THE INFLUENCE OF SPEED OF APPROACH AND HUMIDITY ON THE INTENSITY OF ESD

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Abstract: ESD may be a serious threat to electronic devices and systems. The intensity of ESD can vary strongly in spite of constant charge voltage. The bad reproducibility of ESD is notorious.

The most influencing factors of an ESD are the discharge geometry, the materials, the charge voltage and the arc length. A statistically changing arc length is the reason for strong variations of the intensity of discharges. E.g. the current amplitude may vary up to two orders of magnitude due to different arc lengths.

The arc length is a difficult to handle parameter, therefore it is desirable to know on which more obvious and better observable parameters the arc length and so the intensity depends on.

Some of the most influencing parameters of the arc length are the speed of approach and the ambient humidity. Subject of this paper is to introduce a new method to simulate ESD that considers the statistical nature of ESD. With this method the intensity of ESD depending on important parameters could be determined. Detailed results were presented.

1 Introduction

The high variability and so the bad reproducibility of ESD may cause serious problems in the field of ESD-testing. It can happen that an electronic device or system pass a test one day but fail the other day or at another place, in spite of identical setups. The reason for such a behavior can be the nature of the arc, which can vary strongly. To overcome this variability in nearly all ESD standards, tests with arc were replaced if possible by tests with a vacuum relay. So the arc influence could be diminished. But this method works only, if the metallic subjects under test are directly accessible. Otherwise the relay method do not work and still air discharges must be applied to the test subject. The reproducibility decreases. But even when relay discharges can be applied, they have their own problems. Tests should reproduce the reality as well as possible. A discharge via a relay can't reproduce all properties of an arc.

To increase the reliability of ESD tests a better understanding of the physics of ESD is required to gain a better reproducibility. The speed of approach and the humidity are very important factors, determining the intensity of ESD [1,2]. To understand their influence it is useful to introduce another parameter, the arc length. With fixed geometry, charge voltage and arc length, the intensity of an ESD is well defined [2]. The question is, how the arc length is influenced in detail.

1.1 The Statistical Time lag

Assuming a homogenous static field and static electrodes there is a fixed relation between charge voltage and arc length. This relation can be calculated with Paschen's [3] law:

$$U_d = 24.4\,d + 6.53\sqrt{d} \qquad (U_d\,[kV], d\,[cm]) \qquad (1)$$

If the electrodes are moved, Paschen's law is not valid any more. The voltage for a given arc length can be higher, or for a given voltage the arc length can be shorter. With the reduction of the arc length an increasing current amplitude and a decreasing rise time is associated. For many EUTs (equipment under test) in system level ESD testing this means, that the intensity increases. The reduction of the arc length is determined by the speed of approach, the humidity [4] and the kind of cathode material and surface properties [5,6]. The so called statistical time lag is responsible for a delayed ignition and so the reduction of the arc length. Depending on the degree of ambient ionization near the discharge cathode the delay can range from microseconds up to seconds or even minutes [7]. As the name already implies, the statistical time lag is a statistic quantity and difficult to determine. To investigate the time lag many discharges with well defined speed of approach and environmental conditions must be carried out. To get sufficient data an automatic measurement set up is required that is able to reproduce the influencing factors. To simulate the speed of approach many mechanical problems have to be solved for this purpose.

1.2 Static vs. Moved Bodies

Before a discharge takes place, the approach of a charged body to an uncharged body changes the field strength and field shape in the gap between the bodies. So it is equivalent to the approach of two bodies to control the field in the gap between the bodies. Figure 1 shows such a discharge configuration compared to an approaching sphere. Greason [8] proposed such a method too.

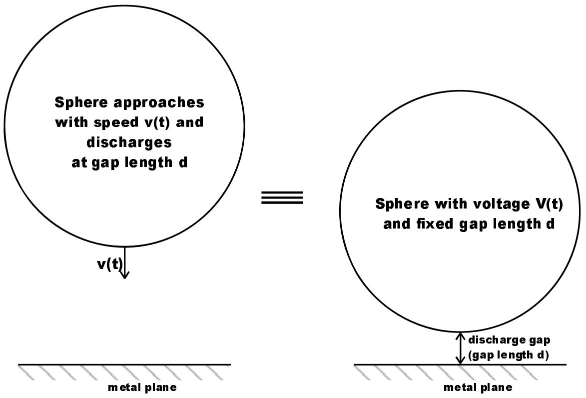

Figure 1: Comparison of an approaching sphere with a sphere with fixed gap length but controlled voltage. Equivalence of field homogenity is given if the radius of sphere >> gap length.

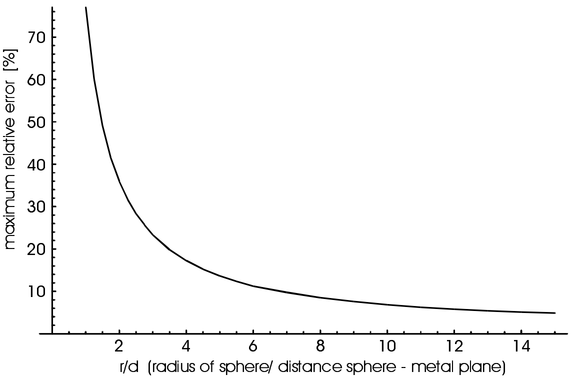

Figure 2: Maximum relative error in calculation of the static electric field between a sphere and a plane with E=U/d

For each discharge, the discharge gap length is fixed and a time dependent voltage is applied to the sphere. There is only one difference to an real approach. The field inhomogenity during a real approach changes, but if the sphere is big compared to the arc length, the inhomogenity can be neglected as shown in Figure 2. Using a sphere with a radius of 5 cm for all interesting arc lengths the error will be far below 10 %. The maximum relative error is calculated by comparing the homogenous field strength between two planes (*E=U/d*) with the maximum field strength between a sphere and a plane. The field strength between the sphere and the plane was calculated using analytical formulas [9]. For the control of the field Greason [8] intended to use a RC network. The disadvantage of this method is the lack of flexibility. It is complicated or even impossible to get realistic field time dependencies with such a network. We choose another method.

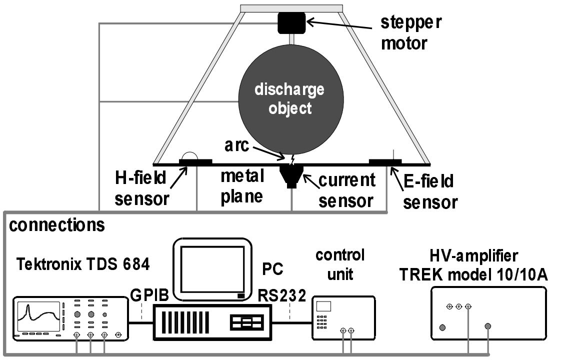

Figure 3: The measurement setup to simulate the speed of approach

2 Experimental Method

The investigated discharge configuration was a sphere over a metal plane. To control the field in the gap we used a high voltage amplifier (TREK 10/10A) with a peak voltage of 10 kV and a bandwidth of 25 kHz. This bandwidth is sufficient to simulate all in reality expectable speeds of approach. Figure 4 shows the geometry used. The sphere with a radius of 5 cm is made of brass with a chrome coating. It discharges in the brass tip of the current sensor or a plane made of other material. Before each discharge series the sphere was cleaned with ethyl. The interesting voltages ranges from 1 kV up to 10 kV. Under dry conditions a reduction of the arc length down to 20% of Paschen length or even less can be expected, so we choose the lower limit of the arc length to 25 µm. But in this ranges the measurements are not very precise. The reason for this behavior may be some additional statistical effects that repeal Paschen's law for very short arc length [10]. The upper limit is the Paschen length of 10 kV. A stepper motor allows to change the arc length with high precision. A specially developed function generator drives the high voltage amplifier. A fast single shot oscilloscope (Tektronix TDS 684) allows the automatic measurement of the intensity of each pulse (current, E-fields, H-fields). A detailed description of the sensors used can be found in [11]. Everything is controllable by a PC. During a normal measurement cycle, the computer executes a list of commands and stores the results. The complete setup is shown in Figure 3.

The field strength between the bodies depends on the time and the kind of approach. There are different kinds of approaches possible. An approach can occur with constant speed, constant slow down or any other speed-time dependency. Table 1 shows some of them and gives formulas to calculate the dependency of the field from the speed, negative acceleration and time.

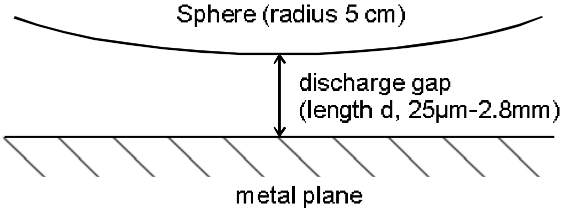

Figure 4: The discharge configuration, sphere with radius 5 cm above a metal plane

All of the experiments presented here were done with constant speed of approach. The advantage of this approach mode is the comparability of the results to other publications [1,2,12].

Under controlled climatic conditions, all interesting arc lengths and all interesting constant speeds of approach were tested. The system adjusts an arc length and controls the voltage over the sphere equivalent to the formulas in Table 1. It sweeps through all interesting speeds for each arc length. In advance the breakdown voltage is unknown. At the moment when a discharge occurs, the voltage over the sphere is measured. With the measured voltage, the given arc length and the estimated data for the voltage time dependency, the equivalent speed can be calculated.

kind of approach	**constant speed**	**constant speed down**	**speed for linear field-time dependency**
Sphere touches plane at:	$s = 0,\ t = 0, v = v_0$	$s = 0,\ t = 0,\ v = 0$	$s = 0,\ t = \infty,\ v = 0$
Acceleration a:	$a = 0$	$a = const.$	$a = \frac{2}{(t - t_0)^3}$; $t > t_0$
Speed:	$v = -v_0 = const.$	$v(t) = -at$; $t < 0$	$v(t) = -\frac{1}{(t - t_0)^2}$; $t > t_0$
Distance Sphere-Plane:	$s(t) = -v_0 t$; $t < 0$	$s(t) = \frac{1}{2} a t^2$; $t < 0$	$s(t) = \frac{1}{t - t_0}$; $t > t_0$
Static E-field in gap: (approximation)	$E(t) = -\frac{U_0}{v_0 t}$; $t < 0$	$E(t) = \frac{U_0}{\frac{1}{2} a t^2}$; $t < 0$	$E(t) = U_0 (t - t_0)$, $t > t_0$
Equivalent HV-Amplifier voltage: **(discharge at gap length d with U_0)**	$U(t) = -\frac{U_0 d}{v_0 t}$; **(1)** $t < 0$	$U(t) = \frac{U_0 d}{\frac{1}{2} a t^2}$; $t < 0$ **(2)**	$U(t) = U_0 d (t - t_0)$; $t > t_0$ **(3)** *(easy to generate, but no practical relevance)*

Table 1: Comparison of the different kinds of approach and equivalent time dependent voltages over a gap with fixed length

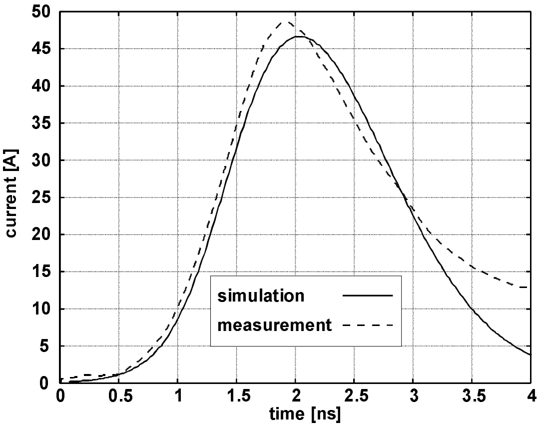

Figure 5: Example for a measured and simulated discharge current at gap length 0.5 mm and 3.8 kV

3 Simulation of Currents

To determine the intensity of the generated ESD, a ESD simulation program package [13,14] was adapted to calculate the discharge of the sphere. This simulation program calculates the currents and radiated fields with the method of moments. The highly non-linear arc is considered by the Rompe-Weizel model. The accuracy of the program package was checked by measurements. Figure 5 shows the good agreement between measurement and simulation. The slow falling slope of the measurement is caused by insufficient decoupling of the sphere from the HV-supply.

4 Experimental Results

Measurements were done under two different relative humidities at constant temperature (25°C). Starting with the lowest arc length of 35 µm the whole possible speed range was swept in small steps. After the measurement of the breakdown behavior for all interesting speeds the arc length was increased by 2.5 % and the speed range was swept again. This procedure was repeated until the maximum arc length was reached. At each arc length and speed 10 discharges were applied. For each full sweep through all arc length and all speeds approximately 40 000 discharges were applied. The time between the discharges was chosen to 100 ms. An influence of the time period between the pulses could not be observed.

High humidity and a rough surface should keep the statistical time lag short. Only a little influence of speed of approach on the arc length should be expected.

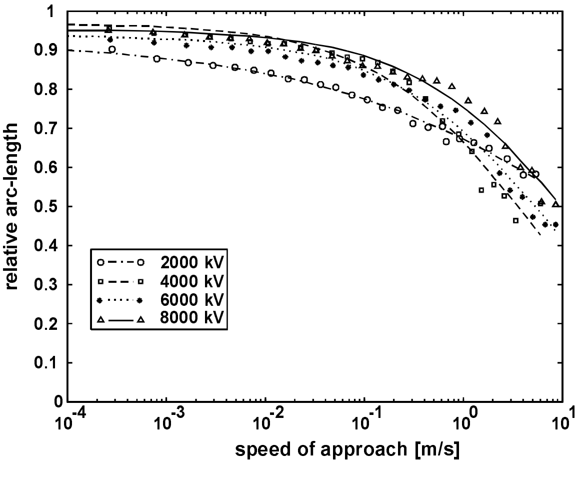

Figure 6: Dependency of the arc length from the speed of approach (70% RH, 20°C, rough kathode surface)

Figure 6 shows a measurement at high humidity with a clean but rough surface. For charge voltages between 2 and 8 kV a speed of 10 m/s can drop the arc length down to 45 %. The lines shows a fit of a suitable approximating function.

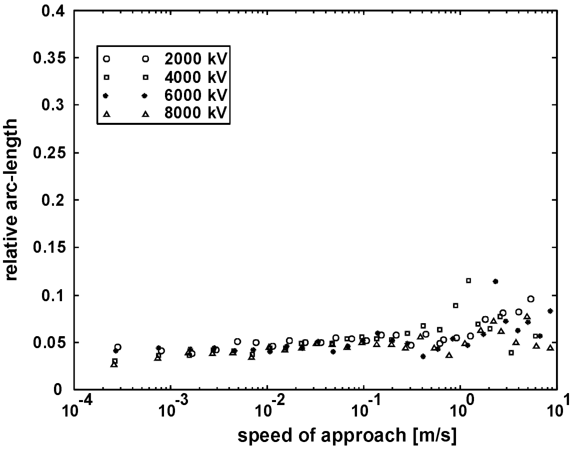

Figure 7: relative (to arc length) standard deviation (70% RH, 20°C, rough surface)

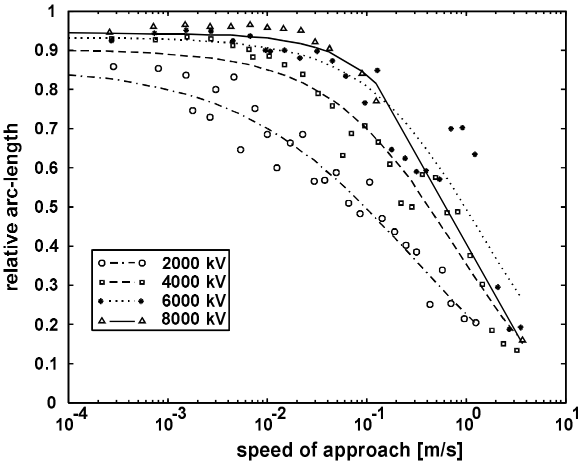

Figure 8: Dependency of the arc length from the speed of approach (20% RH 20°C, polished kathode surface)

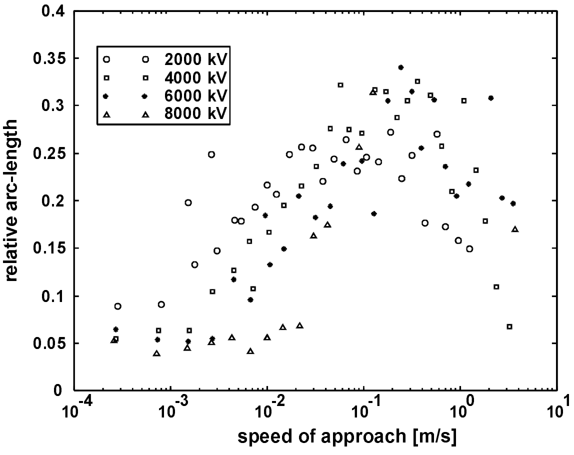

Figure 9: relative (to arc length) standard deviation (20% RH 20°C, polished surface)

Figure 7 shows the relative standard deviation for the different voltages and speeds of Figure 6. It is calculated by dividing the standard deviation over the arc length for the speed zero. With increasing speed the standard deviation increases.

Low humidity and a polished, clean surface should keep the statistical time lag long. The speed of approach will affect extremely the arc length.

In Figure 8 the results of a measurement with a low humidity (20% RH) and a polished surface are shown. With increasing speed the arc length drops down to approximately 10% of the Paschen value (inverse formula 1). For 2 kV the arc length drop is more significant than for the other voltages.

In Figure 9 the standard deviation of the data shown in Figure 8 is plotted via speed. With increasing speed it rises first to a maximum and after that it drops down.

5 Discussion

The measurements show the high influence of the speed of approach on the arc length. At lower humidity, the influence is by far more drastic than at higher humidity. Here the arc length can be very short, less than 10% of the Paschen length. If the voltage is very low, speed of approach affects the arc length more than at higher voltages. A clear dependency of the arc length drop on the voltage like in [1] could not be observed. There are even crossing points (6 kV and 8 kV at 0.1 m/s)

For high humidity the arc length reduction is much weaker. The degree of reduction depends somehow on the charge voltage too, but a clear tendency could not be observed.

The standard deviation and so the repeatability is extremely influenced by speed and humidity. For low humidity (20% RH, 20°C) the variability is small at slow speeds and for very high speeds. Daout et al. [1] observed such a behavior too. Renninger [12] predicted this tendency with the help of theoretical considerations. The upper bound is the static arc length, this is a fixed value and for static electrodes, i.e. lower speeds, this value has to be reached. There is a lower bound too. Field emission [2] limits the arc length drop.

For high humidity (70% RH, 20°C) the decreasing standard deviation could not be observed for high speeds like for low humidity. This area is shifted here to higher speeds outside of the measured range.

For all measured speeds (10^{-4}-10 m/s) the standard deviation is lower at higher humidity than at a low humidity. The maximum relative standard deviation measured at a humidity of 20% RH is 35% compared to the standard deviation at 70% RH of less than 15%.

The low standard deviation at higher speeds and lower humidity would allow the measurement of ESD with sampling scopes, a bandwidth of 10 GHz and more would become possible. In this range of high speed and low humidity the rise times are very short. Even the fastest, now available single shot measurement technology is not fast enough to measure the shortest rise times of ESD. Sampling could be a solution of the problem.

5.1 Intensity of ESD

Unfortunately the intensity can not be described by a simple value. Intensity is a quantity that must be defined in context with the DUT (Device Under Test) or EUT (Equipment Under Test). Depending on the device or equipment each part (e.g. rise time, amplitude, energy) of an ESD can cause failures. Undoubtedly the current amplitude and the rise time play an important role. These two quantities also determine the transient fields of ESD. We will concentrate here on these two quantities.

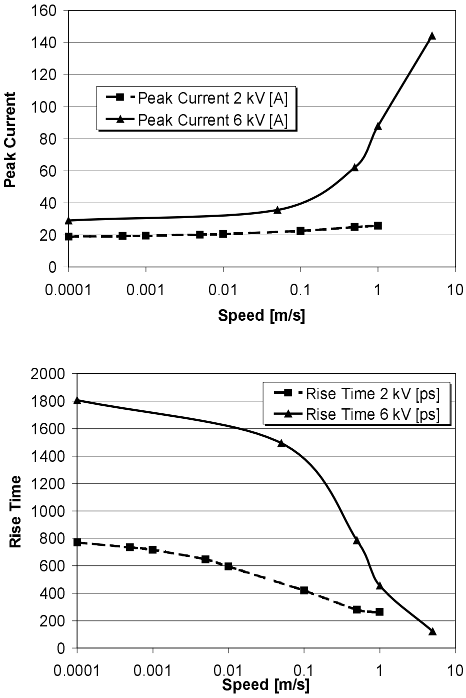

Figure 10: Average peak current and rise time (mean values) vs. speed of approach for constant charge voltages (2 kV and 6 kV, 20% RH, 20°C)

5.2 Dependency of the Humidity on the Intensity of ESD

Table 2 shows the peak currents and the rise times for 6 kV at constant speed, but different relative humidity. The humidity has a very high influence. The peak current value differs by the factor of nearly two. The rise time too depends on the humidity.

RH[%], 20°C	Peak Current [A]	Rise Time [ns]
20	88	0.4
70	48	1.1

Table 2: Peak Current and rise time (mean values) for a constant charge voltage (6 kV) and speed of approach (1 m/s) but different humidity

5.3 Dependency of the Intensity on the Speed of Approach

Figure 10 shows the dependency of the rise time and the current amplitude on the speed of approach for 2 and 6 kV. The arc lengths used for calculation were obtained from measurements at low humidity of 20%. The speed of approach affects the higher voltage more than the lower voltage. With increasing speed the rise time drops down to less than 200 ps. The peak current rises for example for 6 kV from 35 A up to 145 A.

Voltage [V]	Peak Current [A]	Rise Time [ns]
2000	22.5	0.42
4000	52.4	0.52
6000	38.7	1.36
8000	33.4	2.10

Table 3: Peak Current and rise time (mean values) at constant speed of approach (0.1 m/s) and different charge voltages (20% RH, 20°C)

Table 3 compares the peak current and the rise time at low humidity. Due to the voltage dependency of the reduction of the arc length (Figure 6) the peak current of a 4 kV pulse is higher than the current of a 6 or 8 kV discharge. At 6 kV rise time is shorter and amplitude is higher than at 8 kV. This means, if speed of approach and humidity are constant, the intensity of a discharge with a lower charge voltage can be higher than the intensity of a discharge with a significant higher charge voltage.

6 Conclusion

A new method to simulate ESD was developed and applied for parametrical studies. With this new method investigations in the role of humidity and speed of approach on the intensity of ESD were done.

The speed of approach and humidity influences significantly the severity of ESD. This paper shows how misleading the charge voltage as the dominant intensity quantity can be. It could be pointed out that the variance of ESD can decrease drastically, when humidity and speed are controlled. Without well controlled speed of approach and humidity, the reproducibility of an ESD-test can never be satisfying.

To increase the repeatability in ESD testing, it can be a solution to keep the speed of approach of an ESD-simulator very low. The variance remains low. Another method to reduce the variance can be a high ambient humidity.

7 Acknowledgment

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