Highly extended high density filaments in tight focusing geometry in water: from femtoseconds to microseconds

F V Potemkin, E I Mareev, A A Podshivalov and V M Gordienko
Faculty of Physics and International Laser Center M V Lomonosov Moscow State University, Leninskiye Gory, bld.1/62, 119991, Moscow, Russia
E-mail: potemkin@physics.msu.ru

Keywords: femtosecond filament, laser-induced shock waves, aberrations, linear absorption, laser-induced cavitation

Abstract
We report a new regime of filamentation in water in tight focusing geometry, very similar to the so-called superfilamentation seen in air. In this regime there is no observable conical emission and multiple small-scale filaments, but instead a single continuous plasma channel is formed. To achieve this specific regime the principal requirement is the usage of tight focusing and supercritical power of laser radiation. Together they guarantee extremely high intensity in the microvolume in water ($\sim 10^{14}$ W cm$^{-2}$) and clamp the energy in the ultra-thin (approximately several microns) channel with a uniform plasma density distribution in it. Each point of the 'superfilament' becomes a center of spherical shock wave generation. The overlapped shock waves transform into one cylindrical shock wave. At low energies, a single spherical shock wave is generated from the laser beam waist, and its radius tends toward saturation as energy increases. At higher energies, a long stable contrast cylindrical shock wave is generated, whose length increases logarithmically with laser pulse energy. The linear absorption decreases the incoming energy delivered to the focal spot, which dramatically complicates the filament formation, especially in the case of loose focusing. Aberrations added to the optical scheme lead to multiple dotted plasma sources for shock wave formation, spaced along the axis of pulse propagation. Increasing the laser energy launches the filaments at each of the dots, whose overlapping leads to enhancing the length of the whole filament and therefore the shock impact on the material.

Introduction
Various post-effects induced by the optical breakdown in different liquids (shock waves and cavitation bubbles [1]), transparent solids (shock waves, micromodifications, phonon generation [2, 3]) and gases (thermodiffusion and shock waves [4]) have been of keen interest for the past few decades [1, 5–7]. Shock waves induced by femtosecond laser can achieve pressures with TPa values in solids and GPa—in liquids [8, 9]. Such high pressure enables a set of applications including hypervelocity launchers [9], synthesis of new materials [6], high-temperature and high-pressure plasma fields production [10], three-dimensional microfluidic chips fabrication [11], ion separation, new unusual phase transition [12], chemical reaction control [13], and a variety of medical therapies, such as mechanical optical cleaning [1]. In some areas it may be interesting to control the shape and energy of a laser-driven shock wave. For example, an array of shock waves can create a predetermined pressure profile, making the impact on biological tissue more complicated and precise, or can accelerate the process of three-dimensional microfluidic chips fabrication, adding extra degrees of freedom [11].

Briefly, when the femtosecond laser pulse is tightly focused inside the water cell, extremes for the medium’s intensities ($I \sim 10^{13}$ W cm$^{-2}$) are achieved in the focal region, and electron plasma is generated [14]. Due to the high temperatures ($T_e \sim 10$ eV) in the laser plasma, a thin layer of water vapor, surrounding the plasma, is generated. It begins to expand with supersonic speed, then a shock wave separates from the layer and it forms a cavitation bubble. Because the energy is transmitted from the plasma to the medium through electron–ion collisions, initially the cavitation bubble and the shock front shape replicate the shape of the laser-induced...
In order to control the laser-induced plasma shape, one should be mindful of the intensity distribution inside the medium. The first way to do this is by controlling the wavefront of the laser beam. In this manuscript it is implemented by using spherical aberrations, which appear during the tight focusing of the laser radiation into the bulk of transparent material. Here the optic rays, reflected on the boundary between two materials with different refractive indices, are collected at the different points on the optical axis [16]. Aberrations lead to local intensity maxima formation, which becomes the center of plasma generation [17]. The second possible way is to use the nonlinear properties of the medium. In this work the process of filamentation of the intense femtosecond laser beam is applied for this purpose. In comparison with the first case, the quasi-uniform intensity distribution could be achieved. Due to high intensity (up to $10^{14}$ W cm$^{-2}$) on the filament axis, the optical breakdown occurs inside the whole filament. This leads to the launch of one cylindrical shock wave, and corresponding cavitation area, if the energy delivered to the medium is high enough. In the case of spherical aberrations a complex pattern of spherical shock waves and cavitation bubbles are generated [18]. Most importantly, in both cases the parameters of the formed shock waves and the cavitation bubbles strongly depend on the focusing geometry and the laser pulse energy.

In this paper we investigated different regimes of filamentation and corresponding dynamics of filament-induced shock waves and cavitation bubbles in water using different focusing (including aberrations), laser parameters (pulse energy) and medium properties (linear absorption). What is significant about overcoming the critical power of self-focusing and tight focusing geometry (NA > 0.3) is that it gave us an opportunity to observe a new regime of filamentation, so called ‘superfilamentation’ [19]. In this regime one continuous plasma channel is constructed with close to the critical electron density along its axis. This channel becomes the center of cylindrical shock wave and cavitation bubble generation. The transition from the regime of superfilamentation into the regime of multifilamentation is observed in focusing conditions characterized by NA values close to 0.2. In loose focusing (NA < 0.2), a visible filament is seen but there are no shock waves. To compare the role of linear absorption we investigate the filament formation in H$_2$O and D$_2$O, whose physical properties do not significantly differ from each other, except in the case of linear absorption. In conclusion, we added spherical aberrations to the optical scheme, which as a result showed us a complex pattern of shock waves.

**Experimental setup**

In the experiments, a Cr:Forsterite femtosecond laser (wavelength of 1240 nm, pulse duration about 140 fs, laser energy up to 150 μJ, intensity contrast about $5 \times 10^9$ ASE, and repetition rate of 10 Hz) was employed. Shadow photography technique was applied for probing the dynamics of laser-induced shock waves and cavitation bubbles. In this technique, the probe pulse passes through the sample and creates a uniform illumination on a CCD camera. The perturbations in the refractive index, induced by the pressure waves, act as refraction centers and are seen as dark areas on the CCD matrix. The experimental scheme is sketched in figure 1.

The beam splitter divided the initial laser beam into two beams: pump and probe. The half-wave plate with the Glan prism was used for attenuation of the incident pulse energy. In experiments, different focusing geometries were employed: an aspheric lens with numerical aperture NA = 0.4 (hereinafter in air) and focal lengths 3.3 and 4.6 mm; aspheric lens with numeric aperture NA = 0.5 and focal length 8 mm; and microscopic objective with NA = 0.2 and 0.1. The lenses and objectives could be placed in air or in water. In order to investigate the role of aberrations we placed the lens in air, and to avoid aberrations the lenses were placed inside the water cell. When the lens was outside the water cell the focusing was applied through a free air–water boundary to eliminate the influence of the walls. Measuring in air conditions for the lens with a 3.3 mm focal length, the diameter of the focal spot was about 4 μm, and Rayleigh length was 15 μm (20 μm in water). The pump beam was focused into the water cell (wall width is 100 μm), creating plasma, a cavitation bubble and shock waves. For visualization on the CCD camera the frequency of the probe pulse was doubled into the second harmonic in a BBO crystal. Then the probe beam was scattered by the diffuser plate for uniform illumination of the water cell, and then collected on the CCD matrix.

In an incident wavelength, water strongly absorbs laser radiation due to resonance with molecular vibrations, which lead to significant linear absorption. Therefore, taking into account linear absorption of water at 1240 nm about 0.9 cm$^{-1}$, only 74 and 69% of the incoming energy was delivered to the focal waist in the case of the 3.3 and 4.6 mm focusing lenses, respectively. Tight focusing of the laser beam into the water cell led to strong spherical aberrations. Placing the focusing lens inside the water cell allowed us to minimize these aberrations. To exclude the role of aberrations from the aspheric lenses, additional experiments were carried out. The lens, placed in air, focused the laser beam and a bright plasma spark in the focus was observed. The
measured size of the spark is in good agreement with the focus spot sizes. Therefore, we conclude that the influence of the spherical aberrations from the lenses can be neglected. It is also of import to point out that the aspheric lenses are specially created for the minimization of spherical aberrations.

**Results and discussion**

**Role of the focusing geometry on the filament formation**

When laser radiation with power far above critical propagates through a nonlinear medium, filamentation can take place due to the dynamical balance among self-focusing, plasma defocussing and diffraction [20–22]. The process of filament formation can be described by the action of two main nonlinear effects. On the one hand, the optical Kerr effect acts against diffraction and tends to focus the beam on itself. On the other hand, plasma absorption limits the intensity, because the laser-induced plasma acts as a defocusing center. Commonly this phenomenon is accompanied by the conical emission and visible ‘filament’. Normally, in a tight focusing regime (NA > 0.2) the diffraction plays the main role, and the intensity is not high enough for the Kerr self-focusing just after the focal spot. However, the situation is more complicated.

The amplitude and the speed of the laser-induced shock waves strongly depend on the energy conserved in the laser plasma [1]. A crude estimate of the shock pressure can be made through the assumption that the electron gas pressure \( p_e \sim n_e kT \) acts as an initial perturbation launching the shock wave [4]. The visibility of the shock wave is proportional to the modulation of the refractive index and becomes detectable to the experimental technique only at electron density of about \( 10^{19} \text{ cm}^{-3} \) [1, 20, 21]. In the shadow pictures (see figure 5), captured for the lens with a 3.3 mm focusing length, the laser energy for the threshold of shock wave formation could be measured as 6 ± 1 \( \mu \)J. Taking into account linear absorption, this is equal to 4 ± 0.5 \( \mu \)J (laser intensity is about \( 10^{13} \text{ W cm}^{-2} \)). Additionally, the speed of the shock waves and the diameter of the cavitation bubbles \( E \sim D^3 \) are in strong correlation with the energy stored in the electronic subsystem; in other words they are a measure of the energy absorbed in each point of the medium. Therefore, the laser-induced shock waves are the ideal tools for the visualization of the plasma distribution inside the medium. From the shadow pictures, which are shown in figure 5, one can estimate the length of the plasma channel and its spatial homogeneity.

In the experiments we changed focusing conditions to achieve different regimes of filamentation. Since filamentation is a complicated process appearing from the competition between Kerr self-focusing, diffraction, dispersion and plasma defocussing, the abrupt change in the focusing conditions could break the relations between the processes and could dramatically change the ‘life’ of the filament [22].

In the comparatively loose focusing geometry (NA = 0.1) the classical picture of filamentation could be observed. Laser beam focusing increases the intensity along the optical axis, which launches Kerr self-focusing and as a result, leads to the self-channeling of the femtosecond pulse, i.e. filamentation. In this regime a bright conical emission and multifilamentation were observed. It is interesting to point out that the high linear absorption significantly complicates the filament formation; only at high (about 40 \( P_{\text{cr}} \)) power of the laser beam the multiple filaments could be visually observed. In this case, the shadow photographs show no shock wave formation. The explanation of the fact is as follows: the loose focusing of a laser beam cannot achieve high electron densities due to the intensity clamping in the filament, and additionally, the breaking of one filament.
into multiple filaments diffuses the laser energy over a huge area. In these conditions no shock waves are formed, because there is not enough energy localization characterized by electron density not exceeding $3 \times 10^{18}$ cm$^{-3}$ [25]. But if the time delay is increased (in this case the time delay is varied electronically by the delay generator), a random distribution cavitation bubble can be observed. The radii and position of the bubbles change from pulse to pulse, which is in good agreement with the stochastic nature of the filamentation process (see figure 2(a)) [24]. The bubbles are ignited in the nonlinear Kerr foci (the centers of plasma formation in the filament), and the energy issued in each focus determines the diameter of each bubble ($E \sim D^3$).

The opposite case is tight focusing of the laser beam. In this regime no detectable emission is observed, but on the shadow pictures long (much longer than the Rayleigh length) plasma channels are seen [25]. Looking for the explanation of this new phenomenon, it is necessary to consider in detail the physical processes taking place under tight focusing of intense laser radiation into the liquid sample. The tight focusing clamps the laser energy into a microvolume and the laser intensity in the focal spot can reach values up to $10^{14}$ W cm$^{-2}$ (this is the upper limit of a rough estimate; such experimental values were estimated based on the CE broadening in filament under tight focusing in [24]), because the intensity in condensed matter is strongly limited by the nonlinear absorption [14]. Therefore the electron density is about $0.1 n_{eq}$ ($n_{eq} = m_e \omega^2/4\pi\epsilon_0 \epsilon_{cr} \approx 7.3 \times 10^{20}$ cm$^{-3}$) and the plasma electron energy is sufficiently larger than in loosely focusing geometry [26]. Before the focal plane position, the external focusing dominates over the other processes. Only when the electron density becomes close to a critical one does the increase in the intensity stop. At the laser wavelength (1240 nm) the dispersion is negative [27] and tends to suppress pulse duration, which in turn leads to an increase in the laser pulse intensity on the filament axis. To find out the contribution of other processes (plasma defocusing, Kerr self-focusing and diffraction), rough estimates can be made. The length of self-focusing can be estimated as $L_{sf} = \lambda/(2n_2 I) \approx 1 \mu m$ ($n_2 = 1, 6 \times 10^{-16} \text{ cm}^2 \text{ W}^{-1}$), the length scale for plasma defocusing $L_{defoc} = L_{pl} n_{eq} = n_e \rho \omega^2/m_e \approx 5 \mu m$, and the diffraction length, i.e. Rayleigh length, which is about 15 $\mu m$ [24]. To determine when the dispersion will play a significant role, we estimate laser pulse intensity where equilibrium between self-focusing and dispersion occurs: $L_0 = k\lambda/(2k_0 n_2 I_0) \approx 10^{14}$ W cm$^{-2}$, $k' = -75 \text{ fs}^2 \text{ mm}^{-1}$, $k_0 = 2\pi/\lambda$, $t_p = 70 \text{ fs}$—temporal half width; thus in our case ($I \sim 10^{14}$ W cm$^{-2}$) the dispersion is negligible [27]. Therefore one could say that the Kerr self-focusing does not allow the laser radiation to leave the optical axis, and one continuous filament with approximately uniform distribution of electron concentration along the optical axis can be formed. This can be confirmed by the fact that the radius of the shock wave (cavitation bubble) is uniform along the filament axis, and its radius strongly depends on the plasma electrons’ mean energy and density. And so the tight focusing enables production of a contrast steady shock wave, whose profiles are conserved from pulse to pulse [1]. Energy dissipation through linear and nonlinear absorption leads to the filament stopping. To simplify, when the laser beam is tightly focused in the bulk of the condensed matter, it cannot deliver all the energy to one point and then transmit energy further until it will be absorbed. The nonlinear processes limit intensity in each point of such a channel, as will be shown in the text. The conical emission in such a regime strongly diverges (the divergence

Figure 2. The cavitation bubble pattern induced by the laser filament in water (laser pulse energy $190 \pm 10 \mu J$, time delay 2 $\mu s$). (a) There is one semi-cylindrical cavitation bubble induced by the superfilament. (b) There is a plasma channel in the right part of the picture, which transforms into several randomly distributed cavitation bubbles. (c) There are multiple randomly distributed cavitation bubbles, but there is no plasma channel. In this case the visible luminescence from the filament and conical emission were observed. Lenses were placed in the water cell. The white arrow shows the direction of the laser beam. In (b)–(c) the geometrical focus is located on the right border of the picture and on (a) the focus location is indicated by the white point.
The laser-induced plasma. In our case, the extreme intensity in the focal spot led to the formation of a stable amplitude and the initial speed of the shock wave were fully described by the initial pressure distribution inside shock waves were generated only in the areas where the electron density was greater than the threshold. The energy a single, stable (from pulse to pulse), cylindrical shock wave was generated. As was discussed above, the filament-induced shock wave evolution

Now let us concentrate on the filament-induced shock wave evolution taking place on the nanosecond timescale. The shadowgrams, provided in figure 5, show that instead of a spherical shock wave, which is usually observed in the case of tight focusing of the laser beam in water [8], a cylindrical shock wave was generated. At energies just above the threshold, one spherical shock wave was formed (figure 5(a)). With the increase of laser energy a single, stable (from pulse to pulse), cylindrical shock wave was generated. As was discussed above, the shock waves were generated only in the areas where the electron density was greater than the threshold. The amplitude and the initial speed of the shock wave were fully described by the initial pressure distribution inside the laser-induced plasma. In our case, the extreme intensity in the focal spot led to the formation of a stable continuous filament. Each point of the filament became a center of spherical shock wave generation. Together

Role of linear absorption

Water strongly absorbed radiation on the laser wavelength due to a resonance with H\(_2\)O molecule vibrations (about 0.9 cm\(^{-1}\)); such high absorption strongly violates the processes of filament formation and further shock wave and cavitation bubble generation. In order to identify the role of linear absorption, some additional experiments were carried out with D\(_2\)O. Heavy water has similar physical properties to water, but it has different vibrational frequencies that allowed us to avoid resonant interaction between the laser radiation and water molecules.

The value of the absorbed energy is proportional to the distance traveled by the laser beam inside the medium. To achieve high intensities in the focal spot, it is necessary to use lenses with a small focusing distance, or alternately, focus the radiation near the water boundary. In these cases the major part of the incident laser energy will be delivered to the focal spot. Therefore the most significant role the absorption of the laser energy will play is in the case of loose focusing. When the laser radiation was focused into a cell with D\(_2\)O, the visibility of the filament and the number and size of the cavitation bubbles (the volume of the cavitation area determines the energy delivery to the medium) was greater than in the case of H\(_2\)O.

When the laser radiation is tightly focused into the water cell, the role of linear absorption is not as important, because the distance that laser radiation travels through the media is not long enough to absorb a significant part of the energy. To compare the length of the plasma channels it is easy to use the cavitation bubble area. Instead of laser-induced shock waves, cavitation bubbles have a comparatively long lifetime (of about several microseconds), replicate the shape of the laser-induced plasma, and their diameter is a good indicator of the energy delivered to the media. The experiments show that with a decrease of focusing distance, the length of the plasma channel grows. Figure 3 shows that with an increase in the focusing lens from 3.3 to 8 mm, the length of the filament decreases by 1.5 times.

Filament-induced shock wave evolution

Now let us concentrate on the filament-induced shock wave evolution taking place on the nanosecond timescale. The shadowgrams, provided in figure 5, show that instead of a spherical shock wave, which is usually observed in the case of tight focusing of the laser beam in water [8], a cylindrical shock wave was generated. At energies just above the threshold, one spherical shock wave was formed (figure 5(a)). With the increase of laser energy a single, stable (from pulse to pulse), cylindrical shock wave was generated. As was discussed above, the shock waves were generated only in the areas where the electron density was greater than the threshold. The amplitude and the initial speed of the shock wave were fully described by the initial pressure distribution inside the laser-induced plasma. In our case, the extreme intensity in the focal spot led to the formation of a stable continuous filament. Each point of the filament became a center of spherical shock wave generation. Together

Image 156x728 to 516x770

Figure 3. Cavitation area in water after laser pulse focusing (energy 150 ± 4 μJ) by a lens with (a) 3.3 mm focusing distance and (b) 8 mm focusing distance. The length of the cavitation region (and filament length) is 1.5 times higher in the case of a lens with a lower focusing distance. The time delay between pump and probe pulses is 1 μs. The lenses were placed in the water cell. Laser radiation comes from the right.
they overlaid and constructed one contrast cylindrical shock wave. Further, in the paper we operate in terms of the shock wave diameter and length. The length of the shock wave is the distance between the most distant points on the shock wave front along the optical axis, and the diameter is the diameter of one spherical shock wave. As can be seen from the shadow pictures, it is easy to restore both parameters of the shock wave. Initially the cavitation region in the center of the picture replicates the shape of the filament, and therefore the length of the filament can also be restored from the pictures; the errors of such rough estimates do not exceed the diameter of each cavitation bubble. The filament length has a logarithmic dependence on laser pulse energy (figure 4(b)) similar to this, and can be found for various media in [29–31].

The next important point is the estimate of the achieved shock wave pressure. The pressure on the front of the shock wave can be restored from the shock wave speed using the semi-empirical equation

$$p = c_1 \rho_0 u_s \left(10^{(c_1-c_2)/c_2} - 1\right).$$

Here $c_1$, $c_2$ are empirical constants, $c_0$ is the speed of sound in the medium, $\rho_0$ is the density of the undisturbed medium, and $u_s$ is the speed of the shock wave front. In water $c_0 = 1483$ m s$^{-1}$, $\rho_0 = 998$ kg m$^{-3}$, $c_1 = 5190$ m s$^{-1}$ and $c_2 = 25306$ m s$^{-1}$. Thus assuming the exponential decay of the shock wave speed, we can calculate the shock wave speed [32]. For incident laser energy of 130 $\mu$J, shock wave speed is 2300 ± 200 m s$^{-1}$. The shock wave pressure can be estimated as 1.0 ± 0.1 GPa, which is similar to the results in [8, 33, 34].

We performed another series of experiments to investigate the dynamics of filament-induced shock waves on the laser pulse energy. The results are shown in figure 5. We found that shock wave diameter tends toward saturation as a square root of incident pulse energy. The saturation of the shock wave energy (which is proportional to its speed), is caused by the intensity clamping. With the increase of the laser pulse energy, the plasma electron density tends toward saturation due to a limitation of electrons in the effected volume [35]. Thus the energy that can be transferred from laser radiation to plasma and then from plasma to each shock wave in the optical breakdown volume is limited. Nevertheless, the length of the filament continues to increase because there is still enough energy in the energy reservoir. Therefore, in terms of filamentation in the classical sense, the further increase of energy will lead to intensity (and Kerr self-focusing) growth, but it will not change the plasma defocusing and diffraction due to the saturation of plasma electron density. Thus, the filament must collapse, but it does not. Thereby, it could be assumed that a high-order Kerr effect can counterbalance the strong self-focusing, especially at such high laser intensities [36–39]. The shock wave energy is the square root to its radius due to mass flow conservation and its spherical symmetry [7]. Therefore, further increase of the laser energy does not lead to an increase of the shock wave speed, but instead to an increase of the length of the shock wave. Thus varying only the energy of laser pulse shape, we can change the spatial characteristics of the laser-induced shock wave.

**Role of aberrations**

The last way to control the shock wave shape is by using aberrations. The aberrations often limit the possibilities of laser beam tight focusing inside the medium. Briefly, when the laser beam tightly focuses into the bulk of the medium, the convergence angles are big; due to Snell’s law the different rays are focused in different points of the medium, leading to significant spherical aberrations. A more complicated theory of the process can be found in [16]. Following the article, the intensity in each point can be calculated as:

![Figure 4. (a) Plasma channel length $L$ as a function of laser energy $E$ in water. Line corresponds to logarithmic dependence. (b) Shock wave leading (violet) and trailing (red) edge diameters $D$ as a function of time. Laser energy is equal to 125 $\mu$J. Lines show approximation with shock wave velocity exponential decay. The insert picture shows where the $D$ and $L$ were measured.](image-url)
where $\phi_1$ and $\phi_2$ are the convergence angle in the first and second medium, $\phi$ is half the angle of the light convergence, $k_0$ is the wave vector, $\tau_s$ and $\tau_p$ are Fresnel transmission coefficients, $J_0$ is the Bessel function of the zero order, $\Phi = -k_0d(n_1\cos\phi_1 - n_2\cos\phi_2)$ is the spherical aberration function, $n_1$ and $n_2$ are the refractive indices, and $d$ is the depth of the focus location.

As it can be seen from numerical simulations (see figure 6), aberrations are more significant in the case of high numerical apertures of focusing optics. Aberrations give an opportunity to build ‘hot spots’, or complex pattern along the optical axis (see figures 6 and 7). The intensity of laser radiation decreases in each following ‘hot spot’ [16]. In this regime complex spatial patterns of shock waves can be generated. The intensity profile maxima become the centers for cavitation bubble and spherical shock wave generation. At low laser pulse energy only single spherical shock waves are generated (figure 7(a)), while at higher laser pulse energy several dotted sources, isolated from each other, create a complex envelope of shock wave (figures 7(c)–(e)) [40]. With the increase of laser energy additional shock waves are generated from new plasma, forming a cylindrical shock wave (figure 7(f)). This can be caused by filament formation in each ‘hot spot’, which falls in line with similar phenomena, and was observed using the lens with a 3.3 mm focusing length. Such aberrations could effectively
increase the length of the laser filament and laser-induced shock impact on the material. Besides, on the microsecond timescale aberrations lead to generation of a complex 'drop-shaped' pattern of cavitation bubbles, whose evolution ends with a jet emission [41].

Conclusions

In conclusion, we investigated the whole life (from femtoseconds to microseconds) of a new type of filament structure, which we have termed superfilament after [19], fired in water under a supercritical power regime from the laser pulse energy, focusing and linear absorption. The high intensity clamps the energy into a thin layer along the filament axis. It leads to a channel formation with extreme and uniform plasma density distribution. The increase of the laser pulse energy does not change plasma density but sufficiently enlarges the superfilament length. The superfilament became a center of cylindrical cavitation area formation and shock wave generation. The maximal velocities and pressures achieved for the incident laser energy of 130 μJ on the shock wave front were 2300 ± 200 m s⁻¹ and 1.0 ± 0.1 GPa, respectively. The length of the filament was logarithmically dependent on laser pulse energy. The diameter of the filament grew as a square root of laser pulse energy and tended toward saturation, which was caused by the saturation of plasma electrons' density. When the looser (NA < 0.1) focusing was employed there was no continuous plasma channel and shock wave generation, but instead a conical emission and randomly-generated cavitation bubbles were observed, as the energy delivered to the medium by plasma electrons was not high enough for contrast shock wave generation. In the case of medium focusing (0.1 < NA < 0.3), the superfilament, once created close to the water–air boundary, breaks up into a randomly distributed pattern of cavitation bubbles. The linear absorption significantly increased the threshold of filament ignition due to the effective laser energy transferring to the vibrational modes of H₂O molecules. Aberrations added to the optical scheme led to multiple dotted plasma sources for shock wave formation, spaced along the axis of pulse propagation. Increasing the laser energy launches the filaments at each of the dots, whose overlapping enhanced the length of the whole filament and resulted in shock affects to the material.

Thereby, by varying focusing geometry (including aberrations) and laser pulse energy i.e. the regime of laser–matter interaction one could control the change in the refractive index as well as pressure and other properties of the medium. The shape and amplitude of such distortions could be specifically adjusted, ensuring the precise control of the impact on the material. The extreme conditions reached inside the thin and extensional superfilament area gave us the possibility of inducing different phase transitions and molecule dissociations in the specific region of interest both locally and distributively. This feature of the superfilament—high energy delivery to the medium with good handling—could be useful in micro- and nanomachining of transparent materials making through the water interface. The complex pattern of plasma density distribution seems to be very prospective for controlling the evolution of the laser-induced cavitation and the high-velocity jet emission, which could be implemented in various tasks, for instance, in drug delivery in medicine. In addition, we want to point out that many questions remain open in the physics of superfilamentation and post-effect generation in water and require further research and refinement.
Acknowledgments

The authors thank Tatiana Oparina for drawing the experimental setup. This research has been supported by the Russian Foundation for Basic Research (Project No. 14-02-00819a, 14-29-07235) and partly by the M V Lomonosov Moscow State University Program of Development.

References

[1] Lauterborn W and Vogel A 2013 Shock wave emission by laser generated bubbles Bubble Dynamics and Shock Waves ed C F Delale vol 8, pp 67–103 (Berlin: Springer)
[2] Gamaly E G, Luther-Davies B, Hallo L, Nicolai P and Tikhonchuk V T 2006 Laser–matter interaction in the bulk of a transparent solid: confined microexplosion and void formation Phys. Rev. B 73 214101
[3] Potemkin F V, Mareev E I, Mikhkev P M and Khodakovskii N G 2013 Resonant laser-plasma excitation of coherent THz phonons under extreme conditions of femtosecond plasma formation in a bulk of fluorine-containing crystals Laser Phys. Lett. 10 076003
[4] Wahlstrand J K, Hjäli N, Rosenthal E W, Zahedpour S and Milberg H M 2014 Direct imaging of the acoustic waves generated by femtosecond filaments in air Opt. Lett. 39 1290
[5] Pezeril T, Saini G, Veyset D, Kooi S, Fidkowski P, Radovitzky R and Nelson K A 2011 Direct visualization of laser-driven focusing shock waves Phys. Rev. Lett. 106 214503
[6] Vailionis A, Gamaly E G, Mizieks V, Yang W, Rode A V and Juodkazis S 2011 Evidence of superdense aluminum synthesized by ultrafast microexplosion Nat. Commun. 2 445
[7] Kennedy P K, Hammer D X and Rockwell B A 1997 Laser–induced breakdown in aqueous media Prog. Quantum Electron. 21 155–248
[8] Schaffer C, Nishimura N, Glezer E, Kim A and Mazur E 2002 Dynamics of femtosecond laser–induced breakdown in water from femtoseconds to microseconds Opt. Express 10 196–203
[9] Matsuo H and Nakamura Y 1980 Experiments on cylindrically converging blast waves in atmospheric air J. Appl. Phys. 51 3126
[10] Bleizinger P, Ganguly B N, D Van W and Garscadden A 2005 Plasmas in high speed aerodynamics J. Phys. D: Appl. Phys. 38 R33–57
[11] Li Y and Qu S 2013 Water-assisted femtosecond laser ablation for fabricating three-dimensional microfluidic chips Curr. Appl. Phys. 13 1292–5
[12] Mizieks V, Vailionis A, Gamaly E G, Yang W, Rode A V and Juodkazis S 2012 Synthesis of super–dense phase of aluminum under extreme pressure and temperature conditions created by femtosecond laser pulses in suspension ed W V Schoenfeld, R C Rumpf and G von Freymann Proc. SPIE 8249 82490A
[13] Thadhani N N 1994 Shock–induced and shock–assisted solid–state chemical reactions in powder mixtures J. Appl. Phys. 76 257–60
[14] Manenkov A A 2014 Fundamental mechanisms of laser-induced damage in optical materials: today’s state of understanding and problems Opt. Eng. 53 010901
[15] Noack J and Vogel A 1999 Laser–induced plasma formation in water at nanosecond to femtosecond time scales: calculation of thresholds, absorption coefficients, and energy density IEEE J. Quantum Electron. 35 1156–67
[16] Marcinkevičius A, Mizieks V, Juodkazis S, Matsuo S and Misawa H 2003 Effect of refractive index-mismatch on laser microfabrication in silica glass Appl. Phys. A 76 257–60
[17] Vogel A, Nähn K, Theisen D, Birngruber R, Thomas R J and Rockwell B A 1998 Influence of optical aberrations on laser-induced plasma formation in water, and their consequences for intracocular photodisruption Proc. SPIE 3246 120–31
[18] Geisler R 2004 Untersuchungen zur Laserinduzierten Kavitation mit Nanosekunden- und Femtosekundenlasern Dissertation Göttingen University
[19] Point G, Brelet Y, Hourd A, Juka V, Milläni C, Carbonnel J, Liu Y, Couairon A and Mysyrowicz A 2014 Superfilamentation in air Phys. Rev. Lett. 112 223902
[20] Suna K 2001 Pulse electrical discharges in water and their applications Phys. Plasmas 8 2857–94
[21] Zel dovich Y B and Raizer Y P 2002 Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena ed W D Hayes and R F Probstein (New York: Academic)
[22] Lim K, Durand M, Baudelet M and Richardson M 2014 Transition from linear- to nonlinear-focusing regime in Phys. Plasmas 21 096403
[23] Minardi S, Gopal A, Tatarakis M, Couairon A, Tamosauskas R, Piskarskas R, Dubietis A and Di Trapani P 2008 Time-resolved refractive index and absorption mapping of light-plasma filaments in water Opt. Lett. 33 86–8
[24] Couairon A and Mysyrowicz A 2007 Femtosecond filamentation in transparent media Phys. Rep. 441 47–189
[25] Gordienko V M, Potemkin F V and Mikhkev P M 2009 Evolution of a femtosecond laser-induced plasma and energy transfer processes in a SiO2 microvolume detected by the third harmonic generation technique JETP Lett. 90 263–7
[26] Liu W, Kosareva O, Golubtsov I S, Iwasaki A, Becker A, Kandilov V P and Chin S I 2003 Femtosecond laser pulse filamentation versus optical breakdown in H2O Appl. Phys. B 76 215–29
[27] Vasa P, Dharmadhikari J A, Dharmadhikari A K, Sharma R, Singh M and Mathur D 2014 Supercontinuum generation in water by intense, femtosecond laser pulses under anomalous chromatic dispersion Phys. Rev. A 89 043834
[28] Abraham E, Minoshima K and Matsumoto H 2000 Femtosecond laser–induced breakdown in water: time-resolved shadow imaging and two-color interferometric imaging Opt. Spectrosc. 176 141–52
[29] Juhasz T, Kastis G A, Suárez C, Bor Z and Bron W E 1996 Time-resolved observations of shock waves and cavitation bubbles generated by femtosecond laser pulses in corneal tissue and water Lasers Surg. Med. 19 23–31
[30] Gordienko V M, Makarov I A, Mikhkev P M, Savelev A B, Shashkov A A and Volkov R V 2004 Self-channeling of femtosecond laser radiation in transparent two-component condensed medium ed V P Veiko Proc. SPIE 5399 96–9
[31] Liu X-L, Lu X, Liu X, Xi-T-T, Liu F, Ma J-L and Zhang J 2010 Tightly focused femtosecond laser pulse in air: from filamentation to breakdown Opt. Express 18 26007–17
[32] Martí-López L, Ocaña R, Piñeiro E and Asensio A 2011 Laser peening induced shock waves and cavitation bubbles in water studied by optical schlieren visualization Phys. Procedia 12 442–51
[33] Devia–Cruz L F, Camacho–López S, Evans R, García–Casillas D and Stapanov S 2012 Laser–induced cavitation phenomenon studied using three different optically-based approaches—an initial overview of results Photonics Lasers Med. 1 195–205
[34] Strycker B D, Springer M M, Traverso A J, Kolomenskii A A, Kattawar G W and Sokolov A V 2013 Femtosecond-laser-induced shockwaves in water generated at an air–water interface Opt. Express 21 23772–84
[35] Mikheev P M and Potemkin F V 2011 Generation of the third harmonic of near IR femtosecond laser radiation tightly focused into the bulk of a transparent dielectric in the regime of plasma formation Moscow Univ. Phys. Bull. 66 19–24
[36] Béjot P, Kasparian J, Henin S, Loriot V, Vieillard T, Hertz E, Faucher O, Lavorel B and Wolf J-P 2010 Higher-order Kerr terms allow ionization-free filamentation in gases Phys. Rev. Lett. 104 103903
[37] Loriot V, Béjot P, Ettoumi W, Petit Y, Kasparian J, Henin S, Hertz E, Lavorel B, Faucher O and Wolf J-P 2011 On negative higher-order Kerr effect and filamentation Laser Phys. 21 1319–28
[38] Béjot P, Hertz E, Lavorel B, Kasparian J, Wolf J-P and Faucher O 2011 From higher-order Kerr nonlinearities to quantitative modeling of third and fifth harmonic generation in argon Opt. Lett. 36 828–30
[39] Ettoumi W, Béjot P, Petit Y, Loriot V, Hertz E, Faucher O, Lavorel B, Kasparian J and Wolf J-P 2010 Spectral dependence of purely-Kerr-driven filamentation in air and argon Phys. Rev. A 82 033826
[40] Steiner H, Gretler W and Hirschler T 1998 Numerical solution for spherical laser-driven shock waves Shock Waves 8 139–47
[41] Potemkin F V and Mareev E I 2015 Dynamics of multiple bubbles, excited by a femtosecond filament in water Laser Phys. Lett. 12 015405