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Influence of gas pressure on the magnetized plasma parameters of laser-induced breakdown

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Abstract
In this study, the effect of environment gas and working pressure of laser-induced breakdown spectroscopy from ZnO: Al composite target (AZO) enhanced by an external magnetic field on the magnetized characteristics and emission spectra of plasma were investigated. The plasma was induced by a Q-switched nanosecond Nd: YAG laser at a constant pulse laser energy of 300 mJ at different pressures of 0.08, 0.2, 0.4, and 760 Torr in air and argon gas. The atomic and ionic emission lines increased in intensity directly with the working pressure. The plasma temperature (T_e) and electron number density (n_e) were determined at the different environmental conditions according to the intensity-ration method, and Stark broadening effect, respectively. Both n_e and T_e increased with increasing pressure and with the presence of magnetic field as a result of confining effect. The line profile appeared with high broadening at atmospheric pressure compared with vacuumed plasma. The Larmur radius and confinement factor β increased with working pressure. From another hand, using Ar instead of air caused slightly reduced n_e at low pressure, while T_e has the opposite behavior.

Keywords Laser-induced breakdown spectroscopy (LIBS) · Ambient gas pressure influence · Ar · Air · Plasma diagnostics · ZnO: Al target · Magnetized plasma

1 Introduction

Laser-induced breakdown spectroscopy (LIBS) is a powerful spectral analysis technique based on analyzing the emission from plasma-induced on the surface of a sample by a laser source. Recently, LIBS has gained high attention in numerous fields due to its capability for the analysis of small elements, simultaneous multi-element detection, simplicity of sample preparation, remote detection, and in situ real-time analysis (Peng et al. 2016). LIBS also can be conducted with easily-handled and inexpensive devices. It is used for

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the online determination of elemental composition and utilizes a high-intensity laser beam from different types of targets (Rühlmann et al. 2018; Abbas and Adnan 2020).

LIBS applications now spread to additional fields including the diagnostics of atmospheric plasmas in the field of biomedicine (Li et al. 2023) and environmental applications (Zhang et al. 2021). It is also used as an analytical method for steel, alloy, metal, and ceramic industries' geological studies (Panya Panya et al. 2021). It is also used for on-site analyses such as controlling the metallurgical mining processes (Myakalwar et al. 2021). The LIBS technique also allows for the efficient determine the elemental composition (Ahmed et al. 2019), or to assess the final properties of the deposited thin films, and diagnosis of the plasma to see its effect on the deposition process (Depablos-Rivera et al. 2021) or synthesis of nanoparticles (Lu et al. 2023).

LIBS can be applied under atmospheric air or under vacuum. In addition to laser parameters the plasma processes in LIBS are extremely reliant on the surrounding media, and pressure during laser mater interaction (Abbas 2019). LIBS can be enhanced by different techniques such as by applying an external magnetic field, using different working pressures, and using dual pulses inertial confinement (2021).

Atif et al. (2018) studied the effect of an external magnetic field on LIBS as a function of pressures using Nd: YAG (1064 nm, 8 ns) under helium and argon gases at different working pressures (1–80 kPa). It is exposed that emission line intensities and plasma parameters are highly affected by the magnetic field and ambient gas conditions. The stark broadening confirms increasing electron density by the magnetic field at different pressures. Reeson et al. (2020) studied the effects of O_2, He, and Ar Background gases at different pressures used on plasma formation by 355 nm laser in the deposition of AZO by PLD. The OES measurement results show that the emission intensity of the species in O_2 and Ar decreases slightly and then increases exponentially above ~ 5 Pa.

In the present work, the influence of the magnetic field, pressure, and gas type on the LIBS characteristics will study in more detail.

2 Experimental setup

Zinc oxide -aluminum mixture at 0.3 wt.% atomic ratios formed into a capsule of 1 cm diameter by pressing into a stainless-steel mold under 5 tons press for 15 min which was used as a target for Laser-induced breakdown spectroscopy (LIBS). The process was done using a Q-switched Nd: YAG laser of the fundamental wavelength of 9 ns pulse duration, 300 mJ pulse energy, and 2 mm spot diameter perpendicular to the target. The LIBS technique was enhanced without and with a permanent magnet behind the target of a 77 mT magnetic field. A previously calibrated wide-range spectrometer (Thorlabs- CCS 100/M) was used to analyze the emissions plasma plume at a wavelength range of 320–740 nm with a spectral resolution of 0.1 nm. The analyses were done in atmospheric air and a vacuumed chamber in air and Ar at 0.08, 0.2, and 0.4 Torr vacuumed using a double-stage rotary pump. The emissions were taken at a 5 cm distance and 45° angle with the target surface through a quartz window using an optical fiber. A Perini gauge (Edward) was used to control the vacuum pressure of the chamber. Figure 1 shows a schematic of the LIBS system.

The electron temperature was determined at different conditions using the intensity ratio method employing the atomic lines of zinc, while the electron number density was determined using the stark broadening effect using the 481 nm, Zn I line. The

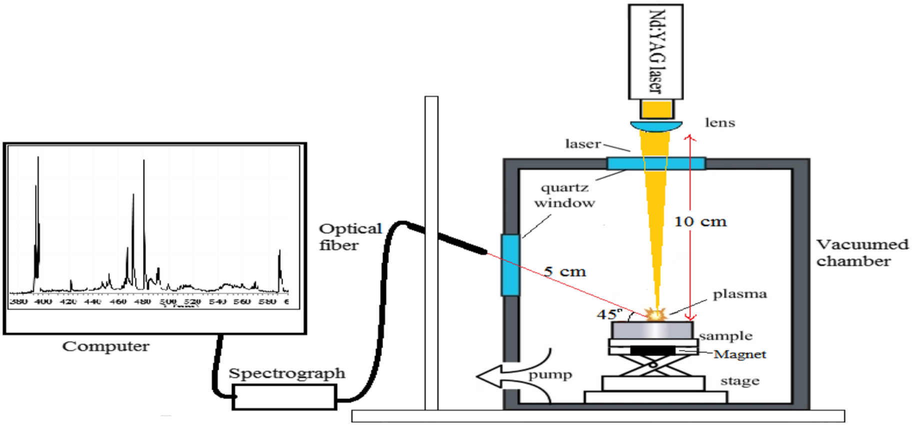

Fig. 1 A schematic of the LIBS system

instrumental line width was determined by fitting the profile of a low-pressure Hg atomic emission line of 435.7 nm using a Hg lamp. The calculated instrumental broadening was 0.248 nm for the used spectrometer. Then the Stark broadening for an experimental emission line which is fitted by a Lorentzian profile is the difference between total line width and instrumental width.

3 Results and discussions

Figures 2, 3, 4 and 5 show the spectroscopic patterns of plasma emission by LIBS in air and argon gases under different vacuum pressures from AZO targets, and another time with the presence of a magnetic field for the two cases, respectively. The appeared emission peak lines were matched with the atomic and ionic standard lines of zinc and aluminum elements (Zn-I, Zn-II, Al-I, and Al-II) according to data from the National Institute of Standards and Technology (NIST) (NIST Chemistry WebBook, U.S. xxxx). The variation of intensities for each pattern at different wavelengths is due to the different transition probabilities and statistical weight of each transition. The intensity of emitted lines for atomic species is higher than that for ionic ones due to the low ionized degree within plasma. On the other hand, the emissions of Zn lines are higher than those of Al lines due to their difference in content in the target. The LIBS emission intensity lines increased in intensity directly with working pressure due to the enhancement of breakdown due to the spatial confinement effect of the surrounded gas molecules. The species confined within a limited space with high-density act as emitted sources during the de-excitation of the excited atoms by the laser (Bredice et al. 2015). According to Stark's principle, the lines become more breadth with increasing the working pressure from 0.08 to 0.4 Torr, which suggests an increase in plasma density. A significant broadening in atmospheric pressure has appeared in the air (Ahmed et al. 2022). The electron number density was determined according to Stark broadening effect by the relation (Palleschi 2021).

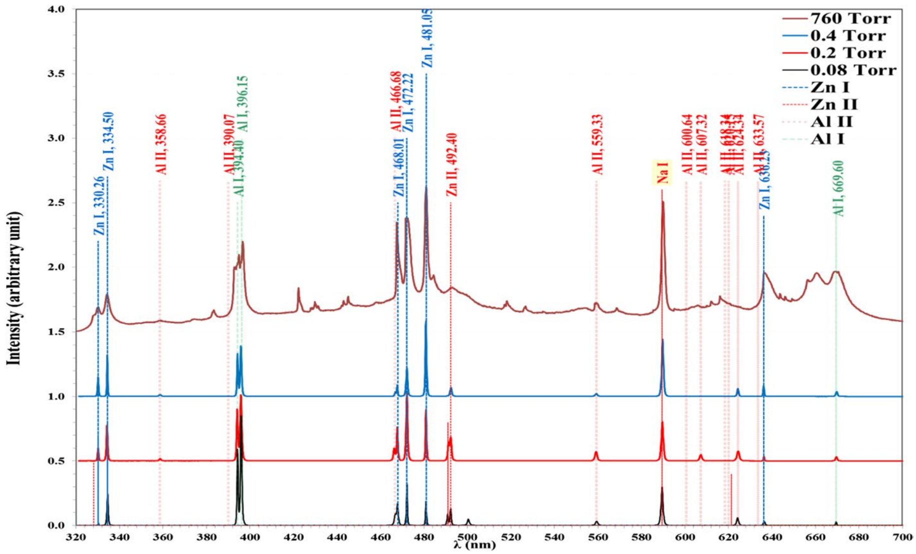

Fig. 2 Emitted spectra induced from AZO target under different pressure in the air

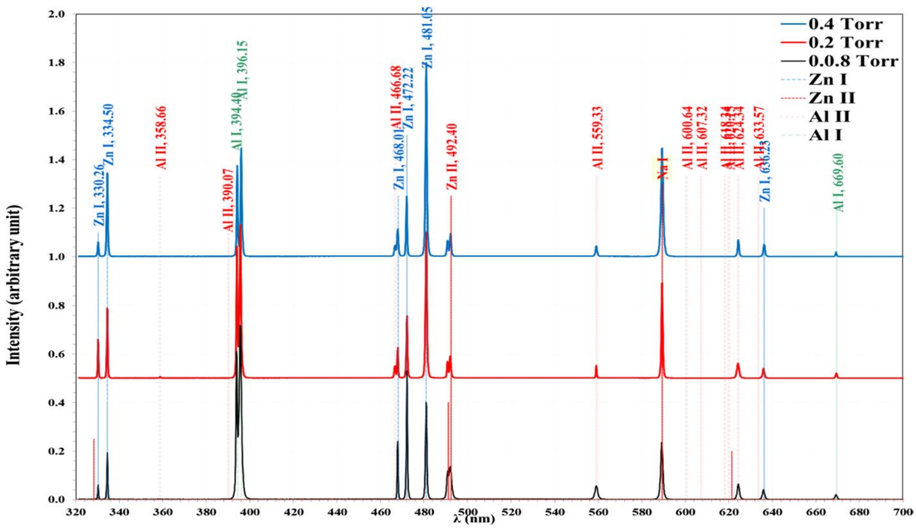

Fig. 3 Emitted spectra induced from AZO target under different pressure in argon

$$n_e = \left(\frac{\Delta \lambda_{FWHM}}{2\omega} \right) \times N_r$$

where $\Delta\lambda_{FWHM}$ is the line emission broadening subtract the instrument broadening, ω is the electron impact factor, N_r is the electron density obtained from the reference data (Dimitrijevic and Sahal 1999).

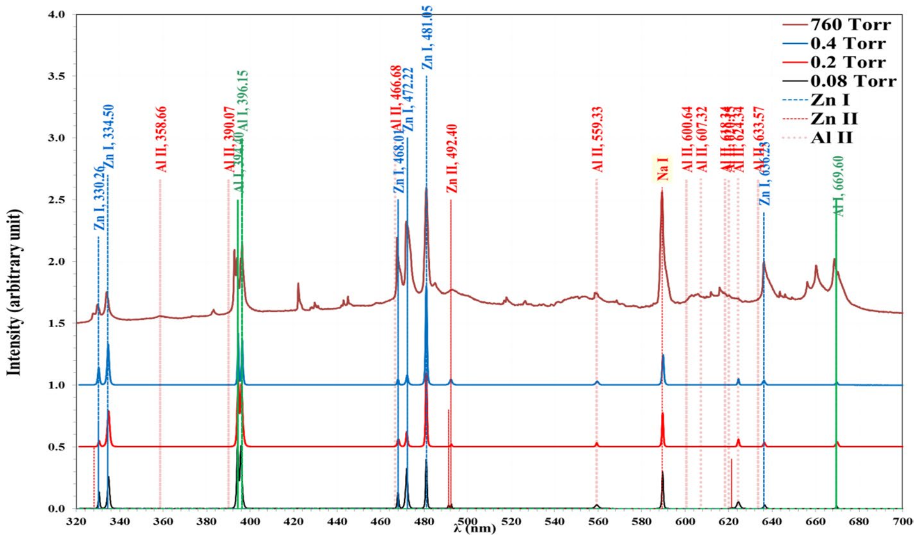

Fig. 4 Emitted spectra induced from AZO target under different pressure in air with the presence of the magnetic field

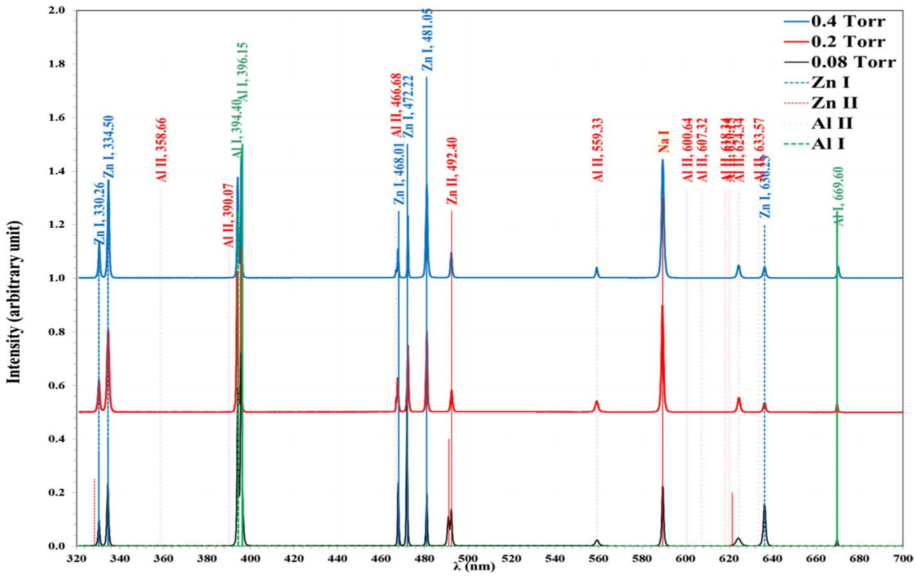

Fig. 5 Emitted spectra induced from AZO target under different pressure in argon with the presence of the magnetic field

Figure 6 illustrates the Lorentzian fitting for the Zn-I 481 nm emission line at different working pressure in air and Argon gas, in the two cases of absence and presence of the external magnetic field. The line broadening increased with increasing the working pressure, especially at atmospheric pressure. When increasing pressure, the high density

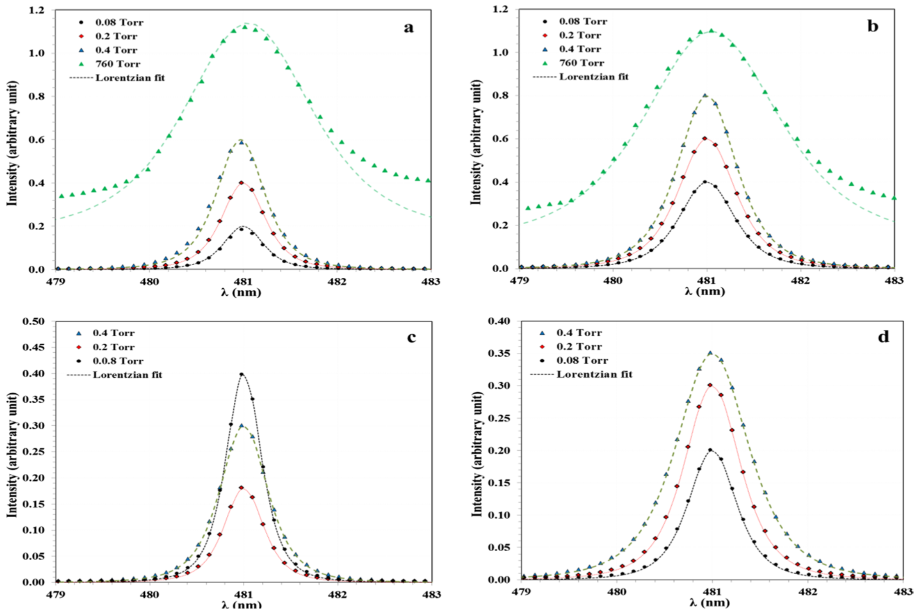

Fig. 6 Lorentzian fitting for Zn-I 481 nm emission lines at different pressures in the air without magnetic field (**a**), in Air with the magnetic field (**b**), in Ar without magnetic field (**c**), and in Ar with the magnetic field (**d**)

of surrounding gas molecules restricted the plasma expansion cause to reflect the shock wave and effectively compress the plasma plume by limiting the plasma plume expansion causing an inertial spatial confinement effect, thereby causing the n_e to increase (Hao et al. 2022). Zinc spectral lines intensity (334.5 and 636.2 nm) were chosen to determine the plasma temperature. The comparison between T_e and n_e values with the absence and presence of the magnetic field and their variation with the working pressure in air and Argon was shown in Figs. 7 and 8.

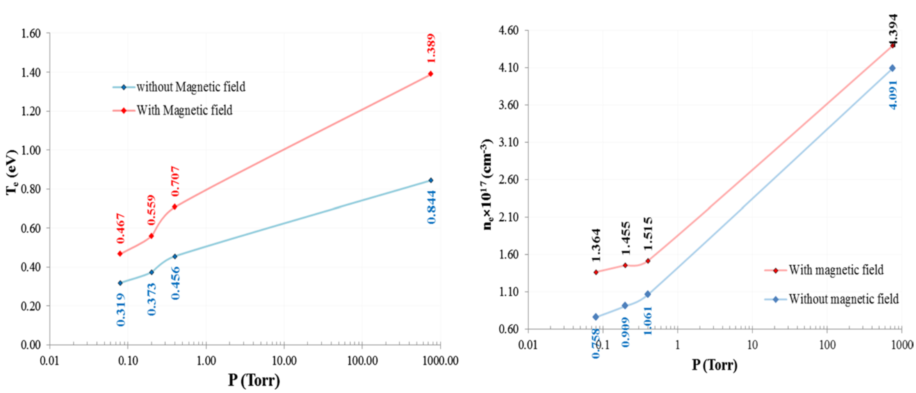

Fig. 7 Electron number density and plasma temperature against working pressure in the air without the presence of the magnetic field

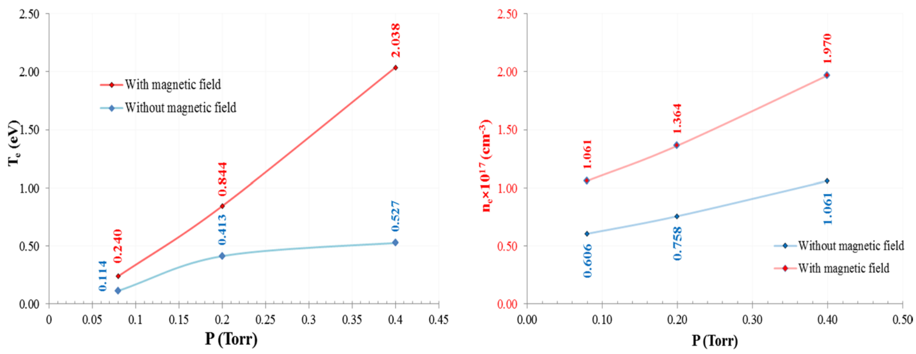

Fig. 8 Electron number density and plasma temperature against working pressure in Argon without the presence of the magnetic field

The electron temperature and its number density increased with increasing surrounding pressure in both gases at a pressure range of 0.08–760 Torr. At the lowest pressure levels, the energetic electrons and other species can travel longer distances before losing some of their energy in different collision types (Weng et al. 2021). Limiting the plasma plume expansion by the surrounded gas (in the air and Ar) with increasing pressure cause to confinement effect, thereby causing the need to increase. T_e in Ar is slightly lower than in air due to the higher cross-section of excitation collision for mono-atomic gases than the domain molecular gases in the air, which give a high probability of loss of energy and causes less dispersion of the plasma energy through fewer interactions with fast electrons (Glumac and Elliott 2007). All values of T_e and n_e are higher with the presence of a magnetic field due to the magnetic confinement effect (Rai et al. 2003). Table 1 listed the plasma parameters of LIBS for the AZO target in the air and argon environments at different vacuum pressure using 300 mJ pulse laser energy. The T_e and n_e increased with increasing the pressure from 0.08 to 760 Torr due to increasing the confinement effect by the surrounding gas pressure (Abbas and Abbas 2021). In addition, the two parameters increased with the presence of a magnetic field indicating the effective magnetic confinement of the plasma induced by a permanent magnet behind the target.

Table 1 Plasma parameters for LIBS from AZO targets in air and Ar at different vacuum pressure without the presence of the magnetic field

Gas	P (Torr)	T_e (eV)		$n_e \times 10^{17}$ (cm^{-3})	
		Without	With Mag. Field	Without	With Mag. field
Air	760	0.319	0.467	0.758	1.364
	0.40	0.373	0.559	0.909	1.455
	0.20	0.456	0.707	1.061	1.515
	0.08	0.844	1.389	4.091	4.394
Ar	0.40	0.114	0.240	0.606	1.061
	0.20	0.413	0.844	0.758	1.364
	0.08	0.527	2.038	1.061	1.970

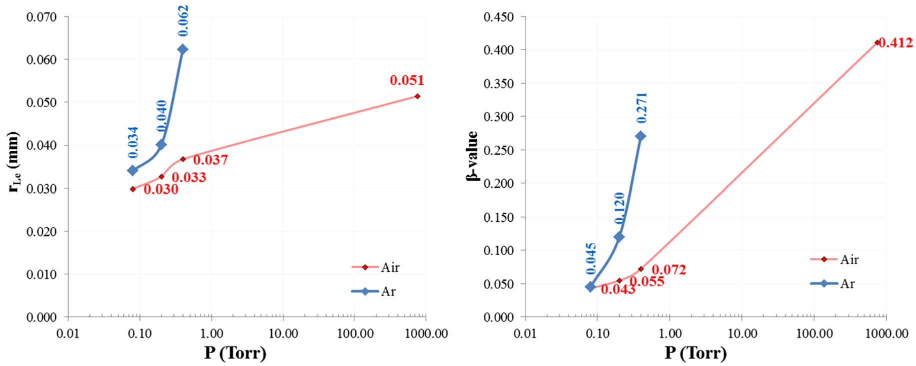

Fig. 9 Variation of Larmur radius and the magnetic confinement factor (β) with working pressure in air and Argon

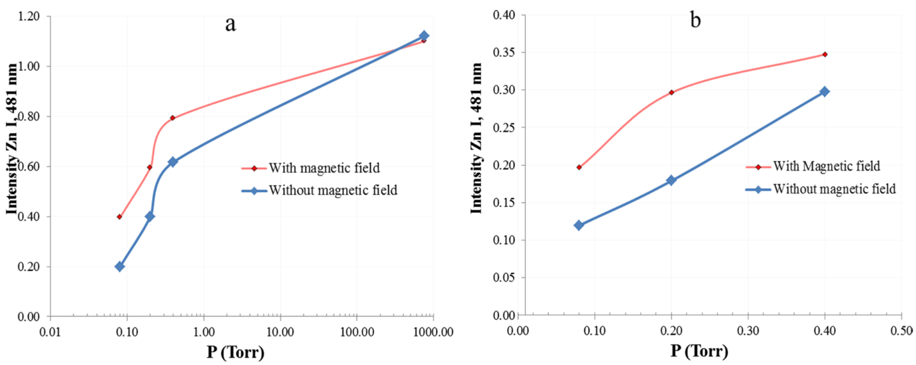

Fig. 10 Variation of emission intensity of Zn-I (481 nm) with working pressures with and without magnetic field in the air (**a**) and argon gas (**b**)

Figure 9 shows the variation of Larmur radius (r_L) of electrons gyration caused by the applied external field with working pressure in air and argon. The Larmur radius in a constant magnetic field is directly related to electron velocity (which is related to their temperature), so r_L is increased with increasing working pressure. The validity of magnetic confinement is confirmed by evaluating the magnetic confinement factor (β), where β is defined as the ratio of plasma pressure to magnetic pressure. Laser-induced plasma under vacuum has $\beta < 1$, indicating the efficiency of magnetic confinement especially at low vacuum, where the magnetic pressure is higher as compared to plasma pressure (Khan et al. 2023). β increased with increasing pressure i.e. reducing the magnetic confinement efficiency, especially at atmospheric pressure with $\beta = 0.412$. Small variation in r_L and β with fewer values in Ar than air. Reducing the confinement efficiency at atmospheric pressure due to the high number of collisions. The vacuum level variation seems more effective on β values in Ar than in Air.

Figure 10 shows the variation of emission intensity of Zn-I (481 nm) with working pressures in air and Argon with and without the magnetic field. The LIBS intensities increase with increasing vacuum pressures from 0.08 to 0.4 Torr in the two types of gases and significantly increased in atmospheric air. The results indicate that the optimum pressure for the LIBS technique is at 0.4 Torr vacuum pressure from the AZO target. Despite the high increase in the emission intensity of the spectral lines at atmospheric pressure, it is not preferred because of the large broadening in the spectral lines, which leads to a decrease in the ability to distinguish between adjacent lines. The use of pure Argon gas which has distinctive spectral lines (especially if the wavelength range of the spectral study area does not contain lines of high intensities for the gas used) is better than using air, which contains different types of gases and impurities that affect the detection process using LIBS technology. On the other hand, the LIBS intensity significantly enhanced the LIBS emission intensity (while it is not affected at atmospheric pressure) as a result of more excitation collisions due to the long bath gyration motion of electrons and increasing the plasma density (Rai et al. 2003).

4 Conclusions

In this study, the effect of environment gas (air and Argon) and working pressure in laser-induced breakdown spectroscopy (LIBS) from an AZO target with an external magnetic field shows the following aspects. The LIBS investigation was enhanced by an external magnetic field on the plasma characteristics and emission. Both n_e and T_e increased with increasing pressure as a result of confining effect. The Larmur radius and confinement factor β increased with working pressure indicating the less effectiveness of the external field on plasma confinement at high working pressure compared with the low vacuum pressure. From another hand, using Ar instead of air caused to slightly reduced in n_e at low pressure. While the T_e has the opposite behavior. The atomic and ionic emission lines increased in intensity directly with the working pressure from 0.08 to 0.4 Torr, enhancing the LIBS detectability but limiting vacuum pressure. Despite the significant enhancement of emission intensity in atmospheric air, it is not preferred for LIBS because of the considerable broadening in the spectral lines, which leads to a decrease in the detection ability of adjacent lines. On the other hand, using pure Argon gas with distinctive spectral lines (especially if the wavelength range of the spectral study area does not contain lines of high intensities for the gas used) is better than using air, which may contain impurities that affect the detection process. Alternative gases can be used to study the spectral emission from different targets with spectral emission at other ranges.

Authors' contributions Each co-author has made specific unique contributions to the work. The authors ZMA prepared the thin films of ZnO and contributed to conceptualizations writing–original draft. The author QAA prepared the special program for optical properties and contributed to supervision and editing analysis.

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Data availability Data sharing is not applicable to this article as no datasets were created or analyzed during the current study.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

Ethical approval Authors would like to declare that they do not have any conflict of interests.

References

Abbas, Z.A., Abbas, Q.A.: Influence of the magnetic field on the characteristic of Au nanoparticles prepared by laser ablation. AIP Conf. Proc. **2372**(1), 080006 (2021)

Abbas, Q.A.: Effect of target properties on the plasma characteristics that produced by laser at atmospheric pressure. Iraq. J. Sci. **60**(6), 1251–1258 (2019)

Abbas, Z.M., Adnan, Q.: Influence of magnetic field on silver nanoparticles synthesized by laser ablation. Iraq. J. Sci., 341–350 (2020)

Ahmed, A.F., Mutlak, F.A.-H., Abbas, Q.A.: Evaluation of cold plasma effect to achieve fullerene and zinc oxide-fullerene hydrophobic thin films. Appl. Phys. A **128**(2), 147 (2022)

Ahmed, A., Salman, M., Alwazzan, M., Meri, A.: Blushers component analysis for unbranded cosmetic brands: elements' concentration levels and its effect on human body. J. Adv. Res. Dyn. Control Syst. **11**(5), 412–419 (2019)

Atif, H., Tanveer, M., Farid, G., Hussain, M.B., Azam, M., Khan, W.: Combined effects of magnetic field and ambient gas condition in the enhancement of laser-induced breakdown spectroscopy signal. Optik (stuttg) **172**, 1012–1018 (2018)

Bredice, F., Pacheco Martinez, P., Sánchez-Aké, C., Villagrán-Muniz, M.: Temporal evolution of the spectral lines emission and temperatures in laser induced plasmas through characteristic parameters. Spectrochim. Acta Part B at. Spectrosc. **107**, 25–31 (2015)

Depablos-Rivera, O., Alvarez-Mendoza, R., Martinez-Fuentes, M., Sanchez-Ake, C., Villagran-Muniz, M., Garcia-Fernandez, T., Muhl, S.: Plasma emission spectroscopy to study the resputtering produced by pulsed laser deposition of Au and in combination with magnetron sputtering of ZnO. IEEE Trans. Plasma Sci. **49**(7), 2125–2132 (2021)

Dimitrijevic, M.S., Sahal, S.: On the Stark broadening of neutral zinc spectral lines. Publ. Astron. Obs. Belgrade **65**, 55–58 (1999)

Glumac, N., Elliott, G.: The effect of ambient pressure on laser-induced plasmas in air. Opt. Lasers Eng. **45**(1), 27–35 (2007)

Hao, Z., Deng, Z., Liu, L., Shi, J., He, X.: Spatial confinement effects of laser-induced breakdown spectroscopy at reduced air pressures. Front. Optoelectron. **15**(1), 17 (2022)

Hussain, A., Xun, G., Asghar, H., Azam, M., Ain, Q., Nawaz, Z.: Enhancement of laser-induced breakdown spectroscopy (LIBS) signal subject to the magnetic confinement and dual pulses. Opt. Spectrosc. **129**(4), 452–459 (2021)

Khan, M.A., Bashir, S., Chishti, N.A., Bonyah, E., Dawood, A., Ahmad, Z.: Effect of ambient environment and magnetic field on laser-induced cobalt plasma. AIP Adv. **13**(1), 015017 (2023)

Li, M., Lu, W., Mao, Y., Qiu, X., Du, D.: An enhanced immunochromatography assay based on gold growth on the surface of *E. coli* carrier for the simultaneous detection of mycotoxins. Talanta **251**, 123798 (2023)

Lu, Y., Yang, C., Wang, H., Ma, L., Xu, M., Xi, L.: Structure, principle, and application of magnetic field-assisted pulsed laser deposition: an overview. Vacuum **211**, 111912 (2023)

Myakalwar, A.K., Sandoval, C., Velásquez, M., Sbarbaro, D., Sepúlveda, B., Yáñez, J.: LIBS as a spectral sensor for monitoring metallic molten phase in metallurgical applications—a review. Minerals **11**(10), 1073 (2021)

NIST Chemistry WebBook, U.S. department of cmmerce, on line avelable (2009)

Palleschi, V.: Effect of plasma inhomogeneity on the determination of Strark broadening coefficients by Laser-Induced Breakdown Spectroscopy. J. Quant. Spectrosc. Radiat. Transf. **271**, 107714 (2021)

Panya Panya, S.N., Galmed, A.H., Maaza, M., Mothudi, B.M., Harith, M.A.: Laser-induced breakdown spectroscopy (LIBS) on geological materials: relative hardness estimation. Mater. Today Proc. **36**, 600–603 (2021)

Peng, J., Liu, F., Zhou, F., Song, K., Zhang, C., Ye, L., He, Y.: Challenging applications for multi-element analysis by laser-induced breakdown spectroscopy in agriculture: a review. TrAC Trends Anal. Chem. **85**, 260–272 (2016)

Rai, V.N., Zhang, H., Yueh, F.Y., Singh, J.P., Kumar, A.: Effect of steady magnetic field on laser-induced breakdown spectroscopy. Appl. Opt. **42**(18), 3662–3669 (2003)

Reeson, K., Yap, S.L., Koh, S.F., Nee, C.H., Tou, T.Y., Yap, S.S.: Effects of background gases and pressure in pulsed laser deposition of Al-doped ZnO. Thin Solid Films **701**, 137953 (2020)

Rühlmann, M., Büchele, D., Ostermann, M., Bald, I., Schmid, T.: Challenges in the quantification of nutrients in soils using laser-induced breakdown spectroscopy—a case study with calcium. Spectrochim. Acta Part B at. Spectrosc. **146**, 115–121 (2018)

Weng, J., Kashiwakura, S., Wagatsuma, K.: Effect of plasma gas and the pressure on spatially and temporally resolved images of copper emission lines in laser induced plasma optical emission spectrometry. Anal. Sci. **37**(2), 367–375 (2021)

Zhang, Y., Zhang, T., Li, H.: Application of laser-induced breakdown spectroscopy (LIBS) in environmental monitoring. Spectrochim. Acta Part B at. Spectrosc. **181**, 106218 (2021)