Hydrogen in Tungsten as Plasma-facing Material

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Introduction:

- H in W: Thermodynamic parameters

Retention due to traps:

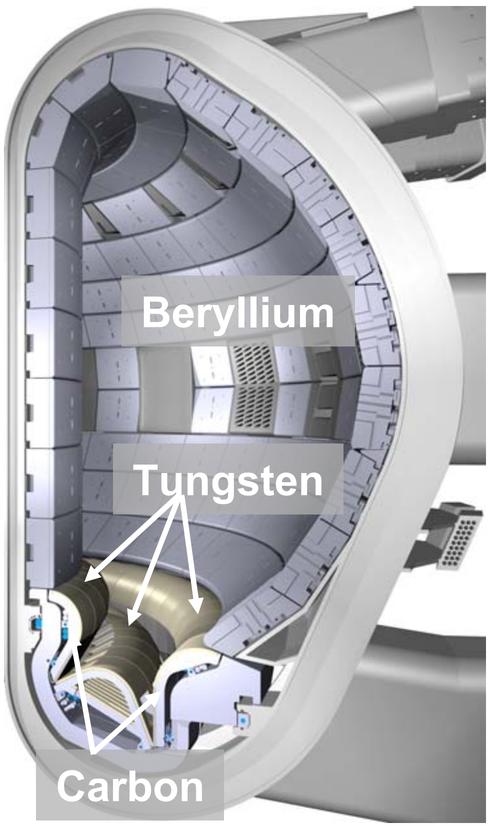
- Intrinsic traps: dependence on W structure
- Trap formation: due to low energy hydrogen ions
  hydrogen and helium ions
  due to neutrons

Consequences:

- for inventory in ITER
- for the use of W in DEMO

Fusion application: Conditions and requirements

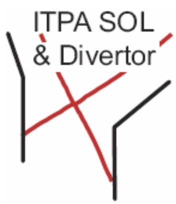
Initial ITER materials



Present strategy for ITER operation

- ❑ change to a **full W-divertor** before DT
- ❑ change to **all-W** as future DEMO relevant choice after extensive operation with Be wall

Predicted edge plasma conditions



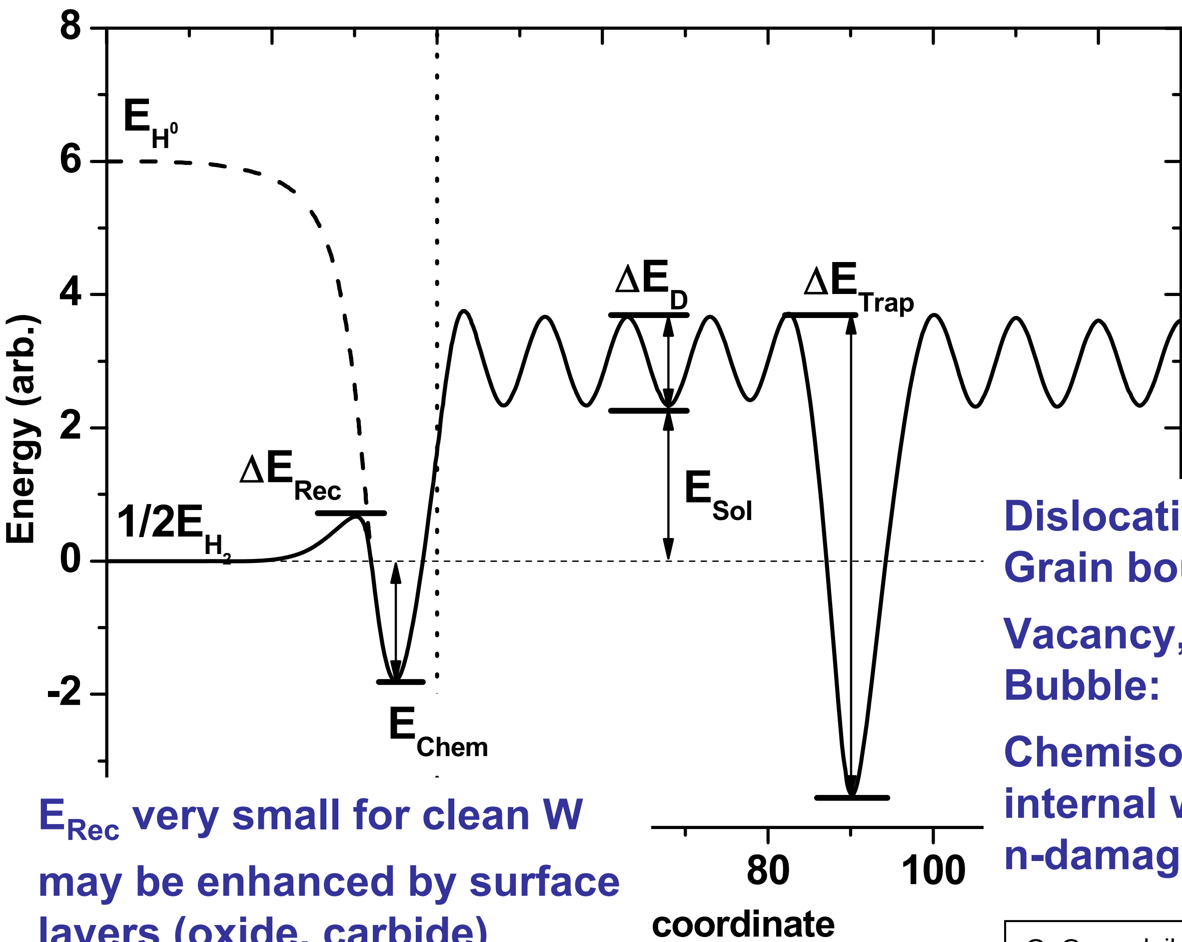
- ❑ Wall: 800 m^2, ~ $1x10^{21}$ /m^2s
  surface temperature: 450 K
- ❑ Divertor: <10 m^2, ~ $1x10^{24}$ /m^2s
  surface temperature: 1000 K

Tritium inventory as safety concern

- ❑ present administration limit
  700 g mobilisable tritium

Hydrogen in W: Thermodynamic parameters

Recombination   Diffusion   Trapping



Dislocation,
Grain boundary: 1 eV

Vacancy,
Bubble: 1.45eV

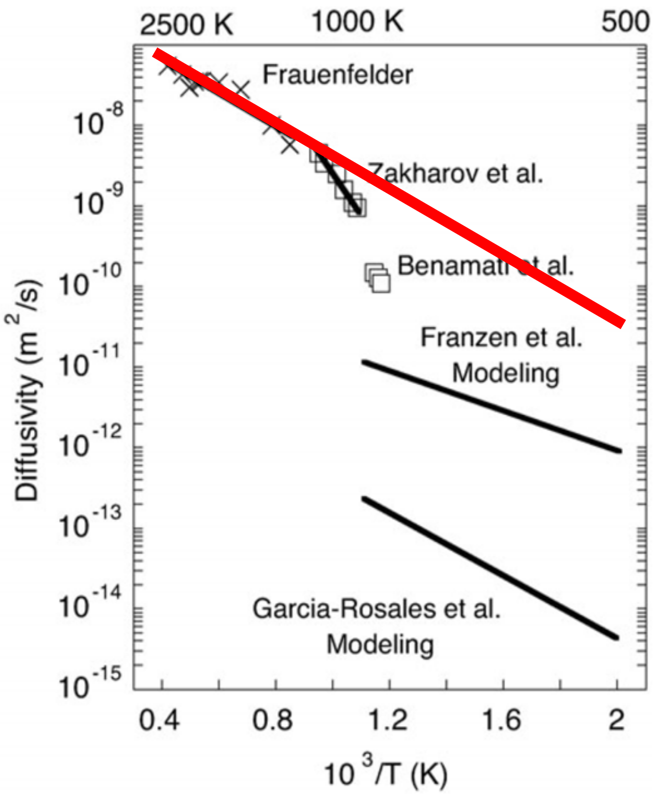
Chemisorption on the internal wall of bubbles,
n-damage: 1.8 eV

E_{Rec} very small for clean W
may be enhanced by surface layers (oxide, carbide)

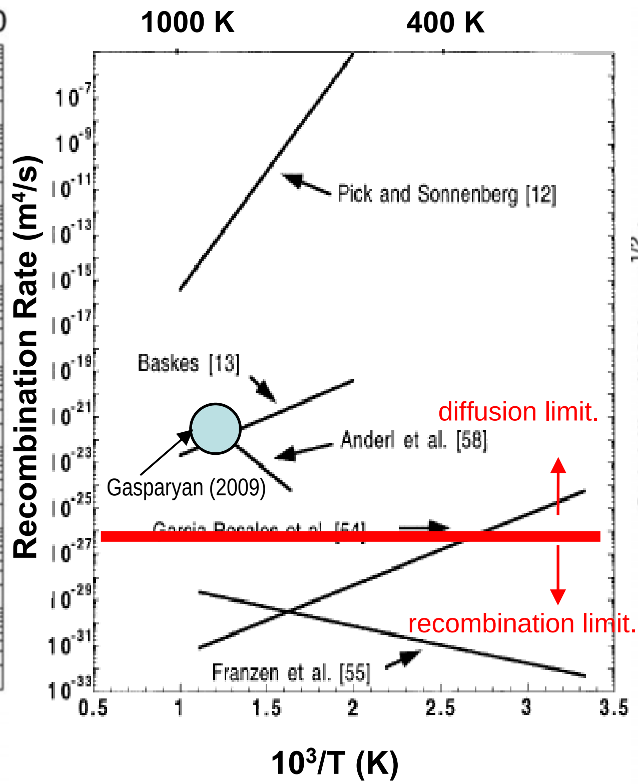
O. Ogorodnikova et al., J. Nucl. Mater 313-316 (2003) 469

Hydrogen in W: Thermodynamic parameters

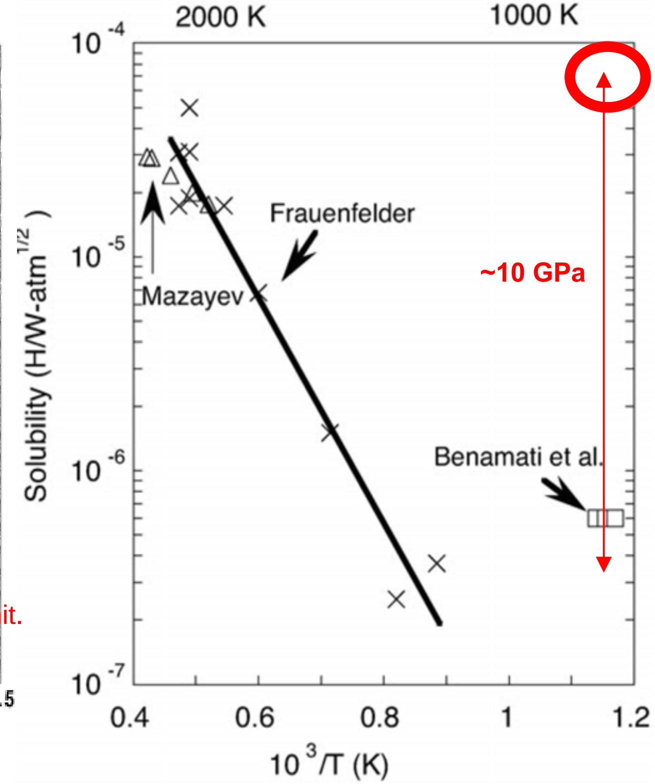
Diffusion coefficient:



Recombination rate coefficient:



Solubility:



- Best values by Frauenfelder
- Lower values "effective" diffusion coefficients

R. Causey, J. Nucl. Mater 300 (2002) 91

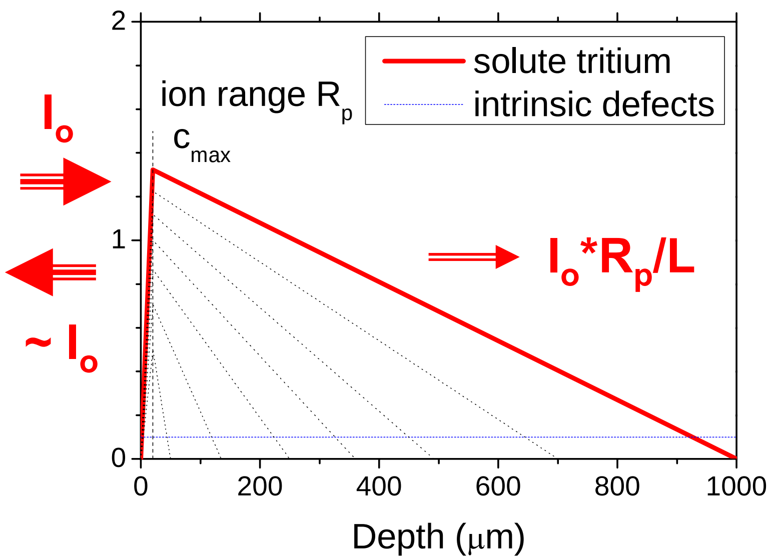
- Large scatter due to surface conditions
- Values above $10^{-26} m^4/s$ equivalent to diffusion limitation

- Very low solubility
- Values reached during implantation are equivalent to pressures of GPa

Hydrogen retention in W:

Schematics of retention in W:

- Example: 38-200eV D^+, 10^{21} D/m^2s, 500 K
  no kinetic vacancy formation



From diffusion limited flux balance:

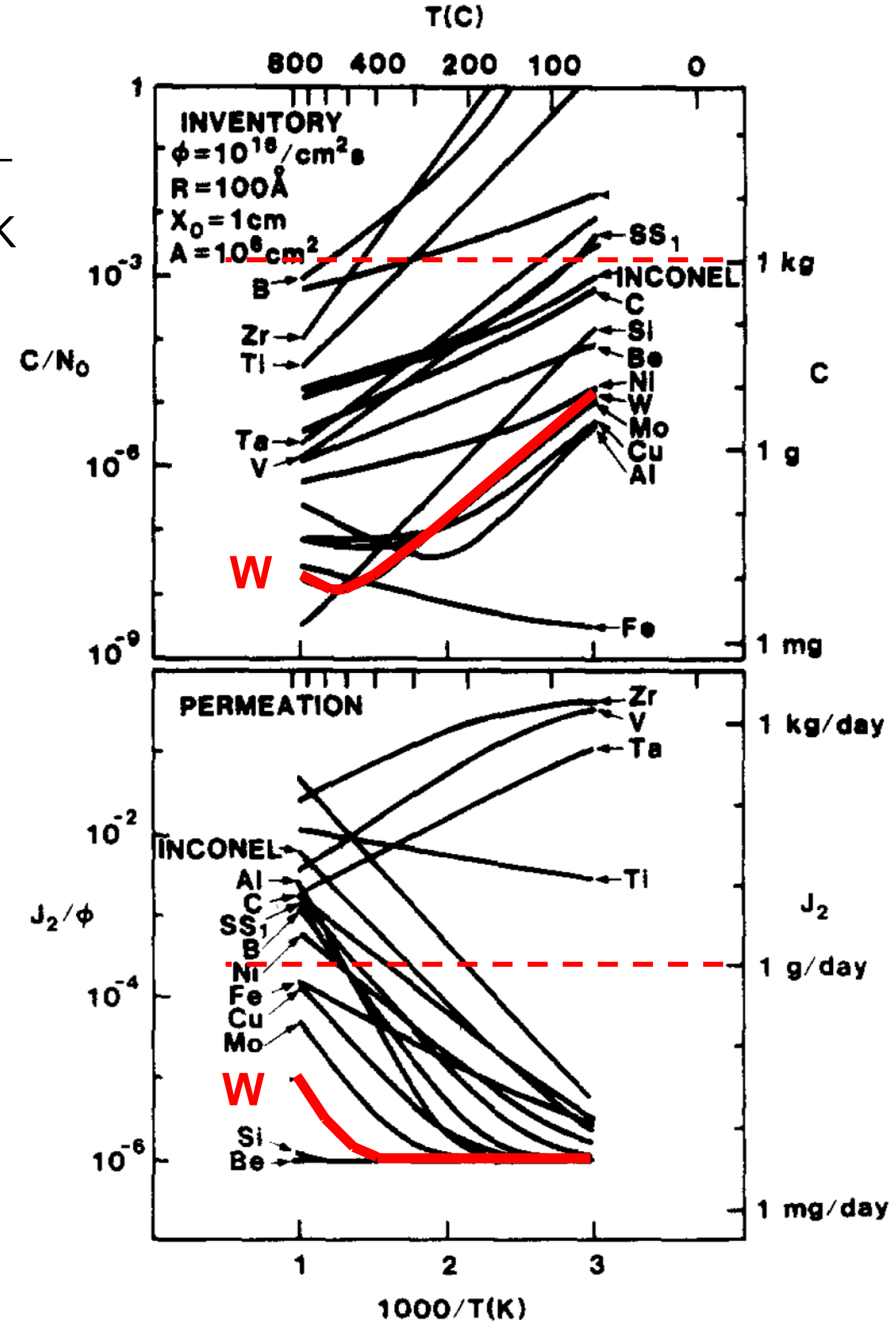
$$I_o = D*c_{max}/R_p$$

Typical ITER wall values:

R_p= 10 nm, I_o= $10^{21}/m^2s$, D = $3*10^{-11}m^2/s$

$$c_{max} = 10^{-5}$$

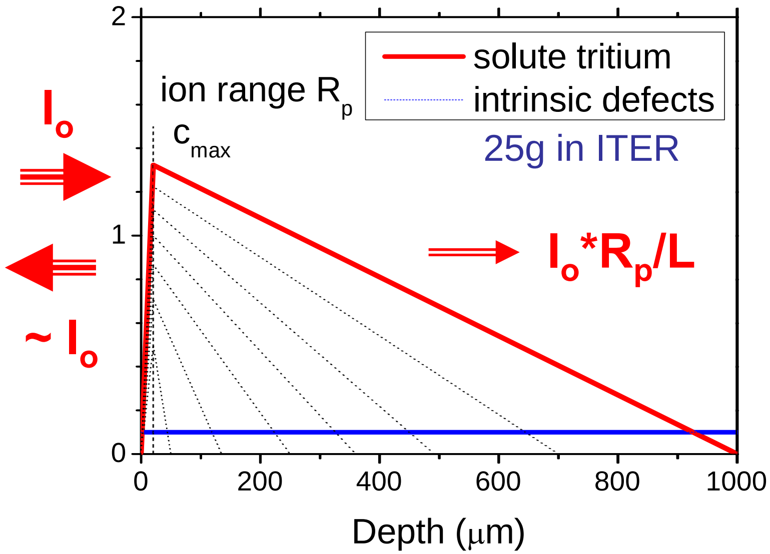
B. Doyle, D. Brice, J. Nucl. Mater (1984)



Hydrogen retention in W: Schematic mechanisms

Schematics of retention in W:

- Example: 38-200eV D^+, 10^{21} D/m^2s, 500 K
  no kinetic vacancy formation



From diffusion limited flux balance:

$$I_o = D*c_{max}/R_p$$

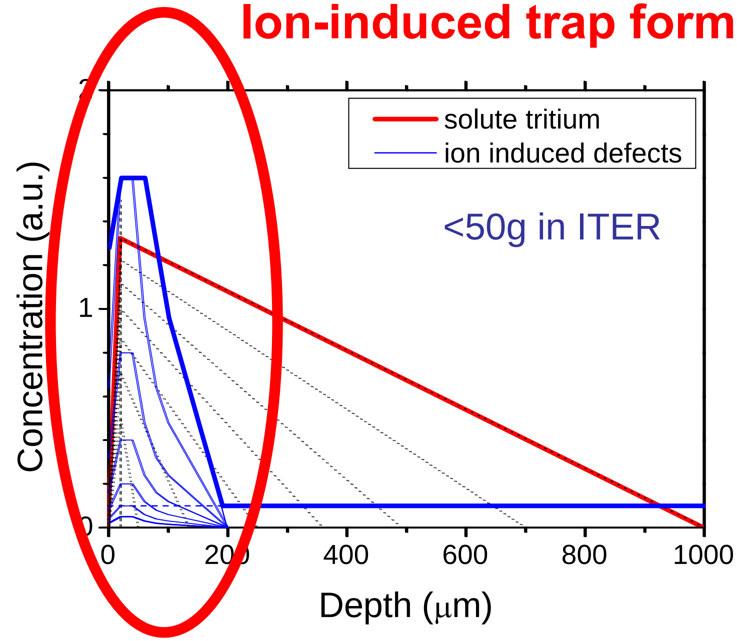
At the vessel wall typical values are

R_p= 10 nm, I_o= $10^{21}/m^2s$, D = $3*10^{-11}m^2/s$

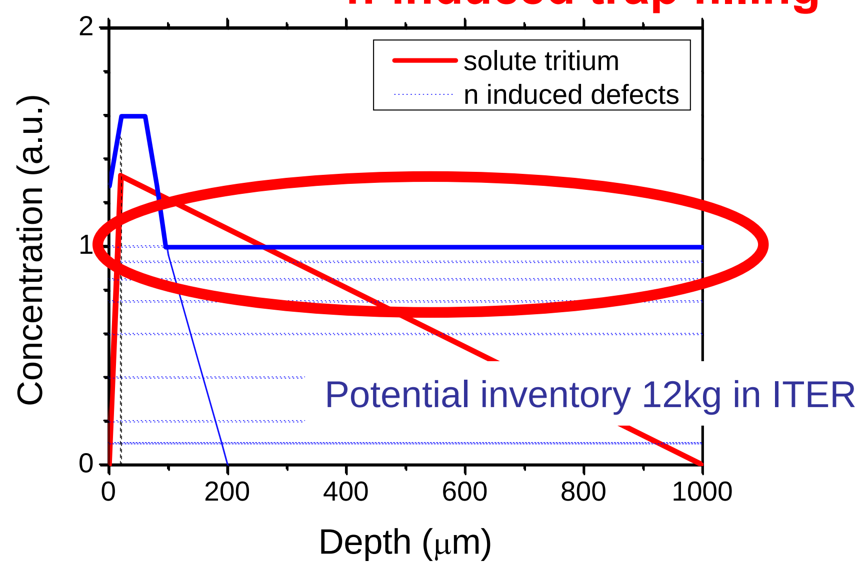
$$c_{max} = 10^{-5}$$

B. Doyle, D. Brice, J. Nucl. Mater (1984)

Ion-induced trap formation

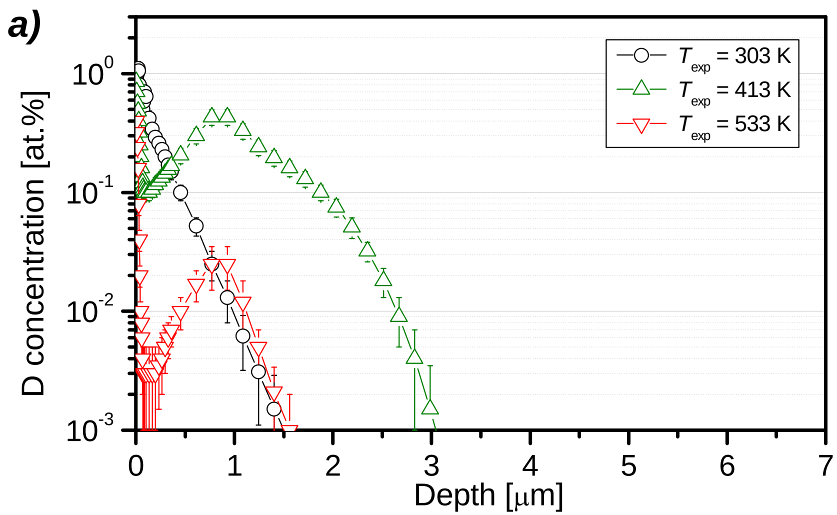


n-induced trap filling



Intrinsic traps: dependence on W micro-structure

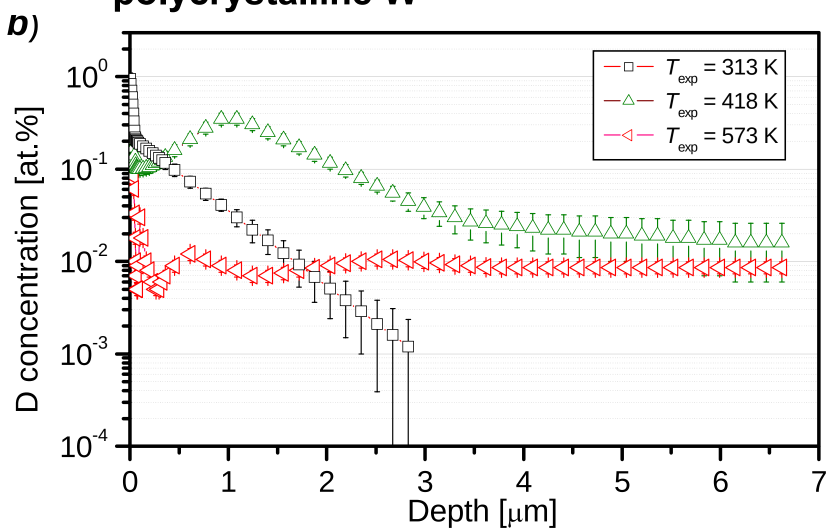
W single crystal



- Bulk trap density below detection limit in single crystalline W
- Bulk trap density about 10^{-2} % in polycrystalline W (re-crystallized)
- Ion-induced damage at similar level

V.Kh. Alimov, J. Roth, M. Mayer, JNM 337–339 (2005) 619

polycrystalline W



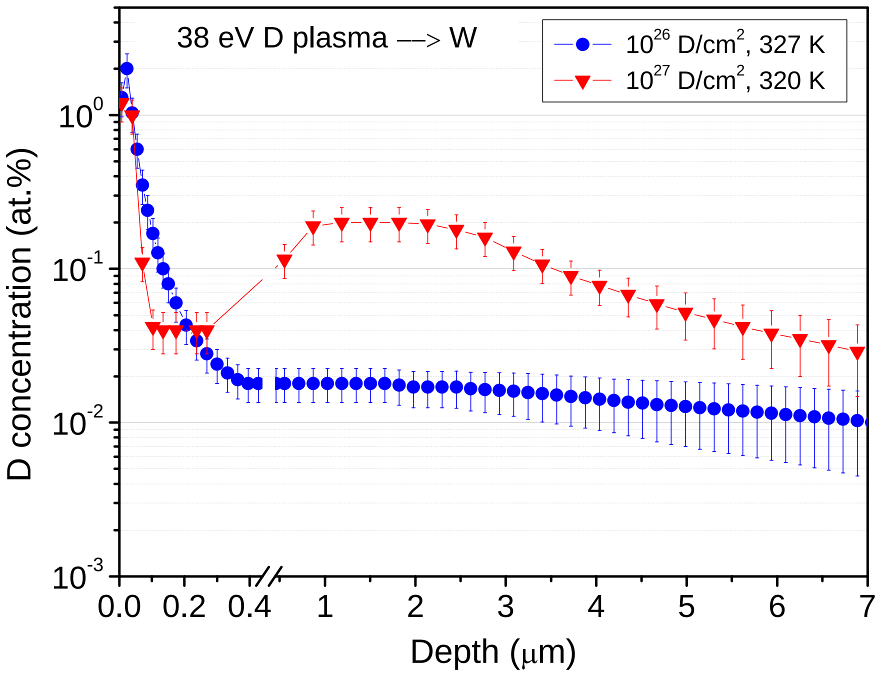
- pores in W/Re alloys and VPS coatings provide additional trapping sites
- At high fluences ion-induced traps dominate

A.V. Golubeva, et al., JNM 363–365 (2007) 893

Trap formation: due to low energy ions

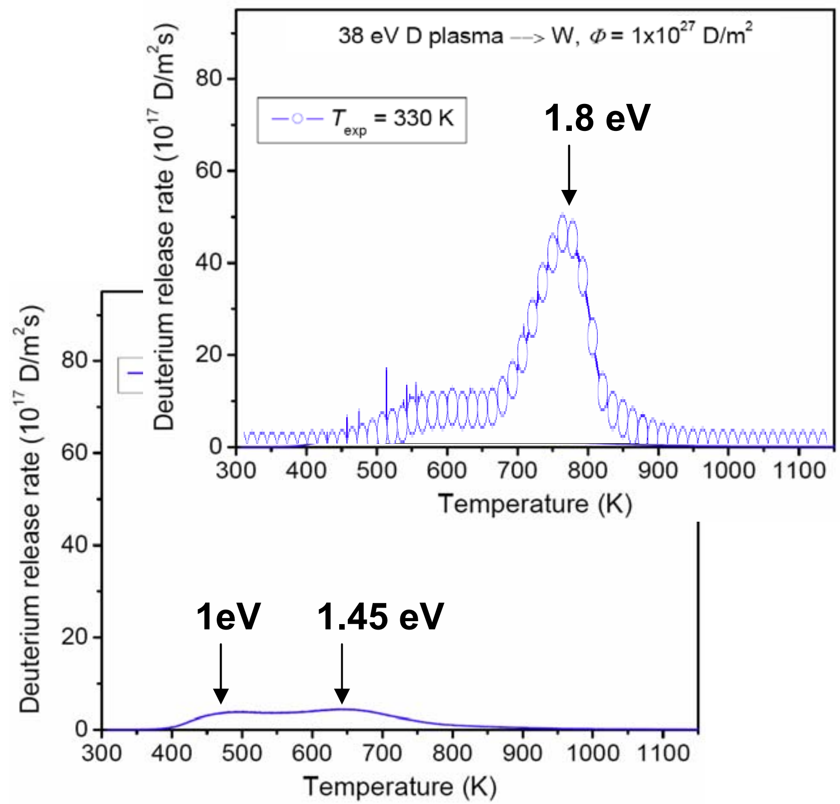
Evidence:

- Depth profile of retained D



V. Alimov et al., Physica Scripta T138 (2009) 014048

- Formation of strong traps from TDS



Modelling must assume damage production far beyond the ion range with activation energy around 1.8 eV : micro-bubbles ?

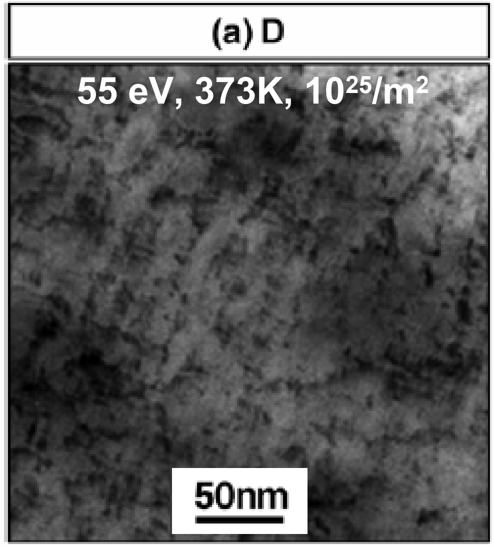
Trap formation: due to low energy hydrogen ions

Evidence:

- Direct sub-surface damage observation:

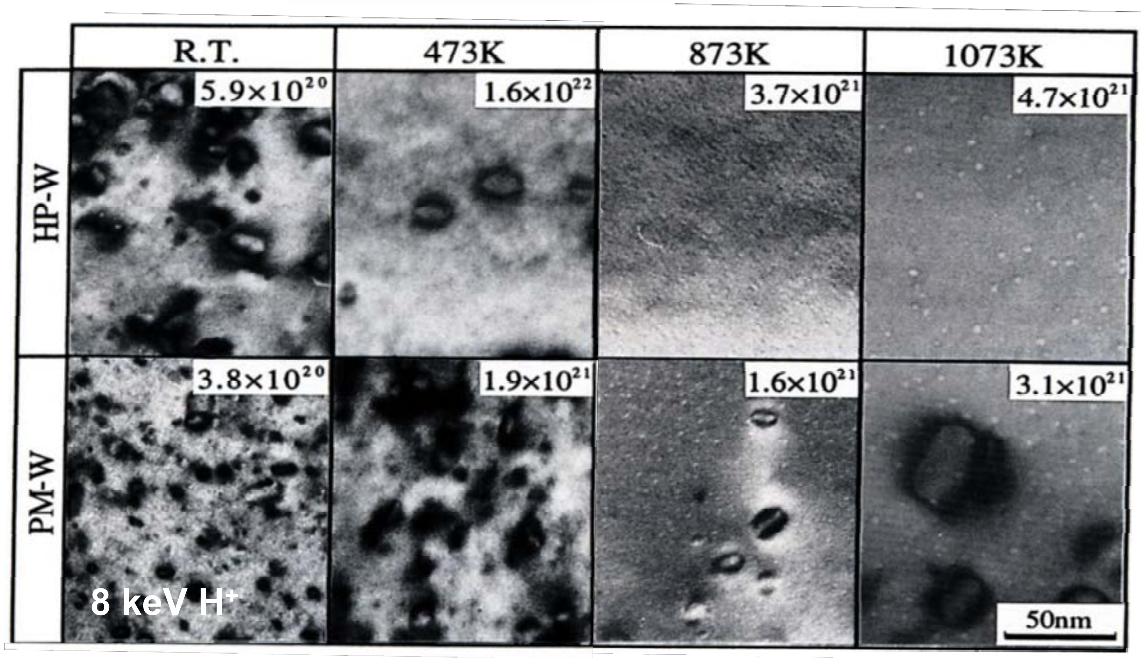
High resolution TEM showing intense strain fields, no voids

M. Miyamoto et al., Nucl. Fusion 49 (2009) 065035



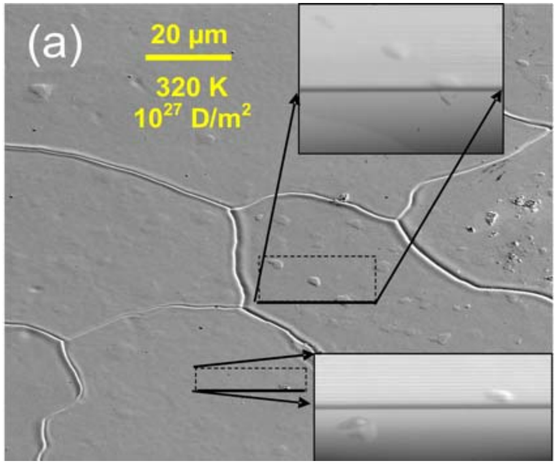
High resolution TEM showing transition from dislocation loops to bubbles <2nm with increasing implantation temperature

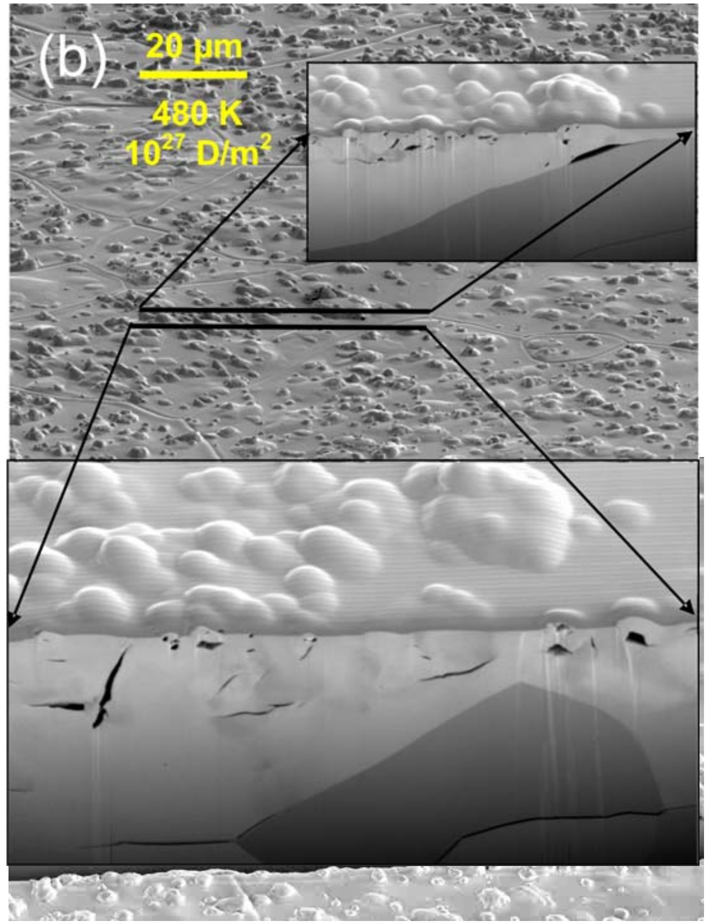
R. Sakamoto et al. JNM 220-222 (1995) 819

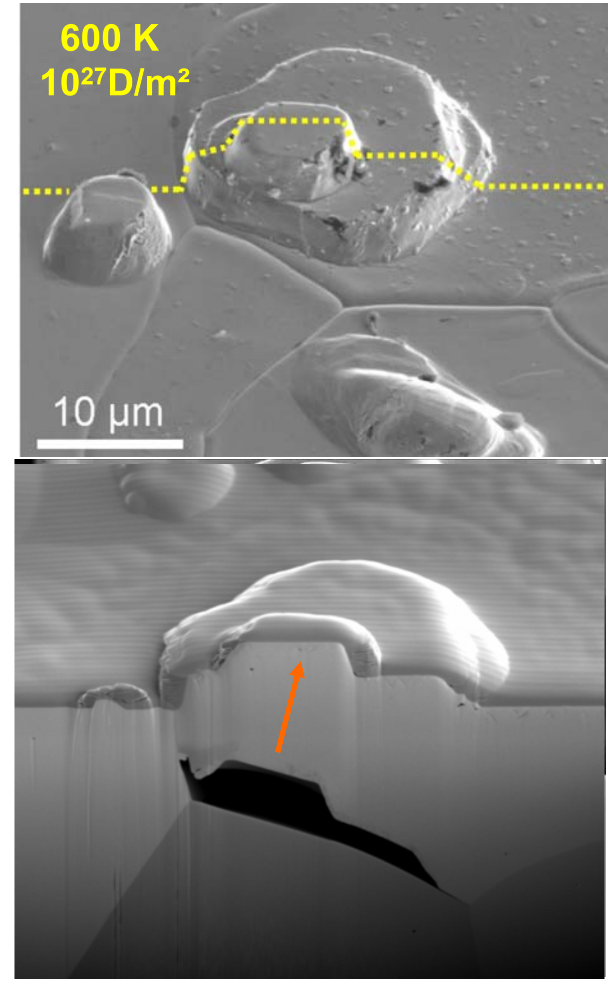


Trap formation: due to low energy ions, high fluence

Ion beam cross-sectioning in SEM







S. Lindig et al., Physica Scripta T138 (2009) 014040

Damage in re-crystallized W:

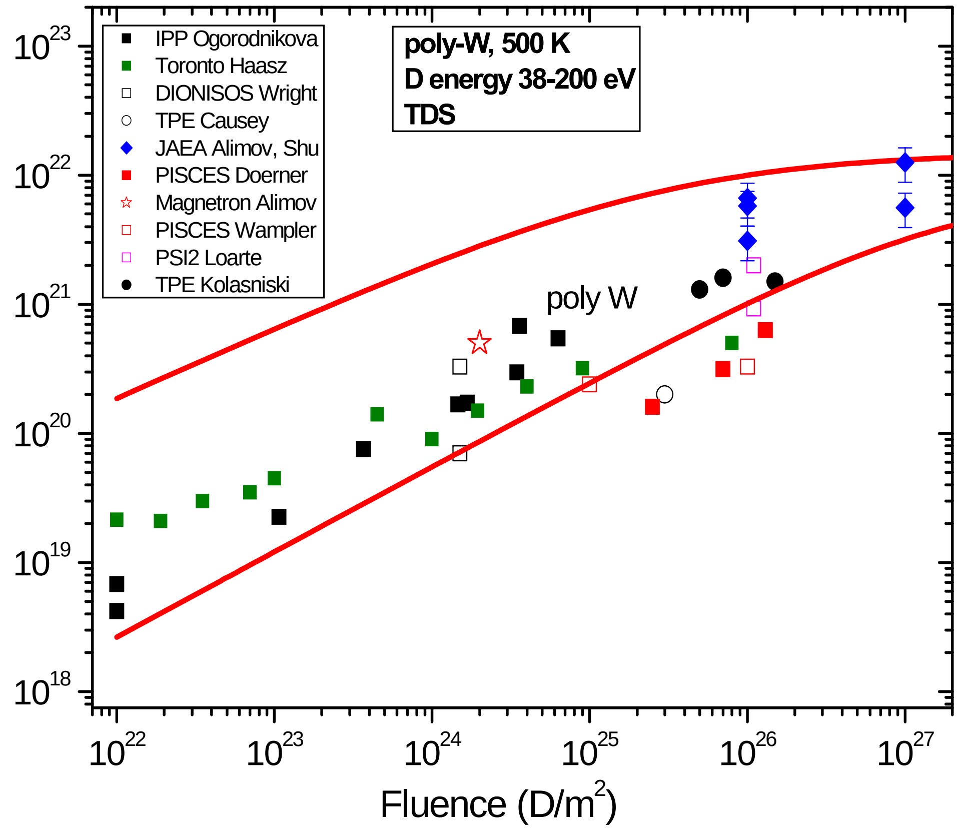
- strong temperature dependence
- brittle to ductile transition (BDT) from cracks to cavities at around 500 K
- cavity formation at grain boundaries and material transport to the surface above BDT
- material moving from grain boundary to surface in sliding plane system {110}<111>

D retention in W: Fluence dependence up to $10^{27}/m^2$

Consequence:

Fluence dependence of retention

- Large margins of uncertainty were assumed by the ITPA SOL/DIV for extrapolation
- Saturation at high fluences due to formation of cracks and pores. Still within uncertainty of data!

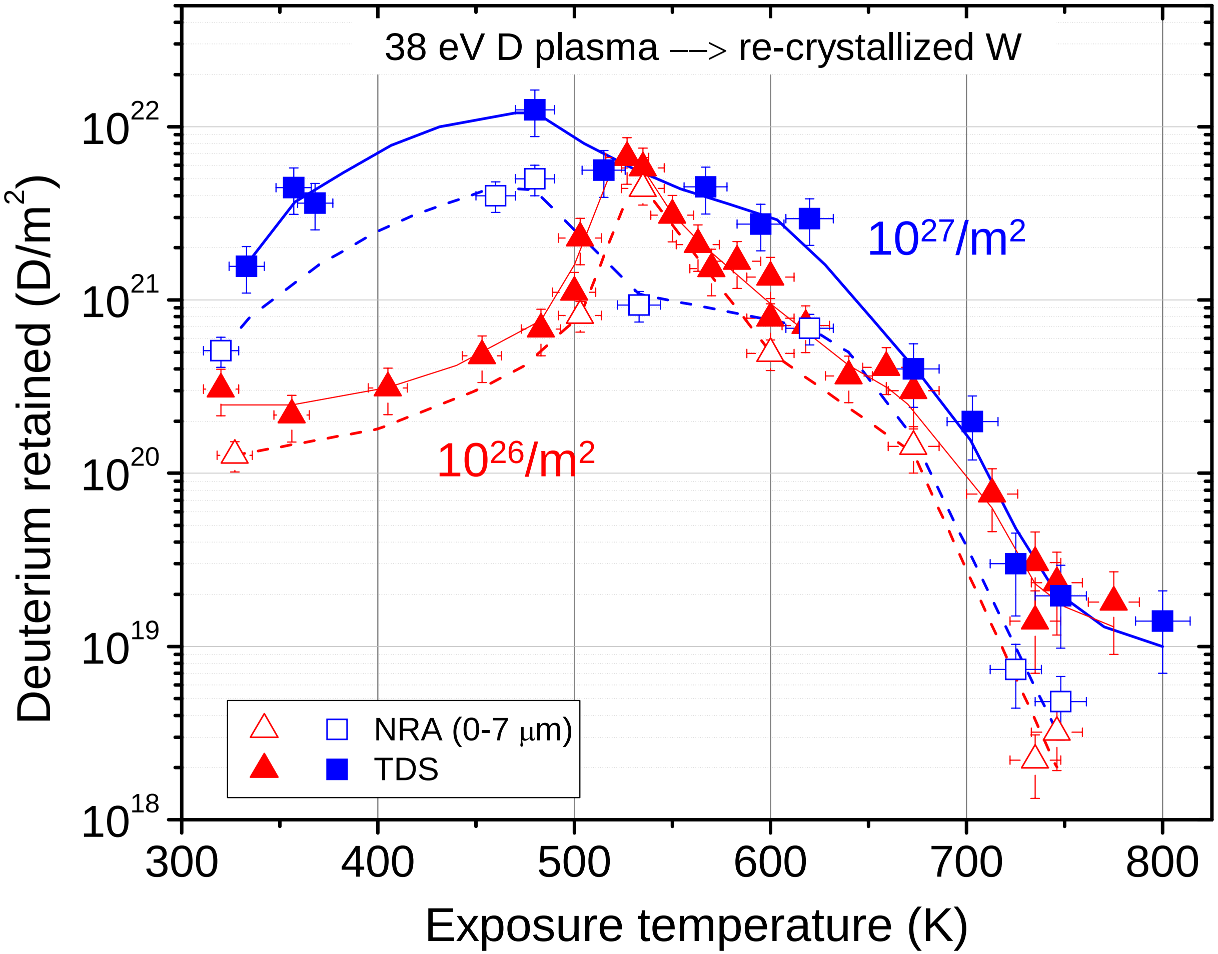


J. Roth et al., IAEA Geneva, IT/P6-16 (2008)
B. Lipschultz, J. Roth, et al., MIT Rep. PSFC/RR-10-4 (2010)

ITPA SOL & Divertor

D retention in W: Temperature dependence

Consequence:



Maximum retention near 500 K saturates at about $10^{22}/m^2$.

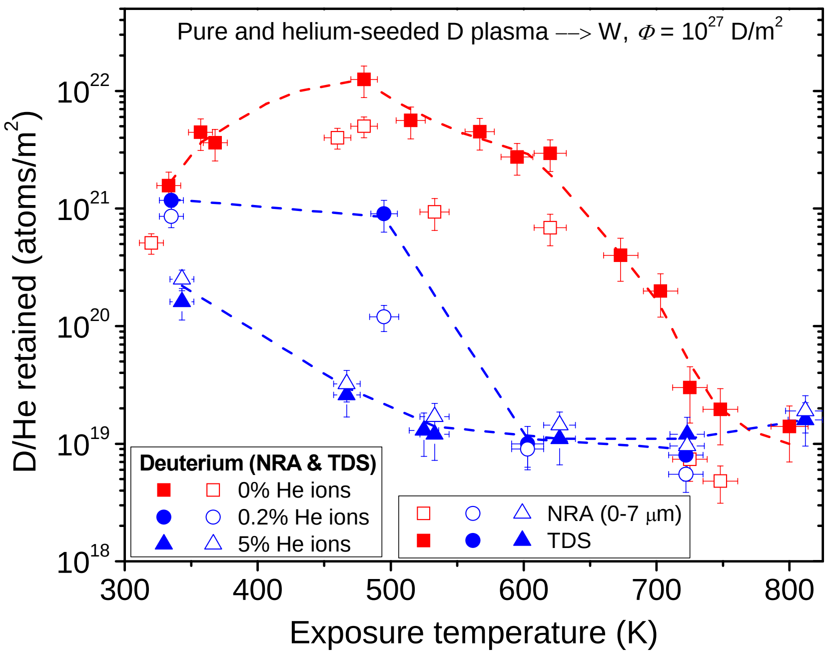
Low retention below 500 K increases with fluence.

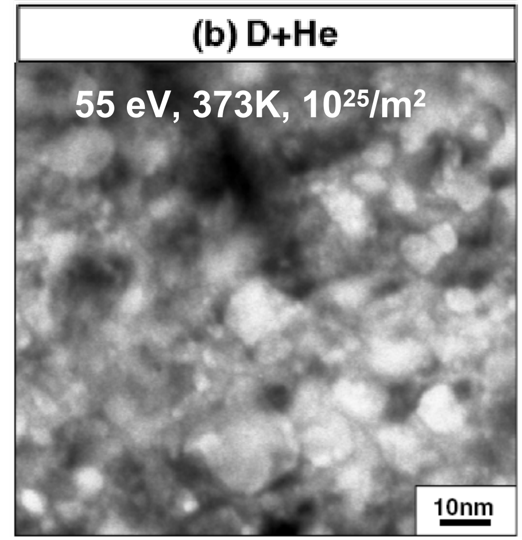
Difference between TDS and NRA (1 to 7 µm) indicates deep penetration and trapping.

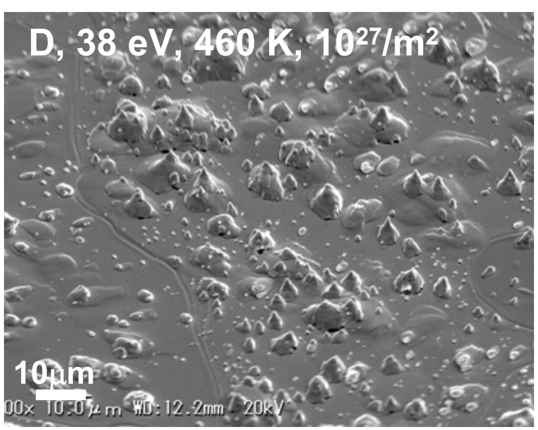
V. Kh. Alimov et al, JNM in press, doi: 10.1016/j.jnucmat.2011.01.088

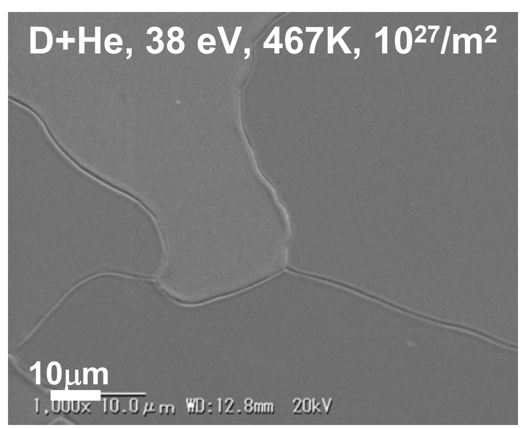
D retention in W: Simultaneous D and He irradiation

M. Miyamoto et al., Nucl. Fusion 49 (2009) 065035









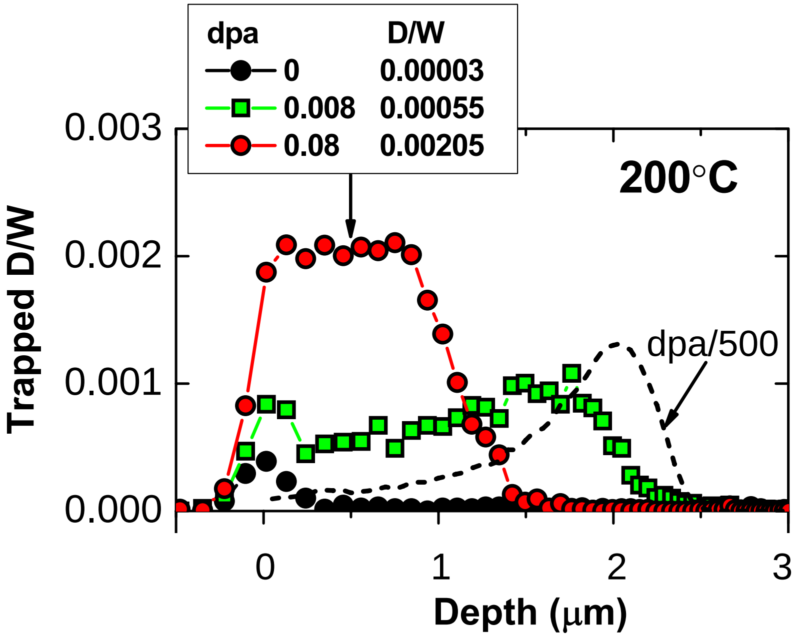
Helium bubbles prevent the penetration and provide outward pathways for D.

V. Kh. Alimov, J. Roth, et al. Phys. Scr. 2009 014048

Trap formation: due to neutrons

Damage simulation:

n-damage simulated by energetic ion bombardment: H, C, Si, W
Heavy ion damage cascade most similar to neutrons



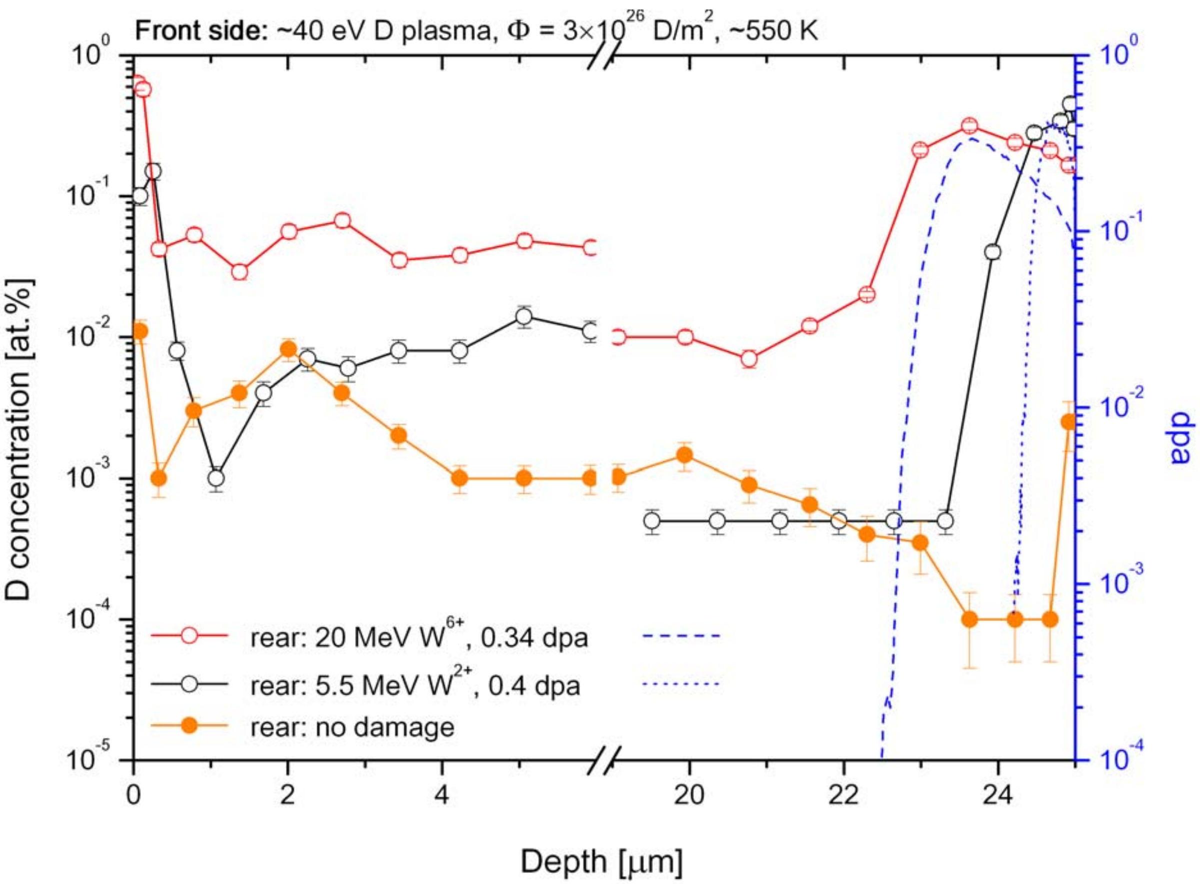
W.R.. Wampler, R. Doerner, Nucl. Fusion 49 (2009) 115023

- 12 MeV Si, subsequent D plasma in PISCES (10^{26} (D+5%He)/m^2, 100 eV)
- At 200ºC D trapping is limited by slow kinetics, ie. permeation.
- Sequential trap filling allows the determination of permeation kinetics.

Trap formation: due to neutrons

Damage simulation:

- Retention in 25 μm W foil
- Irradiation damage at rear surface: 5.5 and 20 MeV W-
- Plasma exposure at front side: 40 eV D^+, $3x10^{26}$ D/m^2

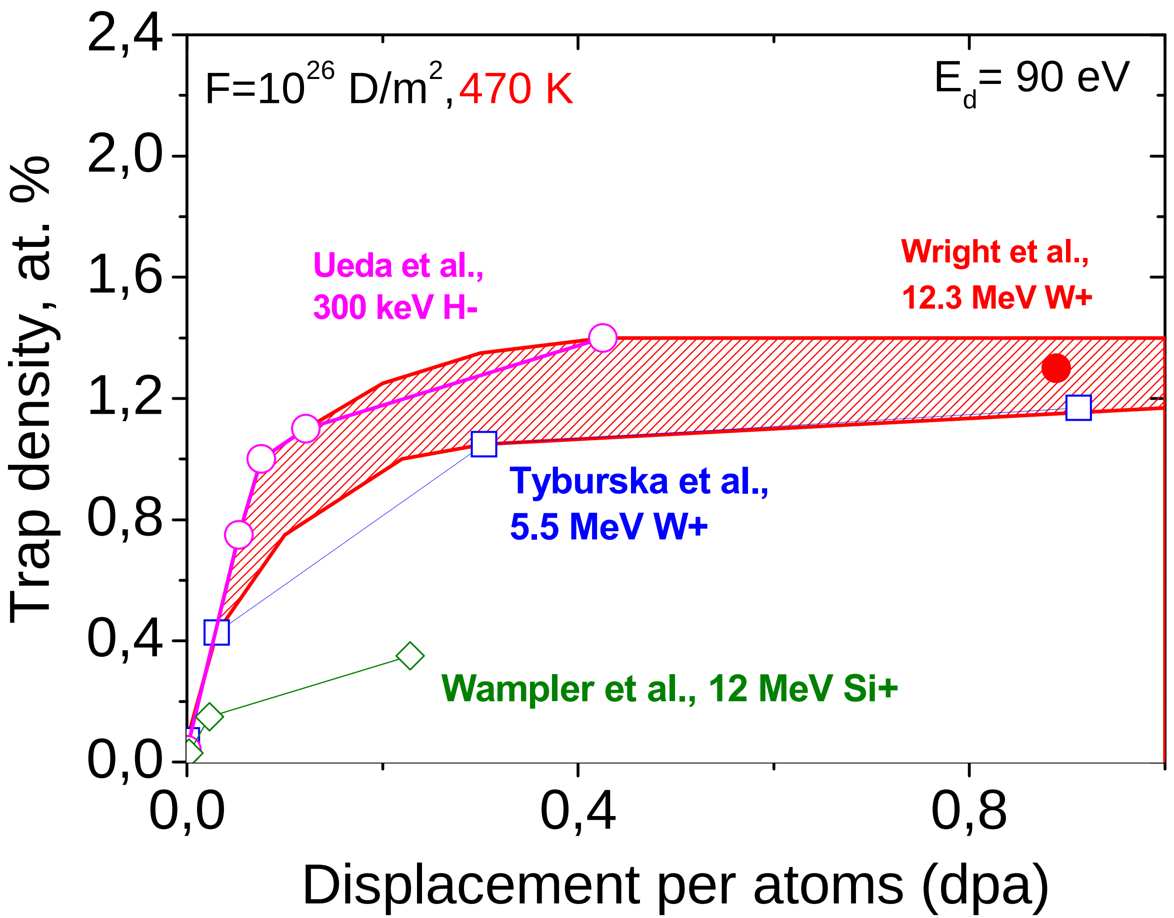


- D permeation and retention in damage on the rear side
- D retention in the plasma side is enhanced by damage on the rear side

B. Tyburska et al., J. Nucl. Mater. 395 (2009) 150

Trap formation: due to neutrons

Damage simulation:



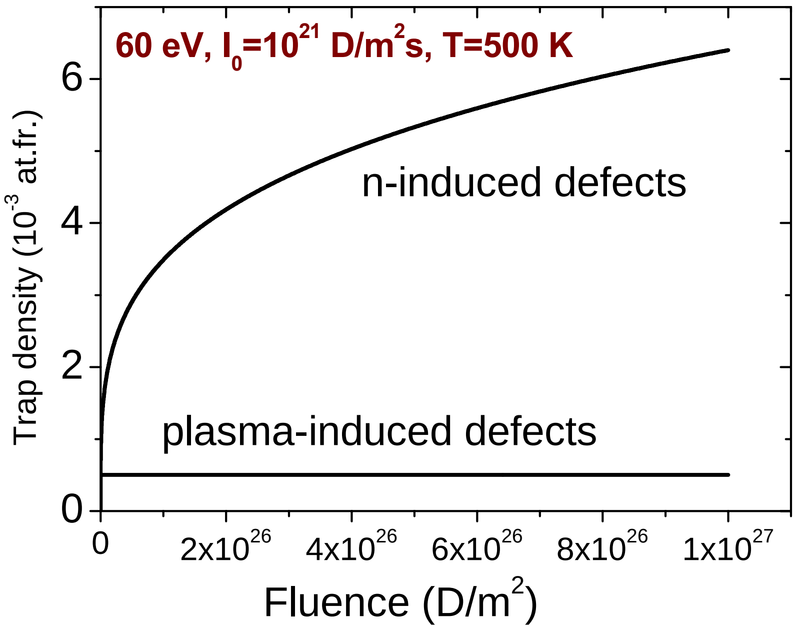
- Radiation induced trap density saturates at 1.2% above 0.4 dpa
- These data provide valuable input for modelling

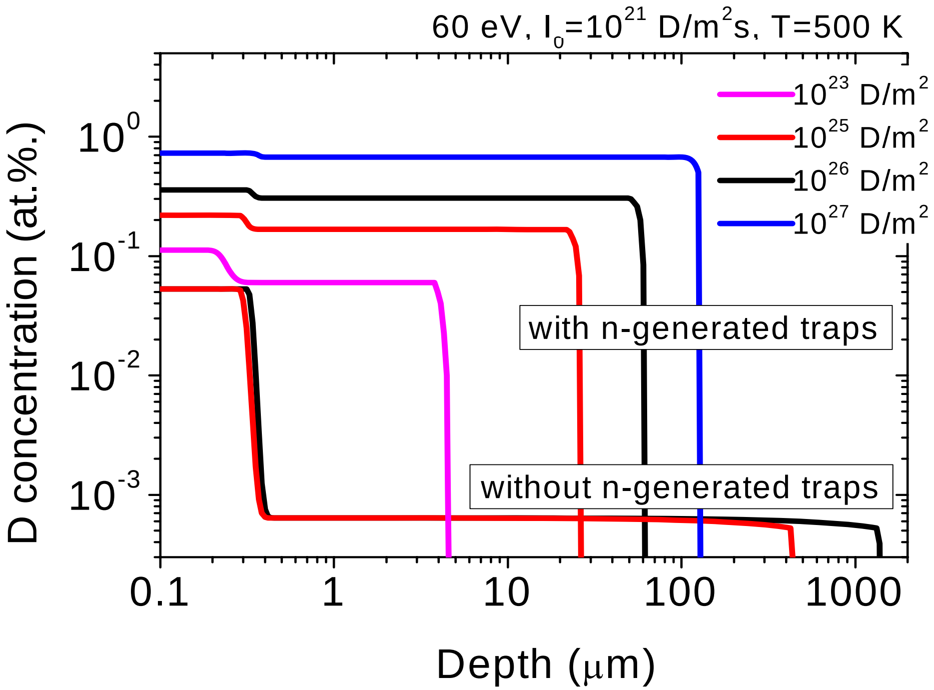
B. Tyburska et al., J. Nucl. Mater. 395 (2009) 150

Trap filling of neutron damage

Modelling of ITER wall conditions:

- Damage evolution:
  10^{-7} dpa/s from IO
  saturation trap density 1%
- Diffusion and trap filling:
  Diffusive trap filling modelled using established diffusion coefficient

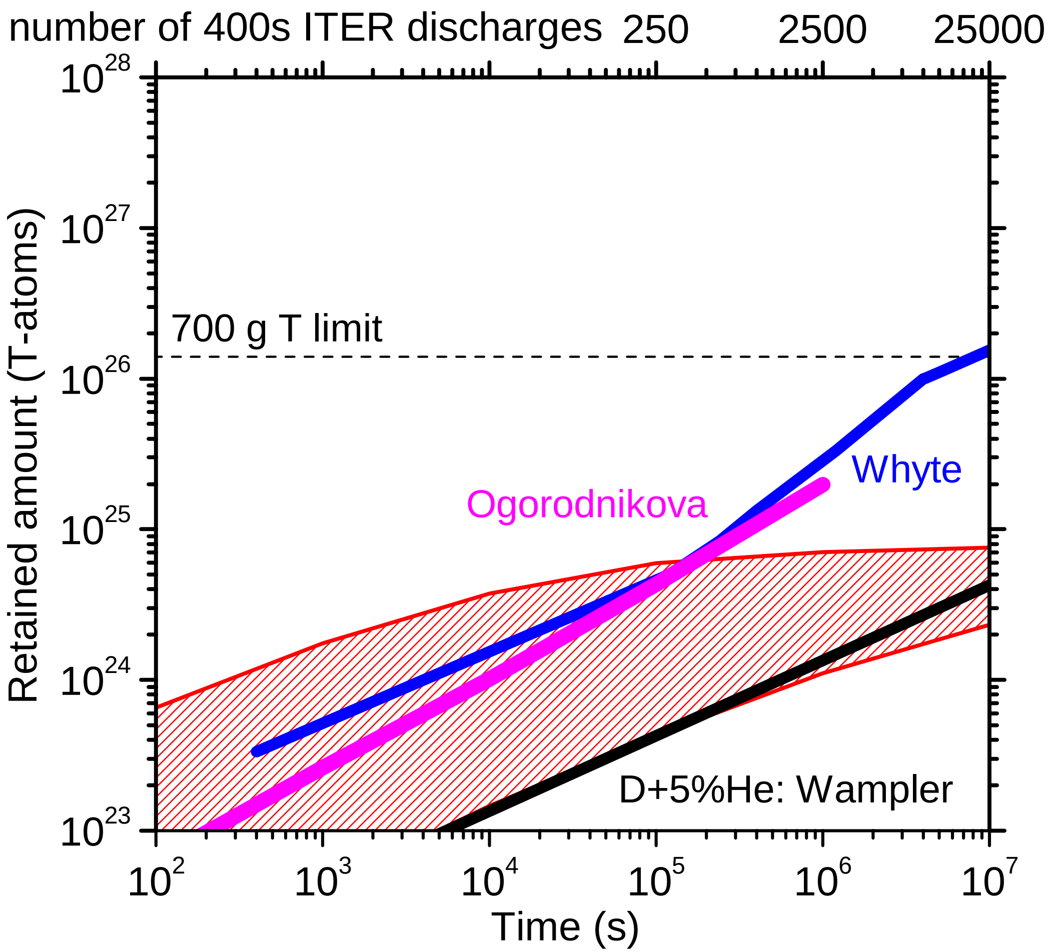




O. Ogorodnikova et al., J. Nucl. Mater. (2011) in press

- Filling of 100μm W armour in about 10^6s,
  ⇨ 1mm in 3 years steady state operation
- Relevant to DEMO rather than ITER

Consequences for inventory in ITER



O. Ogorodnikova et al., J. Nucl. Mater. (2011) in press

- Without additional irradiation damage the tritium limit in an all-W ITER will remain tolerable
- n-irradiation damage has the potential to enhance the inventory up to the tritium limit

Consequences

for the use of W in ITER:

Data base of transport coefficients is **sufficient** for predicting retention in W for ITER.

T inventory in W will not be a challenge within ITER lifetime

Inventory in n-defects contributes only at the end of ITER lifetime. n-induced defect production rate is low, trap filling is diffusion limited and will take many years

High flux low energy ion bombardment leads to stress fields due to over-saturation which **can produce cracks and further trap sites**.

↳ Test **structural stability** of W under hydrogen irradiation and **transient heat loads** (PISCES, AUG, JET)

Consequences

for the use of W in DEMO:

Steady-state operation will result in flux and fluence levels far exceeding those in present devices leading internal stress fields and damage.

Higher wall temperatures (≤ 600°C) will reduce total retention but increase **permeation** to the cooling structure interface.

Brittleness of pure W will be enhanced by n-irradiation

→ **Higher ductility W alloys** with acceptable PWI properties, such as low erosion and T inventory

→ **Study effects of permeation** to the coolant interfaces of components in realistic conditions with large temperature and stress gradients