



Interplay between plasma luminescence and hydrodynamic effects in underwater LIBS at 0.1 – 50 MPa ambient pressure

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Underwater laser-induced breakdown spectroscopy (LIBS) enables remote in-situ material analysis for deep-sea exploration of mineral resources. Atomized excited analytes are produced by optical breakdown of the target material, and the time evolution of plasma luminescence and spectral emission are connected to the temperature history $T(t)$ and pressure history $P(t)$ in the laser-induced cavitation bubble.

Stroboscopic imaging of shock wave emission and bubble dynamics in bulk water produced by 8-ns, 1064-nm, 5-mJ laser pulses is combined with simultaneous time-gated ICCD imaging and continuous PMT-recording of the plasma luminescence. Analysis of line spectra from OH^* radicals yields $T(t)$ [1]. Hydrodynamic modeling based on measured plasma size, bubble oscillation times T_{osc1} and T_{osc2} and shock wave speed provides information on the breakdown pressure, $P(t)$ and on P_{collapse} [2, 3].

Breakdown pressure was ≈ 5 GPa for all ambient pressures p_∞ . Bubble oscillation time and size decreased from 200 μs to 1.1 μs and 1.1 mm to 112 μm at 0.1 and 50 MPa, respectively, while plasma luminescence and emission from spectral lines increases. Hence, deep-sea LIBS is well feasible. Collapse luminescence increased up to 7 MPa and then decreased. For $p_\infty \geq 25$ MPa, luminescence lasts during the full first oscillation, concentrated in the bubble center. The temperature 60 ns after breakdown was always 9700 K. For $p_\infty \geq 40$ MPa, $T(t)$ can be tracked during the entire bubble oscillation. At 50 MPa, we found $T \approx 4700$ K at R_{max} and ≈ 5500 K at collapse.

Remarkably, the bubble temperature at $t = 60$ ns is similar to the blackbody temperature of the breakdown plasma although electron density has then dropped by two orders of magnitude. The heat release by electron-ion and molecular recombination slows the temperature drop during the initial plasma expansion, when continuum emission ceases. The following bubble oscillation is \approx adiabatic during the fast expansion and collapse phases. At low p_∞ it has an isothermal phase around R_{max} , with bubble pressure equaling saturation vapor pressure at ambient temperature. At large p_∞ with short T_{osc} and small R_{max} , the \approx adiabatic phases merge and bubble temperature and pressure remain high at R_{max} . This buffers the collapse and lowers the collapse pressure and, hence, luminescence. However, the dynamics is not fully adiabatic. Thus, the bubble content is cooler near the walls and luminescence concentrates in its center.

References:

- [1] Y. Tian, H. Pan, C. Zhai, Z. Jia et al. , Plasma Sources Sci. Technol., 34, 025012,1-8 (2025)
- [2] X.-X. Liang, N. Linz, S. Freidank, G. Paltauf, A. Vogel , J. Fluid Mech., 940, A5, 1-56 (2022)
- [3] X.-X. Liang, A. Vogel , Preprint <https://arxiv.org/abs/2501.13749> (2025)