CWIEME BERLIN

3-5 JUNE 2025
MESSE BERLIN

A Hyve Event

Lodz University of Technology

IEEE DEIS
Dielectrics & Electrical Insulation Society

Pawel Rozga

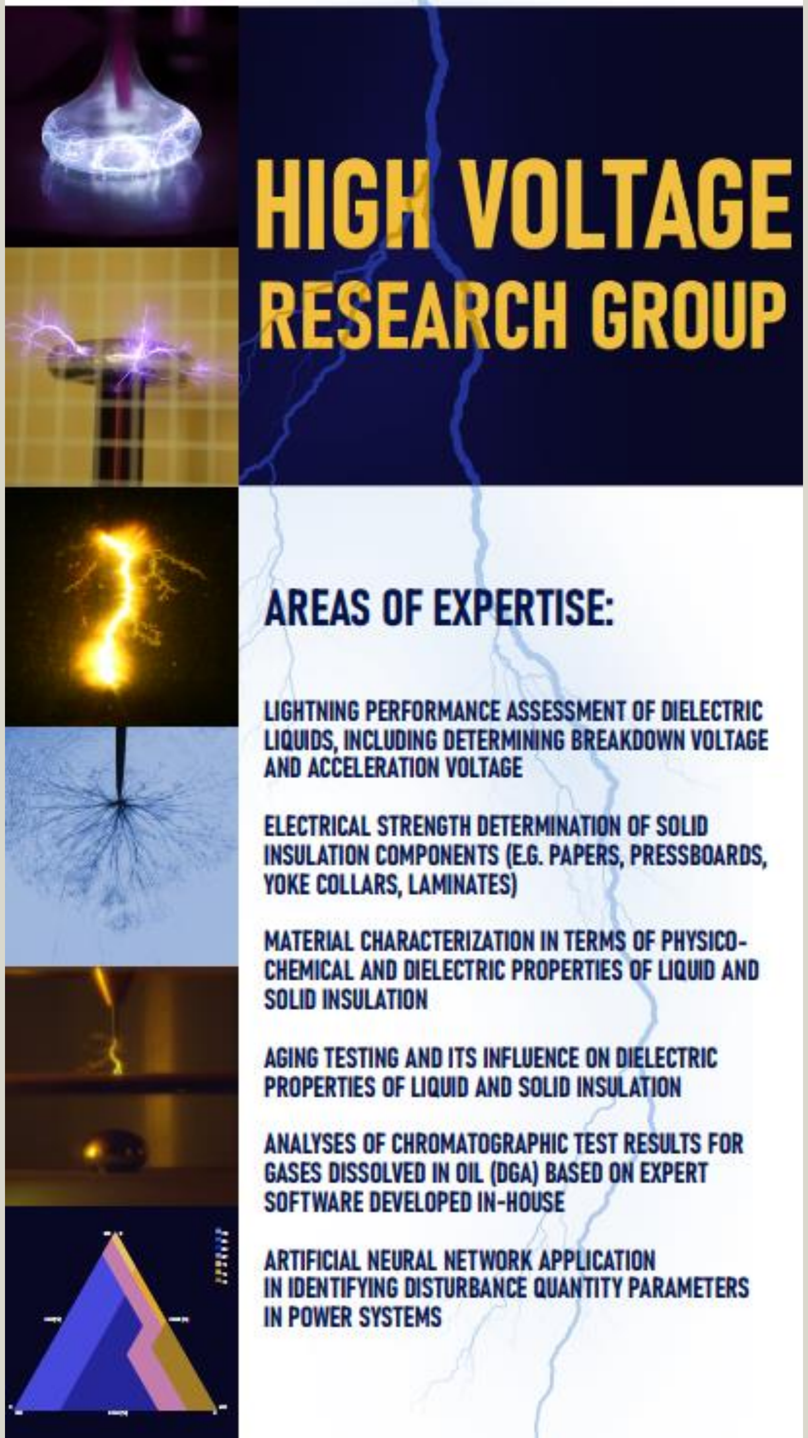
Advancing Transformer Insulation: Non-Standard Lightning Impulse Testing of Dielectric Liquids for Transformers

Pawel Rozga

Lodz University
of Technology

- **Vice-Head for Development at the Institute of Electrical Power Engineering;**

- **Head of the High Voltage Research Team;**



Pawel Rozga

IEEE DEIS Dielectrics & Electrical Insulation Society

- Vice-Chair of the IEEE Technical Committee on Liquid Dielectrics;
- Associate Editor of IEEE Transactions on Dielectrics and Electrical Insulation;
- Member of IAC and Chair of the 2025 IEEE ICDL (18-22/05/2025, Lodz, Poland)

Position Papers of the IEEE TC on LD:

- P. Rozga et al., "Next-Generation Ester Dielectric Liquids: Some Key Findings and Perspectives," in IEEE Electrical Insulation Magazine, vol. 40, no. 5, pp. 23-35, September/October 2024
- Fofana, I.; Rao, U.M.; Rozga, P.; Beroual, A.; Lashbrook, M.; Acosta, J., Dielectric Liquids for Insulation and Cooling: An Electric Vehicles Perspective, 2025 IEEE International Conference on Dielectric Liquids (ICDL), Lodz (Poland), May 18-22 2025.
- Rao, U.M.; Fofana, I.; Rozga, P.; Beroual, A.; Malde, J.; Martin, R.; Wang, F.; Casserly, E.; Pompili, M.; Calcara, L.; Next Generation of Insulating Liquids, 2022 International Conference on Dielectric Liquids (ICDL), Sevilla, Spain.
- U. M. Rao et al., A review on pre-breakdown phenomena in ester fluids: Prepared by the international study group of IEEE DEIS liquid dielectrics technical committee, in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 27, no. 5, pp. 1546-1560, 2020

Content of Talk

- Introduction
- Lighning Impulse Breakdown Voltage (LIBV) and Acceleration Voltage (Va)
- Electrode models with paper/pressboard insulation
- Design Insulation Level (DIL) determination
- Conclusions / Summary

IEC 60296: 2022 Fluids for electrotechnical applications – Mineral insulating oils for electrical equipment
[Mineral oils, GTLs, Bio-based hydrocarbons]

IEC 62770: 2024 Fluids for electrotechnical applications - Unused natural esters for transformers and similar electrical equipment
[Natural esters]

IEC 61099:2010 Insulating liquids - Specifications for unused synthetic organic esters for electrical purposes
[Synthetic esters]

IEC 63012: 2019 Insulating liquids - Unused modified or blended esters for electrotechnical applications
[Blended and modified esters]

Mineral oil
(Hydrocarbons)
IEC 60296

Synthetic Esters
IEC 61099

Natural Esters
IEC 62770

Bio-based Hydrocarbons
IEC 60296

Blended Esters
IEC 63012

GTL Oils
IEC 60296

- readily biodegradable in accordance with the OECD 301B testing procedure

Role of insulating liquid in transformer

- **INSULATING: ensuring electric strength of oil channels (free oil gaps)**
- **COOLING: effective heat dissipation from the windings**
- **PROTECTION and IMPREGNATION OF SOLID INSULATION: improving electrical strength, protection against oxygen, reducing progres of aging**
- **DIAGNOSTIC: DGA, etc.**
- **?????**

Dielectric properties of insulating liquids

AC Breakdown Voltage (AC BDV) – determined as per IEC 60156 Standard;

Dielectric Dissipation Factor (DDF) – determined as per IEC 60247 Standard;

Electrical permittivity – determined as per IEC 60247 Standard;

Lightning performance !!! – resistance of the liquid against lightning impulse voltage ???

Dielectric properties of insulating liquids

Lightning performance – resistance of the liquid against standard lightning impulse voltage

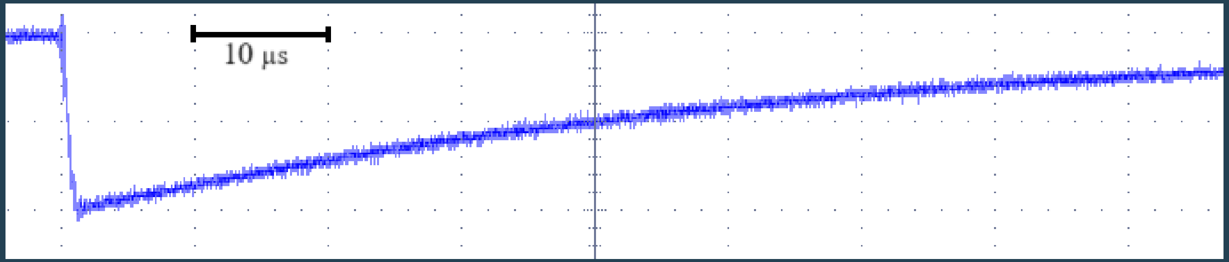
Lighning Impulse Breakdown Voltage (LIBV)
Acceleration Voltage (Va)

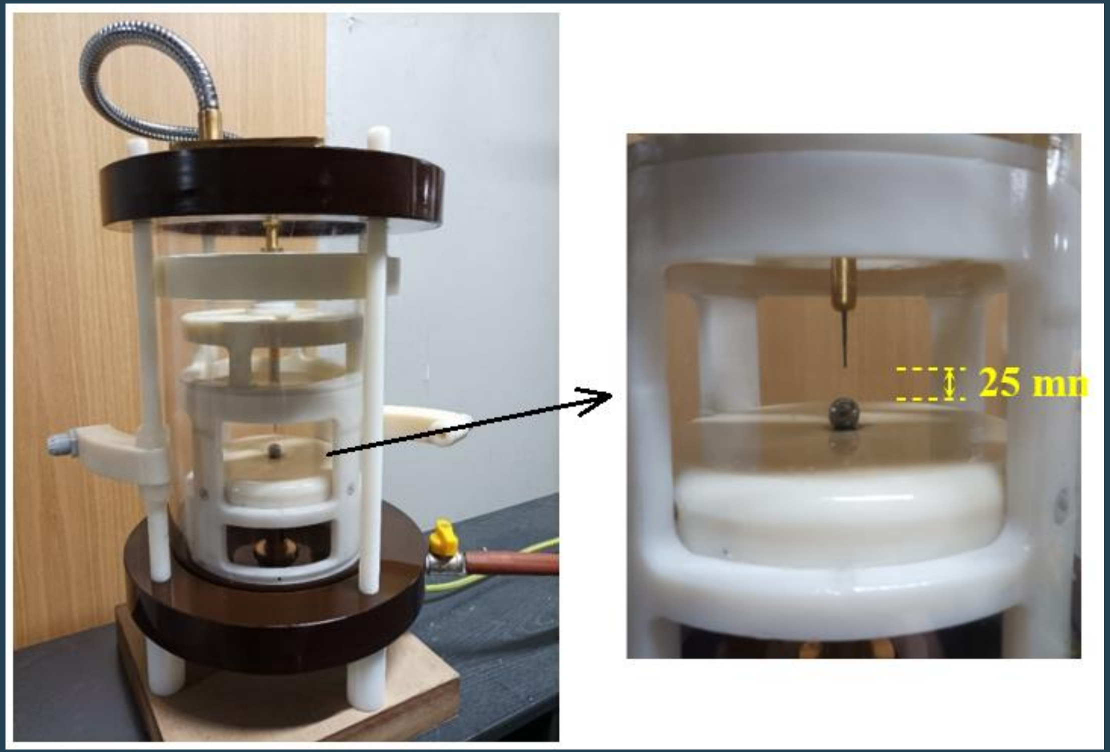
Electrode models with paper/pressboard insulation

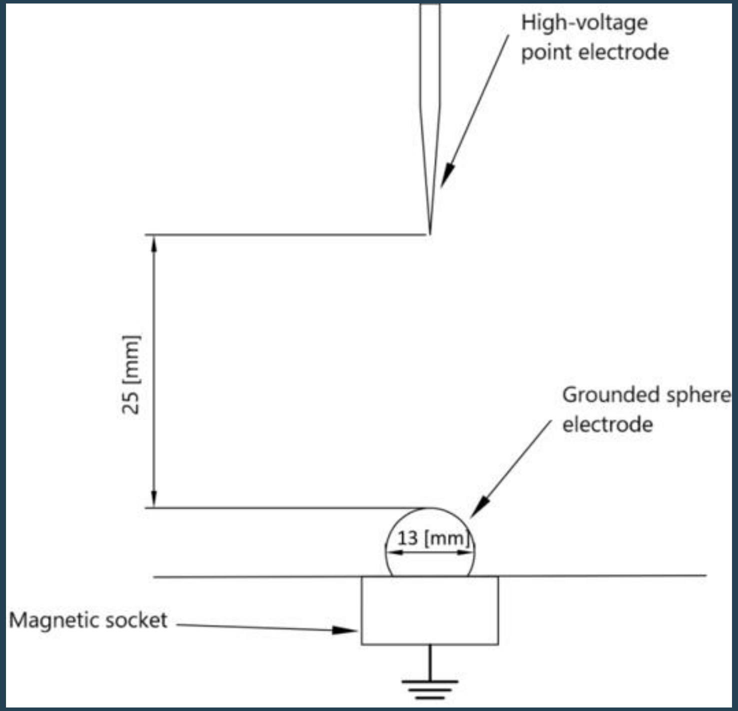
Design Insulation Level (DIL) determination

Lightning Impulse Breakdown Voltage

IEC 897: 1987 - Methods for the determination of the lightning breakdown voltage of insulating liquids

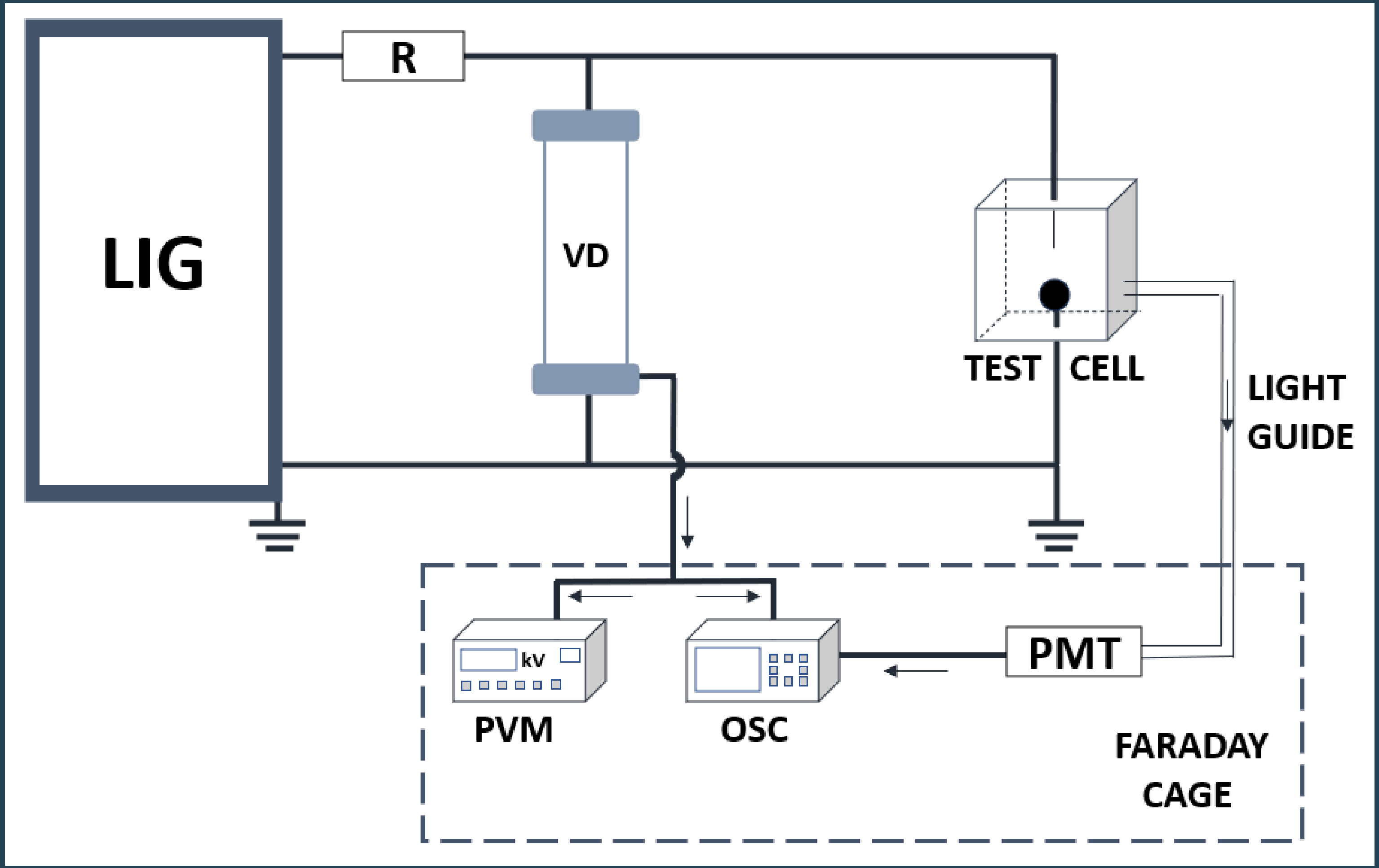






Lightning Impulse Breakdown Voltage

IEC 897 - Methods for the determination of the lightning breakdown voltage of insulating liquids



LIG – lightning Impulse Generator

R – limiting resistor

VD – voltage divider

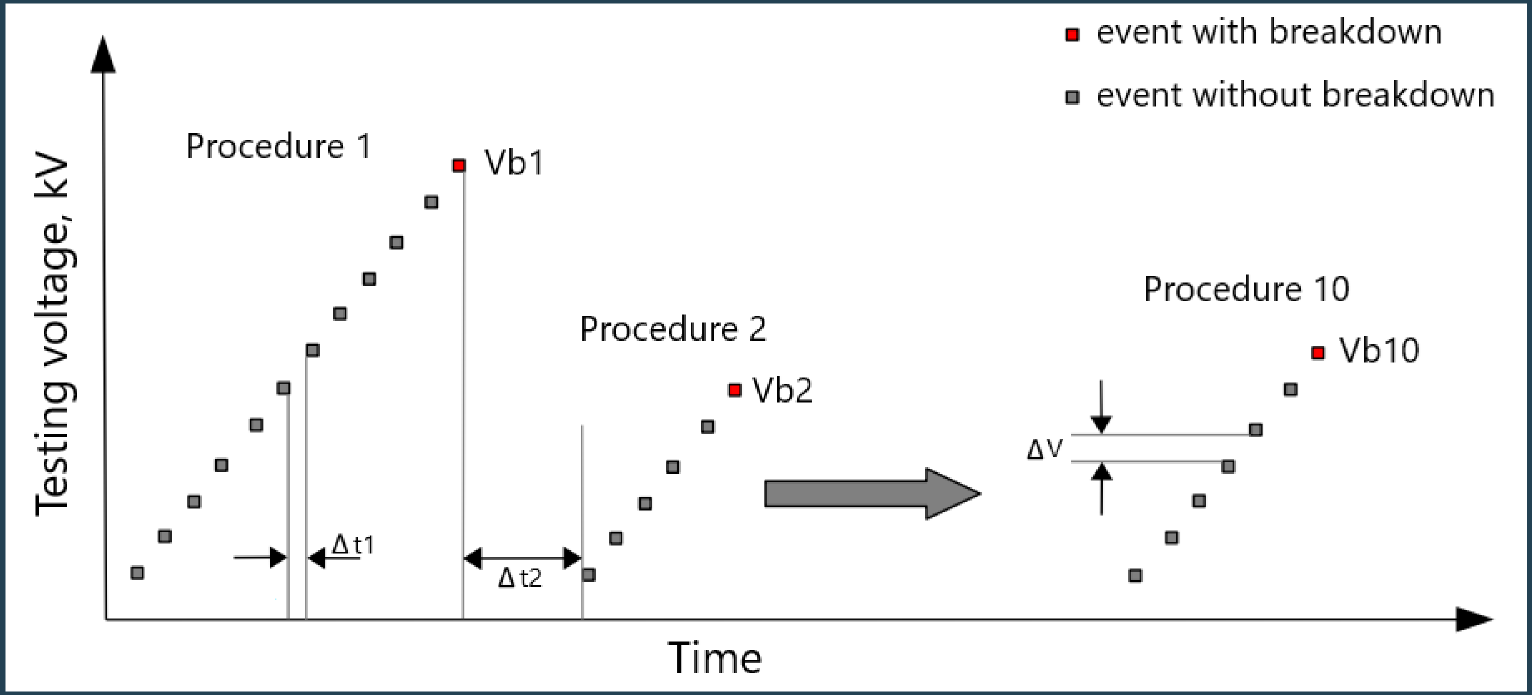
PMT – photomultiplier

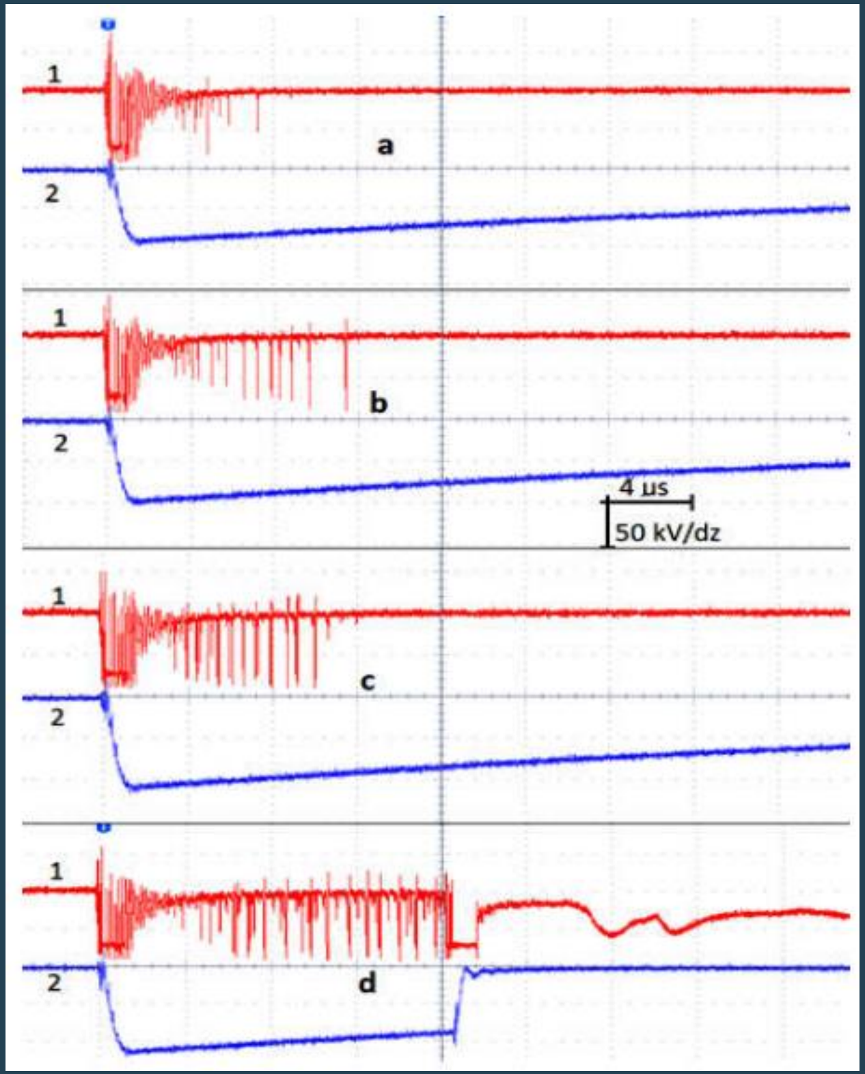
OSC – oscilloscope

PVM – peak value meter

Lightning Impulse Breakdown Voltage

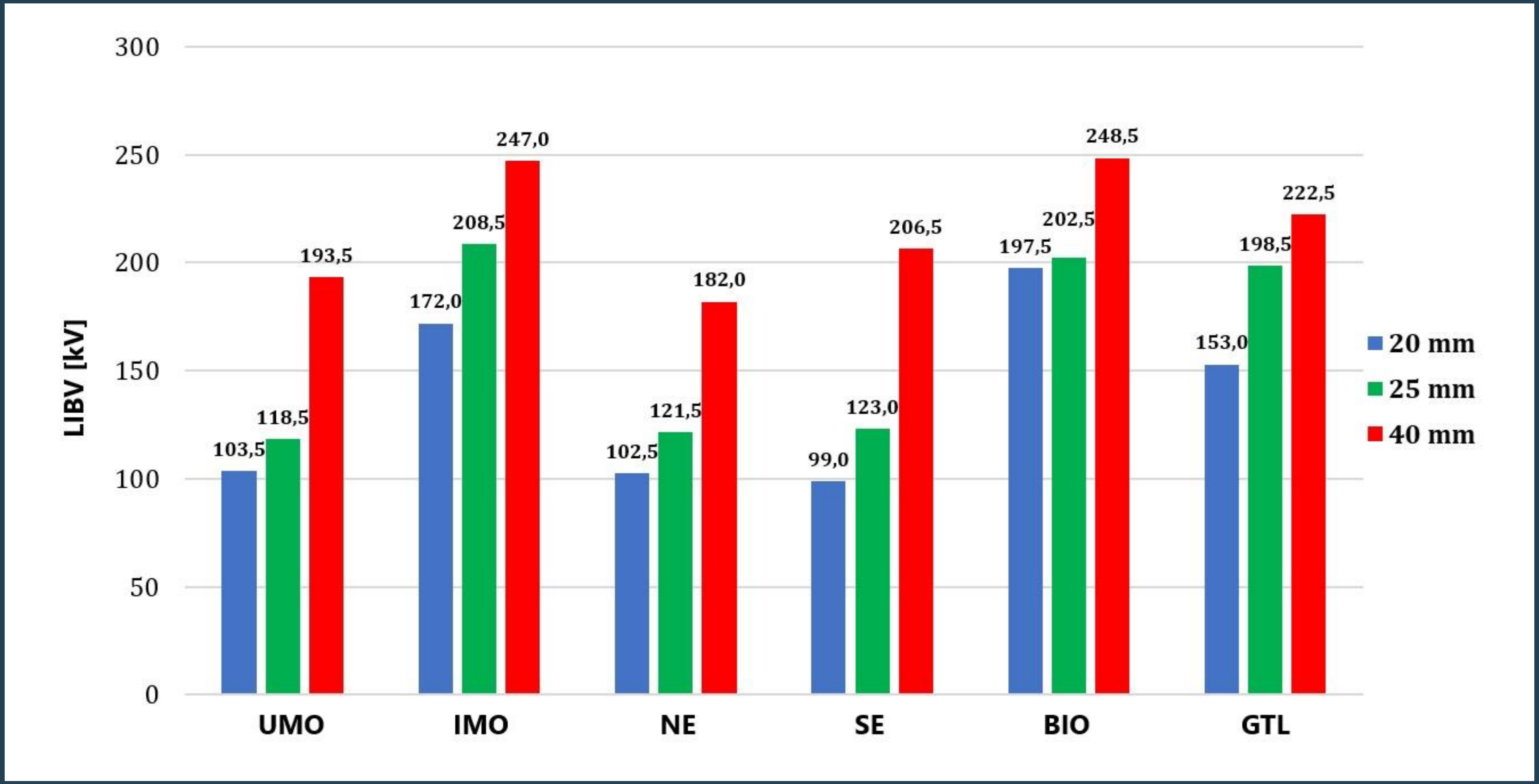
IEC 897 - Methods for the determination of the lightning breakdown voltage of insulating liquids





Lightning Impulse Breakdown Voltage

Negative polarity; 20, 25 and 40 mm gap distance;



UMO – Uninhibited Mineral Oil

IMO – Inhibited Mineral Oil

NE – Natural Ester

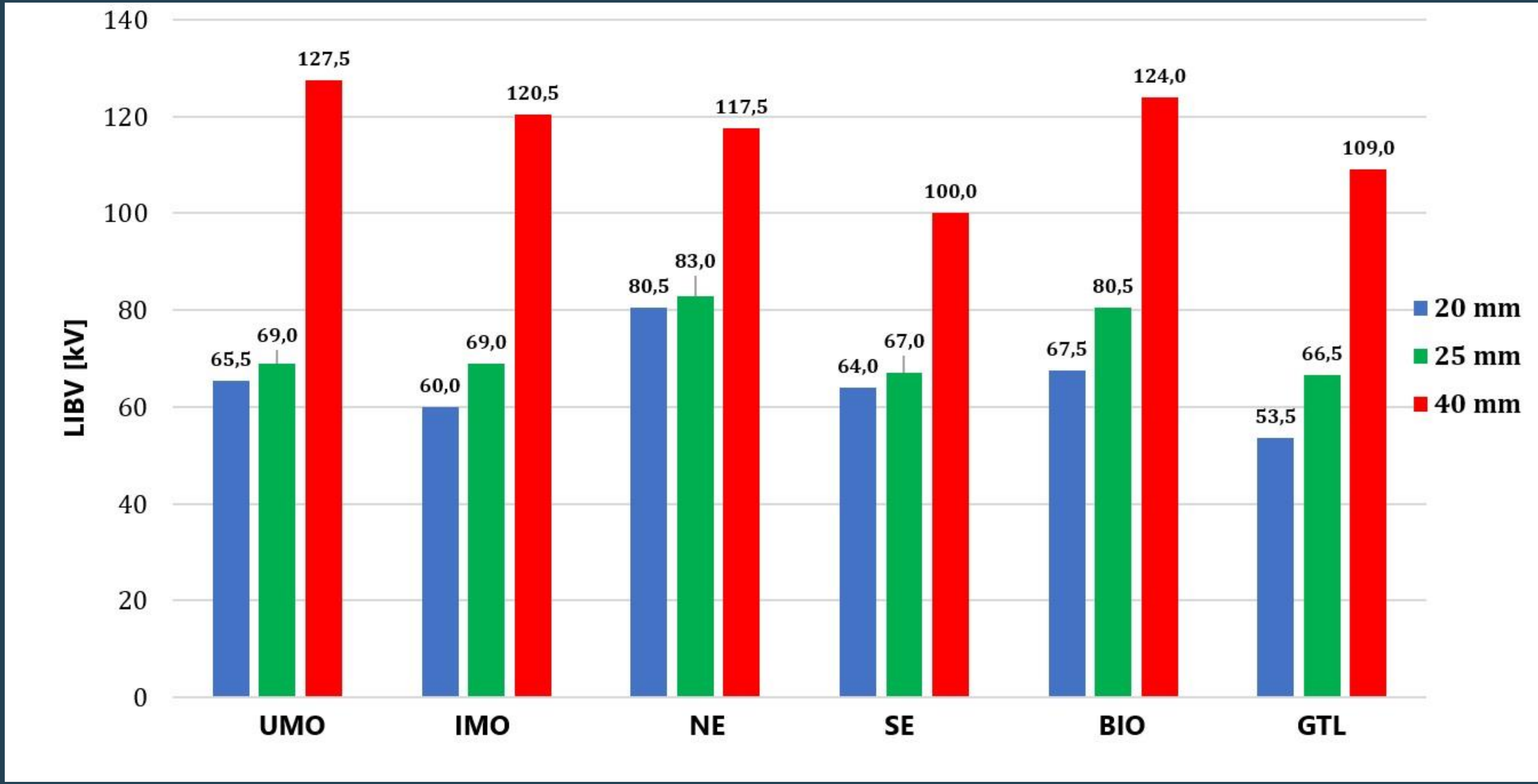
SE – Synthetic Ester

BIO – Bio-based Hydrocarbon

GTL – oil made in Gas-to-Liquid technology

Lightning Impulse Breakdown Voltage

Positive polarity; 20, 25 and 40 mm gap distance;



UMO – Uninhibited Mineral Oil

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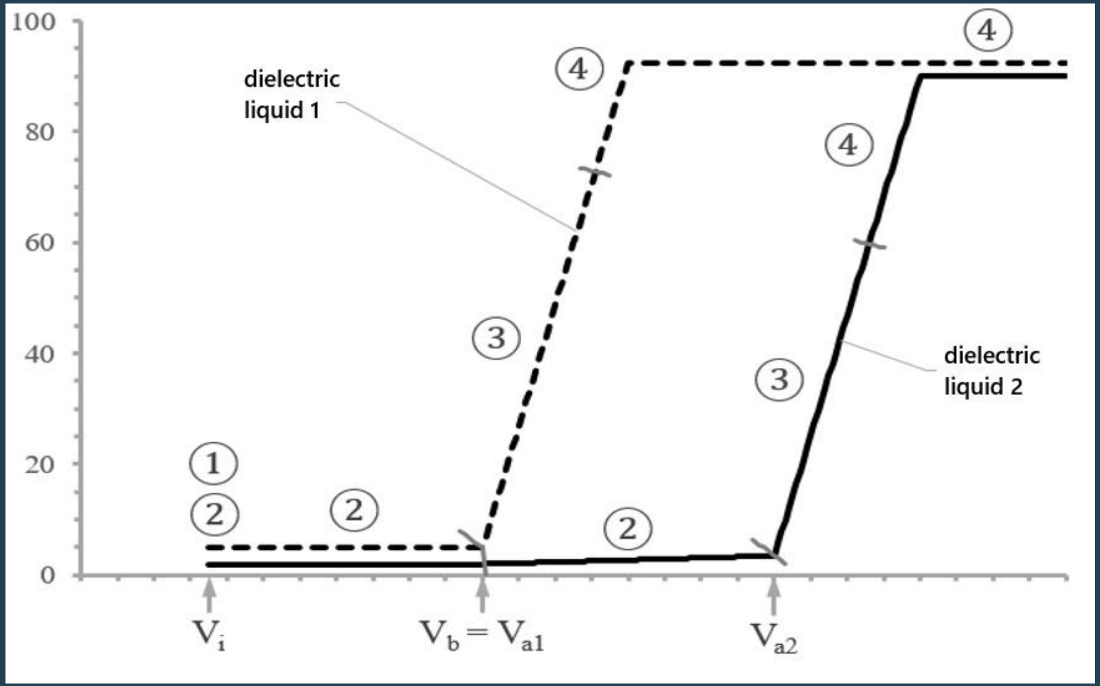
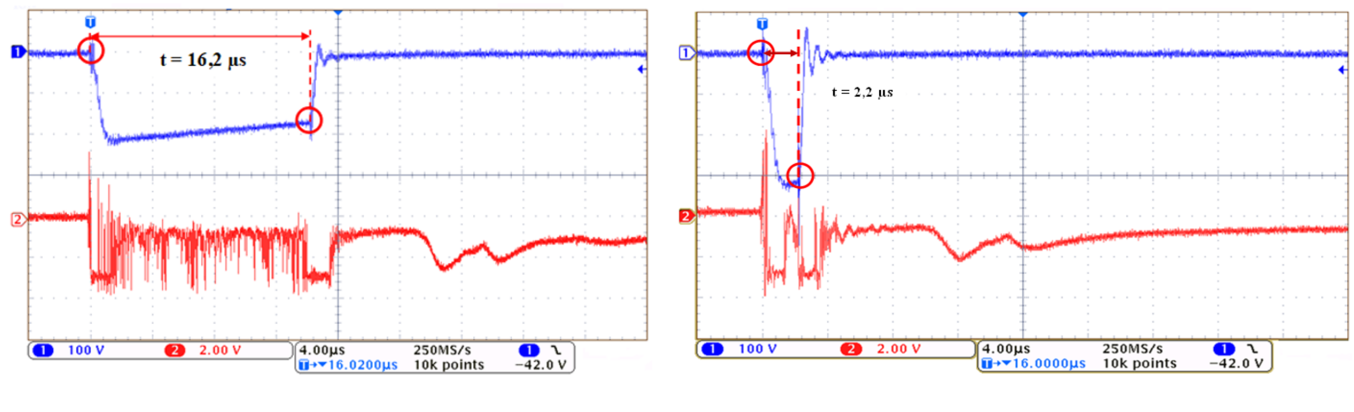
Acceleration Voltage (Va)



Propagation mode	Positive polarity	Negative polarity
(1)	0,1 to 1 km/s	0,1 to 1 km/s
(2)	1-6 km/s	0,5-3 km/s
(3)	20-50 km/s	10-20 km/s
(4)	100 km/s	100 km/s



$$v_p = \frac{d}{t} = \frac{25\ mm}{16,2\ \mu s} \cong 1,54\ \frac{mm}{\mu s}$$

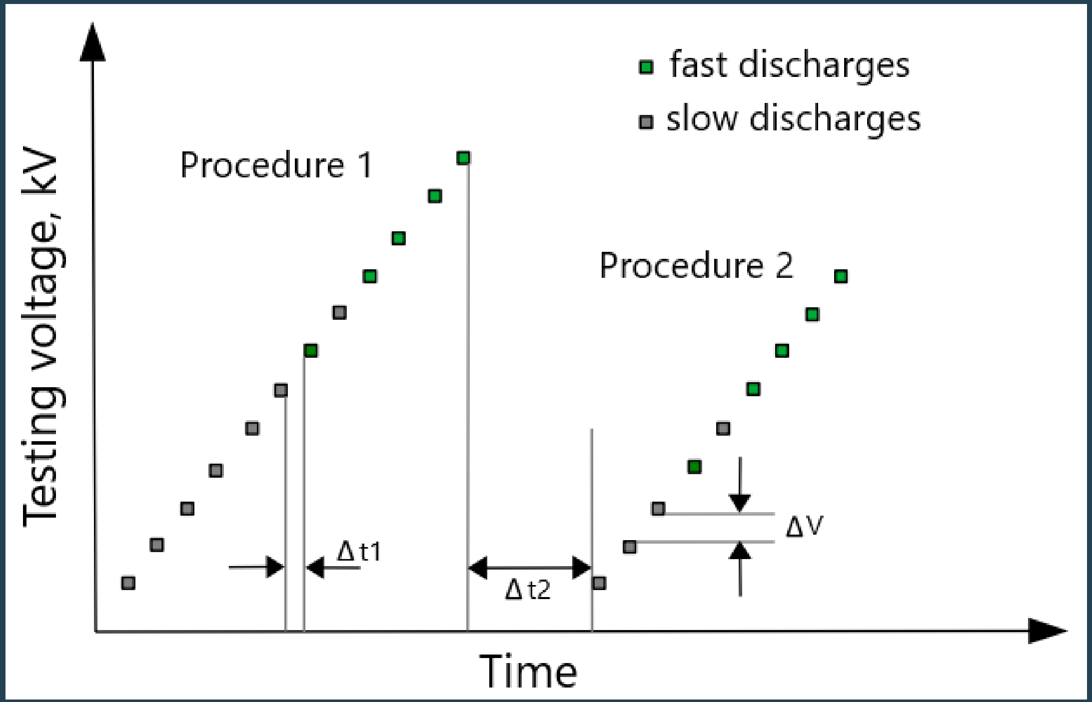
$$v_p = \frac{d}{t} = \frac{25\ mm}{2,2\ \mu s} \cong 11,4\ \frac{mm}{\mu s}$$

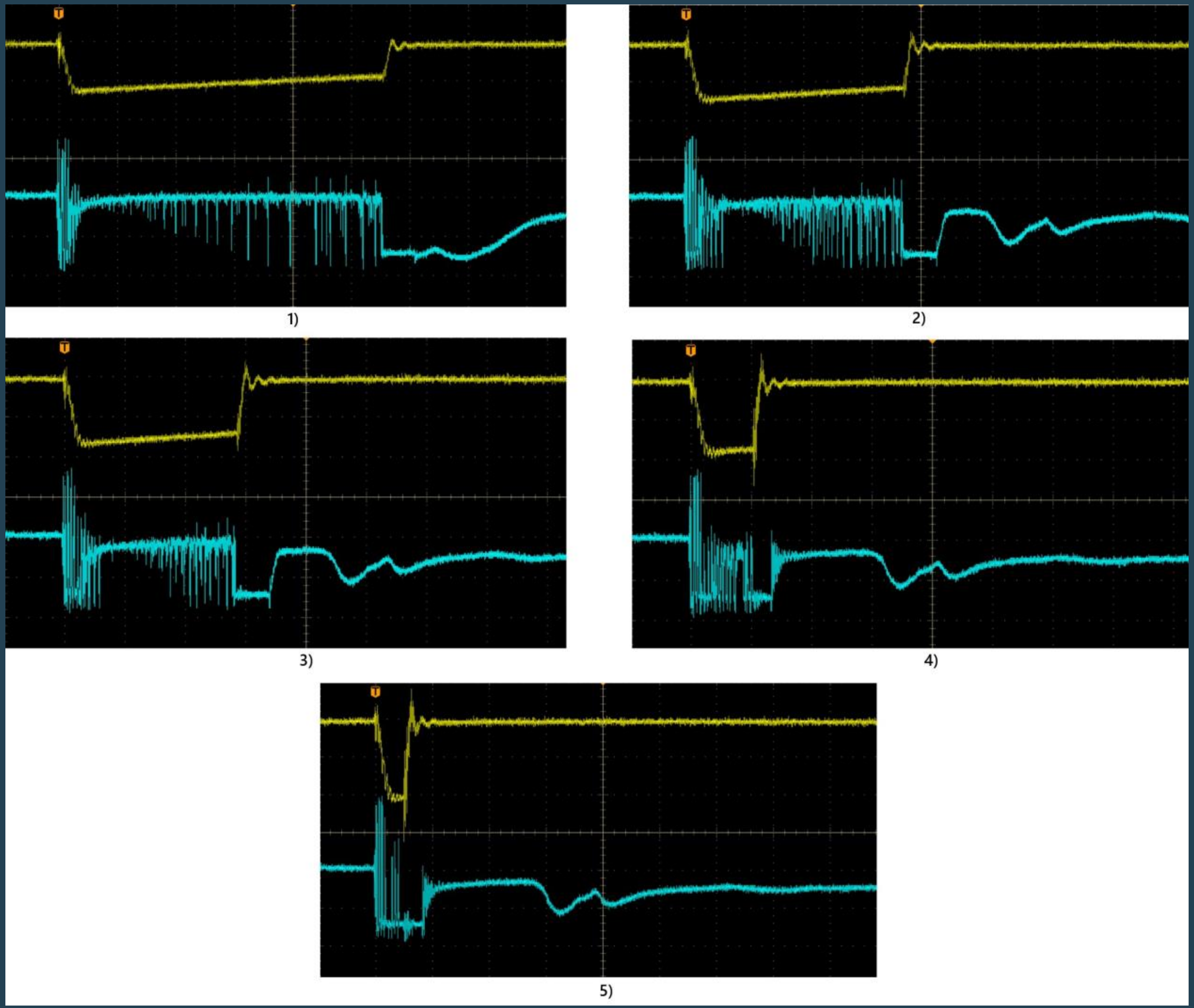
Vi – Inception Voltage

Vb – Lightning Impulse Breakdown Voltage

Va1, Va2 – Acceleration Voltage

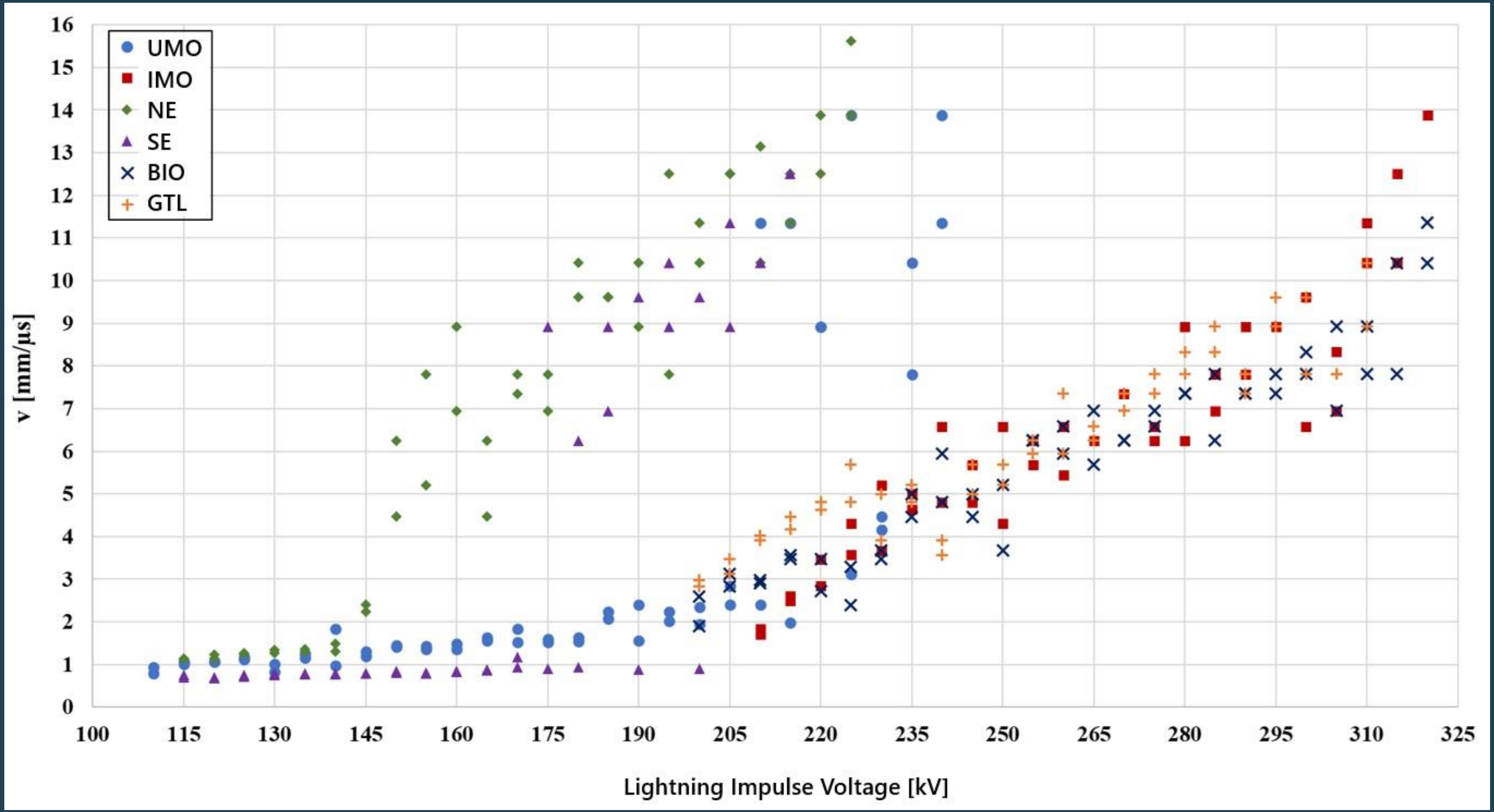
Acceleration Voltage (Va)



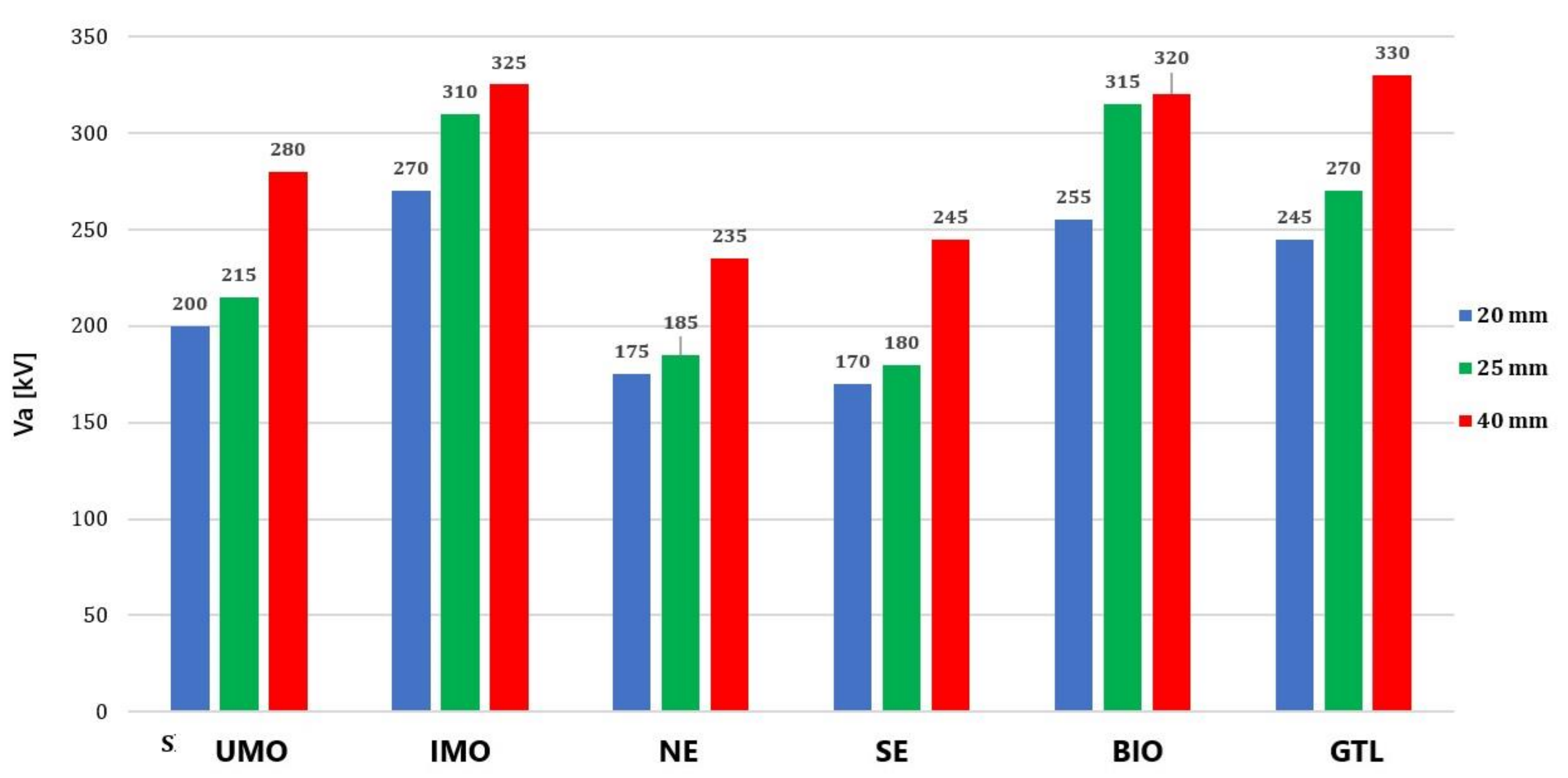


Acceleration Voltage (Va)

Negative polarity – 25 mm gap distance

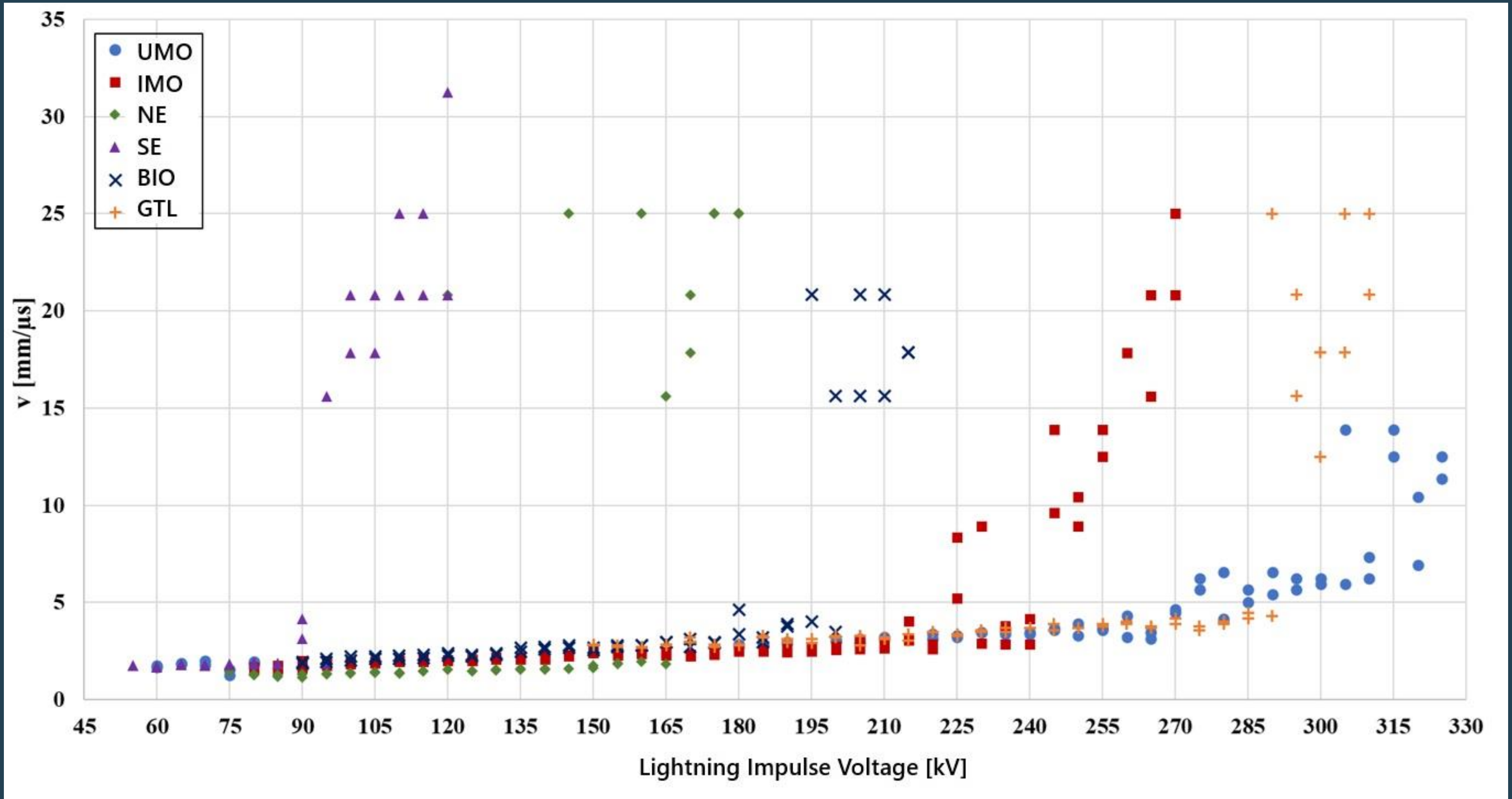


Acceleration Voltage (Va)

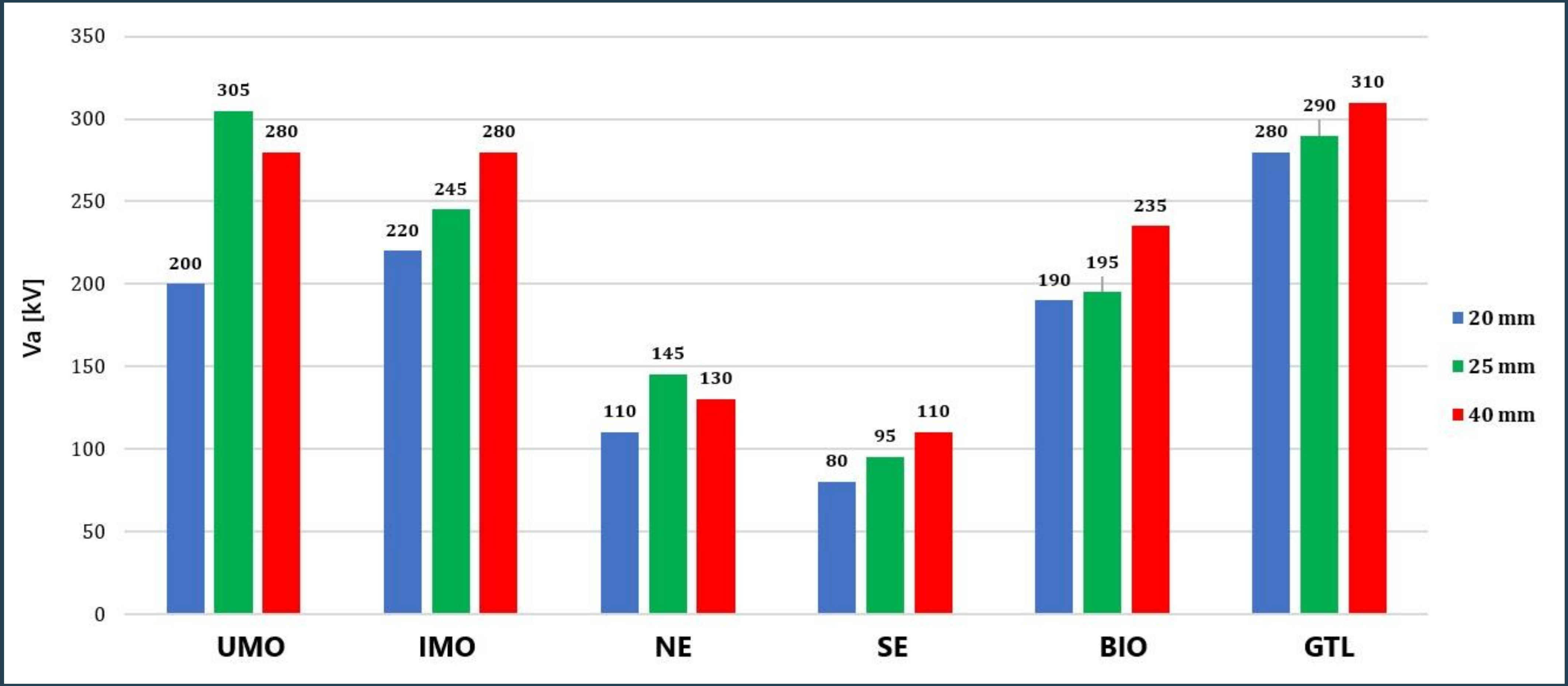


Acceleration Voltage (Va)

Positive polarity – 25 mm gap distance

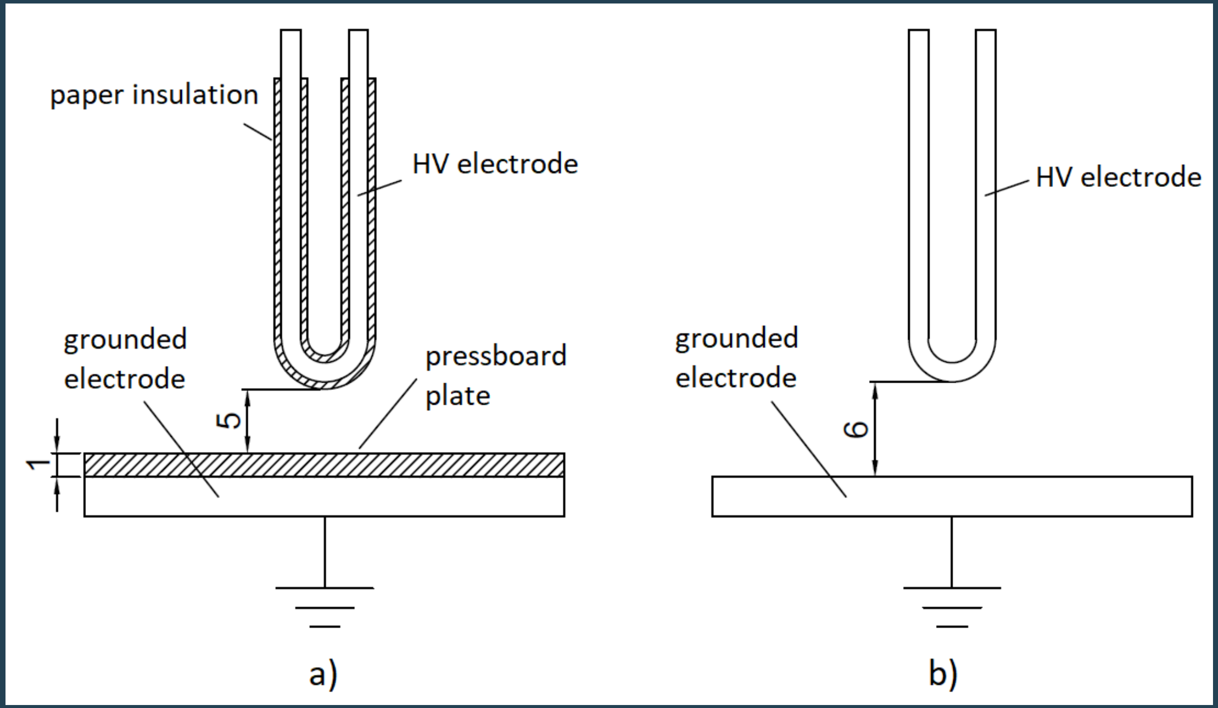


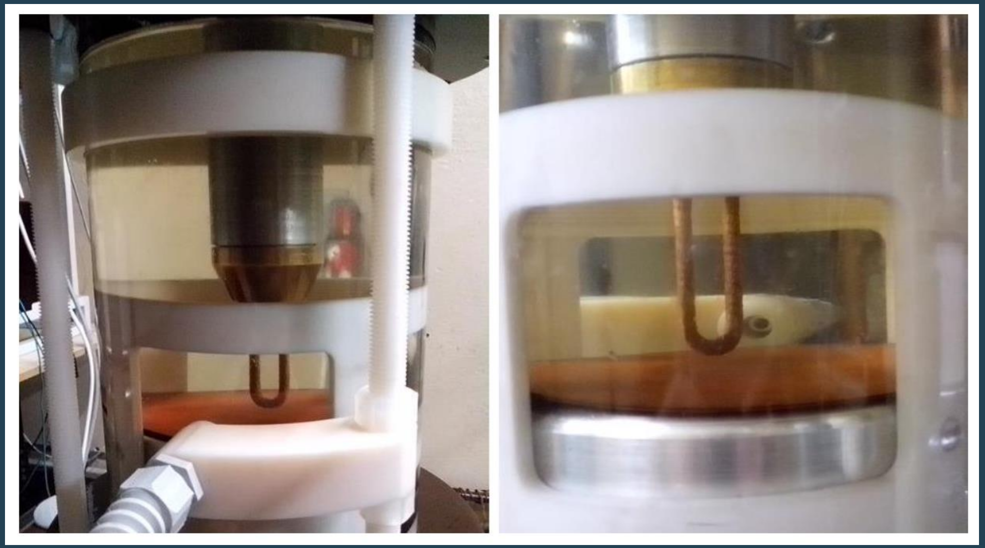
Acceleration Voltage (Va)



Electrode models with paper/pressboard insulation

U-shaped HV electrode model



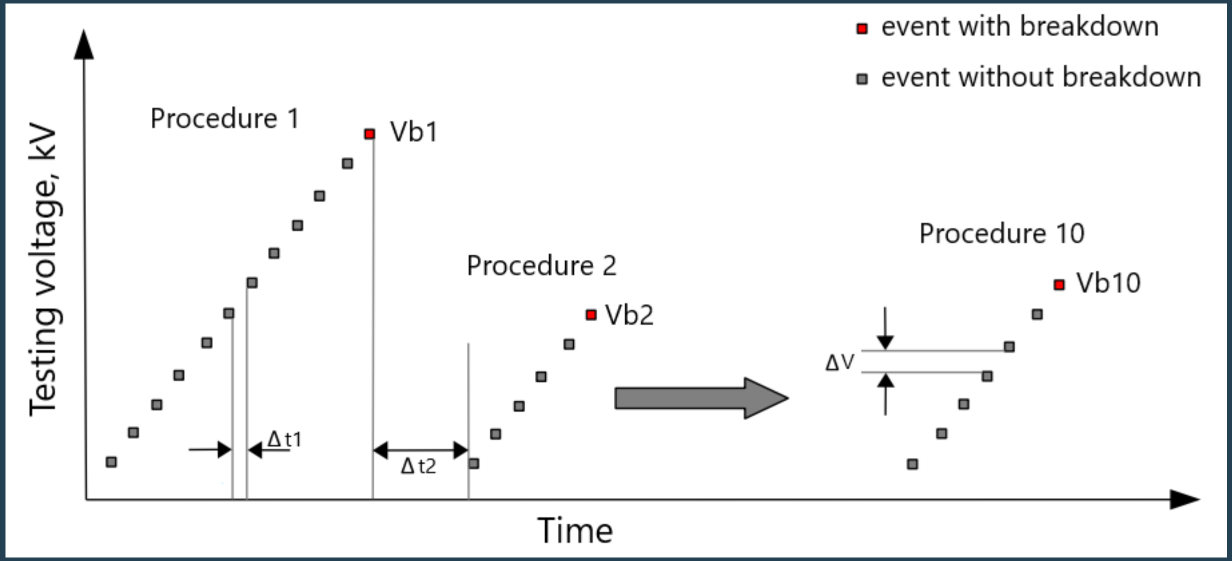


Electrode models with paper/pressboard insulation

U-shaped HV electrode model

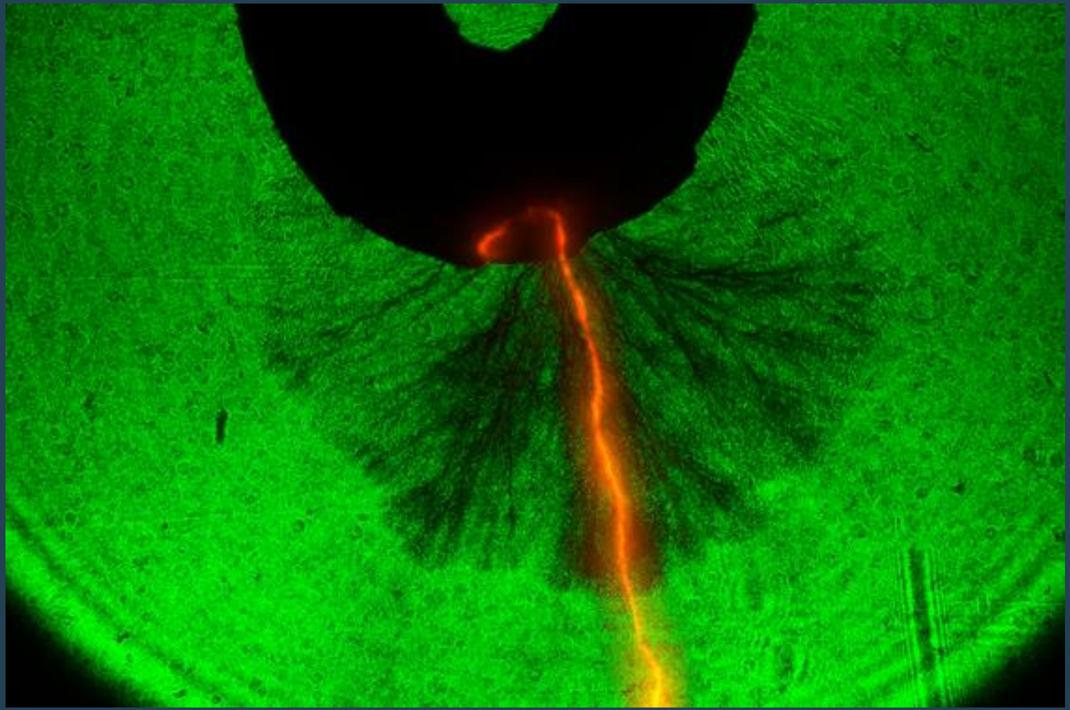
Drying and impregnation:

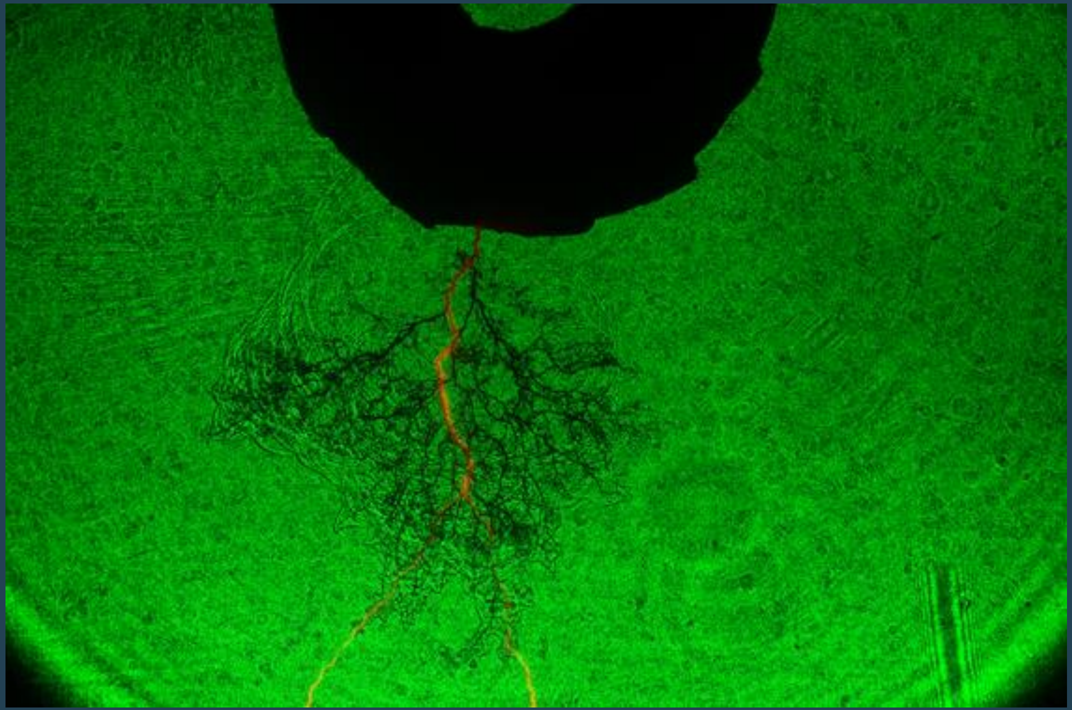
1) Drying the 25 sets of models under vacuum condition through 48 h (based on recommendation of IEC 60641-2, p. 20.3).
2) Pouring the pre-treated liquid into the vacuum chamber with keeping the vacuum condition all the time and impregnating the models through 24 h at the temperature of 80˚C.
3) Cooling the samples to the ambient temperature remaining closed in a vacuum chamber through circa 24 h.
4) Releasing the vacuum and opening the chamber.



Electrode models with paper/pressboard insulation

U-shaped HV electrode model

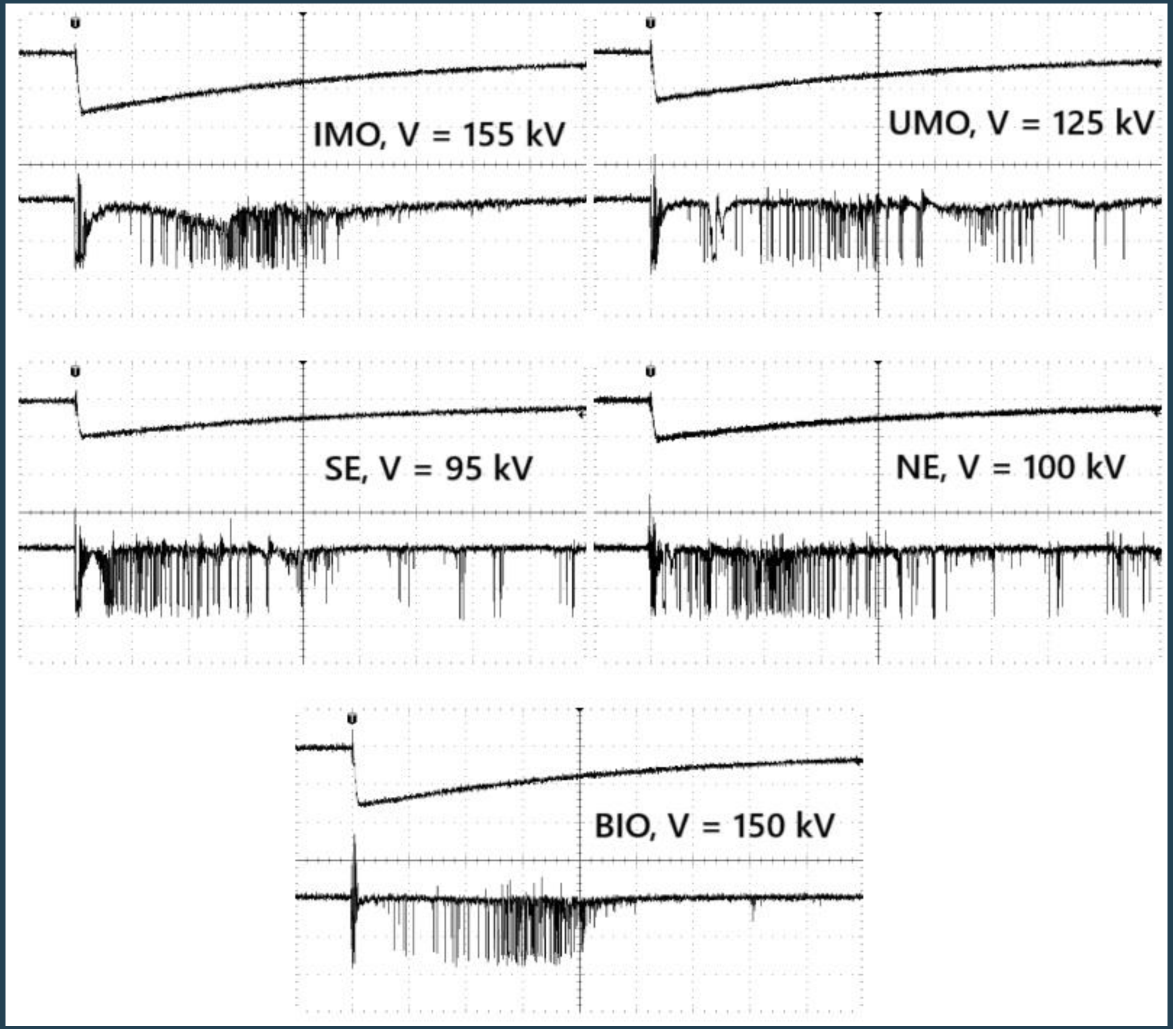




Shadowgraph photos of positive (on the left) and negative (on the right) discharges developing in the system of insulated electrodes

Electrode models with paper/pressboard insulation

U-shaped HV electrode model

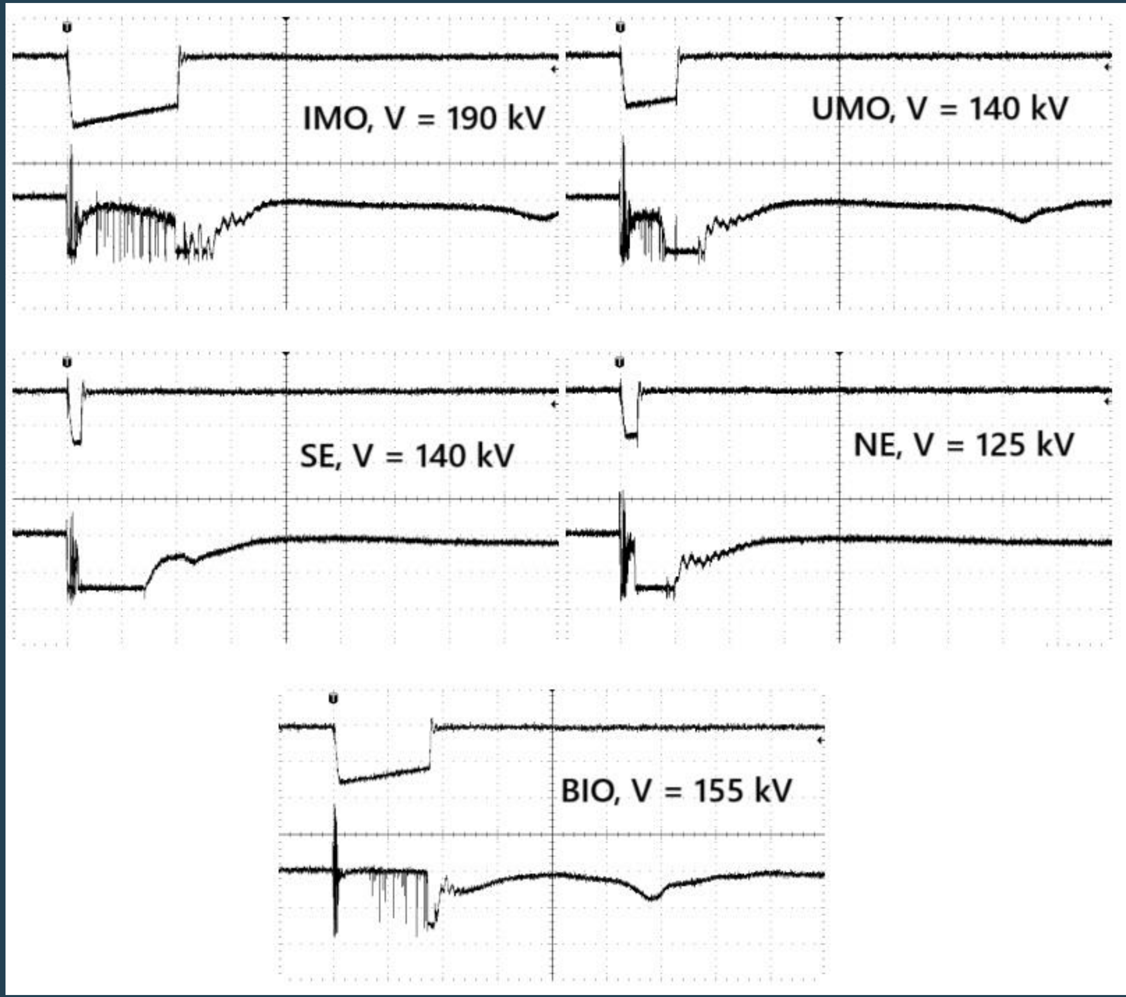


Light oscillograms for U-shaped HV electrode model insulated by paper

- Inception Voltage

Electrode models with paper/pressboard insulation

U-shaped HV electrode model



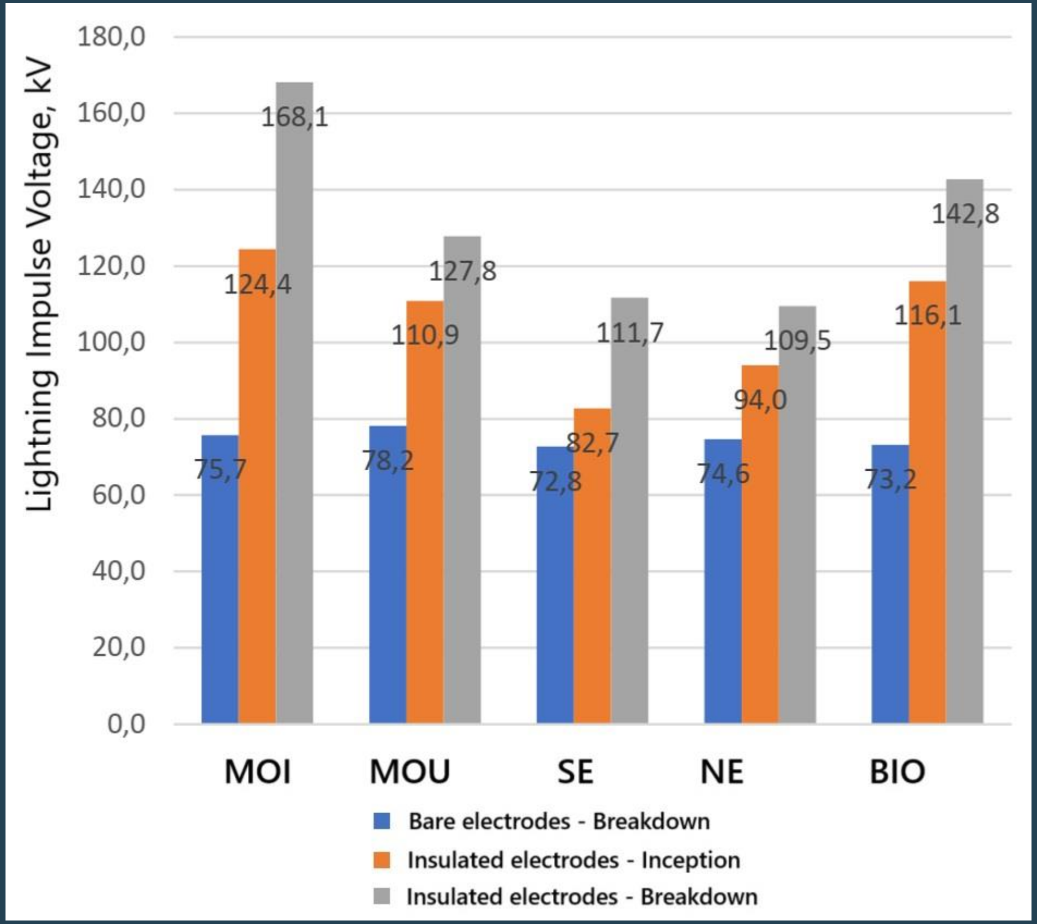
Light oscillograms for U-shaped HV electrode model insulated by paper

- Brekadown Voltage

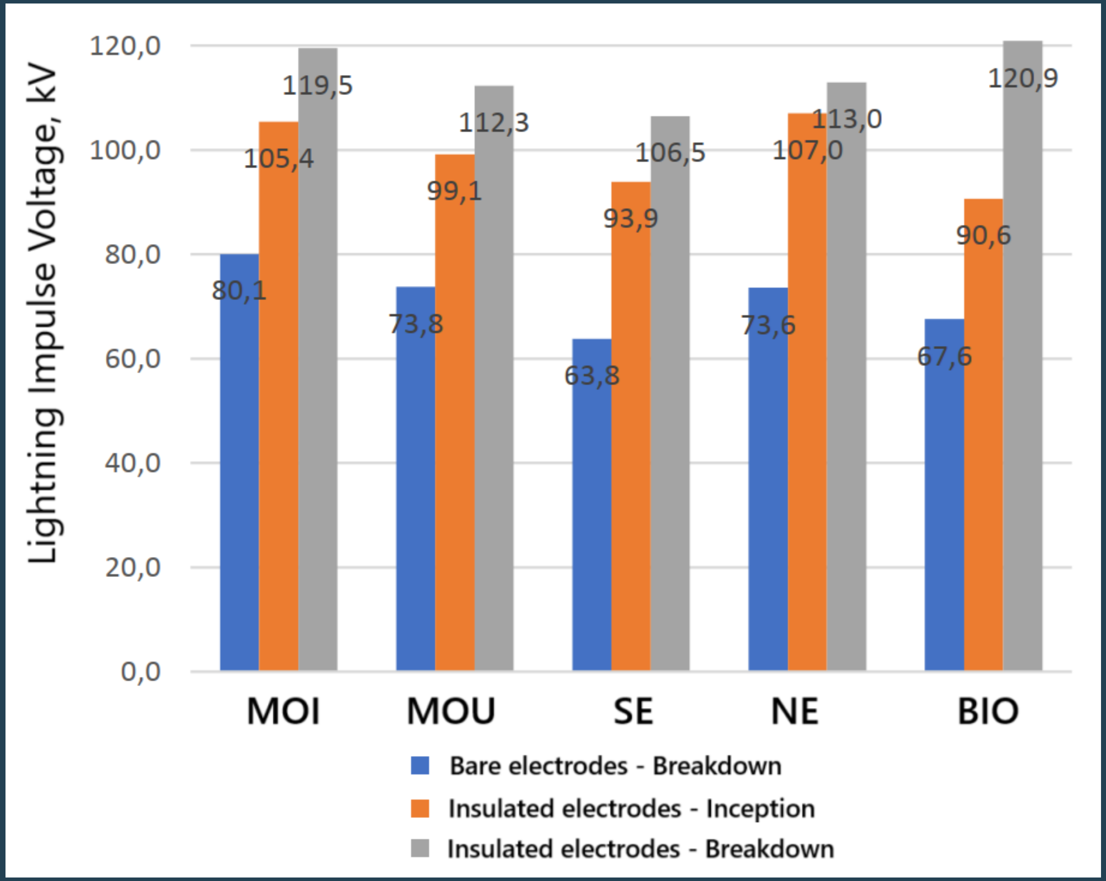
Electrode models with paper/pressboard insulation

U-shaped HV electrode model

Negative polarity

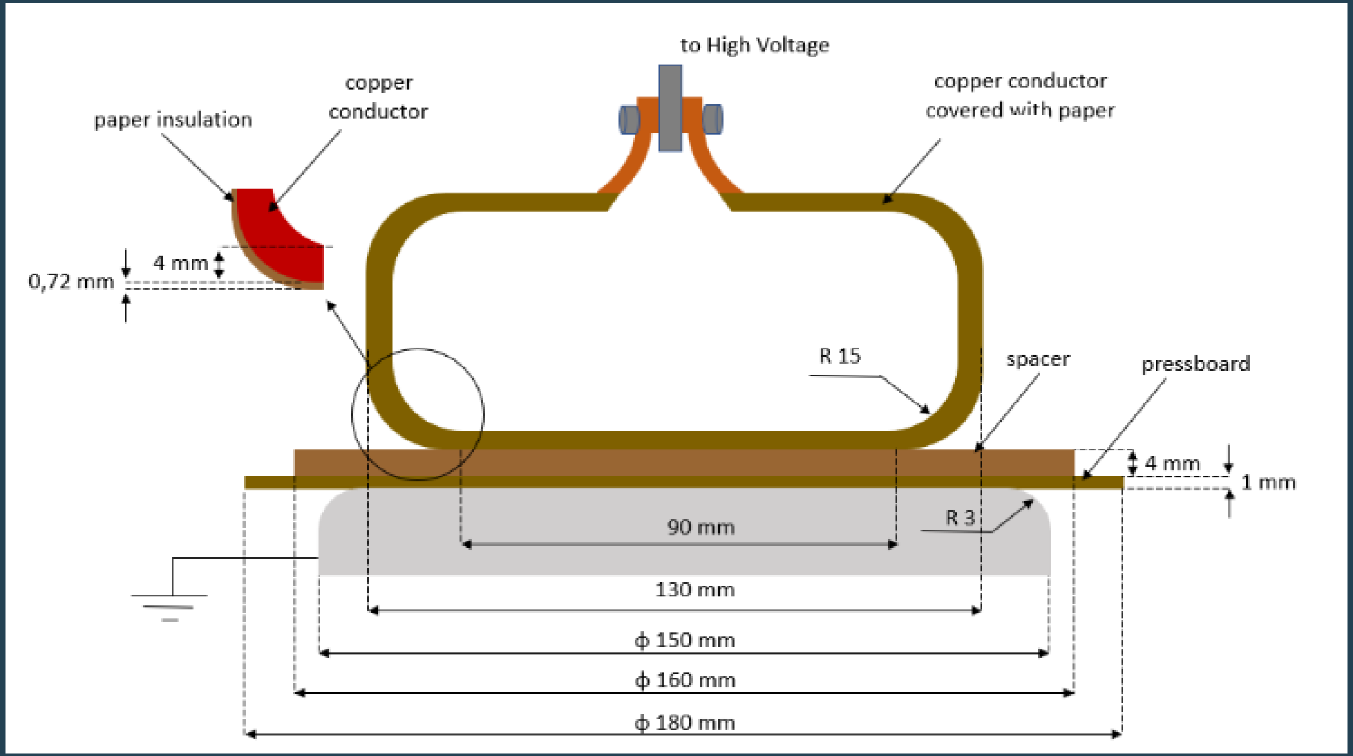


Positive polarity



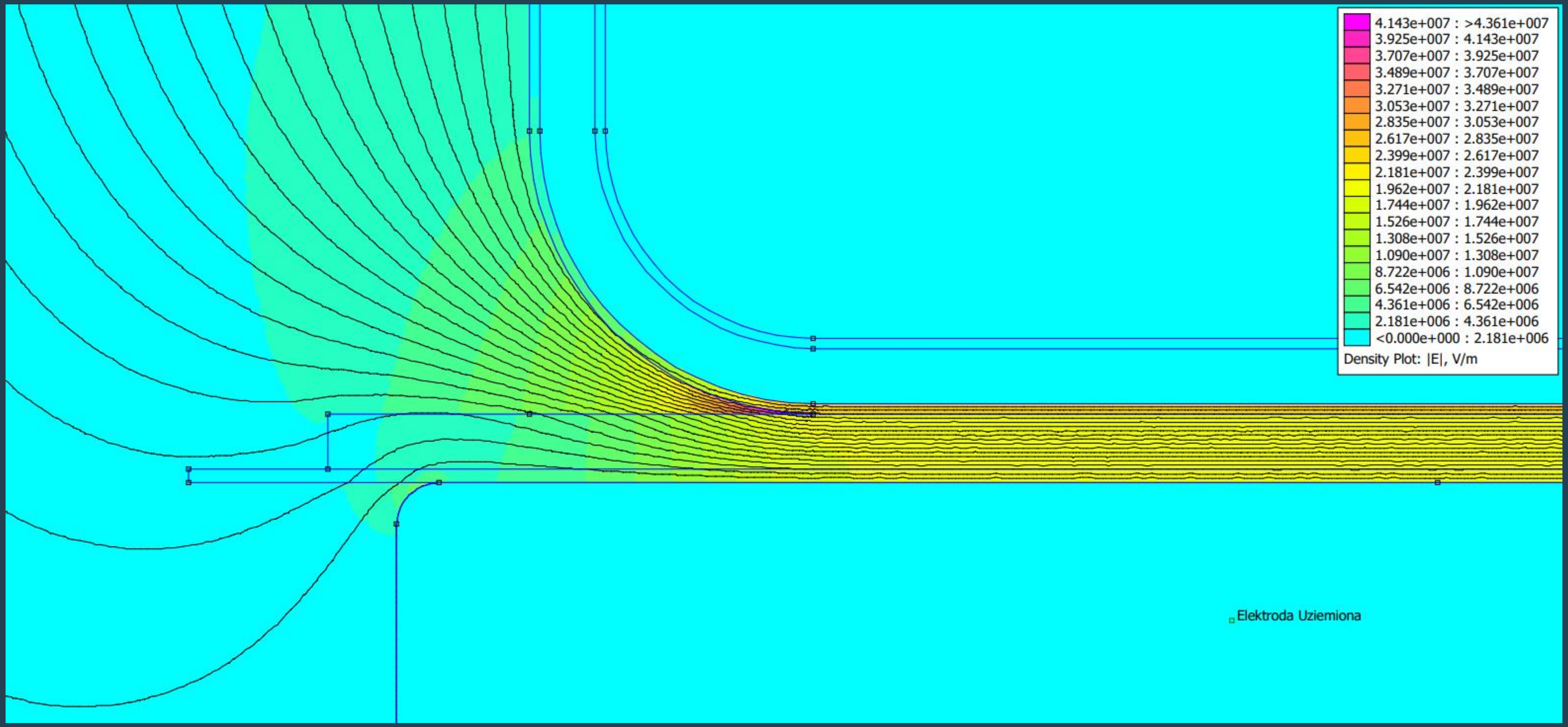
Electrode models with paper/pressboard insulation

Oil-Wedge model



Electrode models with paper/pressboard insulation

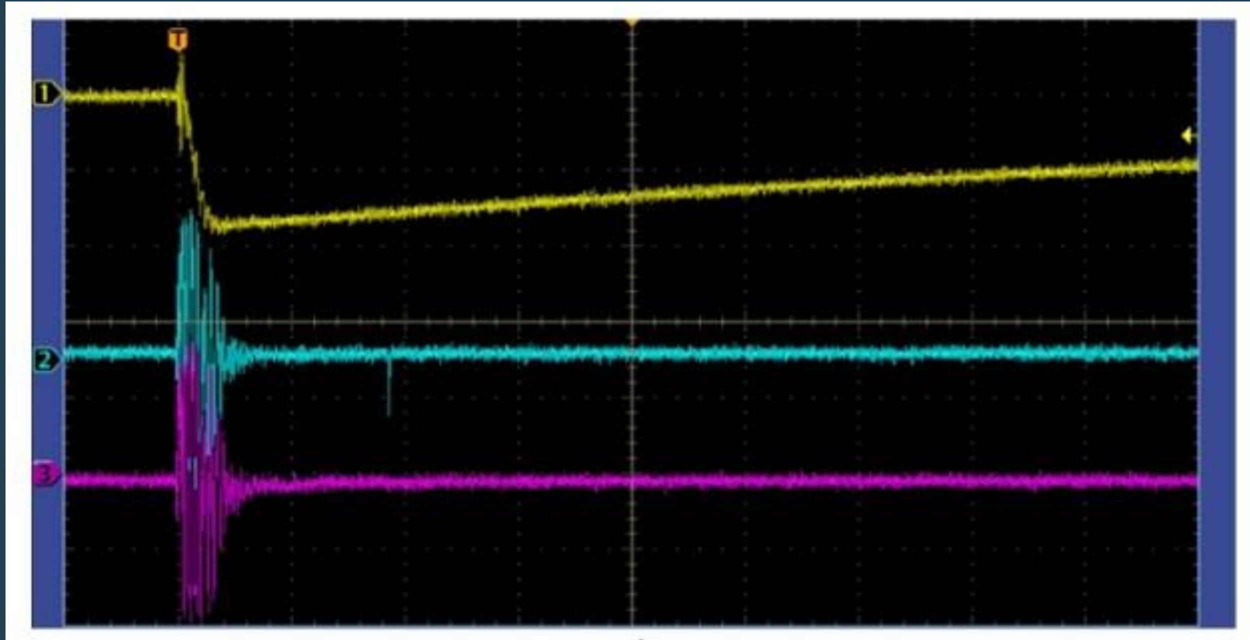
Oil-Wedge model



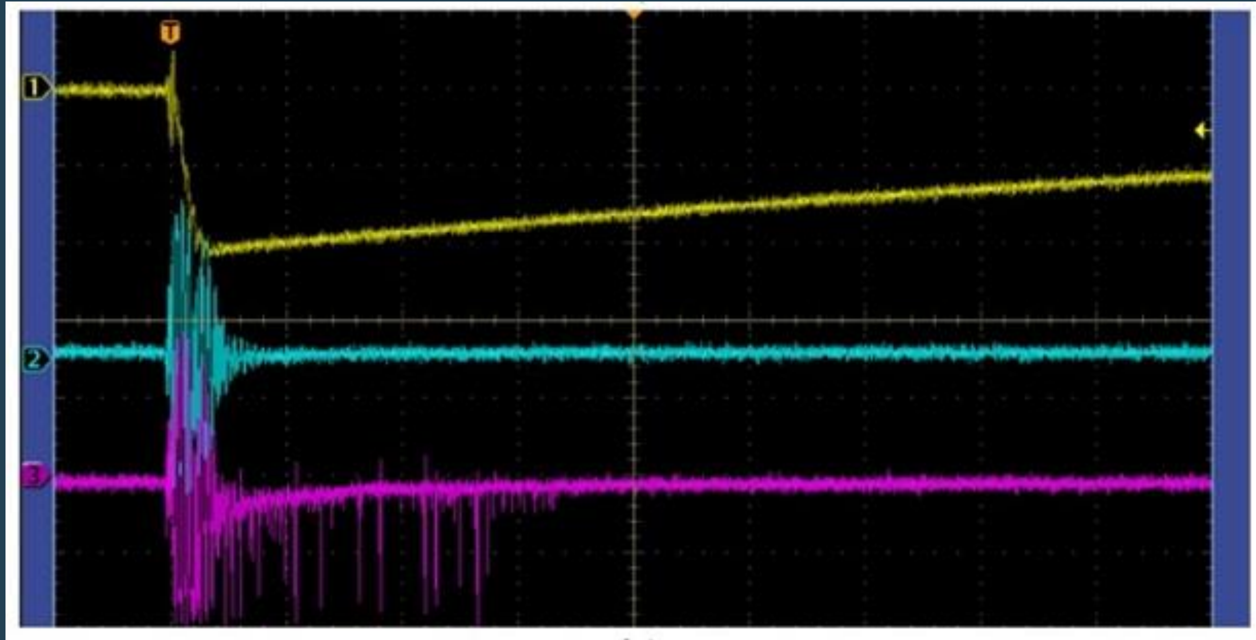
2D electric field distribution in the oil-wedge model

Electrode models with paper/pressboard insulation

Oil-Wedge model



a)



b)

Examples of discharge inception recognition:

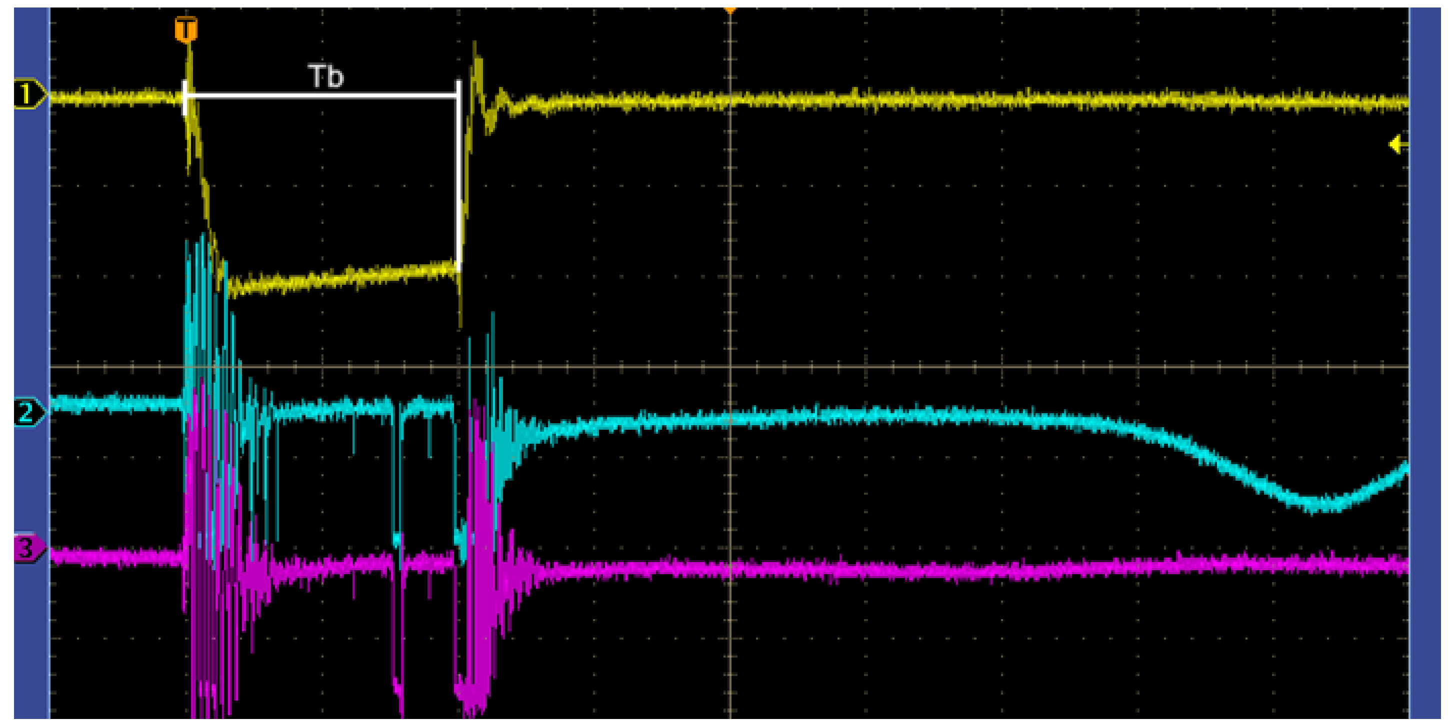
a) a case when defining it on the basis of one light pulse,

b) a case when defining it on the basis of burst of pulses,

yellow color – voltage (100 kV/div.), cyan color – signal from PMT-1 (arb. unit), violet color – signal from PMT-2 (arb. unit)

Electrode models with paper/pressboard insulation

Oil-Wedge model

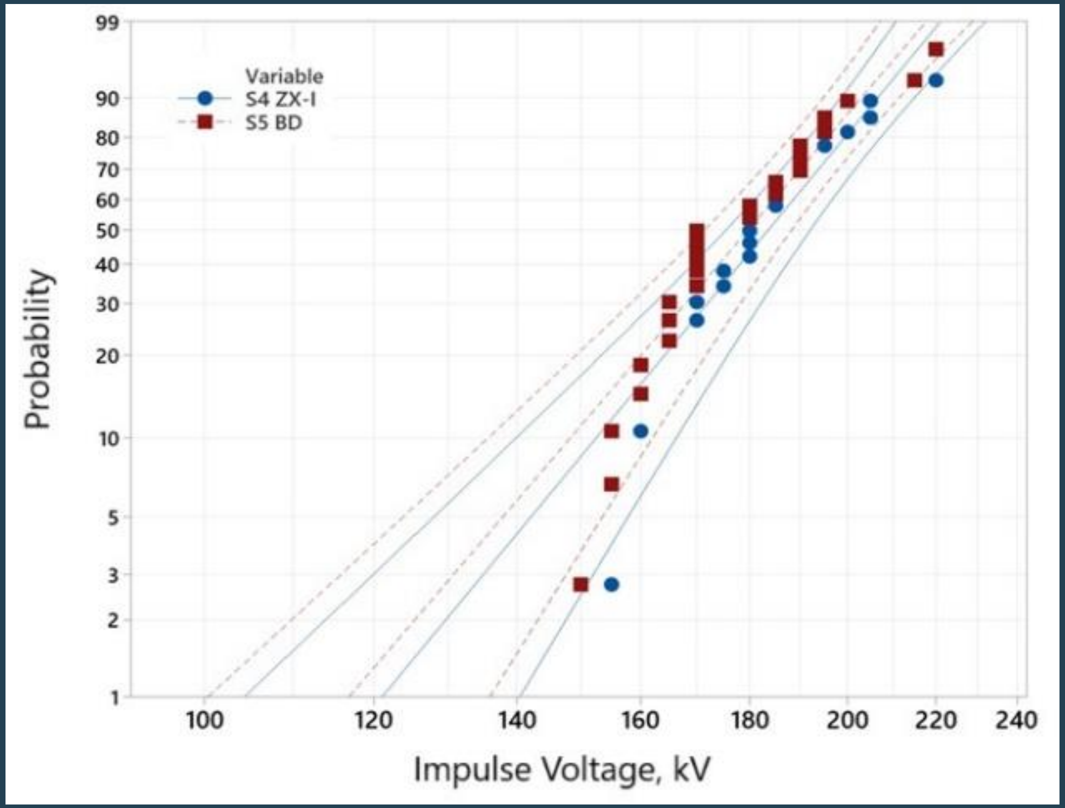


A case of breakdown event:

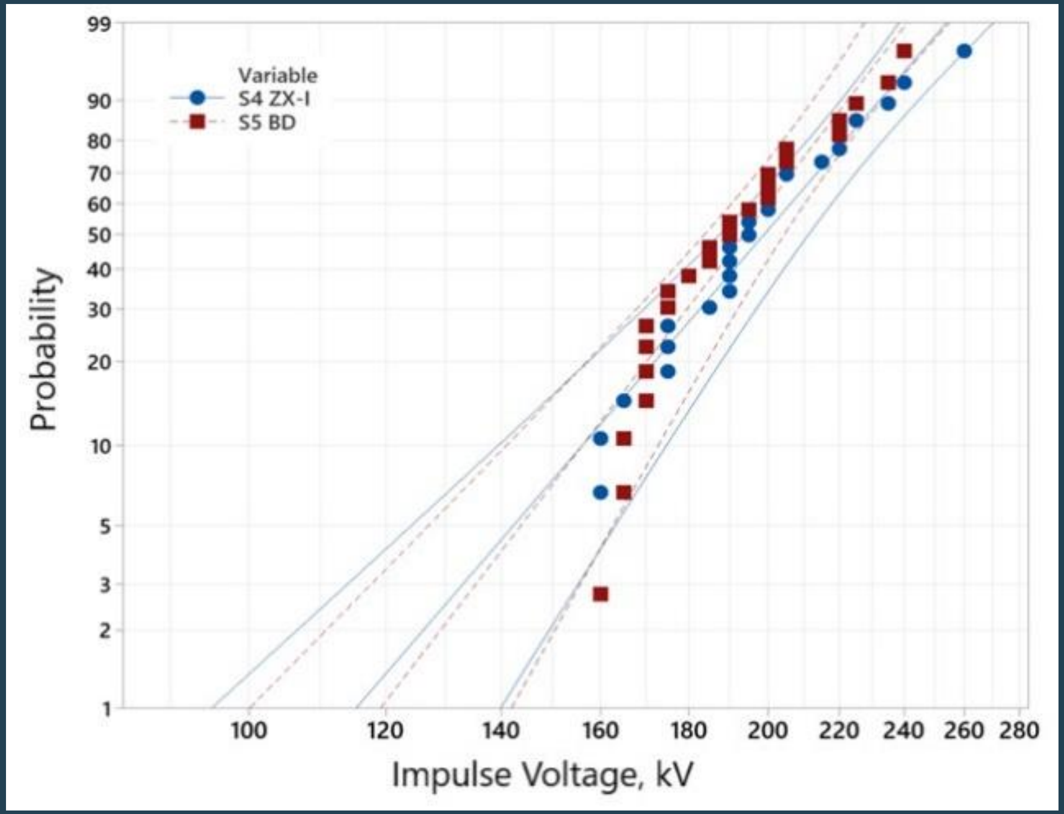
yellow color – voltage (100 kV/div.), cyan color – signal from PMT-1 (arb. unit), violet color – signal from PMT-2 (arb. unit), Tb – time to breakdown

Electrode models with paper/pressboard insulation

Oil-Wedge model



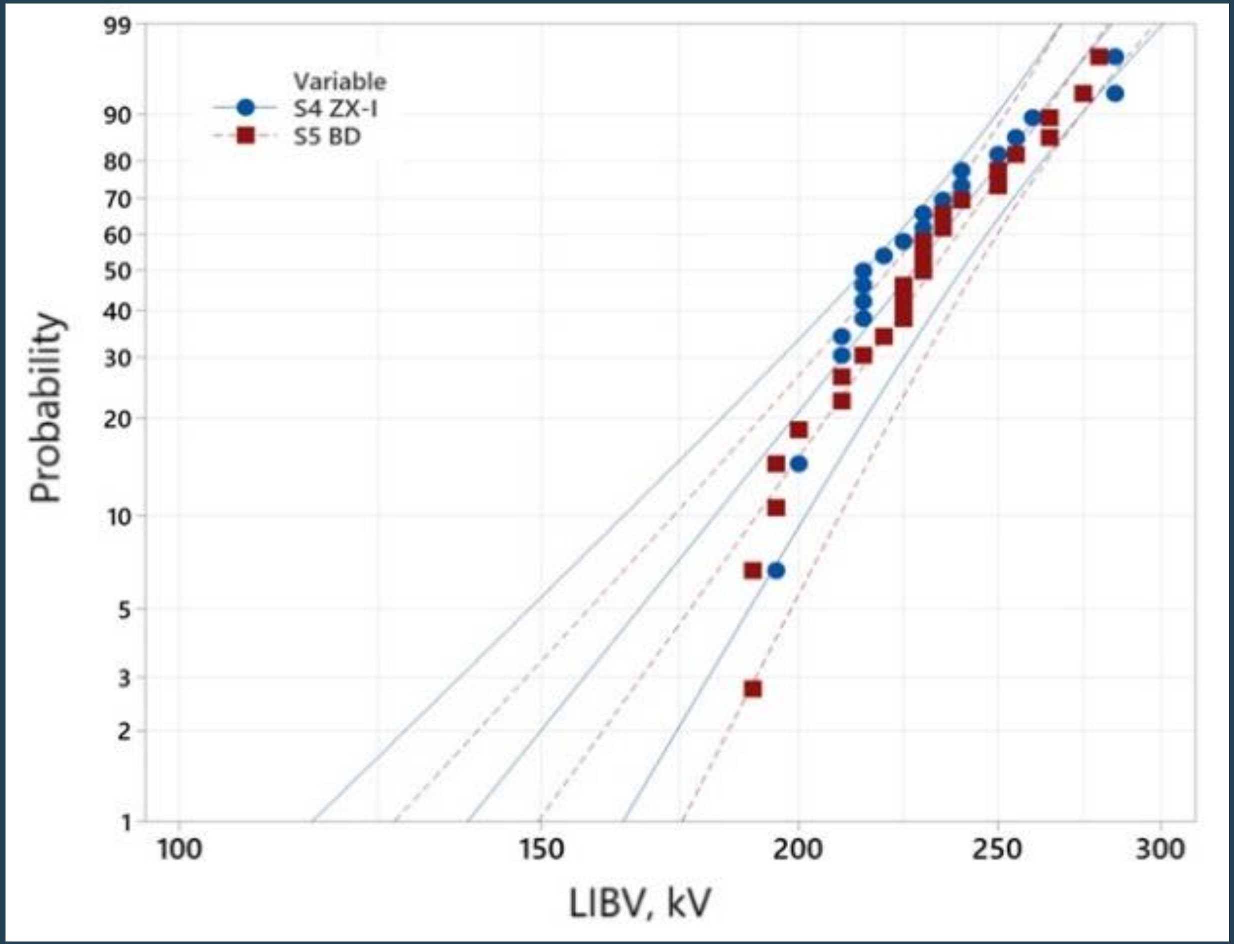
Cumulative Weibull distribution for Vi-1 case



Cumulative Weibull distribution for Vi-2 case

Electrode models with paper/pressboard insulation

Oil-Wedge model



Cumulative Weibull distribution for Vb

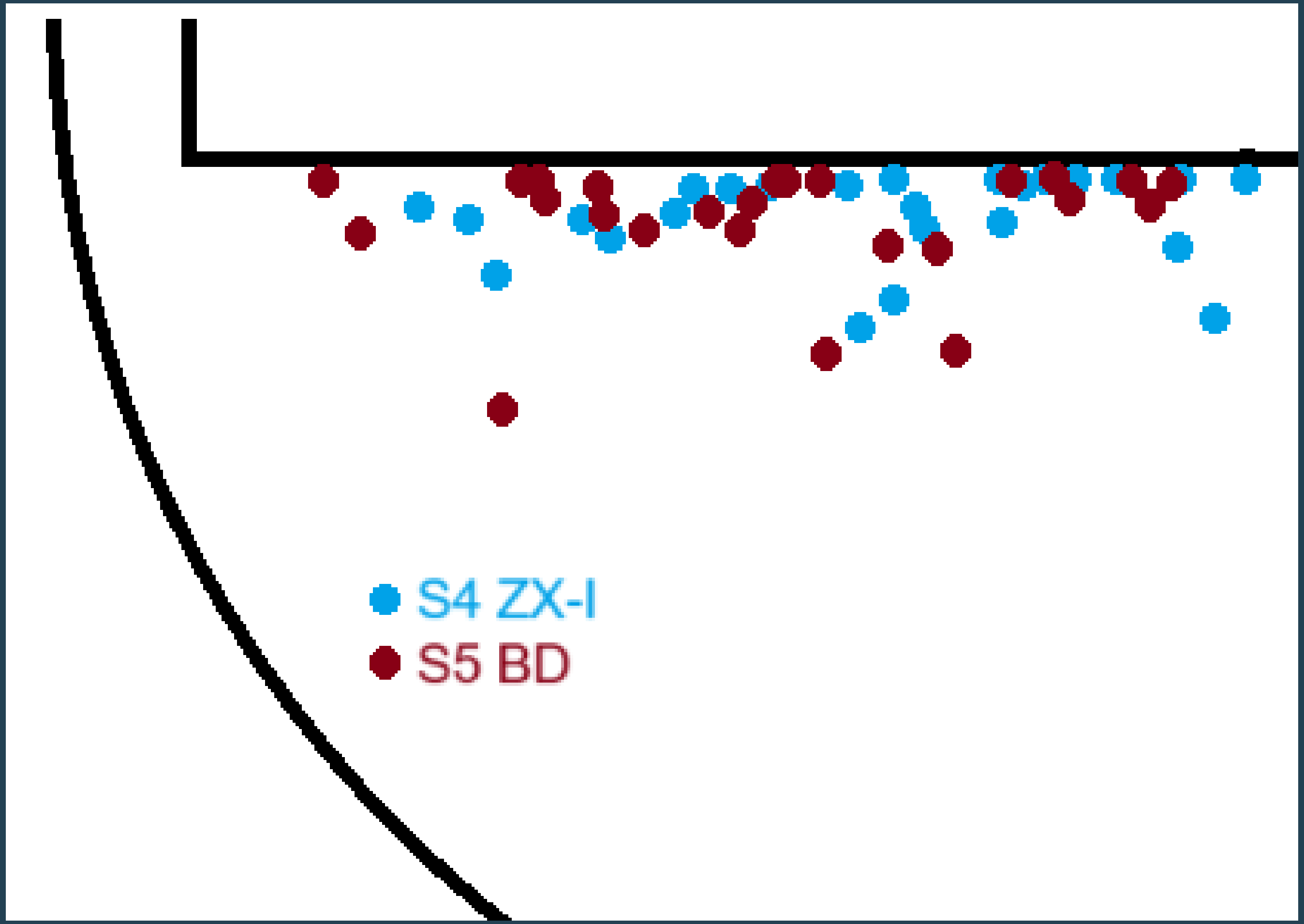
Electrode models with paper/pressboard insulation

Oil-Wedge model

	Considered quantity					
	Vi-1		Vi-2		Vb	
	S4 ZX-I	S5 BD	S4 ZX-I	S5 BD	S4 ZX-I	S5 BD
1% Weibull [kV]	121.0	116.8	115.3	119.1	138.0	149.4
5% Weibull [kV]	142.1	137.8	142.3	143.7	167.2	177.0
50% Weibull [kV]	183.5	179.6	198.9	193.8	227.3	232.2
Mean value [kV]	181,8	178.0	197	191.8	225,4	229.6
St. dev. [kV]	18,5	18.3	26,2	22.9	25.9	26.1
Shape parameter [-]	10.2	9.8	7.8	8.7	8.5	9.6
Tb [μs]	-	-	-	-	10.1	11.3

Electrode models with paper/pressboard insulation

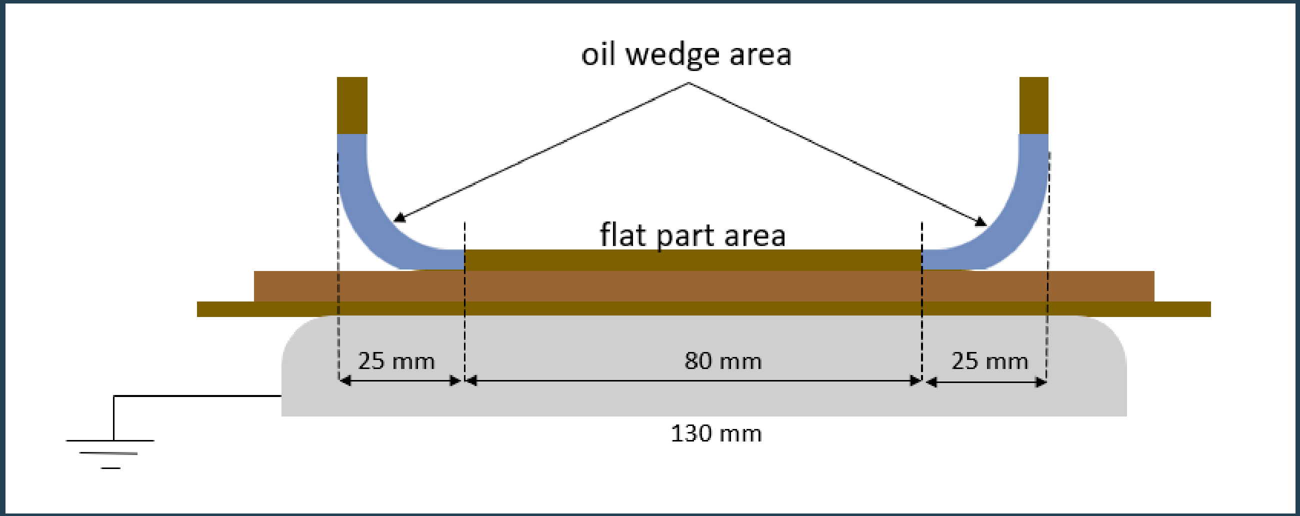
Oil-Wedge model



Distribution of places of puncture on the pressboard plate normalized to one quarter of the circle

Electrode models with paper/pressboard insulation

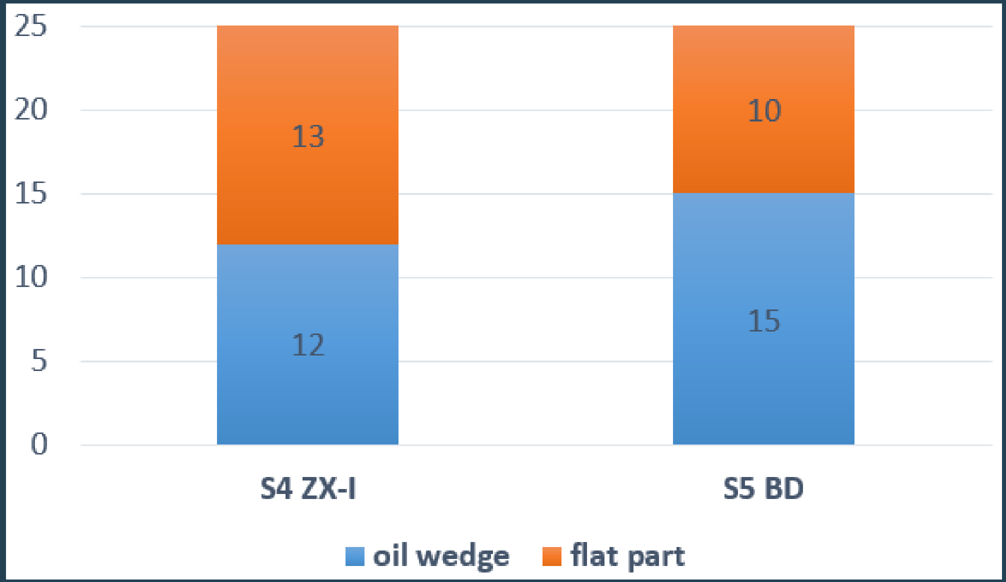
Oil-Wedge model



Division of HV electrode on oil-wedge area and flat part area

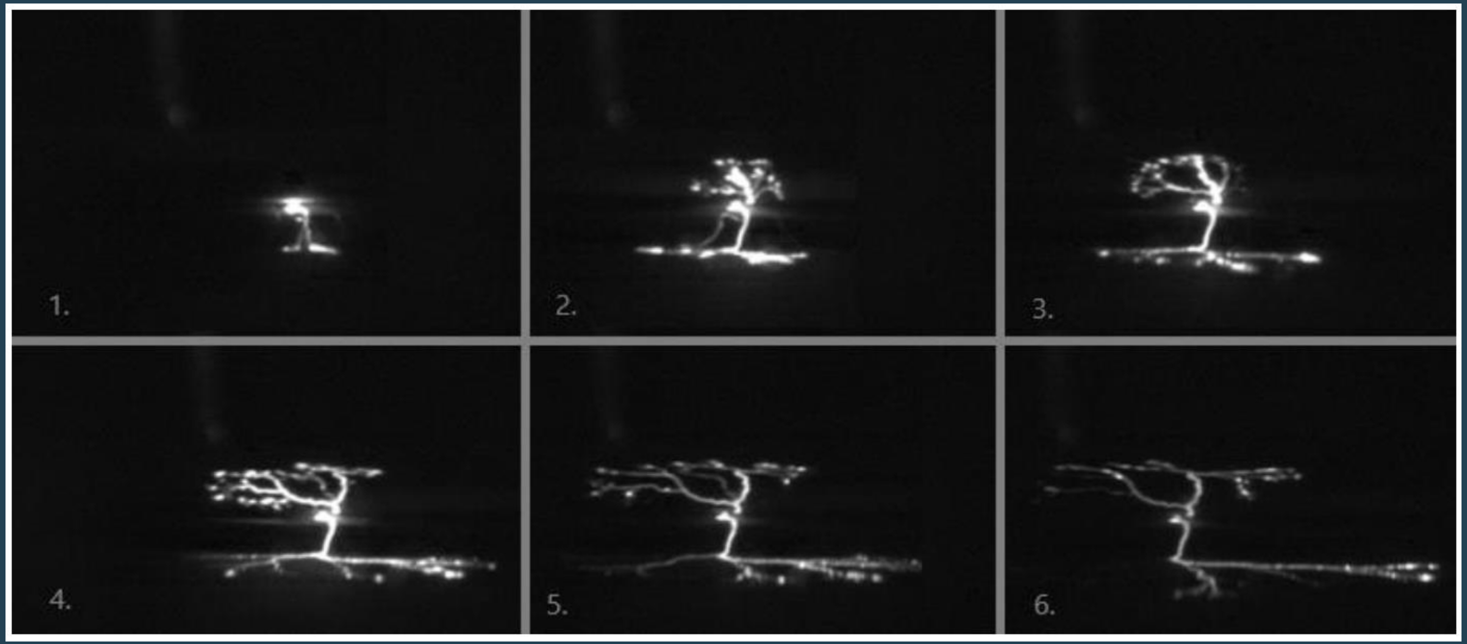
Examples of place of puncture:

a) In the flat part area, b) in the oil-wedge area



Distribution of places of carbonization on HV electrode

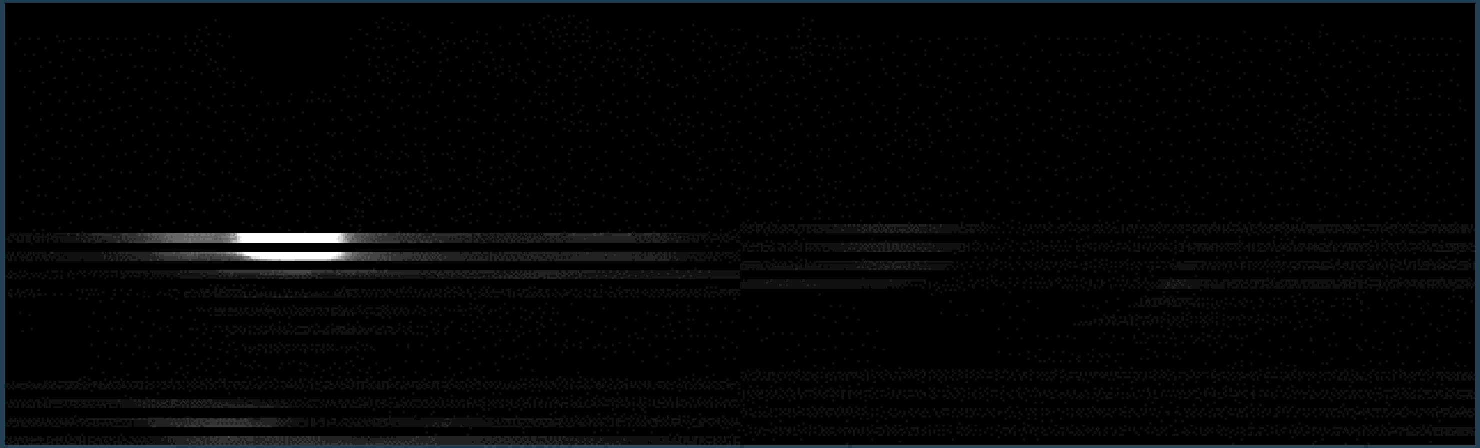
Oil-Wedge model – discharges



Sequence of photos for non-breakdown discharge

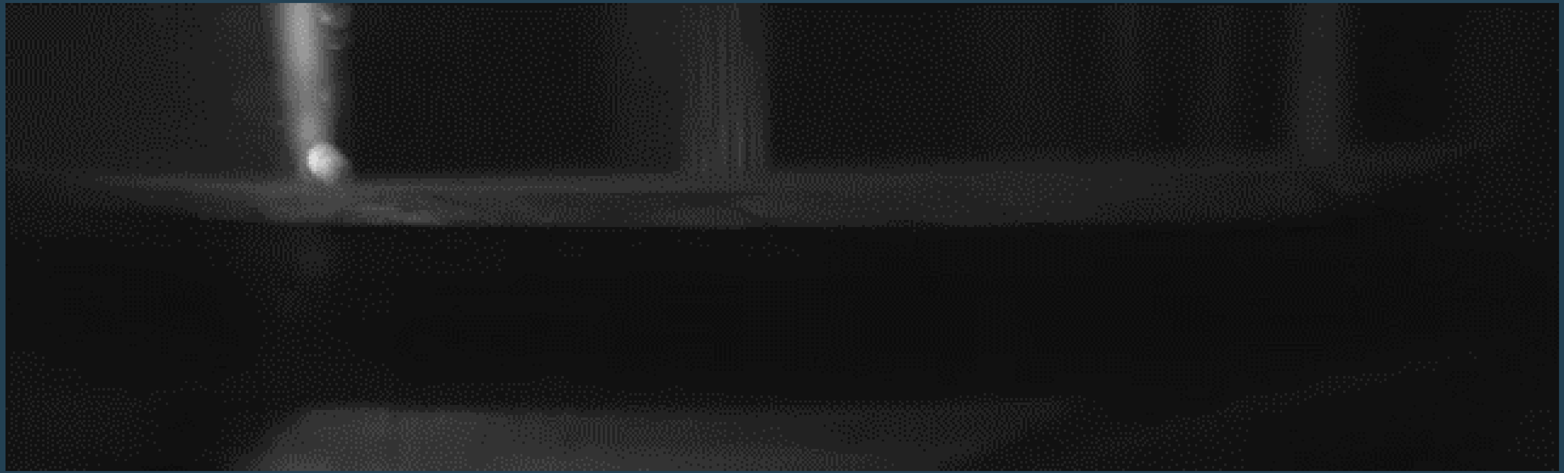
Sequence of photos for discharge leading to breakdown

Oil-Wedge model – discharges

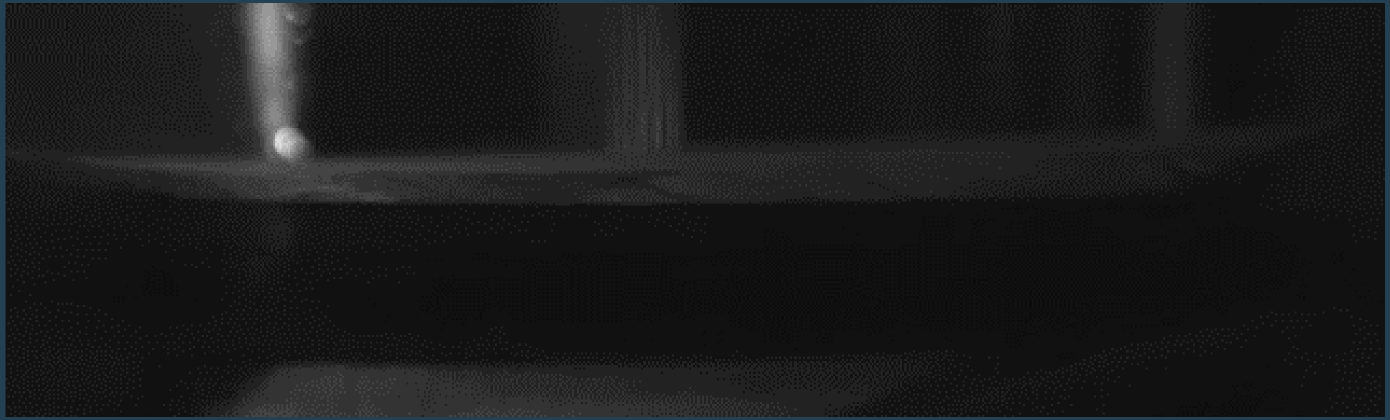


Movies from high-speed camera concerning discharge inception in S4 ZX-I

Oil-Wedge model – discharges



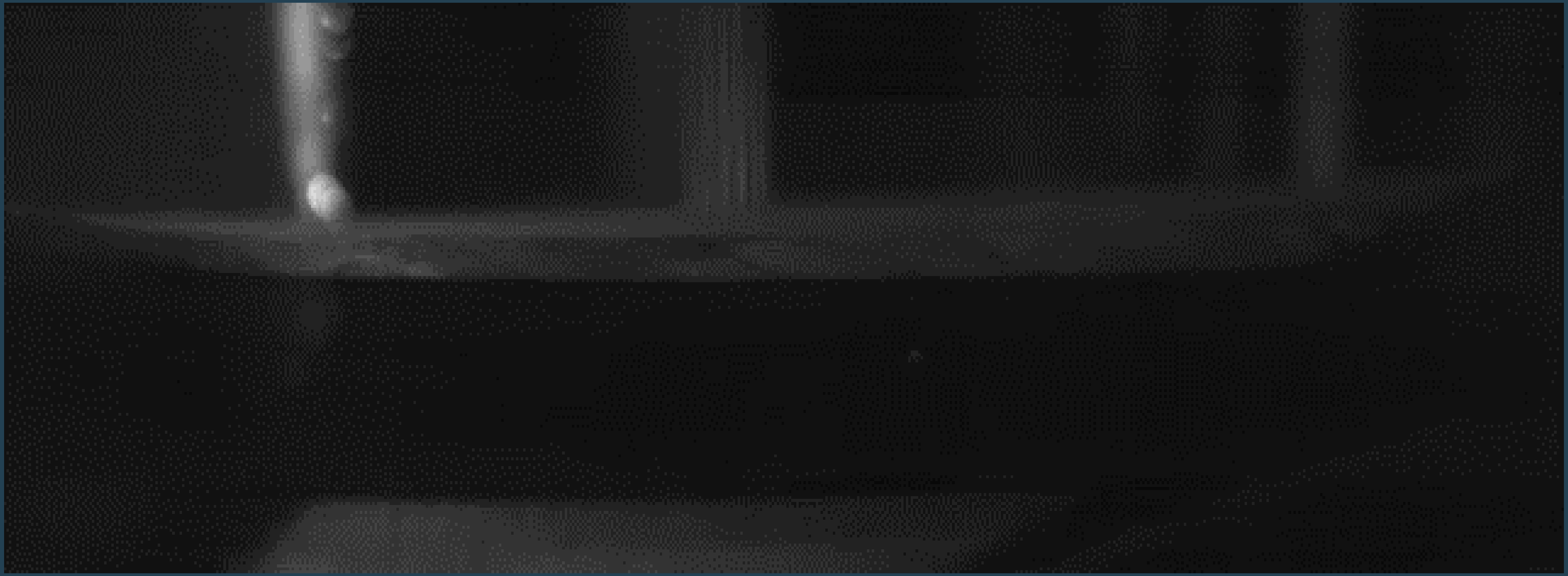
Movies from high-speed camera concerning discharge inception in S5 BD



Oil-Wedge model – discharges

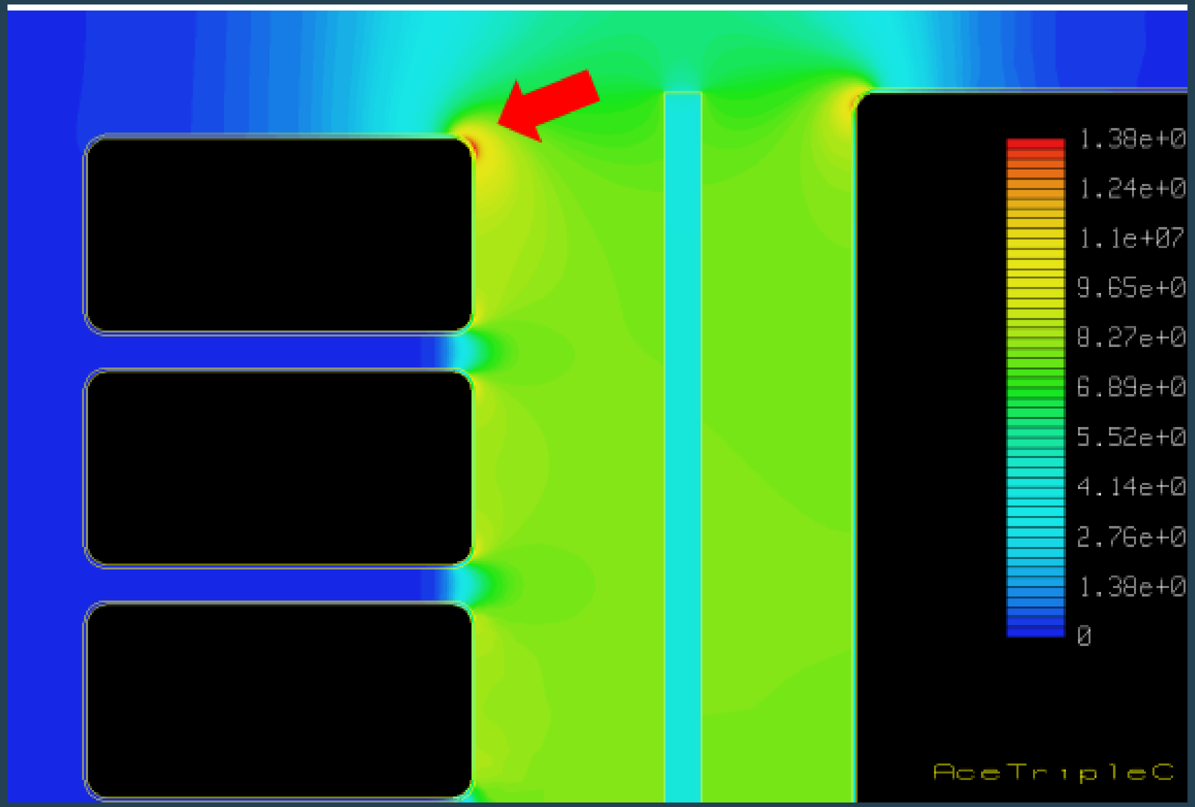
Movies from high-speed camera concerning breakdown in S5 BD

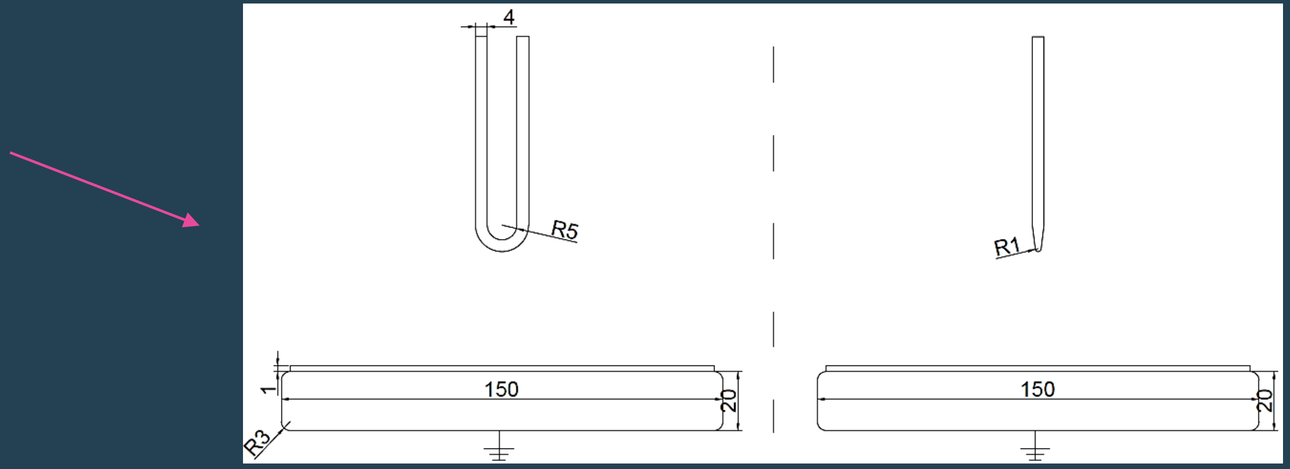
Oil-Wedge model – discharges



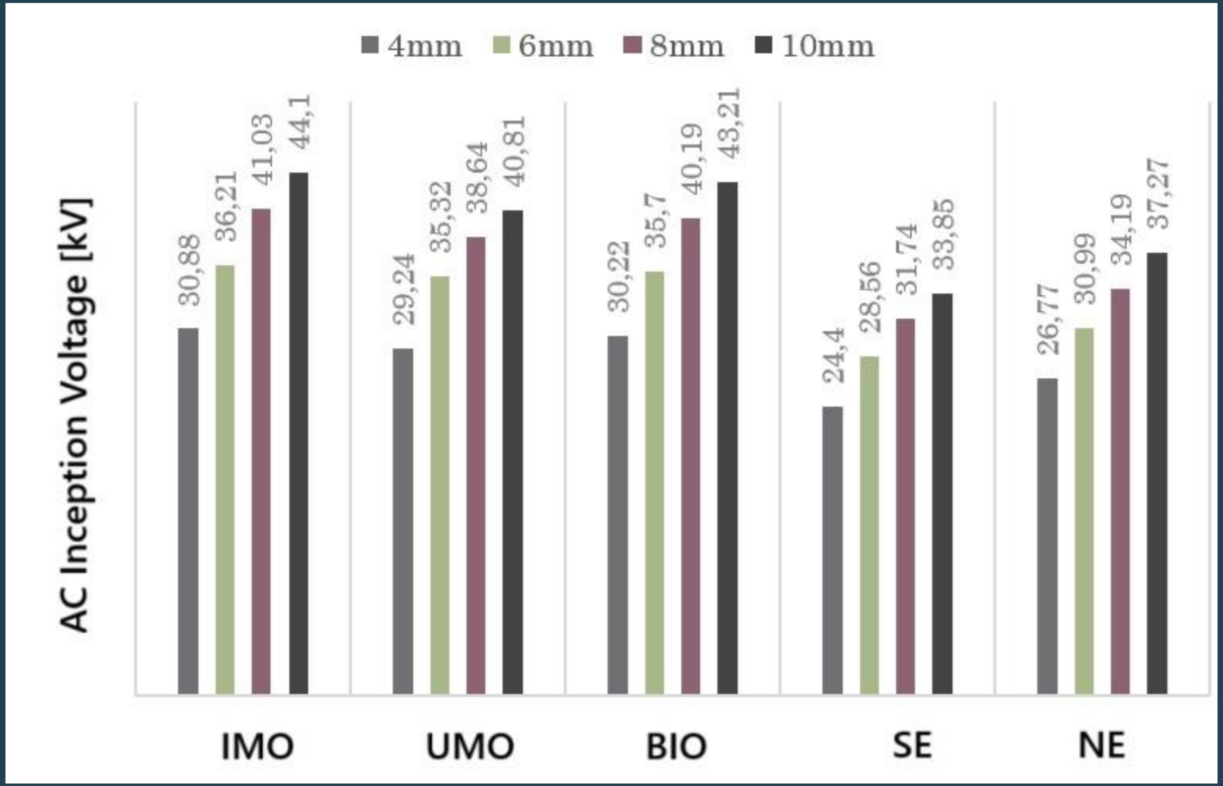
Movies from high-speed camera concerning breakdown in S4 ZX-I

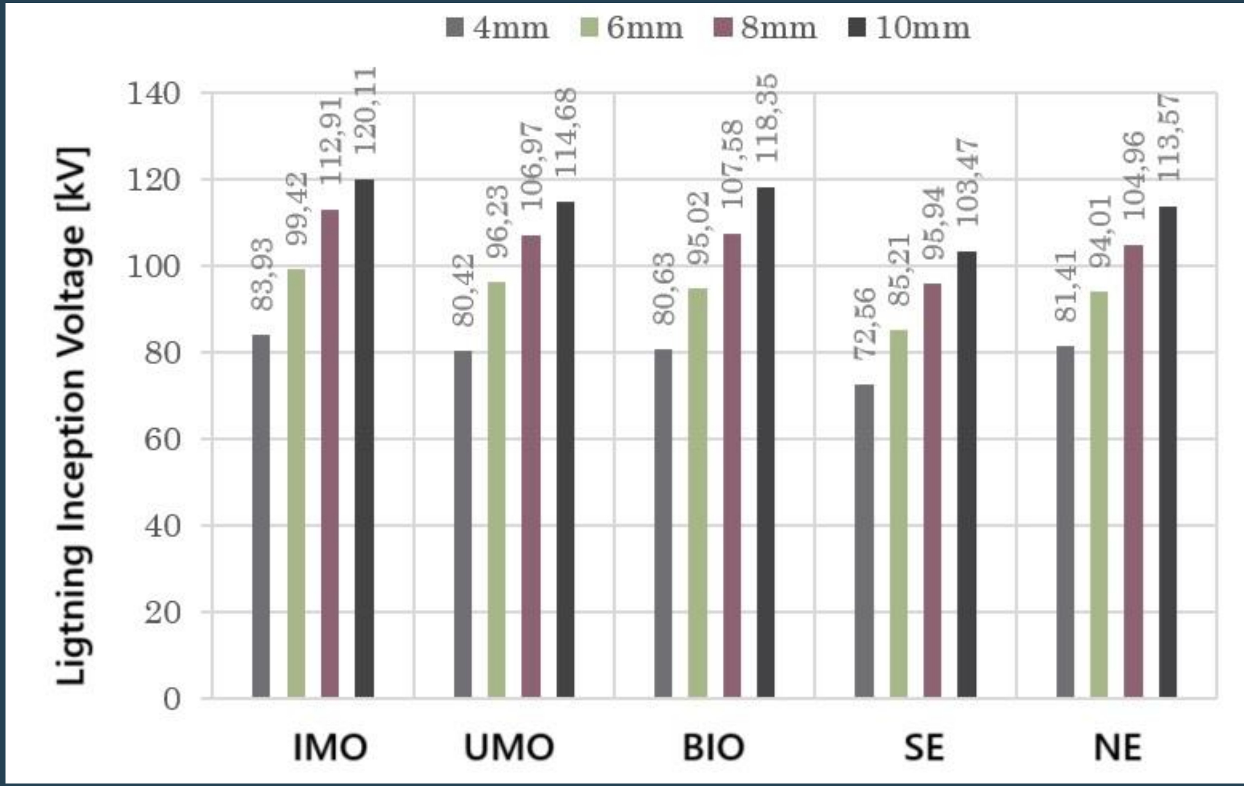
Design Insulation Level (DIL) determination





Design Insulation Level (DIL) determination

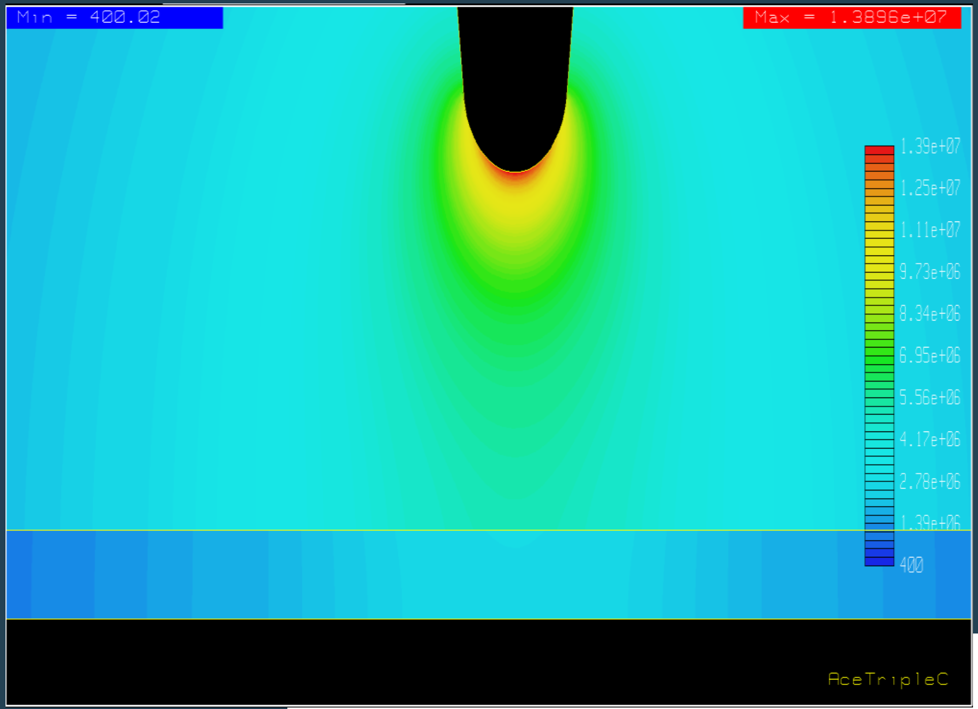




Design Insulation Level (DIL) determination

d [mm]	IMO	UMO	BIO	SE	NE
4 mm	2.72	2.75	2.67	2.97	3.04
6 mm	2.75	2.75	2.66	2.98	3.03
8 mm	2.75	2.75	2.68	3.02	3.07
10 mm	2.72	2.72	2.74	3.06	3.05
Średnia	2.73	2.74	2.69	3.01	3.05

Design Insulation Level (DIL) determination



	d [mm]	IMO	UMO	BIO	SE	NE
Electric field stress values in dielectric liquid [kV/mm]	4	14.19	13.44	13.88	10.98	12.05
	6	13.32	12.99	13.14	10.37	11.25
	8	12.90	12.16	12.64	9.88	10.64
	10	12.29	11.38	12.05	9.55	10.20

Summary

There is no one universal way to assess a resistance of the dielectric liquid against lightning impulse voltage.

Both CIGRE and IEEE TC on LD suggest to consider Acceleration Voltage (Va) as an indicator of lightning performance of dielectric liquid

Based on own expereince of the Lodz University of Technology High Voltage Research Team, it is recommended to consider also insulated electrode models for determining the lightning performance of insulating system with dielectric liquid.

Non-standard approach is proposed to be used by the transformer manufacturers in terms of lightning impulse voltage stress when introducing new dielectric liquid into use / portfolio.