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Hydrogen Retention in Tungsten Materials Studied by Laser Induced Desorption

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Introduction

Tritium retention in plasma facing components (PFCs) due to plasma wall interactions is one of the most critical safety issues for ITER and future fusion devices. Tungsten is foreseen as PFC material in the divertor of ITER and the most promising candidate of PFCs in future reactors. Its fuel retention behaviour is subject of present R&D.

In this work the retention of fuel (deuterium) in bulk tungsten has been studied applying laser induced desorption (LID). This method allows the local measurement of hydrogen isotopes and is also proposed for in situ diagnostic at ITER to monitor tritium retention.

Trapping of hydrogen in tungsten is strongly dependent on material properties and temperature during plasma exposure. Both effects can influence the results obtained by laser induced desorption spectroscopy.

Diagnostic Method

Laboratory:

Laser **I**nduced **D**esorption with **Q**uadrupole **M**ass **S**pectrometer

LID: Nd:YAG laser: λ = 1064 nm, E $\leq$ 40 J, $t_{pulse} \leq$ 3 ms, absorbed intensity: P/A $\leq$ 2 GW/m², f= 6 cm focussing lens

QMS: scan 1-50 amu in 1 s, pressure calibration in H_2, D_2, CH_4, CD_4,…

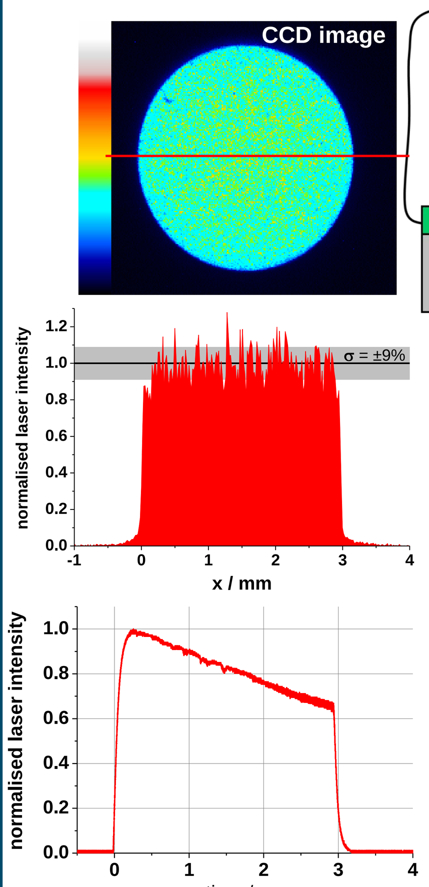
TEXTOR: Laser **I**nduced **D**esorption **S**pectroscopy

LID: Nd:YAG laser: λ = 1064 nm, E $\leq$ 40 J, $t_{pulse} \leq$ 3 ms, absorbed intensity: P/A $\leq$ 500 MW/m², f= 30 cm focussing lens

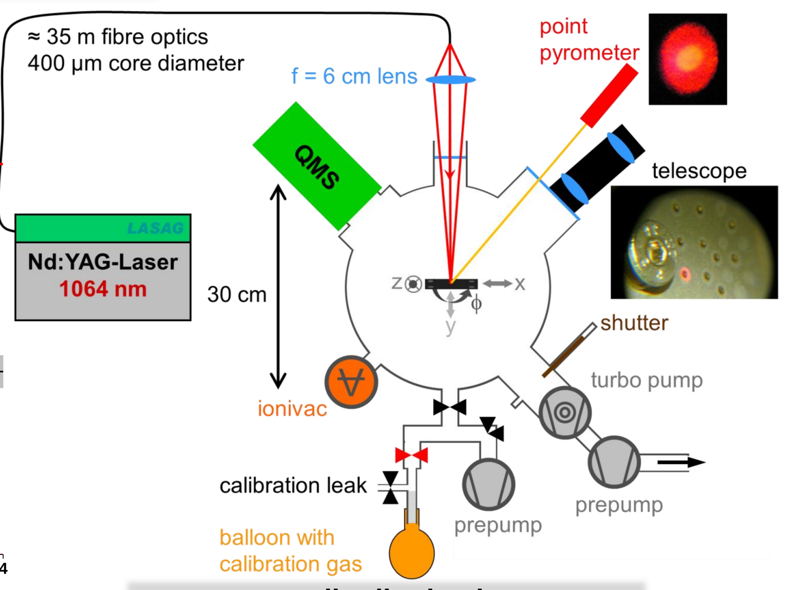
LIDS: optical spectroscopy of Balmer Alpha lines (H_α)

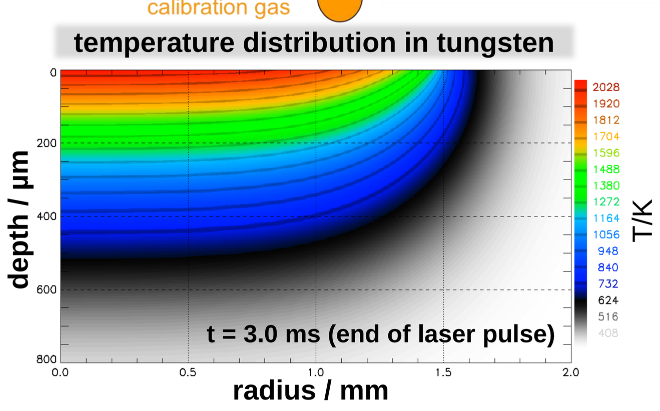
spatial resolution: 3 mm

spatial distribution and temporal development of standard laser pulse at the W target surface



LID-QMS experimental set-up in laboratory





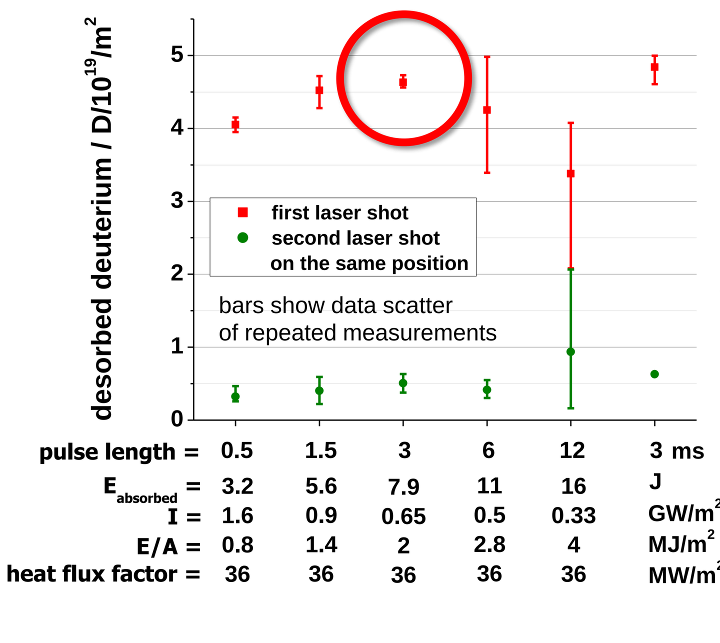
Glow Discharge Exposure

unpolished Goodfellow tungsten, annealed at 1273 K for >1 hour

low flux: **2.8x10¹⁹ D/m²s**, T_{expo}= 533 K

fluence: **2x10²³ D/m² with 2 h exposure time**

twin sample: **7.35x10¹⁹ D/m² (TDS)** after D_2^+ exposure in RF glow discharge



laser parameter optimization on homogenously loaded W by glow discharge

pulse length variation, but keeping the heat flux factor

$$I\sqrt{t} = \frac{P}{A}\sqrt{t} = \frac{E}{A\sqrt{t}}$$

constant by energy adaptation

65% desorbed

short laser pulses ► time for hydrogen diffusion short ► low desorption

too long pulses ► lateral heat diffusion

► a) reduced maximum temperature ► low desorption

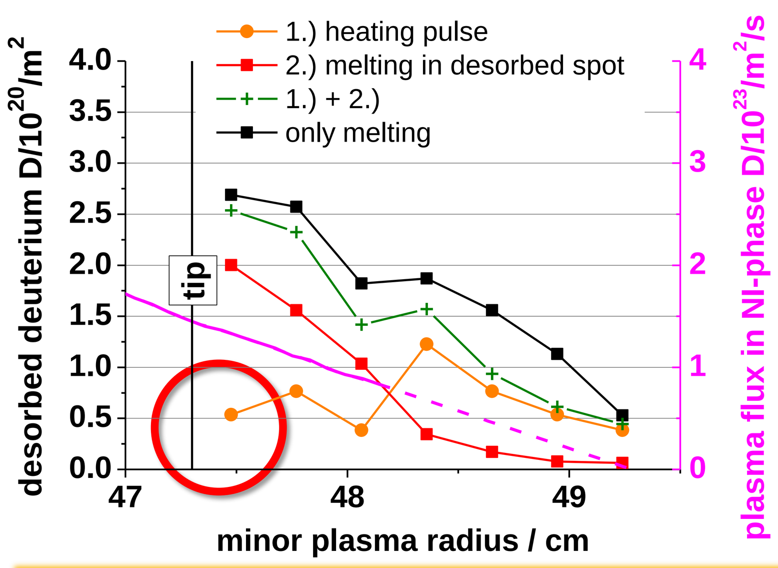
► b) fuzzy temperature profile ► fuzzy desorption volume

► partial overlapping of neighbouring desorption volumes

► scatter

Results

TEXTOR Tokamak Plasma Exposure



unpolished Goodfellow tungsten, annealed at 1273 K for >1 hour

medium flux: **1.5x10²³ D/m²s**

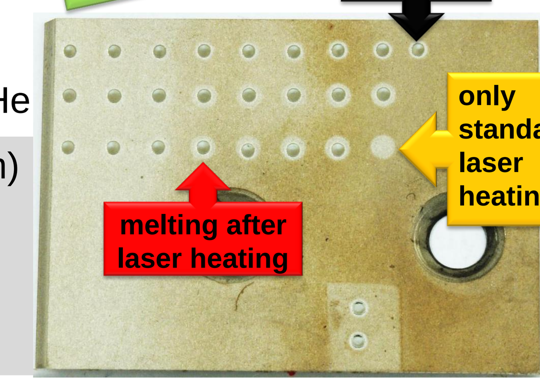
fluence: **1.7x10²⁵ D/m² with 110 s exposure time**

with flux profile decay in SOL

surface temperature: 400 - 650 K, temperature excursions

100-150 eV D and minority impurity fluxes of C (2-4 %), O and He

25% desorbed



bulk W plate on roof limiter, sample tip at 47.3 cm (LCFS: 46 cm)

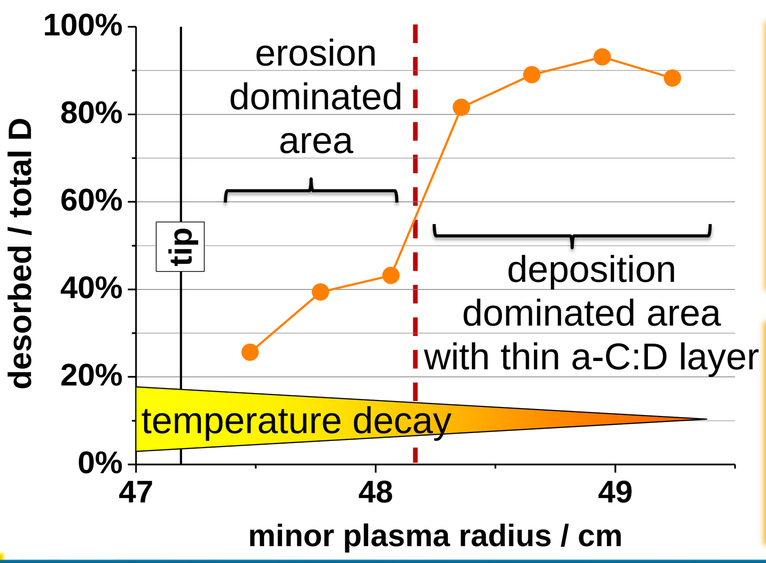
exposed at: $n_e \leq$ 5x10¹⁸ /m³, $T_e \leq$ 30 eV

post mortem analysis by LID:

1.) laser heating pulse: 500 MW/m², ø 3 mm, 1800 K

2.) melting by laser: 1.6 GW/m², ø 2 mm, >4000 K

Melting pulse after heating pulse proves incomplete desorption .



Thin amorphous hydrocarbon layers on the surface prevent D diffusion into the W bulk because D implantation zone is now in the layer .

Combination of heating and melting pulses identifies areas with different retention mechanisms.

High Flux Exposure (Pilot-PSI)

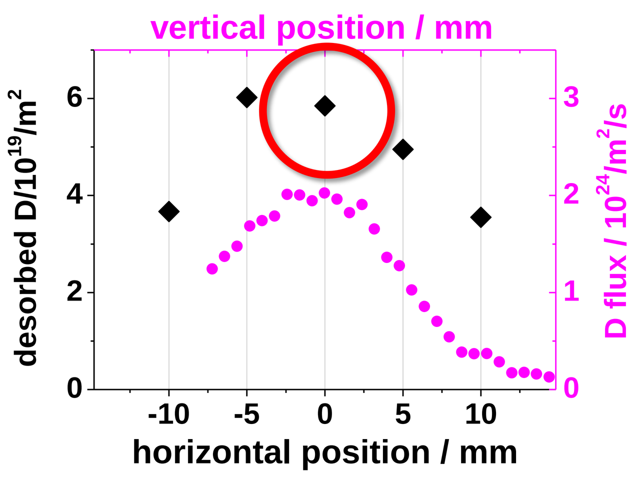
polished Goodfellow tungsten, annealed at 1273 K for >1 hour

high flux: **2x10²⁴ D/m²s**

fluence: **2x10²⁵ D/m² with 10 s exposure time**

T_{max} = 500-580 K, temperature profile according to beam profile, direct water cooling

1.2 eV D, 3.7x10²⁰ /m² with additional -55 V biasing



Similar fluence as in TEXTOR, yields similar amount of desorbed D by standard heating pulse.

Horizontal plasma maximum shift to the left induced by biasing is visible in D inventory.

ECR Plasma Exposure

unpolished Plansee-tungsten, annealed at 1200K for 1 hour

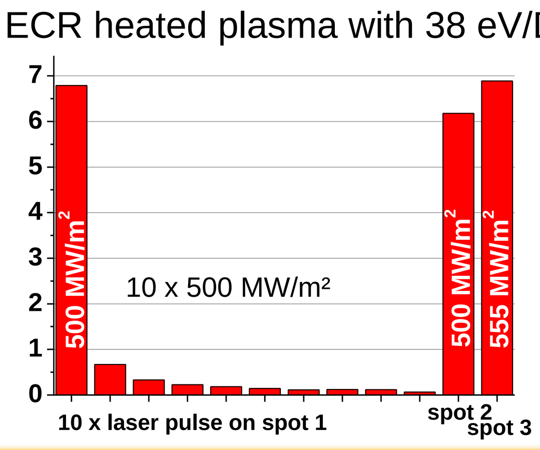
low flux: **10²⁰ D/m²s** at 370 K

deuterium inventory: **TDS: 7.5x10²⁰ D/m²**

fluence: **6x10²⁴ D/m² with 18 h exposure time**

ECR heated plasma with 38 eV/D

91% desorbed



Best match of LID with other methods:

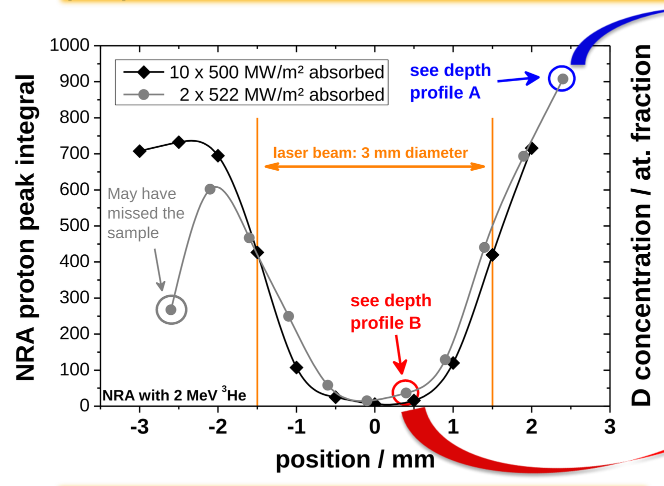
TDS: 7.5 x10²⁰ D/m²

LID: 6.8 x10²⁰ D/m²

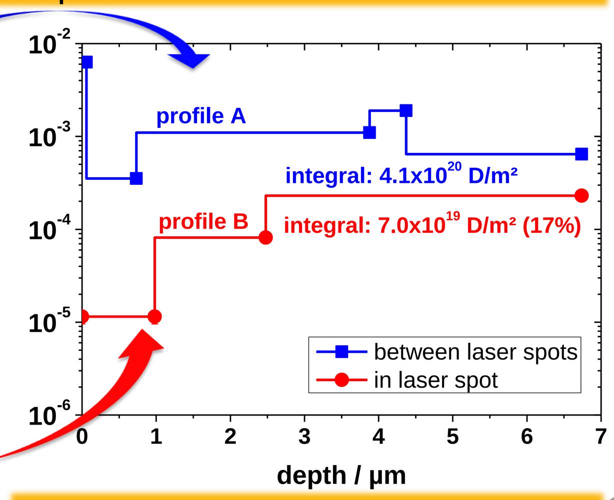
NRA up to 12 µm (with 6 MeV ³He): 5.5 x10²⁰ D/m²

NRA up to 7 µm (with 2 MeV ³He): 4.1 x10²⁰ D/m²

general observation for all samples: Repetitive standard heating pulses on one position yield <10% of first pulse signal due to lateral and perpendicular D diffusion into the desorption volume.



NRA scan over laser spots qualitatively shows the lateral D depletion in the first 7 µm



NRA depth profiles quantitatively prove >83% desorption in first 7 µm and decrease of surface concentration by ~ factor 1000. Compare with diffusion modeling!

Summary

Aim: Measurement of hydrogen isotopes in tungsten by spot laser heating and plasma spectroscopy and/or mass spectroscopic detection (QMS)

→ **in situ** hydrogen monitoring during plasma operation

This work : Laser induced desorption and QMS detection, comparison with NRA and slow ramp thermal desorption

Loading conditions:

370 K $\leq T_W \leq$1500 K

fluence: 2x10²³ D/m² $\leq \Gamma \leq$ 2x10²⁵ D/m²

Laser desorption (single heating pulse)

- > 90 % of fuel from a-C:H layers on W, C, CFC and from bulk C
- max 83 % from bulk W, for low T (≈ 450 K, Plansee material)
- decrease of released hydrogen with increasing loading temperature down to ~ 20%

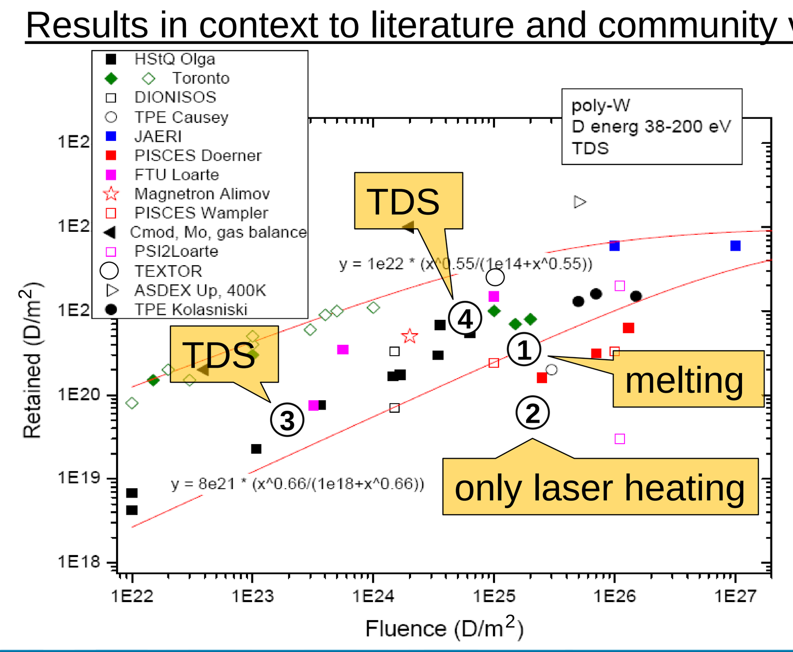
Reasons:

- deep diffusion of part of H in the material for high T_W or long $t_{exposure}$
- different material properties with increased hydrogen storage on traps with higher binding energy

local spot melting releases all stored fuel within depth of ~100 µm

Strategy: frequent desorption of the same monitoring spots on first wall before the fuel is out of laser desorption range

Results in context to literature and community values:



① TEXTOR sample

② high flux exposure

③ RF-glow discharge exposure

④ ECR plasma exposure

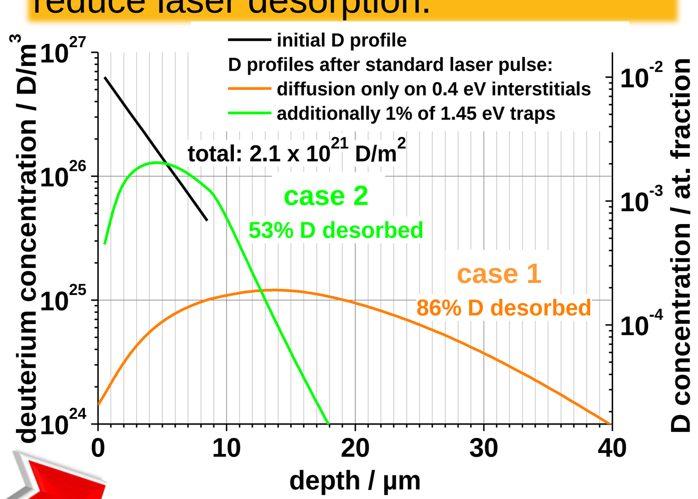
based on [B. Lipschultz et al PSFC/RR-10-4 (2010)]

Laser Heating Simulation

1D-code for diffusion of heat and particles: TMAP7 [G. R. Longhurst et al, INEEL/EXT-04-01657 (2008)]

assumed initial D profile up to 9 µm with 3 µm decay length performing standard heating pulse (500 MW/m², 3 ms)

modeling shows: Stronger trapping and deeper deuterium start profile reduce laser desorption.



case 1: only interstitial sites as "traps"

diffusion on interstitial traps:

D = 4.1 x 10⁻⁷ e^(-0.4eV/kT) m²/s

(experimentally determined by Frauenfelder, 1968)

case 2: additionally 1% of lattice density are 1.45 eV traps

diffusion on these traps only:

D = 1.5·10⁻⁷ e^(-1.45eV/kT) m²/s

The inward diffusing fraction of the inventory can not be desorbed (except it reaches a grain boundary).

The profile maximum shifts deep into the bulk.