Force and current in a contact gap between single highly resistive particles: experimental observations

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Abstract

In case of electrical conduction through highly resistive dust layers, the generation of electrostatic adhesion force is strongly coupled to the mechanism of electrical (current) transport in the solid. High field strengths lead to a significant increase of the adhesive force. Here, more insight into the underlying mechanisms is given by experiments on the microscopic scale. An experimental arrangement is described which allows to study a particle pair subject to a strong electric field. Both the current and the force between the particles (150 μm) can be measured as a function of voltage and gap distance. The results show an extremely complex behaviour of the contact for the case of highly resistive particles. For current transport, both gas discharges and thermionic field emission are observed, depending on the width of the contact gap and the field strength. For both the force and the current across the gap, a strongly non-linear behaviour with pronounced time effects is observed.

1. Introduction/Motivation

In dry particulate systems with highly resistive particles, electrostatic charges on the particles are of great importance for a number of technically interesting effects:

- Electrostatic charging of particles may be used to increase the adhesive forces between particles and surfaces. Intentional applications of this effect include, among others, the electrostatic sorting of minerals, the xerography process and modern laser printers.

- Unintentionally, tribocharged particles may form strongly adhesive layers on metal surfaces inside pneumatic conveying systems, mills, filters and the like.

- Unintentional charging of dust layers leads to disturbances in scanning electron microscopy.

- In the electrostatic bulk flow valve [1], strong electrostatic fields lead to a polarization and probably to an electrostatic charging of the particles. Through the resulting enhancement of adhesive forces, powder flow may be regulated in a wide range.

- In electrostatic precipitators, a certain minimum resistivity of the dust is essential so that the dust layer adheres sufficiently to the precipitation electrodes. But the resistivity must not be too high, so that the adhesion decays sufficiently fast when the precipitation electrode is to be cleaned by rapping.

But additional problems are found with highly resistive dusts in electrostatic precipitators (ESPs). With dust resistivities beyond \(10^{11} \, \Omega \cdot \text{cm}\), the precipitation process itself is disturbed by so called back corona (Masuda in [2, 3–5]). The current interpretation is that the current has to pass through the dust layer on the precipitation electrode. With high dust resistivity, a given current density will cause a strong voltage-drop across the dust layer and hence a strong electric field inside the dust layer. When a critical field strength is surpassed, an electric breakthrough occurs.
This leads to corona discharges of opposite polarity, in most cases from craters which are formed in the dust layer (Masuda in [2, 6]). The formation of corona or craters in the dust layer on the collecting electrodes of ESPs deteriorates the collection efficiency of ESP.

Following the state of knowledge, the occurrence of the back corona in the dust layers should depend on the ohmic resistivity of the dust particles, the porosity of the dust layer and current density only. However, numerous experimental studies show that the back corona in dust layers occurs at a lower current density when the dust layer is thicker [7–11]. In other words, the resistivity of the dust layer depends on the thickness of the dust layer and the current density [6, 10, 11].

Altogether, the current transport through highly resistive dust layers occurs by charge carriers (free electrons or holes) which are injected into the dust layer [10, 11]. This also induces a strong charging of the dust layer, which has been found experimentally.

The aim of this work is to develop a better understanding of the charge transport through layers of highly resistive particles interaction by studying the current transport and the electrostatically induced forces between two single highly resistive particles separated by a contact gap $d_g$ and subject to a strong voltage drop (figure 1).

**2. Mechanisms of charge transport**

Generally, the transport of current through layers of dust particles may occur by volume conduction or by surface conduction. According to experience with gas cleaning by electrostatic precipitators, surface conduction and volume conduction may be distinguished by their different dependence on temperature and relative humidity [3, 4, 6, 9]. In conditions of low relative humidity, the current transport through particulate layers of oxidic materials like fly ashes or glass is dominated by volume conductivity, even though a thin layer of strongly absorbed water molecules may still be present on the surface. Here, we describe experiments which were conducted at a very low value of relative humidity in order to exclude surface conduction. The absence of surface conductivity simplifies the physics and provides a model situation which is relevant for situations of high dust resistivity.

Previous investigations of the authors [10, 11] have shown that the mechanisms of charge transport in highly resistive particle layers correspond to those in electret materials [2, 12]. During current transport, positive and negative charge carriers are injected into the material by various effects (by corona discharges or by contact with metallic electrodes at high field strengths), and significant electrostatic space charges are formed. Strong time effects may occur, as the process of charge injection may be limited by thermionic field emission or Schottky emission, and the mobility of the charge carriers may be low. In addition, charge carriers may lose their mobility due to deep trapping in deep traps. Deep traps are sites (typically structure defects on a molecular scale) where electrons or holes can reside at a lower level of energy. Deeply trapped charges are immobile, but still contribute to the local space charge and play a role by recombination with opposite polarity mobile charge carriers in the electret or dielectric. De-trapping of immobile charge carriers may occur by thermal energy $kT$. The Poole-Frenkel-effect [13, 14] states that the effective depth of traps is reduced by strong electrostatic fields. Hence, the thermal activation energy needed for the re-mobilization of trapped charge carriers is lowered in the presence of strong electrostatic fields. As a consequence, the immobilization of charge carriers is more prominent in case of rather weak fields, and the effective mobility of charge carriers increases with increasing field strength [15]. The authors have observed the analogous effects in case of current transport through macroscopic dust layers as well [10, 11].

In addition to the kinetic effects resulting from charge carrier trapping, detrapping and recombination, current transport through dielectrics is controlled by the space charge effect [10–15]. Each charge carrier, mobile or trapped, contributes to the space charge according to its polarity. As described by the Gauss law or the 1st Maxwell equation, respectively, the space charge produces an electric field and hence a potential difference.
When a dielectric structure is inserted between two electrodes, the amount of space charge which can be injected into the material, and hence the concentration of charge carriers, is limited by the potential drop between the electrodes. A detailed discussion for dust layers is given in [11].

While the charge transport through the volume of highly resistive particles corresponds to the charge transport in electret materials, charge transport across the contact gaps between surfaces or particles might occur by the mechanisms of tunnelling, thermionic emission, thermionic field emission (TFE), field emission and gas discharge [16, 17].

Tunnelling (from surface to surface) occurs with extremely short distances between the surfaces, that is with gap distances in the range of the wavelength of the electron. This is not relevant with the gap distances used in our experiments. With our experiment, extremely short gap distances below about 100 nm could not be evaluated, since some kind of instability (comparable to the snap-on-effect [18]) occurred.

TFE occurs as charge carriers, typically electrons, overcome the work function of the material and leave the surface. The energy necessary to overcome the work function is provided in part by the thermal energy $kT$, while simultaneously strong fields at the surface counteract the attraction by image force and thus lower the energy barrier. Theoretically the range of field strength for TFE is given as $100–1000 \text{ V } \mu\text{m}^{-1}$, but field distortions by nanoscale surface roughness or by gas ions are seen as important mechanisms enhancing TFE. Hence in practice, TFE is found to occur already with $50–100 \text{ V } \mu\text{m}^{-1}$ [16].

Thermionic emission can be seen as a simplified case of TFE, whereby the electric field is negligible and the thermal energy alone is sufficient to overcome the work function of the material. With typical values of the work function in the range of $4–5 \text{ eV}$, thermionic emission is relevant at elevated temperatures only. When the work function is very low however, thermionic emission is possible at ambient temperature.

Field emission is possible with extremely high fields ($E > 100 \text{ V } \mu\text{m}^{-1}$) at the emitting surface. In this case the energy barrier at the surface becomes very narrow and hence the electrons can cross the barrier by tunnelling.

Gas discharges occur when the field is so strong that ions or free electrons can gain enough energy between two collisions with gas molecules, resulting in a multiplication of charge carriers in a kind of avalanche process (Townsend discharge/avalanche) [19]. In addition, a self-sustaining gas discharge requires that new avalanches are started through electrons emitted by ion impact to a surface (augmented/secondary emission) or by UV ionization. With decreasing gap width, the critical field strength for a self-sustaining gas discharge increases. This is described by the Paschen law [17, 20]. When the gap is too narrow, that is below a few mean free path-lengths of the gas, a self-sustaining gas discharge is not possible any more, and TFE, probably with some charge carrier multiplication by avalanches or with enhancement by positive ions [16], is the only remaining mechanism.

### 3. Experimental set-up

The main motivation for the experiments presented here was to understand the behaviour of highly resistive dust layers in electrostatic precipitators (ESPs). Hence, the experimental conditions were designed to cover a range of field strength and current density comparable to that in the dust layer on the precipitation electrode of an ESP.

In highly resistive dust layers deposited to the precipitation electrode of an ESP, strong fields are produced when the current passes through the layer. Back corona is expected when the field strength surpasses the dielectric strength of the dust layer (Masuda in [2, 3, 6]). Typically, in industrial ESPs, this will be at field strengths above 10 to 20 $\text{kV cm}^{-1}$ [3, 21]. In our own laboratory experiments [11], we found field strengths up to $80 \text{ kV cm}^{-1}$ in homogeneous layers of fine dusts. Probably the high field strengths could be reached, because the dust layers used in the laboratory tests had a much lower porosity compared to the dust layers forming in ESPs.

Taking $30 \text{ kV cm}^{-1}$ as the reference value, this gives a voltage of 900 V for a pair of $150 \mu\text{m}$ particles bridging a length of 0.3 mm. A typical current density for ESPs is 0.5 mA m$^{-2}$ [3, 6]. Applied to a $150 \mu\text{m}$ particle occupying a cross section of $2 \times 10^{-8} \text{ m}^2$ in a dense cubic packing gives a current of $10^{-11} \text{ A}$ or 10 pA for a single particle-particle contact.

#### 3.1. General concept

The general concept of the experiment (figure 2) is first to adjust a defined gap width between the particles. Second, a voltage difference is applied to the particles, and the development of interparticle force and current is recorded with time. Force measurement is based on measuring the deflection of a stiff spring holding the second (right side in figure 2) particle, whereby the particle distance is kept constant by readjusting the position of the first (left side) particle.

Compared to typical measurements of van-der Waals (vdW) interaction forces between particles, this type of measurement is more complex, as a defined electrostatic potential has to be supplied to the particles, and the currents have to be measured with a high resolution down to the fA range. In addition, the electret mechanisms...
of charge transport through the particles and the coupling with the gas discharges across the contact gap lead to time effects covering a very broad range from microseconds to hours. On the other hand, the requirements for resolution of the contact force are less challenging, as the electrostatic forces are quite high compared to vdW forces.

Main considerations in the design of the experiment were that with potential differences of up to 1 kV applied to the particles, corona discharges from the set-up (except from the particles under study) should be avoided, and that parasitic electrostatic forces (especially between the wires leading to the particles and the housing) generally scale with $1/d$, where $d$ stands for the distance. Therefore, a set-up with rather big dimensions was constructed, using various components from different suppliers.

### 3.2. Experimental details

Figure 3 gives a view into the measurement box. All metal parts of the experiment are executed in austenitic (non-magnetic) stainless steel 1.4301 and are mounted in a massive stainless-steel box ($140 \text{ mm} \times 310 \text{ mm} \times 175 \text{ mm}$ [$H \times L \times W$]). This minimizes displacements due to differential thermal expansion. During the measurements, the box is covered with a stainless-steel lid. Further, the box is surrounded by a metal cage bearing an electrical heating by halogen bulbs and a thermal insulation ($20 \text{ mm}$ polyurethane foam). Typically, the box temperature is set to $25 ^\circ C$ and controlled with a precision of $0.1 ^\circ C$. The insulated box is placed on a long ($2.5 \text{ m}$) metal board to shield against environmental vibrations. This box is suspended from metal springs, whereby a critical frequency of about $0.5 \text{ Hz}$ is achieved. Viscous and frictional dampers are applied to reach nearly critical dampening for all possible modes of oscillation. The metal board itself is placed inside a wooden housing in order to shield influences from air motion.

Both particles under study are fixed to support constructions consisting of a central wire surrounded by a conical glass capillary (for details see below, figure 4).

The particle on the left side (particle 1) sits on the end of a linear piezo stepping motor (Physik Instrumente GmbH PI N-310 NEXACT) with a max. force of $10 \text{ N}$ and a travel of $45 \text{ mm}$. The particle or motor position is controlled by a capacitive sensor (Physik Instrumente PISeca D-510.020) with a nominal resolution of $0.01 \text{ nm}$. With the motor sitting on a manually operated x-y stage (LINOS) with a resolution of $1 \mu \text{m}$, both particles can be adjusted along the motor axis. A microscope and a mirror allow to observe both x and y positions of the particle simultaneously.

The particle on the right side (particle 2) sits on a metal bar guided by a pair of leaf springs clamped to the bar. The springs allow a linear displacement along the axis of the bar. The width and length of the springs are $12.5 \text{ mm} \times 50 \text{ mm}$, respectively. The theoretical spring constant of this arrangement is calculated according to clamped guided beam theory and amounts to $40 \text{ N m}^{-1}$ for $0.1 \text{ mm}$ thick springs and to $625 \text{ N m}^{-1}$ for $0.25 \text{ mm}$ thick springs. The high stiffness of the spring is chosen to minimize the force-distance hysteresis loop which is a common problem in adhesion force measurements. Together with a second capacitive sensor with a nominal resolution of $0.01 \text{ nm}$, the spring system with the $0.25 \text{ mm}$ spring provides a theoretical force resolution of $6.25 \text{ nN}$.

Together with a sensor controller (PI E-517), a motor control device (PI E-861) and a computer with LabView® software, a closed loop is formed, allowing to control the distance between both particles.
The current across the particle-particle-contact is measured with a resistivity meter (Keithley 6517B). This device includes a programmable voltage source going up to 1 kV and allows current measurements with a nominal resolution down to 0.3 fA.

3.3. Glass particles and particle holders
In order to investigate the charge transport between two highly resistive particles, spherical glass particles of 150 μm diameter were used for measurement. The spherical glass particles are fused with the gradually...
converging glass capillaries (figure 4(b)), which contains the stainless steel wire of 25 μm in diameter to provide the electric contact to the particles. The diameter of the gradually converging quartz glass capillary at the particle–capillary contact end is less than 45–50 μm. The converging quartz glass capillaries with fused particles are mounted on the particle holders as shown in figure 4(a).

3.4. Measurement procedure and conditions
After mounting the particle holders on the piezo motor and the clamping spring as shown in figure 4, the force and current between two particles were measured for wide range of contact gap (100 nm – 13 μm) and applied potential (250V–750V). All experimental measurements with the glass particles (150 μm diameter) were carried out at atmospheric pressure and 25 °C. The atmosphere was produced by expanding compressed air and had a dew point of –26.9 °C (about 4% rel. humidity).

In each experiment with the glass particles, force and current are recorded during a measurement period of 5400 s. In an initialization period (900 s), the measurement is run without voltage (the electrodes contacting the particles are grounded). This allows to make sure that thermal and electrical equilibrium have been reached. At 900 s, the full voltage is switched ‘on’ and maintained for 3600 s. At 4500 s, the voltage is switched ‘off’ while the recording of data continues during this relaxation period (900 s) until 5400 s.

All measurement series were carried out with the same pair of glass particles at 250 V, 500 V and 750 V consecutively. Within each series of measurements, subsequent experiments were carried out by varying the gap size from wide (13 μm) to narrow (100 nm). Zero gap distance (contact point) is found experimentally by approaching the left-side particle towards the right-side particle until the latter is displaced towards the right side.

The durations of the initialization and relaxation period resp., were checked experimentally, and were found to be sufficient for discharging the particles to a negligible level of residual charge. This can be explained based on the force transients shown, for example, in figure 5 or figure 14(a). We see that the force decays very fast by about 90% to 95% when the voltage is switched off. Of course, the remaining force is an indicator of residual charges residing either in the particle volume or on the particle surface. It may take several hundred seconds until the residual forces and charges have disappeared. The residual charges indicate trapped charge carriers as explained above. De-trapping by thermal energy needs sufficient time and is material and temperature dependent. Empirically the duration of the relaxation and initialization periods (in total at least 1800 s with grounded electrodes) was found to be sufficient to return to zero force, which is equivalent to a nearly complete discharging of the glass particles. With other particle materials, a modification of the waiting time might be appropriate.

The stability and resolution of the measurements depends very much on the measurement situation. In spite of all efforts to insulate the set-up from mechanical vibrations, building vibrations are a main source of disturbances. Therefore, the measurements are taken during night in an automated procedure. Typically, measurements for spring deflection (force) and currents are taken with a frequency of 1 Hz and 10 Hz, respectively.

For details on the resolution, see part 4.

4. Calibration and performance data

4.1. Resolution and reproducibility of distance, force and current measurements
The force measurement (or spring constant, resp.) was calibrated with spherical silver particles. Using metal particles, the surface potential is defined, and theoretical solutions are available for the force as a function of potential and distance. According to [22] the force between two conductive particles is given by:

\[ F = -\frac{d_p}{16 d_g} U^2 \frac{4\pi\varepsilon_0\varepsilon_r}{d_g} \]  

where \(d_p\) is the particle diameter and \(d_g\) is the gap distance between the particles. \(U\) stands for the potential difference between the two particles and \(\varepsilon\) stands for dielectric permittivity.

Silver particles with a defined diameter of 250 μm were produced by melting defined pieces of silver wire with a diameter of 25 μm. The silver particles were mounted to glass capillaries in a similar way as the glass particles.

Figure 5(a) shows spring deflection measured as function of gap width for the 250 μm silver particles at 150 V potential difference. The measurements were made on 3 consecutive days in order to check the long-term reproducibility. It appears that the reproducibility of the deflection measurements is around +/− 0.003 μm or 3 nm, respectively. Next, the spring constant was verified experimentally for the 0.25 mm spring. For this, figure 5(b) shows some results (day 2) for various combinations of gap widths and potential. The spring constant
was adapted as to obtain optimum fitting between experimental results and theoretical prediction according to equation (1). This gives a spring constant of 531.25 N m$^{-1}$, which is somewhat lower compared to the theoretical value of 625 N m$^{-1}$. The difference (factor 0.85) can be explained mainly by deviations from an idealized stiff clamping, but also by uncertainties concerning the spring dimensions and the exact value of Young’s modulus. All further experiments are done with the 0.25 mm spring and with this empirically calibrated spring constant.

A closer look to figure 5(b) reveals a systematic deviation in the distance range from 5 μm to 8 μm. As this deviation is found with all voltages, the deviation can most probably be attributed to imperfections of the piezo motor axis, leading to angular variations of the motor axis orientation which translate into a (reproducible) distance error of up to about 0.5 μm. In the further measurements, this position range on the piezo motor axis was avoided by using longer glass capillaries.

Empirical data on the resolution and on the dynamic behaviour can be derived from figure 6. Figure 6 shows the transients of current, force and particle distance for the 250 V/13 μm combination (from figure 7). The potential is switched on at 900 s. Simultaneously, we observe a current peak, and the force between the particles starts to rise while the charge carriers move towards the particle–particle gap from both sides.

The force measurement obviously is affected by vibrations. In the idling mode ($U = 0$ at time $t < 900$ s) or in case of a larger separation (gap $d_g > 1$ μm) between the particles (both conditions are given in figure 6(a)), oscillations of the springs on the force sensor side are excited quite easily, and the force reading shows a rms noise of about 0.531 μN (rms). The same oscillations also activate the particle-particle distance regulation system, and the rms noise on the distance value amounts to around 1 nm (see figure 6(b)). Bursts of force variation appearing in more or less regular time intervals (figure 7 for 250 V/500 V) can be traced back to a compressor installed in the building.

When the potential is switched on at 900 s, the current (figure 6(a)) reaches a very high value within 1 s and immediately drops to a negative value at 901 s (not shown here due to log-scale). Afterwards the current increases again and goes through a second maximum. After the second maximum, the current decays by one order of magnitude within 50 s. This decay is well explained by the physical mechanisms of current transport, see below. However, the initial current peak followed by the immediate drop to negative values must be seen as a measurement artefact: When the voltage is switched on, the polarization of the particles immediately leads to an electrostatic attraction force and to a reduction of the gap width. The system starts to correct the gap width (0.1 s reaction time), the piezo motor moves backward and hence the capacity of the particle-gap–particle arrangement is reduced. Part of the charges that have been stored already has to flow back, and this gives the negative current. After 2–3 s, the system is equilibrated again.

The question of current offset will be discussed below, as the physical background is quite complicated.

5. Experimental results with glass particles (150 μm) and discussion

Here we present results from an extensive series of measurements all made with the same pair of 150 μm spherical glass particles. In all experiments, a positive potential $U$ was applied to particle 1, while particle 2 was
grounded. Table 1 gives an overview of all the combinations of gap distance $d_g$ and potential difference $U$ that have been investigated.

As a basis for the discussion of the measurement results, we introduce the concept of nominal voltage drop and nominal field across the gap. The basic idea is that the particles show quasi-conductive properties in situations when the current across the gap is low, compare figure 7 and the discussion in section 5.1.

With conductive particles, the potential is uniform over the whole surface and equation (1) gives an exact and simple relation between force and potential difference. With conductive particles and a narrow gap ($d_g \ll d_p$), most of the electrostatic attraction force originates from the particle surfaces which are near the gap region, because the electrostatic force (for a given potential difference) scales with $1/(\text{distance})^2$. With non-conductive particles and narrow gaps, the assumption that most of the electrostatic force originates from charges in the gap region is plausible as well.

Hence we define a force-based potential drop across the gap ($U_F$ in volts) by introducing the measured force value into equation (1). The nominal potential drops shown in table 1 are calculated with a force average for the time interval from 3500 s to 4500 s of the measurement cycle. The same, we define a force-based field strength ($E_F$) in the gap, whereby the force-based potential drop is divided by the gap width. Of course, the real field strengths are somewhat smaller, as the force-based field is calculated with the ‘conductive particle’ assumption (equation (1)) and does not consider the voltage drop within the particles.

In cases of periodic current and force variations, $E_{\text{max}}$ is the electric field corresponding to the maximum force value.
Table 1. Overview of all experiments, showing gap width and voltage applied to the electrodes (fat data). Further, values of force-based potential difference $U_p$ and force-based field $E_F$ in the gap were calculated from the force measurements. $E_{\text{max}}$ are the maximum field values reached just before gas discharge starts. The reference values for Paschen critical potential $U_{\text{crit}}$ and critical field $E_{\text{crit}}$ are adopted from [23, 24]. For more details see text.

| Gap [μm] | $U_{\text{crit}}$ [Volt] | $E_{\text{crit}}$ [V/μm] | $U_p$ [Volt] | $E_F$ [V/μm] | Current Trend | $U_p$ [Volt] | $E_{F/\text{max}}$ [V/μm] | Current Trend | Trend |
|---------|-----------------|-----------------|--------------|---------------|---------------|--------------|-----------------|---------------|-------|
| 13      | 388             | 30              | 219          | 17            | DC            | 489          | 38              | DC            |        |
| 10      | 364             | 37              | 228          | 22            | DC            | 475          | 47              | PB            |
| 8       | 353             | 44              | 242          | 30            | DC            | 424          | 53/59           | PB            |
| 6       | 337             | 56              | 260          | 43            | DC            | 368          | 61/68           | PB + CC       |
| 5       | 336             | 67              | 238          | 48            | DC            | 356          | 71              | CC            |
| 4       | 347             | 87              | 235          | 59            | DC            | 352          | 88              | CC            |
| 3       | 361             | 120             | 231          | 77            | DC            | 294          | 98              | CC            |
| 2.5     | 369             | 148             | 175          | 70            | CC            | 275          | 110             | CC            |
| 2       | 383             | 192             | 140          | 70            | CC            | 213          | 106             | CC            |
| 1.5     | 416             | 277             | 113          | 75            | CC            | 179          | 119             | CC            |
| 1       | 495             | 495             | 76           | 76            | CC            | 134          | 134             | CC            |
| 0.75    | 566             | 755             | 69           | 92            | CC            | 105          | 140             | CC            |
| 0.5     | 671             | 1341            | 48           | 96            | CC            | 82           | 163             | CC            |
| 0.25    | 820             | 3279            | 32           | 127           | CC            | 56           | 223             | CC            |
| 0.1     | 937             | 9370            | 21           | 210           | CC            | 32           | 317             | CC            |

Complementary to the field in the gap, we can calculate the average field inside the particle:

$$E_p = \frac{U_p}{d_{p1} + d_{p2}} = \frac{U - U_p}{d_{p1} + d_{p2}} \quad (2)$$

Here $U_p$ is the potential drop inside both particles.

Further details of the table will be explained when the results are discussed. Only a few representative results can be discussed in detail.

5.1. Time effects resulting from dielectric particle material

Probably the most prominent and fundamental result is that pronounced time effects are found in all measurements with the glass particles. As explained above in section 2, time effects basically result from the transport and immobilization of the charge carriers in the dielectric material.

Figure 7 is a typical result showing the temporal evolution of electrostatic force $F$ at $d_g = 13 \, \mu m$ for various potentials. When the potential is switched on at 900 s, the force does not reach a constant value immediately as it would be the case with conductive particles.

With 250 V and 500 V we observe a fast rise of force during the first 100 s, while it takes almost 1 h/3600 s until a constant value of force is reached. For comparison, the dashed lines give the theoretical force for conductive particles as a reference value. Obviously, the reference value for conductive particles is approached, but not reached. When the voltage is switched off at 4500 s, the force drops off sharply, but different from conductive particles, zero force is not reached immediately. Instead, this takes several hundreds to thousands of seconds. As mentioned above, the remaining force is an indicator of residual charges residing either in the particle volume or on the particle surface.

In a rough estimation following the classical theory of dielectrics (e.g. Tobazéon in [2]), we may use the characteristic time $\tau$ of the force or current response to estimate the resistivity $\rho$ of the particle material:

$$\tau = \varepsilon_0 \varepsilon_r \rho \frac{d}{d} \quad (3)$$

Taking $\varepsilon_r = 7.5$ for soda-lime glass and $\tau = 100 \, s$ to $1000 \, s$ , we estimate the resistivity of the glass particles to be in a range of $\rho_p = 1.5 \cdot 10^{13} \, \Omega \cdot m$ to $1.5 \cdot 10^{15} \, \Omega \cdot m$. Equation (3) implies an ohmic behaviour of the material. With an ohmic material behaviour (or, a constant value of $\rho_p$) however, we should observe a simple
exponential decay of the force in figure 7 when the voltage is switched off. Obviously is not the case. The decay is extremely fast in the beginning, but even 1000 s after switch-off, the remaining force still amounts to about 5% of its previous value (figure 7, 500 V).

An adequate qualitative interpretation of the time behaviour of force and current in figures 6–7 is given by the electret-like nature of the glass material. As the glass particles do not contain any significant amount of free charges initially, the current transport takes place essentially by excess charges, which are produced by the injection of electrons and holes. Here, the excess charge carriers are injected into the glass particles from metal electrodes by the mechanism of thermionic field emission (TFE). Initially, these injected charges are mobile and they move through the particles accumulating near the particle-gap interfaces. This increases the electric field in the gap and the electrostatic force \( F \) with time. Simultaneously, a part of the charge carriers is immobilized in the volume of the particles. Hence these charge carriers do not reach the particle (or gap) surface, and the force does not reach the full value which would be expected for conductive particles. When the voltage is switched off, the trapped charges remain inside the particles. The following process of slow charge (and force) decay involves two steps: Re-mobilization of the trapped charges and loss of the mobile charges by electrostatic dispersion (repulsion of like charge carriers). The electrostatic dispersion of mobile charge carriers appears to be a fast process, which is demonstrated by the fast decay of force and charge in the first phase of the relaxation period. In contrast, re-mobilization or de-trapping is a rather slow process, depending on the distribution of the activation energy for leaving the traps (‘depth of the traps’) and on the temperature.

Going to 750 V, we observe a completely different behaviour. The force value reaches only around 22 \( \mu \text{N} \), which is far below the reference value expected for conductive particles (45 \( \mu \text{N} \)). While the force curves for 250 V and 500 V are very smooth (the bursts appearing after regular intervals are caused by an air conditioning system in the same building), the 750 V curve shows strong oscillations. A close-up is shown in figure 10. Obviously at 750 V, the build-up of charges on both sides of the particle-particle gap is interrupted by gas discharges. The discharges die away after very short time when the charge accumulated at the gap surfaces is consumed. In table 1, this regime is designated as the one of ‘Periodic current Bursts’ (PB). Estimations on the electric field strength \( E_{\text{p}} \) in the gap confirm this explanation.

Remarkably, a stable level of oscillations is reached already within about 30 s (figure 10). Also, the remaining charge after switch-off of the voltage is lower compared to the 500 V experiments. From the view of dielectric theory, we may interpret this as follows: Due to the gas discharges, the field across the gap is limited to \( E_{\text{crit}} = 30 \text{ V } \mu \text{m}^{-1} \) (Paschen limit), while the force based measurement value is somewhat higher at \( E_{\text{f}} = 41 \text{ V } \mu \text{m}^{-1} \) (see table 1). Hence the field within the particles must be much stronger compared to the 250 V and 500 V cases, and the charge carriers move faster. Due to the Poole-Frenkel-effect, the immobilization of charge carriers is strongly reduced and the long-lasting time effects are much less prominent. A second effect reducing immobilized charge carriers originates from the gas discharge within the particle-particle gap. As the gas discharge produces gas ions of both polarities, both particles will contain charge carriers of both polarities. This leads to a reduction of immobilized charge carriers by recombination.

A more detailed discussion of the current transport mechanisms across the gap shall follow in section 5.2.

### 5.2. Various mechanisms of current transport across the gap

With respect to current transport across the particle-particle-gap, we may distinguish three different regimes (compare table 1): (i) In the ‘Constant Current’ (CC) regime, a smooth and rather stable current characteristic is reached within short time (typically around 100 s) after switching on the potential difference. (ii) In the ‘Decaying Current’ (DC) regime, the current continues to decay for a long time (typically > 1000 s) and stabilizes at very low values. (iii) In the 'Periodic current Burst’ (PB) regime, electrostatic discharges occur across the gap, leading to a sharp peak of current and an abrupt drop of interparticle force.

#### 5.2.1. Decaying current regime: current offset and current leakage across the gap

In the ‘Decaying Current’ (DC) regime, the current continues to decay for a long time (typically > 1000 s) and stabilizes at very low values. In table 1, these experiments are assigned with DC for ‘Decaying current’. In figure 8(a), current measurements for the DC cases are superimposed. In all of these cases, we find that the current across the gap reaches a value of about 4.5 pA independently from the gap distance and the applied potential difference. This value is about 2.5 fA above the current bias found when no voltage is applied (figure 8(b)).

In all cases as well, the nominal field across the gap is rather low, with values ranging from 17 V \( \mu \text{m}^{-1} \) to 77 V \( \mu \text{m}^{-1} \), and the critical field \( E_{\text{crit}} \) according to the Paschen law (see table 1) is not reached. This might lead to the expectation that zero current should be observed.
However, we also have to consider that the current is on an extremely low level only. The close-up in figure 8(b) reveals that we have a current offset of about 2 fA at zero voltage. As the current offset itself is quite reproducible in all the experiments as well, we need to explain an additional current value of about (4.5 fA − 2 fA) = 2.5 fA.

One possible explanation is the natural production of ions in the air. According to Raizer ([17] p. 345) and [Huertas 1975/25a], ion pairs are formed in air at a rate of about 10^18 cm^-3s^-1 by cosmic rays and natural radioactivity. Hence in a volume of 500 cm^3, a total of 10,000 charge carriers are formed per second. As particle 1 and the wiring are on a positive potential, negative gas ions will be extracted from the gas volume, and there will be a surplus of positive gas ions. By mutual repulsion, the surplus positive ions will be deposited onto grounded surfaces, including particle 2 and its wiring. The insulation of the wires does not prevent that the charges deposited to the surface of the insulation are measured, as the charge carriers (holes) will diffuse through the insulation at a sufficiently high rate.

With 5000 positive charge carriers, a current amounting to I = 5000 e/s × 1.602 × 10^-19 As/e = 0.8 × 10^-15 A is calculated. Of course, there is much uncertainty about the volume contributing to the production of ions. In total, the internal volume of the measurement box is about 5 l. But in large parts of this volume the fields are very weak and the ions will mostly recombine. Also, the charges from the ions are not only injected into the glass particles and their wire connections, but also into any grounded metal surface. Hence, only a tiny fraction of the air ions should contribute to the current measurement, and hence this mechanism does not appear to be sufficient.

A second, additive mechanism is thermionic current. Thermionic currents originate, when electrons overcome the work function of the material due to their thermal energy. Thermionic emission of electrons from a surface is described by [17]

\[ j = A_T \frac{T^2}{e} \exp\left(-\frac{e \varphi}{kT}\right) \]

(4)

where \( j \) is the emitted current density [A/m^2], \( T \) is the temperature [K], \( A_T \) stands for Richardson’s constant [1.202 10^9 A m^-2K^-2], \( k \) is the Boltzmann constant [1.3805 10^-23 J K^-1], \( e \) is the charge of electron [1.602 10^-19 As] and \( e \varphi \) is the barrier height [eV].

In the presence of an electric field, the electrons (or negative gas ions formed from the electrons) drift along the field lines. As only electrons can be emitted at ambient temperature, the relevant area is the area of one side (cathode side, particle 2) only. Considering the experimental situation as shown in figure 4, thermionic emissions from the particle (diam. 150 μm area 0.0706 mm^2), from the conical particle support capillary (length 15 mm, average diam. 0.52 mm, area 24.50 mm^2) and from the metal cap (diam. 8 mm, rim 1 mm, area 74.61 mm^2) add up to a total emitting area of 99.7 mm^2. Figure 9 gives values of the thermionic current as a function of the work function for different temperatures and emitting areas. With a work function of 1.28 eV, an emitting area of 99.7 mm^2 and a temperature of 298 K, the thermionic current is estimated to be around 2.42 fA.

Common values for the work function given in the literature are much higher, amounting to 4-5.3 eV for most of the metals [17, p 68] and metal oxides. The further discussion (see section 5.2.3, figure 15) will show that the value of 1.3 eV for the work function is consistent with the results found for thermionic field emission from...
the glass particles at very narrow gaps and strong fields. Therefore, we think that thermionic emission is the dominating mechanism for the observation discussed above.

5.2.2. Periodic gas discharge in the gap

Going back to 750 V/13 μm in figure 7, we observe that the force remains far below the reference value for conductive particles and shows very strong oscillations with time. To understand this in detail, a close view of the force together with the current is shown in figure 10. When the potential is switched on at 900 s, the force value increases very fast within the first 10 s and simultaneously the current decreases. However, here, as the force value reaches about ~25μN, it drops drastically to about half of its maximum value. Then it increases again and we observe a sawtooth-like function. Simultaneously with each force drop, we observe a sharp current burst, which decays exponentially until the next force drop occurs. In table 1, this behaviour is assigned with ‘PB’ for Periodic Bursts. We see that periodic bursts occur with certain combinations of gap and field strength only. Some more examples of periodic burst behaviour with 500 V are shown in figures 11 and 15.

Figure 15 also includes an example for the transition from periodic bursts to continuous current (‘PB + CC’ in table 1). With time, the frequency of the discharges goes up while the amplitude goes down. We found this transition for a few combinations in between the PB and CC domains. The mechanism of the transition is most probably explained as follows: With time, more charges become trapped near the gap surfaces. This leads to an increasing base level of the electric field, and less mobile charges need to accumulate at the gap surfaces to reach

![Figure 9. Thermionic current for a particle (150 μm diameter, emitting area 0.0706 mm²) and for a particle plus particle holder (total area 99.7 mm²) as a function of work function εΦ.](image)

![Figure 10. Close view of temporal evolution of force/current with periodic gas discharges for 750 V/13 μm (figure 7).](image)
the critical field for a gas discharge avalanche. This explains why the frequency of the discharge avalanches increases with time. Simultaneously, the increase of the base level of electric field across the gap also leads to an increase of thermionic field emission (see part 5.2.3). So finally, the periodic gas discharges are replaced by a constant current emitted through the thermionic field mechanism.

For the electric breakdown of a narrow gap between metal surfaces caused by a gas discharge (Townsend avalanche [19]), the critical field depends on the gap width and the gas density. This is described by the Paschen Law [20]. In the actual scientific discussion, modifications of the Paschen law are discussed for the case of very narrow gaps [25]. While most experimental data on Paschen’s law refer to metallic surfaces, a somewhat different behaviour is reported for Si semiconductor surfaces [23, 24]. For dielectric surfaces, no data are available.

Figure 12 gives a compilation of literature data on breakdown voltages as a function of the gap distance. All data are for air at atmospheric pressure. Table 1 gives the reference critical voltage $V_{\text{crit}}$ and the critical field $E_{\text{crit}}$ for different gap distances. These reference values were calculated with a polynomial fit (see figure 12) to experimental data from the literature [23, 24] for Si particles in air at 1 atmospheric pressure.

Figure 12 also includes the breakdown voltages from our own measurements. Here, the critical or breakdown voltage is defined as the force-based voltage $U_{\text{max}}$ (table 1 shows the corresponding $E_{\text{max}}$ values) which is reached in the average just before the current burst starts. We see that the critical voltages between the glass surfaces are somewhat higher compared to the Si and the metal surfaces.

Different from the case of the Si-Si gaps in the literature, the critical voltage for a gas discharge cannot be reached with the glass-glass gap distances below 4 $\mu$m. Due to the low work function of the glass surface, a high current density is leaked across the gap before a field sufficient for breakdown by gas discharge ($E_{\text{crit}}$) can build up. Accordingly, we find that $E_{\text{G}}$ is smaller than or just slightly above $E_{\text{crit}}$ for all of the CC cases.

Different from micro-discharges between conductive particles or electrodes, the discharges between dielectric particles do not develop into a continuous corona or an arc. Instead, the discharges break down when the charge accumulated at the gap surfaces is consumed. In some way this is comparable to a dielectric barrier discharge. The gas discharge develops within fractions of a microsecond [26] and cannot be resolved in the measurements. After a gas discharge, the current flowing into the particles is still high for a few seconds, because new charge carriers accumulate on both sides of the gap. The frequency of discharge bursts is limited by the transport of charge carriers through the glass particles. For a given gap width, a higher voltage leads to a higher frequency – see figure 13.

5.2.3. Thermionic field emission in the gap
In cases of narrow gap widths ($d_{\text{p}} < 3 \mu$m), one more distinct type of temporal evolution of force/current (Constant Current, CC in table 1) can be observed for all potential differences, see figures 14(a)–(b).

As the potential is switched on at 900 s, the force rises very fast during the first 50 s – 100 s depending on the applied potential. However, way before the level of force corresponding to conductive particles is reached, the force starts to decay rapidly again. After 500 to 1500 s of decay, the force stabilizes at a level which is 20%–30% lower compared to the maximum values. After that, almost constant force values (at 500 V, 750 V) or a slight, continuous decay (at 250 V) are observed over time. Similar behaviour is observed for all the cases of narrow gap.
widths, and generally the maximum value of force is far below the reference value for electrostatic attraction between conductive particles as shown in figure 17.

This behaviour can be explained when we analyse the level of current as a function of gap width (figure 15 and table 1). Indeed, for a given potential difference $U$ the level of current strongly depends on the gap distance. In all cases of CC, the force-based field strength values $E_F$ in the gap (calculated from the electrostatic force and the gap width, see table 1) are higher than $70 \, \text{V} \, \mu\text{m}^{-1}$ or $700 \, \text{kV cm}^{-1}$, especially in the narrow gaps, $E_F$ is reaching $2–3 \, \text{MV cm}^{-1}$. According to the classical field emission theory by Fowler and Nordheim [27], such high field strengths, $\sim 1000–10000 \, \text{kV cm}^{-1}$, should lead to high currents by field emission, where electrons can cross the potential barrier at the metal surface by tunnelling. However at this point, we should remember that the calculation of $E_F$ is based on the ‘conductive particle’ assumption. The real field can be much lower, especially in case of high current density when a strong potential gradient is needed to drive the charge carriers through the dielectric particle material.

It appears more realistic to assume fields below $1 \, \text{MV cm}^{-1}$. In this range of field strength, the emission of charges is described by the mechanism of ‘thermionic field emission’ (TFE) or Schottky effect [28], whereby:
Equation (5) differs from equation (4) only in the last term. The mechanism of TFE is that the external field can counteract the image force retaining the electron to the metal (or dielectric) surface. In this way, the energy barrier for the electron to leave the surface is lowered by an amount of $\frac{eE}{4\pi\varepsilon_0\varepsilon_r}$. Here, $E$ is the electric field [V/m] in the gap and $\varepsilon = \varepsilon_0\varepsilon_r$ is the dielectric permittivity of the gas phase.

A relevant increase of current density is found if the field is quite high ($E > 100$ kV cm$^{-1}$). As the field is above the threshold for Townsend avalanches, and the gaps are wider than the mean free path of the electrons in air (about 0.4 \mu m), the primary Schottky electrons can produce significant amounts of secondary charge carriers (electrons, positive gas ions) by impact ionization. Hence, just as in case of a gas discharge, not only electrons, but also positive gas ions participate in the current transport across the gap.

The bipolar charge carrier generation in the gap produces positive charge carriers which are injected into the glass sphere on the cathode side and can recombine with the immobilized free electrons on this side. In the same way, negative charge carriers/free electrons are injected into the glass sphere on the anode side and can recombine with the immobilized holes on this side.

First, the combination of TFE with secondary impact ionization may explain why we do not see much time effects for the current after the first 100 to 300 s (figure 14(b)). The continuous supply of mobile counter-charges...
to both particle surfaces reduces charge carrier immobilization by the effect of recombination (at least near the gap surfaces) and hence allows a high and constant level of current. Going into detail, we see that the current-time curves have a minimum at around 1000 s (100 s after switch-on), followed by a slight increase until the constant values are reached at around 3000 s.

Second, we are also able to explain qualitatively why the force reduces after the initial maximum (figure 14(a)). In the phase of initial charge carrier invasion into the particles, the charge carriers are mobile and accumulate near the gap surfaces. Later, the supply of counter-charges keeps the charge carrier mobility on a high level near the gap surfaces, while immobile charge carriers accumulate near the electrodes. And hence, the geometric centre of particle charge (sum of mobile and immobile charge carriers) moves just a bit away from the gap surfaces towards the electrodes, and the attraction force is reduced.

When the gap distance is reduced, the force-based field and also the real field in the gap will increase. A higher level of the real field enhances the thermionic field emission. As well, the efficiency of secondary impact ionization in the gas is enhanced, but the number of charge multiplication steps is reduced together with the gap width. Hence in the distance range below 3 μm, a shorter gap produces a higher level of current as shown in figure 15 for the example of 300 V. However, the increase of current is quite moderate, as an increasing part of the overall potential difference U is needed to drive the current through the dielectric particle material.

5.3. Overview diagrams and comparative discussion
Figures 16 and 17 give overviews for current and force, resp., as a function of gap distance and overall potential difference. Both diagrams are based on the experimental data from table 1 and hence represent the long-term values for the time interval from 3500 s to 4500 s.

5.3.1. 250 Volt results
Starting the discussion with the results for 250 V, we can see a clear distinction of three current regimes:

(i) Decaying Current (DC) regime for gap distances of 3 μm and above: The current is initially limited by the transport of charge carriers through the glass. Later on, the current decays due to immobilization and finally only thermal electrons are produced. Meanwhile the interparticle force (figure 17) almost reaches the value corresponding to the ‘conductive particle’ assumption. Hence the real gap field approaches to the force-based $E_F$-field in the long term. In the long term, the current value in the DC regime is constant on a low level, however superimposed by strong electronic noise. Moreover, we find the current to be independent from the gap width and the field in the gap. As discussed above, the production of charge carriers in the gas for the DC regime is explained quantitatively by almost equal contributions, from gas ion deposition and from thermionic emission (work function 1.3 eV) from a larger surface area including parts of the particle holders. The gap field or $E_F$ field, resp., is too weak and/or the gap is too narrow as to allow a significant multiplication of charge carriers by impact ionisation in the gas.

(ii) Transition regime - Constant Current (CC) with limitation by TFE: In the gap distance range of 2.5 μm and 3 μm, the current is rising steeply when the gap distance is reduced. Simultaneously, the force value starts to...
fall back below the analytically calculated value according to the Conductive Particle assumption. The $E_F$ field values are quite high, but most probably the real field in the gap is somewhat lower because more potential drop across the glass particles is needed to drive the charge carriers through the glass particles. In any case, the combination of gap distance and field does not allow a significant multiplication of charge carriers which would lead to bursts of current by self-sustaining gas discharges. Therefore, the current shows a CC behaviour. It appears that the current values are quite well explained by thermionic field emission from the near-gap zone (diameter 30 μm) with a work function of 1.3 eV.

(iii) Constant Current (CC) regime with limitation by current transport through the dielectric: For gap widths in the range from 2 μm down to 0.1 μm, the currents continue to increase with decreasing gap distance. But obviously, the fields in the gap are too weak to produce self-sustaining gas discharges, which again is due to the limitation of current by the dielectric particles. Nevertheless, the long-term current values are falling back significantly compared to the TFE limit, and also the long-term force is significantly lower compared to the Conductive Particle limit. The low force values indicate that most of the overall potential difference $U$ is needed to transport the charge carriers through the dielectric particle material. The details of the force and current transients at short time (compare figure 14 and discussion) reveal that bipolar charge carriers produced by impact ionization in the gap (or at the particle surfaces) lead to a depletion of charge carriers in the near-gap zone, while immobilized charge carriers continue to accumulate in zones further away from the contact gap. Hence the current goes through a shallow minimum, but in the long term it remains limited by the transport through the glass sphere. Altogether, the current limitation by immobilized charge carriers in the particles in combination with potentially high emission current densities from the TFE mechanism limits the field strength which can build up in the gap. As a result, the field remains too low to produce a self-sustaining gas discharge, and we see a high level of constant current.

5.3.2. 500 Volt results

For the 500 V results, we can still see three distinct regimes.

(i) The Decaying Current (DC) regime is still found with the gap distance of 13 μm. In this case as well, the ‘Conductive Particle’ assumption is fulfilled. This is seen from the good match between the measurement value of the attraction force and the analytical calculation result for a conductive particle.

(ii) A transition regime is found in the range from 10 μm down to 6 μm gap distance. Different from the 250 V series, the combination of fields and gap distances allows the formation of self-sustaining gas discharges in most of the cases, as soon as enough charges have accumulated on the particle surfaces. As the gas discharge involves a multiplication of charge carriers by impact ionization, a high amount of charge is transferred by each discharge event. However, the limited current supply through the glass particles limits the frequency of the current bursts. Nevertheless, the averaged currents are high (well above the TFE limit for the respective conditions), while the lower level of average force (compared to the conductive particle limit) indicates the current limitation by the dielectric material. As figure 11 shows for the case of the 500 V/10 μm
combination, the first gas discharge can be delayed, but once a first current burst has happened, the next bursts follow at regular, much shorter time intervals. The explanation is that each gas discharge burst produces a large quantity of bipolar ions/electrons. Hence, on the negative side, positive charge carriers are injected into the particle and vice versa, so that mobile holes can recombine with immobilized electrons (and vice versa) in both particles. In this way, immobilized charge carriers are eliminated and more current can be transported through the dielectric.

(iii) Constant Current (CC) regime with limitation by current transport through the dielectric: For gap widths in the range from 5 \( \mu \text{m} \) down to 0.1 \( \mu \text{m} \), the currents continue to increase with decreasing gap distance. Nevertheless, the long-term current values are falling back significantly compared to the TFE limit, and also the long-term force is significantly lower compared to the Conductive Particle limit. Again, the explanation is the current limitation by the dielectric particle.

5.3.3. 750 Volt results
With 750 V, fields are so strong that a direct transition from periodic burst discharges to TFE is possible. The transition occurs gradually between 8 \( \mu \text{m} \) (PB only) and 3 \( \mu \text{m} \) (CC only) gap distance. The current is on a high level in the whole range of gap distances. The increase of the average current is very steady and only moderate (from 0.2 pA to 0.8 pA) while the gap distance is reduced from 13 \( \mu \text{m} \) to 0.25 \( \mu \text{m} \). The force goes through a maximum at about 3 \( \mu \text{m} \), but always the force is much lower compared to the ‘Conductive Particle’ approximation. The low force values allow to conclude that the potential drop mainly occurs inside the particles. Using equation (2) we find that the potential drop inside the particles varies from 30\% (at 750 V /13 \( \mu \text{m} \)) to 92\% (at 750 V /0.25 \( \mu \text{m} \)) of the overall voltage U. With high field strength inside the particles, charge carrier immobilization is not so important due to the Poole-Frenkel-effect [14], and hence the mode of charge transport across the gap does not influence the charge transport inside the dielectric too much. Hence the current is mainly controlled by the particle dielectric properties.

6. Conclusions
An experimental setup for the measurement of particle-particle interactions with superimposed electric field and electric currents has been developed for particles sizes in the 50 \( \mu \text{m} \)–500 \( \mu \text{m} \) range. Force and current in a contact gap between a pair of highly resistive, spherical glass particles were studied experimentally at ambient pressure and temperature. The gas atmosphere was dry air (dew point – 26.9 °C, 4% rh) which excludes surface conduction as a mechanism of charge transport.

6.1. Characteristics of the experimental setup
The setup is mainly designed for investigations with a constant distance between the particles, as the defined distance is controlled in an active loop and is maintained constant throughout the measurements. Main characteristics of the experiment setup are a distance resolution of 0.6 nm, a force resolution of 0.25 \( \mu \text{N} \) and a current resolution of 0.3 fA.

Calibration experiments were done with electrically conductive silver particles \( (d_p = 250 \mu \text{m}) \). The measurements of the Coulomb force show very good agreement with the theoretical values over a wide range of gap distance \( (1 \mu \text{m} – 15 \mu \text{m}) \) and potential difference.

When a step function of voltage is applied to conductive particles, the electrostatic forces reach a constant value almost instantaneously. The quick response time of less than 1 s and the distance control loop allow to study and to optimize the dynamic behaviour of the measurement system.

6.2. Experimental findings
The experiments with a pair of highly resistive particles (150 \( \mu \text{m} \) glass spheres) for various potential differences and gap distances have shown a complex behaviour of force and current in the contact gap and strong time effects.

The results clearly demonstrate that the mechanisms of the charge transport inside the particles correspond to those in an electret material. Charge carriers (free electrons and holes, respectively) are injected into the particles from the metal electrodes. The charge carriers move through the particles and the accumulation of charges across the gap increases the field in the gap and the attractive force between the particles. A part of the charge carriers later became immobile due to trapping, and the immobilization of charge carriers can limit the current.

For the current transport across the gap, different mechanisms were identified, depending on the gap distance and the field in the gap. Periodic bursts of gas discharges are found for wide gaps and strong fields.
occurrence of these discharges basically is consistent with Paschen’s law. Thermionic field emission is found to dominate in case of narrow gaps and strong fields. In case of weak fields across the gap, a very low current is found which is dominated by thermionic emission. For both cases of thermionic emission and thermionic field emission, an extremely low value (1.3 eV) was found for the work function of the glass surface.

6.3. Material properties

Glass was chosen as an experimental material because spherical particles can be fabricated quite easily, and because time effects are clearly visible, but not too long-lasting. The particle material glass may be seen as a prototype for a dielectric material with moderate electrical resistivity and rather short time constants for charge carrier trapping and de-trapping. Especially with various polymers, prototype for a dielectric material with moderate electrical resistivity and rather short time constants for charge carrier trapping and de-trapping. Especially with various polymers, the time constants for charge carrier de-trapping are higher by several orders of magnitude, and the neutralization of the particles within a series of consecutive measurements would have been a problem. With a change of the dielectric material, many material dependent parameters (charge carrier injection energies (electrode into dielectric), charge carrier mobilities, trapping probabilities and detrapping energies, recombination probabilities, work function for thermionic emission etc) will change. With the change of the material parameters, the relative importance of different mechanisms will change.

On a generalized level, the results demonstrate once more, that the distinction between dielectric particles (\(\varepsilon_r\)) and conductive particles (\(\varepsilon_r = \infty\)), which is a standard topic in the theory of aerosol particle charging [3, 4, 29] and in the discussion of adhesive forces for particle technology applications [30] should be seen as a theoretical concept but not as a physical reality.

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