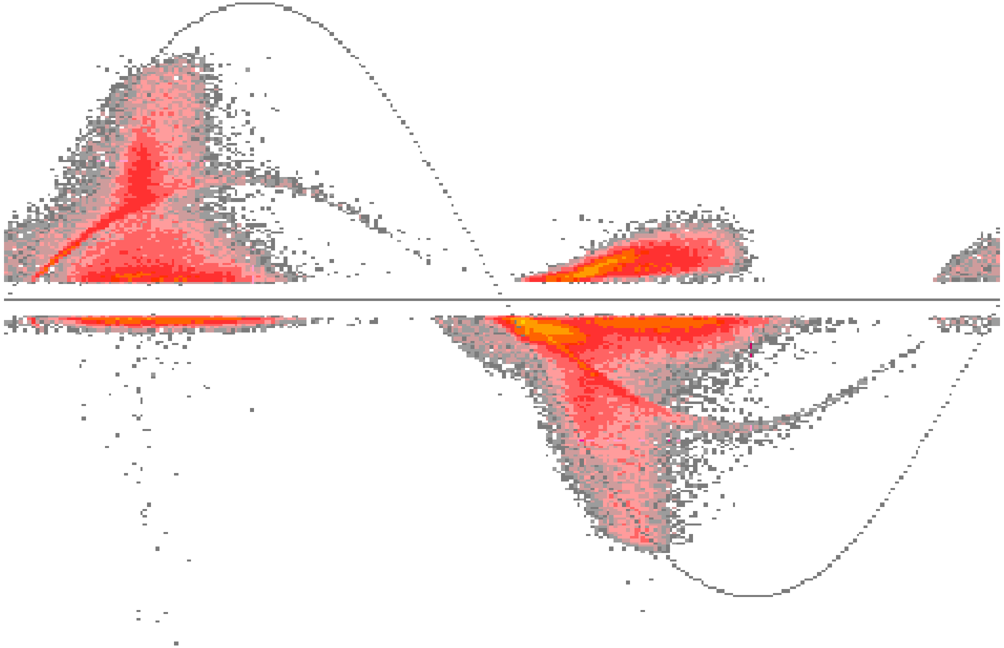
Fundamentals of partial discharge measurements

Ceren Gürbüz
Electrical Engineer
Power Diagnostix Systems
5 February 2020

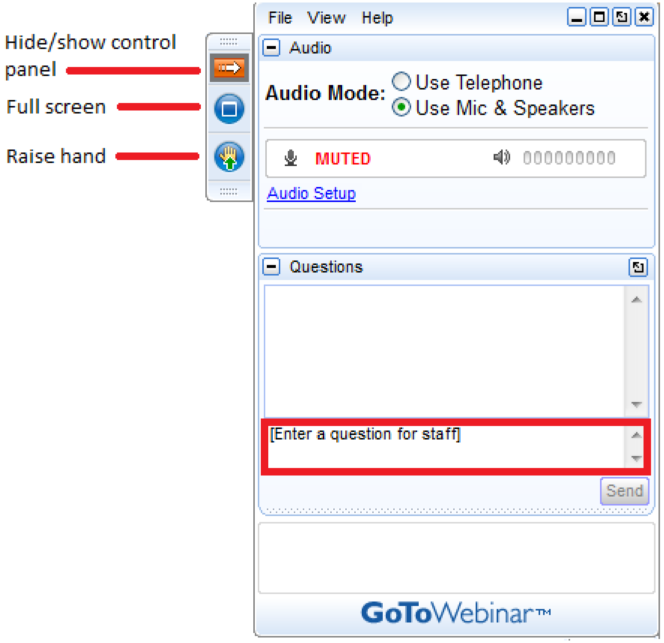


Moderator

- Sebastian Dreher
  - Power Diagnostix Development Engineer

Q&A

- Send us your questions and comments during the presentation



Audio Mode: ○ Use Telephone ● Use Mic & Speakers

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[Enter a question for staff]

Today's Presenter & Panellist

- Presenter:
  - Ceren Gürbüz
    - Power Diagnostix Electrical Engineer

- Panellists:
  - Markus Söller
    - Power Diagnostix Managing Director

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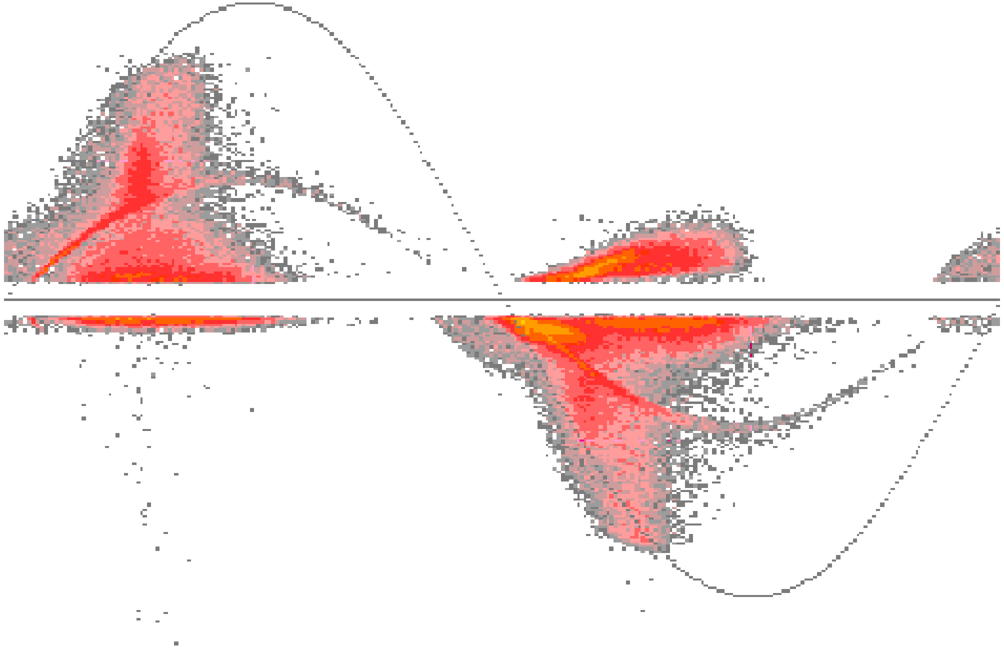
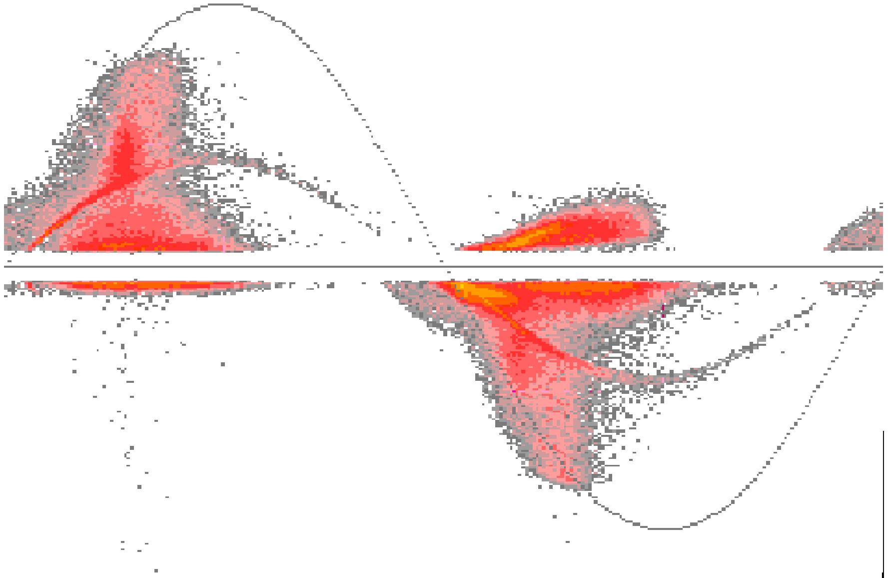


Fundamentals of partial discharge measurements

- Early research on discharge phenomena
- Occurrence of partial discharge
- Evolution of standards
  (Horizontal Standard IEC60270)
- Common PD detector principles
- Properties of electrical PD signals
- Conventional testing methods
- Unconventional testing methods



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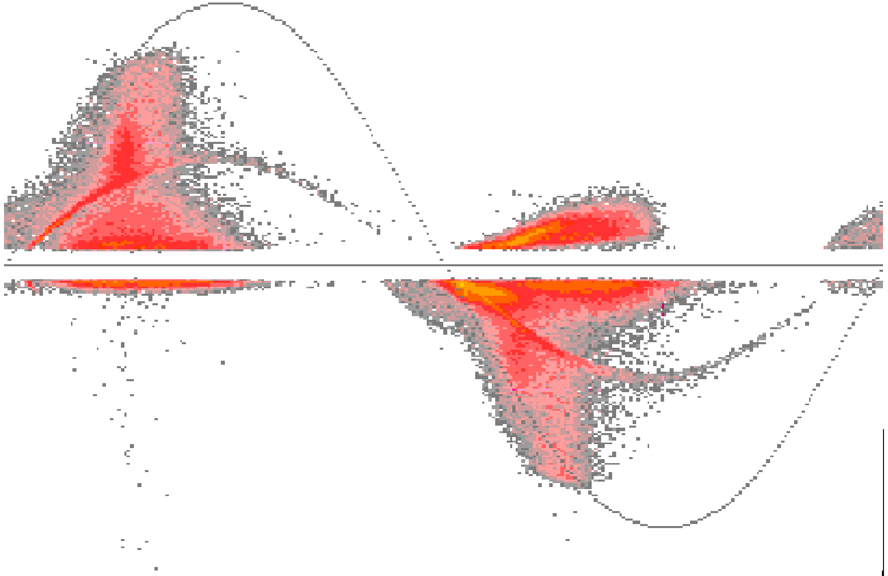
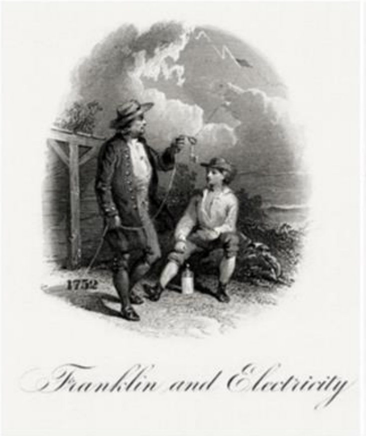
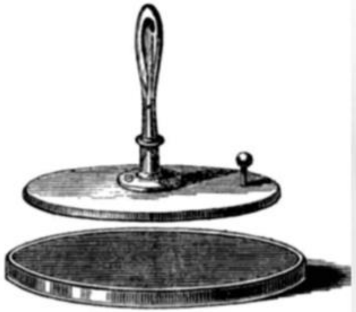


Early research on discharge phenomena

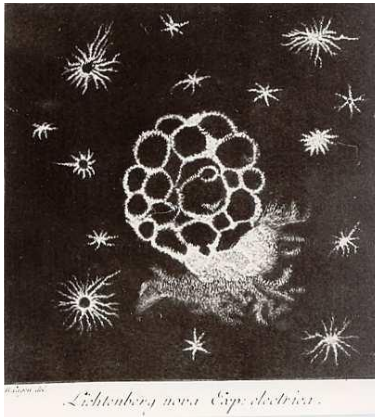
- Electrical discharges, such as lightning or St. Elmo's fire, attracted researchers
- This led Benjamin Franklin to develop a lightning rod, first described in 1749
- In 1762, J. C. Wilcke invented a capacitive generator that produced electrostatic charge

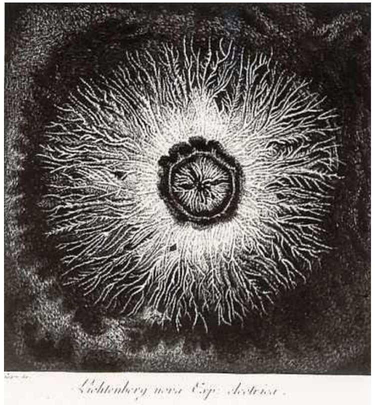


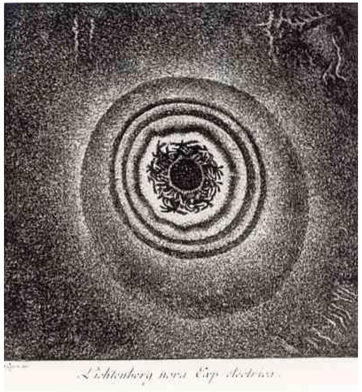


Early research on discharge phenomena

- In 1777, G. C. Lichtenberg conducted the first systematic research on electrostatic discharge
- Lichtenberg built a large version of the electrophorus and found figures formed by dielectric dust on the dielectric plate
- Due to the lack of photographic options, Lichtenberg transferred the dust figures using sticky black paper







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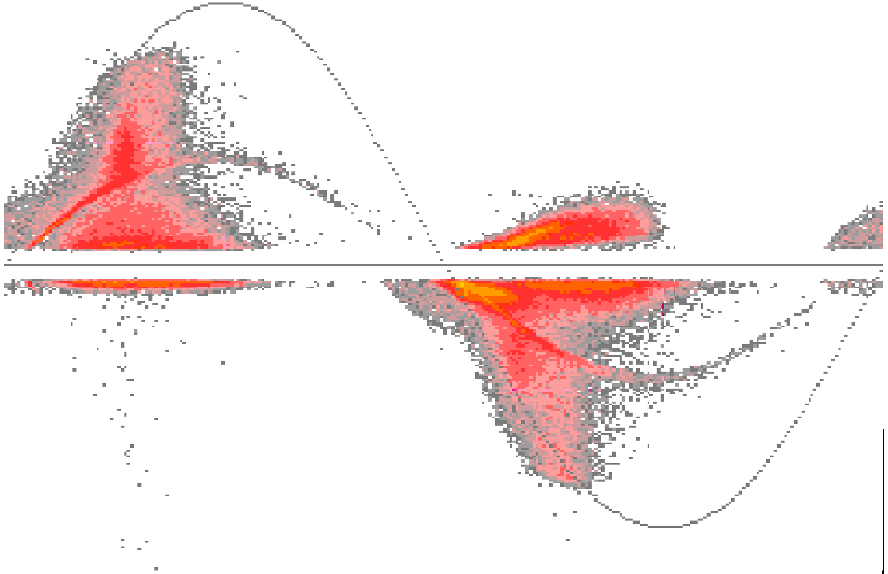
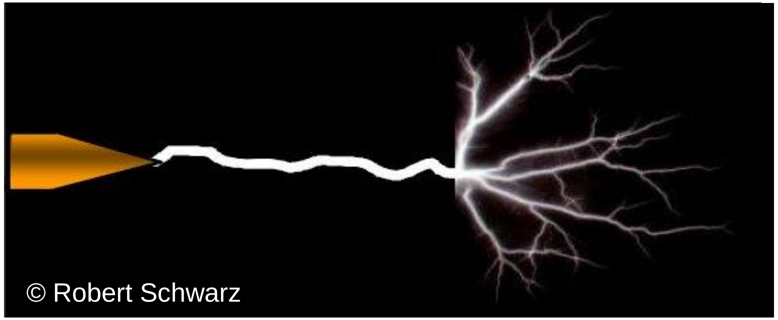


Occurrence of partial discharge

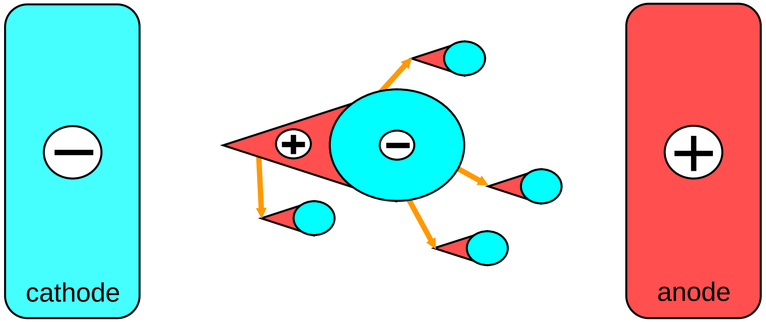
- For the occurrence of partial discharge, two conditions must be met:
  - The local electric field must have reached the critical inception field ($E > E_{crit}$)
  - A free electron must be available to start the discharge avalanche
- Two main processes to derive this initial electron:
  - Ionisation by photons
  - Field emission
- The statistical properties of these processes control the appearance of the PD pattern

Main discharge types – ionisation processes

- *Trichel* discharge (trichel, glow, and "corona")
  Ionisation process: Collision ionisation
- *Streamer* discharge (filament and bunch streamer)
  Ionisation process: Collision and photo ionisation
- *Leader* discharge (stem bunch and spark)
  Ionisation process: Collision, photo and thermal ionisation



© Robert Schwarz



Provision of starting electrons

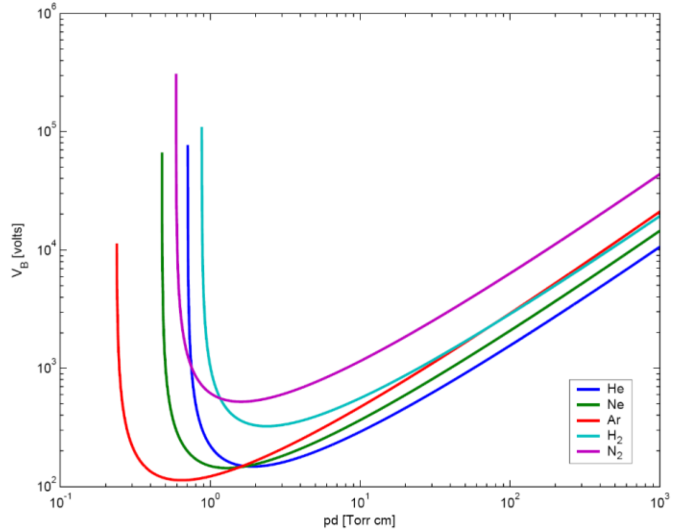
- Plenty of free electrons on metallic surface — immediate inception of partial discharge if $E > E_{crit}$
- Polymeric low energy surfaces (PE, PP, PTFE, etc.) offer literally no free electrons — ionisation needed
- The sources of ambient radioactivity (cosmic photons, ^{222}Rn, soil, fallout) cause ~$2 \cdot 10^6$ free electrons per second and cubic metre — delayed inception

- Hence, it takes on average 15 minutes until a spherical void of 1 mm diameter is hit and discharge starts
- Common testing times of epoxy-moulded equipment often too short, e.g. dry-type transformers 3 minutes

Properties of insulation materials

- Typical breakdown strength:

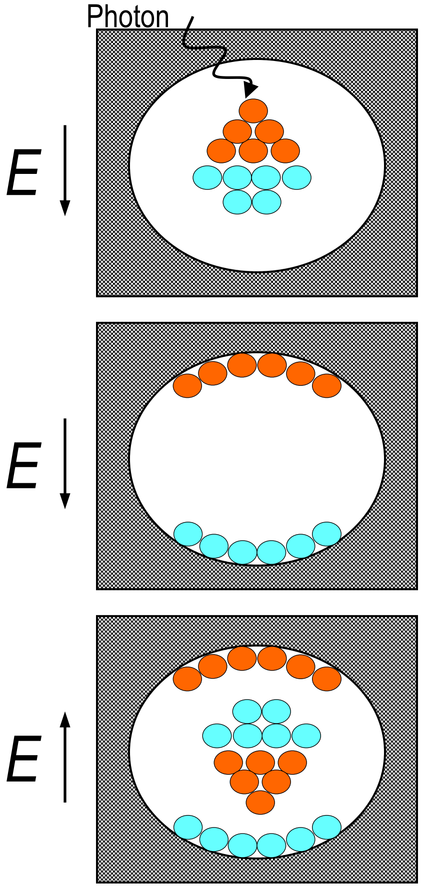
  - Air: 24 kV/cm bar
  - Hydrogen H_2: 16 kV/cm bar
  - SF_6: 88 kV/cm bar
  - Transformer oil: ~150 kV/cm (20°C)
  - Epoxy resin: ~300 kV/cm
  - Polyethylene: >500 kV/cm (Foils up to 8000 kV/cm)



Wiley, 2005

- Paschen's law: $E_{\text{Breakdown}} \sim pd$ (p > 1 bar)
- Hydrogen-cooled generators: 3–7 bar
- SF_6 insulated switchgear: 3–4 bar

Discharges in a spherical gas inclusion



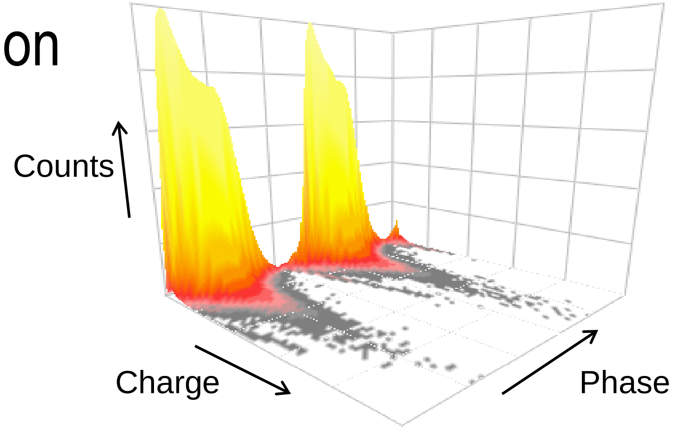
No discharge although $E > E_{crit}$
- Photon provides the initial free electron
- Electric field accelerates the electron
- Discharge avalanche occurs

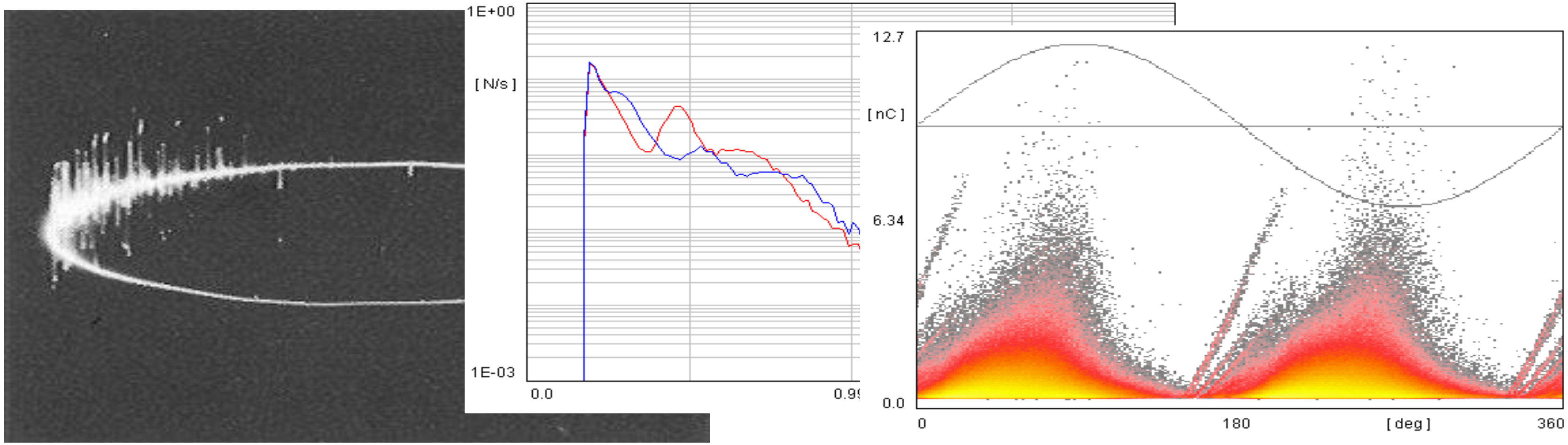
Charge separation after discharge
- Positive gas ions and electronics
- Space charges on the surfaces
- Residual field $E = E_{res}$

Reversed polarity during next half cycle
- De-trapping of electrons, $E > E_{crit}$
- Electric field accelerates the electron
- Discharge avalanche occurs

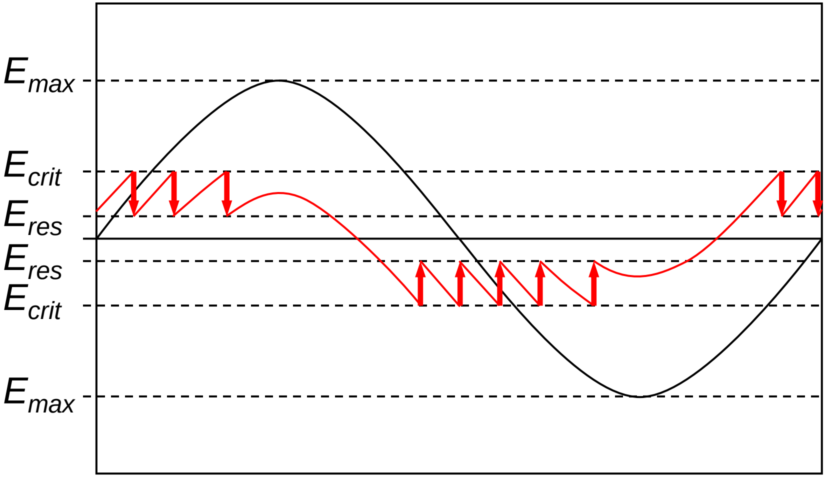
Visualisation of the part discharge activity

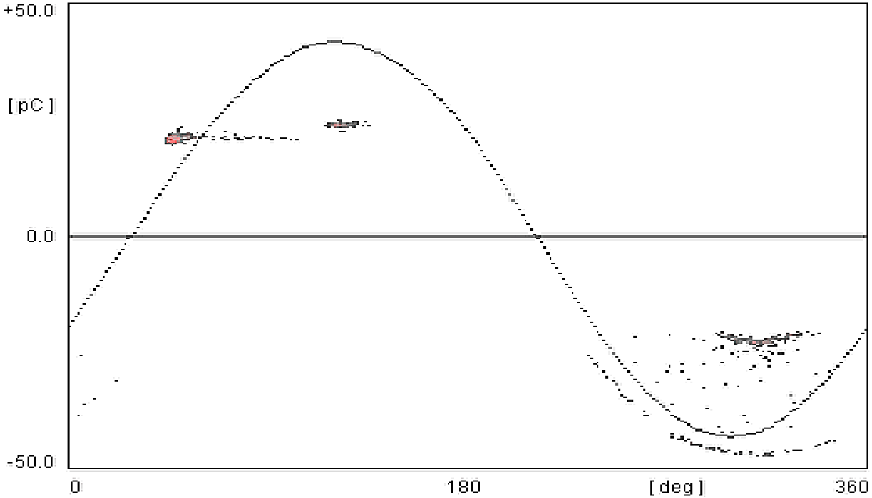
- Historical development of representation
  - Early meter style
  - Oscilloscope, Lissajous
  - Count distribution
  - *φ-q-n* pattern
  - 3D pattern





Discharges in a spherical gas enclosure

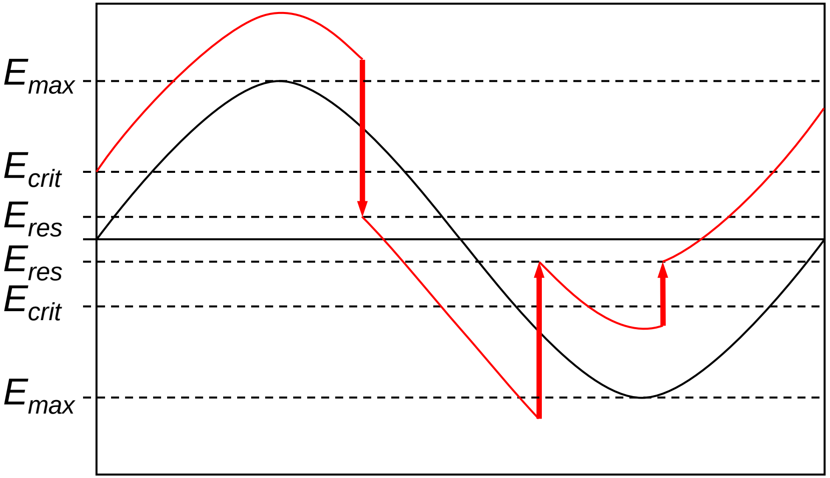


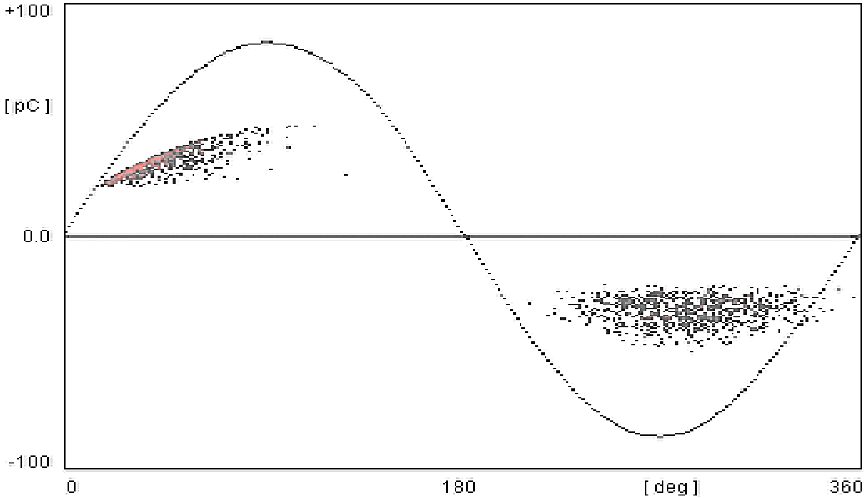


High availability of starting electrons

- Regular discharge for E> Ecrit
- Stable (low) discharge amplitude
- Regular partial discharge

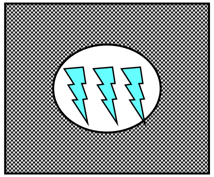
Discharges in a spherical gas inclusion





Low availability of starting electrons

- Random discharge event for E> Ecrit
- Higher discharge amplitude
- Typical distributed PD pattern



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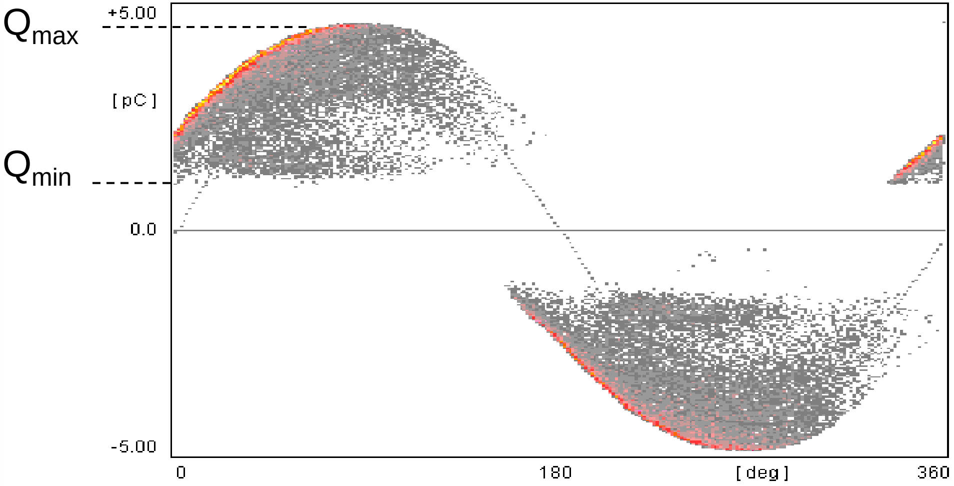
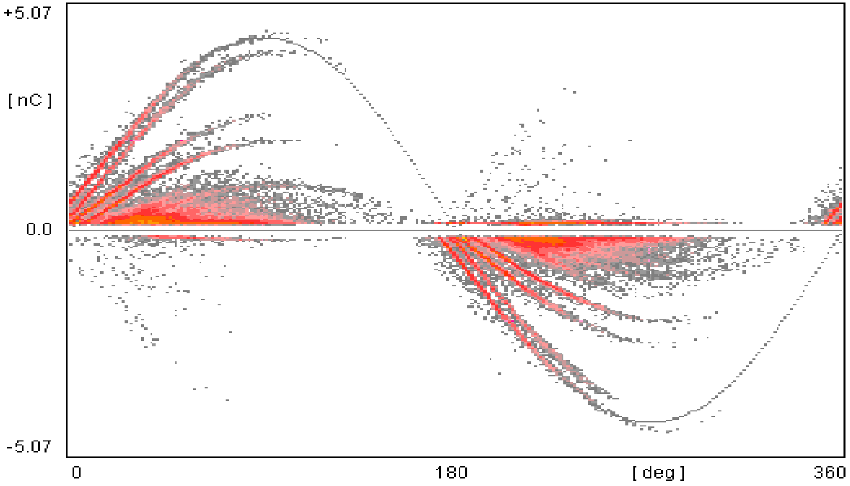
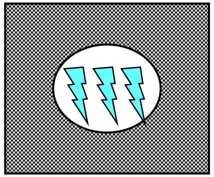




High and low availability of starting electron

- Discharge pattern indicates U/U_{inc}



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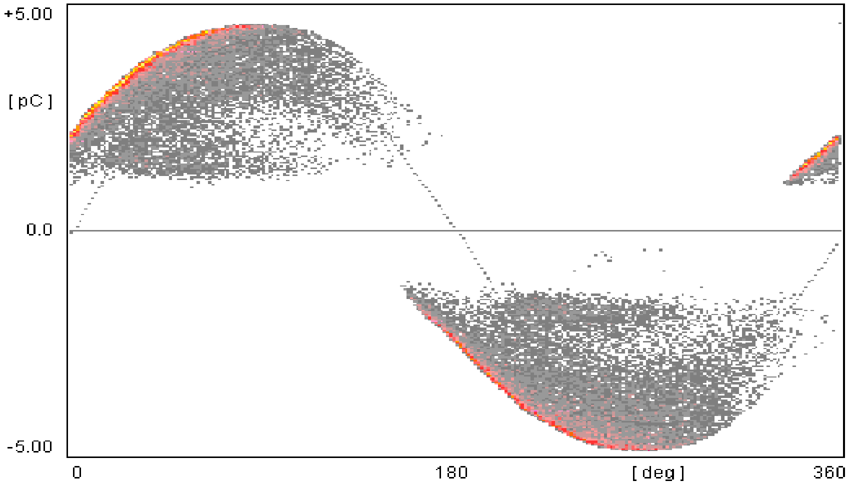
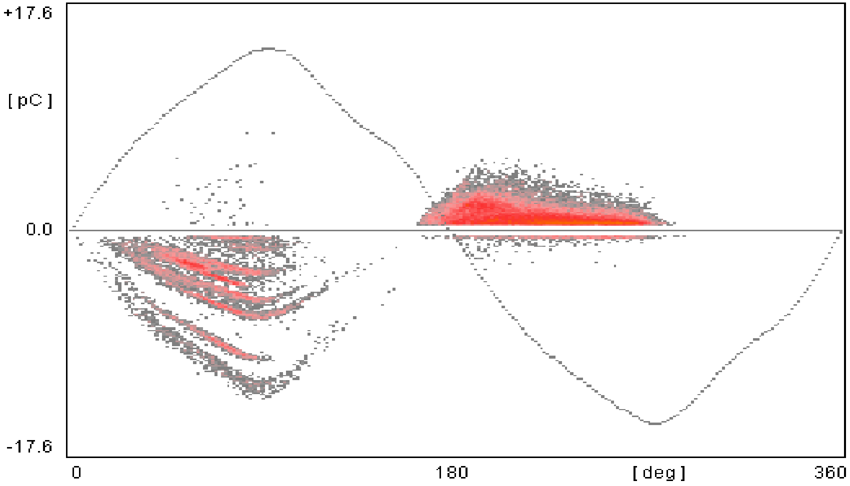
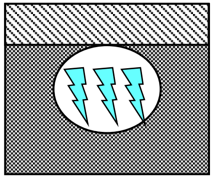


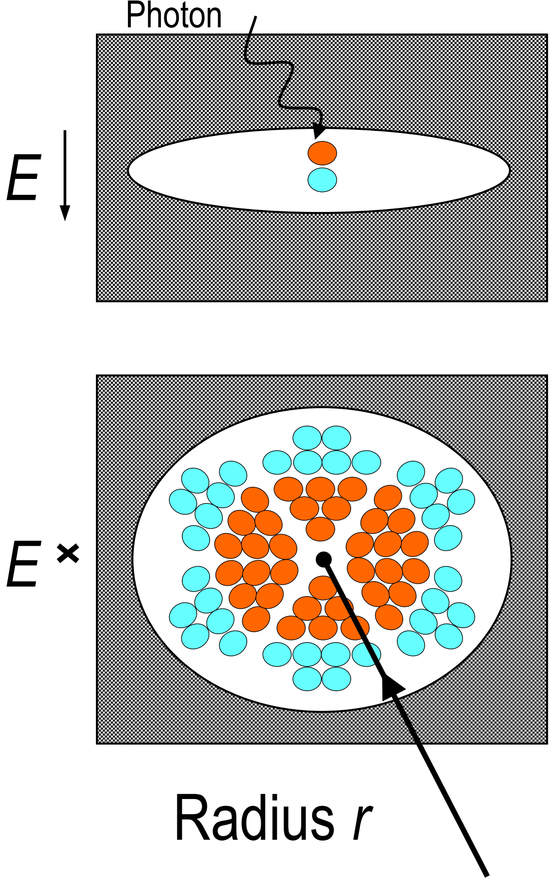


Asymmetrical availability of starting electron

- Different discharge pattern per half cycle
- Positive half cycle: low availability
- Negative half cycle: higher availability



Discharges in a flat delamination



Initial process as with spherical void

- Photon provides the initial free electron
- E field accelerates the electron
- Avalanche bridges the gap

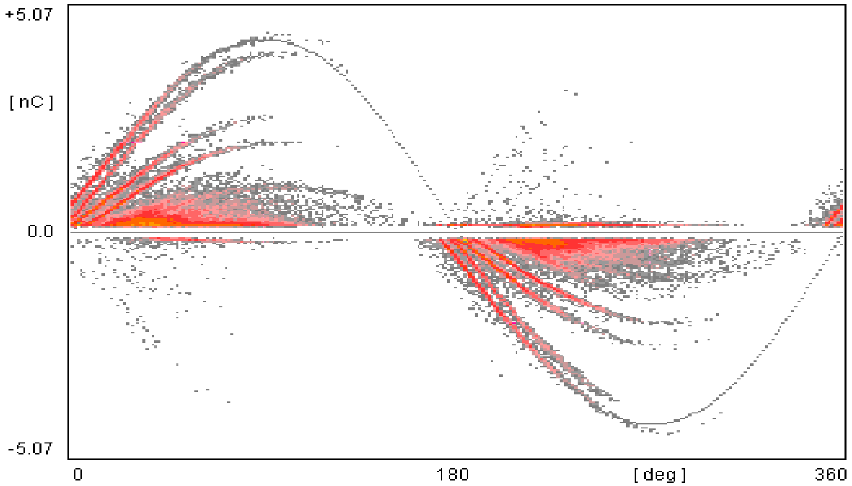
Transition into surface discharge

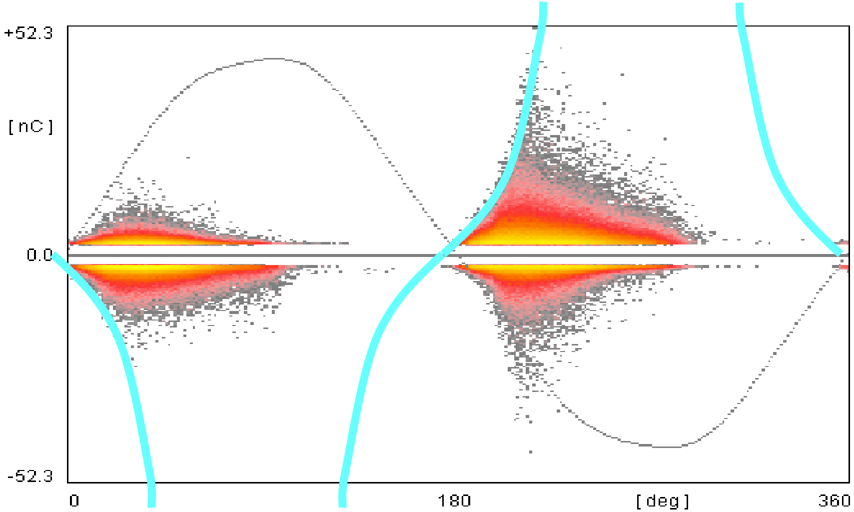
- Produces "Lichtenberg" figure
- Radius $r \sim E$
- "Ideal" delamination > $Q \sim E^3$

Influence of surface properties

- Different materials
- Surface conductivity
- Corrosion, ageing

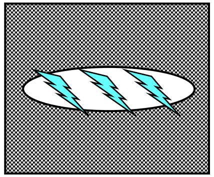
Discharges in a flat delamination



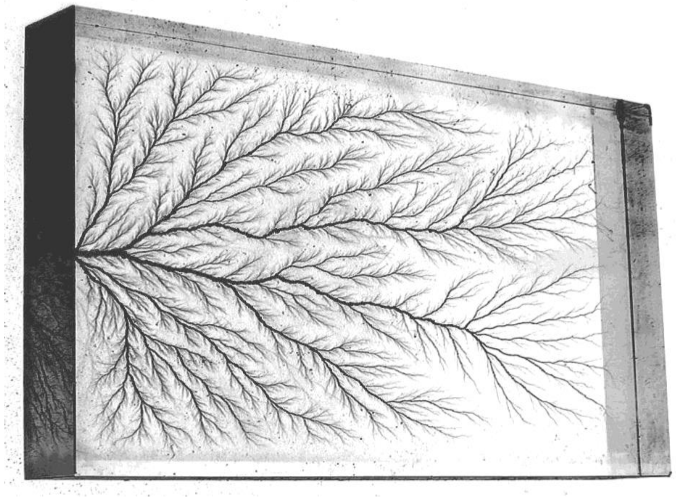


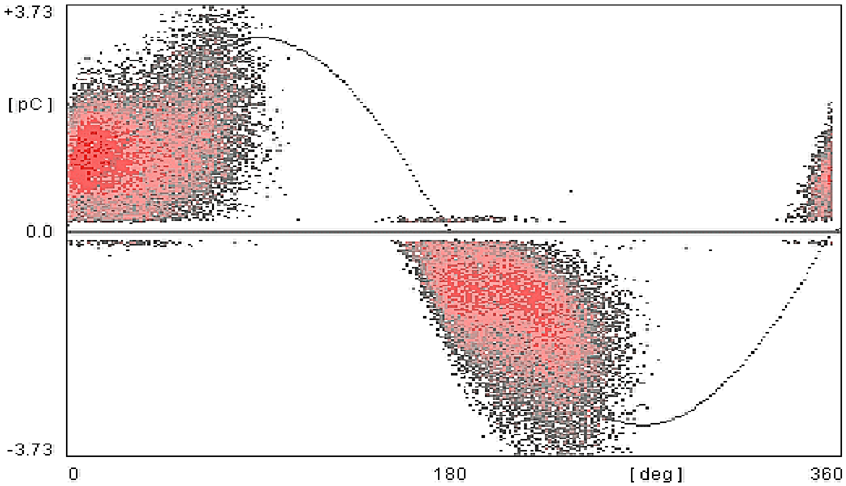
Envelope of pattern unveils discharge type

- Cavity with low electron availability $Q \sim E$
- Envelope of surface discharge type $Q \sim E^3$
- Usually, theoretical envelope only partly filled
- Ageing and corrosion increases electron availability



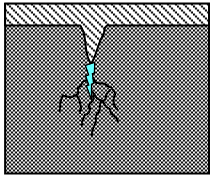
Treeing in polymeric material



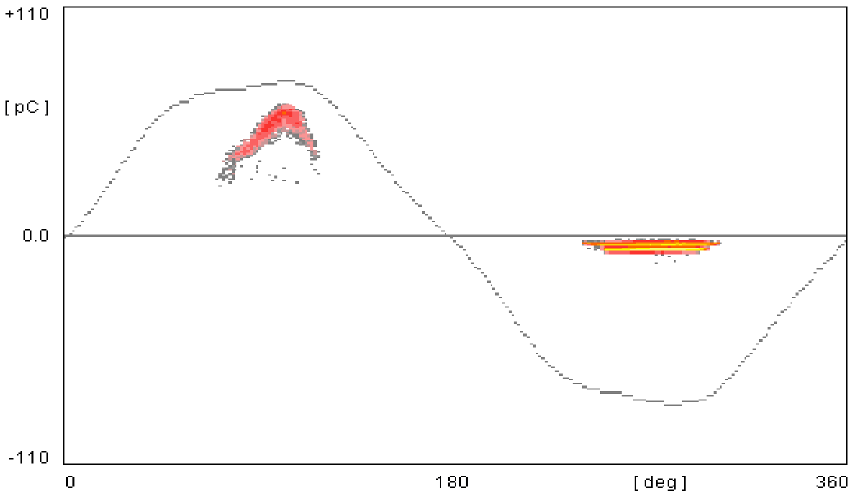


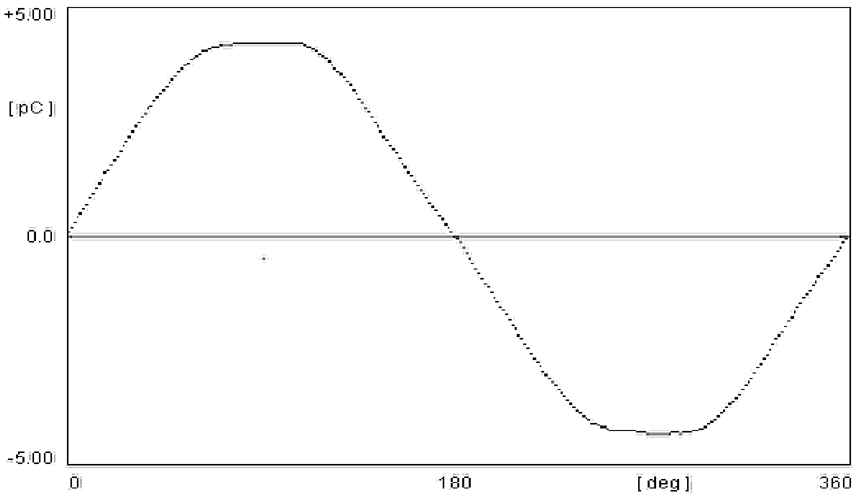
Asymmetrical electrode configuration

- Initial breakup of solid material (PE, PP)
- Continues as gas discharge
- Discharge increases with tree growth



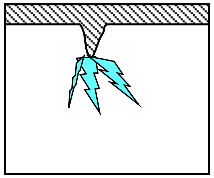
Discharges at a sharp point



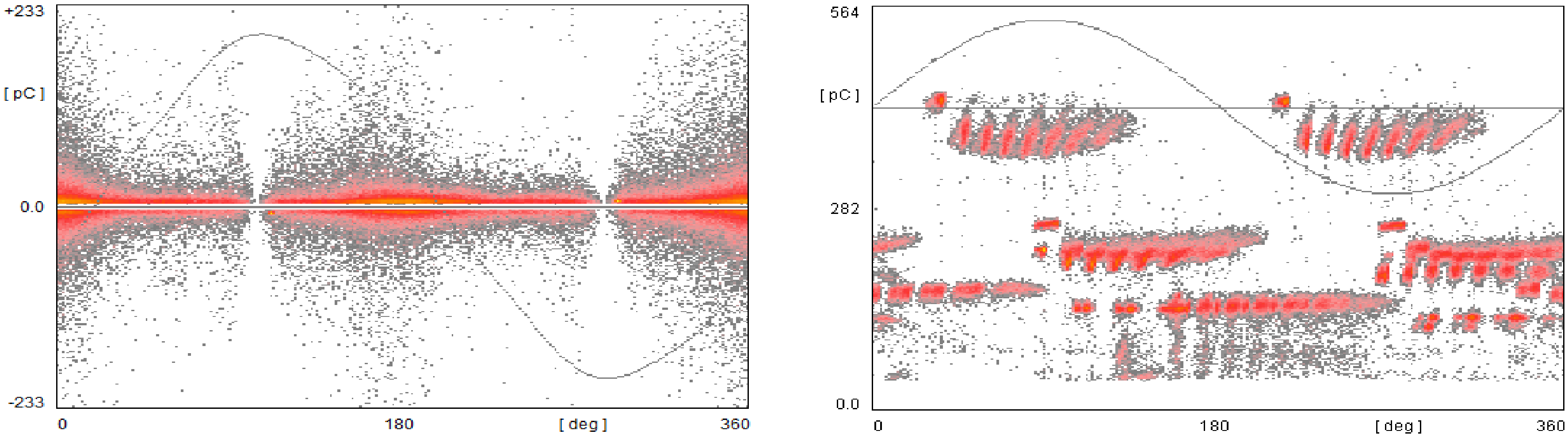


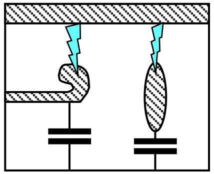
Asymmetrical electrode configuration

- Strongly non-symmetrical electrical field
- Low inception voltage for "Trichel" discharge
- Starts in the negative maximum
- Positive streamer: incipient break down



Discharges of floating potential



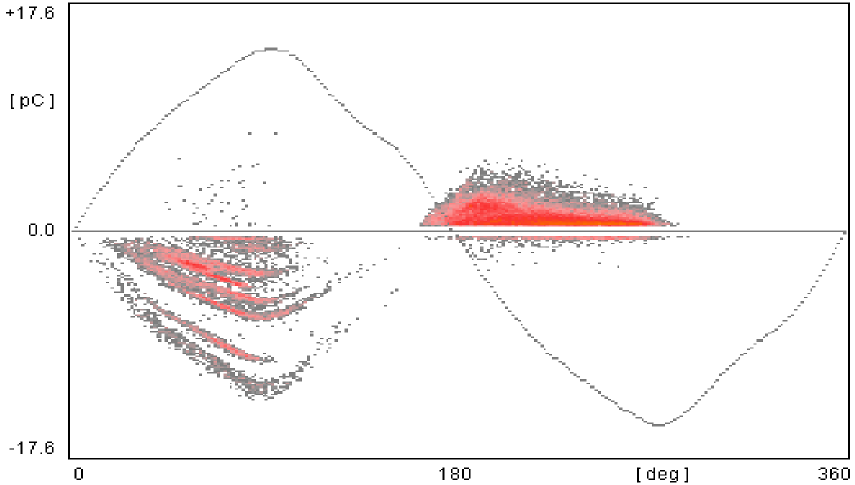


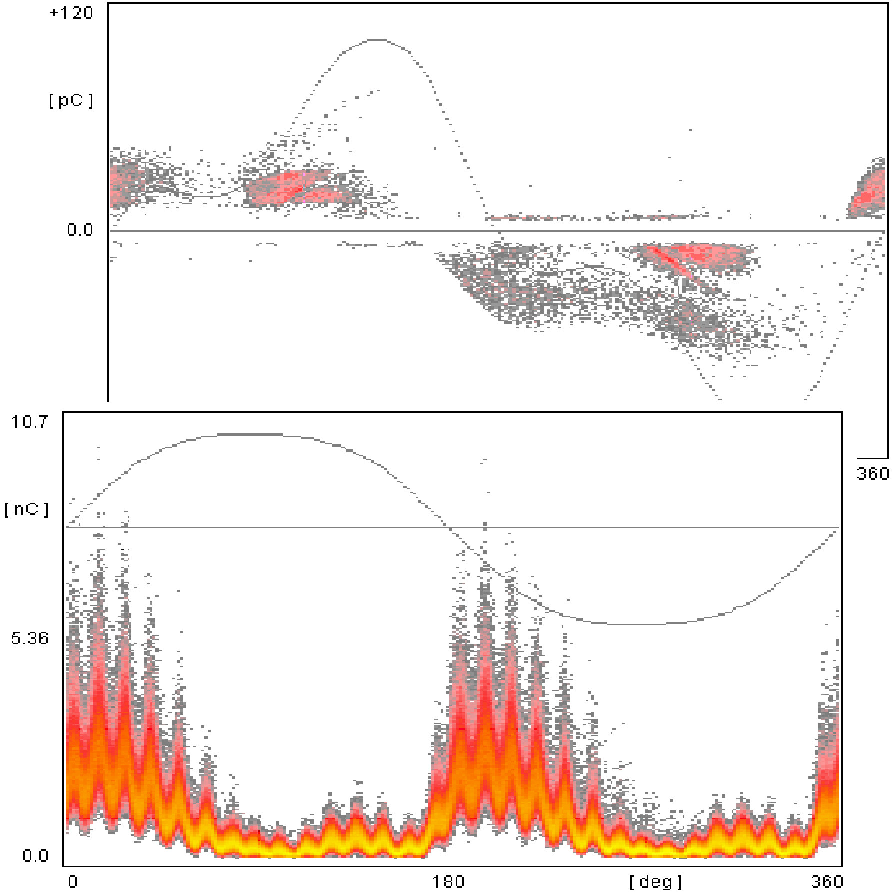
Symmetrical pattern centred with the zero crossing

- Floating shields with small metallic gap
- Compliant in three-phase GIS (right)
- Distributed pattern with insulated gap

Influence of HV harmonics and distortion

- Off-line transformer test: Core saturation
- Power frequency harmonics
- Load current distortion





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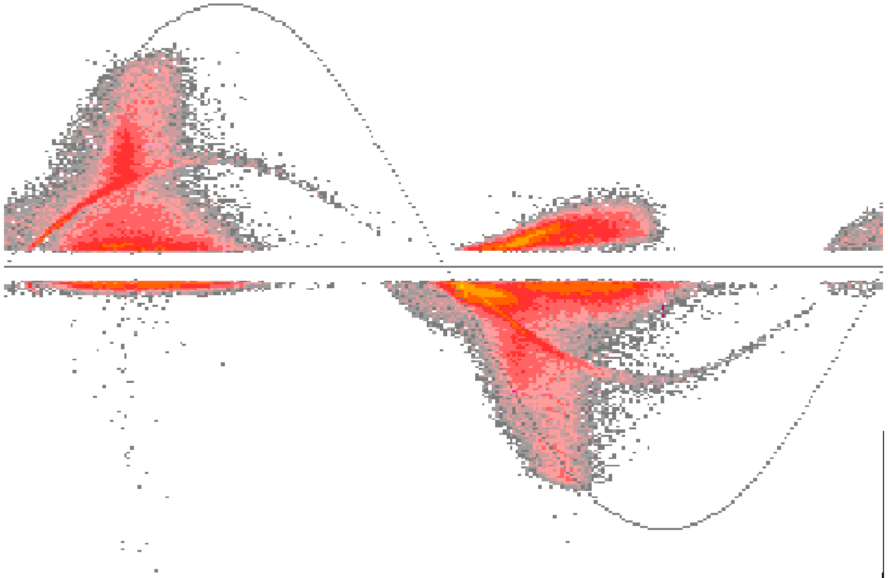

Revision IEC60270 — context

- Horizontal standard: IEC 60270
  - First edition as IEC 270 in 1968
  - Second edition IEC 270 in 1981
  - Third edition IEC 60270:2000
  - Amendment IEC 60270:2015 {Ed 3.1}
  - New revision just started TC42/MT23
- Cigré documents:
  - TB662, D1.37: Guidelines for PD detection using conventional and unconventional methods
  - TB366, D1.33: Guide for PD measurements…
- IEC 62478: MEAS. of PD by el. and acoustic methods

IEC 60270:2000 — Amd1:2015

- Main points introduced
  - Recommended band width expanded
    - Wide-band: $30\ \text{kHz} \leq f_1 \leq 100\ \text{kHz},\ f_2 \leq 1\ \text{MHz}$
      $100\ \text{kHz} \leq \Delta f \leq 900\ \text{kHz}$
  - Further calibration method "Step voltage response", Annex A.4
  - Tightened step voltage requirements
    $\Delta U \leq 0.03\ U_0$ during $t_d \geq 5\ \mu s$ (steady state)
  - Test circuits for performance test of calibrators
  - Annex E showing block diagrams of PD measuring instrument principles
  - Annex H — Test result evaluation with direct voltage

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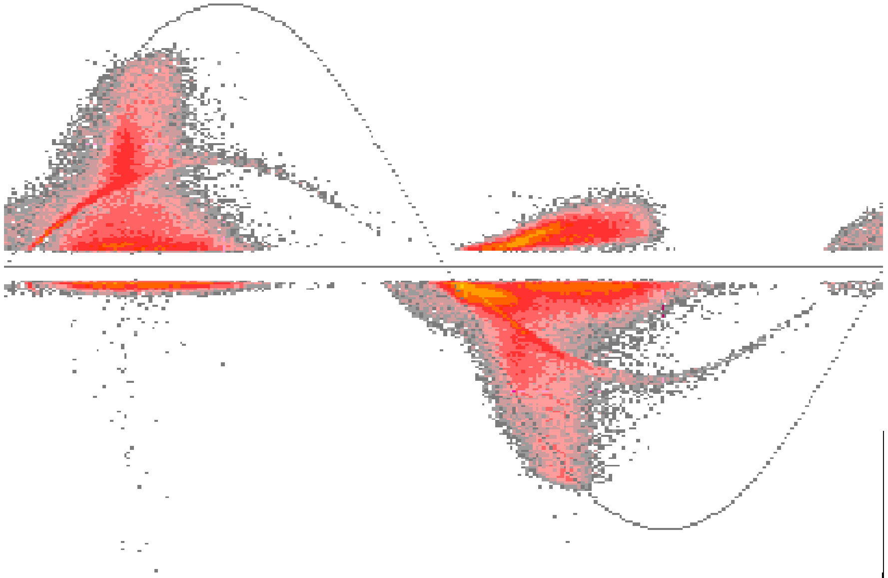
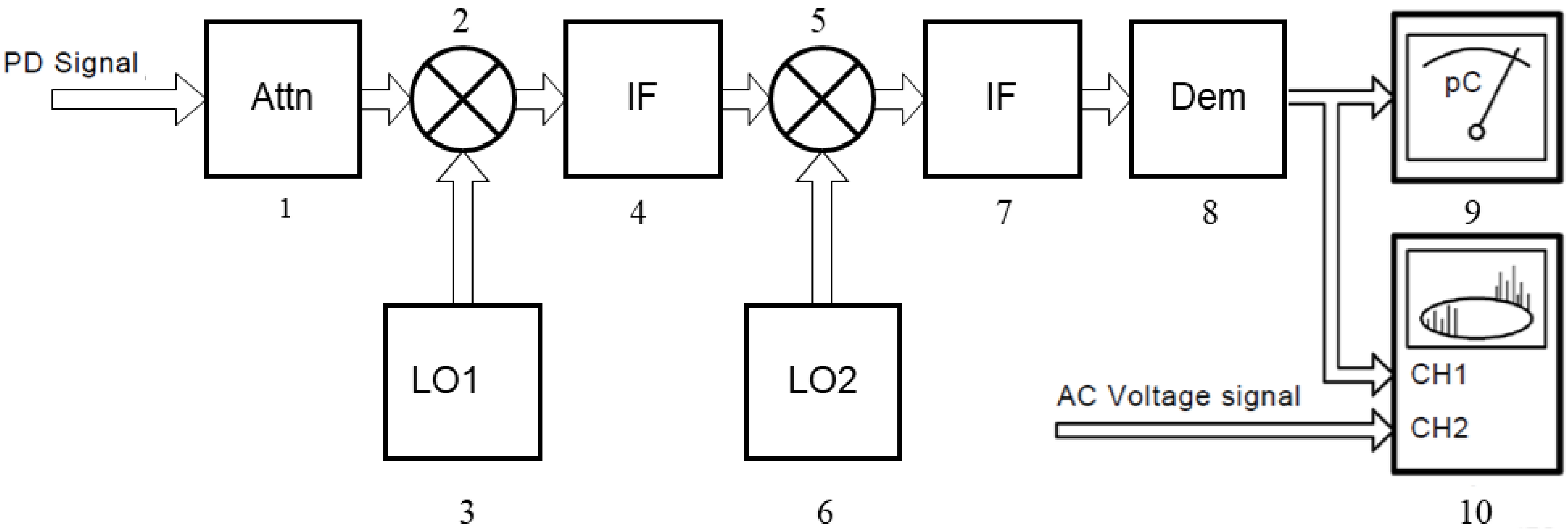


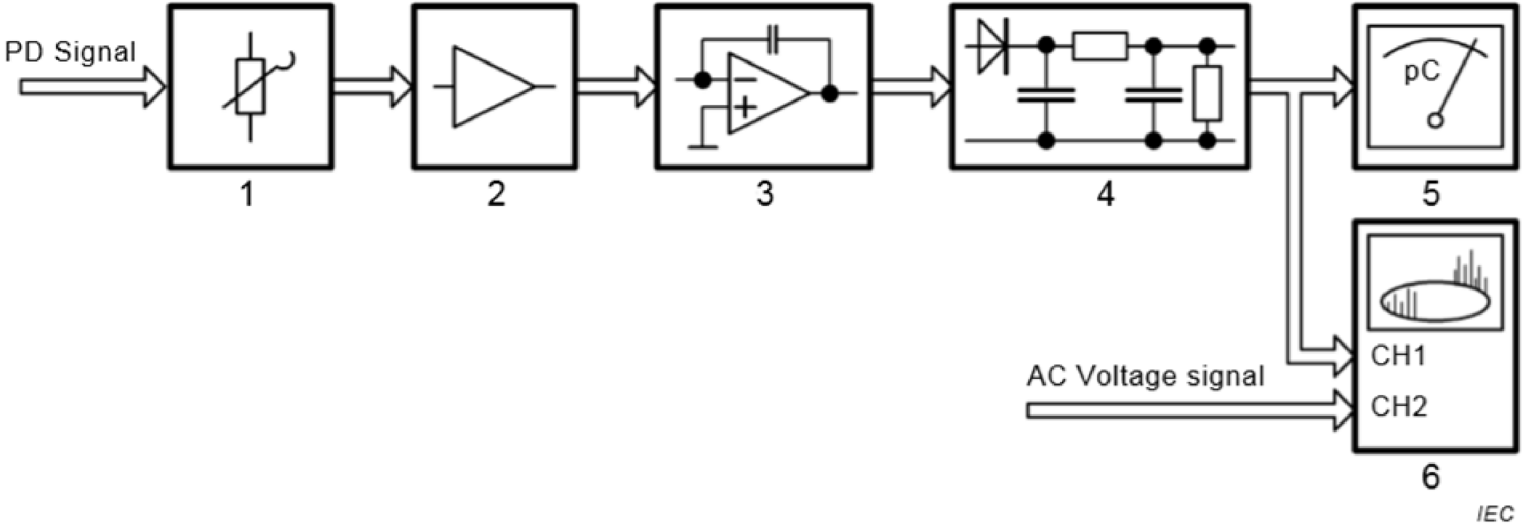
Common PD detector principles

- Instrument with "traditional" analogue super heterodyne principle to allow both narrow and wideband detection



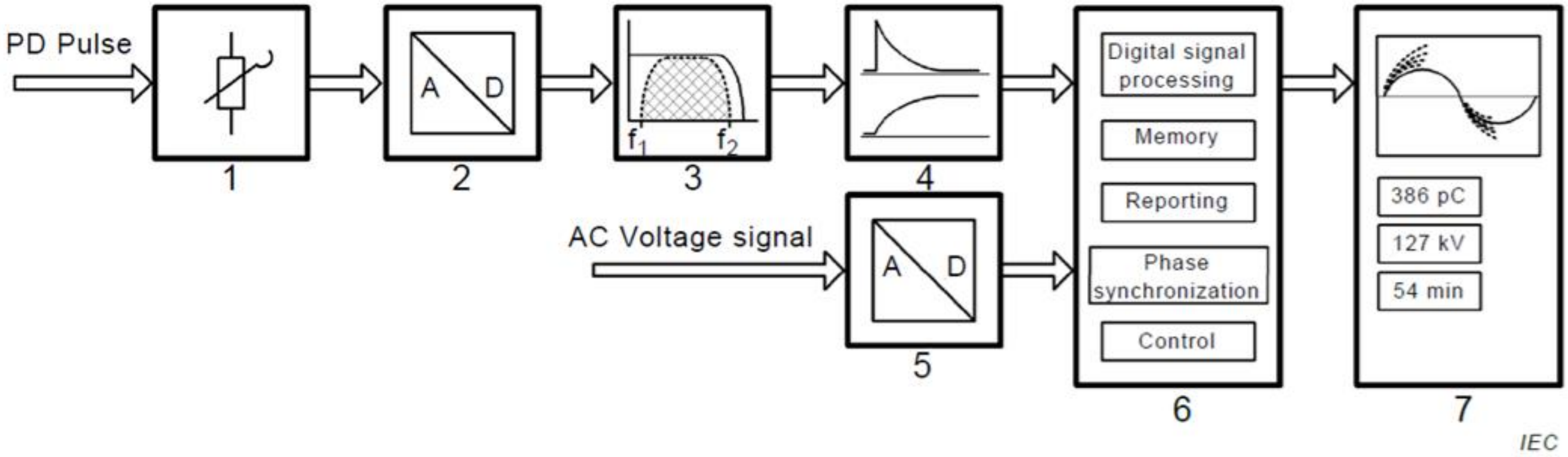
Common PD detector principles

- Instrument with active integration



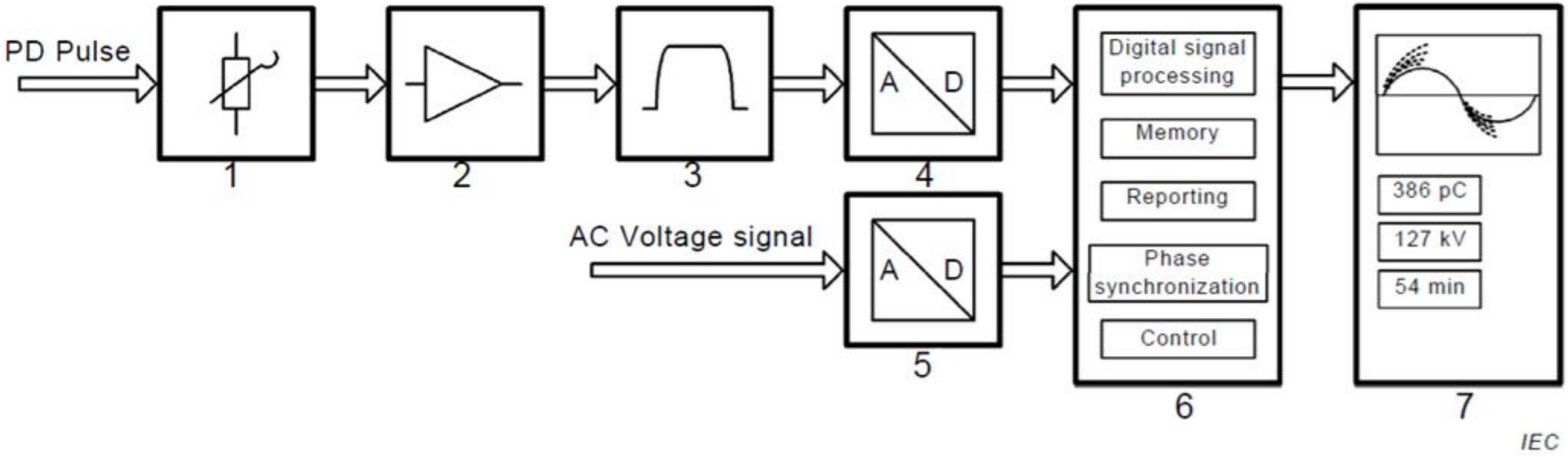
Common PD detector principles

- Instrument with early A/D conversion and digital post processing



Common PD detector principles

- Instrument with "quasi-integration" at a band-pass filter and subsequent A/D conversion



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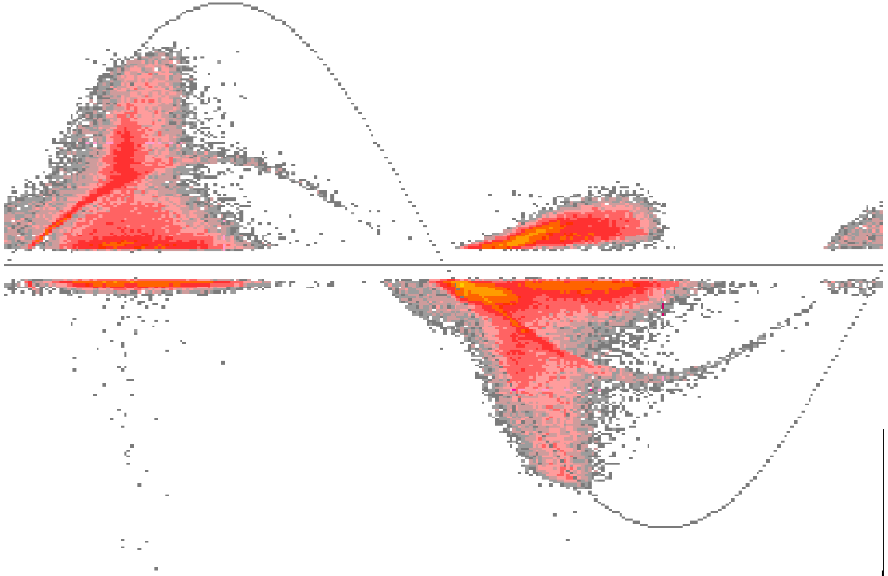
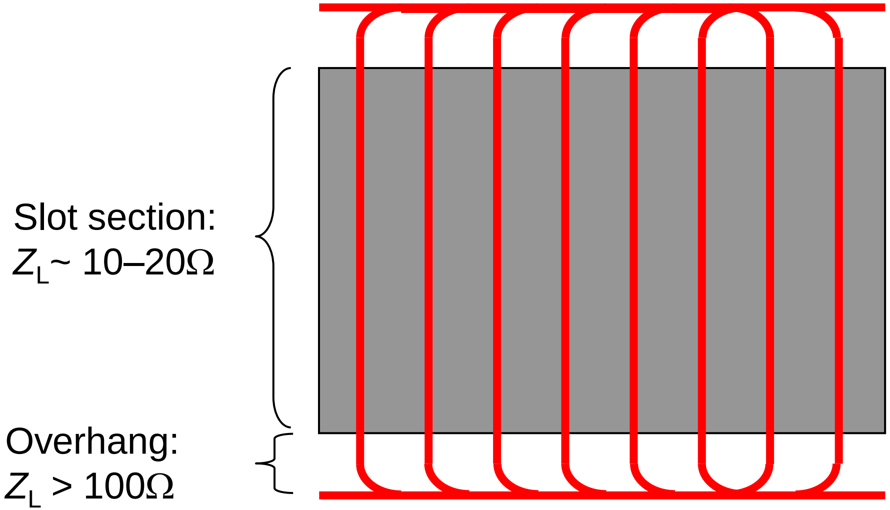


Properties and transmission of electrical PD signals

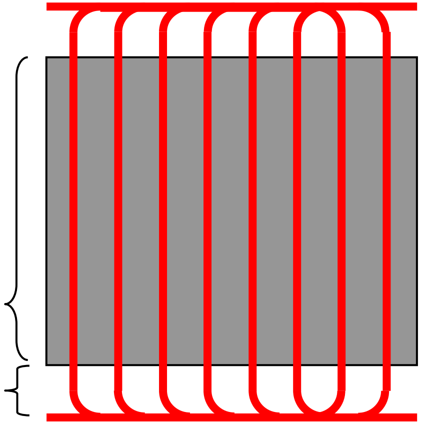
- The rise time of the electron avalanche is determined by the gaseous dielectric:
  - Under Nitrogen atmosphere, the rise time is about 1 ns and, hence, causing a bandwidth of ~350 MHz
  - Under SF_6, an electro-negative gas, the rise time is below 200 ps and the bandwidth is up to 2000 MHz
- Various effects reduce the signal bandwidth:
  - Dispersion, radiation and attenuation
  - Reflection and band-pass effects
- Thus, for distributed power engineering equipment, only a reduced frequency band reaches the detector

Example 1: signal transmission in stator winding

- Modelling: cable sections of different impedance
- Reflections with each impedance change
- Corner frequency depends on the slot length



Stator winding modelling



Slot Section: $Z_L \sim 10–20\Omega$

Overhang: $Z_L > 100\Omega$

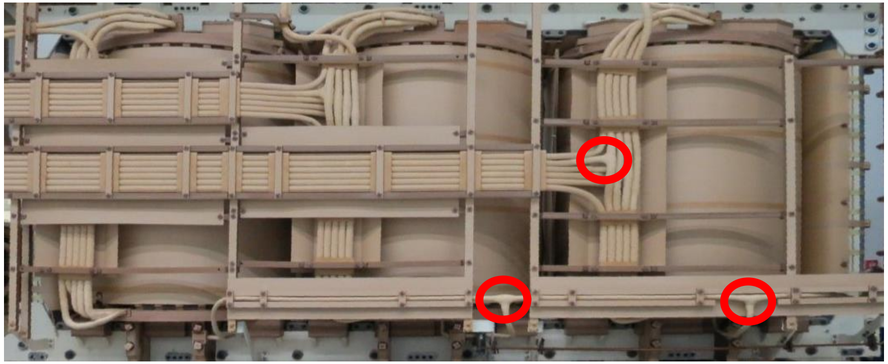
- Core length: 5 m
- Overhang length: 1.5 m
- ε_R : 4 (epoxy-mica)
- Phase velocity C_0: 2.88 x 10^8 m/s
- $C = C_0/\sqrt{(\varepsilon_R)}$

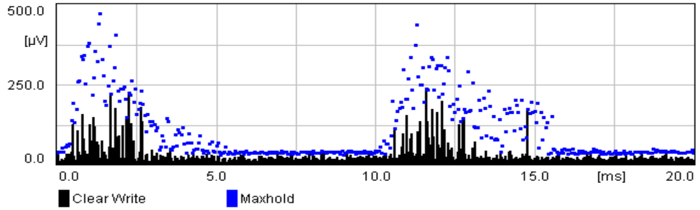
$$r = \frac{Zo - Zc}{Zo + Zc} \qquad \lambda = \frac{C}{2\,\pi f}$$

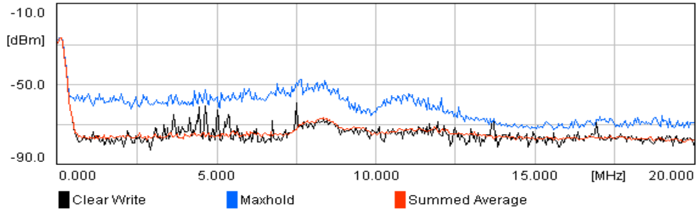
- Considering the wavelength: f_c = 2.86 MHz
- Reflection factor: Positive (Z↑) — from core to overhang
- 80% of the signal will be reflected into the core and will not reach the coupling unit
- Measuring above f_c will strongly affect the sensitivity
- Choosing the proper measurement frequency is very important!

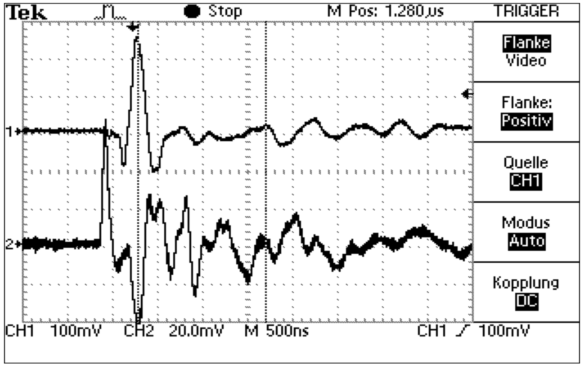
Example 2: signal transmission in transformers

- Signals travelling the conductors
- Capacitive cross-coupling
- Radiation and reception
- Behaviour in freq. domain
- Behaviour in time domain









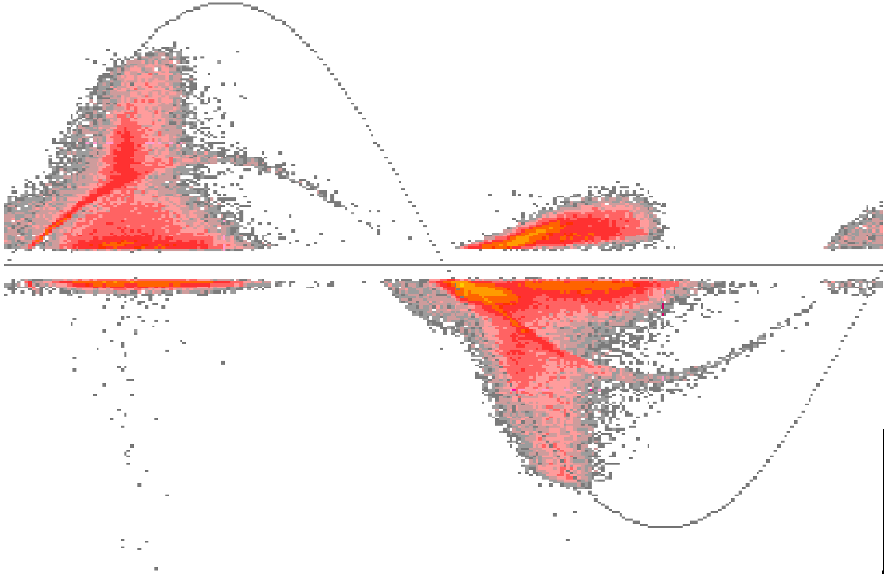
Stop M Pos: 1.280 µs

TRIGGER
Flanke Video
Flanke: Positiv
Quelle CH1
Modus Auto
Kopplung DC

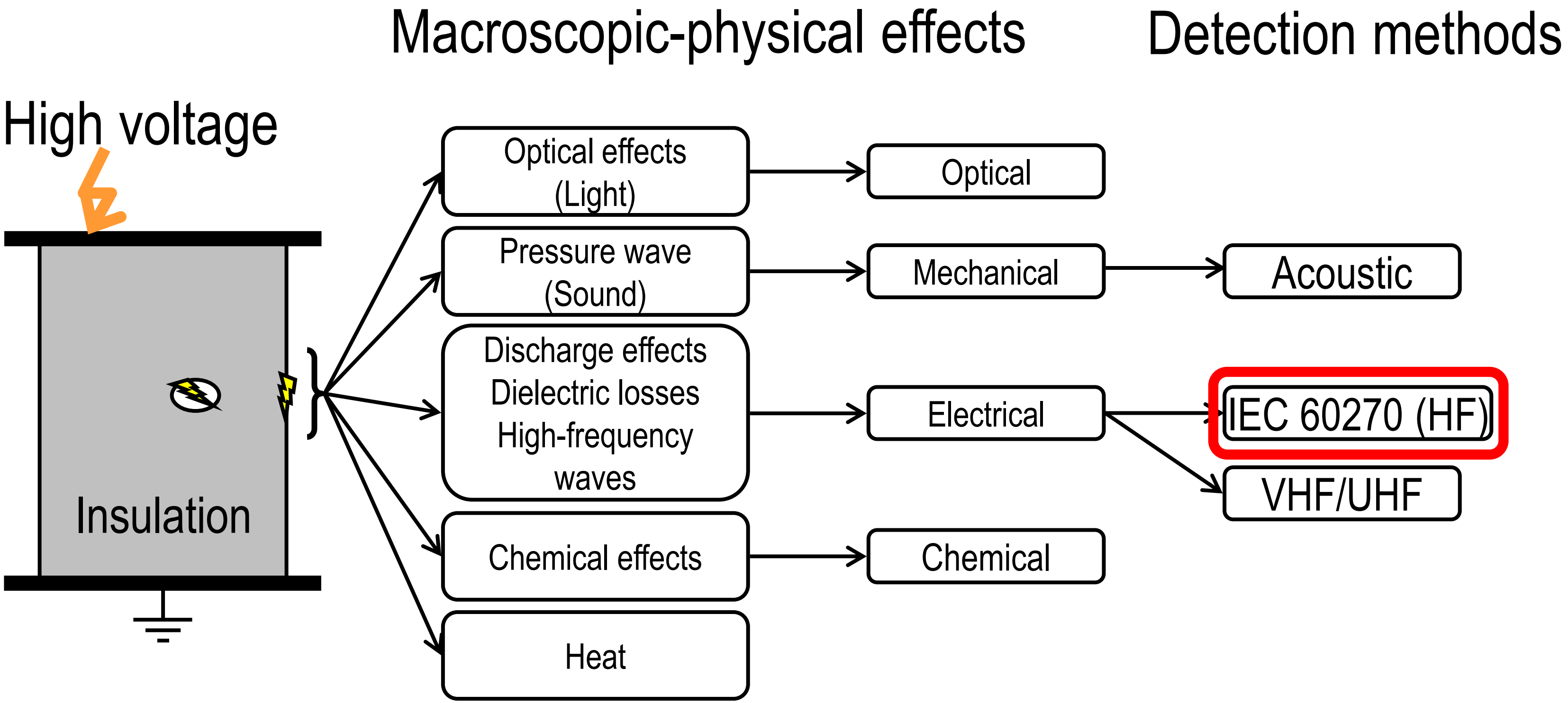
CH1 100mV CH2 20.0mV M 500ns CH1 ⁄ 100mV

Fundamentals of partial discharge measurements

- Early research on discharge phenomena
- Occurrence of partial discharge
- Evolution of standards
  (Horizontal Standard IEC60270)
- Common PD detector principles
- Properties of electrical PD signals
- **Conventional testing methods**
- Unconventional testing methods



Measuring PD



Macroscopic-physical effects

Detection methods

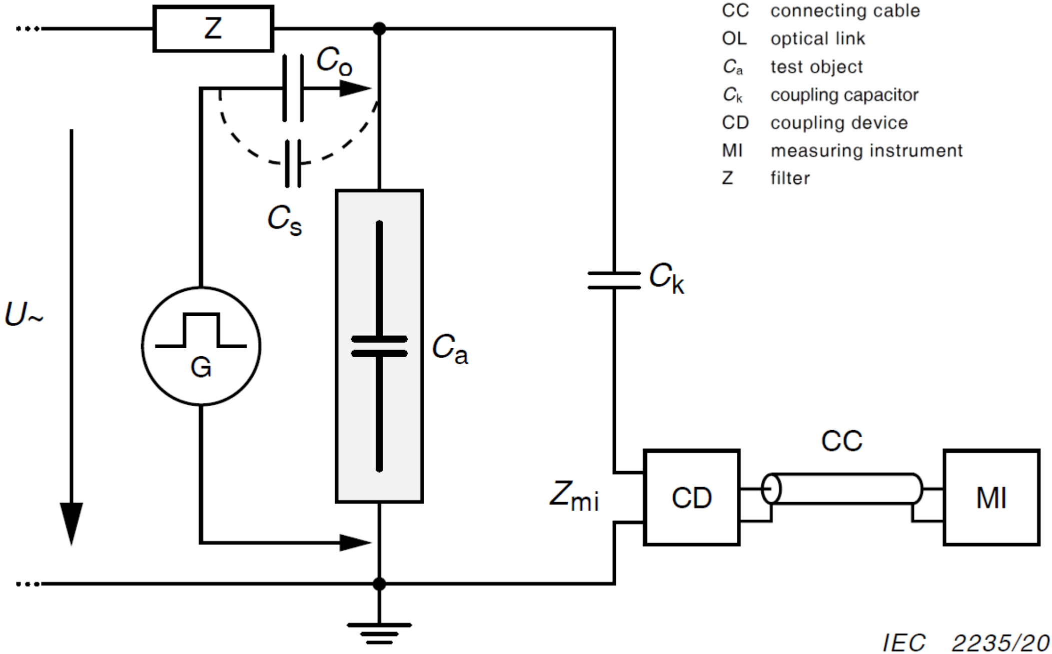
- Optical effects (Light) → Optical
- Pressure wave (Sound) → Mechanical → Acoustic
- Discharge effects, Dielectric losses, High-frequency waves → Electrical → IEC 60270 (HF), VHF/UHF
- Chemical effects → Chemical
- Heat

IEC60270-compliant calibration

- PD measurements are relative
- Charge impulse is generated using a step voltage and an injection capacitor
- $q_0 = U_0 C_0$
- $q = q_0 \frac{C_a}{C_a + C_0}$
- $C_0 < 0.1 \times C_a$

- Charge impulse calibrator connected across the test object to simulate an equivalent discharge

$U_\sim$	high-voltage supply
Z_{mi}	input impedance of measuring system
CC	connecting cable
OL	optical link
C_a	test object
C_k	coupling capacitor
CD	coupling device
MI	measuring instrument
Z	filter

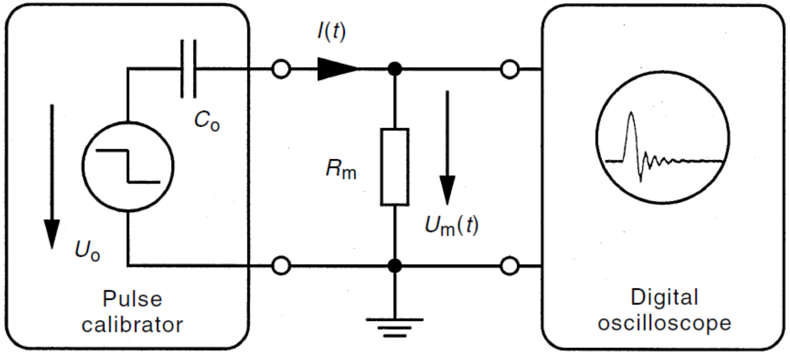


IEC 2235/2000

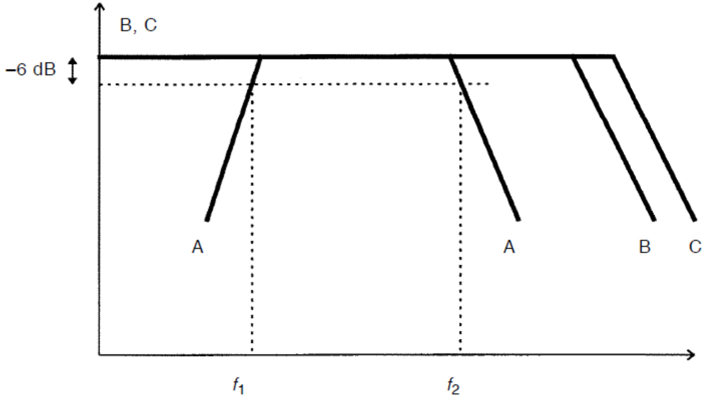
IEC60270-compliant calibration

- Bandwidth relation of detector, PD and calibrator signal
- The rise time of the step voltage must be short
- The resistor R_m will not cause ringing of the signal

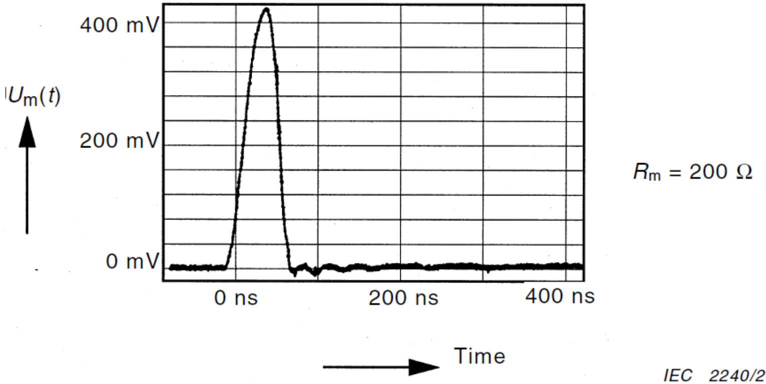
$$q = \int i(t)\mathrm{d}t = \frac{1}{R_m}\int u_m(t)\mathrm{d}t$$



IEC 2239/2000



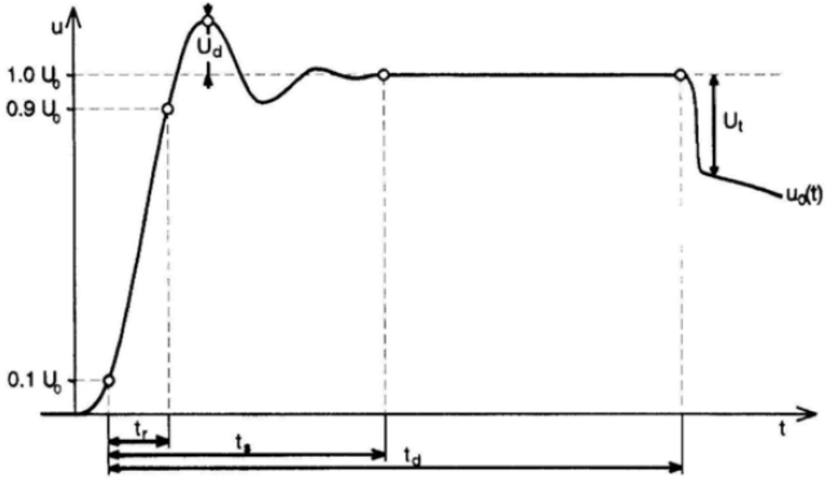
IEC 2238/2000



IEC 2240/2000

IEC60270: 2015 Addendum

- Step voltage response method
- Rise time $t_r \leq 60$ ns
- Time to steady state $ts \leq 200$ ns
- $q_0 = U_0 C_0$




DAkkS Deutsche Akkreditierungsstelle

Deutsche Akkreditierungsstelle GmbH

Entrusted according to Section 8 subsection 1 AkkStelleG in connection with Section 1 subsection 1 AkkStelleGBV
Signatory to the Multilateral Agreements of EA, ILAC and IAF for Mutual Recognition

Accreditation

The Deutsche Akkreditierungsstelle GmbH attests that the calibration laboratory

Power Diagnostix Systems GmbH
Vaalser Strasse 250, 52074 Aachen

is competent under the terms of DIN EN ISO/IEC 17025:2018 to carry out calibrations in the following fields:

Electrical quantities
DC and low frequency quantities
- **High voltage quantities** [a)]
- **High voltage impulse quantities**
- **Impulse charge** [a)]

[a)] also On-site calibration

The accreditation certificate shall only apply in connection with the notice of accreditation of 23.11.2018 with the accreditation number D-K-15068-01. It comprises the cover sheet, the reverse side of the cover sheet and the following annex with a total of 3 pages.

Registration number of the certificate: **D-K-15068-01-00**

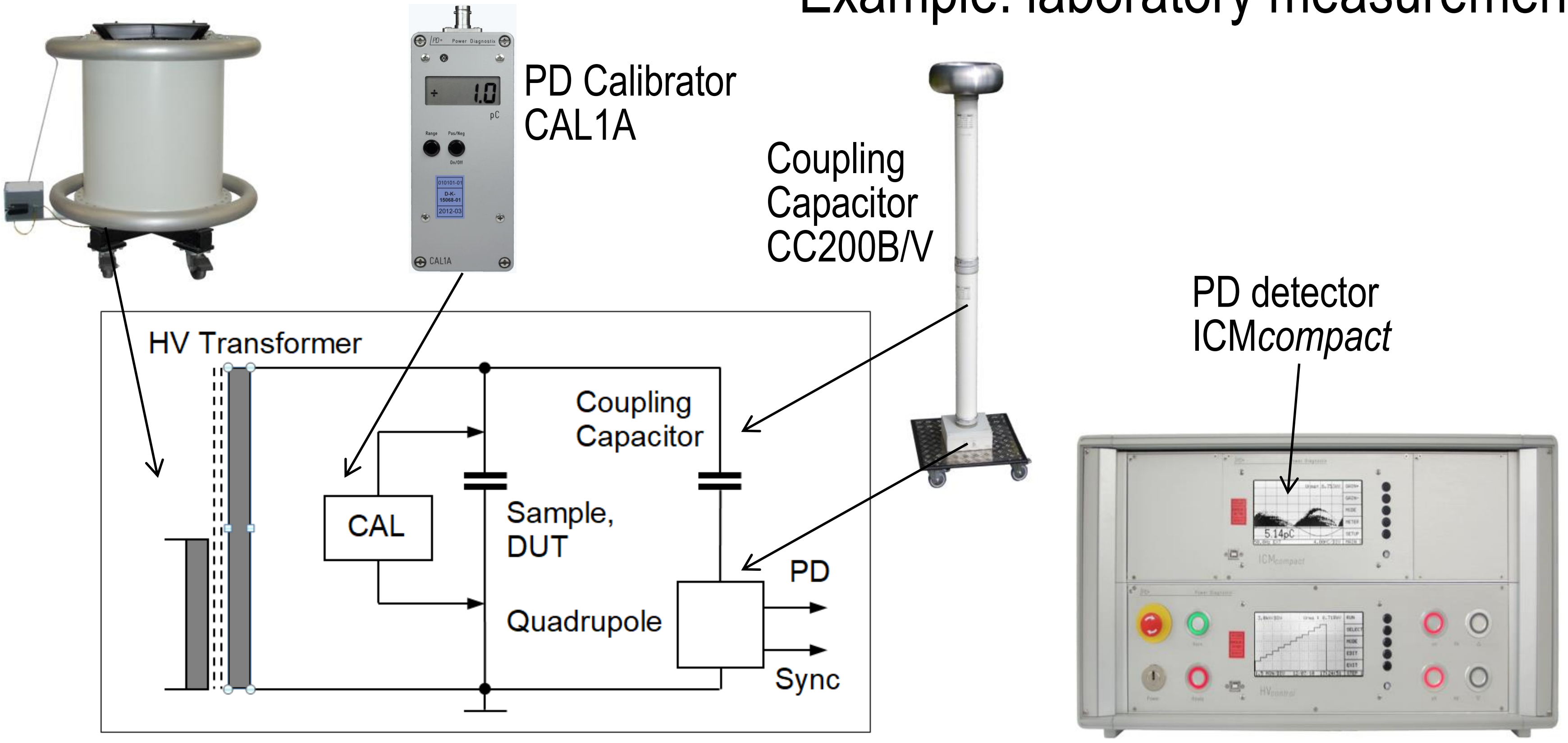
Braunschweig,
23.11.2018

Dr. Heike Manke
Head of Division

The certificate together with its annex reflects the status at the time of the date of issue. The current status of the scope of accreditation can be found in the database of accredited bodies of Deutsche Akkreditierungsstelle GmbH.
https://www.dakks.de/en/content/accredited-bodies-dakks

See notes overleaf.

Example: laboratory measurements



PD Calibrator
CAL1A

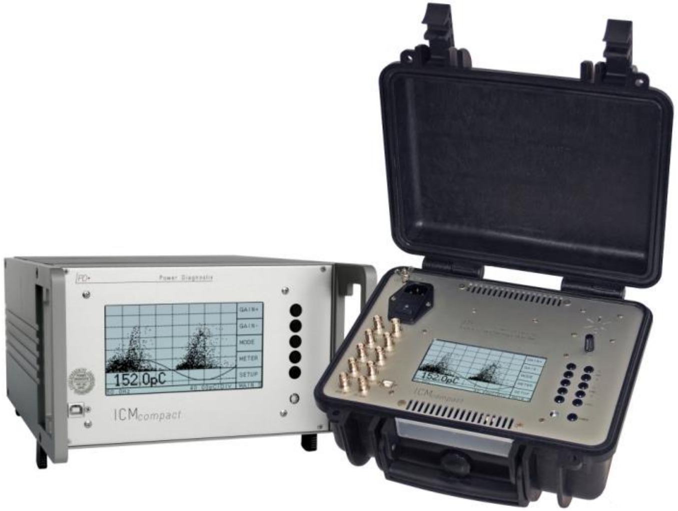
Coupling
Capacitor
CC200B/V

PD detector
ICM*compact*

ICM*compact*

Product at a glance

- Bestselling PD detector for standard measurement tasks during daily work
- User-friendly setups
- High modularity and robustness
- Frequency-selective measurements for noisy environments
- Multiplexer for multi-sample measurements
- Integrated cable fault location feature
- RIV meter optional



Fundamentals of partial discharge measurements

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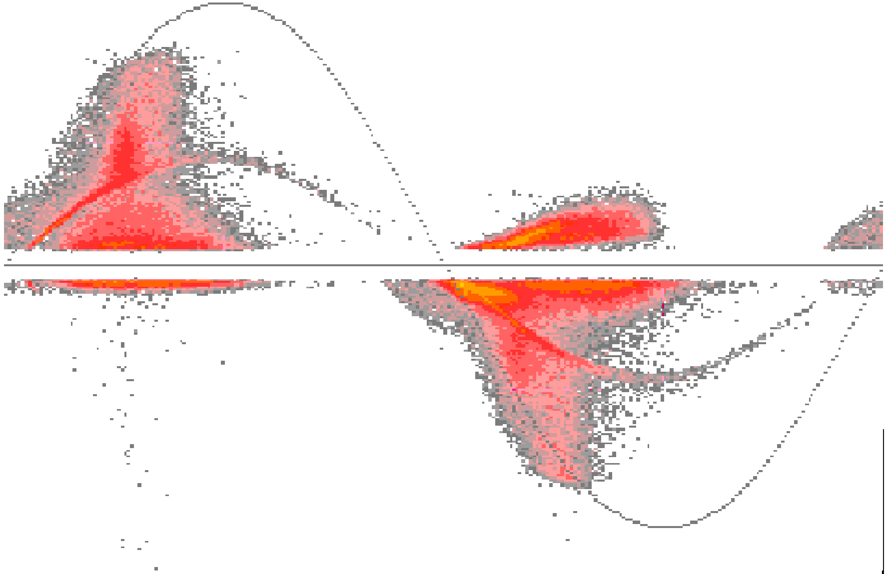
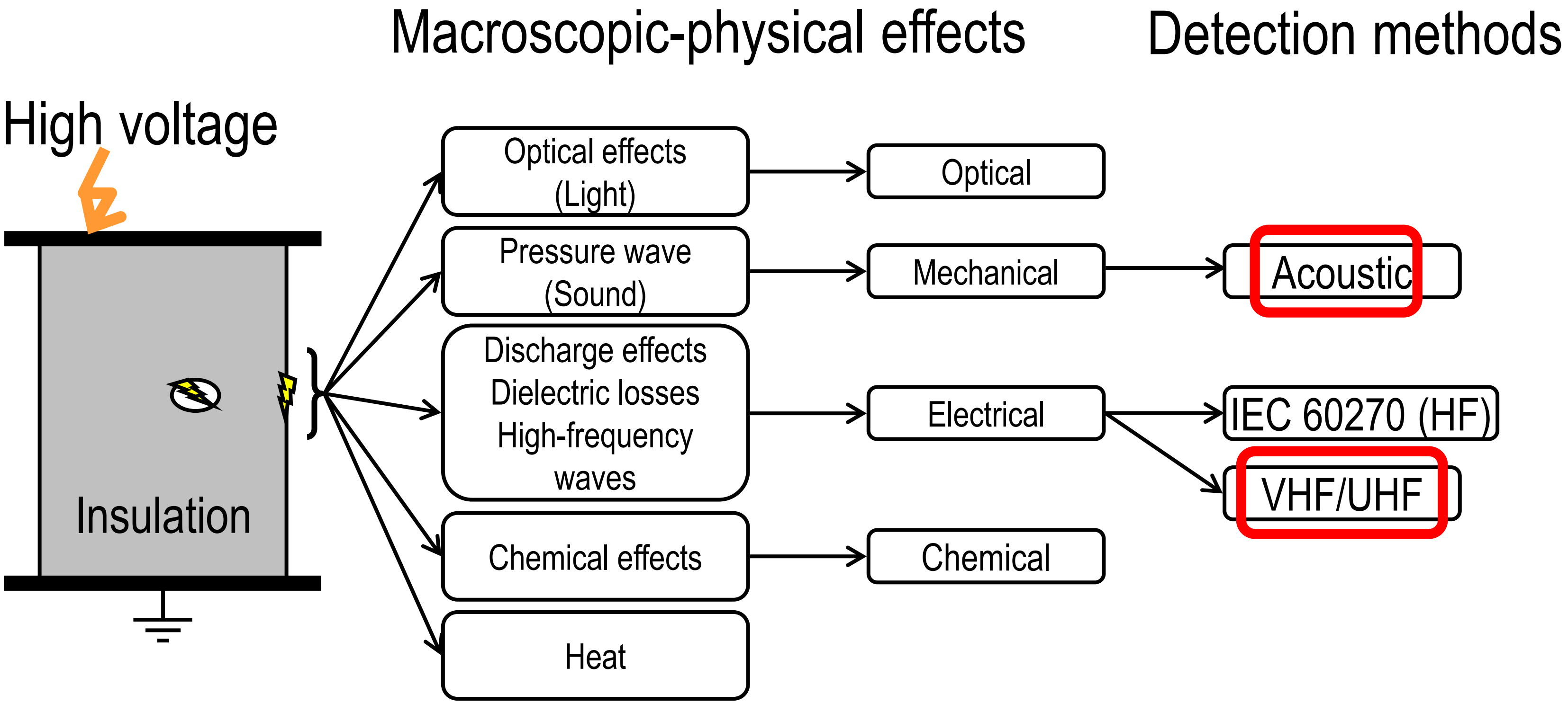


Measuring PD

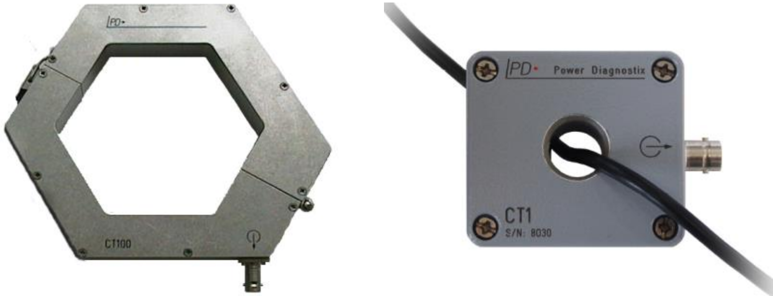


Unconventional testing methods

- RF/VHF (1 Mhz–300 MHz):
  - RF current transformer tapping ground leads and frame connection
  - Clamp-on CTS tapping the neutral bushing

Acoustic:

  - Resonant frequency of 75 kHz or 150 kHz
  - Preamplifiers for acoustic sensors



CT100 and CT1

Acoustic sensor AS75I

Sensor fixture SFX1

for acoustic sensor

Fixed magnet and preamplifier

Unconventional testing methods

- UHF coupling methods (300 Mhz–1.8 GHz):
  - External flange sensor
  - Frequency converter unit and input protection unit
  - Window sensors
    - Different sensor diameters and mounting hole configurations available for all possible GIS windows
  - UHF valve sensor for transformers

External flange sensor EFS1

Window sensors

IPU2B and FCU2

Product at a glance

- Advanced state-of-the-art PD & TD measurement and analysis tool
- High-end signal pre- and post-processing
- Highest modularity and robustness
- Simultaneous real-time acquisition on up to 10 input channels
- Measurements under AC and DC
- Integrated acoustic PD location functions
- Integrated cable fault location feature
- All-in-one measurement system

Useful frequencies for electrical PD measurements

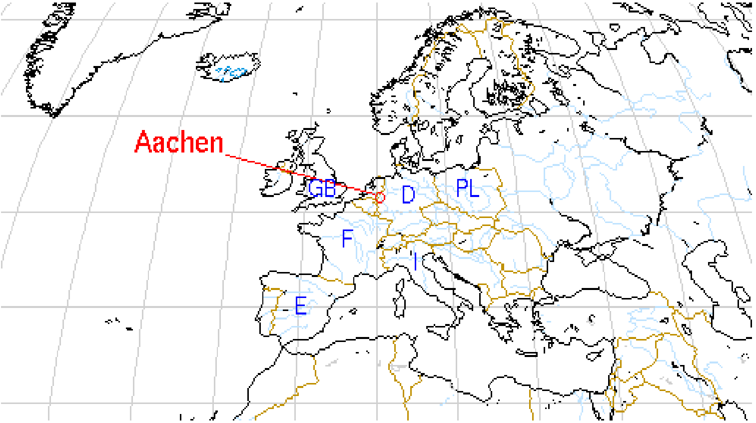
- Low frequency range (IEC 60270, < 1 MHz)
  - Best coverage of the entire device under test
  - Partly hampered by noise interference
  - Best Choice for conventional off-line tests
- Medium frequency range (2–20 MHz)
  - Reasonable coverage (signal transmission)
  - Moderate noise situation
  - Best compromise for on-line monitoring (survey type)
- High frequency range (20–500 MHz)
  - Limited coverage
  - Excellent near-field detection
- Ultra-high frequency range (300–3000 MHz)
  - Reasonable coverage, acceptable number of sensors
  - Comparably low noise interference

Overview of portable products

- ICM*system*
- ICM*compact*
- AIA*compact*
- ICM*flex*
- ICM*monitor* portable

Power Diagnostix

Thank you for your attention!



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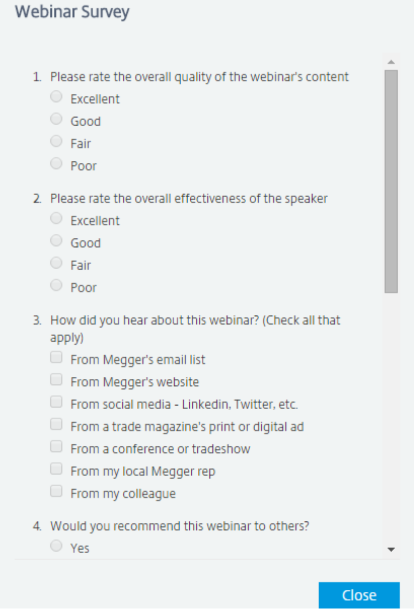

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Power on

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