X-ray Emission Accompanying Cathode Microdischarge

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ABSTRACT

Electrical discharge in vacuum is accompanied by X-ray radiation. Knowledge of the generation mechanism of radiation may lead to its practical use. The analysis of this phenomenon indicates that it is only at the discharge development phase until the moment of the anode plasma generation that the proper conditions for X-ray generation are satisfied. The intensity of radiation is dependent on the field current intensity on the cathode surface as well as on the value of the electron current supplying the anode. The anode current at the vacuum discharge development phase has a pulse character, and the pulse amplitude is dependent on the cathode plasma density. The radiation intensity may be increased by increasing the current amplitude, *e.g.* by artificial plasma generation in the trigger system.

1. INTRODUCTION

It is well known that X-ray emission accompanies the process of current discharge in vacuum [1]. The analysis of this process indicates that optimal conditions for generating X-rays occur at the stage of the discharge development when there is a high current flowing in the presence of the HV [2, 3]. As soon as the discharge develops into the arc stage, the voltage in the electrode gap is lowered considerably with the simultaneous intensity of radiation. Thus, the analysis of the mechanism of electrical discharge in vacuum with special allowance made for prebreakdown current is very important.

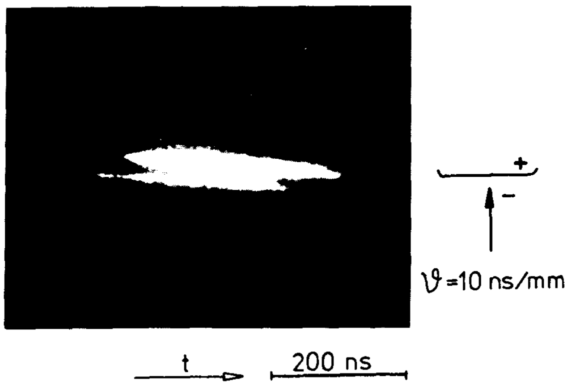

Figure 1.
Streak photograph of the initial stage of electrical breakdown in vacuum.

2. DEVELOPMENT OF ELECTRICAL DISCHARGE IN VACUUM

It follows from numerous publications on this subject that vacuum discharge can develop under the influence of field emission and microdischarges, or can be initiated by microparticles. Of particular interest to this research study is the mechanism of microdischarges [4, 5]. Microdischarges occurring on one of the electrodes result in the formation of plasma which contributes largely to further discharge development. There is no consensus about the mechanism giving rise to microdischarges. Taken here into consideration are explosive emission [6, 7] or discharges in the adsorbed layer near the electrodes [8]. It follows from both these mechanisms that microdischarge are generating plasma on the cathode surface. Thus, this phenomenon is similar to that occurring in a trigatron, the difference being that the plasma near the electrode is produced artificially from an additional source. The formation of the cathode plasma is conditioned by the flow of the current, sufficient for generation of anode plasma, which results in the breakdown. Observations of this phenomenon by means of high-speed photography provide interesting information on this subject. By way of example this is shown in the streak photograph, Figure 1.

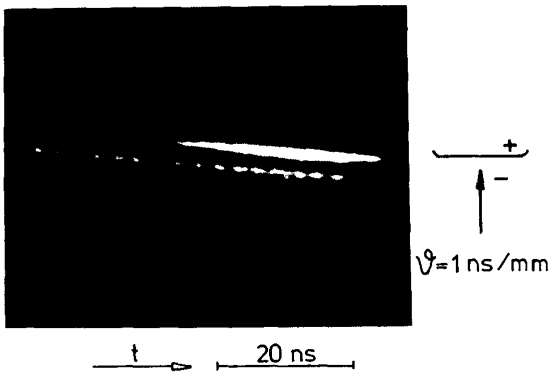

Figure 2.

Streak photograph showing oscillating light emission at the cathode.

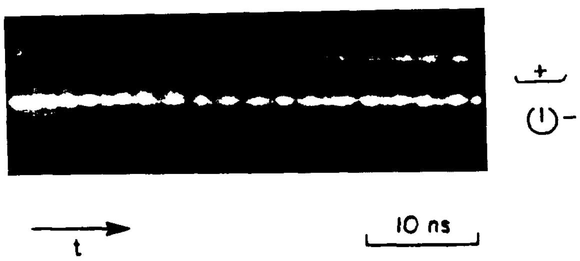

Figure 3.

Streak photograph of cathode light emission for triggered dc breakdown.

These observations indicate that the discharge always starts as a luminous spot on the cathode surface. Then, after a period of time depending, among other things, on the distance between the electrodes as well as on the material and the anode temperature, an intense anode light appears in the interelectrode gap. The appearance of the anode plasma is equal in effect to the loss of the insulating properties of the vacuum gap and to the abrupt drop in the voltage on the electrodes. In this way, the conditions for generating X-rays will disappear. Thus, from this point of view, of much interest to us are only the phenomena accompanying the development of the discharge until the moment when the anode plasma appears. With the use of a high-speed camera it can be observed that the cathode light has a pulsating character, Figure 2. Such an image of the discharge development with distinctly visible phenomena occurring on the cathode and anode is possible only when the focus of the camera and of the image intensifier are set up very accurately. Failure to satisfy these conditions makes it impossible for the cathode pulses to be observed. Cathode pulses are also observed on the trigger cathode, Figure 3.

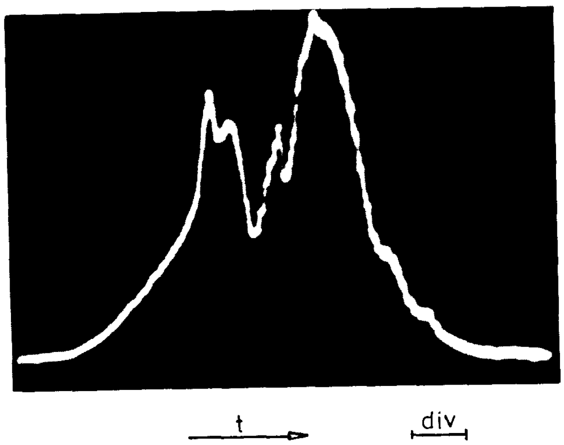

Figure 4.

Current waveform accompanying the breakdown development in vacuum. 50 ns/div, 2 A/div.

The above phenomenon is similar in both cases, the difference being that the artificially generated cathode plasma has a more intensive light and the frequency of pulses, being much higher immediately after their generation, decreases during further development stages. It has been found that the brighter the pulses, the greater their frequency. This allows the frequency of the observed impulses to be associated with the density of the plasma being generated. Such model of the vacuum discharge implies that the anode is bombarded by a stream of electrons accelerated from the cathode area. The source of electrons, in addition to field emission, is mainly the cathode plasma. A possible mechanism of this phenomenon is presented in [10]. The acceptance of such a mechanism

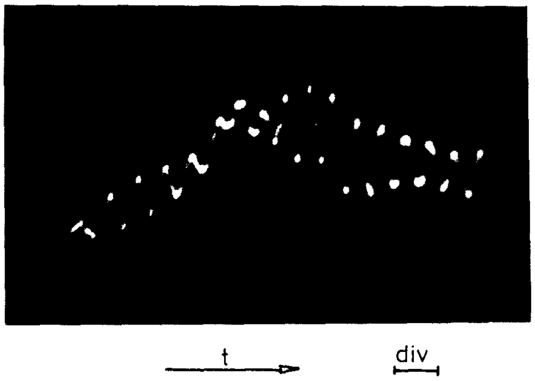

Figure 5.

Sector of the emission current waveform corresponding to the light spots in the current run in Figure 4. 10 ns/div.

assumes that the cathode light pulses should be accompanied by pulses of the current supplying the anode. It follows from photographic observation that the duration of such a current impulse is much shorter than 1 ns, the impulse repetition being 4 to 5 ns. At the 1 ns time, the electromagnetic wave may under optimal conditions cover a distance of $\sim$ 30 cm, which makes the recording of such oscillations very difficult. Additional disturbances introduce inductance of the connecting leads and of the shunt. The above mentioned considerations may account for the negative attempts to carry out such measurements [9,11]. However measurements in the system described in [11,12] using a TEK 7904 oscilloscope (500 MHz bandwidth) have provided very interesting results (Figure 4). We can see here that some distinctly marked bright spots with repetition rate of $\sim$ 5 ns occur on the basic current waveform, the time being the same as in the case of cathode pulses on streak photographs (Figure 2). With the higher recording velocity these spots appear to be current oscillations superimposed on the basic run (Figure 5).

A similar current waveform but for the case of triggering pulse release on the cathode are presented in Figure 6. As can be seen here, the frequency of current pulses is higher than that in Figure 4 and 5, which corresponds with a higher cathode frequency recorded by means of the photographic method on the cathode supplied with the triggering pulse (compare Figure 2 and 3). The current oscillographs presented here have been obtained by screening very accurately the measuring system, but in spite of this we are not certain whether they are not being disturbed by the external field. However, even though these are disturbances, their source has the same frequency as that of light pulses on the cathode recorded with a photographic camera. It may be assumed readily that the

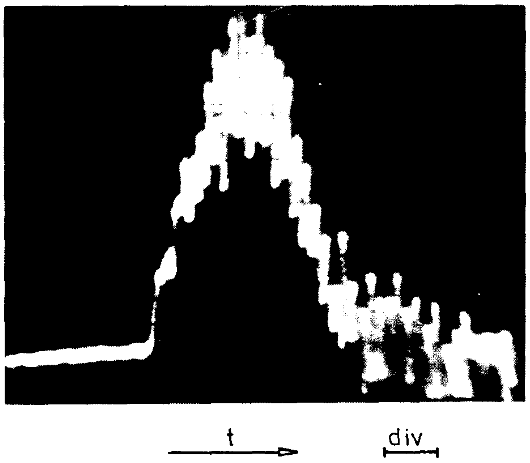

Figure 6.

Current waveform accompanying the breakdown development in the case of trigger pulse release on the cathode. 10 ns/div.

source of disturbances is the pulsation of cathode plasma. It is thus additional confirmation of the pulsating character of the development of vacuum discharge. Apart from the measurement difficulties discussed above, the essential thing is that during the development of the vacuum discharge there are conditions for generating intense X-radiation. This radiation should be relevant to the current with the constant voltage assumed, while the current value can be influenced by the cathode plasma density and through appropriate technological procedures affecting the local field intensity on the cathode.

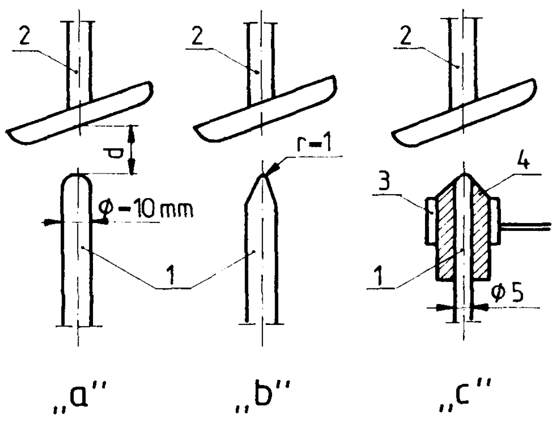

Figure 7.

Schematic diagram of the electrode systems examined: 1: cathode, 2: anode, 3: trigger, 4: ceramic pipe.

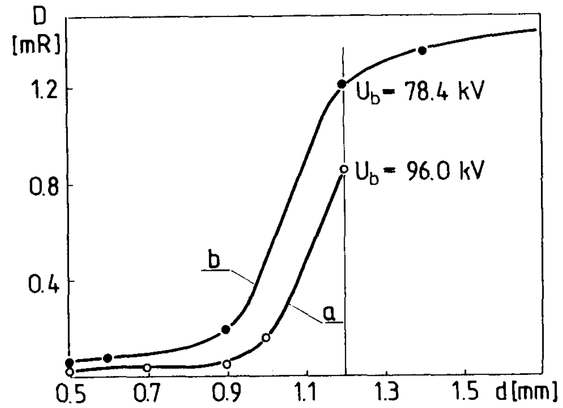

Figure 8.

Dependence of X-radiation dose on the interelectrode gap. U breakdown voltage.

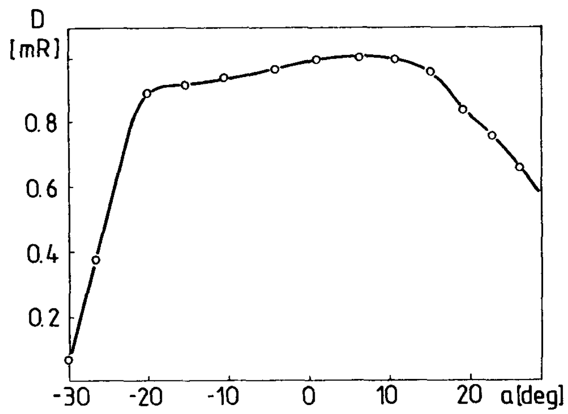

Figure 9.

Distribution angle of radiation in the electrode system a.

3. EXPERIMENTAL PROCEDURE AND RESULTS

STUDIES into X-ray radiation accompanying electrical discharges in vacuum were carried out for two and three electrode (trigatron) systems, Figure 7. Electrodes made of stainless steel were used and the interelectrode gap was changed from 0.5 to 4.0 mm. In the examined system, the anode was 40 mm in diameter and its inclination angle was 10° in relation to the vertical plate. Trigger electrodes were insulated by a $BaTiO_3$ ceramic pipe. The electrodes were put into a metal chamber with glass observation windows. The tests were carried out under a pressure of 7×10^{-3} Pa at dc voltage after the system was conditioned. The trigger electrodes were supplied by the impulse voltage obtained from a 990 pF discharge capacitor at 17 to 18 kV. The initial radiation intensity measurements by means of PIN diodes have shown that the response time of the accessible diodes is too low, which made it impossible to record the radiation impulses accompanying the cathode impulses. This was the reason why further studies were carried out by means of a much cheaper photographic method recording the total radiation dose on Fotopan™ HL photographic plates with ASA 400 sensitivity. They were being placed at the observation window of the test chamber. The plates were calibrated by means of a reference standard radiation source.

Figure 8 shows the dependence between the radiation dose as the function of the electrode gap for a and b electrode systems presented in Figure 7. It has been shown that the system with a more nonuniform electrical field gives a higher radiation dose despite the lower cathode potential. This is evidence that the electron current pulse reaching the anode is dependent not only upon the voltage of the electrodes [13], but also upon the local electric field. As can be seen, the radiation dose is not linearly dependent on the electrodes distances when these distances are small. Such a linear dependence is reported in [13]. This nonlinearity may be connected with the size of the area of the cathode plasma which, while filling the interelectrode space with small distances of electrodes intensively, cuts down the discharge development time and thus the X-ray generation time. Thus we might say that this is connected with the change of the breakdown mechanism from the cathodic mechanism into the anodic one. The increase in the electric field can be obtained by producing microprotrusions. X-ray radiation intensity has a characteristic angle distribution for each particular electrode system, Figure 9.

Table 1.

Radiation dose in the c electrode system. $U_b = 75$ kV, breakdown voltage for $d = 4$ mm.

% U_b	74	63	53	37
U (kV)	55.7	47.7	39.8	27.8
X (mR)	5.7	1.61	0.28	0.11

Table 2.

Radiation intensity in c electrode system with the trigger impulse on and off.

Trigger	U (kV)	X (mR)
off	75.5	0.31
on	55.7	5.7

A further increase in the anode current can be expected by increasing the cathode plasma density. One of the possible solutions could be the plasma generation in the trigger system. The results obtained in the c system with the trigger are presented in Table 1.

Comparison of the radiation intensity in the c electrode system for the 4 mm electrode gap with the trigger on and off is presented in Table 2.

As can be seen from the results presented above, the system with a trigger has made it possible to increase the exposure dose 20× even though the voltage was decreased by ~ 25%.

4. DISCUSSION AND CONCLUSIONS

PHOTOGRAPHIC observations of vacuum discharge development indicate that the discharge starts with a pulse of light on the cathode, and after some delay time, more intensive anodic light appears. The generation of plasma on the cathode with the use of a trigger electrode causes the frequency of cathodic pulses to be increased. The mechanism of this phenomenon has not been fully accounted for, but the results obtained indicate that this is due to the interaction between the space charge of the cathodic plasma and the external field [10]. According to such a mechanism, cathodic pulses should be accompanied by anodic current pulses with a comparable frequency as well as by X-radiation pulses generated on the anode. The attempts made by different researchers to measure current pulses [9, 11, 12] failed to give the expected results. We are of the opinion that this is caused mainly by the imperfection of the measuring system used. It is difficult to agree on conclusions presented in the papers [11, 12]. The streak photographs presented there are markedly out of focus and show a lack of characteristic details of cathodic and anodic phenomena, as can be seen in Figures 1, 2, and 3. Thus, they can be regarded as an image of blurred light streak whose source is discharge in the vacuum gap. The lighting pulsation seen on these photographs are by no means pulses of cathodic lighting. The only reasonable explanation for their existence may be the fact that the operation of the camera was disturbed by a strong external electromagnetic pulse of a definite frequency. This frequency, however, surprisingly corresponds to that generated by cathodic pulses in the course of the vacuum discharge development. A similar image could be obtained from an optional source of light if this is synchronized with the simultaneous vacuum discharge in proximity of a highspeed camera. This type of light pulsation in the streak photograph can be eliminated by appropriate camera screening. It should, however, be pointed out that, similarly to the oscillography of currents, we have here further evidence of generation in the course of the vacuum discharge development of the electromagnetic wave with the characteristic frequency. The conventional electromagnetic noise comprises a total frequency spectrum, whereas in this case there is one prevailing frequency which is always the same on both the photographic pictures and current oscillographs. The above observations are firmly in favor of the thesis that the anode prebreakdown current is of impulse nature and thus it should be accompanied by X-radiation pulses. The difficulty however lies in the fact that the best X-ray sensors available, PIN diodes, are characterized by a resolution time of < 2 ns, whereas the duration time of current pulses should be estimated to be far below 1 ns. This problem is likely to be solved in the near future when measurement techniques are more advanced. On the other hand, the total X-radiation dose sensors in the form of the photographic plates used in the research study and discussed in this paper have made it possible to indirectly confirm the effect of the cathodic plasma space charge and the local electric field on the cathode surface upon the generation of X-radiation.

The results obtained have enabled us to state the following: The radiation intensity is dependent upon the electric field at the cathode surface as well as upon the density of plasma generated on the cathode. The field intensity on the cathode can be increased by increasing the voltage on the electrodes as well as by changing the cathode surface geometry,

Cathode plasma may be produced naturally by means of microdischarges accompanying the development of the vacuum discharge. This method, however, has limited the possibilities of increasing the current amplitude as well as the radiation intensity. Much more promising results can be obtained in the trigger system. In this system, by changing the energy of the trigger discharge, it is possible to change the cathode plasma density which involves an increase in the current amplitude and X-ray intensity.

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