Deuterium retention in tungsten exposed to high flux plasmas

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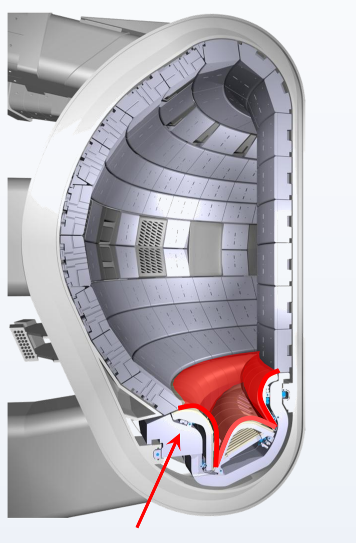
1 Introduction



Fusion reaction:

$$D + T \rightarrow He + n(14.1MeV)$$

Tritium retention in the walls should be kept as low as possible

- to prevent fuel-loss
- for safety reasons (max T = 700 g)

Continuous bombardment with MeV neutrons

- degrades material properties
- introduces damage into the material

Poly-crystalline W targets
purity 99.97%, Plansee
Ø 20 mm x 1 mm
Anneal pre-existing defects (1 h, 1273 K)

2 Irradiation damage W^{4+}

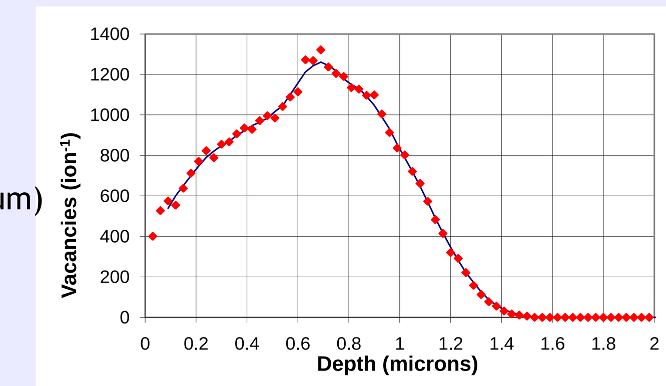
W^{4+} ions (12.3 MeV) were used as proxy for neutron damage.

W^{4+} ions were implanted at fluences up to $6.5 \cdot 10^{20}$ ions m^{-2} at the 3 MV tandem accelerator at IPP-Garching.

When E_{th} = 40 eV is taken in TRIM simulations, these fluences correspond to peak damage levels of 0.1/0.2/0.5/1.0 displacements per atom (dpa).

Damage extends 1.5 µm below surface.

The peak damage (at 0.8 µm) is used as reference for the experiments.

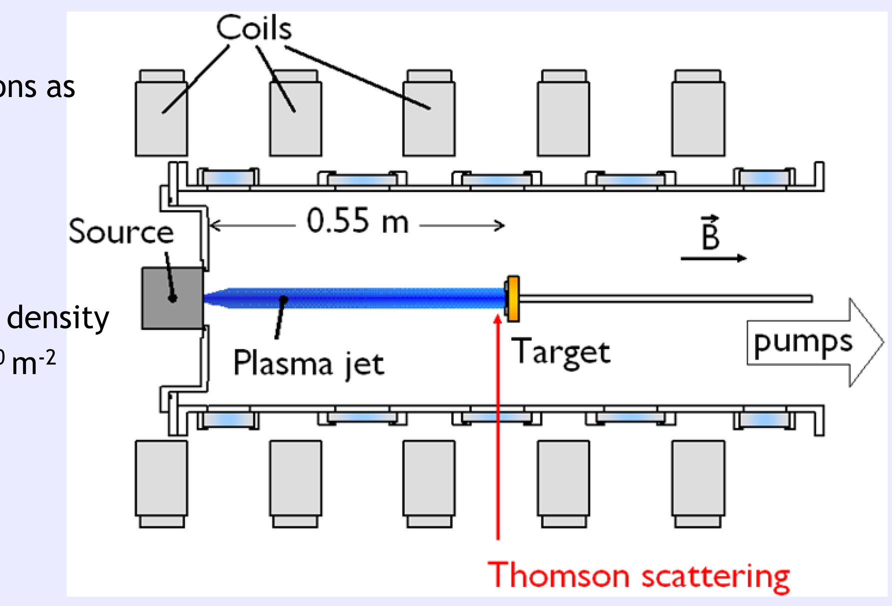


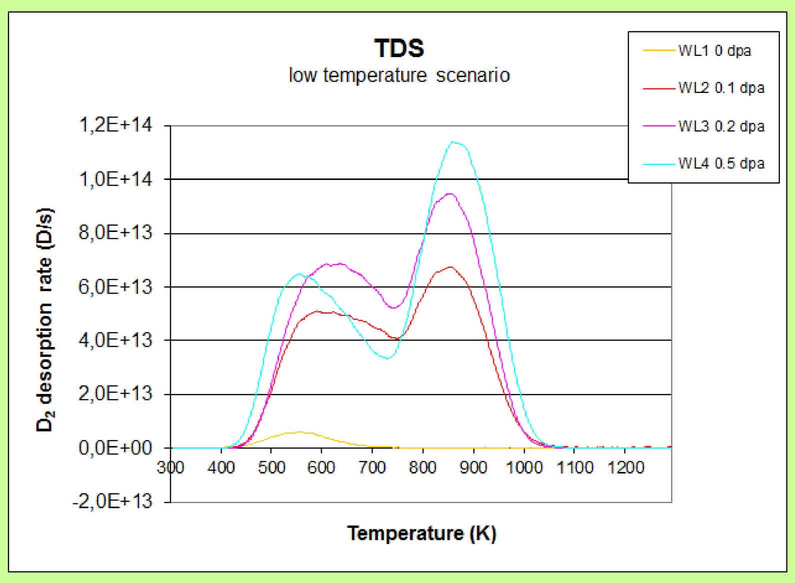
3 Plasma exposure

Pilot PSI (linear plasma generator)

Similar conditions as ITER divertor:

- high ion flux $\Gamma > 10^{24}\ m^{-2}s^{-1}$
- high electron density $n_e \sim 0.5\text{-}10 \cdot 10^{20}\ m^{-2}$
- low electron temperature $T_e \sim 0.3\text{-}3$ eV





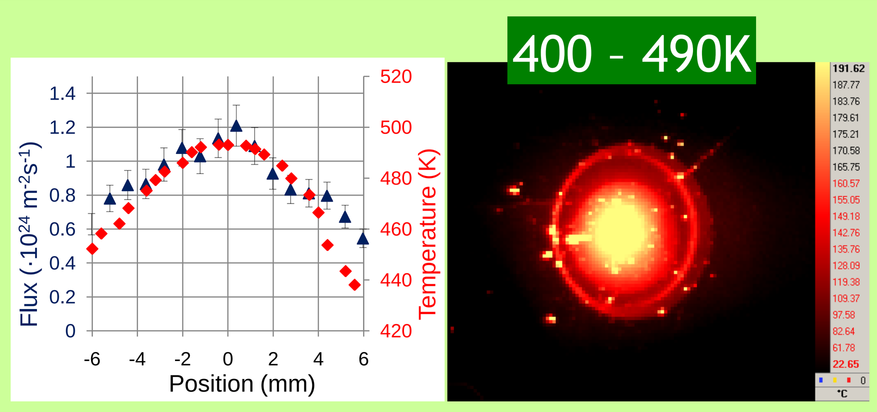
- 0 dpa → only low energy peak at 550 K
- pre-irradiated targets: → energy peaks at 600 K and 850 K

TDS spectra agree well with previous measurements [1]

4 Results - Thermal Desorption Spectroscopy

The sample is heated to 1000C with a heating rate of 1K/s. The desorption peaks correspond to the trap energy.

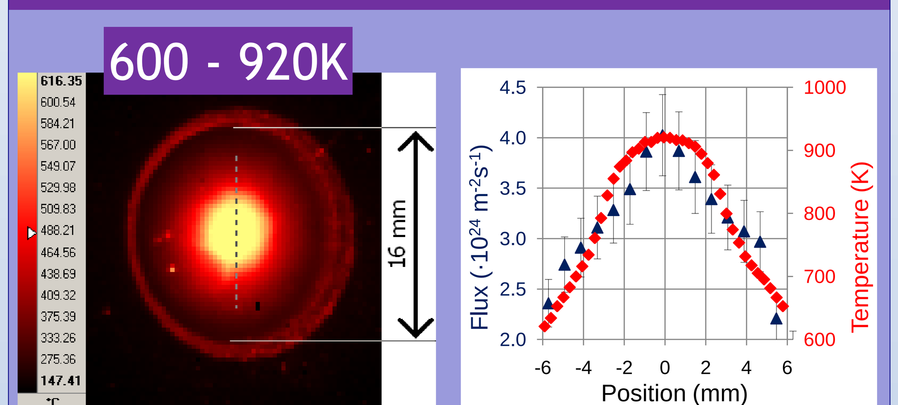
Low temperature exposure



Deuterium implantation
$\Gamma_{max} \approx 1.2 \cdot 10^{24}\ m^{-2}s^{-1}$
$\Gamma_{5mm} \approx 0.7 \cdot 10^{24}\ m^{-2}s^{-1}$

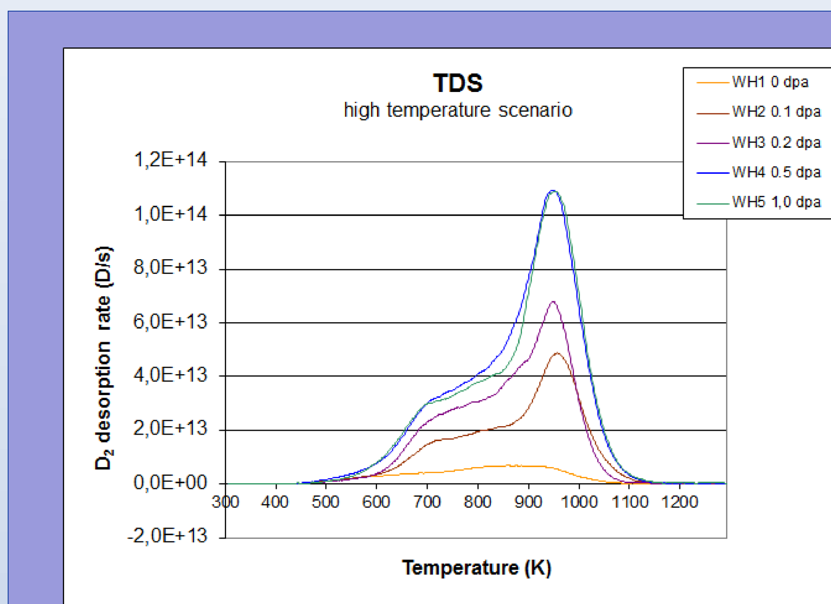
B = 0.4 T
$T_{e,max}$ = 0.7 eV
$n_{e,max}$ = $2.8 \cdot 10^{20}\ m^{-3}$

High temperature exposure



B = 0.8 T
$T_{e,max}$ = 1.6 eV
$n_{e,max}$ = $8.5 \cdot 10^{20}\ m^{-3}$

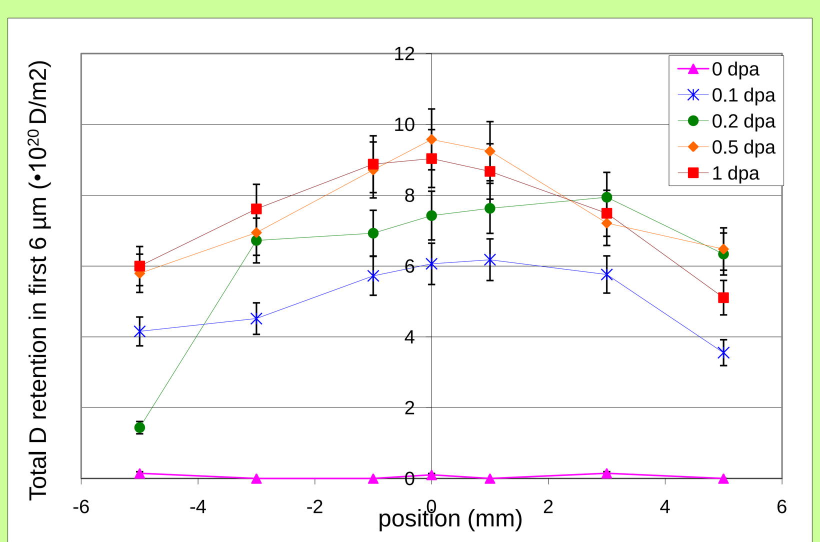
Deuterium implantation
$\Gamma_{max} = 4.0 \cdot 10^{24}\ m^{-2}s^{-1}$
$\Gamma_{5mm} \approx 2.7 \cdot 10^{24}\ m^{-2}s^{-1}$



- 0 dpa → D_2 desorption up to 1000 K
- low energy traps → annealing/ clustering
- high energy traps → shifted to higher temp (~950 K)
- saturation at 0.5 dpa

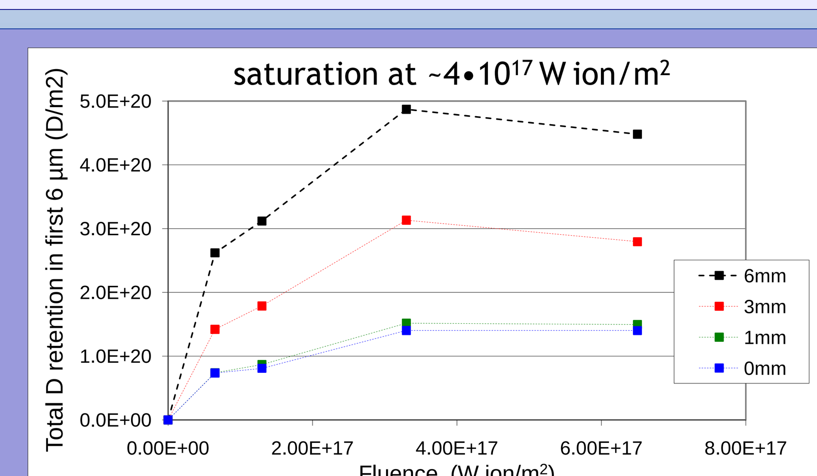
5 Results - Nuclear Reaction Analysis

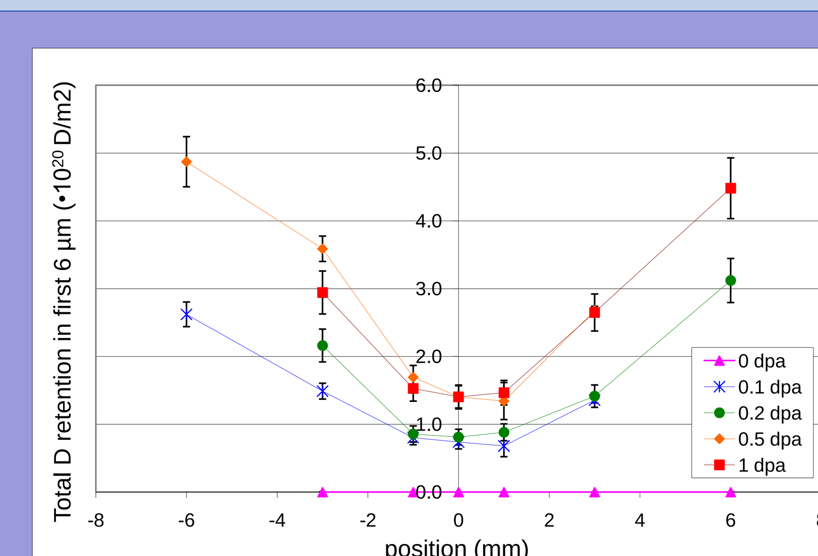
The depth profile of the deuterium retention is measured by using the nuclear reaction: $^3He + D \rightarrow {}^4He + p$



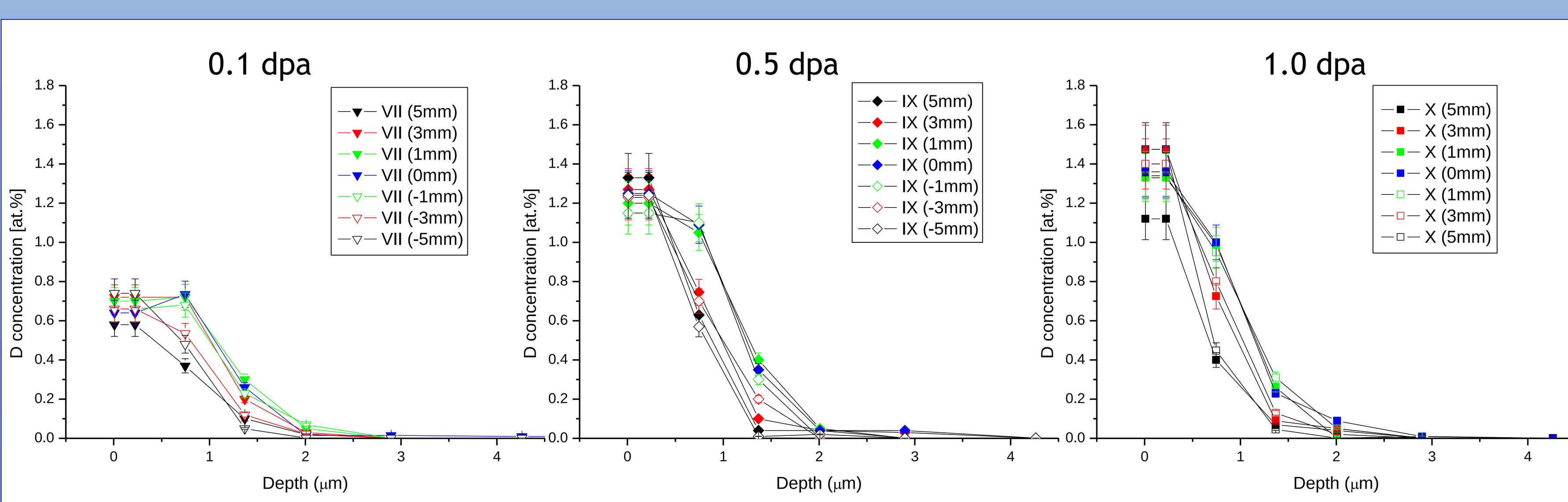
High D retention center: diffusion limited process.

- Deuterium retention is significantly enhanced by W^{4+} pre-irradiation and increases with damage.
- Depth of increased D retention up to 1.5 µm.
- Center: higher temperature → D diffuses deeper into material.
- At the surface → D retention independent of position (independent of flux/ temperature).





Low deuterium retention in the center: thermal detrapping.



The D retention is in the same order of magnitude as experiments performed at much lower fluxes by Tyburska et al [2].
→ High flux ($>10^{24}\ m^{-2}s^{-1}$) does not significantly affect the damage level where saturation takes place.

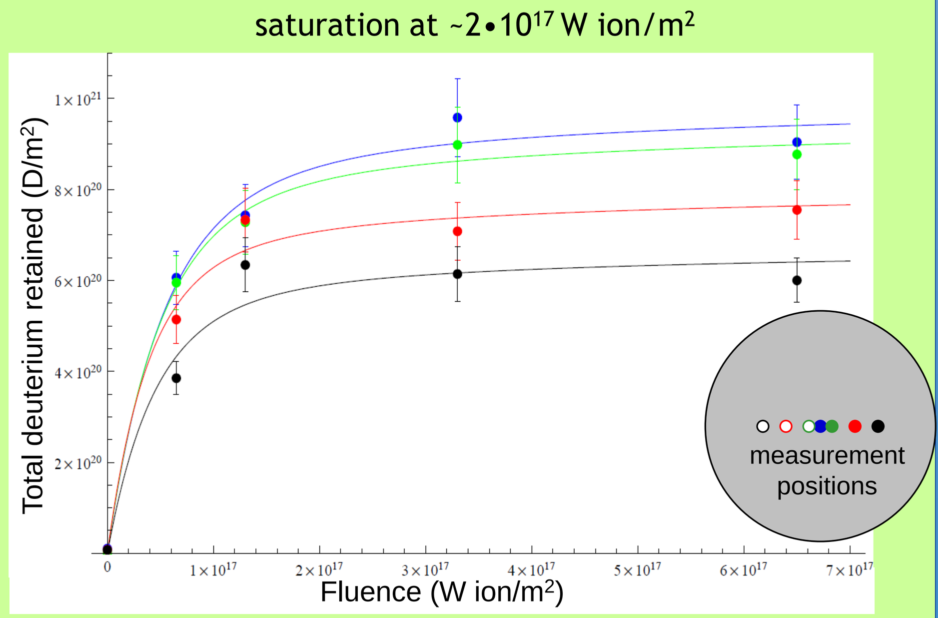
Conclusions

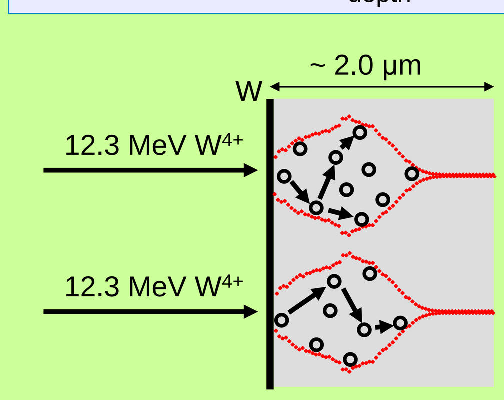
- D retention is significantly enhanced by W^{4+} pre-irradiation and increases with damage level.
- High flux ($>10^{24}\ m^{-2}s^{-1}$) plasma exposure does not significantly affect the damage level where saturation takes place.
- In the low temperature exposure regime deuterium retention is dominated by the diffusion process, for high temperature exposure it is dominated by thermal detrapping.
- Saturation of the deuterium retention occurs at ~0.3 dpa (E_{th} = 40 eV) for $T_{surf,max}$ = 490 K and at ~0.5 dpa (E_{th} = 40eV) for $T_{surf,max}$ = 920 K.
- The average effective damage of one W^{4+} ion is $3 \cdot 10^4\ nm^3$.

Assumptions simple fit:

- Each 12.3 MeV W^{4+} ion displaces many W atoms.
- Vacancies are trap sites for D.
- Material saturates when certain density of vacancies is reached.
- Each MeV ion will create a specific saturated volume (assume TRIM profile).
- MeV ions hit target at arbitrary positions and 'fill' the whole volume.

$$D_{sat}(F) = D_{max} \sum_{depth} 1 - e^{-vac_{TRIM} * V_{eff} * F}$$

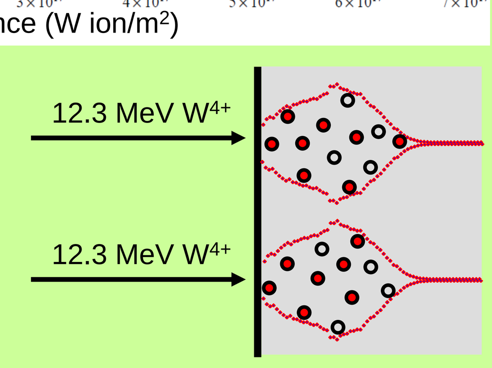




Results: fit parameters

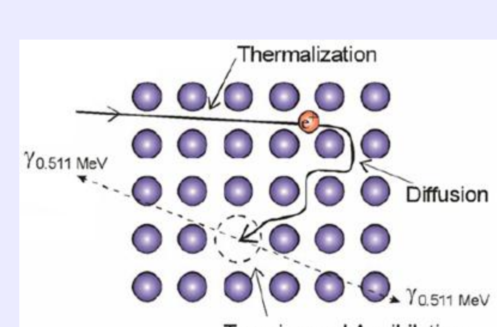
- Saturated volume of one W^{4+} ion: $V_{sat} \sim 3 \cdot 10^4\ nm^3$ → $1.9 \cdot 10^4$ D/ion
- TRIM (E_{th} = 90 eV): one 12.3 MeV ion makes ~ $3.6 \cdot 10^4$ vacancies

→ Occupation degree is ~ 0.5



Not filled to complete depth?
→ larger fluences needed!

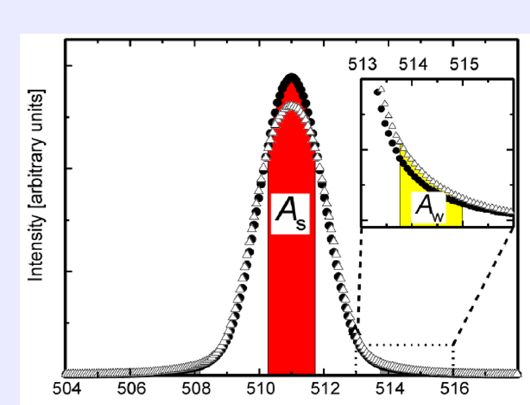
Positron Annihilation Spectroscopy

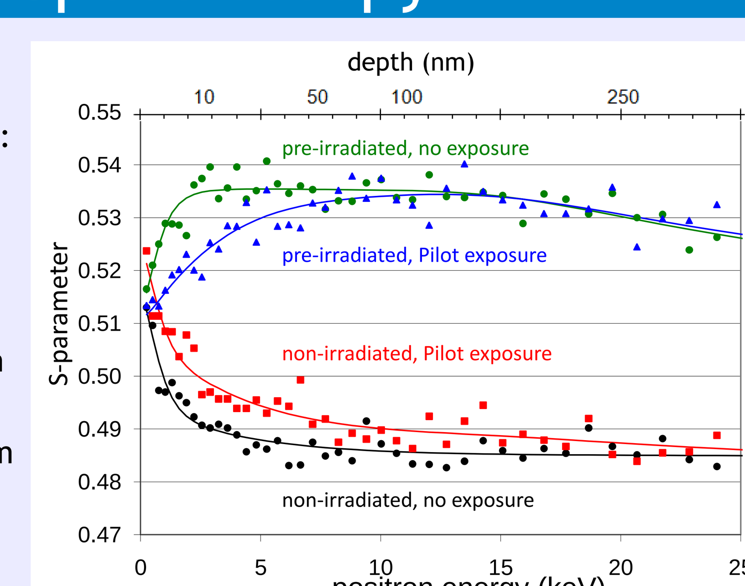


Doppler broadening of the γ (511 keV) from p-e annihilation:

$$2\gamma(511\ keV) + \Delta E (= \frac{p_z c}{2})$$

S-parameter: low-momentum *defect rich*
W-parameter: high-momentum *defect free*





- Non-irradiated and irradiated targets show a clear distinct Doppler broadening profile in the depth range of the ion-implantation.
- Subsequent exposure → change in defect structure in the first 50 nm below surface.
- All targets show a similar behaviour of the bulk material.

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[1] G. Wright et al, Nuclear fusion 50 (2010) 075006
[2] B. Tyburska-Püschel et al., Journal of Nuclear Materials 395 (2009) 150-155