Evaluation of a method to image a laser-initiated propagating streamer

a Diploma work

by

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1. Abstract

A great deal of research has been devoted to the study of a rapid, light-emitting, electrical breakdown phenomenon, known as a propagating streamer. The phenomenon is quite different in the cases of spontaneous versus initiated breakdown. It has been hypothesized that when the breakdown is initiated by a focused laser beam, the streamer phenomenon is associated with a bubble, whose growth and change give rise to the streamer. This paper concerns the development of a method to study the streamer resulting from a breakdown initiated with a laser beam in a laboratory. The primary goal of the experiments was to try this method out, evaluate it, find out what problems it entailed and what could be done about these. As a secondary, more ambitious goal, we hoped that if the method was up to the task, we might be able to actually photograph the bubble, and thus verify the theory.

The method devised, which is an application of the shadow method, has the advantage of using relatively cheap and easily available equipment, but still allow us to study very rapid phenomena. Normally a rapid shutter and a very light-sensitive camera (short exposure time means little time to absorb light) are needed to obtain a good time resolution. It is, however, possible to use a trick that will make an ordinary camera suffice. If the object is dark all the time except during a very short time when it is strongly illuminated, we can achieve a time resolution as short as the illuminating pulse. A pulsed laser, like the Nd:YAG-laser, can produce very much light during a very short, well-defined time and will work admirably. Laser light also has the advantage of being monochromatic, which means you can easily filter out all other light at the detector so working in darkness won't be necessary. Another tribute to the usefulness and versatility of laser technology.

2. Introduction

2.1 The streamer phenomenon

If we have two electrodes in a dielectric fluid and slowly increase the voltage, and thus the electrical field, between the electrodes, breakdown will occur at some voltage. Practical experience in transformer stations has shown that in practice electrical breakdowns in dielectric liquids can occur at voltage levels significantly lower (even by an order of magnitude) than such a simple experiment seems to indicate.

This is due to the fact that the breakdown process can be divided into two different stages: initiation and propagation of the breakdown. The voltage required to initiate the breakdown is very high, whereas the voltage needed to propagate the breakdown is much lower. Once the breakdown is initiated it can propagate at a much lower electrical field. This means that *spontaneous* breakdown, that is a breakdown which is initiated once the electrical field is sufficiently high, requires much higher fields than a breakdown initiated by some other means (henceforth just called initiated break-down).[1,2,3]

The initiation and propagation of breakdown give rise to a propagating streamer, a light-emitting, short-lived (typically of the magnitude of tens or hundreds of microseconds) phenomenon. The streamer also gives rise to several discharges prior to the actual breakdown[4]. The phenomenon apparently generates channel, first for the discharges and then for the breakdown. A great deal of research has been devoted to finding accurate descriptions of the conditions that influence streamer initiation and propagation and the exact mechanisms for the phenomenon. Typically the channel grows from the charged electrode to the grounded one[5]. Positively charged streamers usually result in a treelike channel while negatively charged streamers create a more "bushy" (i.e. broader and more richly branched) channel and often propagate more slowly. The light-emission of the streamer seems to be correlated to the channel's propagation, and thus to the electrical pulses previous to the actual breakdown [3,4].

In the laboratory a breakdown can be initiated with a spark (e.g. from a spark plug) or with a focused laser beam which creates a plasma in the high voltage cell. A spontaneous breakdown is typically created in the laboratory by charging a needle-shaped electrode at a distance from a grounded surface, since this requires less voltage than a homogenous field. The voltage is increased until breakdown is initiated.

It has been hypothesized that in the case of spark- or laser-initiated breakdown, the channel is preceded by a bubble, the growth of which causes initiation of the streamer[3,6,7] . In order to test this hypothesis a method for photographing the bubble in different stages of the breakdown is needed.

2.2 Difficulties encountered in studying a streamer

Many things must be given consideration in the choice of method for studying an initiated propagating streamer and/or the associated bubble. First, it is a rapid and "violent" process[8]. Like many such phenomena, such as explosions, it is not completely predictable. Even if a test is repeated under (seemingly) identical conditions the streamer may look quite different between two tests. Second, the process is of very short duration. All integrating light detectors absorb light during a certain exposure time and display all that it has detected during that time. So if the detected object is moving or growing significantly during the exposure time the detector will smear the picture. We all know that a photo of a rapid-moving object will be blurred unless the exposure time of the camera is very short. In our case, the streamer itself is assumed to move at a speed of about a kilometer per second, and the entire breakdown process takes only a few hundred of microseconds. Third, the rapidity of the process means that the camera will have little time to receive light, and thus a very light-sensitive camera is required. Fourth, if one just wishes to study the expanding gas bubble associated with an initiated streamer, the light emitted by the streamer itself will also pose problems.

Taking these problems into account Anders Sunesson had, prior to the experiments, devised such a method. The primary goal of the experiments was to test this method, finding out if it was practically workable, what problems it entailed and what could be done about these. As a secondary, more ambitious, goal it was hoped that the method might allow us to photograph the bubble associated with the initiated streamer, thus proving the bubble's existence. In order to describe this specific method, some words must also be said concerning different methods to study a streamer in general.

2.3 Methods to study a streamer

Propagating streamers can be studied photographically or by measuring the current associated with streamer propagation. Photographic studies can be single-frame or multi-frame (i.e. taking one or several pictures of one breakdown). It goes without saying that multi-frame is difficult since the breakdown is such a rapid phenomenon (typically hundreds of microseconds), but there is equipment which is up to the task. Both single-frame and multi-frame photography can be used in two fundamentally different ways.

First, it is possible to look only at the light emitted by the streamer itself (passive detection). Since the camera is integrating in nature a rapid shutter can be added for a more instantaneous picture. In that case, the camera must be quite light-sensitive since the camera has little time to absorb light. It is, however, not possible to observe the shape of any bubble with this method.

Second, we can use active detection, looking not only (or not at all) at the light emitted by the propagation of the streamer itself, but also using another light source. With this method it is possible to detect the bubble associated with initiated streamer propagation by illuminating it from behind. The bubble will when create a shadow by deflecting passing light since the bubble has an index of refraction which is different from the surrounding liquid (see figure 1).

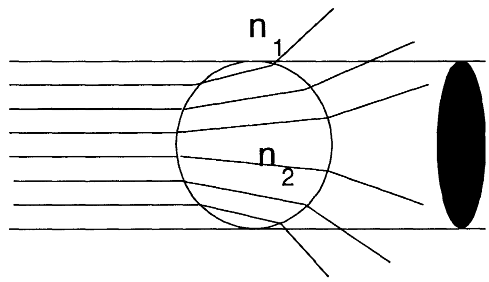

Fig 1. Light passes through a sperical bubble and is defelected since the contents of the bubble has a lower index of refraction, giving rise to a shadow.

This is known as the shadow method. The situation is similar to creating shadow-figures of animals on a wall by using your hands in front of a lamp, though the hands will absorb and reflect light rather than deflecting it. In our case, however, we have an additional problem, since the light emitted from the streamer, from the plasma and from the breakdown itself might otherwise disturb the shadow. This could be solved, or at least significantly reduced, by inserting a spectral filter in front of the detector.

With a fast flashlamp or, as in the case of our experiment, a laser as light source, it is possible to illuminate the object during a very short and carefully preset time. In practice this means that we can take a picture that is integrated during a time period as long as the duration of the laser pulse even though the integration time of the camera is much greater. This is the case since the object is only illuminated during the laser pulse and the camera is filtered so that no light reaches the camera from other sources. The laser has the added advantage of being monochromatic, facilitating filtration of the unwanted light from the breakdown itself or from the laboratory room light. It is chiefly a single-shot arrangement. The brevity and strong light of a laser pulse and the fact that this is typically a single-shot arrangement mean that this method does not require a very light-sensitive or rapid camera. An ordinary video camera, 50/25 Hz interlaced, arranged for single shot will do. Interlacing means that the image is renewed at a rate of 50 Hz, but only every other line at the time (see fig 2).

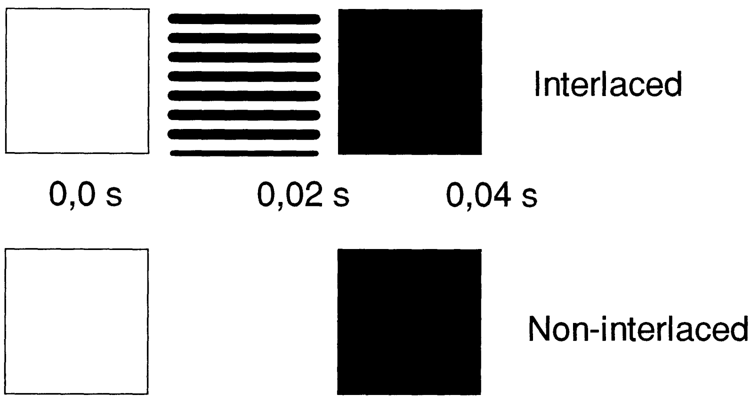

Fig 2. An image going from white to black in 50/25 interlaced (above) and 25 Hz non-interlaced (below).

This improves the illusion of a continuous movement. So in this case a complete new image is formed 25 times a second, but the image is changed 50 times a second. Since we are making a single shot we only get every other line (half the stored image) with an interlaced camera, so a non-interlaced would be preferable, but there is a major difference in cost. (Modern TV and the vast majority of video cameras are interlaced 50/25 Hz and thus these are typically a lot cheaper.)

To summarize: we had concluded that our method uses two lasers: one for starting the streamer and one to create a shadow, an ordinary video camera, a computer, simple electronics for adjustable delay and miscellaneous lenses. We now proceeded to try out the method.

3. First experiment -photographing the shadow of a bubble in an aquarium

Before attempting to actually photograph a propagating streamer, we wished to test the general workability of the imaging system (i.e. the laser beam hitting a bubble and creating a shadow to be recorded by the camera). To do this, we needed to photograph something simpler, but similar, to the bubble associated with the initiated streamer. A bubble in a water-filled aquarium was considered to be useful for this purpose. It was hoped that trying to photograph the shadow created by the laser light and a bubble would make it possible to discover problems with the basic principles of taking such a picture and find solutions to these, before adding the complicating factors of another laser (to induce plasma and thus the breakdown), light from the plasma and electronic synchronization.

3.1 Set-up

In principle, the shadow method requires a light source, an object, a detector and a computer for storing the image data. (See figure 3a.)

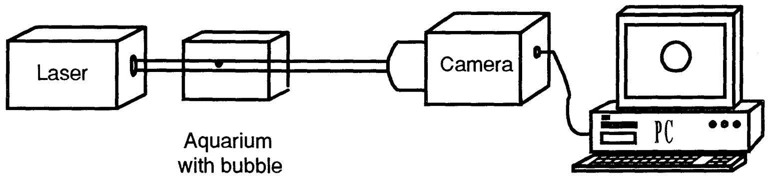

Fig. 3a Schematic set-up.

In our case, the beam from the light source was initially ill-suited for the shadow method and required some treatment. Thus a spatial filter was added (see figure 3b).

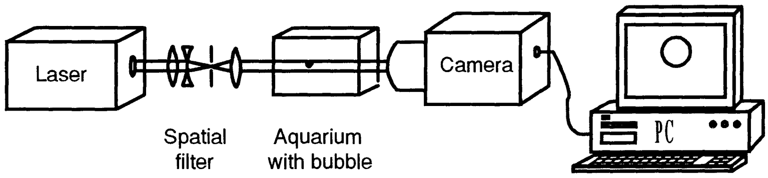

Fig. 3b Schematic set-up.

For this experiment the following equipment was used, set up in order following the beam path:

- An Nd: YAG-laser; Quanta-Ray DCR-2, a frequency doubler Quanta Ray HG-2 and a dichroic mirror intended to separate 532 nm light (constituting the light source) from the 1064 nm light.

- Miscellaneous other lenses and mirrors and a pinhole mounted in such a manner that it could be moved with micrometer screws in order to facilitate centering (all together constituting the spatial filter).

- A water-filled glass container with flat surfaces and an aquarium pump which created bubbles that constituted the object.

- An OSCAR 420D camera with 50/25 Hz interlaced frequency linked to a 486/33 IBM compatible computer with Videoblaster card and pertinent software including a non-commercial pascal program called vblsum (constituting the detector).

3.1.1 Light source and spatial filter

Immediately following the frequency doubler (which transformed some of the 1064 nm light to 532 nm) a dichroic mirror was set up to separate the remaining 1064 nm light from the 532 nm beam and a beam dump to absorb the separated 1064 nm light.

Unfortunately the cross-section of the laser did not have an evenly dispersed intensity, rather, it was, due to the arrangement of the resonator, donut-shaped as in fig. 4. (In most modern YAG-lasers, this problem has been circumvented by various means.)

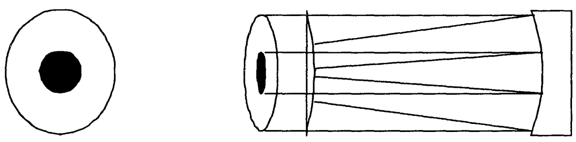

Fig 4. Resonator arrangement of the Nd: YAG-laser cavity. Note that only the center of the mirror to the left is relfective, giving rise to a shadow.

Such a cross section was of course ill-suited for making shadows that accurately show a silhouette of the object creating the shadow. We would not be able to see a shadow in the "hole" in the light intensity. We wanted the intensity of laser light to be reasonably well distributed across the cross section. To remedy the problem a Fourier transform method was used. This is a number of methods based on the fact that if we focus light in such a manner that the focus is diffraction limited (that is the diffraction is the by far most important aberration, significantly greater than spherical and other aberrations) we get a two dimensional Fourier transform of the original beam cross section in the focus. The principle is demonstrated in fig 5.

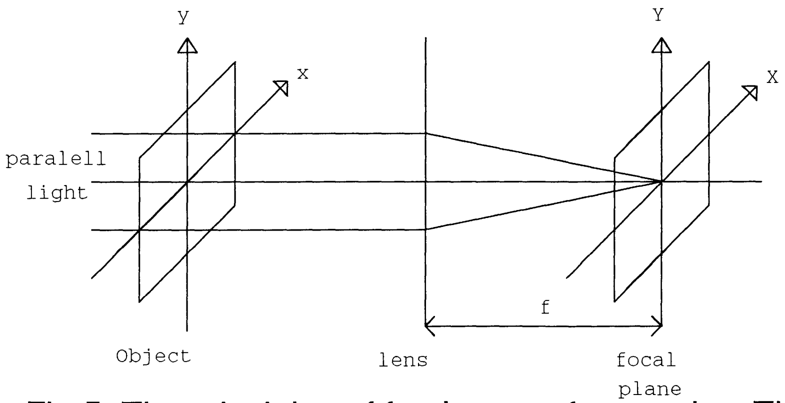

Fig 5. The principles of fourier transform optics. The wavefront in the focal plane is the fourier transform of the wavefront in the object plane.

This means that space coordinates in the focal plane correspond to spatial frequencies in the original beam shape section according to the formulae:

$$f_X = \frac{X}{\lambda \cdot f} \qquad f_Y = \frac{Y}{\lambda \cdot f}$$

There f is the focal length, λ is the wave length of the light f_x and f_Y are spatial frequencies and X and Y are the positions in the focal plane as in figure 5. This means that the spatial frequencies are "sorted" by the Fourier transform with the high frequencies in the periphery and the low frequencies in the center. This can be very useful. Typically Fourier transform is used for filtering by blocking out high or low spatial frequencies (blocking the periphery or center respectively) in the frequency plane after which the light is again made parallel. The net result is a low-pass or high-pass filter respectively. A problem of Fourier transform is that it is necessary to work in the focus, which means that everything in the focal plane is quite small. Great precision is needed and the set-up is sensitive to small movements. Note that from the formula we see that with f_x and f_Y constant, the positions of X and Y on the focal plane are proportional to the focal length f. In our case this means that if we wish to work with reasonably large objects in the focal plane (reducing the need for precision), the focal length must be quite large.

We hoped that by removing the high frequencies with Fourier transform methods, we would get a laser shape that was more even, at least in the center. If we assume that the intensity is the same everywhere except where it is zero the intensity distribution would be the difference between two circ functions. A circ function is described by circ(r)=1 when r<1 and 0 otherwise (see figure 6).

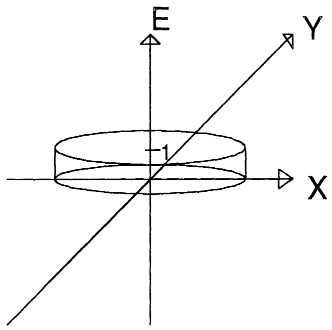

Fig 6. The circ function.

The intensity distribution in fig 4 could then be approximately described as a difference between two circ functions with different radii. The Fourier transform of a circ function is a Bessel function. According to the linearity theorem, the Fourier transform of a sum is the Fourier transform of the terms. Thus the Fourier transform of the difference between two circ functions would be the difference between two Bessel functions. The calculations have been made and the result is shown in fig 7.

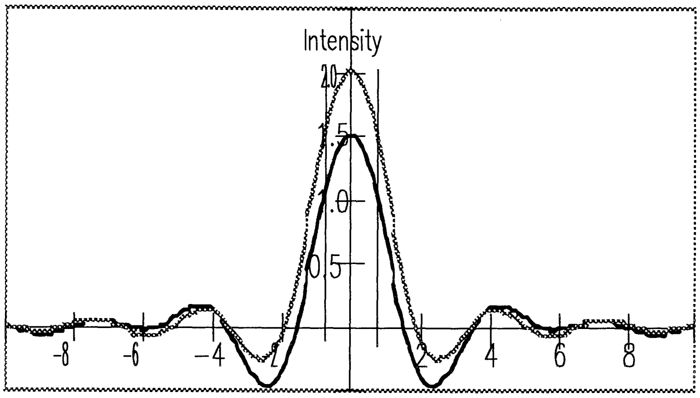

Fig 7. Fourier transform of a circ function (gray) and of the difference between two circ functions with different radii (black). This corresponds to the fourier transform of the crossection without respectively with the "hole". The lines indicate where we wished to cut the image (roughly at 0.6).

We wished to “cut out” the high frequencies as indicated in the picture and when transform the beam back to the focal plane by making it parallel again. Note that with the given cut the two curves in the figure are quite similar except for a constant factor.

In practice the Fourier transform and “cutting out” was achieved by a set-up as in fig. 8.

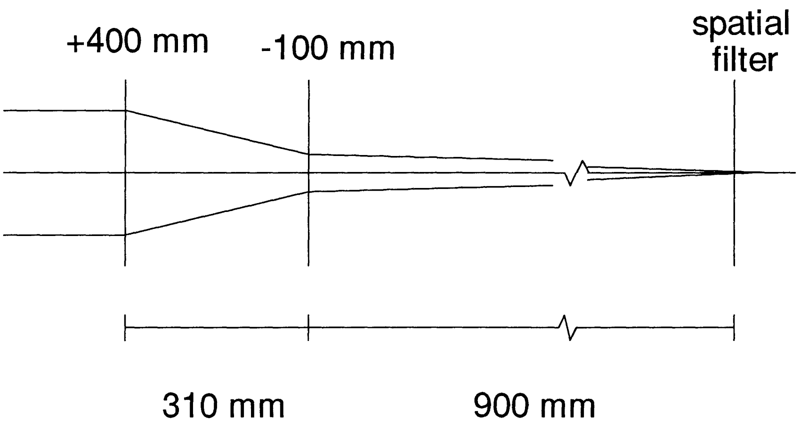

Fig 8. Arrangement of lenses in front of the spatial filter. Note that the apparent focal length) seen from the right is 4 m. It is also to be noted that the figure has been cut and that the second(-100 mm) lens is quite close to the focus of the first lens. Care must be taken lest the second lens is damaged while rearranging lenses with the laser on.

Even when the pinhole was mounted on micrometer screws, it would be hard to target the pinhole with an accuracy exceeding 0.05 mm, so we created a pinhole this size. If we still wished to cut as in the picture, however, it required a focal length of 4.0 m. Due to the limited space on the optical table, using a single lens with a focal length exceeding 1 meter would not be practical even if such a lens was available. One f=-100 mm lens was placed 310 mm in front of a f=+400 mm lens. According to the formula:

$$F = \frac{f_1 \cdot f_2}{f_1 + f_2 - d}$$

where f_1 and f_2 are the focal length of the lenses, d is the distance between them and F is the apparent focal length, this created an apparent focal length of 4 meters. Still, the set-up only occupied slightly more than 1.5 meter of the beam path. Two things are to be noted with this set-up however. First, a moderate displacement of the second (divergent) lens will move the focal plane a great deal. Second, it is also to be noted that this second lens is pretty close to the focus of the first lens. Care must be taken when moving the lenses while the laser is active lest the second lens is damaged.

As was stated above, Fourier optics requires a diffraction limited system. We must now ask ourselves if this set-up truly created a diffraction limited system. This is done by showing that the aberrations are significantly lower than the diffraction limit. Calculations according to the formula

$$d_d = \frac{2 \cdot 1.22\lambda}{D} \cdot b$$

where d_d is the diffraction limit, λ is the wavelength D is the beam diameter (conservatively set to 3.5 cm in our calculations) and b is the distance to the object gives us a diffraction limit of $2 \bullet 10^{-5}$ m. The formula

$$d_a = K(n) \cdot (\frac{D}{f})^3 \cdot b$$

where K(n) must be calculated through ray-tracing, gives the most important, that is spherical, aberration d_a. In this case it is roughly $5 \bullet 10^{-6}$ m. Since this is much less than the diffraction limit, we should have achieved a diffraction limited system. All these theoretical calculations should, however, be taken with a grain of salt.

In reality, the diffraction limited picture was merely reminiscent of -not identical with- the predicted curve (fig. 7). This was probably chiefly due to the fact that when using the formula for spherical aberrations, we assume that the beam is perfectly centered in every lens. Also, the calculations above were based on an idealized version of the intensity distribution. It is also to be noted that we used a +300 mm lens at 250 mm from the spatial filter to make the light parallel after the focal plane. This did not concur with theoretical calculations either. However the net result, that is the light coming out from the spatial filter, proved to be circular and evenly distributed across the cross section -very well suited for our purposes.

Thus we have a system that works well in theory, seems to differ from theoretical predictions, but still achieves the result we want!

3.1.2 Detection and storing

When the beam is improved as in above, it is targeted at the object and detected by a camera. Our camera was an OSCAR 420D with a set of customized camera lenses that was meant to allow focusing on an object at a 300-400 mm distance with a magnification close to 1:1. Testing (photographing a ruler) proved these claims of the supplier to be true.

The camera was modified to turn off Automatic gain control and set gamma correction to 1 (this corresponds to linear gray scale correction). Automatic gain control (AGC) modifies the gain to balance the brightness of the picture, this gives the images a better contrast between the darker and lighter parts, but the brightness of the image is no longer directly correlated to the intensity of the light entering the camera. We preferred to maintain such a correlation and thus turn AGC off. We now proceeded to use the laser as light source for the shadow method. Attenuation filters and a filter that removed all light but that close to the laser's 532 nm were inserted in the beam path before, respectively, after the object. Since the ordinary light in the room and the streamer is distributed over a great many wavelengths, a filter with just a narrow window close to 532 nm removes almost all of this light. Care was taken to avoid too strong or too focused laser light entering the camera since this could damage the cameras CCD (Charged Coupled Device). This is the most important part of any digital camera, which detects light intensity at different positions and transforms this into digital information.

From the CCD the image was sent into a 486 33 MHz IBM computer with a video blaster card. We set the laser to keep giving laser pulses at a fixed rate. The camera kept sending the images of these pulses to the computer which displayed them at the monitor using the program videoblaster (included when buying the videoblaster card). At any time we could order the program to stop and store any one image at any time. Ordering the program to take an entire sequence of running film was theoretically possible, but would cause problems with memory requirements. In practice we kept the laser running at ten shots a second and stopped the program, almost at random, to allow us to view the image taken. If the image was satisfying, we saved it.

Here the interlacing of the camera posed a problem. Since we only received every other line, the image was "striped". Every other line was completely black. The Videoblaster program was ordered to accept the image as if it was not interlaced, which resulted in the image being compressed by a factor 2 vertically rather than striped. Some simple computer treatment of the image, simply ordering the program to increase the height by a factor two, restored the it to normal width-to-height correlation. However, of course, half of the information was still lost. this process is described in figure 9.

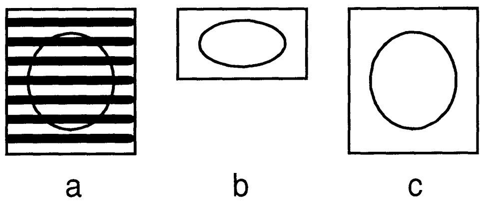

Fig 9.
a) Computer set to receive interlaced image
b) Computer set to recieve non-interlaced image
c) Image b) treated to restore normal height-to-width.

3.2 Results and conclusions

To test if the set-up could effectively photograph a streamer-preceeding gas bubble we first tried the simpler task of photographing bubbles in an aquarium. However, most aquariums have rounded surfaces, and since water has a higher diffraction index than air, this would lead to the aquarium acting as a lens and cause the beam to focus. Thus it proved necessary to use a rectangular aquarium with flat sides. However, even such an aquarium changed the laser light and made slight more "grainy". A picture taken is shown in fig. 10.

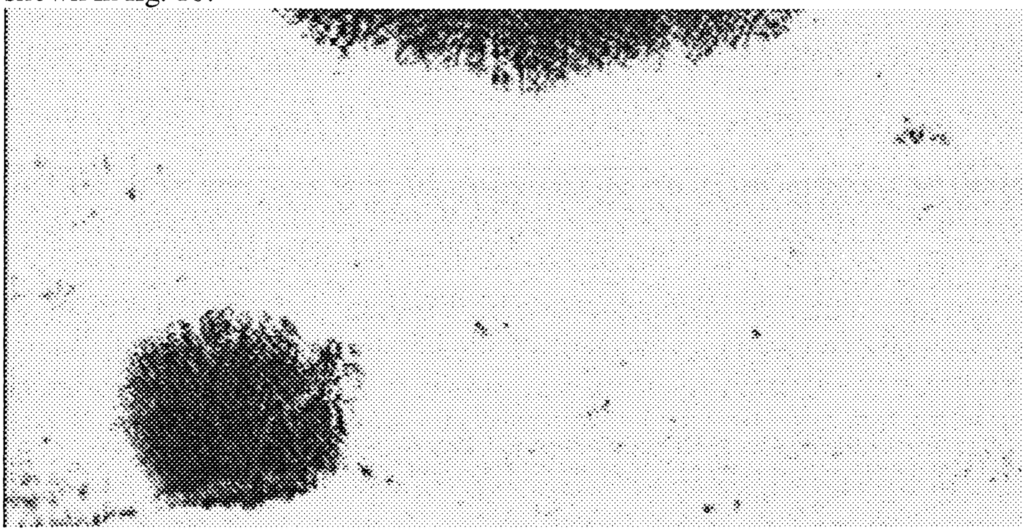

Figure 10. Photography of a bubble. Note that the edges are less than perfectly sharp and that theimage is slightly overexposed.

In order to determine the resolution of the set-up a special object was used. This photography (fig. 11)

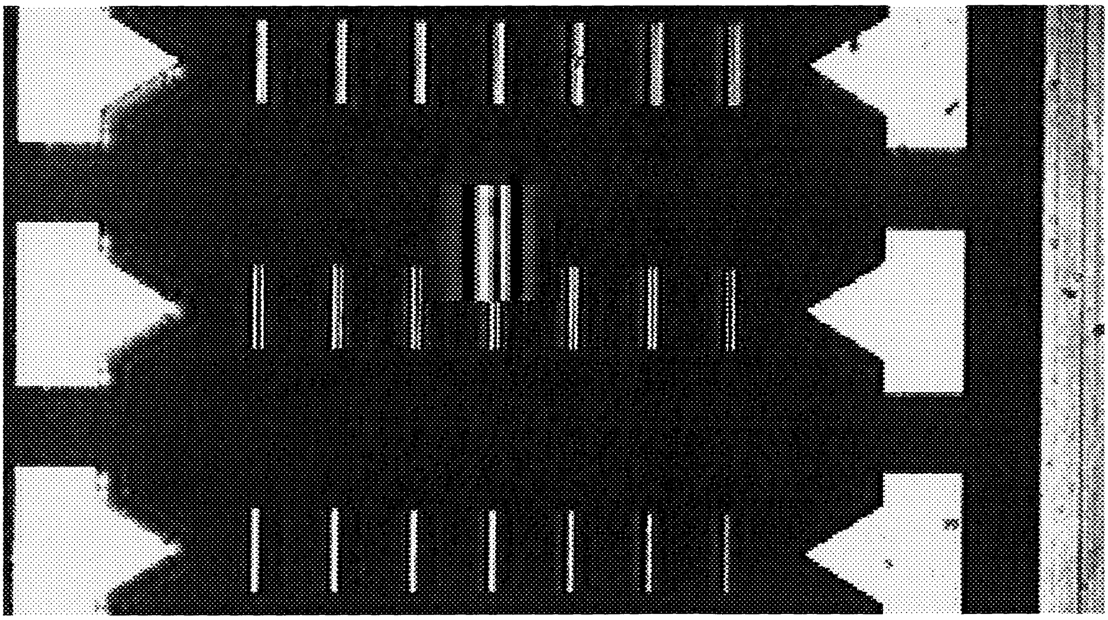

Figure 11. Photography of a special object. Note the enhanced section in the middle which shows that the imaging system can show two lines, only two pixels apart as two different lines.

shows that the set-up is capable of distinguishing between two lines merely two pixels apart. The magnification on the CCD is roughly 1:1 and the CCD is 6.4*4.8 mm with 542*492 pixels. This correlates to a resolution better than 30 µm. However, as can be seen by comparing fig. 10 and 11, the bubbles are not as sharp as the special object used. This problem was exacerbated by the fact that the energy of the shadow-inducing laser varied unpredictably, resulting in problems with over- and underexposure. It was thought that the energy of the laser pulse would vary less, at least proportionally, at a higher pulse energy. So we set the energy of the laser pulse higher and dampened the resulting laser light with attenuation filters. Unfortunately this did not result in any significant improvement.

Failing to find any simple solution to this problem, we nevertheless had a reasonably workable imaging system that could image a gas bubble and that was capable of achieving 30 µm•30 µm resolution. Thus we proceeded to actually try to photograph a propagating streamer.

4. Second experiment -photographing a streamer

The goal of the second experiment was to charge the electrodes in a high voltage cell filled with dielectric liquid, focus a laser beam (henceforth called the plasma-inducing laser) between the electrodes, creating a plasma and initiating breakdown. At a known and adjustable time (0-100 µs) after the plasma-inducing laser shot, a second laser beam should pass between the electrodes and create a shadow. The shadow should then be captured by the camera. The imaging system (laser, bubble, shadow and camera) was thus basically the same as in the previous experiment, though the physical layout was different. However, the object to be detected was now very different: a high voltage cell, filled with transformer oil in which the breakdown was to be initiated by another YAG-laser. This and the increased need for synchronization demanded some added equipment.

4.1 Set-up

The following extra equipment was used for the second experiment:

- A FUG High Voltage supply 0-65 kV DC and high voltage cell, with windows on the sides and filled with transformer oil (constituting the object). The electrodes were half-spherical. In our experiment we had one positively charged elcetrode and one grounded.

- A homemade "starter" which simply gave a "go" signal (an electronic pulse, adapted to TTL electronics) for the set-up.

- A second Nd:YAG-laser: DCR-1 (the plasma-inducing laser).

- Two homemade function generators.

- A homemade program called vblsum which worked in the videoblaster by receiving a signal from one of the printer ports and ordering the videoblaster program to store and keep next image.

- A digital oscilloscope Tektronix TDS 540.

A schematic of the arrangement for synchronizing the laser pulses is shown in figure 12.

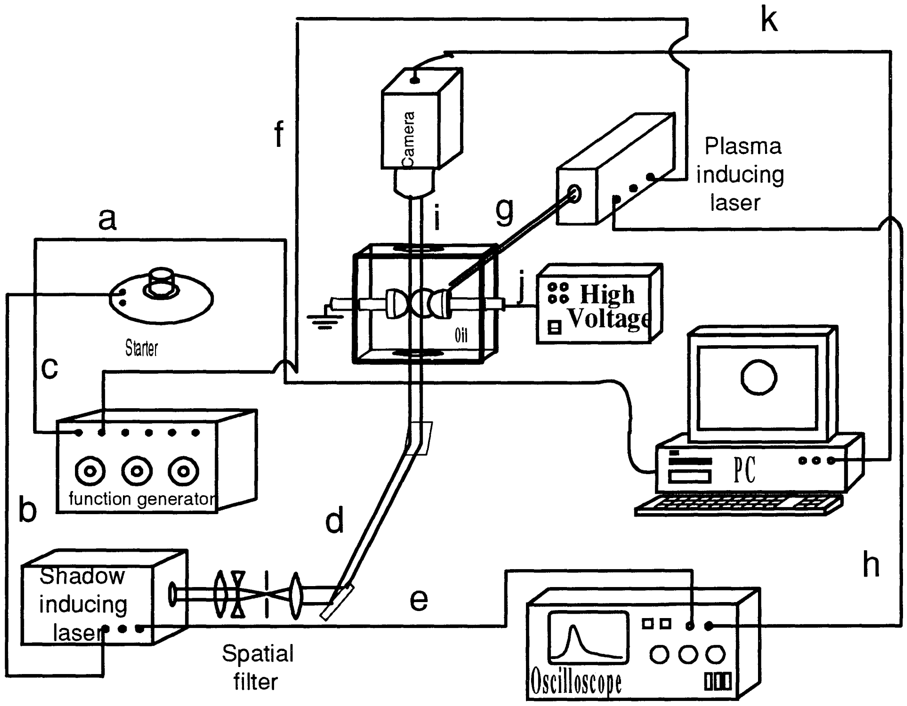

Fig 12. Schema of the set-up in the second experiement

Prior to the experiments high voltage was applied to the electrodes and the process was started by pressing the starter button.

In figure 12 the connections were:

a) A cable from the starter to the computer program vblsum via a printer port. The signal told the program to keep the next image from the camera via k. Vblsum works from the videoblaster program. The operator tells the program to wait for a signal on the printer port ("armed" mode) and when it receives this signal it saves the image received immediately after the signal and takes no new ones.

b) A cable from the starter to the input connection on the shadow inducing Nd:YAG-laser. The signal told the laser to begin lasing. 3.2 ms later lasing occurred during 3.2 ns. A schematic (copy from the manual) of the sync outputs, q-switch high voltage, flashlamp and laser pulse can be found in appendix 1.

c) A cable from the starter to the function generator telling the generator to start counting a variable time roughly 2.9 ms before giving a signal to the plasma inducing laser. This delay should be variable to create a delay of 0-100 μs between the laser pulses (this is dealt with in more detail further down). However, we needed to create a total delay of 2.900 ms with a precision of 1 μs. No single function generator capable of such a feat was available. This meant that in reality two function generators in series were used, one to create a delay slightly slight less than 2.9 ms, and one to create a smaller delay to fine tune the delay. For the sake of simplicity this is displayed in fig 12 as one object.

Note that a), b) and c) carries the same signal.

d) and i) Laser light is passing from the shadow inducing laser to the high voltage cell to finally end up in the camera. Note that this is meant to happen 0-100 μs after plasma has been initiated by the other laser.

e) A cable from the Q-switch synch output on the shadow-inducing laser to the oscilloscope gives us the time when the shadow-inducing laser gave laser light. This will be compared to the time the plasma-inducing laser emits light (coming via h) to determine how long time that had passed from the plasma was induced to until the shadow was made. Appendix 1, a copy from the laser manual describes the synchronization of the laser itself. It is to be noted that the Q-switch synch output goes high 50 ns before lasing occurs. It might also be added that the digital oscilloscope's ability to zoom and the ability to measure an elapsed time between two pulses on screen better than a human eye proved very useful. I would say the digital oscilloscope, as opposed to an analogue one, is a virtual necessity.

f) A cable from the function generator to the external input connection on the plasma-inducing laser. The signal tells the plasma-inducing laser to transmit a light pulse. A schematic of the external control etc. of the plasma-inducing laser can be found in appendix 2.

g) Light from the plasma-inducing laser passes through a lens and creates plasma between the electrodes, initiating breakdown.

h) Cable from the Q-switch synch output of the plasma inducing laser to the digital oscilloscope. Note that this signal goes high roughly 80 ns prior to lasing. However, since we only strive for a precision of 1 μs this is not important. The function of the oscilloscope is described in e).

j) Prior to the laser shots the high voltage supply gives a positive charge to one of the electrodes, allowing us to initiate breakdown with g)

k) A cable from the camera to the video input of the video card on the computer. The information captured by the camera is displayed in the program videoblaster using the program vblsum for synchronization via a).

The exact timing of the various signals is described below. It might be added that the number of cables made labeling the cables to avoid confusion necessary.

The arrangement of the light source was similar to the one in the first experiment. It is however to be noted that the YAG-lasers were in two different rooms, forcing us to lead the laser light from the shadow-inducing laser via a duct to the other room. The shadow inducing laser beam was then led into the cell from below, passing the electrodes and into the camera lens above. The plasma inducing beam was led into the cell from the side between the electrodes as in fig. 13.

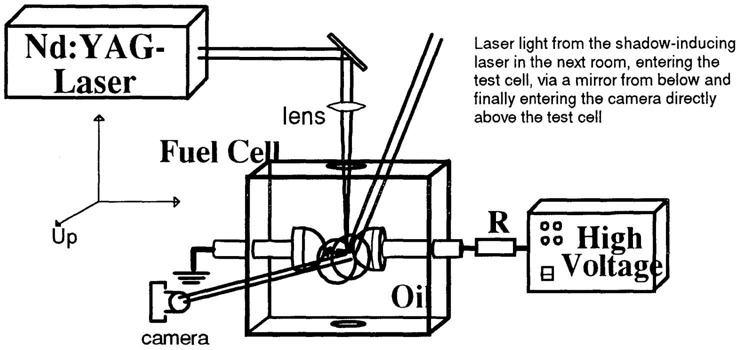

Fig 13. Arrangement of equipment around the test cell. Note that laser light is entering from the side (plasma-inducing laser) and from below (shadow-inducing laser).

4.1.1 Synchronization

Since the idea of the method is to induce a streamer with one laser and photograph it at a specified, but variable time after the initiation, it is of great importance to synchronize the lasers correctly. This was somewhat problematic since the shadow-inducing and plasma inducing lasers were not identical and required different types of external triggering. The internal synchronizations of the laser are described in appendices 1 and 2. As can be seen from these, the light-inducing laser was lasing 3.2 ms after receiving an electronic “go” signal while the plasma-inducing laser was lasing 300 μs after receiving the same signal. Though the time delay from the “go” signal to lasing could vary a little from day to day, it varied very little from shot to shot. Using two home-made function generators and a home-made start pulse inducer we managed to synchronize the lasers and camera as in fig. 14.

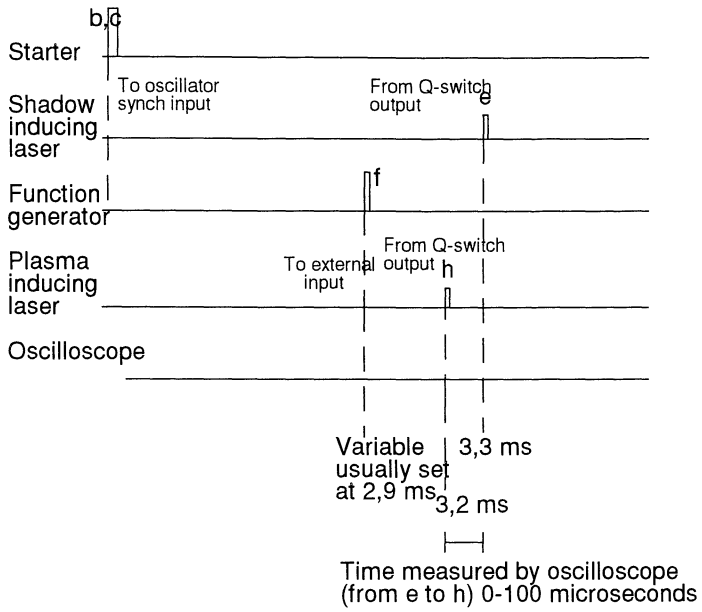

Fig 14. Schematic view of synchronization, not to scale. Note that the generator's time delay (usually 2,9 ms) is variable and that the letters in figure correspond to those in figure 11.

As can be seen, the mechanisms for external triggering of the two lasers were different, requiring that the plasma inducing laser received an external triggering pulse about 2.9 ms after the shadow inducing laser.

Measuring the time between the two laser beams with a digital oscilloscope it was found that this time seldom varied more than a microsecond. Thus we had achieved sufficient time accuracy. Though the exact time elapsed from the plasma-inducement could only be predicted by an accuracy of one microsecond the picture represents an integration over about 8-9 nanoseconds -the duration of the laser pulse for a shadow-inducing YAG-laser according to the supplier (see appendix 1). It is also to be noted that even though the exact time from the plasma-inducing shot could only be *predicted* with an accuracy of 1 µs, once the laser shot had occurred they could be *measured* with better accuracy. If the digital oscilloscope was ordered to sample 50 000 times during 100 µs we would have an accuracy of 2 ns. Unfortunately we are not capable of using the oscilloscopes impressive accuracy since we are not actually measuring at what time the laser gives light, but rather at what time the q-switch sync output goes high (sent to the oscilloscope via the cables e and h). As can be seen from appendix 1 and 2, this happens 50 ns respectively 80 ns before the laser pulses. We have no way of checking these figures from the manuals, but we could conservatively set the *measured* accuracy to 10 ns.

4.2 Problems

At this point we run into four problems:

The laser inducing the plasma created one or more bubbles that distorted subsequent pictures. It was necessary to wait for the bubbles to burst until another picture could be taken. Furthermore the plasma created sprinklings on the upper cell window, further distorting the picture.

There were also problems with reproducibility. The energy of the laser inducing the plasma varied, resulting in different streamer propagations (though the streamer would not propagate in an identical manner even if the energy was constant, this exacerbated the problem). The same was even more true for the laser giving light to the picture. This resulted in problems with over- and underexposure.

Since the lasers were located in two different rooms the beam paths of the lasers were very long. This and the required precision of the beams made the entire setup sensitive to vibrations and often requiring readjustments.

The program vblsum and the electronics for instructing the computer to take the first and only the first picture worked erratically. Usually it behaved as if it had never received the signal. Only about one time in four attempts did it freeze the picture as it was supposed to. This had been a manageable problem in the previous tests when repeated attempts could be made quickly. When this was not the case, due to the problems mentioned above, it proved extremely frustrating.

These facts and the time limit imposed on my access to the equipment prevented me from successfully photographing the streamer propagation or the bubble associated with it. Thus I have failed to achieve the secondary, more ambitious goal, of verifying the existence of the bubble.

However, we have still managed to achieve the primary goal: proving the general workability and try it out to make it possible to evaluate the method.

5. Evaluation

5.1 Evaluation of the method

Thus I consider all the problems mentioned above to be quite manageable (and will present some suggested improvements) and this method of studying a propagating streamer to be a sound, workable method with comparatively cheap and easily available equipment.

One might, however, be wonder if the method would allow us to see the streamer itself. We have failed to prove that, but since the streamer typically has a diameter of between 10 and 100 μm, the resolution, which has been shown to be 30 μm, is probably good enough for all streamers.

An advantage of the method however is the very good time resolution of 10 nanoseconds -the duration of the laser pulse. This can be compared to the time resolution of a shutter in a framing camera which might be 200-1000 nanoseconds. Assuming the streamer propagates by two kilometers per second this represents 20 μm with our method, which is pretty close to the resolution of 30 μm and about the size of a diameter of the streamer. Thus our method might not be good enough to study the very edge of the streamer itself (though far superior to most other methods with much lower time resolution) but definitely sufficient for studying the bubble.

Could our method be used for measuring the velocity of the streamer? It might not seem so since this is a one shot arrangement. It can however be done indirectly in one way with no added equipment. We could simply make two experiments taking two photos at different times after the initiation, see how far at has propagated at these different times and calculate the speed according to:

$$v = \frac{l_2 - l_1}{t_2 - t_1}$$

where v is the velocity l_2 and l_1 is how far the streamer has propagated at the time t_2 and t_1 after the initiation in the second and first shot respectively. With a precision for measured time as 10 ns and a conservative estimate of the precision in space of 100 μm a conservative estimate gives an error margin as 10%, which seems quite good. Unfortunately the calculations assume that the speed is constant during the propagation, that the speed will be the same if the test is repeated under identical circumstances and that test can indeed be repeated under identical circumstances and give identical results. It is particularly doubtful if we can repeat an experiment under identical circumstances in our case since the energy of the plasma-inducing shot varied from shot to shot. Even if we could, however, a streamer is such a phenomenon that it does not behave identically even if the test is repeated under identical circumstances. On the other hand, repeated experiments and statistical treatment of the results could reduce these problems to manageable levels.

If we were to improve the method by measuring the current from the cell's electrodes, which indicates when streamers start, two other methods are possible. Both uses only one picture. Measuring at what time discharges occur gives us the time at which the streamer (t_s) began to propagate and at what time breakdown (t_{bd}) occurred. The q-switch output from the shadow-inducing laser gives us the time at which the picture was taken (t_p). Now we can calculate the speed since the start of the streamer:

$$v = \frac{l}{t_p - t_s}$$

where l is how far the streamer has propagated. A conservative estimate of the error margin is 5%. However, since the discharges are such that t_s is harder to determine exactly than t_{bd}, it would probably be better to look at the distance left to breakdown (Δl) and divide by the time from the picture was taken to breakdown. By comparing the remaining distance to breakdown in the picture with the time remaining to breakdown:

$$v = \frac{\Delta l}{t_{bd} - t_p}$$

we could measure the speed of the last part of the breakdown more accurately. From what has been said above, we have no reason to believe that such a method could not be used to measure the speed of the streamers with some accuracy.

5.2 Suggested improvements

Having to synchronize the laser timings by measuring them with a digital oscilloscope and using two pulse generators for creating suitable delay is a clumsy arrangement. More advanced electronics, preferably customized, could greatly facilitate for the operator.

The problem with bubbles and stains can be circumvented having the light-giving laser beam enter from the side instead of from below. This will require that the plasma-inducing laser beam enters from below or above or a different arrangement of the electrodes.

A high-pass spatial filter might be useful to add just before the camera to enhance the contours.

An non-interlaced camera would increase the resolution (double the information) of the pictures. As has been noted however, there is a major difference in cost between interlaced and non-interlaced cameras.

Further shortening of the beam paths can be made if both lasers are placed in the same room. This can reduce the sensitivity of the set-up to vibrations and unintended movements of lenses.

The program vblsum might be improved so it captures every picture.

The problem with over- and underexposure might be addressed by somehow making the light emitted from the image-producing laser more constant. If this is not possible it might be worth experimenting with turning AGC on, though this means that the brightness of the image will no longer be proportional to the light intensity.

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DCR-2/2A SYNC OUTPUT, Q-SWITCH HIGH VOLTAGE, FLASHLAMP AND LASER PULSE WAVEFORMS

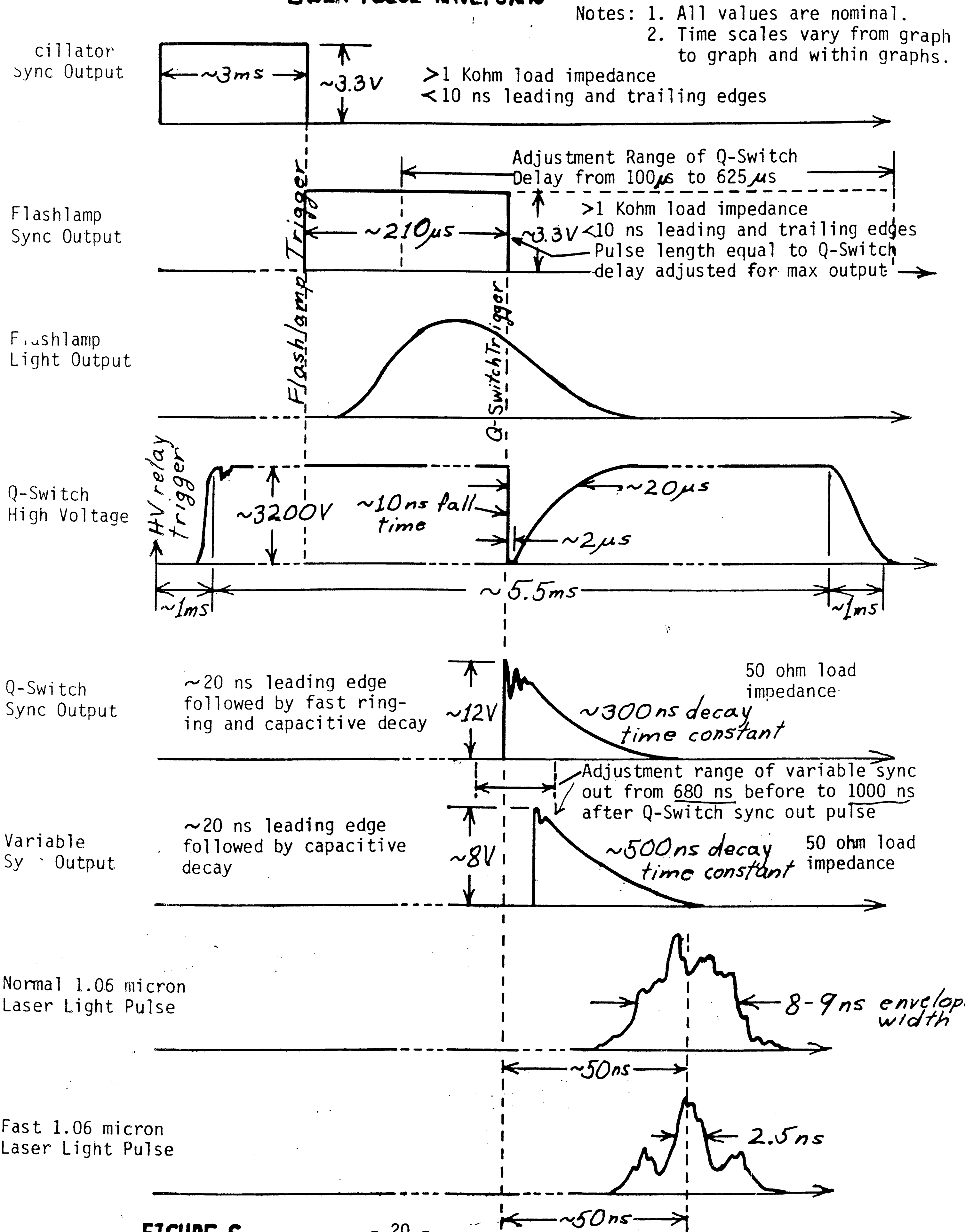
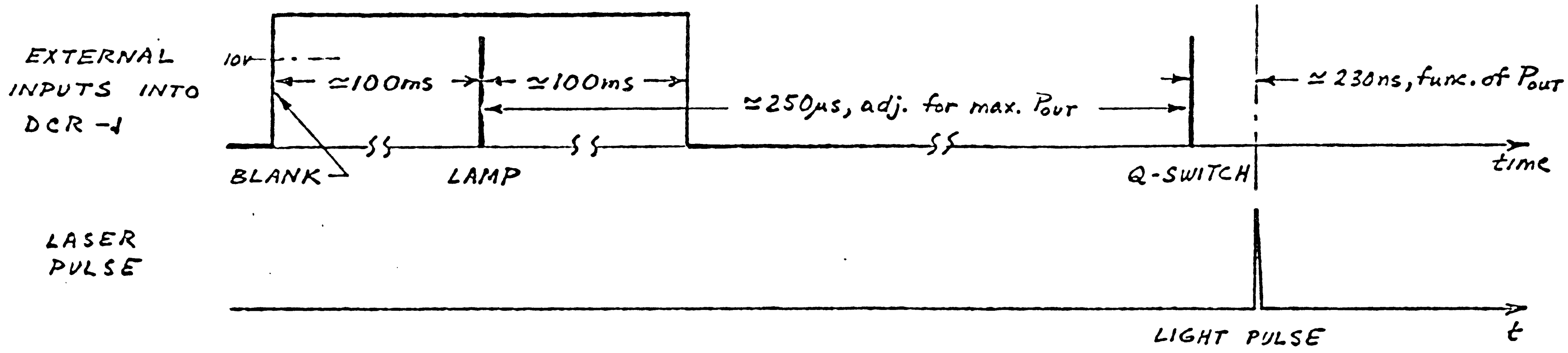


FIGURE 6

EXTERNAL CONTROL WITH INTERNAL LAMP FLASHING (FOR CONSTANT THERMAL FOCUS):

PULSE REP. RATE at 10 Hz,

Q-SWITCH DELAY at EXT.



EXTERNAL LAMP, INTERNAL Q-SWITCH OPERATION: PULSE REP. RATE at OFF,

Q-SWITCH DELAY at NORMAL.