Deuterium retention in tungsten damaged by high-energetic tungsten ions

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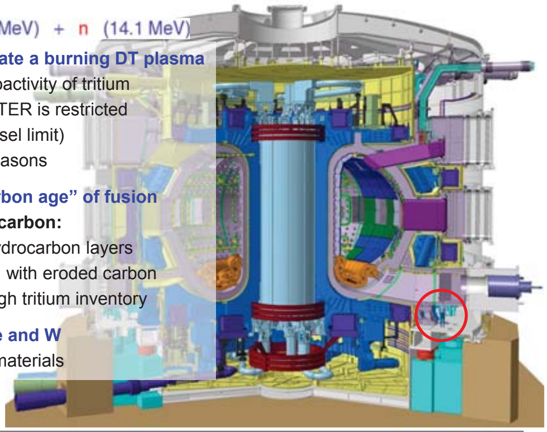
Motivation: Tritium Inventory in ITER



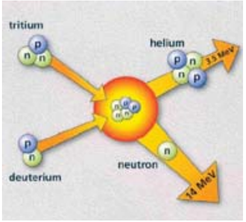
D + T → α (3.5 MeV) + n (14.1 MeV)

- **ITER will investigate a burning DT plasma**
  - ⇒ Problem: Radioactivity of tritium
  - ⇒ T-inventory in ITER is restricted to 700 g (in vessel limit) due to safety reasons
- **1990 – 2010: "Carbon age" of fusion**
  - ⇒ **Knock-out for carbon:** Formation of hydrocarbon layers by codeposition with eroded carbon results in too high tritium inventory

⇒ **ITER will use Be and W** as plasma-facing materials

Neutron damage of tungsten

D + T → α (3.5 MeV) + n (14.1 MeV)



Irradiation of tungsten by fast neutrons results in

- **Displacement damage**
  - ⇒ Vacancies, vacancy clusters, interstitials, …
  - ITER: Maximum ~ 1 dpa
  - DEMO: ≤ 15 dpa per 1 fpy M.R. Gilbert JNM (in press)
- **(n,α) reactions**
  - ⇒ Production of helium in the bulk of the material
  - DEMO: ≤ 4 ppm He per 1 fpy M.R. Gilbert JNM (in press)
- **Transmutation products**
  - ⇒ Rhenium, Osmium

Displacement damage by heavy ions often used as proxy for neutrons

B. Tyburska JNM 395 (2009) 150; O.V. Ogorodnikova JNM 415 (2011) S661; V.Kh. Alimov JNM 420 (2012) 370; …

Simulation of Neutron effects by Ions

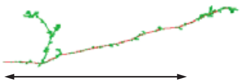
Creation of a collision cascade, starting with primary knock-on (PKA)

- PKA spectrum has some similarities between n and W
  - ⇒ Kinetic aspect can be simulated (to some extend) with ions

Differences between n and ions:

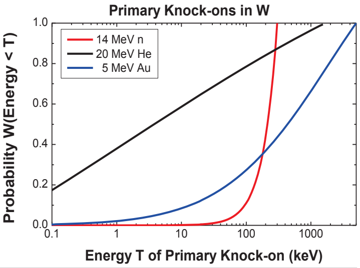
- He-effects, transmutations cannot be simulated directly by ions
- Ions deposit energy by electronic energy loss, ~9 keV/nm @ 20 MeV
  - ⇒ local heating around ion track

20 MeV W in W



1 µm

Primary Knock-ons in W



S. Bouffard, private communication

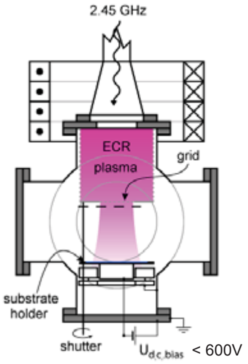
Experimental: Deuterium implantation

Low-temperature ECR plasma (PlaQ):

- ion flux: 0.5 – 1×10^{20} D/(m^{2}s)
  97% as D_3^+
  2% as D_2^+
  1% as D^+

A. Manhard, Plasma Sources Sci. Technol. **20** (2011) 015010

- atom flux > 10^{21} D^0/(m^{2}s)
- energy: „<5eV/D" (floating)
- T = 400-450 K (liquid thermostats)

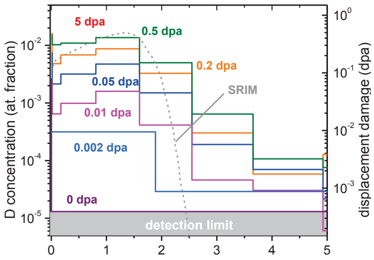


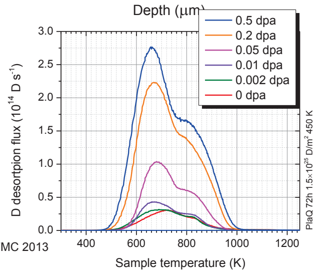
"Gentle" implantation of deuterium

⇒ **Minimal additional damage by implantation**

Retention in damaged W

- Hydrogen retention in natural W: 0.001 – 0.01% at ≤ 450 K
- Displacement damage increases hydrogen retention to 1.5% at 450 K
  - ⇒ In the presence of neutrons retention is dominated by damage



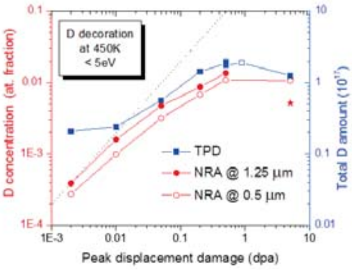


T. Schwarz-Selinger, PFMC 2013

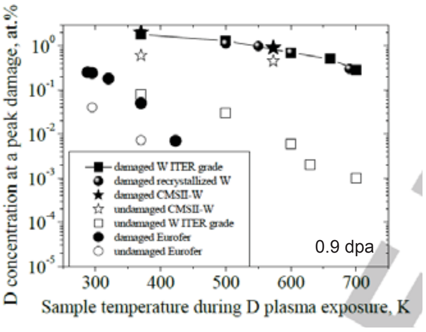
Retention in damaged W

- Retention in displacement damage saturates at 0.5 - 1 dpa

T. Schwarz-Selinger, PFMC 2013



Retention in damaged W (2)

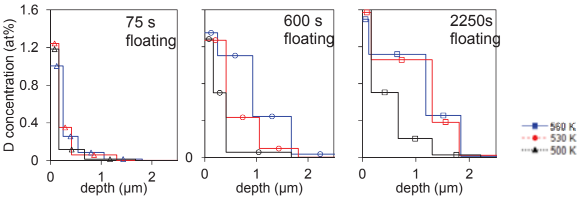


- Retention at ~1 dpa in displacement damage is independent of initial material

O.V. Ogorodnikova, JNM, in press

High flux effects

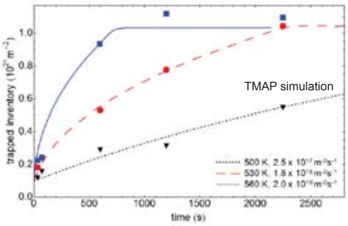
Incident flux: $5x10^{23} – 2x10^{24}$ D/m²s

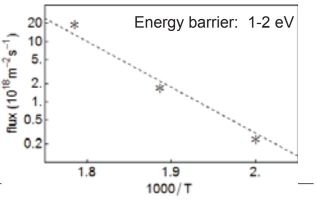


High flux effects (2)

- At high fluxes: Slow diffusion inwards
- Only very small fraction ~10^{-5} of incident D enters the target
  ⇒ Surface energy barrier
  M.H.J. 't Hoen, in print at PRL
- Very high fluences necessary for saturation of damaged layer

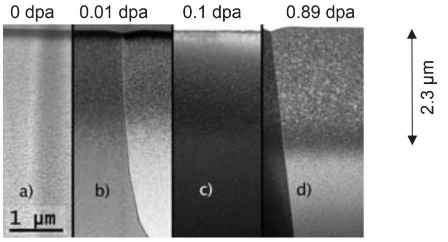
Incident flux: $5x10^{23} – 2x10^{24}$ D/m²s





Self-damaged tungsten: Dislocations

STEM bright field images



Ł. Ciupiński et al. , Nucl. Instr. & Meth. B, in press (2013)

Evolution of microstructure: coarsening up to damage levels of 6 dpa

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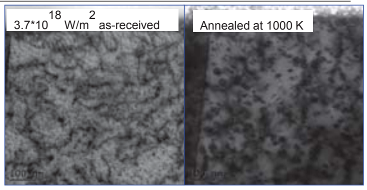
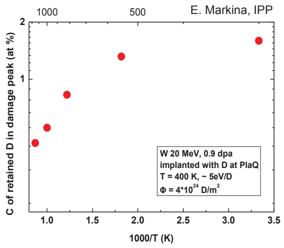
Self-damaged tungsten: Annealing of defects

- Annealing of defects not significant below 800 K
- 30% remaining H-decorable damage after annealing at 1200 K
- Residual damage still visible in TEM after annealing at 1000 K
  ⇒ dislocation loops, long dislocations

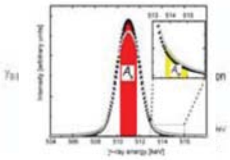


Ł. Ciupiński, Warsaw

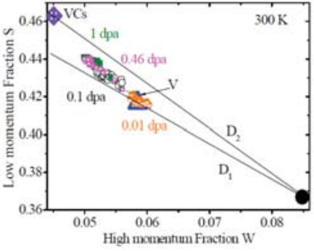


Investigation of defects: Positron Annihilation

- **Positron Annihilation Doppler broadening spectroscopy**
- **Core electrons:**
  high momentum, broad spectrum, low defects
- **Valence electrons:**
  low momentum, narrow spectrum, defect-rich
- 0.01 dpa: Mainly single vacancies, few vacancy clusters
- 1 dpa: Increase of vacancy clusters with n < 30
- No large clusters with n > 30



O.V. Ogorodnikova, M.-F. Barthe



Influence of helium on D retention

E. Markina, PFMC 2013

Recrystallized W samples (2000 K, 10 min)

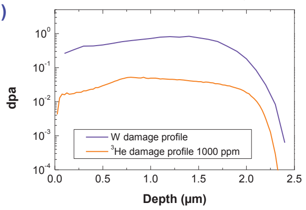
Displacement damage by 20 MeV W^{6+}

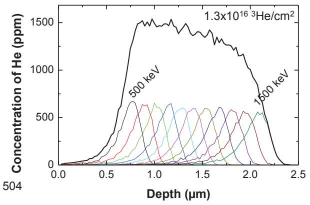
- $1.4x10^{14}$ ions/cm² ~ 0.9 dpa in maximum

Implantation of ^{3}He

- 11 energies 500 – 1500 keV
- 1000, 500, 100, 10 ppm
- Depth profiling of ^{3}He by $^{3}He(d,p)\alpha$ NRA
- ^{3}He distinguishable from D_2 in TDS
- ^{3}He is not released until 2000 K, loss < 2% of implanted amount
  ⇒ in agreement with previous work

A. Debelle JNM 362 (2007) 181, P.E. Lhuillier JNM 417 (2011) 504



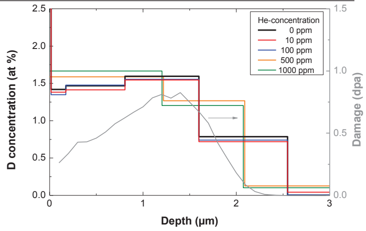


Influence of helium on maximum concentration of D

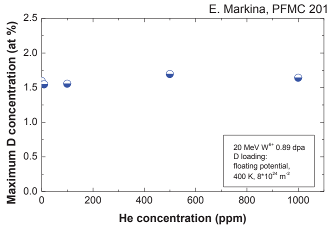
- 0.89 dpa damage by 20 MeV W^{6+}
- Implantation of D until full saturation of all available traps
- Maximum D concentration ~1.6% at 400 K independent of He amount

⇒ Amount of additional trap sites by He is small compared to trap sites by dpa

- Helium probably influences the diffusion coefficient of deuterium, factor ~2 at 1000 ppm



E. Markina, PFMC 2013

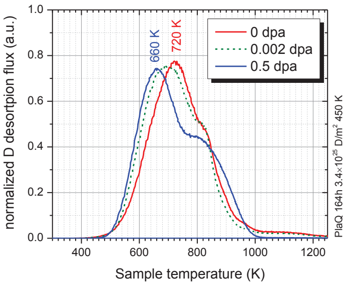


Problem: Determination of trap energies

Common practice in this community:

- ➢ Assigning trap binding energies to peak temperatures
- ➢ Assigning defect nature to trap energies
- ➢ Typically between 0.8 and 2.1 eV for damaged tungsten

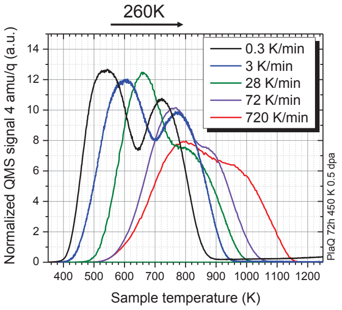
Drawback: input parameter unknown
(pre-exponential factor ν)



Temperature programmed desorption (TPD/TDS)

<u>"Real TPD":</u> Measuring adsorption energies on surfaces

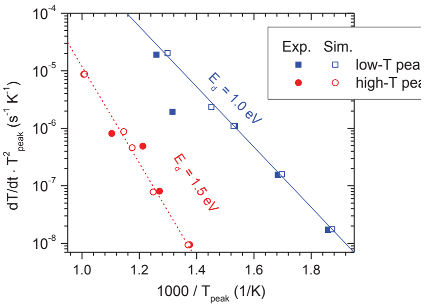
- Different T ramps
- Determine shift of peaks
- Derive trap energies from this peak shift (Redhead or Falconer and Madix method)



Trap energies in damaged tungsten

<u>"Real TPD"</u> analysis according to Falconer and Madix* reveals:

- Two trap energies
  - Ed = 1.0 eV
  - Ed = 1.5 eV
- Pre-exponential factors: 1×10^{10} s^{-1}, 6×10^{10} s^{-1}
- Diffusion trapping modeling shows applicability of the method

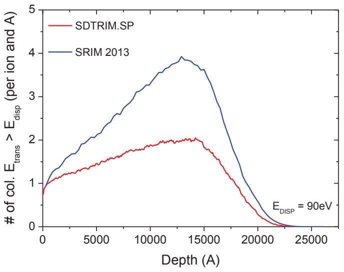


* J.L. Falconer and R.J. Madix, Surf. Science 48 (1975)

Problem: Damage profile

<u>Concern:</u> SRIM versus SDTrim.SP

- Two similar codes deliver different damage profiles although
- Both use Ziegler-Biersack stopping power
- ????



Summary

- Damage by 20 MeV W ions + gentle implantation of D at 450 K
- 1.5% D/W at ~1 dpa for 450 K
- Retention saturates at 0.5 – 1 dpa
- Retention at ~1 dpa is independent of initial material
- High flux effect: Surface barrier
- Evolution of microstructure: coarsening up to 6 dpa
- Annealing of defects not significant below 800 K
- 30% remaining H-decorable damage after annealing at 1200 K
- PAS: Increase of vacancy clusters with n < 30 at 1 dpa
- No additional influence of He up to 1000 ppm
- „Real" TPD using Falconer/Madix method yields different energies/pre-exponential factors than usually assumed
- SRIM 2013 and SDTrim.SP give different dpa: ???