EXPERIMENTAL INVESTIGATION AND MODELING OF SURFACE DISCHARGES FOR CHARGED DIELECTRIC MATERIALS

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Abstract - In this paper, investigations of electrostatic discharges for charged dielectric materials will be presented. The aim of the work is to develop a model that allows the calculation of the dissipated power and energy during brush and surface discharges. With previous measurements for PVC and further measurements for other materials, the parameters for the model will be determined. Furthermore, some investigations to characterize the surface discharge will be carried out and presented. The model could facilitate the ESD-dimensioning of devices and systems.

I. INTRODUCTION

Due to the increasing use of plastics or plastic-coated materials different kinds of problems, like charging and discharging, can occur. Isolated surfaces are considerably charged by material separation, flowing liquids or electrical fields. For this reason discharges can develop between the charged surface and a near grounded conductive object. These transient gas discharges are locally limited.

In the last fifty years these brush discharges have been investigated. Heidelberg [1], [2], Lövstrand [3] or Gibson and Lloyd [4] investigated this kind of discharges referring to the generation of ignition of gas-air mixtures. Among others, Lichtenberg [5] or Toepler [6] have shown that under certain conditions 'Lichtenberg figures' can occur. These surface discharges are able to discharge considerably larger charged areas with a high discharge energy.

An easy model for the charge and discharge phenomena of insulating materials could facilitate the ESD-dimensioning of devices and systems. On the one hand, the conditions influencing the size of the discharged area have to be determined. On the other hand, an easy model is needed to estimate the dissipated power and energy during the discharge process. Therefore, new measurement data are needed. In addition, some parameters, like thickness, size and kind of material, form of electrode and others are varied. A part of these measurements have been already presented and discussed in previous papers [7,8].

II. MEASUREMENT SETUP

The charging and discharging of insulating materials depend on the climatic conditions, like relative humidity and temperature. Therefore, the experimental arrangement is set-up in a climatic chamber for constant climatic conditions. The conditions for all measurements are 25%-30% of relative humidity and 21°C of temperature. Details of the measurement set-up are shown in figure 1 and have been presented in [7].

The plates and foils can be charged using corona discharges. It is possible to acquire the charge distribution on the surface using a scanning system. Then, a grounded electrode is moved to the charged surface until a discharge occurs and the new charge distribution can be acquired. Furthermore, the discharge current pulse can be measured. With the acquired charge distribution values the transported charge and the area of the discharged surface can be determined. The transported charge can also be determined using the measured current pulse.

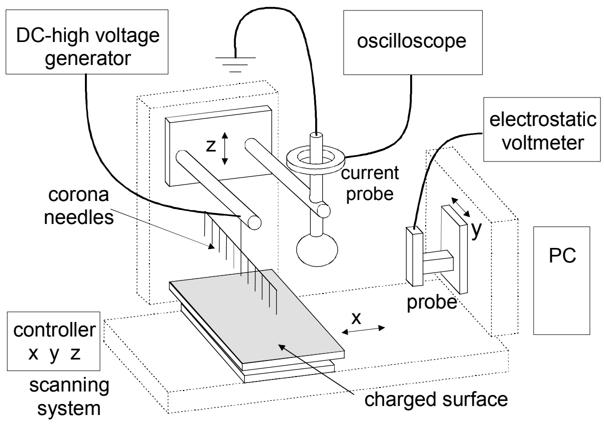


Figure 1 Measurement set-up.

The theoretical maximum value of the surface charge density is 2.7 nAs/cm² for an one-sided charged layer [4]. Due to a conductive layer on the back side the surface charge density can be much higher, because an electric double layer arises. Due to the higher charge density a higher danger potential is possible. Therefore, only these types of plates and foils are investigated. Up to now, only negative corona voltages have been studied.

III. BRUSH AND SURFACE DISCHARGE

Two kinds of discharges can appear depending on the value of the surface charge density. Brush discharges occur especially for thicker plates and a smaller value of the surface charge density. A limited area around the discharge point is discharged. Figure 2a shows a typical charge distribution on the surface from a 1mm PVC-plate has been discharged by a sphere with a diameter of 30 mm. For thin plates or foils a higher value of surface charge density is possible and surface discharges can occur. By these discharges a much larger surface area can be almost completely discharged (see figure 2b).

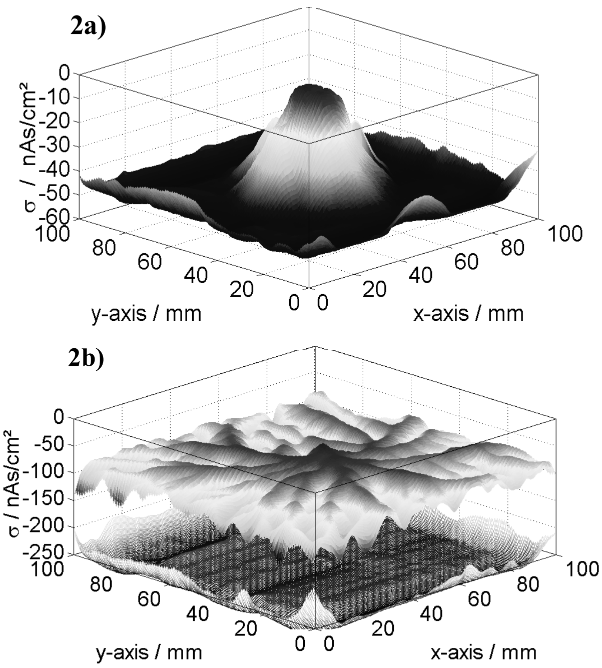


Figure 2 Typical charge distribution for a brush and a surface discharge.

At the beginning, a brush discharge occurs which initiates the following surface discharge. The discharge shorts the charged surface to the grounded backplane. The high tangential electric field strength on the surface causes the following surface discharge, with a very high value of transported charge.
An important point is the value of the surface charge density where the brush discharge changes to the surface discharge. Figure 3 shows the transition from the brush discharge to the surface discharge for three PVC-foils of different thickness.
For thicker foils the transition point of the surface charge density is lower as for thinner foils. The decisive parameter for the propagation of the surface discharges is the tangential electric field strength on the surface. For thicker foils, the critical value of this field strength is reached at a lower value of charge density.

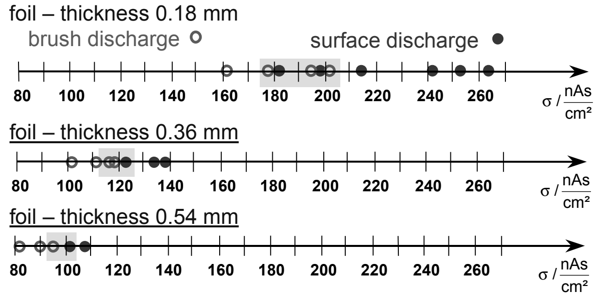


Figure 3 Transition from the brush discharge to the surface discharge for three PVC-foils of different thickness.

IV. INVESTIGATION OF THE SURFACE DISCHARGE

For a better understanding of the surface discharge and as a base for the modeling several aspects are investigated.
The first condition that a surface discharge can occur is a brush discharge. As already mentioned, a limited area around the discharge point is discharged. Therefore, the discharge shorts the charged surface to the grounded backplane. At the boundary between the discharged and still charged area a high tangential electric field strength on the surface arises. If the electric field strength is higher than a critical value a surface discharge follows.

IV.1 Time between brush and surface discharge

Figure 4 shows the initiating brush discharge current pulse and the first part of the surface discharge current pulse for some measurements. These measurements are carried out with equal conditions (the same value of the initial surface charge density 225 nAs/cm² and about the same gap distance 3.5 mm).

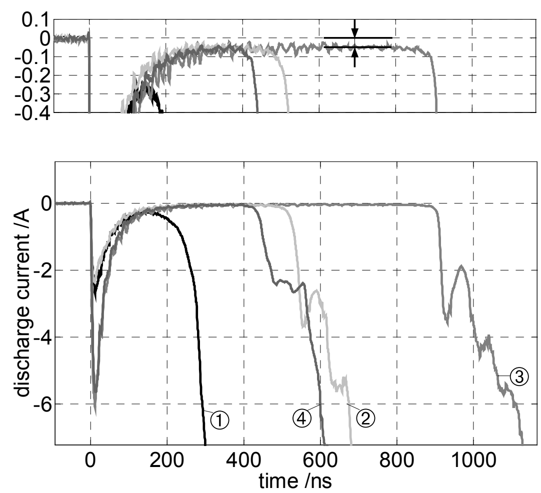


Figure 4 Below: different time delays of the surface discharge current pulse; above (zoomed): the *low current* between the brush and surface discharge pulse

The figure (below) shows a *time delay* between the brush discharge and the start of the surface discharge. For this examples, the time delay is varying in the range from 150 ns to 800 ns. The cause of the time delay is not the absence of a initial electron. Measurements with a UV-lamp show no reduction of the scattering of the time delay.
An other point is the *low current* between the brush and surface discharge pulse in the range of some 10 mA (fig. above). An explanation for this is the movement of the remaining charge carriers (especially the slow ions) in the still existing gas discharge channel. In addition, electrons from the surface around the discharge point are moved without further ionization (ohmic current).

IV.2 Different shape of the current pulse

In figure 5 the whole surface discharge current pulse from the same measurements are plotted. The difference is, that the curves are shifted along the time axis, so that the surface discharge current pulses start at the same time. Now, the shapes of the current pulses can be compared with each other.
The rise times of the surface discharge current pulses are clearly different. The reason for this is that several surface discharge channels start at different times. The inception times of the channels of measurement ① are quite regular distributed and the scattering is low. Therefore, the rising pulse edge is smooth and steep. A contrary example is measurement ③. Here, the rising edge is stepped and less steep. The reason for this is the higher scattering of the onset time of the discharge channels.

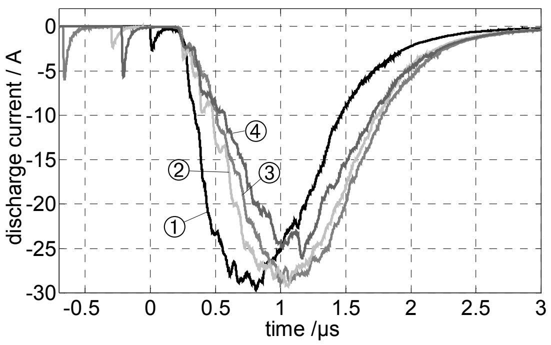


Figure 5 Different shapes of the surface discharge current pulse (equal conditions).

This examples shows even with equal initial conditions the *shape* of the surface discharge current pulse *can be different*. The shape is defined through the statistical distribution of the onset time of the several discharge channels.

IV.3 Discharged average surface charge density as a function of the radius of the annulus

During the measurements both the discharge current and the surface charge density distribution are recorded. Now, the local surface charge density distribution are considered.
The paths of propagation on the surface and the onset time of the discharge channels are statistically distributed. Therefore, it is very difficult and not necessary to simulate each single discharge channel. A simplification of the complex and statistical surface charge distribution is needed.

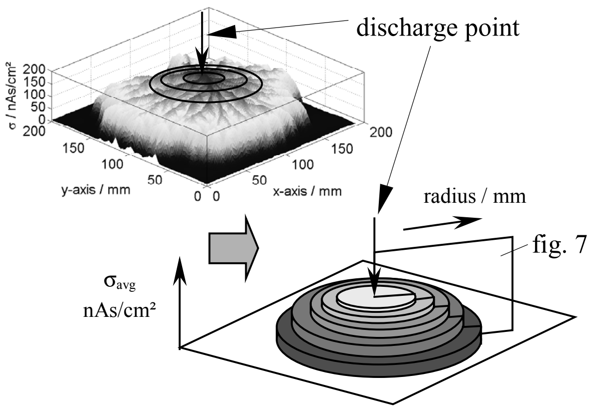


Figure 6 Calculation of the discharged average surface charge density from the measured data.

One possibility for a simplified approach of this problem is the use of the *discharged average surface charge density in an annulus* around the discharge point. For that, the difference of the measured surface charge density before and after the discharge is calculated. The result is the measured discharged surface charge density. From this density the average value is calculated within the area of the annulus (see figure 6). Figure 7 shows the so determined values of the discharged average charge density in an annulus as a function of the radius of the annulus (step size of the radius 2.5 mm). The plotted results are from the same measurements, like in figure 4 and 5.

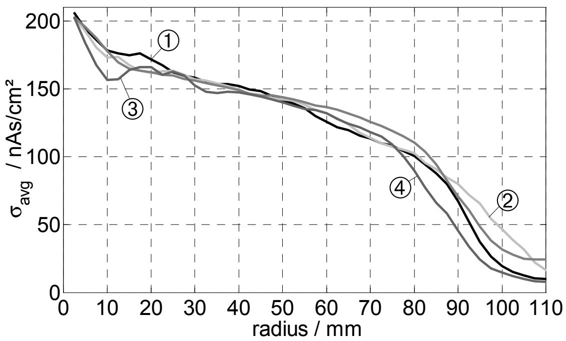


Figure 7 Values of the discharged average surface charge density in a annulus as a function of the radius of the annulus.

In these curves the discharge point is on the left side. Near the discharge point up to about 70 mm the curves are fairly similar. Outwards, at the end of the discharge channels small differences can be found.

In earlier investigations [8], the surface charge density along a single discharge channel as a function of the channel length was determined. The shape of these curves and the here considered curves (figure 7) are similar.

For the simulation the single discharge channels are no longer considered. The simplified model with the discharged average surface charge density is used as the base for the simulation instead.

IV.4 Average velocity of the discharge propagation

The current pulses (figure 5) show different rising edges. The discharge current rising edge corresponds to the velocity of the discharge channels. Now, by using the discharge current pulse and the discharged average charge density the *average velocity* of the discharge propagation can be calculated.

On the one hand, from the current the charge as a function of the time is derived. On the other hand from the charge density the charge as a function of the radius can be calculated. In a next step both curves are stepwise compared. The result is a function between the time and the radius of the discharged area. This is a approximation, because a regular radial propagation is assumed.

Figure 8 shows the average velocity as a function of the radius for the measurements referring to figure 4. The peaks on the left side represent the brush discharges with the rapid rise. The following part characterizes the propagation of the discharge channels.

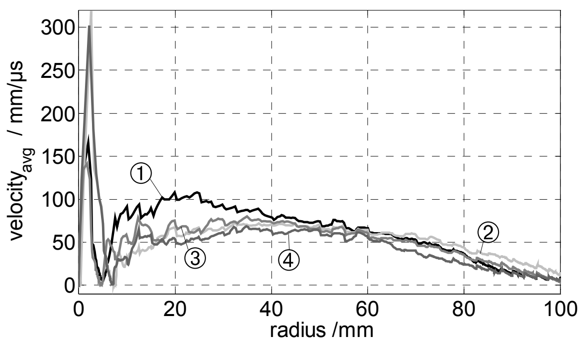


Figure 8 Average velocity of the surface discharge propagation.

The higher velocity of measurement ① (figure 8) in the range from 10 mm to 40 mm corresponds to the steep rising edge of the discharge current ① in figure 5.

IV.5 Radius of the discharged area

From the discharged average charge density the *radius of the discharged area* can be derived. This corresponds to an *average length* of the surface discharge channels. The radius, where the discharged average charge density reaches 20% of the initial surface charge density, is defined as the radius of the discharged area.

Figure 9 shows the radius of the discharged area for several measurements as a function of the initial value of the surface charge density (points in the figure).

The radius of the discharged area is approximately a linear function of the initial value of the surface charge density (see the solid line in figure 9).

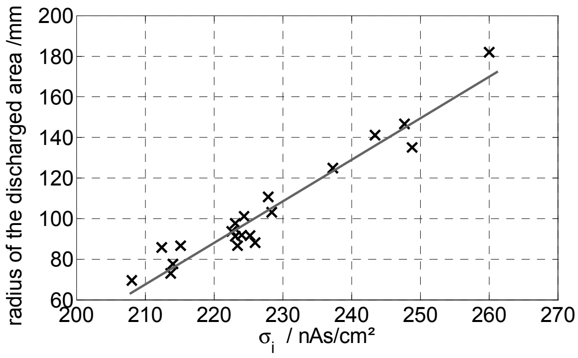


Figure 9 Radius of the discharged area as a function of the initial value of the surface charge density.

IV.6 Time propagation of the surface discharge

IV.6.1 Set-up

In this chapter the time propagation of the surface discharge channels is investigated. The aim is to determine the discharge current referring to the local position of the discharge channel. For this investigation not the total area of the foil but only a line is charged. Only along the charged line the surface discharge is possible.

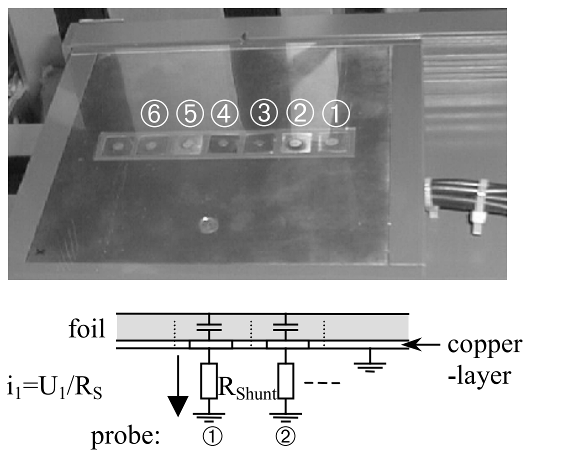


Figure 10 Set-up for the time propagation measurement.

For these investigations, a new measurement set-up was designed. The groundplane on the back side of the test foil are partly divided into partial plates. Along the expected discharge channel these plates are inserted (see figure 10). The probes are isolated from each other and are connected to ground by a shunt resistor. The current through the shunts is measured by using two 4-channel oscilloscopes. The current through one shunt represents the partial current caused in the area of the corresponding small plate.

IV.6.2 Current measurement

Six partial currents ①-⑥ and the total current of a measurement are plotted in figure 11. Figure 12 shows the corresponding surface charge density distribution. The squares indicate the position of the small probe plates. The discharge point is located in the middle of probe ①. The course of the main surface discharge channel and some short branches are also displayed.

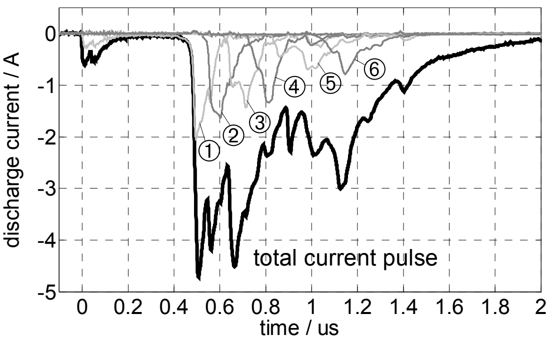


Figure 11 Total and partial discharge currents.

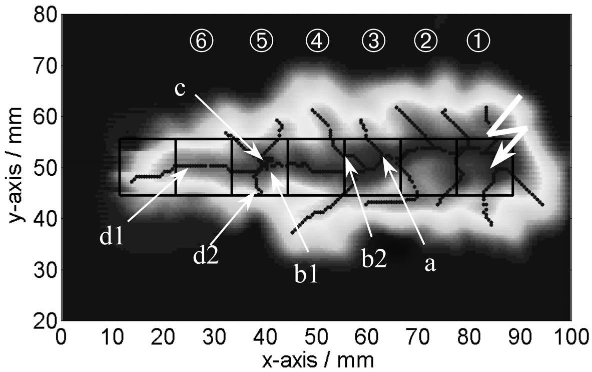


Figure 12 Surface charge density distribution, the area of the small probe plates and the discharge channels.

IV.6.3 Discussion of the time propagation

The time succession of the partial discharge current pulses (in figure 11) represent the propagation of the discharge channel along the surface. The peaks of the partial discharge current pulses occur in fairly regular distances. This shows that the propagation of the main discharge channel as a function of the distance from the discharge point is continuous.
The movement of the discharge channel can be understood by comparing the figure 12 and 13. For example, the partial discharge current pulse ③ has two peaks (‘A’ in the figure 13). This shows that the discharge channel divides into two branches ‘a’.
Later, at the same time with the peak of the pulse ⑤ smaller pulses ‘B’ of curve ③ and ④ occur. That is, the head of the main discharge channel is located at position ⑤ ‘b1’. To the same time, between the position ③ and ④ a small branch channel is added ‘b2’ (compare figure 12 and 13).
The two peaks of current ⑤ ‘C’ represents also a branching ‘c’ of the main channel. Here also, after the partial current ⑥ ‘d1’ a further small pulse of current ⑤ occurs. An another small branch channel ‘d2’ is added.

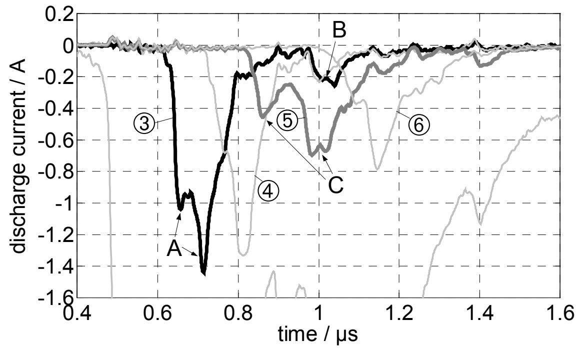


Figure 13 Zoom of the partial discharge currents ③ - ⑥.

This example shows that the surface discharge channels move not only regular and radial outwards. The channels can branch themselves. Furthermore, branches can join the main channel at points between the discharge point and the head of the main channel. These branches are compared to the main channel rather short.

V. SIMULATION

In [7] an easy model to describe brush discharges has been presented. With this model the current and the dissipated power as well as the energy during the discharge can be estimated. For the modeling of surface discharges the model for brush discharges [7] will be enlarged by the gray part (see figure 14). The rather slow and approximately linear rising edge of the surface discharge current can be explained by a continuous addition of surface elements.

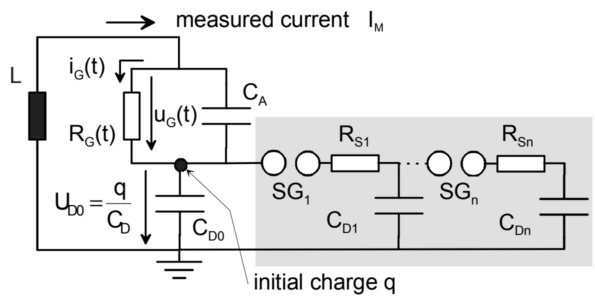


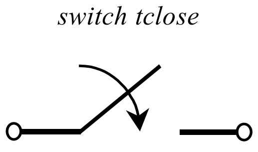
Figure 14 Enlarged model to describe surface discharges.

The simulations are carried out using the program Pspice. The basis for the simulation is the value of the discharged average surface charge density. No single discharge channels are simulated. Instead the value of the discharged average surface charge density in an annulus is used to define the parameter of an element

(see later in this chapter). The selected step size for the annulus and the radius of the discharged area defines the necessary number of elements for the simulation.
The *capacitance's* C_{Dx} can be calculated as

$$C_D = \varepsilon_0 \varepsilon_r \cdot \frac{A}{h}\,. \qquad (1)$$

where h is the thickness of the foil and A is the area of the annulus. The area of the annulus depends on the selected step size. The *initial voltages* of C_{Dx} are calculated by using the value of the discharged average surface charge density in the corresponding section.



parameter (e.g.):
tclose = 50 ns
ttrans = 300 ns
Ropen = 1 GΩ
Rclosed = 1 Ω

Figure 15 Pspice element 'switch' and the parameter.

The *spark gap* and the *resistance* R_S are realized with a switch (figure 15). This element has the property to modify the resistance 'Ropen' to the resistance 'Rclosed' started at the time 'tclose' and with the transit time 'ttrans'. The switch can be interpreted as a time-varying resistance.
Furthermore, the combination spark gap, resistance and capacitance is an *element* and represents one annulus.

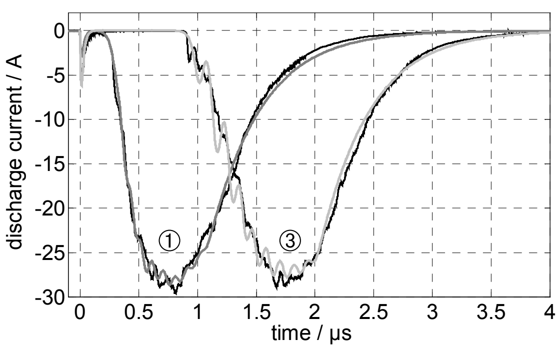


Figure 16 Comparison of the measurement and the simulation of the discharge current pulse for two examples.

To verify this model two measurements with different current pulse shapes are simulated. Here, measurement ① with a steep rising edge of the current pulse and measurement ③ with a less steep rising edge are used (compare with figure 5). For the simulation nine annuluses with a step size of 10 mm (nine elements) are used.
The comparison of the simulated and the measured discharge current pulses are plotted in figure 16. The simulations show a good agreement with the measurements, although a fairly simple model with nine elements was used.
The different pulse shapes of the examples are achieved by varying the start time ('tclose') of the elements.

VI. CONCLUSION

In this paper, a simple model for a surface discharge has been developed. Therefore, some investigations to characterize the surface discharge are carried out and presented. The central results are:

- The measurement of the current with the local distributed partial probes allows a time investigation of the propagation of the discharge channels.
- The simulation is based on the simplified model of the discharged average surface charge density in an annuluses around the discharge point.
- By means of two measurements with a different pulse shape, that the simulated current pulse a good agreement with the measurements shows.
- Now it is possible to estimated the dissipated power and energy during the discharge by using the current pulse.

The model will be improved and optimized in future.

VII. REFERENCES

[1] E. Heidelberg, "Entladungen an elektrostatisch aufgeladenen, nichtleitfähigen Metallbeschichtungen", *PTB-Mitteilungen*, vol. 6, pp. 440-444, 1970.

[2] E. Heidelberg, "Generation of igniting brush discharges by charged layers on earthed conductors", in *static electrication*, pp. 147-155, Inst. Phys. Conf. Ser. No. 4, 1967.

[3] K. G. Lövstrand, "The ignition power of brush discharges - experimental work on the critical charge density", *Journal of Electrostatics*, vol. 10, pp. 161-168, 1981.

[4] N. Gibson and F. C. Lloyd, "Incendivity of discharges from electrostatically charged plastics", *Brit. J. Appl. Phys.*, vol. 16, pp. 1619-1631, 1965.

[5] G. C. Lichtenberg, "Nova Methodo Naturam AC Motum Fluidi Electrici Investigandi", *Comment. Soc. Göttingen* vol. 8, Dec., pp. 65-79, 1778.

[6] M. Toepler, "Über die physikalischen Grundgesetze der in der Isolatorentechnik auftretenden elektrischen Gleiterscheinungen", *Archiv für Elektrotechnik,* vol. 10, pp. 157-185, 1921.

[7] L. Müller, K.Feser, R. Pfendtner, E.Fauser, "Experimental investigation of discharges for charged plastic or plastic-coated materials", *CEIDP 2001,* Kitchener, Canada.

[8] L. Müller, K.Feser, R. Pfendtner, E.Fauser, "Experimentelle Untersuchung der Entladung elektrostatisch aufgeladener Kunststoffe", *EMV 2002,* Düsseldorf, Germany.