# Partial Discharges

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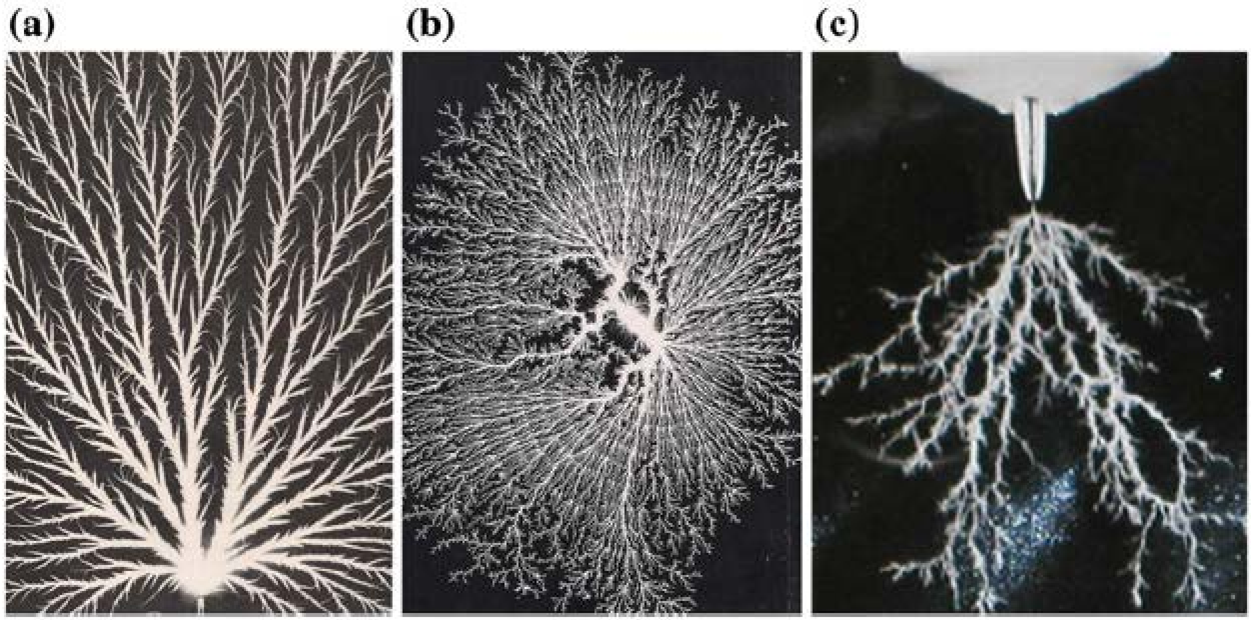
❖ What is partial discharge (PD)?

- IEC 60270: Localized electrical discharges that only partially bridge the insulation betwen conductors and which can or cannot occur adjacent to a conductor. Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Generally such dishcharges appear as pulses having durations of much less than 1μs.

- PD are the consequence of dielectric imperfections, such as sharp edges in ambient air, contaminated surface of solid dielectrics and gaseous inclusions in liquid and solid dielectrics.

## ❖ Partial discharges




In air In oil In solid

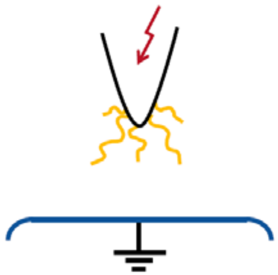
- PD is associated with the ionization of gas molecules, such events occur not only in ambient air but also in gas-filled cavities of solid dielectrics or in bubbles and water vapour of liquid dielectrics.

## ❖ Categories of partial discharges

Partial discharges can be divided to three categories:

- Corona discharges
- Surface discharges
- Internal discharges

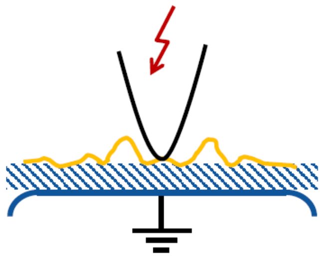
External discharges



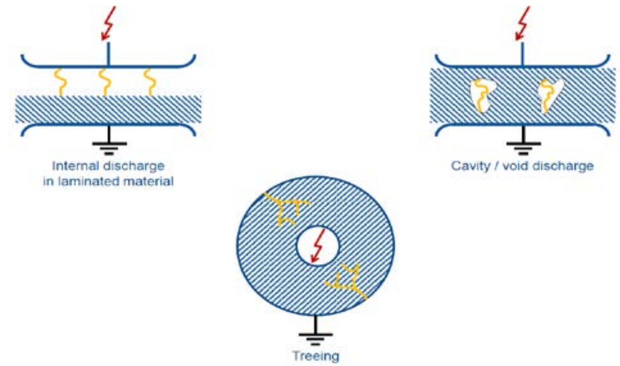
Corona discharge

- **Corona** is partial discharges in an inhomogeneous field (macroscopic or microscopic) in a gaseous dielectric. Example: Corona on overhead power lines;

❖ Categories of partial discharges



Surface discharges




Internal discharges

- **Surface discharges** are partial discharges in boundaries between different dielectrics such as: gas/solid, gas/oil, oil/solid etc. Example: The transistion between the HV part and the moulded plastics of a surge arrester;
- **Internal discharges** are partial discharges in cavities in solid or liquid dielectrics. The cavities can be limited by parts of electrodes. The cavities will mostly contain the gas which was present at the time of manufacture. Example: Small blasters (cavities) in the moulded (extruded) polyethylene of a HV PEX-cable.

❖ Insulation aging by partial diacharges

Up to 85% destructive fault in medium/high voltage devices is caused by partial discharges. Effects of partial discharges on insulation can be classified as the following aspects:

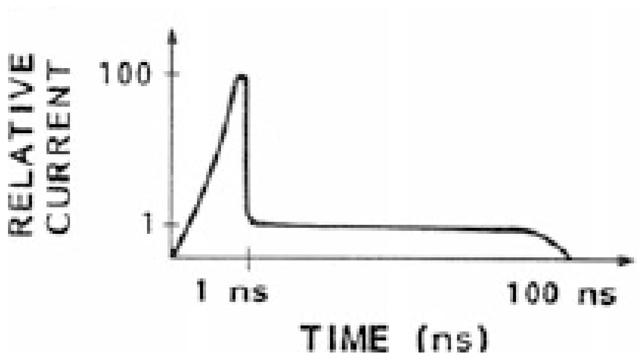
- Energy impact of high energy electrons or accelerated ions;
- Thermal degradation;
- Active products (ozone, nitric acid, nitrous acid, oxilic acid, etc.);
- Irridiation effects;
- Mechanical stress effects.

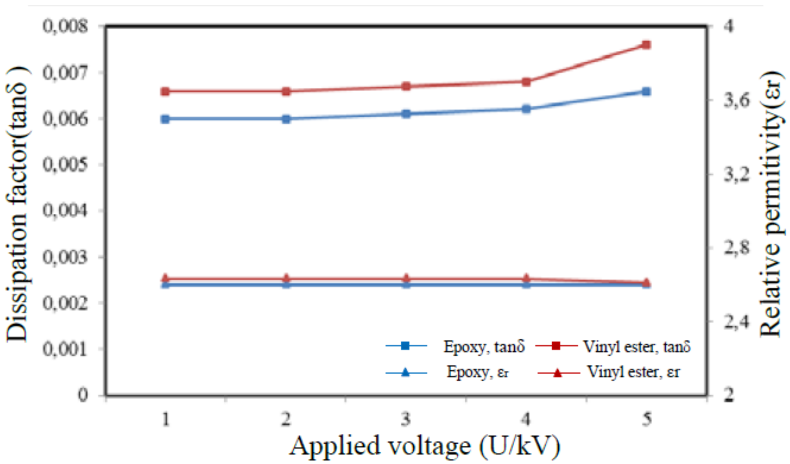
## ❖ How to restrain partial discharges

Since PD are the consequence of dielectric imperfections, such as sharp edges in ambient air, contaminated surface of solid dielectrics and gaseous inclusions in liquid and solid dielectrics. The actions can be taken to restrain PD:

- Avoid sharp edges in HV devices(grading rings, etc);
- Adopt insulation materials with  hydrophobic nature;
- Avoid loose contacts of different dielectrics;
- Optimazing manufacture process, restrain residual of air bubbles in solid or gaseous dielectrics;
- Avoid external particles (dusts, powders) entering devices;

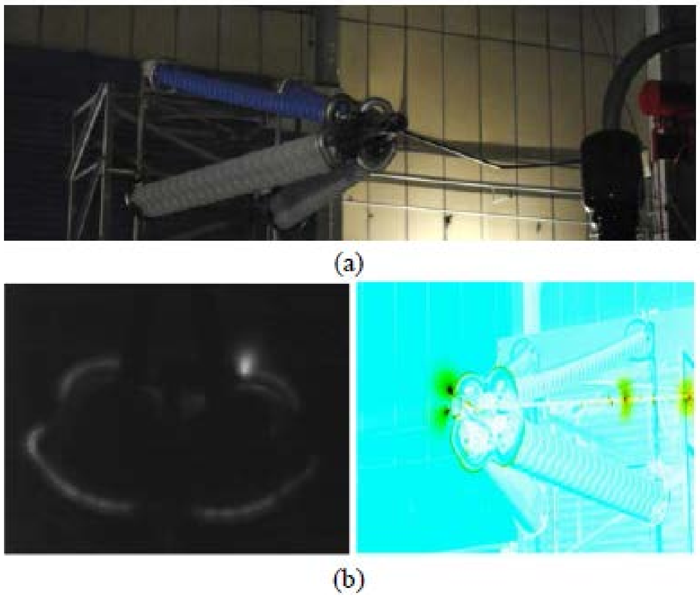
❖ Detection and measurement of partial discharges




- **Eletrical pulse currents**, most frequently used detection method;
- **Dielectric losses**, the energy released by PD will increase the dissipation factor, a measurement of the tanδ in dependency of voltage applied displays an ‘ionization knee’, a bending of the otherwise straight dependency.

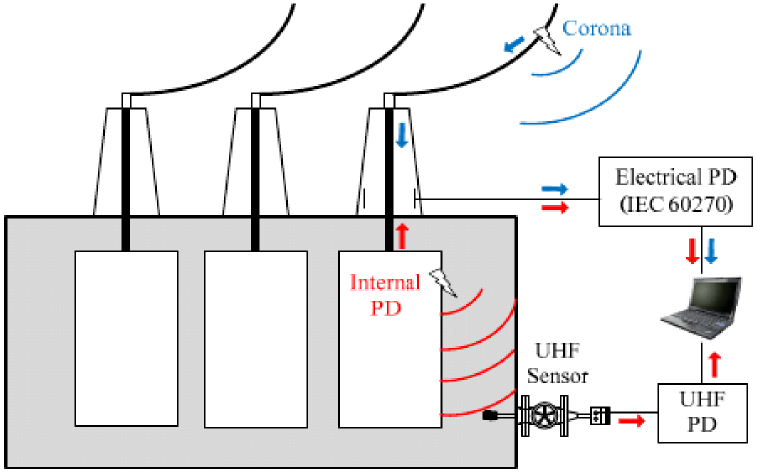
❖ Detection and measurement of partial discharges




Corona captured by UV camera

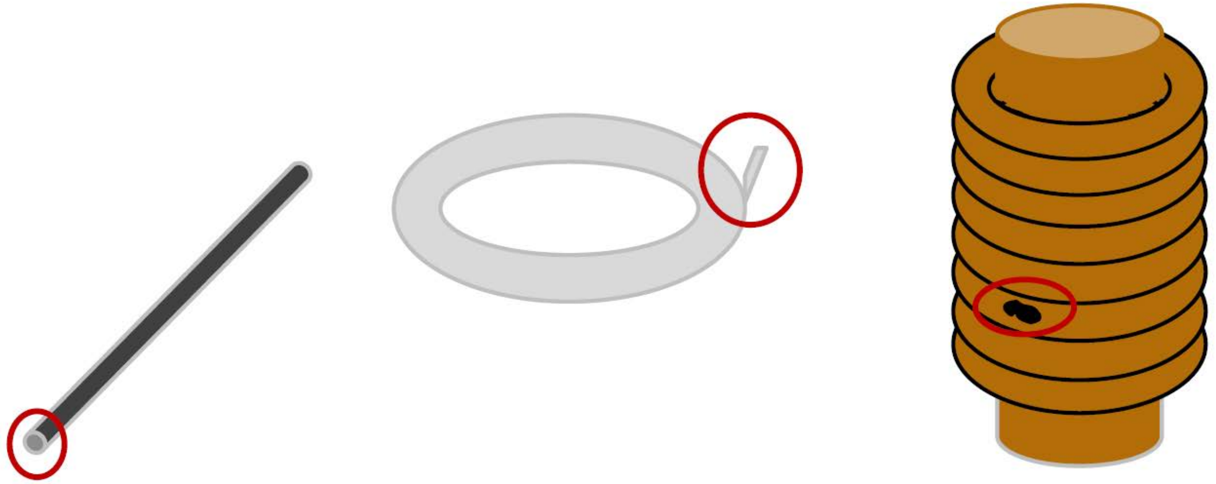
- **Optical techniques;**
- **Sound (noise)-** Listen to the acoustic noise from the discharges, the hissing test;

❖ Detection and measurement of partial discharges




- **Electromagnetism (E.M.) radiation (light**)- E.M. simulation and measurement;
- **Chemical reactions-** Component analysis of the insulation after discharges.

# External partial discharges

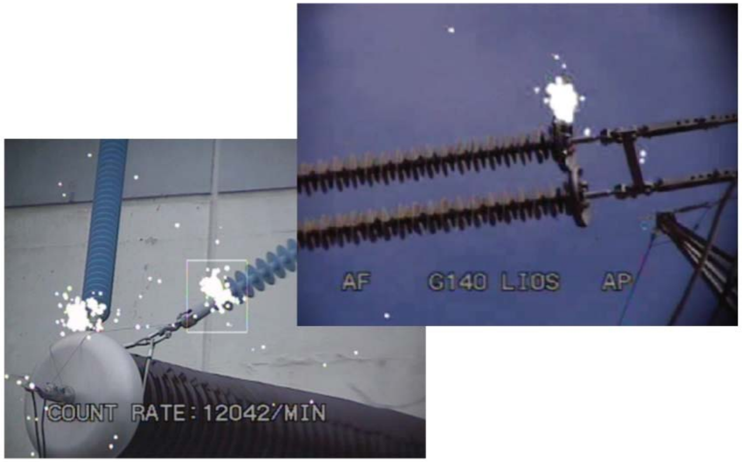


Thin conductors

Cone points/tips

Particles/dirts

$$\mathrm{E} > 12 - 15\ kV/cm$$



## ❖ External partial discharges

- Corona discharge consumes energy- corona losses
- The partial discharges of the corona around the E-field stressed portion of the HV system will cause HF electromagnetic waves which causes radio interference;
- External partial discharges on an experimental setup disturbs the measurement of the internal partial discharges. Test setups are optimized so they produced a minimum of corona;
- Surface discharges in dielectric boundaries gaseous / liquid/ solid will cause erosion of the insulation, which in long terms will cause a complete breakdown.

❖ Weather effects on corona losses

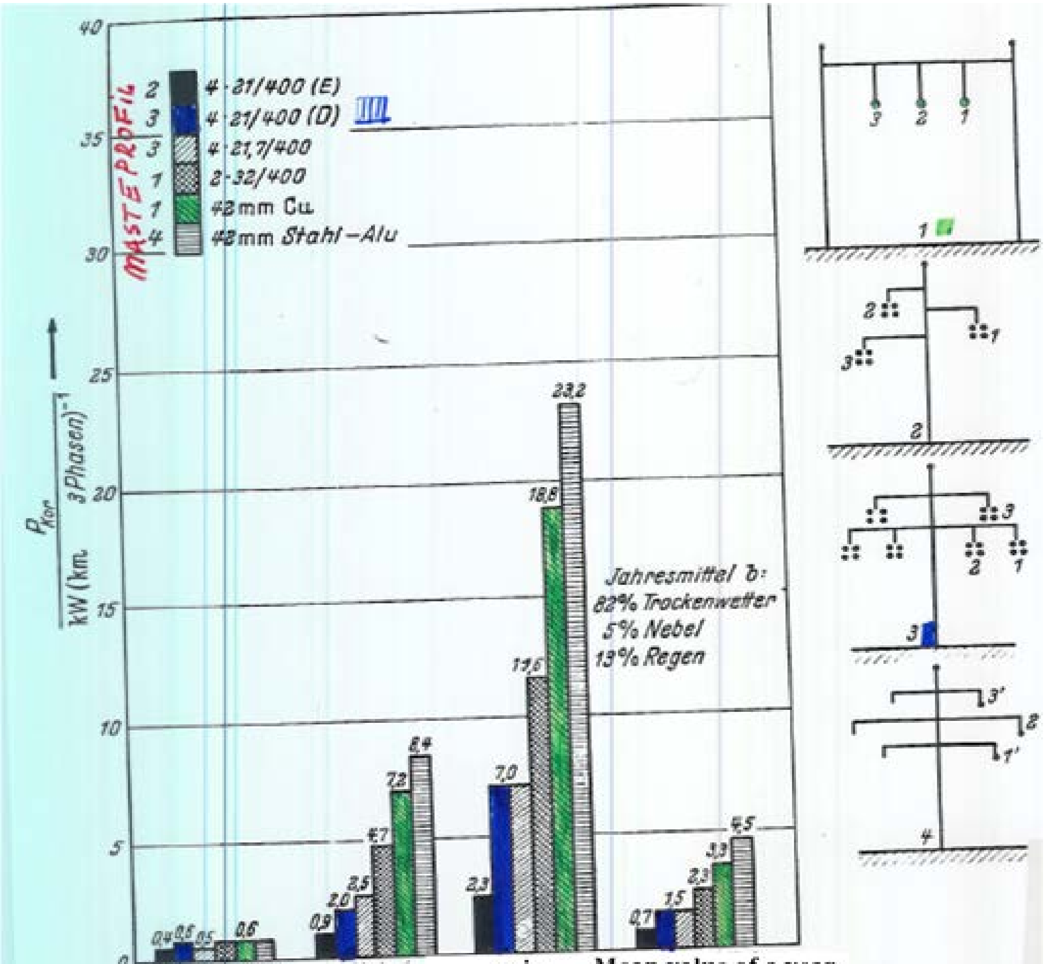
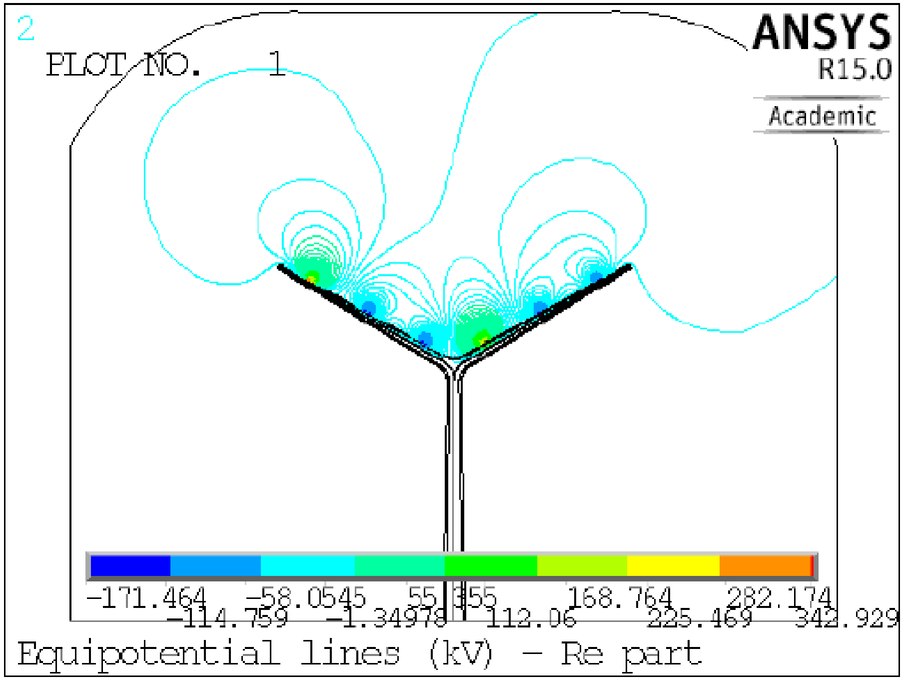


Abb. 7.44. Mittelwerte der Koronaverluste von 380 kV-Leitungen (nach Veröff. Nr. 2 der 400 kV-Forschungsgemeinschaft Heidelberg)

## ❖ Corona in overhead lines

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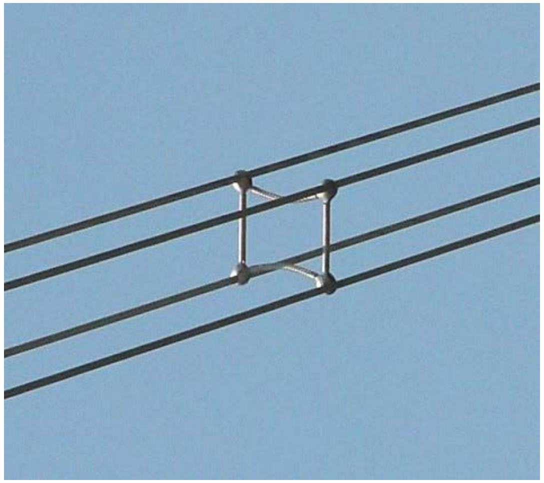
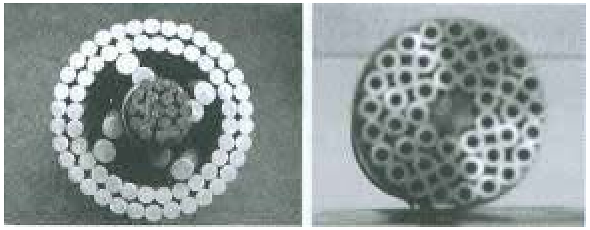
# ❖ How to reduce corona in overhead lines



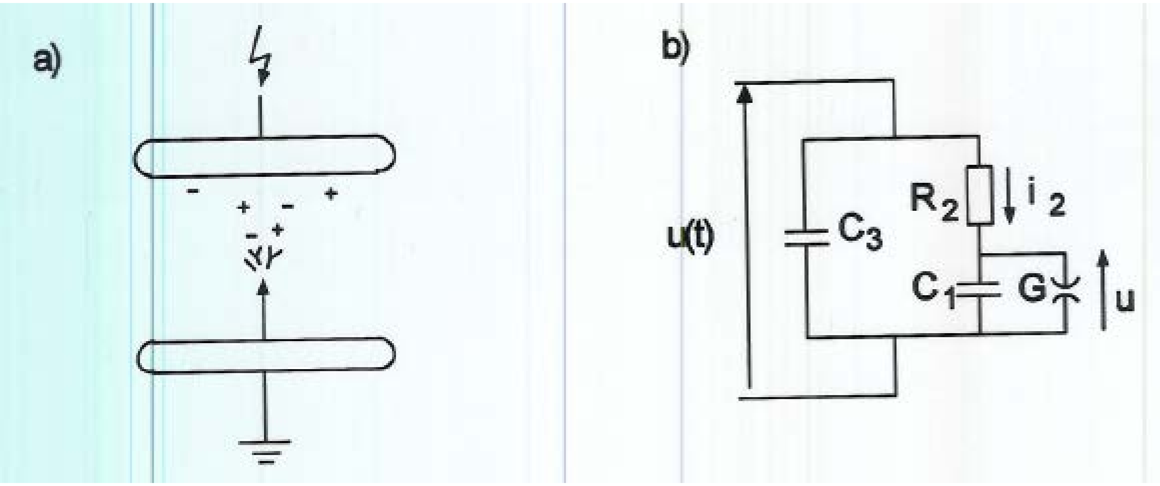
Bundle conductors

Corona rings



Extanded conductors

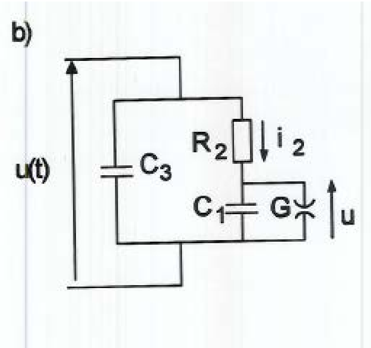
## ❖ Equivalent circuit




- $c_1$ is the capacitance of the gaseous volume(extension) which breaks down, when the applied voltage increases above the ignition voltage $u_t$;
- $G$ is sparking gap which breaks down (short circuits) when the capacitive volume $c_1$ breakds down;
- $R_2$ is the active(resistive) losses caused by the conductivity of the gas;
- $c_3$ is the normal capacitance of the electrode gap setup.

- Assuming $R_2 >> 1/\omega c_1$ makes the current through $R_2$ equal to:

$$i_2 = \frac{u(t)}{R_2}$$




Applied voltage is a sinusoidal waveform:

$$u(t) = \dot{U} sin\omega t$$

The not broken down voltage $U_{10}(t)$ across the discharge capacitance $c_1$ can be calculated as: $u_{10}(t) = X_{c1} * i_2(t)$ phase shifted 90°:

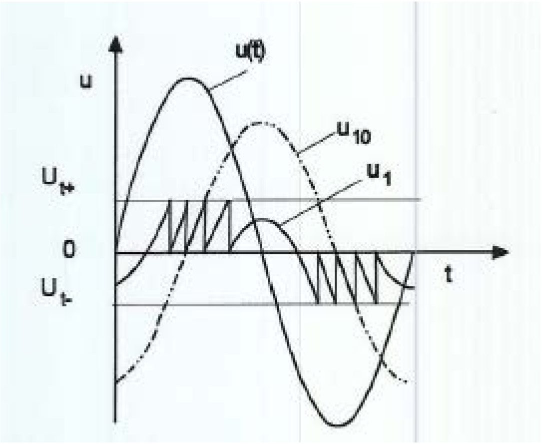
$$u_{10} = \frac{\widehat{U}}{\omega c_1 R_2} \sin(\omega t - \frac{\pi}{2})$$

Increase the voltage until G breaks down, this happens for $\widehat{U}$ equals to:

$$\widehat{U} = \omega c_1 R_2 u_t$$

This discharges $c_1$ and the ‘not broken down’ voltage $u_{10}$ becomes zero.

- Recharging $c_1$ will happen according to the $\pm\frac{du}{dt}$, i.e. a positive $\frac{du}{dt}$ makes a renewed breakdown for $+U_T$ and a nagetive $\frac{du}{dt}$ gives a negative $-U_T$.
- Increasing $\hat{U}$ further increases the number of rechargings to $U_T$ followed by breakdown for each period. The partial breakdown appear (not concentrated) around maximum $\frac{du}{dt}$ for the voltage $u_{10}$, i.e. they appear around the <u>peak of the applied voltage</u>.

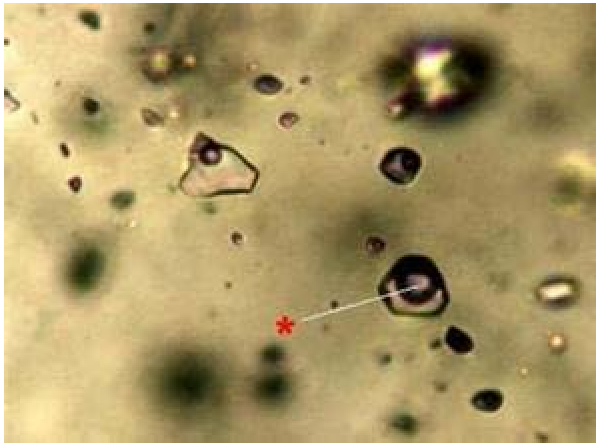


# Internal partial discharges

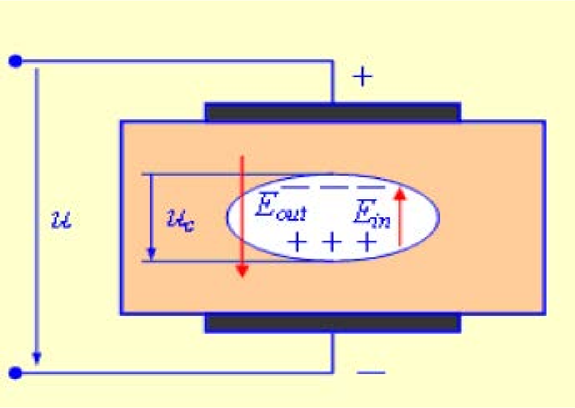


## ❖ Causes for internal PD

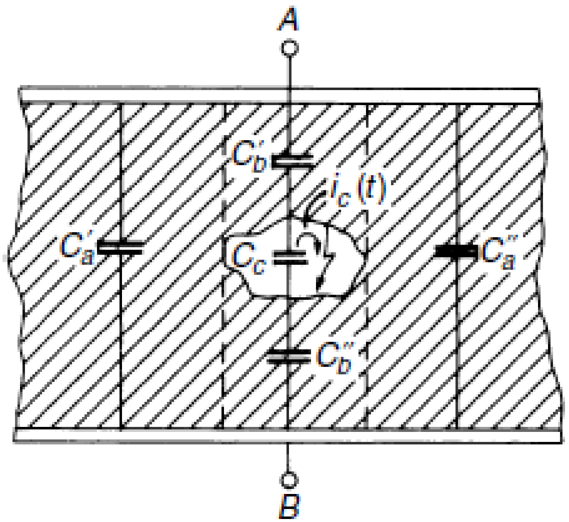
- Unwanted microscopic blasters or cavities can form in an insulating media during the manufacturing;
- Every cavity will posess a significantly higher E-field strength than the surrounding, homogeneous dielectric. This is mainly due to the following reasons:
    1. Difference in permitivity of the (normally) gas filled cavity and the surrounding dielectric;
    2. The geometry of the cavity.

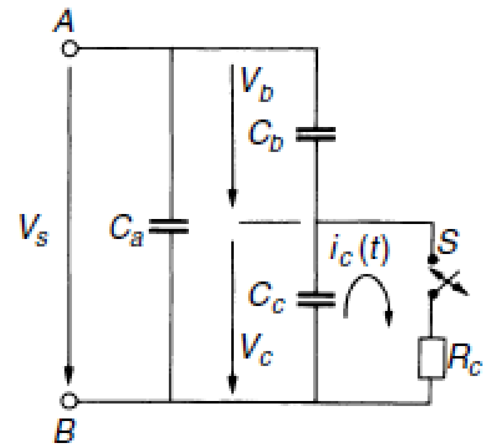


- Exceeding the breakdown voltage $U_d$ of the gas in the cavity will create a breakdown of the cavity;
- The breakdown(s) gives rise to very fast current pulses (ns) which outbalances the field of the cavity by means charge carrier movement from anode to cathode;
- The E-field will be restored when the broken down and the extinguished cavity capacitance recharges. A new breakdown happens as long as the voltage across the cavity $U > U_d$ . Repeated current pulses occur.



❖ Equivalent circuit



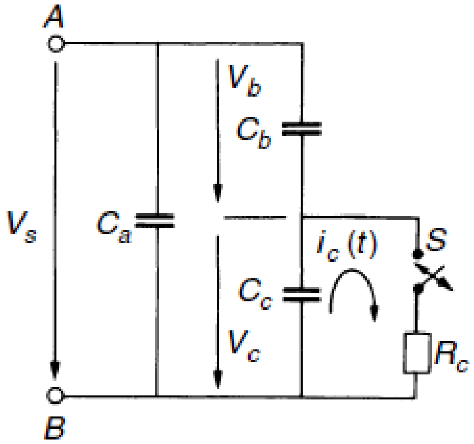




- $c_c$ is the modelling the capacitance of the cavity;
- $c_b$ is the ‘healthy’ series capacitance on both sides of the cavity
- $c_a$ is the parallel capacitance of the dielectric around the ‘sick’ branch.

$$c_a = c'_a + c''_a \quad c_b = c'_b + c''_b$$

$$c_a \gg c_b, \qquad c_c \gg c_b$$

## ❖ Equivalent circuit




- Assuming an applied sinusoidal voltage gives the following voltage across the cavity:

$$u_c = \frac{c_c}{c_b + c_c} * V_s$$

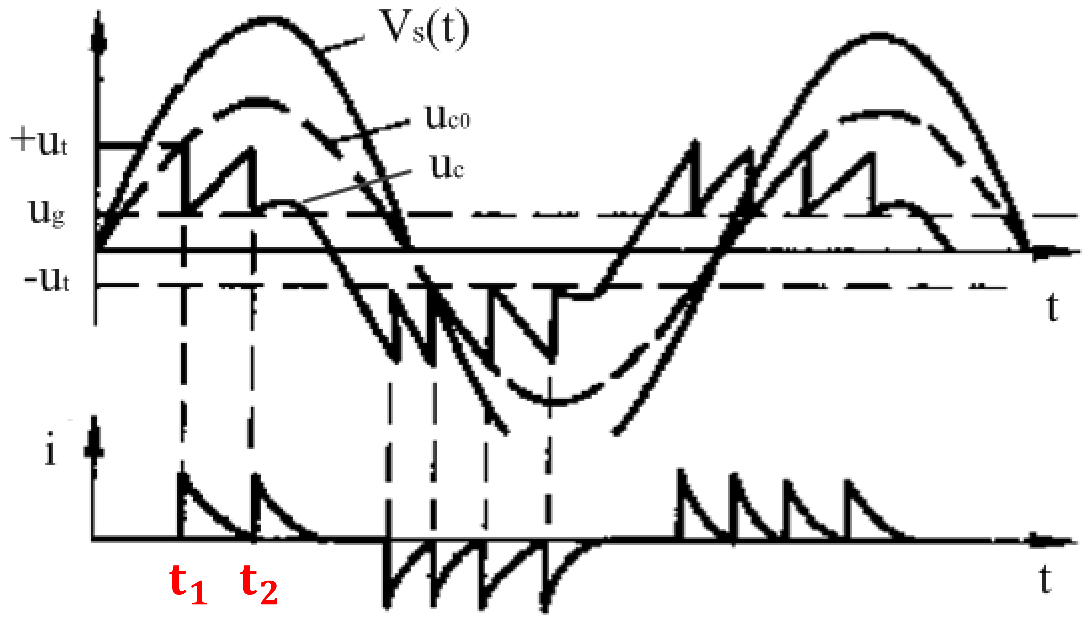
Then:

$$V_s = \frac{c_b + c_c}{c_c} * u_c$$

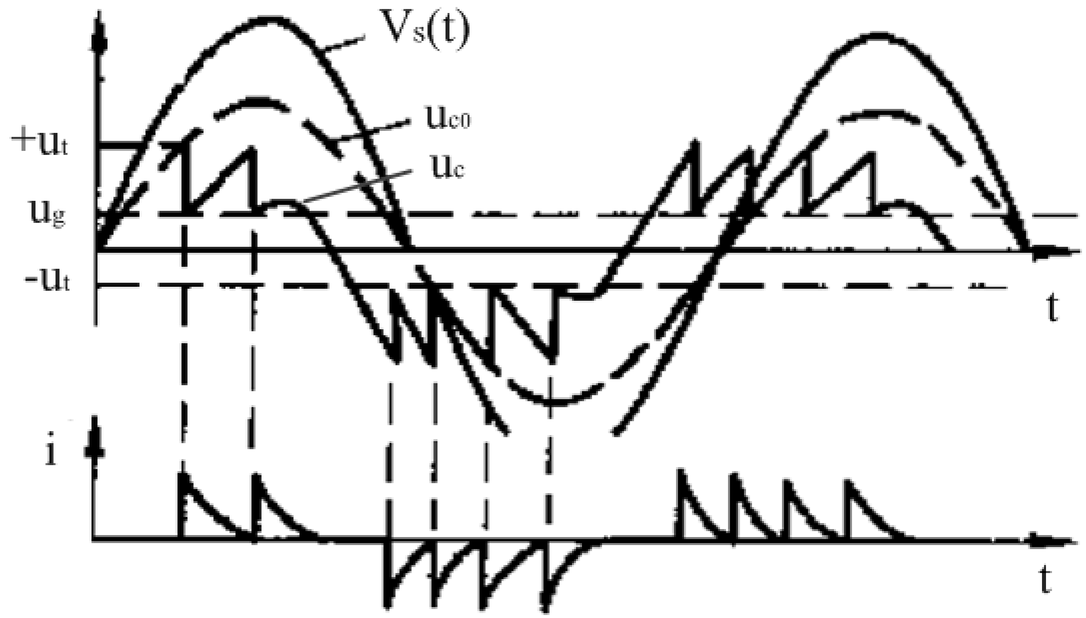
- Assuming the breakdown voltage of the cavity is $u_t$, then the cavity breakdown happens if :

$$u_c \geq u_t, \qquad V_s \geq \frac{c_b + c_c}{c_c} * u_t$$

- Thus increase the applied voltage to a certain value can lead to PD.




- With the incease of the applied voltage $V_s$, the voltage drop at the cavity $u_c$ reaches the breakdown voltage $u_t$ at $t = t_1$; Breakdown happens. The voltage between the cavity decreases to $u_g$;
- Then as the increase of applied voltage, the voltage between the cavity increases to $u_t$ at $t = t_2$, breakdown happens again.




- Cavity breakdown happens repeatedly during a voltage cycle;
- For each breakdown, amount of charges flow through the cavity;
- Thus repeative current pulses (ns) can be measured in the cycle.
- A very important distinction between external and internal PD is the phase localization of the discharge activity. Internal PD takes place around the zero crossing of the applied voltage.

❖ Analyse of the internal PD

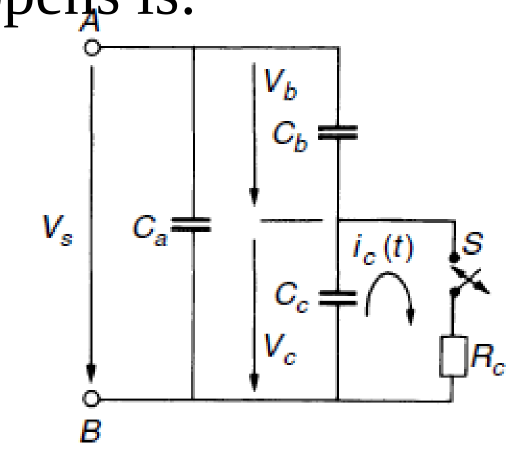
- The voltage drop at the cavity when breakdown happens is:

$$\Delta u_c = u_t - u_g$$

- Thus the quantity of discharges is:

$$\Delta q = (c_c + \frac{c_a c_b}{c_a + c_b}) * \Delta u$$

$$\approx (c_c + c_b) * \Delta u_c$$

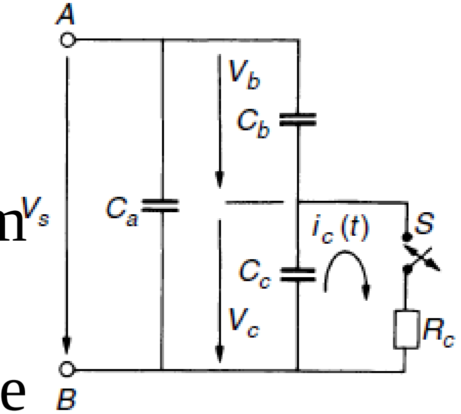



$\Delta q$ is the real discharge quantity. It indicates the information of the PD in a dielectric.

However, since $c_c$, $c_b$, $u_t$, $u_g$ cannot be measured, the real discharge quantity $\Delta q$ cannot be measured.

- The voltage drop at the cavity also causes a voltage change at the $c_a$, i.e. the dielectric.:

$$\Delta u_a = \frac{c_b}{c_a + c_b} * \Delta u_c$$




($c_b$ and $c_a$ is connected seriesly if considered from the two terminals of the cavity.)

- $\Delta u_a$ can be measured because it is the voltage variation at the dielectric.

- Since

$$c_a \gg c_b$$

the voltage drop at the test object during PD is very small.

- Real life practical applications yields:

$$\Delta u_c = 0.1 - 10\ kV$$
$$\Delta u_a = 0.1 - 1V$$
$$U_a = 100 - 1000\ kV$$

- The ratio of the voltage drop $\Delta u_a$ and the applied voltage is in terms of measuring method, very unfavourable.

## ❖ Analyse of the internal PD

- The charge quantity supplied by the voltage source during the breakdown process is:

$$\Delta q_a = c_a * \frac{c_b}{c_a + c_b} * \Delta u$$

- $\Delta q_a$ is the apparent charge. It can be measured since it flows through the main circuit.

$$\begin{cases} \Delta q \approx (c_c + c_b) * \Delta u \\ \Delta q_a \approx c_b * \Delta u \\ c_a \gg c_b, \qquad c_c \gg c_b \end{cases}$$

- Actually, the apparent charge is much smaller than the real discharge:

$$\Delta q_a < \Delta q$$

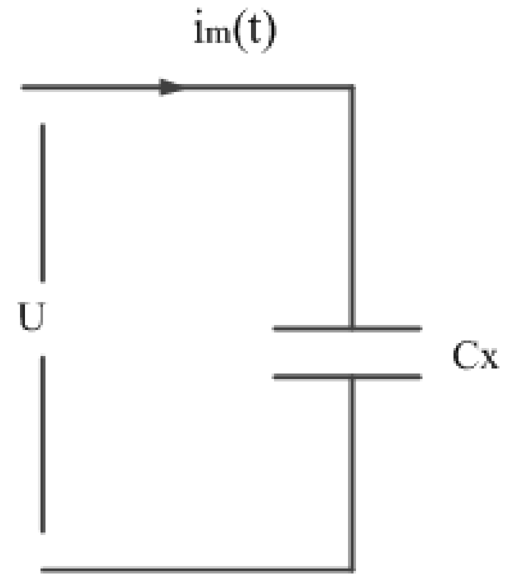
❖ Arrarent charge

- IEC 60270 defines- arrarent charge q of a PD pulse is that unipolar charge which, if injected within a very short time between the terminals of the test object in a specified test circuit, would give the same reading on the measuring instrument as the PD current pulse itself. The apparent charge is usually expressed in picocoulombs;

This definition ends with:

- The apparent charge is not equal to the amount of charge locally involved at the site of the discharge and which cannot be measured directly.

## ❖ Measurement of internal PD




$$i_m(t) = \frac{du}{dt} + i(t)$$

$$\Delta q_a = \int i(t)\, dt$$

- $i(t)$ is very small, thus it is very difficult to differ it from the displacement current $\frac{du}{dt}$;
- Another method is needed to measure the $i(t)$ directly.

## ❖ Measurement of internal PD

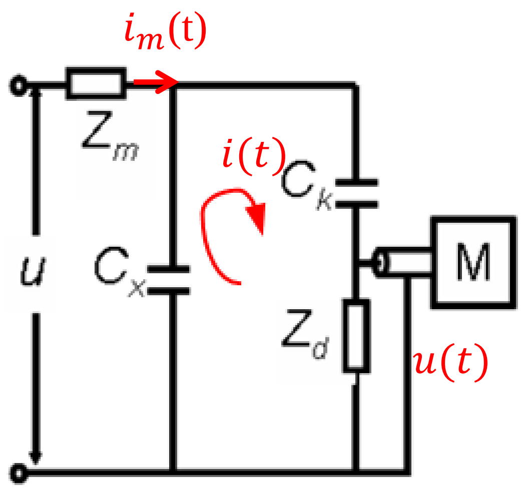
$C_x$ is the test object,

$C_k$ is the coupling capacitor

$Z_m$ is the low-pass filter

$Z_d$ is the measuring impedance,

$M$ is the measuring system.




$$\Delta q_a = \int i\,(t)dt$$

$$i(t) = \frac{u(t)}{Z_d}$$

- $Z_m$ comprise either only the natural impedance of the lead between voltage source and the parallel arrangement of $C_k$ and the test object, or enlarged by a PD-free inductance or filter, may <u>disconnect</u> the ‘coupling capacitor’ $C_k$ and the test object from the voltage source during the short duration PD phenomena only.
- $C_k$ is a storage capacitor or quite a stable voltage source during the short period of the partial discharge.

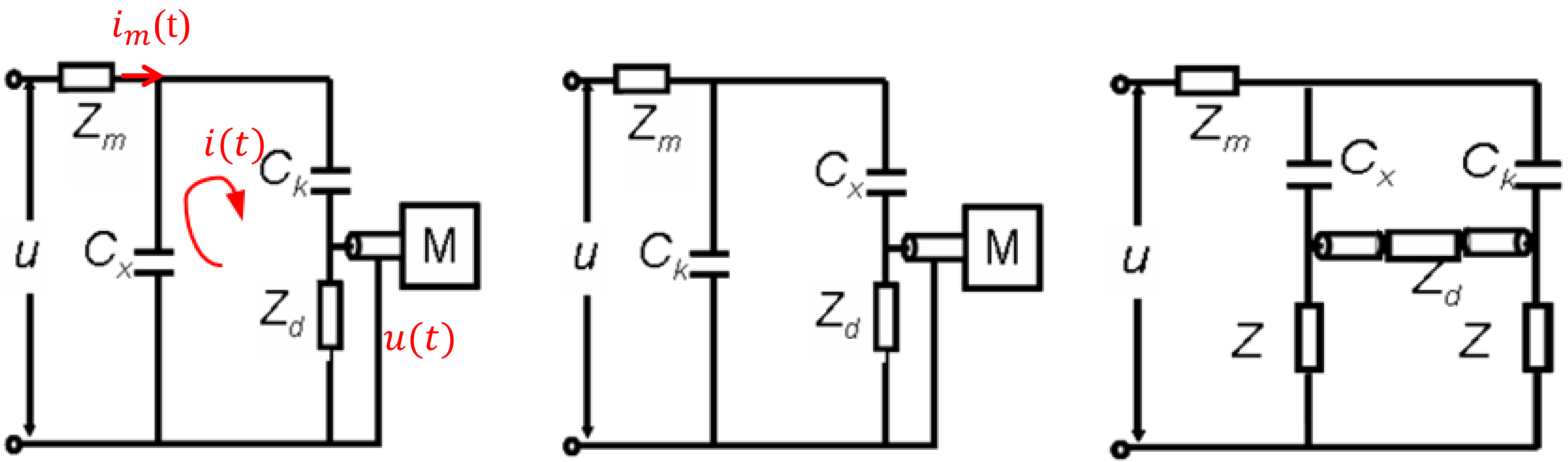
# ❖ Measurement of internal PD

the coupling capacitor $C_k$ shall be of low inductance design and should exhibit a sufficiently low level of partial discharges at the specified test voltage to allow the measurement of the specified partial discharge magnitude. A higher level of partial discharges can be tolerated if the measuring system is capable of separating the discharges from the test object and the coupling capacitor and measuring them separately;

the high-voltage supply shall have sufficiently low level of *background noise* to allow the specified partial discharge magnitude to be measured at the specified test voltage;

high-voltage connections shall have sufficiently low level of *background noise* to allow the specified partial discharge magnitude to be measured at the specified test voltage;

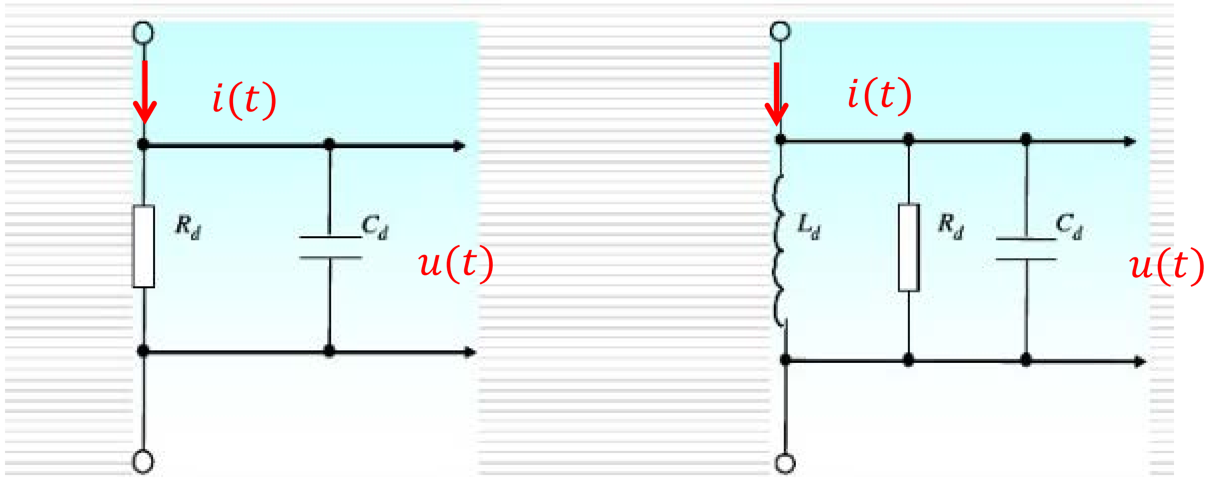
## ❖ Measurement of internal PD



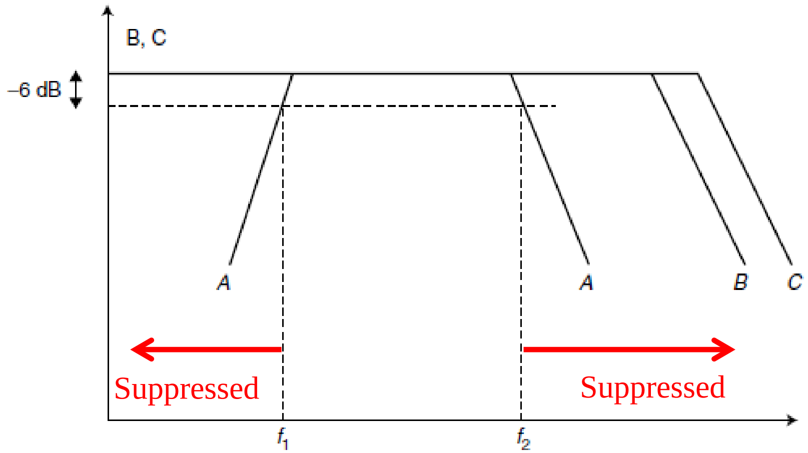

$$\Delta q_a = \int i(t)\, dt$$

- Parallel-connected detection circuit (left)
- Series-connected detection circuit (middle)
- Balanced detection circuit (right)

❖ Measurement impedence $Z_d$




- Function:
    1. To transfer the impulse current into voltage;
    2. To suppress the interferences of power frequency and harmonic from source




| | |
|---|---|
| $A$ | band-pass of the measuring system |
| $B$ | amplitude frequency spectrum of the PD pulse |
| $C$ | amplitude frequency spectrum of calibration pulse |
| $f_1$ | lower limit frequency |
| $f_2$ | upper limit frequency |

- Measuring impedance $Z_d$ (transfer impdedance) is the ratio of the output voltage amplitude to a constant input current amplitude, as a function of frequency f, when the input is sinusoidal.

$$Z_d(f) = \frac{u}{i}$$

- The lower and upper limit frequencies $f_1$ and $f_2$ are the frequencies at which the transfer impedance $Z_d(f)$ has fallen by 6 dB from the peak passband value.

- IEC 60270 recommend: the lower and upper limit frequencies $f_1$ and $f_1$ of the measuring impedance $Z_d(f)$ and the measuring system shall be designed to have the following values for $f_1$ , $f_1$ and $\Delta f$ :

$$30\ kHz \leq f_1 \leq 100\ kHz$$
$$f_2 \leq 500\ kHz$$
$$100\ kHz \leq \Delta f \leq 400\ kHz$$

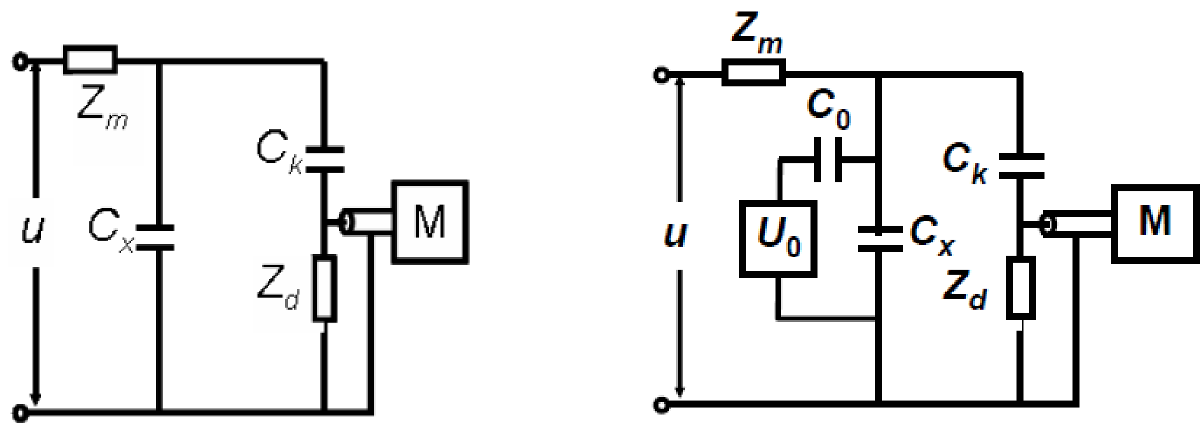
- A narrow-band is also defined:

$$9\ kHz \leq \Delta f \leq 30\ kHz$$

$$50\ kHz \leq f_m \leq 1\ MHz$$

$f_m$ is the central frequency.

## ❖ Calibration




- To determine the scale factor $S_f$ requied for the calculation of the apparent charge $\Delta q_a$, PD calibration should be conducted;
- Insert a known quantity of charge $q_0$ to the test object and obtain the reading $M_0$ from the measuring system; Thus the scale factor is obtained: $S_f = \frac{q_0}{M_0}$;
- Thus in the measurement of apparent charge, if the reading is $M_x$, the apparent charge can be calculated as:

$$q_x = S_f * M_x$$

# Exercise 1

- Assuming that a calibrating charge of $q_0 = 200\,pC$ is injected in the terminals of the test object. This causes a pulse magnitude of 5.4 divisions on the display of the measuring system.
- Performing an actual PD measurment, a reading of 8.6 divisions is obtainded.

Question: what is the real pulse magnitude?

## ❖ Other PD quantities

- The average discharge current $I$ is the sum of the obsolute values of individual apparent charge magnitudes $q_i$ during a chosen reference time interval $T_{ref}$ divided by this time interval, i.e.

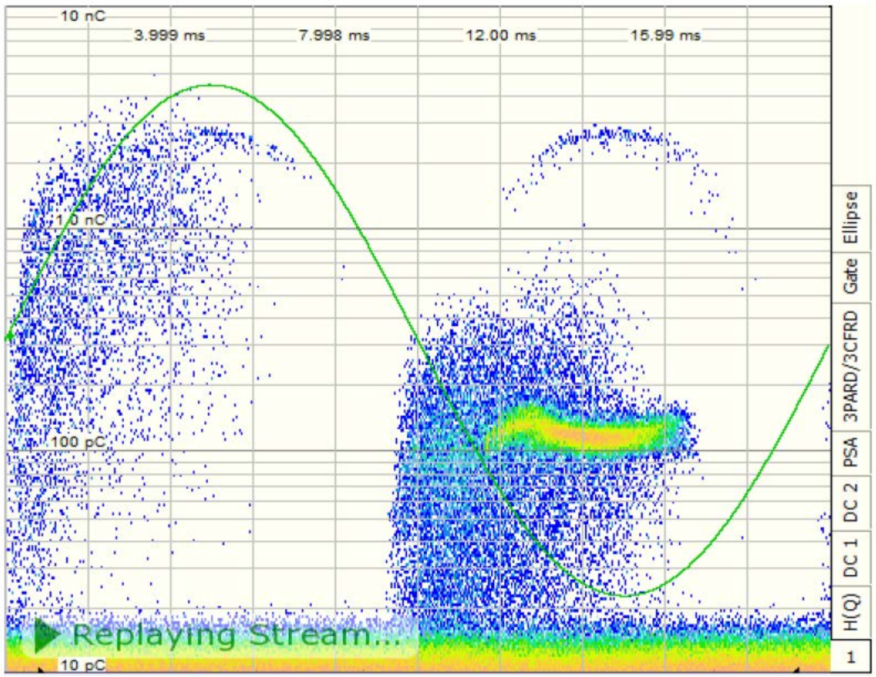
$$I = \frac{1}{T_{ref}}(\left||q_1| + |q_2| + \cdots + |q_i|\right)$$

- The discharge power $P$ is the average pulse power fed into the terminals ofthe test object due to apparent charge magnitudes $q_i$ during a chosen reference time interval $T_{ref}$, i.e.:

$$P = \frac{1}{T_{ref}}(q_1 u_1 + q_2 u_2 + \cdots + q_i u_i)$$

# ❖ Analysis of PD

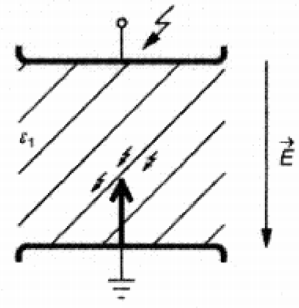
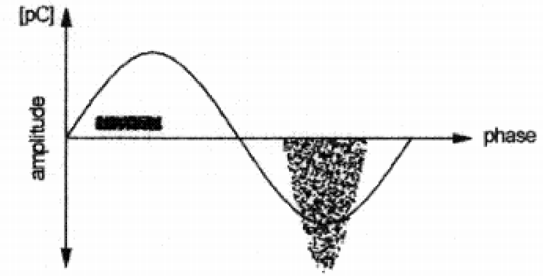
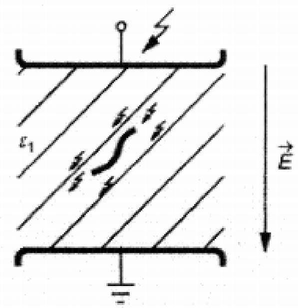
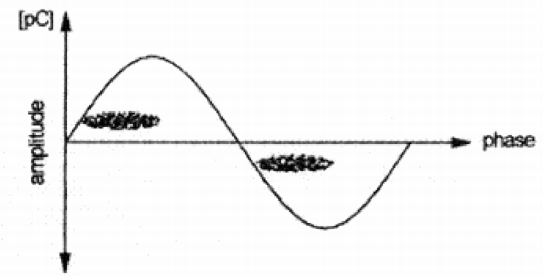
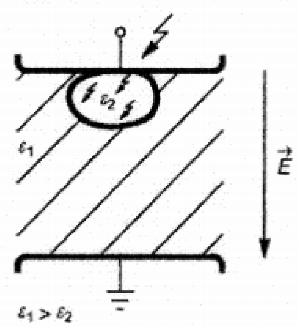
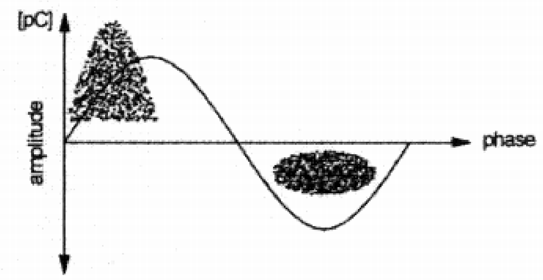
- PRPD (Phase-resolved Partial Discharge)



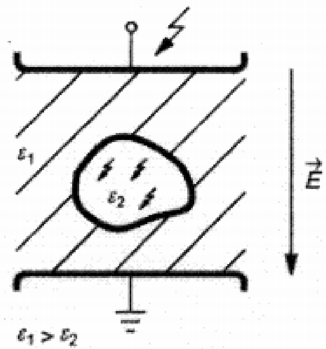
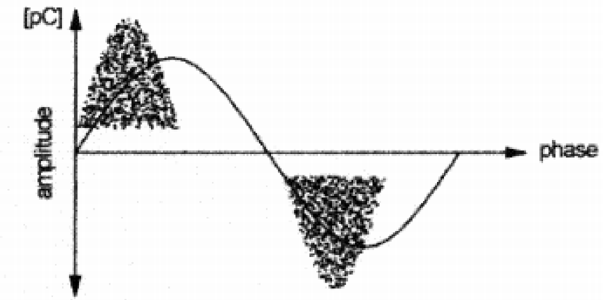
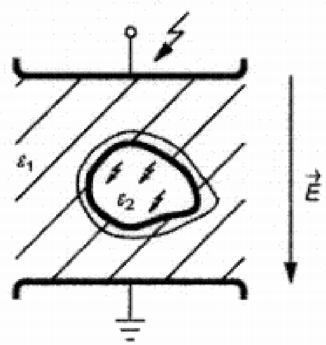
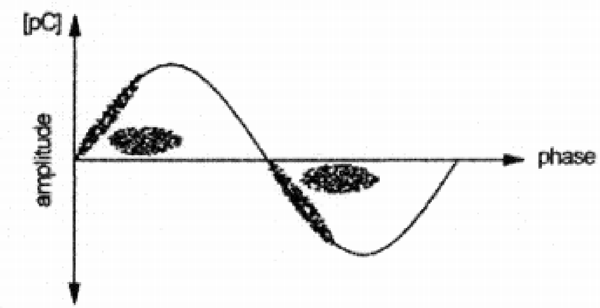

PRPD method

The phase axis (x-axis) consists of one complete cycle of the applied voltage while the PD charge magnitude axis (y-axis) consists of the range of magnitude detected. PD data within certain number of the applied voltage cycle is plotted on the x-axis of one voltage cycle. Therefore, a PRPD pattern shows PD occurrences at a specific phase of the applied voltage with certain charge magnitude within certain number of the applied voltage cycles. PRPD techniques recognizes discharges of different origins!!!

# ❖ Typical PD patterns

| PD - source description | Schematical drawing of the PD - source | Typical PD - pattern |
|---|---|---|
| Conducting material (tip electrode) with a direct contact to metallic electrode |   | PD - pattern type 1   |
| Conducting material without any contact to metallic electrode |   | PD - pattern type 2   |
| Not conducting material (cavity) with a direct contact to metallic electrode |   | PD - pattern type 3   |

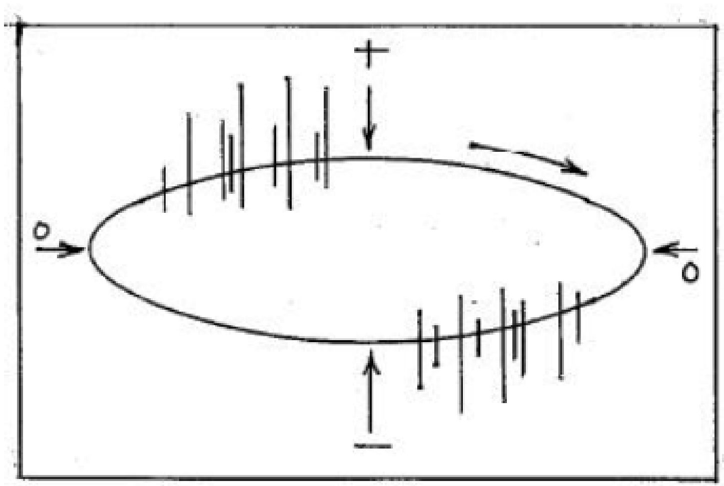
# ❖ Typical PD patterns

| | | |
|---|---|---|
| Not conducting material (cavity) without any contact to metallic electrode |   | PD - pattern type 4   |
| Not conducting material (cavity) without any contact to metallic electrode with changing surface du to the partial discharge |   | PD - pattern type 5   |

# CIGRE WG 21.03

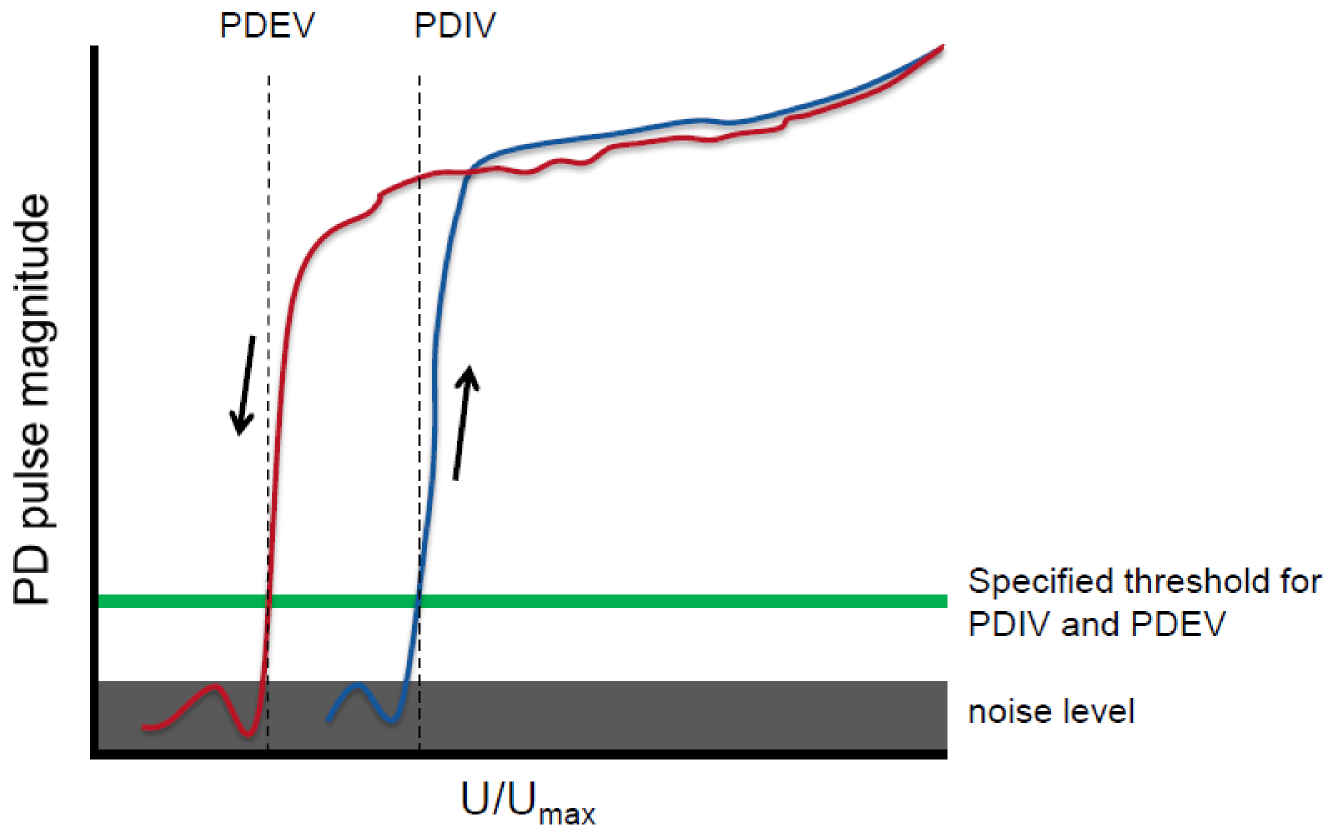
## Recognition of Discharges

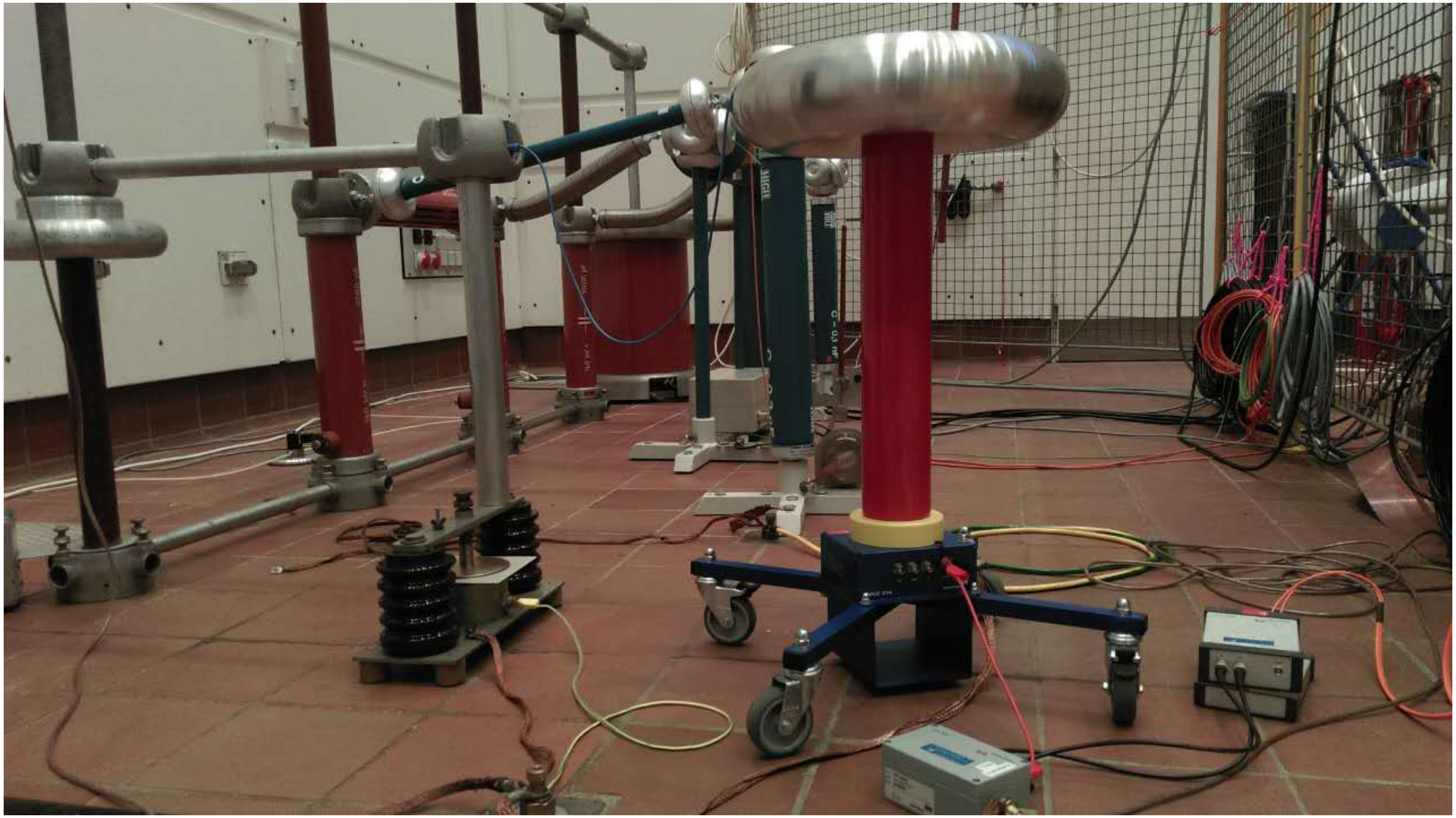
**Case A.**

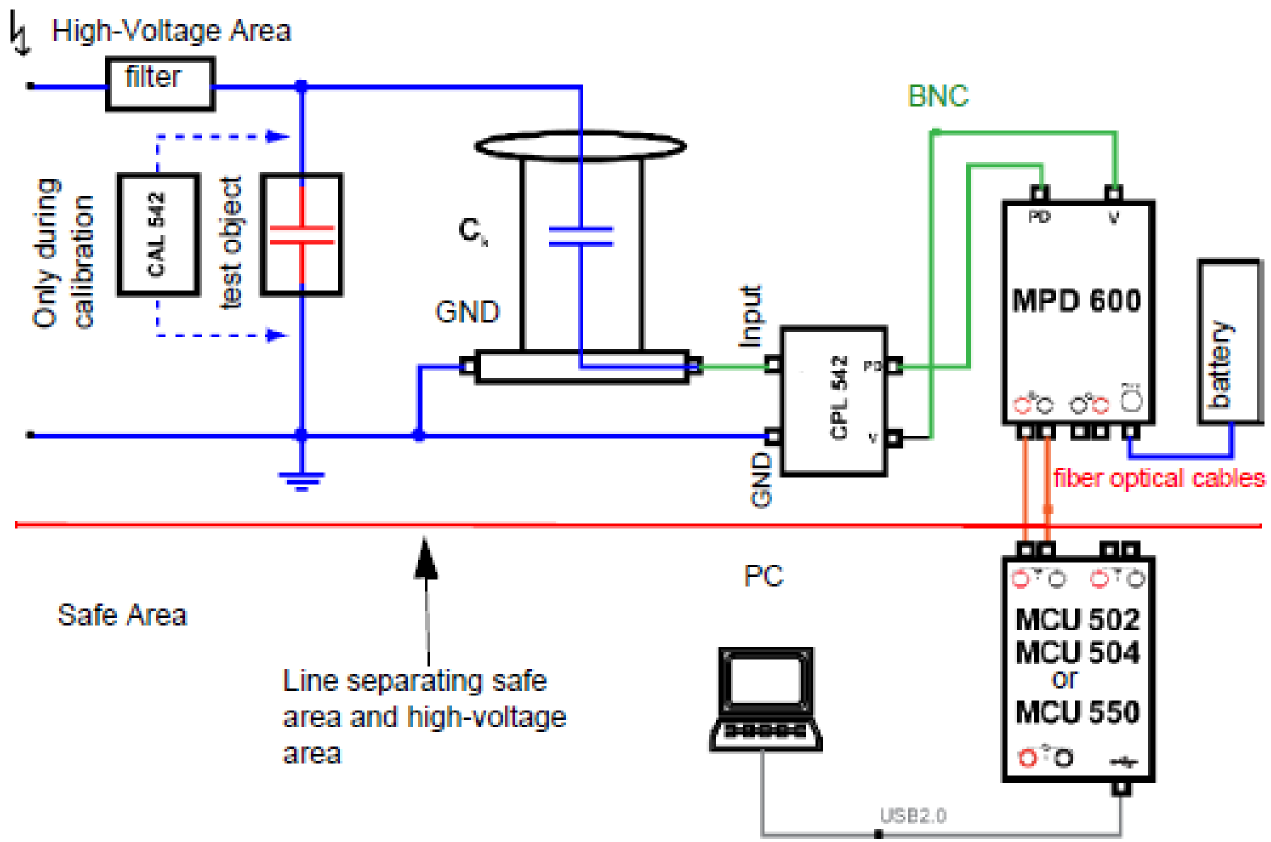


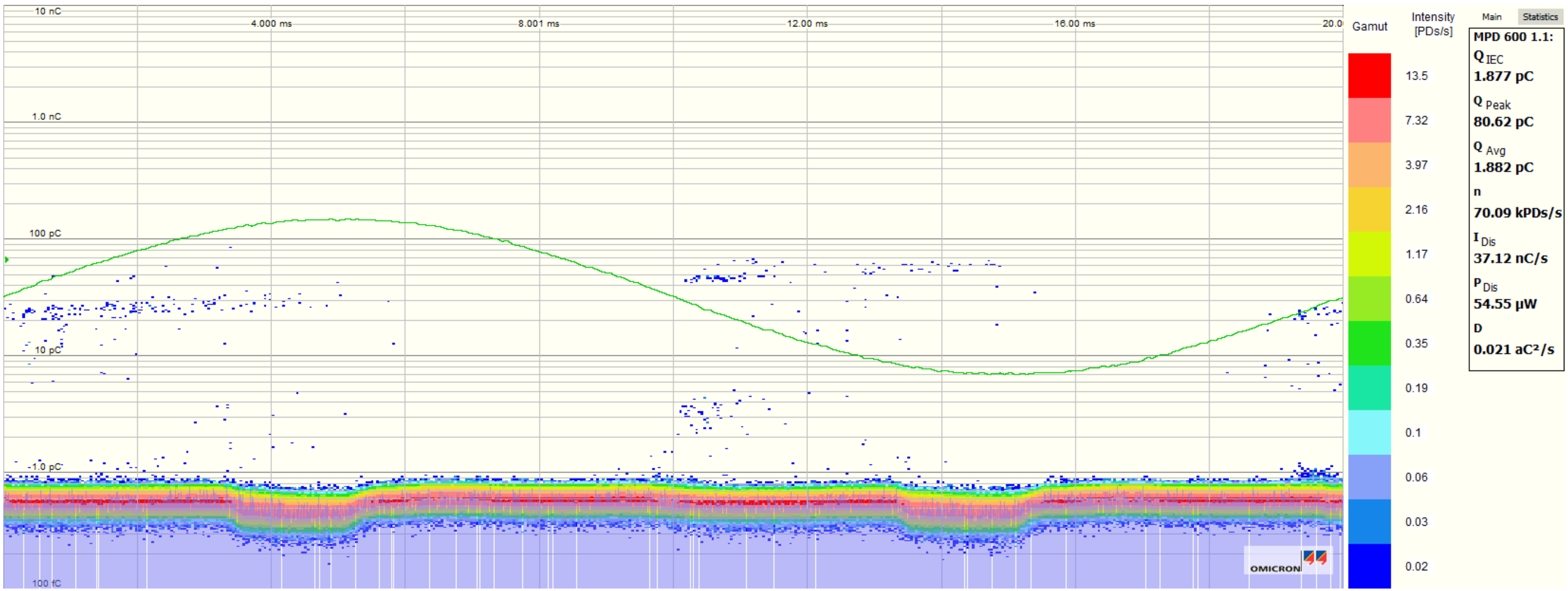
| Discharge Pattern | | | Variation of Discharge Magnitude with : | | |
|---|---|---|---|---|---|
| Location of Discharges on Test Waveform | Variability of Response | Relative Magnitude of Discharges on +ve and −ve half cycles | Test Voltage | Time of Application | Case |
| Most pulses in advance of the voltage peaks | Random movement | Similar magnitude on both half cycles | Constant with test voltage | Constant with time | A |
| | | | | Falls slowly with time | B |
| | | | Rises with test voltage | Constant with time | C |
| | | | | Falls slowly with time | D |
| | | | | Rises slowly with time | E |
| | | | | Rises rapidly with time | F |
| | | Different magnitude on two half cycles | Constant with test voltage | Constant with time | G |
| | | | Rises with test voltage | Constant with time | H |
| | Steady or repeated motion | Similar magnitude on both half cycles | Constant with test voltage | Constant with time | J |
| On both sides of the voltage peaks | Stationary | On one half cycle only | Constant with test voltage | Constant with time | K |
| | | | | | L |
| | Steady | Different magnitude on two half cycles | Constant with test voltage on one half cycle. Rises on other | Constant with time | M |
| On both sides of the voltage zeros | Random movement | Similar magnitude at both voltage zeros | Rises with test voltage | Constant with time | N |

## ❖ Inception and extinction voltage






High-Voltage Area
filter
Only during calibration
CAL 542
test object
$C_x$
GND
Input
CPL 542
PD
V
GND
BNC
PD
V
MPD 600
battery
fiber optical cables
Safe Area
Line separating safe area and high-voltage area
PC
MCU 502
MCU 504
or
MCU 550
USB2.0



10 nC
4.000 ms
8.001 ms
12.00 ms
16.00 ms
1.0 nC
100 pC
10 pC
-1.0 pC
100 fC
OMICRON
Gamut
Intensity [PDs/s]
13.5
7.32
3.97
2.16
1.17
0.64
0.35
0.19
0.1
0.06
0.03
0.02
Main
Statistics
MPD 600 1.1:
Q IEC
1.877 pC
Q Peak
80.62 pC
Q Avg
1.882 pC
n
70.09 kPDs/s
I Dis
37.12 nC/s
P Dis
54.55 µW
D
0.021 aC²/s