Introduction to Partial Discharge (Causes, Effects, and Detection)

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ea technology

EA Technology History & Values

- Originally established as R&D center for the UK Electricity Industry (essentially EA Technology was the EPRI of the UK) in the late 1960's. Privatized in the late 1990s.
- Provides research, strategic engineering consultancy, HV asset condition assessment services, specialized instrumentation, and Asset Management Software and Consulting.
- Instrumental in the development of PAS-55 and ISO-55000
- 100% employee owned and have provided products and service in 92 countries around the world

EA Technology LLC Denville, NJ - USA

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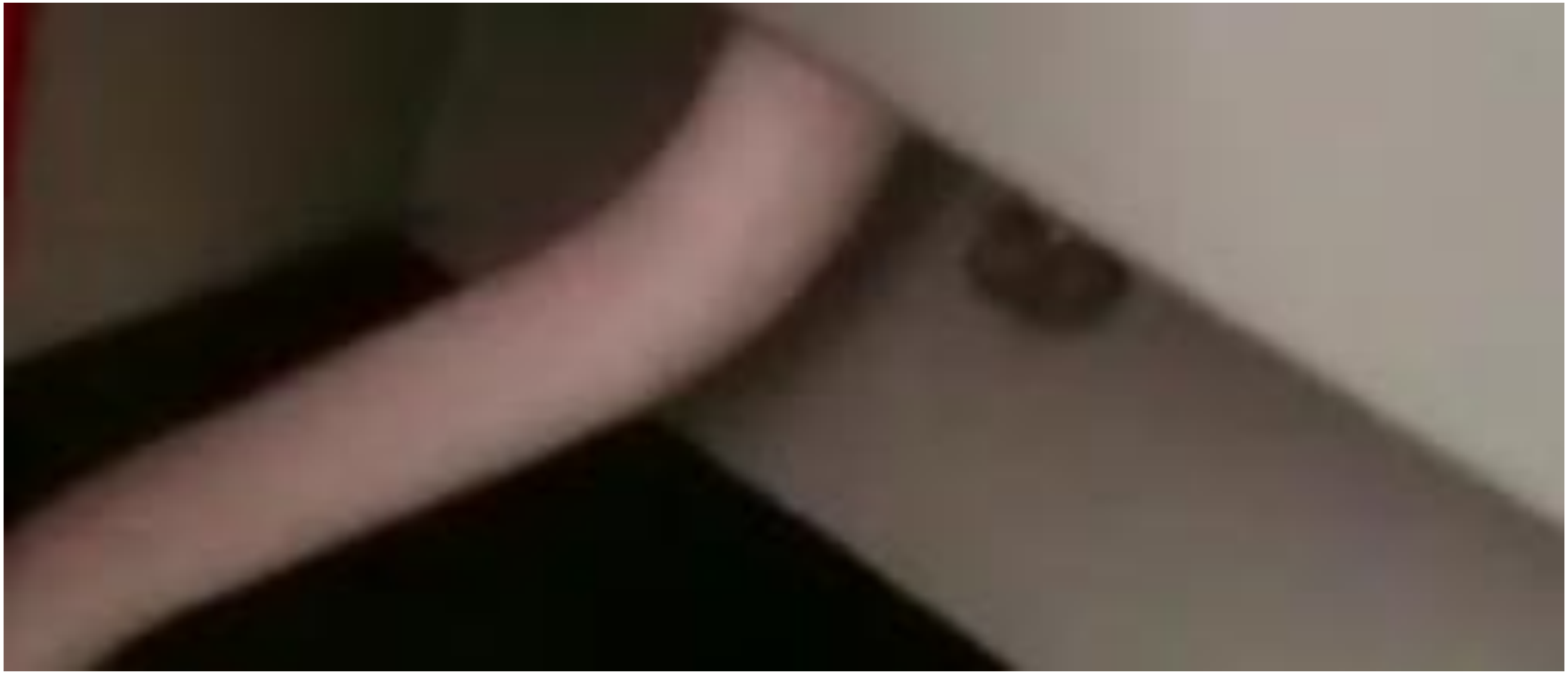
Partial Discharge – What is it and why do we care?

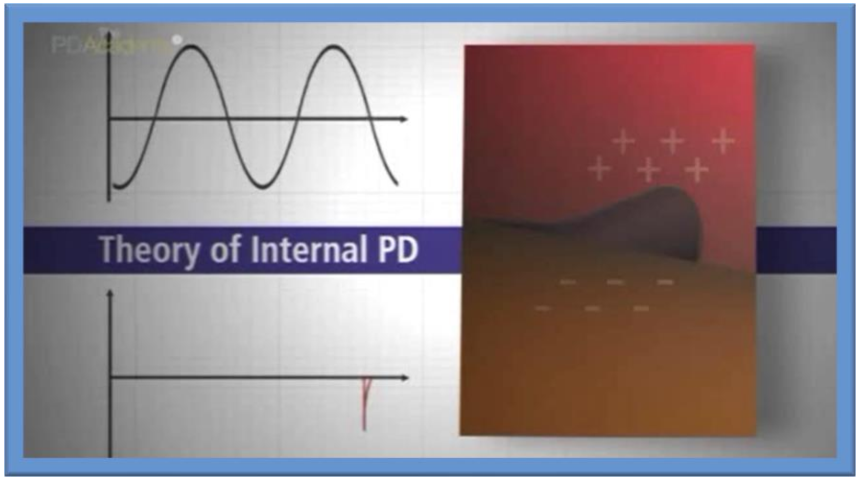
Is Partial Discharge Real?



What is Partial Discharge?

PD failure process

- Multiple causes
- Starts small
- ALWAYS gets worse
- Leads to FLASHOVER



PD is the inability of a portion of the insulation to withstand the electric field applied to it

Partial Discharge (PD)

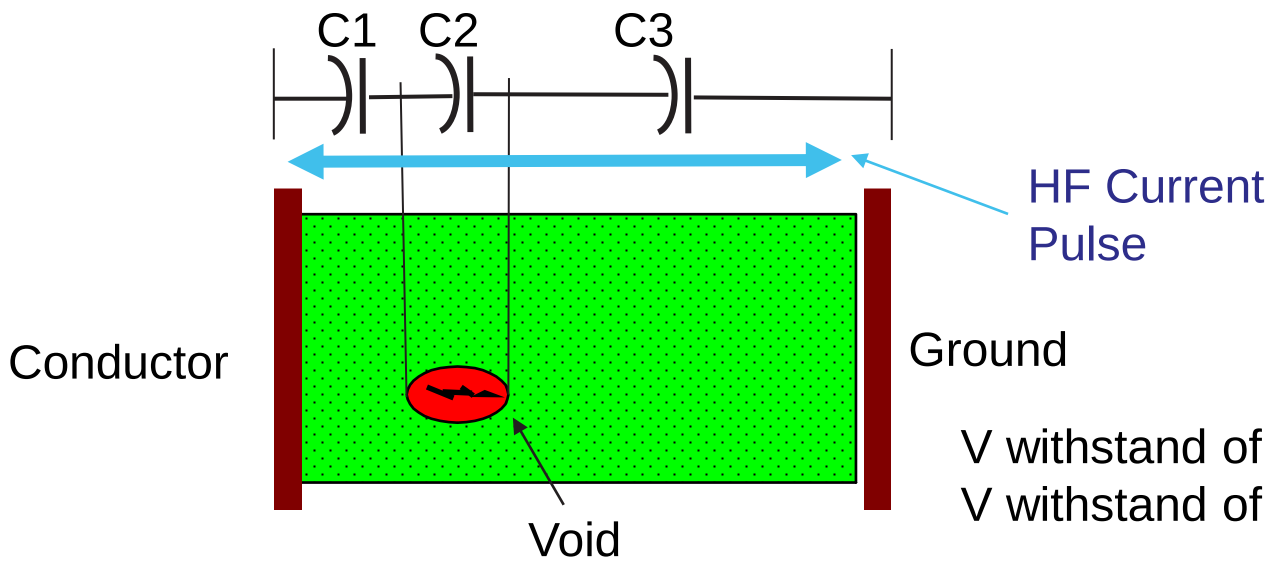
The key to OUTAGE PREVENTION

Where can it occur?

- 3.3kV to 769kV
- Indoor Metal clad switchgear cubicles
- Indoor and Outdoor Insulators
- Transformer Cable Boxes
- MV & HV Cables, Terminations & Underground Vaults
- Transformers
- SF6 GIS / Oil Filled / Air Insulated

What is Partial Discharge (PD)?

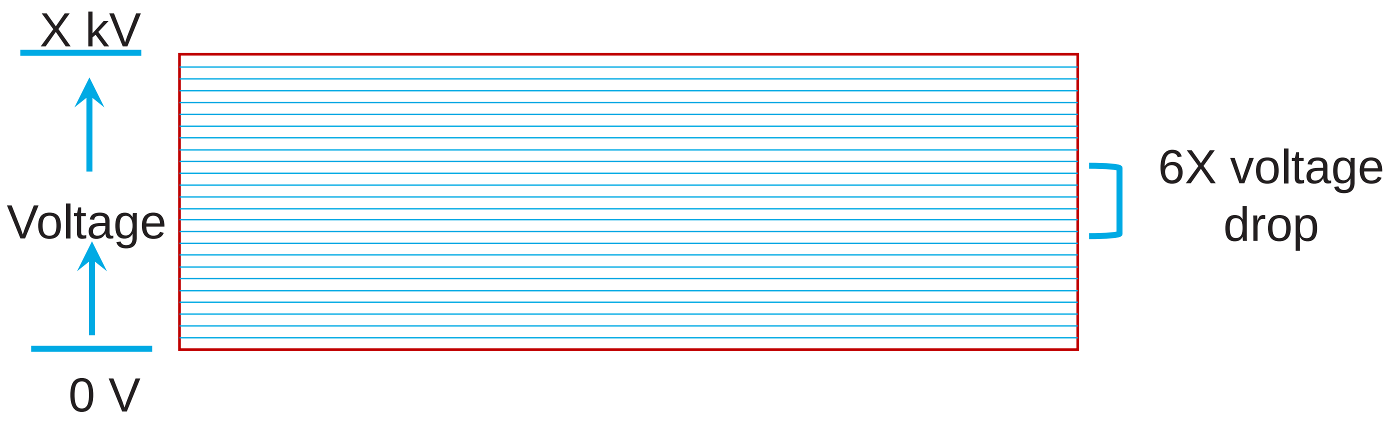
Partial Discharge - A flashover of part of the insulation system due to a localized electric field greater than the dielectric withstand capability of that part where the overall insulation system remains capable of withstanding the applied electrical field.



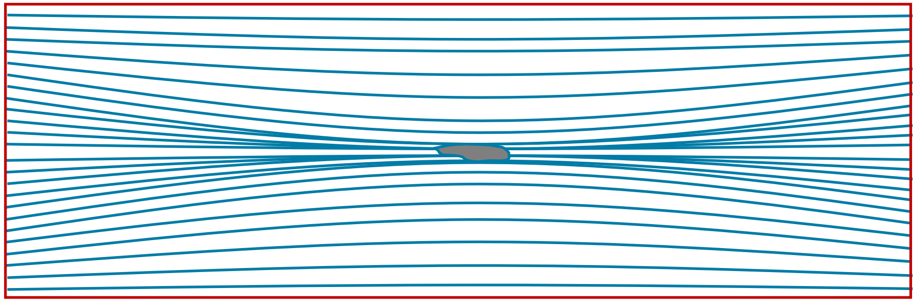
V withstand of C2 < applied field
V withstand of C1&C3 > applied field

One effect of this flashover is a high frequency current pulse that travels through the capacitance of the insulation (C1 & C3)

Equipotential Lines

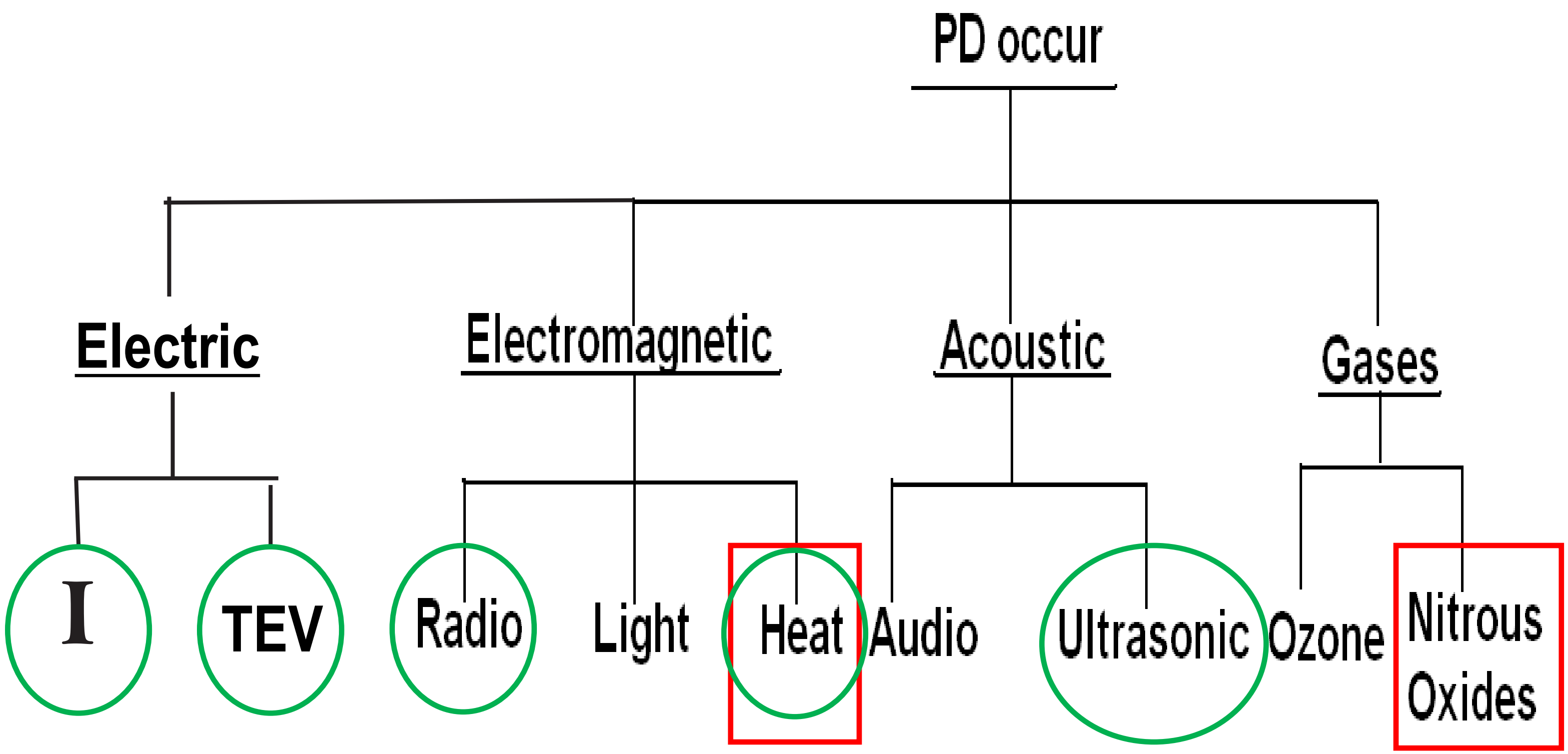


Section through a homogenous insulator showing uniform electrical stress (equipotential) lines. A line indicates where the voltage potential is constant



The same insulator with a void. The lower dielectric of the void causes a concentration of the electrical field through the void high enough to cause breakdown at working voltages

Products of Partial Discharge

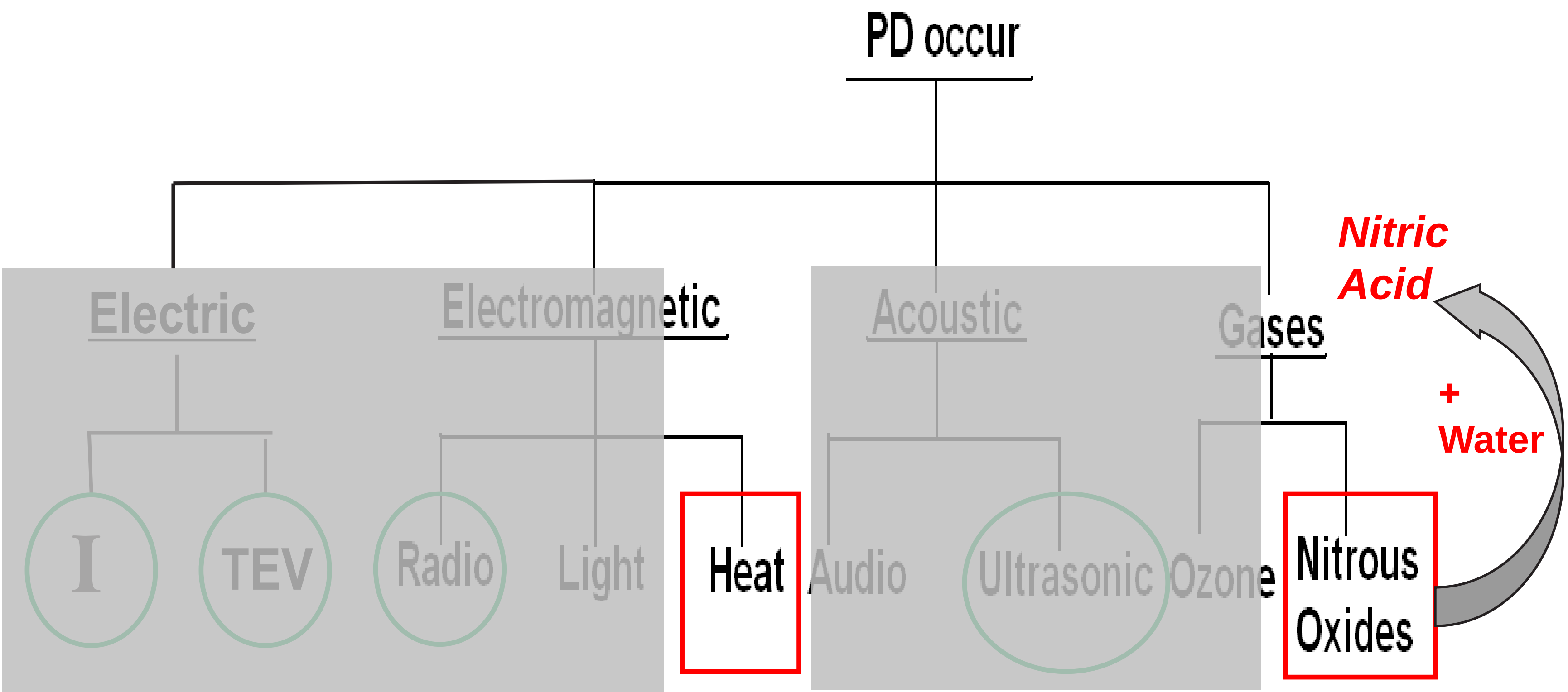


Partial discharge breakdown of insulation produces:

Light, Heat, Smell, Sound, Electromagnetic Waves, and an HF Electric Current

Products of Partial Discharge

How does PD damage insulation?



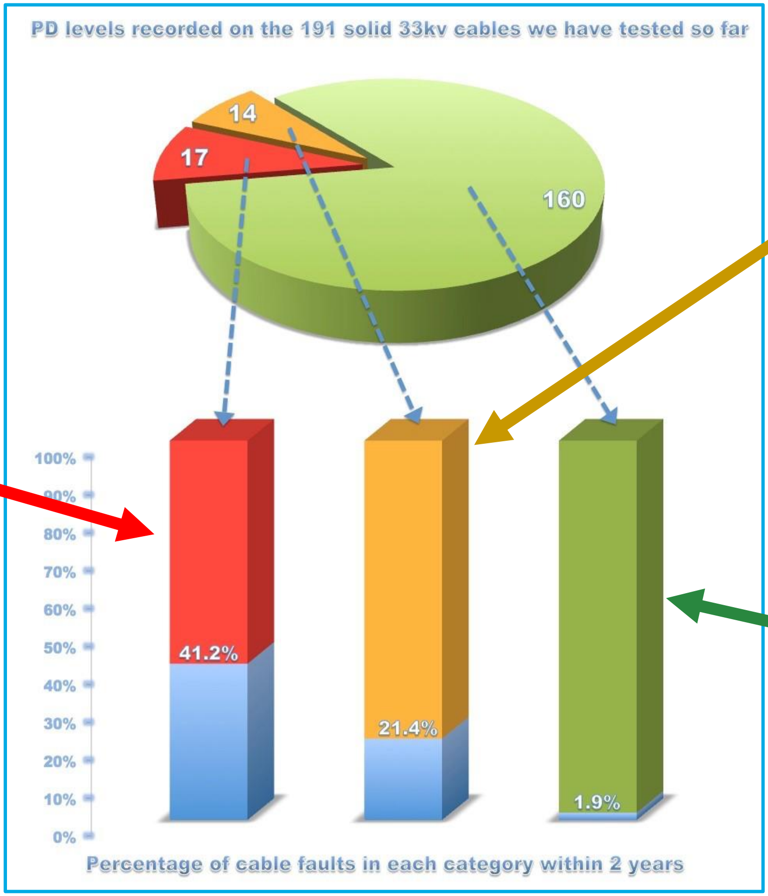
Partial discharge breakdown of insulation produces:
Light, Heat, Smell, Sound, Electromagnetic Waves, and an HF Electric Current

CABLE TESTING Field Example

UK utility undertook a two year evaluation of RFCT based on-line testing that performed a PD condition based assessment of 191 33KV cables on their network over a two year period.

7% rated RED
(no problems)

<40% of those failed within 2 years



7% rated Amber
(no problems)

<21% of those failed within 2 years

84% rated GREEN
(no problems)

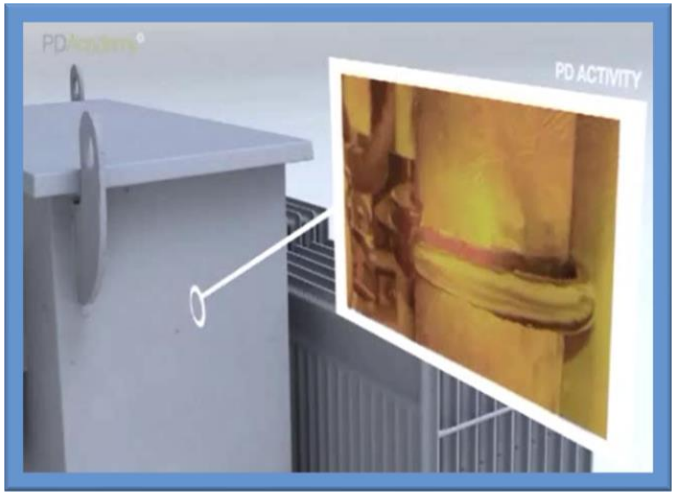
>2% of those failed within 2 years

Types of PD

- **Internal discharges** occurring in defects, voids or cavities within solid insulation
- **Surface discharges** occurring across the insulation surface
- **Contact discharge** occurs on floating metal in high field conditions
- **Corona discharge** occurring in gaseous dielectrics in the presence of inhomogeneous fields

Partial Discharge (PD)

Internal Partial Discharge

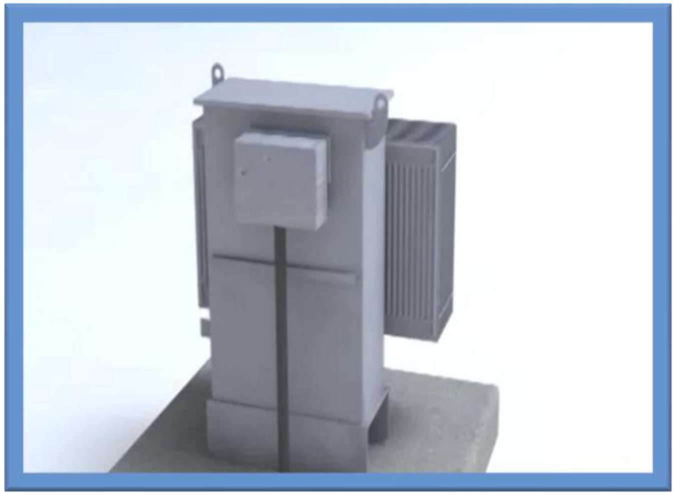


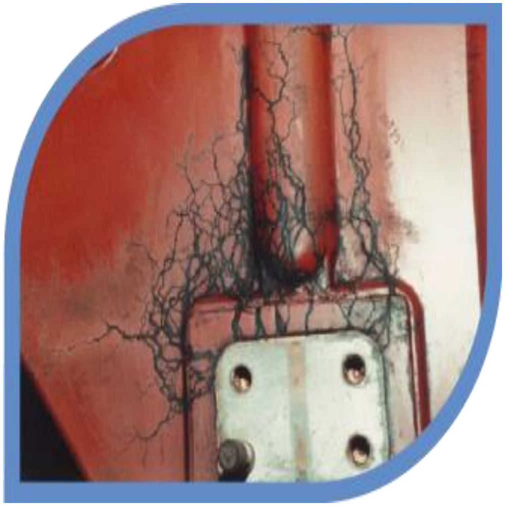
- Internal Discharge occurs in all types of insulation as a result of defects, voids or cavities within solid insulation, also including oil and gas

- Practical Non-Invasive method to detect Internal Partial Discharge Activity is to use Transient Earth Voltage (TEV) detection instruments.

Partial Discharge (PD)

Surface PD





- Surface discharges occurring across the insulation surface Causes treeing and tracking
- Practical Non-Invasive method to detect Surface Partial Discharge Activity is to use Ultrasonic Emission detection instruments.

Causes of PD

- Surface contamination (lack of cleaning)
- Workmanship (poor installation)
- Material defects (manufacturing defects)
- Improper application (wrong parts for the job)
- Salt spray or Salt fog
- Mechanical damage (during install or in service)
- Age (electrical stress wears out insulation)

Standards associated with PD

IEEE 400 Series

IEEE 400 Guide to field testing shielded power cable

- Cables only

IEEE 400.1 Guide to testing shielded power cable with DC

- Not for Aged XLP cable
- Fine for PILC
- i.e.

IEEE 400.2 Guide to field testing shielded power cable with VLF

- Offline
- Time consuming
- Excellent data quality
- PD, Withstand, Tan Delta

IEEE 400.3 Guide to field PD testing of shielded power cable

- It's a guide, not a standard!
- It does not conflict with or support IEC 60270
- It discusses online and offline testing

IEC 60270

IEC 60270 Edition 3.0, 2000

- Direct connection only
- Defines measurement circuit
- Defines measurement technique
- Defines calibration pulse generator
- Measures PD in picoColoumbs

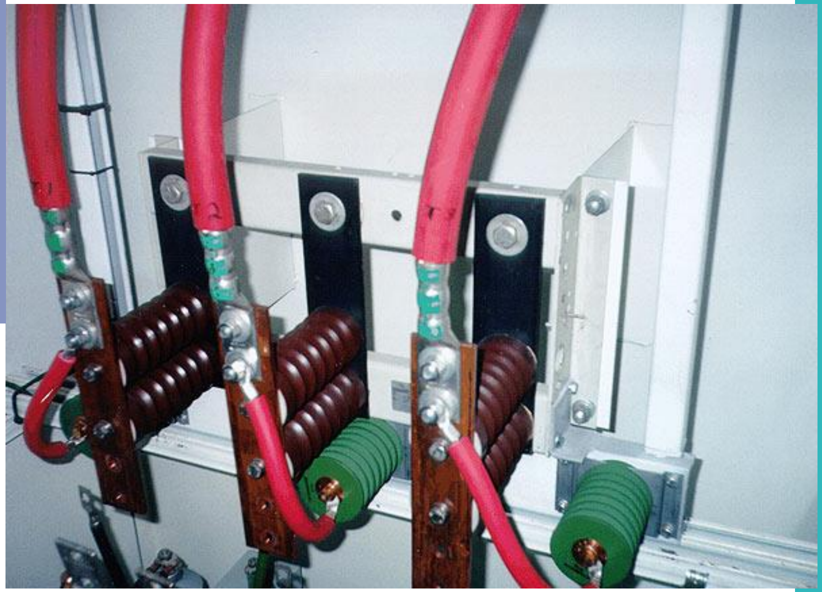
(1 picoColoumb = 1 uA for 1 uS)

Annex D – Use of RF meters for PD detection

Annex F – Non-Electrical methods of PD detection

(Acoustic, Visual, Chemical)

IEC 60270 & IEEE 4000 test equipment



Invasive versus Non-invasive detection techniques

Invasive – Offline

Invasive methods require taking an outage to effect the test. Effectively this includes all direct connected test gear

- All forms of offline testing are by definition invasive
- VLF PD cable testing requires the cable to removed from service for 3-4 hours to test
- Tan-Delta and other cable test methods require removing the cable from service
- System Frequency PD cable testing requires getting truck mounted equipment on site and removing the cable from service
- Permanently installed systems & sensors need to be de-energized to install

Electrical Tests Commonly Done - Offline

- **High Pot (potential)** Tests for ability to withstand voltage for brief periods

- **Insulation Resistance (megger)** Tests for resistance to ground that might cause leakage

- **Tan – Delta** Tests for overall insulation health by comparing resistive and capacitive currents

- **IEEE-400 and IEC 60270 PD** Tests for partial discharge offline (VLF, etc.)

Non-invasive – Online

Also known as No-Outage testing, this type of testing requires no de-energizing of equipment and is safe to do around live voltages.

- **Ultrasonic/Acoustic testing** – through louvers, vents, contact sensors, and parabolic dishes
- **TEV testing** – Makes use of the Transient Earth Voltage phenomenon to safely detect internal discharge from outside cabinets
- **RFCT testing*** - By attaching RFCT to cable ground straps, the PD current can be safely measured on live cables
- **RF Testing** – Specifically designed directional and non-directional radio receivers can pickup the EMI generated by PD

* installing RFCT on live cables requires opening the HV compartment and appropriate safety measures need to be followed

Practical Online PD Detection Methods

Surface Discharge Activity

- Ultrasonic Emission
- TEV Detection - when high amplitude surface discharge
- RFCT Detection of Current Pulse
- RF Detection of EMI

Practical Online PD Detection Methods

Internal Discharge Activity

- Transient Earth Voltage (TEV) Detection
- RFCT Detection of Current Pulse
- RF Detection of EMI

Practical Online PD Detection Methods

Cable Discharge Activity

- RFCT Detection of Current Pulse
- RF Detection of EMI – near terminations
- TEV Detection – on outside of sheath
- Ultrasonic Emission – only when very near surface

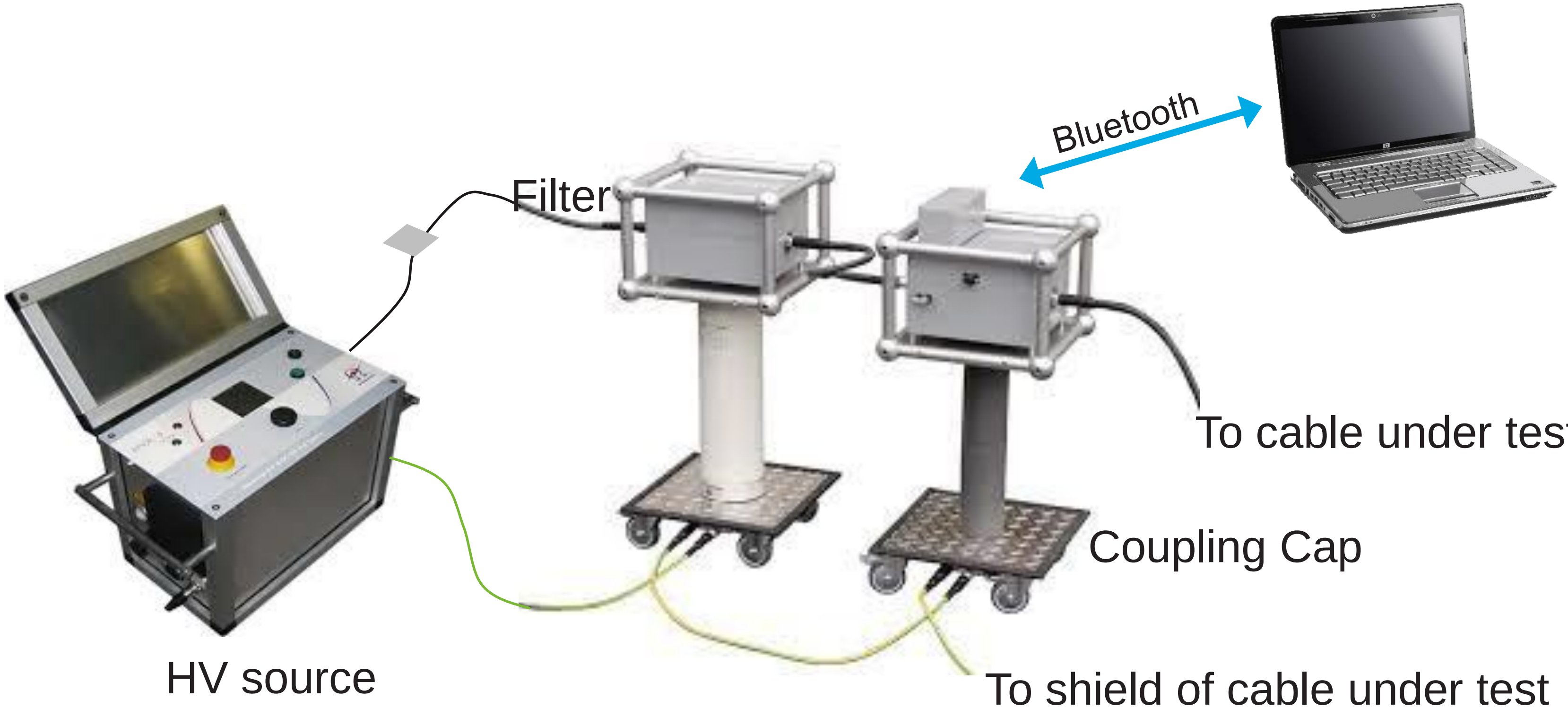
Direct Connected – Offline Testing

Very Low Frequency – VLF

VLF (for PD)

Offline, Very Low Frequency IEC 60270 / IEEE 400.3 compliant test.

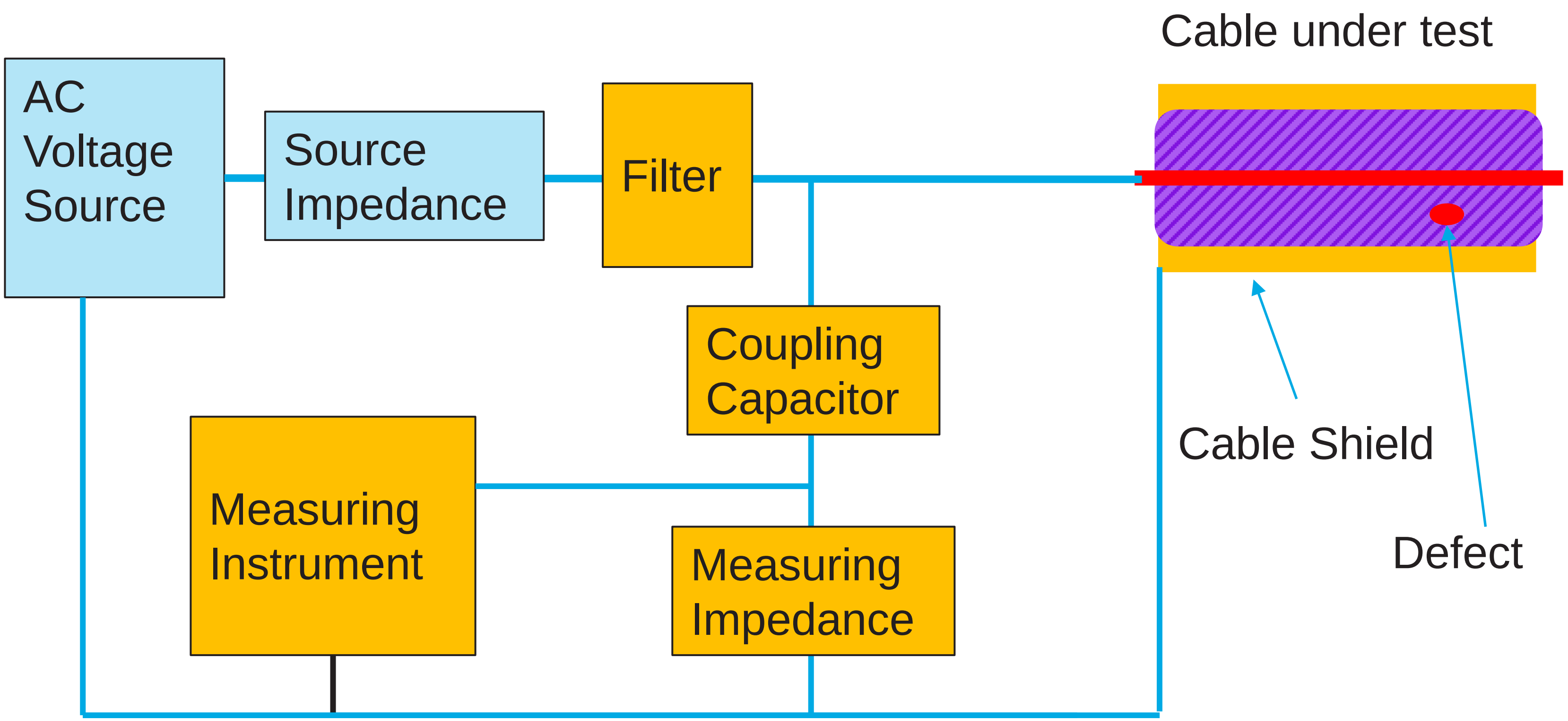
Requires an outage and cable to be disconnected on both ends.



Offline PD Testing

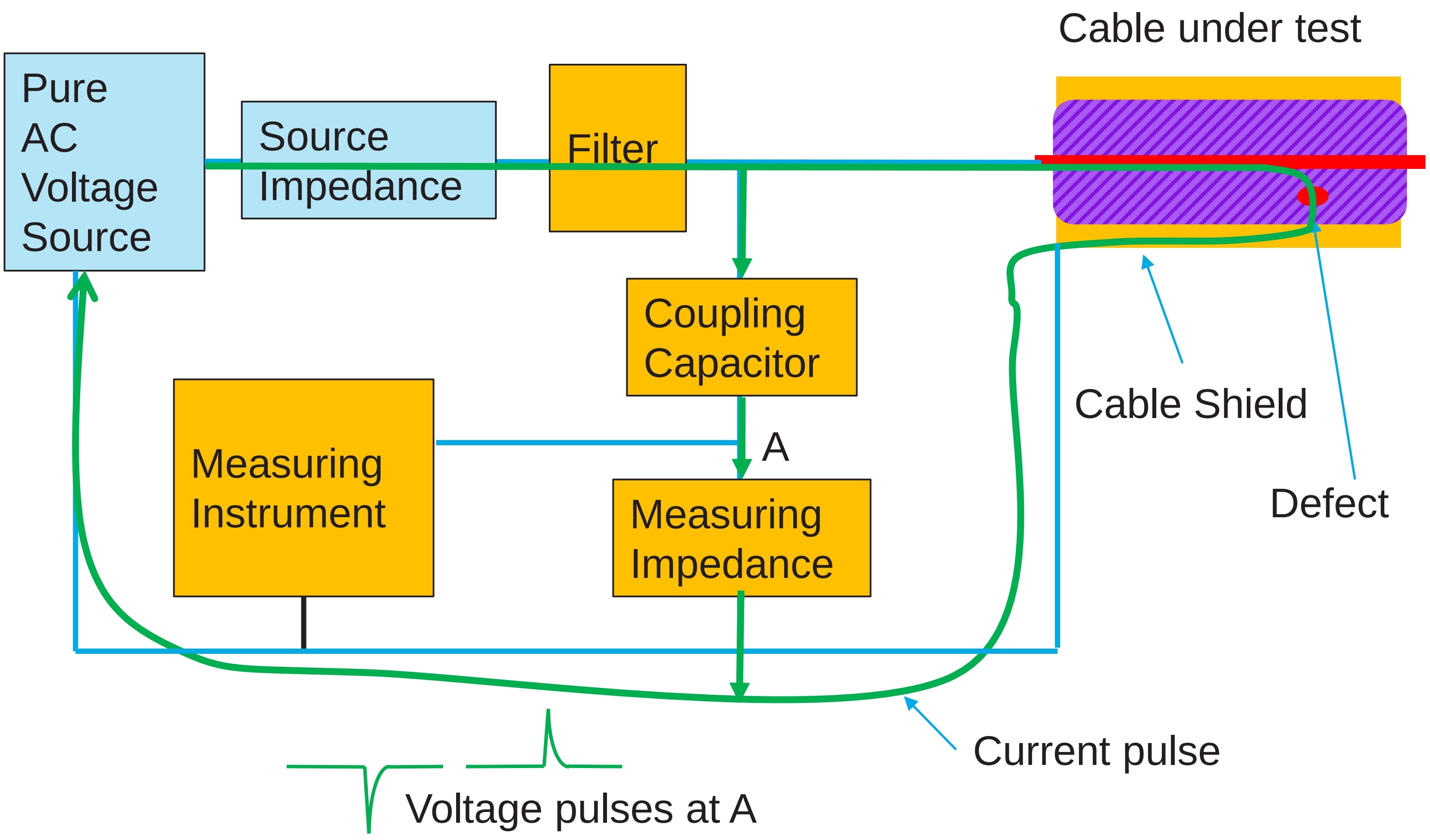
VLF, .01-1 Hz, Resonant AC

(VLF is by far the most prevalent at medium voltage)



Offline PD Testing

HF Current flow due to defect flashover



Direct Connect – PDIV / PDEV

PDIV – PD Inception voltage
PDEV – PD Extinguish voltage

PDIV	16KV
PDEV	13KV
LINE	11KV

PD might start with a transient but won't continue

PDIV	16KV
LINE	11KV
PDEV	10KV

PD might start with a transient but won't <u>stop</u>

Offline Test Equipment - Test Van

Transformer

Test bushings

VLF generator

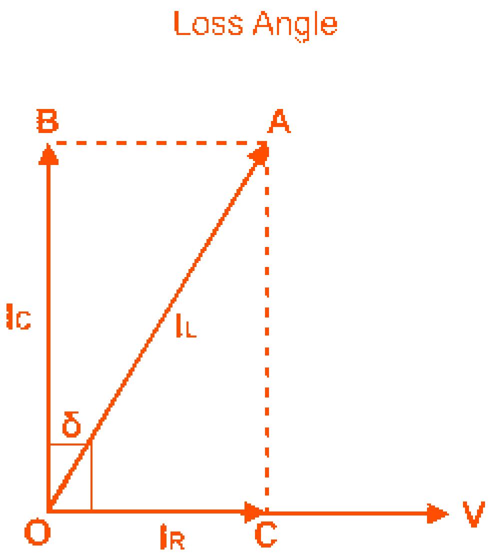
Detector filter (allows LV detection lead to be connected to HV Supply and filters Hz)

Portable Unit -Approximately 500lbs

Direct Connected Offline Testing – Tan Delta

Tan Delta

Tan Delta is a measurement of the loss angle or dissipation factor. Effectively, it is measuring the ratio of the capacitance and resistance in a cable

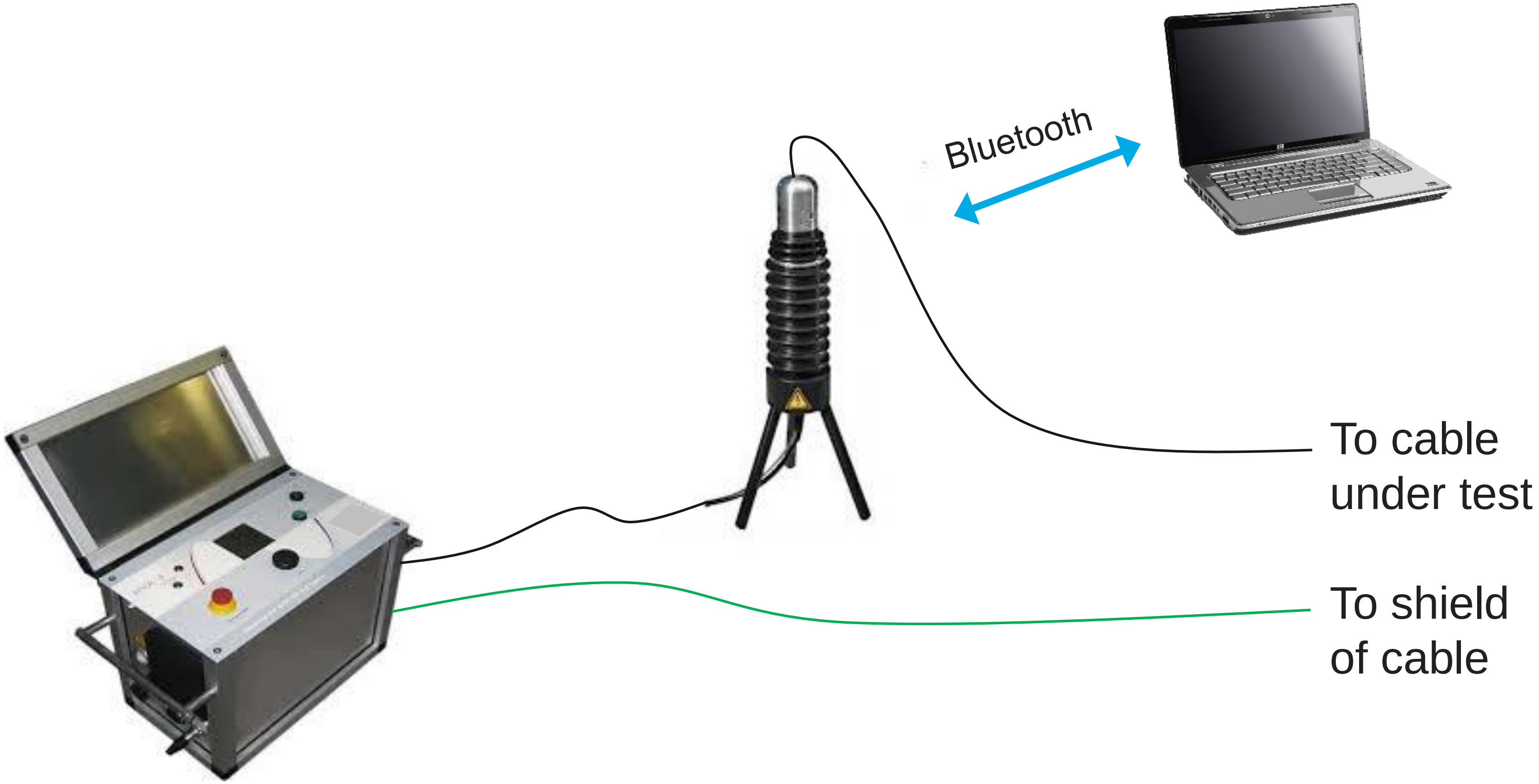


In a perfect cable there would be no I_R and the arrow A would be straight up.

As the cable ages and gets water trees and electrical trees, resistance through the insulation creeps in. This causes I_R and the angle increases.

Tan Delta

Typical set up



Online systems

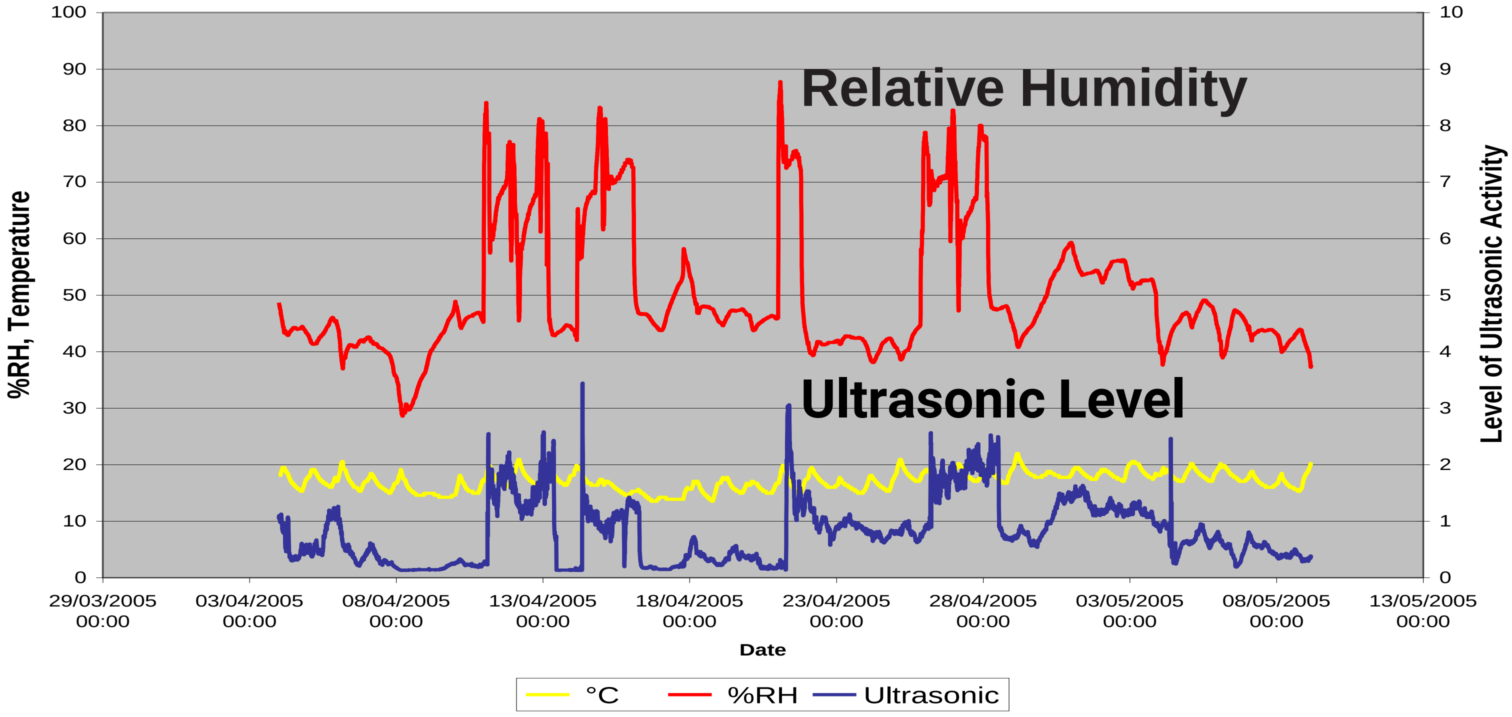
Surface Discharge - Ultrasonic Emission

Ultrasonic Survey
(Practical Considerations)

- Influenced by environment (e.g. temperature, humidity, pollution).
- When monitoring ultrasonically the environmental conditions (%RH and Temperature) should also be monitored
- Discharge has a distinctive crackling noise.
- Often intermittent, particularly during early stages.
- Severity of discharge is not necessarily related to noise amplitude.

Environmental Factors

- Moisture in air will play a significant role in whether discharge is active
- When monitoring ultrasonically the environmental conditions (%RH and Temperature) should also be monitored



Ultrasonic Interpretation

Ultra dB	Category	Comments
< 6	Good background	No observable/measurable deterioration
7 - 10	Fair Very slight fizzing only just above the background	**Minor Deterioration** which requires no specific action
11 - 20	Poor Heavy fizzing or crackling	**Moderate Deterioration** Item can be returned to service. Reinspect in 30 days.
> 20	Action Required Spitting or sparking or heard with the naked ear	**Serious Deterioration** Item cannot be returned to service without shut down or engineering advise

Ultrasonic Sensors

- Four different sensors are available for ultrasonic measurements
  - Built in Sensor – for general purpose airborne ultrasonic measurements

  - Flexible Sensor – for general purpose measurements that are harder to reach

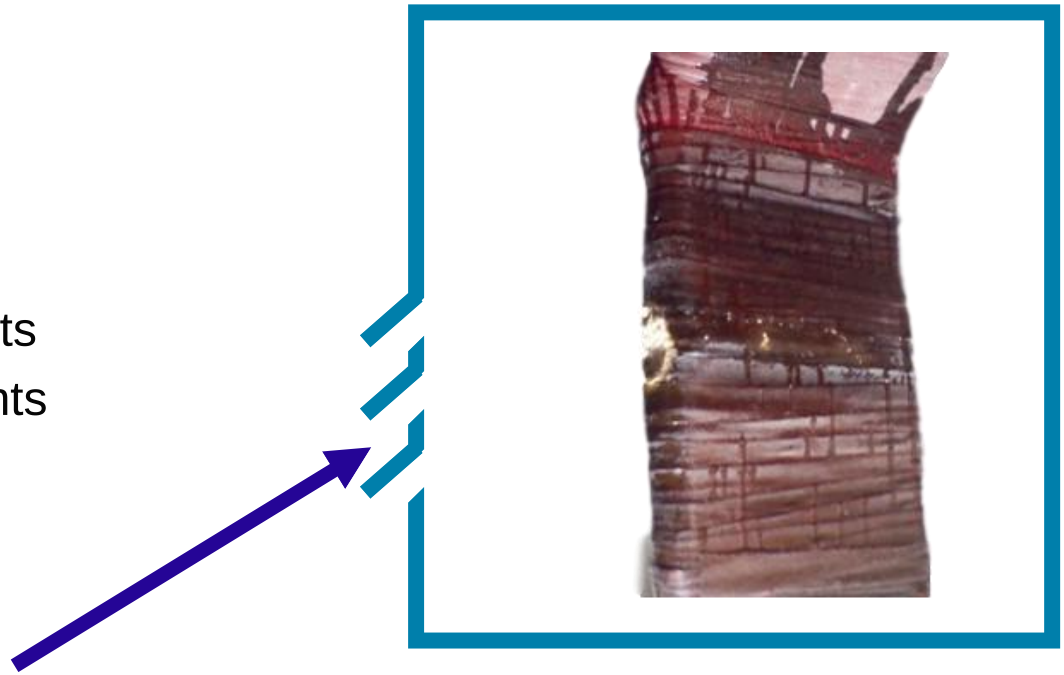
  - UltraDish – Focuses sound energy for making measurements from a greater distance

  - Contact Sensor – for making measurements when there isn't an air path from the source to the sensor

Ultrasonic Detection

- Measurement relies on an air path out of the switchgear

- Types of air paths
  - Vents / Louvers
  - CB Bushings / HV spouts
  - Gaps around panel joints
  - Bolt holes



Discharge noise can be picked up Outside gear via louvers in cabinet

Ultrasonic Detection

- Measurement relies on an air path out of the switchgear
- When there's no air path?
  - Contact sensor turns panel into sensor
  - Designed to work though cabinet metalwork, no direct air path needed

Designed to work though cabinet metalwork, no direct air path needed

Contact probe

Ultrasonic Detection

- Technician takes a minute or two at each cubicle
- Listens to audio via headphones
- Watches display for patterns
- Moves the probes along each air gap

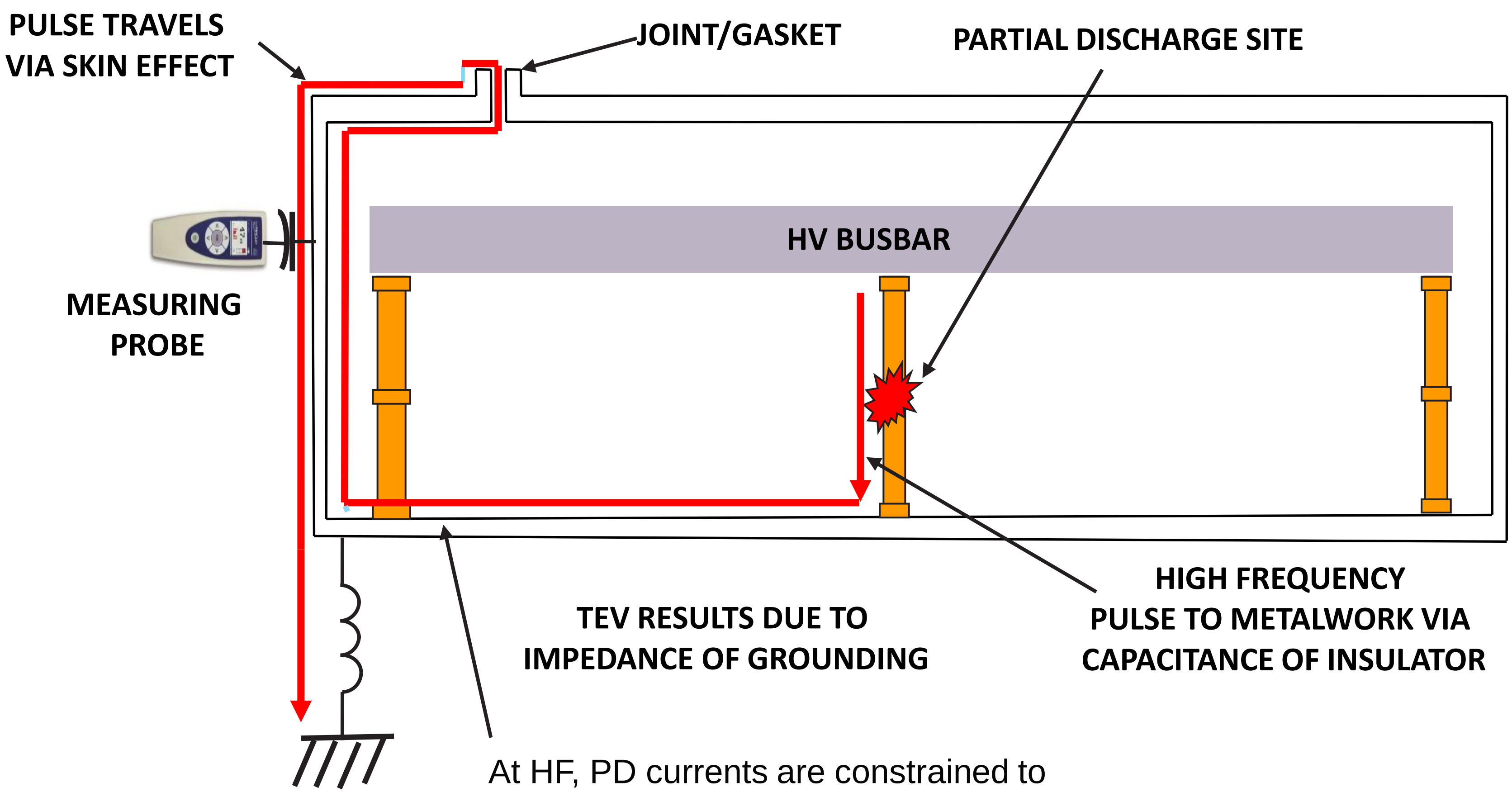
Internal Discharge – TEV Detection

Transient Earth Voltage (TEV)

Identification

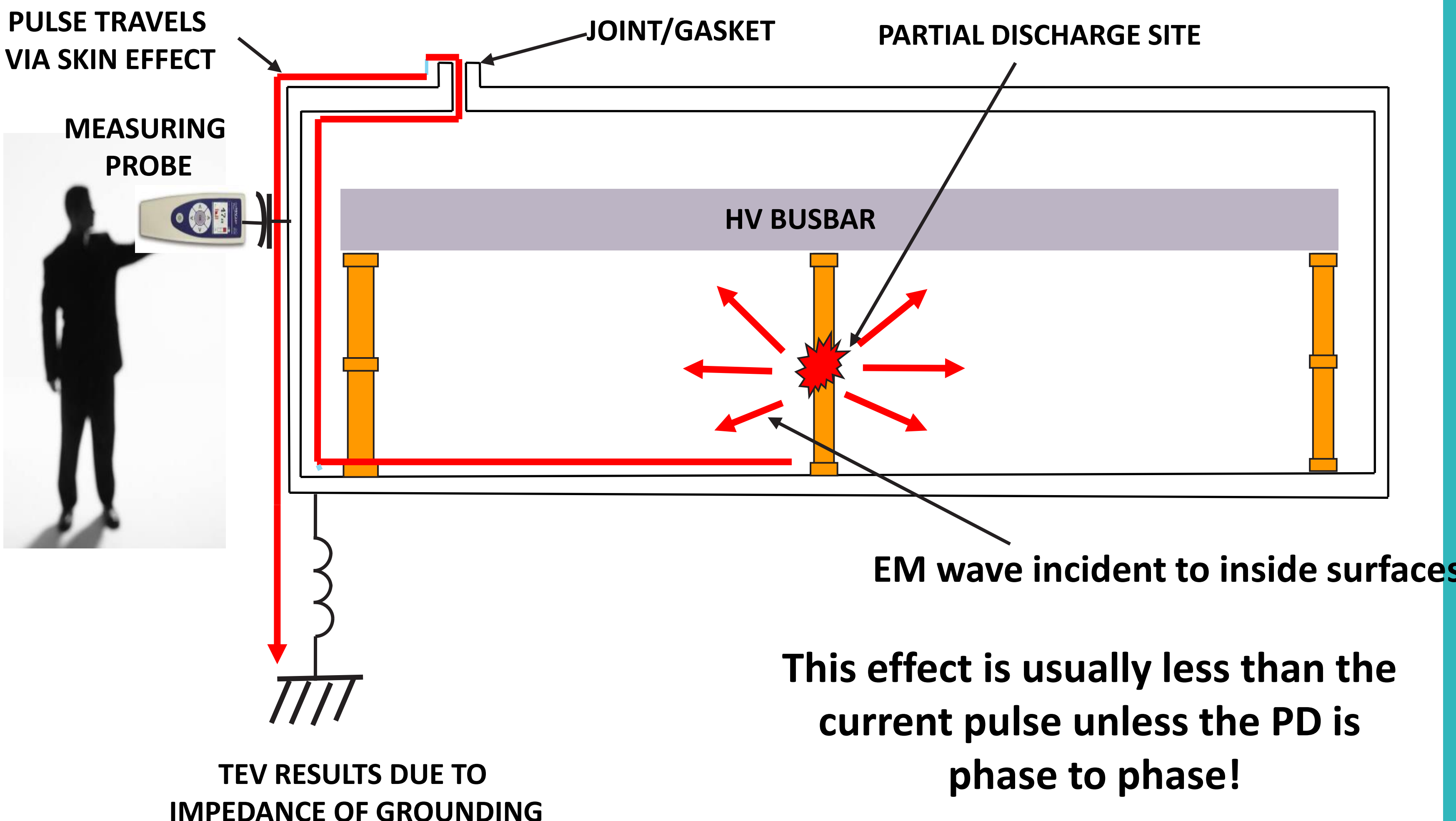
- Identified over 30 years ago
- Measurement bandwidth 2 – 80 MHz
- TEV pulse rise time was found to be circa 5ns
- 3dB Bandwidth = (0.35 / rise time).
- Therefore for 5ns, bandwidth = (0.35 / 5) GHz, i.e. 70 MHz

Internal Partial Discharge Effect 1
(Current pulse - TEV)



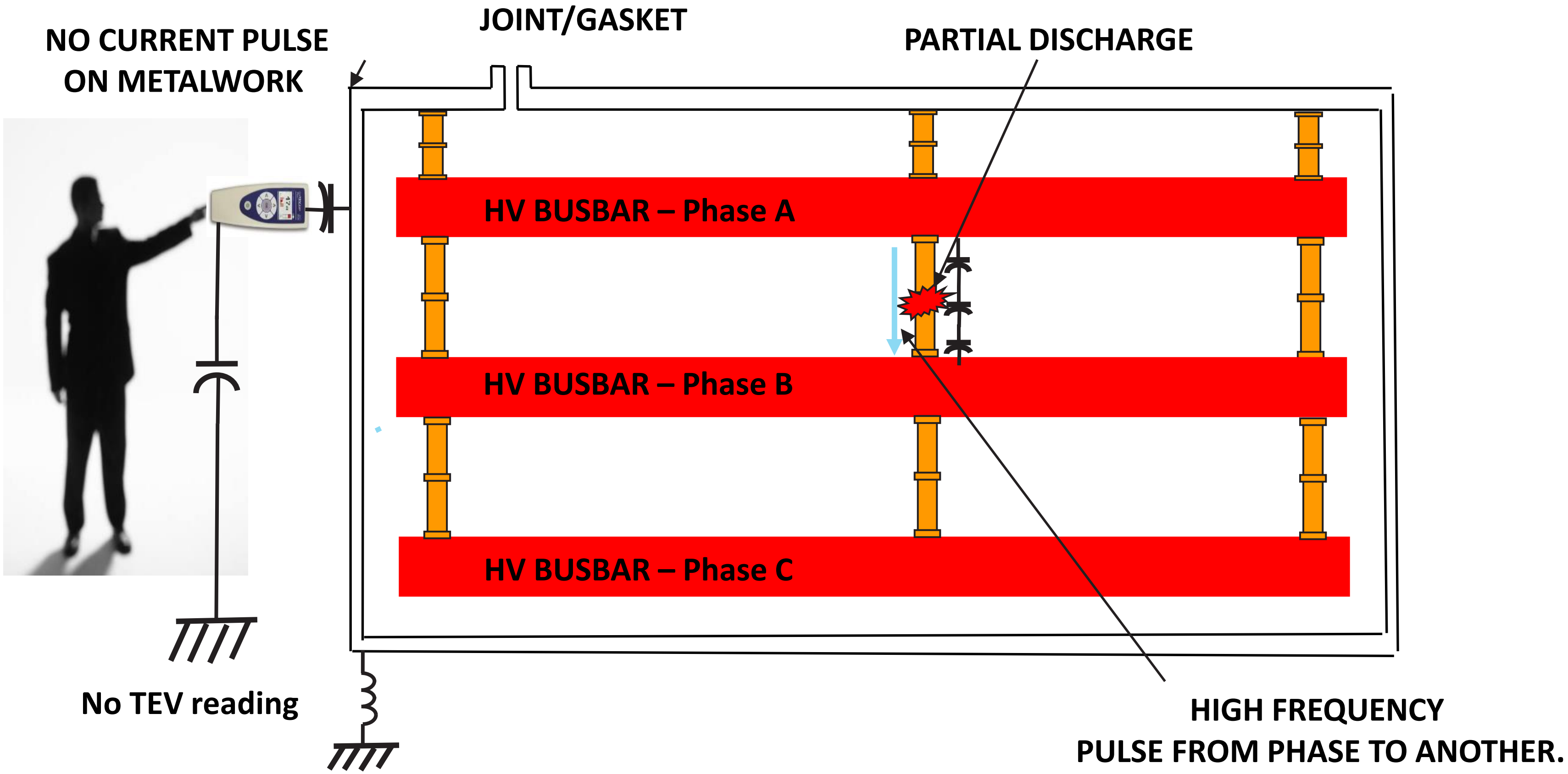
At HF, PD currents are constrained to flow in a thin layer on the surface of conductor. Skin depth in mild steel at 100MHz 0.5um

Internal Partial Discharge Effect 2 (EM Wave)

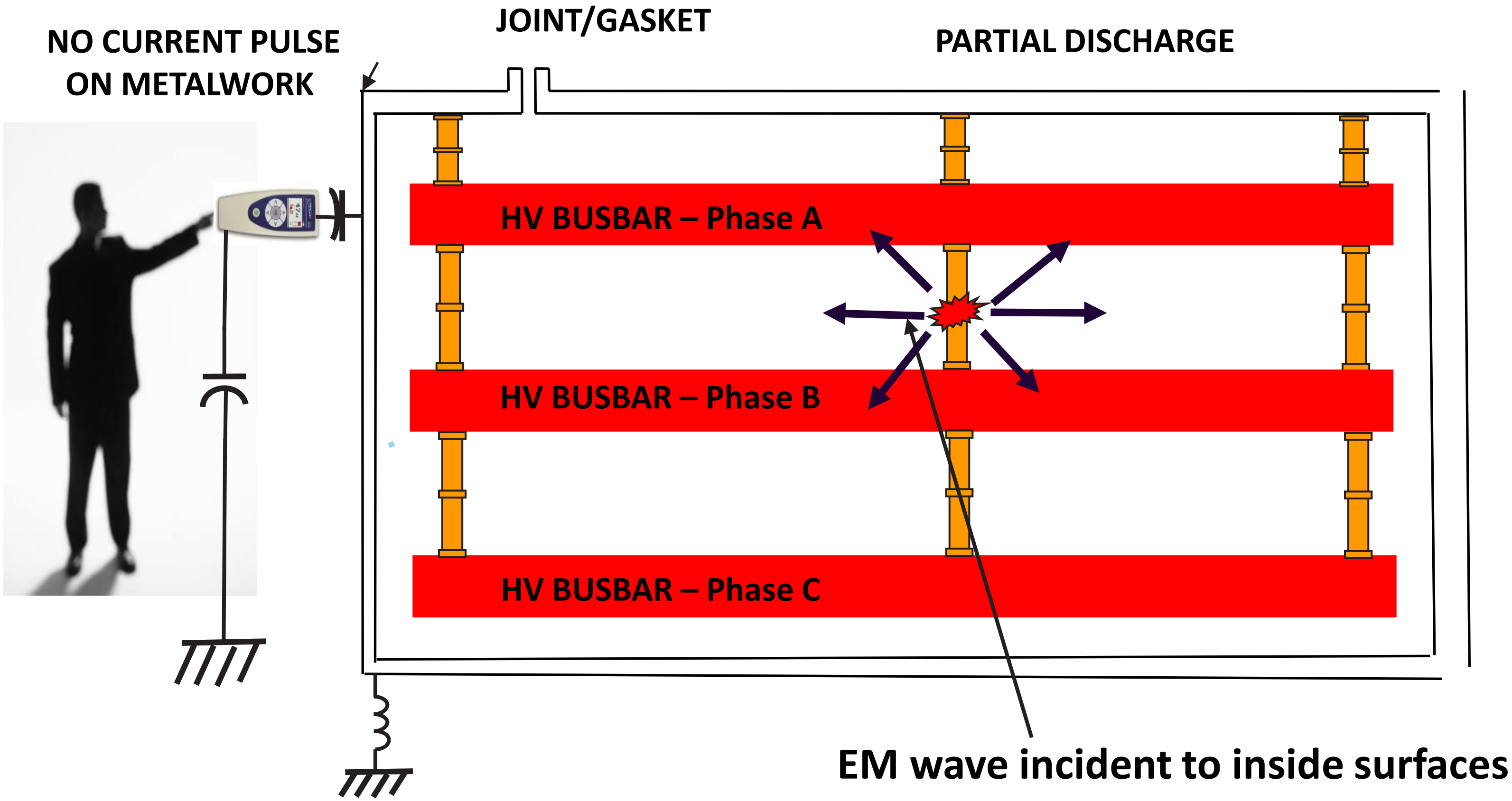


This effect is usually less than the current pulse unless the PD is phase to phase!

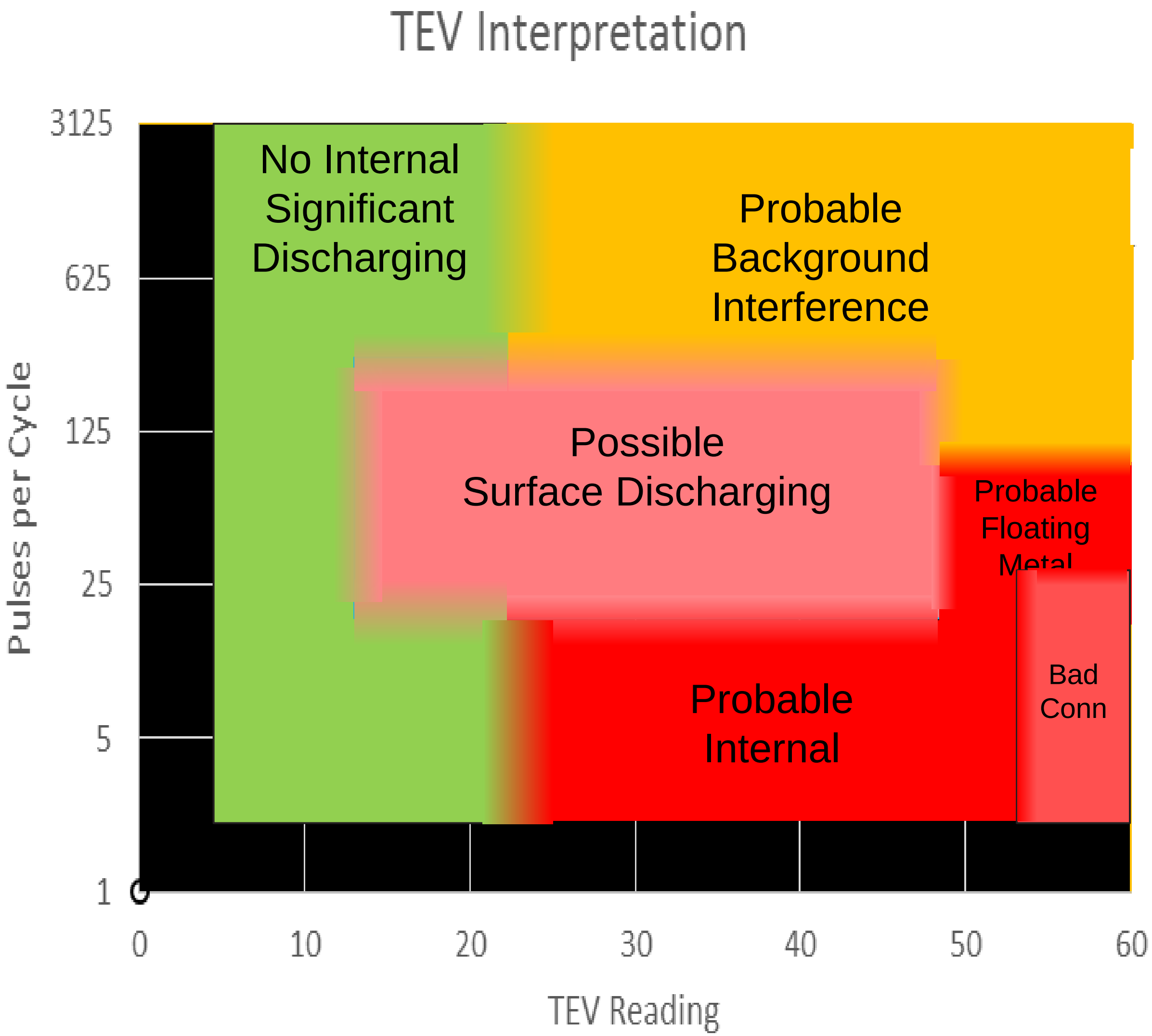
Phase to Phase Partial Discharge (Current pulse – NO TEV)



Phase to Phase Partial Discharge (Current pulse – NO TEV)



Partial Discharge TEV Interpretation

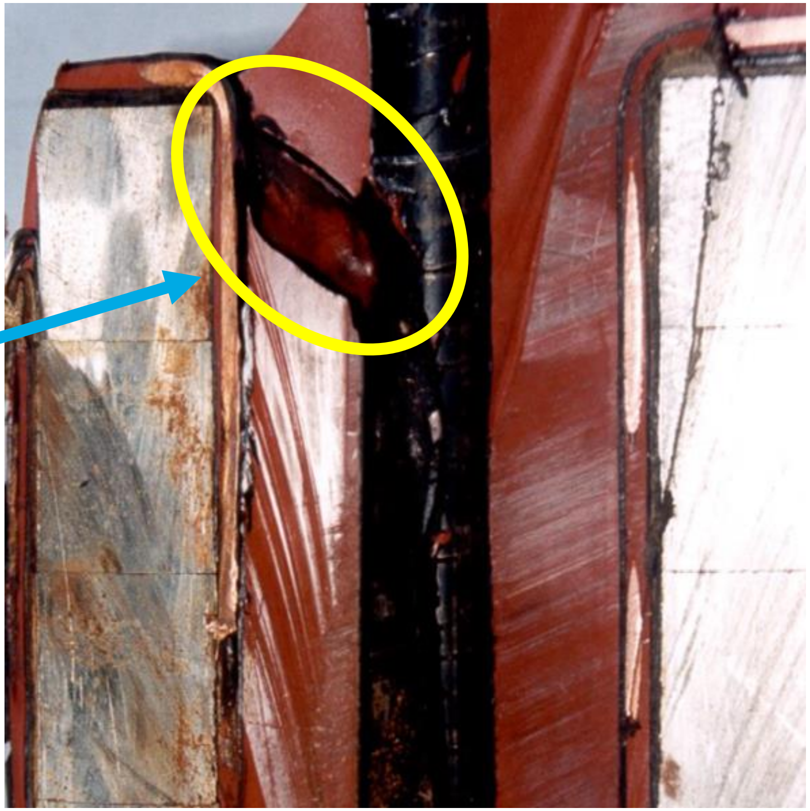


TEV Detection

- Technician takes a minute or two at each cubicle
- Places TEV probe firmly against panel
- Watches display for patterns

PD in resin core CT

Channel cut
through resin
by discharge



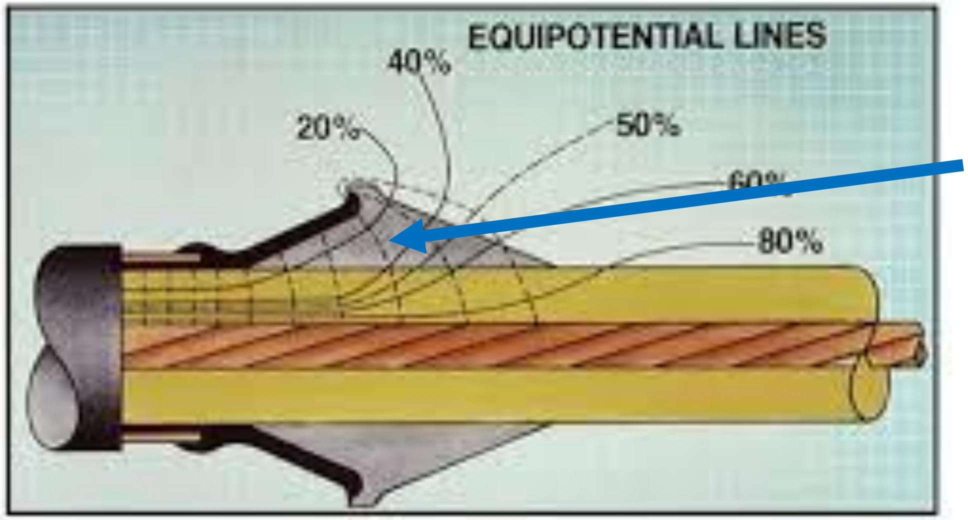
Cause – Manufacturing Defect
(Void in resin)

Surface Discharge and Internal Discharge Differences

Internal PD	External PD
Not affected by Humidity	Affected by Humidity
0.5-6 Pulses per Cycle	6-30 Pulses per Cycle
Rarely Audible	Often Audible
Detected best by TEV	Detected best by Ultrasonic
Hold UltraTEV against Ground or Metalwork	Hold UltraTEV at airgaps of enclosures or point UltraDish at Elbows, T's, or splices.

Cable Partial Discharge

Cable Partial Discharge



Cable partial discharge is a classic example of local concentration of electrical stress.

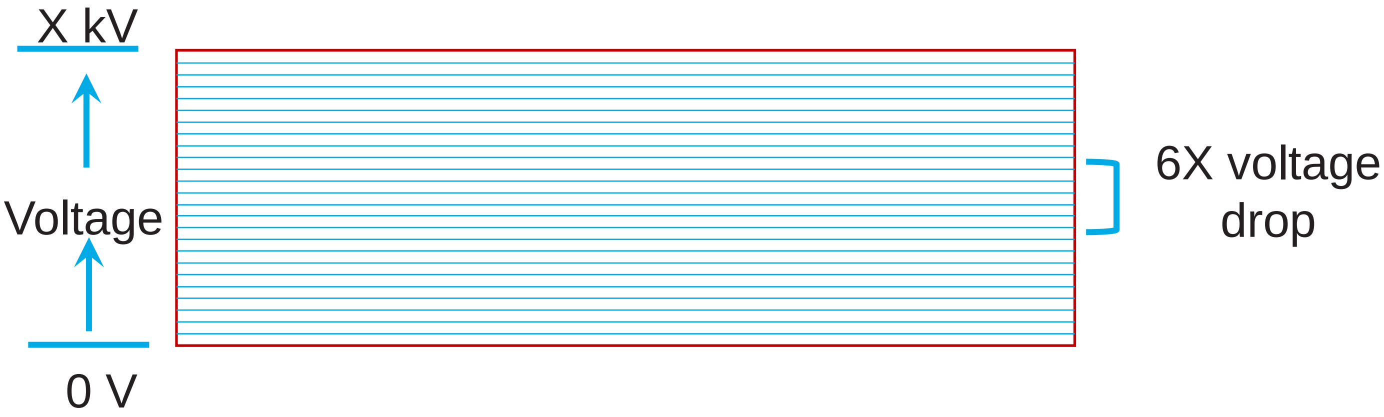
Cable terminations and splices have carefully designed components to distribute the electrical stresses equally.

These components include semiconducting layers and stress cones.

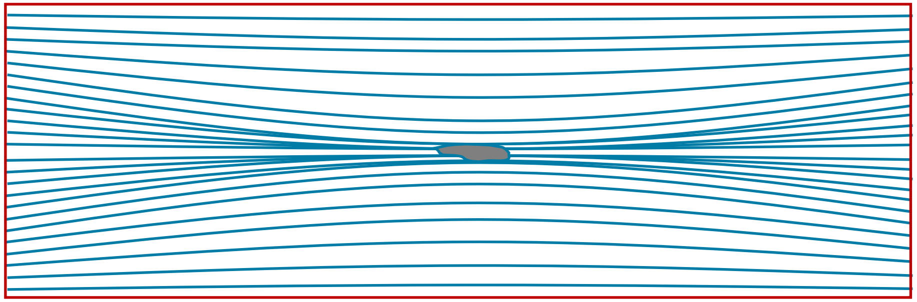
When these cones are not correct discharge occurs.

Discharge can also occur where insulation is defective (holes, voids, damage) in mid-cable.

Equipotential Lines



Section through a homogenous insulator showing uniform electrical stress (equipotential) lines. A line indicates where the voltage potential is constant



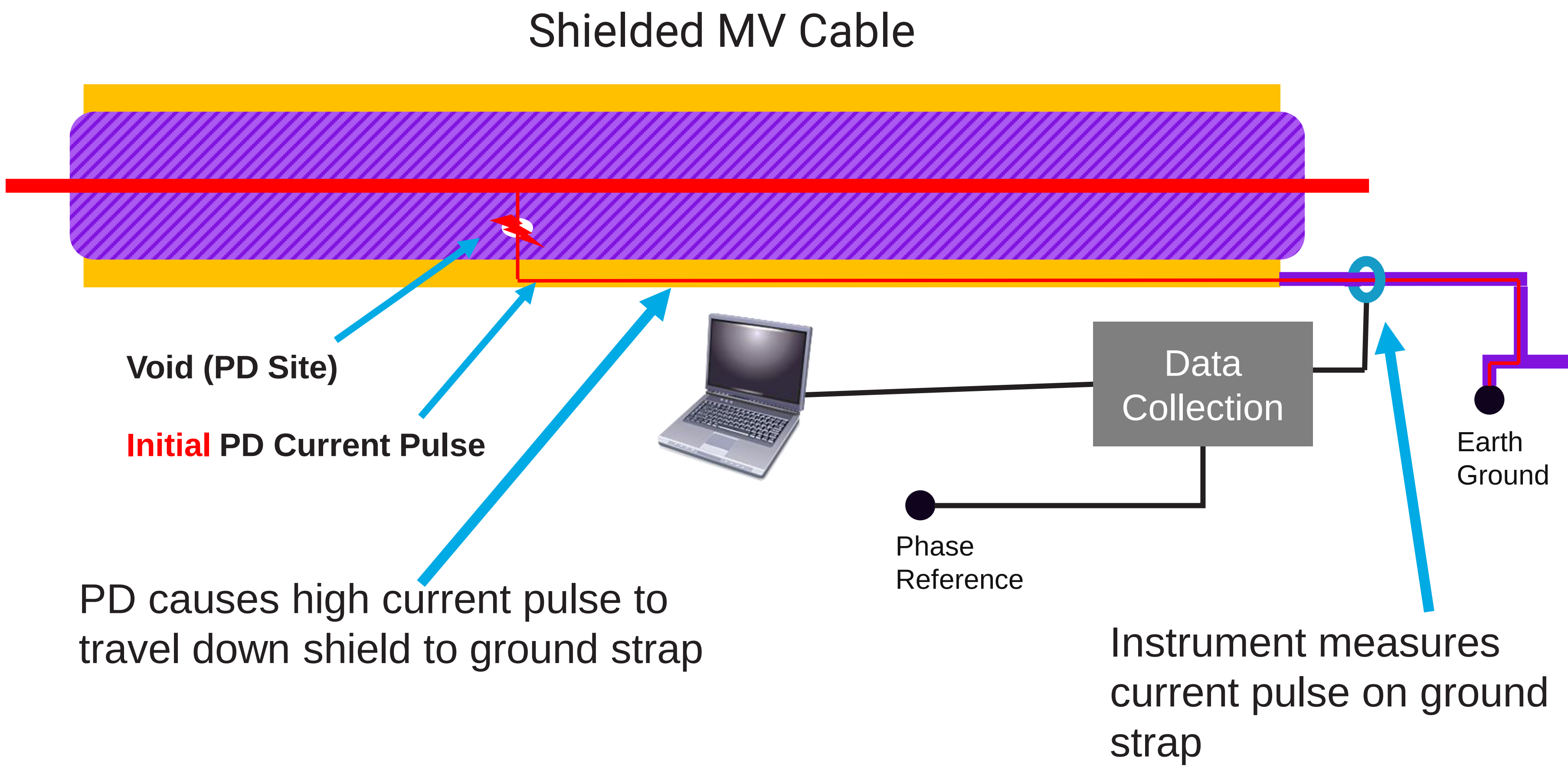
The same insulator with a void. The lower dielectric of the void causes a concentration of the electrical field through the void high enough to cause breakdown at working voltages

Cable PD Detection

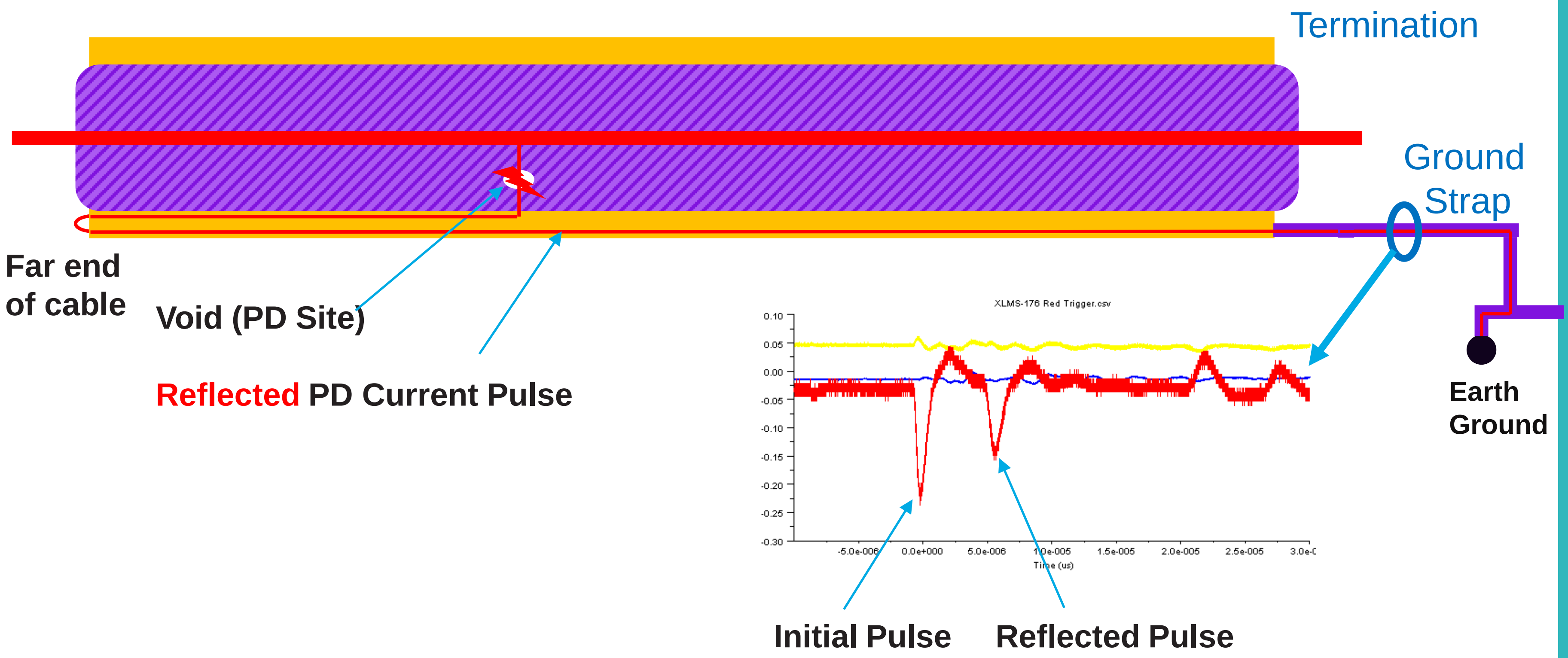
- RFCT placed on ground straps of cables
- Test may do 1 or 3 phases at once
- Test may run automatically or require operator involvement
- Different filters and triggers are applied
- Typically less than 10 minutes to get results

Safety First

RFCT based testing of cables



Cable Partial Discharge



Current through ground strap results from PD down cable.
Entire length of cable can be tested from one end

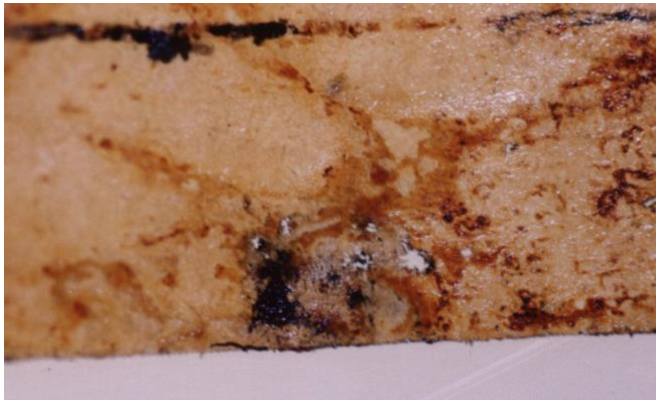
Evaluation Scale

Comments	**Color Code**	**XLPE Cable**	**XLPE Accessories**	**PILC Cable**	**PILC Accessories**
Discharge within “acceptable” limits.		0-250pC	0-500pC	0-2500pC	0-4000pC
Some concern, more frequent monitoring recommended.		250-500pC	500-2500pC	2500-7000pC	4000-10000pC
Major concern, locate PD activity and repair or replace.		>500pC	>2500pC	>7000pC	>10000pC

Cable Partial Discharge Examples

Treeing

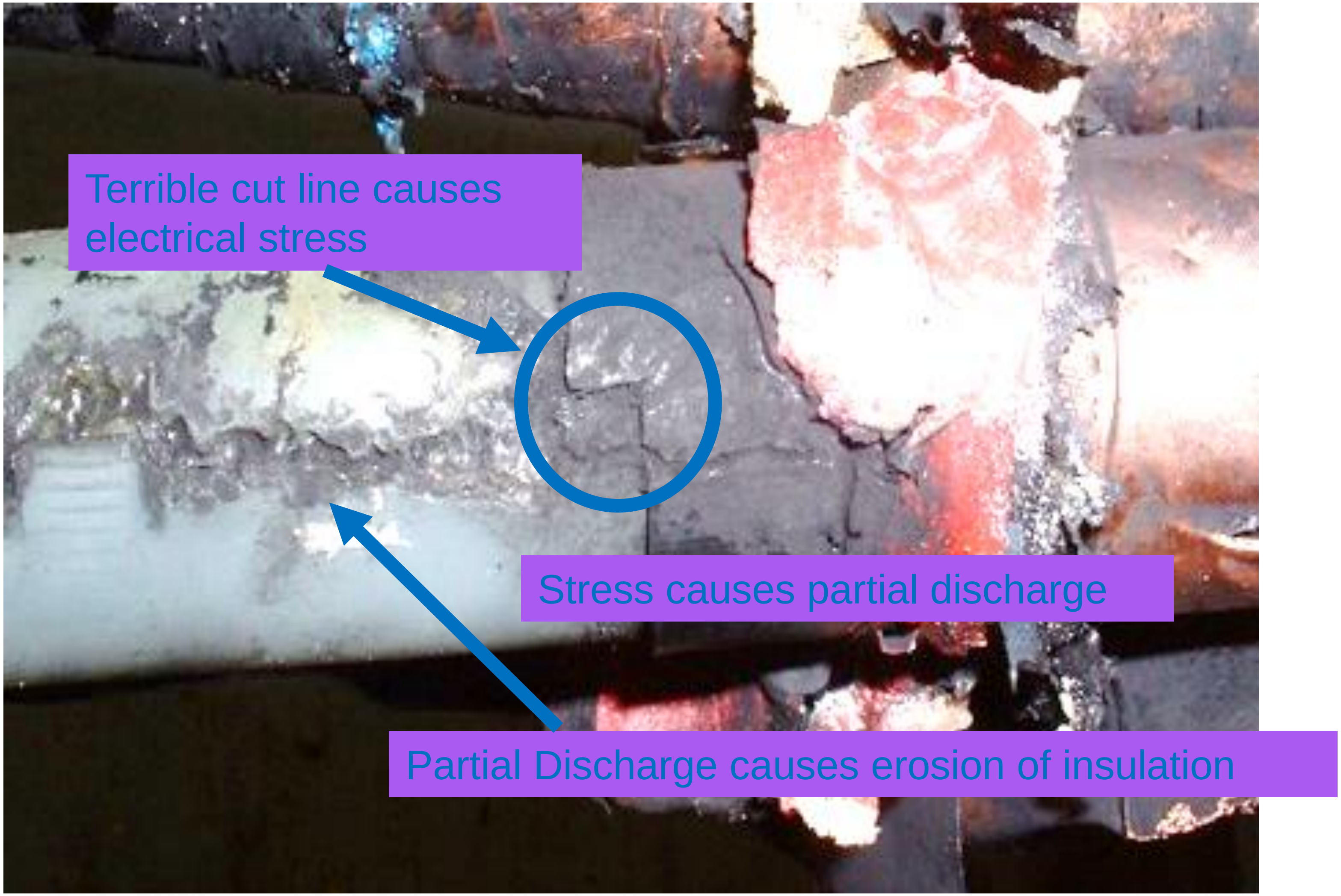
Voids / Carbonisation



Damage from flashover to screen

Erosion from PD

Cable Partial Discharge



Direct connected online systems

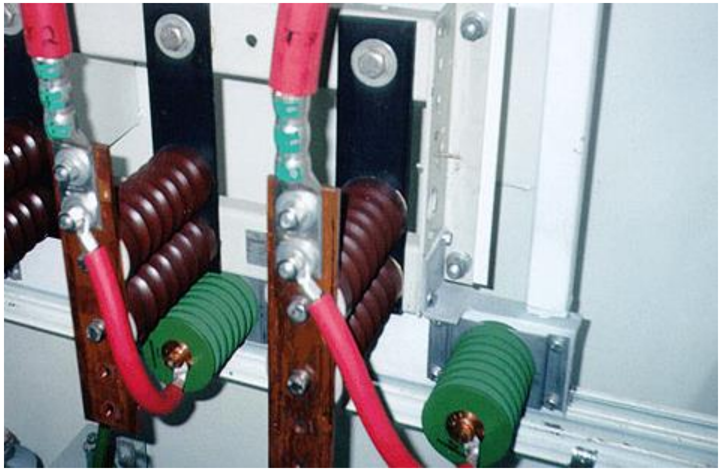
On-Line systems

Direct connected online systems use permanently installed HV capacitors and current transformers to measure PD directly.

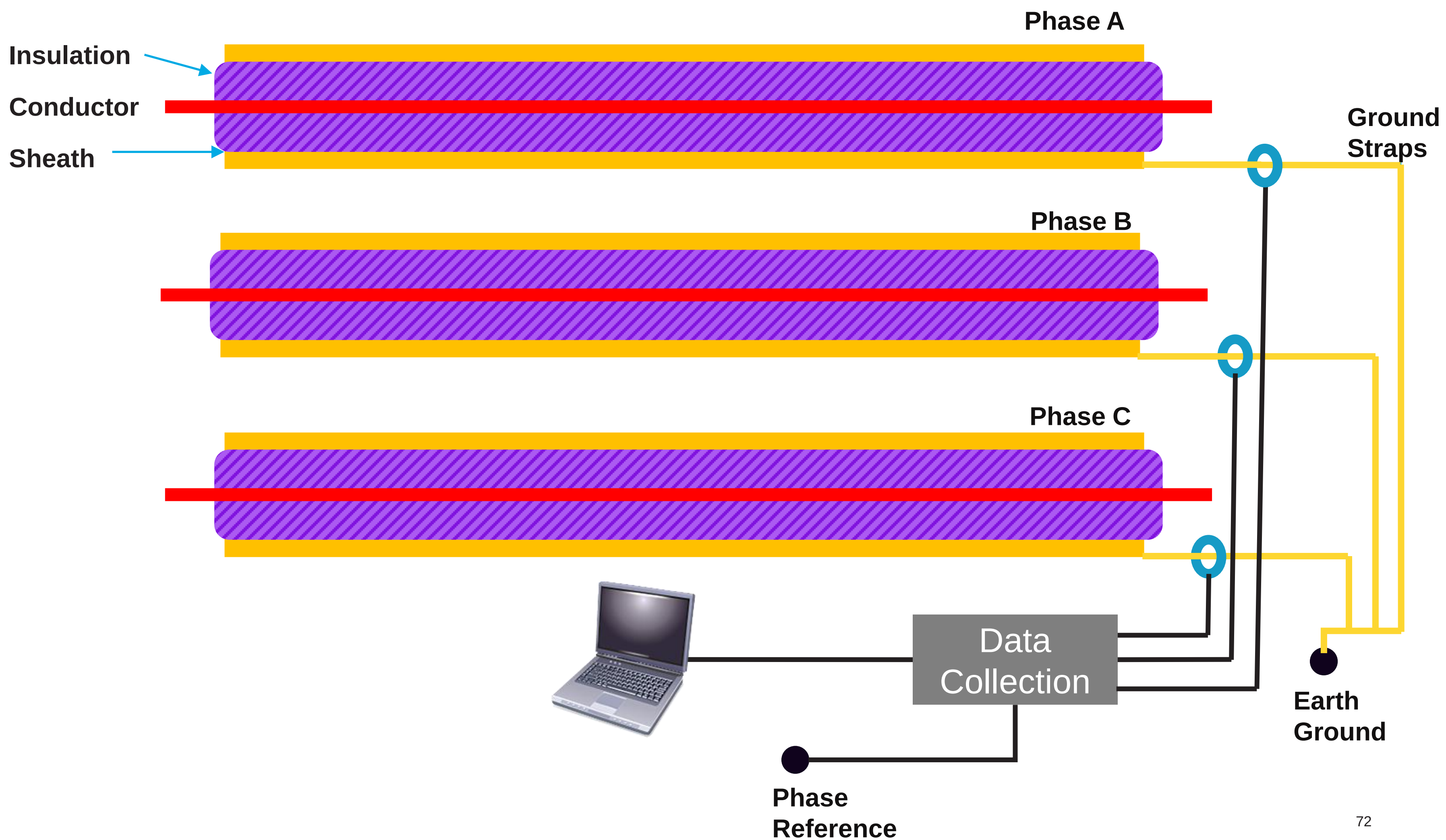
- Periodic or 24x7 monitoring with alarming
- Typically include remote communications
- Can include humidity and load monitoring
- Can be used for Rotating machines, Metal clad switchgear, MV/HV Cables, and Transformers

Direct connected monitoring systems

PD Couplers



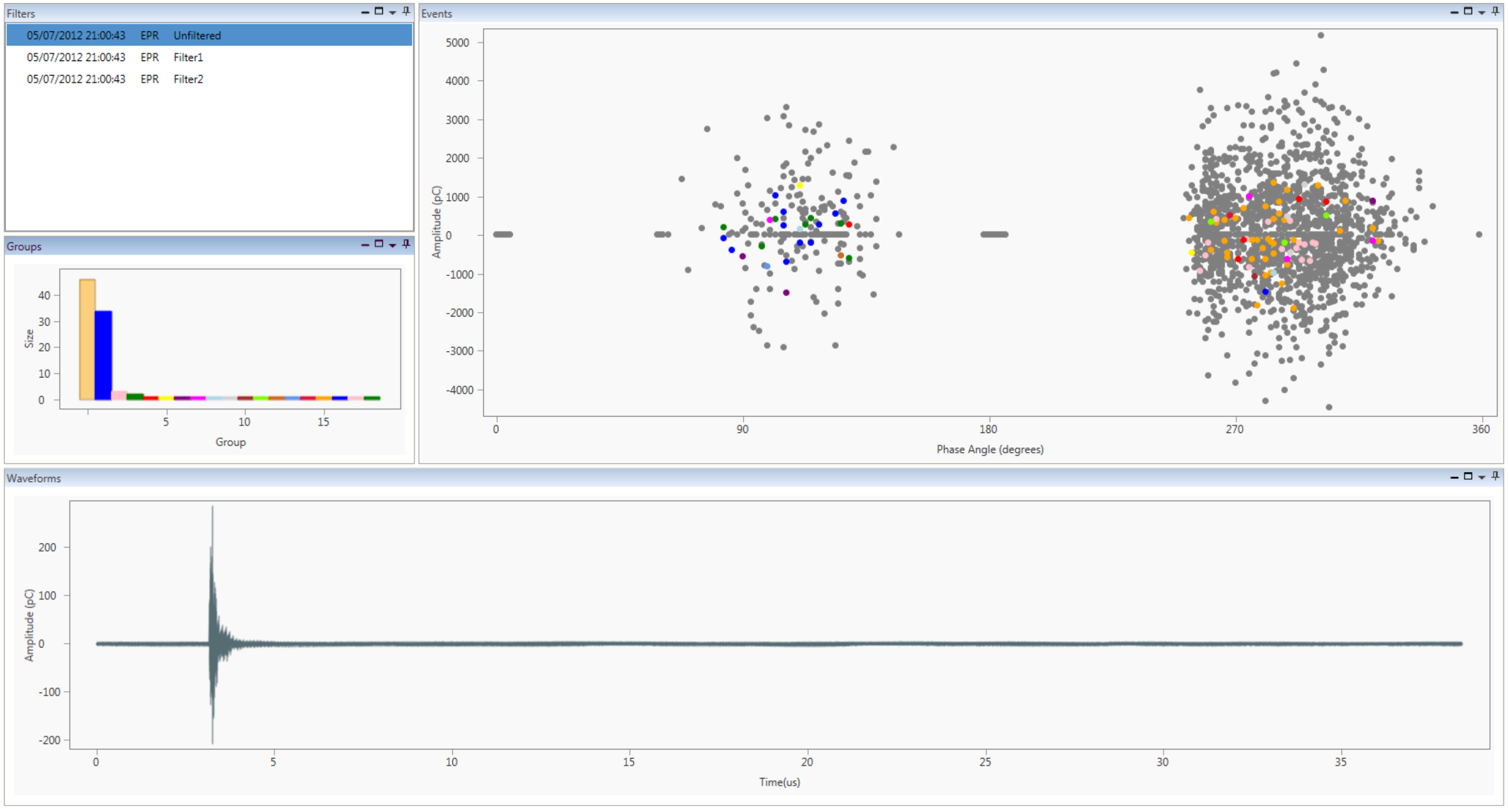
Practical application of spot testing



Data Analysis – VLF, Ultrasonic, TEV, Cable

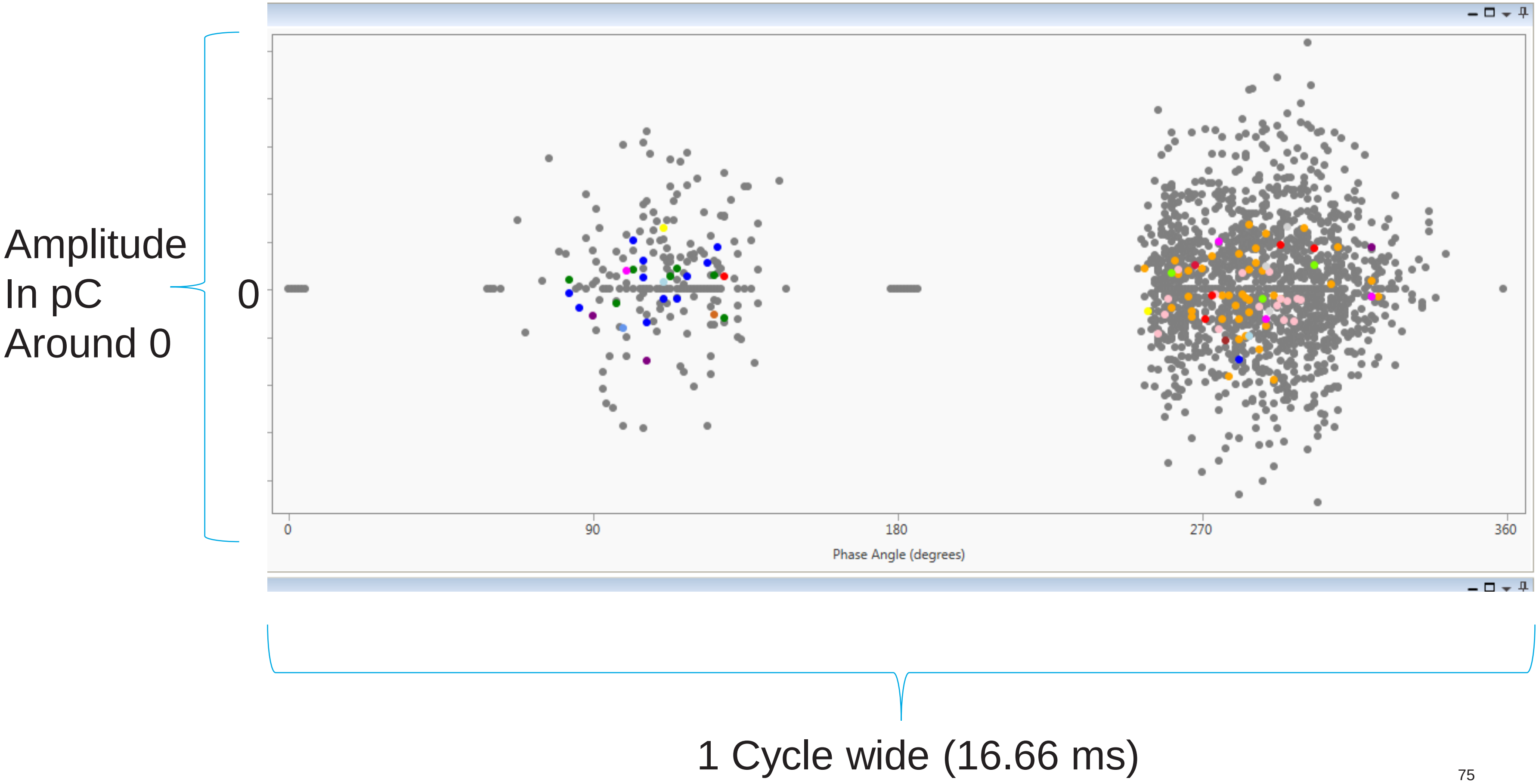
Analyzing Data – Two crucial pieces of data

Picking Milliamps of PD out of Kiloamps of current is not trivial.
Two key pieces of information are vital

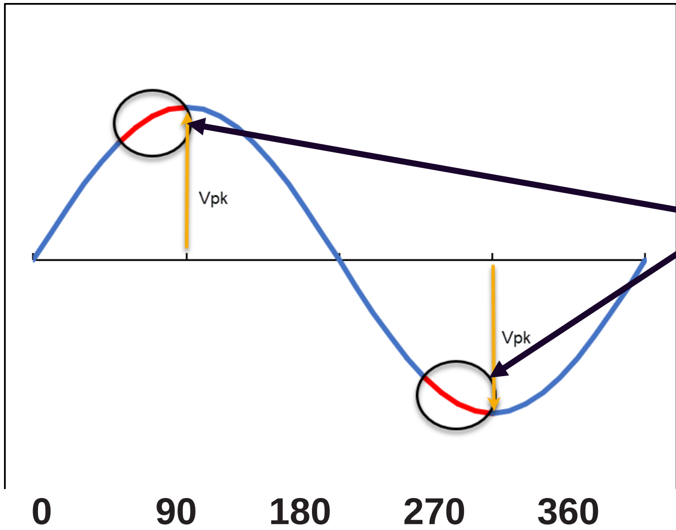


Analyzing Data – Phase Resolved Plots

One sign of recognizable PD Activity is clustering of points on the phase resolve plot at a distance of 180º apart



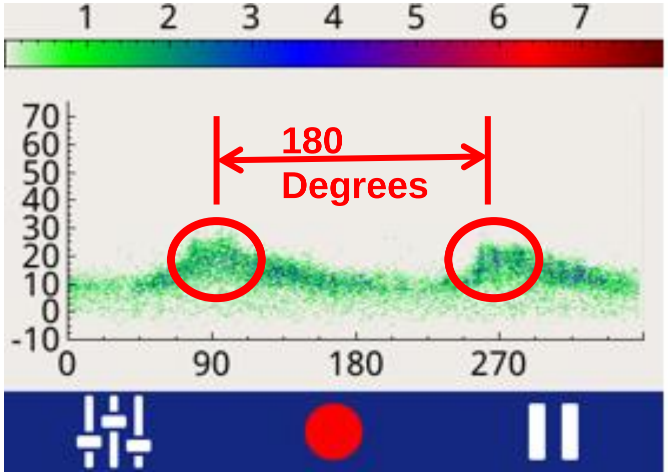
Phase Resolved Plots



Partial Discharge tends to occur on the rising edge of the voltage sine wave. As such, PD impulses tend to be synchronized to the AC waveform and 180 degrees apart.

Phase Resolved plots show PD impulses on a power system cycle so groupings 180 degrees apart can be seen.

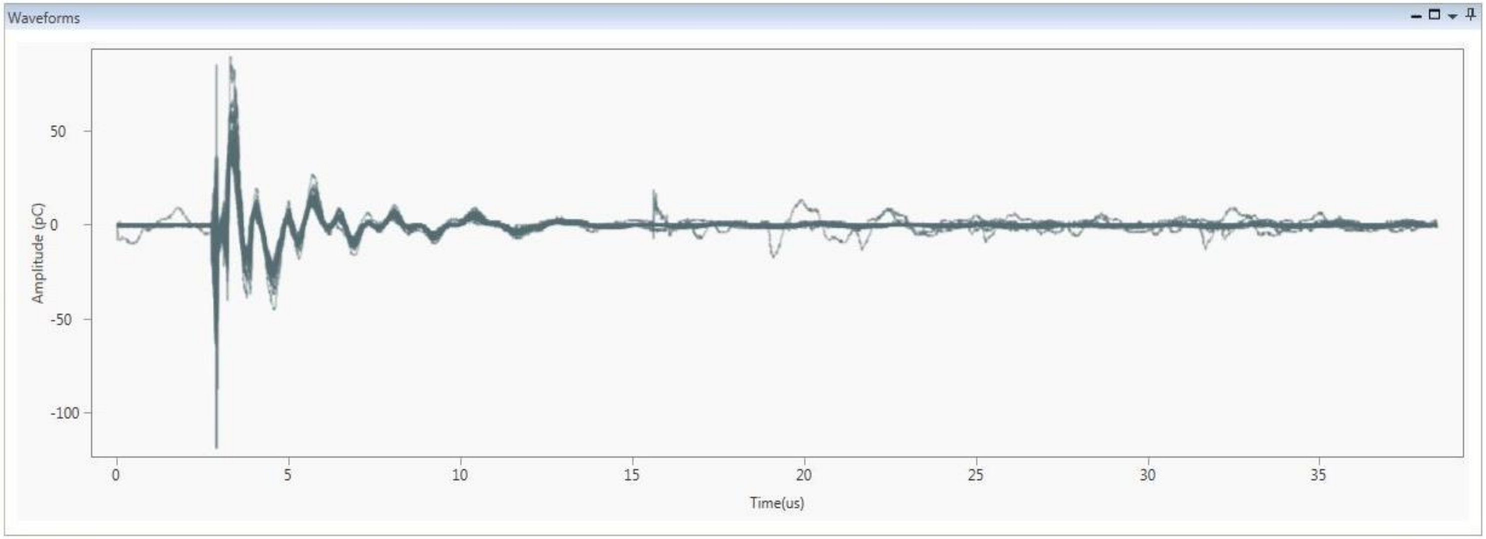
<u>Phase resolved plots are available for TEV, Ultrasonic, and Cable PD modes</u>



Analyzing Data – Waveforms

A typical waveform from online Cable PD testing should have a large unipolar pulse indicating the discharge

Amplitude
In mA
Around 0



Very fast time base (40 uS)

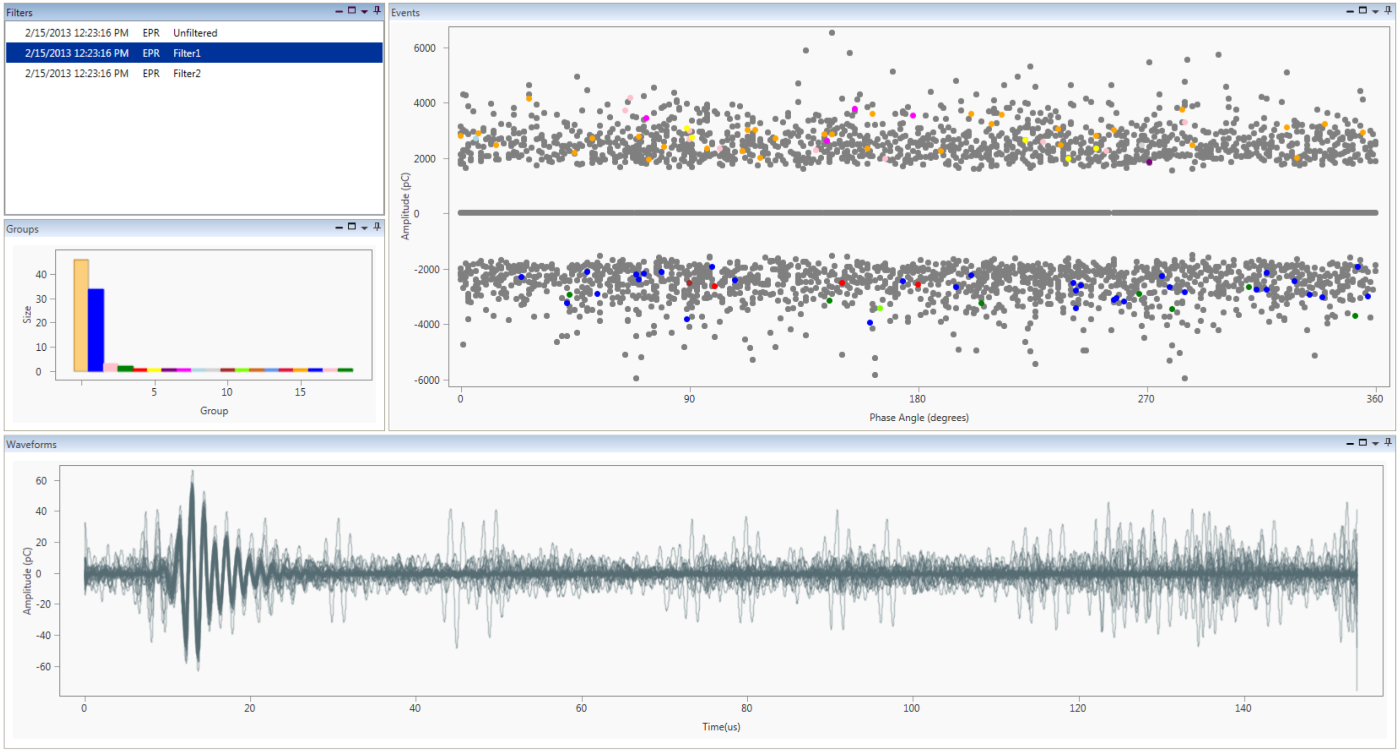
Activity – Actual PD Phase Plot

Non-PD Patterns – Random Noise

Background Noise

- Below is an example of background interference, which is characterized by random activity along the Phase Resolve plot.

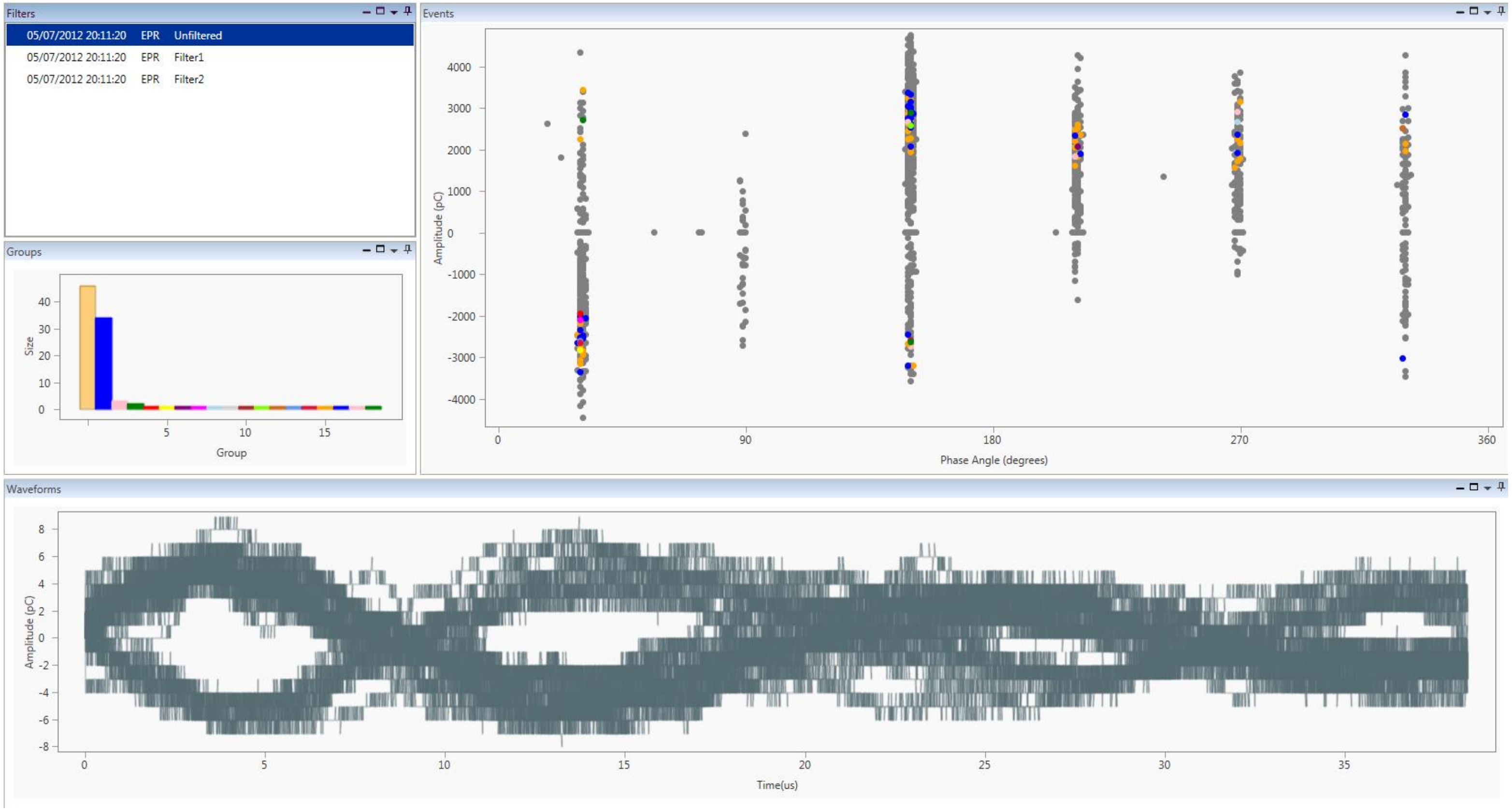
- Background interference may be caused by a number of sources including radio masts and DC light fittings.



Non-PD Patterns – VFD Noise

Machine Noise

- Data captured on circuits which have rotating machines operating on them will contain some machine noise
- Machine noise is characterized by vertical lines spread across the phase resolved plot



Partial Discharge – Examples

PD in unshielded cables

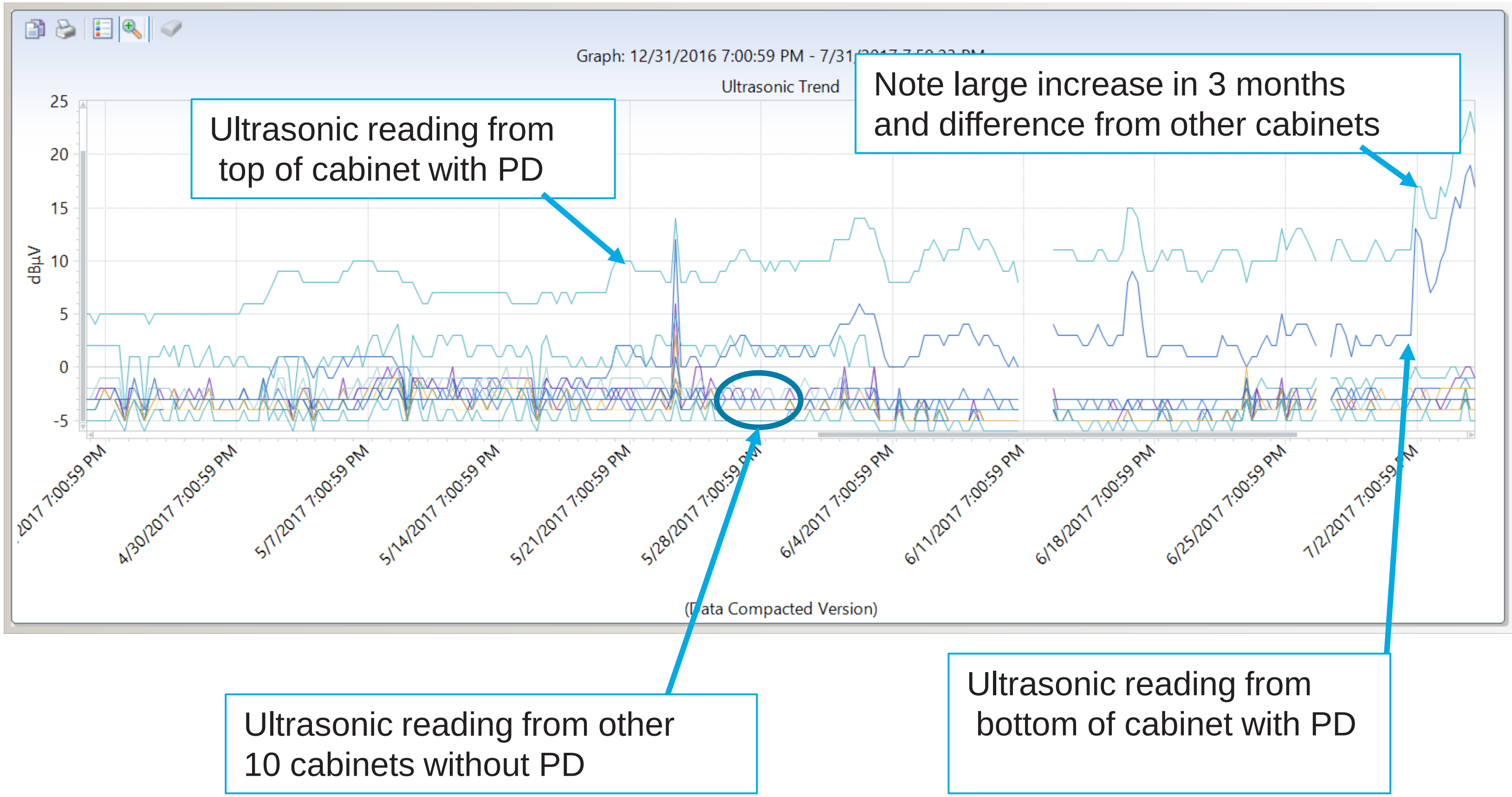
A very large office building had full time partial discharge monitoring installed due to the critical nature of its operations. The monitor had ultrasonic sensing into each compartment from outside as shown below.

The monitor started recording ultrasonic energy when the humidity increased. This was monitored for several months before corrective action was taken. Every cable was damaged!

The cables to the 33VK PTs were unshielded. They were installed in a way that passed Highpot testing. However, electrical field stress was ignored

Ultrasonic Trend line

Ultrasonic Trends over Time



PD in unshielded cables

Cause – Lack of stress control due to poor installation

Termination – Poor workmanship

The same office building had numerous 33KV terminations. The monitor started indicating TEV in one compartment. After several months, Ultrasonic became apparent as well

The yellow phase termination suffered poor workmanship. It started as internal discharge (TEV) but progressed to surface discharge as the termination was eaten away. The final picture shows the fixed assembly

PD in Shielded Cable Terminations

Cause – Lack of stress control due to installation errors

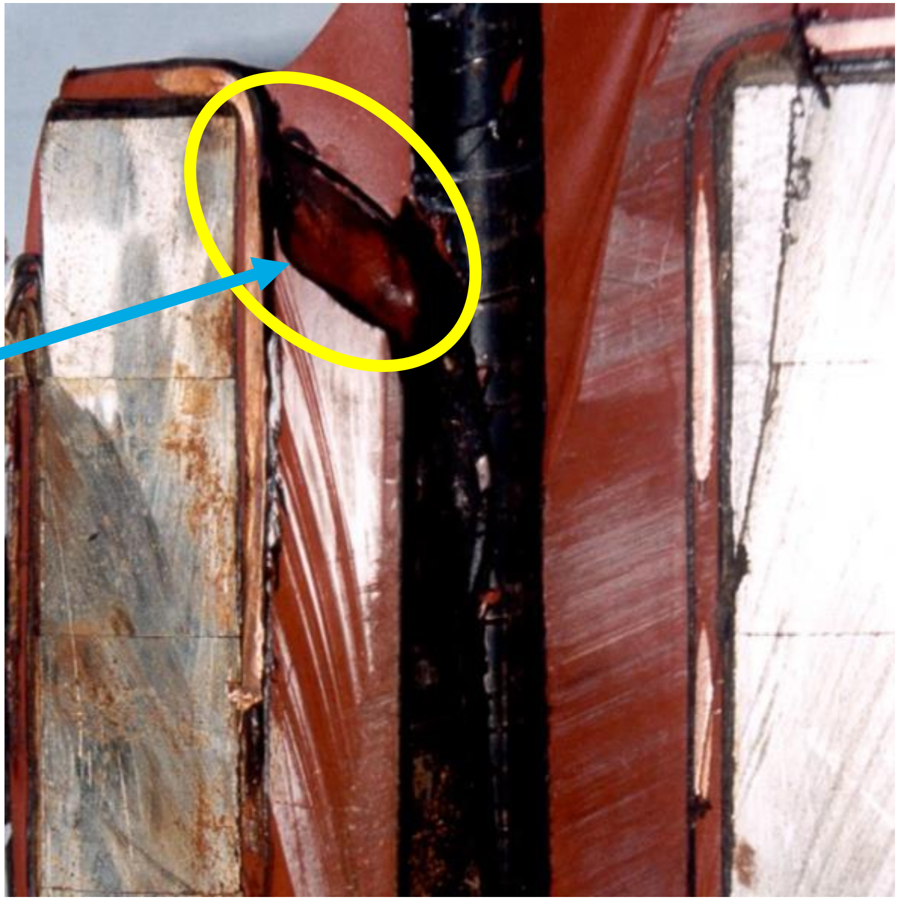
Surface Discharge Activity Detected by Ultrasonics

PD in Switchgear

Cause – Environment (Salt & Humidity)

PD in resin core CT

Channel cut
through resin
by discharge



Cause – Manufacturing Defect
(Void in resin)

Surface Discharge Activity Detected by Ultrasonics

Cable failures – Case Studies

Cable failure example 1

Cable Type – PILC / XLPE

Voltage – 11 KV

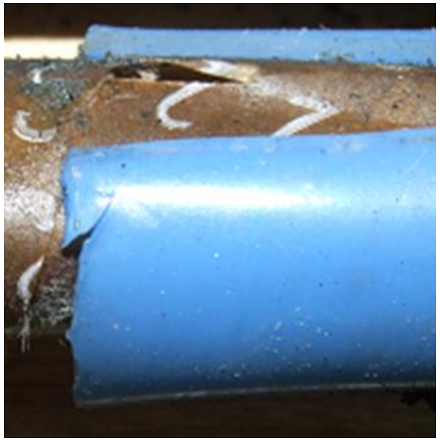
Age – 1 Hour

Failure Location – PICAS to XLPE Branch Adapter

Cable failure example 1

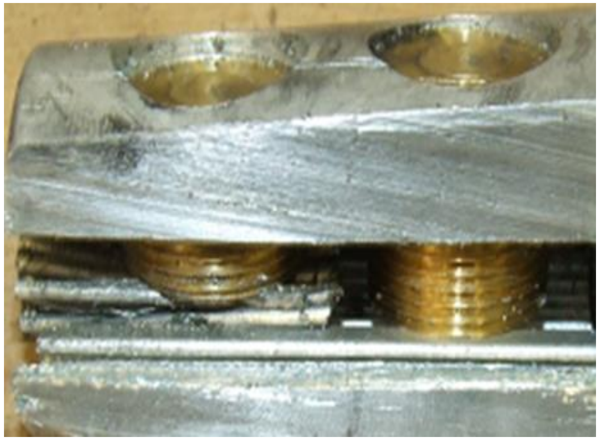
Proximate Cause – Incorrect positioning of adapter tubes
Ultimate Cause – **Workmanship**
Takeaways

- Horrific workmanship
- Numerous <u>future</u> failure points present

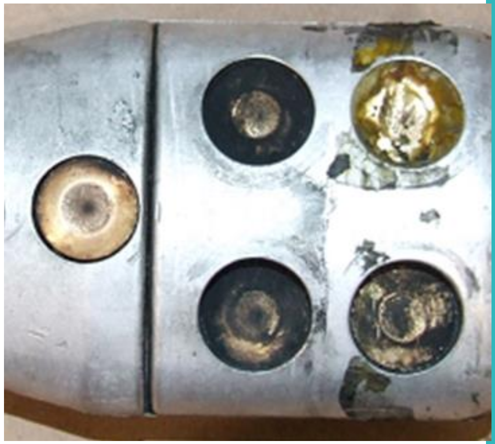


Poorly cut tube

30 mm gap in insulation



Only 1 shear bolt touching



No putty in shear bolts

Cable failure example 2

Cable Type – XLPE

Voltage – 33KV

Age – 18 months

Failure Location – Joint

Cable failure example 2

Proximate Cause – Not deburring connector

Ultimate Cause – **Workmanship**

Takeaways

- Poor understanding of instructions
- Lack of attention to detail
- Lack of training

Cable failure example 3

Cable Type – XLPE

Voltage – 11KV

Age – 28 years

Failure Location – Mid cable

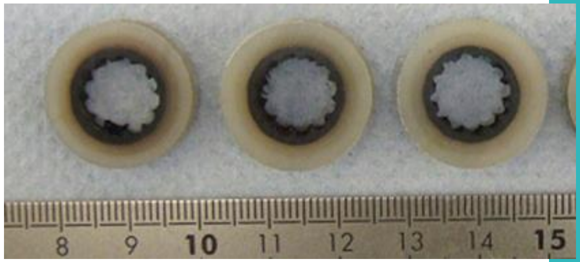
Cable failure example 3

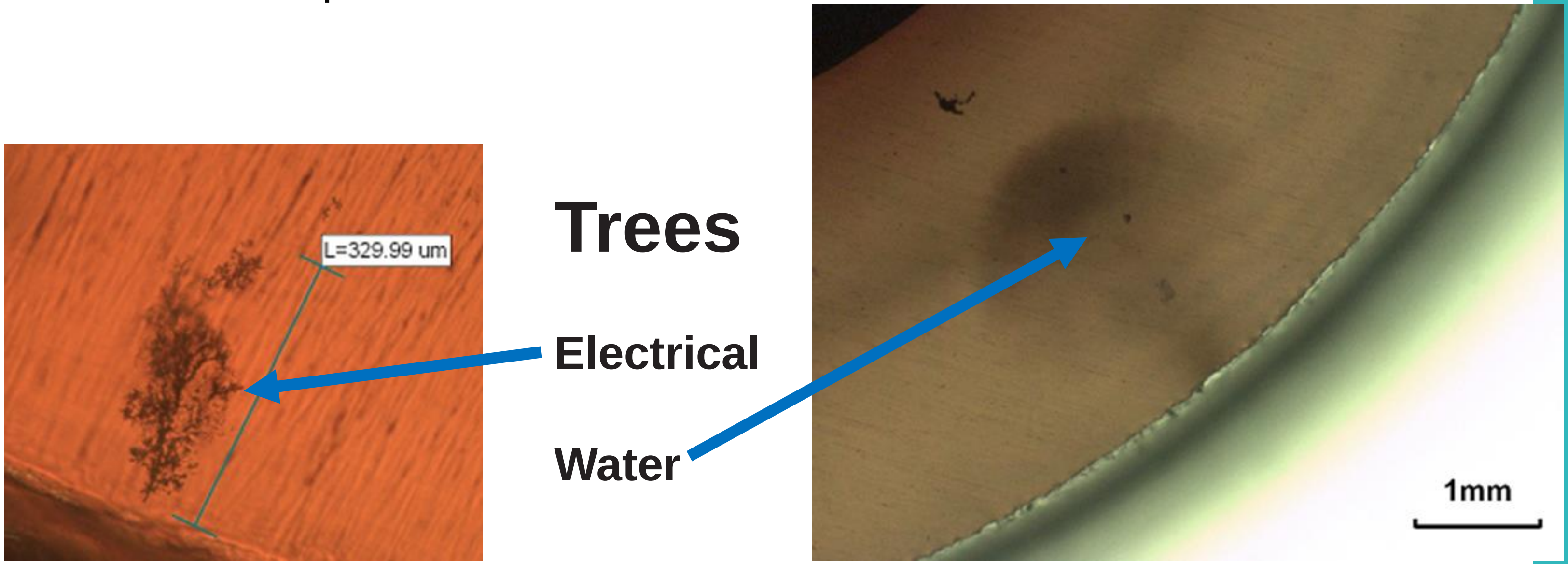
Proximate Cause – Moisture

Ultimate Cause – **Mechanical damage to sheath**

Takeaways

- Mechanical damage to otherwise good cable
- Replace waterlogged section
- Better installation practices





Cable failure example 4

Cable Type – PILC

Voltage – 11KV

Age – 47 Years

Failure Location – Mid cable

Cable failure example 4

Proximate Cause – Partial Discharge

Ultimate Cause – **Age**

Takeaways

- Not a bad lifespan
- Partial discharge testing would have prevented unplanned failure
- Replace Cable

Thank you

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