damaging
  - **W-D-AD-D**
  - W self-damaging
  - **Annealing**
  - D plasma exposure

- **PCW samples:**
  - 1.5 mm thick and 6 mm dia
  - polished and recrystallized

- **W self-damaging:**
  - 20.3 MeV W$^{6+}$ ions at 295 K
  - $7.87 \times 10^{17}$ ions/m$^2 \rightarrow 0.23$ dpa
D decoration of defects

- **W-A-D**
  - W self-damaging

- **W-D-AD-D**
  - W self-damaging
  - D plasma exposure
  - Annealing
  - D plasma exposure
  - NRA & TDS

- **PCW samples:**
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- **W self-damaging:**
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- **D plasma exposure:**
  - temperature 383 K
  - flux 1.1 x 10^{21} D/m^2 s
  - impact energy $\sim$ 67 eV
  - fluence 2 x 10^{25} D/m^2 (5 h)
    (1 x 10^{25} D/m^2 before annealing)
Annealing with or without D plasma

- **PCW samples:**
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- **W self-damaging:**
  - 20.3 MeV W$^{6+}$ ions at 295 K
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  - temperature 383 K
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  - fluence $2 \times 10^{25}$ D/m$^2$ (5 h)
  - $1 \times 10^{25}$ D/m$^2$ before annealing

- **Annealing:**
  - 473 K, 573 K, 673 K, and 773 K for 1 h
  - D fluence $4 \times 10^{24}$ D/m$^2$
Quantification of D retention

**W-A-D**
- **W** self-damaging

**W-D-AD-D**
- **W** self-damaging
- **D** plasma exposure
  - **Annealing**
  - **D** plasma exposure

**PCW samples:**
- 1.5 mm thick and 6 mm dia
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**W self-damaging:**
- 20.3 MeV W$^{6+}$ ions at 295 K
- $7.87 \times 10^{17}$ ions/m$^2 \rightarrow 0.23$ dpa

**NRA & TDS:**
- $^3$He ions with 0.5, 0.69, 0.8, 1.2, 1.8, 2.4, 3.2, and 4.5 MeV $\rightarrow$ protons and alphas
- TDS at 0.05 K/s

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- temperature 383 K
- flux $1.1 \times 10^{21}$ D/m$^2$s
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