

## LASER GENERATED PLASMA FOLLOWED BY SHOCKS AND INCREASING CAVITATION BUBBLE IN A MINI-GLASS TUBE

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### Abstract

There have been tried many types of micro-capillaries, square or round and with different sizes of inner diameter. In which a cavitation bubble was created. The purpose of these experiments was to observe the velocity of the shock wave just after the initial cavitation bubble the rebound ones inside the micro-capillary and outside the micro-capillary. The most of the method was spark to induced superheat limit of liquid. Here we used the laser-induced breakdown (LIB) method. There were described the set cavitation setting that affects the stability and size of the bubble. We used here shadowgraphy setup for visualized the cavitation bubbles and shock wave with a camera. There were observed time development of the shock wave velocity; the velocity of the initial shock wave inside the micro-capillary was higher than the shock velocity outside the micro-capillary.

### Keywords

Shockwave; Cavitation; Explosion bubble; Laser-induced breakdown (LIB).

### Introduction

Cavitation can be defined as a collection of effects connected to the origin, activities and collapse of macroscopic bubbles in liquid. In nature and in real applications cavitation bubbles usually create a cloud, nevertheless, bubbles are not separated. The bubbles create structures which act collectively, however the essential elements of these structures are the individual bubbles. The cavitation phenomena have a great potential to be utilized in the industry, medicine, biology, pharmacy, or tissue engineering [3-4].

The research in the field of cavitation previously focused mainly on the investigation of bubble behavior in the vicinity of rigid or flexible boundaries and the bubble behavior in various liquids; [1-2] however, the current investigations also require the description of the shock waves to be included. The definition of the shock waves response can help in development of new, more resistant structures or layers. The key in understanding of cavitation shock waves interaction with various materials is investigation of impact of an individual shock wave inside a micro-cappillary.

We are still not able to produce a single controllable bubble according to the cavitation definition, by pressure decrease in the liquid volume even though the current state of technology is at a very high level [1-3]. Most methods, such as spark or laser generated bubbles, are based on evaporation of a small volume of liquid, which is closer to the boiling. Another method closer to the cavitation definition is the bubbles generated by the ultrasonic field, but in this case it is almost impossible to produce a single bubble. In any case, we use the technique of laser-induced breakdown (LIB), where is still a lack of information in the experimental part of the bubble cavity investigation [1-2].

LIB is a convenient method for generating a single cavitation bubble that can be very accurately geometrically positioned in a volume of liquid and inside a glass tube [6-10]. The LIB method, using ultrashort pulses of millijoules energy, enables to generate a cavitation bubble. This method also generates natural plasma, as in thermal breakdown. Moreover, if the pulse exposure is from microseconds to femtoseconds, the plasma is in the form of optical breakdown. Multi-photon and cascade ionization occur directly during the LIB. Furthermore, impurities of the medium, spot size, light wavelength and the pulse width during the breakdown play important role. Kennedy [6] explains the entire mechanism of ionization in more detail.

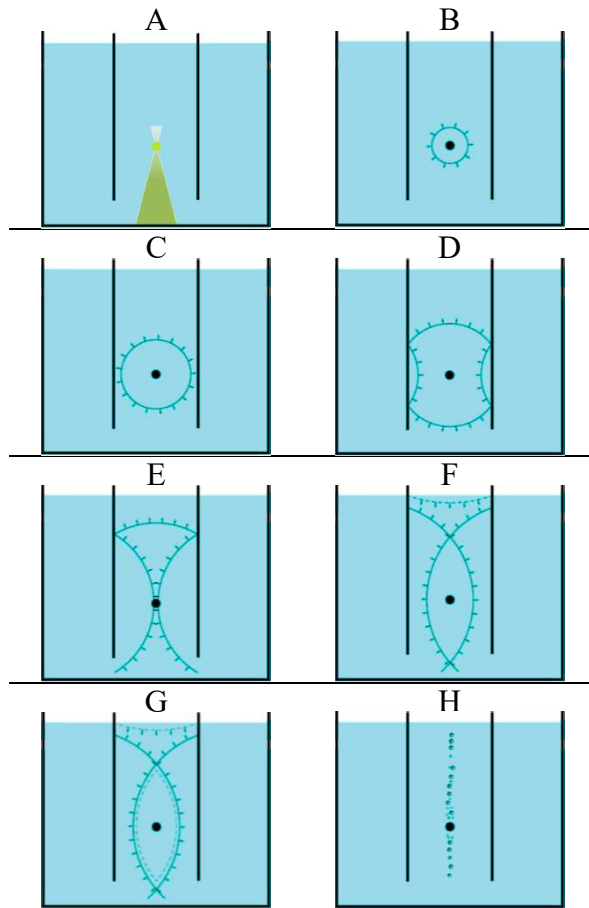
Propagation of shock waves in complex media is one of the most important topics of current shock wave research. Investigation of shock wave emission in distilled water during the first bubble collapse. Shock waves generated by LIB in a glass tube filled with water are investigated experimentally.

## **1 Experimental**

The experiment contains two lasers, a camera and a function generator. One laser serves to generate plasma, shock waves and cavitation bubbles in the liquid by means of the laser-induced breakdown the method. The second laser is double-pulse and is used to illuminate the glass tube in a cuvette for camera to take photos. The function generator serves time synchronization between the lasers and the camera.

### **1.1 Shock Waves in a Micro-Capillary**

Shock waves propagation in the micro-capillary is seen in Fig.1. Frame (A) shows laser induced plasma in focal point that leads to a shock wave. In frame (B) shock wave induces a cavitation bubble. Frame (D) shows reflection from capillary walls. In frame (F) mutual interaction of shock waves is seen. In (G) there is rarefaction wave at cross-section. And in the last frame evolution of gas bubbles is seen [13-14].



*Fig. 1: Propagation of shock wave in a micro-capillary*

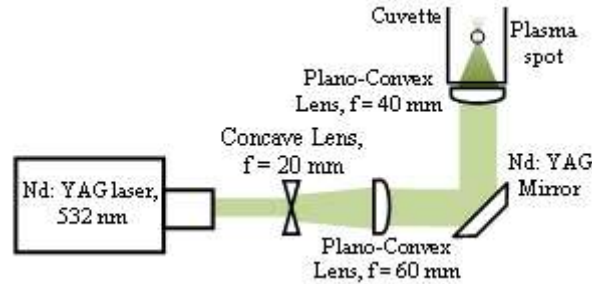
## 1.2 Laser Induced Breakdown

Focusing the laser light through suitably designed optics is the most often produced optical breakdown in the liquid. Kennedy [7] described in detail the laser induced breakdown in aqueous media and its collateral effects. In addition, Vogel in [11] and [12] described the energy distribution during the growth and collapse of a laser induced bubble.

In our case we used a short pulse ( $t = 6$  ns) high power laser ( $\lambda = 532$  nm). The 6 ns short laser pulse was generated using the Q-switched Nd: YAG New Wave Solo III PIV pulse laser. This laser worked with one cavity for single shot generation on the wavelength of 532 nm. The Q-switch signal synchronized the camera running in a triggering mode with laser.

### 1.3 Optical Setup

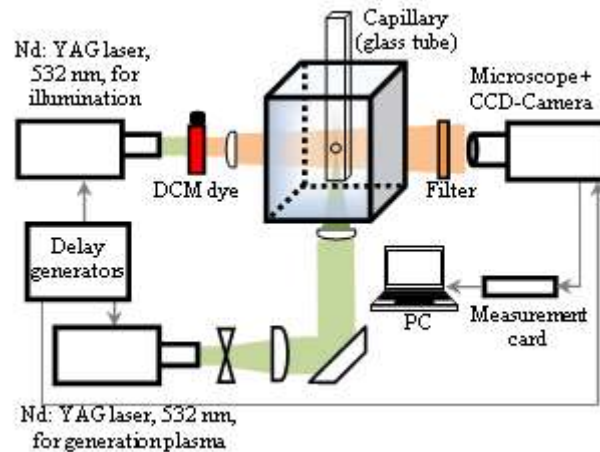
Laser-induced breakdown (LIB) was set as an optical direct way and is seen in Fig. 2. The outlet diameter of the laser beam was 5 mm with Gaussian characteristics of the intensity. This arrangement was followed by a concave lens  $f_s = 20$  mm and two plano-convex lenses  $f_s = 60$  mm and  $f_s = 40$  mm of 1 inch diameter. The focused laser beam created the laser point – probe (diameter  $< 0.1$  mm).



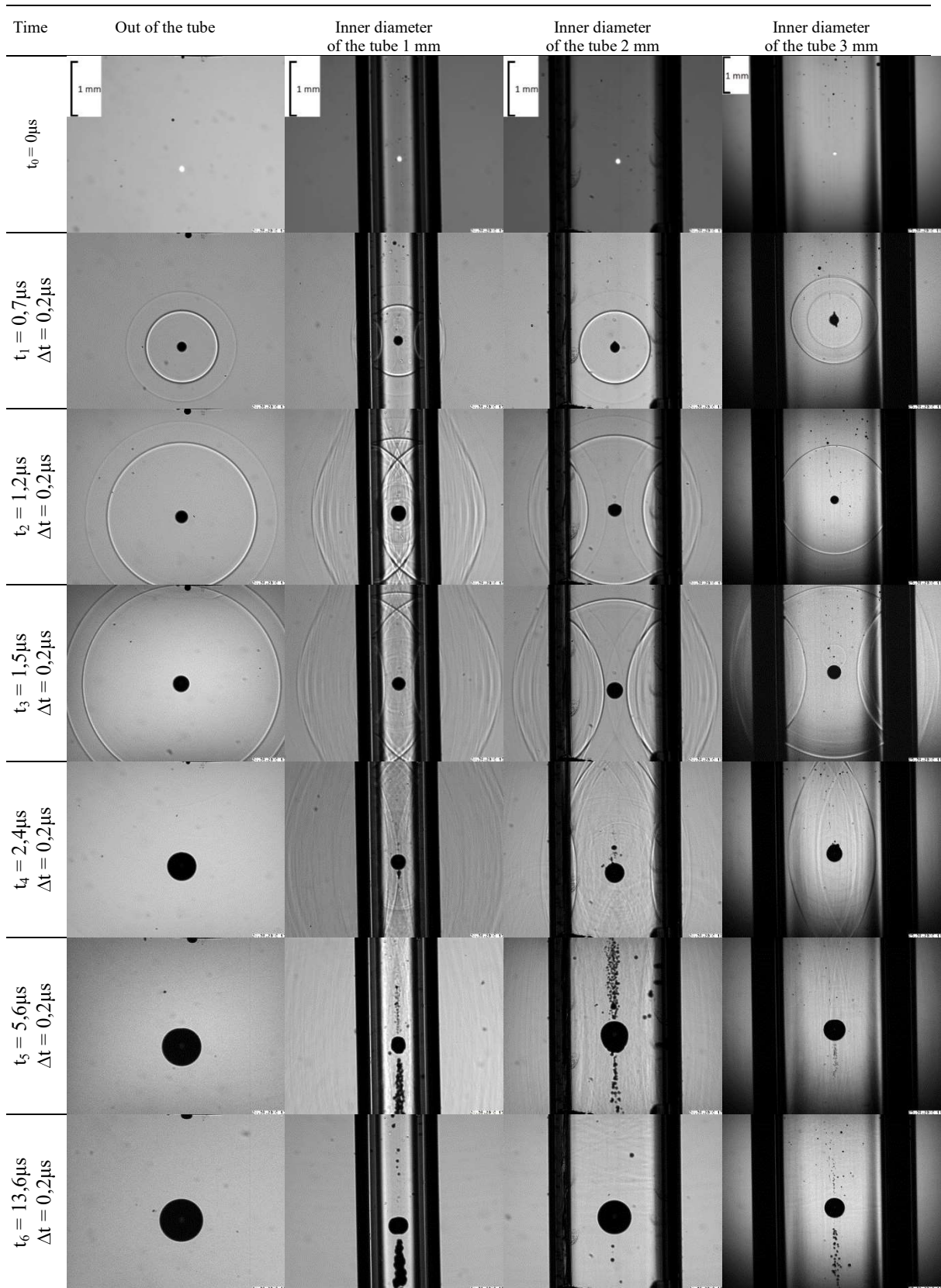
**Fig. 2:** The optical setup of LIB technique

### 1.4 Visualization Setup

Here we used a shadowgraphy setup (Fig. 3) for the shock waves visualization. This setup consists of a Nd: YAG INNOLAS pulse laser, set with DCM dye and optical filter. Opposite to the illumination laser a source CCD camera IMAGER with a microscope was placed. This camera was working in a triggering mode with a resolution of (640 x 480) pixels, and the dynamic range of 12 bit. The camera exposure time was twice 100 ns with a 100 ns time break.



**Fig. 3:** The experimental setup of the visualization system



**Fig. 4:** Evolution of the shock waves in a micro-capillary

## 2 Results

There is the plasma generated in the spot due the concentration of the laser energy and the plasma is visible due the emission. The pressure in liquid increase to 103 bar, and temperature

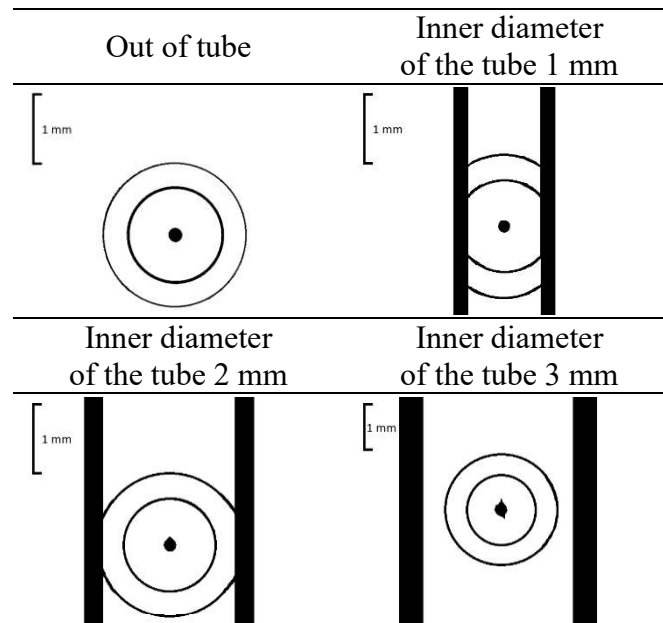
to 103 K in the spot volume. This leads to plasma expansion at supersonic velocities, producing an acoustic shock wave followed by cavitation bubble effect. It is important to mark for the figure 4 that the laser light comes from the bottom side in the pictures.

Figure 4 presents a selected part of a series of images which has an internal frame time of 200 ns and an exposure time of two times of 6 ns. The bubbles have been generated with laser energy of 5.6 mJ. The first frames in the time of  $t_0$  show the position of the optical breakdown. The last frames in the time of  $t_6$  show the enlargement of the cavitation bubble, which is very close to maximum, and the frames between them show the evolution of shock wave inside the micro-capillary and outside the micro-capillary.

The frames in time  $t_1$  show the generated bubble and its shock wave. This shock wave is captured in time 700 ns after the optical breakdown and in the same frame we can see the same shock wave for another 200 ns. The image at time  $t_2$  represents the shock wave progress in additional after 500 ns. In the frames in the  $t_3 - t_4$  time, it can be seen that the shock waves are reflected from the inner wall and move towards the bubble. Shock wave reflections occur later at the tube with a larger inner diameter. Moreover, in the smaller tube there is higher pressure. After the reflection of the shock waves from the wall of tube hits the bubble and gradually come into contact with each other, complex wave structures occur. After reflection of the colliding shock waves, first vapor bubbles become visible in the frame with tube in time  $t_4$ , then increase in number and diameter in frame with tube in time  $t_5 - t_6$ .

Figure 4 in the frame in the time  $t_1$  also shows the velocity of shock wave in the tube and outside of the tube, because we know the time and the sub-pixel resolution. The velocity of the shock wave is seen in Table 1, where we can see that velocity of the initial shock wave inside the micro-capillary was higher than the shock velocity outside the micro-capillary. Also the shock velocity as a function of time depends on the tube diameter as well the 'bubble leakage' after some microseconds.

Figure 5 shows the original pictures transformed to binary for calculation of the magnitude of the velocity of shock wave and the size of the bubble volume.

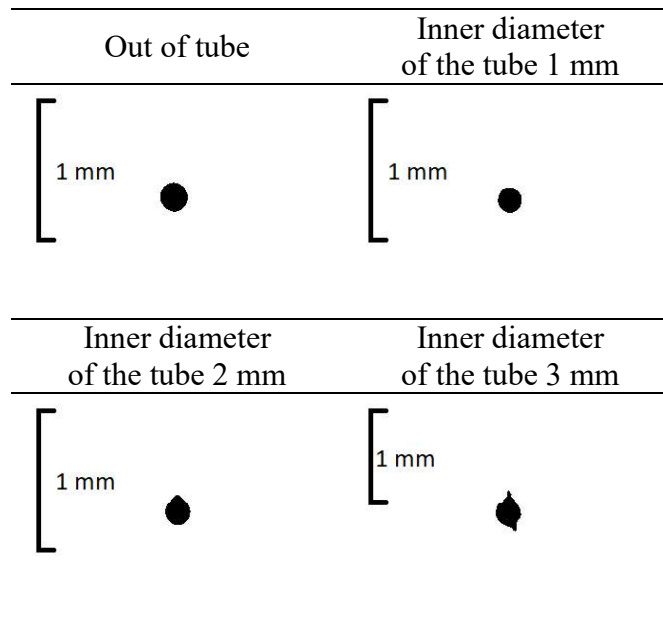


**Fig. 5:** Original pictures (from time  $t_1$ ) transformed to binary.

Unfortunately, after transforming the original image to binary, the shock waves reflected from the inner wall of the tube cannot be seen. But for measurement of velocity of shock wave this

is very convenient. The velocity of the shock wave can seem the same, but the velocity is different, and it even depends on the diameter of the tube.

Figure 6 shows modified binary pictures. In these pictures tubes and shock waves for volume calculation are removed.



**Fig. 6:** Binary pictures (from time  $t_1$ ) for volume calculation.

## Conclusions

The visualization of cavitation bubbles and shock wave is very important and useful tool in study of cavitation process. Here we use several types of tubes where we compare the behavior and velocity of the shock wave. Velocity of propagation of shock wave in the cuvette filled with water corresponds to the speed of sound in liquids, i.e. 1500 m/s. But the velocity of shock wave in the micro-capillary is higher. It is because of pressure increase at a smaller spot, and also that shock velocity is a function of time and depends on tube diameter as well as on 'bubble leak' after several microseconds. The volume in table 1 was obtained by calculating the pixel area of captured image in Figure 6 by the approximation of the sphere.

**Tab. 1:** Velocity of shock wave.

Images in the time $t_1$	Out of the tube	1 mm tube	2 mm tube	3 mm tube
Sub-pixel resolution	1 mm = 150 px	1 mm = 150 px	1 mm = 150 px	1 mm = 100 px
Velocity of shock wave [m/s]	$1500 \pm 67$	$1600 \pm 67$	$1667 \pm 67$	$2000 \pm 100$
Time [s]	$2 \cdot 10^{-7}$	$2 \cdot 10^{-7}$	$2 \cdot 10^{-7}$	$2 \cdot 10^{-7}$
Distance [m]	$3 \cdot 10^{-6}$	$3,2 \cdot 10^{-6}$	$3,3 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
Volume of bubble [mm <sup>3</sup> ]	0,015	0,014	0,015	0,016

However, in spite of these results in Figure 4, it is not yet clear whether the vapor bubbles emerge due to the pressure reduction on the vertical axis from the evaporation in the liquid or from the leakage of the cavitation bubble. Therefore, there will be a great interest in more detailed research with the use of a high-speed camera.



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## LASEROVĚ VYGENEROVANÁ PLASMA NÁSLEDOVANÁ RÁZY A ZVÝŠENOU KAVITAČNÍ BUBLINOU V MIKROKAPILÁŘE

Bylo testováno mnoho typů mikrokapilár, čtvercových, kulatých a různých velikostí vnitřního průměru, ve kterých byla vytvořena kavitační bublina. Účelem těchto experimentů bylo sledovat rychlost rázové vlny těsně po počáteční kavitační bublině a odrazové vlny uvnitř i vně mikrokapilár. Hlavní metodou byla jiskra indukovaného limitu přehřátí kapaliny. Zde jsme použili metodu rozbití indukovanou laserem (LIB). Bylo popsáno nastavení kavitace, které ovlivňuje stabilitu a velikost bubliny. Pro snímání bublinek kavitace a rázové vlny jsme použili radiografické nastavení s kamerou. Byl pozorován časový vývoj rychlosti rázové vlny; rychlost počáteční rázové vlny uvnitř mikrokapiláry byla vyšší než rychlost rázu mimo mikrokapiláru.

## LASERGENERIERTES PLASMA, GEFOLGT VON STÖSSEN UND EINER ERHÖHTEN KAVITATIONSBLASE IN EINER MIKROKAPILLARE

Es wurden viele Typen von Mikrokapillaren getestet, quadratische, runde und verschiedene Größen des inneren Durchschnitts, in welchen eine Kavitationsblase gebildet wurde. Der Zweck dieser Experimente bestand in der Beobachtung der Geschwindigkeit der Stoßwelle gleich nach der anfänglichen Kavitationsblase und der Abprallwelle innerhalb und außerhalb der Mikrokapillare. Die Hauptmethode bestand im Funken des induzierten Limits der Überhitzung der Flüssigkeit. Hier haben wir die mit dem Laser induzierte Methode des Zerschlagens (LIB) angewendet. Es wurde die Einstellung der Kavitation beschrieben, welche die Stabilität und die Größe der Blase beeinflusst. Für die Abnahme der Kavitationsblase und der Stoßwelle haben wir eine radiografische Einstellung mit der Kamera benutzt. Es wurde die zeitliche Entwicklung der Geschwindigkeit der Stoßwelle beobachtet; die Geschwindigkeit der anfänglichen Stoßwelle innerhalb der Mikrokapillare war höher als die Geschwindigkeit des Stoßes außerhalb der Mikrokapillare.

## LASEREM WYGENEROWANA PLAZMA POCIĄGAJĄCA ZA SOBĄ FALE UDERZENIOWE I ZWIĘKSZONY PĘCHERZYK KAWITACYJNY W MIKROKAPILARZE

Testowi poddano wiele rodzajów mikrokapilar, kwadratowych, okrągłych i o różnych wielkościach wewnętrznej średnicy, w których powstał pęcherzyk kawitacyjny. Doświadczenia te miały na celu zbadanie prędkości fali uderzeniowej powstającej tuż po początkowym pęcherzyku kawitacyjnym oraz odbicia fali wewnątrz i na zewnątrz mikrokapilary. Główną zastosowaną metodą było wywołanie indukowanej granicy przegrzania cieczy. W tym przypadku zastosowaliśmy metodę rozbitia indukowaną laserem (LIB). Opisano charakterystykę kawitacji, wpływającą na stabilność i wielkość pęcherzyka. Do badania pęcherzyków kawitacyjnych i fali uderzeniowej zastosowaliśmy radiografię z kamerą. Obserwowano kształtowanie się szybkości fali uderzeniowej w czasie. Prędkość początkowej fali uderzeniowej wewnątrz mikrokapilary była większa od prędkości uderzenia poza mikrokapilarą.