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Citation: Review of Scientific Instruments **65**, 2281 (1994);
View online: https://doi.org/10.1063/1.1144677
View Table of Contents: http://aip.scitation.org/toc/rsi/65/7
Published by the American Institute of Physics

A capacitive probe array for measurements of ionization growth

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(Received 13 October 1993; accepted for publication 12 April 1994)

The design and construction of a novel capacitive probe array to directly measure the ionization growth in high-voltage discharges is presented. By optimizing the design geometry, the probe output is made to be dependent only on the variation of charge development or potential changes at the vicinity of the probe in the interelectrode space. A set of these probes was used in an experiment to allow the time and space development of a virtual anode to be directly observed.

I. INTRODUCTION

In studying the physical development of pulsed electrical discharge formation, it is often desirable to be able to follow the ionization directly with some types of probes and to measure the local evolution of the electric field. Langmuir probes are widely used in weakly ionized plasmas but are less suitable when transient phenomena with submicrosecond features are to be characterized. Furthermore, the finite size of the probe and the direct electrical connection would make the probe invasive and could disturb the local electric-field distribution. A spectroscopic technique[1,2] can provide noninvasive measurements from excited species. However, a highly sensitive system would be required to carry out measurements at the early phase of ionization growth and time dependent information can only be obtained at a single point in space and at a particular set of wavelengths, unless some repetitive scanning process is introduced. The local electric field can be measured with an electron-beam probe,[3] though again it is essentially a single point technique and is suitable only for low-pressure discharge when the effect of the electron beam on the discharge is minimized. The use of a single coaxial capacitive probe has been reported in the past in conjunction with a Faraday cup to measure the electrostatic potential induced by the space charge of a relativistic electron beam.[4] In this article, we report on a novel noninvasive technique for monitoring the ionization growth based on an array of capacitive probes. The probes are simple to construct and allow the local charge formation to be followed in space and time. By using these probes, the formation of a virtual anode in a transient hollow cathode discharge (THCD) is explicitly measured in a single discharge for the first time.[5]

II. CIRCUIT DESCRIPTION

Each capacitive probe is arranged in the form of a ring on the outside of the discharge tube. A schematic of the probe is shown in Fig. 1. The equivalent electric circuit for a single probe is shown in Fig. 2. The probe couples capacitively to the electrodes, ground and interelectrode plasma. The circuit equation for a single probe can be written as follows:

$$\frac{d}{dt}V_0+\left(\frac{1}{C_T}\frac{d}{dt}C_P+\frac{1}{C_TR}\right)V_0 =\frac{C_A}{C_T}\frac{d}{dt}V_A+\frac{C_C}{C_T}\frac{d}{dt}V_C+\frac{1}{C_T}\frac{d}{dt}(C_P\cdot V_p), \tag{1}$$

where V_0 is the probe signal; V_A, V_C, and V_P are the anode, cathode, and plasma potentials; C_A, C_C, and C_P are the probe coupling capacitance to the anode, cathode, and interelectrode plasma; and $C_T=C_A+C_C+C_P+C_G$, with C_G the coupling capacitance to the probe shield at ground potential. C_A, C_C, and C_G are constant in time, as they depend only on the geometry of the probe and electrodes assembly, whereas C_P is in general time dependent, as it is defined by the dimensions of the charge on the plasma cloud in the vicinity of the probe. By maximizing the probe coupling to the earth shield, the conditions $C_A \ll C_G$ and $C_C \ll C_G$ can be easily satisfied. In practice, $C_G \approx 25$ pF for the probes constructed using the present design, which is, at least, two order of magnitudes larger than the coupling capacitance to the live electrode. In this case, both first and second terms on the right-hand side of Eq. (1) can be dropped.

Using a 50 Ω signal cable, $C_T \cdot R \approx 1.2$ ns, which is shorter than any characteristic time of interest in the probe signal. Additionally, the contribution to the circuit equation of the term dC_P/dt becomes important only if charge movements with characteristic radial velocities greater than 100 m/μs take place, which is not the case in these experiments. Under these conditions, the circuit equation (1) can be reduced, in the present experimental configuration, to

$$V_0(t)\approx R\frac{d}{dt}[C_P(t)\cdot V_P(t)]. \tag{2}$$

It can be seen from Eq. (2), than a nonzero probe signal can result from a local variation in the net space charge ($Q=C_P\cdot V_P$), from a change in the local plasma potential or from a combination of both. Bipolar probe signals can be produced either by a moving finite distribution of the net space charge that passes through the probe or, in the case of a conducting media in the probe region, by a changing local potential which rises and falls. For a unipolar signal to be produced by pure charge movement in the probe region, the moving charge has to stop moving at a position close to the

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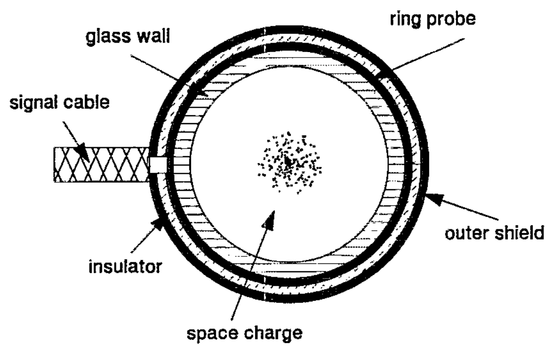

FIG. 1. Schematic of the cross section of a single probe.

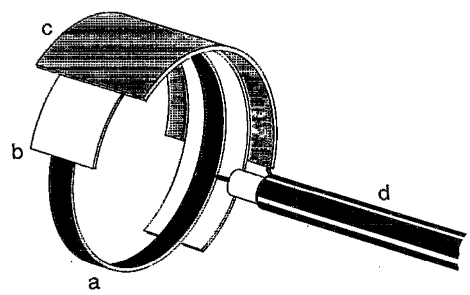

FIG. 3. Layout of a single probe: (a) conducting ring probe electrode, 3 mm wide and 70 μm thick; (b) insulating layer, 135 μm thick; (c) conducting earth return shield; and (d) 50 Ω signal cable.

probe, thus causing a local increase in the net space charge. Unipolar signals can also be produced either by a finite change of the local potential in the vicinity of the probe, or, at constant local potential, by a change in the geometry of the conducting media (ionized gas) in the probe region. Two closely spaced probes can, in principle, be used to differentiate a moving charge that stops at the probe position from a finite change in the local potential.

III. CONSTRUCTION AND PERFORMANCE

The probes are used in an array of six units along the anode-cathode gap region. In the prototype, each unit is made out of a self-adhesive aluminum ribbon, 3 mm wide and 70 μm thick, which is wound around the discharge tube to form the ring. An insulation tape of 135 μm thickness is placed over the ribbon, over which is wound a layer of wide aluminum tape to form the earth return shield. A small coaxial cable is used to take the signal out from each ring element, with the coaxial braid connected to the ground shield. A schematic of the arrangement of one of the probes is shown in Fig. 3. With a finite number of measuring channels, six probes were arranged as three pairs in one set of experiments to provide a compromise between high spatial resolution and covering a large span across the anode-cathode spacing. The paired probes can also, in principle, allow a local increase in net charge to be distinguished from changes in the local potential, as discussed above. In some circumstances, an additional common conducting shield is placed over the ground of all probes to further reduce any inductive pickup. This common shield is in turn connected to the ground electrode of the discharge.

A more refined method was subsequently developed to construct the probe arrays using printed circuit techniques.

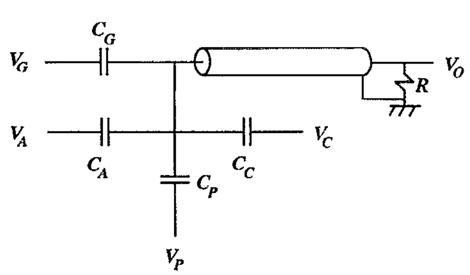

FIG. 2. Equivalent electric circuit for a single probe.

The starting point is a copper cladded polyimide sheet of 50 μm. Etch resistant ink was used to lay down the positions of the probes and a ferric chloride etch was use to remove the surplus area. The sheet is wrapped around the discharge tube to form the probe array, covered on top by another unetched sheet to form the ground return. The technique allows a much more precise capacitance of the probes, as well as their alignment, to be obtained. From the circuit analysis, the largest source of error will come from the capacitive coupling to the live electrode when the voltage is changing rapidly in time. This is minimized in the present method of construction by maximizing the coupling of the sensing electrode to the earth shield.

The capacitive probe arrays have been used to diagnose the space and time evolution of charge growth in the interelectrode space and hollow cathode region of a THCD. Details of the experimental apparatus have been published elsewhere.[6] In this particular case, the anode-cathode separation was 10 cm and the discharge tube was 3 cm in diameter. In this experimental configuration, probe calibration is achieved by introducing a conducting rod at the anode potential along the discharge axis. Typical calibration signals from the paired six probe array using a 19 mm diameter brass rod at 10 kV applied voltage are shown in Fig. 4. As the measurement was performed in vacuum, there is no contribution to the probe signal due to the formation of space charge, hence the signal in each probe depends only on the coupling capacitance to the charged conducting rod. In this way, the data allows a calibration of the probes to be performed.

Figure 5 shows the probe signals obtained with six equally spaced probes in the interelectrode space of a THCD in hydrogen at 195 mTorr, 30 kV applied voltage. The signals are seen to rise in a sequence starting first at the probe which is next to the anode, and then propagating towards the cathode. From the signal, it can be inferred that a conducting plasma region is formed between the anode and a region close to the sensing ring electrode, thereby bringing the anode potential close to the probe and creating a form of virtual anode locally. From the sequence of signals, the formation of a moving virtual anode can be distinguished.[5] Shortly after the virtual anode signal has formed on the probe closest to the cathode, signifying that a plasma region has been created in the interelectrode space, a negative going signal is seen

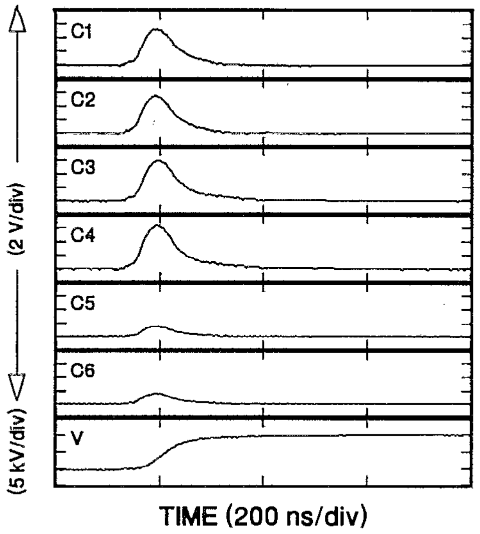

FIG. 4. Calibration signals from paired six probe array using a 19 mm diameter conducting rod at 10 kV applied voltage, along the discharge axis. The probe positions, as measured from the anode, are C1, 2.4 cm, C2, 3.4 cm, C3, 5.0 cm, C4, 5.7 cm, C5, 7.4 cm, and C6, 8.1 cm.

simultaneously across all probe channels. This is the result of the collapse of the applied voltage across the A-K gap, as can be seen in the voltage signal measured. Probe arrays have also been used to study the time correlation of charge formation processes in THCD.[7] For this purpose, capacitive probes are placed in the interelectrode space and inside the hollow cathode region, in conjunction with an electron-beam detection system, based on beam-target x-rays, placed behind a semitransparent anode.[8]

IV. DISCUSSION

The single coaxial capacitive probe reported by Avivi *et al.*[4] was used to study the drift velocity of relativistic electron beams by measuring the electrostatic potential induced by the charge of the electron beams. A typical time scale for the probe signal in these measurements was tens of nanoseconds. As the electron beams propagate in vacuum, no space-charge formation was detected and the absence of live electrodes in the vicinity of the probe imposed a less stringent shielding requirement than in the case reported here. We have successfully used an array of the coaxial capacitive probes to monitor ionization growth in a high-voltage environment. The closely coupled common ground shield of the probe array relieves most of the problems of placing a capacitive element within a high-field region. The design allows the probe signals to depend only on the time variation of the coupling capacitance of the probes to the local charge and the local potential. The time response of the probes is essentially determined by the coupling capacitance to ground and the signal cable impedance. By careful construction the time response can be of the order of one nanosecond, as in the case reported here. Spatial resolution, as inferred from the paired probes measurements discussed above, is of the order of a few millimeters for the present experimental arrangement. Further refinements of the probes signals analysis can be used to provide more quantitative information on the charge growth development in the THCD currently under investigation. In conclusion, we have shown that the capacitive probe array is a simple but effective noninvasive diagnostic tool for direct monitoring of charge developments which can be applied to a variety of experimental configurations in high-voltage electric discharges.

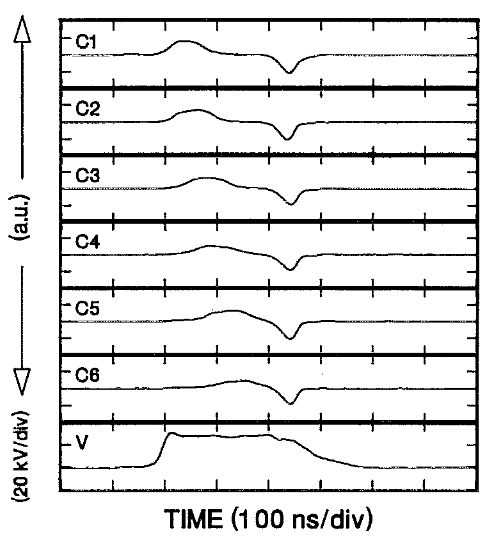

FIG. 5. Observation of a moving virtual anode in a THCD in hydrogen at 195 mTorr with a six, equally spaced, probe array. The applied voltage is 30 kV. The probe positions, as measured from the anode, are: C1, 3.5 cm, C2, 4.0 cm, C3, 4.5 cm, C4, 5.0 cm, C5, 5.5 cm, and C6, 6.0 cm. The probe signals rise in a sequence from the anode towards the cathode.

ACKNOWLEDGMENTS

M. Favre acknowledges a Marie Curie Fellowship awarded by The Commission of the European Communities (CEC). This work has been performed with funding from CEC under a SCIENCE contract and with funding from Fondo Nacional de Ciencia y Tecnologia in Chile, under Grant No. 1930575.

[1] K. Frank and J. Christiansen, in *Proceedings of the XIII International Symposium on Discharges and Electrical Insulation in Vacuum*, edited by J. M. Buzi and A. Septier (Les Editions de Physique, Les Ulis, France, 1988), p. 367.
[2] M. P. Alberta, J. Derouard, L. C. Pitchford, N. Ouadoudi, and J. P. Boeuf, in *Proceedings of the XXI International Conference on Phenomena in Ionized Gases*, edited by G. Ecker, U. Arendt, and J. Böseler (APP, Bochum, Germany, 1993), Vol. II, p. 295.
[3] J. Lucas, in *Proceedings of the Tenth International Conference on Phenomena in Ionized Gases*, edited by H. Maecker (North–Holland, Amsterdam, 1961), p. 693.
[4] P. Avivi, Ch. Cohen, and L. Friedland, Appl. Phys. Lett. **42**, 948 (1983).
[5] P. Choi, R. Aliaga, B. Blottiere, M. Favre, J. Moreno, H. Chuaqui, and E. Wyndham, Appl. Phys. Lett. **63**, 2750 (1993).
[6] P. Choi, H. Chuaqui, M. Favre, and E. Wyndham, IEEE Trans. Plasma Sci. **PS-17**, 770 (1989).
[7] M. Favre, J. Moreno, H. Chuaqui, E. Wyndam, P. Choi, and R. Aliaga, in *Proceedings of the XXI International Conference on Phenomena in Ionized Gases*, edited by G. Ecker, U. Arendt, and J. Böseler (APP, Bochum, Germany, 1993), Vol. II, p. 197.
[8] P. Choi, H. Chuaqui, M. Favre, and E. Wyndham, IEEE Trans. Plasma Sci. **PS-15**, 428 (1987).