FAST ELECTRICAL AND OPTICAL DIAGNOSTICS
FOR THE EARLY PHASE OF DIELECTRIC
SURFACE FLASHOVER

by

FRANK HEGELER, B.S.E.E.

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ABSTRACT

Virtually all concepts for the use of electrical energy at high voltages utilize solid dielectrics as electrical insulators, for which dielectric surface flashover is the primary factor limiting the magnitude of the applicable voltage. The voltage limitations imposed by dielectric surface flashover are particularly onerous because the physical mechanisms leading to flashover are far from being fully understood.

With a new experimental setup, emphasizing high speed and high resolution electrical and optical diagnostic methods, we attempt to elucidate the physical mechanisms leading to surface flashover. The setup consists of a cable discharge, operating at up to 50 kV DC, or 120 kV pulsed via a triggered spark gap, and is connected to a micro-torr vacuum discharge gap. Currently, the system is operated in the dc self-breakdown mode. The geometry of all interconnecting lines and of the discharge chamber is coaxial and the impedances are closely matched to the charging line. Measurement of pre-flashover currents, in the range of milliamperes to amperes, is accomplished via a transmission line type current sensor with a sensitivity of 100 mV/A and a risetime of less than 1 ns. Current sensor output during flashover is limited to the dynamic range of a standard oscilloscope using a switching-diode voltage clipping technique, with negligible pulse shape distortion. Voltage measurements across the flashover gap are performed with a standard capacitive voltage divider. High amplification photomultiplier tubes measure pre-flashover self luminosity and provide spatial resolution of optical phenomena. Soft X-ray emission is measured and correlated to current and luminosity signals. Different materials (Pyrex, PMMA, Lexan, alumina, and boron-nitride) have been investigated. In addition, dc magnetic fields of 100 mT have been applied, using permanent magnets outside of the vacuum chamber.

The results show the existence of a linearly increasing current and a corresponding linearly increasing low amplitude luminosity before flashover occurs, which can be explained by the standard model (saturated electron avalanche and electron stimulated outgassing). Externally applied magnetic fields alter these pre-flashover phenomena drastically. Magnetic field effects have been observed which increase or decrease the flashover voltage, depending on the direction of the $E \times B$ drift. The change of risetime of the pre-flashover current due to application of the magnetic field supports the saturated secondary electron avalanche model.

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CHAPTER I

INTRODUCTION

Insulators between high voltage conductors are essential in electrical systems for structural support or as interfaces between different dielectric materials (e.g., vacuum and liquids). Surface flashover across these insulators limits the power density transferable through high voltage systems. The dielectric surface flashover electric field in vacuum is typically 10% to 50% of the volume breakdown electric field for vacuum.¹ The physical mechanisms leading to surface flashover are poorly understood. Therefore, in high voltage operating systems, the distance between high voltage components is calculated with a large safety factor which increases weight and dimensions of the system. For space applications, for example, where weight is an important factor, the insulator technology has to be improved.

Dielectric surface flashover may be divided into the initiation stage, the development or growth stage, and the final stage. Over the last 30 years, several models have been developed. Most experts agree that the emission of electrons from the triple junction region (where insulator, cathode, and vacuum are in close proximity) is the initiating event which triggers the surface flashover of insulators in vacuum. For the second stage, the development stage, there is much disagreement between the flashover models. General agreement again is found for the final stage, where the final discharge takes place in gas that was desorbed from the insulator's surface.² Experimental data on the pre-flashover phase, such as current, luminosity, charge density distribution, density of desorbed gas, etc., which might support one of the models, are still incomplete.³

Chapter II provides a description of the different models of dielectric surface flashover and the theory of the Saturated Secondary Electron Emission Avalanche model (SSEEA), including magnetic field effects. The experimental arrangement is introduced in Chapter III and describes the vacuum and high voltage system, timing circuits and diagnostics used for data acquisition, the arrangement of electrodes, insulator, and magnetic field, and the insulator sample preparation. Chapter IV presents the experimental results. Chapter V discusses the results, compares the experimental data with the different models in Chapter II, and introduces some modifications for the SSEEA model. A summary of this work is presented in Chapter VI. In the appendices A to C, a selection of measurement results is shown.

CHAPTER II

EXISTING MODELS

Over the past years, many models have been proposed to explain the mechanisms of surface flashover. The first part of this chapter gives a brief, chronologically arranged description about the main models. In Chapter V, the experimental results are compared with the introduced models. It should be noted that this thesis is not an attempt to resolve completely the question of which model is correct; however, it does present new experimental data that tends to support the SSEEA model. In the remainder of the chapter, the SSEEA model is described in more detail.

Models of Dielectric Surface Flashover in Vacuum

Models proposed to explain surface flashover in vacuum can be categorized into three main groups and their subgroups:

- above surface
 - ionization of gas, which is adsorbed on the insulator surface
 - secondary electron emission avalanche leading directly to flashover
 - saturated secondary electron emission avalanche
 - thermal desorption of surface gas
 - electron induced desorption of gas molecules
- below surface
 - collisional ionization
 - thermal runaway
- transitions of below and above surface models.

Many researchers have proposed models to describe the complex mechanism of dielectric surface flashover.⁴ The following paragraphs present the main models of the last 30 years.

Boersch et al. (1963)

The first model of surface flashover was introduced by Boersch and co-workers⁵. The model is based on the secondary electron emission avalanche (SEEA) above the surface. A visualization of the secondary electron emission avalanche is given in Fig. 2.1.

Part of the electrons, field emitted from the cathode, strike the insulator. Electrons with an energy larger than A_1 (see Fig. 2.2) are able to emit secondary electrons from the insulator into the vacuum. The insulator is charged positively due to the emission of secondary electrons and an electric field, perpendicular to the surface, is developed.

Figure 2.1. Secondary electron emission avalanche.

The electrons, emitted from the insulator with an average energy of a few eV, are accelerated by the parallel applied electric field, and return to the surface of the dielectric, due to the perpendicular electric field. This phenomenon occurs until the average secondary emission yield is equal to one. A generic curve of secondary electron emission yield dependent on the electron energy is shown in Fig. 2.2.

Figure 2.2. Generic curve of secondary electron emission yield dependent on electron energy.⁵

The point {energy: A_1 , yield: 1} is stable; it means that the insulator does not increase or decrease the average net surface charge. To explain this phenomenon assume that an electron hits the surface with an energy smaller than A_1 and produces a negative net surface charge. The following electron will be repelled from this charge, remains longer in the parallel accelerating electric field and strikes the surface with an higher energy than it had initially. Repetition of this process forces the electrons to an energy increase towards A_1 before they hit the insulator surface. If an electron strikes the surface with an energy larger than A_1 , then it produces a positive net

surface charge, the emitted electrons from the insulator gain less energy through the parallel electric field and return to the surface with an energy which is lower than initially. Figure 2.3 shows the saturation of the electron emission avalanche due to the surface charge.

Figure 2.3. Saturation of the electron emission avalanche due to the surface charge.

Boersch's model includes micro-breakdowns caused by potential differences on the insulator. The elsewhere positively charged surface generates an increased electric field in front of the cathode which hinder the system from stabilizing. The result is a flashover along the surface.

Watson (1966, 1967)

Watson⁶ developed a theory in which electrons are emitted from the dielectric by thermionic emission of hot electrons. "Electrons liberated from shallow-trap levels within a dielectric can be accelerated by electric fields and heated above the lattice temperature as their energy is randomized by collisions. The electron-energy distribution is approximately Maxwellian with a temperature roughly proportional to the square of the electric field strength."⁶ The hot electrons leave the insulator and produce a number of holes in the surface layer, which form a positive charge. This charge draws other electrons from outside of the insulator onto the surface which causes secondary emission and finally, the breakdown.

Bugaev et al. (1967)

A model had been introduced by Bugaev and co-workers⁷ for a study of dielectric surface flashover in vacuum which assumes a monomolecular layer of adsorbed gas on the surface on the dielectric. Electrons, field emitted from the cathode, ionize the monomolecular layer of gas and cause a discharge to develop along the insulator surface. No SEEA was considered in this model.

Anderson (1974)

Anderson⁸ adopted the secondary electron emission avalanche proposed by Boersch et al. for his model and added a mechanism of thermal desorption of gas from the surface. The saturated SEEA current causes the insulator surface temperature to raise hundreds of kelvin during the

prebreakdown time delay, which is the time between the first electron emission from the cathode to the dielectric surface flashover. The temperature rise on the surface causes the absorbed gas on the surface to desorb, electrons from the SEEA current collide with the gas and ionize it. A discharge is developed in this layer of plasma.

Avdienko and Malev (1977)

The first electron induced desorption of surface absorbed gas model was published by Avdienko and Malev⁹. They assumed that the SEEA causes a positive surface charge on the dielectric and an electric field, perpendicular to the insulator surface like Boersch et al. but a much smaller surface charge amplitude was calculated. Avdienko and Malev proposed that the stable point of the secondary electron emission yield curve is {energy: A_2 , yield: 1} instead of {energy: A_1 , yield: 1} which Boersch et al. assumed (see Fig. 2.2). The electrons move nearly parallel to the insulator surface from the cathode to the anode. These energetic electrons strike the dielectric at a small angle to the surface and desorb the absorbed gas on the surface. Avdienko and Malev estimated that 100 - 200 molecules will be desorbed when an electron strikes the insulator surface. The gas density above the surface increases to more than 10^{18} cm^{-3} , equivalent to approximately 50 torr considering room temperature. The Nd product, which is the product of density and gap distance between the electrodes, varies from 2×10^{18} to $5 \times 10^{18} \text{ cm}^{-2}$ for gap distances of 0.1 to 10 cm. The flashover occurs in form of a streamer discharge.

Cross (1978)

Cross¹⁰ developed a model based on his high speed streak photography of surface flashover in vacuum. Electrons, emitted from the cathode, strike the surface of the insulator, create secondary emission along the insulator, which charges the surface positively. The process of saturated secondary electron emission avalanche (SSEEA) continues until a spot on the cathode becomes unstable and emits a large burst of electrons which hit the insulator surface close to the cathode causing the positive surface charge to be masked by an electron cloud. Electrons in this negative cloud will strike the insulator nearer to the anode, release surface absorbed gas and ionize it. This mechanism occurs until the electron beam strikes the anode. The ionized gas, expanded forward to the anode, provides a channel in which the discharge will be developed within 0.15 ns.

Anderson and Brainard (1978, 1980)

Anderson's earlier model was expanded by Anderson and Brainard¹¹ and includes a mechanism of electron stimulated desorption. SEEA and SSEEA, proposed by Boersch et al., is

assumed to describe the early phase of dielectric surface flashover. Electrons which are hopping across the insulator surface to the anode release adsorbed surface gas. Anderson and Brainard calculated a desorption efficiency of approximately 10^{-2} , where Avdienko and Malev used a much larger desorption efficiency, having a very small surface charge. In Anderson and Brainard's model the ionization probability, which is the probability that an electron hits a gas molecule and ionizes it, is assumed to be of the order of 1% with an electric field strength of 10 MV/m. The electric field at the triple point becomes enhanced by the positive surface charge and some positive ions, resulting from ionization of gas molecules. The mechanism of electric field enhancement at the cathode increase the field emission of electrons, the rate of gas desorption, and gas ionization. This and other processes were proposed to lead to a rapid breakdown.

Anderson (1979)

A study of surface flashover using an electric field mainly perpendicular to the insulator surface was done by Anderson.¹² The anode initiated flashover propagates along the surface of polymeric dielectrics toward the cathode and involves processes related to bulk breakdown. Starting from the anode, a pattern of branches resembling a tree grows forward until one branch reaches the cathode and a breakdown occurs. Anderson notes that the perpendicular electric field lifts the electrons off the surface so that no SEEA is able to develop. Figure 2.4 shows the electrode arrangements for anode initiated breakdown.

Figure 2.4. Electrode arrangements for anode initiated breakdown.

Anderson used an angle of 60 degrees in his experiment. Other experiments have shown that at an angle θ of ± 45 degrees, the surface flashover voltage reaches a maximum.

Pillai and Hackam (1982)

Pillai and Hackam¹³ introduced a method for calculating the surface flashover voltage based on the SSEEA model with electron induced desorption of surface adsorbed gas. Pillai and Hackam assume the same mechanism as Anderson and Brainard but a much larger electron stimulated desorption coefficient is used. The final flashover is predicted in form of a Paschen breakdown.

Enloe et al. (1983-1988)

Experimental investigations on ultraviolet laser induced dielectric surface flashover were done by Enloe and co-workers¹⁴. Their observations of the phenomenon of ultraviolet induced flashover point to the SEEA model. Results indicate that, with an angle θ of ± 45 degrees, surface charge builds up and plays a significant role in the flashover process whereas without laser light the surface charge is negligible.

Vigouroux et al. (1983, 1985)

Vigouroux and co-workers¹⁵ proposed a model based on collisional ionization below the insulator surface. "The electronic structure of an insulator consists of three zones of binding energies for the weakly bound electrons: (a) the valence band composed of filled states, (b) the band gap in which the defects introduce allowed localized levels, (c) the conduction band composed of allowed empty states, the band bottom is at 1.5 eV below the vacuum level."¹⁵ A tunnel injection from the triple point into the insulator initiates collisional ionization primarily in the valence band of the dielectric. Vigouroux and co-workers assume that secondary electron emission comes from interband transitions which does not involve directly the localized levels in the band gap. Figure 2.5 shows the energy band diagram of an insulator. "The charge of the insulator is assumed to result from the trapping of an electron on a pseudo-bond Si-Si (precursor state to E'-center). On the energetic point of view, the state of this electron corresponds to a filled localized level in the gap."¹⁵

Some electrons gain energy due to the collisions, which allow them to leave the conduction band of the insulator and diffuse into the vacuum. The extracted electrons create a number of positive carriers or holes in the valence band and build a positive charge propagating to the anode, following the electron diffusion. These electrons stimulate desorption of adsorbed surface gas; ionization of this gas leads to the final breakdown.

Figure 2.5. Energy band diagram of an insulator.¹⁵

Jaitly and Sudarshan (1987, 1988)

Jaitly and Sudarshan¹⁶ proposed a model based on electron collision-ionization within the subsurface layer at the dielectric-vacuum interface like Vigouroux et al. but do not consider gas desorption to be an essential part in the flashover process.

Electrons in the surface sublayer, produced either by field emptying of traps (or defect sites) or by injection at the cathode triple junction, cause positive charge generation by internal ionization processes. The positive charges drift towards the cathode aiding further electron emission due to the increased local stress. This process becomes regenerative until a threshold level is reached at which a highly conducting plasma is developed along the solid/vacuum surface interface, causing breakdown.¹⁶

Breakdown Criteria from the SSEEA Model

To explain the experimental results, the SSEEA model, introduced by Anderson and Brainard, is chosen and will be described on the following pages. It includes field emitted electrons from the cathode which start the secondary electron emission avalanche, a saturation of the SEEA, electron induced desorption of surface absorbed gas, and the final breakdown. Effects, like ionization of adsorbed gas, will be included in the calculation, also. In Chapter V, the experimental results will be compared to the calculations of the SSEEA model.

Field emitted electrons

Electrons with an energy of 4.3 eV, which is the work function for copper, are able to be emitted from the cathode. The emission occurs at the triple point where cathode, dielectric and vacuum are in close proximity. The emitted current density J is described by the Fowler-Nordheim equation¹⁷ where ϕ is the work function [eV], E is the electric field at the emitter point [V/cm], and $\theta(E, \phi)$ is Nordheim's function:

$$J = \frac{1.54 \times 10^{-6} E^2}{\phi} e^{\frac{-6.83 \times 10^7 \phi^{1.5} \theta(E, \phi)}{E}} \text{ [A/cm}^2\text{]} \quad (2.1)$$

with

$$\theta(E, \phi) \approx 0.956 - 1.53 \times 10^{-7} \frac{E}{\phi^2}. \quad (2.2)$$

Taking an effective field enhancement factor, β (i.e. $E = \beta \frac{V}{d}$), an effective emitting area, S , and a geometrical enhanced electric field¹⁸, E_c , into account, the Fowler-Nordheim equation can be reduced to the form:

$$\log \frac{I}{(E_c d)^2} = -2.84 \times 10^7 \frac{\phi^{1.5}}{\beta E_c} + \frac{4.6}{\sqrt{\phi}} - 5.81 + \log \frac{\beta^2 S}{\phi d^2}, \quad (2.3)$$

where

$$E_c = 0.9 \frac{V}{d} \left[1 + \frac{d}{2r_c} \right] \epsilon_r \text{ [V/cm]}. \quad (2.4)$$

Due to the insulator and to the geometry of the electrode, the electric field E_c at the cathode is increased. With a breakdown voltage V_b of 15,000 V, a ϕ of 4.3 eV, a gap distance d of 0.5 cm, an electrode radius r_c of 0.1 cm, a relative permittivity ϵ_r of 3, an assumed effective emitting area S of 10^{-6} cm^2 , and an effective field enhancement factor β of approximately 300,¹⁸ a current I of 450 A can be emitted from the cathode which is equivalent to an emission of 2.8×10^9 electrons/ps. This emission should be sufficient to start the secondary electron emission avalanche.

Saturated secondary electron emission avalanche (SSEEA)

The field emitted electrons strike the insulator, charging the surface positively due to the emission of secondary electrons from the dielectric which develops an electric field perpendicular

to the surface. The secondary electron emission avalanche saturates (see description of Boersch's model) which is indicated by a constant surface current.

When the steady state of surface charging is reached at unity secondary electron emission yield, the electric field is $\mathbf{E} = \{-E_x, E_y, 0\}$. E_x is the field component parallel to the surface due to the applied gap voltage and E_y results from the surface charge of the dielectric which is perpendicular to the surface. Figure 2.6. shows the trajectory of an electron on an insulator surface with an applied electric field.

Figure 2.6. Trajectory of an electron on an insulator surface with an applied electric field.

The motion of the electrons is described by the Lorentz force

$$\mathbf{F} = q [\mathbf{E} + (\mathbf{v} \times \mathbf{B})] , \quad (2.5)$$

where $\mathbf{F}$ is the force, q is the charge of the particle, and $\mathbf{B}$ is the magnetic flux density. With $\mathbf{B}$ is equal to zero, the equation of motion simplifies to

$$m \frac{d\mathbf{v}}{dt} = q \mathbf{E} , \quad (2.6)$$

where m is the particle mass. In this model, there is no electric field component in z -direction. Therefore, for electrons with a charge of $-e$,

$$\frac{dv_x}{dt} = \frac{e}{m} E_x \quad (2.7)$$

and

$$\frac{dv_y}{dt} = - \frac{e}{m} E_y . \quad (2.8)$$

Integrating the equations (2.7) and (2.8) and assuming that the secondary electrons are emitted from the insulator with an velocity $\mathbf{v} (t=0) = \{0, v_0, 0\}$,

$$v_x = \frac{e}{m} E_x t \quad (2.9)$$

and

$$v_y = v_0 - \frac{e}{m} E_y t. \quad (2.10)$$

Integration of these equations gives the trajectory equations

$$s_x = \frac{e}{m} E_x \frac{t^2}{2} \quad (2.11)$$

and

$$s_y = v_0 t - \frac{e}{m} E_y \frac{t^2}{2} \quad (2.12)$$

with the initial conditions $s_x(0) = 0$ and $s_y(0) = 0$. The emitted electrons leave the surface at $t = 0$ and impact the surface at $t = t_0$. The time t_0 is acquired by setting equation (2.12) to zero:

$$t_0 = \frac{2 m v_0}{e E_y}. \quad (2.13)$$

Solving the equations (2.9) and (2.10), using equation (2.13),

$$v_x(t_0) = 2 v_0 \frac{E_x}{E_y} \quad (2.14)$$

and

$$v_y(t_0) = - v_0. \quad (2.15)$$

The impact electron energy A_i can be obtained from

$$A_i = \frac{m}{2} v^2, \quad (2.16)$$

therefore,

$$A_i = \frac{m}{2} v_0^2 \left[1 + 4 \frac{E_x^2}{E_y^2} \right]. \quad (2.17)$$

Taking into account the cosine law distribution⁵ in the direction of emission, the average value of the impact energy A_1 becomes

$$A_1 = \frac{m}{2} v_0^2 \left(1 + 2 \frac{E_x^2}{E_y^2} \right) \quad (2.18)$$

and the electric field due to the surface charge is given as

$$E_y = E_x \sqrt{\frac{2 A_0}{A_1 - A_0}} \quad (2.19)$$

where

$$A_0 = \frac{m}{2} v_0^2. \quad (2.20)$$

To compare the experimental results with this model, some parameter will be calculated, using the formulations of Boersch,⁵ Anderson-Brainard,¹¹ and Pillai-Hackam.¹³ For the following calculations, some variables, in part related due to the experimental setup, will be fixed. They are:

- Electric field, parallel to the insulator surface E_x : 30 kV/cm
- Gap distance between the electrodes d : 0.5 cm
- channel width of the discharge w : 0.1 cm
- average emission energy of secondary electrons A_0 : 1 eV
- average impact electron energy when the secondary electron emission yield is one (lower operating point) A_1 : 40 eV.

The average electron velocity is defined by

$$v_1 = \sqrt{\frac{2 A_1}{m}} = 3.8 \times 10^8 \text{ cm/s.} \quad (2.21)$$

The angle between the electric field and the insulator surface is given by

$$\tan \theta = \frac{E_y}{E_x}, \quad (2.22)$$

therefore,

$$\tan \theta = \sqrt{\frac{2 A_0}{A_1 - A_0}} = 0.23. \quad (2.23)$$

The electrons are hopping along the insulator surface with a distance of

$$s_x = \frac{A_0}{e E_x} = 13 \mu\text{m} \quad (2.24)$$

and

$$s_y = \frac{A_1}{e E_y} = 1.5 \mu\text{m}. \quad (2.25)$$

The surface charge density can be written as

$$\sigma_+ = 2 \epsilon_0 E_y = 1.2 \times 10^{-9} \text{ As/cm}^2, \quad (2.26)$$

where ϵ_0 is the permittivity of the free space. With the assumption that the electron number per unit area, σ_- , is equal to the surface charge density, σ_+ , the saturated surface current per unit channel width is

$$I_x = \sigma_- v_1 = 45 \text{ A/m}, \quad (2.27)$$

which gives a saturated surface current of

$$I_{\text{sat}} = I_x w = 45 \text{ mA}. \quad (2.28)$$

The current density of electrons incident on the surface is given by

$$J_e = \frac{I_x}{s_x} = 340 \text{ A/cm}^2 \quad (2.29)$$

and the density, N , of desorbed gas molecules is estimated by Pillai-Hackam as

$$N = \frac{\gamma J_e}{e v_{\text{th}}} \quad (2.30)$$

with

$$v_{th} = \sqrt{\frac{8 R T}{\pi M}}, \quad (2.31)$$

where γ is the desorption coefficient, v_{th} is the average thermal velocity of the desorbed gas, R is the molar gas constant, T is the temperature, and M is the molar mass. With $\gamma = 100$ molecules per electron and $T = 300$ K, the gas density above the surface is $N = 4.4 \times 10^{18}$ molecules/cm³ for nitrogen or dry air, which is equivalent to a pressure of 140 torr.

The probability that a desorbed atom or molecule is ionized while drifting through the saturated secondary electrons emission avalanche is ¹¹

$$P = \frac{Q I_x}{e v_{th}} \quad (2.32)$$

where P is the probability of ionization and Q is the effective cross section for ionization. With $Q = 10^{-16}$ cm²,¹¹ the ionization probability is in the order of 1%.

Final breakdown

The final discharge is predicted to take place in the desorbed gas in form of a Paschen breakdown. Figure 2.7 shows the development of the final discharge.

Figure 2.7. Development of the final discharge in the desorbed gas.

The composition of gases, released by surface flashover, was investigated by Miller and Ney.¹⁹ They concluded that the surface gas was not adsorbed system background gas, but was gas adsorbed during the handling and processing of the insulator. Table 2.1. shows gases released from Pyrex. Nitrogen is the major constituent of the system background gas, but is negligible in the breakdown gas. The breakdown is divided into two categories in Ref. 19: moderate and severe breakdown. Most breakdowns produce gas quantities comparable to each other which are considered "moderate." Occasionally, some breakdowns would yield a considerably larger quantity of gas than the average and were denoted as "severe" breakdowns. For surface

flashovers on Pyrex, CO₂, CO, and H₂ are the main components of the breakdown gas. Figure 2.8 shows the Paschen curves for CO₂, N₂, and H₂. The breakdown should occur approximately two orders of magnitude to the right of the voltage minimum for a gas-filled gap (Paschen minimum). In this region, the breakdown voltage for CO₂ and N₂ is about 1-3 kV, which is more than one order of magnitude smaller than the applied gap voltage. It is assumed, that the final discharge starts to develop as soon as there is a sufficient gas pressure in the gap but breakdown does not occur on the lower pressure side of the Paschen curve because the gas pressure increases by several orders of magnitudes in tens of ns due to the electron induced desorption of the surface absorbed gas.

Table 2.1. Gases released by surface flashover on Pyrex in percent.¹⁹

Gas	Background	Breakdown moderate	Breakdown severe
CO ₂	4	38	12
CO	5	27	59
H ₂	18	29	24
CH ₄	1	4	2
N ₂	62	1	1
H ₂ O	8	1	1
other	3 (Ar + He)	< 1	1 (O ₂)

Figure 2.8. Breakdown characteristics of some molecular gases (Paschen curves).²⁰

The SSEEA Model Including Magnetic Field Effects

The influence of magnetic fields on dielectric surface flashover has been investigated by Lehr and Korzekwa.^{1,21,22} With the proper orientation of the magnetic field, flashover voltage increases of a factor of 2 to 3 have been observed.

The motion of the electrons is described by the Lorentz force, equation (2.5). Considering a uniform electric field $\mathbf{E} = \{-E_x, E_y, 0\}$ and a constant magnetic flux density $\mathbf{B} = \{0, 0, B_z\}$, the components of the particle acceleration are given by

$$\frac{dv_x}{dt} = \frac{e}{m} (E_x - v_y B_z) \quad (2.33)$$

and

$$\frac{dv_y}{dt} = -\frac{e}{m} (E_y - v_x B_z), \quad (2.34)$$

which leads to

$$\frac{d^2 v_x}{dt^2} + \omega^2 v_x = \omega^2 \frac{E_y}{B_z} \quad (2.35)$$

and

$$\frac{d^2 v_y}{dt^2} + \omega^2 v_y = \omega^2 \frac{E_x}{B_z} \quad (2.36)$$

with

$$\omega = \frac{e B_z}{m}, \quad (2.37)$$

where ω is the electron cyclotron frequency. With the initial condition $\mathbf{v}(t=0) = \{0, v_0, 0\}$,

$$v_x = -\frac{E_y}{B_z} \cos \omega t - \left(v_0 - \frac{E_x}{B_z} \right) \sin \omega t + \frac{E_y}{B_z} \quad (2.38)$$

and

$$v_y = \left(v_0 - \frac{E_x}{B_z} \right) \cos \omega t - \frac{E_y}{B_z} \sin \omega t + \frac{E_x}{B_z}. \quad (2.39)$$

Integration of these equations with $s_x(0) = 0$ and $s_y(0) = 0$ gives

$$s_x = -\frac{E_y}{\omega B_z} \sin \omega t + \frac{1}{\omega} \left(v_0 - \frac{E_x}{B_z} \right) (\cos \omega t - 1) + \frac{E_y}{B_z} t \quad (2.40)$$

and

$$s_y = \frac{1}{\omega} \left(v_0 - \frac{E_x}{B_z} \right) \sin \omega t + \frac{E_y}{\omega B_z} (\cos \omega t - 1) + \frac{E_x}{B_z} t. \quad (2.41)$$

Bergeron²³ calculated the critical magnetic flux density B_c , required to lift off the saturated avalanche from the insulator. He included the space charge, due to the electron avalanche, and was taking an isotropic distribution of emission angles into account. For this experiment (e.g., $E_x = 30$ kV/cm, $A_0 = 1$ eV, and $A_1 = 40$ eV), Bergeron's critical magnetic flux density is

$$B_c = \left(\frac{1.6 v_0}{v_1^2} \right) E_x = 200 \text{ mT}. \quad (2.42)$$

where v_0 and v_1 are the velocities associated with the energies A_0 and A_1 . Figure 2.9. shows the magnetic flashover inhibition concept. The electron strikes the surface (a) until the magnetic flux density $B > B_c$ (b).

The case in which the vector $\mathbf{E} \times \mathbf{B}$ points into the surface has been investigated, also.^{1,21,22} For small magnetic field strengths, the flashover voltage decreases compared with the breakdown

voltage when no magnetic field is applied. It is assumed that more electrons strike the surface of the insulator whose number then is sufficient to start the electron avalanche on the insulator surface. For larger magnetic field strengths, the flashover voltage increases compared with the breakdown voltage when $\mathbf{B} = 0$. More electrons hit the insulator but the large $\mathbf{E} \times \mathbf{B}$ drift decreases the free path length of the electrons, which means that electrons gain less energy through the parallel electric field than in the case where no magnetic field is applied.

Figure 2.9. Magnetic flashover inhibition concept with (a) $B_z < B_c$ and (b) $B_z > B_c$ ²⁴.

CHAPTER III

EXPERIMENTAL ARRANGEMENT AND TECHNIQUES

The purpose of this experiment was to investigate the early phase of dielectric surface flashover in vacuum. It was thus necessary to design and construct a system with coaxial geometry and constant impedance, along with the diagnostics, timing circuits, and the vacuum system. This chapter outlines the design and operation of each of the major subsystems and explain the techniques used in obtaining the experimental data.

Vacuum Chamber and Pumping System

The vacuum system was constructed using a Sargent Welch roughing pump and a Sargent Welch turbo-molecular high vacuum pump, model number 3106S, with a pumping speed of 400 liters/second for nitrogen, and an ultimate pressure of 1×10^{-8} torr. Aluminum flanges were used to seal the ends of the chamber and to accommodate pressure gauges, valves, and windows. The vacuum chamber was constructed entirely of three inch diameter Pyrex tubing and was able to be separated from the vacuum pump by a four inch mechanical gate valve. The system pressure was monitored using a standard Pirani thermal conductivity and hot-cathode ionization vacuum gauge. The system was capable of attaining a vacuum of approximately 10^{-7} torr.

High Voltage System

A 100 kV high voltage dc power supply charges the transmission line, RG-19, through a $100 \text{ M}\Omega$ high voltage resistor until a discharge in the test gap occurred (self-breakdown). The length of the charging line is approximately 10 m which gives a two-way transit time of 107 ns. Figure 3.1 shows the basic experimental setup. A high voltage connector was designed and constructed for the 50 kV DC or 100 kV pulsed, with coaxial geometry, and closely matched to the impedance of 52Ω of the charging line. Figure 3.2 shows a matched coaxial connector which gives the system the flexibility of changing or adding several diagnostic components. One connector has a diameter of 1.25 inches and is about 35 cm long. The inner conductor is a 0.25 inch diameter copper rod, the outer conductor is a 1.25 inch diameter aluminum tubing. Lexan 3412 with 20% glass fiber is used as a dielectric material for the connector. The system is terminated with a transmission line, RG-19 coaxial cable, with a length of roughly 11 m which is about 10% longer than the charging line, shorted at the end.

Figure 3.1. Basic experimental setup.

Figure 3.2. Matched coaxial connector.

Electrode and Insulator Arrangement

The test chamber consists of a 3 inch inside diameter Pyrex "cross." The outer conductor is a brass mesh to provide optical access to the test sample. The test sample has the dimension of approximately 48 mm x 28 mm and is 1/8 or 1/4 inches thick. Figure 3.3 shows the test sample including test sample holder.

Figure 3.3. Electrode arrangement on the insulator.

The cathode is sharpened with 1200 grit alumina sandpaper to increase the field enhancement factor at the triple point and to decrease the width of the cathode touching the insulator. Due to the Nylon screws, the electrodes have a good contact to the surface of the dielectric. The gap width, d_g , between the electrodes is approximately 0.5 cm.

Magnetic Field Arrangement

The magnetic field is parallel to the insulator surface and perpendicular to the electric field at the centerline of the interelectrode gap. The removable rare-earth permanent magnets are 10 cm apart from each other, yielding a nearly uniform lateral magnetic field within the chamber. To increase the magnitude of the magnetic field density in the test gap to 100 mT, two permanent magnets with the size 12 inches x 4 inches x 1 inch and one with the size 6x4x1 (all dimensions given in inches) were stacked together on each side of the chamber. Figure 3.4 shows the arrangement of the permanent magnets which produce the magnetic field in the test chamber. The direction of the magnetic flux density, B , is indicated by the arrows. To switch the polarity of the magnetic field, the permanent magnets are simply changed to opposite sides.

Figure 3.4. Magnetic field arrangement.

Timing Circuits and Data Acquisition System

The timing system for data acquisition is shown schematically in Fig. 3.5. The output of the current sensor was split with a matched divider in order to generate a trigger signal. The ramp output of the Tektronix (TEK) 7834 oscilloscope triggers externally two TEK 7104 scopes recording the current and luminosity or soft X-ray signals. Andrew 84147/LFL4-50A and 84147/LFL2-50A coaxial cables, which have a band width of several GHz, were used to compensate the delay of signal input to ramp output of the TEK 7834. Table 3.1 shows the delays T_1 to T_{14} for Fig. 3.5.

The TEK 7104 used current signals includes a 7A29 amplifier and a 7B15 time base, the scope used for PMT signals contains a 7A19 amplifier and a 7B15 time base. The outputs of the two TEK 7104 scopes have been recorded with a TEK C1001 and C1002 digitizing camera interfaced with a 486/33 MHz PC using software supplied with the cameras. The simultaneity of the current and luminosity or soft X-ray signal is estimated to be exact within a limit of 1 ns.

The data acquisition system was calibrated each time before measurements were taken with a new test sample. A step pulse with a length of 200 ns and a risetime less than 0.2 ns was generated from a Tektronix pulse generator type 110, split using a Bishop Instruments three port splitter, and fed into the Andrew 84147/LFL4-50A coaxial cable at the output of the current sensor and the PMT (see T_3 and T_{14} in Fig. 4.1.). The cable delay lines T_5 and T_{14} compensate the delays $T_6 - T_{10}$ and the difference of T_1 and T_2 to T_{12} and T_{13} . The end of the calibration procedure is reached when the test signal shown on the oscilloscope for the current signal is delayed by $T_{12} + T_{13} - T_1 - T_2$ from the one shown on the oscilloscope for the PMT signal.

Table 3.1. Delays in the data acquisition system.

T_1	distance of the current probe to the test gap	: 3 ns
T_2	distance of the coil to the inner conductor, coaxial signal cable	: 0.4 ns
T_3	5 m Andrew 84147/LFL4-50A coaxial cable	: 19 ns
T_4	Bishop Instruments three port splitter 080-001	: < 0.2 ns
T_5	Andrew 84147/LFL4-50A and 84147/LFL2-50A coaxial cable	: variable
T_6	1.7 m RG-400/U 07145 coaxial cable, 20 dB attenuator (2 ns)	: 11 ns
T_7	delay between signal input and gate output	: 40 ns
T_8	1.1 m RG-400/U 07145 coaxial cable	: 6 ns
T_9	Bishop Instruments three port splitter 080-001	: < 0.2 ns
T_{10}	0.3 m RG-400/U 07145 coaxial cable	: 2 ns
T_{11}	0.3 m RG-400/U 07145 coaxial cable	: 2 ns
T_{12}	light path from the test gap to the cathode of the PMT	: 0.7 ns
T_{13}	PMT transit time for luminosity (7ns), or X-rays (33 ns), signal cable including PMT socket 1.2 ns (luminosity) or 2 ns (X-rays)	: 8.2 ns or 35ns
T_{14}	Andrew 84147/LFL4-50A and 84147/LFL2-50A coaxial cable	: variable

Diagnostics

Diagnostic tools in this experiment were voltage, current, luminosity, and soft X-ray sensors. The voltage sensor is a standard capacitive divider with a ratio 800 : 1 and a RC-time- constant τ of 95 ns. Until now, only the flashover voltage amplitude was measured. The primary tools, used in this work, are outlined in the following paragraph.

The Current Sensor

Current measurements are accomplished with a transmission line type current sensor²⁵ which has a sub-nanosecond risetime and a sensitivity of approximately 0.1 V/A. The two-way transit time of this sensor is 300 ns during which the primary current is reproduced faithfully, i.e., there are negligible limitations of the amplitude transfer function such as high- or low-frequency cutoffs whereas in standard current sensor these limitations have to be taken into account.

Dispersion on the output of an un-optimized current probe causes ringing to be introduced on the trailing edge of the probe output.²⁵ Minimum dispersion is achieved for the ratio of radii $r_s/r_c = \sqrt{e}$, where r_s is the minor radius of the shield and r_c is the minor radius of the coil.²⁶ Figure 3.6 shows the transmission line current sensor used in this experiment and Table 3.2 gives the probe parameters.

Table 3.2. Parameters of the transmission line current sensor.

N	(number of turns)	: 475
d/2	(major radius)	: 3.75 cm
a	(sides of cross section)	: 1.94 cm
L	(inductance)	: 490 μ H
C	(capacitance)	: 66 pF
Z	(characteristic impedance)	: 2700 Ω
T	(one-way transit time)	: 150 ns
R_w	(wire resistance)	: 8.1 Ω
D	(diode)	: 1N4151
$S = Z / 2 N$	(matched sensitivity)	: 2.9 V/A
S_0	(sensitivity with $Z_0 = 50 \Omega$)	: 0.1 V/A

Figure 3.6. Transmission line current sensor.

For the fully developed discharge, the current reaches an amplitude of 150 A for a typical flashover voltage of $V_b = 15$ kV. To limit the output of this current sensor to amplitudes relevant for the pre-flashover (i.e., input currents < 10 A), a clipping technique using 1N4151 switching diodes has been used. Below the clipping threshold, parallel stacks of two diodes each have been found to slightly degrade a measured 480 ps risetime to 590 ps. Note that the nominal risetime of the oscilloscope used, Tektronix 7104/7A19, is 600 ps. Figures 3.7 and 3.8 show examples for the sensor response to a rectangular input pulse. A current sensor response to a waveform more representative of pre-flashover wave shapes is shown in Fig. 3.8.

Figure 3.7. Current sensor response to a rectangular input pulse with a risetime of less than 1 ns and a pulse length of 200 ns (including clipping diodes).

Figure 3.8. Current sensor response to a rectangular input pulse with a risetime of approximately 9 ns and a pulse length of 45 ns (including clipping diodes).

The response of the clipping diodes was measured using a Tektronix pulse generator type 110 with a risetime less than 0.2 ns. The switching diodes 1N4151 with a clipping threshold of approximately 1.3 V showed no changes in the clipping level, if the input voltage was below 10 V. For an input voltage larger than 15 V, the clipping process was delayed by the turn-on time of the diodes, τ , which had a value of roughly 2 ns. The clipping level of the diodes increased proportional to the input voltage to an amplitude in the order of 1/10 of the input voltage. Figure 3.9 shows the pulse response of the switching diodes.

Figure 3.9. Response of the clipping diodes to a step-pulse input with sub-nanosecond risetime and an amplitude of more than 15 V. The turn-on time, τ , of the diodes is 2 ns, the amplitude of the clipping level is reduced to 10% of the input voltage.

The Luminosity Sensor

A standard technique using a fast photomultiplier, Hamamatsu R 4703, with 800 ps risetime, an anode sensitivity of 2×10^4 A/W, and an S-20 spectral characteristic has been used to measure the luminosity. The whole area of the test gap, including portions of the cathode and anode, was imaged onto the photocathode of the Hamamatsu PMT which has a diameter of 8 mm. A bi-convex optical glass lense, 2 inches in diameter, 50 mm focal length, and with a visible multi-layer anti-reflection coating usable for wavelengths of 430 to 700 nm, was centered 6.5 inches above the test gap which reduced the image to 43% of the original and covered a solid angle of $\Omega = 7.3 \times 10^{-2}$ sr. Figure 3.10 shows the experimental setup of the luminosity sensor.

Figure 3.10. Setup of the luminosity sensor.

The sensitivity of the luminosity measurement setup is estimated to be 1.2×10^4 V/W, i.e., an output voltage of 1V corresponds to a power emitted from the insulator surface of $80 \mu\text{W}$. The linearity of this PMT, with socket assembly Hamamatsu E1761-04, has been tested using the light emission of a fast spark gap, with a 10 ns risetime and 25 ns fall time, and a set of neutral density filters. Figure 3.11 shows the transmission characteristics of the PMT. The response is linear for output amplitudes below 500 mV, and levels off at approximately 1 V. Above 1V, the output saturates slowly to a maximum value of 3 V.

The X-ray Sensor

Soft X-ray emission measurements are accomplished with an Amperex XP 2020 photomultiplier tube, operated at 2.4 kV, in conjunction with an NE 102 plastic scintillator. Figure 3.12 shows the experimental setup of the X-ray sensor. A $16 \mu\text{m}$ aluminum foil absorbs the visible light emitted by the discharge. The transmission characteristic of the foil is shown in Fig. 3.13. In order to find the temporal correlation of the X-rays to the current and luminosity signals, the transit time of this PMT has been determined experimentally. The light emission of the fast spark gap, which is described above, was measured with the Amperex XP 2020 and the Hamamatsu R 4703. Adding the signal delay of the Amperex PMT to the known transit time of the Hamamatsu photomultiplier tube, it was found that the transit time of the Amperex photomultiplier tube is 33 ns. The risetime of the PMT is approximately 3 ns.

Figure 3.11. Transmission characteristics of the luminosity sensor.

Figure 3.12. Setup of the X-ray sensor.

Figure 3.13. Transmission characteristics of the 16 μm aluminum foil as a function of photon energy²⁷.

A solid angle Ω of 0.32 sr was obtained by having the 6 cm diameter scintillator about 3 inches above the insulator surface. The response is linear for output amplitudes of several volts and reaches a maximum value of 50 V when the current output saturates with respect to the input power of the luminosity. To measure the early phase soft X-ray emission, the signal was clipped above 1.3 V using 1N4151 switching diodes which are described above.

The plastic scintillator NE 102 has an fluorescence efficiency²⁷ $\eta_{fe} = 0.02$ and its refractive index $n = 1.58$ which gives an output efficiency by internal total reflection of $\eta_{oe} = 0.11$. The number of gap electrons, which are producing X-rays, can be estimated using the energy conversion efficiency, δ , for Bremsstrahlung²⁸:

$$\delta = 10^{-9} Z E \quad (3.1)$$

where Z is the atomic number of the target material and E is the kinetic electron energy in eV. With $E = 15,000$ eV and $Z = 29$ for copper, $\delta = 4 \times 10^{-4}$.

Due to the transmission characteristics of the aluminum foil (see Fig. 3.13.), the energy conversion efficiency is reduced by the spectral transfer efficiency η_{ste} which is approximately 0.25.

In the scintillator, one X-ray photon with an energy of 15 keV produces N visible photons. With the fluorescence efficiency $\eta_{fe} = 0.02$ and a visible photon energy of 3 eV, $N = 100$.

Assuming a ratio of scintillator light output to PMT light input of $\Omega_{sc-pmt} = 10\%$, a PMT amplification of $\alpha = 10^7$, and a PMT quantum efficiency of $\eta_{qe} = 10\%$, the ratio of X-ray producing gap electrons to PMT-output electrons, η , can be found:

$$\eta = \Omega_{x-sc} \delta \eta_{ste} N \eta_{oe} \Omega_{sc-pmt} \alpha \eta_{qe} = 3, \quad (3.2)$$

where Ω_{x-sc} , the solid angle of the scintillator to the test gap, is approximately 0.32 sr.

Therefore, a X-ray producing electron beam with a current of 10 mA will be indicated by a PMT output-voltage of 1.5 V (i.e., a electron beam current of 10 mA produces a PMT output current of 30 mA, which is equivalent to a PMT output voltage of 1.5 V when the impedance is equal to 50 Ω).

Insulator Sample Preparation

The samples have been prepared using a standard method, cleaning with deionized (DI) water, for some materials with methanol, and treatment in an ultrasonic cleaner. The surface area of the samples was 48 mm x 28 mm and they were 1/8 inch thick, except alumina which had the dimensions of 48 mm x 25 mm by 1/4 inch. All samples have been kept in a low-vacuum chamber for at least 18 hours before they were placed in the test chamber.

Pyrex: The Pyrex samples were cleaned with methanol and treated in an ultrasonic cleaner which used methanol as a medium.

Lexan and PMMA: The surface of the sample was cleaned with deionized water, treated with wet 1200 grit alumina sandpaper, using deionized water, cleaned with DI water, again, and handled in an ultrasonic cleaner which used DI water as a medium.

Boron-nitride: The samples were treated with wet 1200 grit alumina sandpaper, using methanol, and handled in an ultrasonic cleaner which used methanol as a medium.

Alumina: Alumina samples came in contact with an oily liquid when they were cut with a diamond saw. Therefore, they were carefully treated four times in an ultrasonic cleaner with a cleaning solution (1x), DI water (2x), and methanol (1x) as a medium.

CHAPTER IV

EXPERIMENTAL RESULTS

Previous Work

An extensive investigation of dielectric surface flashover in vacuum was done over the last ten years. Reference 29 contains a large bibliography of the recent developments in this field. However, it is not known that an experimental setup with coaxial geometry and closely matched impedance was constructed before to elucidate the physical mechanisms leading to surface flashover.

Preliminary experiments were performed to test the new experimental setup using different materials (Pyrex, PMMA, Lexan, Celcon, G-10 composite epoxy, and boron-nitride ceramics). The current was measured with a sensitivity of 70 mV/A and the sensitivity of the luminosity measurements was 450 V/W (see Appendix C). The results show the existence of a linearly increasing current and a corresponding linearly increasing low amplitude luminosity before flashover occurs and the results were published at the 8th IEEE International Pulsed Power Conference.³ After the preliminary test phase, the signal to noise ratio was improved and the resolution was increased by a factor of 10. In addition, the sensitivity of the diagnostic tools was improved; by 50% for the current probe and by 2,500% for the luminosity measurements. Results will be presented in the remainder of this chapter.

Surface Flashover Across Insulators

For this experiment, five different materials, Pyrex, PMMA, Lexan, alumina, and boron-nitride, have been used to investigate the early phase of dielectric surface flashover in vacuum. Ten shots (dielectric breakdowns) were taken for each sample and the measurements started with virgin samples. The discharge energy per shot normally increased from 0.05 J at $V_b = 7$ kV for the first shot to about 1.6 J at $V_b = 40$ kV for the last shot.

To characterize the basic system (see Fig. 3.1), voltage and current waveforms have been calculated and compared with experimentally obtained waveforms. Figure 4.1 shows a schematic of the current and voltage wave. Note that the one-way transit time from the test gap to the current probe is 3 ns and from the gap to the voltage probe is 5 ns. Both sensors are on the generator side. The far end of the load side is shorted while the transmission line on the generator side is charged through a 100 M Ω resistor.

Figure 4.1. Schematic of the current and voltage wave. The one-way transit time from the gap to the open line generator side is 53.5 ns and from the gap to the short-circuited line load side is 57.5 ns. At $t = 222$ ns, a short occurs between the inner and outer conductor of the transmission line at the gap. The voltage probe is simplified as a RC-circuit with a time constant of 95 ns.

At $t = 0$, a breakdown occurs, which connects the inner conductor (anode and cathode in the test gap) of the transmission line. Charging and load line are combined into one transmission line with a one-way transit time of 111 ns. After the breakdown, at $t = 222$ ns, the gap voltage reaches a maximum in its amplitude for the first time while at the same time the gap current is zero. At this time, the background gas around the dielectric should be partly ionized due to the discharge in the gap. Therefore, a second breakdown is assumed to develop in the gap between the inner and outer conductor of the transmission line which are 1.5 inches away from each other. Figures 4.2 to 4.6 show the measured current, voltage, luminosity, and emitted X-ray for 500 or 1000 ns, respectively. All measurements were done using Pyrex as a test sample with a gap width of $d_g = 5$ mm and a pressure of 10^{-6} torr.

Figure 4.2. Typical result for the flashover current. The breakdown voltage is $V_b = 11$ kV and the shot number $n_s = 4$.

Figure 4.3. Typical result for the X-ray emission measurement. The breakdown voltage is $V_b = 11$ kV and the shot number $n_s = 4$. Note that 1 V is equivalent to an estimated X-ray producing electron beam current of 6.7 mA.

Figure 4.4. Anomalous result for the flashover current. The breakdown voltage is $V_b = 5$ kV and the shot number $n_s = 2$.

Figure 4.5. Typical result for the flashover voltage. The breakdown voltage is $V_b = 22$ kV and the shot number $n_s = 7$. Note that the ratio of the capacitive divider is 800 : 1.

Figure 4.6. Typical result for the luminosity measurement. The breakdown voltage is $V_b = 9$ kV and the shot number $n_s = 2$. Note that the sensitivity of the PMT is 800 μ W/V.

The typical flashover current (see Fig. 4.2) and voltage (see Fig. 4.5) correspond to the calculated waveforms (see Fig. 4.1). Figure 4.3 shows a typical result for the X-ray emission measurement. A few nanoseconds before the gap discharge occurs, a short X-ray emission pulse is measured. Some electrons are accelerated over the whole gap width, d_g , hit the anode, and produce X-rays. The X-ray emission stops, when adsorbed surface gas leaves the insulator surface and minimizes the free path length of the electrons. At the same time, the discharge is developed. Approximately 115 ns after the breakdown develops, the amplitude of the gap voltage becomes negative. At this time, a large amount of electrons should be above the insulator due to the discharge which started at $t = 0$. Many of these electrons are able to strike the anode (which was the cathode at $t = 0$) with a large kinetic energy because the gas density around the anode should be much smaller compared with the gas density when the first discharge in the gas was developed. Therefore, at $t \approx 120$ ns, a second X-ray emission pulse is seen with a longer pulse length than the first one. Note that all given times, t , are related to Fig. 4.1.

An anomalous result for the discharge current is given in Fig. 4.4. It is assumed, that at $t = 222$ ns, a short occurs between the inner- and outer conductor of the transmission line at the gap (see Fig. 4.1), but that the lateral connection between the two conductors opens up again at $t = 329$ ns when the gap voltage is zero and the gap current should jump from a negative maximal amplitude to a positive one. The anomalous current waveform occurs only when the amplitude of the flashover voltage is relatively small (less than 10 kV), which may indicate that the background gas between the inner and outer conductor is poorly ionized. When the current is negative ($222 \text{ ns} < t < 329 \text{ ns}$), the vacuum arc develops from the inner to the outer conductor of the transmission line. At $t = 329$ ns, the arc breaks up because the arc current goes to zero and afterward it should develop in the opposite direction. In the poorly ionized background gas, the vacuum arc does not occur and the lateral short changes to an open circuit. This will double the gap voltage causing ionization of a narrow channel in the background gas to the other conductor which again develops a lateral short between the two conductors. Another explanation for the anomalous current waveform could be the chopping phenomena of vacuum arcs.³⁰⁻³² If the arc current approaches zero and the vacuum arc is not stable, the current is chopping which means that the vacuum arc breaks up.

Figure 4.6 shows a typical result for the luminosity measurement. The rising and falling transitions of the current are visible in the output of the PMT. The amplitude of luminosity was decreased by a factor of 10 using a neutral density filter, ND#1.

Dielectric Flashover Without an External Magnetic Field

The results for Pyrex, PMMA, Lexan, alumina, and boron-nitride are presented in the following paragraphs. In all measurements, the pressure was approximately 10^{-6} torr, and the electrode gap width, $d_g = 5$ mm. The sensitivity of the luminosity measurement is $80 \mu\text{W/V}$, the sensitivity of the current measurement is 20 A/V , and the sensitivity of the X-ray measurement is 6.7 mA/V (ratio of X-ray producing electron beam current to PMT output voltage) for $V_b = 15 \text{ kV}$. Note that the sensitivity of the X-ray measurement is inversely proportional to V_b^2 (see equation 3.2). Measurements were taken with a resolution of 10 mV/div , 50 mV/div , and 200 mV/div (setting of the oscilloscope amplifier in the data acquisition system). For each test material, two typical results are shown for each resolution, one for current and luminosity, and one for current and X-ray emission. A more complete selection of the measurement results is shown in Appendix A. Note that the measurements were taken with a virgin sample which was tested for a maximum number of 10 shots. For each of the three resolution settings (i.e., 10 mV/div , 50 mV/div , and 200 mV/div) a new sample was used, as well as for luminosity and X-ray emission measurements, i.e., each of results shown in the following paragraphs are obtained using new samples.

In general, the results have shown a linearly increasing current which is specified in the following tables. The data for the tables are taken from measurements with a resolution of 50 mV/div . Figure 4.7 shows a generic curve of the flashover current. The flashover current rises linearly (I_{lmin} to I_{lmax}) and reaches an amplitude of I_{lmax} at which the final discharge, indicated by an exponentially increasing current, is developed. The current rise below I_{lmin} is not specified in this chapter (see Chapter V).

Figure 4.7. Generic curve of the flashover current.

Pyrex

Typical results for Pyrex are shown in Fig. 4.8 (a to f). The average flashover voltage varied from $V_b \approx 6$ kV at the first shot to $V_b \approx 35$ kV at the tenth shot. The current rises linearly and reaches an amplitude of 2 to 6 A, depending on the flashover voltage. An example of the slope change of the linearly rising current as a function of the flashover voltage, V_b , is given in Table 4.1. The final discharge current rises proportional to $\exp(t/\tau)$ with $\tau = 2.2$ ns for $V_b = 4$ kV and $\tau = 1.6$ ns for $V_b = 7$ kV. Note that volume discharges in air at one atmosphere in this experimental setup, using Pyrex as a test sample with an electrode gap width of $d_g = 5$ mm, show a strictly exponentially increasing current proportional to $\exp(t/\tau)$ with $\tau = 1.5$ ns for $V_b = 6$ kV.

A fast linear rise of the luminosity is seen; it rises in about 2 ns from a PMT output voltage of 2 mV to saturation of the PMT. The X-ray emission, depending on the flashover voltage, starts with the current and has its maximum when the current is appropriately I_{lmax} .

Table 4.1. Parameters of the linearly rising current for Pyrex.

n_s	I_{lmax} [A]	ΔI [A]	ΔT [ns]	$\Delta I/\Delta T$ [A/ns]	V_b [kV]
1	1.1	0.8	7	0.11	4
2	1.6	1.15	8.5	0.14	6.5
3	4.0	2.5	6	0.42	11
4	4.5	3.2	6.5	0.49	12.5
5	5.0	4.0	7	0.47	15

PMMA

Typical results for PMMA are shown in Fig. 4.9 (a to f). The average flashover voltage varied from $V_b \approx 8$ kV at the first shot to $V_b \approx 30$ kV at the tenth shot. The current rises linearly and reaches an amplitude of 1.5 to 8 A, depending on the flashover voltage. Table 4.2 shows an example of the slope change of the linearly rising current as a function of the flashover voltage V_b . The final discharge current rises proportional to $\exp(t/\tau)$ with $\tau = 0.95$ ns for $V_b = 7$ kV. As for the Pyrex case, a fast linear rise of the luminosity is seen and the X-ray emission has its maximum when the current is appropriately I_{lmax} .

a) $n_s = 2$, $V_b = 7.5$ kV

b) $n_s = 1$, $V_b = 9$ kV

c) $n_s = 2$, $V_b = 6.5$ kV

d) $n_s = 3$, $V_b = 9$ kV

e) $n_s = 1$, $V_b = 7$ kV

f) $n_s = 3$, $V_b = 9$ kV

Figure 4.8. Typical results (a to f) for Pyrex without an external magnetic field.

a) $n_s = 2$, $V_b = 9$ kV

b) $n_s = 1$, $V_b = 7$ kV

c) $n_s = 2$, $V_b = 10$ kV

d) $n_s = 2$, $V_b = 9$ kV

e) $n_s = 1$, $V_b = 9$ kV

f) $n_s = 2$, $V_b = 8.5$ kV

Figure 4.9. Typical results (a to f) for PMMA without an external magnetic field.

Table 4.2. Parameters of the linearly rising current for PMMA.

n_s	I_{Imax} [A]	ΔI [A]	ΔT [ns]	$\Delta I/\Delta T$ [A/ns]	V_b [kV]
1	0.67	0.55	26	0.02	4
2	1.6	1.6	12	0.13	9
3	1.3	0.85	11	0.08	8
4	3.0	1.7	6	0.28	13
5	3.8	2.5	5.5	0.45	15

Lexan

Figure 4.10 (a to f) shows typical results for Lexan. The average flashover voltage varied from $V_b \approx 12$ kV at the first shot to $V_b \approx 45$ kV at the sixth shot. Depending on the flashover voltage, the current rises linearly and reaches an amplitude of 2.5 to 14 A. An example of the slope change of the linearly rising current as a function of the flashover voltage, V_b , is given in Table 4.3. The final discharge current rises proportional to $\exp(t/\tau)$ with $\tau = 1.4$ ns for $V_b = 16$ kV. As for Pyrex and PMMA, a fast linearly rising of the luminosity is seen and the X-ray emission has its maximum when the current is appropriately I_{Imax} .

Table 4.3. Parameters of the linearly rising current for Lexan.

n_s	I_{Imax} [A]	ΔI [A]	ΔT [ns]	$\Delta I/\Delta T$ [A/ns]	V_b [kV]
1	2.9	2.6	8	0.33	13
2	3.0	2.8	7	0.40	14
3	5.0	4.8	6	0.80	18
4	4.4	3.4	7	0.49	17

a) $n_s = 3$, $V_b = 24$ kV

b) $n_s = 1$, $V_b = 7$ kV

c) $n_s = 1$, $V_b = 13$ kV

d) $n_s = 1$, $V_b = 9$ kV

e) $n_s = 1$, $V_b = 16$ kV

f) $n_s = 1$, $V_b = 14$ kV

Figure 4.10. Typical results (a to f) for Lexan without an external magnetic field.

Alumina

The typical results for alumina are shown in Fig. 4.11 (a to f). The average flashover voltage varied from $V_b \approx 4$ kV at the first shot to $V_b \approx 25$ kV at the tenth shot. The current rises linearly and reaches an amplitude of 0.8 to 6 A, depending on the flashover voltage. Table 4.4 shows an example of the slope change of the linearly rising current as a function of the flashover voltage V_b . The final discharge current rises proportional to $\exp(t/\tau)$ with $\tau = 1.2$ ns for $V_b = 7$ kV. As for Pyrex, PMMA, and Lexan, a fast linear rise of the luminosity is seen and the X-ray emission has its maximum appropriately when the final discharge occurs.

Table 4.4. Parameters of the linearly rising current for alumina.

n_s	I_{max} [A]	ΔI [A]	ΔT [ns]	$\Delta I/\Delta T$ [A/ns]	V_b [kV]
1	0.73	0.6	67	0.01	3
2	1.2	0.55	11	0.05	6
3	1.9	1.0	14.5	0.07	8
4	6.0	5.0	9	0.56	18

Boron-nitride

Figure 4.12 (a to f) shows the typical results for boron-nitride. The average flashover voltage with this test sample was $V_b \approx 20$ kV for the first shot. Due to the effect of material destruction which is described at the end of this chapter, not more than three shots were taken with each sample. Therefore, no table showing the slope change of the linearly rising current as a function of the flashover voltage is given. Depending on the flashover voltage, the current rises linearly and reaches an amplitude of 3 to 5 A. The final discharge current rises proportional to $\exp(t/\tau)$ with $\tau = 0.8$ ns for $V_b = 15$ kV.

Like the other materials described above, a fast linear rise of the luminosity is seen. Due to the large amplitude of the flashover voltage, the X-ray emission increases to a maximum value which can not be shown within the resolution used in these experiments.

a) $n_s = 1$, $V_b = 4$ kV

b) $n_s = 5$, $V_b = 7$ kV

c) $n_s = 2$, $V_b = 6$ kV

d) $n_s = 2$, $V_b = 7$ kV

e) $n_s = 3$, $V_b = 6$ kV

f) $n_s = 4$, $V_b = 7$ kV

Figure 4.11. Typical results (a to f) for alumina without an external magnetic field.

a) $n_s = 1$, $V_b = 22$ kV

b) $n_s = 1$, $V_b = 19$ kV

c) $n_s = 2$, $V_b = 20$ kV

d) $n_s = 1$, $V_b = 21$ kV

e) $n_s = 1$, $V_b = 15$ kV

f) $n_s = 1$, $V_b = 25$ kV

Figure 4.12. Typical results (a to f) for boron-nitride without an external magnetic field.

Magnetic Field Effects

The influence of magnetic fields on dielectric surface flashover has been investigated with this experimental setup. By adding permanent magnets outside of the vacuum chamber, a magnetic flux density parallel to the insulator surface and perpendicular to the electric field at the centerline of the interelectrode gap was produced. The following paragraphs describe two cases: (a) magnetic flux density in positive z-direction which produces an $\mathbf{ExB}$ drift away from the insulator surface and (b) magnetic flux density in negative z-direction which leads to an $\mathbf{ExB}$ drift into the insulator surface (see Fig. 2.8. for the coordinate system).

For all measurements, a Pyrex test sample was used with an electrode gap width of $d_g = 5$ mm. A pressure of approximately 10^{-6} torr and a magnetic flux density amplitude of 100 mT was obtained. As for the experiment without an external applied magnetic field, the sensitivities of the diagnostic tools are:

current measurement: 20 A/V

luminosity measurement: 80 $\mu\text{W/V}$

emitted X-ray measurement: 6.7 mA/V for $V_b = 15$ kV.

Measurements were taken with a resolution of 10 mV/div, 50 mV/div, and 200 mV/div (settings of the oscilloscope amplifier in the data acquisition system). Two typical results are shown for each resolution, one for current and luminosity, and one for current and X-ray emission. Each of these results were taken with a new virgin sample of Pyrex. A more complete selection of the measurement results is shown in Appendix B. To compare the magnetic field results with the ones using no external applied magnetic field, measurements with a resolution of 10 mV/div. were taken with and without magnetic field using the same test sample.

ExB Drift Away from the Insulator Surface

With the magnetic field in the positive z-direction, significant changes were observed in the risetime of the current compared to the measurements without a magnetic. Figure 4.13 (a to d) shows the results for $B_z = 0$ and $B_z = +100$ mT. Figures 4.13.a and 4.13.b show the results using the same sample as well as Figures 4.13.c and 4.13.d. In the case of $B_z = +100$ mT, the current shows some plateau formation.

a) $n_s = 2$, $V_b = 8$ kV, $B_z = +100$ mT

b) $n_s = 3$, $V_b = 10$ kV, $B_z = 0$ mT

c) $n_s = 2$, $V_b = 7$ kV, $B_z = +100$ mT

d) $n_s = 4$, $V_b = 7$ kV, $B_z = 0$ mT

Figure 4.13. Typical results (a to d) for Pyrex with $B_z = +100$ mT and $B_z = 0$ mT.

Furthermore, the results show a change of the X-ray emission. For the same flashover voltage of $V_b = 7$ kV, the X-ray emission rises slower and delays approximately 10 ns when $B_z = +100$ mT (compared to $B_z = 0$ mT). The risetime of the luminosity changes from 2 ns to 5 ns when the positive external magnetic field is applied.

An increase of the flashover voltage of roughly 50% is seen for the first shots. Note that Bergeron²³ calculated the critical magnetic flux density, B_c , required to lift off the avalanche from the insulator surface. With $B_c = 100$ mT, a magnetic field effect should be seen up to a maximum flashover voltage of approximately 8 kV. Figure 4.14 (a to f) shows typical results for Pyrex with $B_z = +100$ mT. Note that different samples were used for these measurements.

a) $n_s = 1$, $V_b = 6$ kV

b) $n_s = 2$, $V_b = 8$ kV

c) $n_s = 1$, $V_b = 15$ kV

d) $n_s = 2$, $V_b = 9$ kV

e) $n_s = 1$, $V_b = 10$ kV

f) $n_s = 1$, $V_b = 12$ kV

Figure 4.14. Typical results (a to f) for Pyrex with $B_z = +100$ mT.

ExB Drift Into the Insulator Surface

With the magnetic field in negative z-direction, the flashover voltage decreases about 30% compared to the measurements without a magnetic. Figure 4.15 (a to d) shows the results for $B_z = 0$ and $B_z = -100$ mT. Figures 4.15.a and 4.15.b point out the results using the same sample as well as Figures 4.15.c and 4.15.d. As in the case of $B_z = +100$ mT, the current with a resolution of 10 mV/div shows some plateau formation with the magnetic flux density in negative z-direction. Comparing the X-ray emission for $B_z = -100$ mT and $B_z = 0$ mT at a flashover voltage of $V_b \approx 10$ kV, a considerable decrease of the amplitude is seen. The risetime of the luminosity does not change when the negative external magnetic field is applied.

Figure 4.16 (a to f) shows typical results for Pyrex with $B_z = -100$ mT. Note that different samples were used for these measurements.

a) $n_s = 1$, $V_b = 6$ kV, $B_z = 0$ mT

b) $n_s = 2$, $V_b = 9$ kV, $B_z = -100$ mT

c) $n_s = 1$, $V_b = 5$ kV, $B_z = -100$ mT

d) $n_s = 4$, $V_b = 10$ kV, $B_z = 0$ mT

Figure 4.15. Typical results (a to d) for Pyrex with $B_z = -100$ mT and $B_z = 0$ mT.

a) $n_s = 1$, $V_b = 2.5$ kV

b) $n_s = 1$, $V_b = 5$ kV

c) $n_s = 1$, $V_b = 5$ kV

d) $n_s = 1$, $V_b = 3$ kV

e) $n_s = 1$, $V_b = 5$ kV

f) $n_s = 1$, $V_b = 5$ kV

Figure 4.16. Typical results (a to f) for Pyrex with $B_z = -100$ mT.

The Effect of Material Destruction

Due to the relatively large discharge energy per shot of 0.93 J for $V_b = 30$ kV, material destruction is seen for all five materials at shot numbers higher than 10. Figures 4.17 to 4.21 show anomalous results for the current, luminosity, and X-ray emission measurements. Polarization effects and deposits on the insulator surface cause anomalous behavior of the current, luminosity, and X-ray emission which indicates that the surface of the sample is damaged. A corona discharge is seen for most of the materials with an applied voltage of 35 to 50 kV. Boron-nitride shows surface damage after the first shot with an average breakdown voltage of $V_b = 20$ kV.

a) $n_s = 10$, $V_b = 34$ kV

b) $n_s = 10$, $V_b = 35$ kV

Figure 4.17. Anomalous results (a and b) for Pyrex.

a) $n_s = 5$, $V_b = 33$ kV

b) $n_s = 5$, $V_b = 29$ kV

Figure 4.18. Anomalous results (a and b) for PMMA.

a) $n_s = 5$, $V_b = 34$ kV

b) $n_s = 8$, $V_b = 35$ kV

Figure 4.19. Anomalous results (a and b) for Lexan.

$n_s = 8$, $V_b = 42$ kV

Figure 4.20. Anomalous result for alumina.

a) $n_s = 4$, $V_b = 29$ kV

b) $n_s = 4$, $V_b = 12$ kV

Figure 4.21. Anomalous results (a and b) for boron-nitride.

CHAPTER V DISCUSSION

The results for the early phase, shown in Chapter IV, indicate a linearly rising current with a final amplitude of several amperes for all materials. The X-ray emission shows an electron beam current above the surface on the order of a few to tens of milliamperes. The high sensitivity of the luminosity sensor gives a signal which is used as a timing mark and as an indication factor for material destruction.

To get an idea about the current, a simple phenomenological description of the current is introduced in the following paragraphs. Assume that the time dependence of the current can be described by

$$\frac{dI}{dt} = f(t) + [\alpha I - \beta I^2][1 - u(t - \tau_g)] + \gamma I u(t - \tau_g) \quad (5.1)$$

where $f(t)$ is the source term, e.g., field emission, α is the amplification parameter of the surface avalanche, β is the saturation parameter of the surface avalanche, i.e. $I_{\text{sat av}} = \alpha/\beta$, γ is the amplification parameter of the gas-avalanche, τ_g is the delay time for the build-up of the gas density above the surface, and $u(t)$ is a step function.

With the assumption that there exists a constant emission current, I_e , at $t < 0$,

$$\int_t f(t) = I_e u(-t), \quad (5.2)$$

the current, I , is given by

$$I(t) = I_e u(-t) + \frac{1 - u(t - \tau_g)}{\frac{\beta}{\alpha} [1 - e^{-\alpha t}] + C e^{-\alpha t}} + I(\tau_g) e^{\gamma(t - \tau_g)} u(t - \tau_g), \quad (5.3)$$

where C is an integration constant.

With the boundary conditions $I(0) = I_e$ and $I(\tau_g^-) = I(\tau_g^+)$, the current is found as

$$I(t) = I_e u(-t) + \frac{1 - u(t - \tau_g)}{\frac{\beta}{\alpha} [1 - e^{-\alpha t}] + \frac{1}{I_e} e^{-\alpha t}} + \frac{u(t - \tau_g) e^{\gamma(t - \tau_g)}}{\frac{\beta}{\alpha} [1 - e^{-\alpha \tau_g}] + \frac{1}{I_e} e^{-\alpha \tau_g}}. \quad (5.4)$$

Figure 5.1 show examples of the current which is described by equation (5.4). The current, I , rises exponentially at $t = 0$ when $I(0) = I_e$ and saturates at $I(\tau_{g2}) = I_{sat \text{ av}}$. Note that an approximately linearly rising current is found between I_e and $I_{sat \text{ av}}$. Two cases are shown in Fig. 5.1: (a) the final flashover occurs before the current saturates (I_1) and (b) the current saturates and at $t = \tau_{g2}$ the final discharge is developed.

Figure 5.1. Phenomenological description of the current

The delay time is defined as effective diffusion length divided by the thermal velocity of the desorbed gas and is on the order of tens of nanoseconds. Note that this simple phenomenological description of the current does not describe the measured current in all details. More variables which are still unknown need to be added to the basic equation (5.1).

The electron density in the gas in which the final breakdown develops is given by³³:

$$\frac{dn}{dt} = \frac{n}{\tau} \quad (5.5)$$

and

$$\frac{dn}{dx} = \alpha n \quad (5.6)$$

with

$$\tau = \frac{1}{v_i}, \quad (5.7)$$

where τ is the current risetime constant, v_i is the average ionization frequency, n is the electron density, and α is the first Townsend coefficient. The current risetime constant, τ , can be rewritten as

$$\tau = \frac{1}{v_d \alpha} = \frac{1}{v_d \frac{\alpha}{p} p} \quad (5.8)$$

with

$$x = v_d t, \quad (5.9)$$

where v_d is the electron drift velocity and p is the pressure. Note that the first Townsend coefficient, α , is often given as α/p .

The electron drift velocity is given by

$$v_d = \mu E \quad (5.10)$$

with

$$\mu = \frac{e}{m v_m}. \quad (5.11)$$

It is found³³ that

$$\mu p \sim \sqrt{\frac{p}{E}} \quad (5.12)$$

which leads to

$$v_d \sim \sqrt{\frac{E}{p}}, \quad (5.13)$$

where μ is the mobility constant, E is the electric field, and v_m is the momentum transfer collision frequency.

For CO_2 , a major component of the breakdown gas (see Chapter II), the relationship of current risetime constant, τ , to pressure was found with the parameters v_d and α/p given in reference 33. Note that the electron drift velocity $v_d > 1.5 \times 10^7$ cm/s at $E/p = 20$ V/cm/Torr was calculated using the relation (5.13). Figure 5.2 shows the current risetime constant for CO_2 as a function of the pressure. The measurements shows a current risetime constant of $\tau \approx 1$ ns which indicates a pressure of hundreds of torr.

Figure 5.2. Current risetime constant, τ , for CO_2 as a function of the pressure.

In this thesis, it is assumed that for all given theoretical and experimental results the breakdown voltage is roughly constant until the breakdown is fully developed. To prove this assumption, the test gap resistance will be calculated in the following paragraphs. Figure 5.3 shows the gap model with $R(t)$ as a time dependent gap resistor. The voltage v_1 is the gap voltage at the charging side and v_2 is the gap voltage at the load side. The impedance of the transmission line is Z_0 .

Figure 5.3. Test gap model with $R(t)$ as a time dependent gap resistor.

The voltage, v_1 , is given by

$$v_1 = R(t) i + v_2 \quad (5.14)$$

with

$$v_1 = v_1^{\rightarrow} + v_1^{\leftarrow}, \quad (5.15)$$

$$v_2 = v_1^{\rightarrow} - v_1^{\leftarrow}, \quad (5.16)$$

and

$$i_1 = i_1^{\rightarrow} - i_1^{\leftarrow} = i_2 = i, \quad (5.17)$$

where

$$i_1^{\rightarrow} = \frac{v_1^{\rightarrow}}{Z_0}, \quad (5.18)$$

$$i_1^{\leftarrow} = \frac{v_1^{\leftarrow}}{Z_0}, \quad (5.19)$$

and

$$i_2 = \frac{v_2}{Z_0}. \quad (5.20)$$

Therefore, the voltage, v_1 , can be written as

$$v_1 = \frac{2 \left[1 + \frac{R(t)}{Z_0} \right]}{2 + \frac{R(t)}{Z_0}} v_1^{\rightarrow} \quad (5.21)$$

and the current, i , is given by

$$i = \frac{2}{2 Z_0 + R(t)} v_1^{\rightarrow}. \quad (5.22)$$

Using the equations (5.14) and (5.22), the gap voltage, v_g , is found as

$$v_g = 2 (v_1^{\rightarrow} - Z_0 i), \quad (5.23)$$

where

$$v_g = R (t) i . \quad (5.24)$$

In the early phase of the surface flashover, the gap resistance is on the order of several hundreds of ohms to kilohms when the current, i , has an amplitude smaller than 10 A. With a transmission impedance of $Z_0 = 50 \Omega$, the amplitude of the gap voltage v_g is on the order of a few percent (compared to the breakdown voltage).

Correlation Between Flashover Models and Results

In the following paragraphs, the flashover models described in Chapter II are compared to the results given in Chapter IV in order to limit the number of models which may explain the measured results.

Below surface models

A model which is based on collisional ionization was introduced by Vigouroux et al.¹⁵ and Jaitly and Sudarshan¹⁶. In both cases, the model was explained using a semiconductor as a test material. A tunnel injection from the triple point into the insulator initiates collisional ionization. The collision frequency, ν_m , can be calculated using equation (5.11). With a mobility constant³⁴ of $\mu = 1350 \text{ cm}^2/\text{V-sec}$, $\nu_m = 1.3 \times 10^{12} \text{ s}^{-1}$ for electrons. The results (see Chapter IV) show a significant change of the current rise time using an externally applied magnetic field with a magnetic flux density amplitude of $B = 100 \text{ mT}$. This field produces an electron cyclotron frequency of $\omega_c = 1.8 \times 10^{10} \text{ s}^{-1}$. Magnetic field effects³⁵ are seen, if $(\omega_c/\nu_m)^2 > 10^{-1}$. For the collision frequency and the electron cyclotron frequency which are shown above, $(\omega_c/\nu_m)^2 = 2 \times 10^{-4}$ which means that no magnetic field effects should be seen. In addition, the measured X-ray producing electron beam current indicates that a current on the order of hundreds of milliamperes to a few amperes flows above the surface of the insulator. The collisional ionization model does not explain the magnetic field effects and the large current amplitude above the insulator surface. Therefore, the model will not be considered as an explanation for the surface flashover in vacuum.

The model based on thermal runaway³⁶ is not described in this thesis. The thermal runaway effect, seen in semiconductors, can probably not be applied to insulator materials like Pyrex, Lexan, etc., because these materials have only a vanishing number of free electrons in the

conduction band at room temperature. Due to the higher bandgap energy of polymers, a much larger energy is required for materials like Lexan (see Fermi distribution function) to see a thermal runaway (compared to semiconductors).

Transitions of below and above surface models

Watson⁶ proposed a model which includes thermionic emission of hot electrons from the dielectric and secondary electron emission avalanche above the surface. To emit hot electrons from a insulator like Pyrex and Lexan, an energy of approximately 5 eV is required. It is not known whether the applied electric field causes an increase of temperature of the dielectric to provide this energy.

Above surface models

A surface discharge due to ionization of gas, which is adsorbed on the insulator surface was predict by Bugaev et al.⁷ They assumed that a monomolecular layer of adsorbed gas is ionized by electrons which are field emitted from the cathode. High electron diffusion losses are expected due to the thin layer of surface gas; the delay time, τ_g , will be in the order of microseconds. Furthermore, the discharge of this model would show a strictly exponentially increasing current which is not found in the results shown in Chapter IV.

A model based on secondary electron emission avalanche leading directly to flashover was included in Watson's final flashover assumption. Boersch⁵, who proposed the SEEA model first, predicted a saturation of the current due to the positive surface charge. The theoretical current rise is not known and, therefore, it can not be compared to the measured results but it should be noted that it is generally accepted that for above surface models the final discharge is developed in gas which is adsorbed on the surface of the dielectric. The SEEA model does not include any desorption of surface gas.

The SSEEA model is divided into two parts: (a) thermal desorption of surface gas suggested by Anderson (1974) and (b) electron induced desorption of gas molecules proposed by Avdienko and Malev, Cross, Anderson and Brainard, Pillai and Hackam, and Enloe. In the thermal desorption of surface gas model, the SSEEA causes the insulator surface temperature to increase hundreds of kelvin which leads to a desorption of the surface gas. Due to difficulties in explaining experimental flashover results measured with alumina, where the thermal conductivity is much greater than in plastics, Anderson expanded his model in order to invoke electron stimulated gas desorption. The model, based on electron induced desorption of gas molecules, includes a possible X-ray producing electron beam current above the surface, a desorbed gas pressure of 100 to 200 torr, and a linearly increasing current in the early phase of the dielectric

surface flashover where the early phase current starts off with an exponential rise and then saturates (see Fig. 5.1). A fact which speaks against this model is that no saturated surface current on the order of tens to hundreds of milliamperes was found in the experimental results but a linearly rising current with an amplitude up to several amperes was found.

Suggested Modifications Concerning the SSEEA Model

According to the results described in this thesis, the SSEEA model can be used to explain the results qualitatively. There are, however, some quantitative discrepancies between the predictions of the simple zero-dimensional model (e.g., in the formulation of Pillai and Hackam,¹³ without a dependence on the coordinate between anode and cathode) and the observations. The following points should be considered to improve the SSEEA model:

1. Nonuniform surface charge density. The proposed starting mechanism of electron field emission at the cathode, as well as the processes in the developing avalanche head⁸ are expected to lead to a nonuniform surface charge density. On the time scale of several tens nanoseconds, during which the discharge develops, the positive surface charge consists mainly of immobile ions. For the saturated avalanche, a surface charge density fixed in time, but dependent on the coordinate between cathode and anode, should be considered. Furthermore, the influence of the electron volume charge density above the surface is expected to produce modifications of the saturated avalanche parameters, as discussed by Bergeron²³ in relation to magnetic field effects. Comparing his computer simulations with a self-consistent electron density above the surface with Pillai-Hackam's approximation of a localized electron density above the surface, he found differences in the critical magnetic field amplitude of a factor of two. Since the emerging two-dimensional model cannot be treated analytically, a two-dimensional computer simulation is suggested.
2. Unknown secondary emission parameters. The parameters A_0 and A_1 , as well as the energy and angular distribution of emitted secondary electrons, are virtually unknown, especially their variation as a function of material. More detailed measurements of these parameters would help to understand the build-up of the saturated avalanche more quantitatively.
3. Gas desorption. It is generally accepted that the final discharge develops in the gas desorbed from the insulator surface. Discrepancies in the electron induced desorption rate cover two orders of magnitude. Some detailed measurements of the desorption process, such as high resolution momentum measurements or a direct time resolved measurement

of the gas density above the surface, would be essential to further understanding of this process.

CHAPTER VI

CONCLUSIONS

Fast current, luminosity, and X-ray diagnostic methods have been developed for the investigation of the early phase of surface flashover in vacuum. All methods have a very high dynamic range to cover: the low amplitude phenomena in the early phase as well as the phenomena in the fully developed discharge. Detection threshold for the current, for instance, is on the order of 10 mA, whereas the full discharge current is several 100 amperes.

The results of the current measurements show two distinct phases for the early stage of surface flashover. In a first phase, with a duration of 3 to 60 ns, the current rises linearly from the observable threshold value to several amperes. In a second phase, it rises exponentially, with an e-folding time constant of the order of one nanosecond, to its full impedance limited amplitude. The X-ray emission starts simultaneously with the current, has its maximum at the instant of time when the transition of phase one to phase two occurs, and ceases afterward. The luminosity starts with the onset of the current as well. Using high sensitivity measurements for the luminosity, a fast rise of the light output is seen. The transition from the detectable threshold value of several microwatts to the saturation of the photomultiplier used (several milliwatts total emitted power) occurs typically during a two nanosecond period. Low sensitivity measurements show a luminosity which is roughly proportional to the current (see Appendix C).

Significant changes in the early phase current, luminosity, and X-ray emission are observed with an external magnetic field applied. The current amplitude at the transition from phase one to phase two, with magnetic field, reaches 50% of the value without magnetic field. The X-ray emission decreases as well. The slope of the luminosity decreases if the $\mathbf{ExB}$ drift points away from the insulator surface, but retains its value for the case without magnetic field, if the $\mathbf{ExB}$ drift points into the surface.

The most likely interpretation of these results lies within the framework of the saturated surface avalanche model with electron induced gas desorption. The linear current rise can be associated with avalanche saturation, and the delay from phase one to phase two with the build-up of a sufficient gas density above the surface. The short time constant of the current rise in phase two can be associated with gaseous ionization. The influence of external magnetic fields as well the X-ray emission in the early phase of flashover points to the essential role of free electrons above the surface, i.e., excludes sub-surface models for dielectric surface flashover in vacuum.

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APPENDIX A
SELECTED RESULTS FOR DIELECTRIC FLASHOVER
WITHOUT AN EXTERNAL MAGNETIC FIELD

The purpose of this appendix is to outline the variations of the measurements for each test sample. The results are arranged using following hierarchical structure:

1. by test sample material:

Pyrex

PMMA

Lexan

Alumina

Boron-nitride

2. by diagnostic sensors which were used in the experimental setup:

luminosity with current

X-ray emission with current

3. by the resolution of the measurements (setting of the oscilloscope amplifier in the data acquisition system):

10 mV/div

50 mV/div

200 mV/div.

In all measurements, the pressure was approximately 10^{-6} Torr, and the electrode gap width $d_g = 5$ mm. Note that n_s is the shot number and V_b is the breakdown voltage.

Pyrex

$$n_s = 2, V_b = 7.5 \text{ kV}$$

$$n_s = 3, V_b = 15 \text{ kV}$$

$$n_s = 1, V_b = 4 \text{ kV}$$

$$n_s = 2, V_b = 6.5 \text{ kV}$$

$$n_s = 3, V_b = 11 \text{ kV}$$

$$n_s = 6, V_b = 18 \text{ kV}$$

Pyrex (cont.)

$$n_s = 7, V_b = 19 \text{ kV}$$

$$n_s = 1, V_b = 7 \text{ kV}$$

$$n_s = 2, V_b = 9 \text{ kV}$$

$$n_s = 3, V_b = 9 \text{ kV}$$

$$n_s = 5, V_b = 11 \text{ kV}$$

Pyrex (cont.)

$$n_s = 6, V_b = 20 \text{ kV}$$

$$n_s = 8, V_b = 30 \text{ kV}$$

$$n_s = 9, V_b = 20 \text{ kV}$$

$$n_s = 10, V_b = 34 \text{ kV}$$

$$n_s = 1, V_b = 9 \text{ kV}$$

$$n_s = 4, V_b = 18 \text{ kV}$$

Pyrex (cont.)

$$n_s = 5, V_b = 28 \text{ kV}$$

$$n_s = 1, V_b = 7 \text{ kV}$$

$$n_s = 2, V_b = 10 \text{ kV}$$

$$n_s = 3, V_b = 12 \text{ kV}$$

Pyrex (cont.)

$$n_s = 2, V_b = 7 \text{ kV}$$

$$n_s = 3, V_b = 9 \text{ kV}$$

$$n_s = 4, V_b = 4 \text{ kV}$$

$$n_s = 5, V_b = 11 \text{ kV}$$

$$n_s = 1, V_b = 6 \text{ kV}$$

$$n_s = 2, V_b = 8 \text{ kV}$$

Pyrex (cont.)

$$n_s = 3, V_b = 9 \text{ kV}$$

$$n_s = 1, V_b = 4 \text{ kV}$$

$$n_s = 2, V_b = 7 \text{ kV}$$

$$n_s = 3, V_b = 9 \text{ kV}$$

$$n_s = 4, V_b = 14 \text{ kV}$$

Pyrex (cont.)

$$n_s = 10, V_b = 35 \text{ kV}$$

PMMA

$$n_s = 2, V_b = 9 \text{ kV}$$

$$n_s = 5, V_b = 19 \text{ kV}$$

$$n_s = 1, V_b = 11 \text{ kV}$$

$$n_s = 2, V_b = 10 \text{ kV}$$

$$n_s = 3, V_b = 10 \text{ kV}$$

$$n_s = 4, V_b = 9 \text{ kV}$$

PMMA (cont.)

$$n_s = 5, V_b = 13 \text{ kV}$$

$$n_s = 1, V_b = 9 \text{ kV}$$

$$n_s = 2, V_b = 11 \text{ kV}$$

$$n_s = 3, V_b = 14 \text{ kV}$$

$$n_s = 5, V_b = 33 \text{ kV}$$

PMMA (cont.)

$$n_s = 6, V_b = 34 \text{ kV}$$

$$n_s = 1, V_b = 7 \text{ kV}$$

$$n_s = 3, V_b = 7 \text{ kV}$$

$$n_s = 4, V_b = 15 \text{ kV}$$

$$n_s = 5, V_b = 18 \text{ kV}$$

PMMA (cont.)

$$n_s = 6, V_b = 24 \text{ kV}$$

$$n_s = 1, V_b = 4 \text{ kV}$$

$$n_s = 2, V_b = 9 \text{ kV}$$

$$n_s = 4, V_b = 13 \text{ kV}$$

$$n_s = 5, V_b = 15 \text{ kV}$$

PMMA (cont.)

$$n_s = 8, V_b = 23 \text{ kV}$$

$$n_s = 1, V_b = 7 \text{ kV}$$

$$n_s = 2, V_b = 8.5 \text{ kV}$$

$$n_s = 3, V_b = 12 \text{ kV}$$

$$n_s = 5, V_b = 29 \text{ kV}$$

PMMA (cont.)

$n_s = 6, V_b = 19$ kV

$n_s = 10, V_b = 29$ kV

Lexan

$$n_s = 1, V_b = 13 \text{ kV}$$

$$n_s = 2, V_b = 18 \text{ kV}$$

$$n_s = 3, V_b = 24 \text{ kV}$$

$$n_s = 4, V_b = 33 \text{ kV}$$

$$n_s = 5, V_b = 40 \text{ kV}$$

$$n_s = 6, V_b = 43 \text{ kV}$$

Lexan (cont.)

$$n_s = 1, V_b = 13 \text{ kV}$$

$$n_s = 2, V_b = 14 \text{ kV}$$

$$n_s = 3, V_b = 18 \text{ kV}$$

$$n_s = 6, V_b = 33 \text{ kV}$$

$$n_s = 1, V_b = 16 \text{ kV}$$

$$n_s = 3, V_b = 30 \text{ kV}$$

Lexan (cont.)

$$n_s = 5, V_b = 34\text{kV}$$

$$n_s = 1, V_b = 7\text{ kV}$$

$$n_s = 2, V_b = 11\text{ kV}$$

$$n_s = 8, V_b = 27\text{ kV}$$

Lexan (cont.)

$$n_s = 1, V_b = 9 \text{ kV}$$

$$n_s = 2, V_b = 12 \text{ kV}$$

$$n_s = 3, V_b = 18 \text{ kV}$$

$$n_s = 6, V_b = 32 \text{ kV}$$

$$n_s = 1, V_b = 14 \text{ kV}$$

$$n_s = 2, V_b = 22 \text{ kV}$$

Lexan (cont.)

$n_s = 7, V_b = 33 \text{ kV}$

$n_s = 8, V_b = 35 \text{ kV}$

Alumina

$$n_s = 1, V_b = 4 \text{ kV}$$

$$n_s = 2, V_b = 4.5 \text{ kV}$$

$$n_s = 6, V_b = 8 \text{ kV}$$

$$n_s = 8, V_b = 11 \text{ kV}$$

$$n_s = 1, V_b = 3 \text{ kV}$$

$$n_s = 2, V_b = 6 \text{ kV}$$

Alumina (cont.)

$$n_s = 3, V_b = 8 \text{ kV}$$

$$n_s = 4, V_b = 18 \text{ kV}$$

$$n_s = 8, V_b = 42 \text{ kV}$$

$$n_s = 1, V_b = 3 \text{ kV}$$

$$n_s = 2, V_b = 5 \text{ kV}$$

Alumina (cont.)

$$n_s = 3, V_b = 6 \text{ kV}$$

$$n_s = 4, V_b = 7.5 \text{ kV}$$

$$n_s = 5, V_b = 17 \text{ kV}$$

$$n_s = 1, V_b = 4 \text{ kV}$$

$$n_s = 2, V_b = 5 \text{ kV}$$

Alumina (cont.)

$$n_s = 5, V_b = 7 \text{ kV}$$

$$n_s = 8, V_b = 10 \text{ kV}$$

$$n_s = 1, V_b = 4.5 \text{ kV}$$

$$n_s = 2, V_b = 7 \text{ kV}$$

$$n_s = 4, V_b = 9.5 \text{ kV}$$

$$n_s = 5, V_b = 11 \text{ kV}$$

Alumina (cont.)

$$n_s = 1, V_b = 4 \text{ kV}$$

$$n_s = 4, V_b = 7 \text{ kV}$$

$$n_s = 5, V_b = 9 \text{ kV}$$

$$n_s = 6, V_b = 10 \text{ kV}$$

$$n_s = 9, V_b = 12 \text{ kV}$$

Boron-nitride

$$n_s = 1, V_b = 22 \text{ kV}$$

$$n_s = 4, V_b = 29 \text{ kV}$$

$$n_s = 2, V_b = 20 \text{ kV}$$

$$n_s = 1, V_b = 15 \text{ kV}$$

$$n_s = 2, V_b = 8 \text{ kV}$$

Boron-nitride (cont.)

$n_s = 4, V_b = 12 \text{ kV}$

$n_s = 1, V_b = 19 \text{ kV}$

$n_s = 1, V_b = 21 \text{ kV}$

Boron-nitride (cont.)

$$n_s = 1, V_b = 25 \text{ kV}$$

APPENDIX B
SELECTED RESULTS FOR DIELECTRIC FLASHOVER
WITH AN EXTERNAL MAGNETIC FIELD

A selection of results with applied magnetic field is shown to outline the variations of the measurements. The results are arranged using following hierarchical structure:

1. by the direction of the applied magnetic field:
 - magnetic flux density in positive z-direction
 - magnetic flux density in negative z-direction
2. by diagnostic sensors which were used in this experiment:
 - luminosity with current
 - X-ray emission with current
3. by the resolution of the measurements (setting of the oscilloscope amplifier in the data acquisition system):
 - 10 mV/div
 - 50 mV/div
 - 200 mV/div.

In addition, the measurements are shown, which compare the magnetic field results with the ones using no external applied magnetic field. These results were taken with the same test sample.

In all measurements, Pyrex was used as a test sample. In the test chamber, the pressure was approximately 10^{-6} Torr, and the electrode gap width $d_g = 5$ mm. Note that n_s is the shot number and V_b is the breakdown voltage.

Pyrex with and without external magnetic field

$$n_s = 1, V_b = 5 \text{ kV}, B_z = +100 \text{ mT}$$

$$n_s = 2, V_b = 8 \text{ kV}, B_z = +100 \text{ mT}$$

$$n_s = 3, V_b = 10 \text{ kV}, B_z = 0 \text{ mT}$$

$$n_s = 4, V_b = 12 \text{ kV}, B_z = 0 \text{ mT}$$

Pyrex with and without external magnetic field (cont.)

$$n_s = 1, V_b = 6 \text{ kV}, B_z = +100 \text{ mT}$$

$$n_s = 2, V_b = 7 \text{ kV}, B_z = +100 \text{ mT}$$

$$n_s = 3, V_b = 5 \text{ kV}, B_z = 0 \text{ mT}$$

$$n_s = 4, V_b = 7 \text{ kV}, B_z = 0 \text{ mT}$$

Pyrex with $B_z = +100$ mT

$n_s = 1, V_b = 6$ kV

$n_s = 2, V_b = 13$ kV

$n_s = 3, V_b = 18$ kV

$n_s = 1, V_b = 15$ kV

$n_s = 2, V_b = 21$ kV

Pyrex with $B_z = +100$ mT (cont.)

$$n_s = 6, V_b = 26 \text{ kV}$$

$$n_s = 1, V_b = 10 \text{ kV}$$

$$n_s = 2, V_b = 15 \text{ kV}$$

$$n_s = 3, V_b = 19 \text{ kV}$$

Pyrex with $B_z = +100$ mT (cont.)

$$n_s = 2, V_b = 8 \text{ kV}$$

$$n_s = 3, V_b = 15 \text{ kV}$$

$$n_s = 4, V_b = 13 \text{ kV}$$

$$n_s = 9, V_b = 20 \text{ kV}$$

$$n_s = 1, V_b = 4 \text{ kV}$$

$$n_s = 2, V_b = 9 \text{ kV}$$

Pyrex with $B_z = +100$ mT (cont.)

$$n_s = 4, V_b = 15 \text{ kV}$$

$$n_s = 6, V_b = 23 \text{ kV}$$

$$n_s = 9, V_b = 25 \text{ kV}$$

$$n_s = 1, V_b = 12 \text{ kV}$$

$$n_s = 2, V_b = 21.5 \text{ kV}$$

Pyrex with and without external magnetic field

$$n_s = 1, V_b = 6 \text{ kV}, B_z = 0 \text{ mT}$$

$$n_s = 2, V_b = 9 \text{ kV}, B_z = -100 \text{ mT}$$

$$n_s = 3, V_b = 11 \text{ kV}, B_z = -100 \text{ mT}$$

Pyrex with and without external magnetic field (cont.)

$$n_s = 1, V_b = 5 \text{ kV}, B_z = -100 \text{ mT}$$

$$n_s = 2, V_b = 7 \text{ kV}, B_z = -100 \text{ mT}$$

$$n_s = 3, V_b = 9.5 \text{ kV}, B_z = -100 \text{ mT}$$

$$n_s = 4, V_b = 10 \text{ kV}, B_z = 0 \text{ mT}$$

$$n_s = 5, V_b = 16 \text{ kV}, B_z = 0 \text{ mT}$$

$$n_s = 6, V_b = 24 \text{ kV}, B_z = 0 \text{ mT}$$

Pyrex with $B_z = -100$ mT

$$n_s = 1, V_b = 2.5 \text{ kV}$$

$$n_s = 2, V_b = 6 \text{ kV}$$

$$n_s = 3, V_b = 8 \text{ kV}$$

$$n_s = 4, V_b = 10 \text{ kV}$$

$$n_s = 5, V_b = 14 \text{ kV}$$

Pyrex with $B_z = -100$ mT (cont.)

$$n_s = 1, V_b = 5 \text{ kV}$$

$$n_s = 2, V_b = 6.5 \text{ kV}$$

$$n_s = 3, V_b = 9 \text{ kV}$$

$$n_s = 5, V_b = 12 \text{ kV}$$

$$n_s = 1, V_b = 5 \text{ kV}$$

$$n_s = 2, V_b = 10 \text{ kV}$$

Pyrex with $B_z = -100$ mT (cont.)

$n_s = 3, V_b = 13$ kV

$n_s = 8, V_b = 23$ kV

$n_s = 1, V_b = 5$ kV

$n_s = 2, V_b = 7$ kV

$n_s = 3, V_b = 8.5$ kV

$n_s = 4, V_b = 13$ kV

Pyrex with $B_z = -100$ mT (cont.)

$n_s = 1, V_b = 3$ kV

$n_s = 2, V_b = 8$ kV

$n_s = 3, V_b = 12$ kV

$n_s = 4, V_b = 12$ kV

$n_s = 8, V_b = 24$ kV

Pyrex with $B_z = -100$ mT (cont.)

$$n_s = 1, V_b = 5 \text{ kV}$$

$$n_s = 2, V_b = 7 \text{ kV}$$

$$n_s = 3, V_b = 9.5 \text{ kV}$$

$$n_s = 4, V_b = 10 \text{ kV}$$

$$n_s = 5, V_b = 16 \text{ kV}$$

$$n_s = 6, V_b = 24 \text{ kV}$$

APPENDIX C
SELECTED PRELIMINARY RESULTS
FOR DIELECTRIC FLASHOVER

A selection of preliminary results is shown to outline the luminosity measurements with low sensitivity. The sensitivities of the diagnostic tools are:

current measurement: 30 A/V for Pyrex and PMMA (smooth surface)

current measurement: 20 A/V for all other materials

luminosity measurement: 2 mW/V.

The materials shown in this appendix are:

Pyrex

PMMA (smooth surface)

PMMA (rough surface)

Lexan (rough surface)

Celcon (rough surface)

G-10 (rough surface)

Boron-nitride (rough surface).

The samples labeled "rough surface" have been treated with 600 grit alumina sandpaper. The same test sample was used for measurements on one material. The pressure was approximately 10^{-6} Torr and no external magnetic field was applied. Note that n_s is the shot number, d_g is the electrode gap width, and V_b is the breakdown voltage. Clipping diodes were used in the current measurements (see Chapter III).

Pyrex

$$n_s = 1, V_b = 16 \text{ kV}, d_g = 4.5 \text{ mm}$$

$$n_s = 2, V_b = 17 \text{ kV}, d_g = 4.5 \text{ mm}$$

$$n_s = 3, V_b = 20.5 \text{ kV}, d_g = 4.5 \text{ mm}$$

PMMA (smooth surface)

$$n_s = 1, V_b = 8 \text{ kV}, d_g = 5 \text{ mm}$$

$$n_s = 1, V_b = 11 \text{ kV}, d_g = 5 \text{ mm}$$

$$n_s = 1, V_b = 12.5 \text{ kV}, d_g = 5 \text{ mm}$$

PMMA (rough surface)

$$n_s = 2, V_b = 20.5 \text{ kV}, d_g = 3 \text{ mm}$$

$$n_s = 3, V_b = 18 \text{ kV}, d_g = 3 \text{ mm}$$

Lexan

$$n_s = 6, V_b = 16 \text{ kV}, d_g = 3.5 \text{ mm}$$

Celcon

$$n_s = 1, V_b = 11 \text{ kV}, d_g = 3.5 \text{ mm}$$

$$n_s = 2, V_b = 18 \text{ kV}, d_g = 3.5 \text{ mm}$$

$$n_s = 3, V_b = 19 \text{ kV}, d_g = 3.5 \text{ mm}$$

G-10

$$n_s = 1, V_b = 11 \text{ kV}, d_g = 4 \text{ mm}$$

$$n_s = 2, V_b = 19 \text{ kV}, d_g = 4 \text{ mm}$$

$$n_s = 3, V_b = 14 \text{ kV}, d_g = 4 \text{ mm}$$

Boron-nitride

$$n_s = 1, V_b = 18.5 \text{ kV}, d_g = 4.5 \text{ mm}$$

$$n_s = 2, V_b = 28 \text{ kV}, d_g = 4.5 \text{ mm}$$

$$n_s = 3, V_b = 30 \text{ kV}, d_g = 4.5 \text{ mm}$$