 Plasma Science and Technology

Plasma Sci. Technol. **24** (2022) 080101 (4pp) https://doi.org/10.1088/2058-6272/ac7e26

Editorial

A new stage of the Asian laser-induced breakdown spectroscopy community

Weilun GU (顾炜伦)[1], Lei ZHANG (张雷)[2], Meirong DONG (董美蓉)[3], Cong LI (李聪)[4], Ye TIAN (田野)[5], Zongyu HOU (侯宗余)[1], Zhe WANG (王哲)[1,*] and Ronger ZHENG (郑荣儿)[5,*]

[1] *State Key Laboratory of Power Systems, International Joint Laboratory on Low Carbon Clean Energy Innovation, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, People's Republic of China*

[2] *State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan 030006, People's Republic of China*

[3] *School of Electric Power, South China University of Technology, Guangzhou 510640, People's Republic of China*

[4] *Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, Dalian 116024, People's Republic of China*

[5] *College of Physics and Optoelectronic Engineering, Ocean University of China, Qingdao 266100, People's Republic of China*

E-mail: *zhewang@tsinghua.edu.cn* and *rzheng@ouc.edu.cn*

* Authors to whom any correspondence should be addressed.

Laser-induced breakdown spectroscopy (LIBS) is an atomic emission spectroscopy technique gaining much attention since it was created in 1962 [1]. In 2021, the 4th Asian Symposium on LIBS (ASLIBS) and the ten-year anniversary of Chinese Symposium on LIBS (CSLIBS) were jointly held in Qingdao, symbolizing the development of the Asian and Chinese LIBS communities into a new stage. Since the initiation of CSLIBS in Qingdao (2011) and ASLIBS in Wuhan [2] (2015), both the Chinese and Asian LIBS communities grew quickly and the ASLIBS has become one of the three major LIBS symposiums in the world [3, 4]. In this joint meeting, the Asian Community of LIBS (ACLIBS) was officially formed to better promote cooperation among Asian LIBS researchers and to run ASLIBS in a more efficient way. The formation of ACLIBS is a milestone for the Asian LIBS community.

This special issue is to memorialize the 4th ASLIBS and the ten-year anniversary of CSLIBS, and to mark a starting point for the next stage of growth of ACLIBS and CSLIBS. It collected nine research articles covering fundamental [5], instrumentation [6], data processing [7, 8], and application [9–13] studies. The effects of lens-to-sample distance on plasma morphology and spectrum using a flat-top laser beam were investigated [5]; a LIBS-assisted glow discharge method for liquid samples was developed [6]; a support vector machine combined with restricted Boltzmann machine was proposed for steel classification [7]; and plasma images were utilized to reduce the spectral fluctuation in combustion environments [8]. The other five articles focused on the applications, including the quantitative analysis of ceramic raw materials [9], the identification of mural pigments [10] and volatile organic compounds [11], the determination of aqueous ruthenium by microwave-assisted LIBS [12], and the quantitative analysis of coal by X-ray fluorescence (XRF) assisted LIBS [13].

The special issue is also a witness to the historical rising-up of the Asian and Chinese LIBS communities. Apart from the increase of meeting attendees from ∼40 in 2011 and ∼150 in 2015 to ∼300 in 2021, the Asian LIBS community has accomplished many more achievements, for example, contributing more than 1000 papers (∼1800 total in the world) in the field of LIBS over the past two years (Web of Science, topic: laser-induced breakdown/plasma spectroscopy), and the Chinese researchers have become the main force with more than 750 papers published in the same period. The series of special issues published in *Plasma Science and Technology* witnessed the progress of the Asian and Chinese LIBS communities from small to big [3], and will also witness their growth from big to strong.

This special issue marks the beginning of a new stage of the Asian and Chinese LIBS communities. In the past 10 years, Asian LIBS researchers started by following the work of LIBS colleagues from Europe and the United States and ended up with some leading fields, which provided a strong basis for future development. Specifically, Asian LIBS researchers have a leading basis in the quantification theory and method as well as some important or unique applications.

A framework theory of LIBS quantification was summarized in [14], providing a theoretical direction for continuous improvement of quantification performance. The theory was established on the understanding that the essential obstacle limiting LIBS quantification is that its emission source is a temporally drastically varying and spatially inhomogeneous laser-induced plasma, which is totally consistent with the gradually realized fact that signal uncertainty is the most critical hinder for LIBS quantification [14, 15]. It was further revealed that the fluctuation of the total number density of the measurement element caused by the plasma morphology variation is the main source of signal uncertainty [15–18], and the more stable the plasma morphology, the higher the signal repeatability. Accordingly, plasma modulation to obtain more stable plasma morphology by modulating the plasma evolution process [16, 19–22], and mathematical models compensating for total number density fluctuation either by spectral information [15, 23] or morphological information [24–29] were proved to be effective in uncertainty reduction. While for quantification models, it was recommended to apply hybrid models combining physical principle-based models and data-driven machine learning models considering the overall performance [30, 31]. Meanwhile, several rapid re-calibration methods were proposed for long-term on-field applications [32–34].

Driven by the large market potential, the Asian LIBS community has developed several applications with leading or close-to-leading positions [35]. The most important application field for LIBS in, Asia especially in China, is the online analysis in large-scale process industries such as coal utilization, metallurgy, and cement industry. Encouraged by the large market of coal in China, the investigation of coal analysis using LIBS was very thorough [36]. The best quantification performance was achieved from many fundamental and data processing studies [37–40] and offline, at-line, and inline demonstrations [41–43]. A combination of LIBS with XRF and near-infrared spectroscopy (NIRS) has been successfully applied in coal analysis to further improve the measurement precision and accuracy [44, 45]. The application in the cement industry also attracted much attention because cement production in China accounts for over 50% of the world [46]. The analysis of the cement raw materials, powder, and pastes was conducted in a lab [47–49] and demonstrated in the real cement industry [50, 51]. Metallurgy is another important field because of the tremendous industrial demand [52]. Much work was conducted on the data processing and signal quality improvement of solid metal [53, 54], while more attention was paid to the instrumentation for the analysis of molten metal [55–57]. Among them, the long-short double-pulse configuration seemed very promising [20, 58]. Moreover, LIBS has also been developed to provide multiple effective information for the combustion diagnosis, including temperature [59, 60] and reaction mechanism [61–63]. The incorporation of acoustic signals with LIBS enabled better diagnostic performance [60]. All these investigations provided a good basis for the Asian LIBS community to lead in these fields in the next years.

The LIBS applications in extreme environments were highly regarded because other conventional analytical techniques became inapplicable [64]. Several underwater LIBS devices have been successfully developed and deployed, and the *in situ* analyses of both seawater and mineral deposits were demonstrated at ocean depths of over 1000 m [65–68]. Driven by the deep-sea applications, the laser irradiation schemes including long-pulse [69] and double-pulse techniques [70], as well as the high-pressure impact on underwater plasmas [71] were clarified from a fundamental point of view. In the field of nuclear fusion energy, the *in situ* LIBS system has been developed to diagnose the first wall in Experimental Advanced Superconducting Tokamak (EAST) of China [72, 73]. This was the first time that the LIBS was routinely applied in a fully superconducting nuclear fusion device and demonstrated the great potential of the LIBS application in upcoming nuclear fusion reactors such as the International Thermonuclear Experimental Reactor (ITER). For the exploration of outer space, a LIBS payload named MarSCoDe was deployed on the Tianwen-1 Mars rover launched by China, which made China the second country to reach Mars and to analyze Marian surface materials by LIBS after the United States [74, 75].

To embrace the new stage and to make the Asian LIBS community stronger, we believe that more attention should be paid to the following points based on the current situation. (1) As described above, the most effective way to improve LIBS quantification performance is to find or create an appropriate temporal-spatial window with stable laser-induced plasma for highly repeatable signal detection [14, 18], which should be a very important hint for continuous improvement of quantification performance. (2) LIBS has its intrinsic limitations and advantages, and the combination with other spectroscopic techniques may be a good way out for real applications. For example, LIBS shares the same optical system with Raman spectroscopy and provides the laser-ablation process for LA-ICP-MS naturally, and the easy fusion utilization of LIBS spectra and another one's signal may provide much better quantification results [76–78]. (3) Capabilities of surface/3D scanning and online/*in situ* analysis are the most important features of LIBS, and it needs sustained efforts to demonstrate LIBS in applications with large-scale markets or in indispensable situations. These are the practical strategies to turn LIBS from a 'future super star' to a 'super star'.

References

[1] Brech F and Cross L 1962 *Appl. Spectrosc.* **16** 42
[2] Guo L B *et al* 2016 *Front. Phys.* **11** 115208
[3] Fu Y T *et al* 2019 *Plasma Sci. Technol.* **21** 030101
[4] Hou Z Y *et al* 2020 *Plasma Sci. Technol.* **22** 070101
[5] Fu H B *et al* 2022 *Plasma Sci. Technol.* **24** 084005
[6] Sun D *et al* 2022 *Plasma Sci. Technol.* **24** 084008
[7] Zeng Q *et al* 2022 *Plasma Sci. Technol.* **24** 084009
[8] Chai S *et al* 2022 *Plasma Sci. Technol.* **24** 084001
[9] Zhang P *et al* 2022 *Plasma Sci. Technol.* **24** 084006
[10] Zhang Y M *et al* 2022 *Plasma Sci. Technol.* **24** 084003
[11] Zhang X L *et al* 2022 *Plasma Sci. Technol.* **24** 084002
[12] Abu Kasim A F *et al* 2022 *Plasma Sci. Technol.* **24** 084004
[13] Tian Z *et al* 2022 *Plasma Sci. Technol.* **24** 084007
[14] Wang Z *et al* 2021 *TrAC-Trends Anal. Chem.* **143** 116385
[15] Li L Z *et al* 2011 *J. Anal. At. Spectrom.* **26** 2274
[16] Hou Z Y *et al* 2014 *Opt. Express* **22** 12909
[17] Fu Y T *et al* 2019 *Spectrochim. Acta Part B: At. Spectrosc.* **155** 67
[18] Fu Y T *et al* 2021 *Front. Phys.* **16** 22502
[19] Tian Y *et al* 2016 *Appl. Phys. Lett.* **109** 061104
[20] Cui M C *et al* 2020 *Spectrochim. Acta Part B: At. Spectrosc.* **167** 105839
[21] Hou Z Y *et al* 2020 *J. Anal. At. Spectrom.* **35** 1671
[22] Yu J L *et al* 2020 *Spectrochim. Acta Part B: At. Spectrosc.* **174** 105992
[23] Gu W L *et al* 2022 *Anal. Chim. Acta* **1205** 339752
[24] Ni Z B *et al* 2014 *Front. Phys.* **9** 439
[25] Zhang P *et al* 2017 *J. Anal. At. Spectrom.* **32** 2371
[26] Zhang P *et al* 2018 *Anal. Chem.* **90** 4686
[27] Li Q Y *et al* 2020 *J. Anal. At. Spectrom.* **35** 366
[28] Zhang Y Q *et al* 2022 *Anal. Chim. Acta* **1195** 339423
[29] Zhang D *et al* 2020 *Anal. Chim. Acta* **1107** 14
[30] Feng J *et al* 2011 *Anal. Bioanal. Chem.* **400** 3261
[31] Hou Z Y *et al* 2016 *J. Anal. At. Spectrom.* **31** 722
[32] Hao Z Q *et al* 2018 *J. Anal. At. Spectrom.* **33** 1564
[33] Yuan R *et al* 2019 *Anal. Chim. Acta* **1064** 11

[34] Deng F *et al* 2022 *Opt. Express* **30** 9256
[35] Guo L B *et al* 2021 *Front. Phys.* **16** 22500
[36] Sheta S *et al* 2019 *J. Anal. At. Spectrom.* **34** 1047
[37] Dong M R *et al* 2012 *J. Anal. At. Spectrom.* **27** 2066
[38] Zheng J P *et al* 2014 *Appl. Spectrosc.* **68** 672
[39] Cai J B *et al* 2021 *Spectrochim. Acta Part B: At. Spectrosc.* **180** 106195
[40] Hou Z Y *et al* 2022 *Spectrochim. Acta Part B: At. Spectrosc.* **191** 106406
[41] Yin W B *et al* 2009 *Appl. Spectrosc.* **63** 865
[42] Yao S C *et al* 2018 *Appl. Spectrosc.* **72** 1225
[43] Song W R *et al* 2021 *Fuel* **306** 121667
[44] Li X L *et al* 2020 *J. Anal. At. Spectrom.* **35** 2928
[45] Yao S C *et al* 2022 *At. Spectrosc.* **43** 154
[46] USGS 2021 *Mineral Commodity Summaries 2021* (Reston, VA: U.S. Geological Survey)
[47] Fan J J *et al* 2015 *Plasma Sci. Technol.* **17** 897
[48] Yin H L *et al* 2016 *J. Anal. At. Spectrom.* **31** 2384
[49] Zhang Z *et al* 2022 *Spectrochim. Acta Part B: At. Spectrosc.* **191** 106392
[50] Zhang L *et al* 2017 *IEEE Photon. J.* **9** 6804010
[51] Li Y F *et al* 2016 *Spectrosc. Spectral Anal.* **36** 1494 (in Chinese)
[52] Dong F Z *et al* 2012 *Front. Phys.* **7** 679
[53] Zeng Q D *et al* 2015 *J. Anal. At. Spectrom.* **30** 403
[54] Kashiwakura S and Wagatsuma K 2015 *ISIJ Int.* **55** 2391
[55] Sun L X *et al* 2015 *Spectrochim. Acta Part B: At. Spectrosc.* **112** 40
[56] Zeng Q *et al* 2018 *J. Appl. Spectrosc.* **85** 817
[57] Sun L X *et al* 2018 *Spectrochim. Acta Part B: At. Spectrosc.* **142** 29
[58] Cui M C *et al* 2018 *Spectrochim. Acta Part B: At. Spectrosc.* **142** 14
[59] Tian Z H *et al* 2017 *Spectrochim. Acta Part B: At. Spectrosc.* **136** 8
[60] Wu W D, Adeosun A and Axelbaum R L 2019 *Proc. Combust. Inst.* **37** 1409
[61] Liu Y Z *et al* 2019 *Proc. Combust. Inst.* **37** 2681
[62] Zhang Y Y *et al* 2015 *Proc. Combust. Inst.* **35** 3681
[63] Li S S *et al* 2020 *J. Energy Inst.* **93** 52
[64] Laserna J, Vadillo J M and Purohit P 2018 *Appl. Spectrosc.* **72** 35
[65] Thornton B *et al* 2015 *Deep Sea Res. Part I: Oceanogr. Res. Papers* **95** 20
[66] Takahashi T *et al* 2020 *Deep Sea Res. Part I: Oceanogr. Res. Papers* **158** 103232
[67] Guo J J *et al* 2017 *Appl. Opt.* **56** 8196
[68] Liu C H *et al* 2020 *Sensors* **20** 7341
[69] Li N *et al* 2021 *J. Anal. At. Spectrom.* **36** 1170
[70] Xue B Y *et al* 2020 *J. Anal. At. Spectrom.* **35** 2880
[71] Tian Y *et al* 2020 *Opt. Express* **28** 18122
[72] Li C *et al* 2015 *J. Nucl. Mater.* **463** 915
[73] Zhao D Y *et al* 2018 *Rev. Sci. Instrum.* **89** 073501
[74] Wan X *et al* 2021 *Anal. Chem.* **93** 7970
[75] Xu W M *et al* 2021 *Space Sci. Rev.* **217** 64
[76] Wiens R C *et al* 2005 *Spectrochim. Acta Part A: Mol. Biomol. Spectrosc.* **61** 2324
[77] Dong M R *et al* 2020 *Anal. Chem.* **92** 7003
[78] Ma Y *et al* 2020 *Materials* **13** 2404