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THE RELATIONSHIP BETWEEN CHARGE DISTRIBUTION, CHARGE PACKET FORMATION AND ELECTROLUMINESCENCE IN XLPE UNDER DC

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INTRODUCTION

Different reports describing the internal distribution of space charge in cross-linked polyethylene (XLPE) under DC field have been published recently. Indeed, this material is widely used as insulation for power cables and there is an increasing need to understand the behavior of space charge, which is a limiting factor for the use of XLPE under DC stress. Experiments carried out either on lab specimens [1, 2] or on model cables [3] allowthe observation of the charge distribution up to breakdown. It has been shown that above a material dependent field value of the order of 70-100 kV/mm [1], the space charge can acquire a dynamic character as compared to the situation under lower field. The most striking fact is the organization of the space charge into charge packets that cross the insulation [1, 3, 4, 5, 6]. They appear as the apparent motion of charge particles (being either positive [3] or negative [6] depending on materials [6], LDPE, XLPE, doped or undoped) that may cross the gap between the electrodes with apparent mobilities of the order of 10^{-15} $m^2V^{-1}s^{-1}$ [5]. The electric field is greatly enhanced in front of the packet, and is relaxed at the tail, Figure 1. Two different interpretations have been put forward. The charge packet is described either as a body of excess charge initiated by injection from the electrodes [3, 5], or as a propagating ionization front [1, 6, 7, 8]. In the latter case field-induced ionization of impurities contained in the material occurs in front of the propagating wave, which leads to the supply of carriers to the bulk. All models for packet formation imply that recombination will occur, either as part of the mechanism of ionization-recombination responsible for the packet itself, or through recombination of the excess charge in the packet with a background charge of opposite sign.

This will occur either at the tail of the propagating packet if the phenomenon is due to the propagation of an ionisation front (see Figure 1) or throughout the body of the propagating packet if it consists of an excess charge propagating on a background of charge of opposite sign. As the recombination region is potentially a luminescence one it is of interest to record the EL in this regime. This topic is addressed here.

EXPERIMENTAL

150 μm-thick specimens were obtained from films peeled from unaged cables. A thermal treatment was
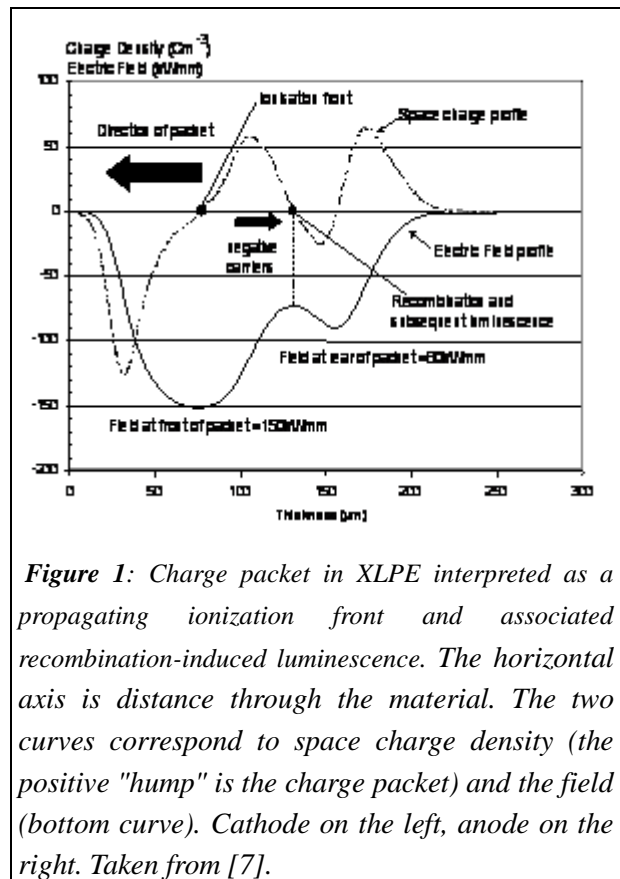

Figure 1: *Charge packet in XLPE interpreted as a propagating ionization front and associated recombination-induced luminescence. The horizontal axis is distance through the material. The two curves correspond to space charge density (the positive "hump" is the charge packet) and the field (bottom curve). Cathode on the left, anode on the right. Taken from [7].*

carried out at 50 °C for 48 hours in order to expel most of the residues of the cross-linking process. The concentration of cross-linking by-products (cumyl alcohol, acetophenone, α-methylstyrene, cumene) measured after such treatment was below the detection level of Fourier Transformed Infrared Spectroscopy and High Performance Liquid Chromatography [9].

Space charge measurements were performed by the pulsed electro-acoustic technique having a sensitivity of about 0.1 C.m^{-3} and a spatial resolution of the order of 10 μm.
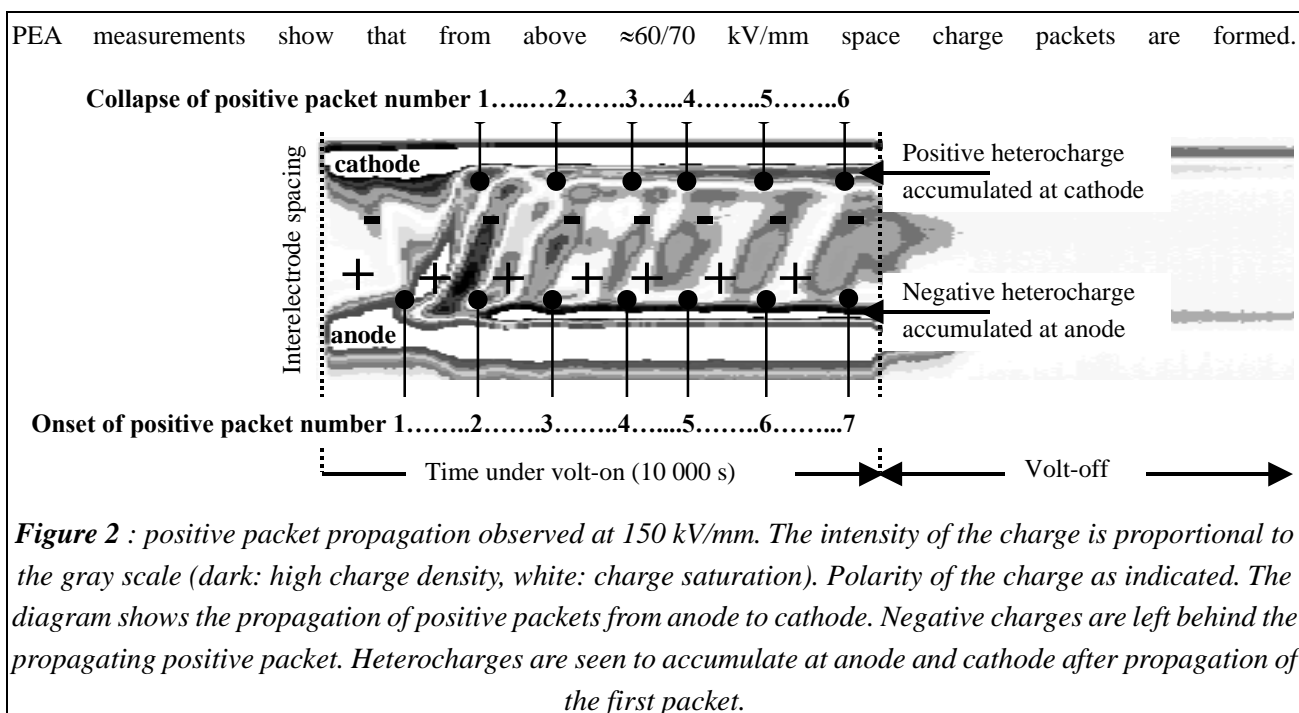
Electroluminescence was detected with a photomultiplier (PM) working in photon counting mode. The external current was measured simultaneously with a sensitivity of 10^{-14} A. The characteristics of the detection set-up have already been given in the literature [10].
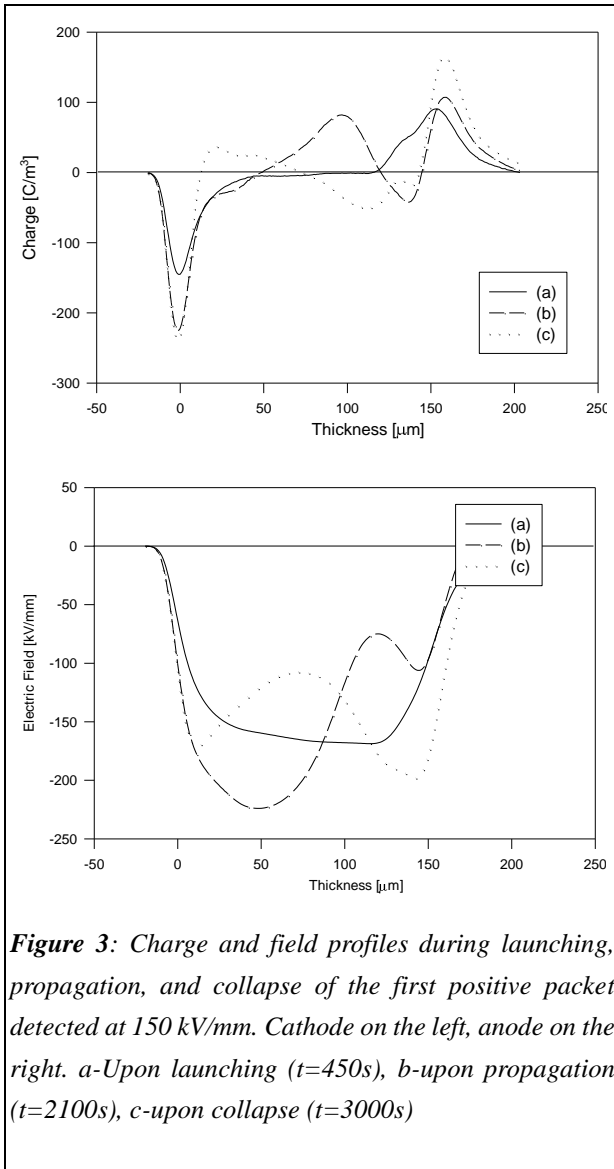
RESULTS AND DISCUSSION

When increasing the field further, the dynamics of the packet propagation is increased. Figure 2 gives a schematic picture of the charge packet formation and propagation at a field of 150 kV/mm. Since the gray scale does not allow to differentiate between positive and negative charges, the polarity of the charge has been indicated on the diagram. Basically, the scenario
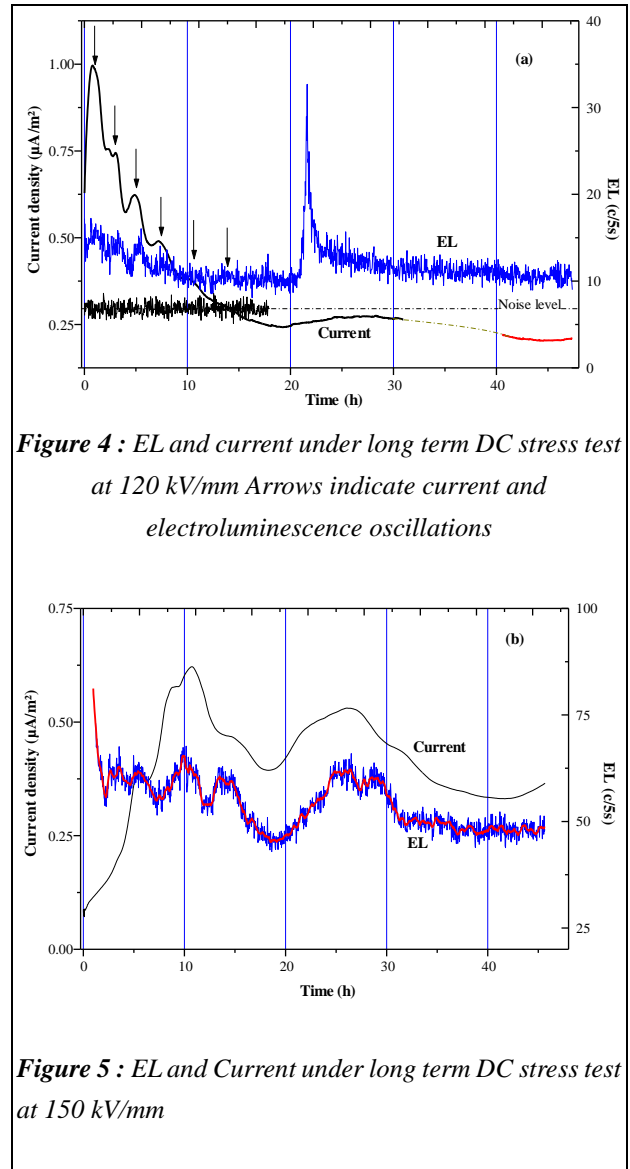
could be described as follows. Homocharge regions are formed by charge injection at both electrodes. A negative charge front propagates fast, and the first positive packet is launched when this front induces a sufficient field enhancement at the anode. The propagating packet leaves a negatively charged region behind it. It is worth noting that a new positive packet is only launched when the previous positive packet has reached the cathode in these samples. This can be easily understood when looking at the charge and field profiles during launching, propagation and collapse of the first positive packet shown in Figure 3. During propagation, the field is a maximum at the front of the propagating packet and is reduced at the anode. The field increases drastically at the cathode when the packet approaches and is progressively restored at the anode when the packet collapses, allowing a new packet to be launched. The anode field is thus modulated by the propagation of the positive charge packets. From the second packet on, the amplitude of the positive packets decrease in time during polarization and the packets become weaker.

Electroluminescence and current have been recorded for up to 48 hours at 120 kV/mm and 150 kV/mm, i.e. at field levels for which charge packets were found. The experiment at 150 kV/mm was performed after an overnight short-circuit of the sample

Figure 2 : *positive packet propagation observed at 150 kV/mm. The intensity of the charge is proportional to the gray scale (dark: high charge density, white: charge saturation). Polarity of the charge as indicated. The diagram shows the propagation of positive packets from anode to cathode. Negative charges are left behind the propagating positive packet. Heterocharges are seen to accumulate at anode and cathode after propagation of the first packet.*

Figure 3: *Charge and field profiles during launching, propagation, and collapse of the first positive packet detected at 150 kV/mm. Cathode on the left, anode on the right. a-Upon launching (t=450s), b-upon propagation (t=2100s), c-upon collapse (t=3000s)*

Figure 4 : *EL and current under long term DC stress test at 120 kV/mm Arrows indicate current and electroluminescence oscillations*

Figure 5 : *EL and Current under long term DC stress test at 150 kV/mm*

Current and electroluminescence are given vs. time in Figures 4 and 5 at 120 kV/mm and 150 kV/mm respectively. From the two sets of data, it is clear that oscillations are being detected in both current and EL, and that they are well correlated in time. Three different periods of time can be considered regarding the experiment at 120 kV/mm. For the whole time range, there is a constant level of EL that is significantly higher than the PM noise, which probably corresponds to a continuous EL excitation level. This level is associated with charge recombination occurring when positive and negative charges have penetrated the bulk of sample as shown in [11]. Up to about 20 h, several current maxima of decreasing amplitudes were observed, each of those being associated with a corresponding EL maximum. From 21 h on, the EL leveled off, followed by a slow decrease. This process is correlated with a slight levelling off of the current, although its variation does not follow the EL variation as in the previous period of time. Turning to the experiments performed at 150 kV/mm, and if the transient EL observed during the first three hours are excluded, the same kinds of conclusion can be drawn; current oscillations match the EL oscillations reasonably well. The order of magnitude of the current and EL oscillation frequency recorded in this work varies from 2 to 3 hours. In some situations, the EL is not reflected by the current variation, typical examples being the slow EL transient observed up to three hours for the 150 kV/mm experiment, and also the EL peak observed at about 21 h for the 120 kV/mm experiment.

As for the current oscillations, they have been clearly associated with charge packet propagation [3, 5]. In particular, it was noticed that they have the same period of oscillation, which depends on field and on investigated material. It has to be emphasised that the maximum of the external current oscillation is associated with the collapse of the propagating packet at or near the opposite electrode [5, 12]. The time dependence of current and EL shown in Figure 3 (120 kV/mm) and 4 (150 kV/mm) is well correlated with the frequency of charge packets evidenced in PEA measurements. Transient EL is detected during the first three hours for the test performed under 150 kV/mm, starting from a level of 3000 c/5 s (not shown in Figure 5) and decreasing regularly to 55 c/5 s, without apparent amplitude modulation or relationship with the external current. The absence of current oscillations in the period of time where transient EL was detected could mean that charge packets were not produced. We think this peculiarity could be due to the previous charging of the sample during the experiment at 120 kV/mm, even though it was short-circuited overnight before being used for the experiment at 150kV/mm.

CONCLUSION

Although further investigation is needed to understand the transient emission, two main conclusions can be drawn. First, the propagation of charge packets has been associated with a specific luminescence pattern, thereby confirming that the excitation is due to charge recombination. Both current and EL oscillations are almost in phase in time, suggesting that recombination is occurring during the propagation of the packet. The time resolution, however, is not sufficient to determine if the recombination occurs throughout the body of the packet or at the rear as implied by the mechanism described in [8]. The maximum of the emission corresponds to the collapse of the charge packet at or near the opposite electrode, but this is also correlated with the launch of subsequent packet, thereby suggesting that recombination could also be taking place in the vicinity of the injecting electrode (injected charges recombining heterocharges). Second, EL can be emitted in a more efficient way in situations where

charge packets were not evidenced on the basis of the current measurements.

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