Deuterium recycling and wall retention characteristics during boron powder injection in EAST

G. Z. Zuo[1*], Z. Wang[1,3], Z. Sun[2], W. Xu[4], Z.T. Zhou[1,3], Y.H. Guan[1,3], M. Huang[1], R. Maingi[2], and J. S. Hu[1,5*]

[1]Institute of Plasma Physics, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei, Anhui 230031, China

[2]Princeton University Plasma Physics Laboratory Princeton, Princeton, NJ 08543, USA

[3]Anhui University, Hefei, Anhui 230601, China

[4]Institute of Energy, Hefei Comprehensive National Science Center, Hefei, Anhui 230026, China

[5]CAS key Laboratory of Photovoltaic and energy conservation materials, Hefei 230031, China

[*]corresponding author: zuoguizh@ipp.ac.cn, hujs@ipp.ac.cn

Abstract

Boron (B), as a low-Z material, is widely employed for wall conditioning to enhance plasma performance in fusion devices. In the Experimental Advanced Superconducting Tokamak, a series of experiments involving real-time B powder injection has been conducted to investigate fuel particle behavior. It was observed that fuel particle recycling decreased with an increase in the amount of B powder injected, resulting in an increase in short-term fuel retention. The fuel recycling decreased by up to 80%, as indicated by divertor neutral pressure and Dα line emission. Furthermore, each B atom exhibited a trapping capacity of 0.3 D particles during B powder injection at a typical flow rate. The real-time B injection had no wall hysteresis effect on D retention, implying that cumulative B injection and deposited film did not affect long-term D retention. The possible mechanism for D retention is the formation of B-C-O-D compounds and co-deposition between B and D particles during discharges. This investigation would be valuable for evaluating T retention when B is used as wall conditioning material in future fusion reactor devices.

1. Introduction

Fuel particle behavior, including recycling and retention, is a critical issue for future fusion devices like ITER and DEMO. During plasma-wall interactions (PWI), a portion of the hydrogen isotope fuel particles released from the wall materials into the plasma leads to an increase in fuel recycling, causing uncontrolled plasma density, which directly impacts plasma confinement and pulse duration. Retained fuel particles within the wall materials escalate operation costs and introduce safety concerns [1, 2]. For the international thermonuclear experimental reactor (ITER), the estimated maximum tritium (T) inventory is 700 g with an all-metal Be/W first wall[3], and the limit for the inventory of releasable T in the vacuum vessel is 350/700 g [4], determined by safety considerations. Additionally, fuel retention also affects the thermomechanical properties of the plasma-facing material, resulting in blisters, cracks, and flaking, ultimately deteriorating plasma performance[5-7].

Numerous wall-conditioning techniques have been developed to mitigate PWI and reduce fuel recycling. These techniques include baking, discharge cleaning, and wall coating [2, 8]. Baking and discharge cleaning, such as glow discharge cleaning (GDC) and ion cyclotron wall conditioning (ICWC), are routine methods for removing fuel particles in fusion machines. Wall coating, such as boronization, lithium coating, and siliconization, is often employed to further improve wall conditions and elevate plasma performance[9]. Boronization involves coating boron films on the first wall surfaces using materials like decaborane $B_{10}H_{14}$[10] and carboranes $C_2B_{10}H_{12}$ [11], assisted by GDC or ICWC plasma discharges. Results indicate that this type of boronization process leads to significant co-deposition of hydrogen isotopes in the B-coated film, making it challenging to reduce particle recycling during plasma operation, even after numerous attempts to remove retained fuel particles [12].

To avoid introducing H isotopes on the wall, pure B powder injection has been developed for wall conditioning and other physical experiments. In the latest B powder injection experiment in EAST, robust suppression of edge-localized modes (ELMs) was observed[13]. During B powder injection, reduced fuel particle recycling was observed. Therefore, a systematic study of fuel recycling and wall retention behaviors has been conducted, which is crucial for evaluating the application of B as a wall conditioning material in ITER and future fusion devices.

This paper investigates the impact of B powder injection on D recycling and retention in EAST. The paper is organized as follows: Section 2 introduces the experimental setup and gas balance method; Section 3 presents some results; and finally, the discussion and conclusion are provided in Section 4.

2. Experimental setup and gas balance method

EAST, with a major radius of R = 1.85 m, a minor radius of a = 0.45 m, plasma current Ip ⩽ 1 MA, and toroidal field Bt ⩽ 3.5 T, was constructed to demonstrate high-power, high-performance, and long-pulse plasma operations. The auxiliary heating power systems are comprised of two oppositely directed tangential neutral beam injection (NBI) systems, low-hybrid waves (LHW), electron cyclotron resonance heating (ECRH), and ion cyclotron resonance heating (ICRH). The upper divertor was upgraded to an ITER-like tungsten divertor structure in 2014, while the lower divertor continued to use graphite until 2021. TZM was applied to the main vessel walls. The novel impurity powder injector (IPD) installed on the upper port of EAST is detailed in [14]. This system can inject boron powder with an average size of 70 μm from a reservoir into the plasma at a velocity of 10 m/s driven by gravity, as shown in Figure 1. The boron powder was injected into the EAST private flux region with an upper single null plasma.

Key diagnostics used in this work include filterscopes, extreme ultraviolet (EUV), and vacuum measures, as depicted in Figure 1. A set of spectral diagnostics called 'filterscopes' with a 50 kHz sampling rate was employed to measure Dα and CIII impurity emission, featuring 13 channels to observe the upper and lower divertor zones. B emission intensity (Bv) could be measured by EUV spectroscopy monitoring in the 2–50 nm wavelength range. Vacuum measures G106 and G109 are located at the lower and upper divertor ports, respectively, to measure the neutral gas pressure during plasma discharges. They were installed on the port flange, which is approximately 4 m away from the plasma.

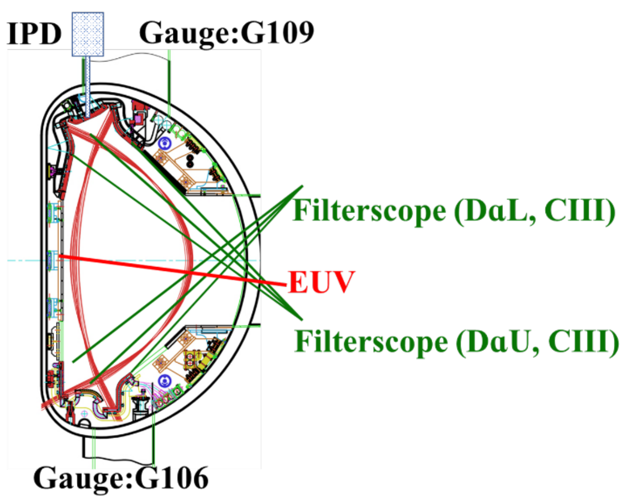

Figure 1. IPD location and key diagnostics for the boron powder injection experiment in EAST. The green line represents Dα, and the red line represents EUV.

Fuel particle recycling can be directly assessed by measuring divertor neutral pressure and Dα line emission. The behavior of fuel particle retention is analyzed using the gas balance method, based on the fundamental principle that the number of retained particles is approximately equal to the number of injected particles minus the number of extracted particles. This relationship can be expressed by Equation (1):

$$Q_{retention} = Q_{puffing} - Q_{pumping} - Q_{vessel} - Q_{plasma} \quad (1)$$

Here, $Q_{retention}$ is the amount of retained D particles in wall, $Q_{puffing}$, $Q_{pumping}$, Q_{vessel} and Q_{plasma} are the amount of injected D particles, pumped D particles, neutral D particles in the vacuum vessel, and deuterium ions in plasma, respectively. The equations used in the calculations were taken from a previous study [15]. Deuterium (D) particles are introduced into the plasma discharge vessel through normal gas puffing, supersonic molecule beam injection (SMBI), and neutral beam injection (NBI).

The following equation describes the retention ratio and rate:

$$\text{Retention ratio(t)} = \frac{Q_{retention}(t)}{Q_{puffing}(t)} \quad (2)$$

$$Retention\ rate(t) = \frac{dQ_{retention}(t)}{dt} \quad (3)$$

The retention ratio (%) represents the retention fraction, while the retention rate (D atoms/s) is the derivative of the retention amount with respect to time, reflecting the real-time rate at which D particles are retained. The detailed gas balance calculation process, as well as the calibrated pumping speeds of all pumping systems, were described in reference [15], and the measurement error in the gas balance was estimated to be approximately 8%.

3. Results

3.1 Effect of B powder injection on the fuel recycling

To examine the characteristics of fuel particles, we initially compared fuel particle recycling between two discharges, one with boron injection and one without, as illustrated in Figure 2. The fundamental plasma parameters for both shots were as follows: plasma current (Ip) was 500 kA, and the line-averaged density (Ne) was 4.8×10^{19} m^{-3}. The total auxiliary heating power was 6.2 MW, comprising 3 MW from LHW, 0.4 MW from ECRH, and 2.8 MW from NBI. During shot 85043, B powder was gradually injected into the plasma from 4 to 6 s, at a flow rate of about 20 mg/s. As shown in Figure 2(d), Bv emission (λ = 4.098 nm) measured by EUV spectroscopy increased with the injection of B powder. Dα light emission started to decrease rapidly around 4.96 s, and the neutral pressure, measured by the measure located at the divertor port, began to drop around 5.04 s. There is a time difference of 0.1 s between the Dα and neutral gas pressure signals, resulting from the neutral gas diffusion time along the 4 m length tube. The controlled reduction of fuel particle recycling gradually occurred with the increase of B powder injection, with the reduction reaching up to 80%. This was monitored by divertor neutral pressure and Dα line emission. The plasma's stored energy and confinement factor saw an increase of 10% with the introduction of B powder, which may be partly attributed to the contribution of reduced fuel recycling.

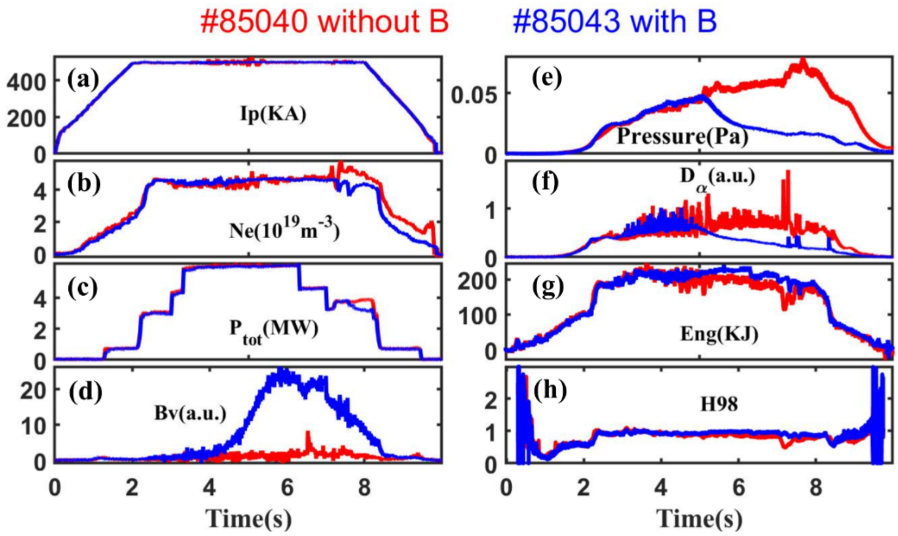

Figure 2. Comparison of fuel particle recycling with and without B powder injection: (a) Plasma current Ip, (b) Line-averaged electron density Ne, (c) total heating power, (d) Bv emission, (e) Neutral pressure from the upper divertor, (f) Dα light emission from the upper divertor zone, (g) Plasma stored energy WMHD, (h) H_{98} factor.

Figure 3 shows the evolution of neutral pressure and Dα light emission intensity as a function of Bv emission intensity during B powder injection in plasmas with similar parameters, such as shots 85043, 85044, 85045, and 85046. Despite these plasma discharges having the same B powder flow rate of 20 mg/s, the thickness of the boron-coated film gradually accumulated over the course of these shots, resulting in an incremental increase in Bv emission from shot 85043 to shot 85046, possibly due to particle sputtering from the B-coated film under high heating power plasma conditions. The data values of Bv, pressure, and Dα, shown in Figure 3, were taken at 5.1 s during these discharges. It was observed that both the neutral pressure from the lower and upper divertor measures and the Dα light emission measured from the upper and lower divertor zones decreased as the Bv emission increased. This indicates that increasing the injected amount of B powder effectively reduced fuel recycling.

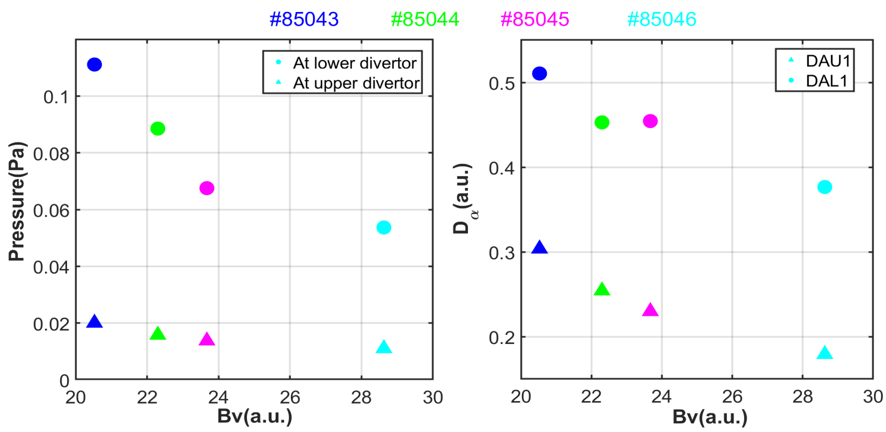

Figure 3. Evolution of neutral pressure and Dα light emission intensity as a function of Bv emission intensity during the B powder injection experiment.

3.2 Effect of B powder injection on D retention

Figure 4 provides a comparison of D puffing, retention, recovery amount, retention rate, and retention ratio during discharges with boron powder injection from 4–6 s (#85043) and without B powder injection (#85040, #85041). The essential plasma parameters for these three shots were similar. Here, D particle recovery amount is defined as the number of particles released from the retained particles during plasma operation and after plasma discharge[15]. Puffing particles increased before 7.4 s, indicating an increased gas injection rate, as shown in Figure 4(a). This resulted in a decrease in the retention ratio with constant or decreasing particle retention, as depicted in Figure 4(b). The D retention rate increased rapidly from 0 to 1.9 s and then decreased as the heating power increased from 1.9 s to 5 s. At 5 s, the D retention rate gradually declined from shot 85040 to shot 85043. Even with B injection starting at 4 s during shot 85043, it did not appear to have a significant effect on D particle retention. This suggests that high heating power results in the more substantial release of retained fuel particles as the plasma discharge progresses. With B powder injection, the retention rate gradually increased from –2.7 × 10^{21}/s (at 5s) to –0.6 × 10^{21}/s (at 8s) during shot 85043 plasma discharge (Figure 4(c)). After approximately 6 s, the retention rate increased further during shot 85043. Without external B powder injection, the D retention rate decreased to –1.7 × 10^{21}/s with a heating power of 6.2 MW during shots 85040 and 85041, with a slight increase when the auxiliary heating power decreased to <1 MW after 8.2 s. This demonstrates that B powder can mitigate the release of fuel particles from the first wall during high-heating power plasma discharges. The maximum recovery of D particles 10 s after plasma discharge termination was similar for all shots: 0.88 × 10^{22} (#85040), 0.92 × 10^{22} (#85041), and 0.96 × 10^{22} (#85043). At 70 s, the maximum recovery of D particles was 1.4 × 10^{22} (#85040), 1.4 × 10^{22} (#85041), and 1.3 × 10^{22} (#85043) (Figure 5(a)). This indicates that B powder injection reduced the release of 0.1 × 10^{22} D particles from the first wall, with an uncertainty of 0.8 × 10^{20}. The total injected B was 0.3 × 10^{22} (#85043) with an uncertainty of ± 0.04 × 10^{22}; each B atom's effect on D released from the wall should be approximately 30%. It is inferred that B powder slightly increased the long-term retention of D. The retention ratio remained at a higher level at around 70 s with B powder injection, as shown in Figure 5(b).

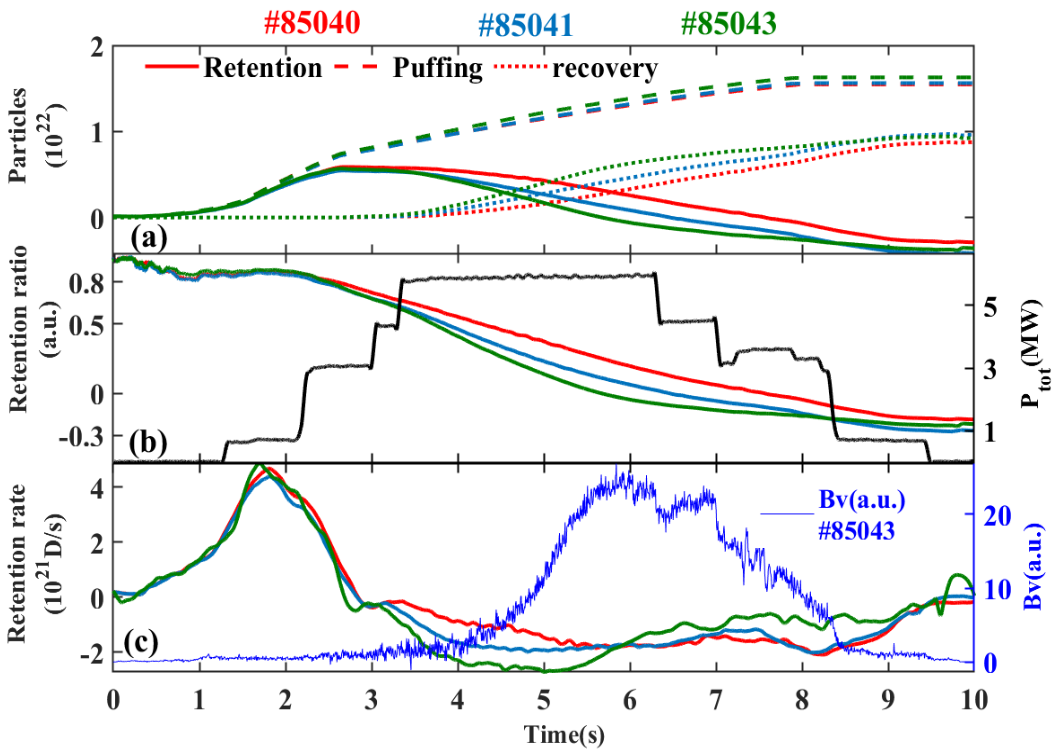

Figure 4. Evolution of particle balance over time for shot 85040 (in red), 85041 (in blue), and 85043 (in green). (a) Changes in puffing, retention, and recovery of fuel D

particles over a 10-s interval. (b) Shifts in retention ratio over a 10-s interval, along with the total auxiliary heating power (indicated by the black line). (c) Bv line emission (indicated by the blue line) and alterations in the retention rate over a 10-s interval.

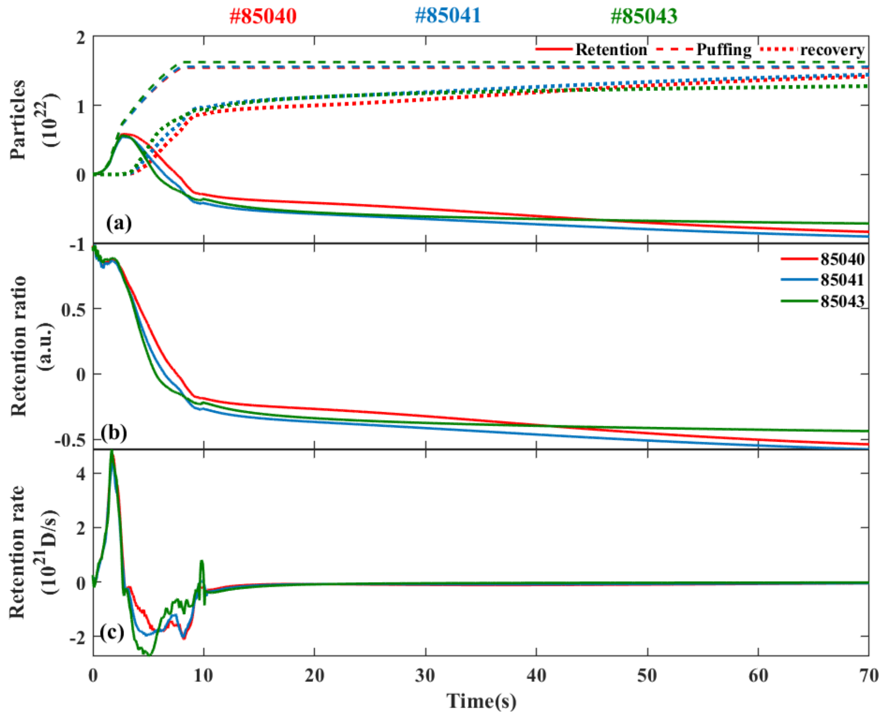

Figure 5. Evolution of particle balance over time for shot 85040 (in red), 85041 (in blue), and 85043 (in green). (a) Changes in puffing, retention, and recovery of fuel D particles over 70 s. (b) Shifts in retention ratio over 70 s. (c) Modifications in the retention rate over the first 70 s (up to 60 s after the discharge).

Figure 6 compares the fuel particle D retention characteristics during plasmas with the same parameters, but with different initial injection times of B powder in a series of discharges. As shown in Figure 6(c), the initial injection time of B powder gradually advanced in four shots (4 s (#85043), 3.5 s (#85044), 2.5 s (#85045), 2 s (#85046)), with the same B injection rate of 20 mg/s. The time at which B had an effect on retention synchronized with the beginning of B injection. The maximum Bv emission increased from shot 85043 to shot 85046, possibly due to particle sputtering from the B-coated film under high heating power plasma conditions. The retention rate increased gradually from -1.2×10^{22}/s, -2×10^{22}/s, -2.4×10^{22}/s, and -2.7×10^{22}/s to near 0 at 7–8 s for #85046, #85045, and #85044, respectively. In addition, the Bv emissions and the fuel retention rates were almost the same from 0 to 3.5 s, indicating that B powder injection did not lead to an obvious cumulative effect on D retention for subsequent discharges, as is the case with Li injection. After 3.5 s, the heating power increased significantly, leading to substantial B sputtering from the B-coated film. This resulted in a gradual increase in Bv emissions, shot by shot, and led to an increase in the fuel retention rate. Therefore, there is a positive correlation between the retention rate and the Bv emission (not B accumulation on the first wall). In other words, even if B accumulation on the wall gradually increased, if no B was sputtered and no obvious Bv emission was observed in the plasma, the fuel retention had little effect.

Notably, the recovery of D from the wall one minute after discharge was 0.63×10^{22} (#85043), 0.89×10^{22} (#85044), 1×10^{22} (#85045), and 1.3×10^{22} (#85046) (Figure 7(a)). Furthermore, the recovery of the D retention amount changed very little from approximately 40 to 70 s, indicating that the retained D in the wall was released within the first 40 s. The D retention amount was less than it was before the discharges. Considering that the retention rate remained less than 0 during the discharges, it suggests that B powder can only mitigate the release of D from the first wall during these high heating power discharges and fails to effectively cause long-term D retention in a wall due to wall outgassing.

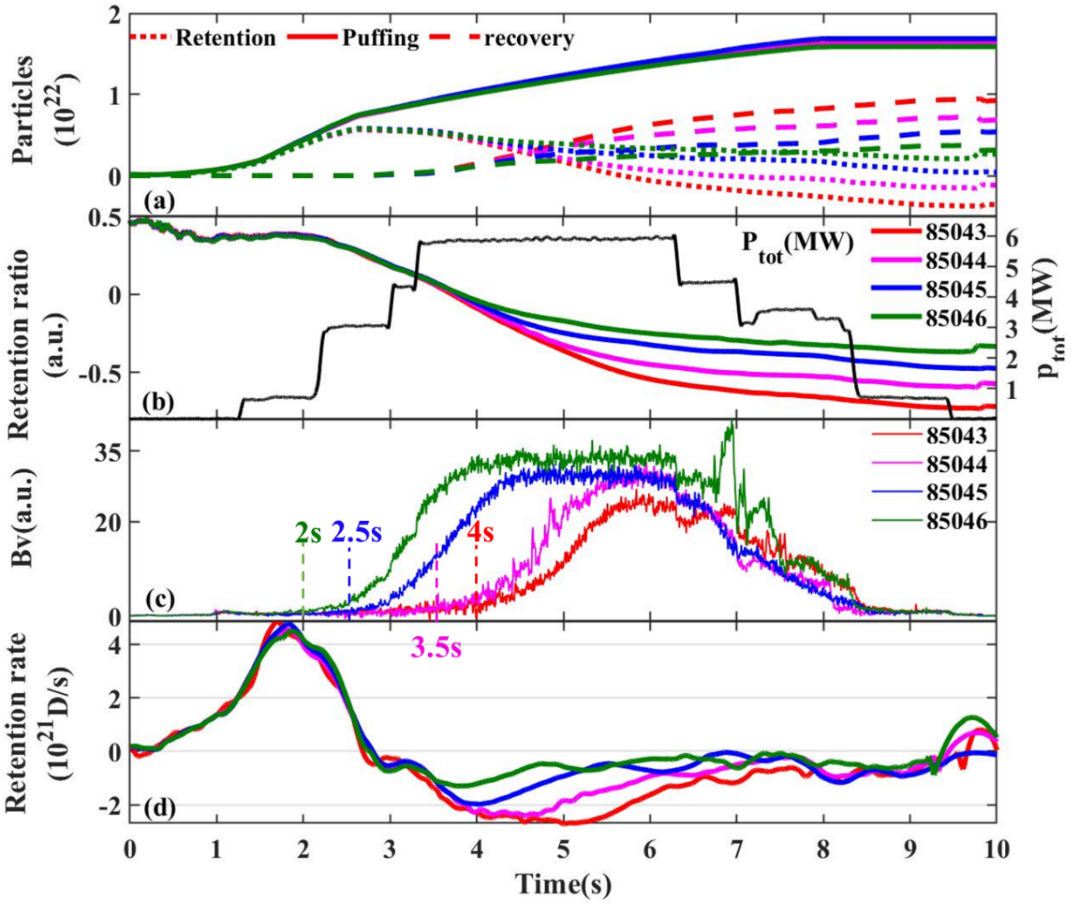

Figure 6. Evolution of particle balance over time with B powder injection for Shot 85043 (in red), 85044 (in pink), 85045 (in blue), and 85046 (in green). (a) Changes in puffing, retention, and recovery of fuel D particles over a 10-s interval. (b) Shifts in retention ratio over a 10-s interval, along with the total auxiliary heating power (indicated by the black line). (c) Bv line emission (indicated by the green line). (d) Modifications in the retention rate over a 10-s interval.

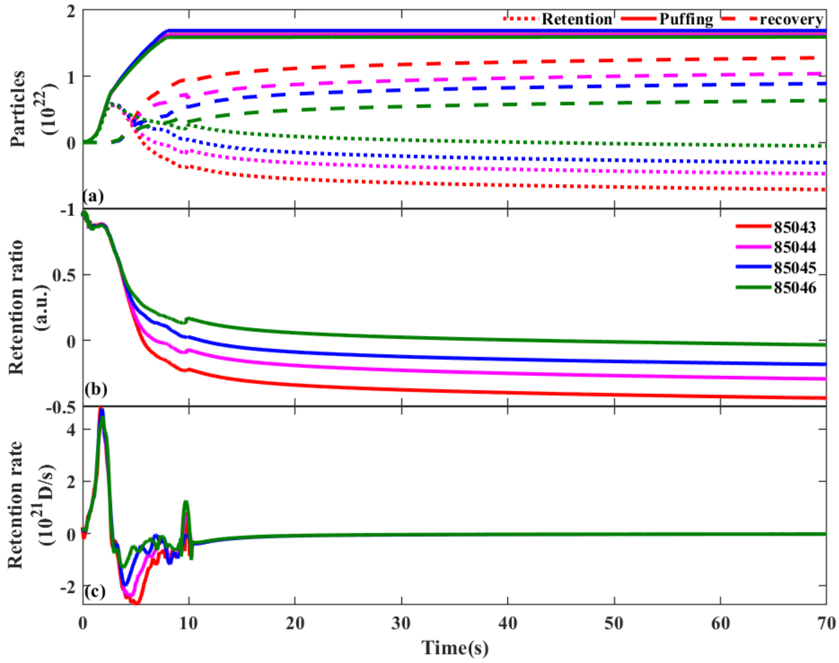

Figure 7. Evolution of particle balance over time for shots 85043 (in red), 85044 (in pink), 85045 (in blue), and 85046 (in green). (a) Changes in puffing, retention, and recovery of fuel D particles over 70 s. (b) Shifts in retention ratio over 70 s. (c) Changes in the retention/puffing rate over 70 s.

Figure 8 depicts the evolution of D retention, puffing, and recovery during plasma operations at the 70s mark in relation to the shot number, along with the injected B mass. It is evident that the amount of D retention was positively correlated with the injection of B powder. Prior to shot #85056, the total auxiliary heating power was 6.2 MW. When the total mass of B injected in a single plasma discharge was less than 150 mg (0.9×10^{22}), it proved challenging to induce long-term D retention after the injection of B powder. However, for shots 85061 and 85062, even though the B powder injection amount was higher than in previous shots, the D retention was lower compared to D retention in shot 85055. This discrepancy could be attributed to wall outgassing resulting from four continuous plasma disruptions($t_{duration}$<3.5 s). When the total amount of injected B powder was increased to 420 mg (2.5×10^{22}) in shot #85063, the D retention reached 0.46×10^{22} at 70s. This demonstrates that a substantial injection of B powder can lead to high D retention. However, for the following two shots, the B powder injection was intentionally reduced to 100 mg, and the retained particle number became negative, indicating that fuel particles were still being released from the first wall, similar to previous shots with the same B injection amount. Therefore, these results further confirm that there is no wall hysteresis effect on D retention following some shots of B injection.

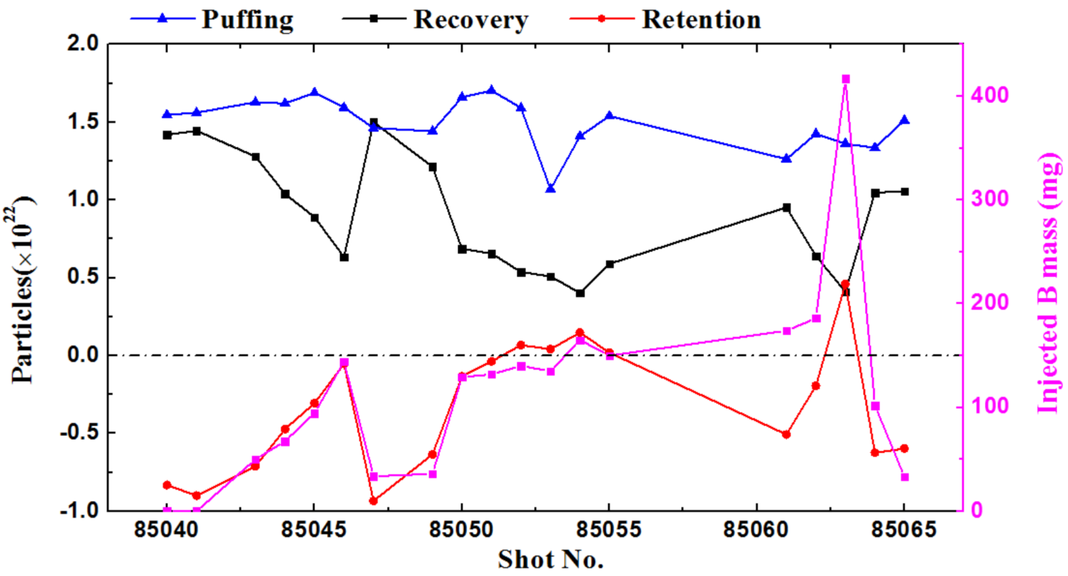

Figure 8. Evolution of D retention, puffing, and recovery, as well as the total mass of injected B at 70 s after each respective discharge, plotted against shot numbers.

To investigate the potential mechanisms underlying D retention in the presence of B, we analyzed low atomic number impurities, such as C and O, as depicted in Figure 9. It compares the behavior of CIII, CVI, and OVII without B powder injection. It was observed that the emissions of CIII (measured by filterscope), CVI, and OVII (measured by EUV spectroscopy) exhibited a clear decrease with the introduction of B powder. This suggests that a chemical reaction between B, C, O, and D may lead to a reduction in fuel particles, including C and O as well. This result aligns with previous studies [16] and [17], which elucidated the roles of oxygen and boron in deuterium retention and predicted deuterium uptake into a boronized carbon surface. The dominant mechanism is likely similar to deuterium uptake in the resulting Li-C-O-D system [18]. The probable mechanism for D retention with B powder injection primarily involves the formation of B-C-O-D compounds. Additionally, co-deposition between B and D could also enhance D retention in the B-coated film during real-time B injection plasma discharges. The formation of B-C-O-D compounds is the main reason for long-term retention, whereas D particles from co-deposition would tend to be released from the wall after the plasma discharge, contributing mainly to short-term retention.

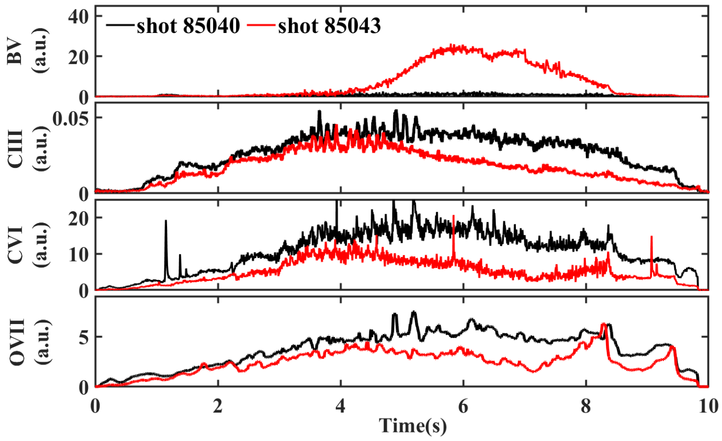

Figure 9. Comparison of C and O impurity behaviors without B powder injection.

4 Discussion and Conclusion

The behavior of fuel particles at the plasma edge plays a crucial role in plasma confinement and plasma density control during long pulse plasma operation. It was observed that the injection of B powder effectively controlled the recycling of fuel particles in the EAST tokamak. As the B injection amount increased, both the neutral pressure and Dα light emission intensity gradually decreased, indicating a positive correlation between the fuel particle control effect and the B injection rate.

The primary source of fuel recycling was the release of fuel from the first wall during plasma discharge. This implies that wall outgassing can be effectively mitigated after B powder injection. Compared to the D retention of the reference shot, the B powder injection at a rate of approximately 1.2×10^{21}/s with a total heating power of 6.2 MW led to an increase in the retention rate from -2.7×10^{21} to -0.6×10^{21}. This indicates that B powder injection can effectively reduce the release of D particles from the first wall. Furthermore, it was observed that a higher rate of B powder injection into the plasma resulted in less D outgassing from the wall. A substantial B injection rate reversed the wall's ability to pump outgassed particles from the wall to absorbing them.

Compared to Li injection or Li coating before plasma operation, B injection does not exhibit wall hysteresis effects on D retention. The D retention rate depends solely on the B injection mass or the strength of Bv emission. Even as B accumulates on the first wall over time, it does not directly capture D particles through physical absorption or a chemical reaction between B and D. Therefore, the use of B as a wall conditioning material may present fewer tritium retention issues than Li application in future fusion reactors. Nevertheless, the removal of retained fuel particles and B-coated film must be considered to address the tritium retention issue and further extend the use of B in future fusion reactors.

In summary, this study on D recycling and retention in discharges with B powder injection demonstrates that such injection can reduce fuel recycling and mitigate the release of fuel particles from the first wall. Massively injecting B powder into the plasma can lead to high D retention, equivalent to 0.3D captured per B atom. The amount of D retention is positively correlated with the quantity of B powder injected. The probable mechanism for D retention involves the formation of B-C-O-D compounds and co-deposition between B and D particles. These results provide valuable insights for the application of B materials in wall conditioning for ITER and future tokamak devices.

Acknowledgments

This research is funded by the National Key Research and Development Program of China (2022YFE03130000) and Interdisciplinary and Collaborative Teams of CAS.

Reference

[1] R.A. Causey, Hydrogen isotope retention and recycling in fusion reactor plasma-facing components, Journal of Nuclear Materials, 300 (2002) 91-117.

[2] G. Federici, C.H. Skinner, J.N. Brooks, J.P. Coad, C. Grisolia, A.A. Haasz, A. Hassanein, V. Philipps, C.S. Pitcher, J. Roth, W.R. Wampler, D.G. Whyte, Plasma-material interactions in current tokamaks and their implications for next step fusion reactors, Nuclear Fusion, 41 (2001) 1967-2137.

[3] J. Roth, E. Tsitrone, T. Loarer, V. Philipps, S. Brezinsek, A. Loarte, G.F. Counsell, R.P. Doerner, K. Schmid, O.V. Ogorodnikova, R.A. Causey, Tritium inventory in ITER plasma-facing materials and tritium removal procedures, Plasma Phys. Control. Fusion, 50 (2008) 103001.

[4] T. Loarer, Fuel retention in tokamaks, Journal of Nuclear Materials, 390-91 (2009) 20-28.

[5] T. Wang, M. Ren, X.-L. Zhu, X. Ma, Y. Yuan, L. Cheng, G.-H. Lu, Effect of initial exposure temperature on the deuterium retention and surface blistering in tungsten, Nuclear Materials and Energy, 33 (2022) 101245.

[6] M. Oya, H.T. Lee, Y. Ueda, H. Kurishita, M. Oyaidzu, T. Hayashi, N. Yoshida, T.W. Morgan, G. De Temmerman, Surface morphology changes and deuterium retention in Toughened, Fine-grained Recrystallized Tungsten under high-flux irradiation conditions, J. Nucl. Mater., 463 (2015) 1037-1040.

[7] U. Ueda, T. Funabiki, T. Shimada, K. Fukumoto, H. Kurishita, M. Nishikawa, Hydrogen blister formation and cracking behavior for various tungsten materials, J. Nucl. Mater., 337 (2005) 1010-1014.

[8] J. Winter, Wall conditioning in fusion devices and its influence on plasma performance, Plasma Phys. Control. Fusion, 38 (1996) 1503–1542.

[9] J. Winter, TOKAMAK WALL COATINGS, Plasma Phys. Control. Fusion, 36 (1994) B263-B276.

[10] M. Saidoh, H. Hiratsuka, T. Arai, Y. Neyatani, M. Shimada, T. Koike, A BORONIZATION SYSTEM IN THE JT-60U TOKAMAK - APPLICATION OF A NEW METHOD USING A LESS HAZARDOUS SUBSTANCE, Fusion Eng. Des., 22 (1993) 271-275.

[11] V.K. Alimov, D.B. Bogomolov, M.N. Churaeva, A.E. Gorodetsky, S.L. Kanashenko, A.I. Kanaev, S.Y. Rybakov, V.M. Sharapov, A.P. Zakharov, R.K. Zalavutdinov, O.I. Buzhinsky, A.P. Chernobay, S.A. Grashin, S.V. Mirnov, V.I. Bregadze, A.Y. Usyatinsky, CHARACTERIZATION OF A-B/CH FILMS DEPOSITED FROM DIFFERENT BORON CONTAINING PRECURSORS, J. Nucl. Mater., 196 (1992) 670-675.

[12] G.Z. Zuo, J.S. Hu, S. Zhen, J.G. Li, D.K. Mansfield, B. Cao, J.H. Wu, L.E. Zakharov, Comparison of various wall conditionings on the reduction of H content and particle recycling in EAST, Plasma Phys. Control. Fusion, 54 (2012) 015014.

[13] Z. Sun, A. Diallo, R. Maingi, Y.Z. Qian, K. Tritz, Y.F. Wang, Y.M. Wang, A. Bortolon, A. Nagy, L. Zhang, Y.M. Duan, Y. Ye, H.L. Zhao, H.Q. Wang, X. Gu, G.Z. Zuo, W. Xu, M. Huang, C.L. Li, X.C. Meng, C. Zhou, H.Q. Liu, Q. Zang, L. Wang, J.P. Qian, G.S. Xu, X.Z. Gong, J.S. Hu, E. Team, Suppression of edge localized modes with real-time boron injection using the tungsten divertor in EAST, Nucl. Fusion, 61 (2021) 014002.

[14] A. Nagy, A. Bortolon, D.M. Mauzey, E. Wolfe, E.P. Gilson, R. Lunsford, R. Maingi, D.K. Mansfield, R. Nazikian, A.L. Roquemore, A multi-species powder dropper for magnetic fusion applications, Rev. Sci. Instrum., 89 (2018).

[15] C.L. Li, G.Z. Zuo, R. Maingi, B. Cao, W. Xu, X.C. Meng, Z. Sun, M. Huang, Z.L. Tang, D.H. Zhang, Y.Z. Qian, D. Andruczyk, K. Tritz, J.S. Hu, Deuterium retention characteristics in Li film by coating and during flowing liquid Li limiter operation in experimental advanced superconducting tokamak, Plasma Phys. Control. Fusion, 63 (2021) 015001.

[16] F.J. Dominguez-Gutierrez, F. Bedoya, P.S. Krstic, J.P. Allain, A.L. Neff, K. Luitjohan, Studies of lithiumization and boronization of ATJ graphite PFCs in NSTX-U, Nuclear Materials and Energy, 12 (2017) 334-340.

[17] F.J. Dominguez-Gutierrez, F. Bedoya, P.S. Krstic, J.P. Allain, S. Irle, C.H. Skinner, R. Kaita, B. Koel, Unraveling the plasma-material interface with real time diagnosis of dynamic boron conditioning in extreme tokamak plasmas, Nucl. Fusion, 57 (2017) 086050.
[18] P.S. Krstic, J.P. Allain, C.N. Taylor, J. Dadras, S. Maeda, K. Morokuma, J. Jakowski, A. Allouche, C.H. Skinner, Deuterium Uptake in Magnetic-Fusion Devices with Lithium-Conditioned Carbon Walls, Phys. Rev. Lett., 110 (2013) 105001.