CONFERENCE PRE-PRINT

ENDOSCOPE LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS) FOR IN SITU ELEMENTAL DISTRIBUTION DIAGNOSIS ON THE SURFACE OF DIVERTOR IN EAST

Cong Li
Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian, P.R. China
Email: cli@dlut.edu.cn

Huace Wu, Longfei Li, Zhonglin He, Ran Hai, Ding Wu, Hongbin Ding
Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian, P.R. China

Zhenhua Hu, Fang Ding, Rui Ding, Guang-nan Luo
Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, P.R. China

Abstract

The online elemental analysis of plasma-facing components (PFCs) is crucial for magnetic confinement nuclear fusion deceives, such as tokamak and stellarator. Elemental distribution directly reflects the conditions of PFCs and processes of plasma-wall interaction (PWI). The laser-induced breakdown spectroscopy (LIBS) diagnostic technology provides a promising method for wall composition monitoring for nuclear fusion deceives. An *in situ* LIBS system in EAST has been built to provide elemental composition on the first wall since 2014. Recently, an *in situ* endoscopic LIBS diagnostic system for the full tungsten divertor in EAST has been developed since the 2021 experimental campaign. This system provides online elemental distributions on the divertor with various discharge parameters and wall conditions. This work focuses on using the *in situ* LIBS system to study D fuel retention evolution in the tungsten upper divertor region, the impact of wall conditions on the H-D ratio, fuel retention behavior during long-pulse discharges, and short-term retention phenomena. The H/(D+H) decreases from 100% to 17%~24% after the wall conditioning of baking and glowing discharge clean. The D and Li signal intensities measured at different poloidal positions are positively correlated with the EAST plasma discharge duration. In addition, the short-term fuel retention study shows that the dynamic D content on the W divertor decreases after the plasma exposure due to the dominant short retention with the outgassing process. The results provide direct experimental data for *in situ* research on fuel retention in magnetic confinement fusion devices.

1. INTRODUCTION

Online elemental analysis of plasma-facing components (PFCs) is essential for understanding magnetic confinement nuclear fusion devices. The elemental distribution provides direct insights into the state of PFCs and the plasma-wall interaction (PWI) processes. [1-3] As deuterium-tritium (D-T) experiments become more imminent in fusion reactors like ITER, real-time monitoring of H isotopes, such as T, has become increasingly important. PWI processes lead to the retention of T within PFCs, which is a significant factor in ensuring safe operation and effective fuel recycling in these fusion reactors. Fuel can be retained in PFCs for days or even years, posing a direct risk to the safe operation of the fusion reactor. The ITER vacuum chamber has a safety limit of 700 g of T. Additionally, the short-term retention behavior of fuel is important to observe. The rate at which fuel particles decrease in plasma-facing components (PFCs) is faster during short-term retention than long-term retention [4, 5]. A large amount of fuel particles can be released and remain on the wall surface in a short period. Short-term retention impacts fuel recycling efficiency and can potentially cause plasma disruptions, which are critical for maintaining stable high-confinement mode plasmas. [6]

Therefore, it is essential to have real-time online monitoring of the fuel in PFCs of magnetic confinement fusion devices. Traditional methods, such as thermal desorption spectroscopy (TDS), residual gas analysis (RGA), and nuclear reaction analysis (NRA) [7-9], are primarily used for offline analysis after events, providing data on long-term D retention. These techniques do not offer real-time insights into the fuel distribution on the wall surface. Laser-induced breakdown spectroscopy (LIBS) is an advanced elemental analysis technique widely used in fields such as metallurgical analysis, coal testing, cultural relic appraisal, environmental monitoring, and Mars exploration, due to its capability for rapid, multi-element, *in situ*, and real-time assessments [10-13]. Recently, as research into magnetic confinement fusion has advanced, LIBS has become vital for elemental diagnostics of PFCs in tokamak fusion devices. [14, 15]

Remote *in situ* online LIBS diagnostic technology does not require dismantling the device's wall materials. It enables real-time analysis of the dynamic evolution of fuel retention and impurity migration on the device wall surface, thereby avoiding atmospheric contamination and the safety risks associated with radioactive elements during diagnosis. Additionally, this technology facilitates accurate detection and measurement of H, D, and T fuels in a vacuum environment. As a result, remote *in situ* online LIBS is considered one of the most promising solutions for studying the changing composition and amounts of fuel and impurity elements on the wall surface, helping to infer the PWI process under specific discharges or discharge types. Tokamak devices such as TEXTOR [16], JET [17], EAST [18], FTU [19], and WEST [20] have implemented *in situ* LIBS systems, providing essential diagnostic capabilities for PWI research in fusion technology. The TEXTOR team first proposed this diagnostic method in 2011 and successfully demonstrated its use [16]. Subsequently, the JET and FTU teams used this approach in 2016 [17] and 2019 [19], respectively, to perform preliminary measurements and analysis of fuel and impurity elements on small-scale PFCs surfaces. In 2023, the WEST tokamak team in France developed a robotic arm-type *in situ* LIBS diagnostic system [20]. Additionally, a remote *in situ* LIBS online diagnostic system was designed for the HL-3 device at the Southwestern Institute of Physics [21].

In 2014, Dalian University of Technology collaborated with the Institute of Plasma Physics of the Chinese Academy of Sciences to develop an *in situ* online LIBS diagnostic system on the EAST device. The diagnostic focused on a 12×12 cm² area on the Mo tiles located at the mid-plane on the high-field side of the EAST device's first wall [18, 22]. Later, studies examined phenomena such as fuel retention on the PFCs, the deposition rate of lithium (Li) particles, and how the thickness of the deposition layer changed during discharges, between discharges, and during night-time wall conditioning phases of the EAST device [23-24]. In 2021, the research team successfully developed a new generation of in situ online LIBS diagnostic system based on the optical endoscope structure. After the upgrade, *the in situ* LIBS system can perform real-time online measurements of surface elements on the inner target plate baffle, plane, dome of the divertor, and parts of the high-field side Mo first wall area in the EAST device. This work focuses on using the *in situ* LIBS system to study D fuel retention evolution in the W upper divertor region, the impact of wall conditions on the H-D ratio, fuel retention behavior during long-pulse discharges, and short-term retention phenomena, providing direct experimental data for *in situ* research on fuel retention in magnetic confinement fusion devices.

2. EXPERIMENTAL SETUP

EAST [25, 26] is the world's first superconducting tokamak. Because of the demands of superconducting coils, the optical windows available on EAST are very limited. There isn't a suitable window that allows a direct, large-area view of the divertor region. To support LIBS for *in situ* diagnosis of the EAST divertor, we developed a LIBS system based on an endoscope structure for the EAST divertor. The endoscopic optical system is inserted into the H port of the EAST vacuum chamber (see Figure 1 (a)). It is inserted to a depth of about 1.4 meters. The tube is a sealed structure capable of forming an independent secondary vacuum system. The front end has a vacuum window, while at the distal end, both a vacuum window and a mirror are installed to direct the laser toward the divertor. The same mirror also collects signals from the LIBS plasma. Inside the endoscope, a non-magnetic rotating table is mounted, connected to an external motor via a transmission rod, which allows the mirror to rotate. This setup enables LIBS to scan the divertor surface in the poloidal direction. A scanning system rotates the endoscope mirror to scan the laser spot across the divertor. Since the distance between the divertor surface and the mirror varies during scanning, an online optical focusing system is installed to keep the laser focus on the divertor surface.

The optical system outside the EAST vacuum chamber is mounted on an optical platform measuring 1200 mm × 600 mm (see Figure 1 (b)). It uses a Q-switched Nd:YAG laser (Qsmart 850, Quantel) as the source, providing up to 850 mJ per pulse, with a 5 ns pulse duration and a 1064 nm wavelength. The laser energy stability (RMS) is ≤ 1%. A dichroic mirror aligns the laser focusing path and the signal collection path coaxially. A first-stage beam expander and a focusing system enlarge the laser spot. Two 100 mm diameter aluminum-coated mirrors, capable of reflecting signals from 380 nm to 900 nm and the 1064 nm laser (with a damage threshold > 1 J/cm²), are placed before and after the focusing system to direct the laser into the vacuum endoscope system. The endoscope's front includes a plano-convex lens with a 2 m focal length and an adjustable aluminum-coated mirror (150 mm by 60 mm) on a rotating stage. After the laser ablates the wall to produce plasma, the emitted light is collected along the same optical path, passes through the dichroic mirror, and is focused into the fiber optic spectrometer by an achromatic lens. This experiment can utilize multiple spectrometers, with common examples including:

(1) LIBS2500+ (customized by Ocean Optics Inc), a 7-channel CCD fiber-optic spectrometer covering wavelengths from 200 nm to 925 nm, with approximately 0.1 nm resolution (0.05 nm between 630 nm-670 nm), and an integration time of 1 ms.

(2) HoloSpec (Andor), a fiber-optic spectrometer featuring a transmission holographic grating, primarily used to measure the Hα spectrum in fuel retention studies. It is equipped with an ICCD (iStar 334T, Andor) camera. When configured with a specific grating, it covers wavelengths from 640 nm to 671 nm, has a resolution better than 0.1 nm, and allows gating and adjustment of the integration time, typically set to 1 μs.

All mechanical parts of the LIBS system are protected by magnetic shielding. The LIBS scanning area includes the W upper divertor (inner target, inner baffle, and dome) and part of the Mo first wall. The laser spot can be scanned with a resolution of 0.4 mm, and the repeatability is under 0.2 mm. Due to mirror reflectivity and detector efficiency, the LIBS system measures wavelengths primarily between 400 nm and 780 nm. The scanning region covers the inner target, baffle, dome of the W upper divertor, and part of the Mo first wall. The poloidal coordinate is illustrated in the Figure 1 (b), with the Zero-point coordinate set between the first wall and the divertor.

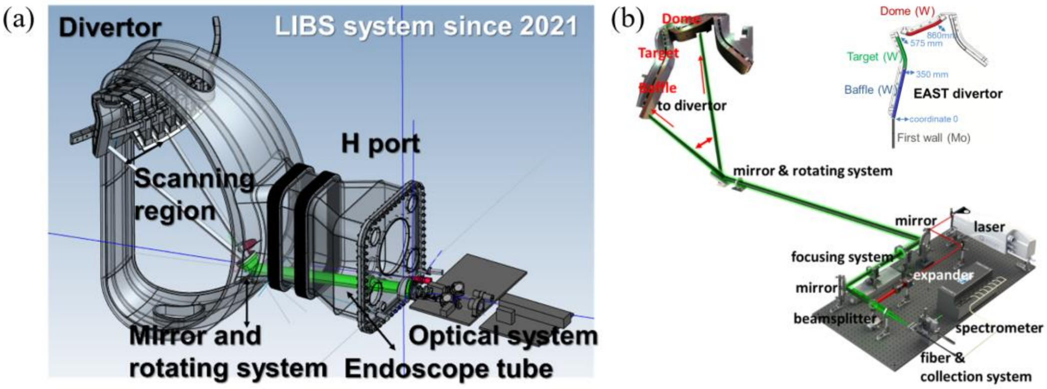

Figure 1. (a) The schematic diagram of *in situ* endoscope LIBS system for EAST divertor, (b) the schematic diagram of LIBS optical system and the coordinate on divertor

3. RESULTS AND DISCUESSION

3.1. Influence of wall conditioning on the H/(H+D) ratio

The H to D ratio (H/(D+H)) can be determined through LIBS spectral fitting. Figure 2 presents LIBS results showing H/(D+H) on the divertor surface during baking and glowing discharge cleaning. This ratio drops from 100% to between 17% and 24% after wall conditioning. The intensities of H, D, and O on the divertor surface also decline when the wall is clean. Since D is the primary fuel in the EAST tokamak, small H impurities typically originate from background water vapor or wall desorption. The H/(H+D) ratio is a key parameter in EAST plasma discharges, indicating H content within the D plasma. Past studies on EAST demonstrate that maintaining a low H/(H+D) ratio not only improves ICRF heating efficiency but also facilitates the plasma's transition from L-mode to H-mode. LIBS offers spectral data of the fuel and its isotopes, enabling precise determination of the H/(H+D) ratio through spectral analysis.

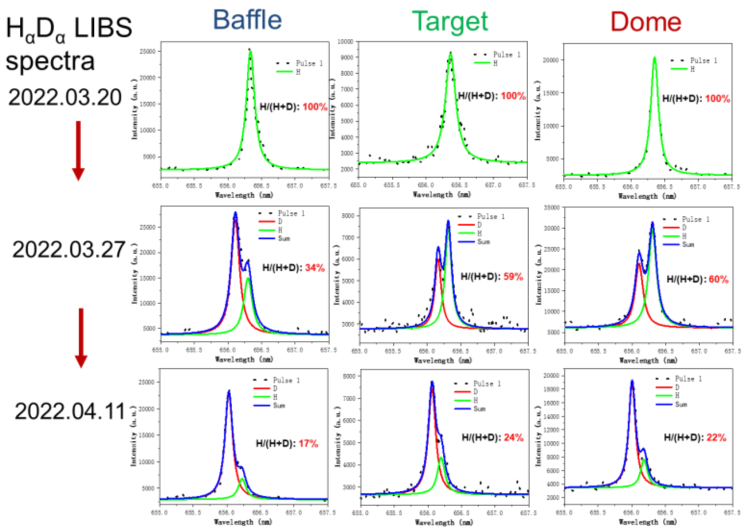

Figure 2. The LIBS spectra of H_α and D_α on the surface of the divertor after wall conditioning with different poloidal positions

From March 15, 2022, when the EAST device was sealed for vacuum, to April 25, the *in situ* LIBS diagnostic system measured fuel retention on the upper W divertor's surface and tracked the evolution of the H/(H+D) ratio. Figure 3 compares these ratios at different poloidal positions on the upper divertor surface at three key time points. All spectra originate from the first LIBS laser pulse. On March 20, with the vacuum chamber pressure at 1.5×10^{-4} Pa and no wall treatment initiated, no D signals were detected across the divertor surface, and spectral fitting showed the H/(H+D) ratio was 100%. Starting March 21, the first wall underwent high-temperature baking with hot nitrogen at 150°C. From March 24, DC-GDC wall plasma cleaning with alternating D/He gases commenced. Due to isotope effects and D particle retention, by March 27, the H intensity at various poloidal positions significantly decreased, and the H/(H+D) ratio also dropped. The most notable decrease occurred in the inner target plate baffle area, likely due to more effective cleaning by DC-GDC. On April 10, the device cooled the first wall to 30°C, and on April 11, D plasma discharge experiments were attempted during the day. Figure 3 shows the *in situ* LIBS results from the evening of April 11. After extensive baking, D/He alternating DC-GDC treatments, and early D discharge plasma operations, the H/(H+D) ratio in the inner target plate baffle area dropped to 17%, while in the inner target plate plane and dome area, ratios decreased to 24% and 22%, respectively.

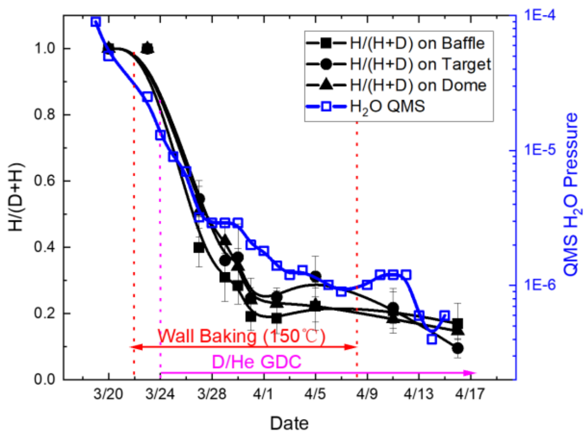

Figure 3. The variation of H/(H+D) from LIBS and H_2O from QMS with different date

By averaging the measured values from the three regions of the upper divertor obtained in each LIBS measurement, the mean values and error bars for each region are derived, as shown in Figure 3. The results indicate that the H/(H+D) ratios in the three regions decrease after the DC-GDC wall conditioning. Notably, the ratio in the inner target baffle declines more rapidly than in the inner target plane and the dome region, aligning with the findings in Figure 3. From March 31st onward, these ratios stabilize across all three regions. Following Li evaporation wall conditioning with a crucible on the night of April 16th, the H/(H+D) ratios in all three regions drop below 20%. To validate the LIBS data, we also compare the partial pressure of H_2O measured by the QMS in the vacuum chamber of the EAST device. As shown in Figure 3, the LIBS results agree with the QMS water peak partial pressures.

3.2. Fuel retention under long-pulse discharges

Understanding the retention and recycling of fuel requires measuring how the amount of fuel retained varies at different poloidal positions on the divertor surface over a discharge period. The second round of experiments on the EAST device in 2021 aimed to sustain ultra-long plasma discharges longer than 1000 s at high parameters. These experiments used a divertor double-null configuration with heating methods such as lower hybrid current drive and electron cyclotron heating. On December 30th, a successful long-pulse plasma operation lasted 1,056 s (shot #106915). Between December 22nd and 26th, during the device's target phase, an *in situ* LIBS system was employed to study how the deposition and retention intensities of Li and D varied at different poloidal positions on the upper divertor surface as a function of plasma discharge duration. The LIBS diagnostic experiment flow chart is shown in Figure 4 (a).

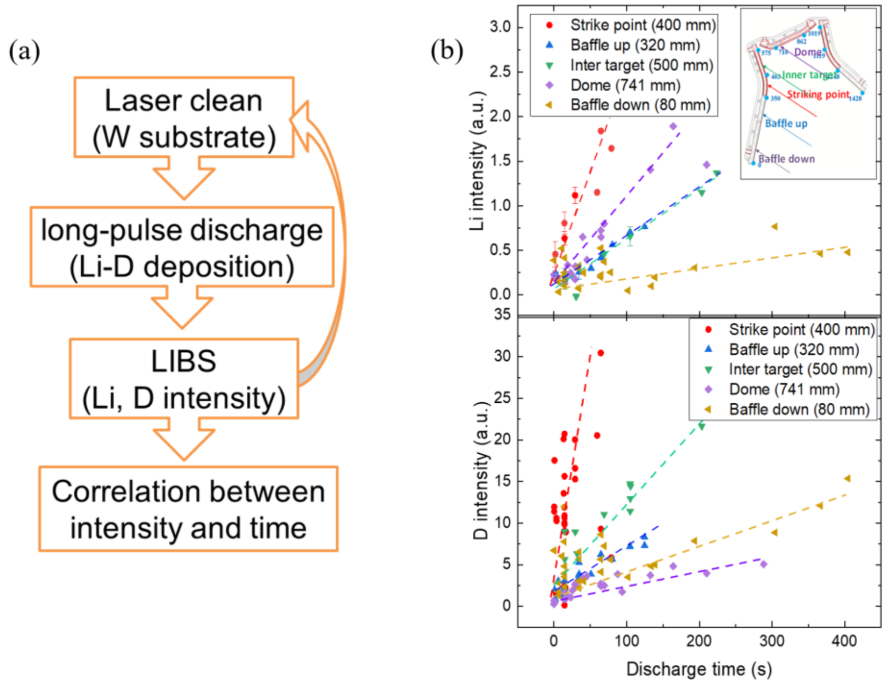

Figure 4. (a) The LIBS diagnostic experiment flow chart about fuel retention on divertor under long-pulse discharges, (b) The relationship between Li and D signal intensities and discharge duration at different positions on the upper divertor surface.

Figure 4 (b) illustrates the relationship between Li and D signal intensities and discharge duration at several typical poloidal positions on the upper divertor surface. The LIBS diagnostic results show that both the Li deposition intensity and the D retention increase as the plasma discharge time lengthens. The Li and D signal intensities measured at different poloidal positions are positively correlated with the device's plasma discharge duration. This suggests a strong link between the amounts of Li and D deposited or retained and the recycling process. [27] However, the growth rates of the Li and D signals vary significantly across different regions of the upper divertor. Notably, the highest growth rates of both Li and D signals are observed near the strike point position close to the inner target plate of the upper divertor.

3.3. Fuel short-term retention behaviour

In 2021, the first use of *in situ* online LIBS technology examined the short-term retention of D fuel particles in the inner target plate baffle area (128 mm-156 mm) of the upper divertor after plasma discharge in the fully superconducting tokamak EAST device. The findings are shown in Figure 5. The LIBS diagnostic procedure for D retention involved, one minute after shot No. 103436 discharge, conducting LIBS measurements at the 128 mm position on the inner target plate baffle to capture the D spectrum. The measurement was then moved to 130 mm, with another LIBS measurement taken 2 minutes after discharge. This process was repeated to gather D spectra at 142 mm, 8 minutes post-discharge. The device initiated plasma discharge for shot No. 103437 at the 9th minute. Since the measurement positions were only 2 mm apart, the effect of position change on the LIBS signals was minimal. Additionally, because the emission intensity of H I at 656.28 nm was much lower than that of D I at 656.10 nm (H/(H+D) < 15%), the spectral peak was considered to represent a pure D signal. Figure 5 depicts how D retention intensity evolved over time in the inner target plate baffle area after plasma discharge. The D signal intensity decreased markedly after discharge, then gradually leveled off after the fifth minute. Function fitting showed that D retention intensity follows a negative power-law with a coefficient of -0.31, indicating it diminishes over time post-discharge.

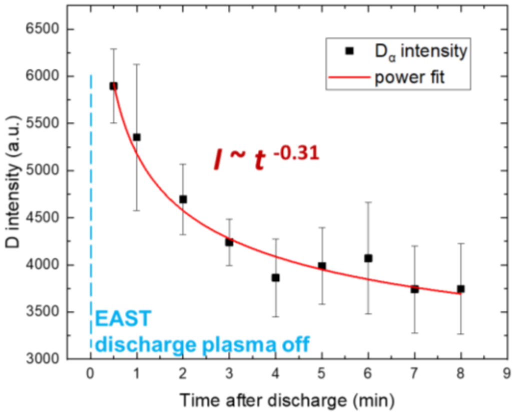

Figure 5. The dynamical evolution of D on the surface of divertor after long-pulse discharge

Research on the short-term retention of fuel has also been conducted using linear plasma devices. For instance, in 2018, Nishijima et al. [28] used LIBS to study how D fuel degasses from W targets after plasma irradiation on the PISCES-A device. Their results indicated that the D retention intensity followed a power-law decay of -0.34 with time after plasma discharge ended. In 2019, Jiang et al. [29] applied the LIBS technique to examine D fuel degassing in W targets on the PSI-2 device. They found that the D retention intensity decreased with a power-law of -0.53 over time after plasma exposure.

Compared to the simulation experiments on the linear plasma device, the measurement results of D short-term retention behavior on the EAST divertor surface, obtained with the *in situ* LIBS system, are similar. However, the decay of D short-term retention intensity on the EAST divertor surface is slower after plasma discharge ends than on the linear device. This is due to Li wall treatment in EAST, which deposits a Li layer with strong adsorption capacity for D fuel, reducing the immediate desorption of fuel particles from the PFCs [30]. Additionally, this marks the first use of online LIBS technology on a fully superconducting tokamak to directly confirm that D short-term retention on the divertor surface follows a -0.31 decay law.

4. CONCLUSION

An *in situ* endoscopic laser-induced breakdown spectroscopy (LIBS) diagnostic system for the full W divertor in EAST has been developed since the 2021 experimental campaign. This system provides online elemental distributions on the divertor with various discharge parameters and wall conditions. This work focuses on using the *in situ* LIBS system to study D fuel retention evolution in the W upper divertor region, the impact of wall conditions on the H-D ratio, fuel retention behavior during long-pulse discharges, and short-term retention phenomena. The H/(D+H) decreases from 100% to 17%~24% after the wall conditioning of baking and glowing discharge clean. the LIBS results agree with the QMS water peak partial pressures. The D and Li signal intensities measured at different poloidal positions are positively correlated with the EAST plasma discharge duration. Notably, the highest growth rates of both Li and D signals are observed near the strike point position close to the inner target plate of the upper divertor. In addition, the short-term fuel retention study shows that the dynamic D content on the W divertor decreases after the plasma exposure due to the dominant short retention with the outgassing process.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Nos. 12375203, 12375208), National Key R&D Program of China (Nos. 2024YFE03250100, 2022YFE03200100, 2019YFE03080100, 2023YFF0714900).

REFERENCES

[1] G. Federici et al., Plasma-material interactions in current tokamaks and their implications for next step fusion reactors, Nucl. Fusion, 2001, 41: 1967-2137.

[2] S. Brezinsek et al., Fuel retention studies with the ITER-Like Wall in JET, Nucl. Fusion, 2013, 53: 083023.

[3] V. Philipps, A. Malaquias, A. Hakola, et al., Development of laser-based techniques for in situ characterization of the first wall in ITER and future fusion devices. Nuclear fusion 53, 093002 (2013).

[4] V. Philipps, T. Loarer, H. G. Esser, et al., Dynamic fuel retention and release under ITER like wall conditions in JET. Journal of Nuclear Materials, 2013, 438: S1067-S1071.

[5] X. Jiang, G. Sergienko, A. Kreter, et al., In situ study of short-term retention of deuterium in tungsten during and after plasma exposure in PSI-2. Nuclear Fusion, 2021, 61(9): 096006.

[6] J. Wesson, D. J. Campbell. Tokamaks. Oxford University Press, 2011.

[7] A. D. Quastel, J. W. Davis, A. A. Haasz, et al., Effect of post-D+-irradiation time delay and pre-TDS heating on D retention in single crystal tungsten. Journal of Nuclear Materials, 2006, 359(1-2): 8-16.

[8] T. Watanabe, T. Kaneko, N. Matsunami, et al., In situ measurement of deuterium retention in W under plasma exposure. Journal of Nuclear Materials, 2015, 463: 1049-1052.

[9] S. Möller, D. Matveev, Y. Martynova, et al., Dynamic outgassing of deuterium, helium and nitrogen from plasma-facing materials under DEMO relevant conditions. Nuclear Fusion, 2017, 57(1): 016020.

[10] L.B. Guo, D. Zhang, L.X. Sun, et al., Development in the application of laser-induced breakdown spectroscopy in recent years: A review., Frontiers of Physics 16(2), 22500 (2021).

[11] Z. Wang, M. S. Afgan, W. Gu, et al., Recent advances in laser-induced breakdown spectroscopy quantification: From fundamental understanding to data processing. TrAC Trends in Analytical Chemistry 143, 116385 (2021).

[12] H. T. Manelski, R. C. Wiens, B. Bousquet, et al., LIBS plasma diagnostics with SuperCam on Mars: Implications for quantification of elemental abundances. Spectrochimica Acta Part B: Atomic Spectroscopy 222, 107061 (2024).

[13] X. Wan, C. Li, H. Wang, et al., Design, Function, and Implementation of China's First LIBS Instrument (MarSCoDe) on the Zhurong Mars Rover. Atomic Spectroscopy 42, 294-298 (2021).

[14] C. Li, C.L. Feng, H. Y. Oderji, et al., Review of LIBS application in nuclear fusion technology. Frontiers of Physics 11, 114214 (2016).

[15] H. van der Meiden et al., Monitoring of tritium and impurities in the first wall of fusion devices using a LIBS based diagnostic, Nucl. Fusion, 2021, 61: 125001.

[16] A. Huber, B. Schweer, V. Philipps, et al., Study of the feasibility of applying laser-induced breakdown spectroscopy for in situ characterization of deposited layers in fusion devices. Physica Scripta T145, 014028 (2011).

[17] A. Semerok, D. L'Hermite, J M. Weulersse, et al., Laser induced breakdown spectroscopy application in joint European torus. Spectrochimica Acta Part B: Atomic Spectroscopy 123, 121-128 (2016).

[18] D. Zhao, C. Li, Z. Hu, et al., Remote in situ laser-induced breakdown spectroscopic approach for diagnosis of the plasma facing components on experimental advanced superconducting tokamak. Review of Scientific Instruments 89(7), 073501 (2018).

[19] G. Maddaluno, S. Almaviva, L. Caneve, et al., Detection by LIBS of the deuterium retained in the FTU toroidal limiter. Nuclear Materials and Energy, 2019, 18: 208-211.

[20] A. Favre, A. Bultel, M. L. Sankhe, et al., A step towards the diagnostic of the ITER first wall: in situ LIBS measurements in the WEST tokamak. Physica Scripta 99, 035609 (2024).

[21] L. Z. Cai, Z. Wang, C. Li, et al., Development of an in situ diagnostic system for mapping the deposition distribution on plasma facing components of the HL-2M tokamak. Review of Scientific Instruments, 2019, 90(5): 053503.

[22] Z. H. Hu, C. Li, Q. M. Xiao, et al., Preliminary results of in situ laser-induced breakdown spectroscopy for the first wall diagnostics on EAST. Plasma Science & Technology, 2017, 19(2): 025502.

[23] P. Liu, D. Y. Zhao, L. Y. Sun, et al., In situ diagnosis of Li-wall conditioning and H/D co-deposition on the first wall of EAST using laser-induced breakdown spectroscopy. Plasma Physics and Controlled Fusion, 2018, 60(8): 085019.

[24] C. Li, L. Y. Sun, Z. H. Hu, et al., An in situ diagnostic method for monitoring of fuel retention on the first wall under long-pulse operation of Experimental Advanced Superconducting Tokamak. Physica Scripta, 2020, T171(1): 014069.
[25] J. Li et al., A long-pulse high-confinement plasma regime in the Experimental Advanced Superconducting Tokamak, Nat. Phys., 2013, 9: 817-821.
[26] G.-N. Luo et al., Overview of decade-long development of plasma-facing components at ASIPP, Nucl. Fusion, 2017, 57: 065001.
[27] J. Hu et al., First results of the use of a continuously flowing lithium limiter in high performance discharges in the EAST device, Nucl. Fusion, 2016, 56: 046011.
[28] D. Nishijima, M. Patino, R. P. Doerner, Development of a LIBS system for in situ surface measurements during plasma exposure in PISCES-A. Review of Scientific Instruments, 2018, 89(10): 10j105.
[29] X. Jiang, G. Sergienko, B. Schweer, et al., An upgraded LIBS system on linear plasma device PSI-2 for in situ diagnostics of plasma-facing materials. Fusion Engineering and Design, 2019, 146: 96-99.
[30] C. Li et al., Deuterium retention characteristics in Li film by coating and during flowing liquid Li limiter operation in experimental advanced superconducting tokamak, Plasma Phys. Control. Fusion, 2021, 63: 015001.