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Time- and space-resolved spectroscopic characterization of laser-induced swine muscle tissue plasma☆

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ABSTRACT

The spatial-temporal evolution of muscle tissue sample plasma induced by a high-power transversely excited atmospheric (TEA) CO_2 pulsed laser at vacuum conditions (0.1–0.01 Pa) has been investigated using high-resolution optical emission spectroscopy (OES) and imaging methods. The induced plasma shows mainly electronically excited neutral Na, K, C, Mg, H, Ca, N and O atoms, ionized C^+, C^{2+}, C^{3+}, Mg^+, Mg^{2+}, N^+, N^{2+}, Ca^+, O^+ and O^{2+} species and molecular band systems of CN($B^2\Sigma^+$–$X^2\Sigma^+$), C_2($d^3\Pi_g$–$a^3\Pi_u$), CH($B^2\Sigma^-$–$X^2\Pi$; $A^2\Delta$–$X^2\Pi$), NH($A^3\Pi$–$X^3\Sigma^-$), OH($A^2\Sigma^+$–$X^2\Sigma^+$), and CaOH($B^2\Sigma^+$–$X^2\Sigma^+$; $A^2\Pi$–$X^2\Sigma^+$). Time-resolved two-dimensional emission spectroscopy is used to study the expanded distribution of different species ejected during ablation. Spatial and temporal variations of different atoms and ionic excited species are reported. Plasma parameters such as electron density and temperature were measured from the spatio-temporal analysis of different species. Average velocities of some plasma species were estimated.

1. Introduction

Laser-produced plasmas (LPPs) are formed by focusing a high-power laser onto a sample. The induced plasma expands quickly and its characteristic parameters change with distance and time. Because of the transient characteristics of the plasma-plume, optical emission spectroscopy (OES) technique with time and space resolution is especially suitable to obtain information about the behavior of the produced species as well as to study the dynamics of the plasma expansion. Although OES gives only partial information about the plasma particles, this diagnostic technique helped us to draw a picture of the plasma in terms of the emitting chemical species, to evaluate its possible mechanisms of excitation and formation and to study the role of gas-phase reactions in the plasma expansion process. Measurements of the plasma density and temperatures are important to obtain information about plasma expansion dynamics. The plasma characteristics vary considerably with distance from the target surface both in the plume expansion direction (axial) and orthogonal to plume expansion directions (radial), as well as with time following the beginning of plasma-plume formation.

Currently there are numerous applications for LPPs in a wide variety of fields, including laser-induced breakdown spectroscopy (LIBS) [1–4], pulsed-laser deposition (PLD) [5,6], distinguishing of explosives [7–13], environmental science [14–16], production of classical and novel materials [17,18], cultural heritage monitoring [19] or space exploration [20–22]. Beyond traditional applications of LIBS, where inorganic materials are mainly studied for analytical purposes, recent progresses in LIBS lead to an analysis of organic and biological samples for detection of chemical and biological warfare agent materials [23–28], animal tissues studies [29–37], identification of bacteria [38–48], etc. Several reviews have been published that discuss various aspects of LIBS biomedical application [1–4,49,50]. Recent developments of LIBS for biological material analysis potentially provide fast sensor systems for pathogen biological agent detection and analysis.

Because of highly transient nature of the LPP, the plasma-plume properties should be optimized for each application and the plasma diagnostics play a key role in this regard. In particular, the estimation of the post-mortem interval (PMI) by LIBS using swine muscle has created interest due to its cost-effective analysis [50]. It can be expected that the determination of PMI can be improved by using high resolution OES.

This article reports the first spatial and temporal study the dynamics of the ablated swine tissue plasma-plume produced in vacuum. The plasma was generated by focusing a transversely excited atmospheric (TEA) CO_2 pulsed laser on the target placed in a vacuum chamber. We have studied the dynamics of laser ablated plasma expanding into vacuum using simultaneous imaging and spectroscopic techniques. Time-resolved spectra, that were also spatially resolved in one dimension

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along the axis of plasma expansion, were obtained using a time gated intensified charge-coupled device (ICCD). We discuss the dynamics of the plume expansion and formation of different atomic and ionic species for different positions and delay times with respect to the beginning of the laser pulse. Analysis of the image spectra provides useful plasma parameters such as velocities of different plasma species, electron density and temperature.

2. Experimental procedures

The schematic of the experimental setup is given in Fig. 1. Pulses from a TEA CO_2 laser (Lumonics K-103) emitting at 10.591 μm are used for producing plasmas on a skeletal muscle sample of a swine [51]. To ensure sample homogeneity, swine tissues were lyophilized and compressed into a pellet. The excitation wavelength was checked with a spectrum analyzer (Optical Eng. Co.). At the sample position, the laser delivered up to 3.16 J at 10.591 μm, leading to an estimated power of 49.5 MW, power density or intensity of 6.31 GW × cm^{-2}, fluence of 410 J × cm^{-2}, photon flux of 3.1 × 10^{29} photon × cm^{-2} × s^{-1}, electric field of 1.54 MV × cm^{-1} and radiation pressure of 421 kPa [51,52]. The primary laser beam (divergence of 3 mrad) was angularly defined and attenuated by an iris of 17.5 mm diameter before entering into the vacuum chamber. A beam splitter was employed to redirect about 10% of the laser pulse energy on a pyroelectric detector (Luminics 20D) or on a photon drag detector (Rofin Sinar 7415) for energy and temporal shape monitoring and triggering, respectively, through a digital oscilloscope (Tektronix TDS 540). The temporal profile of the laser pulse is 65 ns full width at half maximum (FWHM) followed by a tail lower than 2 μs controlled by changing the gas mixture flowing through the cavity (typically 8:8:84 mixture of CO_2:N_2:He). The laser-pulse energy was varied by using several CaF_2 attenuating plates.

The target is placed at the center of a vacuum chamber pumped using a turbomolecular pump, and a vacuum of 0.01 Pa has been achieved in all our experiments. The target was mounted on a rotating holder to diminish the effects produced by crater formation. The laser beam was focused on the target by a NaCl lens of 24 cm focal length being the measured focused-spot area ≈ 7.9 × 10^{-3} cm^2. The laser fluence was calculated as the ratio of the pulse energy (Lumonics 20D pyroelectric detector through a Tektronix TDS digital oscilloscope) and 1/*e* cross-sectional beam area (measured at the target position with a pyroelectric array Delta Development Mark IV). Two spectrometers were used: one with a resolution of ≈1 nm (portable BWTEK, 25 μm slit, 600 grooves × mm^{-1} grating) and the other with a resolution of ≈0.02 nm (ISA Jobin Yvon Spex HR320, adjustable width slit, 2400 grooves × mm^{-1} holographic grating). For performing time and space resolved OES, the plasma emission was collected and imaged onto the slit of the high-resolution spectrograph. We have set the origin of axial distance, $z = 0$ mm, as the target surface. In our setup target and focusing lens can be displaced across the beam axis. The intensity response of the detection system was calibrated with a standard halogen lamp (Osram number 4385, 6.6 A, 200 W) [53]. Several hollow-cathode lamps were used for wavelength calibration. A quartz Dove prism was inserted into the optical path for capturing two-dimensional (2D) spectral imaging and rotating the plasma image by 90°, projecting the direction of the plasma expansion (Z-axis) onto the entrance slit. The Dove prism is placed between two crystal lenses with focal distances of 80 mm (L1) and 40 mm (L2). The magnification of the final image formed by the optical system was found to be 1:0.5. The 2D spectral images were recorded by a gateable ICCD (Andor iStar DH-734, 1024 × 1024 pixels, 13 μm pixels). For time-resolved measurements, the ICCD detector is synchronized with the trigger of the laser pulse. The 2D spectral imaging studies were performed by operating the ICCD in the imaging mode. Each spectrum corresponds to an accumulation of 10 laser pulses.

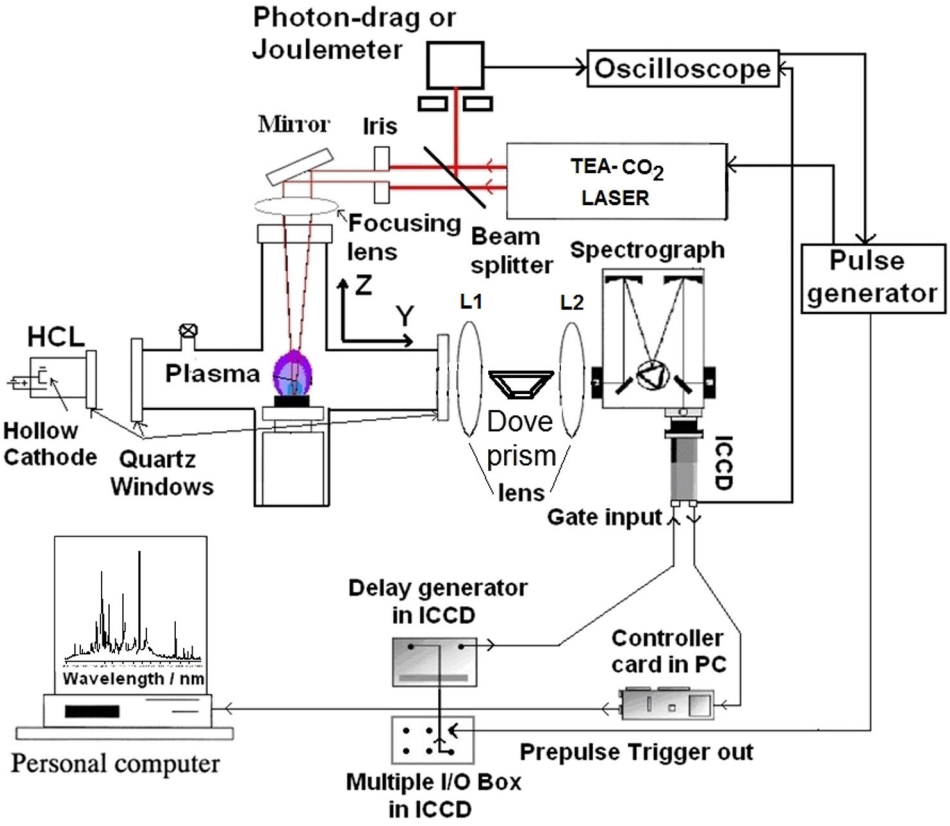

Fig. 1. Schematic of the experimental setup.