Budapest University of Technology and Economics
Department of Electric Power Engineering

Role and methods of partial discharge measurement in the evaluation of electrical insulation systems

Visegrad Fund – Innovation of polymer nanocomposite materials for electrical engineering
Žilina session, 11th April 2024
/online lecture/

HIGH VOLTAGE LABORATORY BUDAPEST

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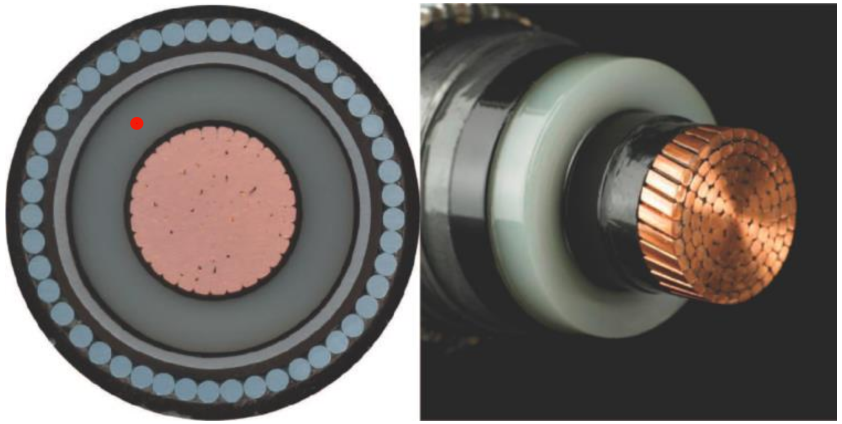
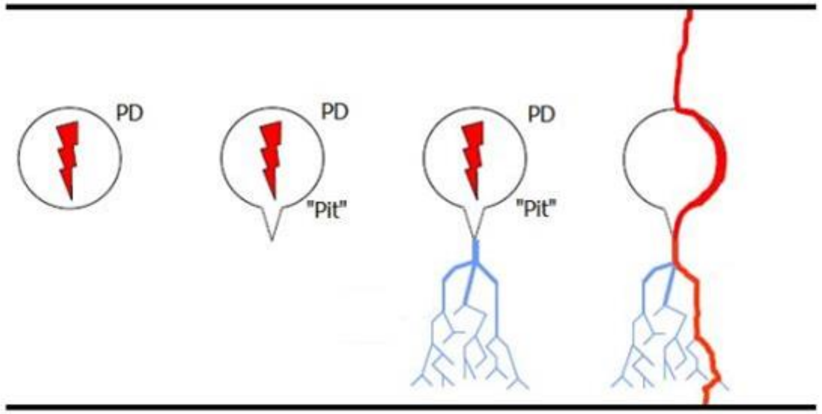
DEFINITION OF PARTIAL DISCHARGES

Definition of PD

- Partial discharges (PD): **localized discharges** that **do not bridge** the complete gap between the electrodes
- The current is limited by small capacitances → much lower power/energy than in case of electric arc → generally, no immediate destruction

- **Detect localized defects in an insulation system**

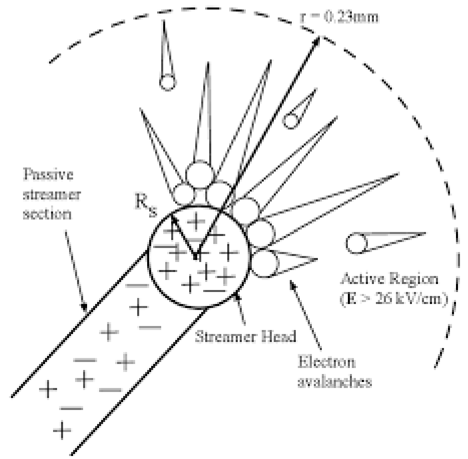


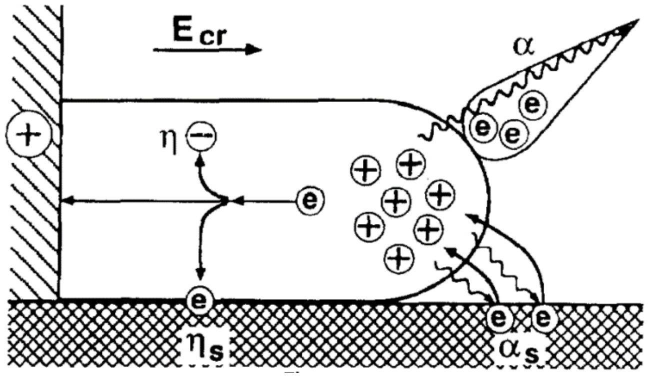


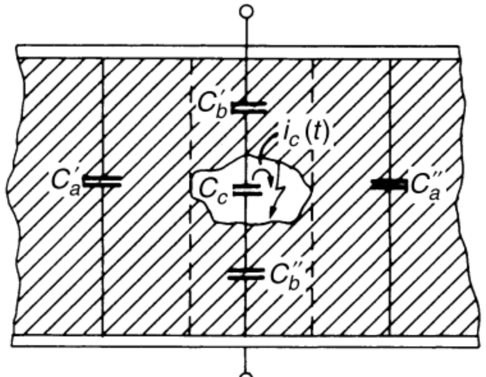
Types of partial discharges

- They occur at sites where the **electric field** or/and the **material** has **inhomogeneity**

- Basic classification:
  - **Corona discharges**: at sharp metallic points
  - **Surface discharges**: at triple point, high field parallel to the solid/gas, solid/liquid or liquid/gas surface
  - **Internal discharge**: void within the insulating material



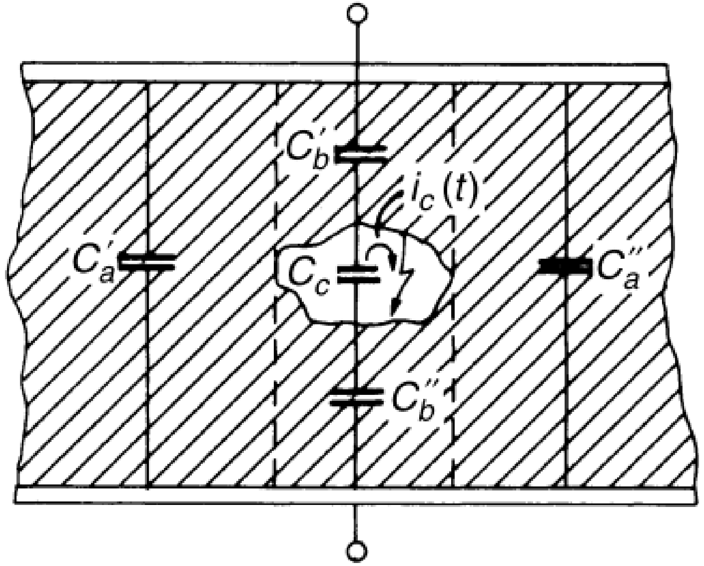




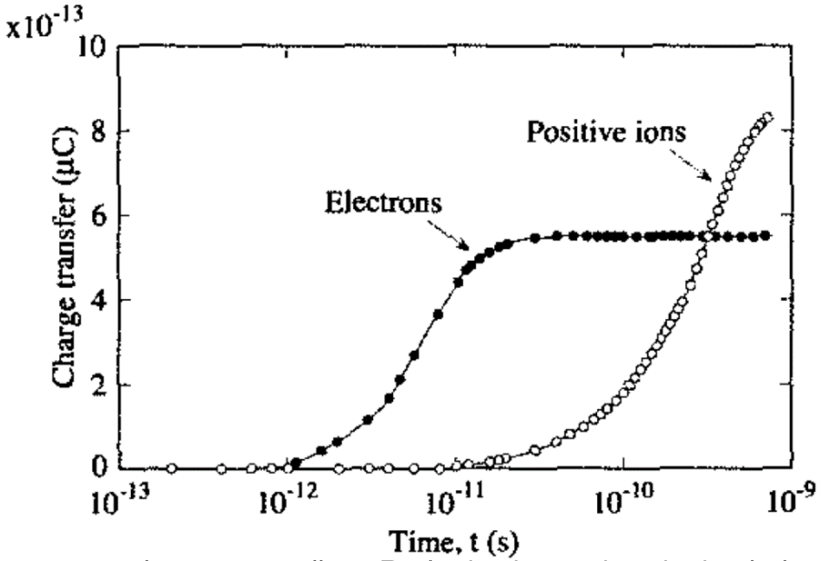
WHAT DOES PD CAUSE?

What is happening when a PD occurs

- A volume of gas is ionized due to the external electric field
- Ionization → positive/negative charge carriers separate and experience force → charge movement
  - Quick electron current followed by slow ionic current (difference in mobility)



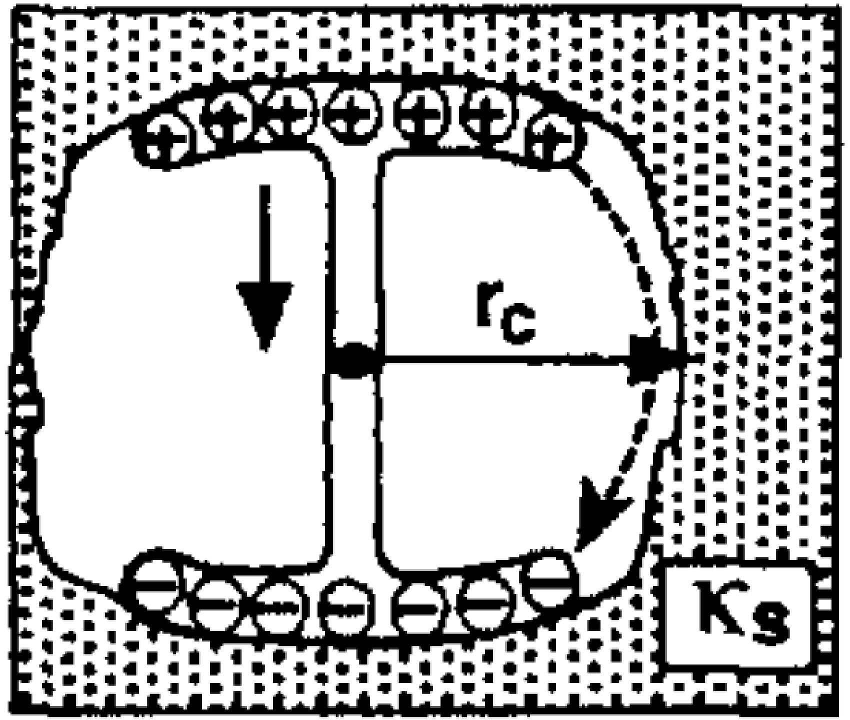
W.S. Zaengl: High Voltage Engineering, Fundamentals, Butterworth-Heinemann, 2000



Novak, J.P., Bartnikas, R. „Ionization and excitation behavior in a microcavity", IEEE Transactions on Dielectrics and Electrical Insulation, (Volume:2 , Issue: 5)

What is happening when a PD occurs

- **Charges accumulate** on the wall of the void, which causes an internal field in the opposite direction to the external field
- **Charge decay**, primarily through the wall of the void (finite resistivity)
- After adequate decay, **discharges are repeated**
- In case of **AC voltage**, when the external field reverses, the accumulated charges increase the field in the void
  → PD occurs repeatedly, thus, even though the energy involved in the individual discharges is low, it will degrade the material over time

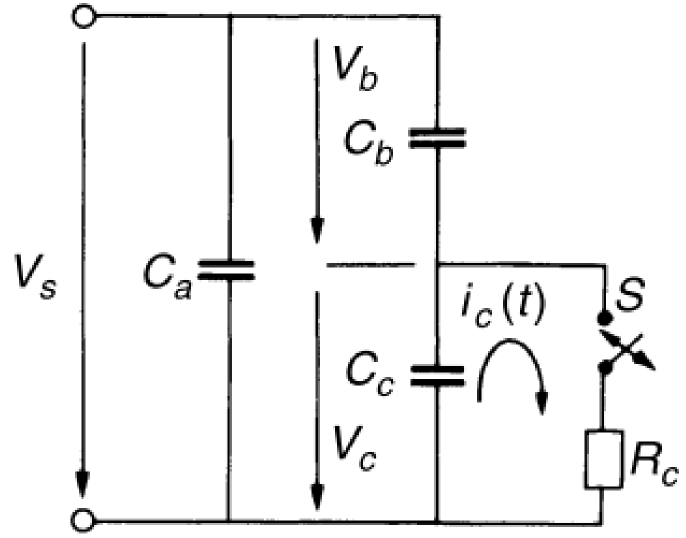


L.Niemeyer, „A Generalized Approach to Partial Discahrge Modeling, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.2.No.4, 1995

What does charge movement do to the insulation

- Even in smaller voids, the **electrons can gain 50-70 eV energy** before they collide into the insulating material
- **Polymeric bonds** may be as weak as **7-8 eV → PD causes material degradation**

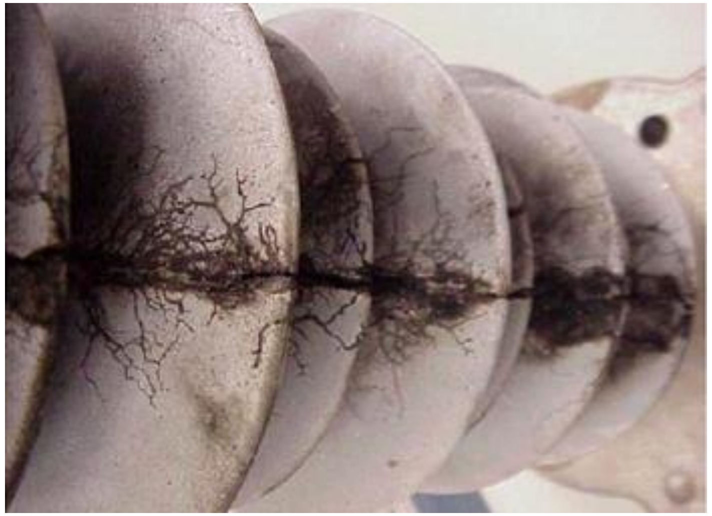
- This is why traditionally the charge involved in the process is measured, as it is considered to be proportional to the degradation speed/level
- PD detectors show the ”apparent charge”, as the actual charge in unknown
  - It is impossible to measure within the void
  - On the electrodes, only the apparent charge can be measured due to the other capacitances involved (”ABC model”)



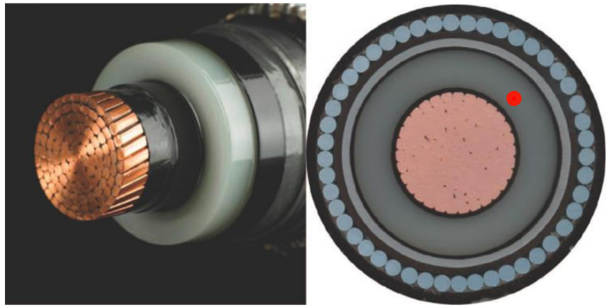
Degradation caused by partial discharges

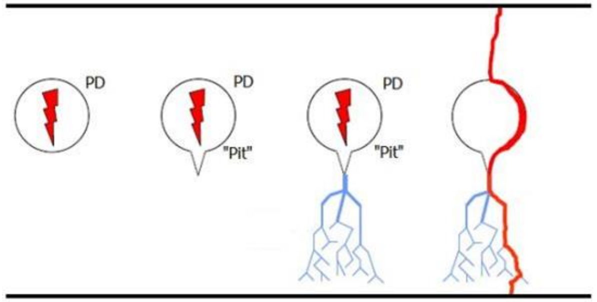
- Corona discharge
  → **if excessive, degradation of flashover capability**

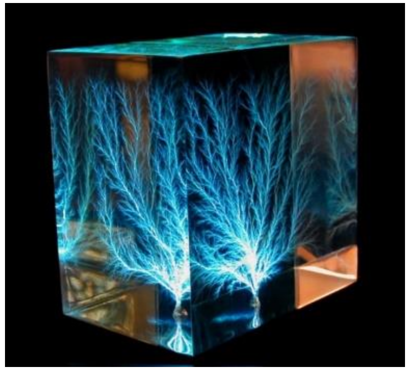
- Surface discharge → **tracking, erosion**



- Internal/void discharge
  → **treeing**







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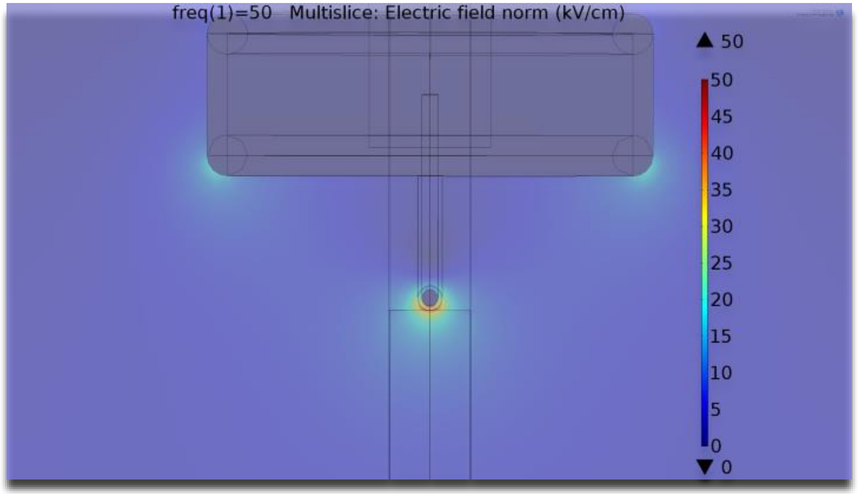
How to fight against the adverse effects of partial discharges

- Design of insulation systems that **minimizes or excludes** the appearance of partial discharges
  - MV/HV Polymeric cables: reduction of maximum cavity and contaminant size (~10-20 micrometres), so that internal PD does not ignite
  - Transformers: use of design curves (”Weidmann-curves”) that ensure that there will be no PD, neither in volume, nor on surfaces (typical problem in case of transformers)



→ *PD measurement to prove that insulation system is PD free or in other words, free from local defects*

- Use of materials **resistant to partial discharges**
  - Electrical machines, especially at higher voltages
    - Requirements of the magnetic circuit does not allow such control of the field (Mica - inorganic material, high resistance to PD)
    - Sheds of composite insulators: silicone rubber filled with ATH
  - One reason to develop **nanocomposites is to achieve PD retardancy** while keeping the other ways better organic base materials

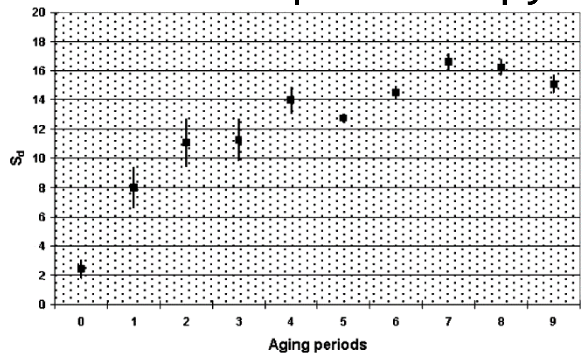
→ *PD / electrical aging test to prove that the material resists degradation from PD*

METHOD EXAMPLE
#LOW-VOLTAGE NUCLEAR CONTROL CABLES

Available other state-of-the art methods

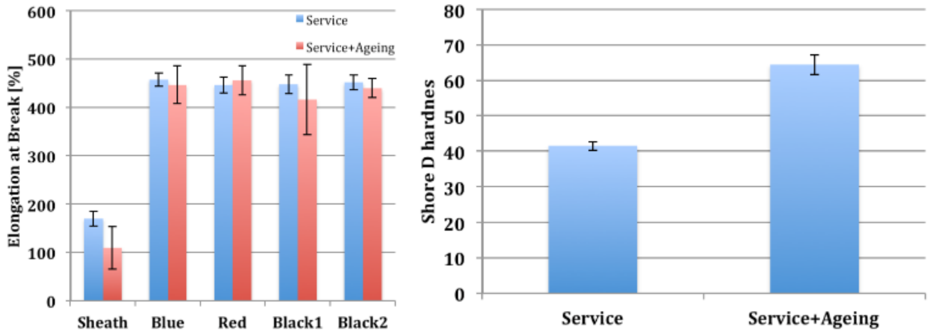
BULK MATERIAL AGEING

Dielectric spectroscopy



Changes in the steepness of decay voltage s_d [v/s] with electrical ageing
Z. A. Tamus, B. Németh, I. Berta, „Effect of Voltage Stress on Diagnostic Parameters of Low Voltage Cables", IEEE Int. Symp. on El. Ins. 2008, Vancouver, Canada, pp. 43-46.

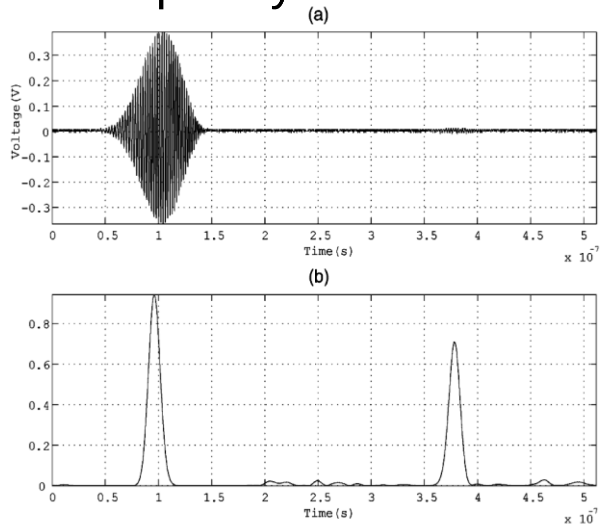
Mechanical properties



Changes in elongation at break and Shore D hardness on cable cores and sheath, respectively, after service and artificial ageing
Z. A. Tamus, “Practical Consideration of Mechanical Measurements in Cable Diagnostics”, 2011 Electrical Insulation Conference

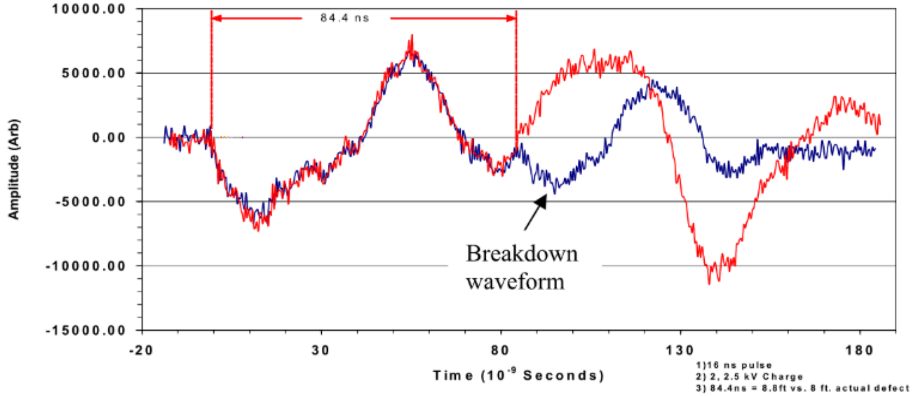
LOCAL DEFECTS

Time-frequency domain reflectometry



Measured signal and joint time-frequency domain cross correlation function for fault location detection
Y.-J. Shin et al., “Application of Time-frequency Domain Reflectometry for Detection and Localization of a Fault on a Coaxial Cable”, IEEE Transactions on Instrumentation and Measurement

Pulse arrested spark discharge



Waveforms acquired from a cable with chafed insulation by PASD method
Final Report on Development of Pulse Arrested Spark Discharge (PASD) for Aging Aircraft Wiring Application”, Sandia National Laboratories, September 2006

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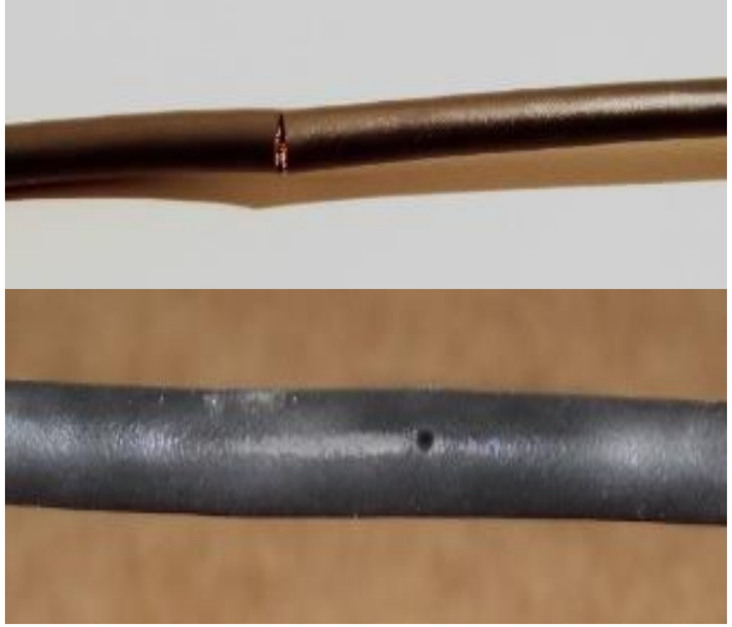
Role of partial discharge measurement

	General material degradation	Major local faults	Minor local faults
Dielectric spectroscopy	Yes	Indirectly	Indirectly
Shore D hardness	Yes, but only at terminals / measured spot	Indirectly	Indirectly
TDR/FDR	No	Yes	No
PASD	No	Yes, but only in small diameter wires	Yes, but only in small diameter wires
PD	No, only if they have mechanical effects e.g. cracks	Yes	Yes

- Local damages that may lead to actual failure in case of critical events (e.g. LOCA – loss of coolant accident)

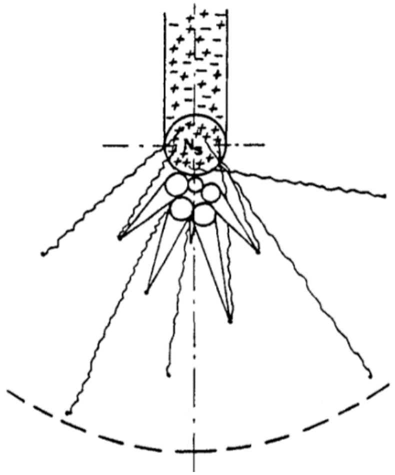


Partial discharge inception in low-voltage cables

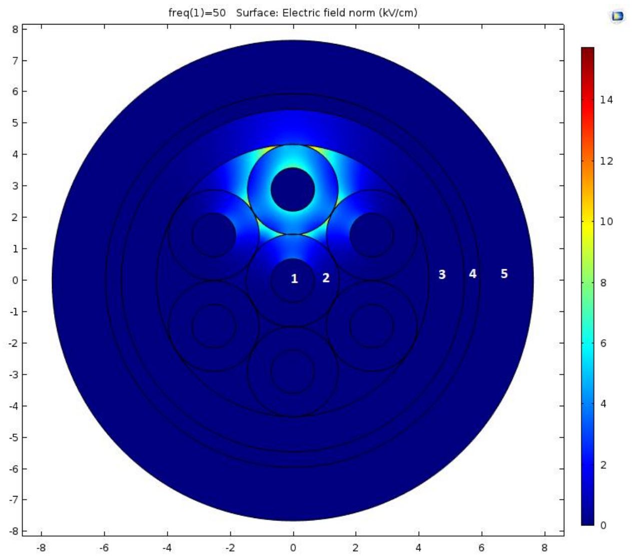
- Streamer inception model: inception field dependent on the cavity size

$$E_{inc} = 24.2 * 10^5 * \left(1 + \frac{8.6}{\sqrt{2 * r * 10^5}}\right)$$

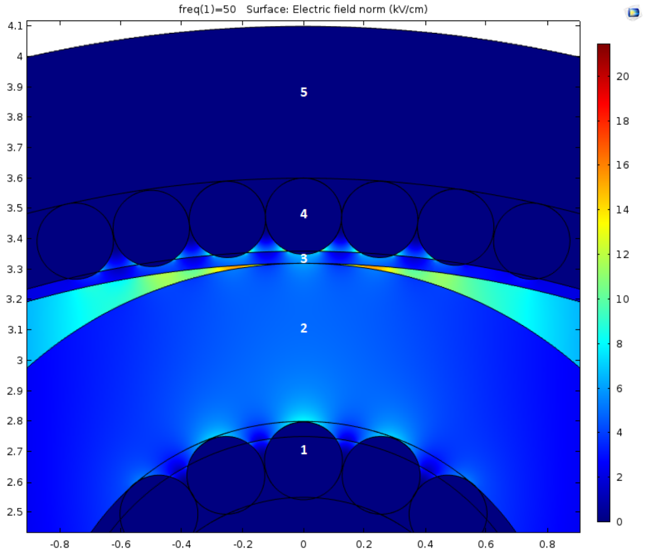
- → 53.6 kV/cm…90 kV/cm
- PD will ignite at a defect, but in case of LV cables, at other spots, too → need to separate harmful and acceptable PD

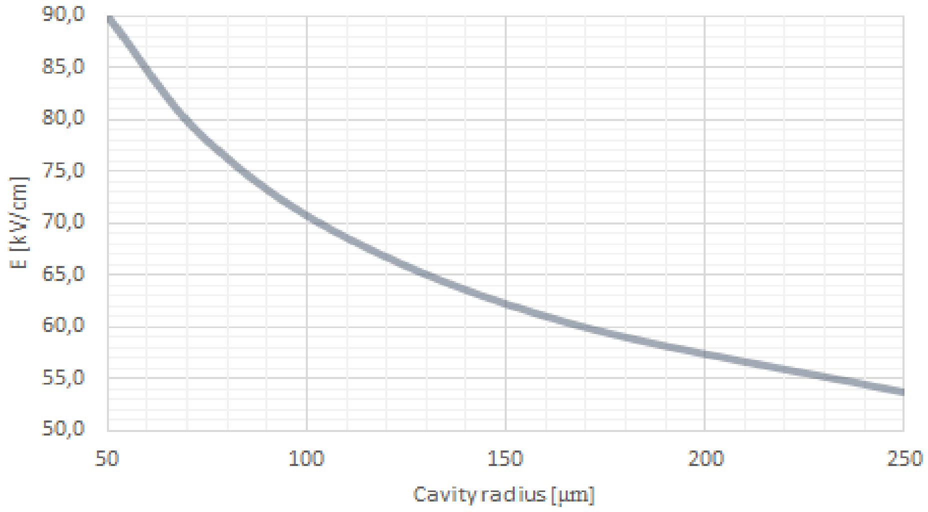


SZRMKVM-J (tape shielded, solid conductor)



YSLCY (braid shielded, stranded conductor)





S. A. Boggs, „Partial Discharge. III. Cavity-induced PD in Solid Dielectrics," in IEEE Electrical Insulation Magazine, Vol. 6, No. 6, pp. 11-16, Nov.-Dec. 1990

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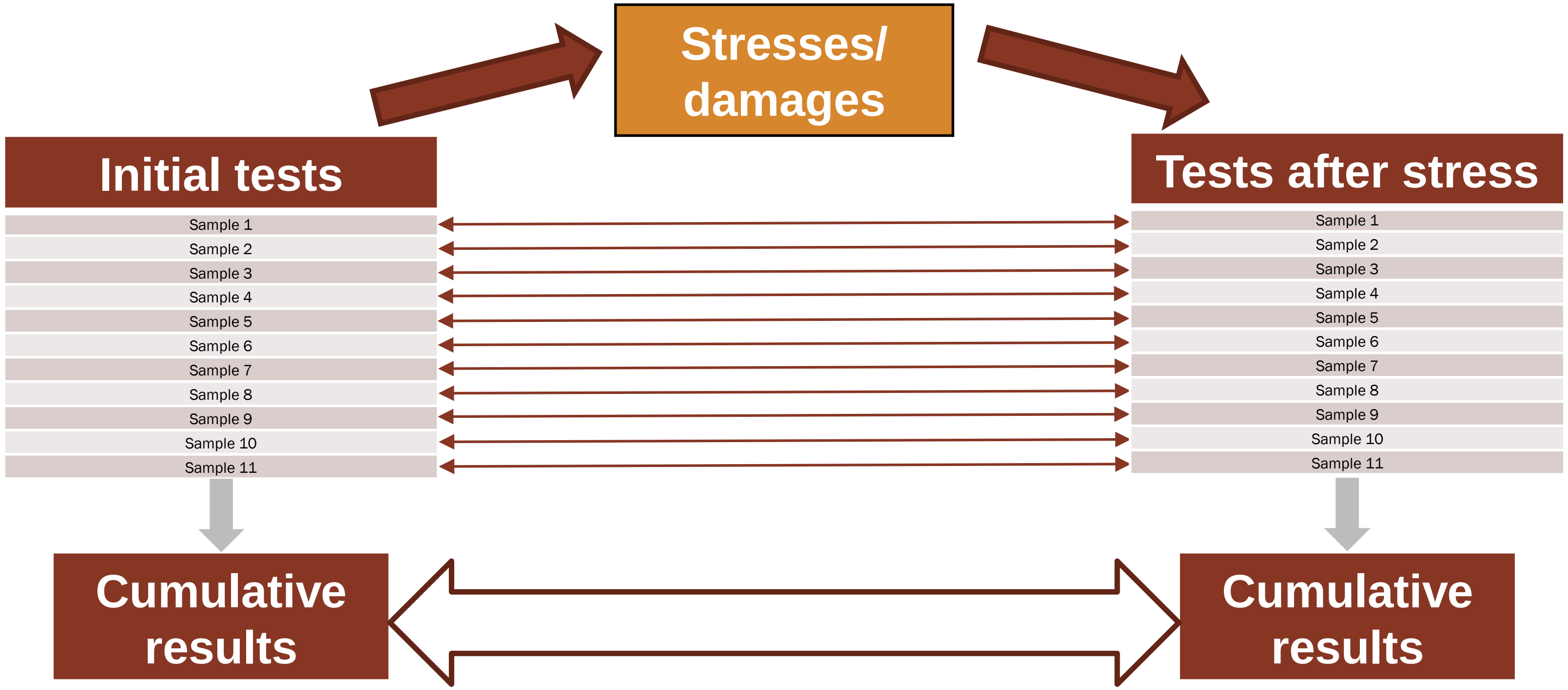
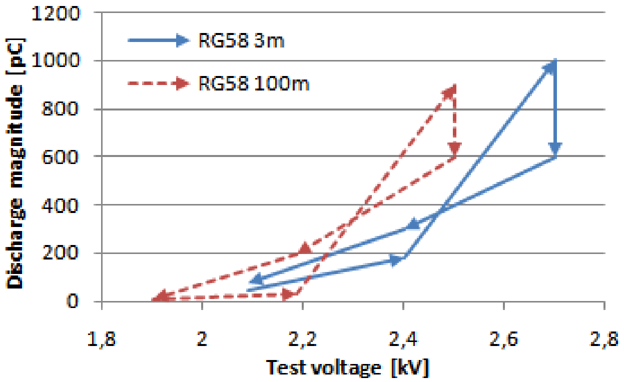
Partial discharge diagnostics of low-voltage cables

- MV, HV cables are designed to be PD free → a simple magnitude based decision (e.g. 5 pC) can be applied
- **LV cables are not PD free at their test voltage**, thus more complex evaluation is required
- Diagnostic parameters need to show significant changes in response to stresses

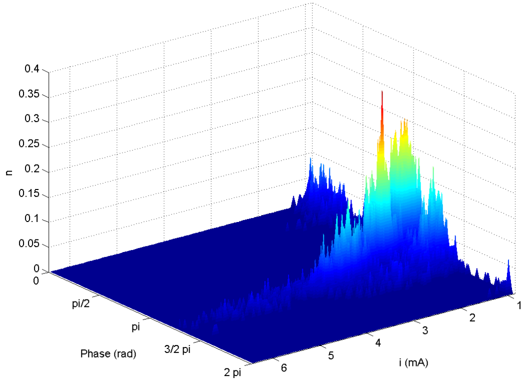


Evaluation methods

- PDIV/PDEV: inception and extinction



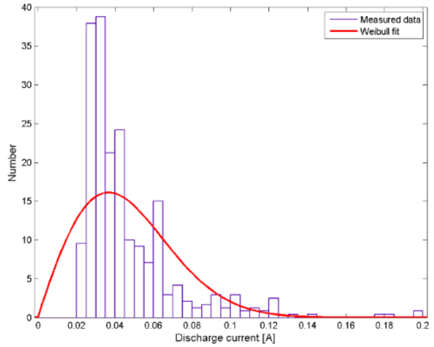
- Phase-resolved PD pattern and statistical tools



$$Sk = \frac{\sum (x_i - \mu)^3 p_i}{\sigma^3} \qquad Ku = \frac{\sum (x_i - \mu)^4 p_i}{\sigma^4} - 3$$

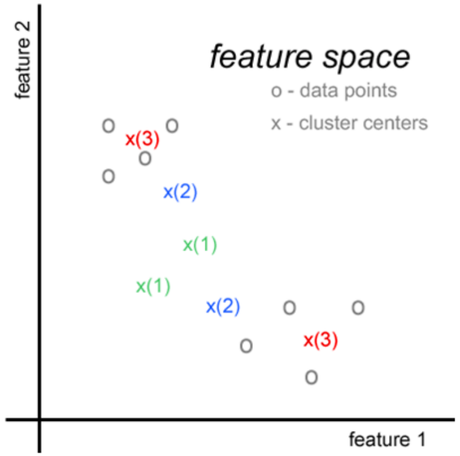
$$Q = \frac{Q_S^- / N^-}{Q_S^+ / N^+} \qquad cc = \frac{\sum xy - \sum x \sum y / n}{\sqrt{[\sum x^2 - (\sum x)^2/n][\sum y^2 - (\sum y)^2/n]}}$$

- PD height distribution



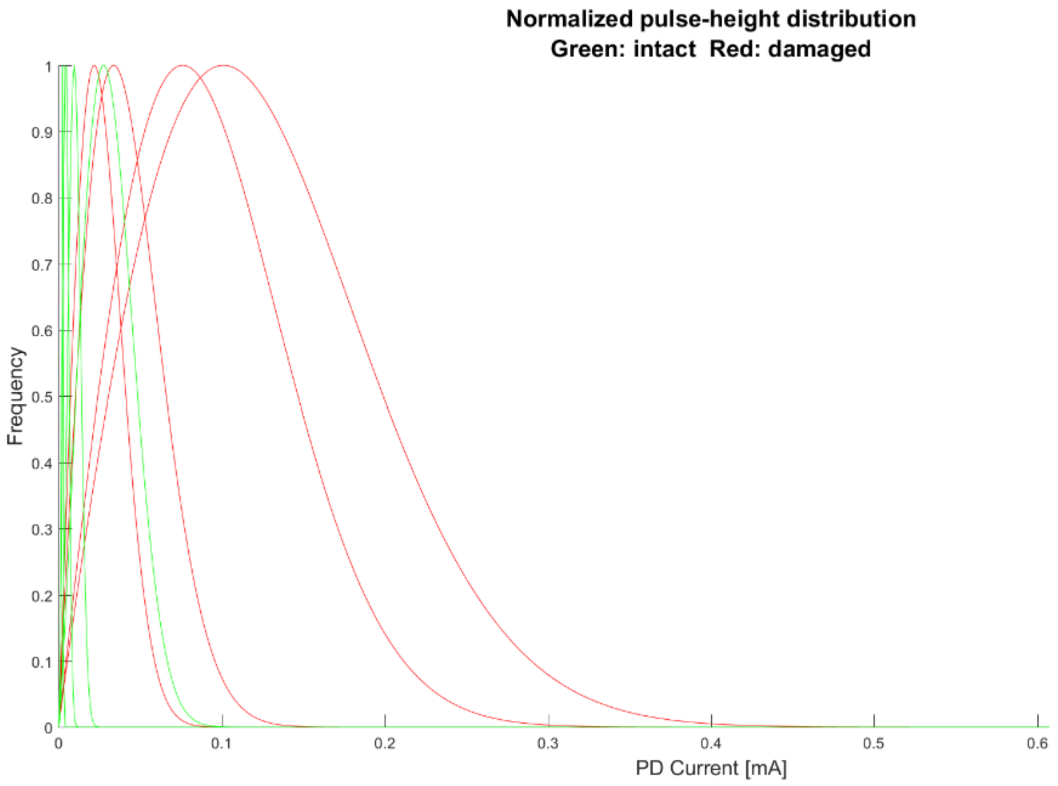
$$f(x) = \frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \; for \; x \geq 0$$

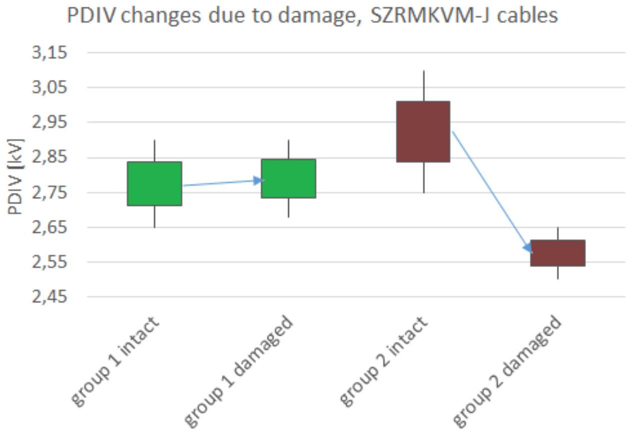
- Fuzzy c-means clustering

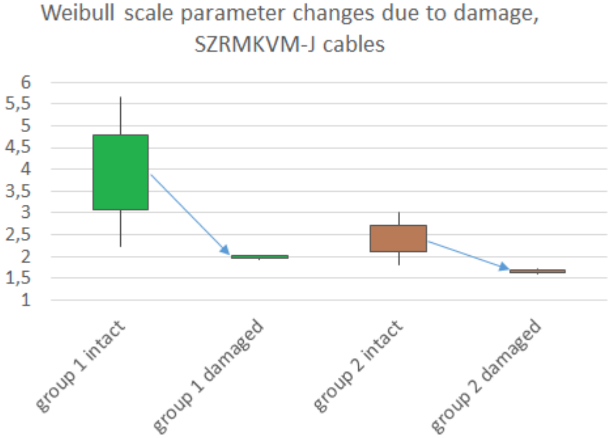


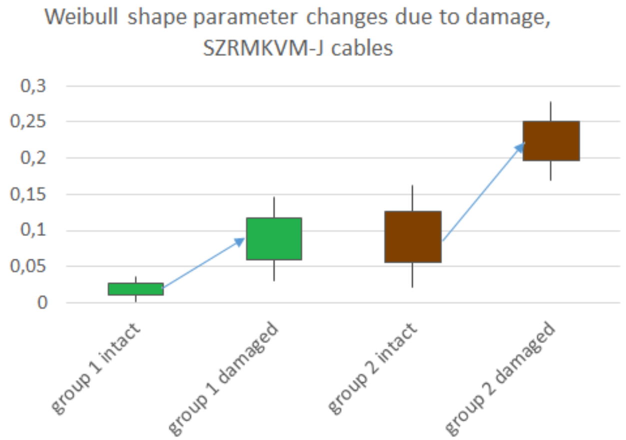
Example: PDIV and PDHD evaluation of SZRMKVM-J cables

- Comparison of results on intact and damaged cables
  - Damage down to the shielding, but core insulation kept intact
- PDIV changes
- Weibull distribution fitted to the PDHD
  - Parameters compared









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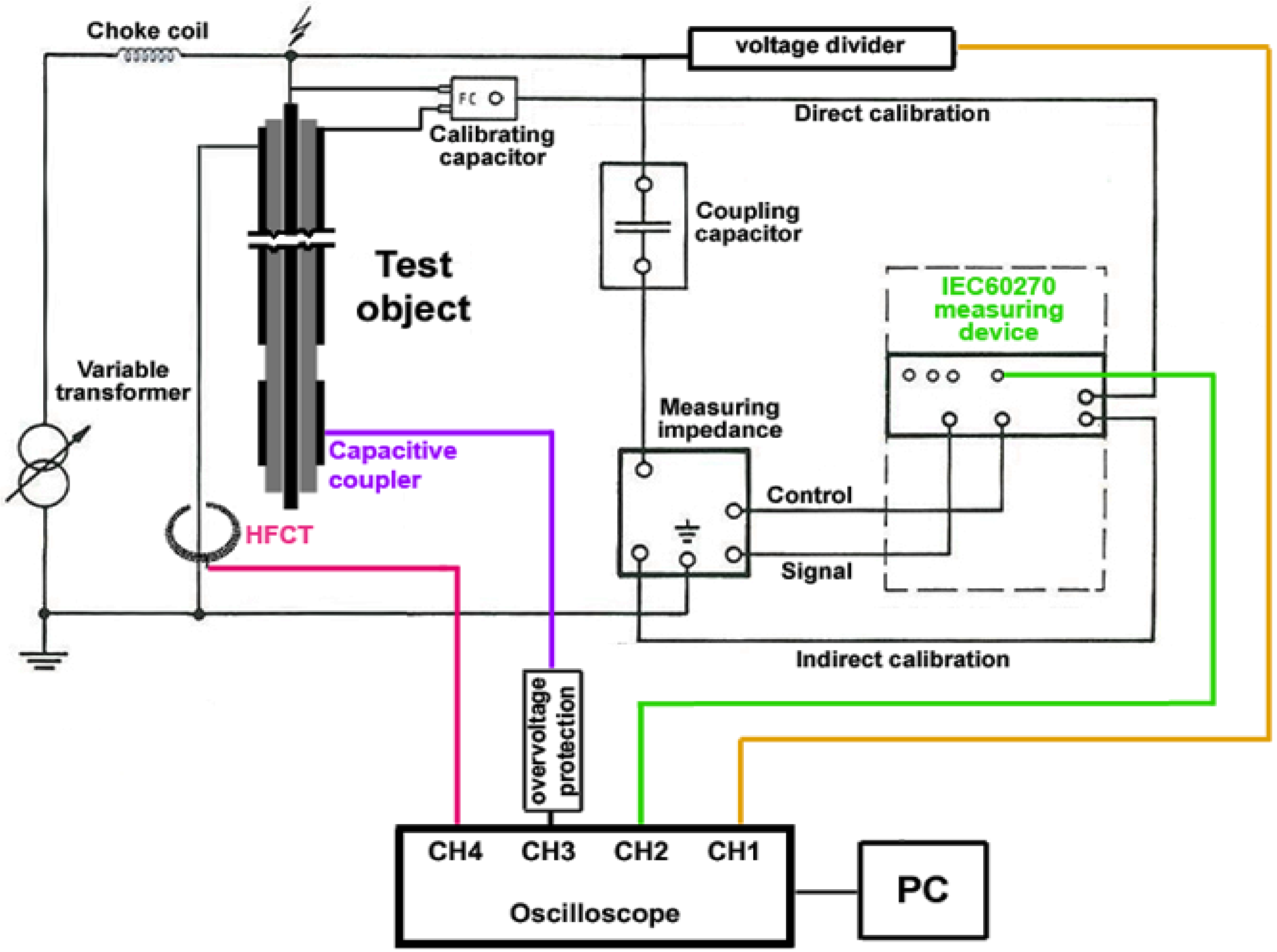
METHOD EXAMPLE
#PD MEASUREMENT IN TRANSFORMERS IN THE UHF RANGE

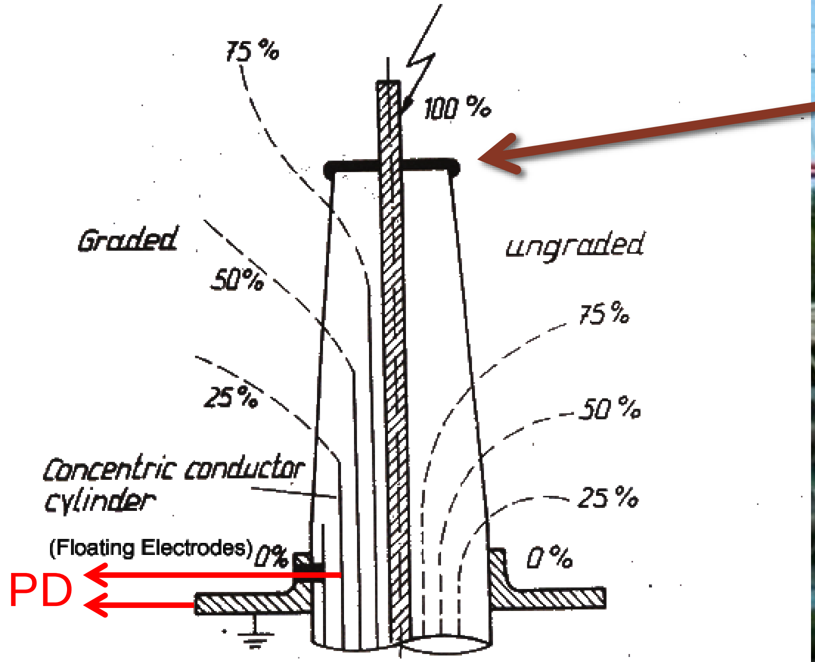
Available measurement methods (conducted electrical signals)

- Separate the high-frequency PD signal from the test voltage
- High sensitivity – impulses carry charges in range of pC
- Noise suppression



Classical measurement – conventional coupling

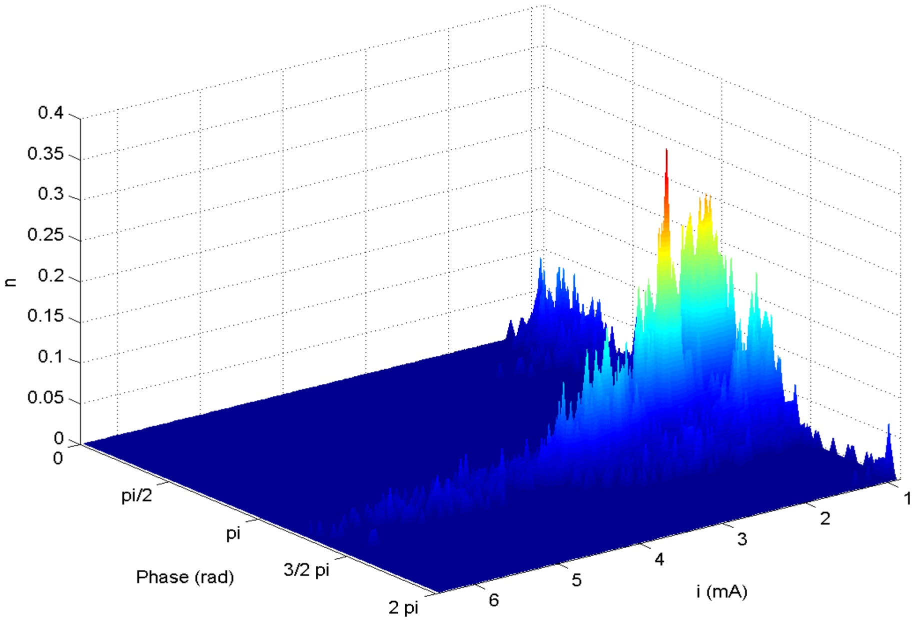
- Transformer bushing tap as capacitive coupler



http://nptel.ac.in/courses/108104048/lecture3/images/3.4.gif

Goal of application of the UHF range

- It is the interest of both the manufacturer and the user to have the transformer **properly and sensitively tested for partial discharge issues**, as it helps avoiding unexpected failures
- The conventional method according to IEC 60270 usually **doesn’t give information about the exact location** of the discharge

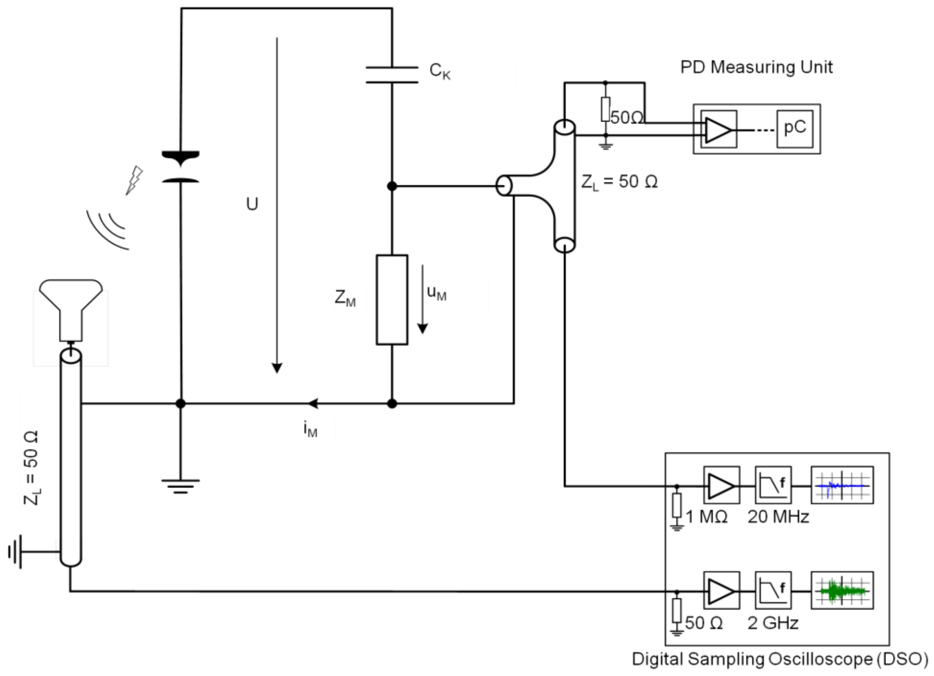


- UHF PD measurement, contrary to the conventional method based on conducted signals, measures **radiated electromagnetic signals**
- There is considerably **less experience with the UHF method** – best practices are still being formed

Correlation of conventional and UHF measurements

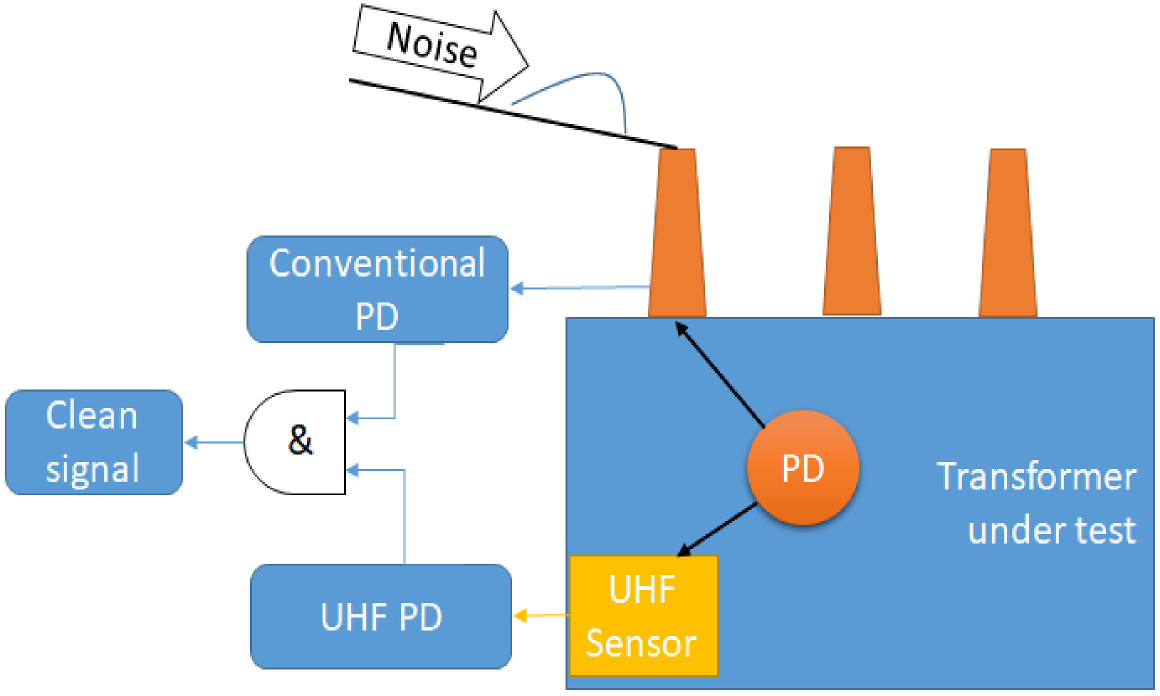
- Sensitivity, location dependence
  - IEC: in some cases, impulses from discharges originating from deep in the winding suffer **damping** while travelling through the winding and bushing, eventually **becoming unmeasurable**
  - Similarly, there are some cases when UHF signal cannot be measured
  - **Both methods have blind spots**, but these are different

- Correlation
  - **In a given position,** IEC and UHF signals are in linear dependence
  - But both are dependent on the location, thus there is no general conversion factor; it is theoretically excluded



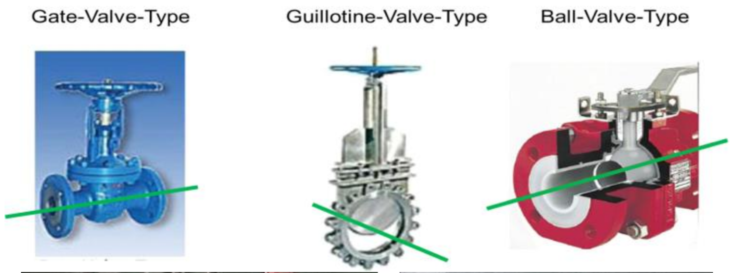
Noise issues in case of UHF measurement

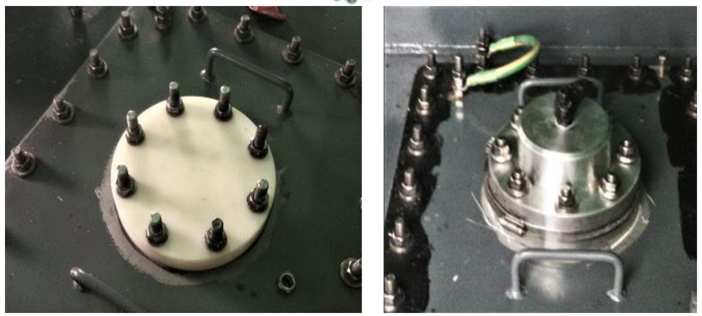
- **The tank is as Faraday cage,** while the **bushing acts as a low-pass filter →** in the UHF range, there is almost total silence
- If both signals are measurable, the conventional signal can be cleaned by gating with the UHF signal

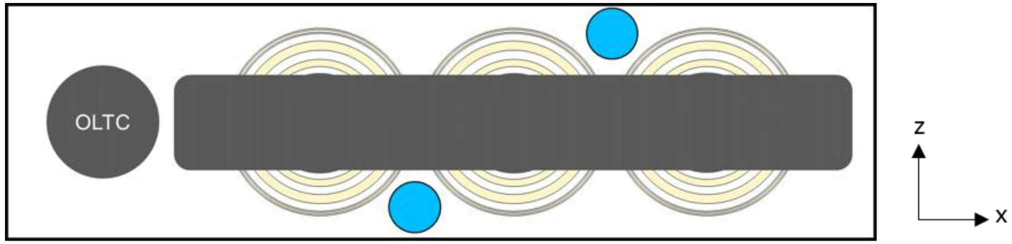


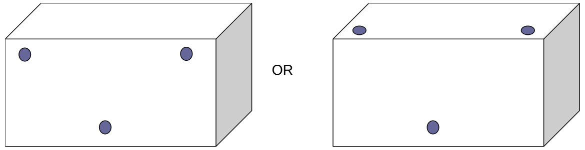
How to use the UHF method in transformers

- Number of sensors:
  - Minimum 2, recommended 4, very good 6-8
- Types of sensors:
  - Oil-valve type (not optimal)
    - Need to find the right depth (vs. safety)
    - Placement of oil valves is not correlating with the optimal PD measurement locations
  - Dielectric window sensors (during manufacturing)
    - Optimal placement
    - Adjusted to sensor physics – better performance
- Location of sensors
  - Sensitivity & location (time-of-flight method)









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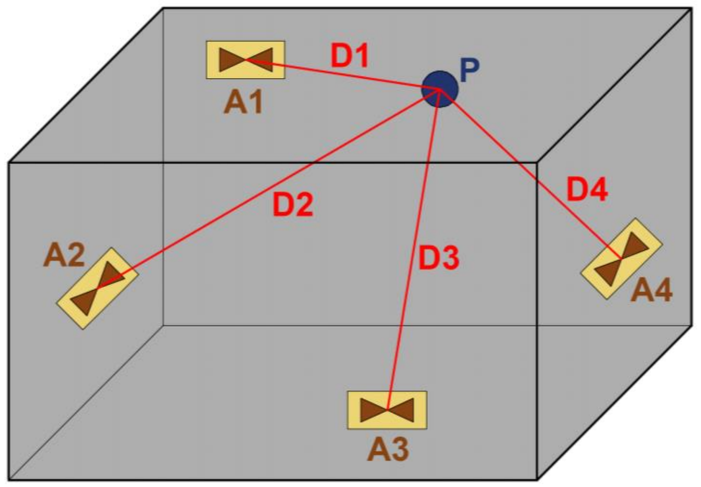
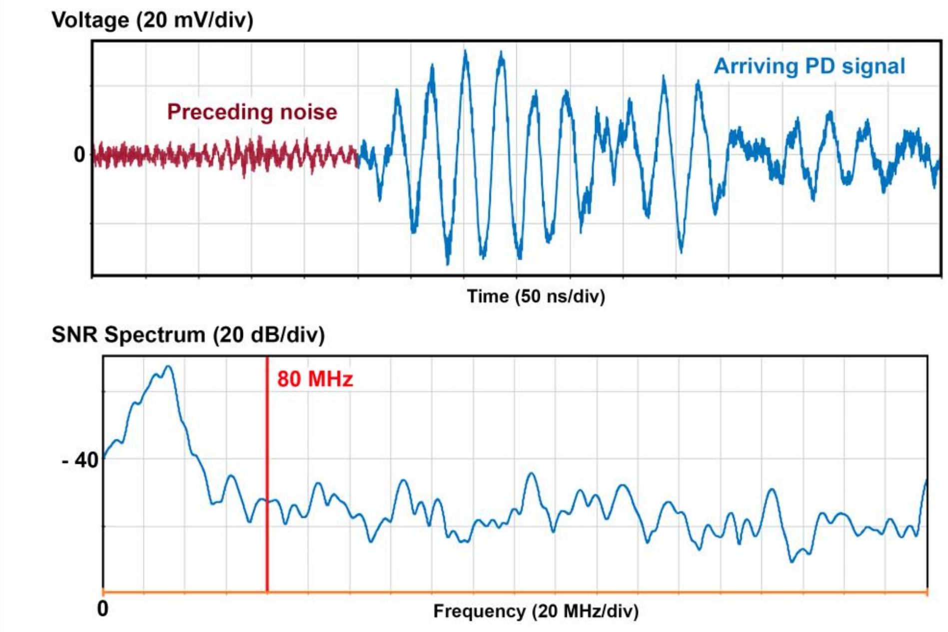
Noise filtering and location

- The detected signals allow the location of the PD source
- Time of arrival (TOA), or more exactly, the time difference of arrival (TDOA) need to be determined



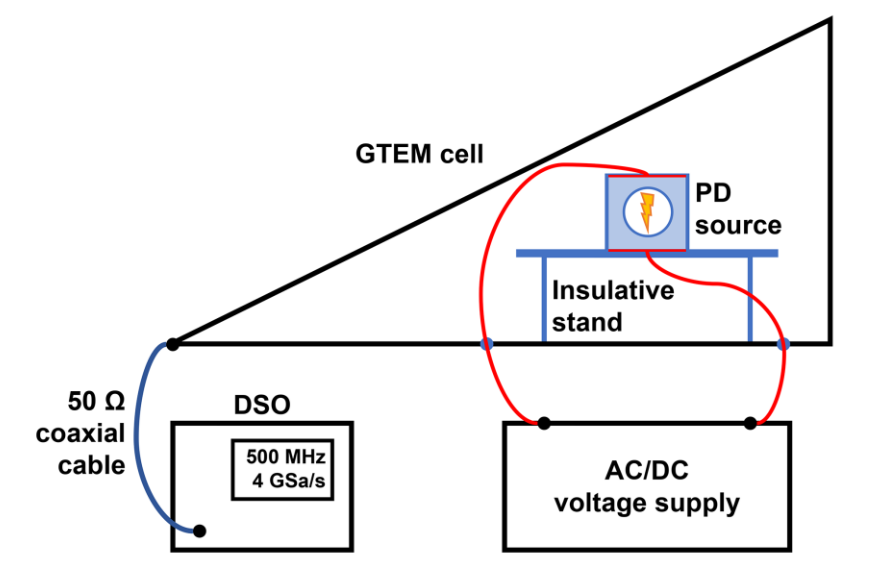
- Difficulties:
  - Determine the exact moment of arrival
  - Due to measurement inaccuracies, we might get results that are different from any physically possible cases

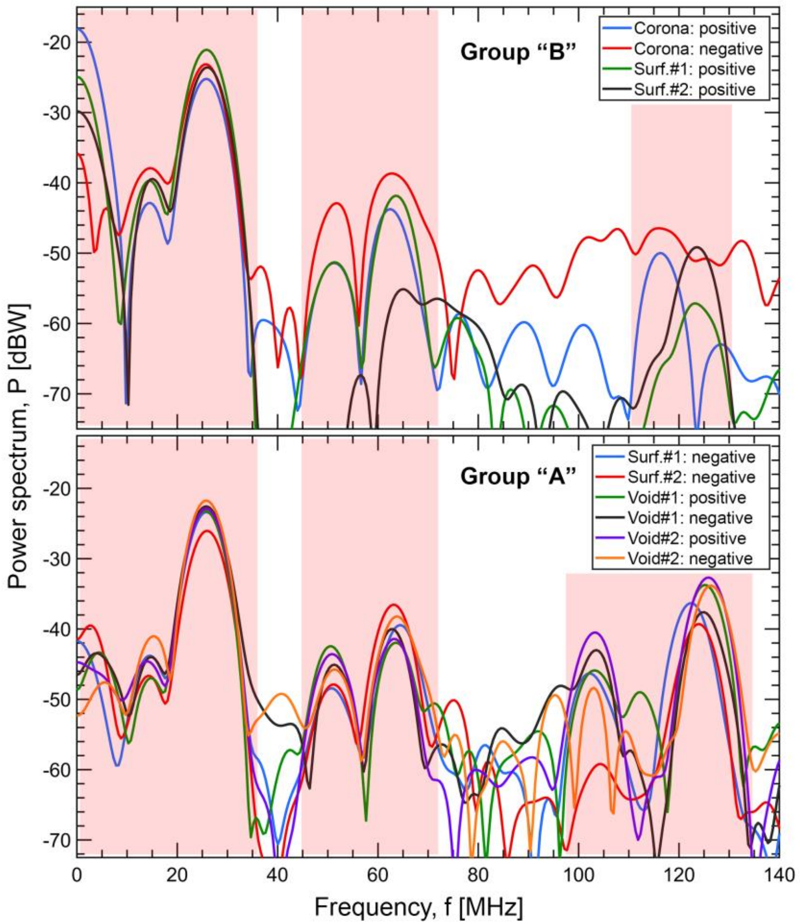


- Goal: characterize the discharges / emitted signals in order to set up the most effective noise suppression and location

Noise filtering and location

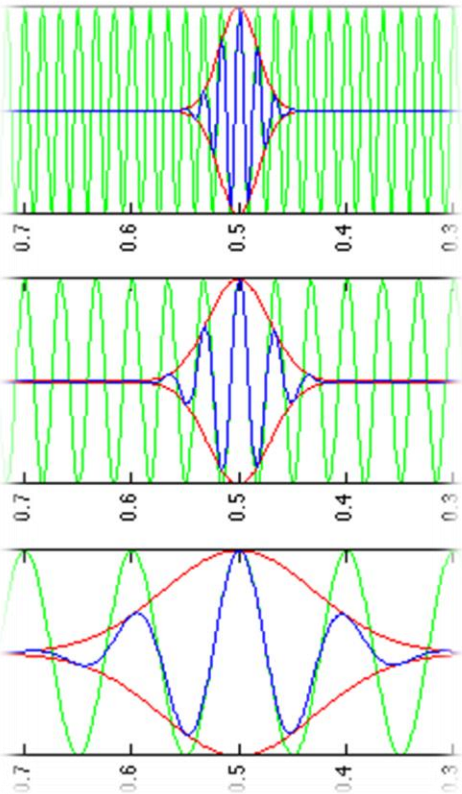
- Tests in GTEM cell
  - Very good shielding, allows to record the clean signal



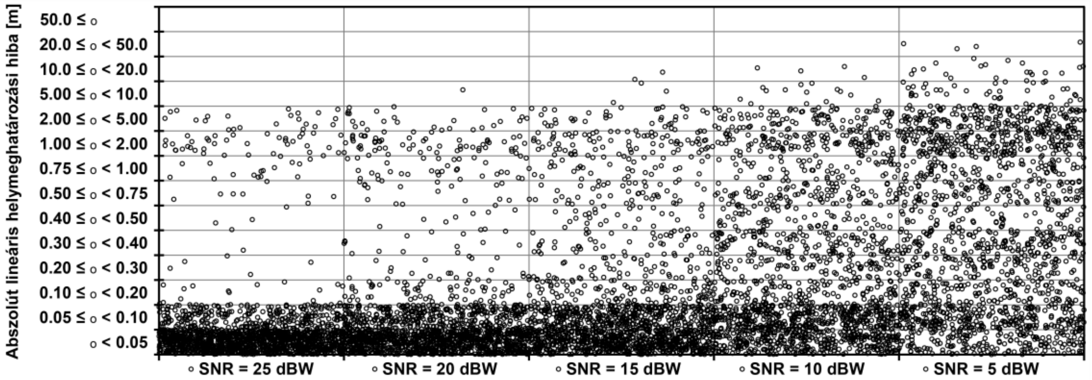


Noise filtering and location

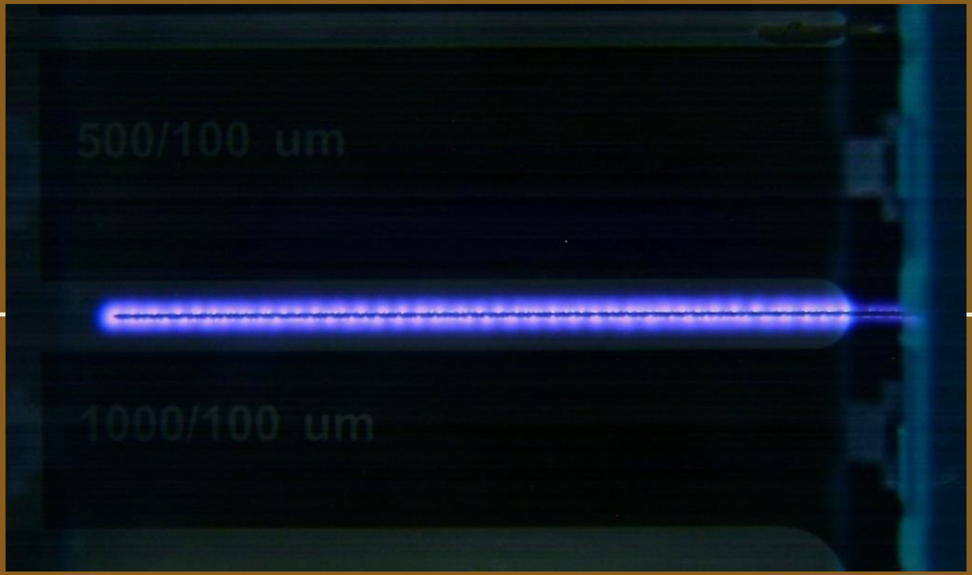
- One method is wavelet filters. Properties of wavelets:
  - Limited in time
  - Oscillating
  - Special shape properties → there are a high number of types
    - The applied wavelet can be selected to match the signal

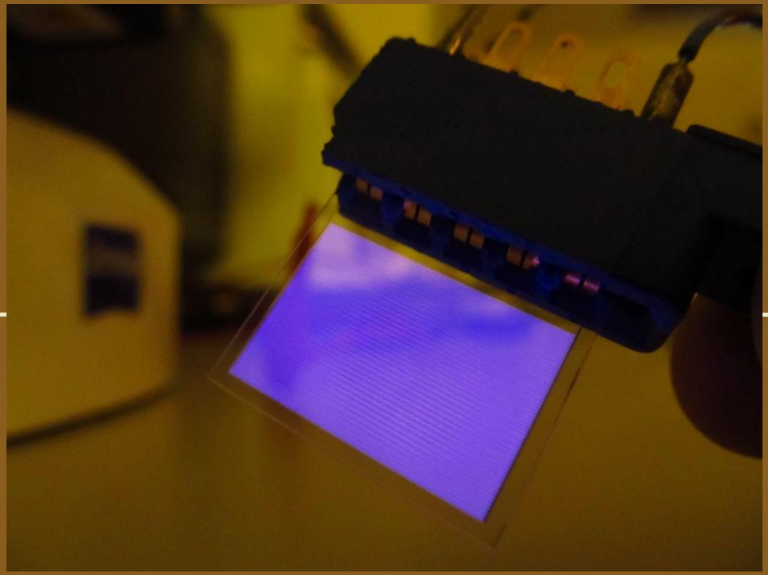


- 22 Wavelet types tested
- Optimization method:
  - TDOA estimation errors and deviation
  - TDOA averages vs. position averages
  - Best results were given by:
    - 5. order Coiflet (coif5)
    - 3. order Daubechie (db3)
    - 4. order Symlet (sym4)



THANK YOU FOR YOUR ATTENTION!





DBD (dielectric barrier discharges – intentional void discharges) in a MEMS technology device to generate ozone for medical disinfection purposes