

DESIGN AND OPTIMIZATION OF A SPECIMEN

FOR MEASURING NONLINEAR ELECTRICAL CONDUCTIVITY IN SMALL
MATERIAL VOLUMES FOR SEMICONDUCTOR APPLICATIONS

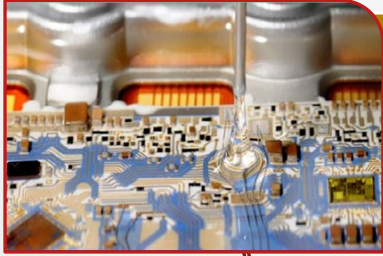
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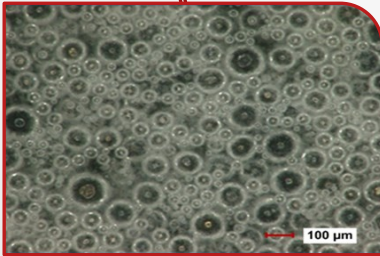
Agenda

1. Background
2. Design Methodology
3. Results and Comparison
4. Summary and outlook

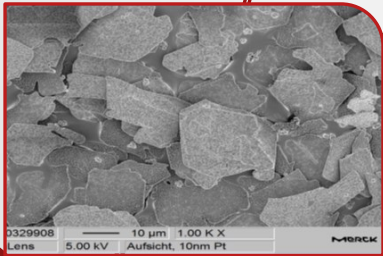
1. Background



Phase I (2000 – 2005):
Evaluation of the behavior of (pure) silicone gel

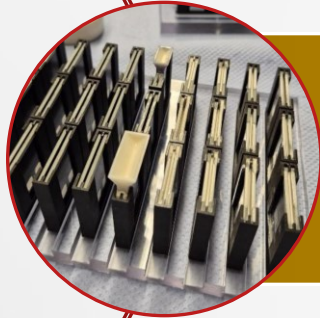


Phase II (2006 – 2010):
Investigation of hollow microsphere-filled silicone gel



Phase III (2011 – 2021):
Field-controlling nonlinear gels: Smart Gel (NLCCM)

1. Background



GelGuard* (2026 -2027):
New Project to Optimize and further investigate possible use cases for NLCM



Exzellente Forschung für
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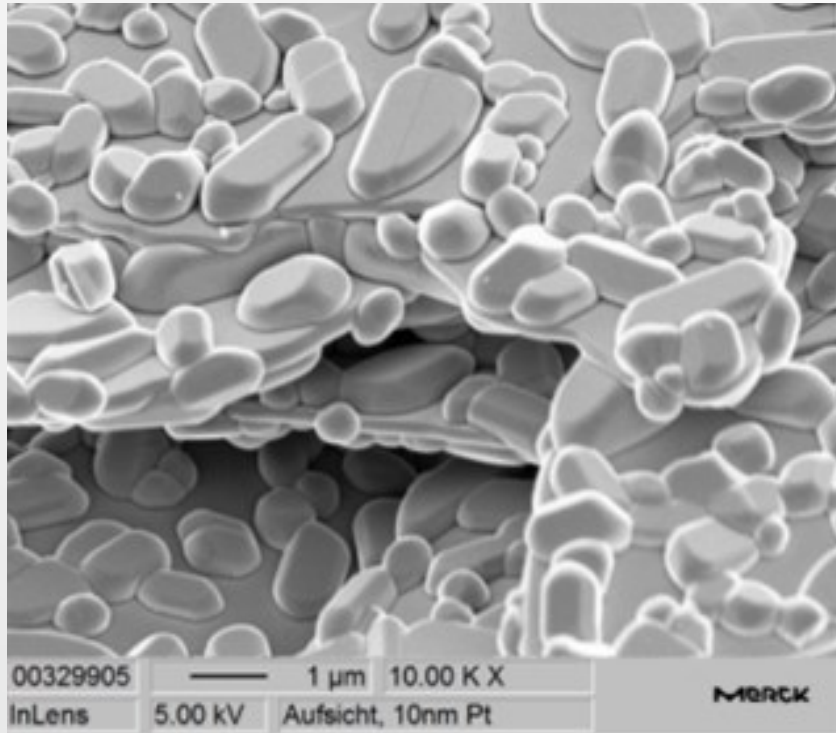
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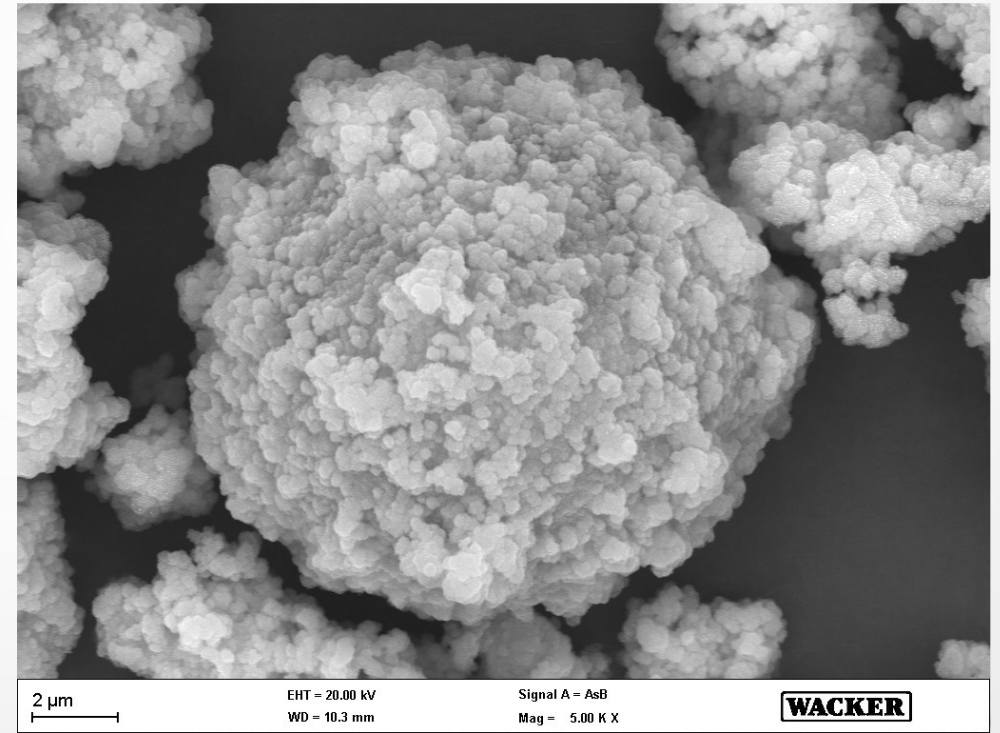
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1. Background - Nonlinear Conductive Materials (NLCM)

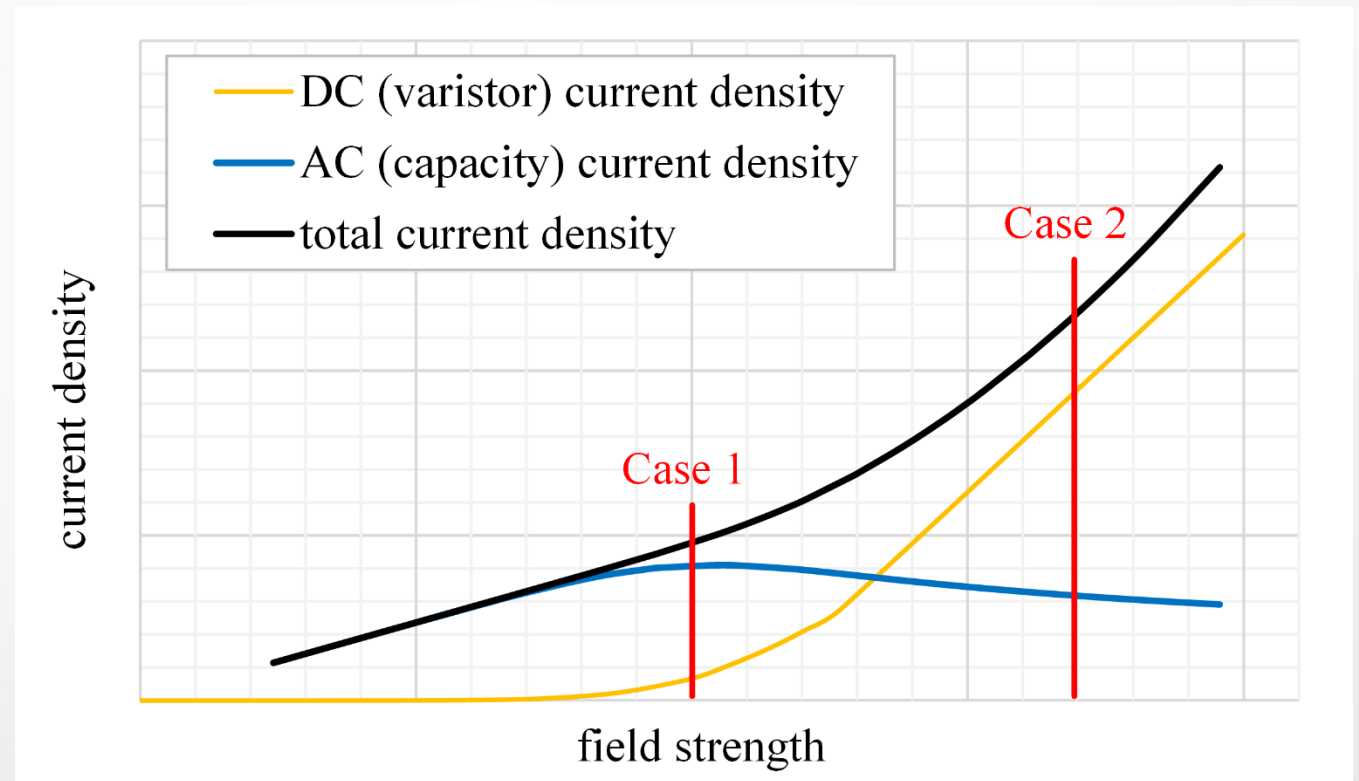
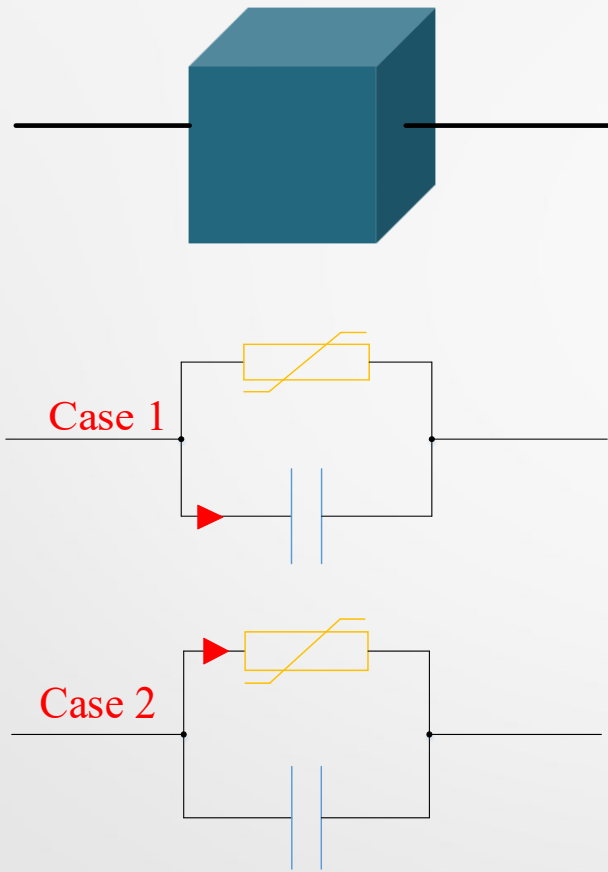


SEM Image of mica platelets with doped metal oxide coating



SEM Image of spherical substrate with doped TiO₂ coating

1. Background - ECD and Functionality of NLCM

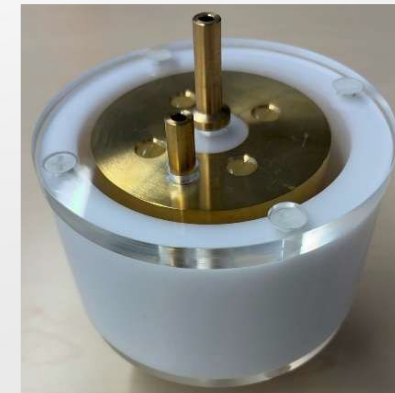
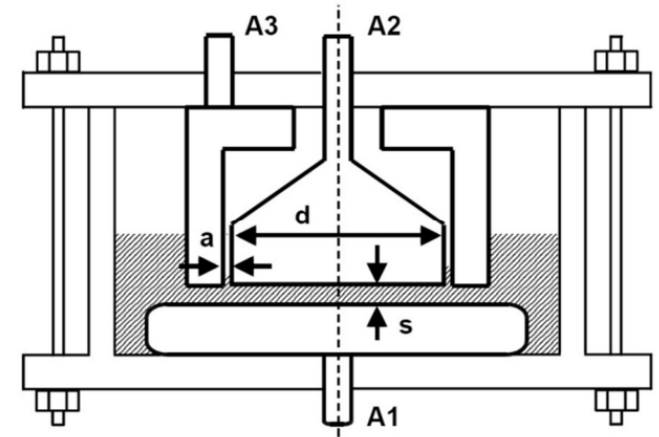


2. Design Methodology



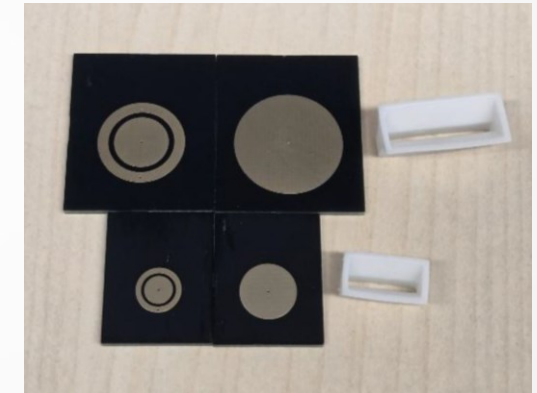
2. Design Methodology - Standard Specimen Configuration (Reference)

- ▶ **Standard:** DIN EN IEC 62631-2-1:2018-12 (Guard ring electrode measurements)
- ▶ **Construction:** Machined brass electrodes housed in an acrylic enclosure.
- ▶ **Dimensions:**
 - ▶ HV Electrode: 80 mm diameter.
 - ▶ Measuring Electrode: 49 mm diameter.
 - ▶ Guard Ring: 51–78 mm (Inner/Outer).
 - ▶ Spacing: 2.1 mm (maintained by adhesive spacers).
- ▶ **Scale:** Effective volume ~80 ml (total ~104 ml with buffer); Weight ~2.7 kg.
- ▶ **Limitations:** Manual assembly required; high material consumption; low throughput for R&D.



2. Design Methodology - Miniaturized PCB-Based Specimen Design

- ▶ **Technology:** Printed Circuit Board (PCB) with evaporated electrode patterns on FR4 substrates.
- ▶ **Two Sizes Developed:**
 - ▶ **Medium:** HV 20mm, Measuring 10mm, Volume 1 ml, Weight 9g.
 - ▶ **Small:** HV 10mm, Measuring 5mm, Volume 0.5 ml, Weight 5g.
- ▶ **Key Features:**
 - ▶ Integrated 1 mm spacers within the mount (no adhesive).
 - ▶ Via connections for external contact (no soldering/wire bonding).
 - ▶ Mounts fabricated via stereolithography (photopolymer resin).
- ▶ **Advantages:** Mass reduction >300x; high dimensional accuracy (± 0.1 mm); thermal stability up to 100°C.



2. Design Methodology – Measurement Methodology

- ▶ **Capacitance & Permittivity:** LCR meter (1 kHz – 1 MHz); Grounded guard ring to eliminate fringe fields.
- ▶ **Nonlinear Conductivity (DC):** Automated MATLAB-controlled setup.
 - ▶ Voltage steps: 500 V.
 - ▶ Settling time: 5 seconds.
- ▶ **Breakdown Strength:** Transformer with rectification.
 - ▶ Voltage ramp: 1 kV/s.
 - ▶ Analysis: Weibull statistical distribution.

3. Results and Comparison

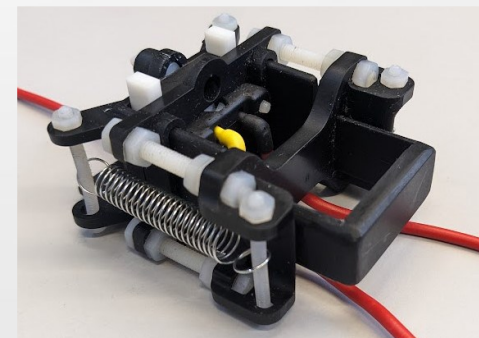
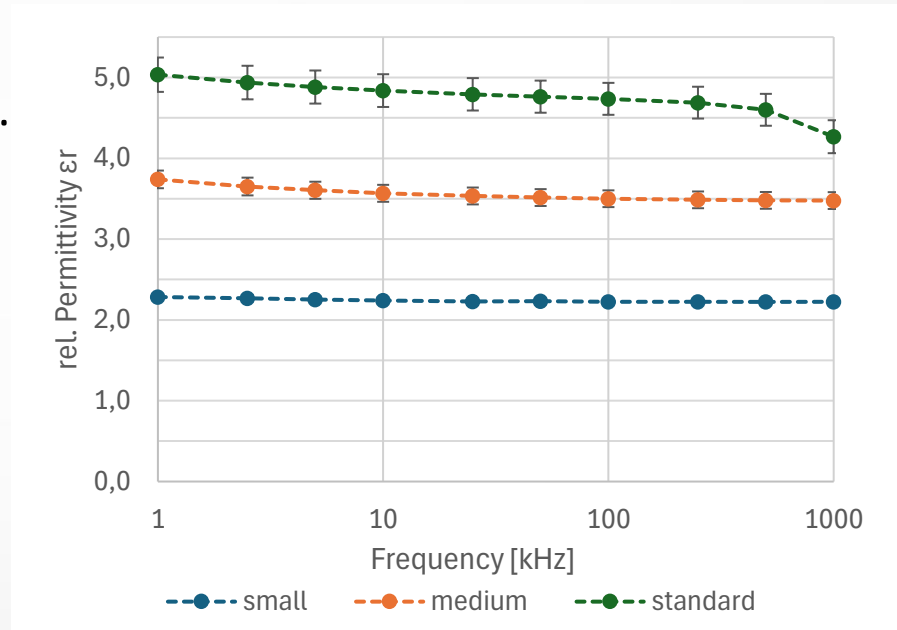
3. Results and Comparison – Resource Efficiency Analysis

Test parameter	Standard Specimen	Medium Miniaturized	Reduction factor
V_{Gel} per Specimen	104 ml	1.5 ml	69x
Additive mass (35 % fill, 10 pcs)	364 g	5.25 g	69x
Est. cost per 10 pcs	€1,040	€16.50	63x
Preparation time	1 – 1.5 h	0.5 – 1 h	2-3x
Weight	2,715 g	9 g	302x

3. Results and Comparison – Capacitance & Permittivity

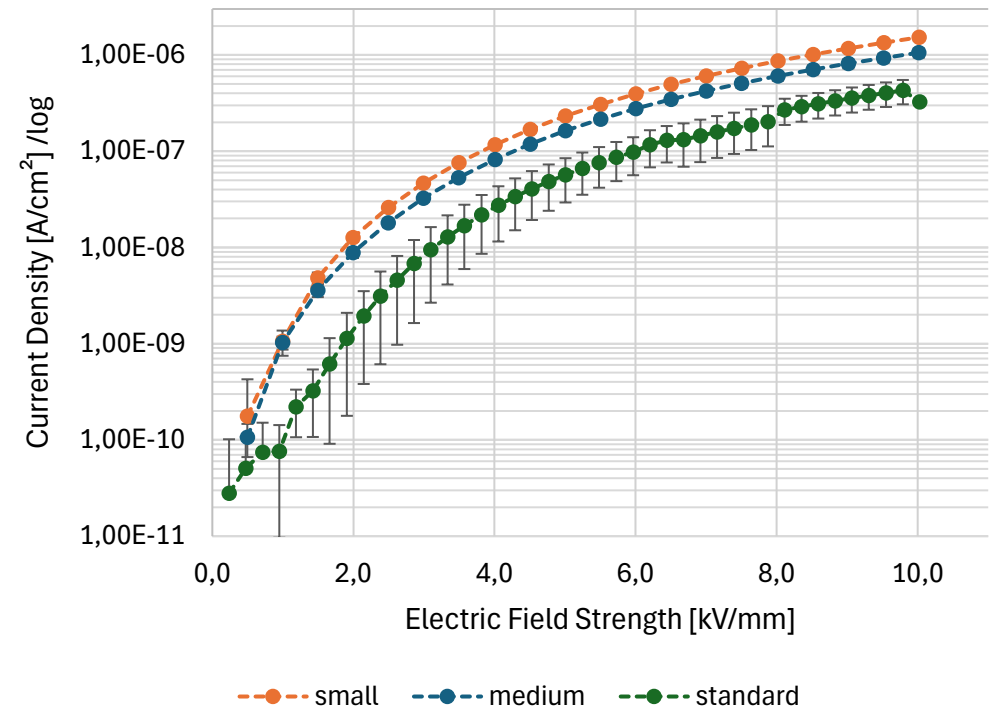
▶ Observations:

- ▶ **Standard:** Highest ϵ_r (5.0 @ 1kHz \rightarrow 4.27 @ 1MHz).
 - ▶ **Medium:** Lower ϵ_r (3.74 \rightarrow 3.48); Standard deviation halved.
 - ▶ **Small:** Lowest apparent ϵ_r (2.28 \rightarrow 2.22); Falling below pure silicone gel specs.
- ▶ **Root Cause:** Systematic error due to contact fixture capacitance affecting measurements of bare PCB specimens (<5 pF).
- ▶ **Conclusion:** Despite artifacts, the design is superior for screening; issues solvable via cable compensation or improved fixtures.



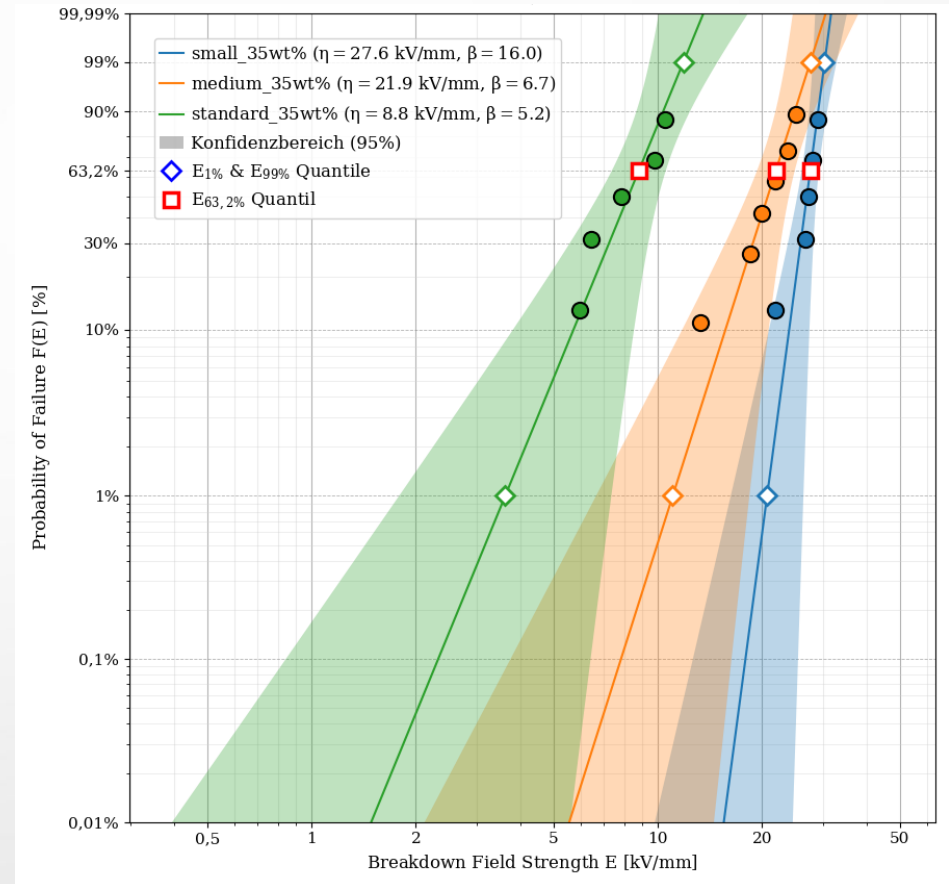
3. Results and Comparison – Nonlinear Current Density Characteristics

- ▶ **Validation:** Miniaturized designs successfully capture fundamental nonlinear conductivity curves comparable to standard specimens.
- ▶ **Volume Effect:**
 - ▶ Standard deviation *increases* with specimen size.
 - ▶ Larger volumes have higher probability of critical defects.
- ▶ **Implication:** Miniaturized specimens are ideal for **comparative material screening** and identifying relative differences between formulations.
- ▶ **Future Work:** Planned validation with inhomogeneous geometries (e.g., needle-plane).



3. Results and Comparison – DC Breakdown Strength

- ▶ **Quantitative Volume Effect:** Characteristic breakdown field strength (η) decreases as volume increases.
 - ▶ **Small:** 27.6 kV/mm
 - ▶ **Medium:** 21.9 kV/mm
 - ▶ **Large:** 8.8 kV/mm
- ▶ **Failure Mode Analysis:**
 - ▶ **Large Specimens:** Failures occurred at spacer-compound interfaces (weak points introduced by mechanical assembly).
 - ▶ **Miniaturized:** Elimination of adhesive spacers reduces interface-related failures.
- ▶ **Reliability:** Higher shape parameter (β) for small/medium specimens indicates better data consistency.





4. Summary and Outlook

4. Summary and Outlook – Validation of Miniaturized Design

▶ **Successes:**

- ▶ Replicates electrical measurement capabilities of IEC 62631 standards.
- ▶ Guard ring effectively eliminates fringe fields.
- ▶ PCB integration ensures geometric reproducibility (no manual alignment errors).

▶ **Limitations to Address:**

- ▶ AC measurement artifacts for specimens <5 pF (requires calibration).
- ▶ Resin mounts are less durable than brass for long-term industrial QC (but sufficient for R&D).

4. Summary and Outlook – Implications of the Volume Effect

- ▶ **Critical Insight:** Properties measured on small specimens may **overestimate** breakdown strength for bulk materials.
- ▶ **Extrapolation Risk:** Caution required when scaling lab results to industrial components.
- ▶ **Screening Advantage:** Smaller specimens allow faster identification of promising formulations due to lower defect probability.
- ▶ **Standardization Gap:** Current IEC standards do not address volume scaling for nonlinear materials.
 - ▶ *Recommendation:* Future standards should include volume correction factors or minimum dimension specifications.

4. Summary and Outlook – Practical Recommendations

- ▶ **Optimal Strategy:** Use **Medium-sized specimens (1 ml)** for initial characterization (best balance of validity vs. efficiency).
- ▶ **Verification:** Validate critical findings with at least one large specimen to ensure industrial relevance.
- ▶ **Measurement Setup:** Implement cable compensation for AC measurements on small specimens.
- ▶ **Throughput:** Enable batch processing (20–50 specimens) for comprehensive statistical analysis previously very time and material consuming with standard methods.

4. Summary and Outlook – Conclusion & Future Research

- ▶ **Main Conclusion:** PCB-based miniaturized guard ring specimens are a **viable, highly efficient alternative** to conventional brass assemblies.
- ▶ **Key Achievement:** 70–140x material reduction while maintaining validity for DC nonlinear conductivity.
- ▶ **Future Research Directions:**
 1. Refine cable measurement compensation for small specimens.
 2. Investigate correlation between volume effect, electrode spacing, and absolute volume.
 3. Develop automated fabrication of integrated guard ring geometries.
 4. Expand testing to inhomogeneous field configurations (needle-plane).

Thank you for your attention



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