Diagnostic Measurements and Condition Assessment of High Voltage Bushings

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CEPED Conference on Electrical Power Equipment Diagnostics
September 2-4, 2015, Kuala Lumpur, Malaysia

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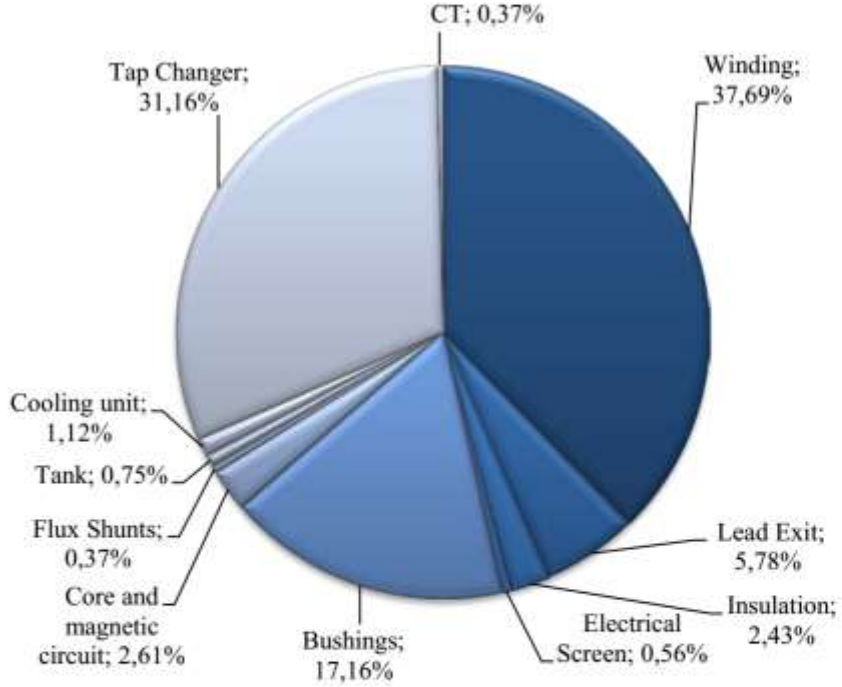
Cigre A2.37 Transformer Failure Statistics

22.000 grid transformers with 150.000 sercice years

Causes for transformer breakdowns



Bushings = 17,16 %

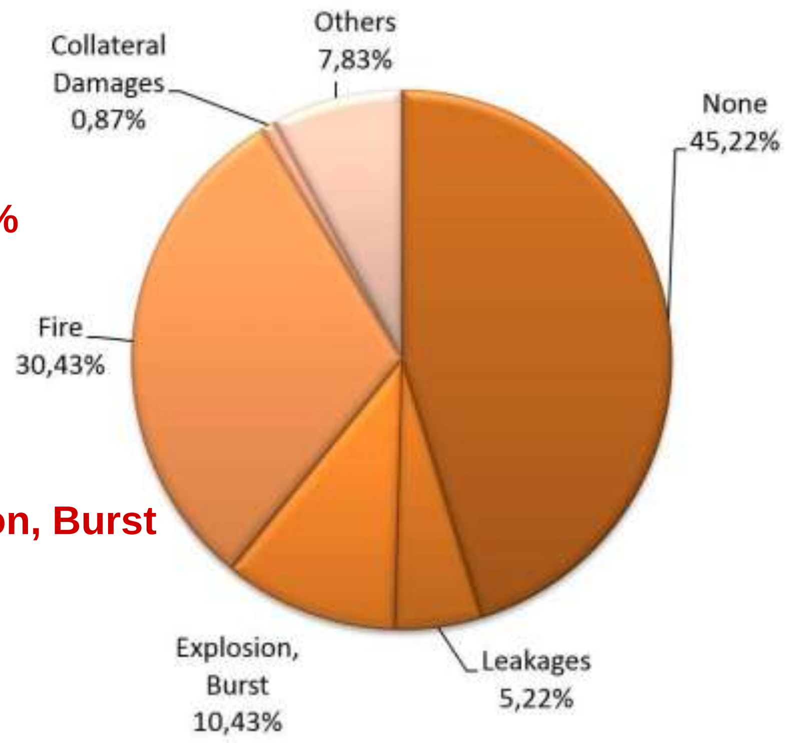
Tenbohlen et. al.: „ DEVELOPMENT AND RESULTS OF A WORLDWIDE TRANSFORMER RELIABILITY SURVEY" CIGRE SC A2 COLLOQUIUM 2015, Shanghai

Cigre A2.37 Transformer Failure Statistics

External effects of bushing failures

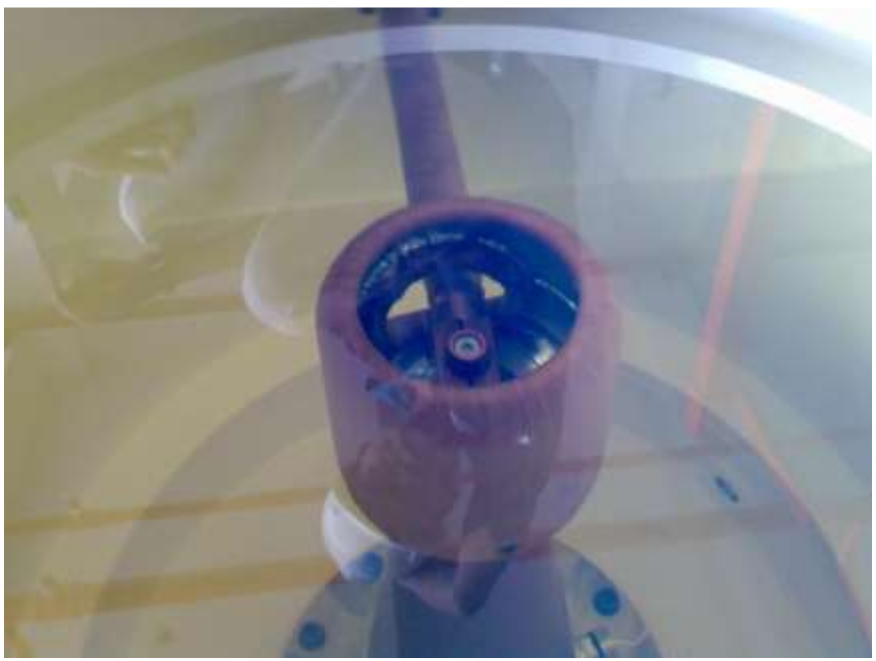
Fire 30%

Explosion, Burst 10%



Tenbohlen et. al.: „ DEVELOPMENT AND RESULTS OF A WORLDWIDE TRANSFORMER RELIABILITY SURVEY” CIGRE SC A2 COLLOQUIUM 2015, Shanghai

Transformer Oil-Oil Bushings



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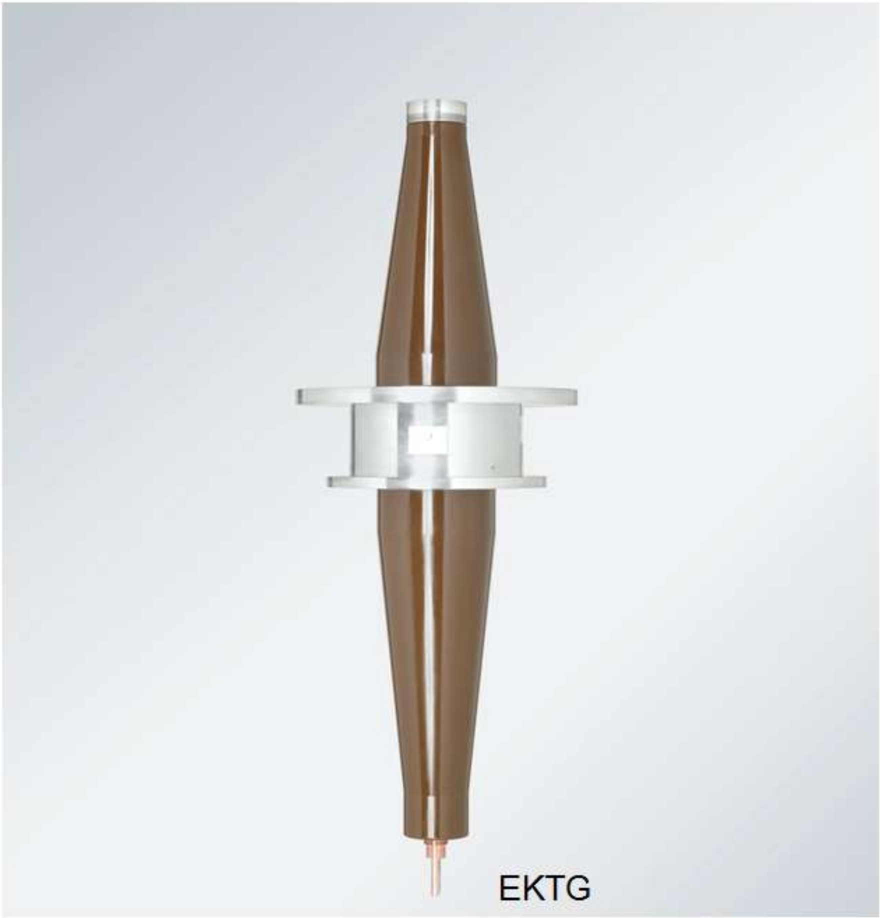
Transformer Oil-Gas Bushings



EKTG	
Application	Transformer Bushing (Oil–Gas)
Voltage Range	52 kV–1000 kV
Current Range	Up to 4000 A
Design	RIP condenser core

Source: HSP Germany

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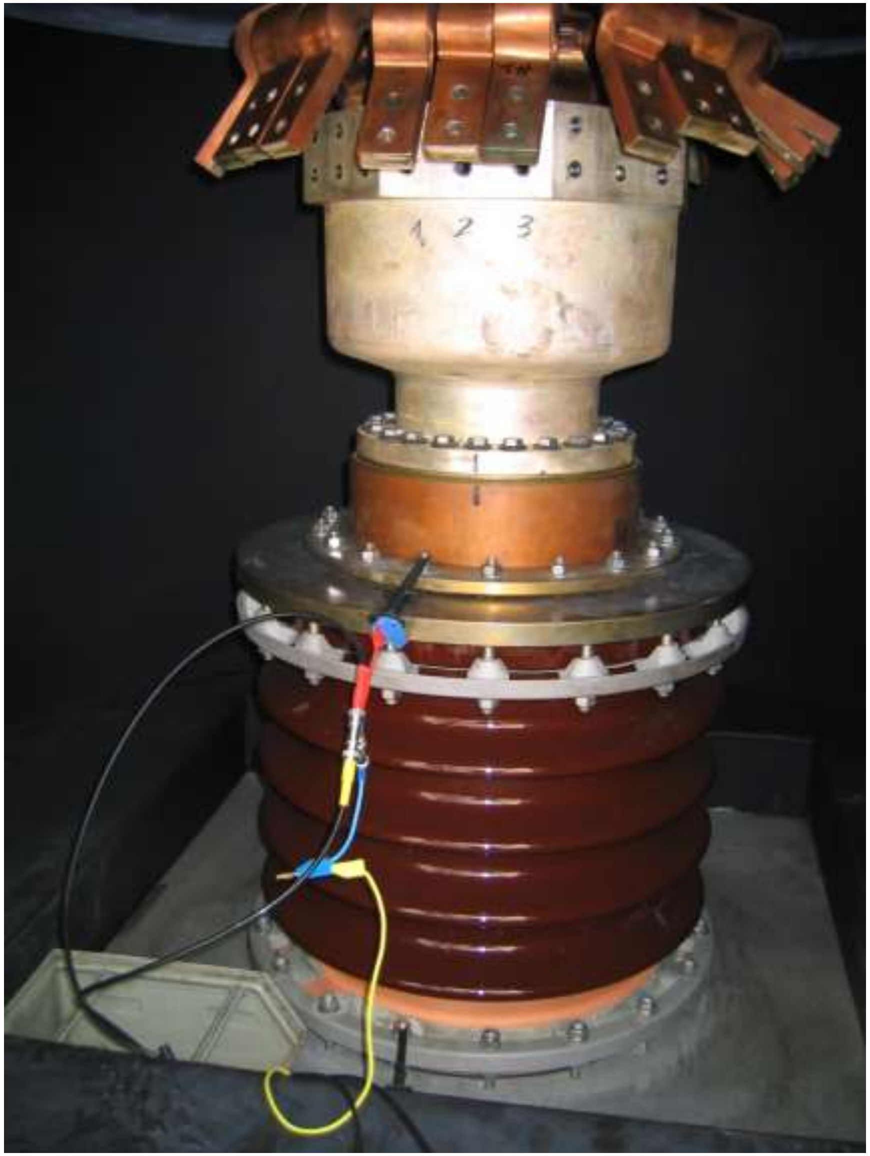
LV Bushings of GSU Transformers

Technical Data:

U_r = 36 kV

I_r = 17 kA



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Outdoor GIS-Air Bushings

400kV GIS Substation, Vorarlberger Illwerke, Buers Austria

Source: HSP Germany

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Wall Bushings

Wall Bushing, HSP Germany

Generator Bushings

EMH/EKMI	
Application	Generator Bushing (Air–Air)
Voltage Range	12 kV–36 kV
Current Range	Up to 36000 A
Design	RIP condenser core

Insulation Systems of High Voltage Bushings

Insulation Systems of High Voltage Bushings

1913 to 1974

since 1950

since 1960

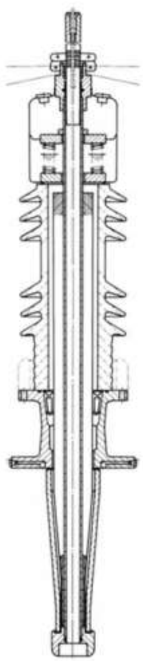
Recommended measures	Time schedule
Visual check – leakage and mechanical damage	In case of maintenance work
Measurement of capacitance and dielectric dissipation factor	- after installation as reference for later measurements (fingerprint) - 10 years after commissioning - dependend on results after each 5 years (uncritical values) or shorter

Source: B. Heil (HSP Troisdorf, Germany), „Diagnose und Bewertung von Durchführungen“, OMICRON AWT Germany 2010

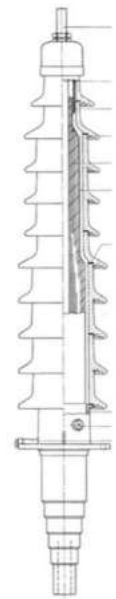
Share of Products

- **OIP (65-70%)** - Oil Impregnated Paper
- **RBP (gering)** - Resin Bonded Paper
- **RIP (30%-35%)** - Resin Impregnated Paper
- **Neu RIS (0%)** - Resin Impregnated Synthetics

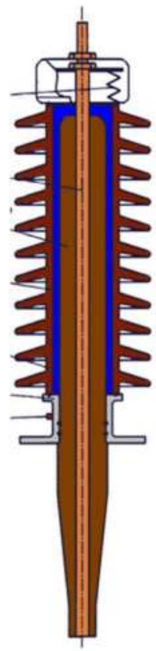
OIP



RBP



RIP



RIS

Source: MICAFIL

Resin Impregnated Synthetics (RIS)

- Craped paper is replaced by a open synthetic textile
- Textile can be impregnated with a filled resin with high viscosity (filler = Aluminiumoxide or Siliciumoxide)
- Filled resin systems are proven to be reliable for use in HV applications for several 10 years
- Improved thermal conductivity and mechanical strength
- No long drying period needed
- Reduced manufacturing time and costs
- **Available up to 170kV today**

Source: MICAFIL

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Resin Impregnated Synthetics (RIS)

Source: MICAFIL

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High Voltage AC Test in the Factory

Lower Part in a Oil Filled Vessel

Source: MICAFIL

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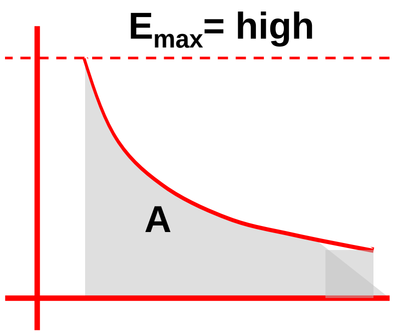
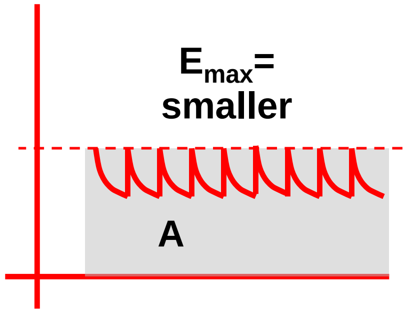
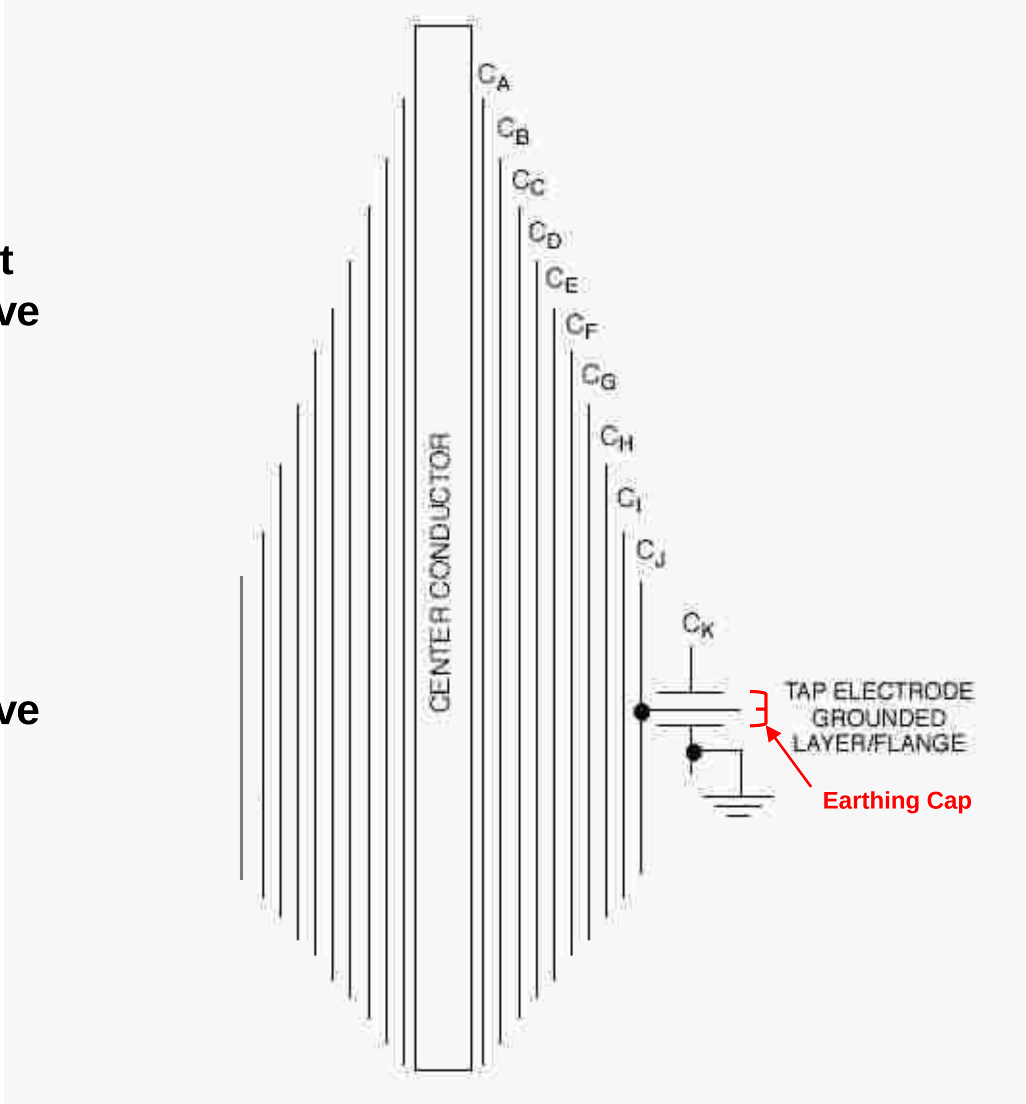
Capacitive Bushings (1)



without capacitive layers



with capacitive layers



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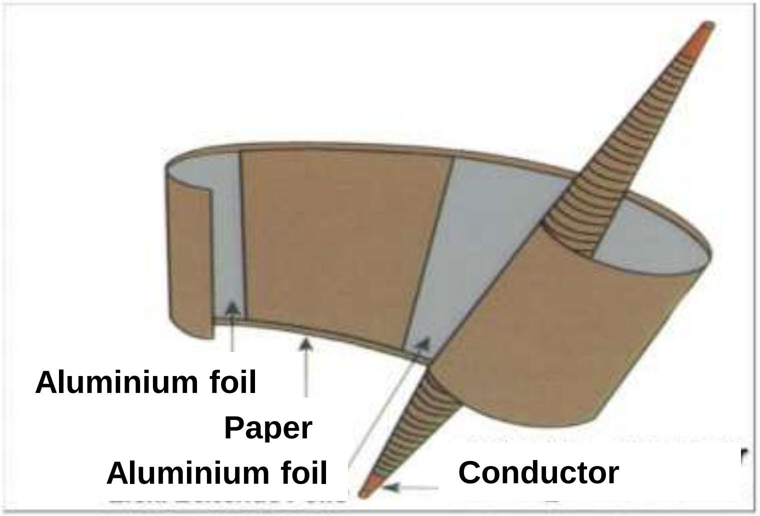
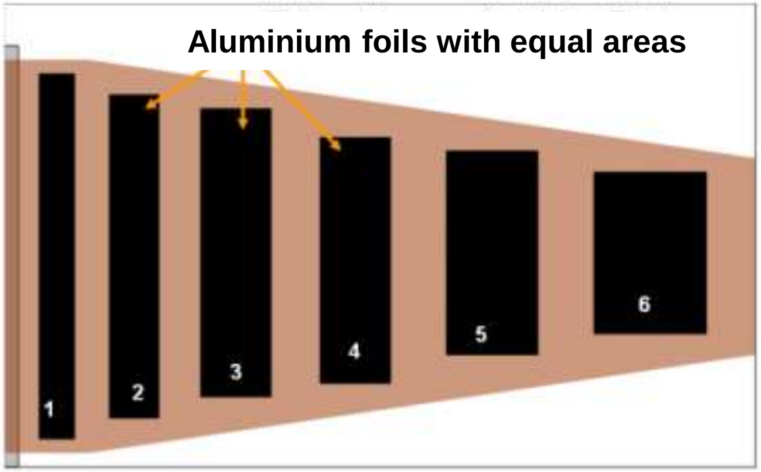
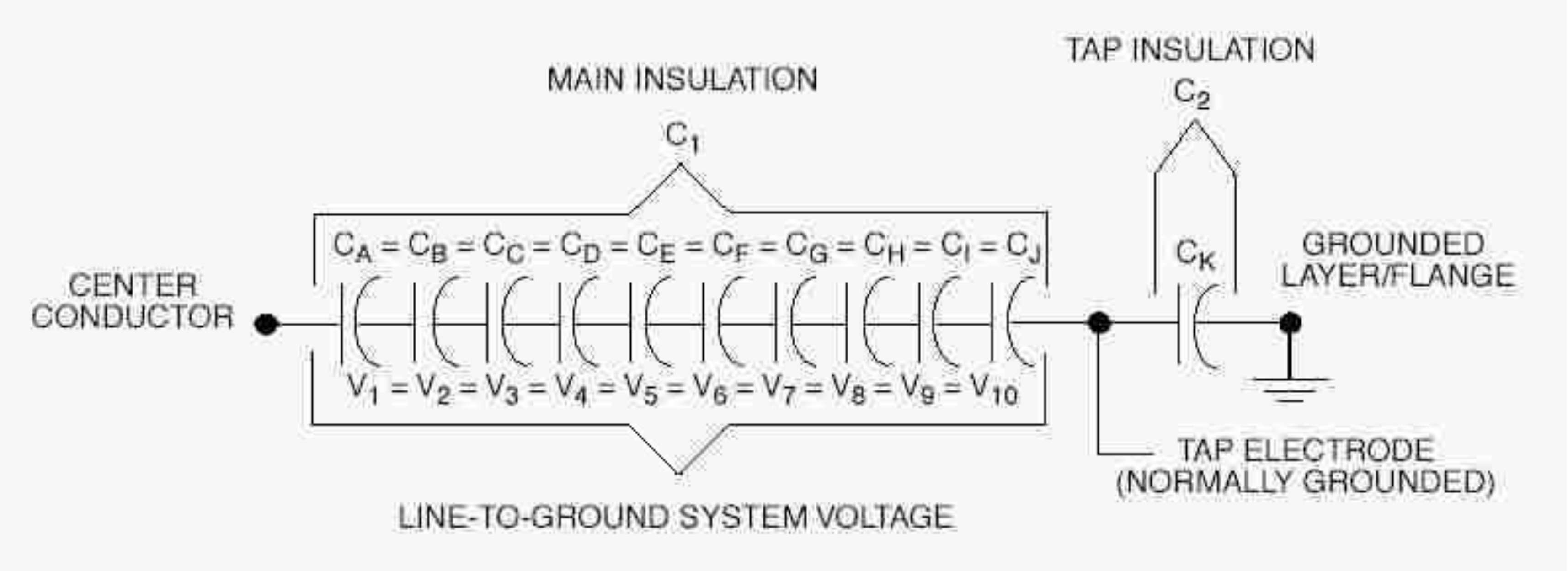
Capacitive Bushings (2)





Capacitive Bushings (3)



Current at the Measurement Tap

$$50Hz \rightarrow I_C = U\,\omega\,C \quad = 10 \,\ldots 100mA$$

$$BIL\ 1.2\mu s \rightarrow I_C = C\,dU/dt = 200A$$

Capacitive Bushing of a 123kV CT

Measuring and Voltage Tap

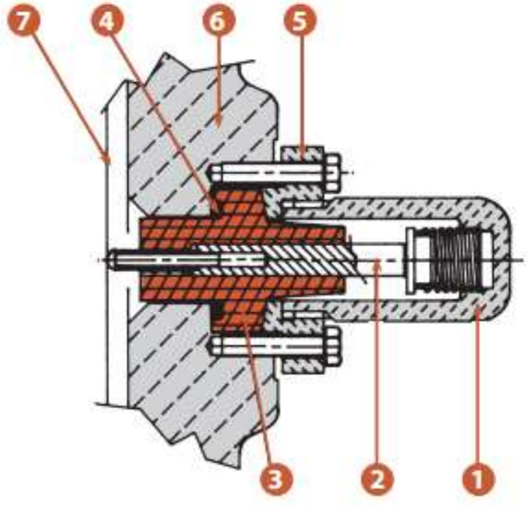


Fig. 4: Power Factor Tap

1 - Closing and grounding cap
2 - Measurement electrode
3 - Insulation tap
4 - Gasket
5 - Tap flange
6 - Bushing flange
7 - Last layer

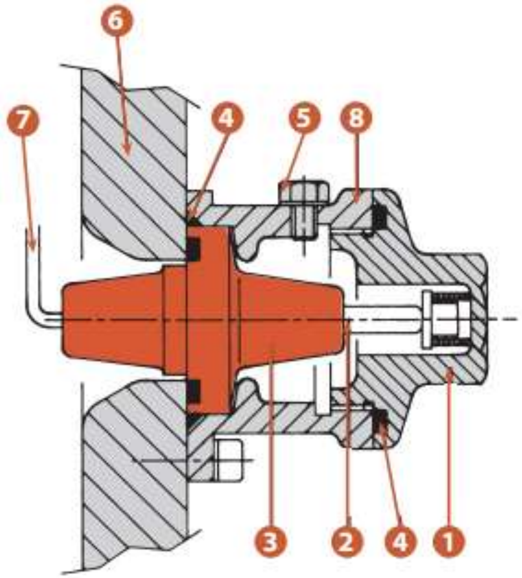


Fig. 5 : Voltage Tap
(upon request for 245 kV bushings)

1 - Closing and grounding cap
2 - Measurement electrode
3 - Insulation tap
4 - Gasket
5 - Filling plug
6 - Bushing flange
7 - Connection to internal layer
8 - Tap external housing

Source: Passoni & Villa

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Bushing Measuring Tap

Measuring Taps

MICAFIL

ABB

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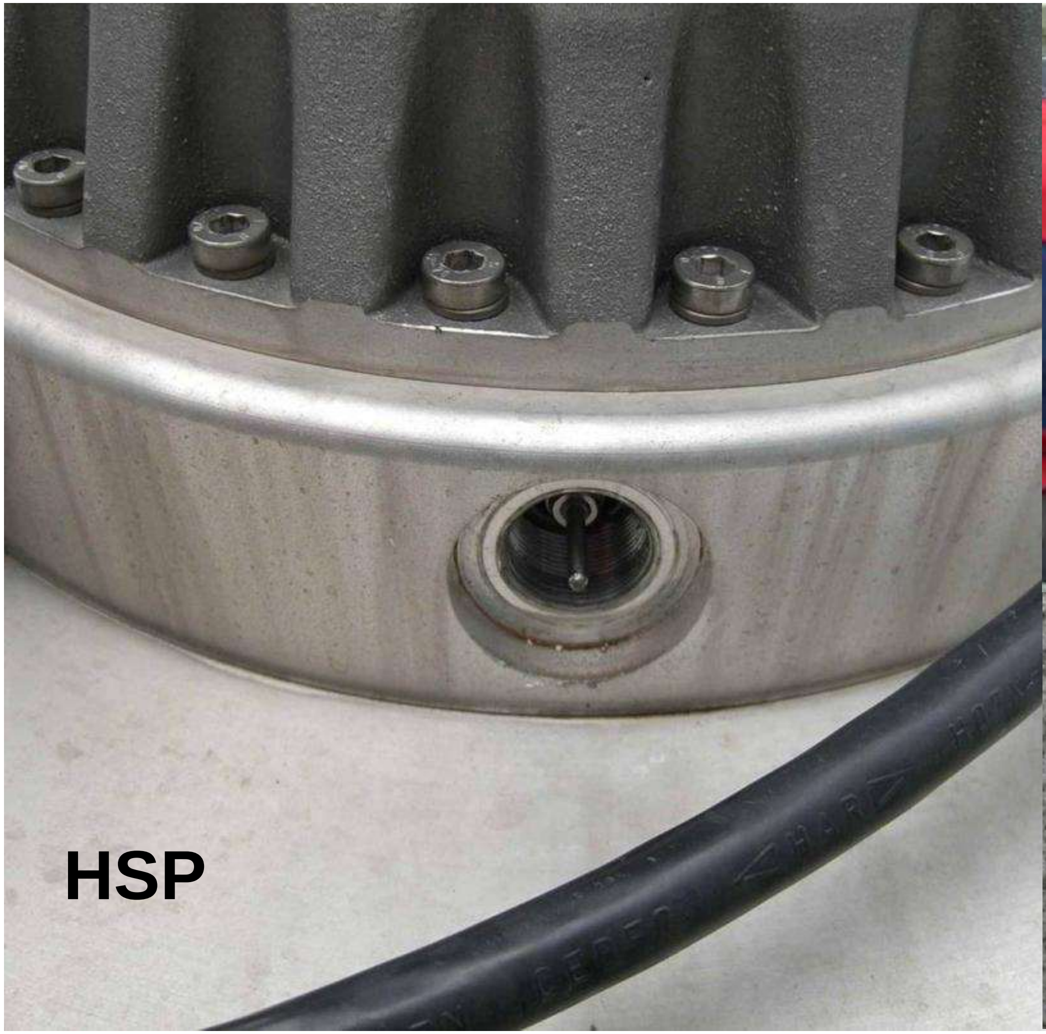
Measuring Taps



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Measuring Taps

GE

Arcing at the Measurement Tap

Source: Norbert Koch „Diagnoseverfahren an Hochspannungsdurchführungen aus Herstellersicht“, Diagnoseverfahren an Schaltanlagen und Transformatoren, HdT Essen 2013

Partly Burned Measurement Tap of a 245kV-RIP Busing

Source: Hubert Goebel GmbH

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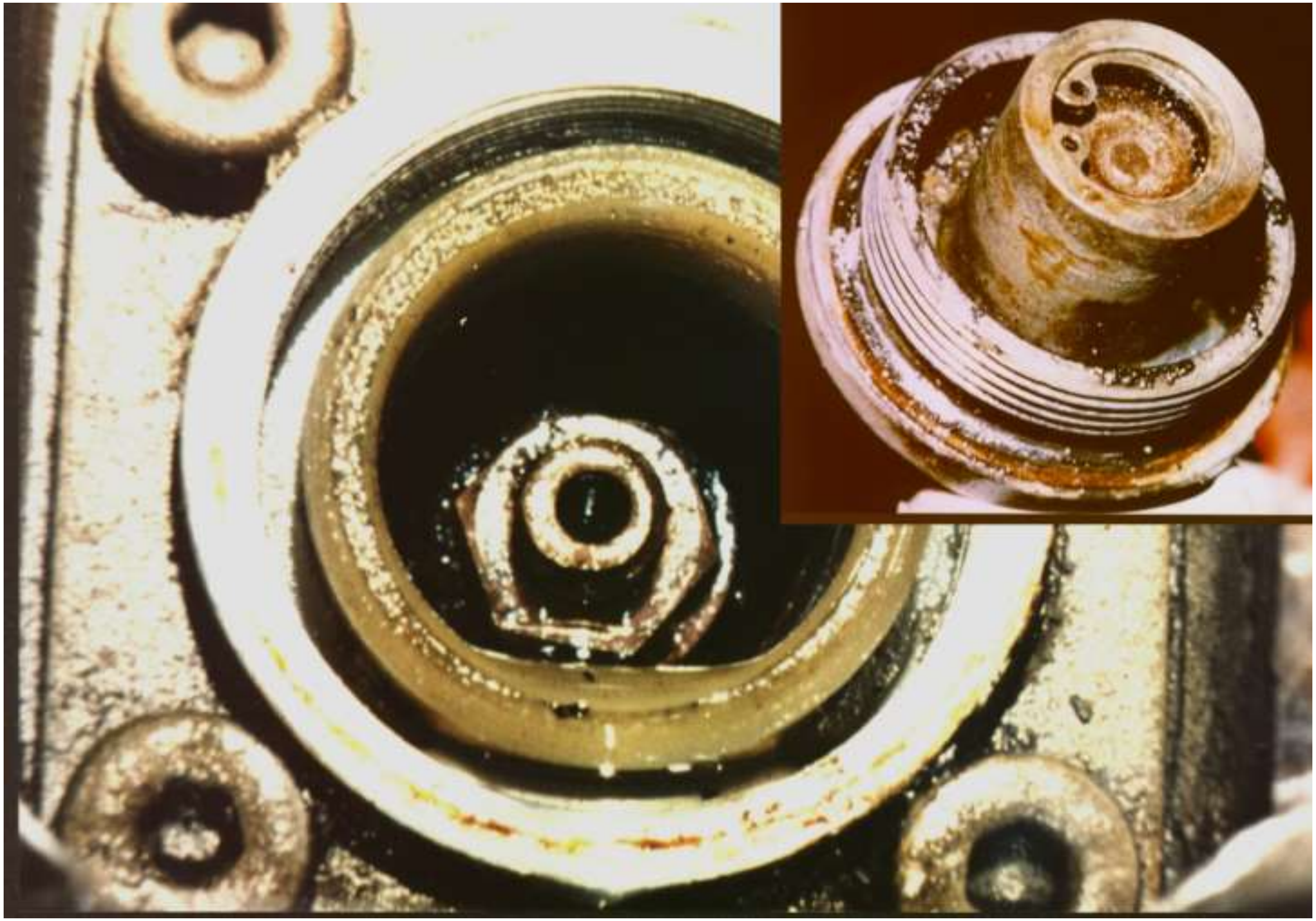
Partly Burned Measurement Tap of a 400kV-OIP Busing



Source: Hubert Goebel GmbH

Diagnostic Methods

Category	Diagnostic Technique	Type	Partial discharges	Leakage	Shorted grading layers	Contact problems and high impedance faults between layers	Ageing	Moisture
General	Visual Inspection	OIP	5	1	5	5	5	5
		RBP	5	1	5	5	5	5
		RIP	5	1	5	5	5	5
	Thermography	OIP	4	5	4	3	4	5
		RBP	4	5	4	3	4	5
		RIP	4	5	4	3	4	5
Electrical Basic	Capacitance	OIP	5	4*	1	3	4	4
		RBP	5	4*	1	3	4	4
		RIP	5	4*	1	3	4	4
	DF/PF	OIP	3	5	3	1**	2	2
		RBP	3	5	3	1**	2	2
		RIP	3	5	3	1**	2	2
Electrical Advanced	Dielectric Response with FDS / PDC	OIP	3	5	1	1	1	1
		RBP	3	5	1	1	1	1
		RIP	3	5	1	1	1	1
	Partial discharge measurement	OIP	1	5	3	1	5	4
		RBP	1	5	3	1	5	4
		RIP	1	5	3	1	5	4
Oil	Dissolved gas analysis	OIP	1	5	1	1	4	5
	Moisture in oil	OIP	5	5	4	5	3	1
	DF/PF	OIP	4	5	4	3	2	2
	Conductivity of oil (IEC 61620)	OIP	4	5	4	3	2	2
	Particles in oil	OIP	5	5	5	5	2	5
	Analysis of Furanic components	OIP	5	5	5	5	1	5
	Test for corrosive Sulfur	OIP	5	5	5	5	2	5

1=very good, 2=good 3=fair 4=poor 5=not applicable

*big leakages can be detected with hot collar test **DF/PF from 2-12kV

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Infrared Thermography

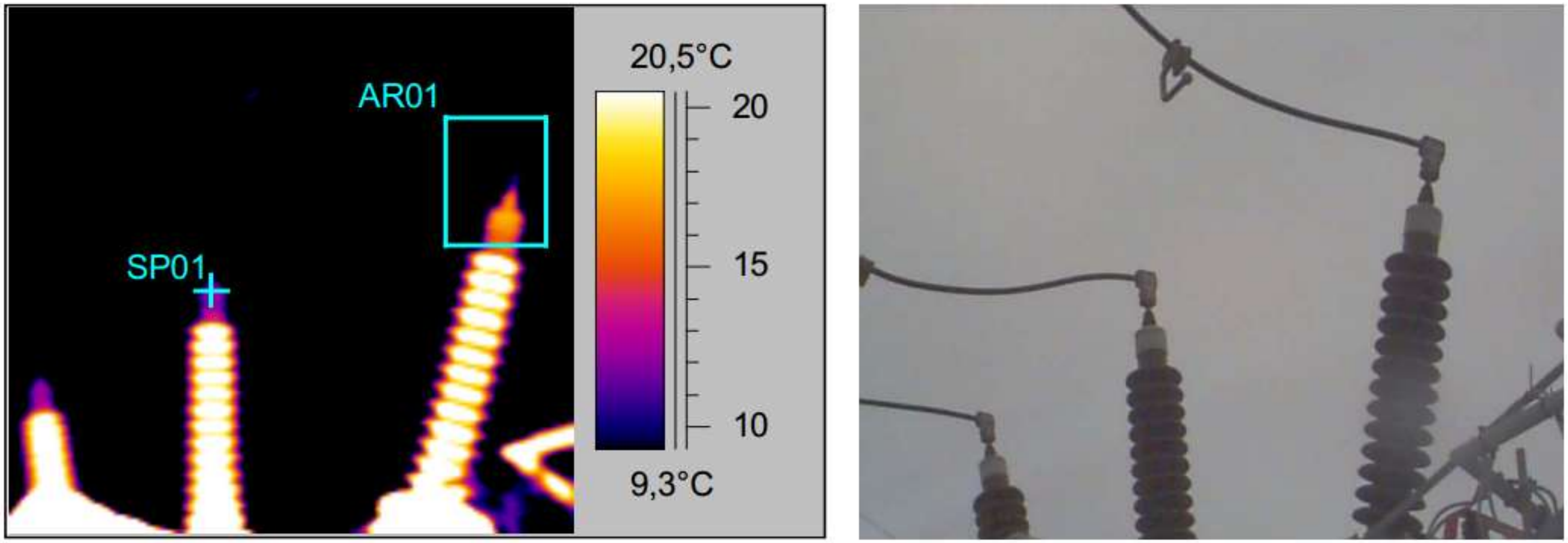
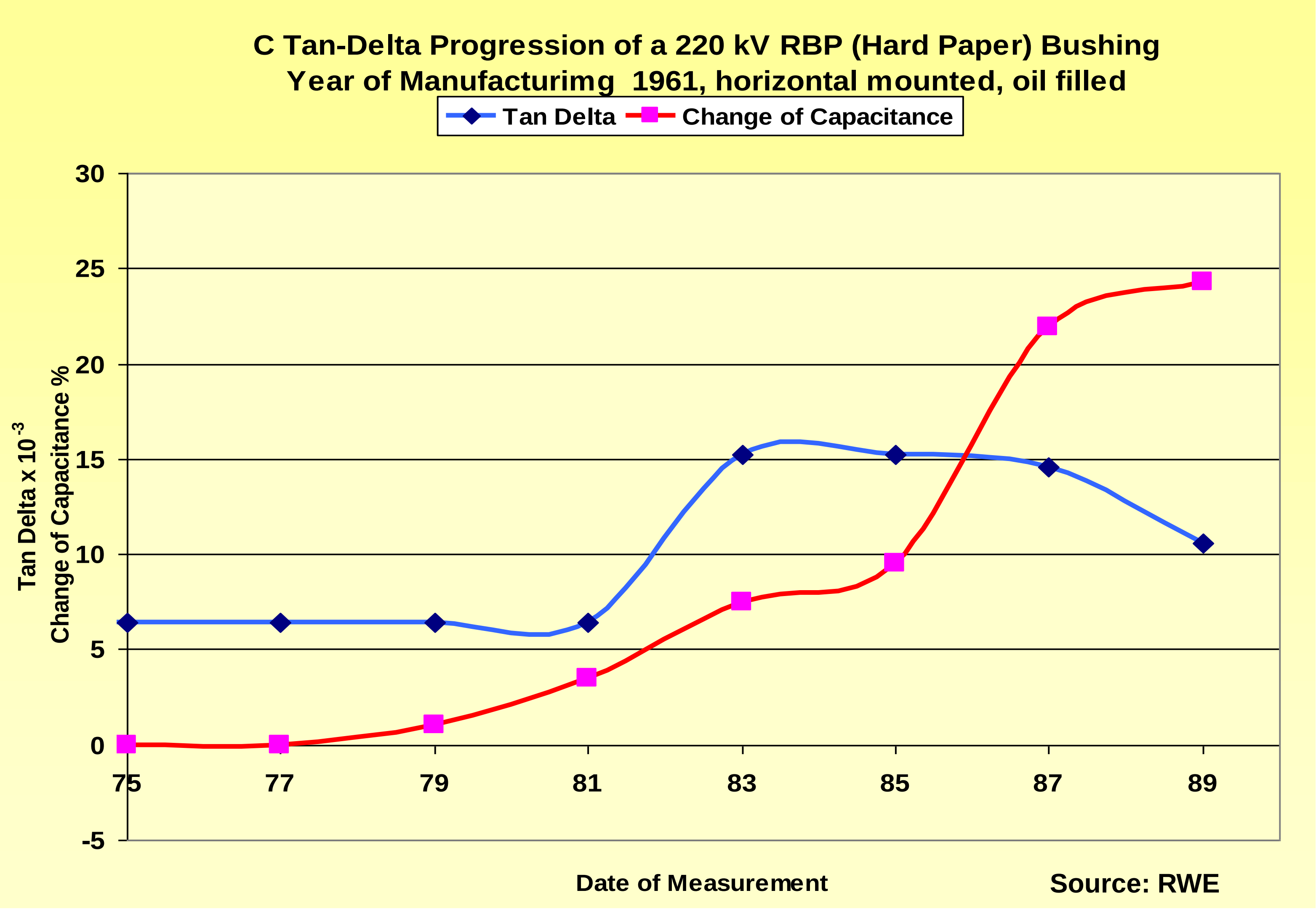


Fig.13. Measurement indicating poor current path between bushing inner and outer terminal.

Source: ABB Brochure „Bushing diagnostics and conditioning“, 2750 515-142 en

C-Tan δ Progression of a Bushing

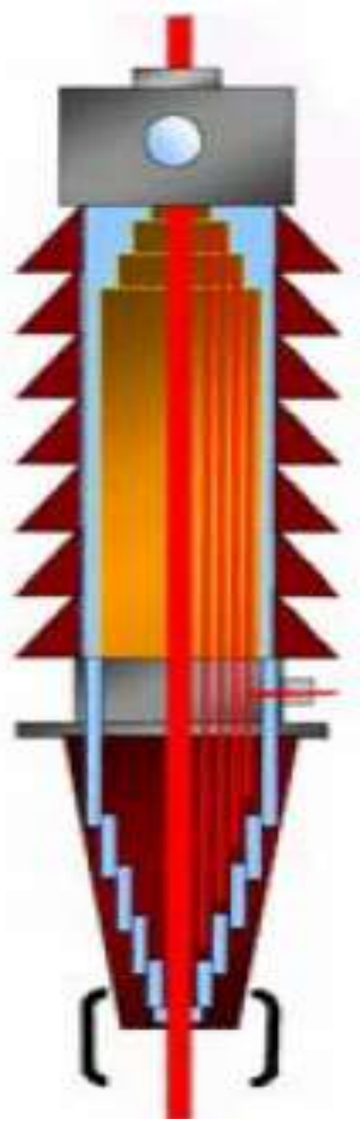


Source: Volker Seitz: „Vorbeugende Instandhaltung an Leistungstransformatoren", OMICRON Anwendertagung 2003, Friedrichshafen

Bushing Fault

Source: Volker Seitz: „Vorbeugende Instandhaltung an Leistungstransformatoren", OMICRON Anwendertagung 2003, Friedrichshafen

Fault Mechanisms and Diagnosis



- Partial breakdowns
  - Measurement of capacitance
  - TanDelta measurement
  - PD measurement
- Voids, cracks
  - Measurement of capacitance (RBP)
  - PD measurement
- Contact problems on measurement taps
  - Tan Delta voltage sweep (tip-up test)
- Ageing, moisture
  - Dielectric response measurements
  - TanDelta

Voltage [kV]	No. of layers	% change
123	14	7.1
245	30	3.3
420	40	2.5
550	55	1.8

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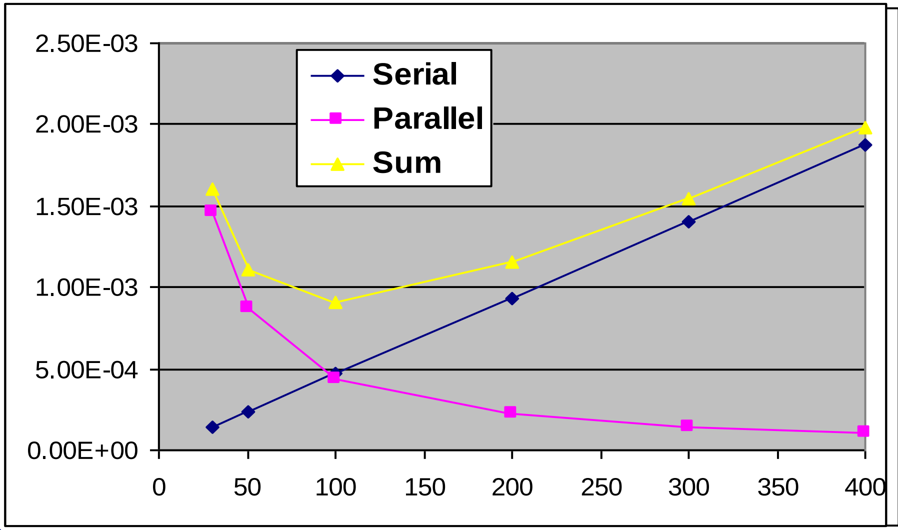
Definitions of Dielectric Losses

Dielectric losses are caused by

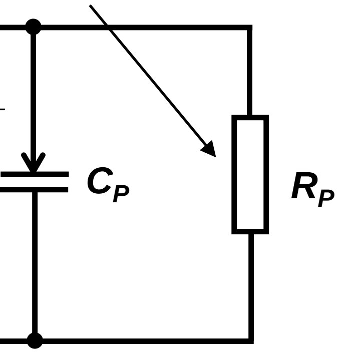
- **Conductive losses**
- **Polarization losses**
- Partial discharges



Parallel circuit

$$\text{DF:}\ \tan\delta = \frac{|I_{RP}|}{|I_{CP}|} = \frac{1}{R_P \cdot \omega \cdot C_P}$$

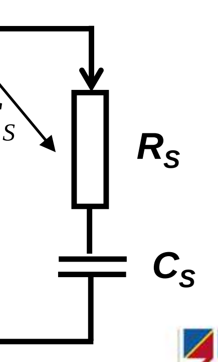
$$\text{PF:}\ \cos\varphi = \frac{|I_{RP}|}{|I_{tot}|}$$



Serial circuit

$$\text{DF:}\ \tan\delta = \frac{U_R}{U_C} = R_S \cdot \omega \cdot C_S$$

$$\text{PF:}\ \cos\varphi = \frac{U_R}{U_{tot}}$$

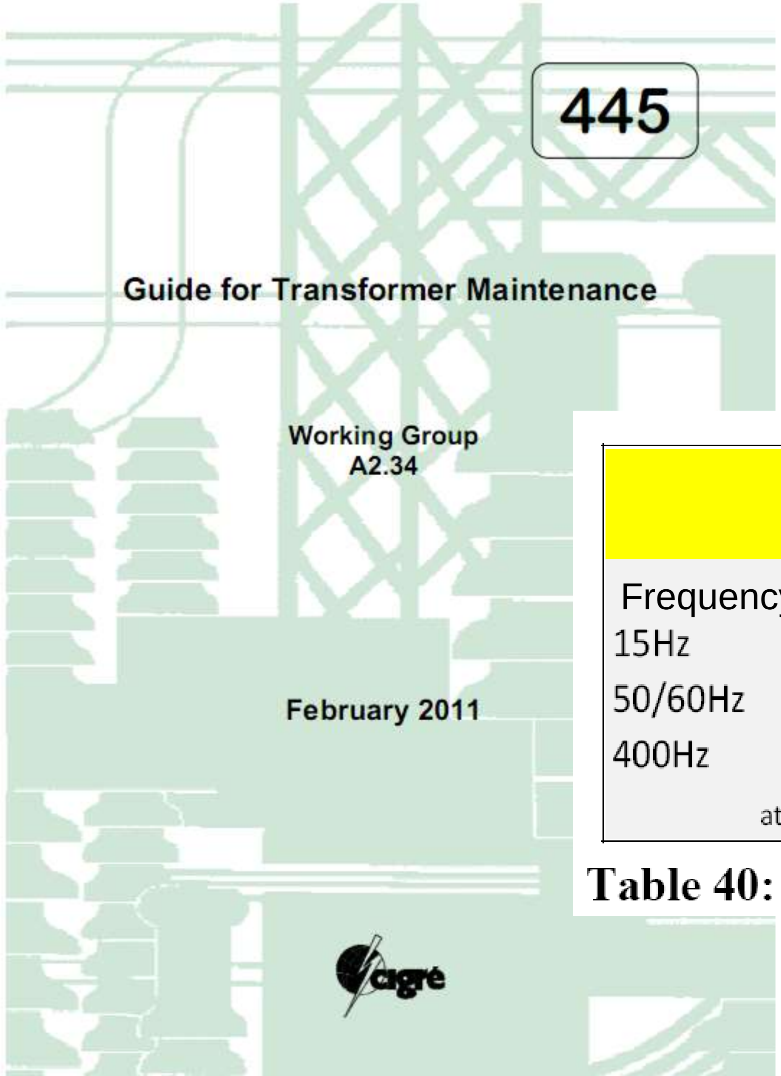


Standards

Type	RIP	OIP	RBP
Main insulation	Resin impregnated paper	Oil impregnated paper	Resin bonded paper
DF / tan delta (20°C, IEC60137)	< 0.7 %	< 0.7 %	< 1.5 %
PF cos phi (20°C, IEEE C57.19.01)	< 0.85 %	< 0.5 %	< 2 %
Typical new values	0.3-0.4 %	0.2-0.4 %	0.5-0.6 %
PD (IEC60137) at U_m $1.5\ U_m/\sqrt{3}$ $1.05\ U_m/\sqrt{3}$	< 10 pC < 5 pC < 5 pC	< 10 pC < 5 pC < 5 pC	 < 300 pC

Cigre WG A2.34 Brochure 445

Guide for Transformer Maintenance



www.e-cigre.org

	RIP Resin impregnated		OIP Oil impregnated		RBP Resin bonded paper	
Frequency	new	aged	new	aged	new	aged
15Hz	<0.6%	<0.7%	<0.5%	<0.7%	<0.7%	<1.5%
50/60Hz	<0.5%	<0.5%	<0.4%	<0.5%	<0.6%	<1%
400Hz	<0.6%	<0.7%	<0.5%	<0.7%	<0.7%	<1.5%
at 20°C						

Table 40: Indicative DF/PF Limit Values for Condenser Bushings

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RBP - Bushings

- Not free of cavities – Partial Discharges possible also at rated voltage

- Higher dielectric losses can feed to thermal instability

- RPB has cavities and cracks in the paper which are normally filled with the surrounding oil

- Increase of capacitance

- After a longer storage period this oil is running out. The PD level is increasing and the capacitance is getting smaller

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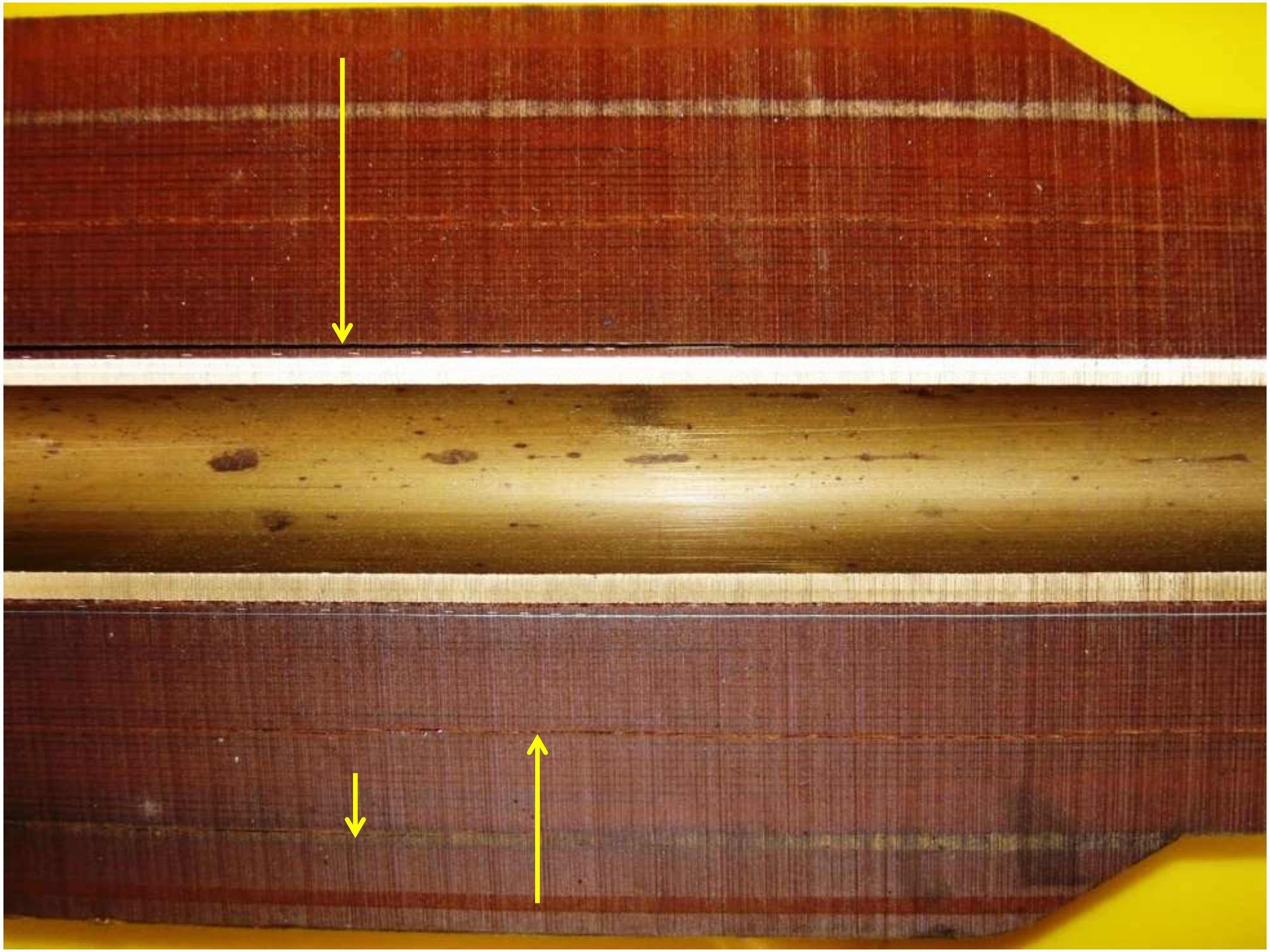
RBP – Bushings Cracks in the Insulation



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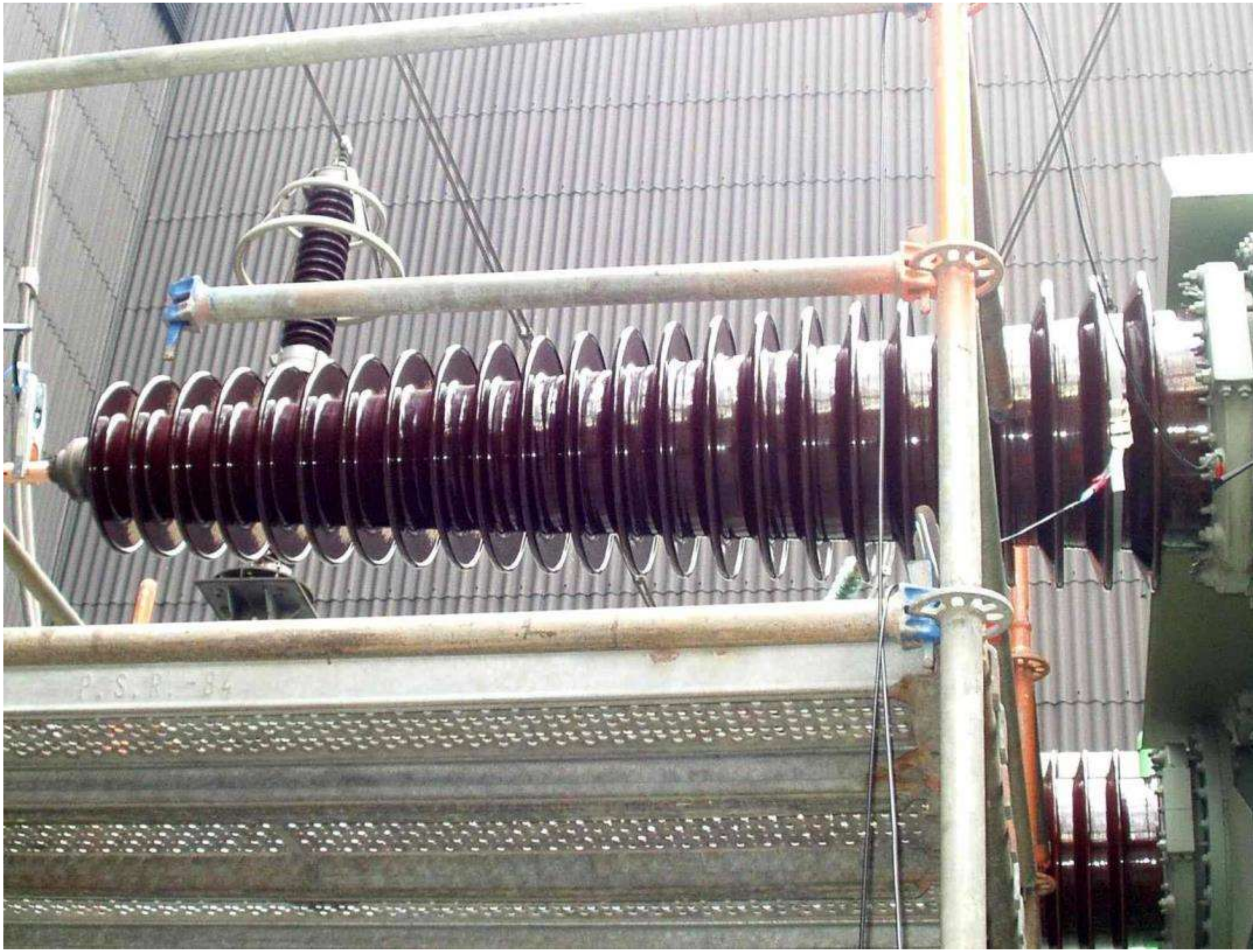
Measurement on 220kV RBP Bushings (1971)



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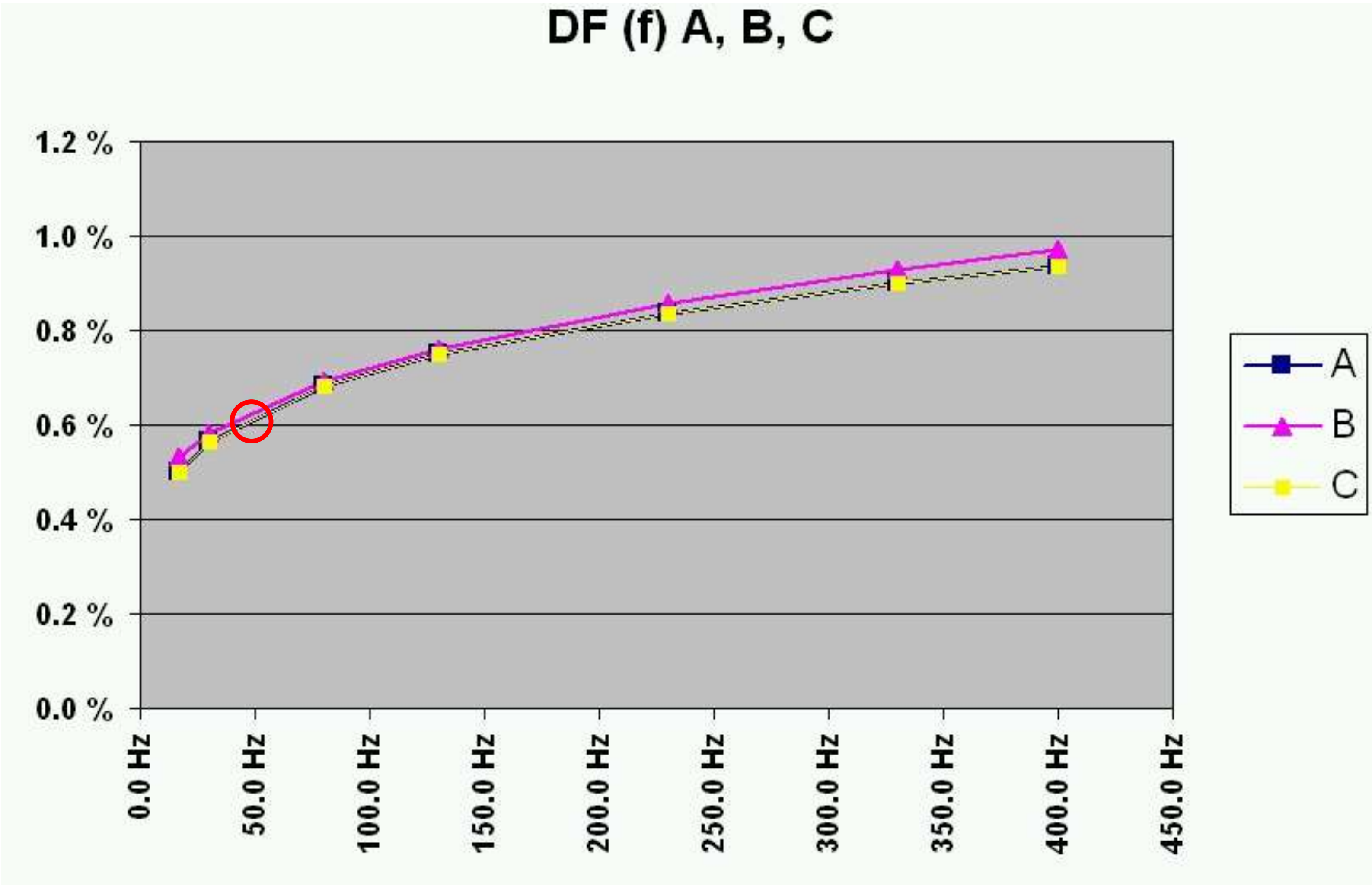
TanDelta 15-400Hz



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RBP Bushing Oil-Filled Cracks
Oil Ingress by Capillare Effect

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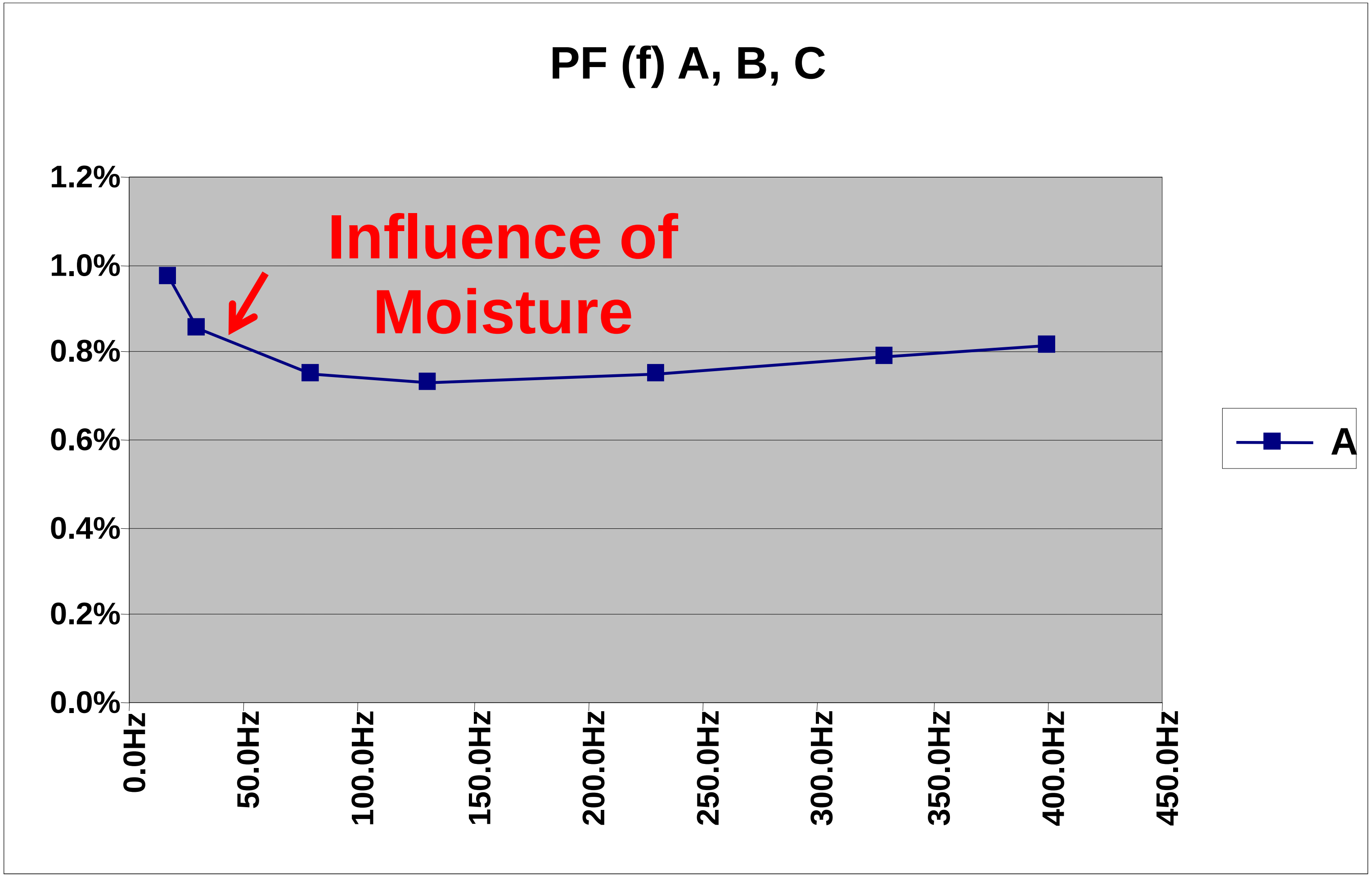
RBP Bushing 123kV (1963)



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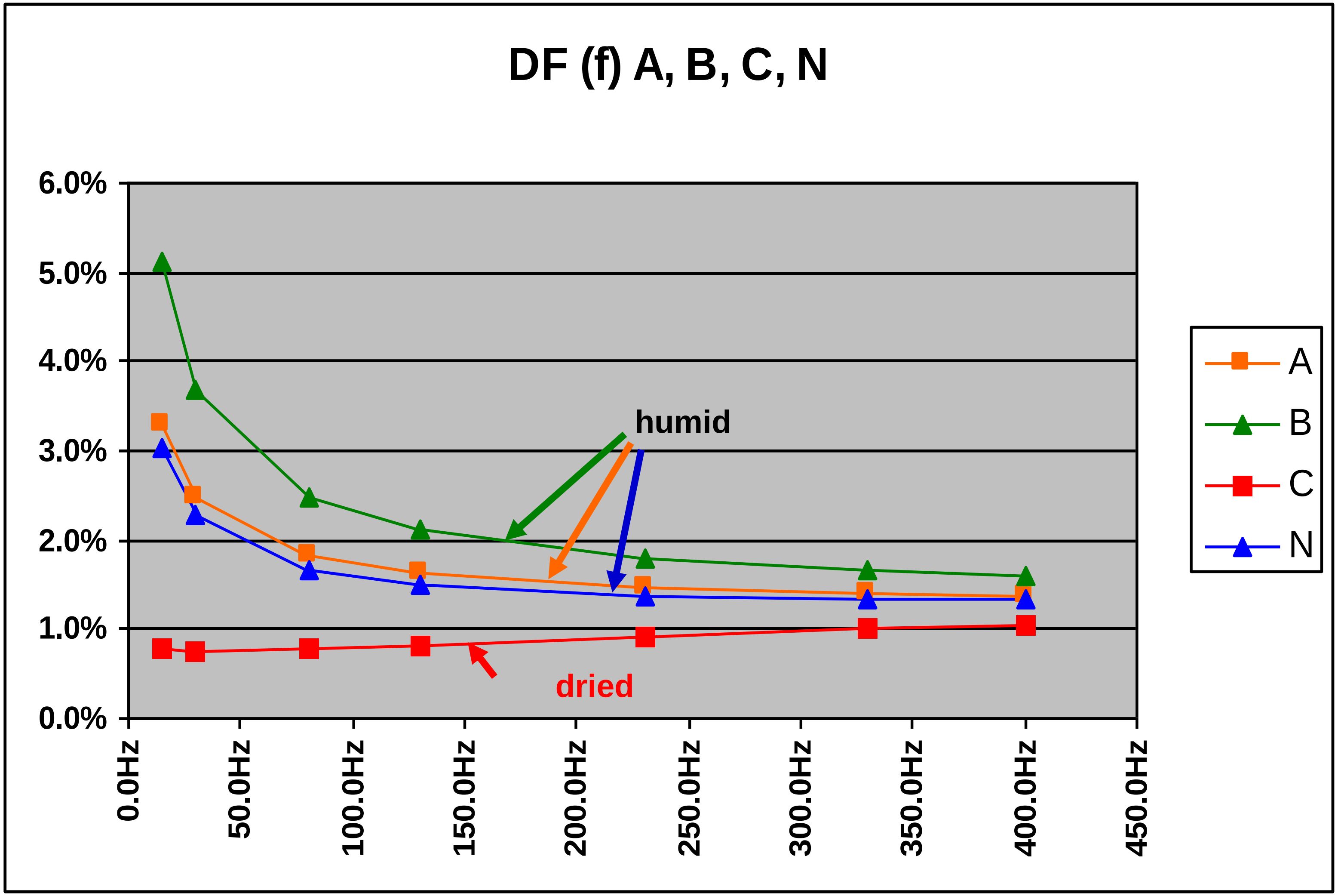
Micafil UTXF 24 (Drysomic) RBP Bushings

A,B,N humid after wrong storage

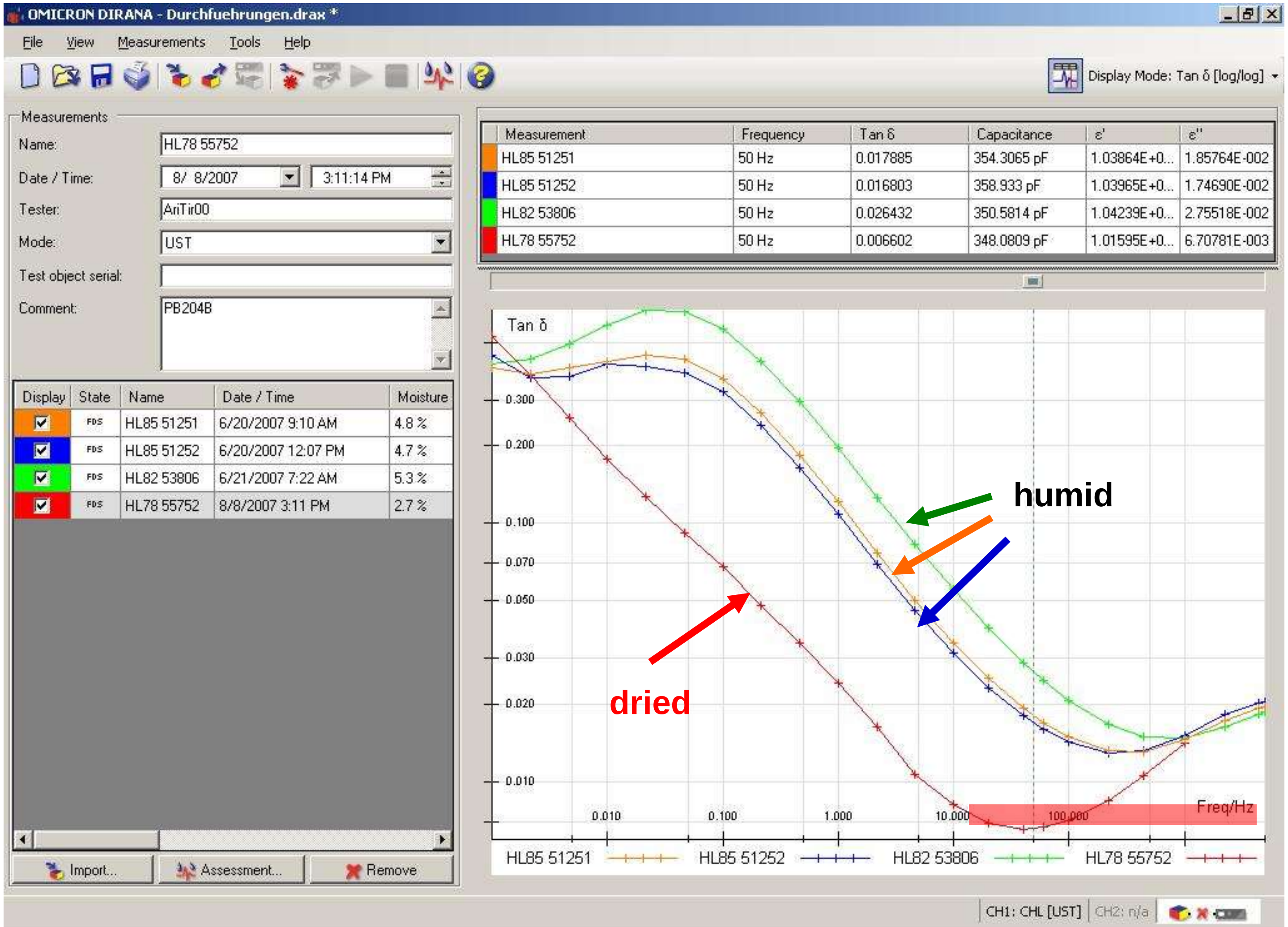
C dried

Micafil UTXF 24 RBP Bushings

A,B,N never used, wrongly stored, C dried



Micafil UTXF 24 FDS Messung



RBP Bushing 123kV

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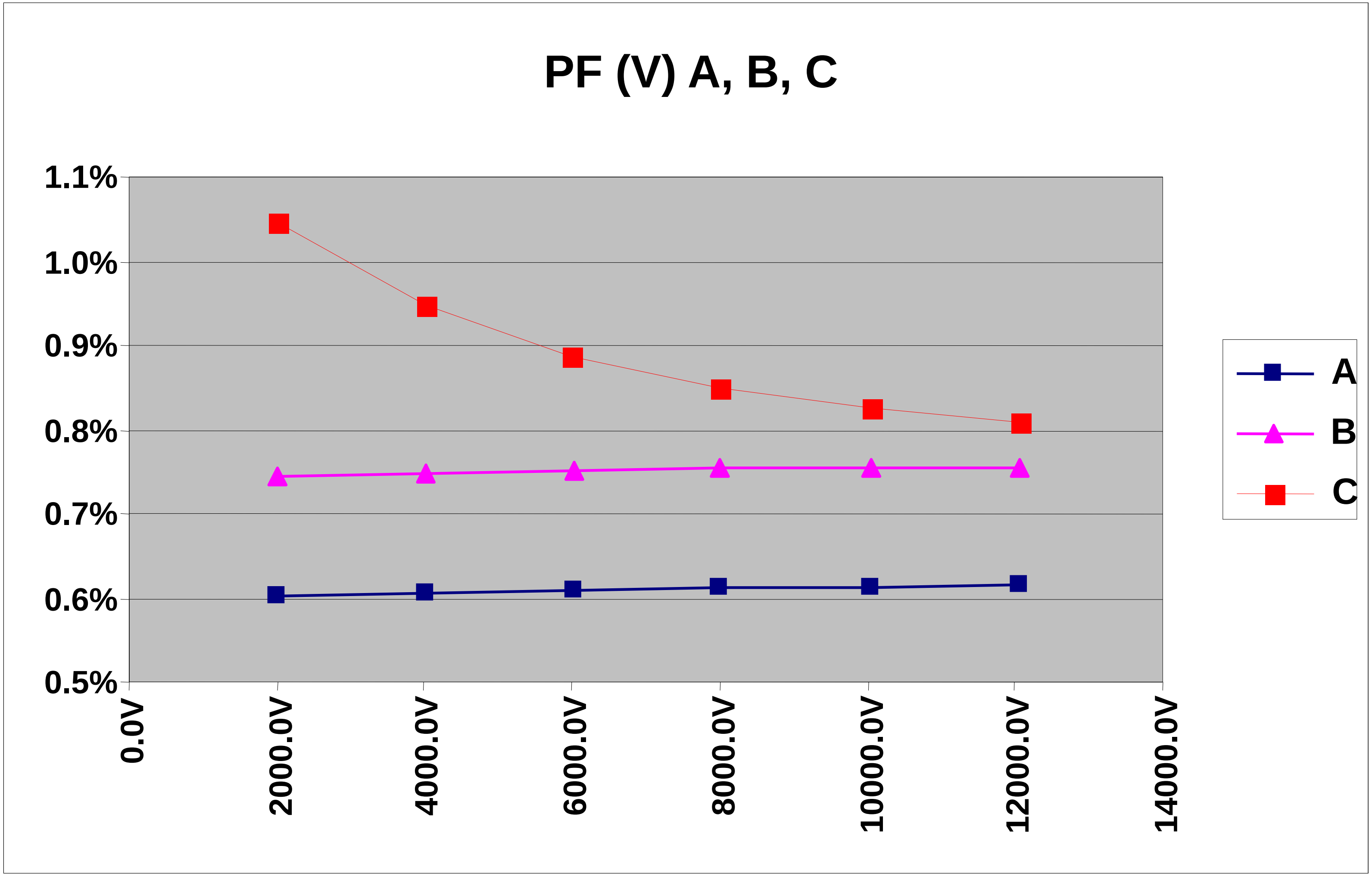
RBP Bushing 123kV



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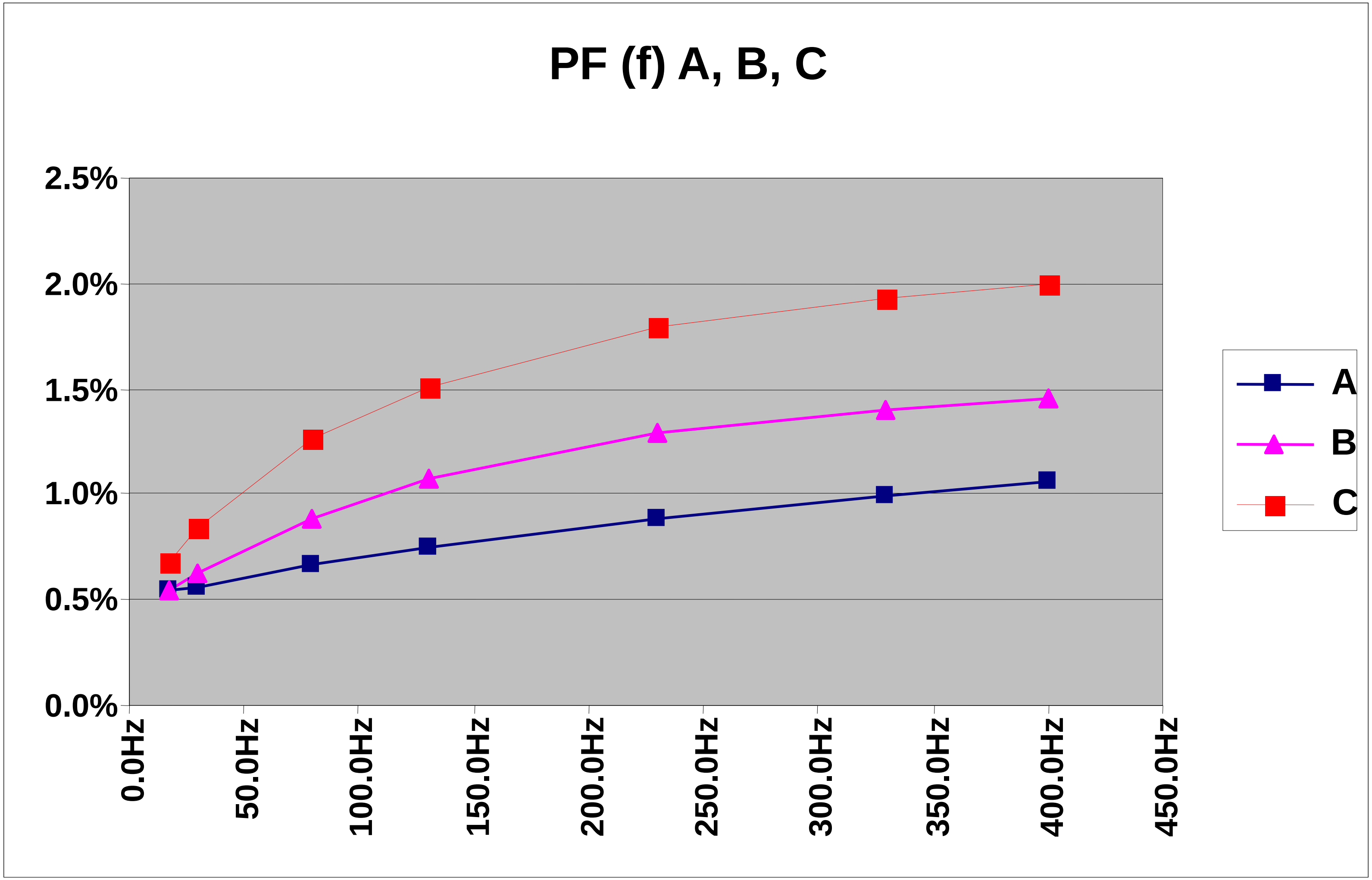
RBP Bushing 123kV



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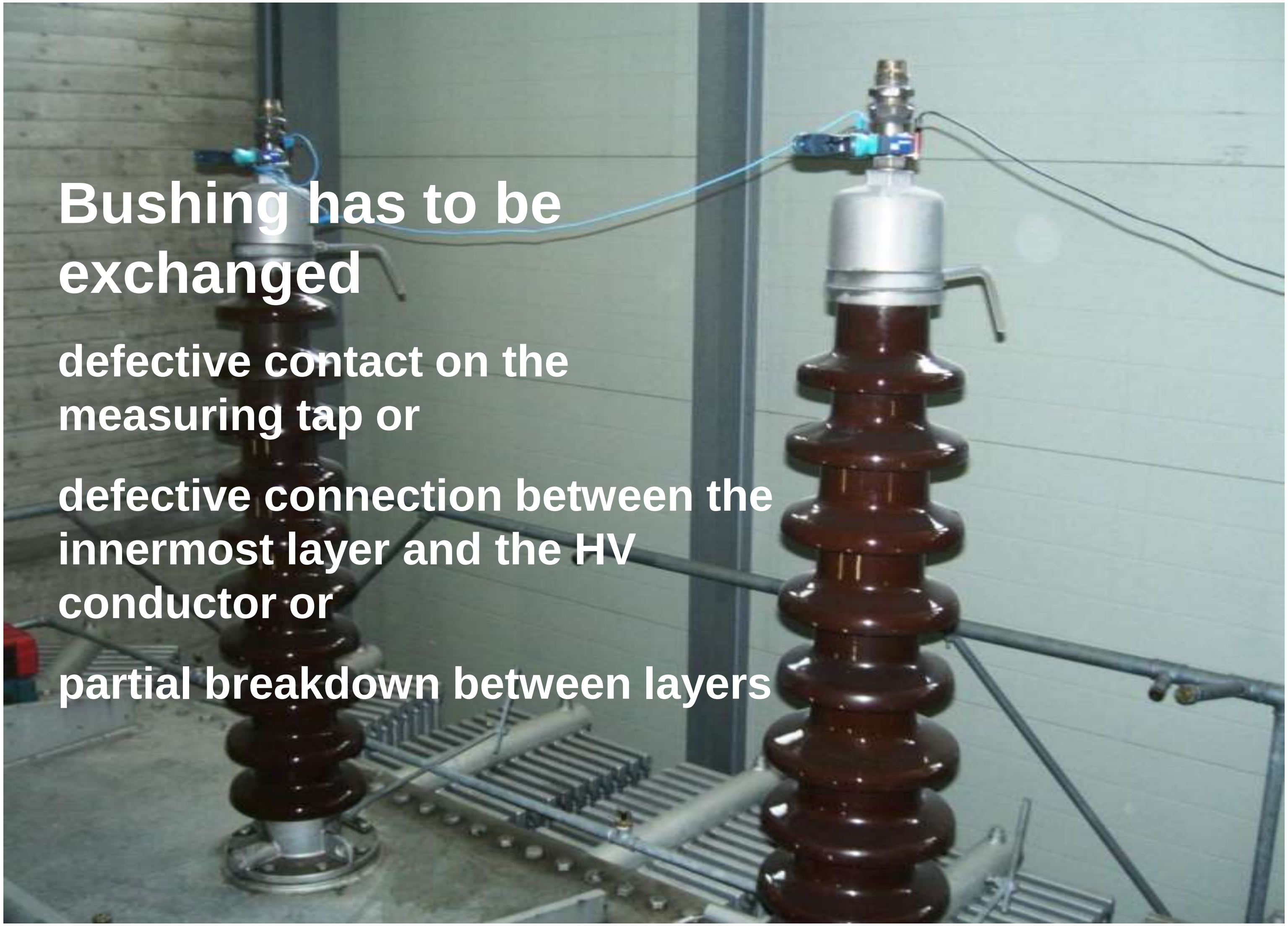
RBP Bushing 123kV



Bushing has to be exchanged

defective contact on the measuring tap or

defective connection between the innermost layer and the HV conductor or

partial breakdown between layers

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Measurement Tap O.K.

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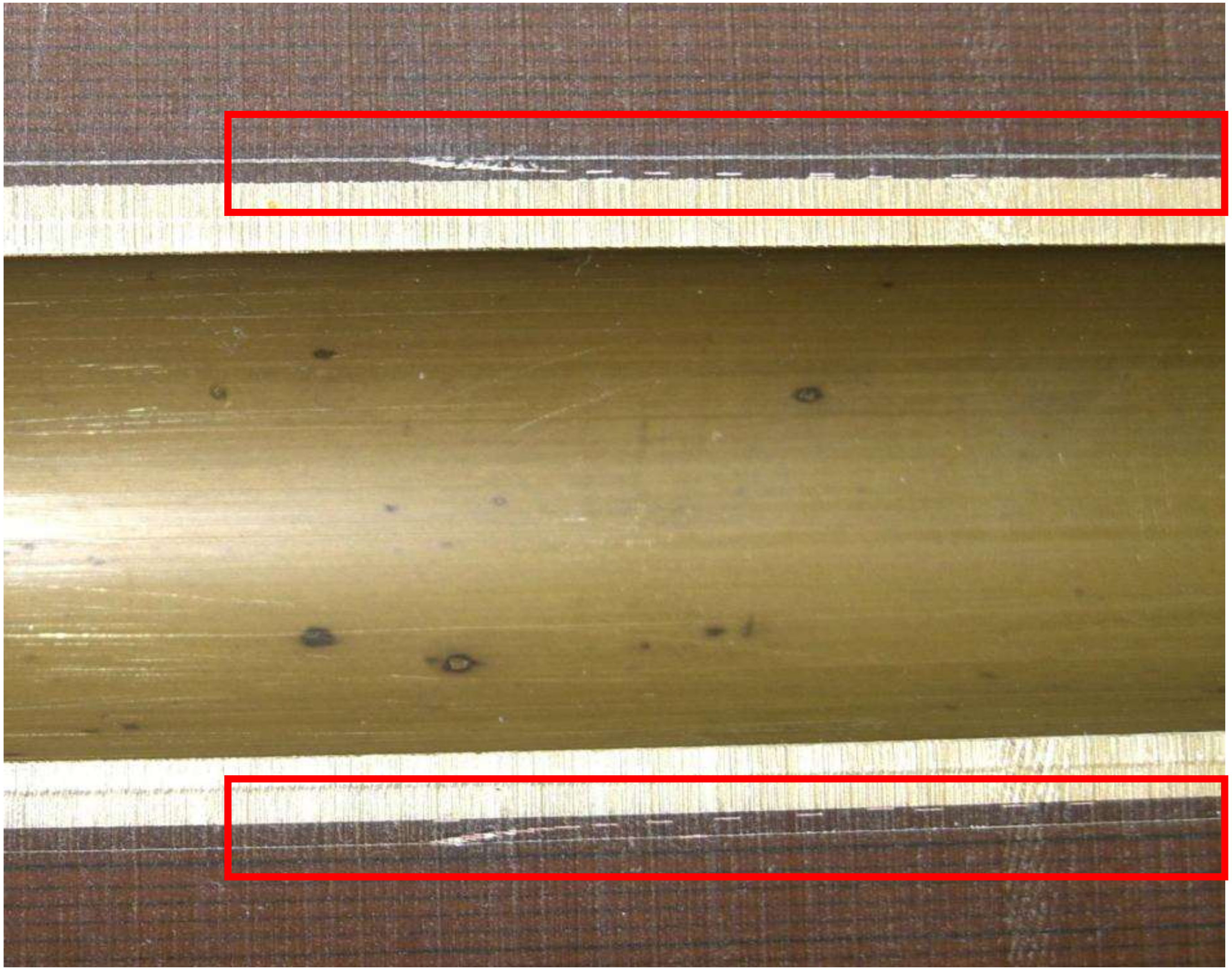
Innermost Layer was not Properly Connected to the HV Conductor.



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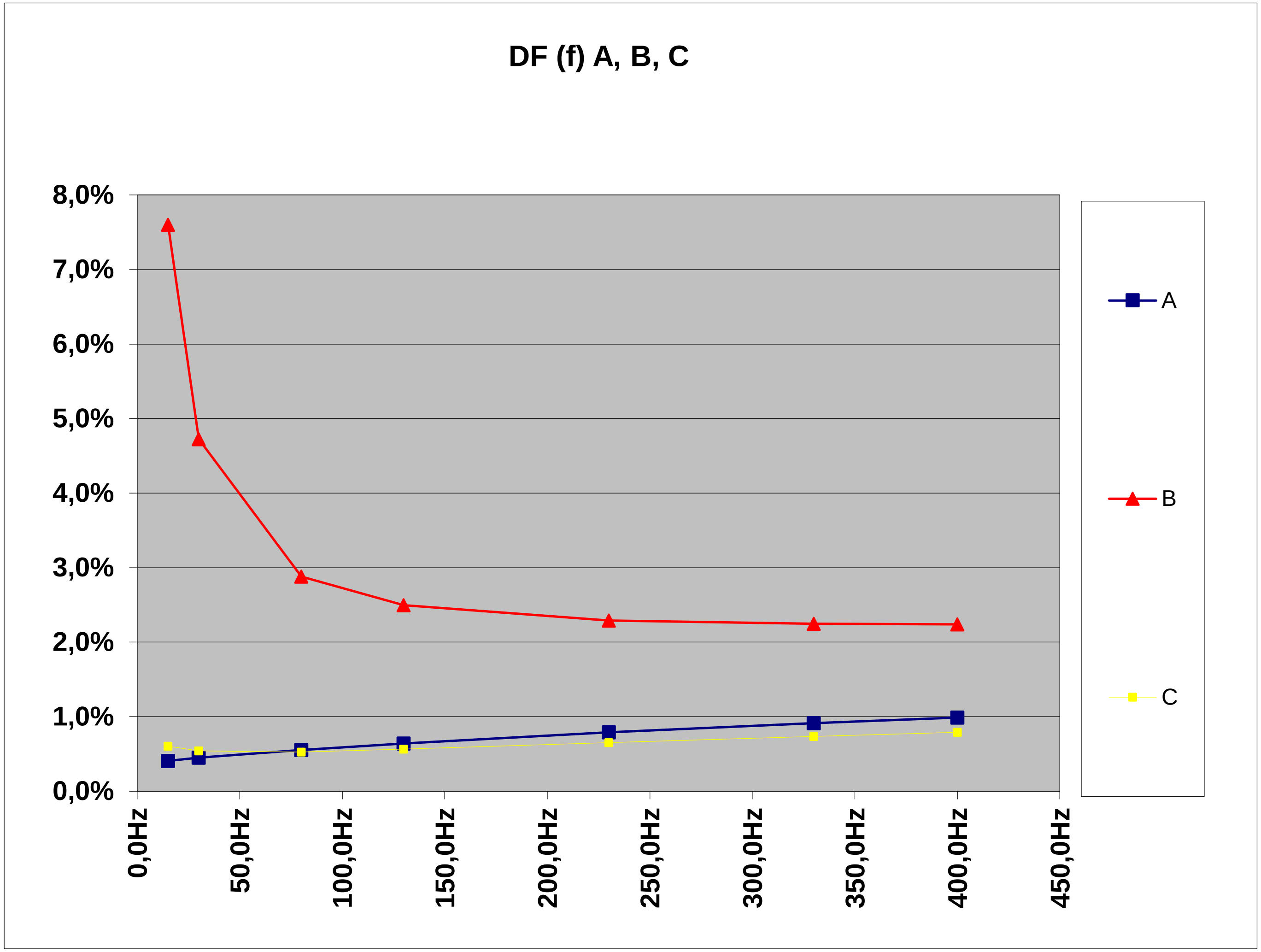
123kV RBP Bushing

Dissipation Factor Measurement



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Measurement of the Removed Bushing

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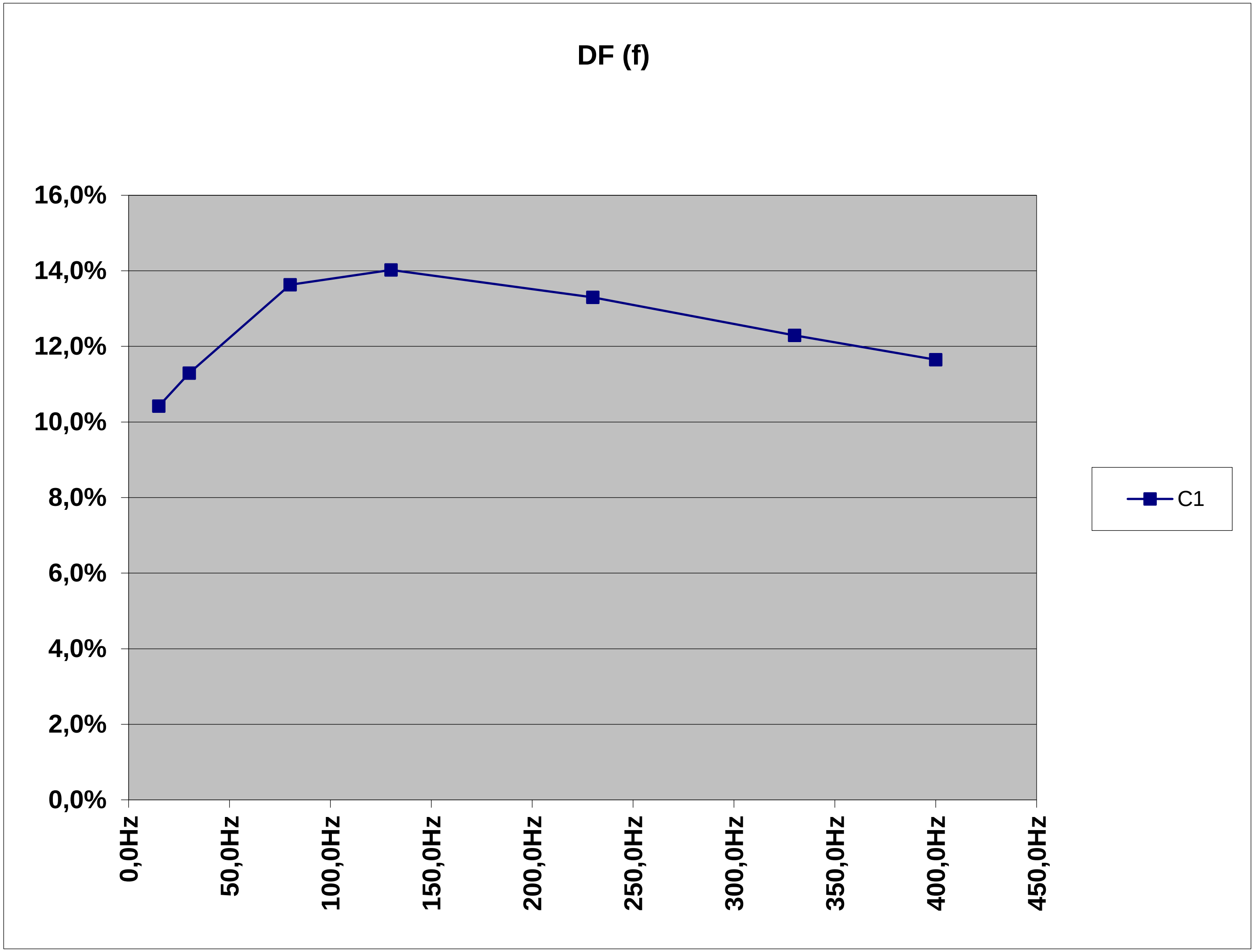
Measurement of the Removed Bushing



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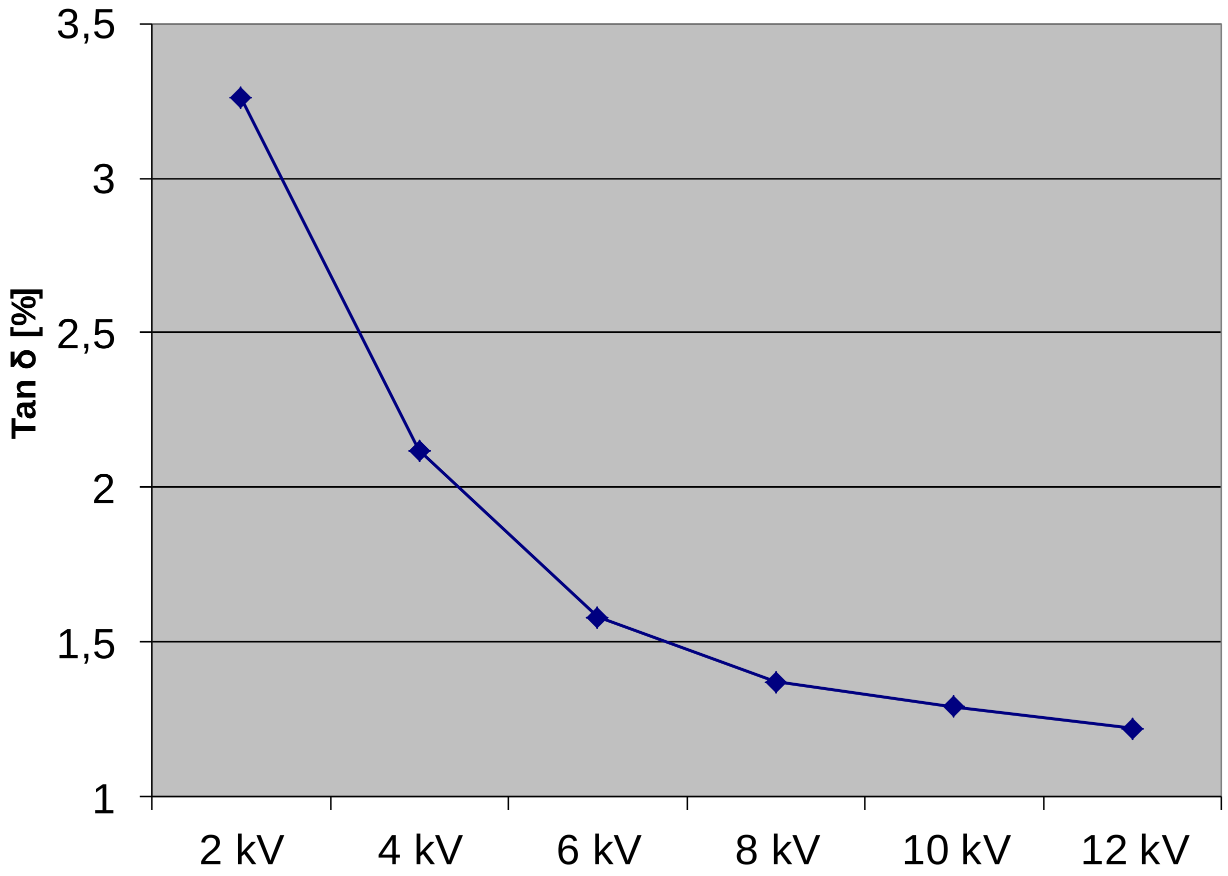
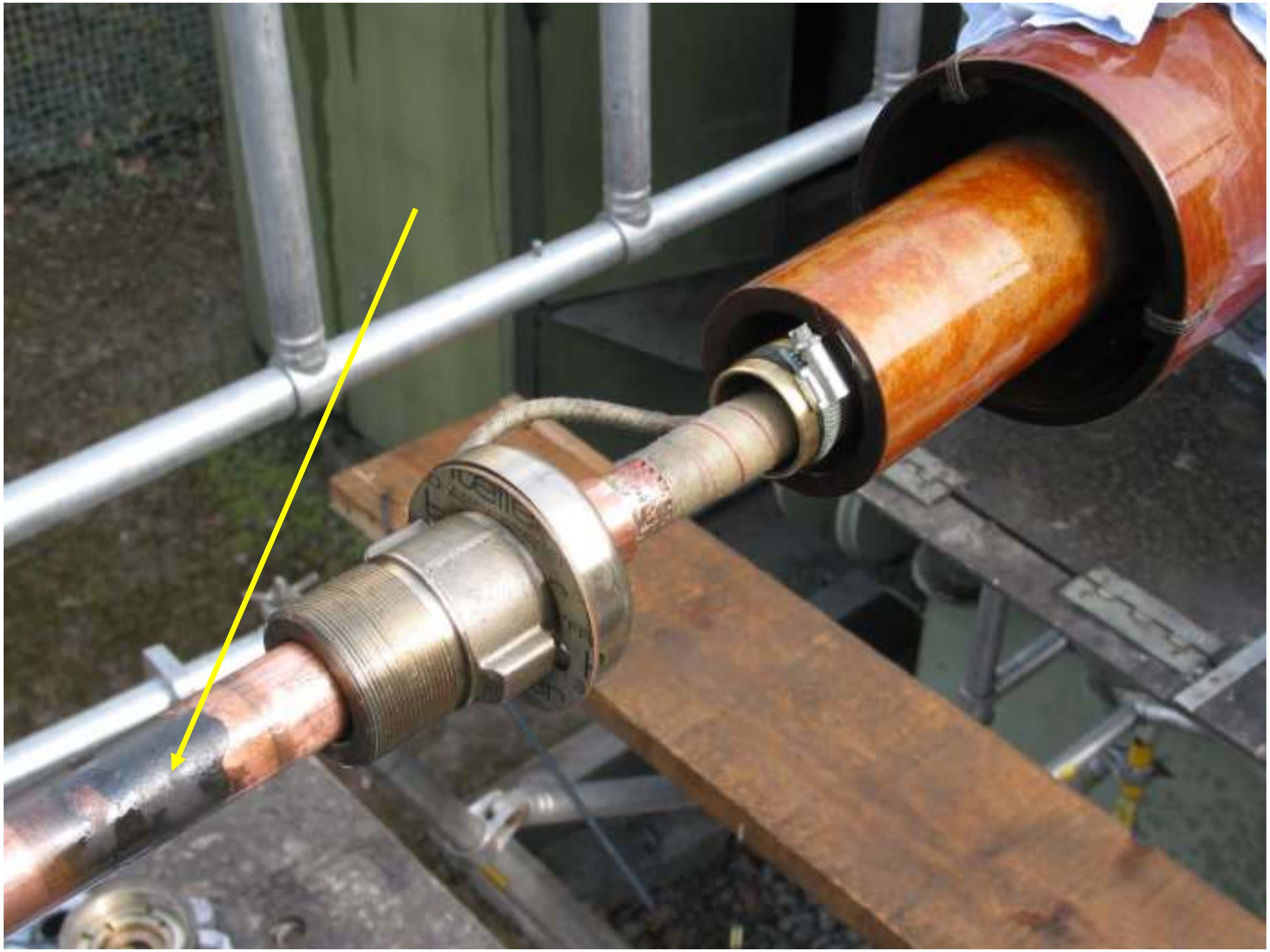
Faulty Contact on a Head Connection
245kV RBP Bushing



Source: Hubert Goebel GmbH

Faulty Contact on a Head Connection
245kV RBP Bushing



Source: Hubert Goebel GmbH

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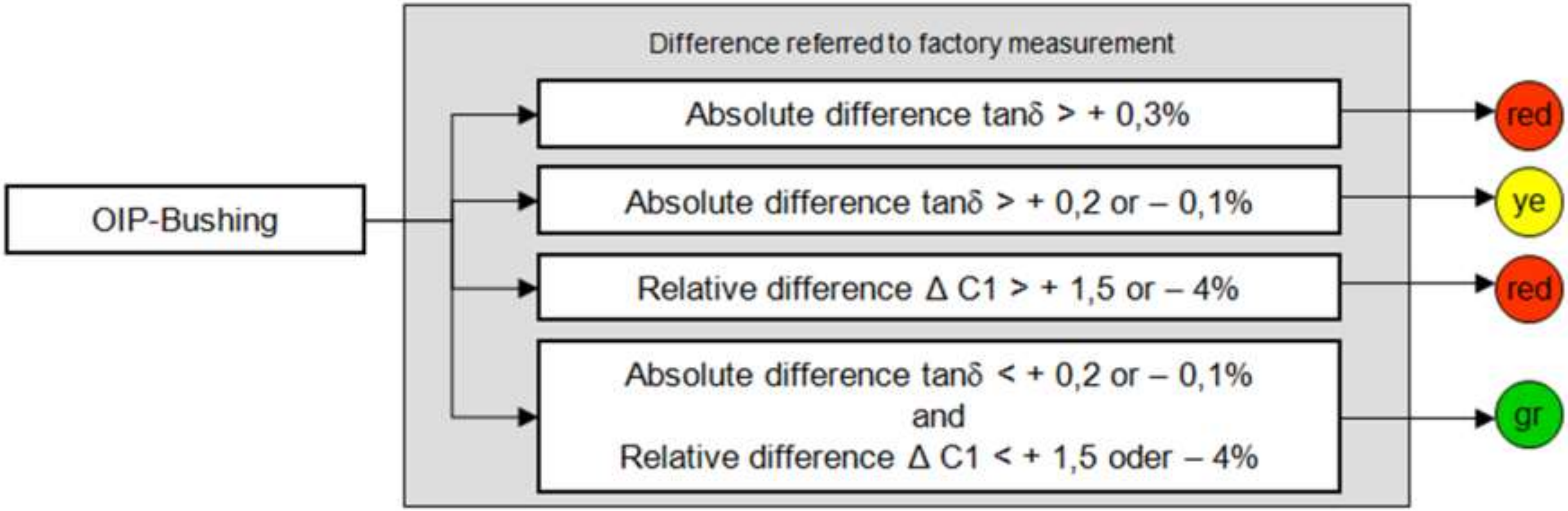
OIP Bushings

- Paper of the OIP bushings ages particularly at high temperatures
- Through aging the dielectric losses will increase
  -> this increases the power factor
- Temperature dependent aging decomposes the Paper and produces additional water
  -> this accellerates the aging

OIP Bushings Winding Machine

Source: Trench Brochure „OIP Transformer Outdoor Bushings“

Assessment of 50/60Hz C-Tanδ Results (OIP)



Source: Proposal from OMICRON, GÖBEL and HSP for the Cigre Working Group A2.43 „Reliability of HV Bushings“

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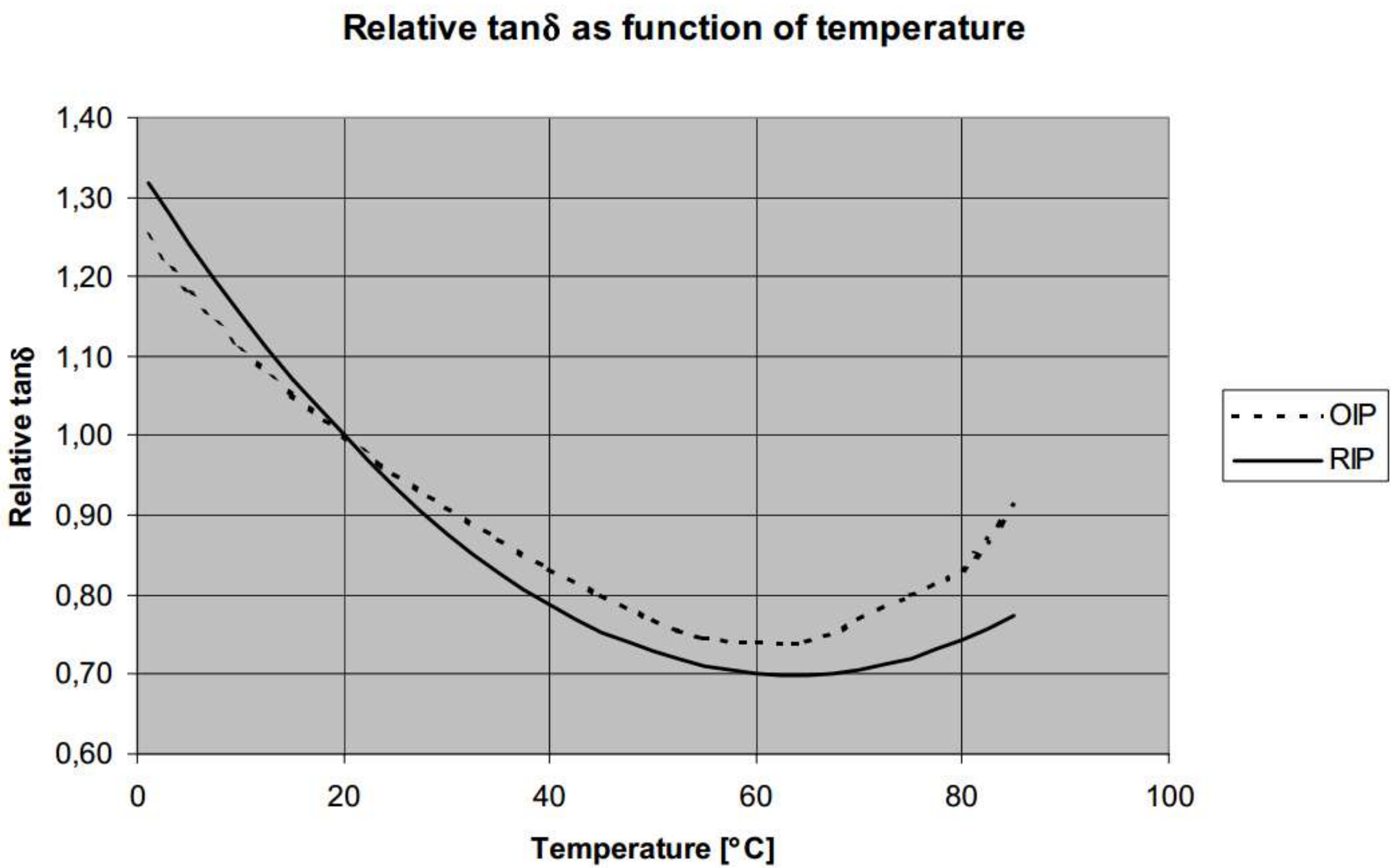
Tan δ Dependency on the Temperature



Source: ABB: „Bushing Diagnostics and Conditioning“ Brochure 2750515-142 en, Ludvika 2000

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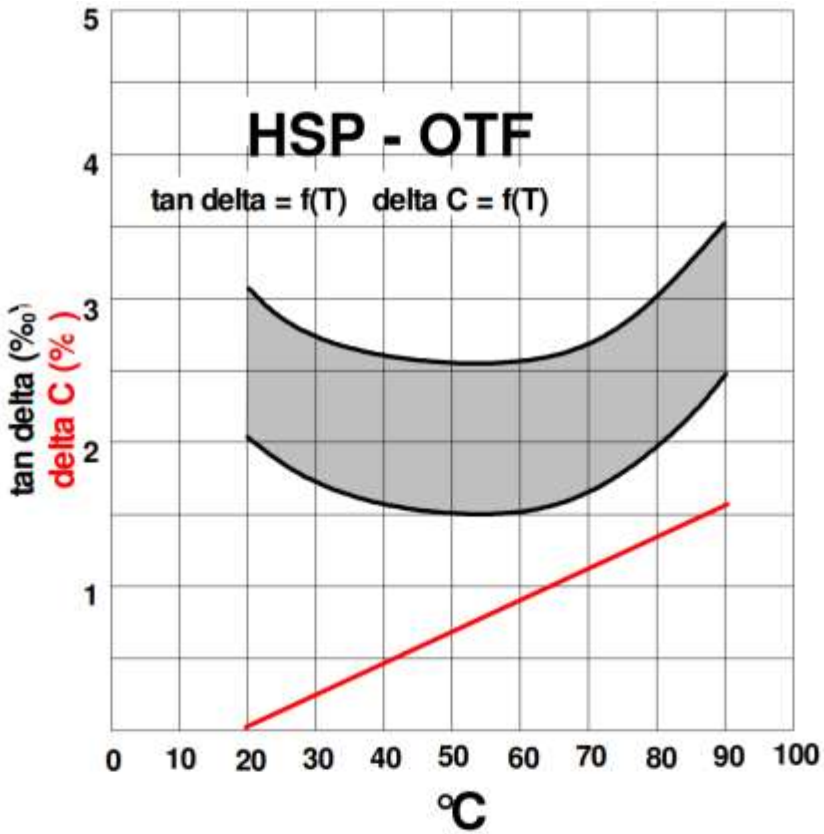
C-Tan δ Dependency on the Temperature



Limits für Measurement Results

a) Capacity:

Voltage Level / Change of Capacitance

≥245 kV 2.3 %

≥362 kV 1.7 %

≥420 kV 1.5 %

≥550 kV 1.3 %

>550 kV 0.8 %

b) tan delta

Normal values are between 0.2 % and 0.4 %

The Temperature Influence can be neglected between 20°C bis 70°C.

Values between 0.4 % and 0.5 %: → Contact HSP

Values > 0.55 % can be an indicator for an internal problem and should be investigated by a DGA

Source: HSP Manual

Breakdown in a OIP Bushing

Source: B. Heil, „Diagnose und Bewertung von Durchführungen”, OMICRON AWT Dresden 2010

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OIP Bushing Fault

Source: Hubert Goebel GmbH

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OIP Bushing Fault

Source: Hubert Goebel GmbH

OIP Bushing Fault

Source: Hubert Goebel GmbH

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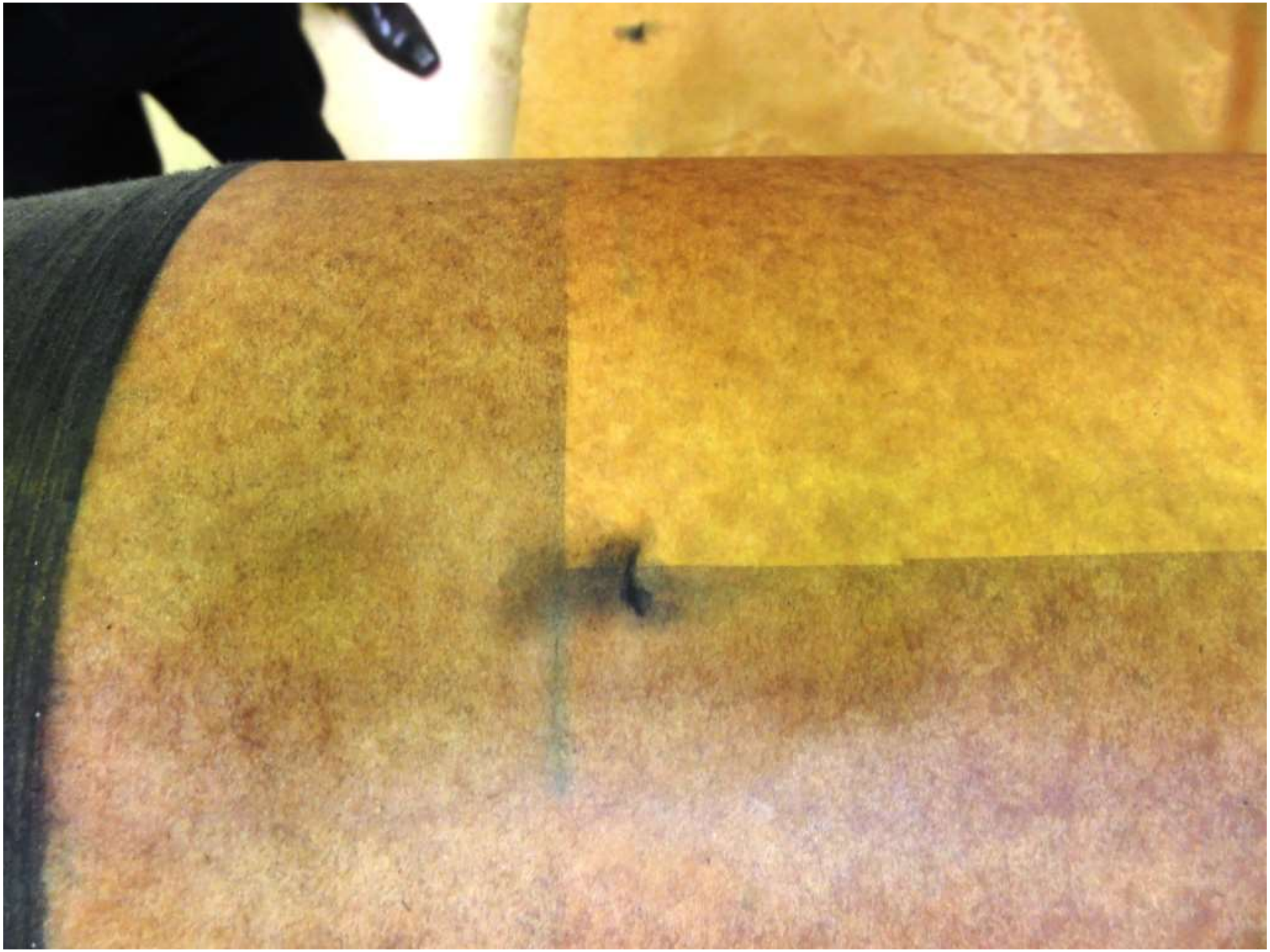
OIP Bushing
at the Sharp Edge of the Foil

Breakdown



Source: Hubert Goebel GmbH

OIP Bushing

Source: Hubert Goebel GmbH

33kV OIP Bushings

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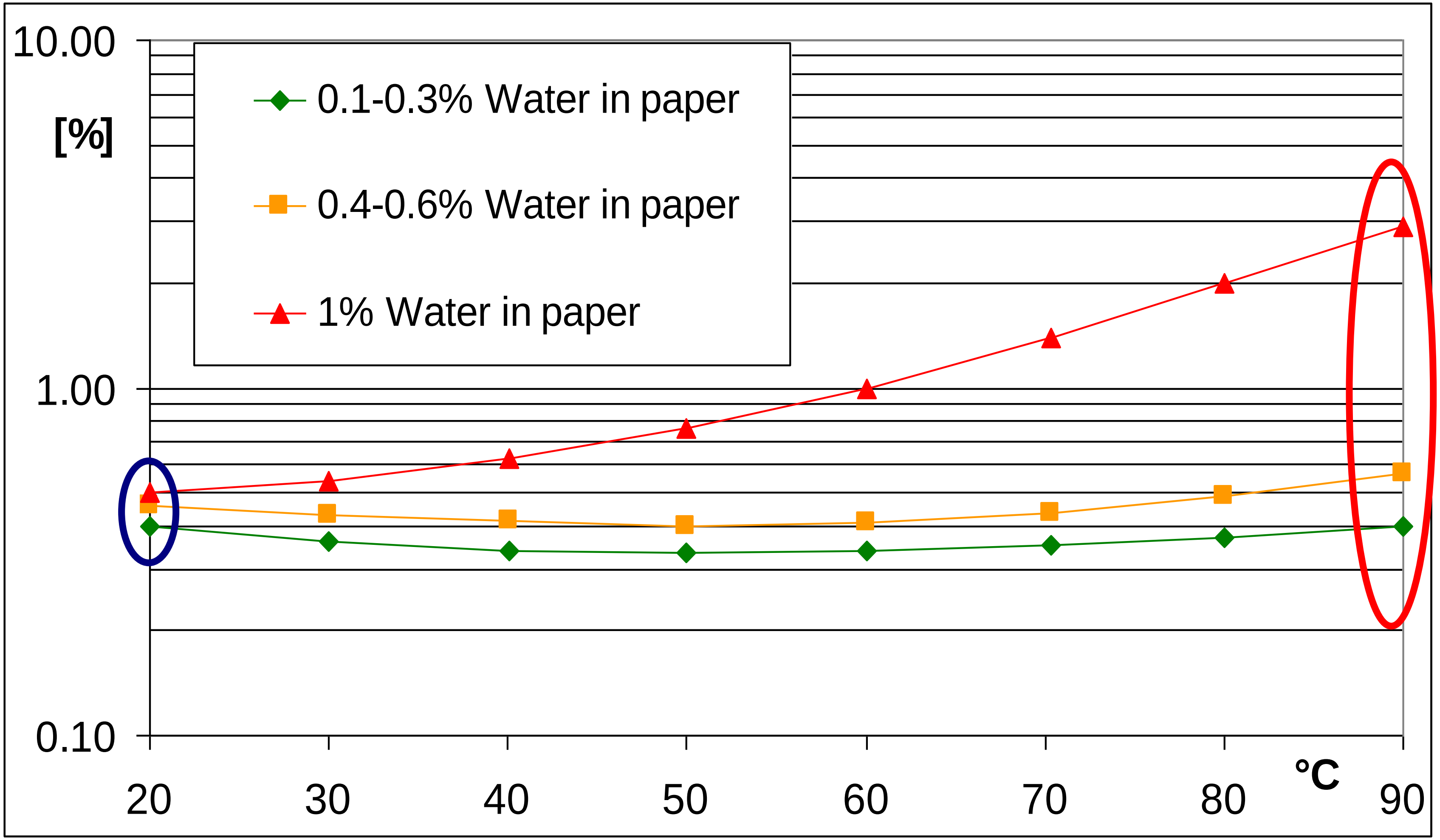
Tan Delta (T) at 50Hz (OIP DF)



Source: ABB, Bushing diagnostics and conditioning

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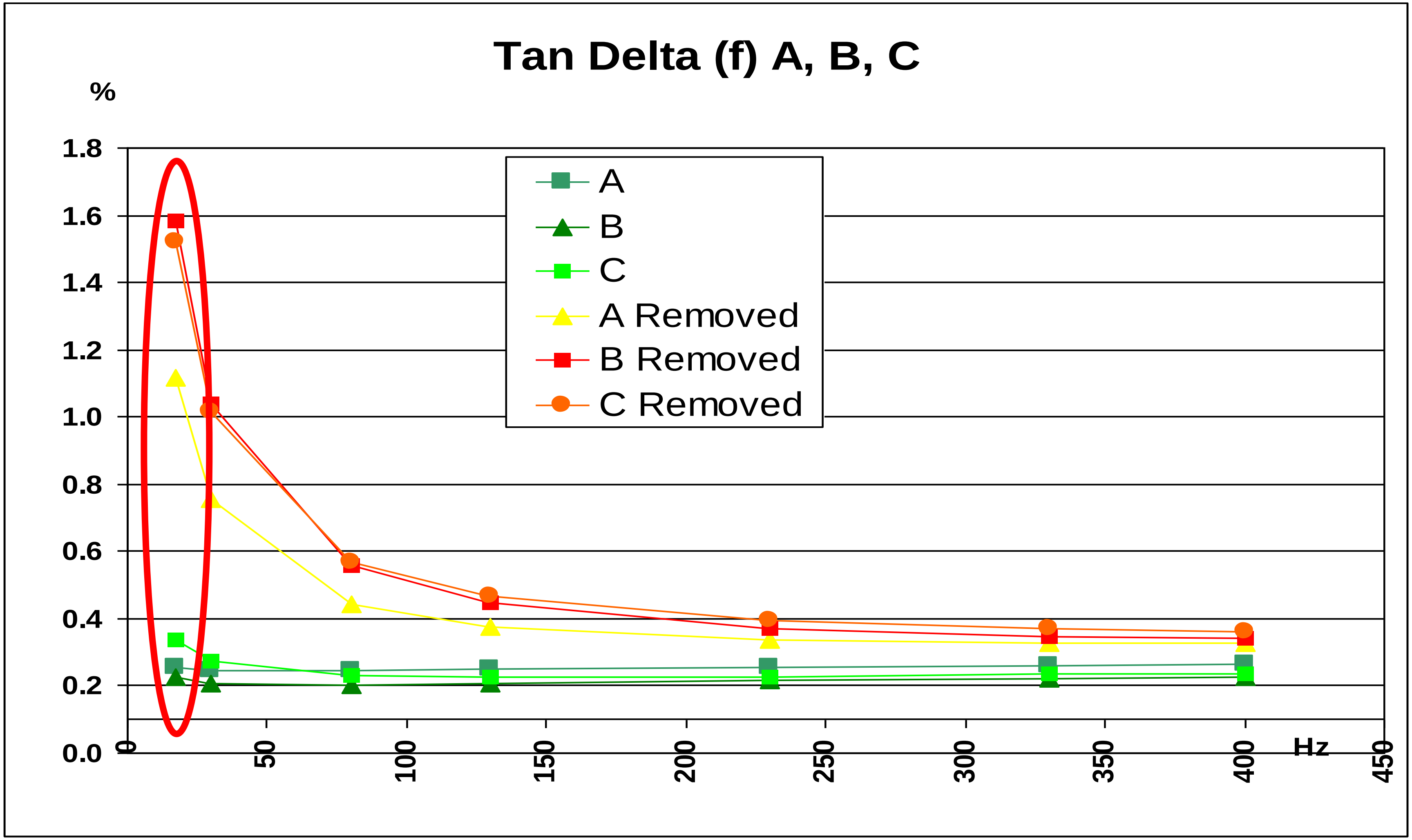
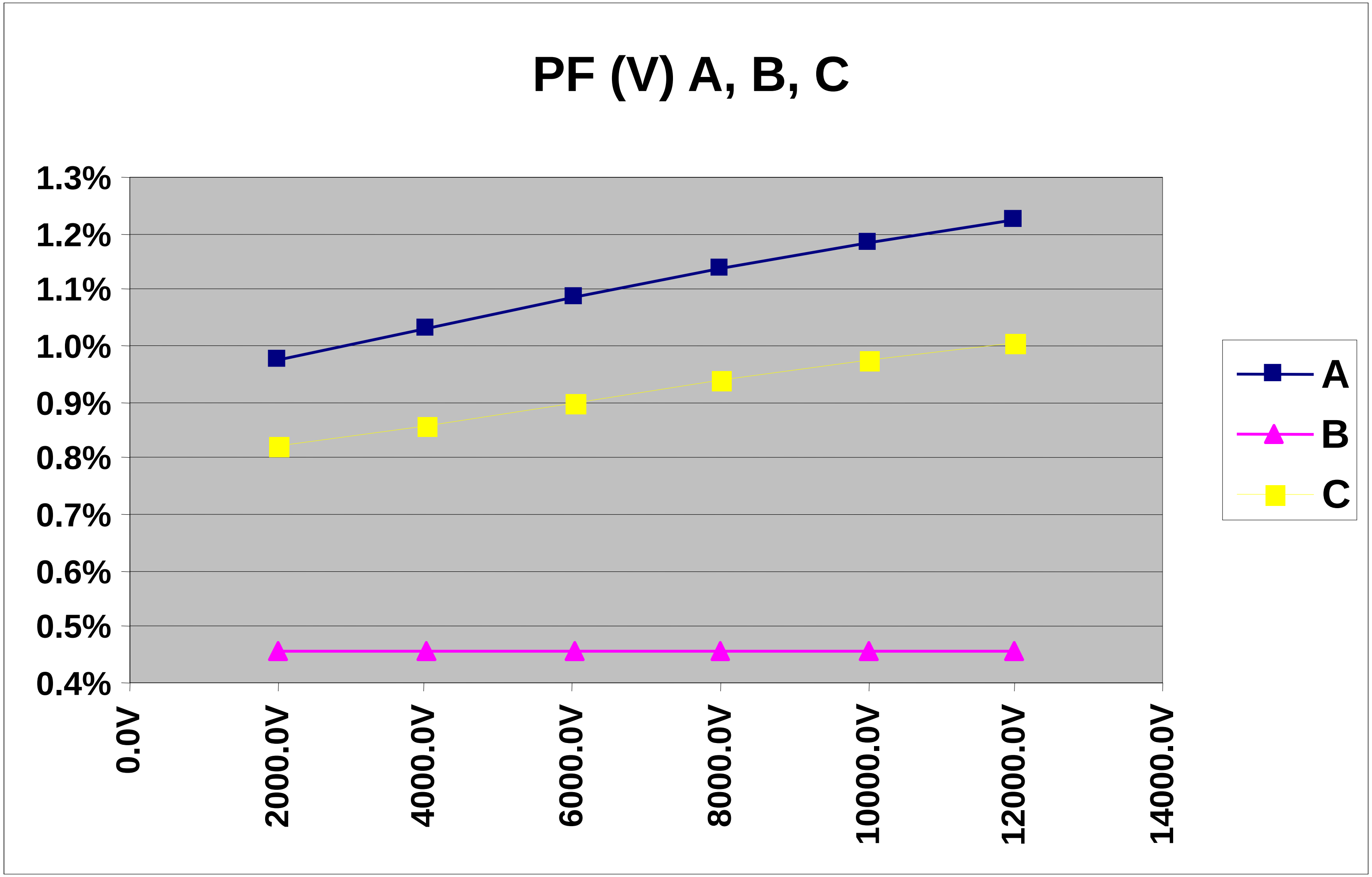
Tan Delta (f) at 30°C (33kV OIP DF)



123kV OIP Bushings TanDelta = f(U)



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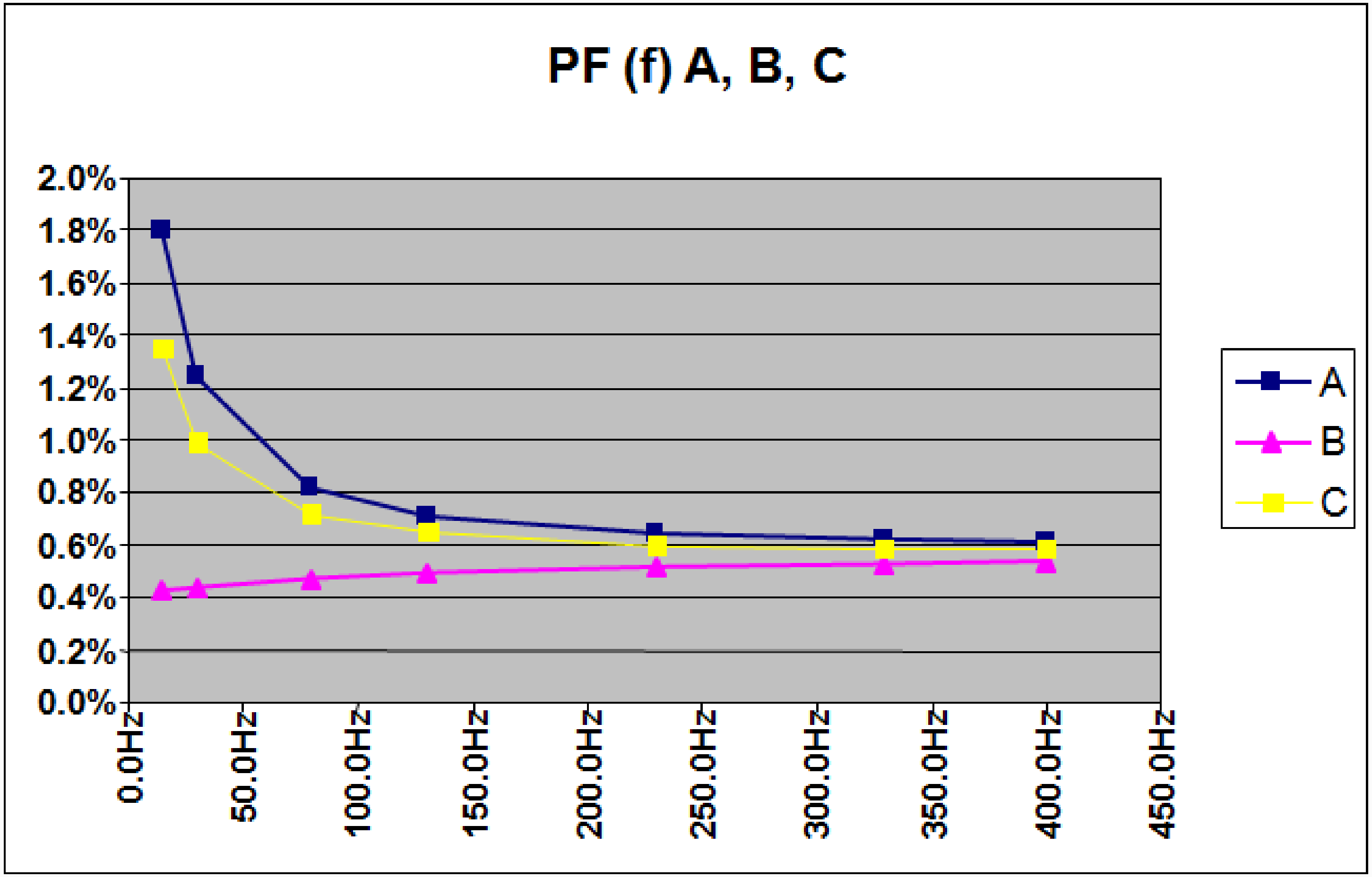
123kV OIP Bushings TanDelta = f(f)



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123kV OIP DF Corroded Measuring Tap

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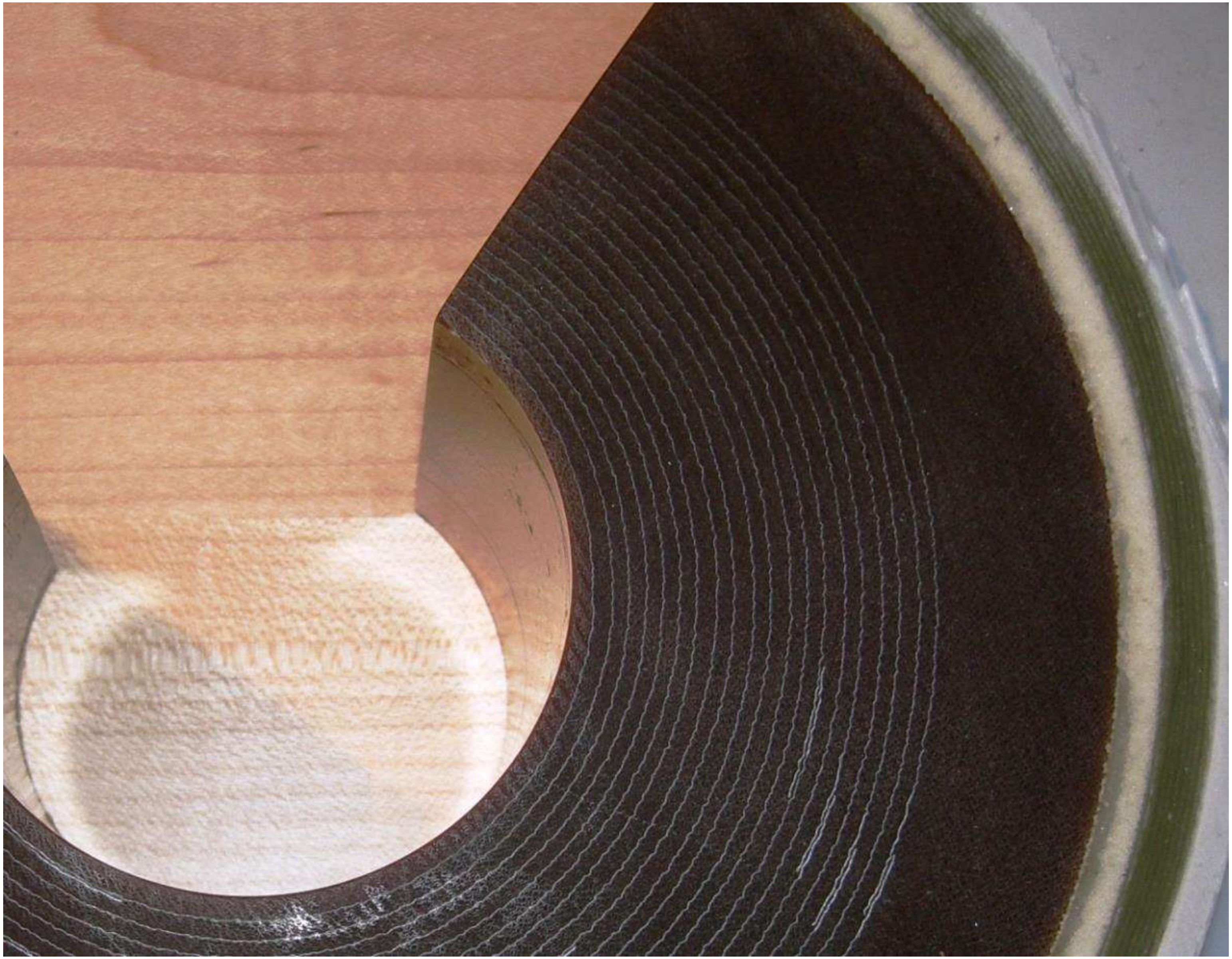
Ageing of RIP Bushings

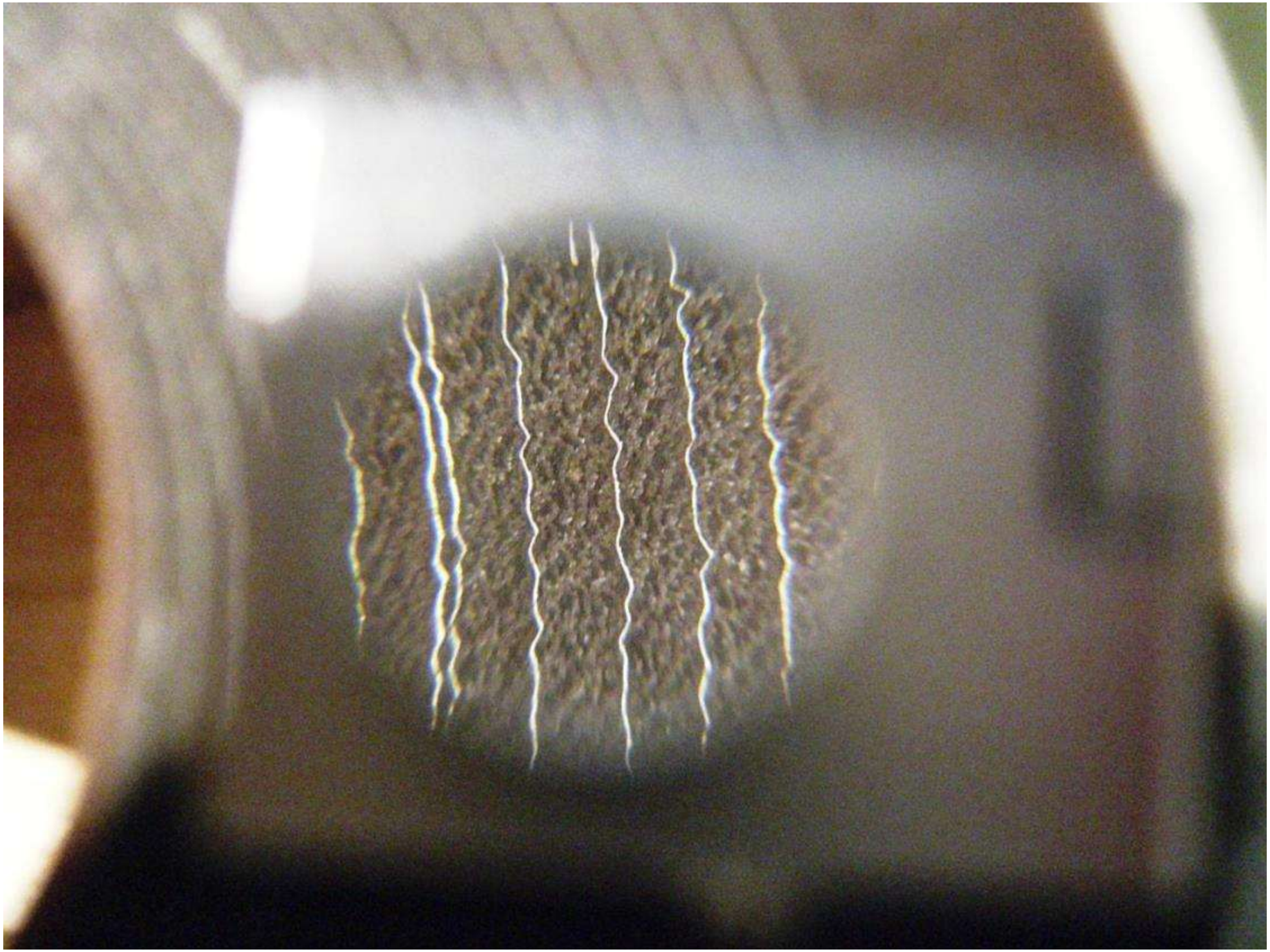
- Partial breakdowns between capacitive layers are rather seldom
- Decrease of the power factor with increasing test voltage can be an indicator for partial breakdowns
- Also defective connections of the measurement layer to the test tap or of the innermost layer to the high voltage conductor may be the reason for a decrease of the power factor with increasing test voltage
- Increase of the capacitance after a partial breakdown between two layers:
- $C_{new} = C_{old} \times n / (n-1)$

  n= number of layers approx. 4-7 kV per layer

RIP Bushings



RIP Bushing



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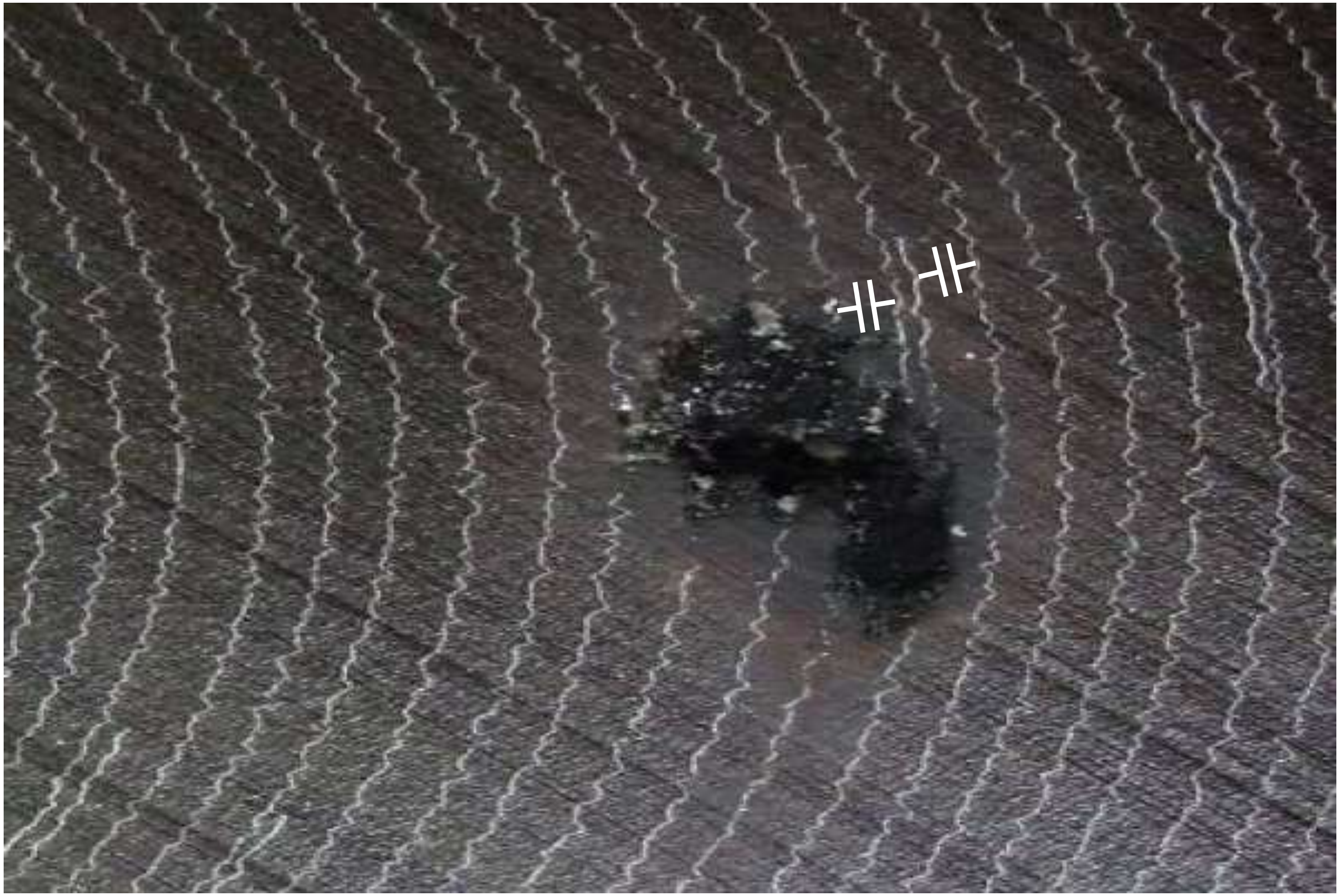
Partial Breakdown on a RIP Bushing



Source: B. Heil, „Diagnose und Bewertung von Durchführungen”, OMICRON AWT Germany 2010

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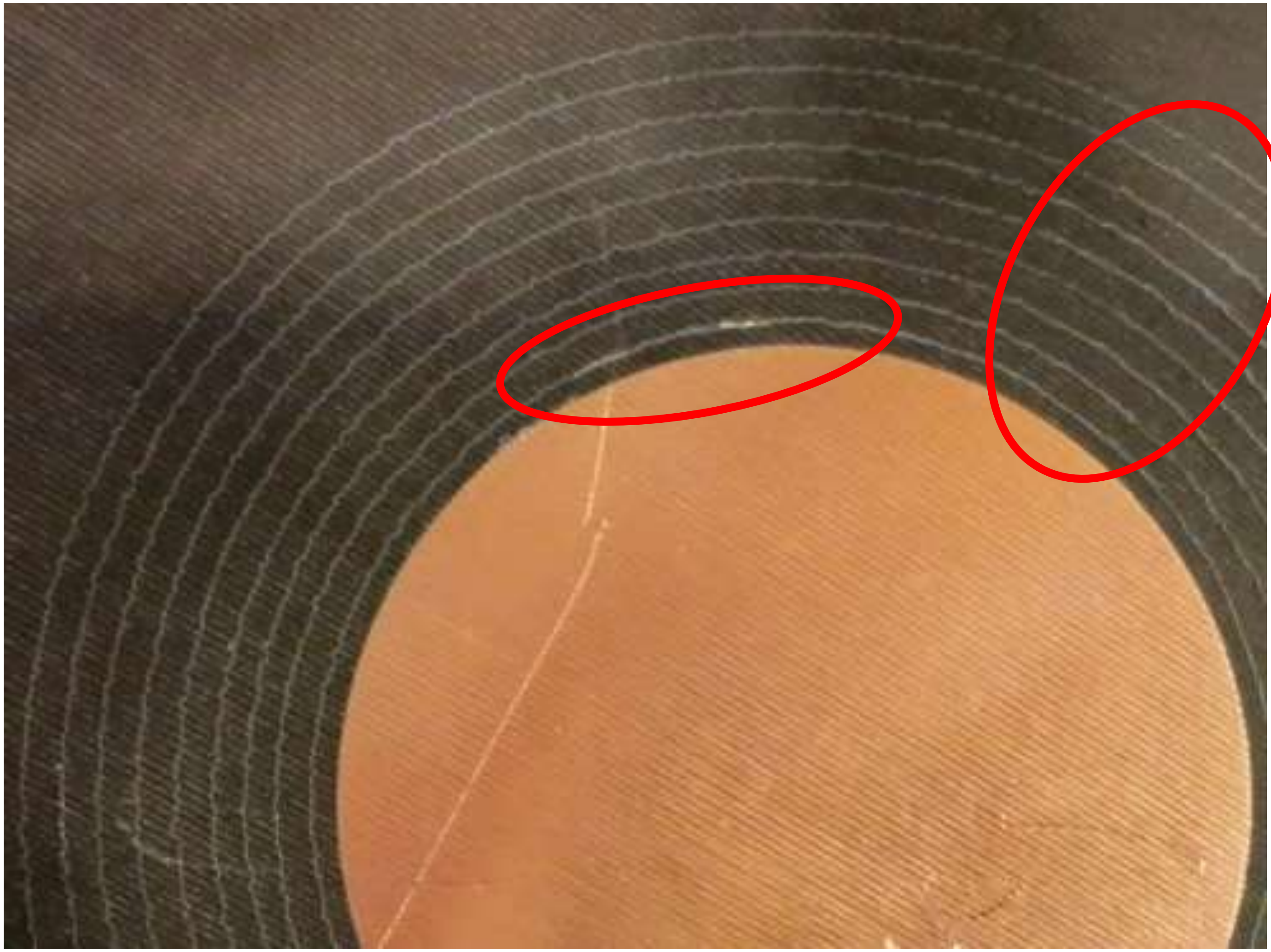
Closed Grading Foils

Better design for Very Fast Transients (VFT)



Breakdown in Oil Causes a Flash-Over in the Earth Lead

due to Fast Transient Earth Currents

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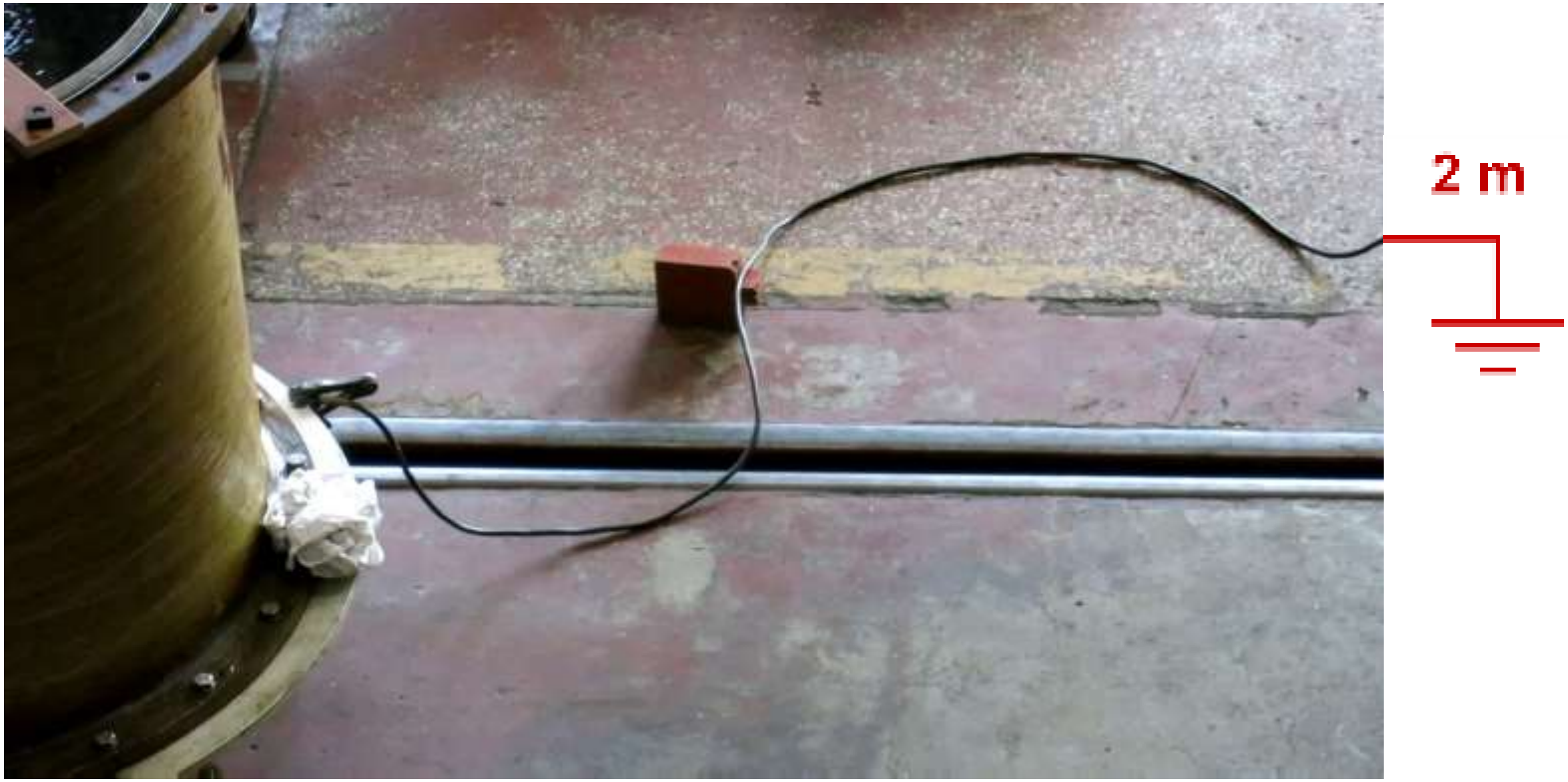
Breakdown in Oil Causes a Flash-Over in the Earth Lead

due to Fast Transient Earth Currents



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Measurement on a 420kV Bushing

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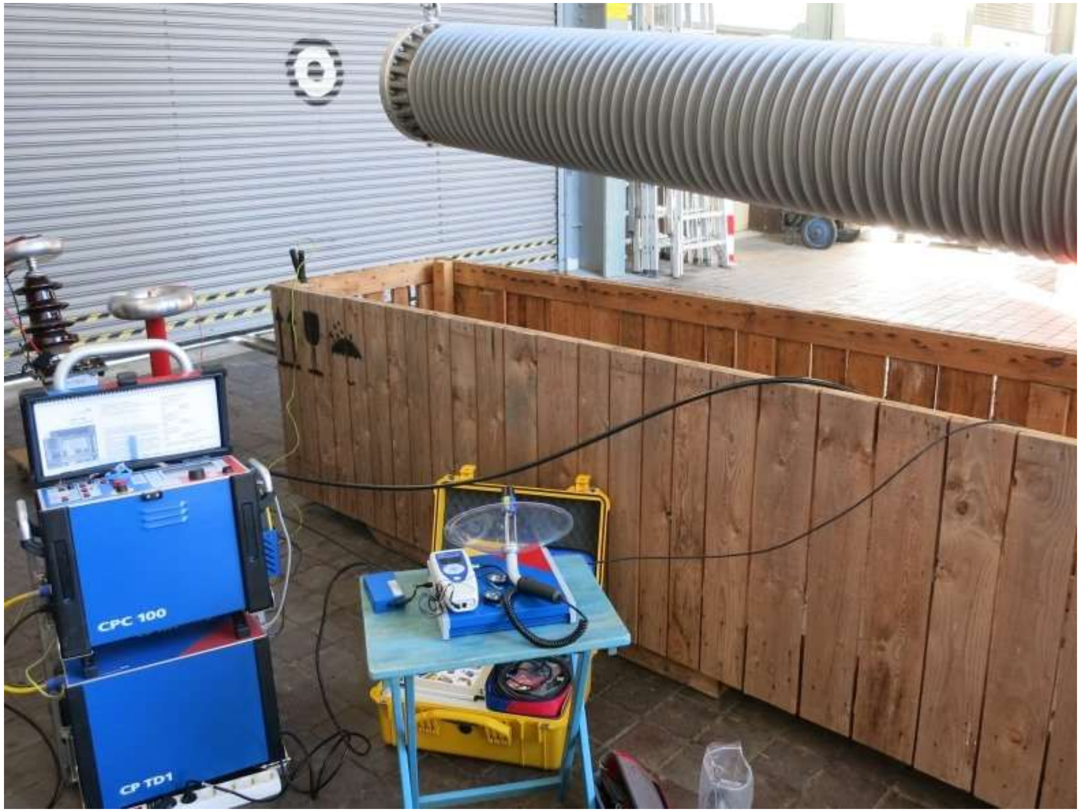
Measurement of the Capacitance and the Dielectric Dissipation Factor on C1



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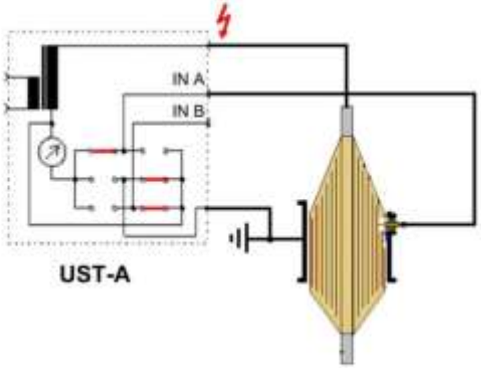
Measurement of the Capacitance and the Dielectric Dissipation Factor on C1

Kapazität und Verlustfaktor bei U=10kV und f=50Hz
UST Messung am Messanschluss mit geerdetem Flansch (Guard)

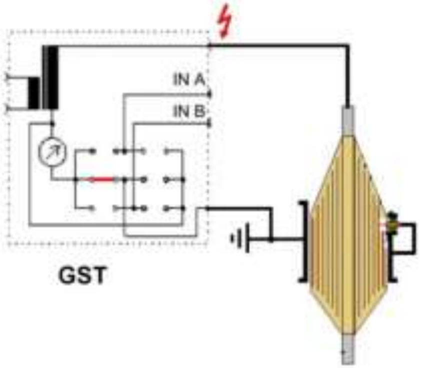
U PRÜF* [V]	I PRÜF [A]	C [F]	VF [%] gemessen
10001,00	1,21E-03	3,852E-10	4,0732



UST

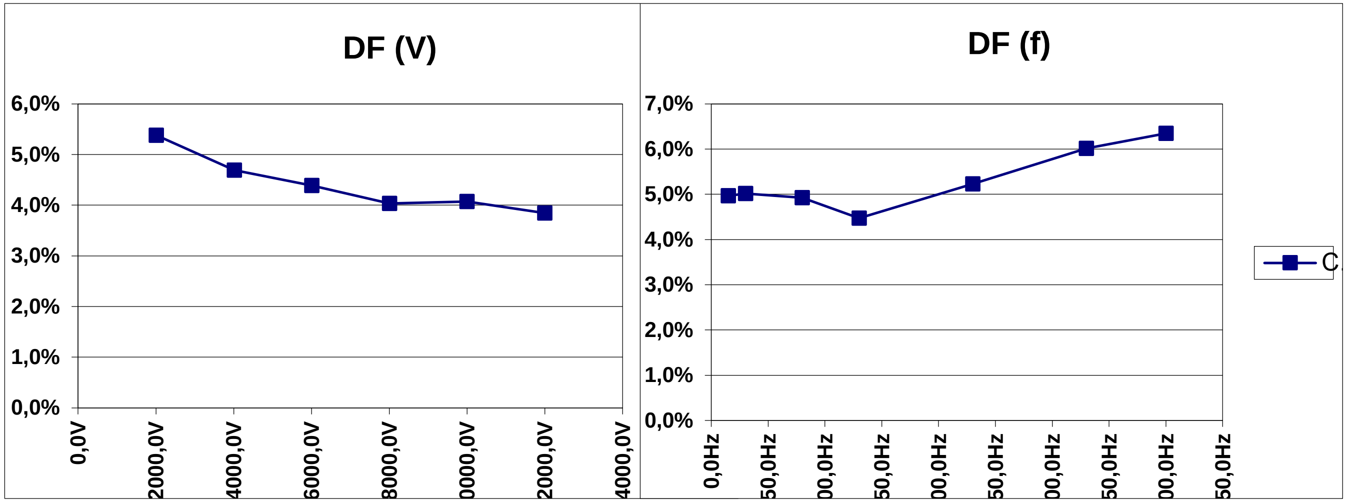
Kapazität und Verlustfaktor bei U=10kV und f=50Hz
GST Messung gegen Flansch mit montierter Messanschlusskappe,
Messanschluss kurzgeschlossen gegen Flansch

U PRÜF* [V]	I PRÜF [A]	C [F]	VF [%] gemessen
10000,00	2,13E-03	6,784E-10	4,0387



GST

Measurement of the Capacitance and the Dielectric Dissipation Factor on C1



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Insulation Resistance Measuring Tap against Flange

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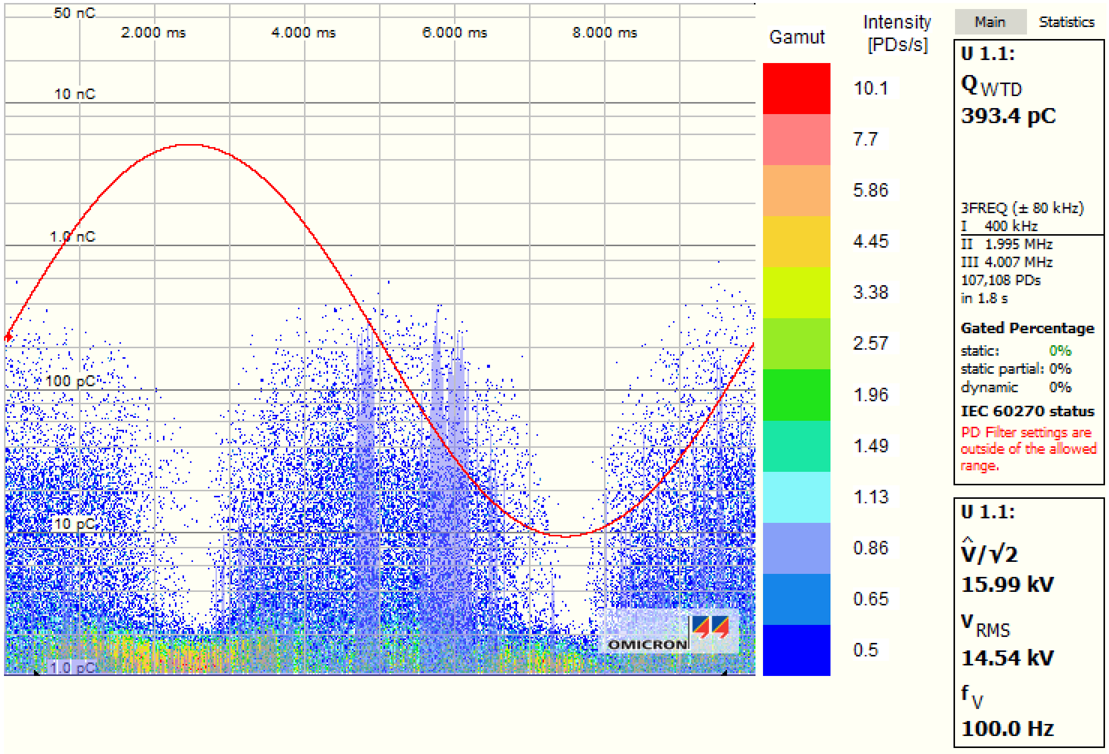
Partial Discharge Measurement

Inception Voltage below 20kV



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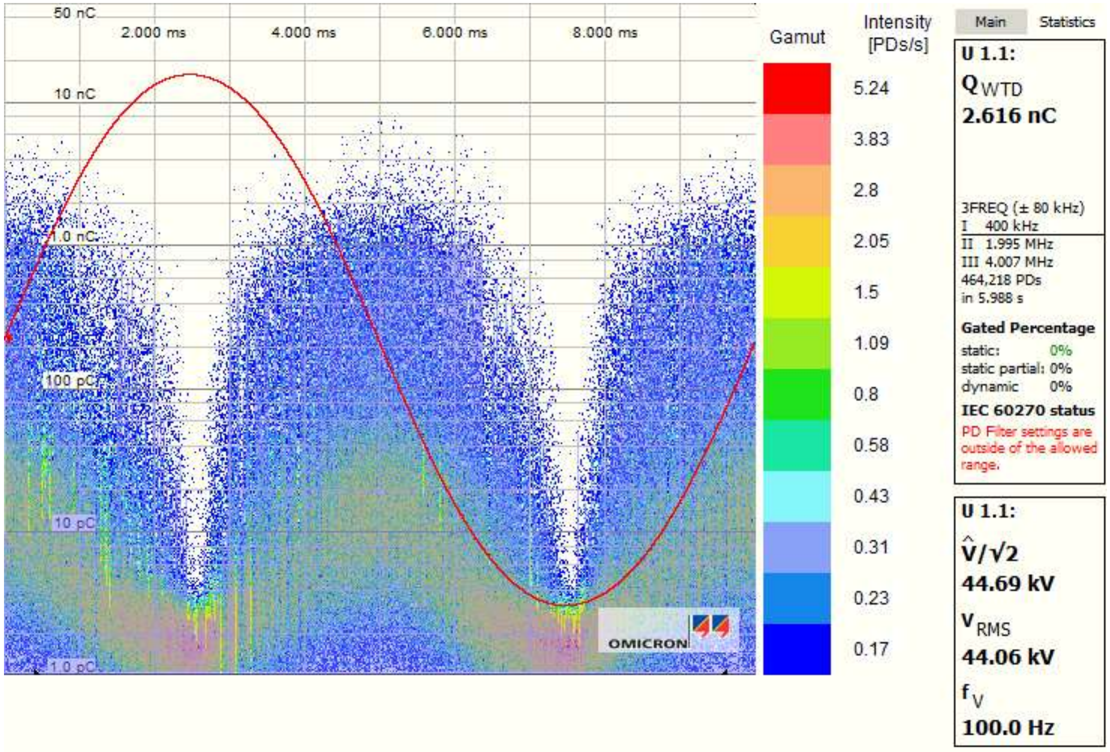
Partial Discharges > 2nC at 45 kV



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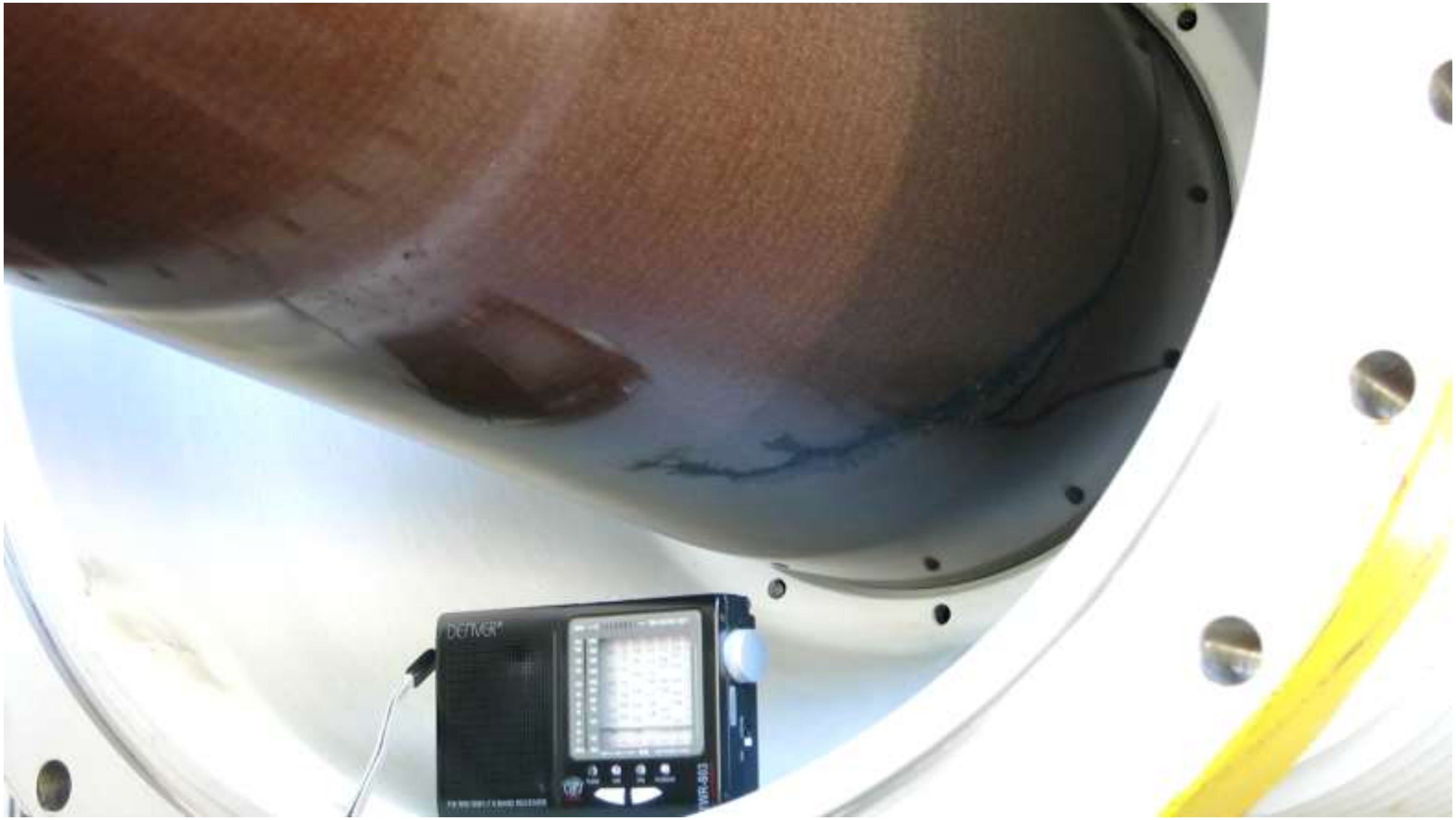
PD Location



Measuring Tap

Measuring Tap

Cutted Bushing

Burned Contact Spring

50Hz: $I = U \omega C \approx 37$ mA

VFT: $I = C \, du/dt > 100$A

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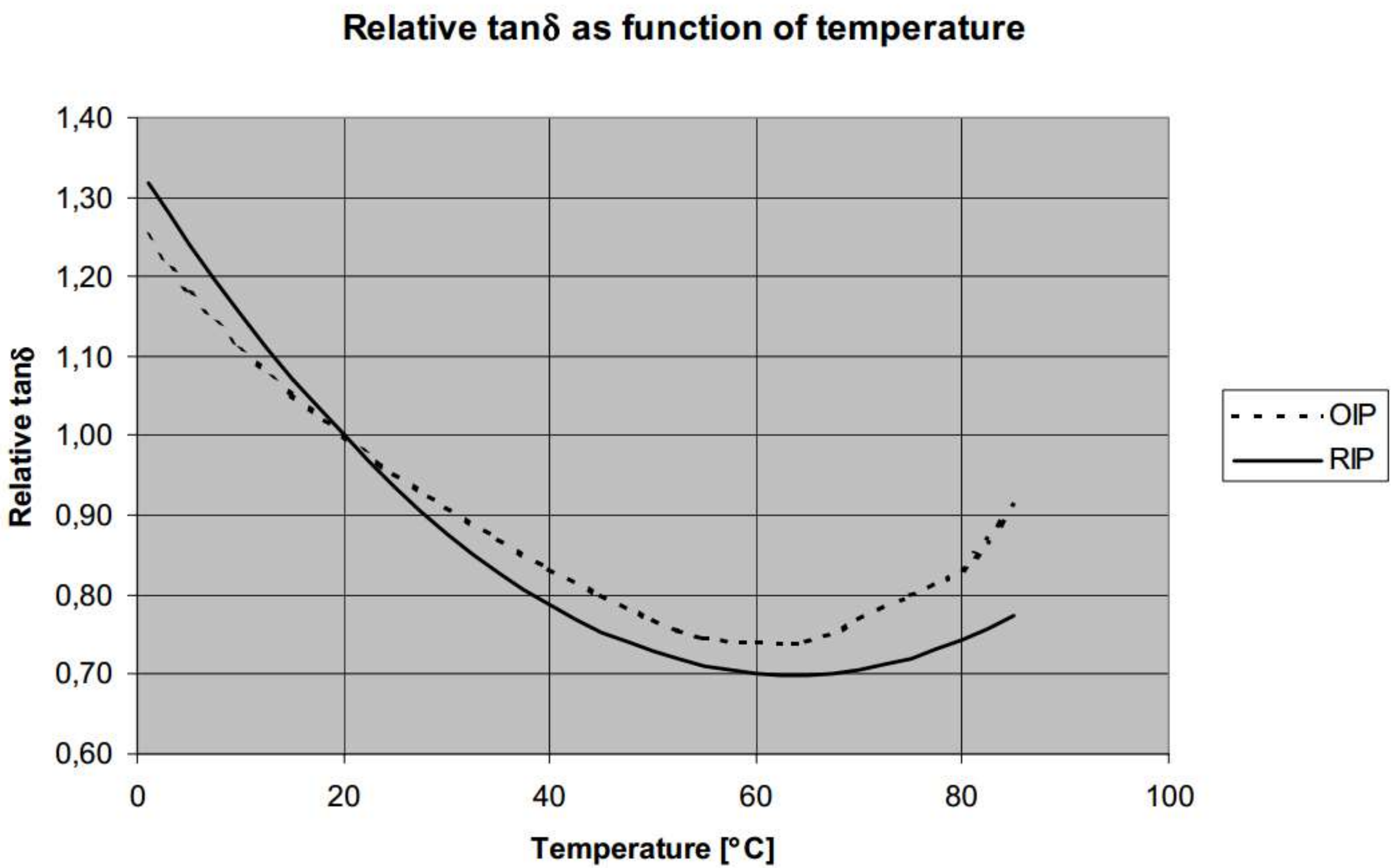
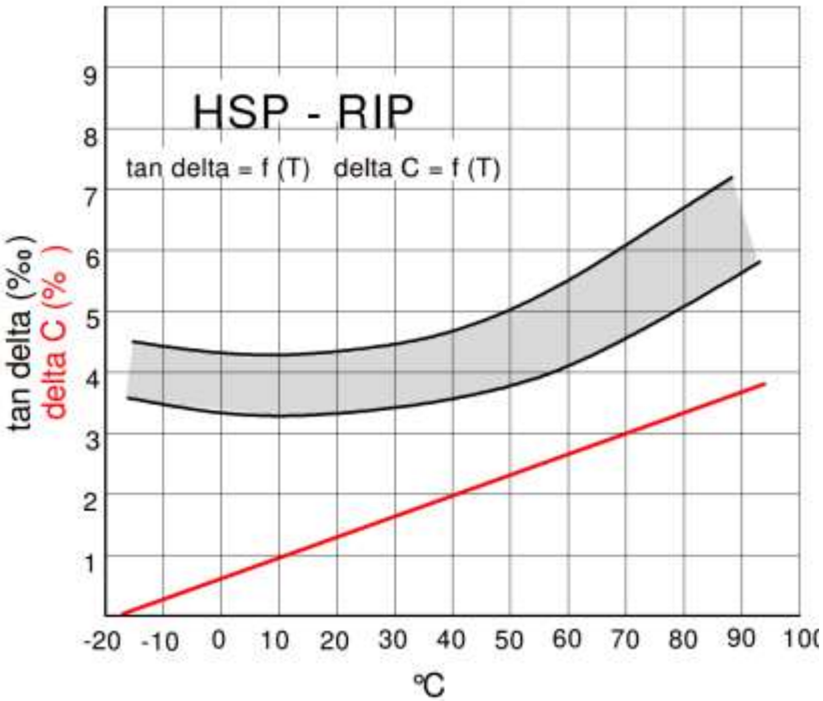
Relative Tan δ Dependency on the Temperature



Source: ABB: „Bushing Diagnostics and Conditioning“ Brochure 2750515-142 en, Ludvika 2000

C-Tan δ

Dependency on the Temperature



5.4 Electrical measurements

Measurements on bushings require experience with measuring equipment, test set up and the interpretation of measurement results.
This is for some part due to the relatively small capacitance values, which are corrupted by the ambient influence of the environment alone. The measurement of the dielectric dissipation factor can be influenced by the voltage feed on the GIS-side by humidity, weather etc.

Example of mobile measuring equipment

Fig.23

5.5 Measuring procedures

Mainly the measuring procedures differ by the coupling of the measuring signal. In case of so-called “not grounded” measurements the test voltage is applied to the conductor of the bushing and the measuring signal is taken at the test tap of the bushing.
The “grounded” measuring procedure is applied, if the bushing which has to be measured does not have a test tap. This is not applicable for the bushing type EKTG.
The devices required for the measurement are usually equipped specifically for the measurement of bushings. The measurement methods are described in comprehensive manuals.

5.6 Equipment

Measuring equipment is available from several manufacturers. Data can be found in the internet or enquired at HSP.

5.7 Limits

For the measurement the influence of the ambient temperature has to be taken into consideration. In the diagram on the left side for C and tan delta the variation through temperature is shown. (Fig.24).

For the material RIP, resin impregnated paper there are limit values for the deviation of the capacitance and the dielectric dissipation factor with relation to the “new value”.
This value is reliably deducted from the reference measurement described under 4.4.

In case the deviations are larger than mentioned in the table below, HSP has to be contacted in any case. When there are very large deviations the bushing may have to be taken out of operation.

Voltage level	C-Deviation
< 123 kV	10 %
≥ 123 kV	5 %
≥ 245 kV	3 %
≥ 420 kV	1 %
Guide value tan delta	0.004 – 0.006

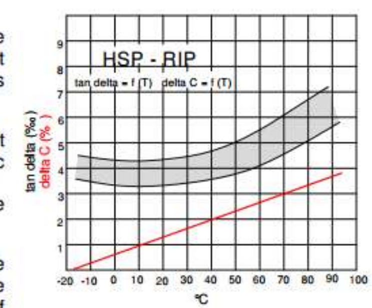


Fig.24

Source: HSP Operation Instruction BAL EKTG03e

220kV RIP Bushing, Stored Outside

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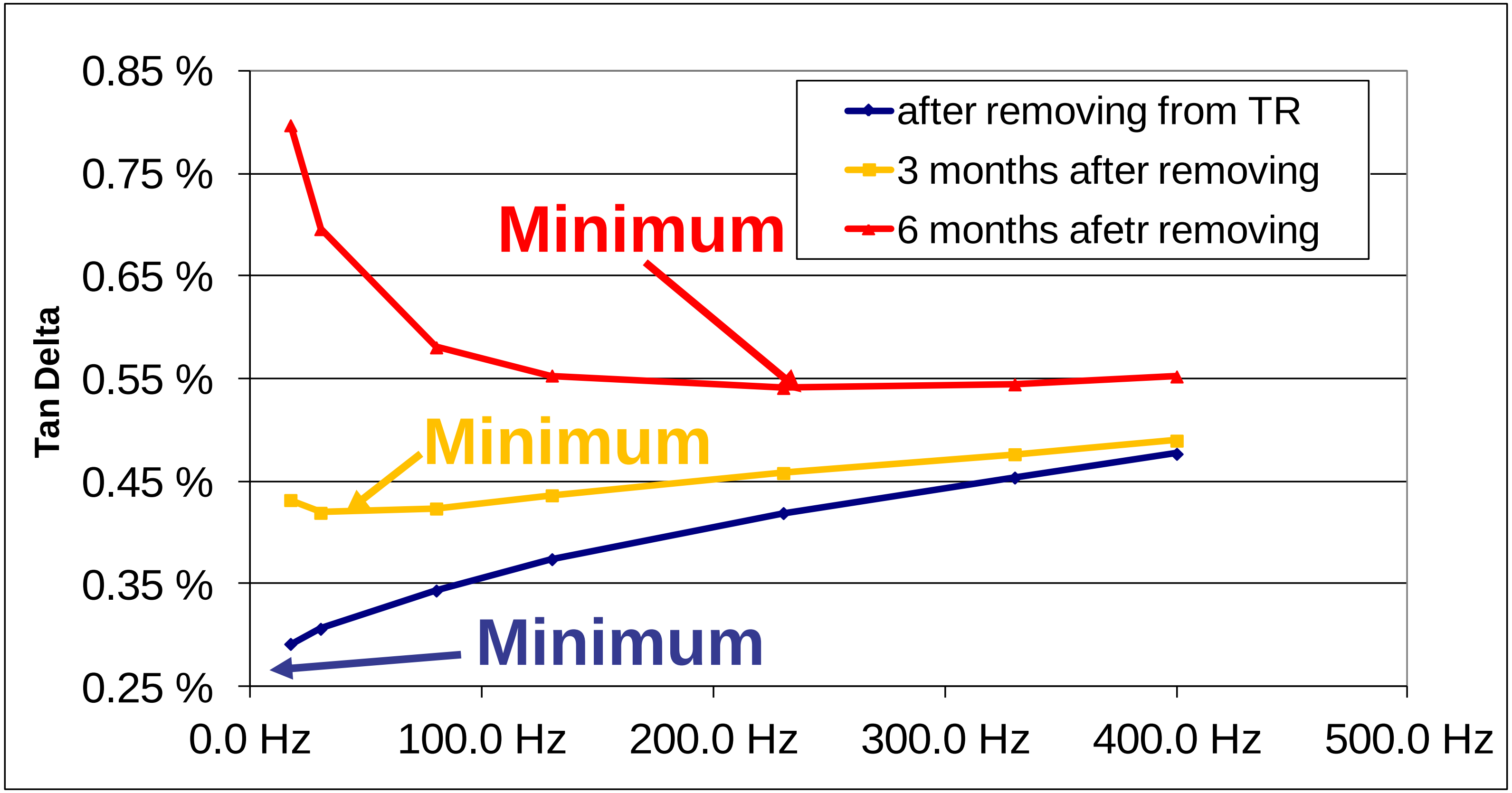
220kV RIP Bushing, Stored Outside



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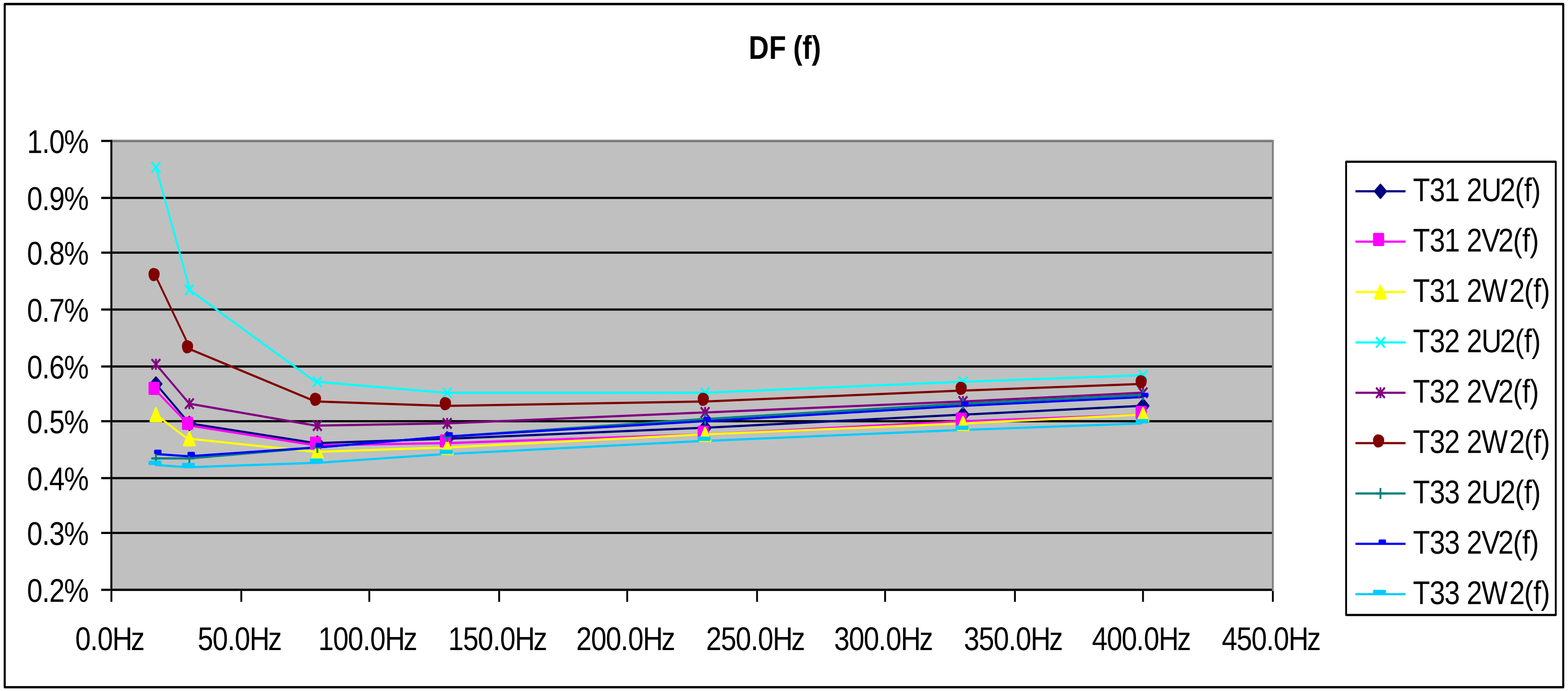
Influence of Humidity –

for 123kV Bushings with Silicone Coated Composite Insulators Mounted Horizontally

Influence of Humidity –

for 123kV Bushings with Silicone Coated Composite Insulators Mounted Horizontally



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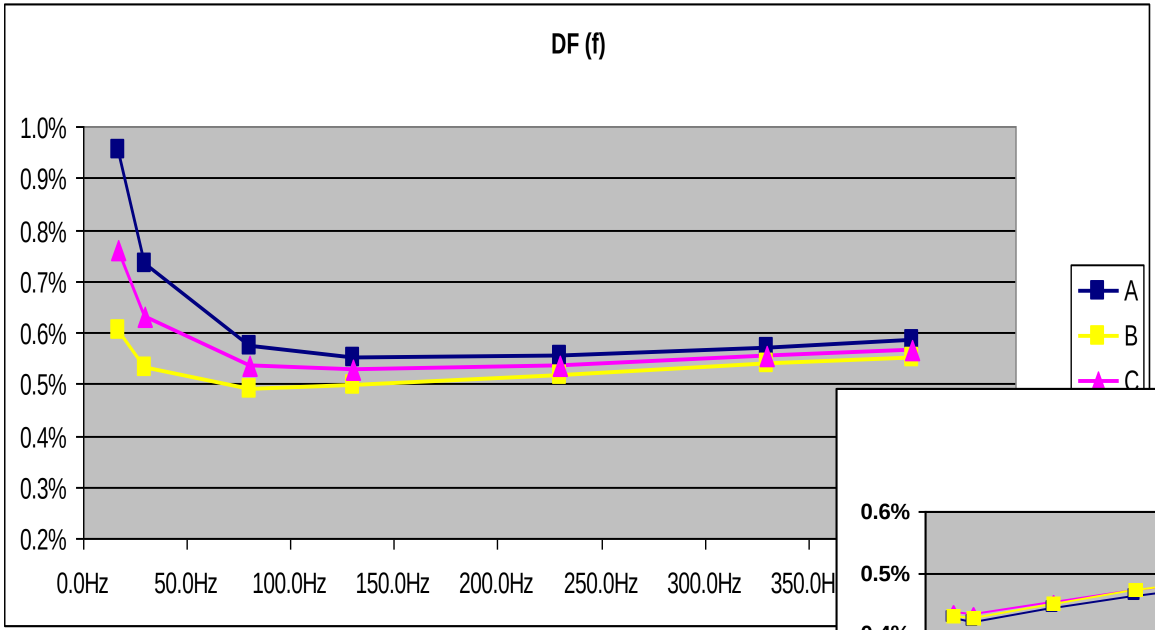
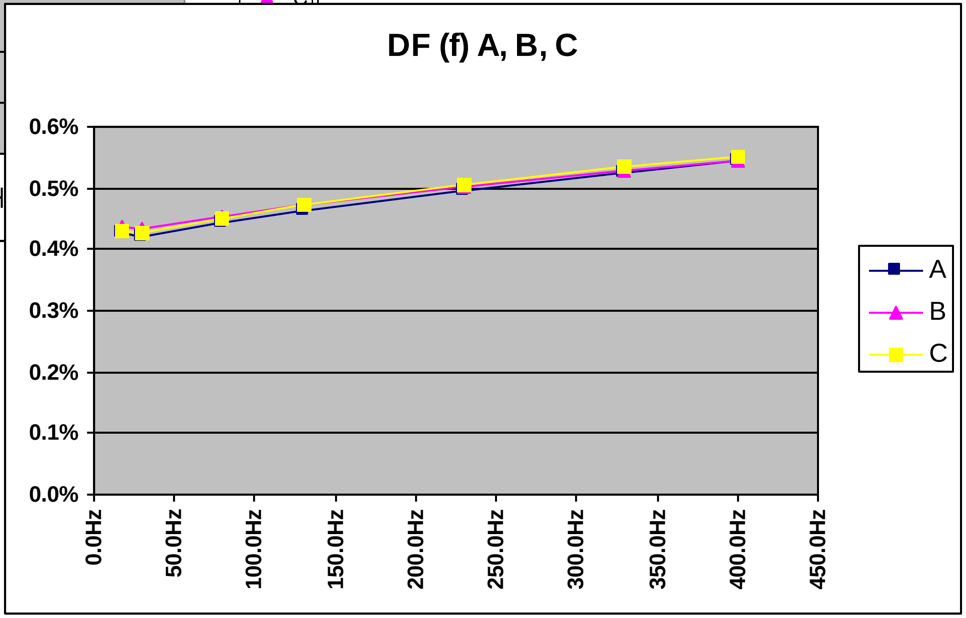
Influence of Humidity

for 123kV Bushings with Silicone Coated Composite Insulators Mounted Horizontally



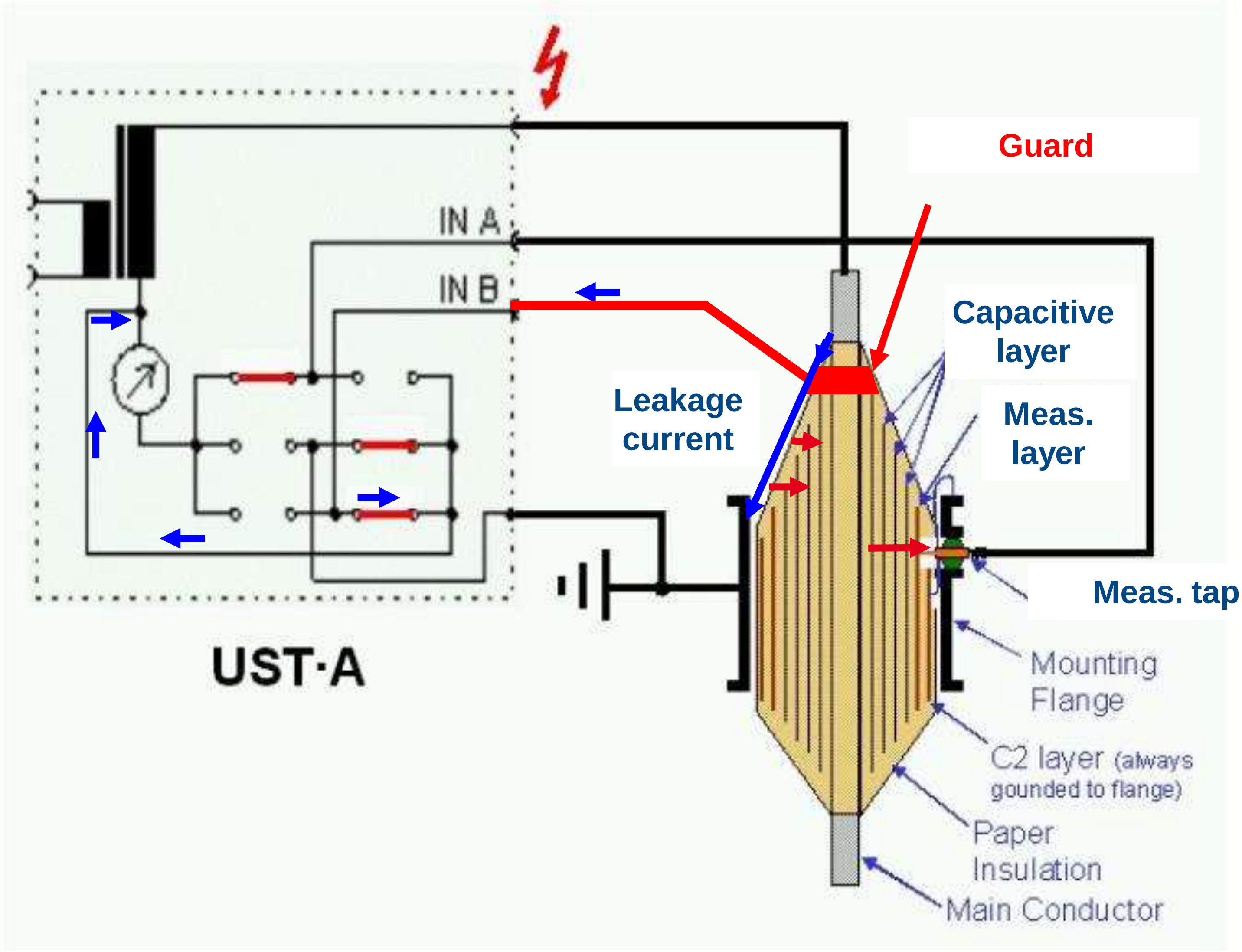
Bushings with moss and outer humidity



Bushings cleaned, measured at dry weather

Measurement with Guard

Leakage current is bypassing the meter



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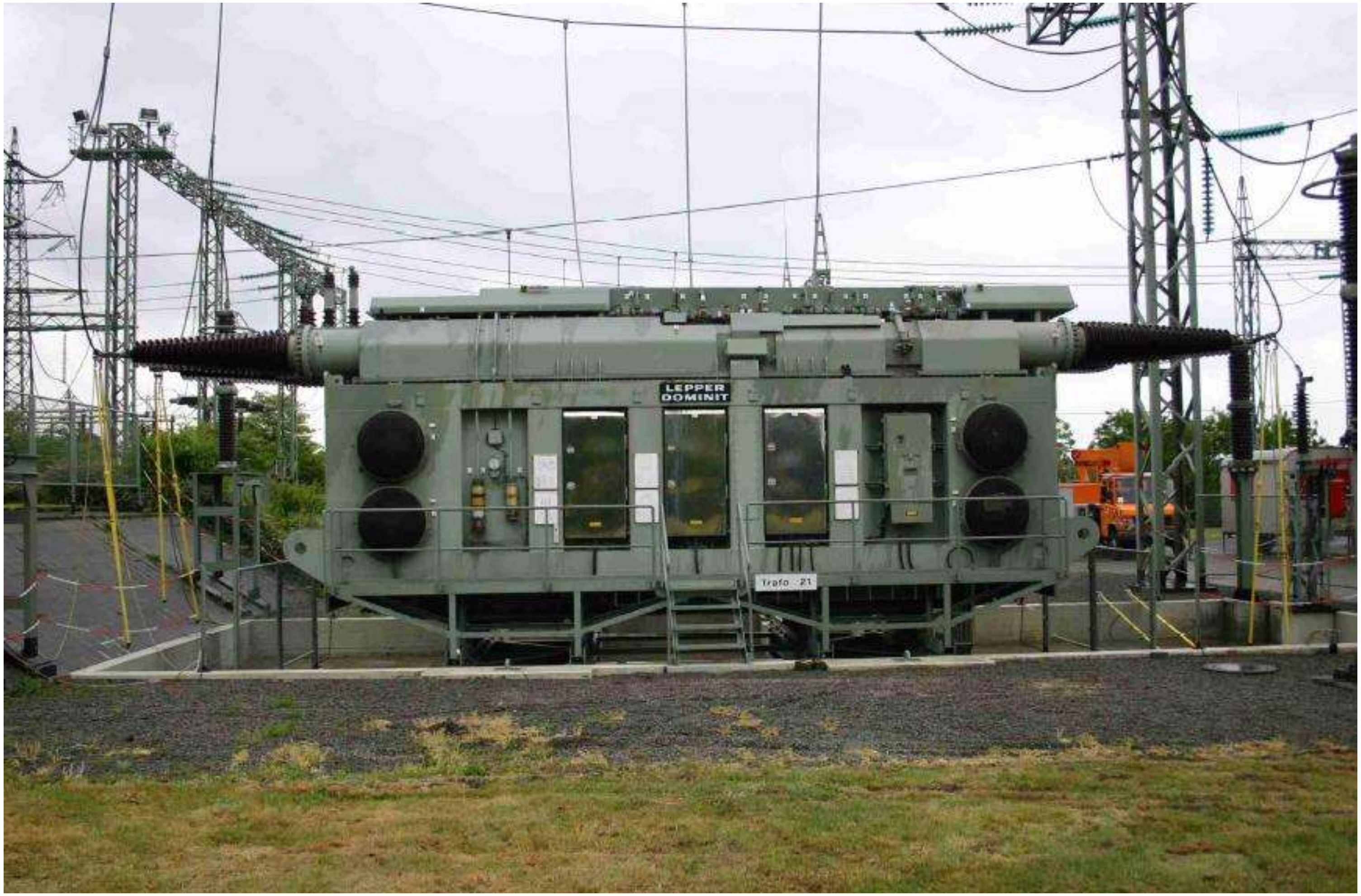
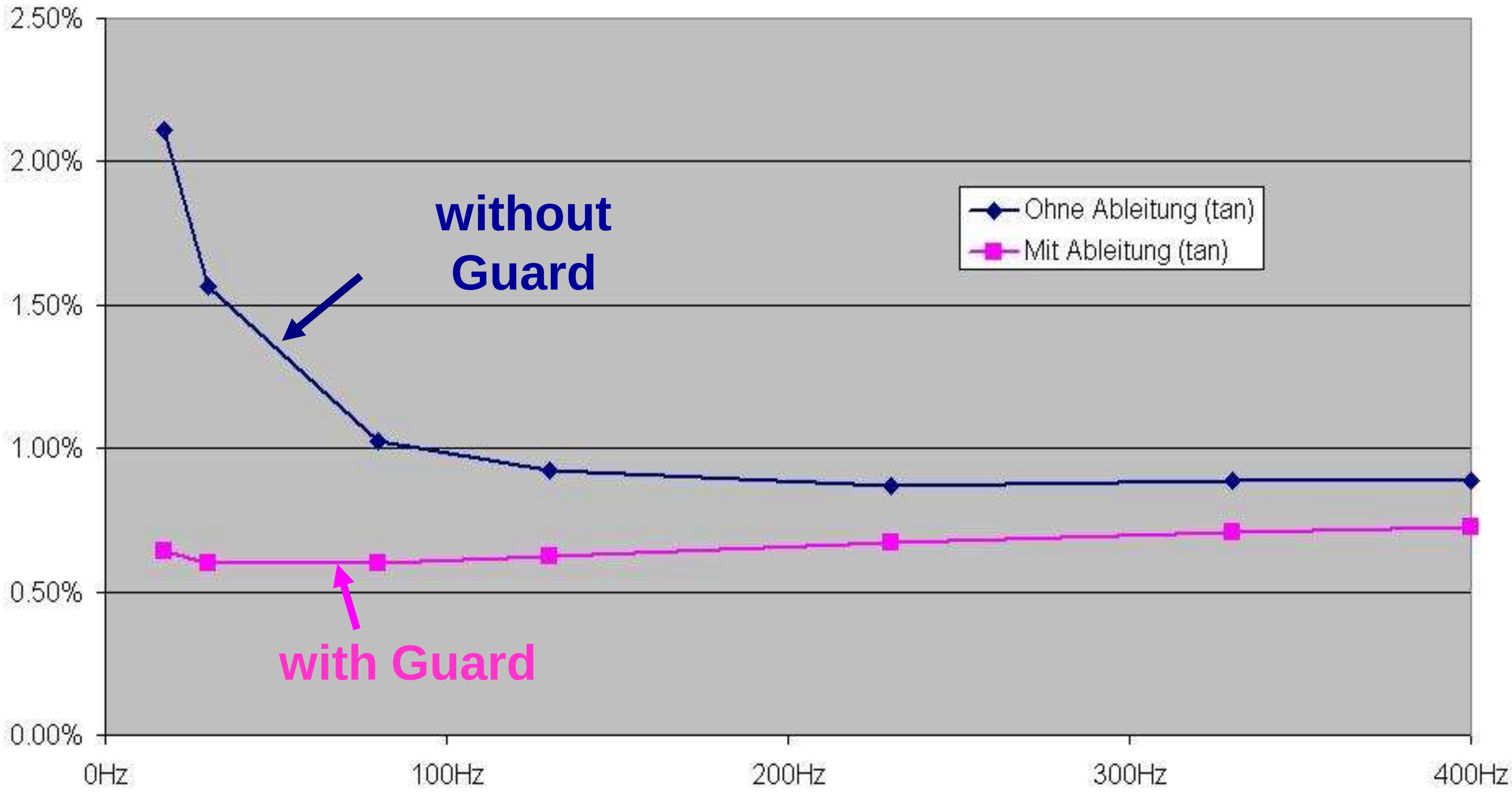
Measurement With High Humidity With and Without Guard



Measurement With High Humidity With and Without Guard



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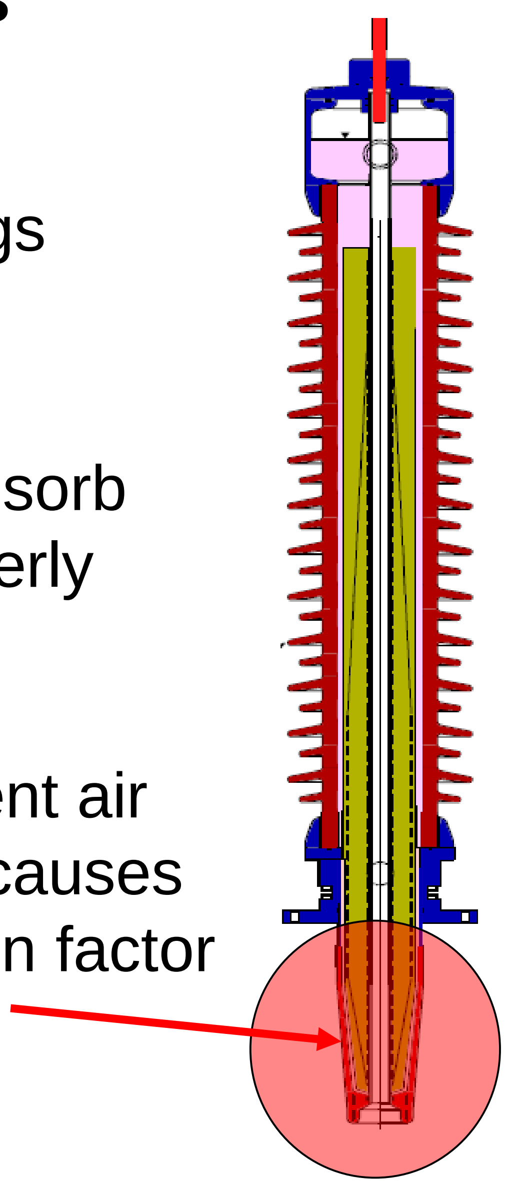
Moisture in RBP and RIP Bushings

- The oil side of RBP and RIP bushings doesn't need a housing

- Cellulose near to the surface can absorb water, if bushings are not stored properly

- Incoming water, also from the ambient air reduces the dielectric strength – this causes an increase of the dielectric dissipation factor



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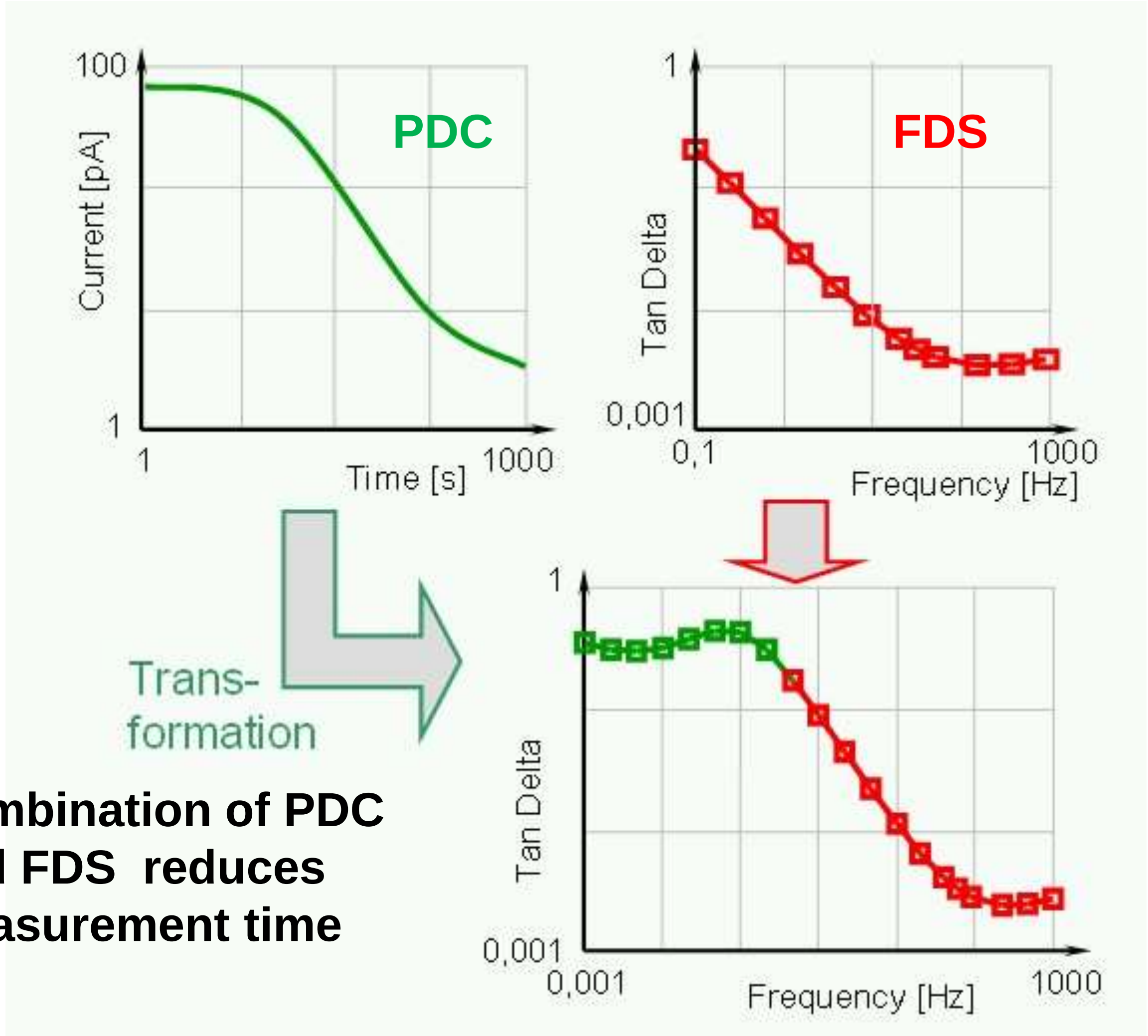
Water in RBP and RIP Bushings

RIP wet RIP dry

Measurement of the Dielectric Response with FDS und PDC



Combination of PDC und FDS reduces measurement time

Combined FDS-PDC Measurement on a RIP Bushing

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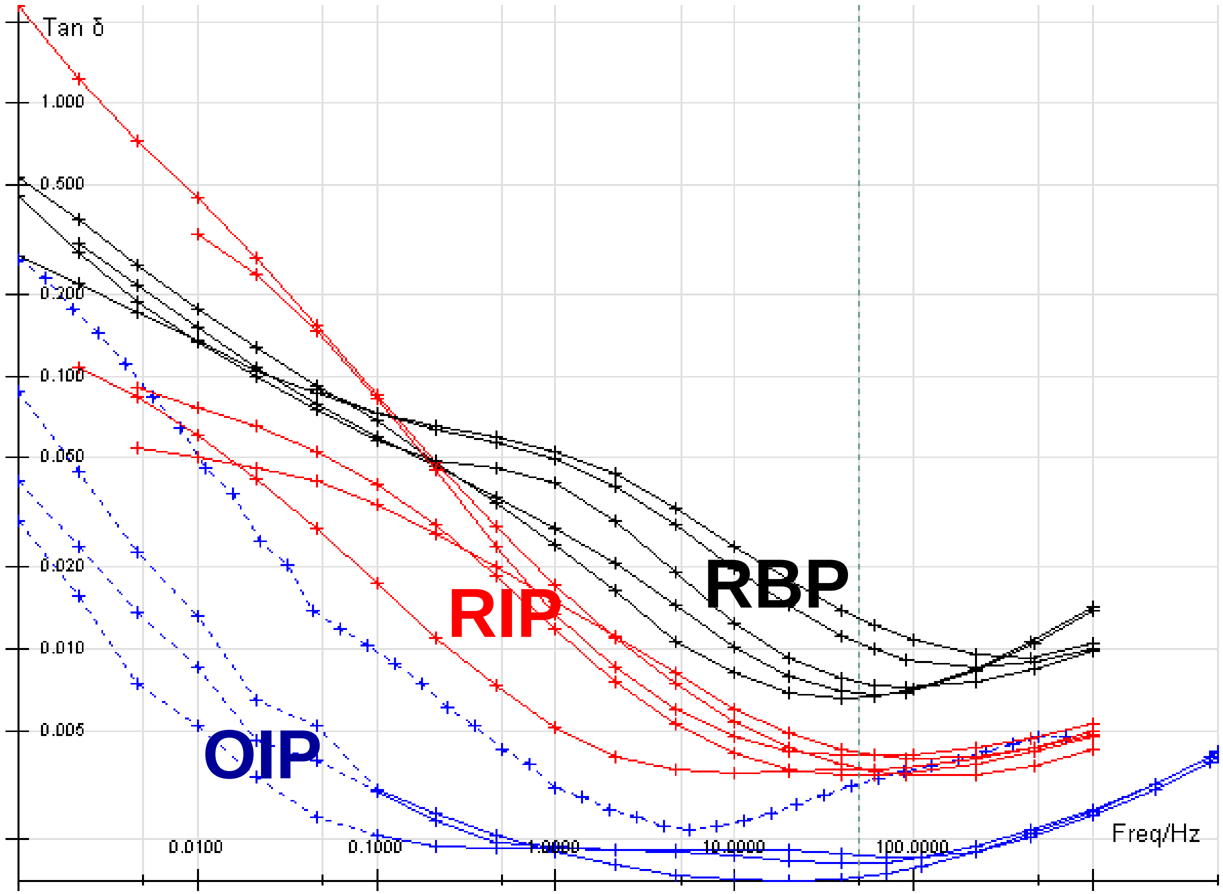
FDS Results on RIP, RBP and OIP Bushings



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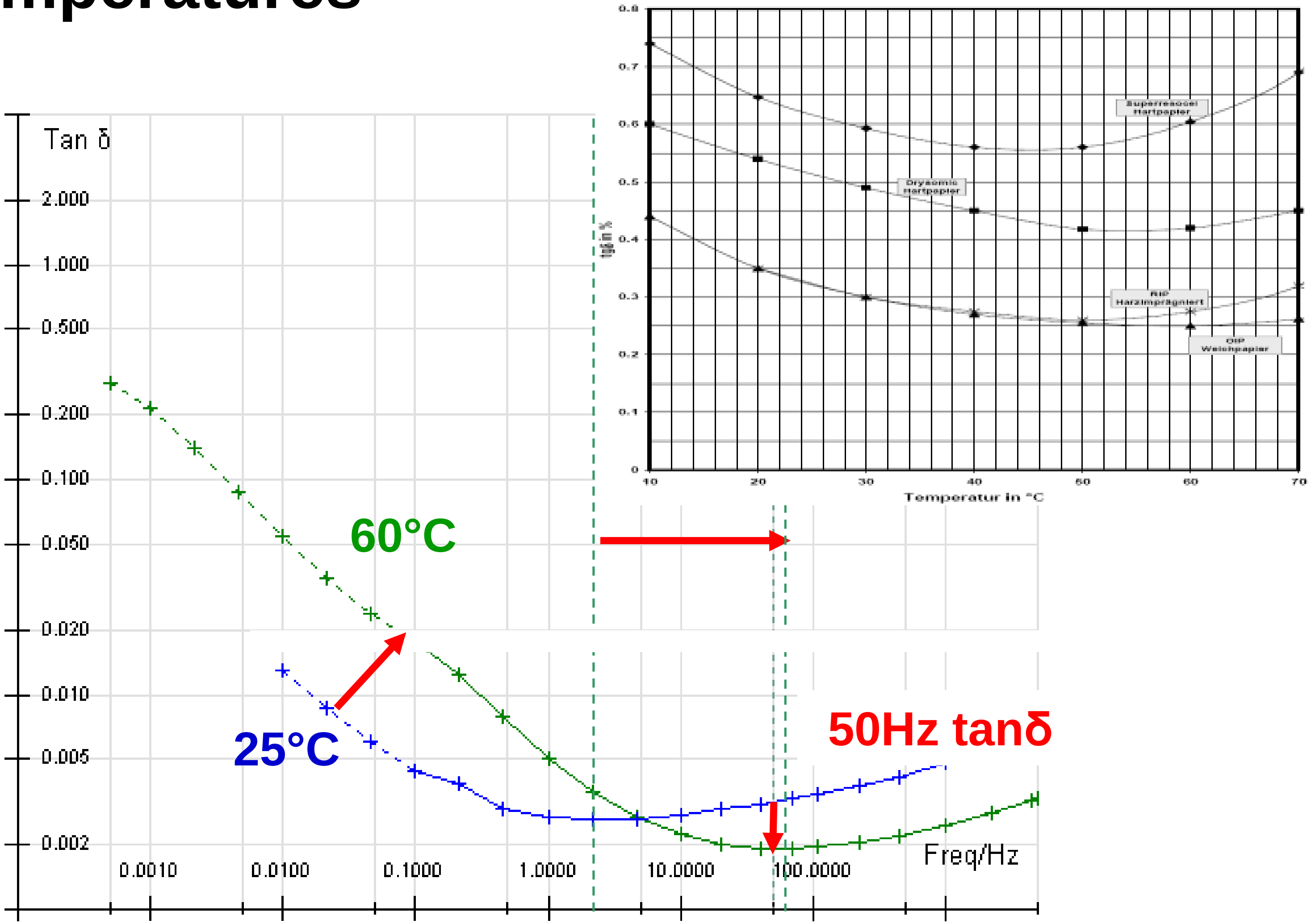
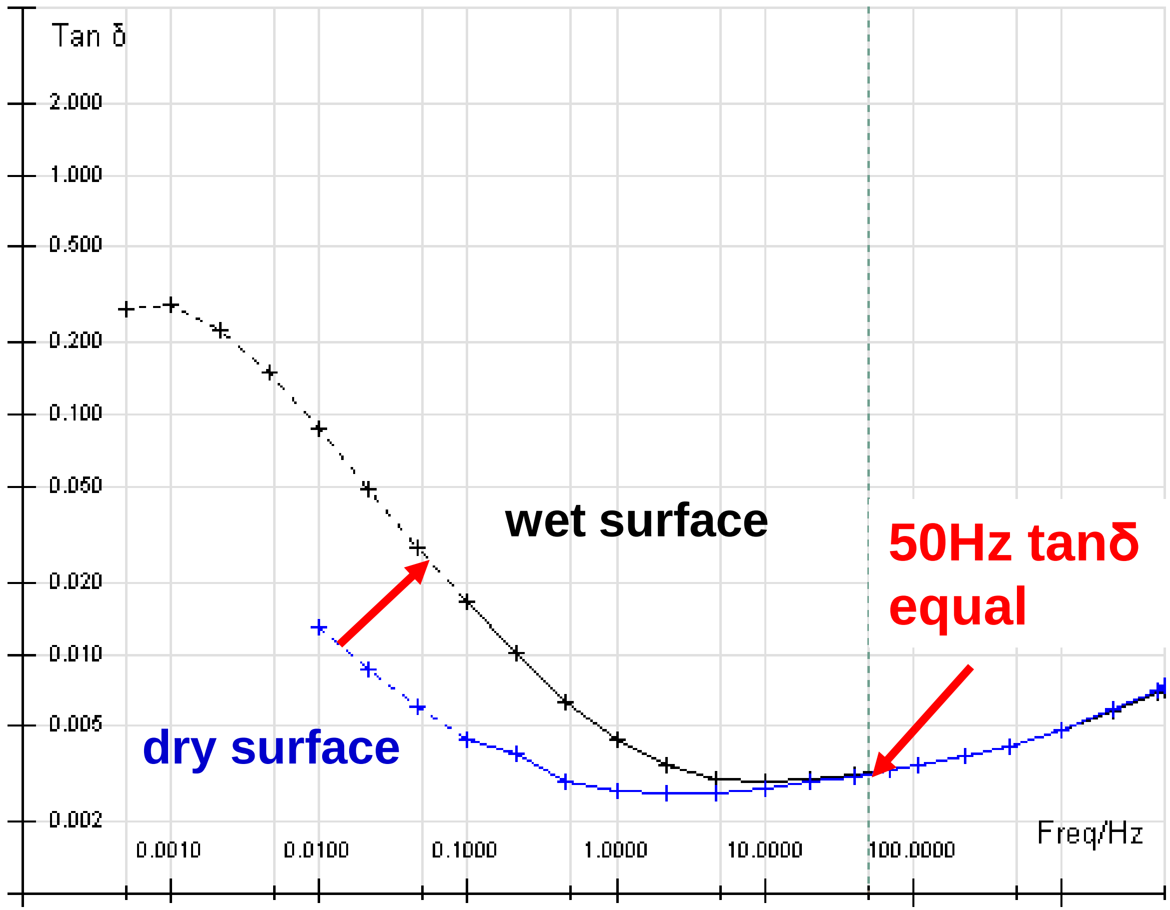
FDS/PDC on a RIP Bushing at Different Temperatures



Source: G. Kopp, „Measurement of the dielectric response on HV bushings "

FDS/PDC with Dry and Wet Surface



Source: G. Kopp, „ Measurement of the dielectric response on HV bushings “

Drying of a 145kV RBP Bushing TanDelta Measurement

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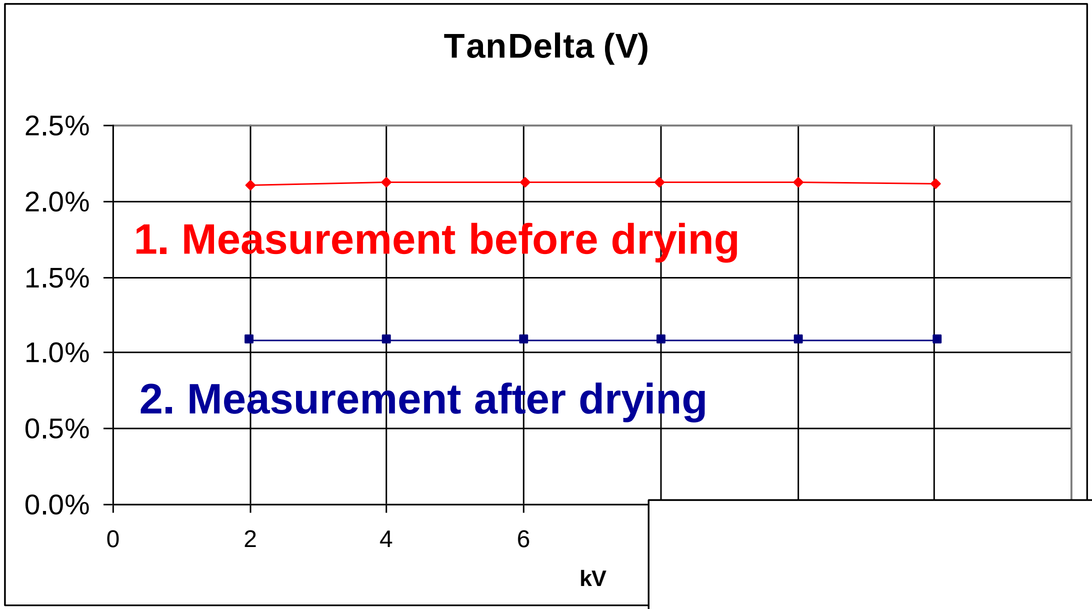
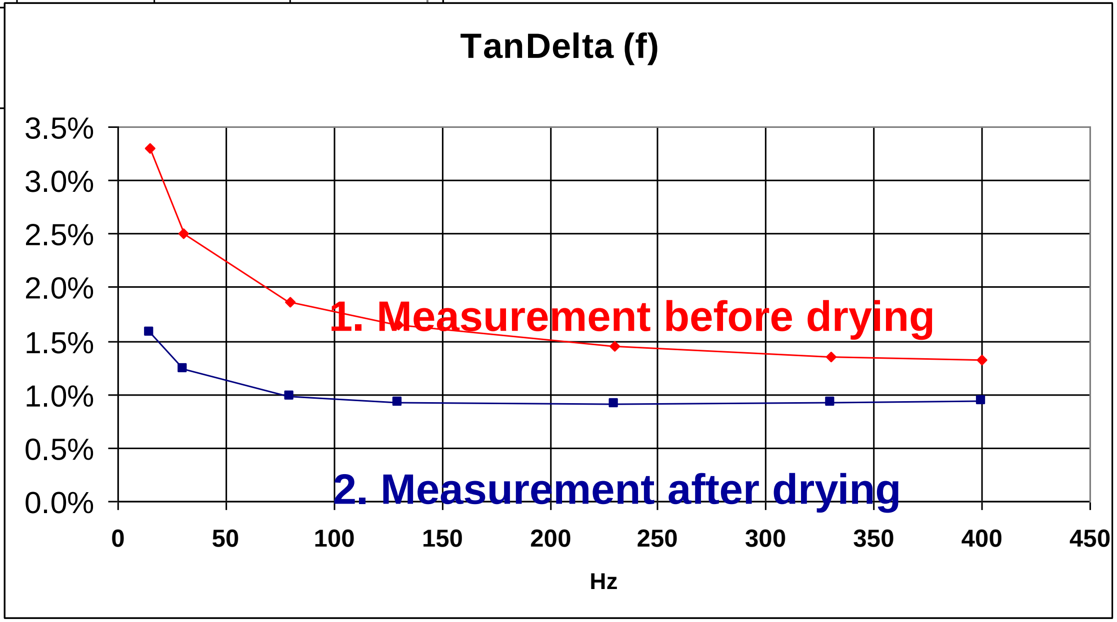
Drying of a 145kV RBP Bushing



Drying:

1200h at 90°C / 200°F



High Voltage Test with PD Measurement

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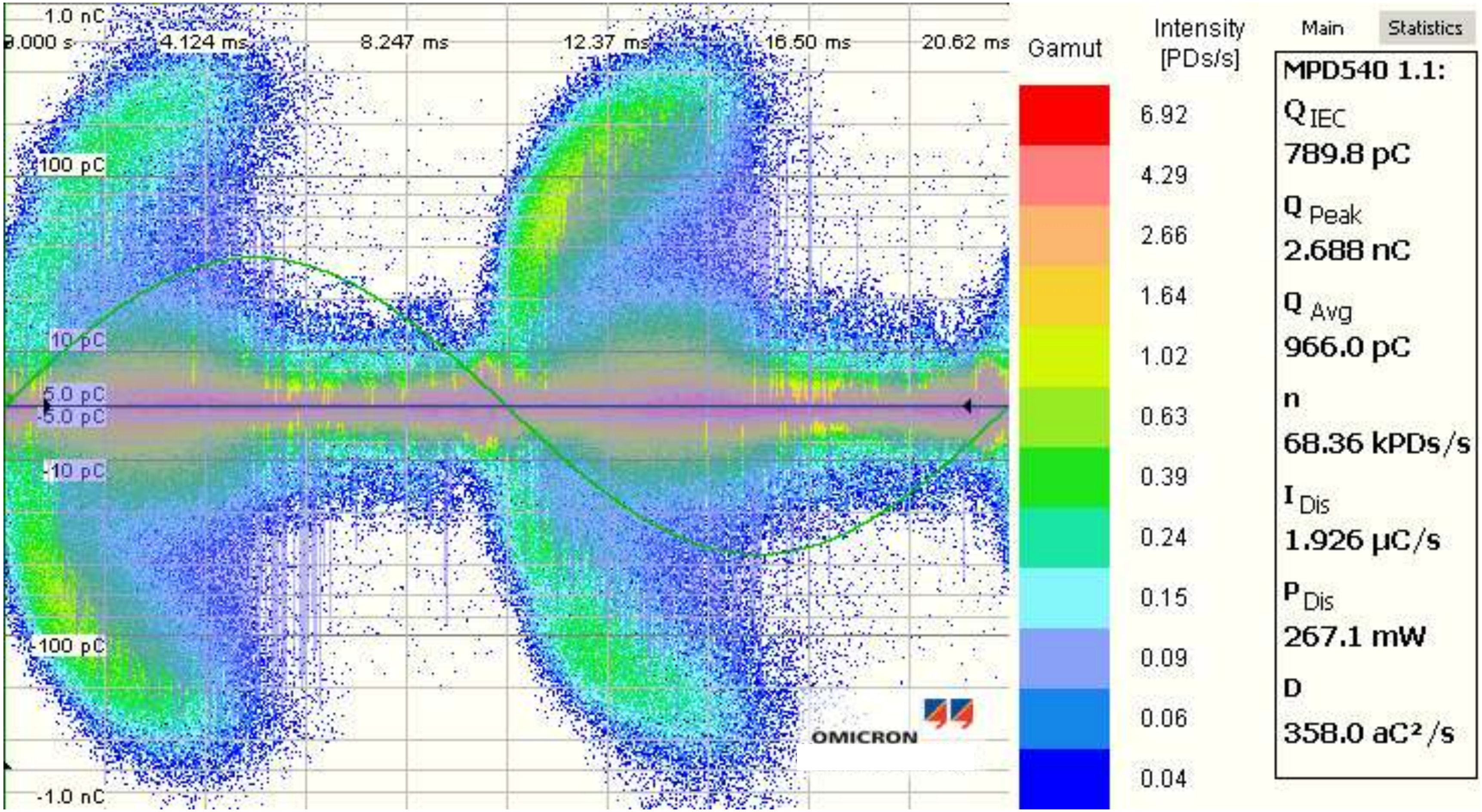
PD Measurement - Phase Resolved Pattern @ 157kV



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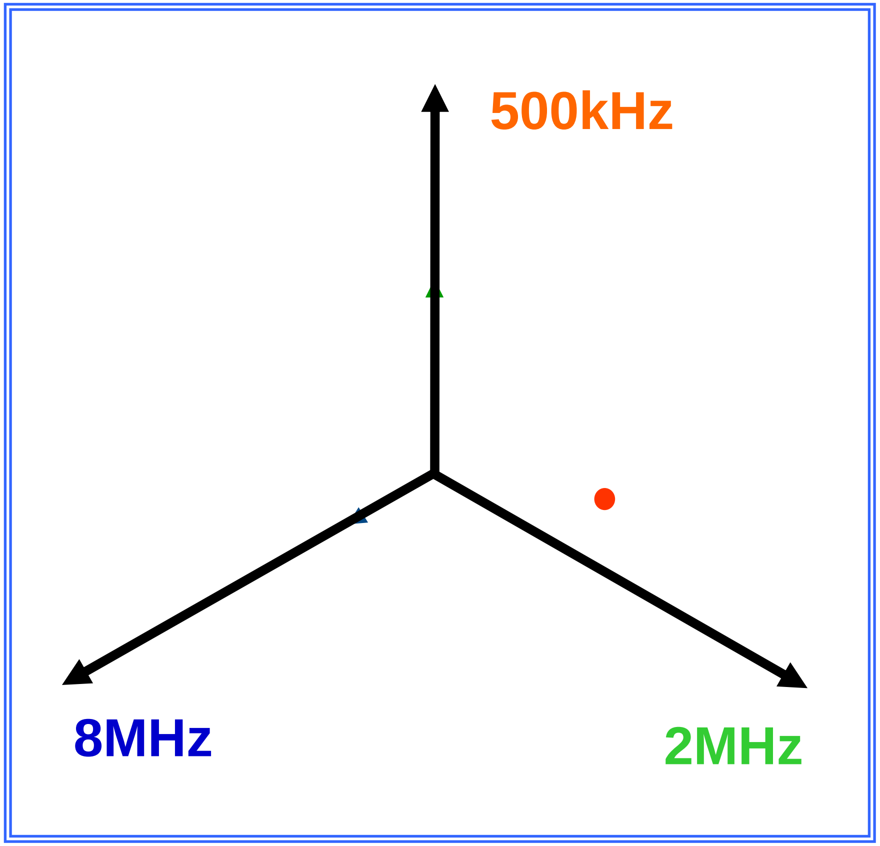
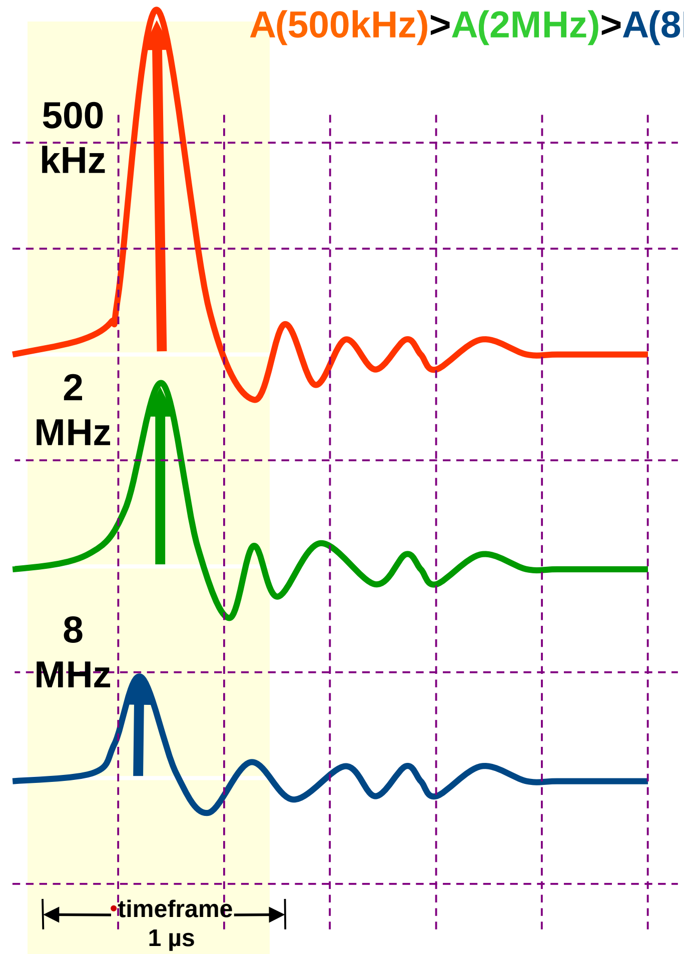
Separation of PD Sources in 3CFRD

3CFRD





3CFRD = 3 Center Frequency Relation Diagram

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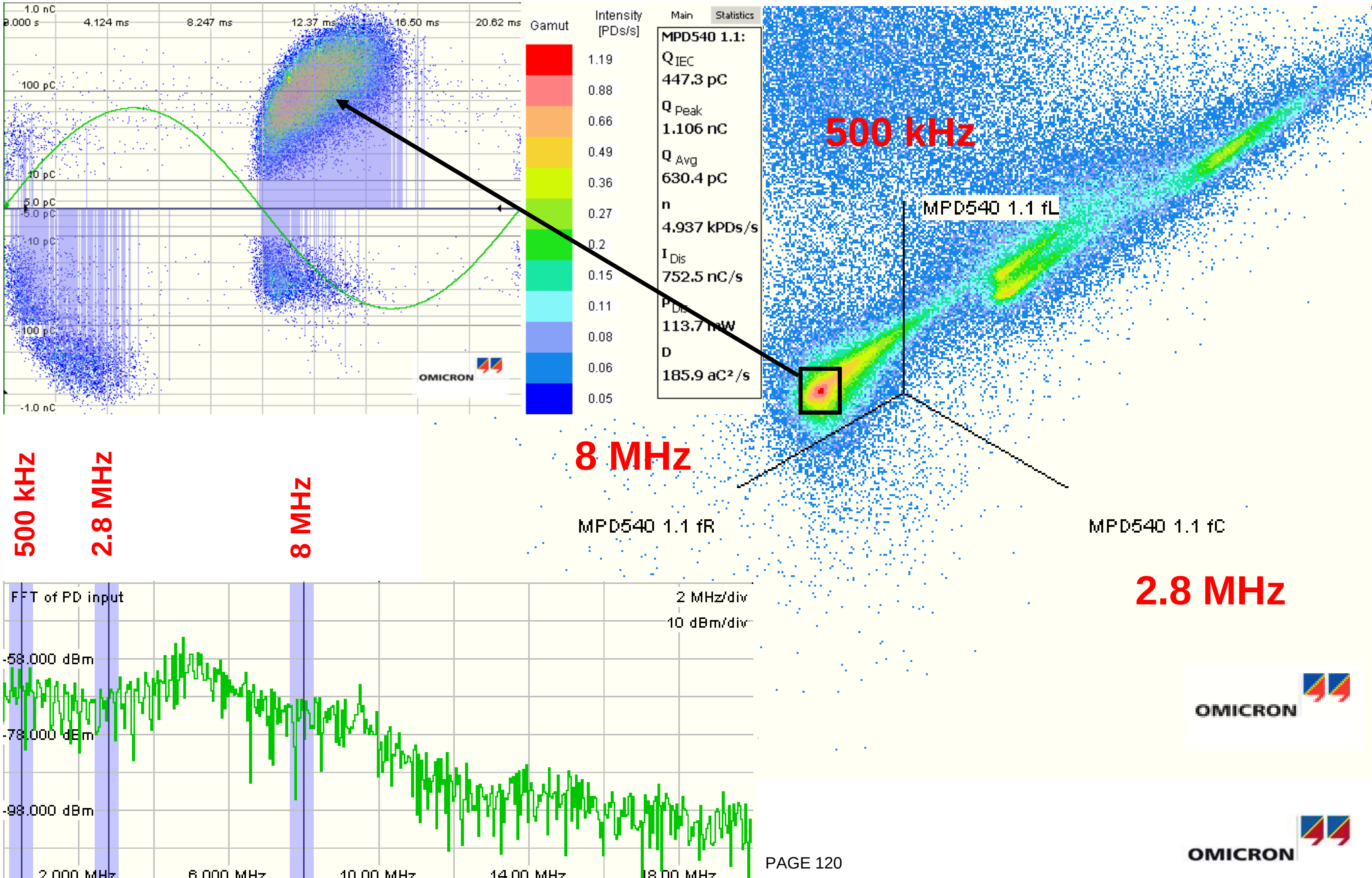
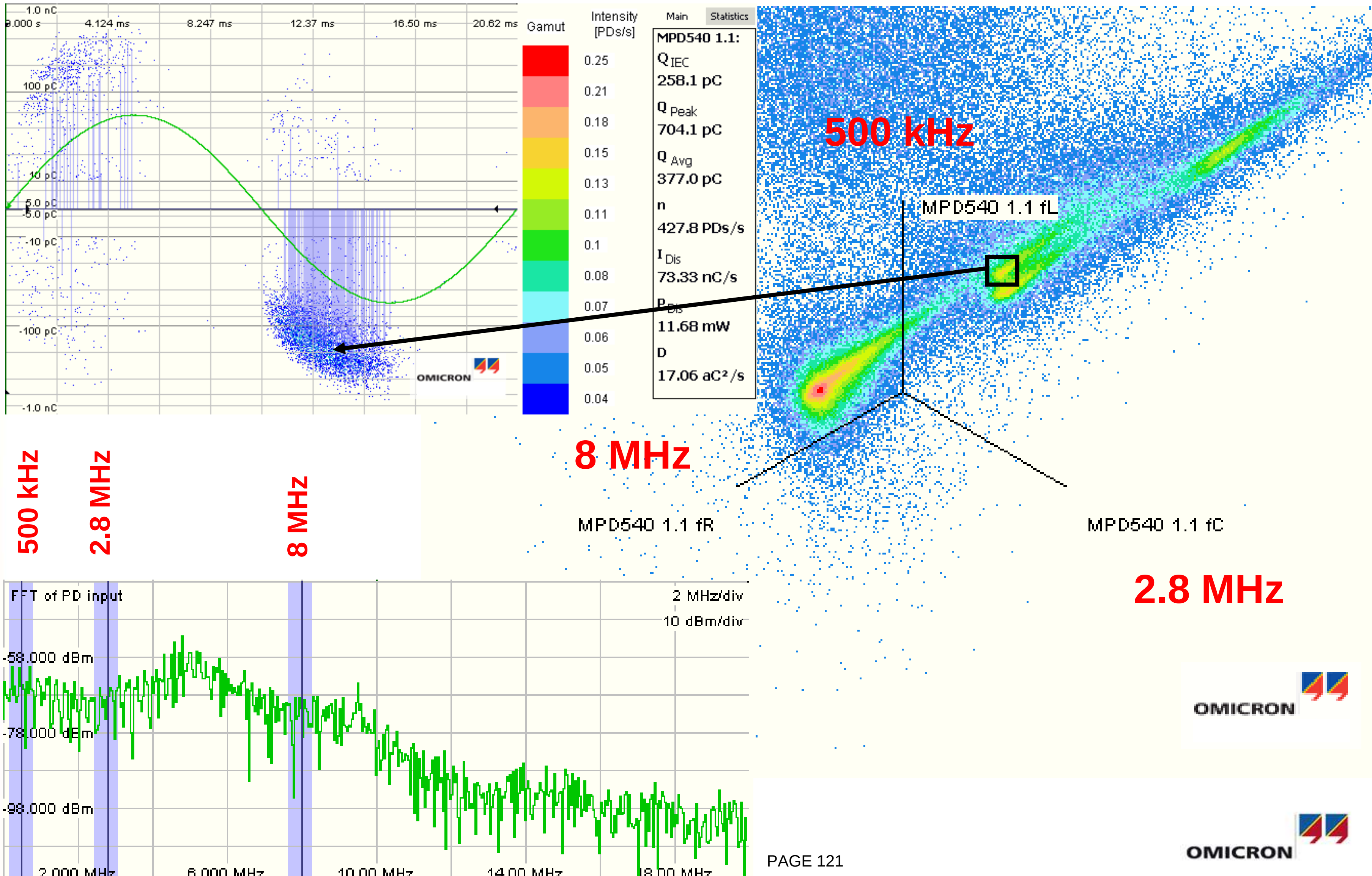
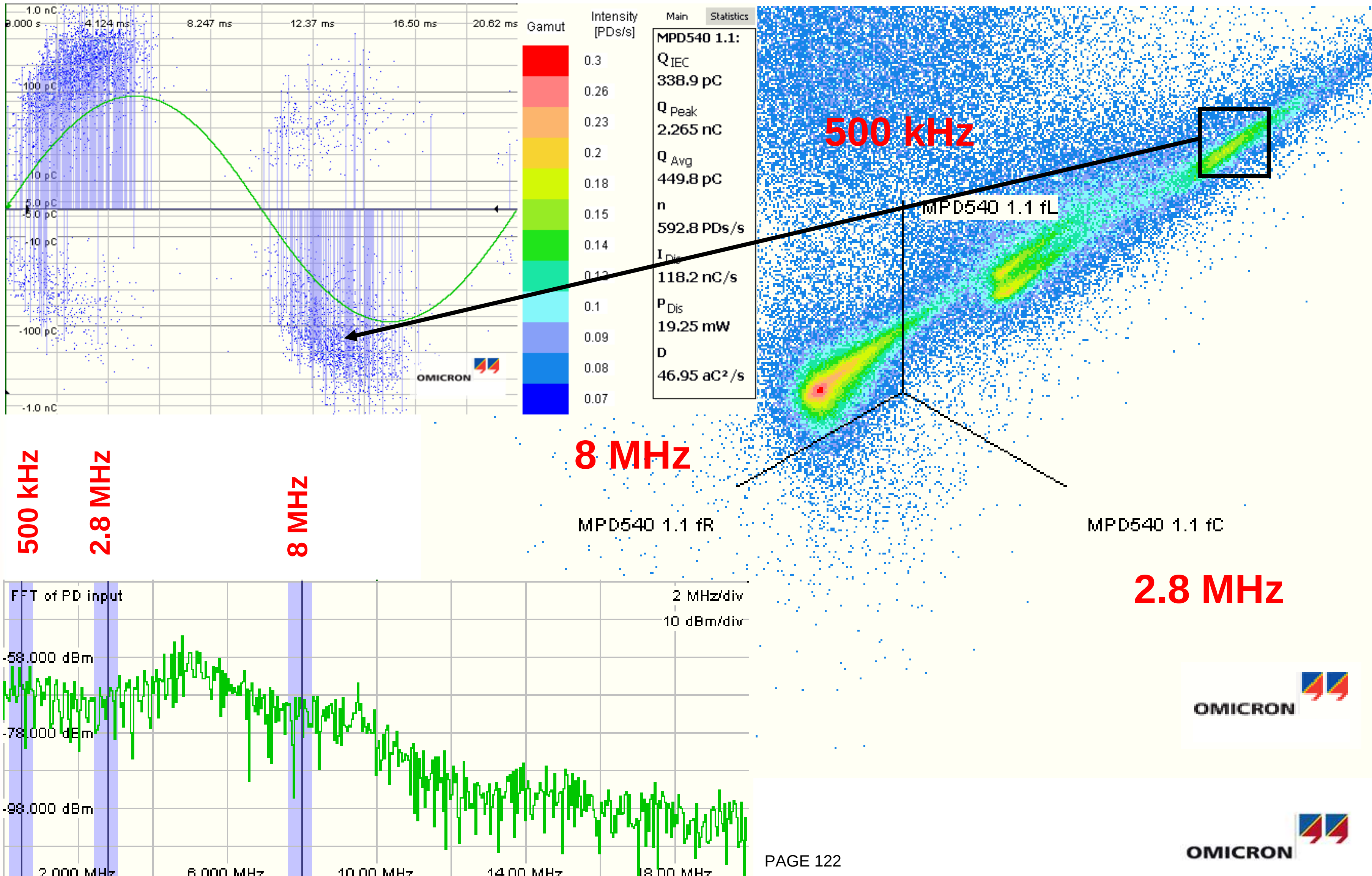
PD Measurement Cluster 1



PD Measurement Cluster 2



PD Measurement Cluster 3



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Assessment and Interpretation

Indication	RBP	OIP	RIP
increase of capacitance	oil in cracks or partial breakdowns	partial breakdowns	partial breakdowns
high dissipation factor	partial breakdowns; insulator surface wet or dirty (clean the insulator); ageing of the inner insulation; water in the inner insulation;	partial breakdowns; insulator surface wet or dirty (clean the insulator); ageing of the inner insulation; water in the inner insulation;	partial breakdowns; insulator surface wet or dirty (clean the insulator); ageing of the inner insulation; water in the inner insulation;
dissipation factor is decreasing with increasing voltage	bad potential connections; partial breakdowns	bad potential connections; partial breakdowns	bad potential connections; partial breakdowns
dissipation factor is strongly increasing with increasing temperature	high moisture in the insulation; high degree of ageing	high moisture in the insulation; high degree of ageing	high moisture in the insulation; high degree of ageing
partial discharges	normal, if constant	Discharges produce gasses; Errosion of the cellulose; production of x-wax	partial breakdowns; cracks or voids after electrical or mechanical stress;

michael.krueger@omicron.at

Questions and Remarks?