2015 Asia-Pacific International Conference on Lightning (APL), Nagoya, Japan

Simulation of Lightning Initiation from Hydrometeors

Vladislav Mazur, Clayborne D. Taylor, Danyal A. Petersen

Abstract --- The objective of this research was to test, by means of an experiment in a high-voltage laboratory, the key aspects of the hydrometeor hypothesis of lightning initiation, namely, the effect of an array of hydrometeors on processes involved in the streamer-leader formation of lightning. Because the common types of hydrometeors present in all regions of lightning initiation in thunderstorms are ice particles (graupel, hail, or ice crystals), we used, in this experiment, conductive particles similar to hail in size, with various spacings between them, but all under normal atmospheric pressure and room temperature. The laboratory array was suspended on dielectric threads in a uniform electric field of 1 MV m^{-1} in the middle of the gap between the high-voltage and ground electrodes. During the first phase of the experiment, we studied the formation of a bidirectional arc discharge from the array, and the effects on the array's size on the electrical characteristics of the discharge. We continued with the same objectives in the second phase of the experiment, by adding the high-speed video observations with a recording speed of 10 Mfps.

***Keywords*—lightning initiation**

I. INTRODUCTION

The fundamental question of the physics of lightning initiation still remains unresolved, despite the tremendous progress achieved in lightning research in recent years. There are only two rather vague hypotheses that attempt to explain lightning initiation in thunderstorms. The first of these considers hydrometeors as potential nuclei, from which a bipolar lightning leader emerges in the region of a high electric field (the "hydrometeor theory"). This hypothesis, however, does not refer to a specific mechanism of lightning initiation; the laboratory experiments relevant to confirming this hypothesis have been limited to the investigation of corona formation on hydrometeors of different types and in various environmental conditions [e.g., Griffiths and Latham, 1974; Coquillat et al., 1995]. The second hypothesis suggests that cosmic rays, by means of the "runaway electrons theory," cause an electrical breakdown leading to the initiation of a lightning leader. This hypothesis was put forward as a possible consequence of gamma-ray emissions detected in thunderstorms by air- and balloon-borne measurements [Gurevich et al., 1992, and Roussel-Dupre et al., 1993]. However, observations of gamma-ray radiation in thunderstorms [Eack et al., 1996; Moore et al., 2001] and in a high-voltage laboratory [Kochkin et al., 2015] suggest that this radiation, indicative of runaway electrons, can be produced by lightning leaders, rather than be associated with the initiation phase of lightning. So far, there are no observational data to support the involvement of any high-energy processes (runaway electrons, X-rays, gamma rays) in lightning initiation. The tremendous progress made in the field of high-energy atmospheric phenomena, stimulated by introduction of the "runaway electrons theory," confirmed only the consequential relationship of these phenomena to lightning processes, characterizing them as a result of lightning development, rather than the cause of lightning occurrence [Dwyer and Uman, 2014].

On the other hand, the testing of major aspects of the hydrometeor hypothesis of lightning initiation did not attract the attention it deserved from researchers, to address these aspects in laboratory experiments.

There are two interrelated aspects of the hydrometeor theory of lightning initiation that need to be considered by researchers in laboratory experiments. The first one, the microphysical aspect, should provide answers to the following questions: (1) What are the realistic sizes, types, and concentration of hydrometeors involved in lightning initiation, (2) what are the ambient electric fields required for leader initiation to occur in ambient temperatures inside thunderstorms, and (3) how realistic is it to be able to meet these environmental conditions, to initiate a lightning discharge? The second aspect of the hydrometeor theory, the electrical one, defines the physical mechanism for the transition from corona streamers, started either on a single hydrometeor, or on a group of hydrometeors, to a bipolar and bidirectional leader that becomes a lightning flash.

A study of the microphysical aspect of lightning initiation, with reproduction of the ambient temperature, pressure and electric field inside the thunderstorm regions, is possible only in a chamber of small size. However, the small size of the chamber immediately imposes a limit on the length of the corona streamers obtainable in the experiment before they attach to the walls of the chamber. Therefore, no experiment in a small environmental chamber can proceed beyond studying corona formation. The only alternative is to study corona-leader transition from particles that simulate some of the relevant properties of hydrometeors (but without addressing the environmental conditions inside the cloud),

V. Mazur is with the NOAA/National Severe Storms Laboratory, Norman, OK 73072, USA (vlad.mazur@noaa.gov)

C. D. Taylor is with the Department of Electrical and Computer Engineering, College of Engineering, Mississippi State University, Starkville, MS, 39759, USA (cdt4@msstate.edu)

D. A. Petersen is with the School of Meteorology, University of Oklahoma, Norman, OK, 73072, USA (danp@ou.edu).

which can be done in a large cloud chamber, or in a large gap in a high-voltage facility. This was the objective of the study described in this paper.

II. CONSIDERATIONS FOR THE EXPERIMENT

The possibility of leader initiation on individual hydrometeors is affected by the field-enhancement factor of a particle (e.g., for a spherical particle, this factor is 3) that magnifies the ambient electric field on the surface of the particle. This field should be sufficiently high to sustain creation of the multiple streamers necessary to produce the streamer-leader transition. Lalande et al. (2002) have shown that the electric field at the hydrometeor surface should be two orders of magnitude higher than the internal field of a forming leader, in order for the streamer-leader transition to occur. The shapes of hydrometeors that can create such field enhancements are not found in cloud particles. Therefore, we believe streamer-leader transition on a single particle in a cluster of widely spaced particles in a cloud to be unrealistic.

The suggestion that lightning initiation involves precipitation particles in closely-spaced clusters was first discussed by Nguyen & Michnovsky [1996]. The behavior of such closely-spaced arrays of particles in a uniform electric field in the laboratory may provide an important clue to the understanding of the streamer-leader transition in the regions of lightning initiation. However, no such study has ever been conducted.

We know that in nature, hydrometeors, may indeed exist in closely-spaced clusters (arrays) of particles of similar sizes (e.g., ice crystals), or mixed sizes (e.g., hail and graupel). Gardiner et al. (1985) reported from airborne measurements in summer thunderstorms that graupels “in sizes from <100 μm to >1 mm, are in total concentrations ranging from 2 to 40 L^{-1}.” From measurements with a sailplane, at altitudes from 7 to 9 km and radar reflectivity from 20 to 45 dbZ, Dye et al.(1986) reported that ”as the cloud evolves to a mature stage of microphysical development, the total ice particle concentration can increase up to several hundred per liter.” Based on these estimates of the concentration of ice particles in a cloud, the assumption we used in the laboratory experiment, of spacing of a few centimeters between particles, seems realistic.

Corona streamers can easily bridge the gaps of a few centimeters between the suspended particles placed in a strong ambient electric field. We postulate that an array of particles may behave as the equivalent of a single large, weakly-conductive-and charged body (with a total field enhancement factor significantly greater than that of any individual particle). From such a body suspended in an ambient electric field of realistic values the bipolar and bidirectional leader may emerge. The experimental testing of this hypothesis is another objective of this study.

Field observations of the locations, in which lightning originates in storms, conducted with both the time-of-arrival technique and interferometers for mapping lightning radiation sources [see, e.g., Proctor, 1991; Shao & Krehbiel, 1996], show that lightning initiation occurs primarily in three thunderstorm regions, centered roughly at -10 ^{0}C, -20 ^{0}C and -40 ^{0}C. Two of these three regions have temperatures cooler than the so-called “reversal temperature” of ~20 ^{0}C --- believed to be the lowest temperature possible for streamer formation on a frozen particle [Griffiths and Latham, 1974]. However, in laboratory investigations of streamer formation from simulated ice particles, Petersen et al. [2006] has found -38 C to be the lowest temperature for occurrence of streamers, confirming the results of lightning radiation source mapping.

Despite the difference in environmental and electrical conditions, the common types of hydrometeors in all three regions are ice particles, either graupel or hail, or ice crystals. For this reason, in the laboratory array of particles we simulated hail in sizes and the spacing between particles. Small hollow aluminum balls of diameter ¾” that we have chosen are of sizes similar to hail particles, but certainly not similar to them in their conductivity. Although hail is not a pure dielectric, due to the impurities it contains, it is also not a perfect conductor. Therefore, an experiment with an array of metal ball as substitutes for hail may only be used to investigate the array’s effect on the formation of a leader. The other properties of hail particles, besides their sizes and numbers in an array, may be addressed in future stages of a similar experiment.

III. SETUP OF THE EXPERIMENT

The experiment was conducted in the high-voltage facility of the Department of Electrical and Computer Engineering at Mississippi State University. The 56 kJ impulse generator in this facility is capable of producing maximum voltage of ~ 2.4 MV.

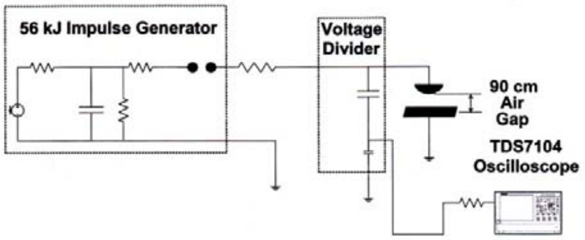
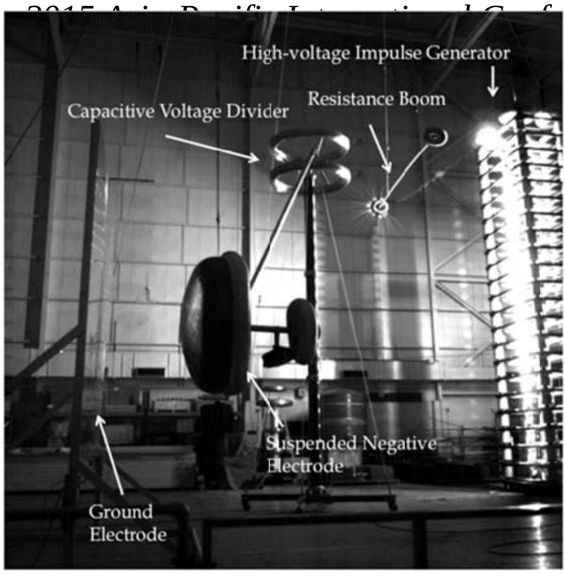


Fig. 1. Diagram of the measurement system for the test gap in the high-voltage facility of the Mississippi State University. .

During the first phase of the experiment, we intended to reproduce the streamer formation and streamer-leader transition from an array of uncharged conducting particles suspended in the gap between the high-voltage and ground electrodes, in the ambient E-field of 1 MV m^{-1}. An electric field such as this is sufficient to produce electrical breakdown from the surface of spherical particles, at normal atmospheric conditions. A uniform E-field in a 0.9 m-long gap was produced by an impulse generator that charged the *RC* circuit that consisted of a capacitive voltage divider, *C*, and a resistance boom, *R* (see Fig.2). The time constant of the *RC* circuit is ~ 64 μs. In addition to measurements of the applied voltage and current to ground, we used, during the first phase of the experiment, a high-speed video camera Photron SA 1.1, operated at a speed of 360,000-450,000 fps.

Fig.2. Setup of the first phase of the experiment in the high-voltage facility. The electric field in the gap is horizontal, and particles of the array are



suspended vertically as seen in Fig. 3.

Fig.3. Three metal balls of ¾” diameter separated by ¾” spaces and suspended in a uniform E-field of 1 MV m^{-1} between the negative high-voltage (on the right) and the ground (on the left) electrodes.

The hollow metal balls on vertical Teflon threads were suspended from PVC pipes (installed on the ground electrode), and placed in the uniform E-field at about half-length of the gap (see Fig. 3).

IV. FIRST PHASE RESULTS

As anticipated, a plasma channel has formed between the conductive particles at the ambient E-field that was approximately one third of the breakdown E-field at normal atmospheric conditions (3 MVm^{-1}). A discharge channel formed bidirectionally, with positive and negative streamers from the outer side of a single ball and from the outer balls in the array (Fig.4).

The four subsequent video frames in Fig. 4 show the formation of the plasma channel from three separated balls, shown in Fig. 3. The first two frames of the sequence are absolutely dark, even after image enhancement --- an indication of the absence of any streamers. During the third frame, the fuzzy images of numerous streamers fill the space between the electrodes, and a bright, luminous plasma channel becomes visible between the balls. Plasma stems at the outer edges on the left and on the right are clearly seen (see Fig.5) --- all taking place during a single frame exposure of 1 μs. The fourth frame, in Fig. 4, depicts the flashover that occurs when the bidirectional leader reaches the opposite electrodes.

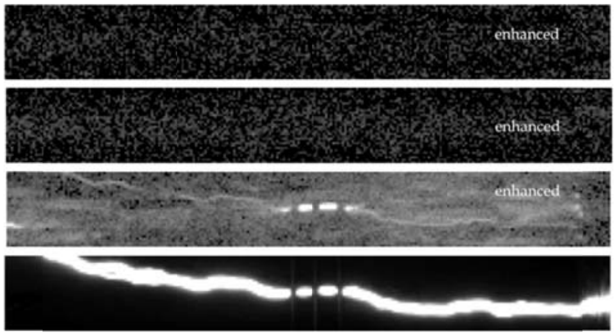


Fig. 4. Stages of the discharge formation between three metal balls separated by a gap equal to their diameter (3/4”). Sequential video frames start from the top, and move downward: Recording speed is 360,000 fps, 1μs exposure time, 2.8 μs – the interval between frames.

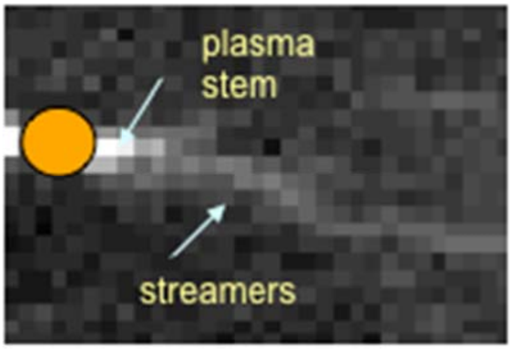
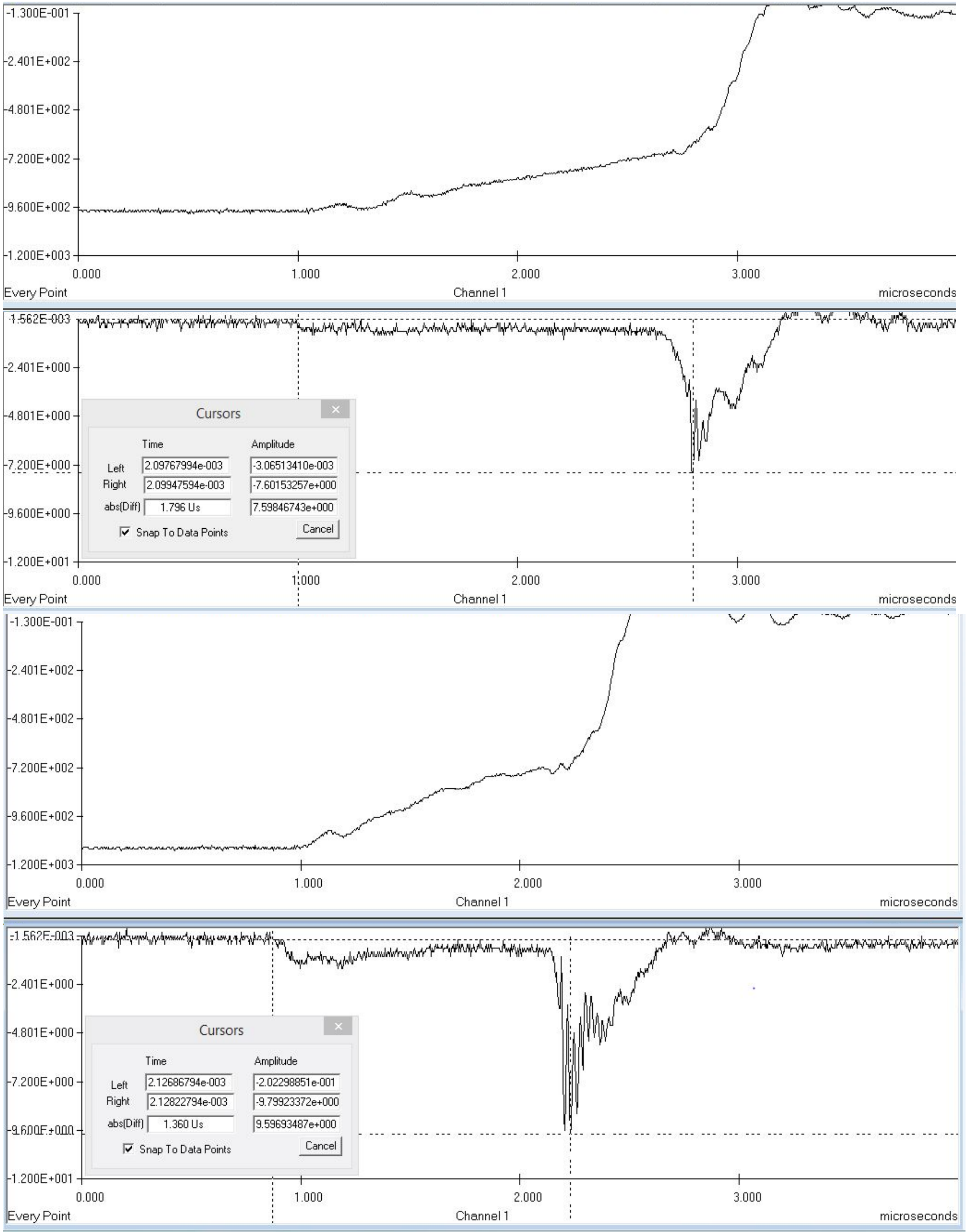


Fig. 5. A plasma stem at the outer edge of the outer ball and streamers. The ball is marked by a circle.

The sequence of video images in Fig. 4 was a lucky occurrence, because in most other events of the same type, the Photron SA 1.1 camera captured only the images of the flashover. This means that the streamer-leader transition phase did occur during the 2.8 μs-long time intervals between video frames, rather than during the frame exposure time of 1 μs. Obviously, we needed a much faster speed of video recording to capture this transition.

The time variation of both the voltage in the gap between electrodes and the current to ground, prior to the flashover, is presented, in Fig. 6, for two tested cases: with a single ball, and with three aligned balls, seen in Fig. 3. Comparison of these records shows that the voltage needed to start a discharge for a single ball is greater than that for three balls. The rise in voltage following the beginning of the discharge is expected, because the introduction of the uncharged conducting bodies into the gap decreases the energy of the field, and thus, the ambient E-field [Stratton. 1941, section 2.13]



Cursors

	Time	Amplitude
Left	2.09767994e-003	-3.06513410e-003
Right	2.09947594e-003	-7.60153257e+000
abs(Diff)	1.796 Us	7.59846743e+000

☑ Snap To Data Points

Cursors

	Time	Amplitude
Left	2.12686794e-003	-2.02298851e-001
Right	2.12822794e-003	-9.79923372e+000
abs(Diff)	1.360 Us	9.59693487e+000

☑ Snap To Data Points

Fig. 6. Comparison of breakdown conditions for a single ball and a three-ball array (see symbols). The upper part of each panel shows voltage, ***V(t)***, in kV, and the lower part shows, ***I(t)***, in kA, prior to the flashover. Two vertical dashed lines in the graph for current identify the period, ***delta T***, of rising voltage between occurrence of the first streamers and the beginning of a flashover, which is the duration of the discharge: 1.8 μs for a single ball and 1.36 μs for the three-ball array.

A comparison of the two sets of records in Fig. 6 also indicates that the duration of the discharge, which is the period from the appearance of streamers to the flashover, is shorter for the three-ball array (1.36 μs) than for the single ball (1.8 μs). This difference suggests a faster transition from the streamer to the leader phase for the larger array of particles.

During the discharge formation, the current to ground was steady at amplitude of 400A, for the case of the single ball, but deepened initially to a maximum value of 1.2 kA, and then settled at a steady level of 600A, in the case of the three -ball array.

An accurate interpretation of the records obtained at the first stage, beyond that presented here, was not possible, because of the insufficiently high speed of the video observations.

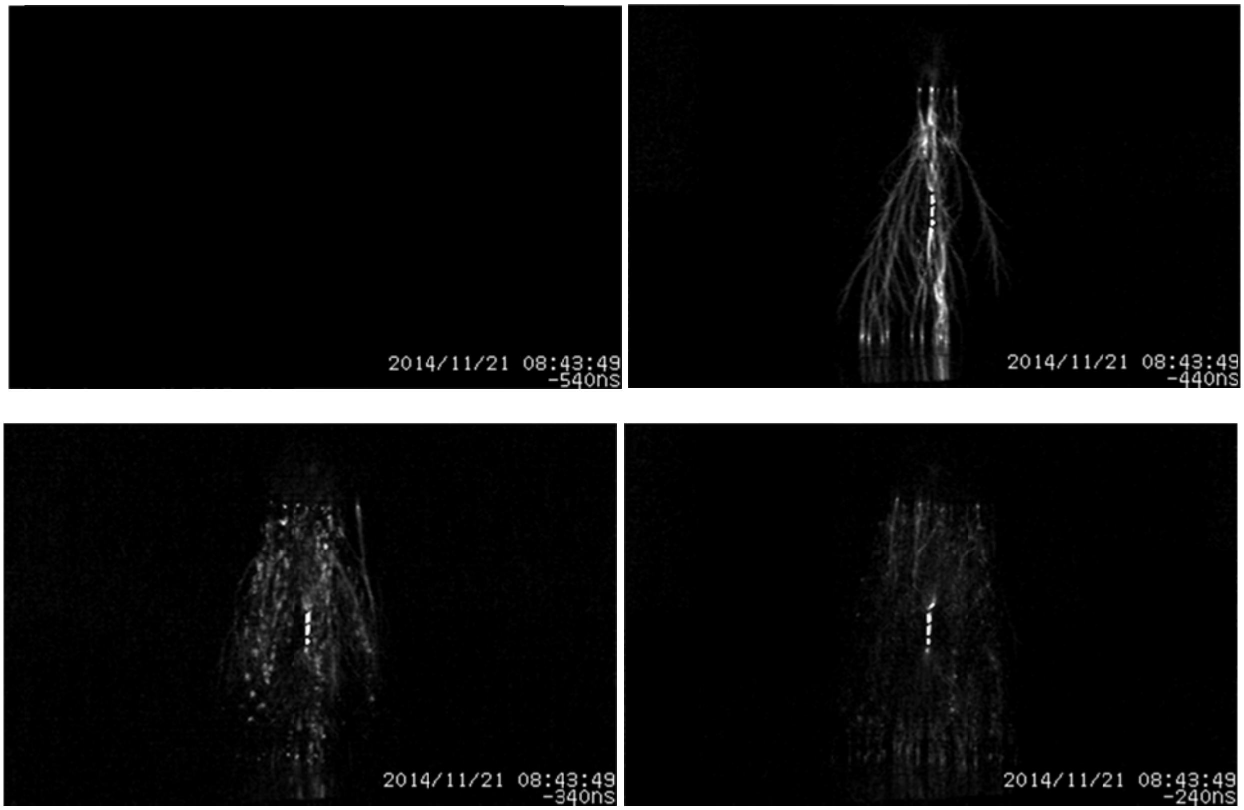
V. SECOND PHASE RESULTS

The first phase of the experiment had limited objectives, and we had limited time in the high-voltage facility in which to achieve them. We learned, from the voltage and current records in Fig. 6, that the total duration of the discharge is less than 2 μs, which indicated the need to use a much higher speed of video recording, i.e., greater than 2 Mfps, in order to be able to observe and interpret the streamer-leader transition in more than one video frame.

The second phase of the experiment, conducted in the same high-voltage facility (Fig. 7), tested several somewhat different spatial arrangements of conducting particles in an array, accomplished by adding more balls, and increasing the distances between them. High-speed video observations during the second phase were performed with the speed of 10 Mfps, using Hyper Vision manufactured by Shimadzu Scientific Instruments. This high-speed camera has a continuous recording capability of 256 frames maximum, at 10 bits and an exposure time of 50 ns at 10 Mfps. An extremely valuable feature of this camera for our experiment was the feature of an external trigger-point setting on any video frame.

Fig.7. The setup for the second phase of the experiment at the high-voltage facility at Mississippi State University. The ambient E-field between electrodes in the 0.9 m wide gap is vertical; the particles were suspended on horizontal dielectric threads.

The sequence of video images of the discharge from the array of four aligned balls, obtained with the HPV-X High-Speed Video Camera, is shown in Fig. 8.



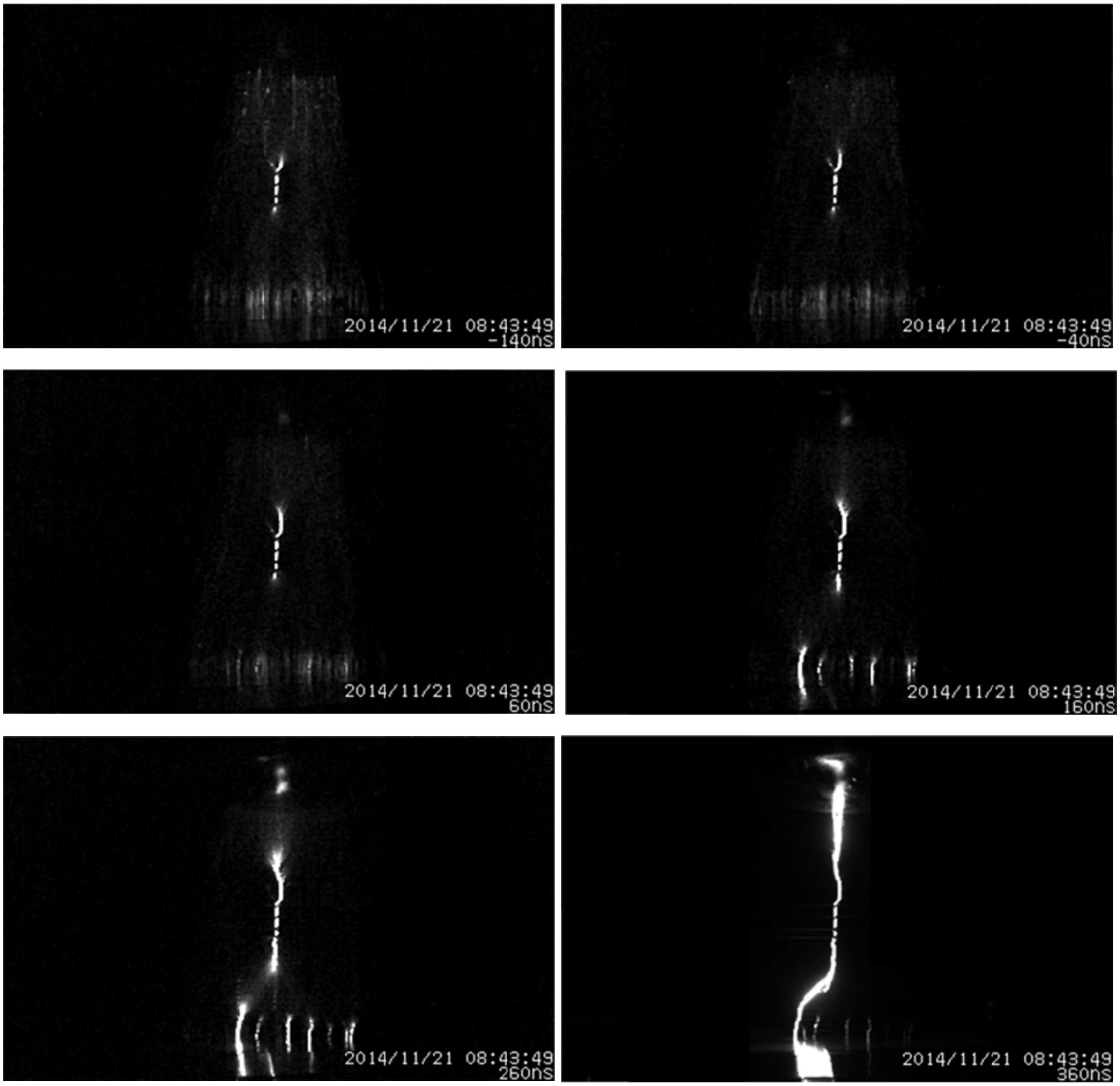


Fig. 8. Sequence of video frames of the discharge development from four aligned metal balls of ¾” diameter each that are suspended is a 0.9 m gap between electrodes. The sinterval separating the balls was (from top to button) 3/4”, 1 1/2”, and 3/4.” The duration of the discharge is ~800ns. The exposure time is 50 ns. All images except the last one are enhanced to the same level of light intensity. The last image is unmodified.

The following description of the discharge process characterizes all configurations of the balls, regardless of their number in the array. All discharges exhibited from the very beginning (in the first video frame) a strong burst of branched negative streamers that originated at the negative electrode; the streamers fanned toward the ground electrode. Simultaneously, a plasma channel connected all the suspended balls (see frame at -440 ns), with the plasma stems clearly visible at the outer edges of the outer balls of the array. No positive streamers from the ground electrode were observed during this time; they did appear hundreds of nanoseconds later (see frame at -140 ns). With time, the number of negative streamers from the negative electrode decreased, while the plasma channel was developing upward and undirectionally as a positively charged leader (starting at frame of -240 ns). The development of the negatively charged leader from the array was delayed by ~400 ns after the start of the upward positive leader, and occurred simultaneously with the appearance of multiple non-branching positive leaders from the ground electrode (see frame of 160 ns).

The results of the second stage of the experiment confirmed the findings of the first stage, namely, the effect of the number of particles in the array on the duration of the discharge, which is clear from these data: durations of 1.3 μs, 1.0 μs, and 0.8 μs for arrays made of two, three, and four balls, respectively. Less noticeable is the effect of the number of particles on the maximum voltage in the gap prior to the start of the discharge. From the results of the first stage of the experiment, we infer that the combined corona and arc current, making together a current to ground of several hundreds of Amperes, grows with the number of particles.

VI. CONCLUDING REMARKS

By using an array of conducting particles in a high-voltage chamber experiment, we achieved an accurate laboratory simulation of the conditions that lead to lightning initiation. Placed in an ambient E-field sufficient to start breakdown on a single particle, the array of particles, turned from the start of the discharge, into a larger plasma-connected body from which the bidirectional and bipolar leader developed.

We observed that, as the number of particles in the array is increased, the total current of the discharge grows, and the duration of the discharge diminishes. The effects of electrodes, noticeable during a discharge in a high-voltage laboratory, may not exist in a cloud. They do not, however, mask the stages of leader development from an array of particles, which should be similar to those inside the thunderstorm.

ACKNOWLEDGMENTS

We are grateful to Dr. Stan Grzybowski of Mississippi State University for his invaluable support of this project and to Jeremy Hamilton for his assistance in facilitating our experiment. We thank Todd Rumbaugh of HyperVision for his essential help in our effforts to obtain unique video images of leader initiation process. The project has been funded in part by the Director's Directed Research Fund of the National Severe Storms Laboratory.

REFERENCES

[1] R. F. Griffiths, and J. Latham, Electrical corona from ice hydrometeors, *Quart. J. R. Met. Soc.*, 100, 163-180, 1974.

[2] S. Coquillat, , S. Chauzy, and J. C. Medale, Micro discharges between ice particles, *J. Geophys. Res*., 100, 14,327-14,334, 1995.

[3] A. V., Gurevich, K. P. Zybin and R. A. Roussel-Dupre, Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, *Phys. Lett. A*, 165, 463-468, 1992.

[4] R.A., Roussel-Dupre, A. V. Gurevich, T. Tunnell, and G. M. Milikh, "Kinetic theory of runaway air breakdown and the implications for lightning initiation," Los Alamos Natl. Lab, Los Alamos, N.M., 1993, Rep. LA-12601-MS,.

[5] K. B Eack, W. H. Beasley, W.D. Rust, T. C. Marshall, and M. Stolzenburg, Initial results from simultaneous observations of X rays and electric fields in a thunderstorm, *J. Geophys. Res.*, 101, 29,637-29,640, 1996.

[6] C. B., Moore, K. B. Eack, G. D. Aulich, and W. Rison, Energetic radiation associated with lightning stepped-leaders, *Geophys. Res. Lettr*, 28, 2141-2144, 2001.

[7] P. Kochkin , A P J van Deursen, U Ebert, Experimental study on hard X-rays emitted from meter-scale negative discharges in air, *J. Phys. D: Appl. Phys.*, 40 025205 doi:10.1088/0022-3727/48/2/025205, 2015.

[8] J. R. Dwyer and M. A. Uman, The physics of lightning, *Physics Reports 534*, 147-241, 2014.

[9] P. Lalande, A. Bondiou-Clergerie, I. Gallimberti, G. L. Bacchiega, Observations and modeling of lightning leaders, *C. R. Physique 3*, 1375-1392, 2002.

[10] Nguyen & Michnovsky, On the initiation of lightning discharge in a cloud. 2, The lightning initiation on precipitation particles, *J. Geophys. Res.*, 101, 26,675-26,680, 1996.

[11] B. Gardher, D. Lame, R. L .Pitter and J. Hallett, Measurements of initial potential gradient and particle charges in a Montana summer thunderstorm, *J. Geophys. Res*., 90, 6079-6086, 1985.

[12] J. E. Dye, J. J. Johnes, W. P. Winn, T. A., Cerni, B. Gardener, D. Lamb, R. L. Pitter, J. Hallett, and C. P. R. Saunders, Early electrification and precipitation development in a small isolated Montana Cumulonimbus, *J. Geophys. Res*., 91, 1231-1247, 1986.

[13] D. E. Proctor, Regions where lightning flashes begin, *J. Geophys. Res*., 96, 5099-5112, 1991.

[14] X. M. Shao, and P. R. Krehbiel, The spatial and temporal development of intracloud lightning, *J. Geophys. Res*., 101, 26,641-26,668, 1996.

15] D**.** Petersen, M. Bailey, J. Hallett, W. Beasley, Laboratory investigation of positive streamer discharges from simulated ice hydrometeors, *Quart. J. R. Met. Soc*., 132, No. 615, pp. 263-273, 2006.

[16] J. A. Stratton, *Electromagnetic Theory*, McGraw-Hill, New York and London, 1941.