

Article

Deuterium Retention in Tungsten and Its Removal by Glow Discharge Cleaning and Baking

Guanghui Ma ^{1,*}  and Hailin Bi ² ¹ School of Integrated Circuits, Anhui Polytechnic University, Wuhu 241000, China² School of Mechanical Engineering, Hefei University of Technology, Hefei 230009, China; bi.hailin@hfut.edu.cn

* Correspondence: maguanghui@ahpu.edu.cn

Abstract

Hydrogen isotope retention in tungsten plasma-facing components affects particle recycling, plasma-density control, and tritium inventory management in fusion devices. In this study, a glow discharge cleaning (GDC) platform and a thermal desorption spectroscopy (TDS) system were used to investigate deuterium (D) retention in polished tungsten and the response of the retained D signal to He-GDC, H₂-GDC, and thermal baking treatments. Tungsten samples were first loaded by D₂-GDC and then characterized by TDS during programmed heating from room temperature to 917 °C at 10 K min^{−1}. Under the present data-reduction procedure, the D₂-GDC-only sample gave an apparent TDS-equivalent D inventory of approximately 7.85×10^{19} D m^{−2}, corresponding to about 29.5% of the estimated incident D fluence. Relative to this D₂-GDC reference sample, the normalized removal fractions were 9.3% for low-power He-GDC, 28.2% for high-power He-GDC, and 65.6% for the tested H₂-GDC condition. The H₂-GDC result is consistent with an isotope-exchange-assisted removal pathway, but the gas-species effect cannot be isolated because the H₂ and He treatments were not performed with identical pressure, duration, current, voltage, and sample-temperature histories. Stepwise baking at 240–350 °C did not fully suppress subsequent D-derived TDS release, indicating that part of the retained D remained in more stable trapping states. Because independent replicates and certified HD/D₂ sensitivity calibration were not available for all conditions, the inventories are reported as apparent values and the conclusions are restricted to normalized comparisons under the tested laboratory conditions.

Keywords: tungsten; deuterium retention; glow discharge cleaning; thermal desorption spectroscopy; deuterium removal; plasma-facing components



Academic Editor: Fabio Moro

Received: 28 May 2026

Revised: 2 July 2026

Accepted: 13 July 2026

Published: 16 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Tungsten is a leading plasma-facing material for divertor and high-heat-flux regions in magnetic-confinement fusion devices because of its high melting point, low physical sputtering yield, and comparatively low hydrogen solubility. However, even in high-Z metallic materials, hydrogen isotopes can be implanted, trapped at defects, diffuse into the near-surface region, and later be released during plasma operation. This retention and re-emission process affects particle recycling, fueling efficiency, and boundary plasma conditions. In deuterium-tritium devices, the retained tritium inventory also raises nuclear safety concerns [1–9].

Wall conditioning is therefore an essential technique for fusion operation. Baking can enhance the desorption of weakly bound gases, while discharge cleaning can induce des-

orption, isotope exchange, and surface chemical reactions through energetic ions and neutrals [10,11]. Glow discharge cleaning (GDC) remains one of the simplest and most widely used conditioning methods because it can be operated without the main toroidal magnetic field and can expose a large wall area to low-temperature plasma. In ITER-oriented (ITER, International Thermonuclear Experimental Reactor) and metallic-wall tokamak studies, D₂-, H₂-, and He-based discharge cleaning, lithium conditioning, cryopumping and fuel gas changeover have been investigated for impurity reduction, hydrogen-isotope control, recycling control and tritium removal [4,7,12–19].

Despite these important device-scale studies, a remaining knowledge gap is the lack of a direct laboratory-scale comparison of He-GDC, H₂-GDC, and moderate-temperature baking for removing deuterium retained in tungsten under the same initial D-loading history. Device experiments in Joint European Torus (JET), W Environment in Steady-state Tokamak (WEST), Experimental Advanced Superconducting Tokamak (EAST), and ITER-relevant studies evaluate wall conditioning in complex mixed-material and long-pulse environments, whereas the present work isolates tungsten samples and uses TDS to quantify the remaining deuterium inventory after each treatment. This design allows the relative contributions of inert ion-induced desorption, hydrogen-isotope exchange, and thermal desorption to be compared under controlled conditions.

Recent discharge-plasma studies involving metallic or tungsten electrodes have also shown that the discharge regime, electrode geometry, cathode sheath, and possible transition from glow-like behavior to arc or abnormal-glow conditions can strongly influence ion bombardment and surface modification. These studies emphasize the need to report the discharge configuration and to avoid over-generalizing results obtained under a limited set of GDC parameters [20,21].

Thermal desorption spectroscopy (TDS) is a direct method for evaluating retained hydrogen isotopes in materials. By recording the partial pressures of desorbed species as a function of temperature, TDS can provide information on the retained inventory and the relative stability of trapping states [1,2,22–24]. The combination of GDC loading/removal experiments with TDS quantification is therefore well suited to evaluate potential wall-conditioning procedures for tungsten components.

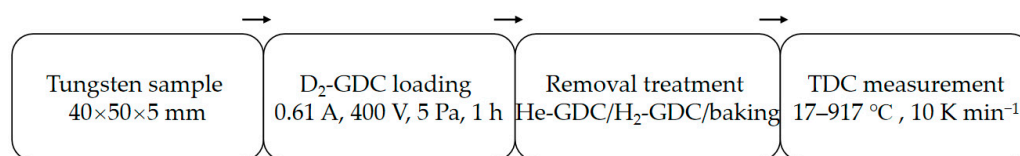
This work aims to provide a laboratory-scale experimental reference for evaluating how selected wall-conditioning treatments affect deuterium retained in polished tungsten. In this paper, D₂-GDC was used as a deuterium (D) loading source, TDS was used to quantify the subsequent D-derived release signal, and He-GDC, H₂-GDC, and baking treatments were compared as post-treatment methods. The comparison is intentionally restricted to the tested parameter set because the discharge duration, pressure, current, and voltage were not identical for all gases.

The specific issue targeted here is therefore not whether GDC can condition a fusion wall in general, but how different post-treatment routes modify the apparent retained-D signal when the initial D-loading history is kept nominally identical. The results are intended to complement, rather than replace, tokamak-scale isotope-removal experiments by providing sample-level evidence that can help interpret wall-conditioning behavior in tungsten-dominated plasma-facing components.

2. Materials and Methods

2.1. Tungsten Samples and Experimental Sequence

Commercial tungsten samples supplied by Advanced Technology & Materials Co., Ltd. (Hefei, China) were used, consistent with tungsten material used for EAST (Hefei, China) divertor applications. The sample dimensions were 40 × 50 × 5 mm, and the surface was mechanically polished before testing. The experiment sequence is shown in Figure 1.



Quantification of retained D from HD ($m/z=3$) and D₂ ($m/z=4$) desorption signals

Figure 1. Schematic of the experimental workflow for D implantation, removal treatment, and TDS quantification.

According to the supplier information available for the present commercial tungsten plates, the material was high-purity tungsten with nominal purity not lower than 99.95 wt%. The average grain size and trace-impurity distribution were not independently measured in this work; this limitation has been added because grain boundaries, vacancies, and impurity-related traps can affect the TDS peak structure and the absolute retained inventory.

Each treatment condition in this preliminary study was performed on one independent tungsten specimen. Therefore, standard deviations and confidence intervals cannot be reported. This limitation is important because the reported removal fractions should be interpreted as indicative values under the tested conditions rather than statistically optimized or universally transferable removal efficiencies. Additional replicate tests will be required in future work to quantify data scatter.

2.2. Glow Discharge Treatment

A dedicated glow discharge platform was used to expose tungsten samples to D₂, He, or H₂ glow discharges. The sample acted as the cathode during discharge treatment, so positive ions were accelerated through the cathode sheath and bombarded the sample surface with energies on the order of hundreds of electronvolts. The reference sample 1 was untreated. Samples 2–6 were subjected to deuterium implantation via D₂-GDC for 1 h with a discharge current of 0.61 A, voltage of approximately 400 V, and gas pressure of 5 Pa. The incident D flux was calculated from the ion-current-equivalent flux collected by the cathode sample, using the effective exposed area and assuming singly charged deuterium ions as a first-order estimate. The corrected average incident D flux used for the inventory calculation was approximately $7.4 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$, corresponding to a 1 h fluence of approximately $2.66 \times 10^{20} \text{ D m}^{-2}$. This value should be regarded as an engineering estimate because the plasma contains ions, neutrals, and recombining species, and the local sheath distribution is not spatially uniform.

The discharge cell used the tungsten specimen as the negatively biased cathode. The surrounding stainless-steel chamber wall and auxiliary electrode were electrically grounded and served as the anode/return path. Thus, the reported discharge voltage corresponds to the cathode bias with respect to the grounded anode structure.

For post-treatment removal tests, samples 1–2 were untreated and samples 3–5 with the same D₂-GDC loading history were treated by low-power He-GDC, high-power He-GDC, and low-power H₂-GDC, respectively. Low-power He-GDC was performed for 1.5 h at 0.6 A, approximately 230 V, and 5 Pa. High-power He-GDC was performed for 1.5 h at 1.8 A, approximately 266 V, and 5 Pa. H₂-GDC was performed for 1 h at 0.61 A, approximately 308 V, and 1.0 Pa. After discharge, the sample chamber was filled with nitrogen, and samples were transferred to the TDS system.

2.3. Thermal Desorption Spectroscopy

TDS measurements were carried out using a programmed heating system coupled with residual gas analyzer (RGA). The untreated sample 1, sample 2 without post-treatment and discharge-treated samples 3–5 were heated from room temperature (17 °C) to 917 °C at 10 K min^{−1}. Sample 6 was baked at selected temperatures in TDS system after D₂-GDC loading to explore the effect of baking temperature. The experiment matrix for tungsten sample treatment and TDS measurement is summarized in Table 1. The partial pressures of HD (Hydrogen Deuteride, mass-to-charge ratio $m/z = 3$) and D₂ ($m/z = 4$) were recorded as functions of time and converted to temperature-dependent desorption spectra according to the programmed temperature ramp.

Table 1. Experimental matrix for tungsten sample treatment and TDS measurement.

Sample	D Loading	Removal Treatment	TDS Program
1	None	None	17–917 °C, 10 K min ^{−1}
2	D ₂ -GDC, 1 h, 0.61 A, ~400 V, 5 Pa	None	same as sample 1
3	same as sample 2	He-GDC, 1.5 h, 0.6 A, ~230 V, 5 Pa	same as sample 1
4	same as sample 2	He-GDC, 1.5 h, 1.8 A, ~266 V, 5 Pa	same as sample 1
5	same as sample 2	H ₂ -GDC, 1 h, 0.61 A, ~308 V, 1.0 Pa	same as sample 1
6	same as sample 2	Baking at selected temperatures	Isothermal baking and TDS monitoring

The sample temperature during TDS was measured by a thermocouple attached to the sample holder in close thermal contact with the tungsten specimen. The temperature program was controlled at 10 K min^{−1} from room temperature to 917 °C, and the recorded time axis of the RGA signal was converted to sample temperature according to this measured ramp.

The RGA was operated after mass calibration and background stabilization. The $m/z = 3$ and $m/z = 4$ channels were monitored for HD and D₂, respectively. Because a certified HD calibration gas was not available, the HD sensitivity was treated using the same order-of-magnitude sensitivity as the hydrogen-isotope channels after background subtraction, and the same data-reduction procedure was applied to all samples. Therefore, the comparison among samples is more reliable than the absolute inventory value, and this uncertainty is explicitly considered in the interpretation.

Because certified HD and D₂ sensitivity calibration was not available for all relevant channels, all inventory values are reported as apparent TDS-equivalent inventories rather than fully traceable absolute deuterium inventories. The removal fractions were calculated by normalizing each post-treated sample to the D₂-GDC-only reference measured with the same RGA, chamber volume, pumping configuration, heating program, and data-reduction procedure. This normalization reduces, but does not eliminate, the influence of an unknown absolute sensitivity factor. Possible systematic errors from different HD and D₂ sensitivities therefore remain a limitation of the present work.

The retained D amount was evaluated from the measured partial pressures using a gas-balance relation that includes both desorption from the sample and pumping by the vacuum system. The TDS chamber volume was approximately 5 L. For a given species, the desorption throughput was calculated from

$$Q = V \frac{dP}{dt} + SP, \quad (1)$$

where Q is the desorption throughput, V is the system volume, P is the partial pressure of the selected species, and S is the effective pumping speed in m³ s^{−1} for that species.

The desorption rate is defined as the number of deuterium particles desorbed per unit surface area per unit time. For a given sample, the desorption rate was calculated from

$$R = \Sigma \frac{nQ}{aKT}, \quad (2)$$

where R is the desorption rate, n is the number of deuterium atoms contained per gas molecule, a is the surface area in m^2 of the sample, K is the Boltzmann constant, equal to $1.38 \times 10^{-23} \text{ J K}^{-1}$, T is the gas temperature in K.

Considering that during the sample heating process, deuterium was primarily desorbed in the forms of HD and D_2 . The desorption rates of deuterium atoms released in these two forms from the sample were calculated separately using Equations (1) and (2), accordingly. The total D inventory was then obtained by integrating the contributions of HD and D_2 throughout the entire heating process.

For D_2 , two deuterium atoms were counted per molecule, while for HD one deuterium atom was counted per molecule. The retained D inventory reported here is therefore the sum of D atoms released as HD and D atoms released as D_2 . Background signals measured before the main desorption event were subtracted before integration. The main sources of uncertainty are the effective pumping speed, RGA sensitivity factors for HD and D_2 , the estimated ion-current-equivalent incident flux, and sample-to-sample variation in surface condition.

3. Results

3.1. D Retention After D_2 -GDC

The untreated tungsten sample 1 did not show detectable HD ($m/z = 3$) or D_2 ($m/z = 4$) desorption peaks, indicating that the observed deuterium signal in treated samples originated from D_2 -GDC loading. According to the calculation results, the separated HD and D_2 desorption rate curves for the D-loaded and post-treated samples 2–5 are shown in Figure 2. After 1 h of D_2 -GDC, HD desorption appeared at approximately 200°C and showed multiple small peaks around 430°C , 510°C , and 580°C . D_2 desorption also began near 200°C , reached a maximum near 300°C , and was nearly depleted by approximately 460°C .

The retained D inventory includes both D atoms desorbed as HD and D atoms desorbed as D_2 . Therefore, the apparent retained D fraction is not calculated from the D_2 signal alone, but from the integrated total deuterium amount released through both monitored molecular channels.

During heating process, the maximum desorption rate of deuterium atoms released as HD from sample 2 was $2.5 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$, while that for D_2 was $4.4 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$. For sample 3, the peak desorption rate for HD reached $4.1 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$, compared with $2.3 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$ for D_2 . For sample 4, the maximum desorption rate for HD was $2.0 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$, while that for D_2 was $2.1 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$. For sample 5, the values dropped to $0.9 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$ for HD and $0.6 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$ for D_2 . Among the tested post-treatment cases, sample 5 subjected to the H_2 -GDC condition showed the lowest D-derived TDS signal.

According to the calculation results, the cumulative desorbed D amounts used for inventory analysis are shown in Figure 3. The integrated inventory for the D_2 -GDC-only sample 2 was $7.85 \times 10^{19} \text{ D m}^{-2}$, consisting of $4.79 \times 10^{19} \text{ D m}^{-2}$ released as HD and $3.06 \times 10^{19} \text{ D m}^{-2}$ released as D_2 . The corresponding values for sample 3 were $7.12 \times 10^{19} \text{ D m}^{-2}$, with $5.33 \times 10^{19} \text{ D m}^{-2}$ as HD and $1.78 \times 10^{19} \text{ D m}^{-2}$ as D_2 . For sample 4, the integrated inventory was $5.64 \times 10^{19} \text{ D m}^{-2}$, including $2.94 \times 10^{19} \text{ D m}^{-2}$

released as HD and $2.7 \times 10^{19} \text{ D m}^{-2}$ released as D_2 . The integrated inventory for sample 5 was $2.7 \times 10^{19} \text{ D m}^{-2}$, with $1.79 \times 10^{19} \text{ D m}^{-2}$ as HD and $0.9 \times 10^{19} \text{ D m}^{-2}$ as D_2 .

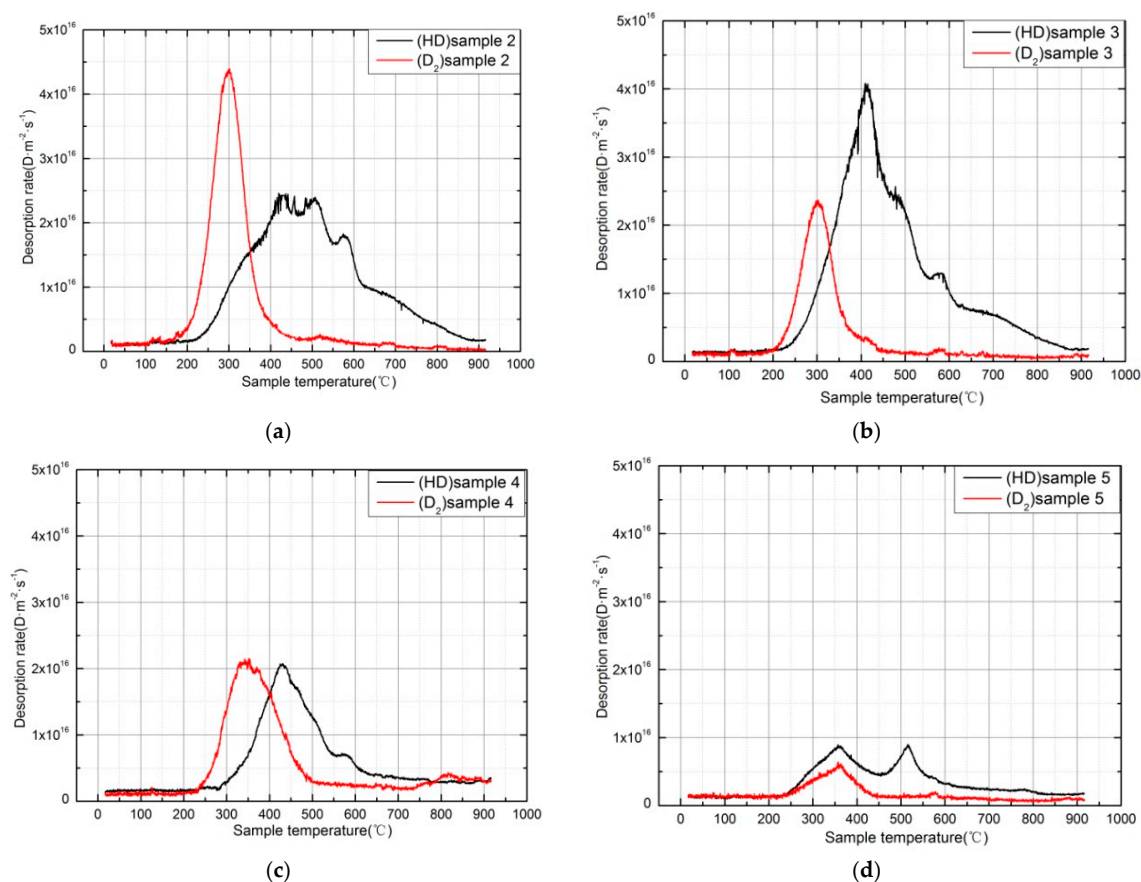


Figure 2. Desorption rates of D released in HD and D_2 forms from D-loaded and post-treated tungsten samples during TDS heating (vertical axis: Desorption Rate ($\text{D m}^{-2} \text{ s}^{-1}$)): (a) sample 2; (b) sample 3; (c) sample 4; (d) sample 5.

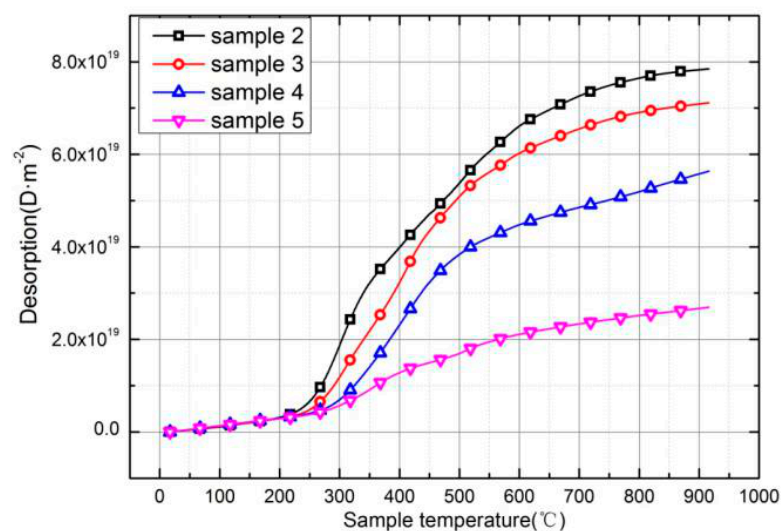


Figure 3. Cumulative desorbed D amount as a function of sample temperature for tungsten samples subjected to different post-treatment conditions.

Because certified HD and D_2 sensitivity calibration was not available, these inventories should be regarded as apparent TDS-equivalent inventories rather than traceable absolute D inventories. Consequently, the principal comparison in this work is based on normalized

remaining fractions and removal fractions relative to sample 2, not on the absolute inventory values alone.

Using the corrected ion-current-equivalent D flux of approximately $7.4 \times 10^{16} \text{ D m}^{-2} \text{ s}^{-1}$ and the 1 h exposure time, the total incident D fluence was approximately $2.66 \times 10^{20} \text{ D m}^{-2}$. Therefore, the apparent retained D fraction, including D released as both HD and D₂ during TDS, was estimated to be 29.5% under the present D₂-GDC implantation conditions.

3.2. Effect of He-GDC on Retained D

The normalized removal fractions calculated from the apparent TDS-equivalent inventories are shown in Figure 4. The apparent D inventory remaining in tungsten after different removal treatments is summarized in Table 2. Post-treatment by He-GDC reduced the D-derived TDS signal, and the removal fraction increased with discharge current. After low-power He-GDC, the apparent remaining inventory decreased from 7.85×10^{19} to $7.12 \times 10^{19} \text{ D m}^{-2}$, corresponding to a normalized removal fraction of 9.3%. After high-power He-GDC, the apparent remaining inventory was further reduced to $5.64 \times 10^{19} \text{ D m}^{-2}$, corresponding to a normalized removal fraction of 28.2%. The continued use of helium and hydrogen-based conditioning and the changeover between helium and hydrogen-fueled plasmas in metallic-wall devices have also been emphasized in recent JET and WEST studies [16–18].

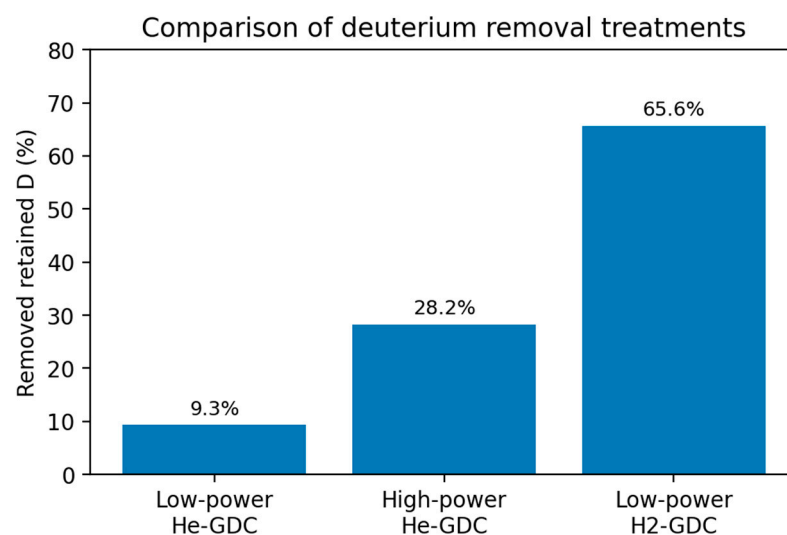


Figure 4. Normalized removal fractions of retained deuterium after different glow discharge cleaning treatments. Values are calculated relative to the apparent TDS-equivalent D inventory measured after D₂-GDC loading without post-treatment.

Table 2. D inventory remaining in tungsten after different removal treatments.

Sample	Removal Treatment	Apparent D Released as HD (TDS-Equivalent D m^{-2})	Apparent D Released as D ₂ (TDS-Equivalent D m^{-2})	Apparent Total D Remaining (TDS-Equivalent D m^{-2})	Normalized Removal Fraction (%)
1	Untreated	0	0	0	-
2	None after D ₂ -GDC	4.79×10^{19} (61%)	3.06×10^{19}	7.85×10^{19}	0
3	He-GDC, 0.6 A, 5 Pa	5.33×10^{19} (75%)	1.78×10^{19}	7.12×10^{19}	9.3
4	He-GDC, 1.8 A, 5 Pa	2.94×10^{19} (52%)	2.70×10^{19}	5.64×10^{19}	28.2
5	H ₂ -GDC, 0.61 A, 1 Pa	1.79×10^{19} (66%)	0.90×10^{19}	2.70×10^{19}	65.6

Because the high-power He-GDC condition used both a higher current and a slightly higher discharge voltage than the low-power condition, the improved removal cannot be attributed to a single variable unambiguously. It is plausibly associated with the combined increase in ion fluence and ion-bombardment energy. The present experiment therefore

demonstrates a power-dependent He-GDC trend under the tested conditions, but it does not independently separate ion fluence from ion energy.

Under the specific tested conditions, the lowest remaining apparent D inventory was obtained after the H₂-GDC treatment. However, the H₂-GDC and He-GDC cases were not performed with identical treatment time, pressure, current, voltage, or sample-temperature history. Therefore, the present data cannot isolate the working-gas effect alone. The result is more cautiously interpreted as showing that the tested H₂-GDC condition yielded a lower remaining D-derived signal than the tested He-GDC conditions and that isotope-exchange-assisted removal is a plausible hypothesis requiring further validation.

The isotope-exchange interpretation is therefore presented as a plausible mechanism supported indirectly by the relatively large reduction in the D-derived TDS signal after the tested H₂-GDC condition. Alternative or concurrent effects, including differences in ion flux, pressure-dependent plasma density, sample heating, surface recombination, and sputtering behavior, may also contribute. Direct verification would require post-treatment H/D depth profiling by nuclear reaction analysis (NRA), elastic recoil detection analysis (ERDA), or a similar method; such measurements were not performed in the present study.

3.3. Effect of Baking Temperature

The baking experiment was performed using sample 6 after D₂-GDC loading under the same conditions used for the reference D-loaded sample 2. The retained inventory before baking was therefore taken to be approximately 7.85×10^{19} D m⁻². The TDS system was then used as a controlled baking platform at selected temperatures relevant to fusion wall conditioning. For ITER, 240 °C baking is relevant to internal components, while higher-temperature baking around 350 °C has been considered for divertor tritium removal.

The stepwise baking sequence and the corresponding HD/D₂ pressure responses are shown in Figure 5. The desorption behavior showed that 240 °C baking could not remove all retained D. Even after baking at 350 °C for 1.5 h, HD release was still observed at higher temperatures during subsequent heating. This indicates that part of the D inventory remains trapped in tungsten under the tested moderate-temperature baking conditions, consistent with recent observations that high-fluence plasma exposure, helium irradiation and microstructural defects can enhance stable hydrogen-isotope trapping in tungsten [1,2]. Longer baking duration or discharge-assisted removal would therefore be required when the allowable wall temperature is limited.

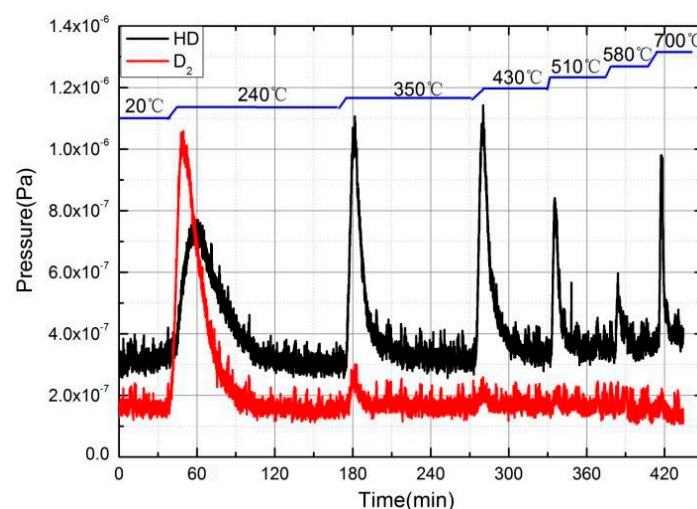


Figure 5. HD and D₂ partial-pressure responses during stepwise baking of a D-loaded tungsten sample at different temperatures.

The stepwise baking experiment was used mainly to identify whether detectable deuterium release persisted after each temperature plateau. Because the sample was heated in a non-identical isothermal sequence rather than by the same complete TDS ramp used for samples 2–5, an exact remaining fraction after the whole baking sequence was not assigned. However, the continued HD release after the 350 °C stage indicates that a non-negligible fraction of the original inventory remained in deeper or more stable trapping states. Longer baking at 350 °C may remove additional weakly and moderately trapped D, but the persistence of higher-temperature release suggests that baking alone may be kinetically limited for deeper traps under practical durations.

This result is not claimed as a new discovery by itself. It is consistent with previous TDS studies showing that deuterium trapped at vacancies, dislocations, grain boundaries, impurity-related traps, or irradiation-induced defects in tungsten can require substantially higher temperatures for complete release. In the present paper, the baking section is retained only as a comparative reference for the GDC removal tests and is discussed in a shortened, literature-consistent manner.

4. Discussion

The experiment reveals several useful but preliminary features of hydrogen isotope control in tungsten. First, D₂-GDC is a convenient laboratory method for introducing a measurable D-derived TDS signal into tungsten samples with a controlled exposure history. Because only one specimen was used for each condition, the retained fractions and removal fractions should be treated as apparent comparative values rather than statistically validated averages.

The peak positions in the TDS spectra provide qualitative information about trapping states. The D₂ peak near 300 °C can be associated with relatively weak near-surface trapping and recombination-limited release, whereas the HD peaks around 430 °C, 510 °C, and 580 °C suggest progressively stronger trapping states. Based on typical TDS interpretations for hydrogen isotopes in tungsten, these higher-temperature features may be related to dislocations, grain boundaries, vacancy-like defects, and impurity-associated traps. This assignment is tentative because the present work did not include independent microstructural characterization such as transmission electron microscope (TEM), scanning electron microscope (SEM), or positron-annihilation measurements.

The change in HD/D₂ partitioning among samples may reflect a combination of residual hydrogen availability, recombination kinetics, surface state, and trap distribution. In particular, the increased HD fraction after low-power He-GDC should not be overinterpreted without repeat measurements. Accordingly, this observation is treated qualitatively and is not used as independent proof of a distinct removal mechanism.

Second, He-GDC can remove retained D through ion-induced desorption and energy transfer. Because helium is chemically inert and does not participate directly in hydrogen isotope exchange, the observed He-GDC effect is expected to depend on discharge power, ion fluence, and ion-bombardment energy. The increase from 9.3% removal at 0.6 A to 28.2% removal at 1.8 A is consistent with this interpretation, although the present experiment does not separate these variables independently.

Helium implantation may also modify the near-surface defect structure of tungsten. Such defects can assist D release by transferring energy and disturbing existing D-trap configurations, but they may also create additional trapping sites for hydrogen isotopes. This dual effect means that the measured He-GDC removal efficiency reflects a competition between ion-induced desorption and defect-mediated retrapping. The increased removal observed at higher He-GDC current should therefore be interpreted as the net effect under the present discharge conditions.

The surface morphology and near-surface damage state after the GDC treatments were not characterized in the present work. Therefore, possible He-induced blisters, nanostructures, sputtering roughening, or H-rich surface layers after H₂-GDC cannot be excluded. These effects may influence both removal kinetics and the interpretation of the TDS spectra, and they are listed as priorities for future SEM/TEM, X-ray photoelectron spectroscopy (XPS), and depth-profile measurements.

Third, the tested H₂-GDC condition produced a lower remaining D-derived signal than the tested He-GDC conditions. The likely contribution of isotope exchange is physically reasonable because incoming hydrogen can recombine with retained deuterium and promote HD desorption. Nevertheless, because the discharge parameters were not matched and no direct H depth-profile measurement was performed after H₂-GDC, this mechanism is treated as a hypothesis rather than a direct experimental proof.

From a simple apparent-inventory balance, the D-derived TDS-equivalent signal decreased from 7.85×10^{19} to 2.70×10^{19} D m⁻² after the tested H₂-GDC condition, corresponding to an apparent reduction of 5.15×10^{19} D m⁻². This reduction is larger than that obtained under the tested high-power He-GDC condition. Together with the HD contribution in the desorption spectra, this behavior is consistent with, but does not prove, an isotope-exchange-assisted pathway in which incoming H may replace trapped D and promote release as HD and D₂. A more rigorous kinetic model would require independent measurements of H uptake, near-surface D depth profiles, sample temperature during GDC, and discharge-particle energy distributions.

Baking remains useful for desorbing weakly bound hydrogen isotopes and residual gases, but the present results indicate that 240–350 °C baking alone may be insufficient for full D removal from tungsten over practical time scales. Combining baking with discharge cleaning may therefore be a promising wall-conditioning strategy [4,16,17,19]. The present study is preliminary and should be extended by repeating each condition with multiple independent samples, calibrating mass-spectrometer sensitivities for HD and D₂, and examining the influence of surface roughness, defect density, discharge current density, and sample temperature during GDC.

Future work should therefore include at least three independent samples for each condition, calibrated HD and D₂ sensitivities using reference leaks or calibrated gas dosing, matched H₂/He discharge parameters, ion-energy-resolved GDC experiments, sample-temperature monitoring during GDC, post-exposure H/D depth profiling by NRA or ERDA, and surface characterization by SEM/TEM or XPS. These experiments are necessary before the intrinsic effects of working gas species, discharge power, pressure, treatment duration, and sample temperature can be ranked quantitatively for reactor-relevant wall-conditioning scenarios.

5. Conclusions

This paper investigated deuterium retention in polished tungsten after D₂ glow discharge loading and compared the responses of the retained D-derived TDS signal to He-GDC, H₂-GDC, and moderate-temperature baking. Because the study used one specimen for each condition and did not include certified HD/D₂ sensitivity calibration, the conclusions are restricted to apparent TDS-equivalent inventories and normalized comparisons under the tested laboratory conditions:

- D₂-GDC introduced a measurable D-derived TDS signal into polished tungsten. Because certified HD/D₂ sensitivity calibration was not available, the main conclusion is based on normalized remaining fractions relative to the D₂-GDC-only reference rather than traceable absolute inventory values;

- He-GDC reduced the apparent retained-D signal, and the normalized removal fraction increased from 9.3% under the low-power He-GDC condition to 28.2% under the high-power He-GDC condition; this trend is consistent with stronger ion-bombardment conditions but does not independently separate ion fluence and ion energy;
- Among the tested non-identical discharge conditions, the H₂-GDC case gave the lowest remaining D-derived TDS signal and a normalized removal fraction of 65.6%; this observation is consistent with isotope-exchange-assisted removal but does not by itself exclude contributions from different discharge time, pressure, current density, or sample heating;
- Moderate-temperature baking at 240 °C and the tested 350 °C sequence did not fully suppress the subsequent D-derived TDS signal, consistent with literature reports of stable trapping states in tungsten;
- Within the limited parameter space investigated in this work, the results indicate that discharge-assisted treatments are promising for reducing retained hydrogen-isotope signals in tungsten, while matched-parameter, calibrated, and statistically repeated experiments are still needed before general removal efficiencies can be ranked.

This work provides a preliminary laboratory-scale reference for wall-conditioning and hydrogen-isotope removal studies on tungsten plasma-facing components. The findings may be useful for tritium inventory-control studies in long-pulse tokamaks and future fusion reactors, but they should be interpreted together with the stated calibration, replication, and parameter-matching limitations.

Overall, the present results should be viewed as a comparative sample-level dataset rather than a complete optimization of wall-conditioning parameters for reactor-relevant environments.

Author Contributions: Conceptualization, G.M. and H.B.; methodology, G.M. and H.B.; formal analysis, G.M. and H.B.; investigation, H.B.; data curation, H.B.; writing—original draft preparation, G.M.; writing—review and editing, H.B. and G.M.; visualization, G.M. and H.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

D	Deuterium
GDC	Glow discharge cleaning
RGA	Residual gas analyzer
TDS	Thermal desorption spectroscopy
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
WEST	W Environment in Steady-state Tokamak
EAST	Experimental Advanced Superconducting Tokamak
HD	Hydrogen Deuteride
NRA	Nuclear reaction analysis
ERDA	Elastic recoil detection analysis
TEM	Transmission electron microscope
SEM	Scanning electron microscope
XPS	X-ray photoelectron spectroscopy

References

1. Sun, Y.W.; Yin, H.; Song, H.F.; Wang, J.; Wang, H.Q.; Cheng, L.; Yuan, Y.; Zhou, H.S.; Schwarz-Selinger, T.; Morgan, T.W.; et al. Deuterium retention in recrystallized tungsten exposed to high-flux plasma with fluences up to $1 \times 10^{29} \text{ m}^{-2}$. *Nucl. Fusion* **2025**, *65*, 046030. [\[CrossRef\]](#)
2. Ding, X.; Fang, J.; Xu, Q.; Zhang, P.; Zhang, H.; Luo, L.; Wu, Y.; Yao, J. Microstructure Evolution and Effect on Deuterium Retention in TiC- and ZrC-Doped Tungsten under He^+ Ion Irradiation. *Metals* **2023**, *13*, 783. [\[CrossRef\]](#)
3. Widdowson, A.; Coad, J.P.; Zayachuk, Y.; Jepu, I.; Alves, E.; Catarino, N.; Corregidor, V.; Mayer, M.; Krat, S.; Likonen, J.; et al. Evaluation of tritium retention in plasma-facing components during JET tritium operations. *Phys. Scr.* **2021**, *96*, 124075. [\[CrossRef\]](#)
4. Yu, Y.W.; Hu, J.S.; Zuo, G.Z.; Sun, Z.; Wang, L.; Xu, W.; Wang, J.R.; Cao, B.; Gao, W.; Xu, J.C.; et al. Control of hydrogen content and fuel recycling for long pulse high performance plasma operation in EAST. *Nucl. Fusion* **2019**, *59*, 126036. [\[CrossRef\]](#)
5. Causey, R.A. Hydrogen isotope retention and recycling in fusion reactor plasma-facing components. *J. Nucl. Mater.* **2002**, *300*, 91–117. [\[CrossRef\]](#)
6. Federici, G.; Skinner, C.H.; Brooks, J.N.; Coad, J.P.; Grisolia, C.; Haasz, A.A.; Hassanein, A.; Philipps, V.; Pitcher, C.S.; Roth, J.; et al. Plasma-material interactions in current tokamaks and their implications for next step fusion reactors. *Nucl. Fusion* **2001**, *41*, 1967. [\[CrossRef\]](#)
7. Roth, J.; Tsitrone, E.; Loarer, T.; Philipps, V.; Brezinsek, S.; Loarte, A.; Counsell, G.F.; Doerner, R.P.; Schmid, K.; Ogorodnikova, O.V.; et al. Tritium inventory in ITER plasma-facing materials and tritium removal procedures. *Plasma Phys. Control. Fusion* **2008**, *50*, 103001. [\[CrossRef\]](#)
8. Neu, R.; Asmussen, K.; Deschka, S.; Thoma, A.; Bessenrodt-Weberpals, M.; Dux, R.; Engelhardt, W.; Fuchs, J.C.; Gaffert, J.; García-Rosales, C.; et al. The tungsten experiment in ASDEX Upgrade. *J. Nucl. Mater.* **1997**, *241–243*, 678–683. [\[CrossRef\]](#)
9. Anderl, R.A.; Causey, R.A.; Davis, J.W.; Doerner, R.P.; Federici, G.; Haasz, A.A.; Longhurst, G.R.; Wampler, W.R.; Wilson, K.L. Hydrogen isotope retention in beryllium for tokamak plasma-facing applications. *J. Nucl. Mater.* **1999**, *273*, 1–26. [\[CrossRef\]](#)
10. Hu, J.S.; Wang, X.M.; Li, J.H.; Wu, J.H.; Chen, Y.; Wang, H.Y.; Yang, D.W.; Luo, N.C.; Li, S.F.; Li, G.Y.; et al. Vacuum and wall conditioning system on EAST. *Fusion Eng. Des.* **2009**, *84*, 2167–2173. [\[CrossRef\]](#)
11. Winter, J. Wall conditioning in fusion devices and its influence on plasma performance. *Plasma Phys. Control. Fusion* **1996**, *38*, 1503–1542. [\[CrossRef\]](#)
12. Li, J.; Shimada, M.; Zhao, Y.; Hu, J.; Gong, X.; Yu, Y.W.; Zhuo, G.Z. Wall conditioning towards the utilization in ITER. *J. Nucl. Mater.* **2011**, *415*, S35–S41. [\[CrossRef\]](#)
13. Bucalossi, J.; Brosset, C.; Garnier, D.; Grisolia, C.; Grosman, A.; Martin, G.; Saint Laurent, F. The conditioning procedures in Tore Supra after CIEL implementation. *J. Nucl. Mater.* **2003**, *313–316*, 263–268. [\[CrossRef\]](#)
14. Nakamura, H.; Higashijima, S.; Isobe, K.; Kaminaga, A.; Horikawa, T.; Kubo, H.; Miya, N.; Nishi, M.; Konishi, S.; Tanabe, T. Application of glow discharges for tritium removal from JT-60U vacuum vessel. *Fusion Eng. Des.* **2004**, *70*, 163–173. [\[CrossRef\]](#)
15. Wauters, T.; Marchuk, O.; Mollard, P.; Paul, M.K.; Pegourié, B.; Reimer, H.; Sergienko, G.; Tsitrone, E.; Vervier, M.; Van Wassenhove, G.; et al. Isotope exchange experiments on TEXTOR and Tore Supra using ion cyclotron wall conditioning and glow discharge conditioning. *J. Nucl. Mater.* **2011**, *415*, S1033–S1036. [\[CrossRef\]](#)
16. Wauters, T.; Matveev, D.; Douai, D.; Banks, J.; Buckingham, R.; Carvalho, I.S.; de la Cal, E.; Delabie, E.; Dittmar, T.; Gaspar, J.; et al. Isotope removal experiment in JET-ILW in view of T-removal after the 2nd DT campaign at JET. *Phys. Scr.* **2022**, *97*, 044001. [\[CrossRef\]](#)
17. Matveev, D.; Douai, D.; Wauters, T.; Widdowson, A.; Jepu, I.; Maslov, M.; Brezinsek, S.; Dittmar, T.; Monakhov, I.; Jacquet, P.; et al. Tritium removal from JET-ILW after T and D-T experimental campaigns. *Nucl. Fusion* **2023**, *63*, 112014. [\[CrossRef\]](#)
18. Wauters, T.; Bisson, R.; Delabie, E.; Douai, D.; Gallo, A.; Gaspar, J.; Jepu, I.; Kovtun, Y.; Pawelec, E.; Matveev, D.; et al. Changeover between helium and hydrogen fueled plasmas in JET and WEST. *Nucl. Mater. Energy* **2024**, *38*, 101587. [\[CrossRef\]](#)
19. Yu, Y.; Zhou, D.; Sakamoto, M.; Cao, B.; Zuo, G.; Hu, J. Fuel recycling control in long pulse operation with full tungsten divertors in EAST tokamak. *Nucl. Mater. Energy* **2023**, *34*, 101333. [\[CrossRef\]](#)
20. Saifutdinov, A.I. Numerical study of various scenarios for the formation of atmospheric pressure DC discharge characteristics in argon: From glow to arc discharge. *Plasma Sources Sci. Technol.* **2022**, *31*, 094008. [\[CrossRef\]](#)
21. Santos, D.F.N.; Lisnyak, M.; Almeida, N.A.; Benilova, L.G.; Benilov, M.S. Numerical investigation of AC arc ignition on cold electrodes in atmospheric-pressure argon. *J. Phys. D Appl. Phys.* **2021**, *54*, 195202. [\[CrossRef\]](#)
22. Eleveld, H.; van Veen, A. Deuterium interaction with impurities in tungsten studied with TDS. *J. Nucl. Mater.* **1992**, *191–194*, 433–438. [\[CrossRef\]](#)

23. Haasz, A.A.; Davis, J.W. Deuterium retention in beryllium, molybdenum and tungsten at high fluences. *J. Nucl. Mater.* **1997**, *241–243*, 1076–1081. [[CrossRef](#)]
24. Castro, F.J.; Meyer, G. Thermal desorption spectroscopy (TDS) method for hydrogen desorption characterization (I): Theoretical aspects. *J. Alloys Compd.* **2002**, *330–332*, 59–63. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.