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Advances in Electronic and Photonic Technologies

Editors

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I. Lettrichova

ADept

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June 15 - 18, 2025

UNDER THE AUSPICES OF

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Introduction

The international conference on

ADVANCES IN ELECTRONIC AND PHOTONIC TECHNOLOGIES (ADEPT 2025)

is the 13th conference focused on the latest results of research and development in the area of novel materials, structures, devices and systems for micro/nano- electronics, sensors and photonic solutions. Its goal is to bring together leading experts with young generation of researchers from universities, as well as institutes interested in progress of advanced technologies.

The conference attracted young and senior scientists from Slovakia and other countries to submit 69 abstracts. In review process 64 papers have been accepted for publishing in conference proceedings as 63 contributed and 1 invited paper divided in 36 oral and 28 poster presentations. At this point, we would like to thank all reviewers for review activities and valuable comments.

The objective of ADEPT 2025 is to provide a forum for researchers, teachers and engineers involved in general areas of electronics, photonics and material engineering to disseminate their research results, exchange views on future research directions and to create partnership for further fruitful collaboration in specified fields. We believe that ADEPT will create this new space for scientist from field of electronics and photonics.

Editors

MICROWAVE ASSISTED LASER INDUCED PLASMA

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Abstract *Laser-induced breakdown spectroscopy (LIBS) is a promising "online" & "remote" analytical method for depth profile quantitative analysis of re-deposition and D/T fuel retention in the fusion devices first walls. In ps LIBS the plasma temperature is often around 0.5 eV which is insufficient for efficient excitation of H/D/T states. The proposed Microwave-assisted LIBS (MW-LIBS) enhances laser induced plasma by heating it with MW discharge, significantly improving spectral intensity. This study compares LIBS and MW-LIBS spectra generated at different Ar gas pressure. Obtained plasma lifetime was extended by a factor of 10 with plasma temperature ranging from 0.55 eV at lower pressure to 0.91 eV at atm. pressure.*

Keywords Laser induced breakdown spectroscopy, LIBS, Microwave-assisted LIBS,

1. INTRODUCTION

Microwave-assisted LIBS (MW-LIBS) is a LIBS enhancement technique in which microwave (MW) discharge is used as a secondary excitation source of the laser-induced plasma (LIP). The MW electric field accelerates free electrons in the plasma, leading to re-excitation and ionization of species through collisions [1]. This technique offers a relatively easy and effective solution for LIP re-excitation [2-4].

In nuclear fusion, the first wall (FW) of fusion reactor is exposed to the high heat fluxes, energetic neutral particles, neutrons and plasma radiation from hot fusion plasma. Fuel retention (mainly T) in the FW poses safety concerns, which requires constant monitoring on-site. LIBS is one of the techniques which is suitable for depth profile elemental analysis of all elements including low Z elements such as D/T and can be used "*in situ*" and "*remotely*" [5-6].

Lasers with shorter pulse duration (e.g. picosecond (ps) or femtosecond (fs)) are more advantageous for gas detection (e.g. He, D/T quantification) in material due to shorter ablation time and low heat-affected zones affected resulting in better depth resolution. However, ps-laser-generated plasma often exhibits lower plasma temperature T_e, insufficient for efficient excitation H/D/T atomic states. This study explores LIP re-excitation using MW-LIBS to address this limitation.

2. EXPERIMENTAL SET-UP

LIBS plasma was generated by laser ablation of Al alloy sample (at 45°) using Q-switched Nd:YAG laser (CFR200, Quantel, operating at 1064 nm, pulse duration 7 ns, energy 5 mJ/pulse). The sample was placed in the vacuum vessel under Ar gas flow, with measurements conducted at different gas pressure from 100 to 1000 mbar. The 45° ablation angle allowed placement of monopole MW antenna perpendicular to the laser beam (also at 45° to surface normal). A pulsed MW generator operating at 2.4 GHz (maximum power 38 W) was used, with MW signal passing through a coaxial circulator (redirecting reflected power to a 50 Ω load) and a 50 Ω impedance coaxial cable to the antenna [4].

The emitted optical signal was collected at 30° from the sample surface normal (15° from laser beam axis) , focused into an optical fibre (Thorlabs, 0.5 NA, 1000 µm core diameter) and transmitted to a broadband echelle spectrometer (ME5000, Andor Technology, aperture F/7, resolving power λ/Δλ= 4000, 200–975 nm) equipped with an iCCD camera (iStar DH734I-18F-03, Andor Technology). The LIBS and MW-LIBS spectra were recorded with the same gate width (5 µs), however MW-LIBS signal was observed much longer than in case of LIBS as discussed further. This configuration enabled precise control over laser ablation, MW enhancement, and spectral acquisition, supporting systematic studies of plasma dynamics at different gas pressure and delay time.

3. RESULTS AND DISCUSSION

When MW Ar plasma is ignited close to LIP, the two plasmas exhibit different parameters. At the onset of LIP, the high electron density shields MW, as the electron density decreases below the critical density, the MW discharge penetrates the LIP, enabling efficient re-heating and plasma expansion, which extends plasma lifetime and improves signal-to-noise ratio (S/N). In the studied aluminium sample, Fig. 1 presents the time-resolved emission of Al I line at 396.15 nm as a function of delay time in LIBS (black points) and MW-LIBS (red points) [4]. We observed that the same line intensity is obtained at 25 µs gate delay in LIBS and at 250 µs gate delay in MW-LIBS, indicating a 10-fold prolongation of plasma lifetime.

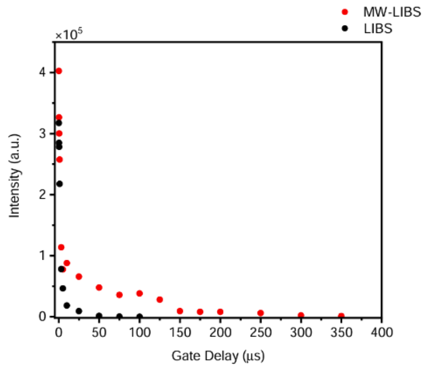

Fig. 1 Time-resolved emission of Al I lines at 396.15 nm generated by LIBS (black points) or MW-LIBS (red points) in Ar at 400 mbar pressure at gate width of 5µs.

LIBS and MW-LIBS spectra were recorded for various Ar gas pressure and longer delays for MW-LIBS. Key atomic lines of Al I, Mg I-II, Cu I, Si I were observed in both spectra (as shown in Fig. 2) and were the main elements of study. In MW-LIBS spectrum, due to the longer gate delay and gate width (5µ and 5µ), the atomic reassociation occurred and some molecular bonds such as AlO (transition $B^2\Sigma^+ \rightarrow X^2\Sigma^+$) and N_2 (transition $C^3\Pi_u \rightarrow B^3\Pi_g$) were observed in spectral range 483–513 nm and 331–338 nm, resp. - see Fig. 2. These molecular radicals likely resulted from air desorption in the vacuum vessel or minor system leaks.

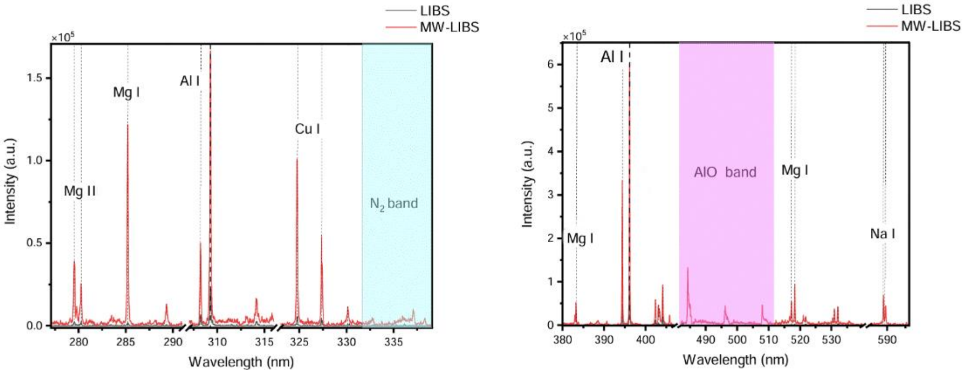

Fig. 2 LIBS and MW-LIBS spectra of Al alloy generated in Ar at 400 mbar pressure in two wavelength range 273-340 nm (left) and 380-596 nm (right). Gate delay and gate width was 5 μs for both LIBS and MW-LIBS. The atomic lines Al I, Mg I-II, Cu I, Si I, Na I and the molecular bands of AlO (transition $B^2\Sigma^+ \rightarrow X^2\Sigma^+$ between vibrational levels 0-0, 1-1 and 2-2) and second positive system of N_2 (transition $C^3\Pi_u \rightarrow B^3\Pi_g$ for 2-0 and 3-1) were observed. Figure was adopted from [4].

The interaction of MW with LIP at earlier stages is characterised as a transient phenomenon. Singal enhancements by MW is observed even when the electron density, calculated from Stark broadening, is on the order of 10^{15}-10^{16}cm^{-3}. While MW field cannot penetrate the high-density plasma core, it enhances re-excitation in lower-density regions, reducing self-absorption effect, longer plasma lifetime which leads to improved plasma uniformity, better S/N ratio, reduction of temperature and electron density gradients. This improves line intensity variations and precision, as a key factor for CF LIBS techniques.

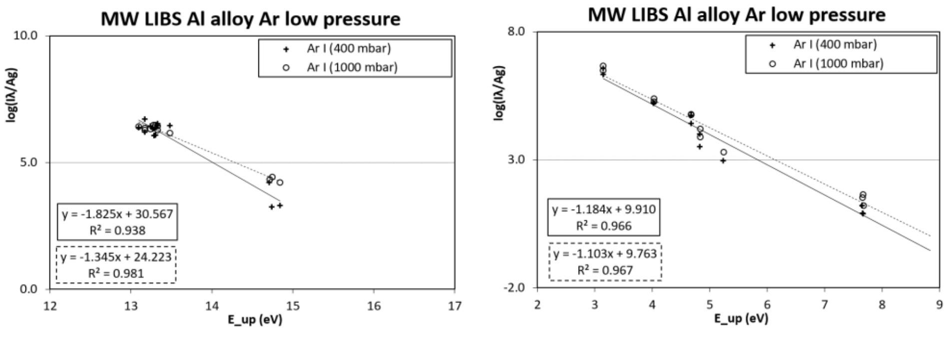

Fig. 3 Boltzmann plots constructed for Ar I (left) and Al I spectral lines (right) observed in MW-LIBS spectra at two different argon pressure: 400 mbar and 1000 mbar.

The plasma evaluation (T_e) in MW-LIBS was evaluated using Boltzmann plots (BP) of Ar I (left) and Al I lines (right)) (Fig. 3) at 400 mbar and 1000 mbar Ar pressure. Line intensities were derived from the sensitivity corrected spectra after background substruction using spectral parameters (transition probabilities, degeneracy, wavelength of the transition and upper-level energy) from databases [7-8].

The evaluated T_e values for MW-LIBS were:

- At 400 mbar: 0.85 eV (Al I) and 0.55 eV (Ar I).
- At 1-00 mbar and 0.91 eV (Al I) and 0.77 eV (Ar I).

The observed T_e is lower at 400 mbar than at 1000 mbar pressure and the difference between T_e obtained from Al I and from Ar I BPs decreases with increasing pressure. This is likely due to the early-stage transient effects, where the plasma is not yet in thermodynamical equilibrium, and MW Ar based plasma begins to penetrate the hotter LIP generated by Al species.

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