TẠP CHÍ KHOA HỌC VÀ CÔNG NGHỆ ĐẠI HỌC DUY TÂN
DTU Journal of Science and Technology 02(69) (2025) 50-54

ĐẠI HỌC DUY TÂN
DUYTAN UNIVERSITY

Early-stage observation of nanosecond laser-induced breakdown in air

Quan sát giai đoạn ban đầu của quá trình đánh thủng bằng tia laser trong không khí

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(Date of receiving article: 19/09/2024, date of completion of review: 02/10/2024, date of acceptance for posting: 08/10/2024)

Abstract

We focused a nanosecond laser pulse in normal air and observed the expansion of laser-induced plasma and shock waves during the pulse. Our observation revealed that most of the laser energy was not absorbed in the focal region but at the tip of the breakdown zone. As the breakdown occurred, the plasma expanded more rapidly vertically than horizontally, resulting in an inverted water-drop shape at the end of the laser pulse. Compared to a breakdown in water, the plasma in the air grew faster.

Keywords: Laser-induced breakdown in air; early-stage expansion; laser-supported absorption wave.

Tóm tắt

Chúng tôi hội tụ một chùm tia laser nano giây trong không khí và quan sát sự giãn nở của plasma và sóng xung kích trong khoảng thời gian độ dài của xung. Chúng tôi thấy rằng phần lớn năng lượng laser không được hấp thụ tại mặt phẳng tiêu điểm của chùm tia mà tại đỉnh của vùng đánh thủng. Trong suốt quá trình đánh thủng, plasma phát triển nhanh hơn theo phương đứng so với phương ngang, và có hình dạng giọt nước ngược vào thời điểm kết thúc xung laser. So với quá trình đánh thủng trong nước, plasma trong không khí phát triển nhanh hơn.

Từ khóa: Đánh thủng không khí bằng tia laser; quá trình giãn nở sớm; sóng hấp thụ hỗ trợ bởi laser.

1. Introduction

Air is transparent to light. However, when tightly focusing a laser beam in ambient air, the intensity at the focal region can be extremely high, reaching the level of $TW cm^{-2}$. This high optical intensity generates seed electrons through the multiphoton ionization process at the front of the laser pulse [1,2]. These initial electrons then absorb the rest of the laser pulse energy and create a plasma, following by a rapid expansion of shockwave from the energy release point [3]. This whole process is known as laser-induced breakdown.

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Laser-induced breakdown in air has many applications, including laser propulsion, laser ignition of combustible gas, laser-induced nuclear fusion and laser-induced breakdown spectroscopy [1,4,5]. Laser-induced breakdown in air can also be a severe problem in laser machining since it significantly reduces the amount of energy reaching the target and affects the machining efficiency and accuracy. Thus, it is important to understand the mechanism of laser-induced breakdown in air, especially during the early stage.

In this paper, we present a direct observation of the early expansion of the laser-induced breakdown zone from the beginning of laser pulse until $100\,ns$ after irradiation. The observation was made using time-resolved shadowgraph imaging technique. We also compared the laser-induced breakdown in air and underwater.

2. Experimental set up

We used a Q-switched Nd:YAG laser to deliver a laser pulse at the fundamental wavelength of $\mathbf{1064\,nm}$ (pump laser). The pulse full width duration is $\mathbf{40\,ns}$. The beam is focused by a 5x objective lens in the air to induce the breakdown. Pulse energy was $\mathbf{60\,mJ}$, equivalent to an intensity of $\mathbf{0.5 \times 10^{12}\,Wcm^{-2}}$ at the focal plane.

The laser-induced breakdown was observed using a conventional pump-and-probe imaging technique. We used another laser source to provide the illumination beam at a wavelength of $\mathbf{532\,nm}$ (probe laser). We regulated the delay time between the pump laser and the probe laser using an optical delay system or a delay generator. The image was captured using an ICCD camera (Fig.1). Details of the imaging system can be found in our previous report [6].

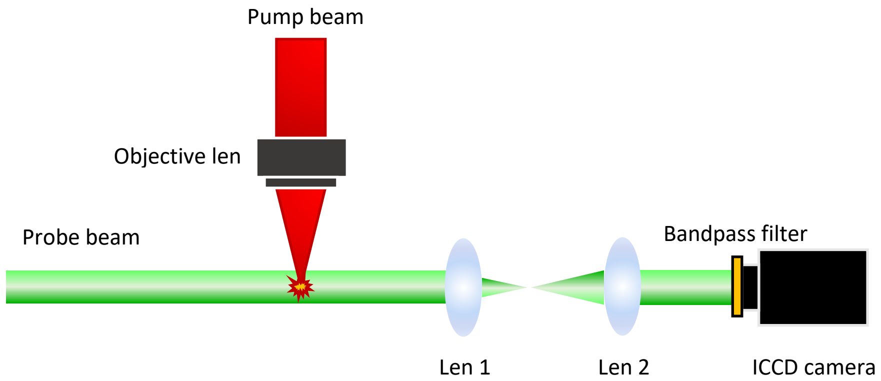

Figure 1. Diagram of the imaging system.

3. Results and discussion

Figure 2 shows the evolution of breakdown in normal air from the beginning of the laser pulse until $100\,ns$ after irradiation. At the beginning of the laser pulse, the breakdown occurred at the best focus position. Because the plasma induced at the breakdown deflects light, it appeared as a tiny shadow in the image. This initial plasma has a length of $0.2\,mm$, approximately the system's depth-of-focal.

During the laser pulse, the initial breakdown zone rapidly expanded towards the laser beam and reached a size of $1.2\,mm$ at $40\,ns$ (end of laser pulse). The rapid expansion of plasma generated a shock wave in the air. When the laser pulse was turned off, the shock wave continued propagating in the air while the plasma cooled down and became transparent. However, the induced shockwave was still visible, manifesting itself as a thin wave in the image. The induced shockwave continued to propagate in the air and reached a size of $2\,mm$ in the vertical direction at $100\,ns$.

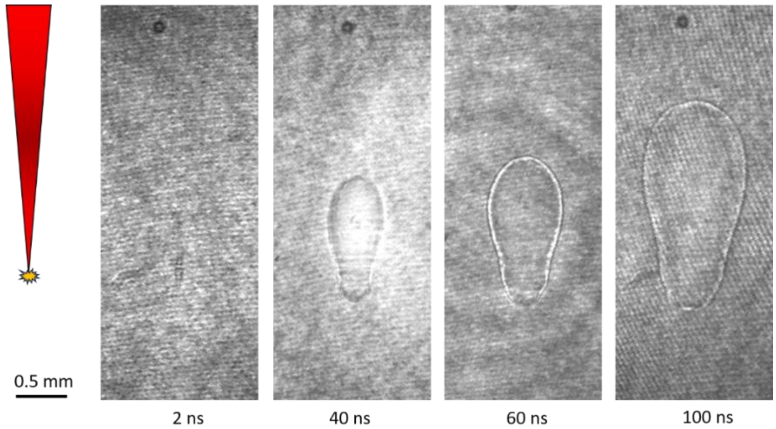

Figure 2. Early-stage expansion of nanosecond-laser-induced breakdown in air.

Our observation showed that the plasma expanded more rapidly in the vertical direction than in the horizontal direction during the laser pulse. Within the pulse, the average growing velocity of the breakdown zone was estimated to be approximately $2.5 \times 10^4\ ms^{-1}$ vertically and $1.3 \times 10^4\ ms^{-1}$ horrizontally. The high pressure of ionized gas caused the plasma to expand. Additionally, the vertical expansion was also supported by the coming laser, leading to a rapid growth of the plasma toward the laser source.

In Fig. 3, with appropriate adjustments to the imaging system, we were able to capture the plasma and shock wave simultaneously. The image showed that the brightest region of plasma was not observed at the focal plane, but slightly above it. It is commonly believed that the focal point is located at the center of the observed plasma. However, our observation indicates that the focal plane is actually at the lower end of the plasma zone, and the energy absorption point moves upward during the energy deposition process.

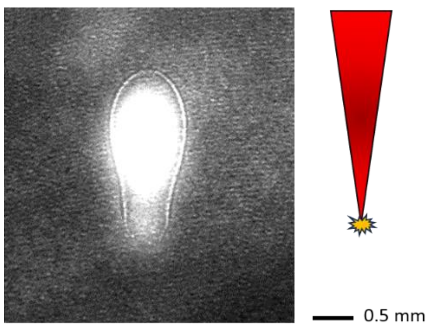

Figure 3. Plasma observed at 50 ns delay time.

The growth of plasma vertically during the laser pulse is known as the laser-supported absorption wave (LSAW), which has qualitatively different features at different ablation conditions: laser breakdown wave, fast ionization wave, laser-supported radiation wave, laser-supported detonation, and laser-supported combustion wave [4,7,8]. Since the intensity at focal point in our experiment exceeded the breakdown threshold in air ($10^{10} W cm^{-2}$) [4,9], the laser breakdown wave primarily occurred in the focal region. The electron density here rapidly approached the critical value, preventing further energy absorption in the focal region.

However, the initial plasma acted as a radiation source that ionized the air to create free electrons, which continue to absorb the coming laser. Through this mechanism, the plasma grew vertically toward the laser source during the laser pulse, with most of the laser energy being absorbed in a thin layer at the tip of the growing plasma. Consequently, the plasma formed an inverse water-drop shape, larger at the tip, as observed in our image.

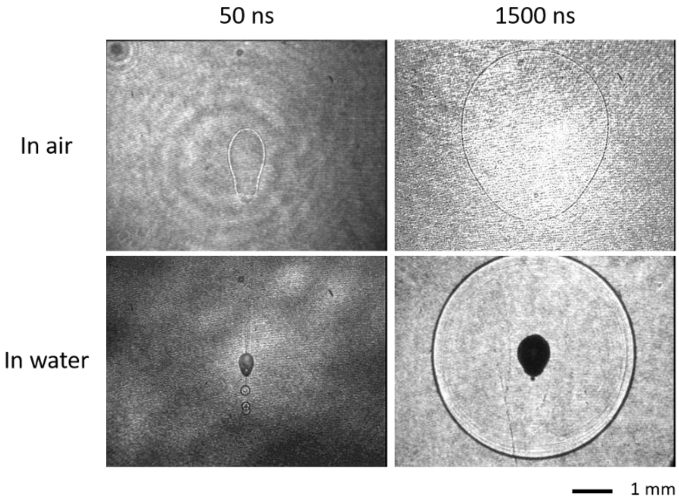

Figure 4. A comparison of laser-induced breakdown in air and in water.

This observation is consistent with previous observation of laser-induced breakdown in water, where the laser energy initially generates the plasma at the focal point, which continues to expand throughout the rest of the laser pulse and moves toward the laser source [10,11]. In Fig. 4, we compared the laser-induced breakdown in water and in air at delays time $50\,ns$ and $1500\,ns$ after the energy release. Because of the water's confinement effect on the expansion of plasma, the breakdown zone in air developed faster than in water during the laser pulse, resulting in a larger size observed at $50\,ns$. However, the induced shock wave propagated much faster in water than in air, as being observed at $1500\,n$s. The plasma in the air died after a few hundreds of nanoseconds and was not visible at late delay time. In contrast, the plasma in water instituted a cavitation bubble, which appeared as the dark area at the center of the shock wave.

The observation of laser-induced breakdown has been the subject of extensive researches, with primary focus on the process during the later stages. Our work provides a direct visualization of the initial expansion of laser-induced breakdown. Our results enhance the understanding of the growth mechanism of nanosecond laser-induced plasma in air and are beneficial for optimizing associated processes.

4. Conclusions

We conducted a study on the laser-induced breakdown zone from the beginning of laser pulse to a hundred nanoseconds after irradiation. This work provides a direct observation of the plasma growth during the energy deposition process. Initially, the laser induces a breakdown at the focal plane, which then expands toward the laser source at a velocity in the order of $10^4\ ms^{-1}$ during the laser pulse. The majority of the laser energy is absorbed in a thin layer at the tip of the growing plasma, resulting in the breakdown zone taking on an inverse water-drop shape. The brightest region of plasma is not observed at the focal plane, but slightly above it.

Acknowledgment

The results presented in this paper are based on the experiments conducted at the Laser Laboratory, Nagaoka University of Technology, Japan. We appreciate the support from Emeritus Prof. Yoshiro Ito from the Nagaoka University of Technology, and Associate Prof. Tanabe from the Fukuoka Institute of Technology.

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