EXPERIMENTAL INVESTIGATION AND MODELING OF BRUSH DISCHARGES FOR CHARGED DIELECTRIC MATERIALS

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Abstract: The paper presents investigations of electrostatic discharges for charged dielectric materials. 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. In this paper, the emphasis is put on the brush discharge. For this discharge pattern, the measured discharged charge density and the measured discharge current are analyzed for the parameters 'initial charge density', 'thickness of charged foil' and 'discharge gap length'. The aim is to estimate the discharged charge density and the discharge current, without carrying out a measurement.

1. 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. A part of these aspects have been already presented and discussed in previous papers [8-11].

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. Fig. 1a shows a typical charge distribution on the surface at a 1 mm PVC-plate after the discharge 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 (Fig. 1b).

The condition for a surface discharge is a brush discharge. A limited area around the discharge point is discharged. 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.

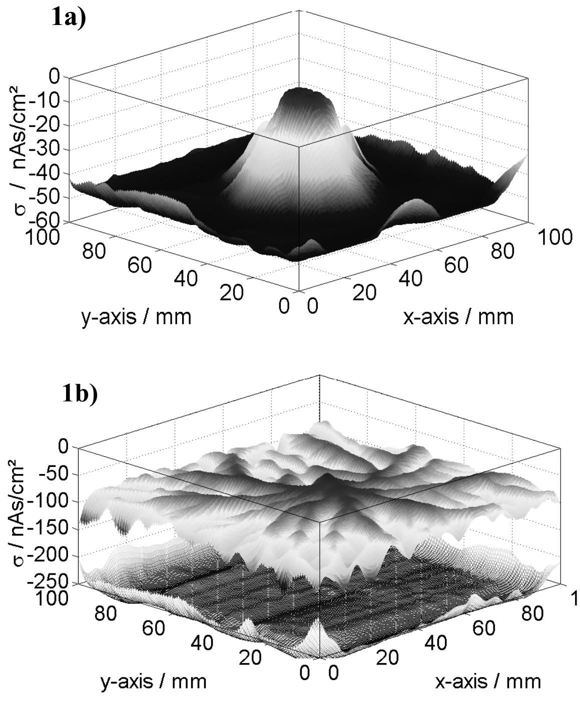

Fig. 1: Typical charge distribution for a brush a) and a surface discharge b).

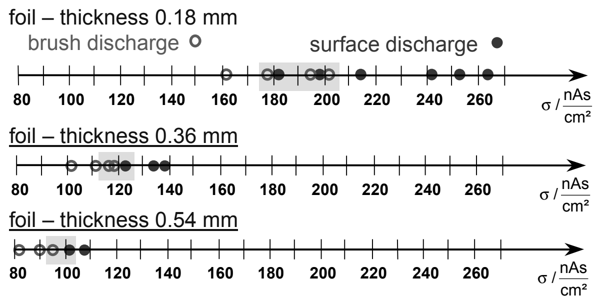

Fig. 2: Transition from the brush discharge to the surface discharge for three PVC-foils of different thickness.

An important point is the value of the surface charge density where the brush discharge changes to the surface discharge. Fig. 2 shows the transition from the brush discharge to the surface discharge for three PVC-foils of different thickness.

For thicker foils the transition point 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.

2. 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 [8].

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.

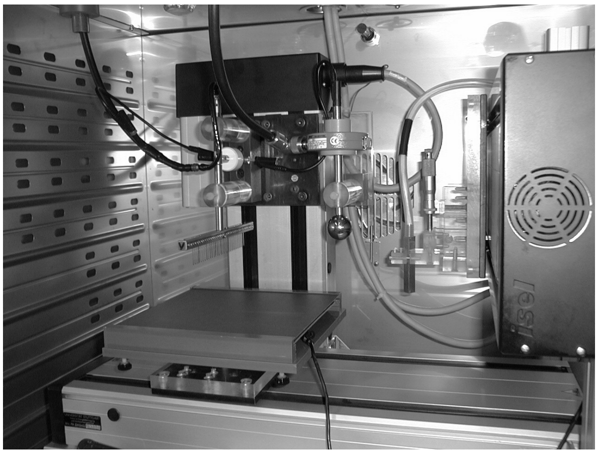

Fig. 3: Measurement set-up.

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.

3. Investigation of the brush discharge

Between a charged isolated surface and a near grounded conductive object a brush- or a surface discharge can occur. In this paper, the emphasis is put on the brush discharge. For the evaluation of the ESD-danger potential an easy model or a estimation of the discharge phenomena of insulating materials is helpful. A criterion of the evaluation of the danger potential is the dissipated power respectively the energy during the discharge. This values can be calculated by using an easy model [8]. The measured discharged charge density and the measured discharge current are the basis for this model.

The aim is to estimate the discharged charge density and the discharge current without carrying out a measurement. For this reason in this paper, the measured discharged charge density and the measured discharge current for some parameters (initial charge density σ_i, thickness of the charged foil *h,* length of the discharge gap *d*, ε_r) are analyzed. The next step in a further paper will be to describe this parameters by equations.

For a better understanding and as a base for the following chapter some aspects have to be investigated.

3.1 Surface charge density distribution

By a brush discharge, a limited area around the discharge point is discharged. Before and after the discharge the charge distribution are measured. Along a cut line across this discharged area the charge density is considered (Fig. 4). The difference between the charge density before and after the discharge is the *discharged charge density* σ_d .

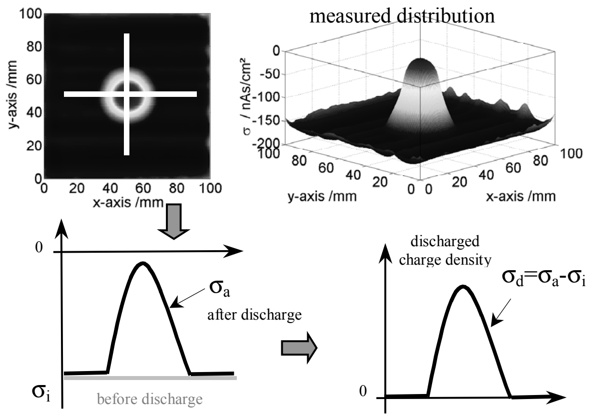

Fig. 4: The discharged charge density.

3.2 Normalization of the discharged charge density

One parameter is the initial charge density σ_i. The shape of the charge distribution varied for different σ_i. Therefore, the charge distribution is normalized with σ_i and centered so that the shapes are better comparable (Fig. 5). This is also advantageous for the shape fitting (see chapter 4.1).

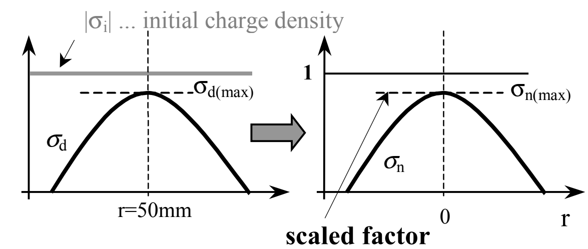

Fig. 5: Normalization of the surface charge density.

3.3 Determination of the discharge gap length

For the further investigations the determination of the discharge gap length is needed. Here, the basis for the simulation is the constant initial surface charge density. Fig. 6 shows the geometrical set-up.

For a higher radius of the sphere electrode (> 10 mm) and smaller gap widths (< 10 mm) the electric field is rather uniform. For uniform fields the Paschen's law [7] of breakdown defines the breakdown voltage respectively electric field strength.

For the sphere-plane set-up the maximum field strength arises on the vertex of the sphere. At this point the value of the electric field strength E_s is simulated for different gap lengths d. The curve E_s as a function of d is compared with the curve of the breakdown field strength of 'Paschen'. The point of intersection of both curves indicates the *discharge gap length* d_P for 'Paschen'. At this gap length the breakdown condition is met. The values of the discharge gap length d_P are determined as a function of the initial charge density. This function with thickness h as parameter is plotted in Fig. 7 (solid line).

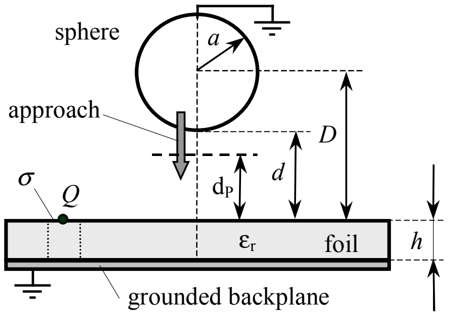

Fig. 6: Geometrical set-up.

For some values of the surface charge density the discharge gap length are measured (Fig. 7 crosses). The measured values show a good agreement with the simulated values.

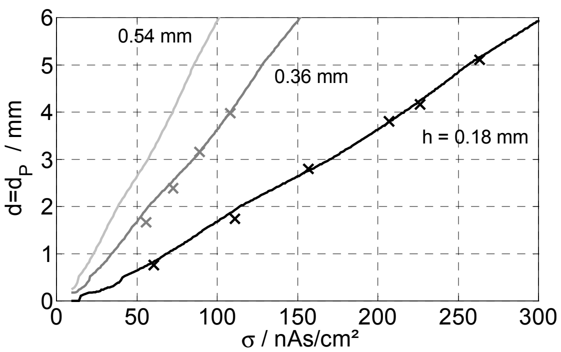

Fig. 7: Simulated (solid line) and measured (x) discharge gap length as a function of the surface charge density.

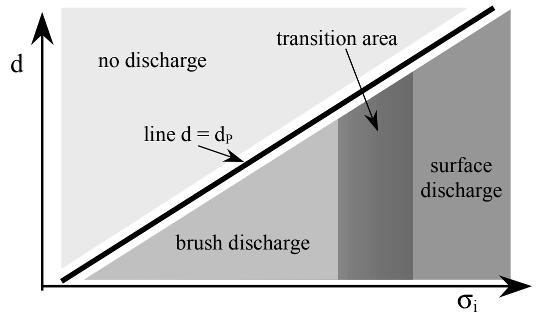

Fig. 8: Areas of the kinds of discharges (compare Fig. 2)

The start condition of a discharge is that an initial electron in the gap area exists. When the sphere arrives at the distance d_P (where according to Paschen the discharge should occur) and no initial electron exists, the sphere can continue to approach until the discharge starts. In this case, a value $d < d_P$ (d up to 0.1 mm - 0.5 mm, dependent on the thickness h) and a higher value of field strength E_s is possible. Measurements carried out with a UV-lamp confirm this fact. Here, the discharge always occurs at d close to d_P. Therefore, the calculated values for d_P are maximum values.

In Fig. 8 the areas where the different kinds of discharge occur are shown.

4. Approximation

4.1 Approximation of the discharged surface charge density

The basis for the fitting of the shape of the charge distribution is the normalized and centered charge density along the described cut line (compare chapter 4.1 and 4.2).

$$f(r) = p_1 \cdot (1 - \frac{r^2}{p_2^2})^2 \tag{1}$$

For different measurements some fitting function are tested and compared. The best results are achieved with the function (1). This function is derived from the function of the circular aperture of a antenna. Here, r is the distance from the discharge point, parameter p_1 is the maximum of the amplitude and parameter p_2 is a factor for the width of the shape of the discharged charge density.

For two different examples the normalized measured curve and the fitted curve are plotted in Fig. 9. It is obvious that the agreement is rather good.

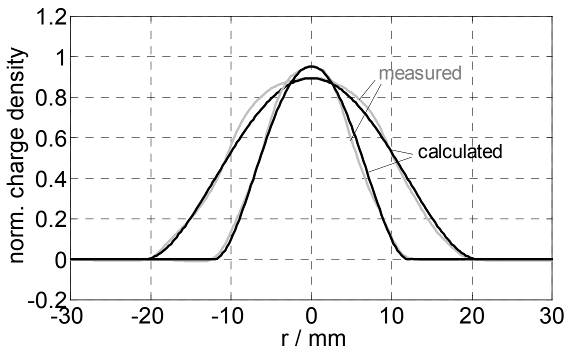

Fig. 9: Measured and fitted curves normalized for two examples.

Now, with this approximation function the *discharged charge value* Q_d can be derived (2).

$$Q_d = \sigma_i \cdot \int_0^{2\pi} \int_0^{p_2} p_1 \cdot (1 - \frac{r^2}{p_2^2})^2 \, r \, dr \, d\varphi \tag{2}$$

The result of the integration is an easy function, only dependent on the parameter p_1 and p_2.

$$Q_d = \frac{\pi}{3} \cdot \sigma_i \cdot p_1 \cdot p_2^2 \tag{3}$$

4.2 Approximation of the discharge current

In general, the discharge current can be described by a double exponential pulse (4). The parameters t_1 and t_2 define values for the rise and the fall time. The parameter i_1 represents a factor for the peak value, but this parameter is not independent of t_1 and t_2.

$$i(t) = i_1 \cdot (e^{\frac{t}{t_1}} - e^{\frac{t}{t_2}}) \tag{4}$$

For the fit of the pulse and for the interpretation a independent parameter i_0 for the peak value of the discharge current is necessary. Therefore, the fit function is normalized with (5).

$$i_i = i_0 / (e^{\frac{t_{max}}{t_1}} - e^{\frac{t_{max}}{t_2}}) \tag{5}$$

In this case, the *discharged charge value* Q_c can also be derived (6) by using the approximation function of the current. The result of the integration is an easy function, only dependent on i_1, t_1 and t_2.

$$Q_c = \int_0^{t_x \to \infty} i(t)\, dt = i_1 \cdot (t_2 - t_1) \qquad (6)$$

For an example, in Fig. 10 the measured current pulse and the fit with function (2) are plotted. The agreement is rather good up to 30 ns. A better fit of the flat part of the curve is given when function (7) is used. In this function a second double exponential pulse is added. The fit curve is also plotted in Fig. 10 and shows a rather good agreement for the total pulse.

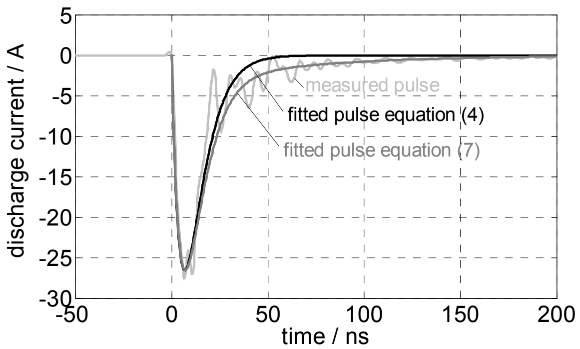

Fig. 10: Measured and two fitted current pulse.

$$i(t) = p_3 \cdot (\mathrm{e}^{\frac{t}{\tau_1}} - \mathrm{e}^{\frac{t}{\tau_2}}) + p_4 \cdot (\mathrm{e}^{\frac{t}{\tau_3}} - \mathrm{e}^{\frac{t}{\tau_4}}) \qquad (7)$$

5. Measurements

The brush discharge is dependent on some physical parameters, like the initial charge density σ_i, the thickness of the charged foil h, the length of the discharge gap d or the dielectric constant of the material ε_r. For this reason, the measured discharged charge density and the measured discharge current are investigated, so that later the fit parameter as a function of the physical parameter can be determined.

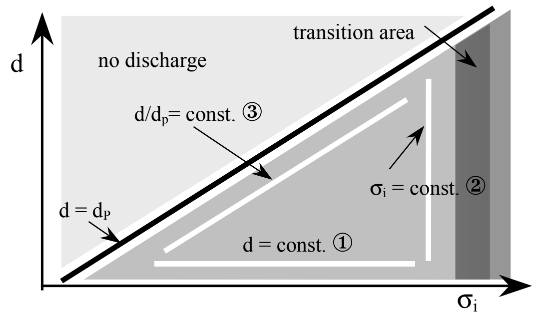

Fig. 11: Overview of the areas of the kinds of discharge and a representation of the investigated parameters.

The measurements are carried out with PVC-foils (thickness $h = 0.18$ mm, dielectric constant of $\varepsilon_r = 3.1$) and PVC-plates (thickness $h = 1.0$ mm, dielectric constant of $\varepsilon_r = 3.4$).

5.1 Parameter as a function of the initial charge density σ_i

First, the dependence on the *initial charge density* is investigated. Therefore, some measurements with a constant gap length $d = 0.5$ mm and an increasing value of σ_i are carried out (compare Fig. 11 ①). For these measurements, a cutaway view of the discharged charge density distribution is shown in Fig. 12 (foil thickness $h = 0.18$ mm). For a higher value of σ_i a larger area is discharged and it is evident that the absolute maximum value increases. However, the normalized (on σ_i) maximum value decreases a little bit for increasing values of σ_i. The corresponding discharge current pulses have a similar rising edge and small differences in the trailing edge. The amplitude of the pulse increases for a higher value of σ_i.

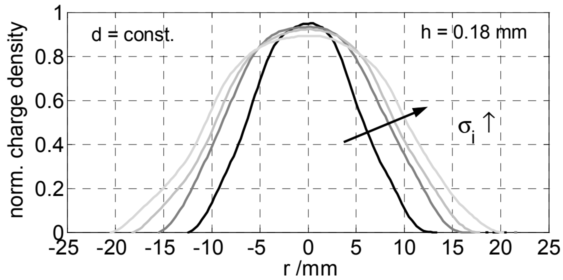

Fig. 12: The discharged charge density for increasing value of σ_i (d constant).

5.2 Parameter as a function of the discharge gap length

As already mentioned, a lower value of the gap length $d < d_P$ is possible (compare chapter 3.3). The effect of this is a higher value of electric field strength. This fact influences the brush discharge. The size of the discharged area and the shape of the surface charge density distribution after the discharge is varying. Therefore, the influence of the *discharge gap length* on the fit parameter is investigated.

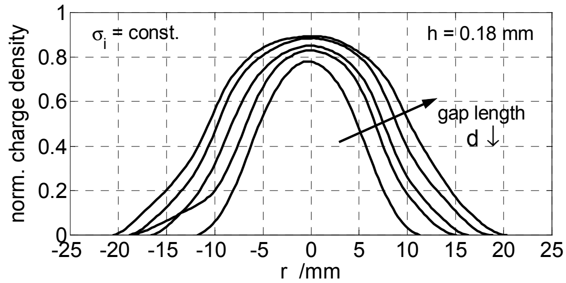

Fig. 13: Discharged charge density for decreasing value of d (σ_i constant).

As already mentioned, a lower value of the gap length $d < d_P$ is possible (compare chapter 3.3). The effect of this is a higher value of electric field strength. This fact influences the brush discharge. The size of the discharged area and the shape of the surface charge density distribution after the discharge is varying. Therefore, the influence of the *discharge gap length* on the fit parameter is investigated.

Here, some measurements with a constant value of σ_i and different gap length d are carried out (Fig. 11 ②). A cutaway view of the discharged charge density distribution σ_n of the measurements (for the foil thickness $h = 0.18$ mm) is shown in Fig. 13. For a lower value of the discharge gap length d a larger area is discharged.

5.3 Parameter as a function of σ_i by const. d/d_p

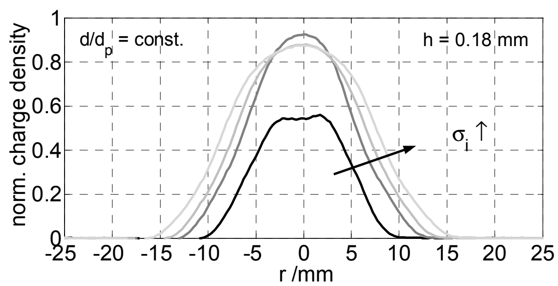

Fig. 14: The discharged charge density for increasing value of σ_i (d/d_p constant).

In the case of chapter 5.1 the parameter depends on σ_i whereas d in constant. However, for different σ_i the factor d/d_p varies. The previous chapter 5.2 describes the dependence on the gap length d, but it is more correct to describe this dependence on the factor d/d_p. Therefore the measurements in chapter 5.1 are dependent on two parameters σ_i and the factor d/d_p.

Additional to chapter 5.1 some measurements with a *constant factor* d/d_p and an increasing value of σ_i are carried out (compare Fig. 11 ③). The factor is defined to $d/d_p = 0.5$. A cutaway view of the discharged charge density distribution σ_n of the measurements ($h = 0.18$ mm) is shown in Fig. 14. For a higher value of σ_i a larger area is discharged.

5.4 Parameter as a function of the thickness of the foil

To investigate the dependence on the *thickness of the foil h* all measurements in chapter 5.1 to 5.3 are carried out for foils with different thickness ($h = 0.18$ mm; 0.36 mm; 0.54 mm, and 1 mm).

6. Parameter studies

The measured discharged charge density and the measured discharge current dependent on some physical parameters. In this chapter, these are analyzed. The aim is to estimate the fit parameters as a function of the physical parameters.

The following interpretations are based on the average value of 2-3 measurements with the same parameters. Rarely the measurments at the same parameters are deviated more then 5 % from each other.

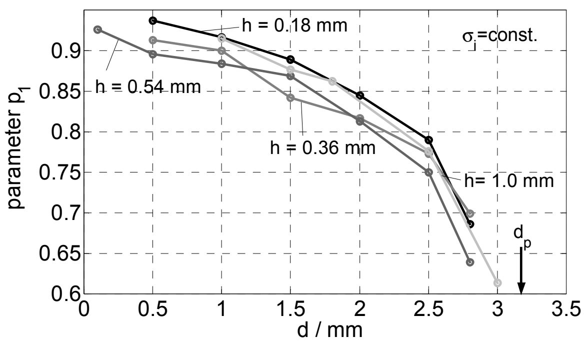

Fig. 15: Fit parameter p_1 as function of the gap length d with h as parameter (σ_i constant).

First, the dependence on the gap length d of the parameter p_1 and p_2 of the discharged surface charge density is considered. In Fig. 15 the fit parameter p_1 as a function of the gap length d with h as parameter are plotted for constant σ_i (σ_i constant for one thickness). The parameter p_1 corresponds to the maximum value of the charge distribution. For decreasing values of d the parameter p_1 increases. A description of the curves by a function is possible. The curves for different thickness have a similar shape, and the differences are small. In a first approximation the thickness h is not needed for a description of the curves.

The arrow in the figure indicate the gap length d_p for Paschen (chapter 3.3). For $d<d_p$ a discharge is possible.

The fit parameter p_2 as a function of the gap length d with h as parameter are shown in Fig. 16 for constant σ_i (σ_i constant for one thickness). The parameter p_2 corresponds to the width of the charge distribution. For decreasing values of d the parameter p_2 increases. The parameter p_2 is almost linear dependent on the gap length d. For increasing values of the thickness h the parameter p_2 increases. (For lower values of d the parameter p_2 increases more as for higher values). A description of the curves by a group of linear functions is possible. For a first approximation the linear lines have the same origin near the value $d = d_p$.

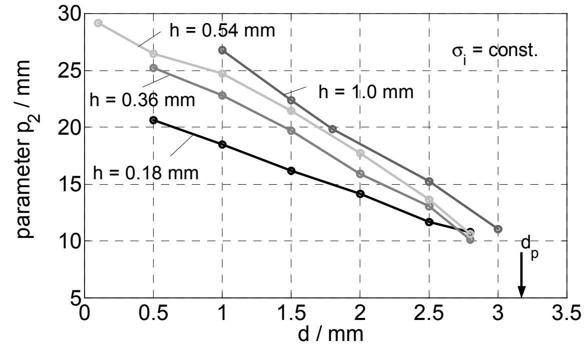

Fig. 16: Fit parameter p_2 as function of the gap length d with h as parameter (σ_i constant).

In Fig. 17 the discharged charge value Q as a function of the gap length d with h as parameter is plotted for constant σ_i. The charge value Q is derived from the measured current. The discharged charge value increases for decreasing values of d, too. For a lower value of the thickness h the discharged charge value is higher.

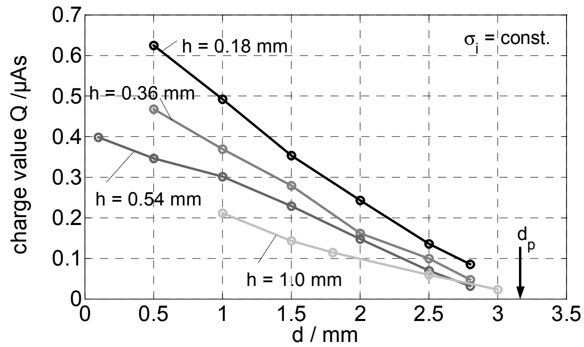

Fig. 17: Discharged charge value as function of the gap length (σ_i constant).

In a second part the dependence on the initial charge density σ_i of the parameter p_1 and p_2 of the discharged surface charge density is considered. The factor d/d_p is constant ($d/d_p = 0.5$) so that the parameter only depend on the the initial charge density σ_i. In Fig. 18 the fit parameter p_1 as a function of the the initial charge density σ_i with h as parameter are plotted for a constant factor d/d_p. Due to the thickness h different value sections of the initial charge density σ_i are obtained.

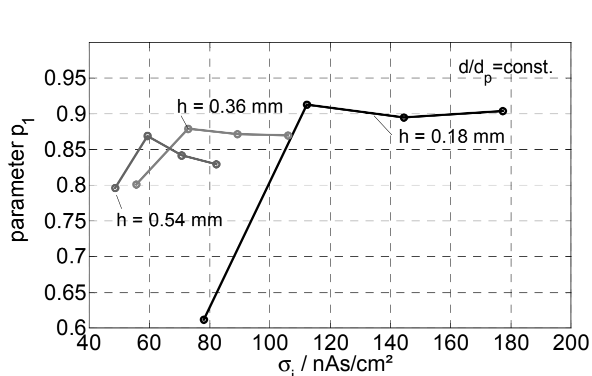

Fig. 18: Fit parameter p_1 as function of the initial charge density σ_i with h as parameter (factor d/d_p = const.).

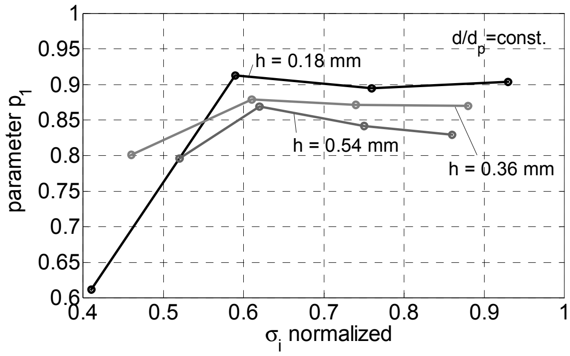

Fig. 19: Fit parameter p_1 as function of the normalized initial charge density σ_i with h as parameter (factor d/d_p = const.).

Therefore, for each thickness the initial charge density σ_i is normalized on the transition value of the surface charge density. Here, the brush discharge changes to the surface discharge, compare Fig. 2. The normalization factor for the h = 0.18 mm (0.36 mm, 0.54 mm) is σ_t = 190 nAs/cm² (120 nAs/cm², 95 nAs/cm²). Fig. 19 shows these plots. The value '1' of the abscissa defines the transition were the brush discharge changes to the surface discharge. Now, the curves with the different thickness h can be better compared. For higher values of σ_i the parameter p_1 is fairly equal. For lower values of σ_i parameter p_1 decreases.

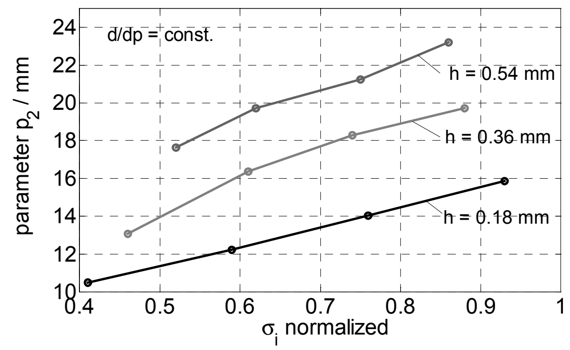

Fig. 20: Fit parameter p_2 as function of the normalized initial charge density σ_i with h as parameter (factor d/d_p = const.).

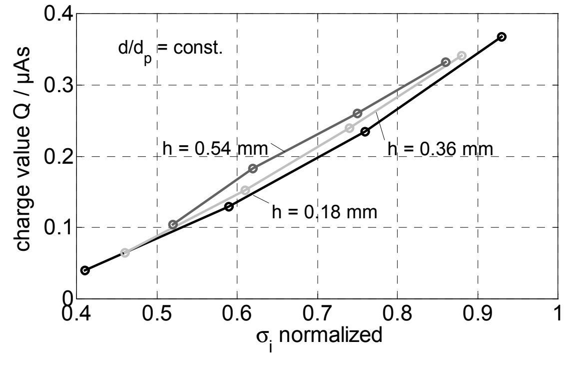

Fig. 21: Discharged charge value as function of the normalized initial charge density σ_i with h as parameter (factor d/d_p = const.).

The fit parameter p_2 as a function of σ_i with h as parameter for a constant factor d/d_p are shown in Fig. 20. Here also the normalized σ_i is plotted. For increasing values of σ_i the parameter p_2 increases in a almost linear way. For increasing value of the thickness h the parameter p_2 increases, too.

In Fig. 21 the discharged charge value Q as a function of σ_i with h as parameter for a constant factor d/d_p is plotted. The charge value Q is derived from the measured current. The discharged charge value increases for increasing values of σ_i, too. The value of discharged charge value Q in almost independ of the thickness h.

7. Conclusion

In this paper, the brush discharge is investigated. The measured *discharged charge density* and the measured *discharge current* are analyzed for the physical parameter '*initial charge density*', '*thickness of charged foil'* and '*discharge gap length'*. The main results are:

The discharged surface charge density distribution can be described by a easy function with only two parameters.

A double exponential pulse describes the discharge current rather good with three parameters.

By using the charge a relation between the parameter of the charge density distribution and the discharge current can be derived.

A description of the fitted parameter as a function of the physical parameter is possible.

The next step will be to describe the here presented parameters by equations.Therfore the pre-investigations were presented in this paper. Furthermore measurements with other materials will be carried out.

8. References

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