Dependence of PD pattern from a stator coil on recent excitation

Nathaniel, 2007-03-04

Introduction

Needs and Aims

Results of PD measurements can be very significantly dependent on the history of the test-object and on ambient conditions. For example, maximum and mean PD charge have been seen in the cases investigated here to vary by several *times* depending on whether there has or has not recently been HV excitation of the test-object prior to a measurement being made.

Factors seen as likely to have effect upon PD measurements include:

> Long term effects: irreversible aging due to prior PD activity.
>
> Short term largely reversible effects: charging of dielectrics and surfaces, presence of ions and reactive chemicals in a cavity, and gas-pressure and temperature due to PD activity.
>
> Ambient effects: temperature, long-term humidity and gas composition.

For simple diagnostic measurements, as commonly practised in industry with power-frequency PR-PD measurements, one is generally interested in comparing measurements at a single frequency and a few voltages with those from a previous date or from other similar apparatus. The pattern (visually interpreted) and a maximum PD value are the most important quantities, and differences have to be severe to cause excitement; a company generally has a standard measurement method that makes the history likely to be quite similar between different occasions, e.g. power-frequency tip-up measurements are followed by PD measurements after the time needed for reconnecting the measuring apparatus.

For laboratory use with our varied low-frequency interests, a "bigger deal" will be made of the interpretation of differences between between occasions and between different V-f (voltage amplitude and frequency) points, making use of indices such as mean charge, maximum charge, total charge, number of discharges and change in complex capacitance due to the PD's polarisation. The sequence of V-f points used is likely to vary depending on time-constraints and the range of these variables of interest in a particular case. These points make the short-term effects of excitation upon following measurements important for us to consider.

Earlier measurements on thermally aged stator coils, comparing results from sequential and randomised V-f points, have suggested a strong effect of the foregoing measurement, with HV LF (high V, low f) ones apparently having the largest effect on the next; this led to the idea of trapped charge or polarisation in the material as being of importance.

The ideal value from such a PD measurement, in order best to reflect the physical consequences of a particlar V-f excitation, is:

> "The result one would obtain if this V-f excitation had been applied for so long before making the measurement that the system of insulation and cavity is in equilibrium, without any trend between cycles."

If this cannot reasonably be approximated, due to the need to keep the measurement time acceptable for measurement of tens of V-f points, or due to irreversible aging being significant in the timescale needed for reversible effects to equilibriate, then one can consider:

> "How should I perform and describe my measurements so that I can make meaningful comparisons between different measurement points and measurement occasions, confident that a different ordering of the measurements, or a different recent history before the measurements began, would not make more than x difference?"

The test-object and measurement system

The test object is a form-wound stator coil 'B2' made for a 7.2kV motor, subjected from newly cured condition to 4 weeks at 160°C. Several DS and PD measurements have already been made, subjecting the test object to maximum 9kV peak excitation.

The coil was connected with HV applied to the internal conductors; the conductors' ends were joined together with adhesive copper tape, and a stress-reducing metal cap was used on the connection to the conductor ends. The outer semicon of the coil was wrapped with aluminium foil, bound with tape, and the end of each of the slot-sections closest to the end where the conductors emerge was connected to earth through the detection impedance [what is this? — values?].

The four 2mm guard-bands near the ends of the slots were covered with conductive-gummed copper tape which was then rubbed firmly against the insulation surface; the same treatment on unaged coils gave negligible PD, i.e. only some few % of the amount of charge that would be measured on the aged coils. The coupling capacitors were two parallel 100pF ones, and the HF circuit of coupling capacitors, connections to the coil, measuring impedance and earth connections had an area in the order of 1m^2. Subcritically but well-damped oscillations (about two cycles visible, time of 10μs) seen on the oscilloscope led to the use of a 20μs dead-time.

Scope of experiment

PD measurements are made several times after some low and some high frequencies of applied voltage.

So far, there are many questions (desires for further measurements) raised by the results: more work is needed before formulating a "best practices" advice or going seriously into analysis of the underlying phenomena. Some limitations in the work reported here are:

Only one test object is used here; different types of cavity and material may behave quite differently.

Only short-term effects — timescales of minutes to an hour — are considered; the large changes noticed from these are assumed to make the long-term changes negligible, and measurement points are repeated as a check.

Ambient temperature was not controlled, though was around 20°C (±4°C is a safe claim based on occasional measurements made in the lab).

Only two amplitude-frequency measurement points, 9kV 10Hz and 9kV 1Hz, have yet been used for the comparisons.

Seeing directly how much variation occurs within the first cycles of a measurement, i.e. the time-development, is impractical at this frequency, 10Hz, with our equipment: several seconds elapse between consecutive measurements, and all cycles in a single measurement are treated together in the analysis equipment.

A lot of discharges are near the minimum threshold of detection, so a modest reduction in PD magnitude, e.g. by making PD easier to occur by much free charge, could result in smaller numbers of PDs and smaller total charge being measured even if the values are in fact similar or greater.

The measurement system is thought to have some bias in its amplification, making negative PD charge register as greater than positive. This is important mainly to any attempt to interpret the different in $+$ and $-$ charge per cycle that is displayed in the following figures.

Original expectations

Not very definite! Based around simple reasoning and the observation from some randomised V-f sweeps, that a LF excitation seems to increase the measured PD (when seen as capacitance) of a following measurement.

Charging of dielectric/cavity? The result may be strong initial discharge during the next measurement's first cycles; expect that higher V and lower f (more charging) of preceding point increase the effect.

Presence of charge, active chemicals, heat, more carbonised surfaces, in cavities, remnant from previous PD. The result of easily available charge and heat would be to facilitate PD and therefore to give more, smaller PDs rather than fewer, larger as in the case of difficult inception; total charge is not expected to change much (guess: some 10 %) over the frequency range (10Hz–1mHz). Result of more carbonised (or, generally, more conductive) surfaces would be to reduce total PD charge at lower frequencies, as charge is conducted away.

The effect of HF excitation was expected to be short term, in the order of seconds or less, and this to be less important than the matter of charging by LF. (It seems both of these expectations are wrong, at least for this object.)

One can only start speculating on the nature of the cavities (many, similar sizes, how different in 'aspect ratio': the nature of PD sources in this object is not well-known, and there are many that may have very different characteristics.

Results

Prior excitation by high-frequency, low-frequency or nothing.

This is a comparison of the effects of charging (e.g. trapping in surfaces, polarisation mechanisms) with other effects of general PD activity (ionisation, chemical by-products, heat). The former effects are expected to be increased by low-frequency pre-excitation, and the latter ones by high-frequencies.

Set `b2pd06` consisted of 9 measurements at 9kV, 10Hz, 200s. The first was made when no excitation had been applied for several hours. Then the subsequent measurements were alternated with excitations at HF (9kV, 20Hz, 100s) and LF (9kV, 1mHz, 1000s). The pattern was:

`none,meas,HF,meas,HF,meas,LF,meas,LF,meas,HF,meas,HF,meas,LF,meas,LF,meas`

Set `b2pd07` was a repitition of `b2pd06`, after a delay of some 3h.

PR-PD patterns Some example PD patterns are shown here (figures 1, 2, 3), all measured at 9kV 10Hz 200s. The most visually striking difference is between no pre-excitation and some pre-excitation, rather than between the low and high frequencies. All eight of the LF pre-excitation cases were very similar to each other, and likewise the HF cases. but there is a perceptible difference between the LF and HF cases so that if any HF-LF pair were compared it would be possible to distinguish them. The LF pre-excitation gave more high-charge PDs around the zero phase ($V(t) = 0$). This makes it closer to the case of no pre-excitation.

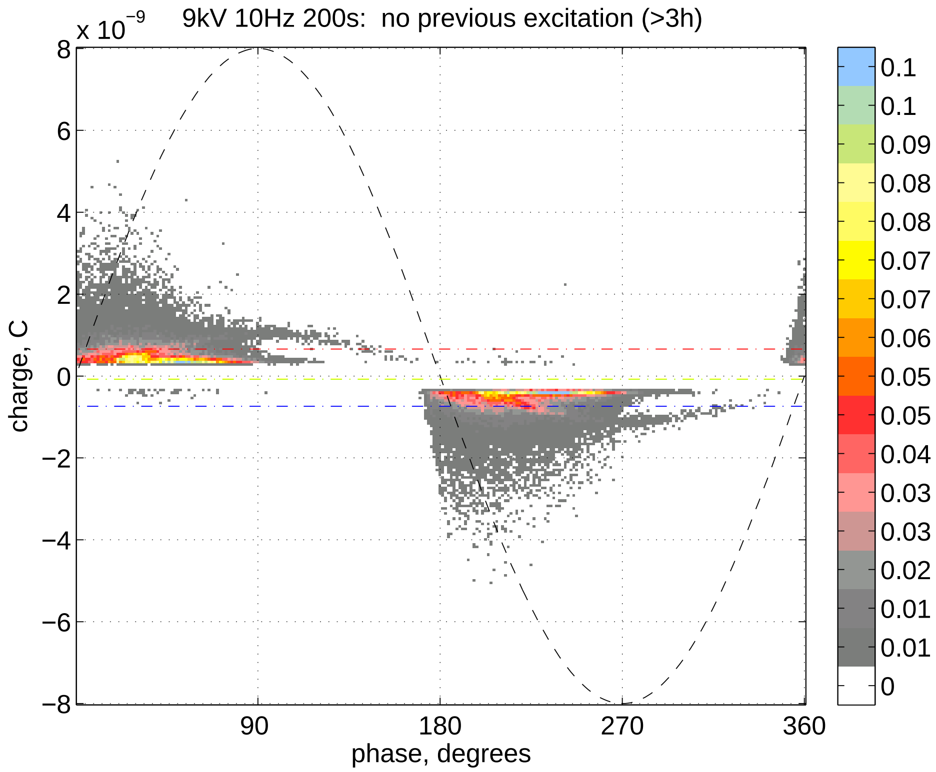

Figure 1: PD pattern with no pre-excitation for several hours

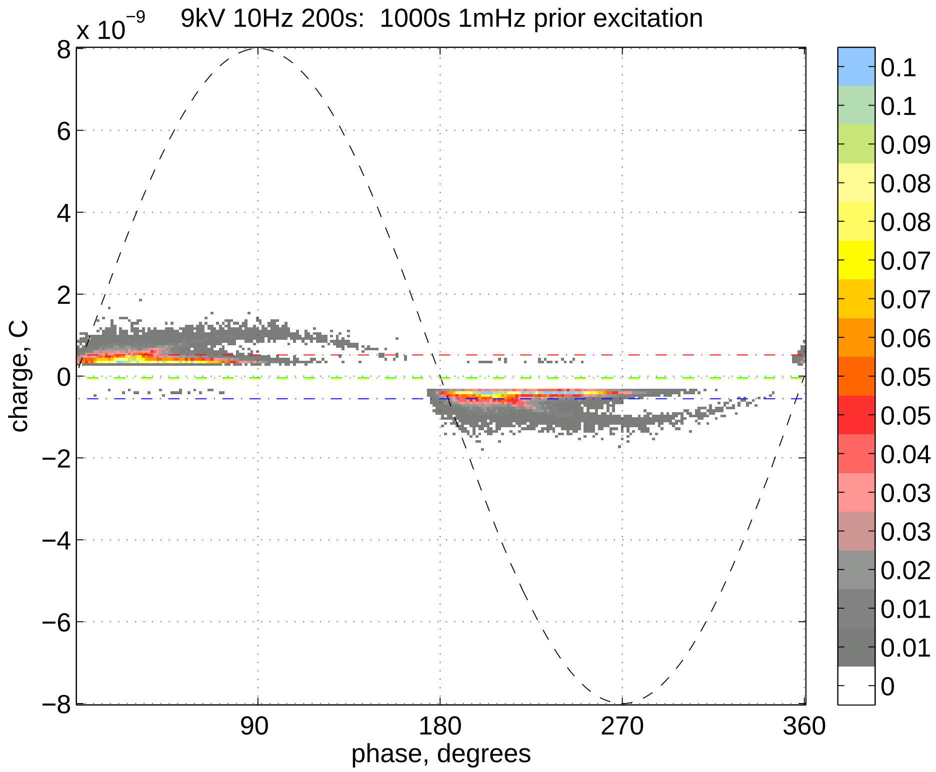

Figure 2: Most recent excitation: 9kV 1mHz 1000s

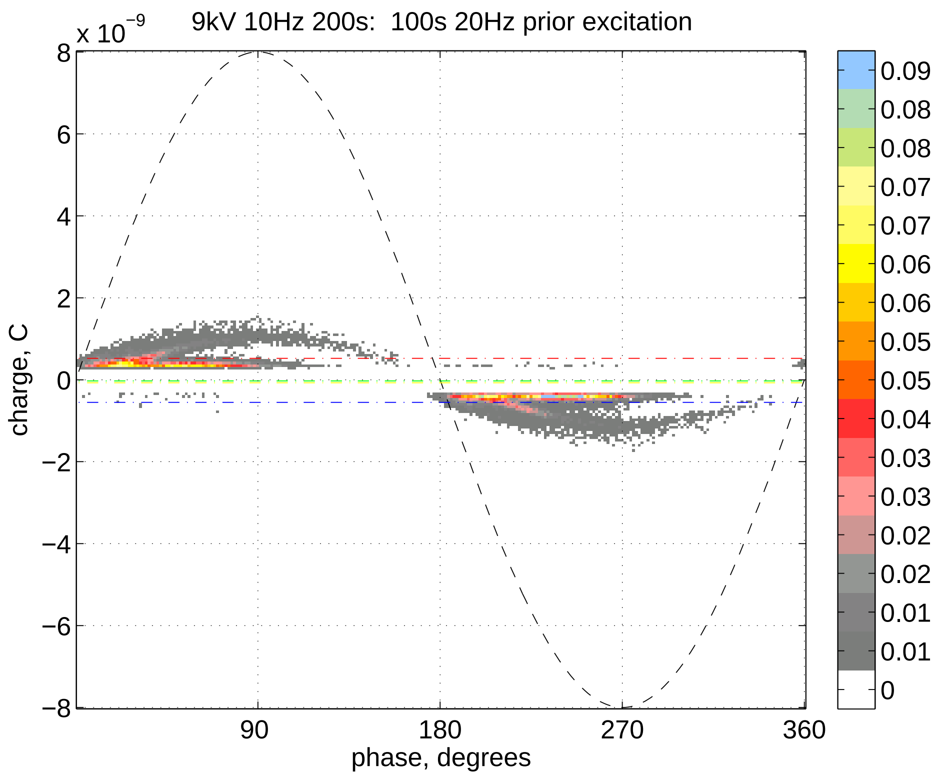

Figure 3: Most recent excitation: 9kV 20Hz 100s

Indices Some indices (single or paired values for each measurement point) are given for comparison of the different points.

Complex capacitance is shown in (figure 4), The complex capacitance is calculated as $C'(\omega) - \mathrm{i}C''(\omega) = \frac{I(\omega)}{\mathrm{i}\omega V(\omega)}$, where $V(\omega)$ is the applied voltage and $I(\omega)$ is the fundamental frequency component of the smoothed PD current obtained from the PR-PD pattern by taking the mean current for each phase channel. Since the current measured is from PD pulses, and therefore is due only to polarisation mechanisms, the use of C' and C'' has no 'prompt' part: it is equivalent to $\Delta C'$ and C''. The notation of capacitance is used since the more appropriate susceptibility $\bar{\chi}(\omega)$ is a material property and we are dealing with an object and desiring to compare PD currents with measurements of capacitance by Dielectric Spectroscopy.

Total + and − PD charges (figure 5) include the whole charge as a mean value per cycle, not just a fundamental frequency component. If the PD charge is largely capacitive (classic cavity in good insulation with low wall-conductivity) then the variation of charge per cycle with f will be low.

Maximum and mean + and − PD magnitude (figure 7) are shown, then the mean number of + and − PDs per cycle (figure 6).

It should be noted that all results come from the output data of PR-PD patterns that have put results from several (here, 2000) cycles together — it can very well be that for example most cycles had a mean and maximum value of PD quite close to each other, but that just the first few cycles had large PDs, leading to a large displayed difference between maximum and mean PD charge.

The indices are displayed in chronological order of measurement, set `b2pd06` then `b2pd07` on each figure.

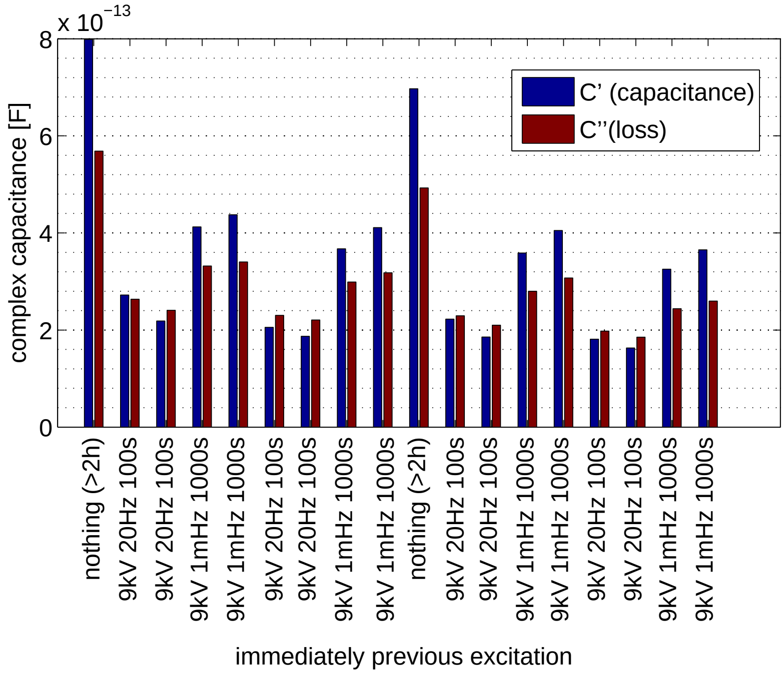

Figure 4: PD charges seen as fundamental frequency components of the smoothed PD current, scaled by V and f: complex capacitance in rectangular form, C' and C''. Note that x-labels refer to *previous* excitation: all measurements are at 9kV 10Hz. The order is chronological.

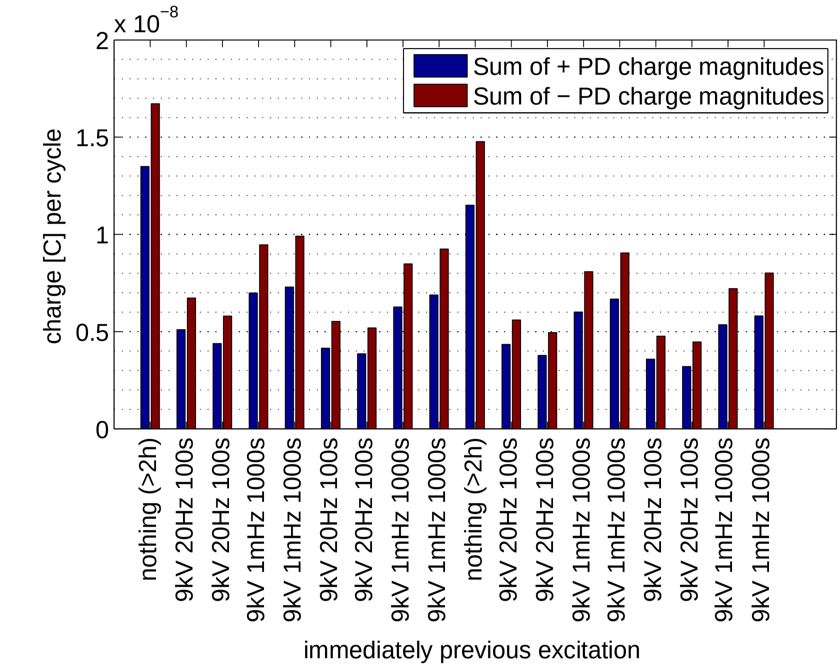

Figure 5: PD charges seen as total + and − PD charges, as a mean per-cycle value over 2000 cycles. Note that x-labels refer to *previous* excitation: all measurements are at 9kV 10Hz. The order is chronological.

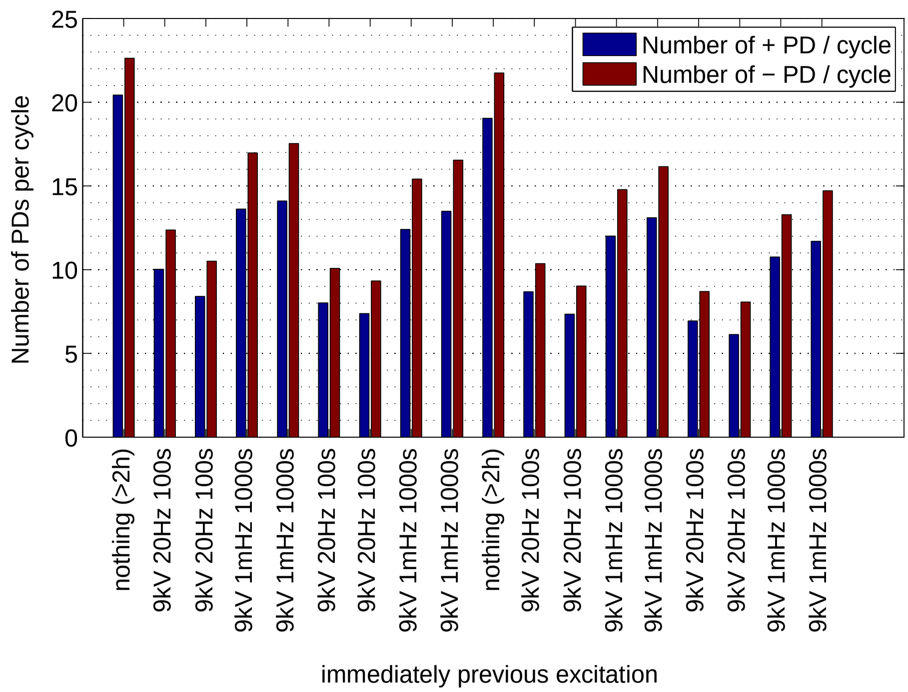

Figure 6: Mean number of PDs per cycle, + and −. Note that x-labels refer to *previous* excitation: all measurements are at 9kV 10Hz. The order is chronological.

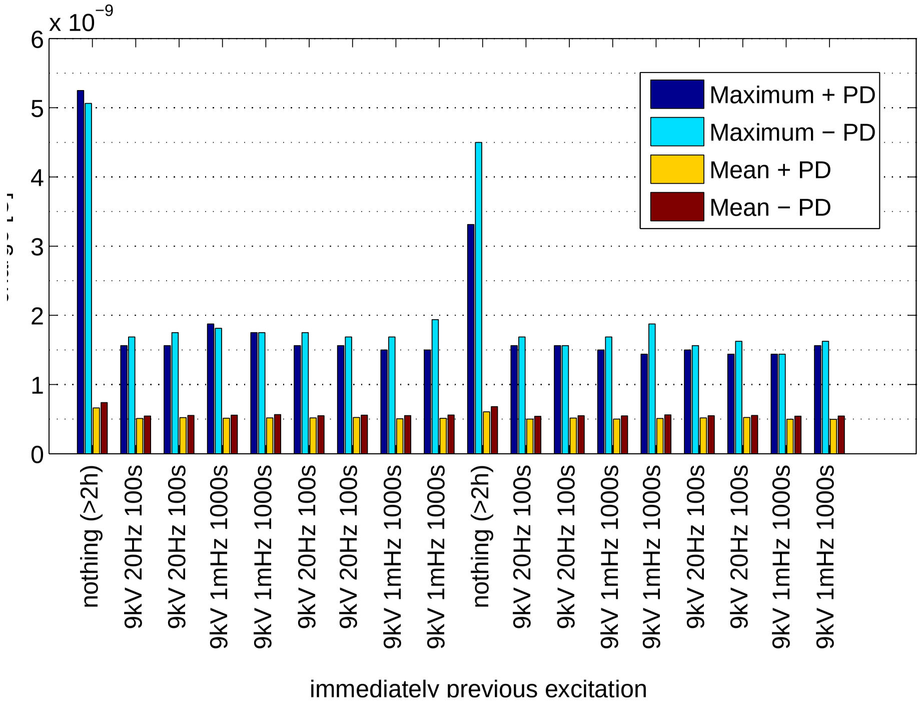

Figure 7: PD maximum discharge sizes, + and −, over all cycles. Note that x-labels refer to *previous* excitation: all measurements are at 9kV 10Hz. The order is chronological.

The same, with lower frequency measurements.

Set `b2pd08` repeated the pattern of sets 06 and 07, but used 9kV 1Hz as the measurement V-f point. Figures 8 to 11 show the same indices as have been plotted previously for the 10Hz measurements.

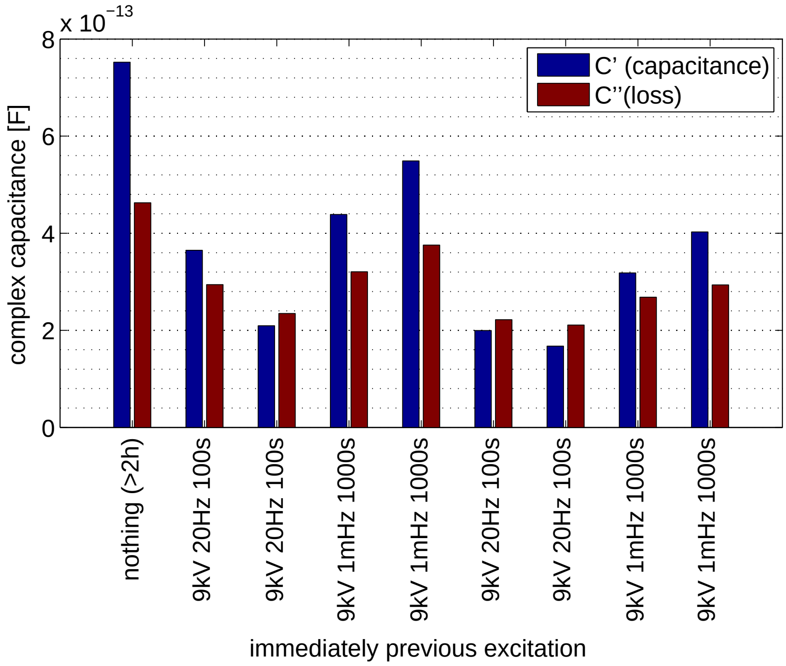

Figure 8: PD charges seen as fundamental frequency components of the smoothed PD current, scaled by V and f: complex capacitance in rectangular form, C' and C''. Note that x-labels refer to *previous* excitation: all measurements are at 9kV 1Hz. The order is chronological.

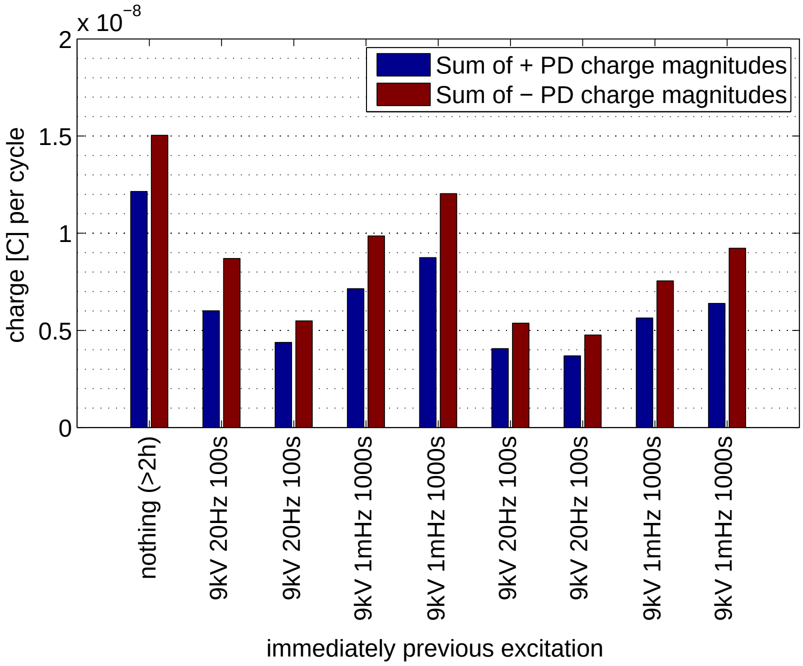

Figure 9: PD charges seen as total $+$ and $-$ PD charges, as a mean per-cycle value over 2000 cycles. Note that x-labels refer to *previous* excitation: all measurements are at 9kV 1Hz. The order is chronological.

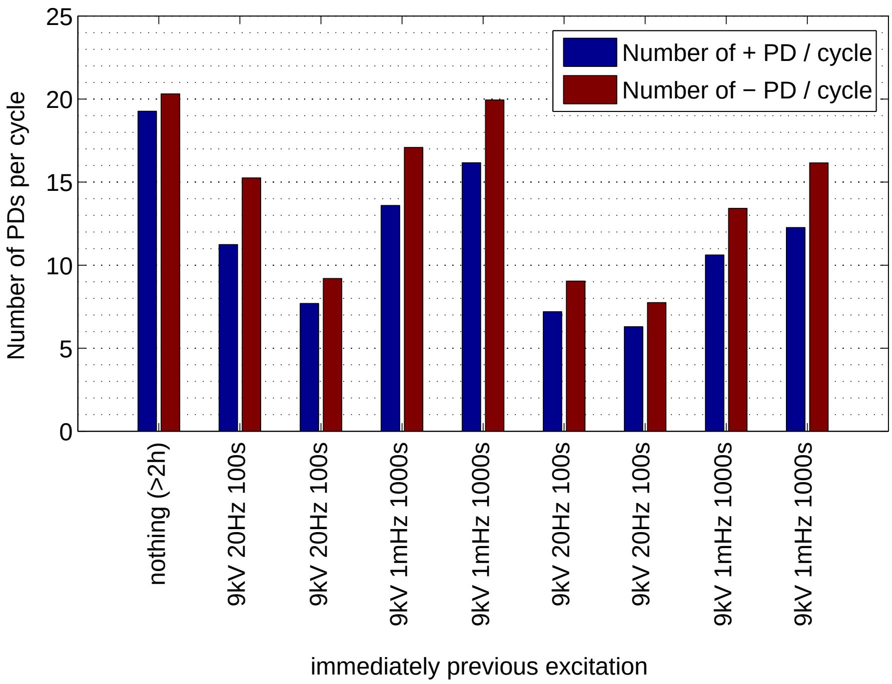

Figure 10: Mean number of PDs per cycle, $+$ and $-$. The x-labels refer to the length of the dead-time since the previous measurement: all measurements are at 9kV 1Hz. Note that x-labels refer to *previous* excitation: all measurements are at 9kV 1Hz. The order is chronological.

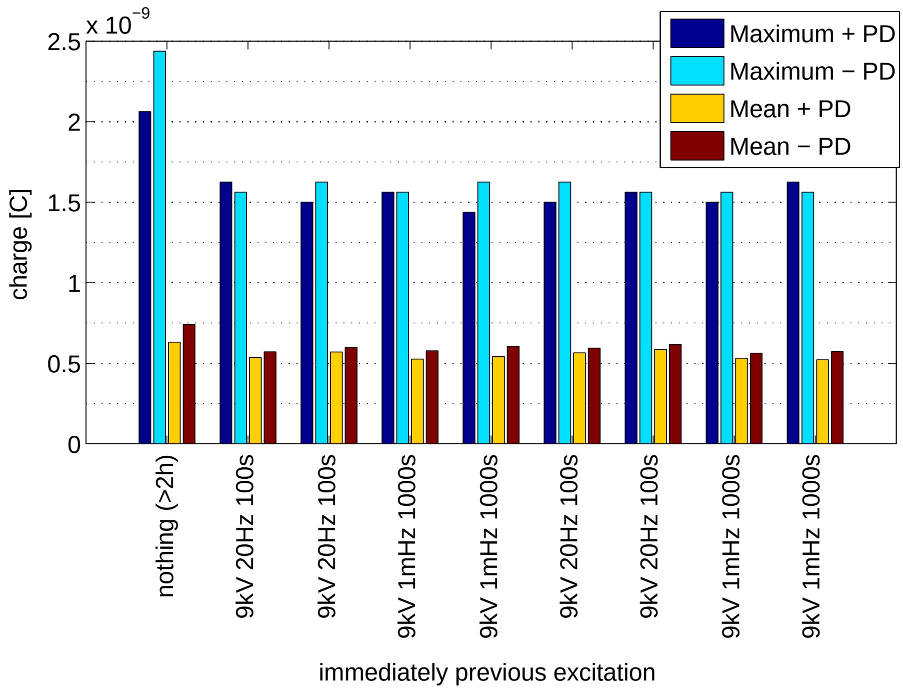

Figure 11: PD maximum discharge sizes, + and −, over all cycles. Note that x-labels refer to *previous* excitation: all measurements are at 9kV 1Hz. The order is chronological.

Effect of duration of non-excitation.

Set `b2pd09` made 9kV 10Hz 2000 cycle measurements following decreasing periods of no excitation: the measurements and 'no excitation' periods followed each other directly, apart from the delay of a few seconds due to the system's data transfer.

10000, 3600, 1800, 900, 300, 180, 60, 30 seconds

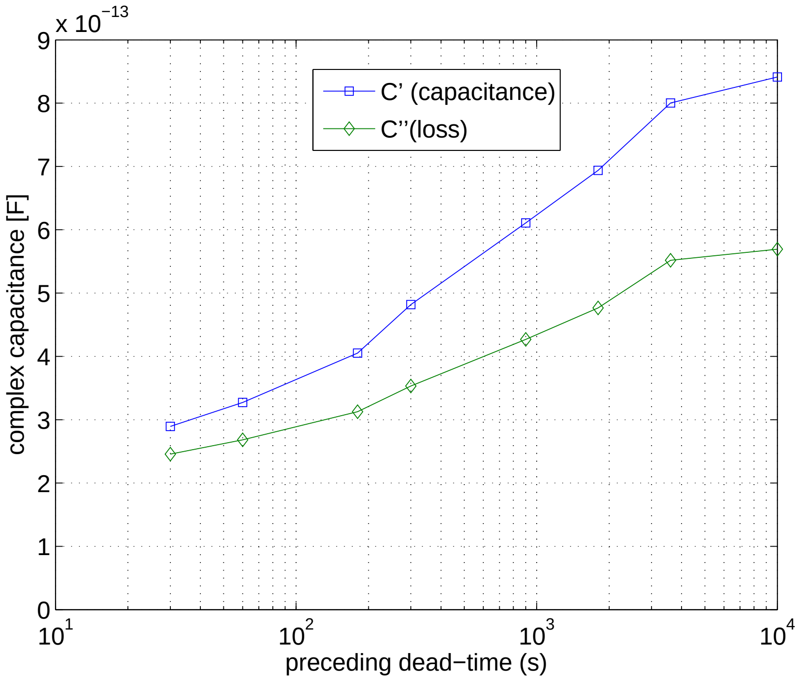

Figure 12: PD charges seen as fundamental frequency components of the smoothed PD current, scaled by V and f, giving complex capacitance in rectangular form, C' and C''. The x-labels refer to the length of the dead-time since the previous measurement: all measurements are at 9kV 10Hz. The order is *reverse*-chronological.

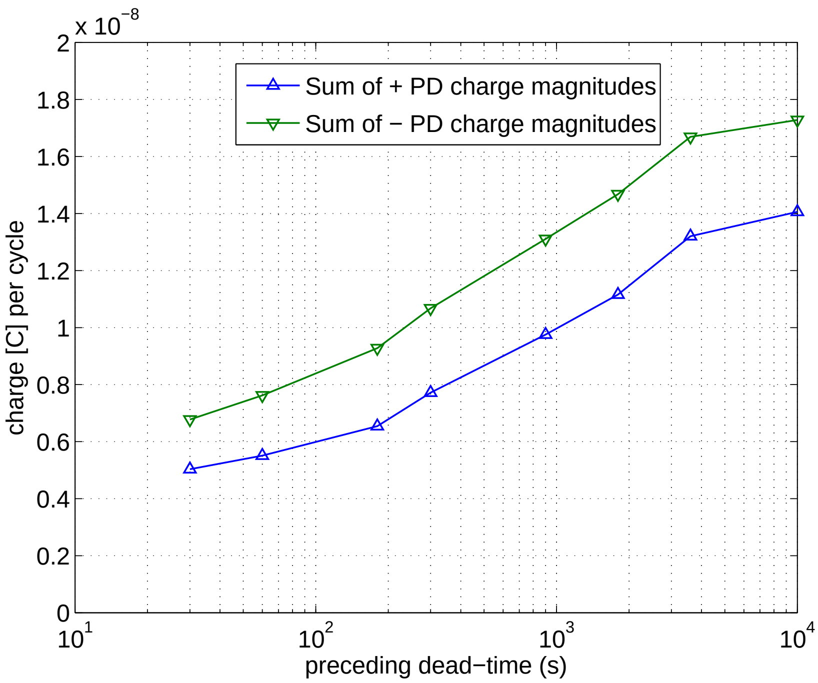

Figure 13: PD charges seen as total + and − PD charges, as a mean per-cycle value over 2000 cycles. The x-labels refer to the length of the dead-time since the previous measurement: all measurements are at 9kV 10Hz. The order is *reverse*-chronological.

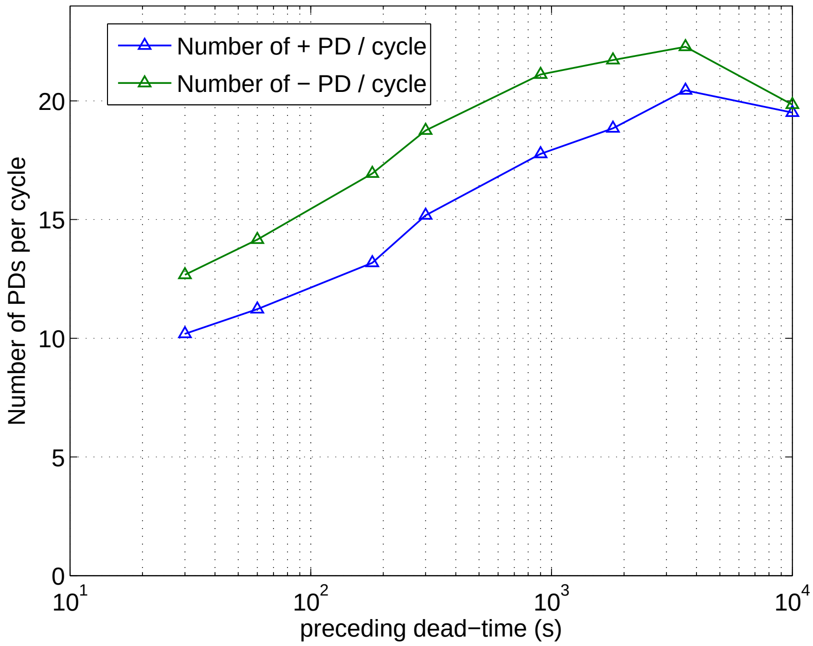

Figure 14: Mean number of PDs per cycle, + and −. The x-labels refer to the length of the dead-time since the previous measurement: all measurements are at 9kV 10Hz. The order is *reverse*-chronological.

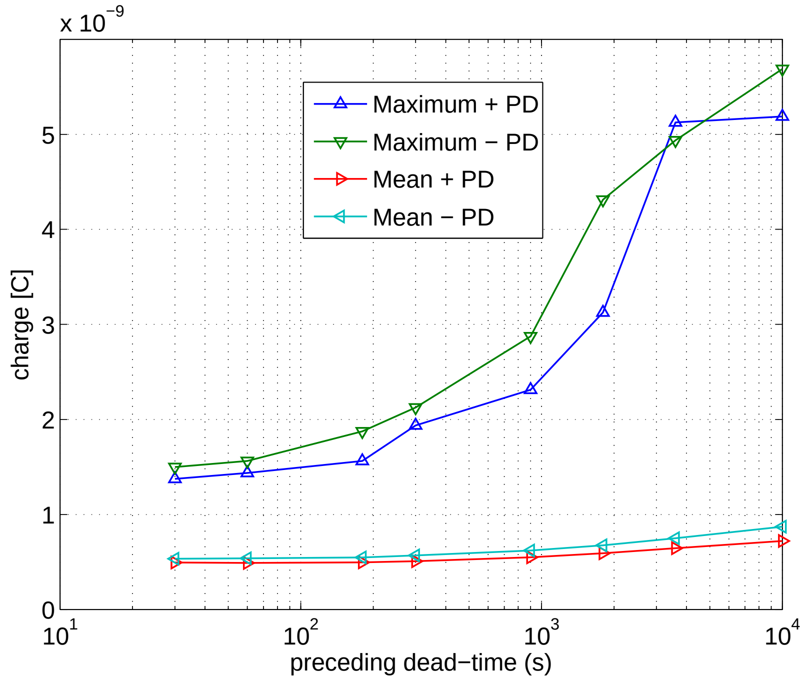

Figure 15: PD maximum discharge sizes, + and −, over all cycles. The x-labels refer to the length of the dead-time since the previous measurement: all measurements are at 9kV 10Hz. The order is *reverse*-chronological.

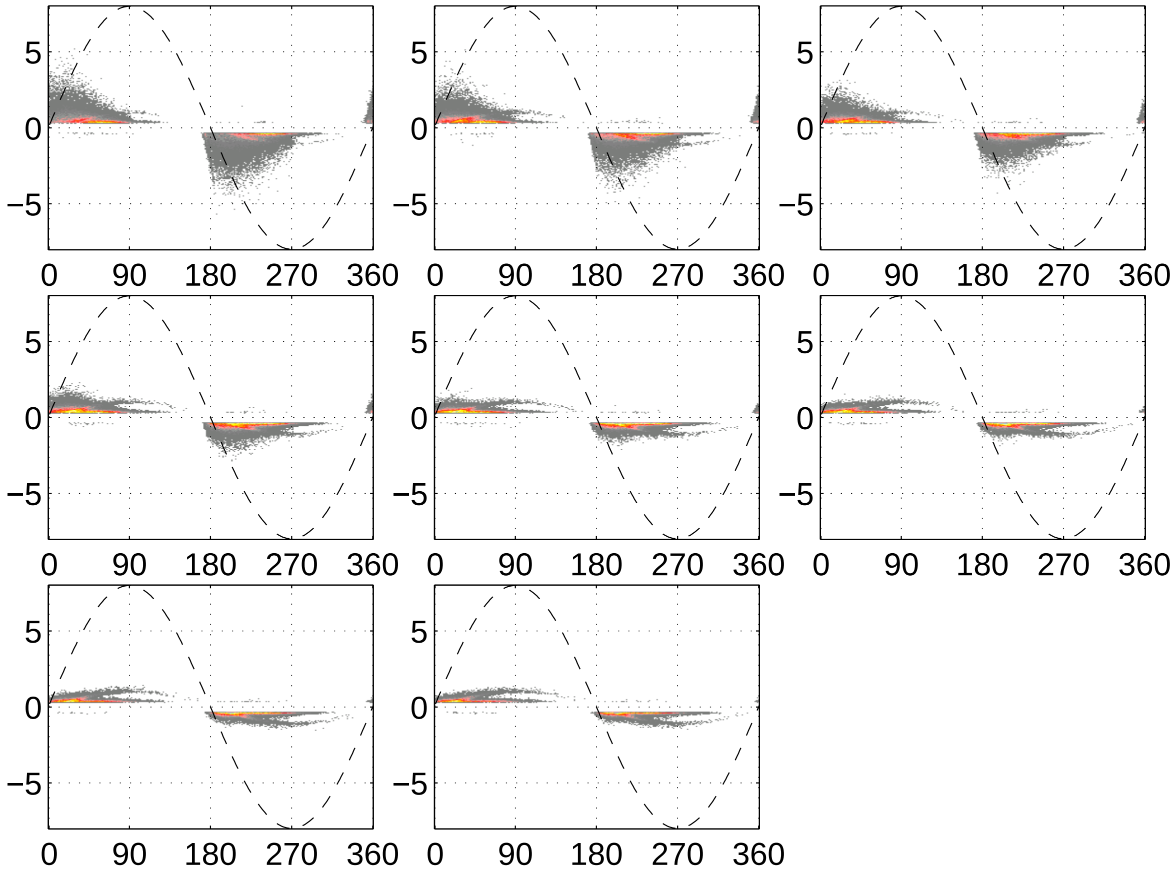

Figure 16: PD patterns, to same scale, for eight decreasing lengths of time between last excitation and measurement point. All measurements are 9kV 10Hz 2000cycles. The chronological order of the plots is left to right, top to bottom, and the corresponding dead-times prior to measurement are 10000, 3600, 1800, 900, 300, 180, 60, 30 seconds. y-axis labels show PD charge in nC.

FAILED: A long sweep with breaks

Set b2pd10 was a repeat of a measurement sequence performed twice before (prior to the above measurements of dependence on previous excitations) now trying to get meaningful, i.e. not strongly dependent on order of measurement, data for many V and f points.

The two previous occasions when these points were measured were one with random ordering of V-f points, and one with decreasing f within increasing V. Measurement points followed each other with only the delay due to the system transferring PD data (a few seconds).

This time, a 300s pause of no excitation, followed by 5s of 7kV 20Hz, was applied before each measurement. The initial measurement was preceded by just one such 20Hz excitation, this being preceded by several hours of no excitation.

In the absence of good data on how much effect, say, 20s or 1s of the 7kV 20Hz would have, compared to the 5s used, or how much effect a very low preceding frequency still has after 300 dead seconds and 5 excited seconds, the chosen sequence cannot be claimed as coming close to the ideal aim mentioned in the introduction.

This sequence was in fact a failure as many of the points were missed due to a “decimal wrap-around” of well over 100 points being set and the system only being able to cope with 99 in one go. The results that remain look far from a smooth sequence.

Summary of results

Preceding excitation: nothing, LF, HF

The measurements following the three cases: 9kV at 1mHz or 20Hz, or no excitation, showed the following results:

> Having no excitation (several hours) rather than recent excitation increased very greatly the measured maximum, mean and total PD charges, capacitance and number of PDs measured directly afterwards.
>
> The different frequency of previous excitation (which also implies a different number of seconds and cycles) corresponded to much less change — only a few percent — in the maximum or mean

PD charge, and to rather less change — some 50% — in capacitance and total PD charge; the lower preceding frequency gave the higher values.

$\tan\delta$ increased as $|C|$ decreased, being ≈ 1 after HF excitation and about 0.7 after no excitation; the fundamen component of the PD current is thus seen to have moved close to a voltage zero in the case of LF or no excitation. This is apparent from the PD patterns, where the low-phase (around a zero), high-charge PDs are the main change when going from HF to LF then to no excitation.

The same trends as in the above points were seen when the measurements were made at a the lower frequency, 1Hz.

Length of dead-time (no excitation)

Within the variation of 3h down to 30s, more recent prior excitation (shorter dead-time) resulted in:

$\tan\delta$ is greater: ≈ 0.7 for $\frac{C''}{C'}$ after a 3h dead-time becomes about 0.9 after only 30s; i.e. the fundamental component of current is shifted with its peak closer to the voltage zero for longer no-excitation times.

Maximum PD magnitude is reduced to about $\frac{1}{3}$ at short dead-times.

Mean PD magnitude is reduced by a few tens of percent for the recent excitation.

The number of recorded PDs falls to a little over half of the value when coming from long-ago to recent excitation (note that this could be just because of them becoming sub-threshold).

From the PD patterns, it seems that an underlying pattern of low-charge PDS, including two quite horizontal tails reaching even later than the voltage peak, is present in all cases, and with long dead-times prior to measurement the PDs close to the voltage-zero either become larger or get supplemented by some other sources.

Thoughts on sources of statefulness (memory)

A few ideas are considered, and primitive predictions from them are compared to the experimental data presented previously. Note it's just my thoughts on simple models, so don't take anything as being true and do give feedback on any parts thought to be dubious!

Polarisation of dielectric, and surface charge in cavity

This could be molecular or interfacial polarisation, with effects over long times that are many cycles of the higher frequency measurements.

Consider a simplified case of a delamination: this is a sort of "Maxwell-Wagner capacitor", with one of the series dielectrics being the solid material and the other the gas. The gas part can be seen as a strange non-linear dielectric: it has polarisation by PD when the voltage exceeds a certain amount, and if conduction through the walls is considered this adds a more linear interfacial polarisation component. During charging by a low frequency and high voltage (LF HV), PD or surface conduction will largely polarise the sides of the gaseous part, reducing the field in the gas. The solid dielectric will attain some long time-constant polarisation.

The polarisation remnant from LF contributes a DC term to the HF excitation, and these two sources together with the short-term polarisation of the solid dielectric in the applied field set the voltage across the system of the cavity and its surface charges. To acheive a quite balanced + and − PD total charge (this must be the equilibrium situation in the absence of strong conduction) the cavity's surface charge must have a DC component to resist this extra applied field (unless the cavity already has asymmetric electrodes that allow similar PD charges in spite of a DC component of field).

Now consider the hypothetical cases of starting a measurement (at HF, i.e. > 1Hz) in a pure cavity(surface)-charge case (e.g. dielectric material has very low dispersion) and a pure dielectric polarisation case (e.g.

applied pre-excitation voltage was not enough for PD, and surface leakage was negligible due to geometry and materials of the cavity).

The main effect of polarisation of the dielectric by LF before a HF measurement is initially a potentially (if not balanced out by PD) enhanced voltage across the cavity in one polarity, and reduced in the other; a long-term imbalance of surface charges in the cavity would arise to balance this, lasting for a time dependent on the polarisation mechanism.

The main effect of surface charges in the cavity before the HF measurement is easy initial availability of charges, but the charges will quickly get into an equilibrium for the measurement V-f combination.

In a realistic case, with both types of charging (solid polarisation, cavity surface-charge) present, the events of the first cycle or so depend a lot on the degree of each of the forms of charging and on whether the initial half-cycle is the same or the opposite polarity as the source that caused the charges.

The cavity charges alone put a field in the cavity of the opposite polarity to the field from the applied voltage that caused the charging of the cavity, but the polarisation in the solid dielectric causes a field in the cavity that is in the same sense as the field from the charging voltage.

Running a few different numbers of HF measurement cycles after a long LF excitation could be interesting to see approximately how much change in the PD indices occurs in the first few cycles. Testing the relation to number of LF cycles (expect not very important after one or two) and to the applied LF voltage would be interesting for showing the important parameters. These would be time-consuming measurements with so much LF involved.

Any attempt to predict the variation of total, maximum etc. PD charges meets the problem of the many variables that need to be defined (voltage, cavity inception voltage, conductivity, . . .).

Remnant ionisation in gas, or chemical products of PD in gas or on walls

Presence of ions, ozone, organic decomposition products etc. may facilitate or hinder PD. Without a much better idea of the extent of each of these effects, which together or even alone may have a non-monotonic dependence on frequency or time of excitation, it seems a little silly to theorise much here. The presence of more ions and electrons is expected to have similar effects to those of charges on the surfaces: an easier inception, with the possible low maximum charge and greater overall charge (though perhaps not all detected).

Pressure

(As pointed out to me again last week): PD causes violent changes in pressure, hence the ultrasound spectrum of mechanical shocks that it produces. Chemical and heating effects of PD in a cavity may change the pressure a lot. What this does to the breakdown voltage depends then on the size of the cavity [how likely that pd is low enough to be on "the other side" of the Paschen curve?].

One would surely expect that higher pressure is produced by HF than by LF (at least until τ_{stat} becomes so dominant as to reduce strongly the PD per cycle), and by LF than by nothing. This pattern: none, LF, HF was seen to a greater (several times) or lesser (some ten percent) extent in all the indices.

With the well-defined single cavity test-object, it could be instructive to vary the clamping pressure of the layers of dielectric, to see if the decay time of the effect of previous excitation can be changed such that tighter clamping increases the time of the memory effect. More sophistication with metering may be done by others than me, from what I've heard.

Heat

This is of course intimately related to pressure. Higher temperature at similar pressure is expected to increase ease of PD. The credible decay time of heat (thermal time-constant of a cavity in solid insulation) can't plausibly explain the many minutes and even hours over which the effect of a previous excitation can be felt, unless the whole material gets heated (many cavities) and PD is remarkably sensitive even to small variations in temperature. Perhaps there's a significant effect of heat in the shorter timescales of seconds and minutes between excitations. If pressure turns out to have long decay-times, that suggests the presence of extra molecules in the gas as being the origin of some of the excess pressure.

To test more

Immediate things:

> Decay of gas-pressure: modified clamping force of layered objects, even pressure measurement (not now).
>
> Variation between the first cycles: measurement of 1, 2, 4, etc. cycles after a few minutes' dead-time: needs to be done several times since single-cycle measurements have such susceptibility to statistical variation.
>
> Duration of pre-excitation: after a dead-time and before a measurement, is the effect of a very few cycles of excitation (say, HF, for simplicity) similar to the effect of some thousand as used here?
>
> Repeat these variations (dead-time, length of pre-excitation, pre-excitation frequency) with more than just two points of the controlled variable, to get a more thorough idea of the nature of the relation.

For later, effects of other variables such as mild changes in temperature and recent time-integral of humidity are of interest. Perhaps best left to an ex-jobb, as its rather a lot of experimental work and analysis of a subject that is only incidental to our main aims but is nevertheless useful and would be educational in experimentation; a problem is the use of high-contention (i.e. we all want to use it) equipment!

Detailed work on making and verifying models of the physical causes of the statefulness of PD activity in solid insulation sounds likely to be worked on by KW. And perhaps someone else has some references I haven't yet found, studying this matter in a useful way?

Suggestions for the next step to a good measurement guide

For CF & NT the fundamentals are of course of interest but the most important thing for immediate use is more the practical matter of how best to perform one's own measurements, which is still not well determined after the few measurements described here.

I would like it if we (NT, CF, KW if immediately interested) could have a lab-session with single-cavity and/or "massively-multiple"-cavity (stator coil) objects, aiming to test the extent of as many as possible of the factors of importance: dead-time, length of previous excitation, length of measurement, for a start. Testing of theories as to the origin of such effects is of interest, albeit secondary.