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Put Strong Limits on All Proposed Theories so far Assessing Electrostatic Propulsion: Does a Charged High-Voltage Capacitor Produce Thrust?

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Abstract

Several claims appeared in the literature that a charged high-voltage capacitor produces thrust. This dates back to the so-called Biefeld-Brown effect that was later explained as a Corona-wind effect. However, part of the claim was that the capacitor still moves even if no ionization takes place and a dielectric is used. Recently, theories appeared supporting such an electrostatic propulsion-scheme. Here we describe an experimental-setup allowing to measure weight changes/forces of capacitors up to 10kV, eliminating important side-effects from high-voltages down to +/-0.3mg. No force was detected for a variety of configurations ruling out most theories by many orders of magnitude.

Keywords: Biefeld-Brown effect, Anomalous forces

1. Introduction

Does a charged high-voltage capacitor produce thrust? This question was first raised nearly 100 years ago in a patent [1] and follow-up paper [2] by T.T. Brown, which later became known as the Biefeld-Brown effect. In this early work, a parallel plate or spherical high voltage capacitor with a dielectric between the electrodes was observed to move towards its positive electrode while charged up to very high voltages (up to 300 kV). The capacitor was placed on a torsion pendulum connected with thin wires in order to observe the movement. It was claimed that the force depended on the applied voltage and the mass of the dielectric. The applied current was only necessary to overcome the overall leakages in order to maintain the applied voltage. This was further illustrated by showing that the capacitor was put inside an insulating oil tank in order to limit any discharge effect or leakage. It was claimed that this observation is a new electro-gravitational effect.

Brown later worked on larger models without oil insulation and observed high thrusts in ambient air with or without dielectric isolation, observing that the effect increased, if the shape of the electrodes were asymmetrical (e.g. flat cathode and wire anode) [3,4]. This became mainstream science known as electrohydrodynamics (EHD), corona/ion wind propulsion or plasma actuators [5,6], an active field of research up to the present day investigating alternative propulsion means for heavier-then-air model-airplane propulsion [7] or micro-drones [8]. The explanation is rather simple: A corona discharge drags ambient air molecules generating thrust. This seems to put the claim of a new electro-gravitational effect at rest [6,9] – at least for configurations with discharges in air.

Still, a few publications appeared with claims that there is a force in addition to the usual corona wind effect which is only electrostatic in nature [10–14], crucially linking it to the dielectric material between the electrodes similar to Brown's original observation. A recent paper also reports of an anomalous force, if there is a discharge through the dielectric [15]. However, like Brown's work, these claims lack a proper setup to definitely rule out conventional explanations. In addition, theoretical models appeared predicting such an electrostatic effect [12,13,16–19]. If true, this could lead among many other things to a novel space propulsion scheme which would be of high interest [20].

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Previously, we assessed claimed weight anomalies with permanently polarized dielectric materials (electrets) finding a null-result within our resolution [21]. However, capacitors are better suited to obtain drift-free measurements because the dielectric polarization can be turned on and off in a controlled manner. In this paper, we want to review predictions for anomalous forces due to electrostatic polarization of dielectrics and present an experimental setup that is well suited to investigate such polarization-thrust claims, taking not only ion winds but also other high-voltage induced side-effects into account. Finally, we will present a set of measurements targeting to evaluate each of the claims to answer the question if a high voltage capacitor indeed generates an anomalous force. This included standard parallel-plate capacitors that have symmetric or asymmetric electrodes, a capacitor with an asymmetrical dielectric as well as a capacitor that allows a leakage current through its dielectric (see **Fig. 1**).

2. Theoretical Predictions

Here we want to shortly review the models that have appeared recently, predicting an electrostatic effect causing the self-acceleration of a dielectric when polarized. Although one would immediately dismiss any such claims on the basis of energy and momentum conservation, self-acceleration is a known consequence of an inertial dipole that has even been observed in the laboratory [22]. Inertial dipoles may be created in an environment that generates a negative effective mass, which allows self-acceleration without violating conservation rules [23]. Most of the models presented here do not involve negative inertial effects, however, it would seem plausible that such a connection must exist if any of the experimental claims turns out to be true.

The first model predicting an electrostatic self-acceleration effect has been proposed by Ivanov [16]. He argues that static electric or magnetic fields induce so-called Weyl-Majumdar-Papapetrou solutions for the metric of spacetime that create effects many orders of magnitude larger than usually expected. An electrostatic field is predicted to generate a gravitational field which accelerates the dielectric. The generated force for a simple parallel-plate capacitor (see **Fig. 1a**) is given by

$$F_{Ivanov} = \sqrt{G\varepsilon_0\varepsilon_r} \cdot \frac{m}{d} \cdot V \tag{1}$$

where *G* is Newton's gravitational constant, ε_0 and ε_r the vacuum and relative electric permittivity, *m* the mass of the dielectric, *d* it's thickness and *V* the applied voltage. An analogous relationship is also predicted for magnetic fields. Musha proposed a similar equation with the addition that it is multiplied with the atomic number *Z* [12]. His model includes an electro-gravitational coupling that indeed assumes a gravitational dipole around the center of the atom that generates the self-acceleration force. Also Zhu [17] arrived at a same relationship (without dielectric) based on the gravitational redshift/blueshift and the law of conservation of energy. This remarkably simple **Equ. (1)** leads to forces in the order of up to 10 µN (or an equivalent of 1 mg of mass change if put on a balance) for standard high-voltage capacitors. This force is small enough that it may not have been clearly identified yet.

Another model was proposed by Porcelli and dos Santos Filho [13,14], which is empirically based on the Clausius-Mossotti relationship for the polarizability of dielectric materials as well as the similarity to dielectrophoretic forces. It is given by

$$F_{Porcelli} = \frac{0.102}{16\pi^2} \cdot \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \cdot \varepsilon_0 A E^2 \tag{2}$$

where E is the applied electric field and A is the area of the plate for a symmetrical parallel-plate capacitor. For asymmetrical capacitors, this equation is modified to

$$F_{Porcelli} = \frac{0.102}{16\pi^2} \cdot \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \cdot \varepsilon_0 \frac{A_1^2}{A_2} E^2 \tag{3}$$

where A_1 is the area of the larger electrode and A_2 the area of the smaller one. These equations are expected to provide much larger forces up to several 1000s of µN (or equivalent several 100s of mg) for typical high voltage capacitors, which should be detected rather easily.

The next model was recently proposed by Minotti [19], who derived his relationship as a consequence of a scalar-tensor theory of gravitation proposed by Mbelek and Lachièze-Rey [18]. It is based on a Kaluza-Klein-type 5D theory with an additional stabilizing scalar field of electromagnetic origin that is minimally coupling to gravity. Following Minotti's notation, the coupling constant Γ is empirically found by fitting temporal changes of the Earth's magnetic field to the large error bar when comparing different measurements of the gravitational constant. He proposed a force equation for a spherical capacitor, which is only half-filled with a dielectric as shown in Fig. 1b, that is given by

$$F_{Minotti} = -\frac{\pi \Gamma \rho V^2 b^2}{\left(\frac{b}{a} - 1\right)^2} \cdot \left[1 + ln\left(\frac{b}{a}\right) - \frac{b}{a}\right] \tag{4}$$

where ρ is the density of the dielectric material and a and b are the inner and outer radius of the spherical capacitor respectively. However, Minotti forgot to include the relative permittivity of the dielectric in his derivation (which leads to multiply **Equ. (4)** with ε_r^{-2}). Moreover, also here we can simply use the case of a parallel-plate capacitor to arrive at a much simpler equation given by

$$F_{Minotti} = -\frac{\Gamma A \rho V^2}{2\varepsilon_r^2} \tag{5}$$

With a coupling constant of $\Gamma = 3.35 \times 10^{-12}\ \frac{A^2}{N^2}$, the predicted forces are right between Ivanov's and Porcelli and dos Santos Filho's values with hundreds of µN (or equivalent tens of mg). Note that Minotti re-evaluated Mbelek and Lachièze-Rey's original theory and arrived at a 4 orders of magnitude lower coupling constant than originally proposed [24]. It should also be noted that Mbelek claims to have evidence for his original coupling constant by a recently published experiment [25]. The values derived with Minotti's latest constant should therefore be considered as a lower minimum value and that even much higher forces could be observable.

The last claim we investigated is based on a discharge through a thin dielectric sheet [15]. The authors say that their effect can by predicted by a modified inertia model based on Unruh radiation forming a so-called Rindler horizon which is affecting the electron's mass [26]. However, no actual force model is shown that allows calculating thrust based on their experimental conditions. We digitized their plot of measured force versus discharge power for various dielectric thicknesses and performed an exponential fit (similar to the authors observation). We arrive at the following empirical relationship:

$$F_{Bhatt} = P \cdot \left(2.7 + 114.8 \cdot e^{-\frac{d}{16.9}} + 2679 \cdot e^{-\frac{d}{3.6}}\right) \tag{6}$$

where P is the discharge power in mW, d the dielectric thickness in µm and F the force in µN. This matches their observed forces well (R^2=0.9996) leading to a deviation of only a few percent at the thickness we will use for our test.

3. Experimental Setup

Most published measurements were done with commercial analytical balances; therefore, we chose to follow a similar approach. The reliable measurement of small weight changes of a high voltage capacitor on a balance causes many side-effects which can cause false readings. During our experiments, the most important factors were:

1. Corona wind effects: Most papers do not disclose which high voltage cable was used to connect the capacitor to the high voltage power supply, which was always next to the balance. If a thin cable was used, probably not even isolated to reduce cable stiffness for high resolution weight readings, air will get ionized around the wire causing a corona discharge. This will produce the well-known EHD force that masks any anomalous effect. The origin of corona winds must not be limited to the cable but also to the connection between the cable and the capacitor, which needs to be protected properly. Sharp edges (e.g. due to soldering the end of the cable to the capacitor) create much higher field strengths which can cause ionization even if (too thin) isolation tape is used.
2. High voltage induced mechanical stress: Wires under high voltage bend due to electrostatic forces. This happens not only between different wires (e.g. the connection to the positive and negative polarity) but also along a single wire itself. This can immediately cause false balance readings if the cable is coming from an outside fixed power supply to the capacitor on the balance. But there is even a more sophisticated error which we observed in our measurements: A slight bending of a wire under high voltage causes a shift of the center of mass, which in turn can again lead to a recorded weight change which may falsely be identified as a new effect.
3. Buoyancy: If a power supply is used on the balance, heat is generated depending on the generated voltage. This can cause buoyancy and again false balance readings. Just imagine a box of 10x10x10 cm^3. A change of 1°C in that volume causes a buoyancy force equivalent to 4 mg of mass. Therefore, temperature stability is very important for reliable sub-mg readings.
4. Electromagnetic interactions with the environment: The experiment is surrounded by electromagnetic fields which may influence the measurement such as the Earth's magnetic field or not properly shielded power supplies. An onboard power supply may e.g. create a magnetic field if not properly shielded.

In addition, air movement and seismic noise must be taken into account to obtain high resolution. And most important: The experiment must include some sort of null measurement where a zero reading on the balance should occur even if the full high voltage is applied. If that is the case, typically most of the important side-effects should be covered.

After many iterations, we arrived at the following setup as illustrated in **Fig. 2**:

The experiment was done inside a custom-built Faraday cage with a front door that can be closed airtight. This large box sits on top of a massive granite table which is isolated to the ground with rubber isolation pads. The overall setup therefore provides a good seismic isolation as well as protection from air flow in addition to basic EMI shielding.

We used a Sartorius MSE1203S-100-DE analytical balance which has a maximum weight capacity of 1200 g with a custom enhanced resolution to 0.1 mg (standard is 1 mg). This was necessary as usual 0.1 mg balances have a too low maximum weight capability for all of our experiments. This balance sits on top of a stable aluminum profile construction. It features a hook which allows to connect our experiment from the bottom to a single point. This was essential to reduce side-effects from changes due to center of mass shifts e.g. from bending cables or rotating the capacitors.

The experiment was done inside a lightweight box with a base of 150x150 mm and a height of 100 mm which consisted of thin aluminum profiles on the edges for mechanical stability. The base plate was 0.5 mm thick and made from mu-metal and the sides are covered with 100 µm mu-metal foil. This cage therefore shields both electric and lower-frequency magnetic fields due to the high magnetic permeability of mu-metal. The connection to the hook is done with a three plastic cord suspension, which can be adjusted in length using screws. A small tubular spirit level enables to properly orient the box.

The inside of the box consisted of two parts: an on-board high voltage power supply and a rotation rig which allows to mount capacitors and change their orientation without opening and influencing the experiment. We used an EMCO CB101 power supply which can generate up to 10 kV at 100 µA and includes a voltage and current monitor signal. This compact and lightweight power supply was wrapped inside a box made of thermal isolation foam in order to limit heat conduction from the power supply to the ambient air which can cause buoyancy effects (see **Fig. 2c**). The temperature of the power supply was monitored with a TI LM35 sensor. The rotation rig next to the power supply was made from 3D printed PLA parts. It features a small 28BYJ-48 stepper motor and a Megatron MAD12AH absolute position encoder (see **Fig. 2d**) as well as a mounting structure for the capacitors. All electric connections are going through a 16-pin Galinstan liquid-metal feedthrough as shown in **Fig. 2e**. This allows to power and control all components inside the box with only low-voltage signals without any mechanical influence. That is a huge advantage compared to all other experiments published so far [11–14]. One of the pin-connectors is used to externally ground the experiment box. All pins go through a Sub-D pin connector through the outer box and are connected to a power supply, a LabJack T7 data acquisition board and a unipolar stepper motor driver (Weedtech WTSMD-M).

A LabView software is executing the measurements. It runs pre-defined profiles with an off- and on-period and different voltage settings. Several identical profiles can be signal-averaged in order to improve the signal-to-noise ratio and get statistical significance. Moreover, the software can automatically eliminate drifts by using a linear fit along the off-periods.

The balance was calibrated with a voice-coil (BEI Kimco LA05-05-000A), which was mounted in the middle of the bottom of the experiment box as shown in **Fig. 3a**. This allows verifying if the liquid-metal feedthroughs have any influence on the measurement down to our digital resolution of 0.1 mg. The voice-coil itself was calibrated on a dedicated setup which verified its calibration constant of 0.758 µN/µA. A precise current, commanded with a Keithley 2450 SourceMeter, through the coil generated a force, which we used to check the balance response. **Fig. 3b** shows the excellent linearity of the balance between 0.1-10 mg (it was actually tested until 100 mg without any change). It was difficult to mount the voice-coil such that both the magnet and the experiment box were perfectly aligned due to the hanging mounting of the experiment box. Nevertheless, we measured a weight change on the balance corresponding to 92% of the commanded force. **Fig. 3c** shows a representative measurement of a commanded force of 10 µN and the balance response (equivalent to 1 mg). We see that the balance only takes a few seconds to record that low change in weight. Our profile settings later on are always much larger than that to ensure that there is enough time to record a weight change. We conclude that our setup can reliably measure forces/weight changes with a precision down to the 0.1 mg resolution limit.

The complete setup then was verified by performing a null-measurement: Instead of a capacitor, a high voltage resistor (EMCO V1G) was used instead. Because no dielectric polarization takes place (ignoring capacity effects from the on-board high voltage power supply which is cover by this measurement), no weight-change should be recorded if voltage is applied to the resistor only. The measurement is shown in **Fig. 4** with the weight changes for several voltage settings ranging from 2-10 kV on the top and the normalized voltage signal that corresponds to the profile settings on the bottom. All measurements are signal-averaged from 20 individual profiles and the voltage on/off-period was set to 60 seconds each with a sampling rate of 1 Hz. We can see that most profiles are within the +/- 0.1 mg range, which is the digital resolution/precision of our balance. Only the 10 kV signal raises to a peak of 0.3 mg at the end of the profile, however the average along the profile is also at the 0.1 mg resolution level. Taking a 3σ approach, we can say that up to 10 kV, all signals averaged along the on-period below 0.3 mg are noise. Our accuracy is therefore +/- 0.3 mg.

4. Capacitor Measurements

A summary of all tests performed with a description of the test items and a comparison to the theoretical predictions is given in **Table 1**.

4.1 Symmetric Plate-Plate Capacitor with Ceramic Dielectric

In our first test, we used commercially available high voltage capacitors with a high permittivity ceramic dielectric (Murata DHRB34A102MF1B). Two of them were mounted in a parallel configuration on the rotation rig with their expected force showing in the same direction (+/- aligned). Next, we made profile measurements up to 10 kV with the capacitor assembly pointing at different directions as shown in **Fig. 5**, using an average of 10 profiles for each direction. A real force would have been easily identified: At 0° a weight change would be recorded, at 180° the same value would have appeared with a different sign, and at 90° and 270° no weight change would be visible. As shown in our measurements, no such behavior is visible. All data is below our previously defined +/-0.3 mg resolution.

From the theoretical models, only Ivanov's **Equ. (1)** predicts weight changes above our threshold with Δm_{Ivanov}=2.4 mg, which is around one order of magnitude above our noise.

4.2 Symmetric Plate-Plate Capacitor with Teflon Dielectric

Next, we tested a self-assembled symmetric capacitor using Teflon as dielectric. According to the theoretical models, this large difference in electric permittivity compared to the commercial ceramic capacitor ($\varepsilon_{r,Teflon}$=2.1 versus $\varepsilon_{r,Ceramic}$=4500) should results in significant differences. The assembly of the Teflon capacitor is shown in **Fig. 6a-b**. Copper plates with a thickness of 1 mm and a diameter of 40 mm were used as the electrodes and a Teflon plate with a thickness of 1.5 mm and a diameter of 50 mm was used as the dielectric. After attaching the connection wires with a silver-filled adhesive, the whole capacitor was covered with Scotchweld 2216 B/A adhesive, which is an excellent isolator. In addition, a urethane spray with an isolation of 80 kV/mm was applied several times as a second isolation layer.

The same procedure as with the ceramic capacitor was executed with one single Teflon capacitor, averaging 10 profiles for a voltage of 10 kV at different orientations as shown in **Fig. 7**. Also here, all signals were below our resolution threshold of 0.3 mg. Porcelli's and Minotti's **Equs. (2)** and **(5)** for symmetric capacitors predicted much higher forces, which should have resulted in $\Delta m_{Porcelli}$=118.8 mg for the case of Porcelli and $\Delta m_{Minotti}$=11.8 mg for the case of Minotti. Porcelli's model can be safely ruled out with nearly three orders of magnitude above our noise. It should be noted that Porcelli and dos Santos Filho used polystyrene (C_8H_8) for their symmetric capacitor, which has a similar relative permittivity ($\varepsilon_{r,C8H8}$=2.4-2.7) compared to Teflon ($\varepsilon_{r,Teflon}$=2.1). However, they did not use this number for their analysis but an even lower value of ε_r=1.086 based on hydrogen atoms weakly bounded in the styrene monomer. This doubles the prediction of the force and rules out their model even more. Similarly, also Minotti's prediction is two orders of magnitude above our noise which should have been easily detectable.

4.3 Asymmetric Plate-Plate Capacitor with Teflon Dielectric

We now tried to investigate asymmetrically shaped capacitors, which according to Brown's claim [3,4] and Filho and Porcelli's measurements and models [14] should produce even larger forces. The capacitor was made similar to our Teflon capacitor before, but here we replaced one copper electrode with a high-voltage cable having a conductor wire in the middle with 0.8 mm diameter that was mounted directly through a hole in the middle of a second Teflon dielectric plate, which served as a good alignment and could be easily mounted on top of the first dielectric plate (see **Fig. 6c**). The whole assembly was then isolated with Scotchweld and urethane spray as before. No current was recorded when charged up to high voltage indicating that the dielectric was not damaged from electric breakdowns that can occur from sharper edges like our thin conductor electrode.

Fig. 8 shows the measurement done at 0° and 90° with 20 averaged profiles. No change is visible within our 0.3 mg threshold. The Filho and Porcelli model predicted an astonishing $\Delta m_{Porcelli}$=29.7 kg (the whole experiment would have lifted off), which is again ruled out with even higher margin by this measurement.

4.4 Asymmetric Spherical Capacitor – Half-Filled with Bee-Wax

Next, we tried to replicate the setup that was suggested in Minotti's paper [19] with a spherical capacitor that was half-filled with bee wax as a dielectric (see **Fig. 1b**). Our assembly is illustrated in **Fig. 9**. It consists of two hollow spheres that could be disassembled into two halves. First, the bottom half of the larger sphere with an inner diameter of 56 mm was filled with bee wax with the full second sphere in the middle with an outer diameter of 30 mm. Then a 7 mm diameter hole was drilled through the second half of the larger sphere and a high-voltage cable was connected from the outside towards the inner sphere fixed again with silver-filled epoxy. Then the outer sphere was put together and sealed with Kapton tape in the middle and a second electric connection to the outer surface was done. The total weight of the finished spherical capacitor was 315 g.

The spherical capacitor was put into the experiment box with the high voltage cable pointing upwards and the bee wax at the bottom half as illustrated in **Fig. 1b**. The measurement at 10 kV with 20 averaged profiles is shown in **Fig. 10**. Again, all data points are without our 0.3 mg resolution. According to Minotti, a $\Delta m_{Minotti}$=24.4 mg was predicted according to **Equ. (4)** (and a smaller $\Delta m_{Minotti}$=7.5 mg if one corrects for the missing ε_r^{-2}). This is nearly two orders of magnitude above our noise level.

4.5 Capacitor with Leakage Current

This was the most difficult experiment because the setup was poorly described and hard to replicate (discharge always at 5 kV, cutting of electrode or using sandpaper on the cathode surface to facilitate field emission) [15]. We decided to use 90 µm thick aluminum foil for the electrodes with a diameter of 40 mm. The surface of one electrode was perforated several times with a needle for better electron emission as shown in **Fig. 11**. A 90 µm thick polyethylene (PE) foil was used as a dielectric, which was close to the ones used by Bhatt and Becker (13-80 µm thicknesses). After connection wires were again fixed to the electrodes with silver-filled epoxy, the whole capacitor was isolated with Scotchweld epoxy. This gave both electrical isolation and mechanical strength and thus allowed the capacitor to retain its flat and plane shape.

For the experiments, a 100 MOhm resistor was put in series in order to limit the current and to protect the high voltage power supply. We first tried to determine the voltage to emit a current of 10 µA, which was the maximum current observed in the Bhatt and Becker experiments [15]. Initially, the voltage went up to 4 kV until the discharge was triggered. However, later tests showed a reduced discharge voltage down to 2.1 kV, indicating that the first discharge probably increased the leakage of the dielectric through conduction paths. In order to not further damage the dielectric, we decided to reduce the on/off-period to 30 s each and to an average of 5 profiles only. The results are shown in **Fig. 12** with the weight change on the top and the emitted current on the bottom, for anode orientations pointing upwards, downwards and vertical (which should give a zero result). Also here, we still do not measure signals above our noise threshold of 0.3 mg.

Using the extrapolation formula in **Equ. (6)**, we estimate the predicted weight change as Δm_{Bhatt}=6.8 mg, which is an order of magnitude above our noise level. However, there are some differences in our setup and capacitor which may influence this result: The discharge voltage was lower with 2.1 kV instead of 5 kV, the dielectric foil was bigger than the largest one's used by Bhatt and Becker (90 µm versus 80 µm) and the distance of the capacitor to the experimental box may be different to the one of Bhatt and Becker which could influence the force as they observed force blocking by bringing conductive materials close to their capacitor. Still, our null result is important for comparison with a clean setup although it may not completely rule out the claim due to the exact replica uncertainties.

Conclusion

We described a novel experimental setup that allows to measure weight changes of capacitors up to 10 kV using an analytical balance that eliminates all important side-effects triggered by working at high voltages down to an accuracy of +/-0.3 mg with a precision of +/-0.1 mg. It features a thermally isolated on-board high voltage power supply inside a mu-metal/Faraday cage powered by liquid-metal fed low-voltage only-connection lines and a rotation rig, which allows to test capacitors at different orientations without re-opening the experimental setup. This significantly improves the reliability of such measurements contrary to previously reported results [10–14] and allows for testing theoretical predictions claiming forces for electrically polarized dielectrics with high accuracy [12,13,16–19].

In general, all measurements showed no force or weight change within our resolution including symmetric and asymmetric capacitors as well as capacitors with leakage currents. This allows to rule out the models proposed by Porcelli and Filho [13,14] by close to three orders of magnitude and the model by Minotti [19] by two orders of magnitude. As Minotti's model is a consequence of the scalar-tensor theory of gravitation proposed by Mbelek and Lachièze-Rey [18], it may put strong limits on that theory as well.

The model by Ivanov and others [12,16,17] is ruled out by one order of magnitude, however this is quite close to our resolution. Considering that some assumptions were used to derive the models, further tests should be done at even higher resolution. Similarly, the force claim from Bhatt and Becker [15] on leakage current capacitors is ruled out by an order of magnitude, but also here, the actual experimental configuration leaves enough uncertainty that this should be re-checked with a higher resolution. Nevertheless, important constraints can be made on these two claims based on our measurements.

Can we answer the question if a charged high-voltage capacitor produces thrust? So far, our answer must be: No – within our measurement accuracy. Some of the presented models (Ivanov [16], Bhatt [15]) are worth to be pursued with better setups in the future. Our balance also allows testing for mass changes and not only forces, which may arise from polarized dielectrics. Some theories point into such a possibility, however without a clear prediction of the magnitude yet [27,28].

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Type	Configuration	Theory [13–16,19]	Experiment (3σ)
Symmetric Capacitor (V=10 kV)	2xCeramic dielectric (Murata DHRB34A102MF1B): 2x1000 pF, m=2x5.8 g, $\varepsilon_r = 4500$, r=7.5 mm, d=7 mm	**Δm_{Ivanov}=2.4 mg** $\Delta m_{Porcelli}$=0.4 mg $\Delta m_{Minotti}$=8.6×10^{-6} mg	Δm<0.3 mg (all)
	Teflon dielectric: m=4.1 g, $\varepsilon_r = 2.1$, r=20 mm, d=1.5 mm	Δm_{Ivanov}=0.1 mg **$\Delta m_{Porcelli}$=118.8 mg** **$\Delta m_{Minotti}$=11.8 mg**	
Asymmetric Capacitor (V=10 kV)	Teflon Dielectric: $\varepsilon_r = 2.1$, r_1=20 mm, r_2=0.04 mm, d=1.5 mm	**$\Delta m_{Porcelli}$=29.7 kg**	
	Spherical Capacitor with half-filled Wax dielectric: $\varepsilon_r = 1.8$, $\rho = 0.9$ g/cm³, a=15 mm, b=28 mm	**$\Delta m_{Minotti}$=24.4 mg** **$\Delta m_{Minotti}$=7.5 mg (with ε_r^{-2} correction)**	
Capacitor with Leakage Current	Anode: 90 µm Al foil, r=20 mm Cathode: 90 µm Al foil, r=20 mm, perforated Dielectric: 90 µm PE foil Discharge: 2100 V, ≈10 µA, P=21 mW	**Δm_{Bhatt}≈7 mg (Extrapolation)**	

Table 1 Summary of Measurements and Comparison to Theoretical Models ($\Delta m=F/g_0$ using **Equs. (1-6)**), Bold Theory Values are much Larger than Experimental Limit

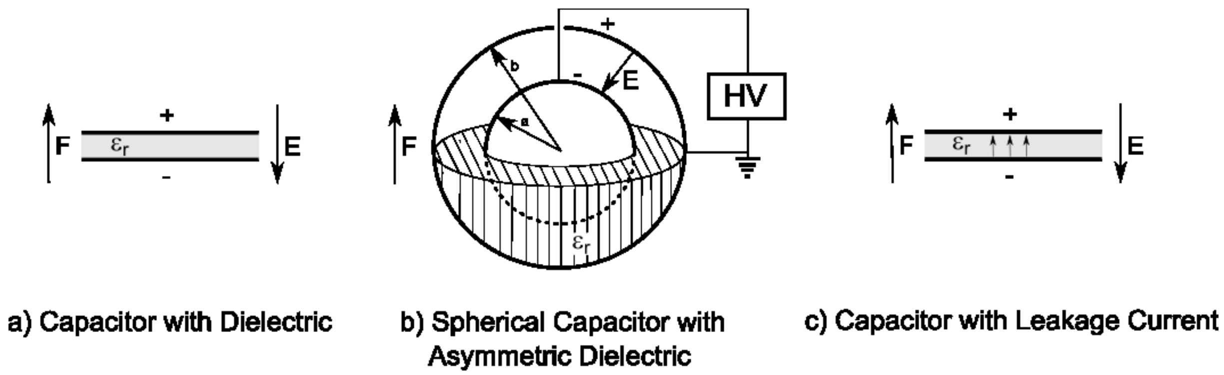
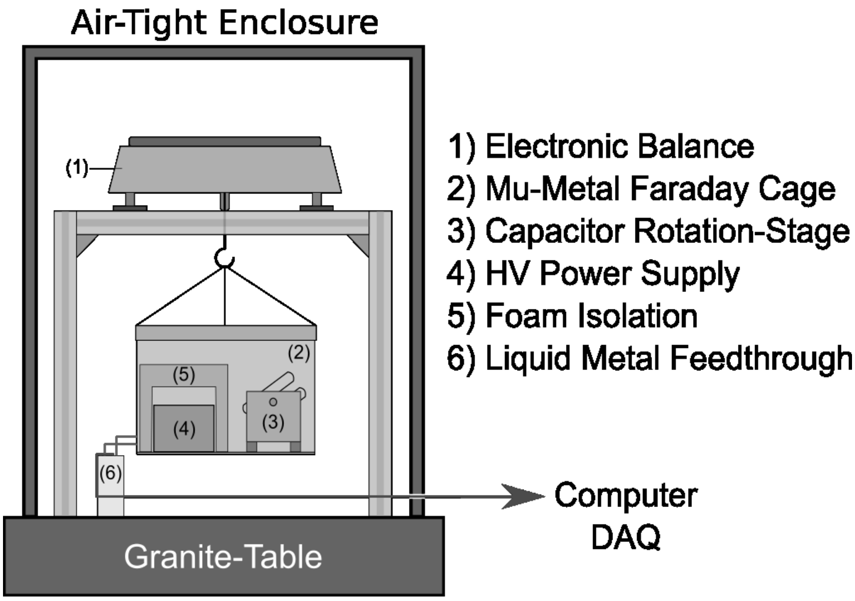
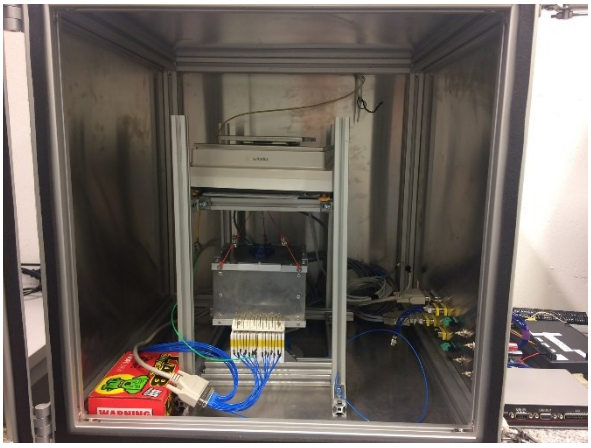


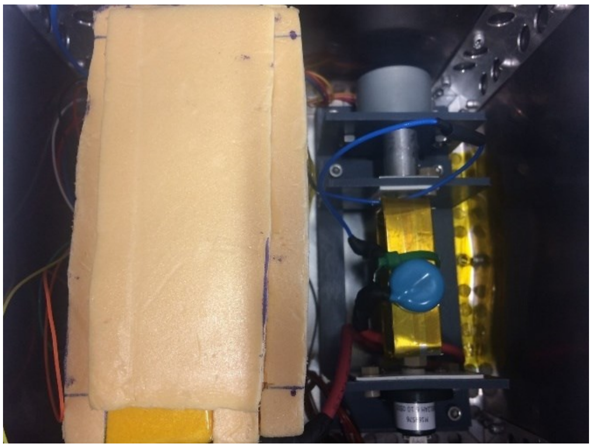
Fig. 1 Different Capacitor Configurations with Dielectric Permittivity (ε_r), Electric Field (E), Force (F), High Voltage (HV) as well as Radius a, b



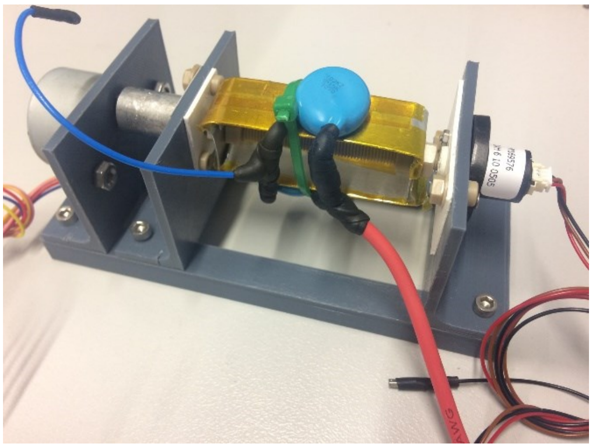
a) Schematic Sketch



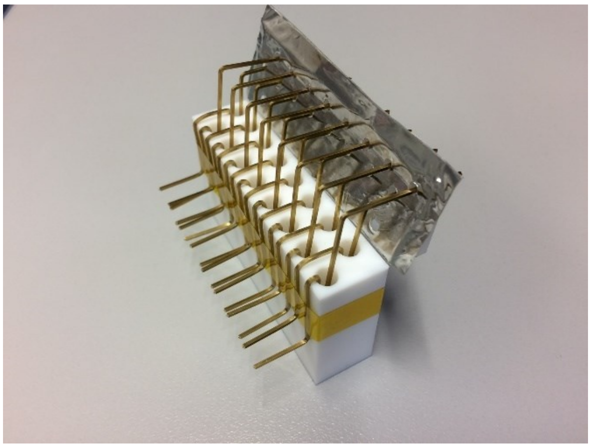
b) Picture of Experiment in Enclosure Box



c) Inside of Experiment Box

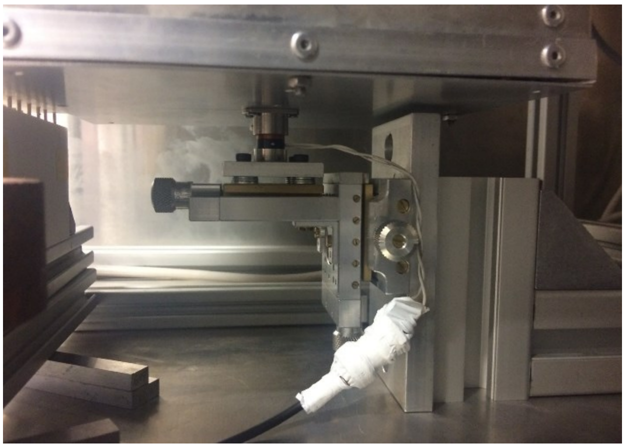


d) Rotation Stage with HV Ceramic Capacitor

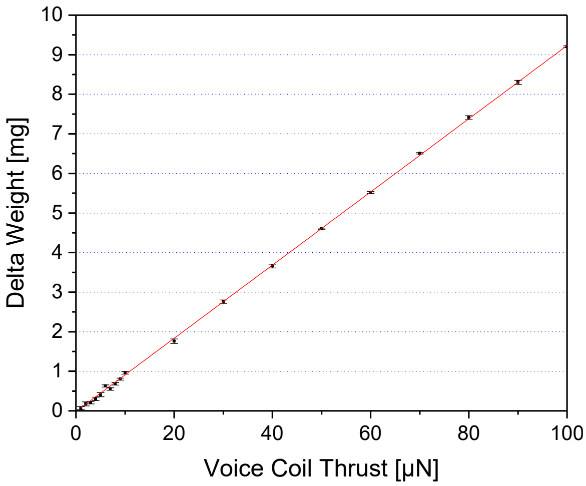


e) Liquid-Metal Connection Pins

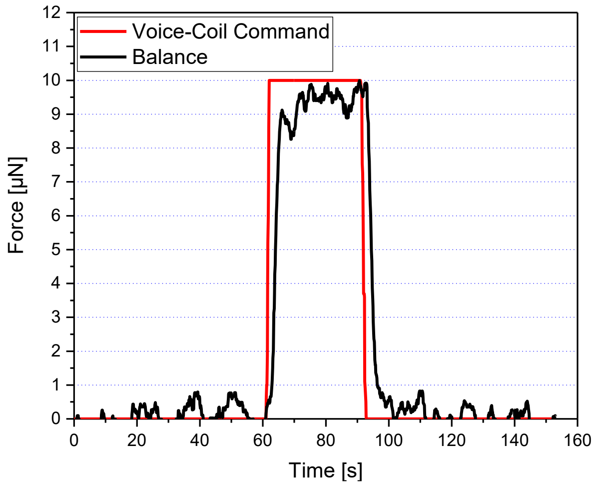
Fig. 2 Balance Setup



a) Voice-Coil below Experiment Box



b) Balance Linearity



c) Balance Response at 10 µN (=1 mg)

Fig. 3 Balance Calibration

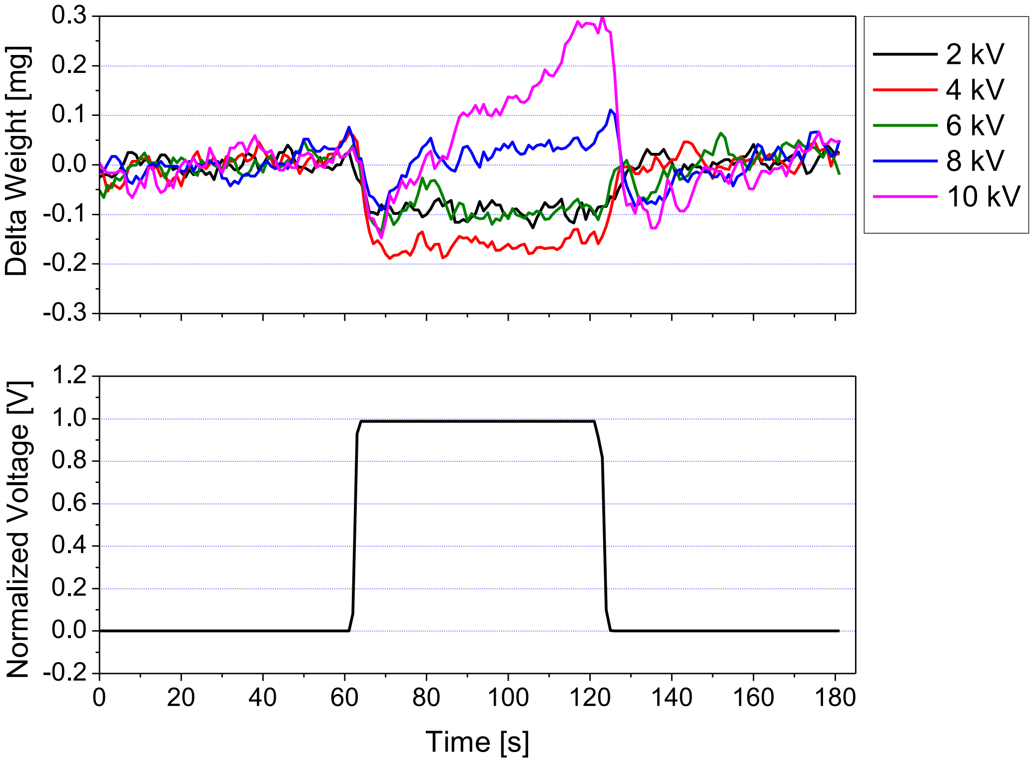


Fig. 4 Setup Verification

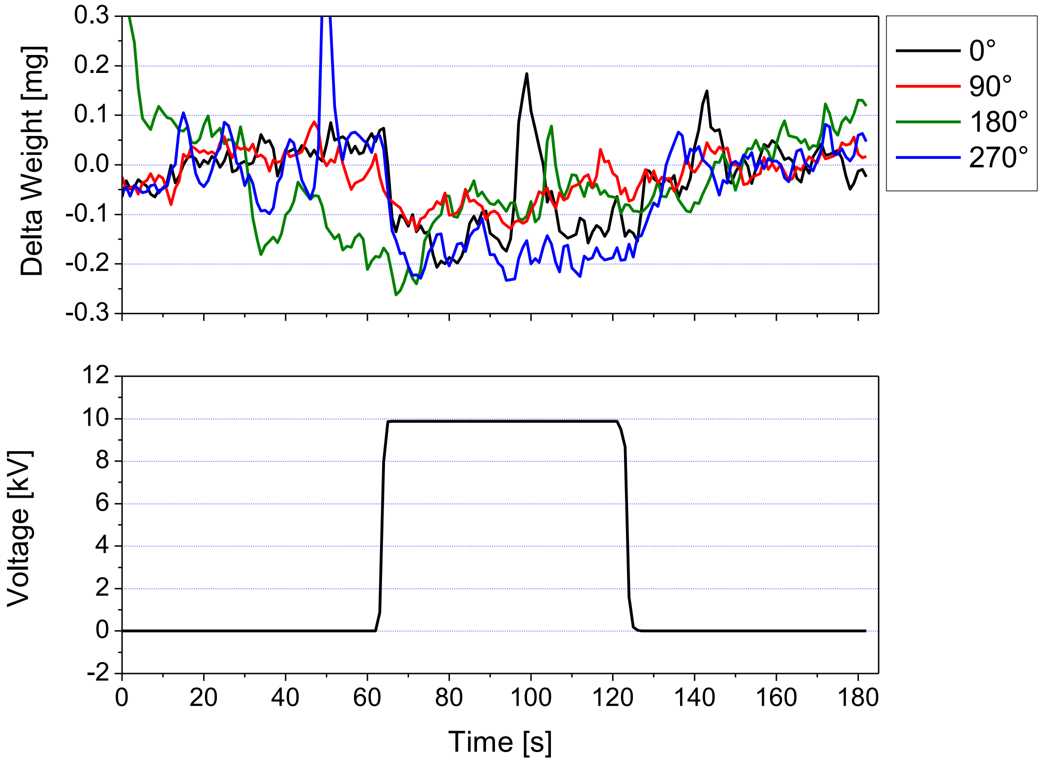
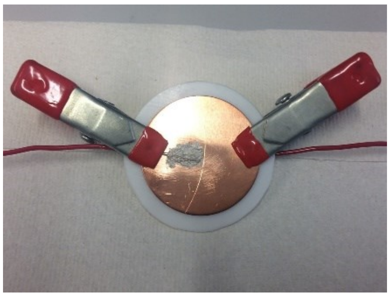
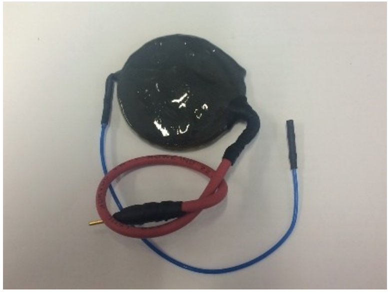


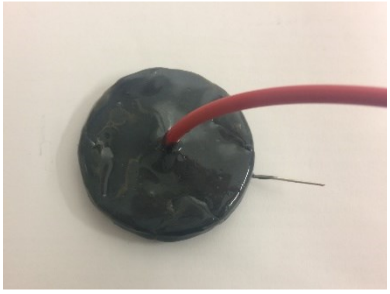
Fig. 5 Weight Change of High Voltage Ceramic Capacitor



a) Building Capacitor



b) Symmetric Capacitor



c) Asymmetric Capacitor

Fig. 6 Teflon Capacitors

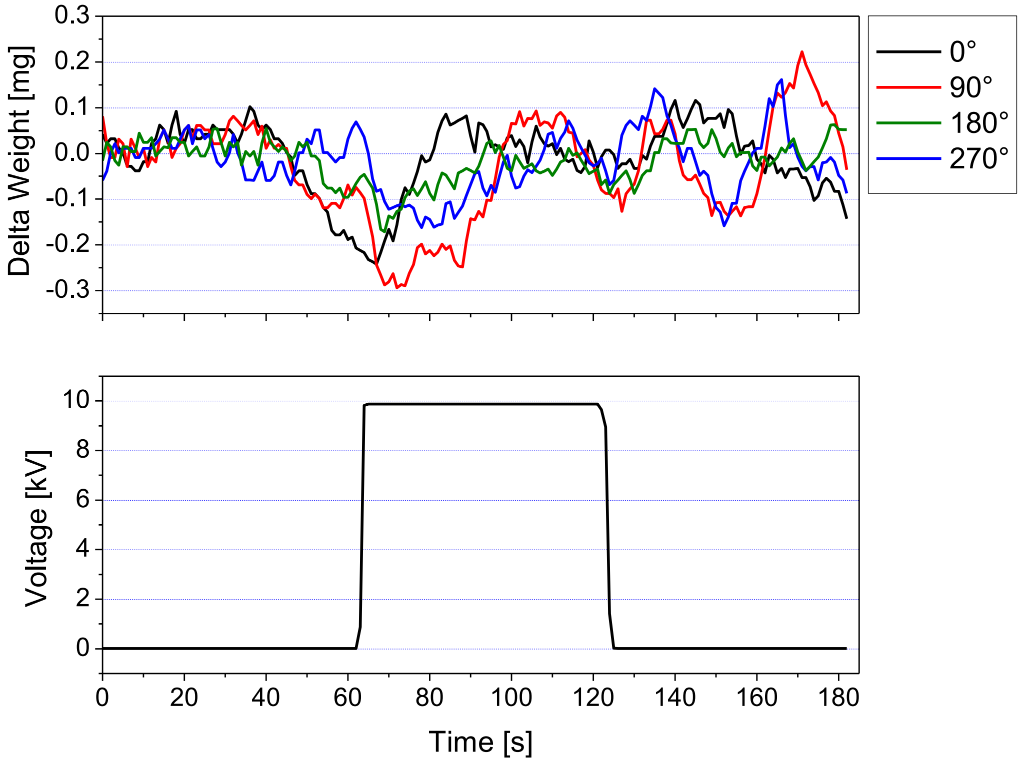


Fig. 7 Weight Change of Symmetric Teflon Capacitor

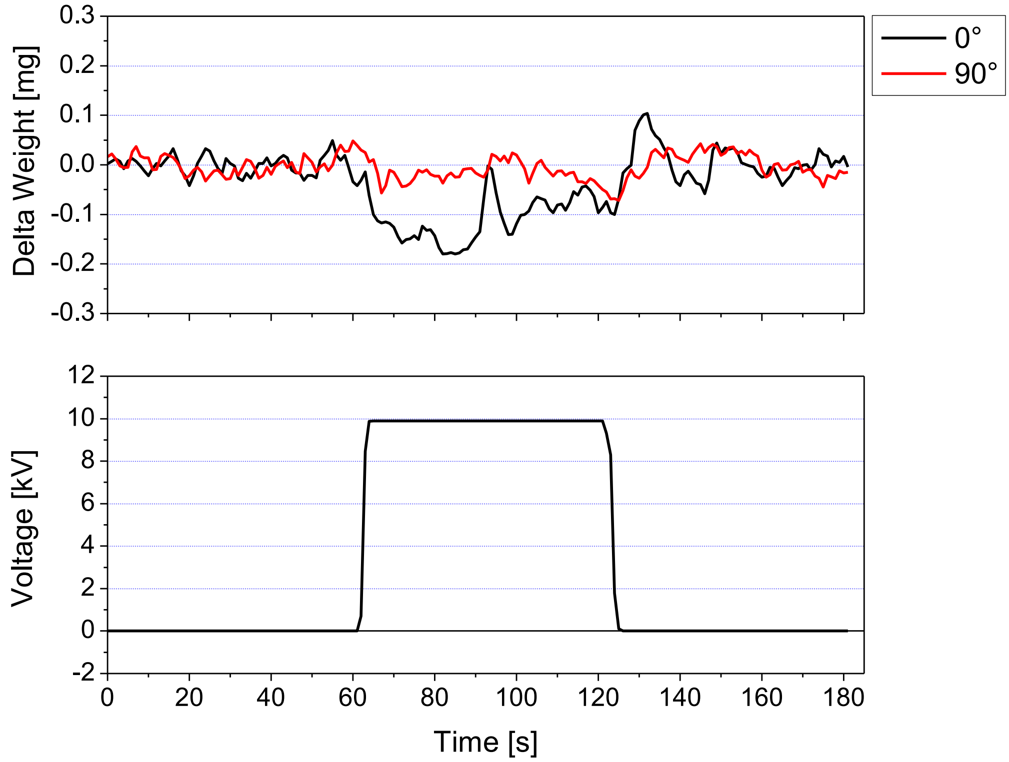


Fig. 8 Weight Change of Asymmetric Teflon Capacitor

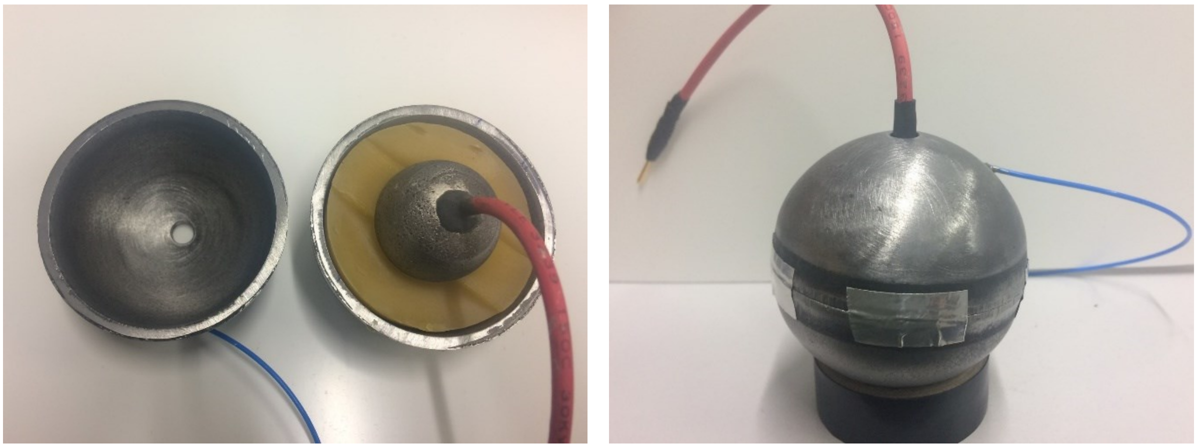


Fig. 9 Spherical Capacitor with Wax Dielectric in Bottom Half

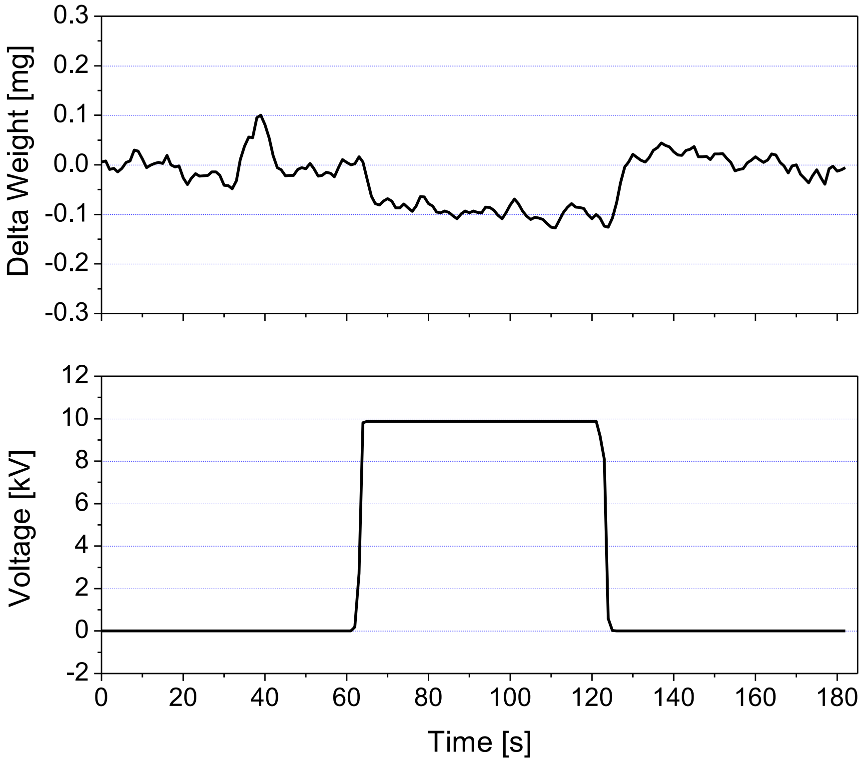


Fig. 10 Weight Change of Spherical Capacitor

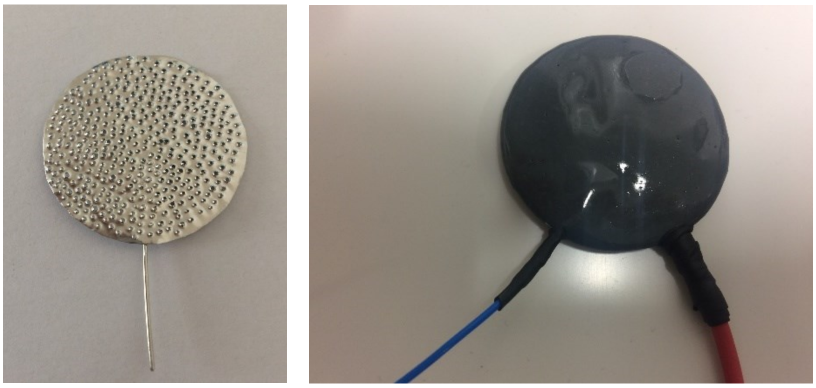


Fig. 11 Leakage Current Capacitor with Perforated Cathode

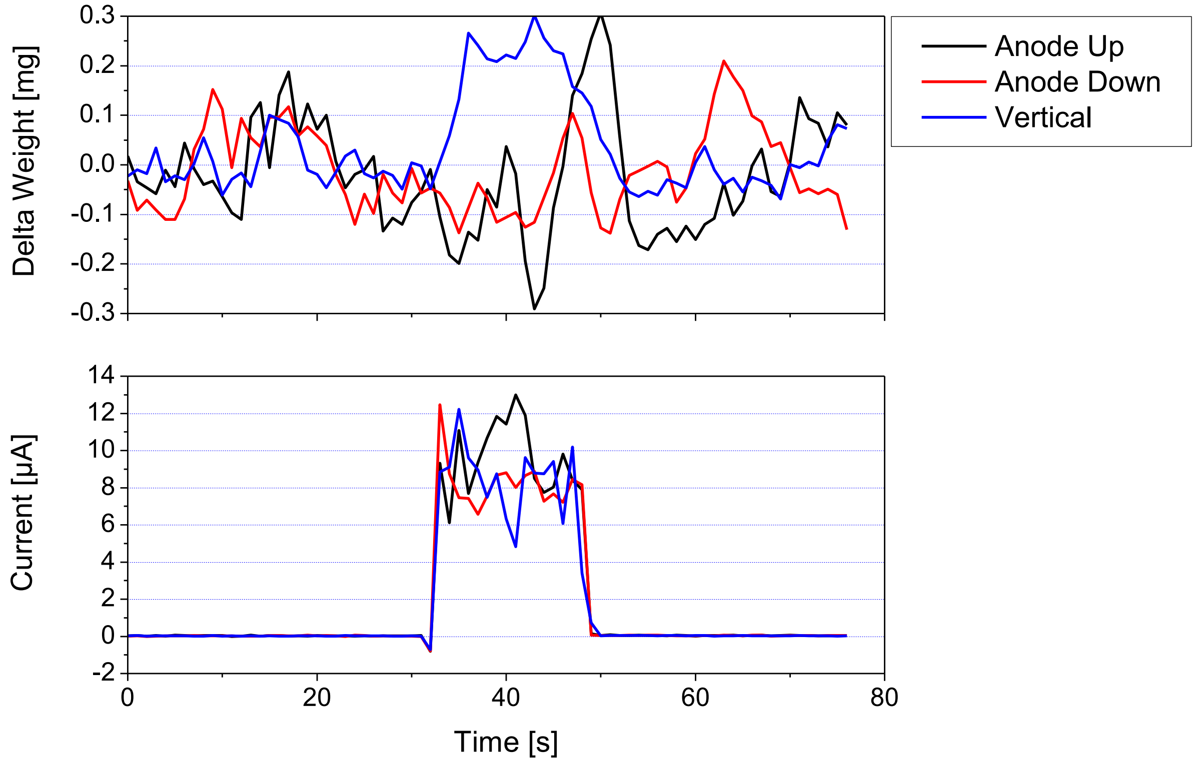


Fig. 12 Weight Change of Leakage Capacitor at 2100 V