Measurements of the Motion of Filaments in a Plasma Ball

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Abstract

Measurements were made of the motion of the filamentary structures in a plasma ball using high speed cameras and other optical detectors. These filaments traverse the ball radially at ~10^6 cm/sec at the driving frequency of ~26 kHz, and drift upward through the ball at ~1 cm/sec. The number of filaments and their radial speed increase approximately linearly with the applied voltage above some threshold. A custom plasma ball was constructed to observe the effects of varying gas pressure, gas species, and electrode properties on the filament structures.

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1. Introduction

Plasma balls (sometimes called plasma globes) are popular science toys that show the complexity and beauty of plasmas, as illustrated in Fig. 1. However, the motion of the filamentary structures in these plasmas has not been described in the literature, and the physics of this motion is not yet well understood.

This paper is intended as a tutorial that describes observations of the motion of the filaments in a plasma ball. Most of the measurements were made on a commercial plasma ball using high-speed cameras and other optical detectors available at PPPL. We also describe some experiments made with a custom plasma ball in which other variables of interest such as the gas composition, applied voltage, frequency and electrode properties can be adjusted.

Of course, similar filamentary plasma structures have been observed and studied for many years in sparks, lightning, streamers, and dielectric barrier discharges. A spark is a transient high voltage breakdown occurring between two conducting surfaces [1], in contrast to plasma balls, which discharge between insulating surfaces. Lightning depends on hard-to-measure properties of clouds so is not well understood [2]. Streamers are "narrow rapidly growing ionized channels that generally emerge from sharp tips when a high voltage is applied, and prepare the path of sparks of all sizes" [3]. The physics of streamers involves a self-generated field enhancement and ionization at the head of a growing discharge channel [4]. Fast images of streamers have been made in air between a point electrode and a plane electrode with a time resolution of ~1 ns, and show a complex multi-scale branching structure similar to lightning, with a propagation speed of the streamer head into the neutral gas of ~10^7-10^8 cm/sec [5]. Streamers are normally transient one-time events, in contrast to the periodic steady-state nature of plasma balls.

Dielectric barrier discharges (DBDs) are filamentary AC plasmas made between insulating surfaces, i.e. the electrodes are located behind these insulators and are not in contact with the discharge [6]. Their frequency and pressure range is ~1 kHz-10 MHz and ~10 kPa–500 kPa, which are close to the normal ranges for a plasma ball. However, DBD plasmas are normally short-lived (~ ns) and short-length (~ mm) 'micro-discharges', which tend to occur in large numbers and move across the dielectric surfaces. Some forms of dielectric barrier discharges show interesting self-organized structures [7-11], which are understood to some extent through numerical simulations. A steady-state atmospheric pressure DBD has been made with cm-scale filament structures at ~10 kV and 45 kHz [12], but these structures do not move or branch like those in a plasma ball.

Thus there seems to be no description in the literature of the behavior of the filaments such as the ones in Fig. 1, except for a brief overview of its properties for physics teachers [13]. In this report we first describe the basic construction of a commercial plasma ball in Sec. 2, and then describe the short term and long term motion of the filaments in Secs. 3 and 4. Variations with applied frequency and voltage are discussed in Sec. 5 and 6, the filament brightness vs. radial distance in Sec. 7, and the discharge startup process in Sec. 8. A description of the design and properties of a custom-made ball are in Sec. 9. Some other observations and a list of open questions are in Sec. 10 and 11, respectively.

2. Basic Construction of the Ball

The basic properties and construction of a typical commercial plasma ball (Edmund Scientific "Nebula Plasma Ball") are shown in Table 1 and Fig. 2. The main gas species were identified by a high resolution visible spectrometer to be neon and xenon, with a possible trace of nitrogen. The total pressure was measured to be 740 Torr, i.e. just under atmospheric pressure, and the only species visible on a mass spectrometer at $M < 40$ were isotopes of neon. The ball is powered by an oscillator/transformer circuit inside the base of the ball which produces a ~5kV, ~26kHz signal applied to the wire running up the central glass tube, as shown in Fig. 2. This wire is held in place by a net of steel wool trapped inside the spherical glass bulb at the top of the central glass tube. The steel wool touches a layer of black conducting paint on the inner surface of the bulb which forms the electrode itself.

The current is capacitively coupled through the inner glass bulb to the plasma filaments, and from the outside glass sphere back to the power supply in the base. The current inside the plasma ball is presumably carried by the visible filaments. The filament structure inside the ball can be changed by touching the outer glass sphere with a grounded wire or a finger, which produces a single bright filament. The current through such a filament was measured by an external AC Pearson meter to be ~1 mA. The ball frequency can be measured using the electromagnetic 'pickup' detected by any short antenna attached to a nearby oscilloscope.

<u>Table 1: Basic properties of a commercial plasma ball</u>

gas species – neon + xenon
pressure ~ 740 Torr
frequency ~26 kHz
voltage ~5 kV max.
current ~1 mA max.
filament length ~ 6 cm
filament diameter ~ 1 mm

The typical appearance of this commercial plasma ball is shown at the top left of Fig. 1, with a close-up view at the right in Fig. 2. The filaments themselves are blue for most of their length, but are red near the outer glass sphere. Several different balls from this company were tried, all of which had nearly the same appearance. However, the number and length of the filaments in this ball did vary significantly with different applied voltages and frequencies, as described in Sec. 5.

3. Radial propagation of the filaments

While the filaments appear to be continuous in time to the human eye, they actually only exist for a fraction of each oscillating voltage cycle. Figure 3 shows photographs of the commercial plasma ball taken at 500,000 frames/sec using a Princeton Scientific Instruments PSI-5 camera at 2 μs/frame with a 64x64 pixel resolution. The images are in sequence from the upper left to the lower right, and displayed in a false color scale for clarity. The filaments can be seen to start at the surface of the inner electrode (upper left in each frame) and propagate radially outward to the outer glass sphere and then dissipate over ~3-4 frames, i.e. 6-8 μsec. Therefore the propagation speed is ~10^6 cm/sec, and the filaments are bright for only ~20% of the discharge cycle.

Note that the filaments appear to follow the same path during each cycle. This was confirmed quantitatively by subtracting pixel intensities of consecutive discharge images. Filaments only begin to drift significantly with respect to their ~1 mm diameter over ~80 ms on average, i.e. they move at ~1 cm/sec. Thus the filaments which appear stable to the eye are the superposition of thousands of AC discharge cycles. The cause of this memory characteristic is most likely the ionization channel left by the previous high voltage pulse. Note that the light intensity falls by up to 99% over the pulse cycle.

4. Long term Filament Behavior

Some truly remarkable behavior occurs as these filaments drift through the ball, as illustrated in Fig. 4. These images were captured using a Phantom 7.3 high speed camera with a framing rate of a few kHz. The relative time for each frame is indicated in each of the images.

Filaments are typically (but not always) "born" near the bottom of the ball structure and drift upward over a typical time of a few seconds. When they die, they retract back into the electrode over ~0.5 msec, as illustrated in Fig. 4(a). Interestingly, this differs from how filaments 'dissipate' after each individual discharge cycle, as shown in Fig. 3.

At normal operating frequency, filaments in the standard ball bifurcate, i.e. split into two over their ~few second lifetimes; however, at higher frequencies, filaments were seen forming as many as 5 branches. Bifurcated filaments migrate upward in a fascinating manner. As the main body drifts upward, the lower branch will disintegrate and then a new branch will form above the surviving branch, so that the filament appears to "walk". In some regimes, single-stem filaments would "unzip" themselves into two disjoint filaments. Sometimes, filaments would "intercept" each other as shown in Figure 4(b). These aforementioned phenomena typically occurred over milliseconds.

5. Variations with Frequency and Voltage

The commercial ball circuit was modified so that the internal 26 kHz oscillator was replaced by an externally applied low voltage pulse from a signal generator. In this way the frequency of the high voltage waveform could be adjusted, although not at a constant voltage. In addition, the magnitude of the high voltage was varied by plugging the AC adaptor of the ball into a Variac, instead of into a 110 VAC line.

There was a clear variation in the relative number of filaments observed vs. frequency of the applied voltage, as shown in Fig. 5(a). At frequencies below 4 kHz, a uniform glow was observed in the ball. At 5 kHz, the first filamentary structure appeared. This filament was very diffuse, unlike those in the commercial ball under normal operation. The number of diffuse filaments increased with increasing frequency, but above 10 kHz the filaments sharpened and the surrounding glow disappeared. Between ~17-40 kHz, filaments looked as they do at the standard operation, and the maximum number of filaments occurred at ~24 kHz. The number of filaments then decreased beyond ~50 kHz, and also decreased in length and no longer had red tips, as shown in Fig. 5(b). The last filament disappeared at ~100 kHz, with length about a third of the ball radius.

For the results of Fig. 5 both the frequency and the pulse length of the high voltage waveform were varying with the frequency. To help isolate these effects, the width of the applied low voltage pulse was separately varied from ~1 μs to the full period over the range of frequencies between 5-100 kHz. In general, there was no noticeable change in the filaments until the pulse width was reduced below 5 μs, below which the filament length was roughly proportionally to the pulse length. Since the propagation time was previously determined to be about 6-8 μs (Sec. 3), the apparent explanation is that for pulse lengths below 5 μs the filaments do not have enough time to traverse the ball before the voltage drops below some critical value. Thus unless very short pulses are used, plasma balls are mostly indifferent to pulse shape, but always sensitive to frequency.

At standard operating frequency (26 kHz), the electrode high voltage was ~5 kV, but as frequency increased the circuit's output voltage decreased roughly linearly down to ~0.5 kV at 100 kHz. Thus, the frequency scan of Fig. 5 was also correlated with a voltage scan. To help distinguish these effects, Fig. 6 shows the variation in the number of filaments vs. the magnitude of the applied AC voltage at the standard 26 kHz frequency (the high voltage was checked to be linear with the applied AC voltage). As the voltage is raised from 0, filaments first form at around 70 V and the number of filaments increases with voltage up to the standard operating value of 120 V. Thus the decrease in the number of filaments with increasing frequency above ~25 kHz in Fig. 5 is probably due in part to the decrease in voltage with frequency of the circuit.

Another observation from the voltage scan is that at voltages below 80 VAC the filaments do not reach the outer glass sphere, but do retain their overall shape, sharpness and color qualities (blue with red tips) at all voltages. Thus, the phenomena observed with changing frequency are at least in part due to the frequency increase rather than the voltage decrease. Note that upon decreasing the voltage, a filament often remains at voltages as low as 55V, but it always disappears after a few seconds. Stable filaments persist as low as 60V. This hysteresis property is just a general property of these discharges. It takes a certain critical AC voltage of ~70V to break down the neutral gas, but after breakdown, lower voltages can still maintain the discharge.

6. Radial Filament Speed vs. Voltage

The radial filament speed was estimated in Sec. 3 using the PSI-5 fast-framing camera to be ~6 cm/6 μs ~10^6 cm/sec (Fig. 3), but the accuracy of that measurement was limited due to the frame integration time of 2 μs. A second method used to measure the radial filament speed was a lens and fiber optic system which collected light from three chords along the radial dimension of the plasma ball, each chord having a diameter of ~0.5 cm. These light signals were sent to three photomultiplier (PM) tubes to measure the time-dependence of this light with a ~1 μs time resolution.

A typical result of this detection method is shown in Fig. 7(a). The three traces at the bottom are the signals from the three PM tubes, and the trace at the top is an electromagnetic "pickup" signal from the plasma ball measured by a short antenna. In this case the three channels were aligned vertically above the center of the ball to view any filament that passed through a vertical line. The peaks in the signals identify the times at which the filament passed the corresponding points in the ball during each discharge cycle. Clearly, this method only works when a filament happens to move into the path of all three points, but even though the filaments drift rapidly, for brief time intervals three peaks can be observed with the expected time lag of a few microseconds. By triggering with respect to the third (outer) peak and setting the scope trigger level appropriately, the traces will only be recorded when a filament passes through that point. Since it will most likely have passed through the first two points as well, all three peaks will be present for comparison.

The variation of the radial speed measured this way vs. the applied AC voltage is shown in Fig. 7(b). The average speed increases almost linearly with voltage between 60-120 VAC, with a value of ~1.3 x10^6 cm/sec at the normal operating voltage of 110 VAC. This is close to the speed inferred from the filament motion shown in Fig. 3. Note that in Fig. 7(a) the gap between the first two peaks is smaller than the gap between the second and third, suggesting that the radial filament speeds decreases with radius.

7. Filament brightness vs. radius

Figure 9(a) shows a false-color image of the commercial ball taken under normal conditions with a moderate exposure time (integrating over many AC cycles), where red is brightest and blue is dimmest. It seems as if the filaments are brighter and thicker near the central electrode than they are near the outer glass sphere. A similar conclusion could be drawn from the PSI camera images of Fig. 3.

However, this conclusion is apparently inconsistent with the intensity vs. time traces from the PM tubes shown in Fig. 7. For example, Fig. 8 shows the intensities along the filaments in three successive images taken from the PSI-5 camera. These intensities were always maximum near the central electrode (at the left), and decreased towards the outer glass sphere (to the right). A filament with that intensity profile, moving in space, should produce a strictly increasing intensity in time as it passes by a given point, until it disintegrates.. Thus, we would expect the each of the 3 PM tube channels to rise in sequence, and not decrease before the next channel reaches its maximum.

It turns out that the decreasing intensity with radius in Fig. 8 is just an illusion caused by the exposure time of the PSI-5 camera. As the filament propagates from point A to point B during exposure, pixels near A collect light for a longer time than those near B, so even if the filament tip is the brightest point in reality, there will always be an intensity decrease near the tip, with a characteristic decay depending on the exposure time. Knowing that the total propagation takes 6-8 μs, notice how the graphs of the intensity along the filament in Figure 8 show a roughly steady high intensity and then a roughly exponential drop-off. The duration of this drop-off appears to be about half of the full length of the plot, i.e. ~2 μs, which is the exposure time.

To verify this effect, photographs of the ball were taken with a Andor Istar camera capable of even shorter exposure times. As shown in Fig. 9, at 400 ns exposure, the filament moves very little during exposure and the photograph shows that the intensity actually increases with radius, as suggested by the PM tube traces of Fig. 7.

8. Plasma Ball Startup

To understand the steady state behavior of the plasma ball, it may help to explore how the filaments originate. When the AC power to the commercial plasma ball is first turned on, normal filaments do not form instantaneously, as shown by the high speed videos taken with a Phantom 7.3 camera in Figure 10. These videos reveal that the initial discharge is a diffuse glow with some amorphous filamentary structures visible, and the normal ~1 mm thick filaments take ~100 ms to develop, which is ~3000 discharge cycles. However, up to ~20 msec these filaments are short compared to the ball diameter, and up to ~100 msec these filaments are still radially straight, and take up to ~1 sec to reach their normal curved and bifurcated structure. The evolution is sometimes qualitatively different from this, apparently depending on the phase of the 60 Hz wall voltage at startup, but overall, filaments evolve at startup over ~1 sec.

9. Custom ball design and filament structures

A custom plasma ball was built at PPPL during the summer of 2009 in which additional factors, such as gas composition, gas pressure, and electrode properties could be adjusted. The apparatus is pictured in Figure 11. A spherical 2 liter (thick-walled) pyrex chemistry flask with three necks was used as the ball. It was evacuated with a roughing pump and filled with a mixture of up to two pure gases through one of the necks, which were sealed with rubber stoppers and vacuum grease. The central electrode was a wad of steel wool housed inside a test tube which was inserted through the middle neck so that the power supply could connect to the wool from outside. The third neck could be used in the future for inserting internal diagnostics. Neon was used as the primary gas, and xenon, nitrogen or air were used as trace gases. The externally controlled pulse circuit of Sec. 5 was used to apply variable waveforms to the central electrode.

The array of images in Fig. 12 shows some of the fascinating variety of filaments which were produced with this custom ball. At the lowest pressure achievable with our pump, a static orange glow fills the ball. In a typical experiment, the ball was filled with neon to about 0.2 atm., when the first diffuse filamentary structures were observed. Then, a small amount of trace gas was added, which typically sharpened the filaments. Then, additional neon was incrementally added up to atmospheric pressure. The same qualitative behavior with frequency was often observed as with the commercial ball. Notice for example, at the top right of Fig 12, that the filaments at low frequency (19 kHz) were very diffuse and those at high frequency (81 kHz) were short.

Sometimes with pure neon, sharp filaments did not appear at any pressure or frequency. However, leaking in a small amount of air drastically changed behavior, often producing filaments resembling those in a commercial ball (Fig. 5). But with just slightly more air, the filaments would become flame-like and shrink. With additional air, they eventually disappear completely. The same phenomenon occurred with small amounts of xenon. Adding a small amount of xenon sharpened filaments, altered their colors, or even extinguished them, though the characteristic colors were different from those with air.

Since such small amounts of gas strongly affected behavior, it is not surprising that residual gas remaining from the previous experiment influenced the subsequent experiment. Even when the ball was evacuated and refilled with pure neon, filament behavior could be different each time.

Because the concentration of these trace gases could not be measured with our equipment, but are so critical to operation, a clear procedure for producing filaments of a certain type can not be specified at this time. However, filaments most resembling commercial balls were achieved at pressures ~0.2-0.8 atm. and at frequencies from 30-60 kHz, with mostly neon gas fill. Starting from below 5 kHz and raising the frequency, the ball would evolve from diffuse glow to diffuse filaments to ideal sharp filaments, until filaments began to shrink and eventually disappear at a few hundred kHz.

Experiments were also done with various central electrodes to see how they affected filament behavior and to understand why the configuration in the commercial product was chosen. At first, a small chunk of steel wool was used as the electrode in the test tube; however the filaments were formed preferentially at the points where the steel contacted the tube. Since the stems remained fixed at these points, as the filaments drifted upward they would become highly curved and break, just as highly curved filaments tended to break in the commercial ball. But when the inner surface of the top of the test tube was coated with conductive paint, the stems were mobile, so the filaments could move more freely without breaking as often.

10. Other observations

This section describes a few other observations and speculations made during these experiments, which can be topics for further experiments.

a) Filament color

The filaments in the commercial ball are blue for most of their length and red near the tip (see Figure 2). The color change is presumably caused by the lower electron energy or electric field strength as the filaments propagate away from the electrode; in other words, at a certain radius, the electrons may be not energetic enough to excite the blue transitions. Thus, it seems likely that even when filaments only appear to traverse part of radius of the ball, as in Fig. 5(b), the ionization channel actually extends to the glass, but is simply not bright enough to produce observable light.

This seems to be corroborated by placing a finger on the glass. Under normal operation, this attracts a large percentage of the current because the human body serves as a better ground than the surrounding air. But even at lower voltages where the filaments only partially traverse the ball, the finger causes an intense, full-length filament to form. This suggests that the electron stream was always reaching the outer glass, but the additional energy concentrated in a single filament, due to the hand, was enough to excite visible light throughout its full length.

b) Convective motion

In the commercial plasma ball almost all of the filaments are born at the bottom of the ball (nearest the power supply base), and move upward at ~1 cm/sec toward the top of the ball, where they eventually die. However, when the ball is turned upside down, the filaments are born at the former ‘top’ of the ball, but still move upward, now toward the base. This suggests that the filaments move upward against gravity, presumably due to the upward convection of the warm gas surrounding the filament.

This was tested by putting ice on the top of a plasma ball to change the temperature gradient inside the ball. The result, as shown in Fig. 13, was that almost all of the filaments of the “ice-top” ball bent away from the cold air, except for one filament attached to the ice cube. Apparently the temperature distribution inside the ball affects the formation and slows convective motion of the filaments. However, heating the top of the ball with a hot air blower did not significantly affect the filament distribution.

c) Attachment to the central electrode

While filaments often twist and bend, they always seem to emerge perpendicular to the central glass bulb. This is most likely due to the fact that the local electric field near the surface of a conductor is always in the normal direction. The above effect may explain why the filaments in our custom ball were almost entirely in the upper hemisphere (Fig. 12). We used the tip of a test tube (upside-down) as our electrode container, and thus there were no normal surfaces pointing downward from the central electrode. Incidentally, with the conductive paint, it may no longer seem clear why the steel wool is needed. But if the wire tip was touched directly to the paint, the paint would evaporate there because of the extremely high current density at the point of contact, so then contact would be lost. So, the steel wool prevents evaporation by distributing the current more uniformly. It also holds the wire securely in place, guaranteeing permanent contact better than if the wire were loosely touching the paint.

11. Directions for further research

This report described observations and measurements of the structure and motion of filaments in a plasma ball. For example, these filaments traverse the ball radially at ~10^6 cm/sec at the driving frequency of ~26 kHz (Fig. 3), and drift upward through the ball at ~1 cm/sec. The number of filaments and filament radial speed increase approximately linearly with the applied voltage above some threshold (Figs. 6 and 7). However, we did not discuss the physics which causes these phenomena, so there are many open questions and directions for new experiments , such as:

a) What determines the number of filaments ?

The relative number of filaments varies in a systematic way with the externally applied frequency and voltage in the commercial plasma ball, as shown in Figs. 5 and 6. It is not yet clear what determines this number, or how this number varies with gas species mix, pressure, or electrode geometry. Therefore more experiments should be done to measure the number of filaments in the custom plasma ball as a function of frequency and voltage for a variety of gas species and pressures. These measurements can be made using a simple digital camera, since the filaments evolve only slowly (~1 sec) in a normal plasma ball. It is possible that some systematic space-time pattern in this data can be discovered, analogous to the self-organized structures sometimes seen in dielectric barrier discharges [e.g. 6-10]. Further experiments can determine the influence of electrode geometry, e.g. spherical vs. flat vs. bumpy electrode surfaces.

b) What determines the slow dynamics of the filaments ?

The filaments in a commercial plasma ball are mainly created near the bottom of the ball and normally move upward at ~1 cm/sec. Thus the main filament motion seems to be driven by thermal convection of the gas near the filaments. However, there is at least one frequency range in which the filaments spontaneously moved *downward* in a commercial plasma ball. Therefore experiments should be done to understand the general motion of the filaments, e.g. by controlled heating or forced gas flow inside the ball, or by varying the gas density or pressure. It would also be interesting to investigate how other forces might act on the filaments, e.g. by applying internal or external electric or magnetic fields. The filaments can also bifurcate from one into two as they move through the ball over a ~1 second timescale. This mutual interaction between filaments can be systematically measured and compared with observations and explanations for qualitatively similar behavior in sparks and streamers.

c) What determines the diameter of the filaments ?

Perhaps the most remarkable property of the filaments in a plasma ball is their very small diameter, which we have estimated to be ~0.5-1 mm for the commercial plasma ball (based on the light emission). On the other hand, at different gas pressures the diameter of the filaments can be up to ~1 cm (see Fig. 12), and also varies systematically with the driving frequency and voltage. The filament diameter most likely determined by a balance between the ionization and radial diffusion processes in the filament, neither of which is well understood at present. It is also possible, but less likely, that self-generated electric or magnetic fields affect the filament diameter (i.e. as in a pinch). There exists a fairly well developed theory for the diameter of a single streamer [4], but it is not clear whether this applies to the near-stationary-state of filaments in a plasma ball.

d) How are the filaments formed during the initial turn-on ?

Based on images of the startup of a commercial plasma ball like those in Fig. 10, it appears that the filaments initially form and evolve over a timescale of 0.1-1 sec, i.e. over thousands of cycles of the high voltage drive. Their formation seems to start from a diffuse glow around the central electrode, out of which the first few filaments begin to grow, somewhat similarly to streamers [3]. The initial filaments are very straight radially and only after ~0.3 sec do they begin to curve and branch into the complex slowly moving structures seen in the steady-state. This picture is clearly incomplete since the startup process of the high voltage circuit itself is not known, and very likely evolves over ~0.1 sec. Therefore a systematic set of experiments is needed to characterize the formation process of the filaments and its dependence on the driving frequency, gas species and pressure, and electrode geometry. These experiments should use a well-controlled high voltage source with a programmable waveform, with a bandwidth ~1 kHz-1 MHz and a larger voltage range and current capability than the high voltage supply in a commercial plasma ball.

e) How do the filaments propagate radially ?

The initial measurements of the commercial plasma ball as in Figs. 3 and 7 show that the filaments in the steady-state plasma ball propagate radially from the central electrode to the outer glass sphere at $\sim 10^6$ cm/sec. This is near the lowest range of velocity measured for streamers, which have typical velocities of $\sim 10^7$–10^8 cm/sec [1,10]. However, in contrast with streamers, the plasma ball filaments almost always form exactly in the narrow channels left behind by previous filaments, even when the previous filaments are nearly invisible, as shown in Fig. 3. It is not clear yet whether the new filaments follow a very dilute electron cloud left behind by the previous filament, or perhaps follow a path of the low neutral density or the excited neutrals or metastable states left behind by the previous filament. Therefore more systematic data should be obtained on radial filament propagation speed as a function of pressure, species, voltage, and frequency. Creative experiments will be needed to identify the mechanism(s) by which the filaments retrace the path of previous filaments.

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Figure Captions:

1 (color online). Various forms of plasma balls. The commercial plasma ball used for the present report is shown at the upper left, and in Fig. 2.

2 (color online). The Edmund Scientific "Nebula Plasma Ball", manufactured by "Can You Imagine ?". The high voltage power supply is in the base, and the high voltage is connected to the inner electrode with the wire as shown. A larger picture of the filaments in this ball is shown at the right.

3 (color online). High speed images of the commercial plasma ball taken using a Princeton Scientific PSI-5 camera at 500,000 frames/sec and 2 μs exposure time per frame. The frames are shown sequentially from top left to lower right, with false coloring. The central electrode is at the upper left in each frame, and the outer glass sphere is at the lower right.

4. Images of filaments taken using a Phantom 7.3 high speed camera, with relative times indicated within each image. In (a) the filament highlighted by the arrow in the first frame "dies" by withdrawing back into the electrode over ~0.5 ms. In (b), the filament highlighted in the second frame emerges from the electrode and intercepts a branch of the neighboring bifurcated filament over ~7 ms.

5 (color online). In (a) is a measurement of the relative number of filaments vs. applied frequency for the commercial plasma ball. In (b) are images of the plasma ball with increasing frequency from left-to-right. At high

frequencies (such as 90 kHz shown at the right), the filaments decrease in length and appear to end before they reach the outer glass sphere. The high voltage is also decreasing with frequency in this scan.

6 (color online). Relative number of filaments vs. externally applied AC voltage at the standard 26 kHz frequency. The high voltage was checked to be linear with the applied AC voltage. As the voltage is raised from 0, the number of filaments increases with voltage up to the standard operating value of 120 V. No filaments were observed below 50 VAC.

7 (color online). In (a) are digital oscilloscope traces of three PM tube signals measuring the light emission from three points along a vertical radius above the center of the ball (lower traces), along with an electromagnetic pickup signal of the ball from a nearby wire antenna (upper trace). In (b) is an estimate of the radial propagation speed as a function of the applied AC voltage for a fixed frequency of ~26 kHz.

8 (color online). Pixel intensities along the filaments in three consecutive video frames of PSI-5 camera images such as shown in Fig. 3. The first trace at 2 μs shows the filament as it emerges from the electrode. The other two traces were respectively taken 2 μs and 4 μs later. The filament was at its full length (reached the glass) in the red trace. Note that the background darkness registered a nonzero intensity (~1800) on the camera so this level should be considered the zero of intensity. The radial propagation speed inferred from these images is similar to that of Fig. 7.

9 (color online). In (a) is a false-color image of the commercial plasma ball, showing the light intensity as brightest (red) near the central electrode. In (b) are two photographs of the same ball taken with the Andor Istar camera, the left at 400 ns exposure time and the right at 2 μs exposure. The shorter exposure time shows the instantaneous brightness is actually higher at the filament tip than at the central electrode.

10. Startup of a commercial plasma ball as viewed by a Phantom 7.3 camera. The times indicated are measured from the first appearance of light in the ball. The filaments initially are very diffuse, then form short radial spokes, then extend radially to the outer sphere, and finally after ~0.3 sec start to bend as in a steady-state globe.

11 (color online). Custom-made plasma ball based on a three-neck chemical flask. The vacuum roughing pump is at the bottom, and the high voltage supply is in the middle section. The gas bottles are out of the picture at the right.

12 (color online). Various types of plasma filaments formed in the custom ball with different gases, pressures and frequencies. There are wide variations in lengths, colors, straightness and sharpness under different conditions (labeled by pressure, trace gases, and frequency). Filament bifurcation and the varying-colored tips are seen in some instances, as in the commercial ball.

13. Effect of an ice cube placed on top of a commercial plasma ball (right). Most of the filaments are “repelled” from the cold top.

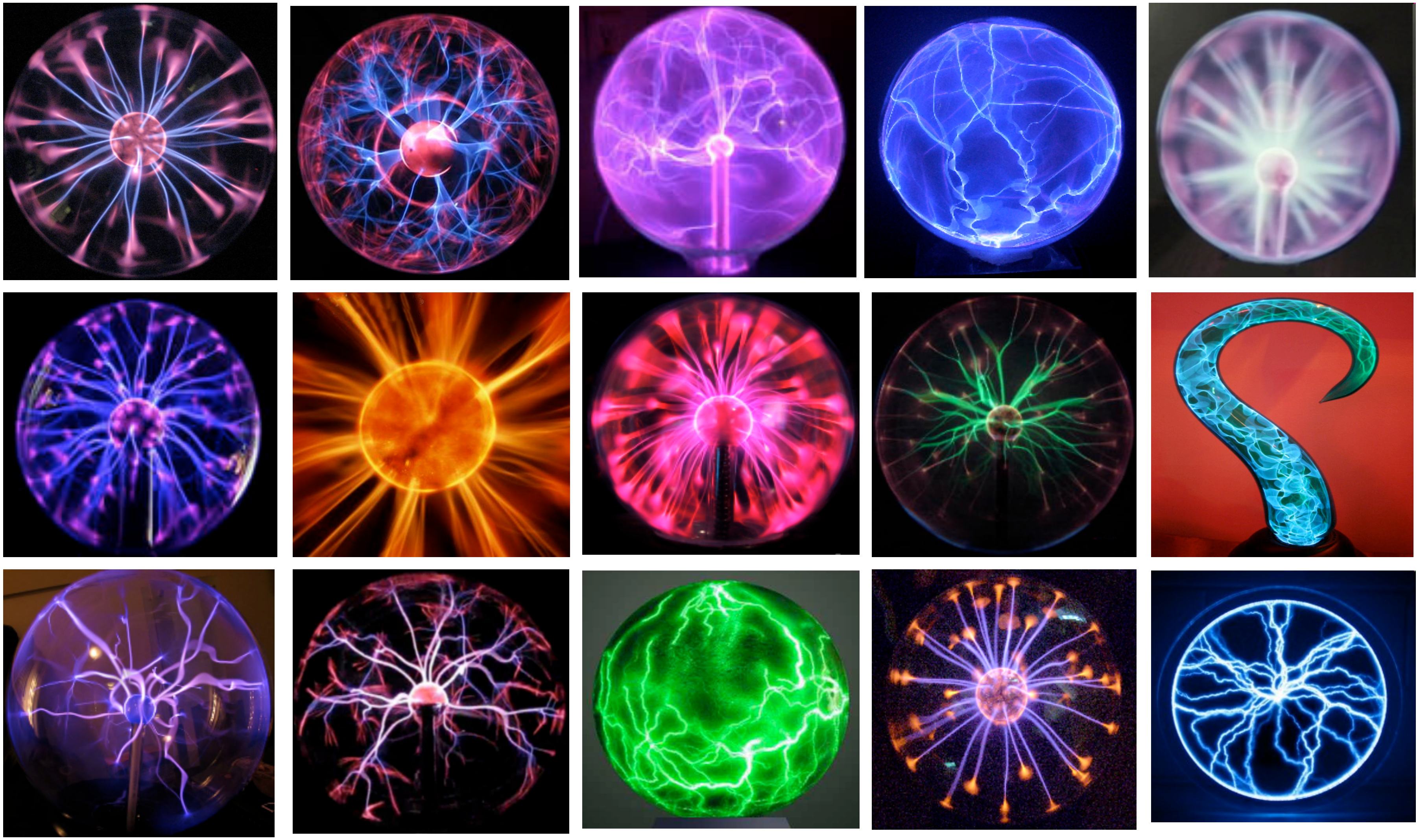


Fig. 1

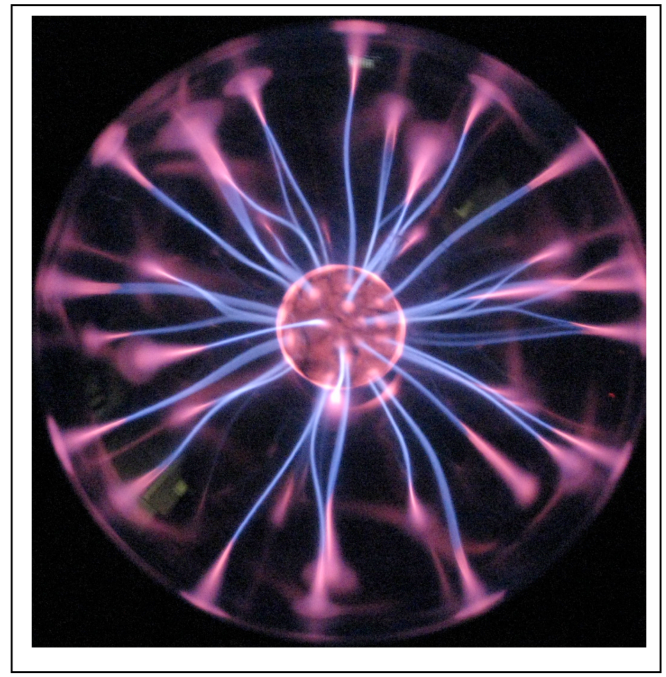


Fig. 2

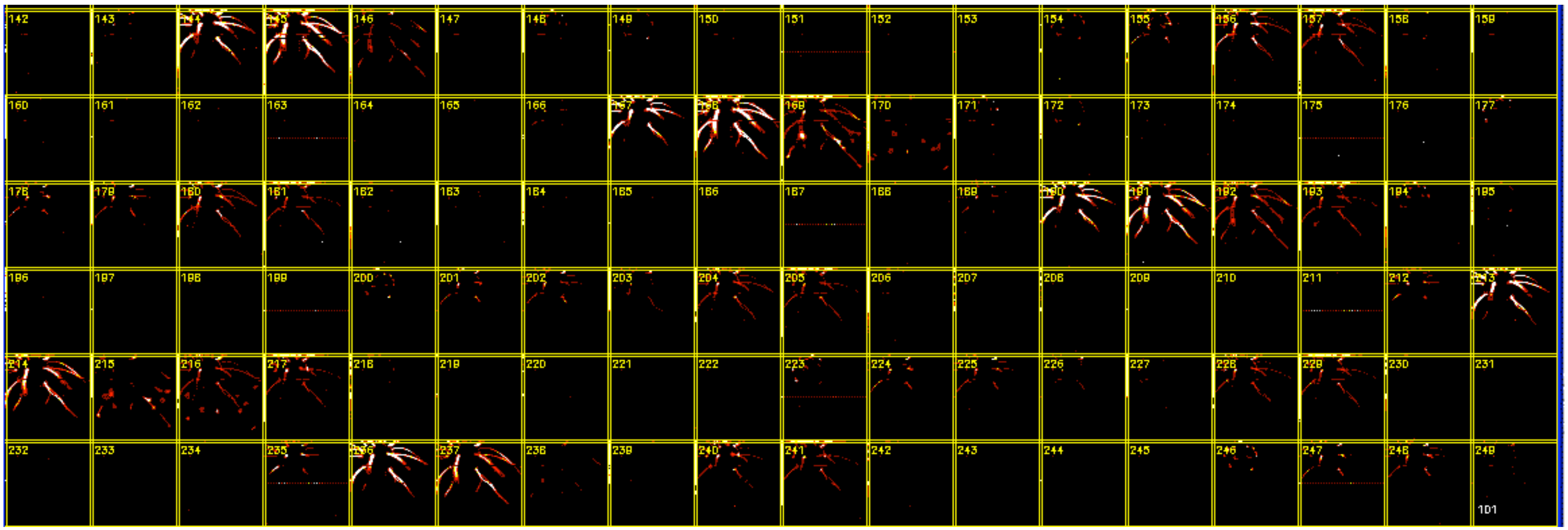


Fig. 3

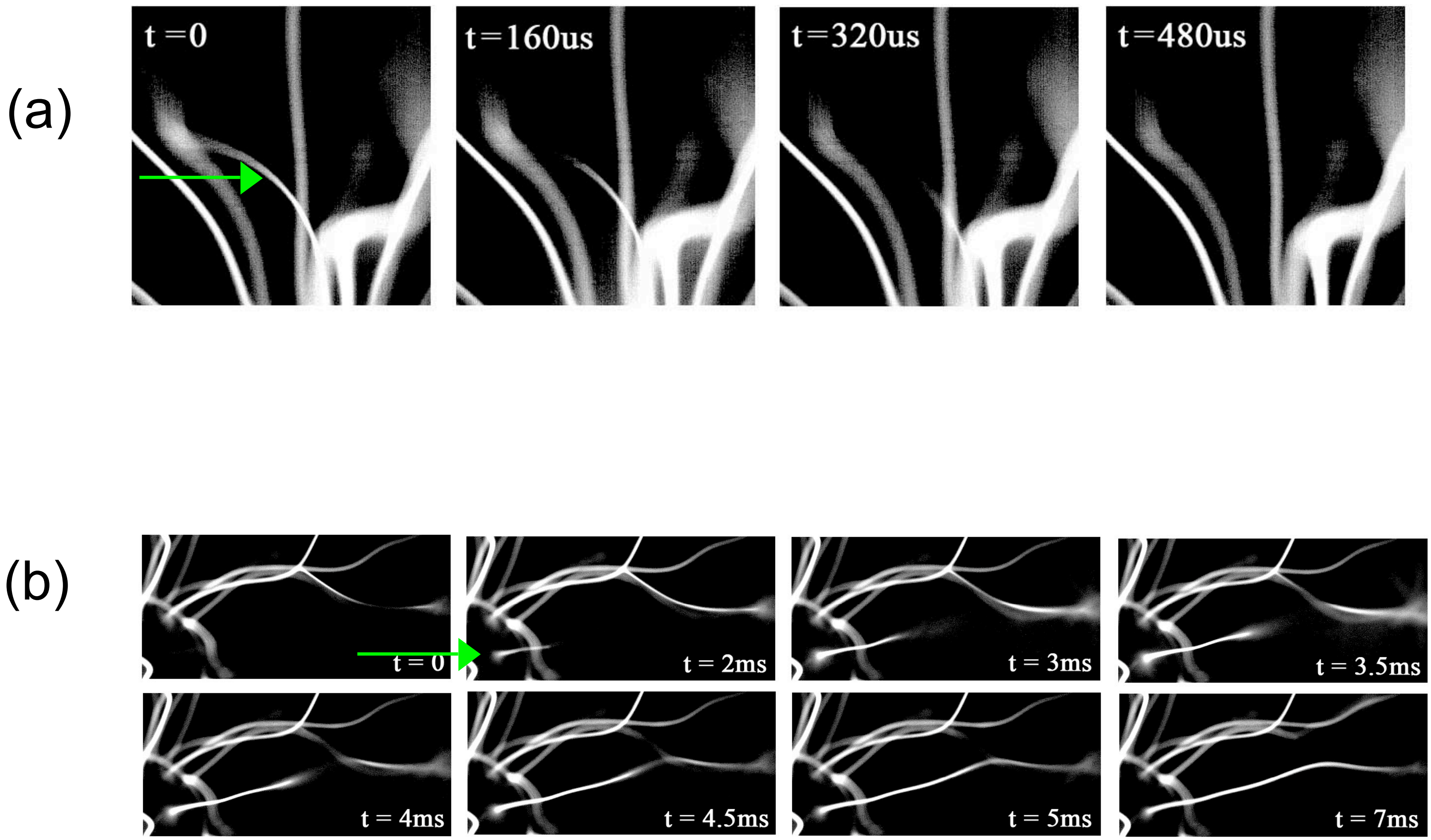
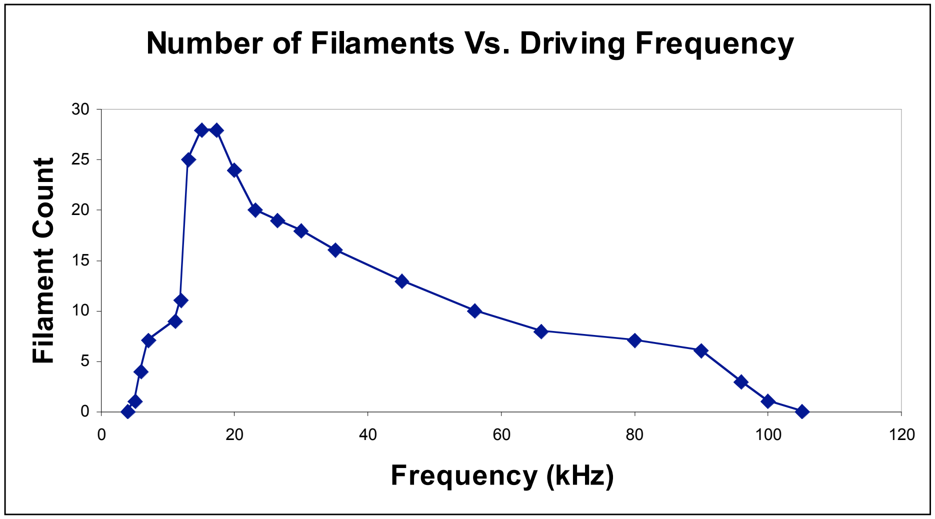

(a)
t =0
t=160us
t=320us
t=480us
(b)
t = 0
t = 2ms
t = 3ms
t = 3.5ms
t = 4ms
t = 4.5ms
t = 5ms
t = 7ms

Fig. 4

(a)


Number of Filaments Vs. Driving Frequency
Filament Count
30
25
20
15
10
5
0
0
20
40
60
80
100
120
Frequency (kHz)

(b)

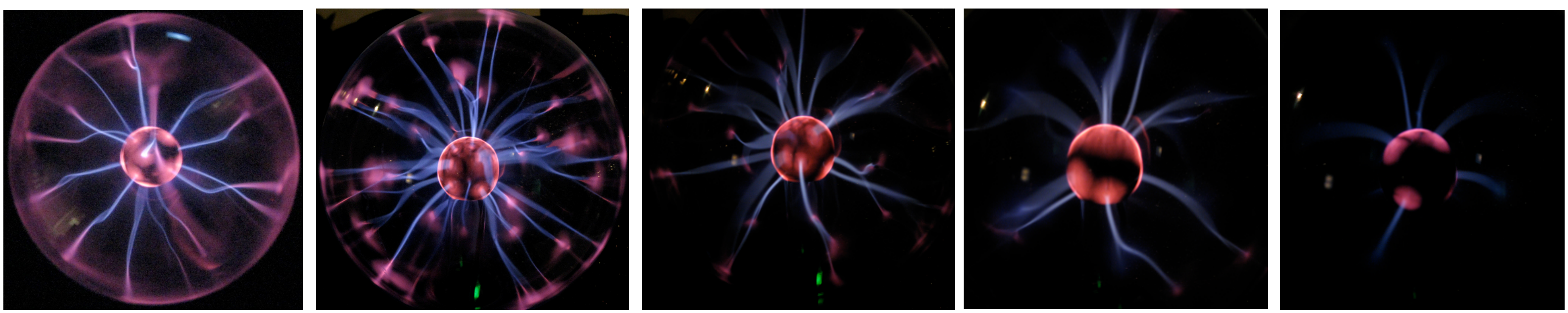


Fig. 5

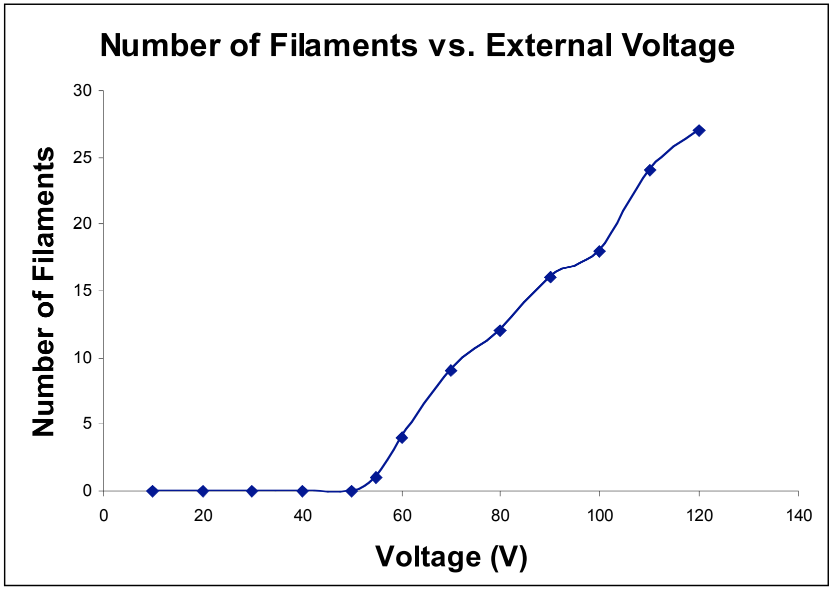
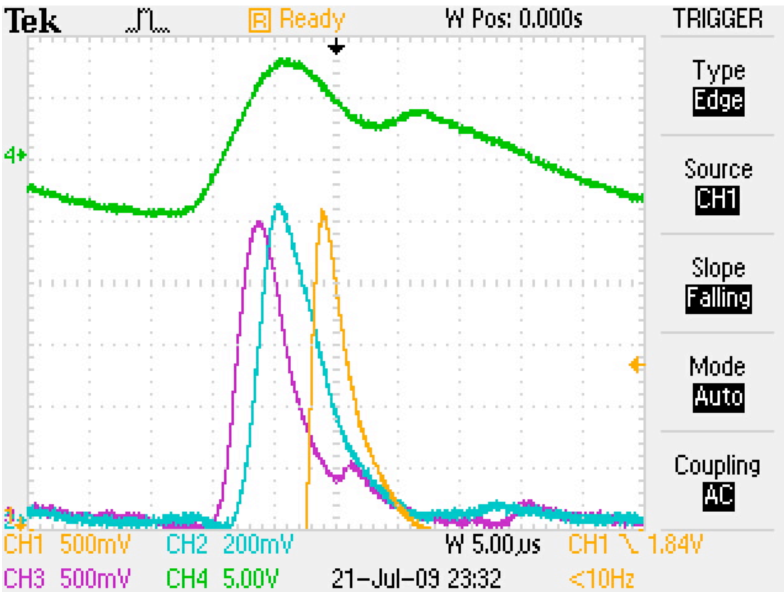

Number of Filaments vs. External Voltage
Number of Filaments
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
Voltage (V)

Fig. 6

(a)



time (5 μs/division)

(b)

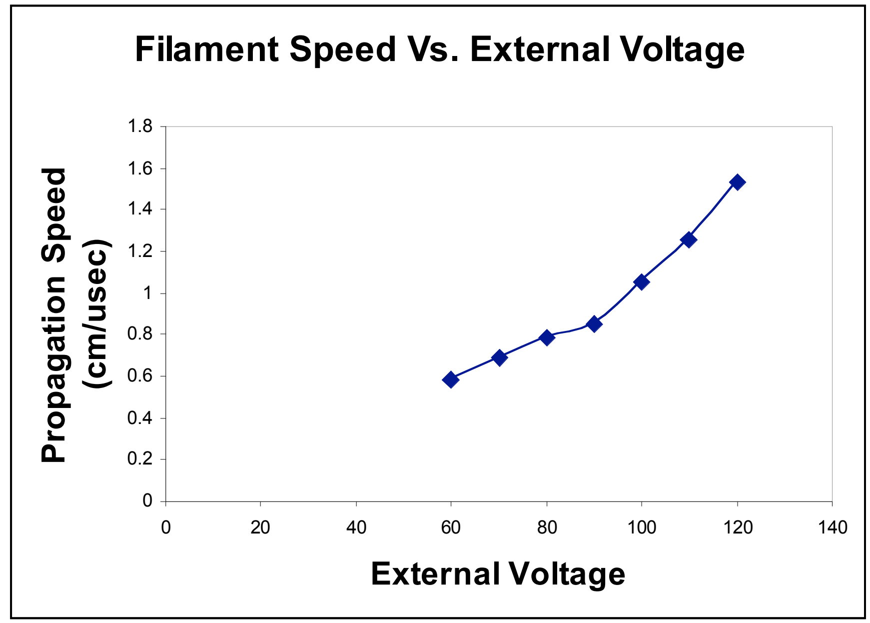
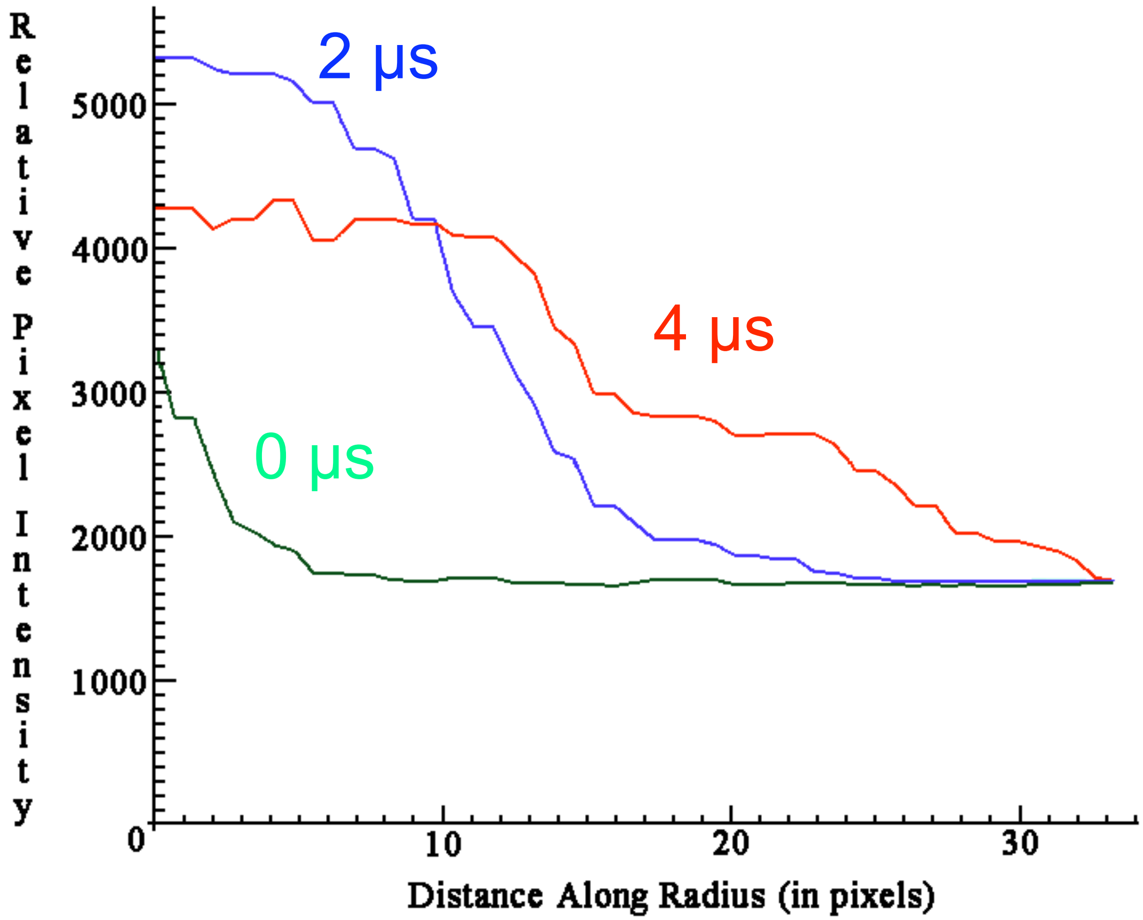


Fig. 7



Relative Pixel Intensity
5000
4000
3000
2000
1000
0
10
20
30
Distance Along Radius (in pixels)
2 μs
4 μs
0 μs

Fig. 8

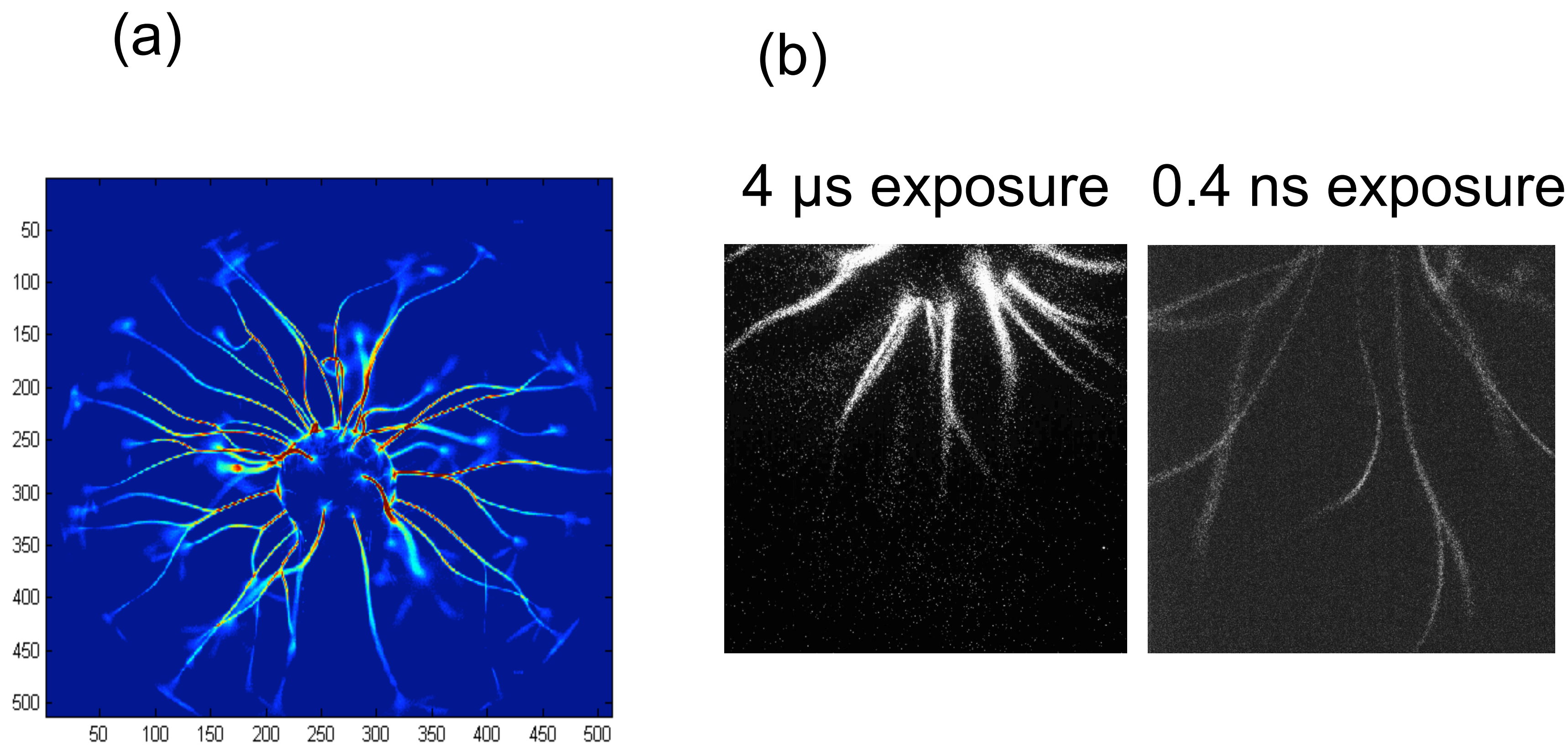

(a)
(b)
4 μs exposure
0.4 ns exposure
50
100
150
200
250
300
350
400
450
500

Fig. 9

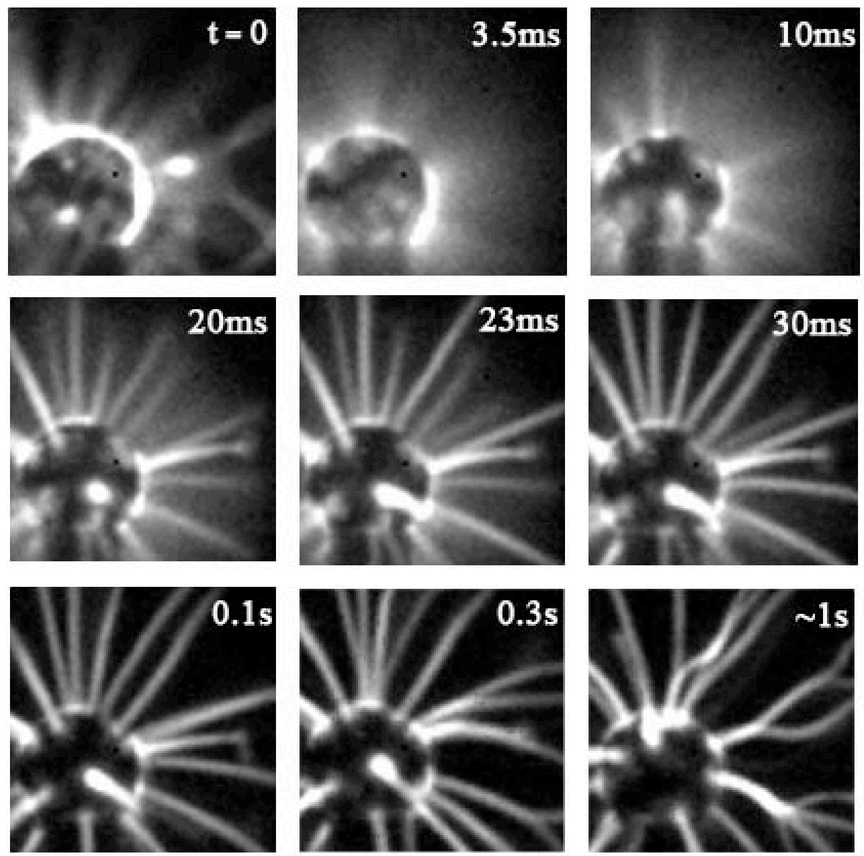


Fig. 10

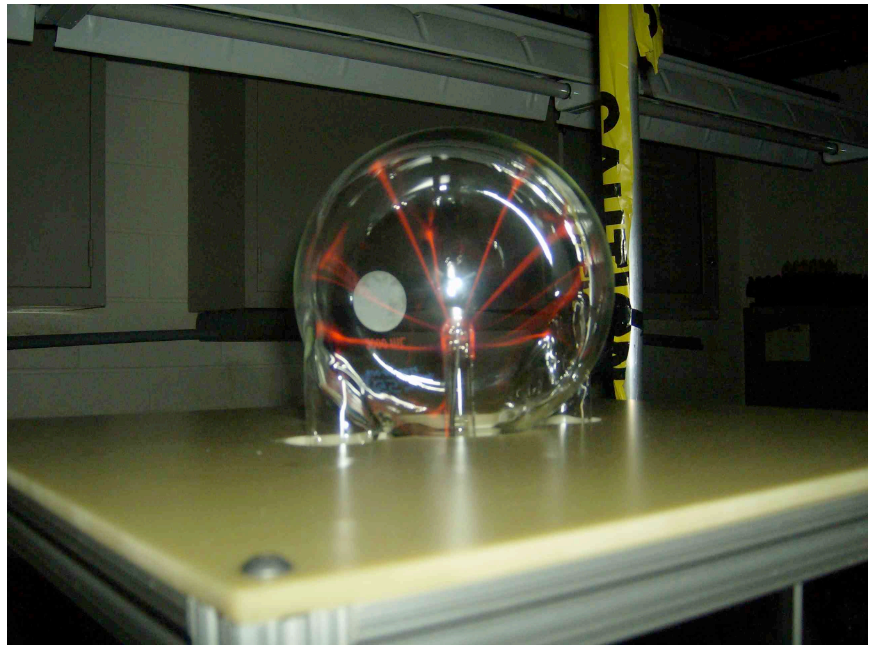
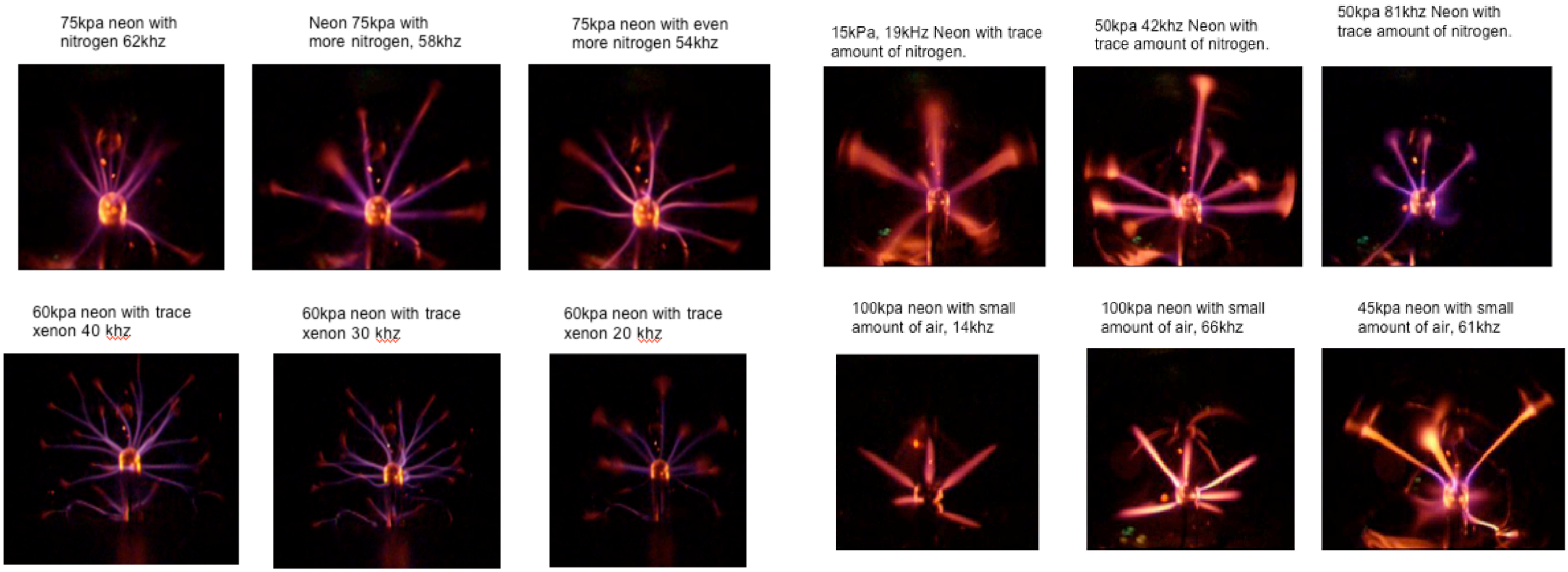


Fig. 11



75kpa neon with nitrogen 62khz
Neon 75kpa with more nitrogen, 58khz
75kpa neon with even more nitrogen 54khz
15kPa, 19kHz Neon with trace amount of nitrogen.
50kpa 42khz Neon with trace amount of nitrogen.
50kpa 81khz Neon with trace amount of nitrogen.
60kpa neon with trace xenon 40 khz
60kpa neon with trace xenon 30 khz
60kpa neon with trace xenon 20 khz
100kpa neon with small amount of air, 14khz
100kpa neon with small amount of air, 66khz
45kpa neon with small amount of air, 61khz

Fig. 12

normal ice on top

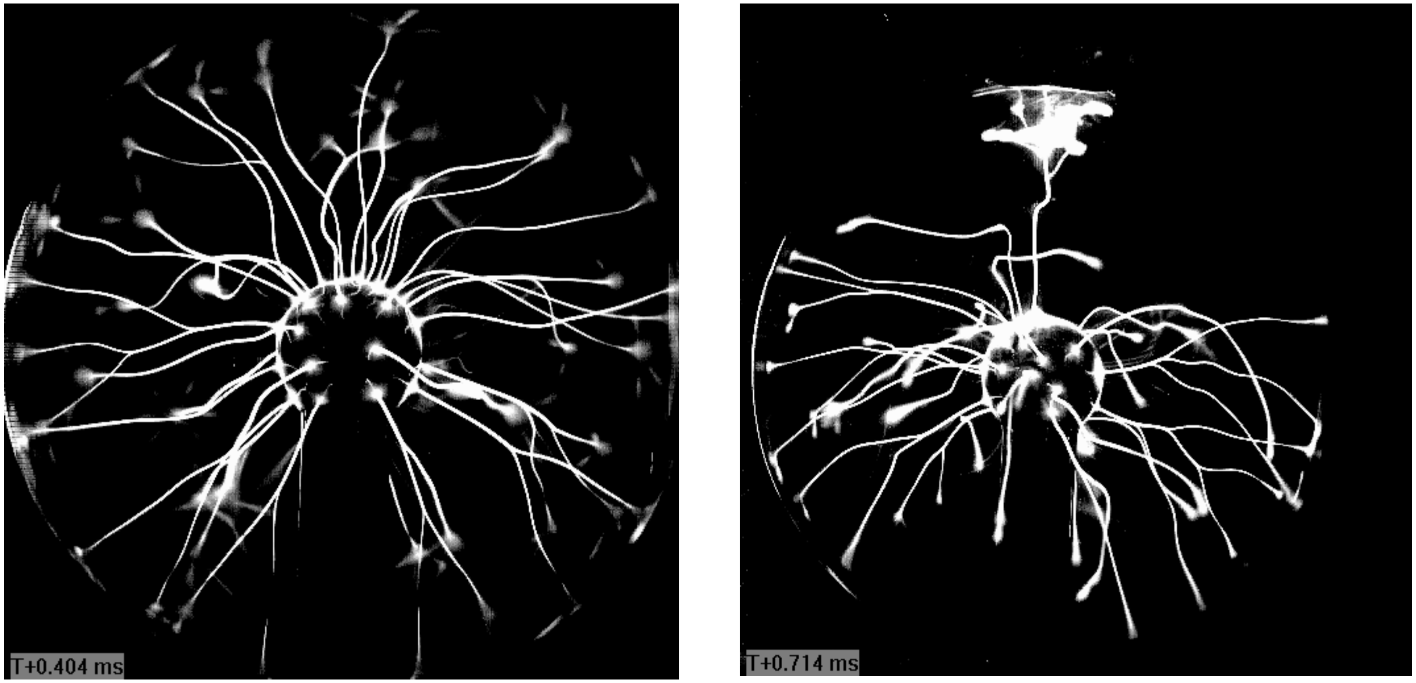


Fig. 13