CAPACITIVE GAP DISTANCE CONTROL IN PIN-PLANE ELECTRODE DC SPARK SYSTEMS AT CERN

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Abstract

Capacitive inter-electrode gap distance measurement and control has been implemented into DC Spark System II, used by the DC Spark Study to conduct vacuum electrical breakdown experiments as a complement to breakdown experiments in RF accelerating structures. The implemented system is described, along with the calibration measurements needed for its use. Sources of experimental uncertainty in gap distance were investigated. It was found that the lowest relative uncertainty of gap distance the system is capable of achieving is 3%, or an absolute uncertainty of about 1 µm for a 30 µm gap.
1. Overview

This document describes the system currently in place in DC Spark System II for the monitoring and control of inter-electrode gap distance. It includes descriptions of how the system works, of the development work that was done to get it to its current state, and of conducted investigations of possible error sources.

The system consists of a pin-shaped anode with a rounded tip moved longitudinally by a linear stepper-motor. It is matched with a planar cathode perpendicular to the anode. Inter-electrode capacitance is measured and used to monitor and control inter-electrode gap distance. To enable this, two acts of calibration are needed: That of the anode pusher and that of gap capacitance. Calibrating the anode pusher is the mapping of the relationship between number of steps taken by the stepper-motor and the longitudinal position of the anode. This enables calibration of gap capacitance, which is the mapping of the relationship between gap distance and gap capacitance with the anode placed over a specific point on the cathode (hereafter referred to as cathode spot).

Electrode contact altering the cathode surface at the measurement spot has been an issue in previous experiments using the DC spark systems. The capacitive gap control system allows for gap distance control with minimal contact between the electrodes. A single slight contact is made during the calibration, after which the gap can be set and controlled at the current cathode spot without further contact. Certain experiments might require that no contact whatsoever be made between the electrodes at the measurement spot. This can be accomplished by performing the calibration at a calibration spot and the measurement at an adjacent, pristine measurement spot. Doing so comes at an increase in gap distance uncertainty. The possibility of completely contactless calibration was also investigated but found to be unfeasible.

This document also describes the LabVIEW virtual instrument StepMotorControl_Anders_6.vi, which is at time of writing the latest system control software.
2. Background

The *DC Spark Study* is a study taking place at CLIC under the leadership of Walter Wuensch. Its purpose is to provide an alternative to using radio-frequency (RF) prototype accelerating cavities for breakdown studies. The study is conducted using so-called *DC Spark Systems*, in which breakdown takes place in ultra-high vacuum between electrodes placed tens of μm apart. With the application of kV voltages over the electrode gap, the resulting inter-electrode electric fields are of hundreds of MV/m, which is the order of magnitude of the surface electric fields accelerating cavities are subjected to if CLIC is built according to current specifications. Hence, the DC Spark Systems allow for the creation of the electric conditions that cause breakdown. The systems provide an experimental environment which has a number of advantages over the RF test stands at CERN, such as lower hardware cost, higher measurement repetition rate, control of experimental conditions, and study of the breakdown plasma and the electrical characteristics of the breakdown process.

Two of the systems in use, named *DC Spark System I* and *II*, use electrode setups where the cathode is planar and the anode is pin-shaped with a rounded tip. The cathode is mounted on a tray which is movable in two dimensions along the plane, while the anode is mounted on a pusher which allows it to be moved in one dimension perpendicular to the cathode plane. The electric field in the gap is directly proportional to the voltage applied over the gap and inversely proportional to the gap distance as $E = V/d$. As $E$ cannot be measured directly, $d$ must be known to calculate it, and be kept constant to maintain the value of $E$.

Prior to the performance of this work, the gap would be set in both systems by moving the anode manually with a micrometre screw into contact with the cathode (as determined by using the probe mode of an electrical multimeter), and withdrawing it the desired amount. Such a method is inadequate for a number of reasons. As the anode tip hits the cathode with considerable force, it might alter the surface and thus affect the breakdown process. More importantly, setting the gap manually in such a way is inaccurate and provides no way to verify or monitor the gap distance, or stabilize it via feedback control under circumstances in which it may change over time, such as from thermal expansion of the electrodes in measurements of temperature dependency on breakdown rate. To address all these issues, a system was developed that uses the inter-electrode capacitance to measure gap distance and a stepper-motor to move the anode, forming together a negative feedback loop.
3. Description of the system

The system moves the anode by a stepper motor (PM600 Motion Controller, McLennan Servo Supplies Ltd) that pushes the anode via the mediation of a gearing system. The gearing system converts the steps made by the stepper-motor to smaller steps of movement by the anode, improving the resolution with which the gap can be set. The stepper-motor makes steps of a constant length of 1 µm. The resulting steps in anode position are in the order of 0.1 µm.

The stepper-motor is provided by the supplier together with its own standard rack-sized control electronics box, which provides the stepper motor with power and its control signal. The control box communicates with a PC by ASCII commands via an RS232 serial port.

The gearing system consists of a series of plates connected via sapphire balls, pushing each other in a sequence. The gearing system was originally designed by Mauro Taborelli.

Image 1: Stepper-motor, integrated into flange with vacuum feedthrough

The range over which the stepper-motor is able to move is set by a pair of limit switches that trigger when a limit is hit, preventing the further movement of the stepper motor beyond the limit. Changing the position of the limit switches causes the need to recalibrate the stepper-motor. At the time of writing, the stepper-motor has a movable range of about 3.75 mm, corresponding to a range of about 380 µm for the position of the anode. The range has been set to be redundantly large to avoid the need for repositioning the switches in the future.

Inter-electrode gap capacitance is measured by a precision LCR bridge capacitance meter, HP 4284A by Hewlett-Packard, which communicates with a PC through a GPIB interface. LabVIEW programs that interact with both the stepper-motor and the capacitance meter are used to create a closed feedback loop for gap control and provide an integrated user environment.

Conducting high-voltage experiments in the system would interfere with gap control and possibly damage the hardware used for the purpose. Thus, gap control and high-voltage application must be alternated, which required disconnecting the capacitance meter before applying voltage. Completely automated measurements that require active switching between voltage application and gap control can be done, but require a further hardware upgrade in the form of a switching system.
4. Calibration of the anode pusher

3.1. Overview of anode pusher

A new calibration of the anode pusher must be carried out whenever the limit switches are moved, or other physical modifications made that could be expected to change the relationship between stepper-motor steps taken and anode longitudinal position.

The anode pusher has twice been calibrated at the CERN metrology workshop with the assistance of Didier Glaude, at 16.4.2013 and 15.11.2013. The latter calibration was carried out after the limit switches were moved in order to expand the range of anode position. The latter calibration is valid for the system in its state at time of writing. The former calibration measurement is presented as well, as it was accompanied by an investigation of hysteresis, the results of which have certain implications regarding the proper use of the system.

The stepper-motor keeps internally track of its position by the use of a variable called step count. In this section, movement in the positive step count direction (towards the cathode) will be referred to as upward movement, and movement in the negative direction respectively as downward movement. Step count is incremented (resp. decremented) by one whenever a step upward (resp. downward) is made by the system. It thus acts as an effective longitudinal position coordinate of the stepper-motor, as backlash and other hysteresis effects in the stepper-motor itself are minimal relative to the step length of 1 µm.

The control electronics of the stepper-motor define step count to be zero at the moment power is turned on to the system. In this work, however, for clarity, we define step count to be zero at the lower bound of the range of the stepper-motor.

3.2. Hysteresis study

The entire range of the stepper-motor was 1635 steps. The measurement was started at the lower bound of the range. From there, it was moved upwards in increments of 10 steps, measuring anode tip position relative to its original position after each increment. Upon hitting the upper bound of the range, the direction of measurement was reversed and the stepper-motor moved back to the lower bound, after which it was again moved up and finally down again, giving four calibration curves.

![Figure 1: Four calibration curves measured at the anode pusher calibration 16.4.2013](image)

The distance the anode tip moves for each stepper-motor step increases from about 0.06 µm at the start of the range to about 0.10 µm at the end. The difference between curves Up 1 and Up 2 indicate a
standard deviation of 0.33 µm in anode tip position, for a given step count from the lower bound. Comparing the mean of both Up curves with the mean of both Down curves shows a maximum hysteresis of 3.4 µm. These numbers are only valid for this particular stepper-motor range, but give a general indication of the scale of the uncertainties present in the system.

A further study of hysteresis, which we call the back-and-forth study, was conducted as follows: Each step count multiple of 100 in the range had its corresponding anode tip position measured twice, first by approaching it from below by moving 100 steps upward to it, then from above by moving another 100 steps up after which back down again by 100 steps. Afterward, the entire measurement series was repeated.

![Figure 2: Hysteresis test, approaching the same step count value from 100 steps below or above. Approaching from above consistently yielded a higher value of anode tip position than approaching from below, the difference between the two at each step count shown.](image)

As can be seen from Figure 2, hysteresis reached over 1.6 µm at worst, and varied significantly over the range, but was remarkably identical between the two repeat measurements. Of the two, measurement 2 consistently yielded lower values of anode tip position, a difference that averaged to 0.42 µm, a value consistent with the previously obtained standard deviation of 0.33 µm.

To complement the back-and-forth study, another like it was carried out between step count values 900 and 1000, for approaches of 10 steps from above and below. It was only carried out once.

![Figure 3: Back-and-forth study in the step count range 900 to 1000, for approaches of 10 steps.](image)
We see from Figure 3 that the magnitude of hysteresis is effectively constant within the resolution of the measurement. The magnitude of hysteresis is smaller by about a factor 3 or 4 than in the same range in the previous measurement, presumably due to the approaches being only 10 steps as opposed to 100.

Together, the three measurements presented in Figures 1-3 suggest that using a direct one-to-one correspondence between step count and anode tip position should not be used for gap distance control, due to hysteresis effects of a magnitude of over 1 µm being present, and depending on stepper-motor movement history in complex ways. Thus, the correspondence between step count and anode tip position shown by the calibration curves in Figure 1 only apply as long as one is moving monotonically upwards from the lower bound. This suggests that the proper way to carry out gap distance control is to use the correspondence between step count and anode tip position where it is known in order to map the correspondence between gap distance and gap capacitance, and afterward use only gap capacitance as a control input and ignore step count.

3.3. Final calibration measurement

The latter calibration measurement done on 15.11.2013 did not repeat any of these investigations of error. Consistent with the conclusions described above, a calibration curve was measured by moving monotonically from the bottom of the range to the top. The entire range had a length of 3750 steps, corresponding to a range of about 380 µm for anode tip position. The movement was done in increments of 50 steps at a time. The measurement was repeated 10 times to obtain a more precise average calibration curve and to provide an estimate of uncertainty of anode tip position as a function of step count.

![Figure 4: Calibration curve measured 15.11.2013. 10 measured curves were used to obtain an average curve and an estimate of anode tip position uncertainty as a function of step count.](image)

The obtained calibration curve has a visibly wavy shape, with the waves appearing in roughly the same way in every individual measured curve and in the average. This suggests that they are a systemic feature following from the mechanics of the gearing system. We observe that the uncertainty in anode position increases with step count, presumably due to the compounding of added uncertainty at every step taken on the way. We finally note that anode tip position remains largely unchanged at the very bottom of the range. These observations together suggest that measurements using the system should be conducted in the lower end of the range of the stepper-motor, though not at the very bottom. A suitable example range would be from step count 250 to 1350, giving an anode tip position range of about 100 µm. This sub-range has a mean anode tip position uncertainty of 0.79 µm, as opposed to 1.04 µm for the entire range.
The number of waves observable on the calibration curve suggest the use of a sixth degree polynomial for relating step count to anode tip position. The best possible sixth-order polynomial fit gives a root mean square error of 0.98 µm between the measured average calibration curve and the polynomial. Its fit parameters are given below.

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<th>Parameter</th>
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<tr>
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</tr>
<tr>
<td>$a_7 x^0$</td>
<td>-1.867</td>
</tr>
</tbody>
</table>

Table 1: Calibration parameters for the anode pusher, determined 15.11.2015 and valid for DC Spark System II at time of writing.
5. Calibration of gap capacitance

With the anode pusher being calibrated, gap distance can be calibrated. While a single anode pusher calibration is sufficient and can be used until the anode pusher is physically altered, gap distance needs to be calibrated separately for each electrode pair used, as the functional form of the capacitance-distance relationship differs significantly between different pairs, as well as between different cathode spots for one electrode pair. This is unfortunate since it prevents completely contact-less gap control, but understandable when one considers that typical electrode gaps are on the order of tens of µm, which is of the same or a nearby order of magnitude as the surface roughness and shape irregularities one can expect of the electrodes.

When moving the anode tip towards the cathode one step at a time, contact can be inferred from the capacitance meter suddenly turning volatile and starting to show extreme values. A test for contact that has been used successfully is to check whether the last measured capacitance value is either negative or more than twice the second-last value measured, and deem it to be in contact if either one of these two conditions is fulfilled.

The calibration of gap capacitance is done by carrying out the following steps:

1. The anode is pulled back all the way to the lower end of the range.

2. The cathode tray is manually moved until it can be expected to be a comfortable distance from the anode tip, a few tens of µm farther than the gap distance one intends to set. This is ultimately a matter of trial and error, but one can get it roughly right by looking at gap capacitance displayed in real-time by the capacitance meter, and rely on previous experience of the relationship between gap distance and capacitance. Given reasonable caution not to force the electrodes into contact, this part should at worst be time-consuming.

3. The anode tip is moved one step forward at a time, measuring and recording capacitance after each step. This creates a table of values for gap capacitance as a function of anode tip distance from the lower end of the range. This is done until the electrodes are deemed to be in contact. This calibration measurement can be done automatically by StepmotorControl_Anders_6.vi.

4. When contact has been achieved, we know that the gap distance when the anode is at the lower end of the range is equal to the total distance we moved to get into contact. Knowing that distance together with the table of capacitance values at different distances from the lower end of the range, we can calculate a corresponding table of values for capacitance at different gap distances.

Thus, one has obtained a calibration table of values for capacitance versus gap distance. It can be used to obtain a gap distance value corresponding to any capacitance value, and thus convert a measured current value of capacitance to a current value of gap distance. Conversely, if one wishes to set and maintain a chosen gap size, one can obtain the corresponding capacitance value and use negative feedback control to stabilize capacitance at that value. StepmotorControl_Anders_6.vi carries out gap control by fitting a second-order polynomial to the calibration curve in a region of gap distance set value ± 2 µm, and computes an adjustable-size, corresponding acceptable interval of capacitance values.
Figure 5: An example of a gap capacitance calibration curve, measured and displayed by StepmotorControl_Anders_6.vi
6. Investigation of error sources

5.1. Uncertainty of gap capacitance calibration

To find out the uncertainty of gap capacitance calibration, and thus the uncertainty of a set gap size, gap capacitance calibration was repeated five times at the same cathode spot. The resulting calibration curves are shown below.

![Figure 6: Five gap capacitance calibration curves measured successively with the same anode at the same cathode spot.](image)

Uncertainty was estimated by using the measured calibration curves and simulating the process by which *StepmotorControl_Anders_6.vi* determines the capacitance corresponding to the desired gap size: A second-order polynomial is fit to a region of ± 2 µm around the gap distance set value. Doing this to the set of five calibration curves gives a set of five capacitance values. The standard deviation of this set of capacitance values, together with the derivative of the calibration curve at this value (as obtained by the fit polynomial), gives a corresponding standard deviation of gap distance values. This simulation was performed at gap distances from 10 µm to 45 µm to map how relative and absolute uncertainties vary with gap distance set value.

![Figure 7: Relative and absolute uncertainty in gap distance at different values of it. Shown are measured absolute uncertainties, a third-order polynomial trendline, and a corresponding relative uncertainty trendline.](image)
As can be seen from Figure 7, absolute gap distance uncertainty increases with gap distance, though not in linear proportion to it. It is noteworthy that about up to 30 µm, gap distance absolute uncertainty is about the same as that of anode tip position as a function of step count in the lower half of the movable range of the stepper-motor (Figure 3). Hence, in this region, the calibration of gap capacitance does not add additional uncertainty to gap distance control. After about 35 µm, absolute uncertainty starts to rise rapidly due to gap capacitance becoming less responsive to gap distance.

Consequently, it can be concluded that if one needs to minimize absolute uncertainty in gap distance, the smaller the gap the better, with the lowest uncertainty being approximately 0.6 µm at a gap distance of 10 µm. However, if one wishes to minimize relative uncertainty in gap distance (as is usually the case), one should use gap distances in the region 30 to 35 µm, where the gap size assumes a relative uncertainty of about 2.8%.

5.2. Added uncertainty from using different calibration and measurement spots

As previously mentioned, conducting a completely contact-free measurement requires performing gap capacitance calibration at one cathode spot and calibration at another. To determine possible added uncertainty from doing so, calibration curves were measured on a 5x5 square grid of cathode spots of a grid square side length of 2 mm. Hence, a total of 25 calibration curves were measured over an area of 8 mm x 8 mm. The cathode used was rectangular with a height of 45 mm and a width of 10 mm.

It was discovered that moving horizontally across the cathode changed the capacitance-distance relationship significantly more than moving vertically along it, presumably due to the edge of the electrode. This difference between moving in the vertical or horizontal direction was made the basis for the data analysis that followed. The 25 spots were grouped into 10 sets of 5 points each, each point belonging to a vertical and a horizontal set of spots. Thus, we had 5 non-overlapping sets of 5 horizontally aligned spots each; and regrouping the spots, 5 other non-overlapping sets of 5 vertically aligned spots each. Each one of these 10 sets was subjected to the analysis described in section 5.1. The resulting relative and absolute uncertainties were averaged over all horizontally, resp. vertically aligned spots, and are presented in Figure 8.
As Figure 8 shows, the horizontal sets of spots caused much larger relative and absolute uncertainties, with absolute uncertainty growing almost linearly with gap distance, and relative uncertainty consequently being rather constant in the 12% to 14% range. This result should be generalizable to any move of cathode spot along an axis on which there is a nearby electrode edge. The vertical sets of spots, for which any edge effect should be negligible in comparison, consequently show lower uncertainty, and trends of uncertainty as a function of gap distance similar to those in section 5.1 and Figure 7. However, the lowest obtainable relative uncertainty turned out to be about 5%, about twice the relative uncertainty achievable by performing gap capacitance calibration and gap distance control at the same cathode spot. As edge effects should be negligible in this case, the difference is probably mostly caused by differences in cathode spot microgeometry.

5.3. Mechanical gap distance fluctuation

When measuring capacitance, one notices certain fluctuation in the capacitance value displayed by the capacitance-meter. For this reason, when measuring capacitance, it is good practice to average over a number of readings provided by the meter, in order to average out the fluctuation. In StepMotorControl_Anders_6.vi one can adjust the number of readings averaged over, with 10 being a good rule of thumb, making obtaining a capacitance value take approximately one second.

However, the presence of the fluctuation raises the question of whether it is electrical noise, or an actual mechanical vibration that causes the real value of gap distance to fluctuate and capacitance to fluctuate accordingly. To investigate this, the magnitude of the fluctuation was measured at a number of different
gap distances. As can be seen from e.g. Figure 5, the gradient of capacitance with respect to gap distance varies greatly as a function of gap distance, with the gradient being largest when gap distance is small and smallest when gap distance is large. Hence, if there is a mechanical fluctuation of a given magnitude in gap distance, it would correspond to a larger fluctuation in capacitance when gap distance is small than when gap distance is large. Thus, by measuring the magnitude of the capacitance fluctuation at different gap distances, one can infer whether the fluctuation in capacitance is electrical or mechanical in origin.

As we see from Figure 9, the difference in the magnitude of capacitance fluctuation at different gap distances is negligible and does not show the trend that would be expected if the fluctuation was mechanical in origin. Thus, we can conclude that vibrations or other mechanical short-term fluctuations in gap distance are not present in the system to any significant degree.

5.4. Long-term mechanical gap distance drift

A final possible source of experimental uncertainty that was investigated was longer-term drift in gap distance, after having set a gap and then turned off feedback control. This was done by measuring a gap capacitance calibration curve, setting the gap to a suitable value, and automatically measuring gap capacitance every minute for about 40 hours. The measured gap capacitance values were converted to corresponding gap distance values, and the time-series of gap distance versus time analyzed.

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Figure 10 shows how gap distance is expected to drift over time, showing expected gap distance change in root mean square terms, as a function of time waited. We note a dip almost to zero at 24 hours, suggesting that the cause of the drift is diurnal, probably a diurnal temperature variation in the laboratory environment. We see that this effect can add as much as about 1 µm more uncertainty to gap distance over the course of long measurements. This suggests that during such long measurements, gap distance should regularly be verified, either by regular temporary resumptions of feedback control or a full recalibration of gap capacitance.
7. Conclusions and Recommendations

Capacitive gap distance control as currently implemented in DC Spark System II is capable of setting intra-electrode gaps with a relative uncertainty of about 3% and an absolute uncertainty of about 1 µm, for a gap of distance 30 µm. Thus, unless there is a compelling, measurement-specific reason to choose otherwise, 30 µm should be used as gap distance. Achieving this accuracy requires making a single, slight contact between the electrodes at the measurement spot as part of the calibration process. Furthermore, once set, gap size has been found not to be subject to drift in the short term, thus the aforementioned precision should be achievable despite the fact that gap distance monitoring and control cannot be engaged simultaneously with the application of voltages over the electrodes.

Completely non-contact gap distance control at a measurement spot is possible at the expense of higher gap distance uncertainty, with the lowest attainable relative uncertainty being about 5%. This accuracy requires the mitigation of edge effects, and thus cathodes which are fairly large at least in the direction moved from calibration spot to measurement spot. The 12 mm disc electrodes that are currently the main samples used in DC Spark System II are certainly too small for the purpose.

Whether the precision in gap distance obtainable by capacitive gap distance control is satisfactory would depend on the experiment in question. For example, if breakdown threshold fields are measured, a 3% relative uncertainty in gap distance would directly cause a 3% uncertainty in threshold field, which probably would be precise enough. However, in measurements of actual breakdown rate, given that breakdown rate is thought to be proportional to electric field strength to the power 30, a 3% difference in gap distance would change breakdown rate by as much as a factor $1.03^{30} = 2.43$.

After having reduced gap distance uncertainty by best practices, the remaining uncertainty is mostly caused by the mechanics of the gearing system of the anode pusher. Thus, if higher precision is required, it might be worth investigating the possibility of using a piezoelectric actuator instead for pushing the anode. Piezoelectricity offers the advantages of high precision, high spatial resolution and low hysteresis.

However, the recent trend of the DC Spark Lab has been to move towards the use of the so-called Large Electrode Systems (or, in older terminology, Fixed Gap Systems). These offer several advantages, one of them being easy, reliable and precise gap distance control by stacking disc-shaped electrodes and ceramic spacers. Before making upgrades to either DC Spark System I or II, it should be considered whether the intended experiments can be satisfactorily performed in a Large Electrode System.