Supplementary Material to:

Combined enhancement of fiber-optic laser-induced breakdown spectroscopy coupling spatial confinement and double-pulse irradiation

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This document provides supplementary materials to our paper "Combined enhancement of fiber-optic laser-induced breakdown spectroscopy coupling spatial confinement and dual-pulse irradiation" which we wish to be considered for publication in **Journal of Analytical Atomic Spectrometry**.

Appendix 1 details the beam-splitting fiber used for simultaneously transmitting laser energy and returning plasma emissions. Appendix 2 provide evidence that the new shock wave, formed by the merging of the second-generation and primary shock waves, propagates faster than the primary shock wave.

Appendix 1: Description of the beam-splitting fiber

Figure S1 illustrates a schematic cross-section of the beam-splitting fiber. The large fiber core (800 microns) located at the center was used for transmitting high-power laser, while the ten small fiber cores (200 microns, high UV transmission efficiency) evenly distributed around it were used for returning plasma emissions. A group of plano-convex lenses focused the laser beam emitted from the large fiber core onto the sample surface to generate plasma, and the photons emitted by the plasma were collected in reverse by the ten small fiber cores in a common end. The other ends of nine small fiber cores were connected to a multi-channel grating spectrometer (AvaSpec-ULS2048-USB2-RM, 0.14-0.18 nm resolution, 180-1060 nm spectral range, 1200 lines/mm NC grating) for spectral calibration, while one small fiber core was connected to an echelle spectrometer (Aryelle Butterfly, 270-690 nm spectral range, 12500 resolution) for spectral diagnostics.

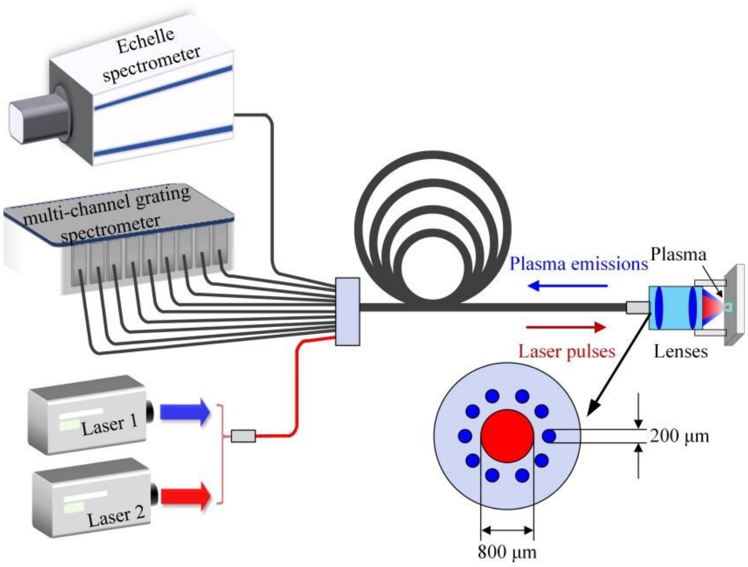

Fig. S1 Details of 1-to-11 beam-splitting optical fiber used in this work.

Appendix 2: The early propagation of shock waves and the positional changes before and after shock wave merging

Figure S2 illustrates the propagation of longitudinal shock waves 4.5 μs after the first pulse and lateral shock waves 2.0 μs after the first pulse, with a plate spacing of 4 mm and the introduction of the second pulse at various times, i.e., the locally magnified images in Fig. 5 of the main text.

When a spherical shock wave propagates forward and a secondary shock wave is generated within it, if the secondary spherical shock wave propagates faster than the primary shock wave, shock wave merging can occur once the secondary shock wave catches up with the primary shock wave.[1] Seen in Fig. S2, the propagation velocity of the merged shock wave was faster than that of the primary shock wave, since whether along the longitudinal or lateral propagation paths, the merged shock wave remained ahead of the primary shock wave. This is reasonable, based on Rankine-Hugoniot relations,[2] the merged shock wave combined the energy and momentum of the two shock waves, thereby enhancing its strength and propagation velocity.[3] As a result, The onset time of plasma plume compression by the merged shock wave, after being reflected by the plate, was slightly earlier than that of the primary shock wave.

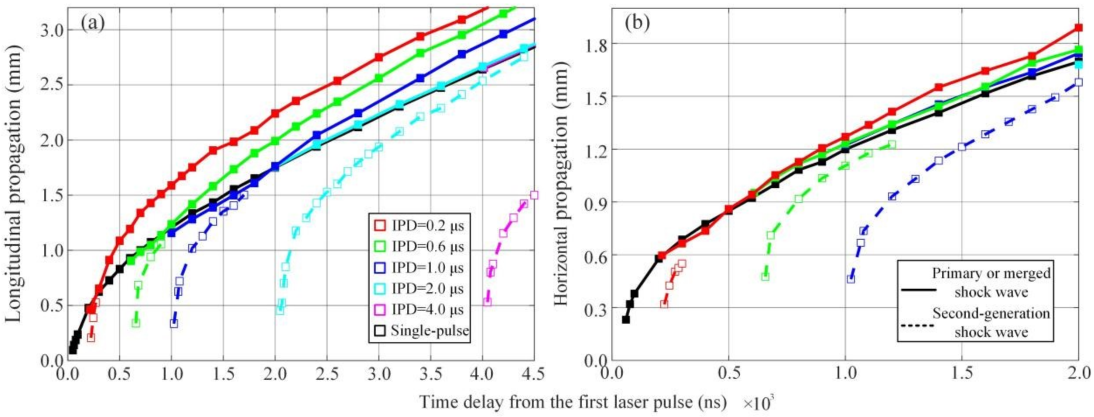

Fig. S2 Longitudinal (a) and horizontal (b) propagation of primary and merged shock waves (solid curves), and second-generation shock waves (dashed curves).

References

1 G. B. Whitham, Linear and Nonlinear Waves, Wiley-Interscience, 1974.

2 Y. C. Whang, Shock interactions in the outer heliosphere, Space Sci. Rev., 1991, 57, 339.

3 J. Yu, J. Hu, Y. Liu, Y. Liu, D. Gao, Y. Zhang, Numerical investigations of the interactions between bubble induced shock waves and particle based on OpenFOAM, J. Hydrodyn., 2024, 36, 355.