OBSERVATION OF STEPPED CREATION OF OSCILLATORY LUMINOUS BEADS IN CHAIN OF AIR PLASMA

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الخلاصـــة :

لقد وجدنا أنَّ التفريغ الكهربائي في الهواء تحت ضغط يقارب مئة ملم من الزئبق ، ينتقل باتجاه القطب السالب مُتخِـذاً شكل عقود مضيئة . وأظهرت الدراسة الضوئية أُحادية الجبهة المتقدمة ، وفي حين كانت العقود المضيئة مراكز انبعاث ضوء متردد فإنَّ الانبعاث الضوئي كان مُخمداً من المناطق المظلمة .

ABSTRACT

Cathode-directed electrical discharge in air at 100 torr, advancing under the influence of single modulated high voltage pulses, have been found to have the appearance of a necklace of luminous beads. Photomultiplier studies reveal the monotonic advance of the wavefront, the oscillatory nature of the bright regions and suppressed emission from the dark spaces.

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1. INTRODUCTION

The study of the macroscopic behavior of plasmas is an incomplete field of physics. Gas discharges under laboratory conditions were investigated more than two centuries ago, and indeed G. C. Lichtenberg wrote his account on the figures associated with his name in 1777. Townsend developed his concept of the electron avalanche in 1880 and proposed that multiplication of electrons in an electric field could be expressed by $n_e = e^{\alpha x}$ where x is the distance traveled by the avalanche head. Subsequent studies, including important contributions from Meek and Craggs [1] and Raether [2] on the streamer model, increased our empirical knowledge of discharges under a variety of conditions and these were valiantly summarized by, among others, Loeb [3], Meek and Craggs [4], and Nasser [5]. There are currently several groups working on the fundamentals of discharge (*e.g.* Davies *et al.* [6], Tran Ngoc An *et al.* [7], Stritzke *et al.* [8], and Lozanskii [9]). Stationary striation-like structures have been observed in high frequency discharges from a few MHz (Wood [10], Klerk [11], Takeyama *et al.* [12], and Nakata *et al.* [13]) to microwave range (Takeyama *et al.* [12] and Massey [14]). Most of the work has been conducted with inert gases.

DC striations are now generally believed to be ionization waves which are perpetuated by the electric field associated with local variations in the space charge and in which the DC electric field plays a vital role in providing a positive gain to the wave feedback mechanism (Peka'rek *et al.* [15]). However, there is no confirmed theory to support a belief that striation-like structures observed in RF plasma and the moving striation observed in DC plasma are part of the same general family. Supported by experimental evidence, Penfold *et al.* [16], suggest that stationary HF striations in inert gases are standing waves, the component moving waves being essentially the same as those encountered in DC charges. This suggestion is not a trivial one but it requires an understanding of the role of the underlying physical effects, and a statistical treatment of how the component moving waves combine to produce the macroscopic effect observed. The stimulus for theoretical work will come only from a systematic classification of empirical phenomena and a rigorous measurement programme with modern diagnostic apparatus.

Here we report the observation of a necklace of bright beads of plasma, created in an experimental regime that allows the time-development of the beads to be studied from their inception. These bright beads might, in our opinion, shed some light on the process of the formation and structure of the stationary striations observed in high frequency discharges.

2. OSCILLARY OPTICAL EMISSION FROM AIR

Recently we described [17] the light emission from an air plasma expanding in a point to plane geometry under a modulated high voltage pulse regime. Photographs showed distinctive patterns in the spatial development of the discharges, and a telescope incorporating a photomultiplier recorded the light output from selected points in the discharge. The novel result to emerge was in the case of a positive point; the discharge commenced at the point and advanced towards the plane (negative electrons move towards the point) presumably by photoionization, but one well-defined bright stationary localized region was clearly visible. The photomultiplier showed this region emitted its photons in an oscillatory manner, unlike the surrounding regions which emitted only a single main pulse of light. We concluded that the oscillatory condition was associated with the modulation frequency of the high voltage pulse which exhibited the same period. This observation in air was quite unlike the monotonic advance that a discharge maintains in the noble gas mixture of 70% neon/30% helium [18], but had a connection with the finding of oscillatory emission in nitrogen by Haydon and Plumb [19].

3. EXPERIMENTATION

The discharges were created within the volume of a streamer chamber (Rice-Evans [20]). The point-to-plane geometry (Figure 1) consisted of a 10 μm diameter gold plated tungsten wire placed above an earthed aluminum plane of $61 \times 61\ cm^2$. The wire tip could be placed up to a maximum of 18 cm above the plane electrode which was covered with a 1.2 cm thick perspex sheet, that formed part of the gas enclosure. Modulated positive pulses of mean duration 7 μs with 100 ns modulation derived from a 100 pF capacitor charged by a 0–30 kV power

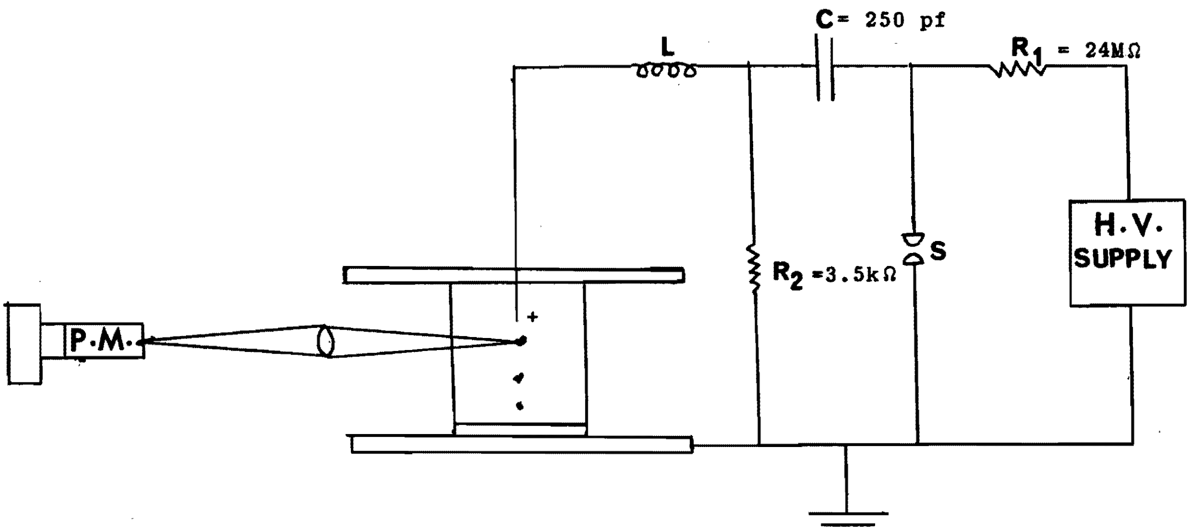

Figure 1. Schematic Diagram of the Electrical Equipment Used in the Point-to-Plane Discharge.

supply through a spark gap network were applied to the point and a typical voltage waveform is shown in Figure 2; the variation of DC (time-averaged) current T with voltage V is shown in Figure 3. The air pressure was optimized in the range 40–120 torr to give the clearest patterns.

The light emission from selected points in the discharge patterns was determined with a 56 AVP photomultiplier. In effect, areas of 1 mm^2 were focused onto an aperture of 1 mm^2 before the photocathodes.

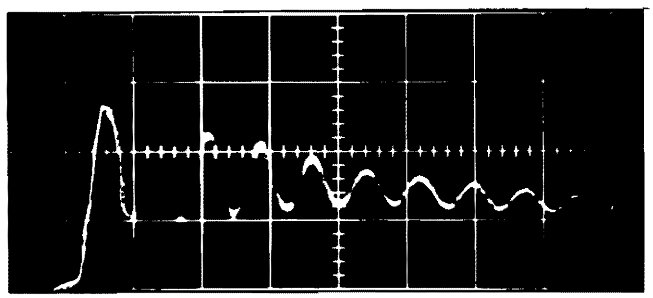

Figure 2. Typical High Voltage Pulse of Mean Duration 7 μs with a 100 ns Modulation, Derived from a 1000 PF Capacitor Charged to a 30 kV (10 kV cm^{-1}, 100 ns cm^{-1}).

4. RESULTS

In studying the single localized oscillatory region of light emission (see Section 2) it was observed that if the gap size were increased manually then another such region emerged from the neighborhood of the cathode. Subsequently, we have been able to obtain three bright regions. Figure 4 shows their appearance (distances not to scale), the photographs being obtained with an open-shuttered camera exposed to about ten successive discharges. To the eye, the color is purple.

Alternatively, if one reduces the pressure from atmospheric, under the pulsed region, one observes first a corona at the anode tip; then filamentary streaming; then the beads we now report; and then a uniform glow at low pressure.

Figure 5 shows the time development of the light output from various regions in the discharge for the case of two bright beads—the regions being identified by letter in Figure 4. The emission from the bright region just below the anode tip (a) is synchronized with the HV modulation frequency. The first

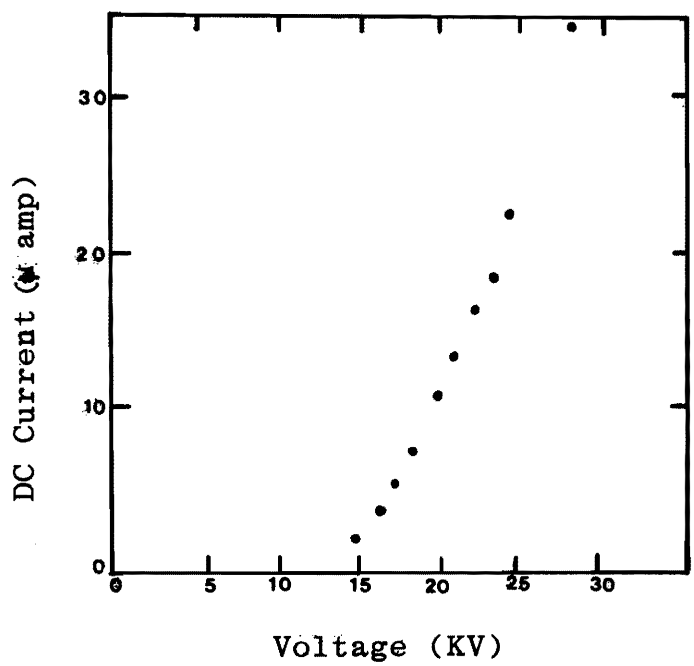

Figure 3. The Variation of the DC (Time-Averaged) Current with Voltage.

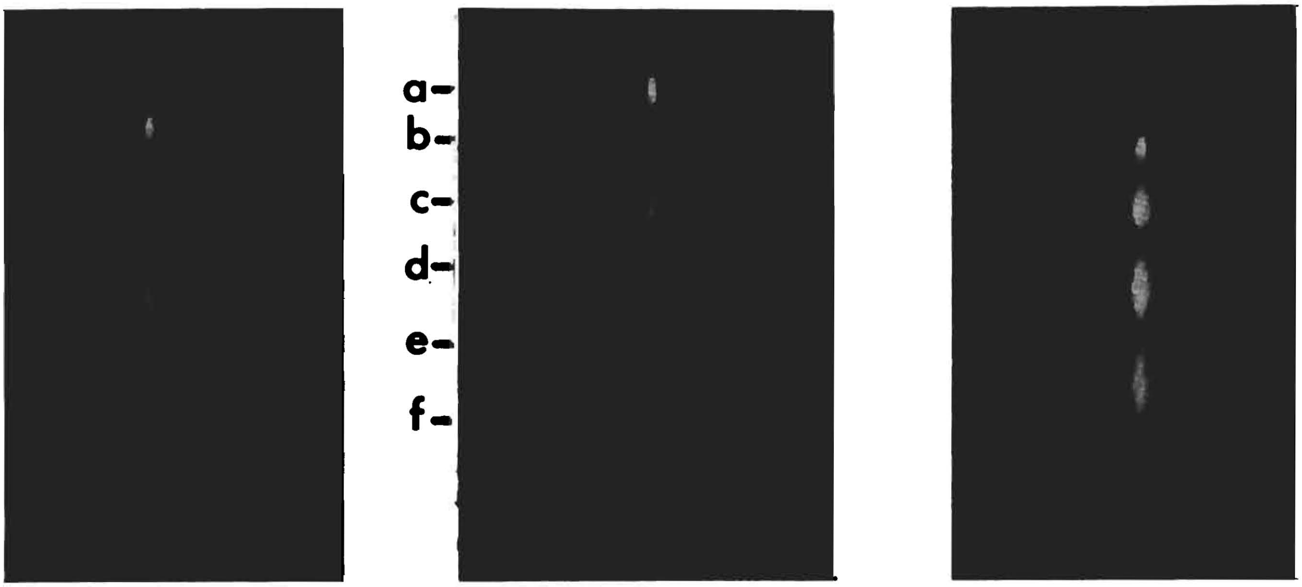

Figure 4. Three Examples of Breakdown Under the Pulsed Regime, the Discharge Advancing Downwards from the Anode Wire at the Top which Glows in Each Case. From the Left, One, Two, and Three Luminous Beads of Plasma are Visible, the Respective Gaps Being 13.5, 15, and 16.5 cm—Not to Scale Here, with Optimal Pressure of 112, 108, and 106 Torr Respectively.

dark space (b) emits an initial main burst of light; the bright region (c) gives off a sequence of light pulses; and second dark region (d) essentially one pulse; the second bright region (e) again emits oscillating light; and the third dark region (f) again yields one main burst of light. We obtained similar signals when we studied the output from three oscillatory regions (right-hand photograph in Figure 4), the pattern repeating itself for the lowest region.

The times of the first burst of light from the regions ($a \rightarrow f$) are 30 ns, 60 ns, 70 ns, 140 ns, 160 ns, 230 ns, respectively. These are approximate due to uncertainties in the triggering of the oscilloscopes, but they indicate the advance of the discharge downwards from the anode point with a velocity of the order of $5 \times 10^7\ \mathrm{cm\,s^{-1}}$.

5. CONNECTION WITH MICROWAVE PLASMAS

Recently, Huerta and Magnan [21] have referred to photographs of spatial structures in plasmas excited by radio frequency fields that are very similar in appearance to the stationary striations we now report. As in our work, the number of bright regions was proportional to the length of the discharge. Robertson and Herring [22] originally reported a string of balls of plasma in argon at 7.8 torr and 87 MHz and suggested their existence depended upon the gas ionization being a two-stage electron collision process, the first stage being excitation to a metastable state. The two-stage hypothesis was supported by the fact that balls of plasma were found in argon, krypton, and xenon which have metastable first excited states, but not in air or nitrogen which do not; and by the discovery that the introduction of cesium vapor into argon eliminated the striations due to single ionization processes.

Goldstein, Huerta, and Nearing [23] developed a two-time perturbation theory in which an unstable uniform steady bifurcates to a new state with a sinusoidal electron density variation in space leading to the formulation of balls of glowing plasma in argon.

In spite of the similarity in appearance between our present findings and these microwave structures, it must be significant that the latter have not been seen in nitrogen. In our discharge work with noble gases [18] we have observed bright and dark patterns in a neon–helium mixture but, as we showed, the bright regions did not yield the prolonged oscillatory bursts of light we now find for air but rather a single transient emission, even though both helium and neon have metastable first excited states.

We conclude that the microwave calculations are of limited relevance for the present work, and that

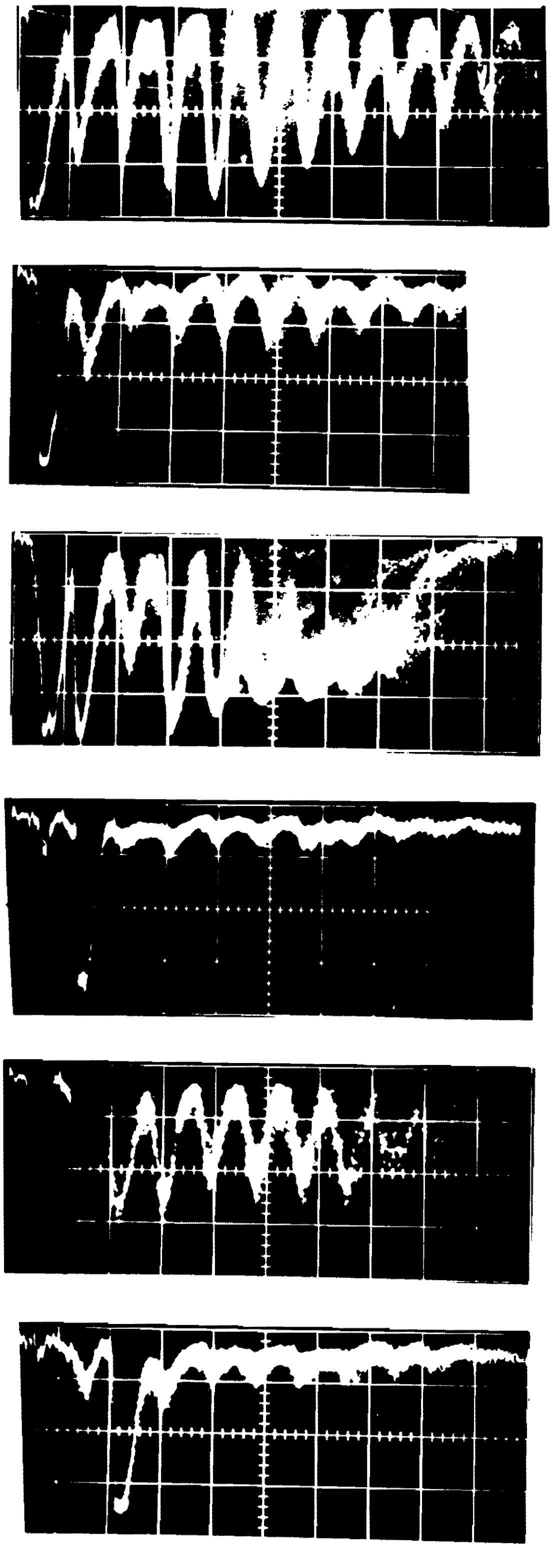

Figure 5. Light Output from the Regions (Identified by Letter) in the Expanding Plasma (Figure 4 Central Photograph) Indicated by Oscilloscope Traces (100 ns cm^{-1}).

explanation are more likely to be found in the instantaneous disposition of space charges resulting from ionization in the varying applied electric field.

6. DISCUSSION

Under the conditions of the experiment—*i.e.* gas pressure 100 torr and frequency 10 MHz—the electron neutral atom collision frequency greatly exceeds the applied HV frequency. Thus the electron current which flows in the gas as a result of ionization is in phase with the applied voltage, and accordingly the discharge presents essentially a resistive load to the circuit [19]. We can assume that in the weakly ionized plasma electron–neutral collisions will govern the transport processes, and that electron–ion collisions and recombination may be neglected.

The instantaneous excitation and the ionization will be related to the electric field at any moment and, once the plasma has been established, one might expect to see a uniform glow along its length with, assuming rapid de-excitation, the light output from all points oscillating in sympathy with the fluctuating field. But uniformity is not observed; rather we see stationary isolated regions of emission.

The discharge starts by fields ionization at the tip of the wire anode. Electron multiplication must occur, and the electrons will be attracted and move upwards towards the anode. For the time scale involved, say 50 ns, the positive ions will drift only about 0.1 mm and their movement can therefore be ignored. Apart from recombination, their existence in the plasma is permanent and stationary and it is likely that the fields arising from their space charges are crucial in determining the action of the discharge.

Fifty nanoseconds after the commencement, that is in the first decline of the applied field, many of the electrons will have entered the anode and helped negate the applied potential. But the continued existence of large numbers of positive ions in the column beneath the anode will ensure the field in the adjacent region below does not disappear, but remains strong enough to promote the advance of the discharge by excitation, photoionization, and electron multiplication as before. Thus to a certain extent the discharge proceeds independently of the fluctuations in the applied voltage, and this is supported by the steady advance of the plasma front indicated by the timing of the first light pulse.

The precise mechanism of advance of the plasma away from the anode is not established. Lozanskii [9] has argued for reverse streamers that the photon absorption coefficients in air are so high that resonance radiation would not emerge by diffusion from avalanches fast enough to account for a rapid streamer advance — in our case $5 \times 10^5\,\mathrm{m\,s^{-1}}$. Rather, he suggests that excitation of atoms occurs at large distances from avalanches due to photons acquiring a high penetrating power as a result of a broadening of excitation levels by atomic collisions. For streamers in noble gases the ionization mechanism is probably a quenching reaction of the type $A^* + A \rightarrow A_2^+ + e^-$, but in molecular air the reaction is not clear. Indeed, Davidenko *et al.* [24] have remarked on the apparently different photoionization processes in neon and nitrogen, and we therefore regard the question as open.

From the photomultiplier studied we learn that the bright regions emit oscillatory light; the dark regions yield a little light except for the single main burst of photons. The discharge advances from the anode region until eventually it reaches the neighborhood of the cathode. The intensity of light in the first peak remains approximately constant as the advance proceeds irrespective of position and hence the brightness is a consequence of repeated emission of light. In view of the oscillatory nature of the applied field, the bright beads are perhaps less remarkable than the dark regions in which later light emission appears suppressed.

One may hypothesize that during a peak of the applied voltage, in a bright region, a large cloud of electrons is generated. Subsequently during the following depression of voltage, some of these may recombine, but most will drift through the adjacent dark space without large ionization to arrive at the next bright region when the voltage is again on the ascendant and where the electrons will once more accelerate and stimulate ionization with another burst of light emission, *etc.* It will be the positive space charge on the cathode side of a dark region that will reduce the field within the region and inhibit the electron acceleration.

The results therefore suggest that the electron clouds drift from one bright region to the next in unison with the high voltage cycle. The general observation that increasing the electrode gap length results in the creation of more bright regions supports this conclusion.

It is natural to speculate on the connection between such a chain and the striations that can be observed in the positive glow of DC discharges of many gases. Standing striations, at least to the eye, appear better-defined and less diffused than the present beads. Furthermore, striations are renowned for their propensity to move, and we have no analogy in our experiment. Nevertheless, Donahue and Dieke [25] and Pilon [26] have shown that striations do emit light in an oscillatory fashion.

It is clear that the model is incomplete. The uncertainties will be resolved with a quantitative description of advancing plasma in a fluctuating electric field.

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