Tailoring of new Field Grading Materials for HVDC Systems

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Structure

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- **Motivation**
- **Challenges of DC-Insulation-Systems**
- **Introduction of a characteristic nonlinear κ-E-curve**
- **Design of a FGM for HVDC Cable Joints**
- **Conclusions**

Motivation

Requirements towards the future grid

- Integration of de-centralized, renewable energy sources
- Transportation of electrical energy over long distances

Approach: HVDC

(one) prerequisite:

Robust DC-Insulation systems

Example: german grid

Challenges of DC-Insulation-Systems

"DC does not occur" – F.H. Kreuger

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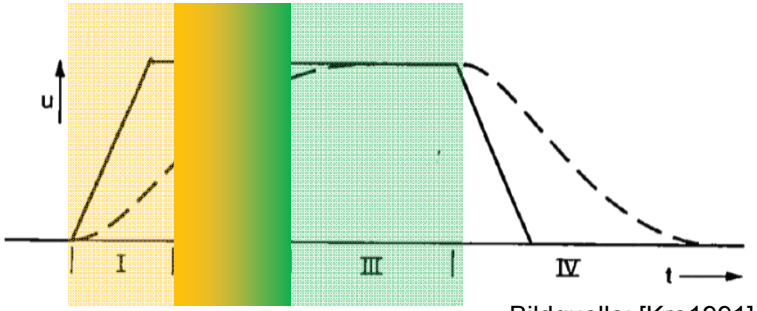
The insulation system undergoes two states:

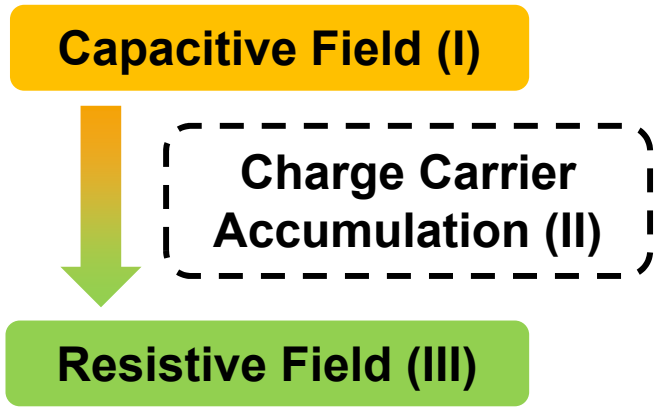
- **Capacitive graded** (after switching on the system, polarity reversals, transient overvoltages)
- **Resistively graded** (steady state)
- …and everything in between



Bildquelle: [Kre1991]

The **conductivities** of the system

- govern the steady state (as well as the accumulation of charge carriers)
- Are not always well known (long measurement times, complex mechanisms)
- Can vary widely with temperature, humidity, age, etc.



(Nonlinear) Field grading as a simplification

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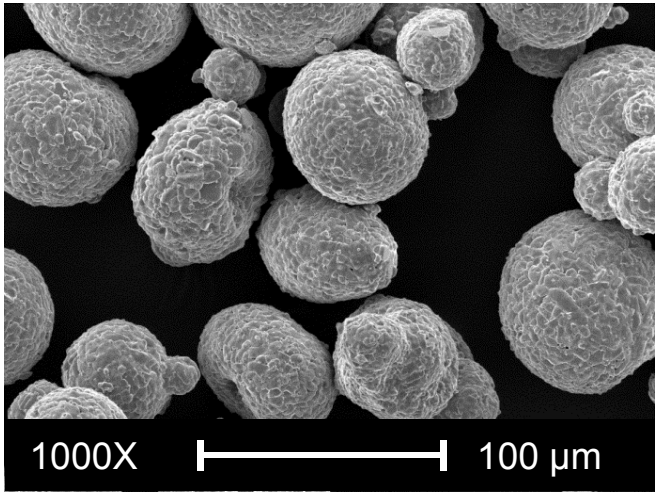
Introducing a **well-known field grading material (FGM)**…

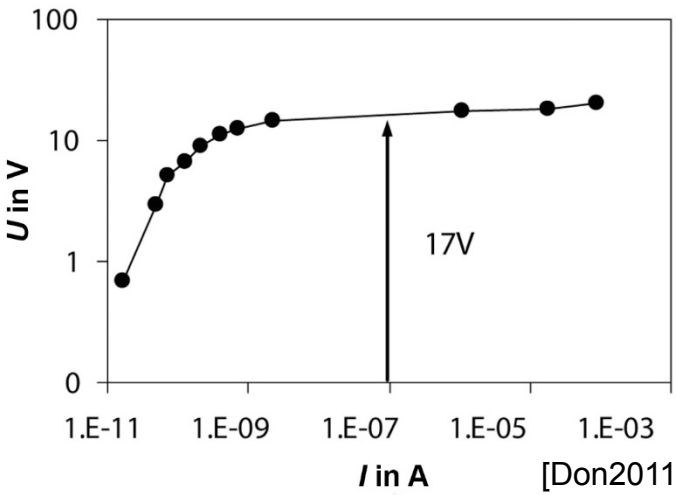
- helps **defining the field distribution** (conductivity higher compared with surrounding materials)
- enables **field grading** even in the event of **transient overvoltages** (when using a nonlinear FGM)



Today not often used in HV-components

Possible obstacles:

- Riskier when not properly designed/chosen
- Lack of standards
- Lack of (commonly agreed) terminology



[Don2011]

Introduction of a model characteristic curve

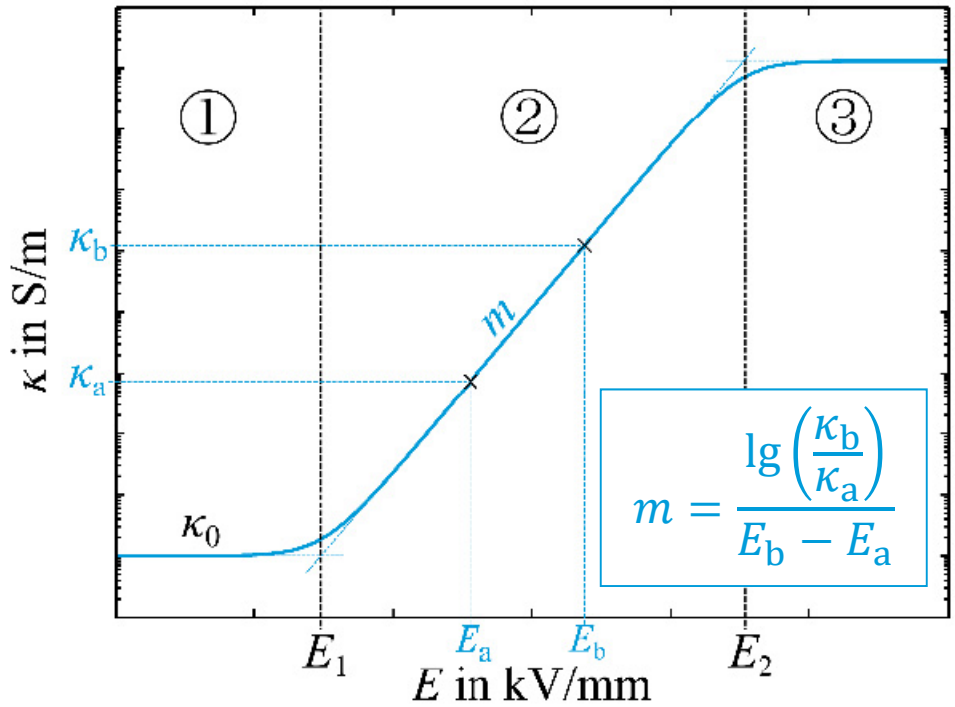
… and some new parameters

- Simple description via κ-E-curve (S. Blatt [Bla2016])
  - Fits nonlinear materials, like MO-Varistors, Microvaristors, etc.
  - Enables simulations over the full range of conditions
  - Makes use of a small set of comparably intuitive parameters

$$\kappa(E) = \kappa_0 \cdot \frac{\sqrt[N_1]{1 + X^{N_1 \cdot \frac{E - E_1}{E_1}}}}{\sqrt[N_2]{1 + X^{N_2 \cdot \frac{E - E_2}{E_1}}}}$$

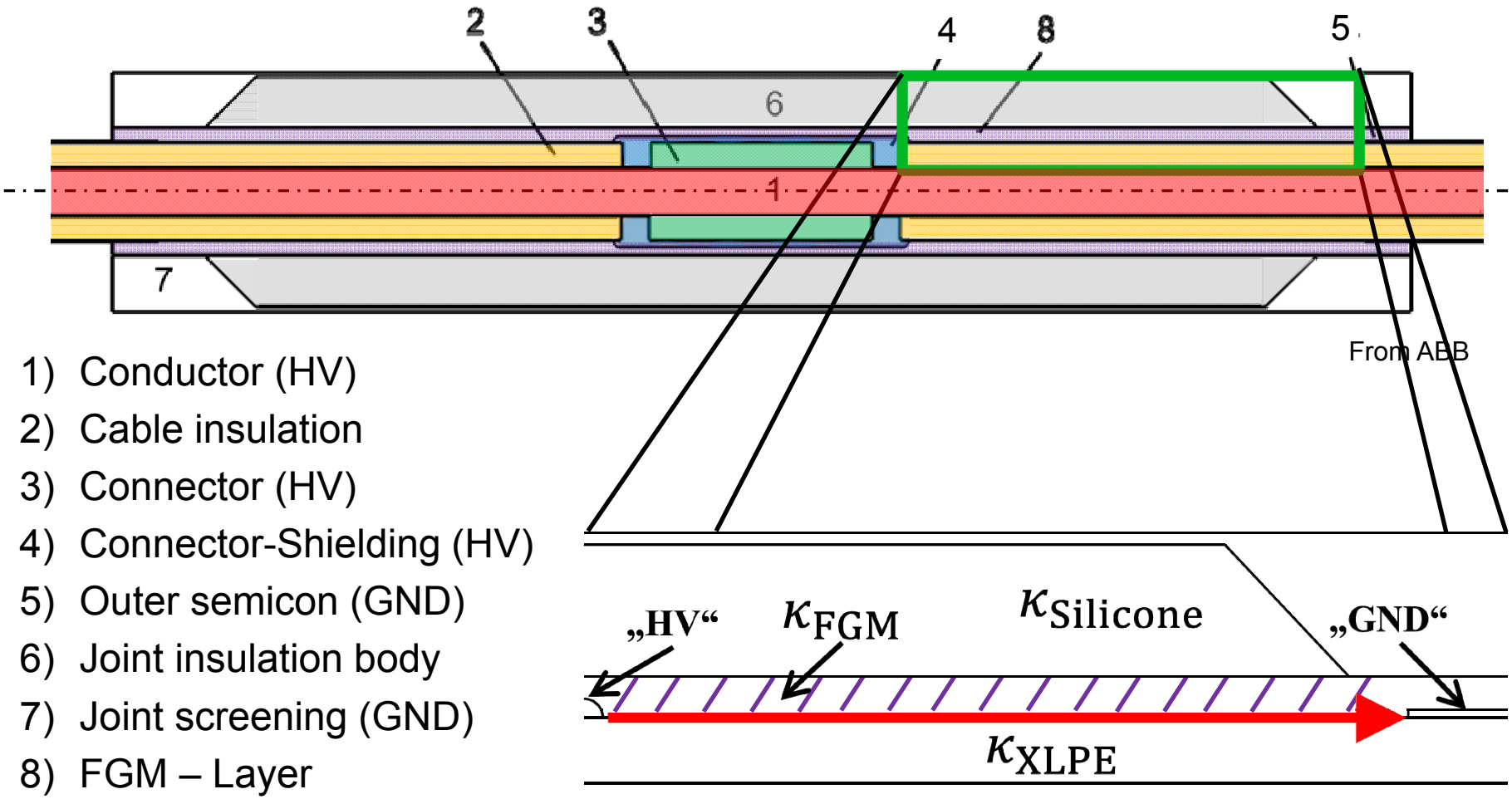
Basic requirements can be described, using only:

- Base conductivity: κ_0
- Switching point: E_1
- Slope of nonlinearity: m
- (Nonlinearity modeling Parameter: X)
- Saturation field strength: E_2



$$m = \frac{\lg\left(\frac{\kappa_b}{\kappa_a}\right)}{E_b - E_a}$$

Design of a FGM for HVDC Cable Joints

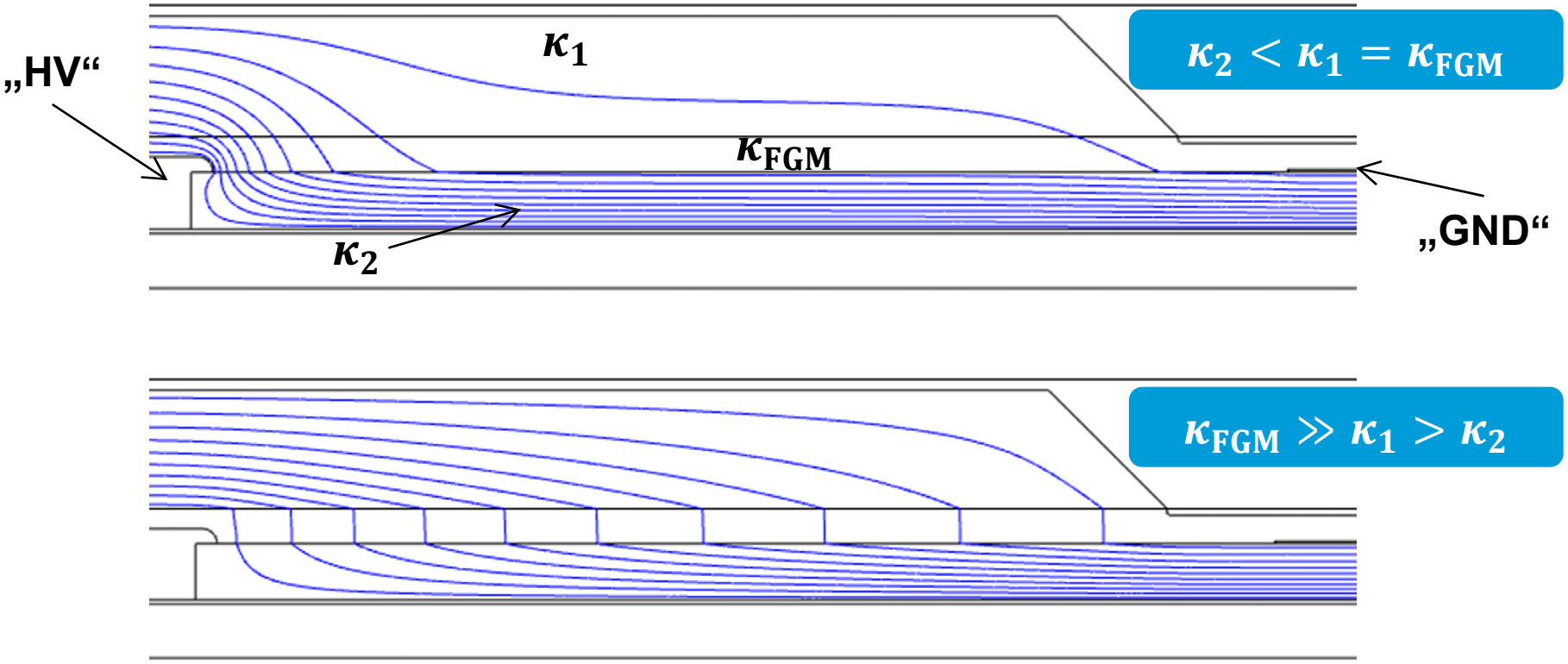


1) Conductor (HV)
2) Cable insulation
3) Connector (HV)
4) Connector-Shielding (HV)
5) Outer semicon (GND)
6) Joint insulation body
7) Joint screening (GND)
8) FGM – Layer

Design of a FGM for HVDC Cable Joints

Stationary electrical simulation

- Goal: Finding allowed range for conductivity in stationary operation
- 1st step: Optimize conductivity according to tangential field stress



Design of a FGM for HVDC Cable Joints

Lower Limit for Base Conductivity

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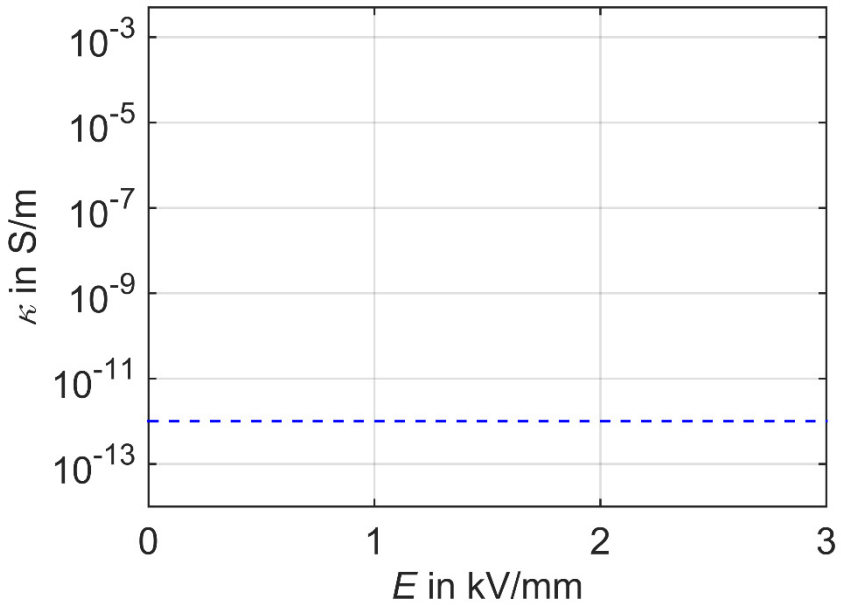
Measured Values:

- Silicone Rubber: $\kappa_{\mathrm{Silicone}} \approx 10^{-15} \ldots 10^{-14}\,\frac{\mathrm{S}}{\mathrm{m}}$
- XLPE: $\kappa_{\mathrm{XLPE}} \approx 10^{-16} \ldots 10^{-15}\,\mathrm{S/m}$

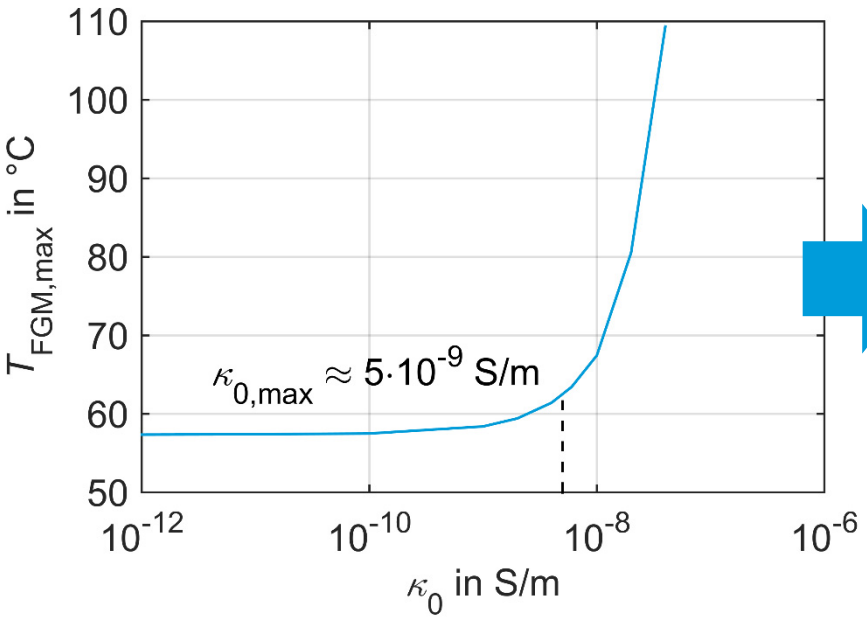
$$\boldsymbol{\kappa_0 \geq 100 \cdot \max\{\kappa_{\mathrm{Silicone}}, \kappa_{\mathrm{XLPE}}\}}$$

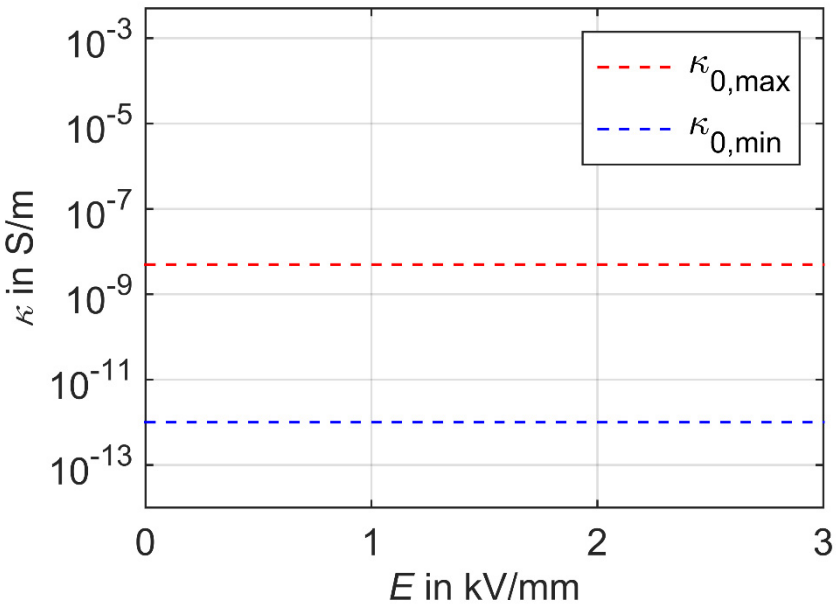


Design of a FGM for HVDC Cable Joints

Stationary thermal simulation

- Goal: Finding allowed range for conductivity in stationary operation
- 1st step: Optimize conductivity according to tangential field stress
- 2nd step: Maximum allowed conductivity according to temperature





Design of a FGM for HVDC Cable Joints

Transient electrical simulation

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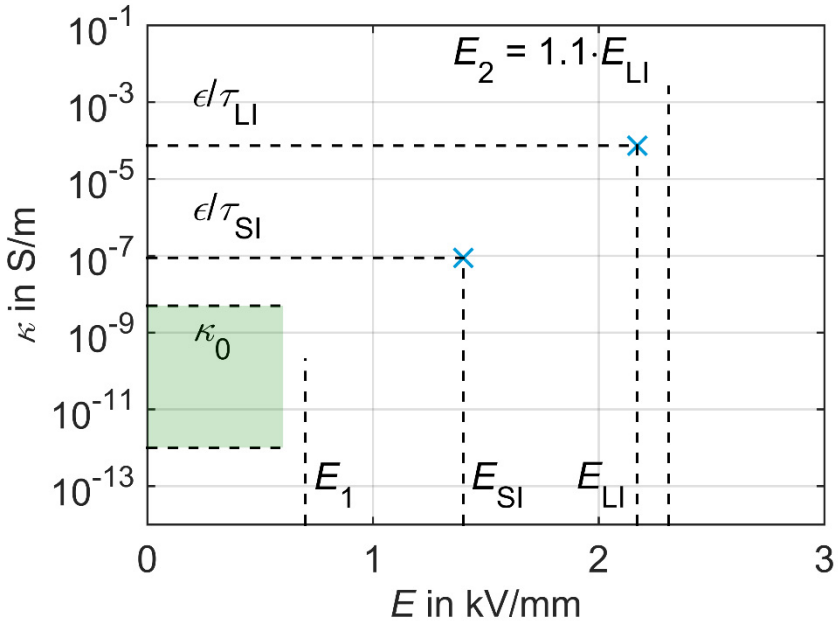
- Goal: Finding allowed range for conductivity in transient operation *
- 1st step: Calculate desired conductivities for standard switching and lightning impulse according to $\kappa = \frac{\varepsilon_0 \varepsilon_r}{\tau}$
- 2nd step: Apply safety margin to previously calculated values



* Process according to [Chr2010]

Design of a FGM for HVDC Cable Joints

Transient electrical simulation

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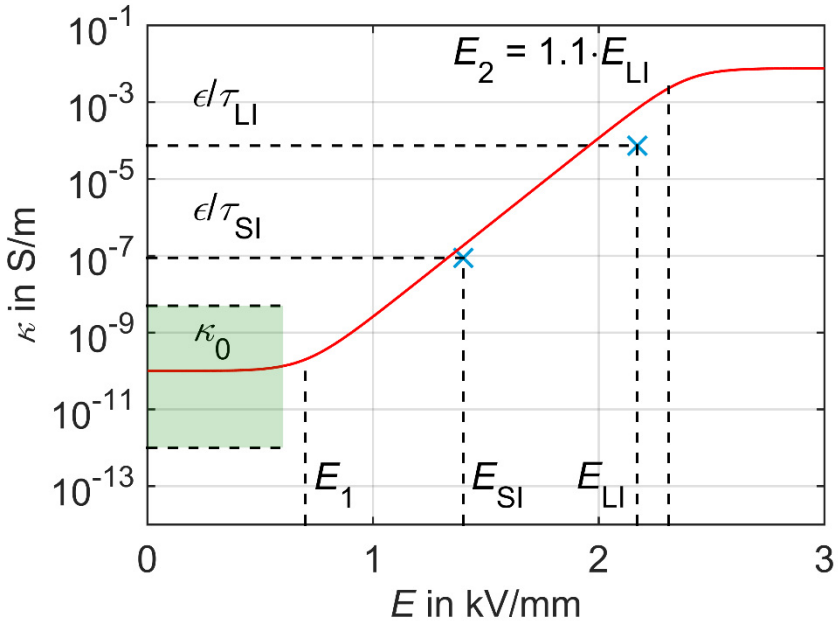

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Design of a FGM for HVDC Cable Joints

Comparison Linear vs Nonlinear FGM

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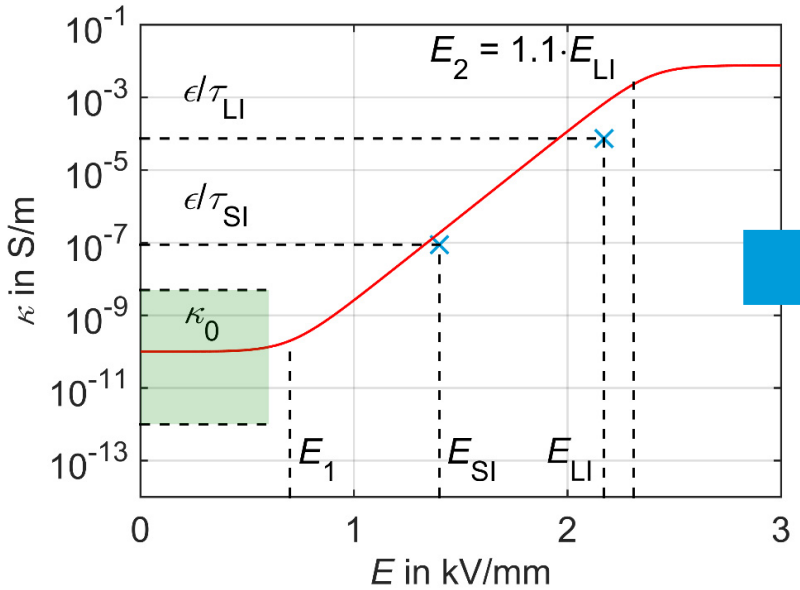
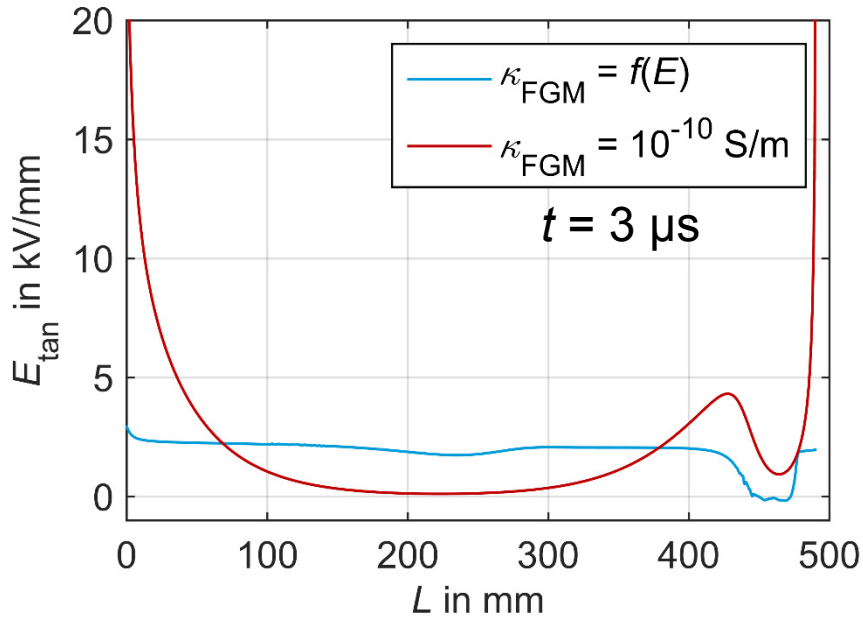
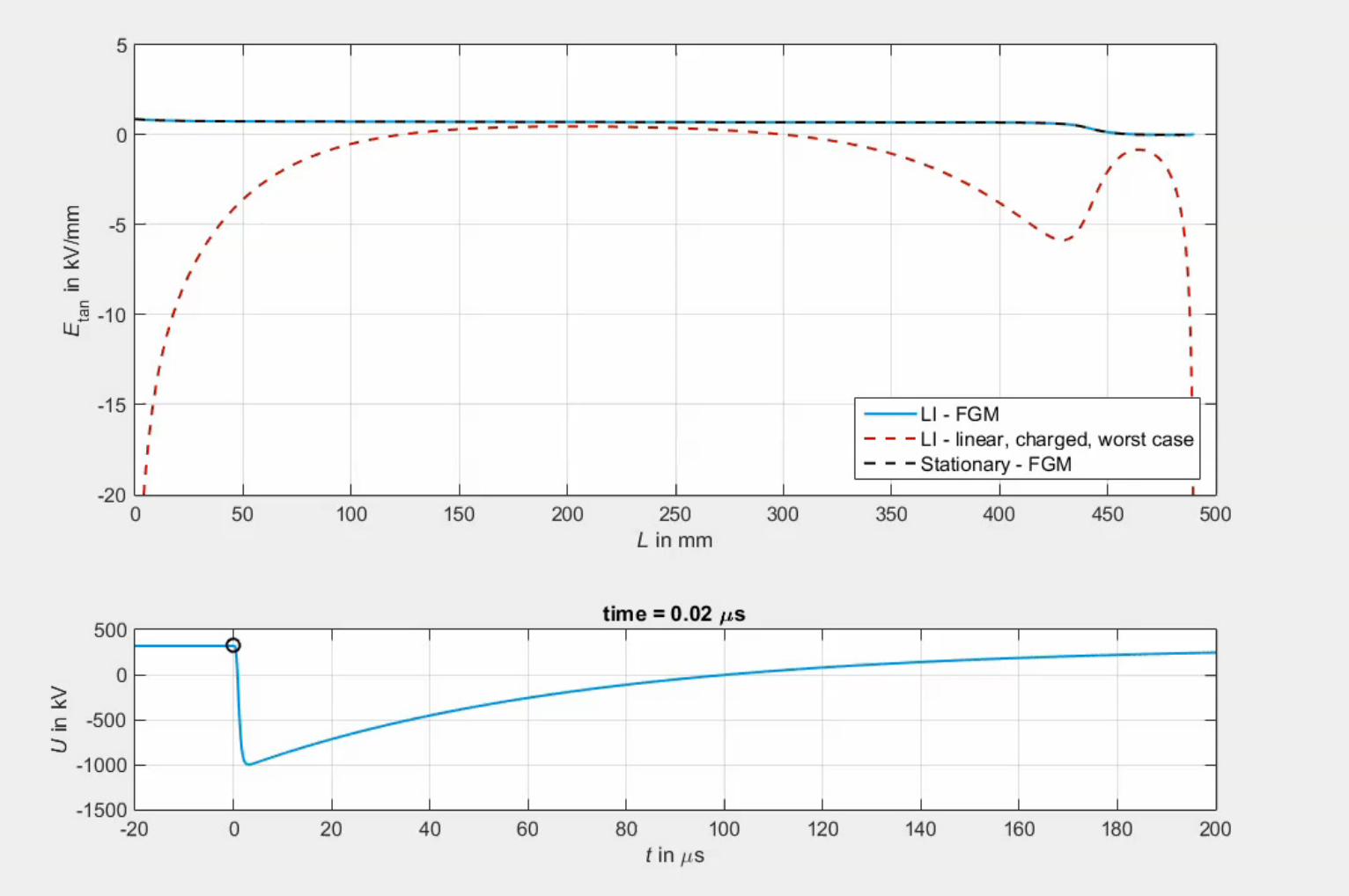




Comparison of Results

Linear vs. Nonlinear – time dependent



Conclusions

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- HVDC-Insulation systems still provide challenges
  - Conductivities (or more general charge transport effects) are influenced by many factors
  - Therefore the buildup of space and surface charges is hard to predict
- Introducing (nonlinear) field grading materials makes the systems easier predictable
  - …and can help creating more reliable devices
- A wider range of nonlinear FGMs that can be tailored to address the specific needs of a device would be very useful
- A prerequisite for this are commonly understood models and termini for describing this class of materials

End of Slides

Start of Questions and Discussion

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Thank you for your attention!

References:

[Kreu1991] F. H. Kreuger, *Industrial High DC Voltage*, Delft University Press, 1991

[Bla2015] S. Blatt, V. Hinrichsen: *Mathmatical model for numerical simulation of current density in microvaristor filled insulation materials*, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 22, Issue 2, pp. 1161-1170, April 2015

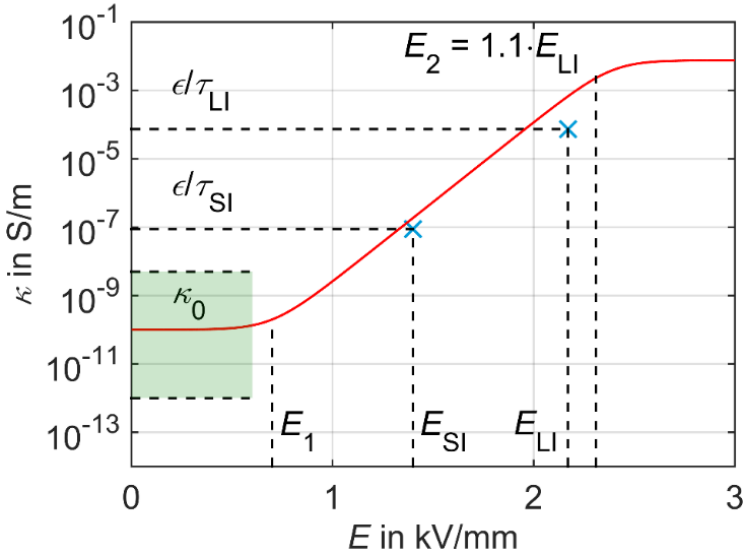
[Chr2010] T. Christen, L. Donzel, and F. Greuter, *Non-linear resistive electric field grading part 1: Theory and simulation*, IEEE Electr. Insul. Mag., vol. 26, no. 6, pp. 48-60, 2010.

[Don2011] L. Donzel, F. Greuter, T. Christen, *Nonlinear resistive electric field grading Part 2: Materials and applications*, Electrical Insulation Magazine, IEEE, Volume 27, Issue 2, pp. 18-29, 2011

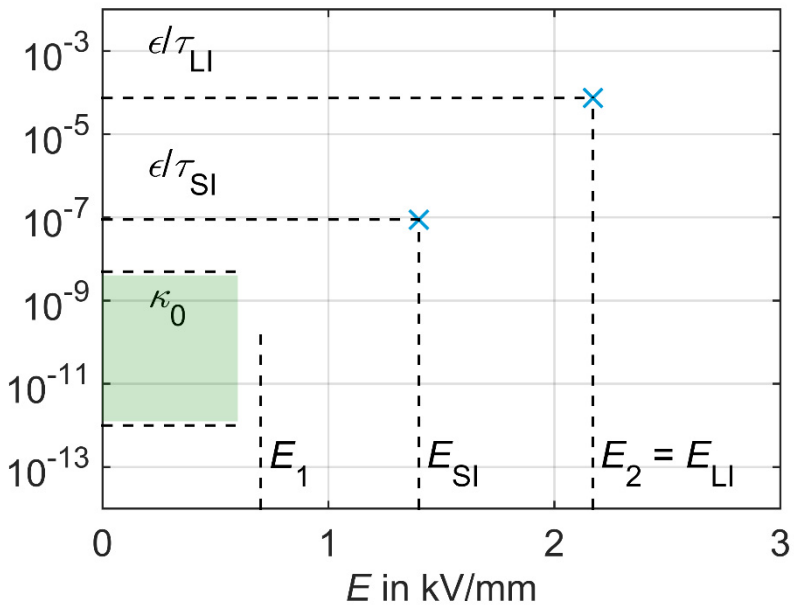
Summary

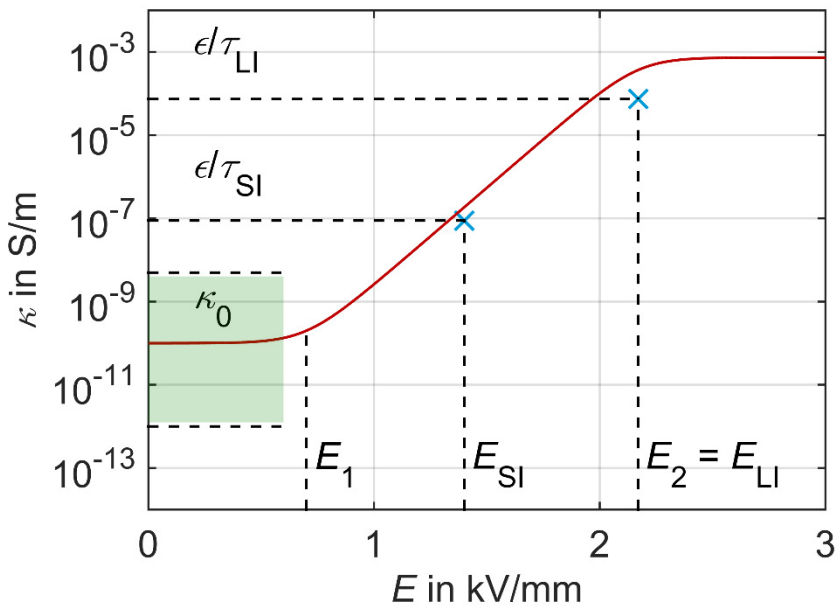
- **Determined Parameters** for specific nonlinear curve:

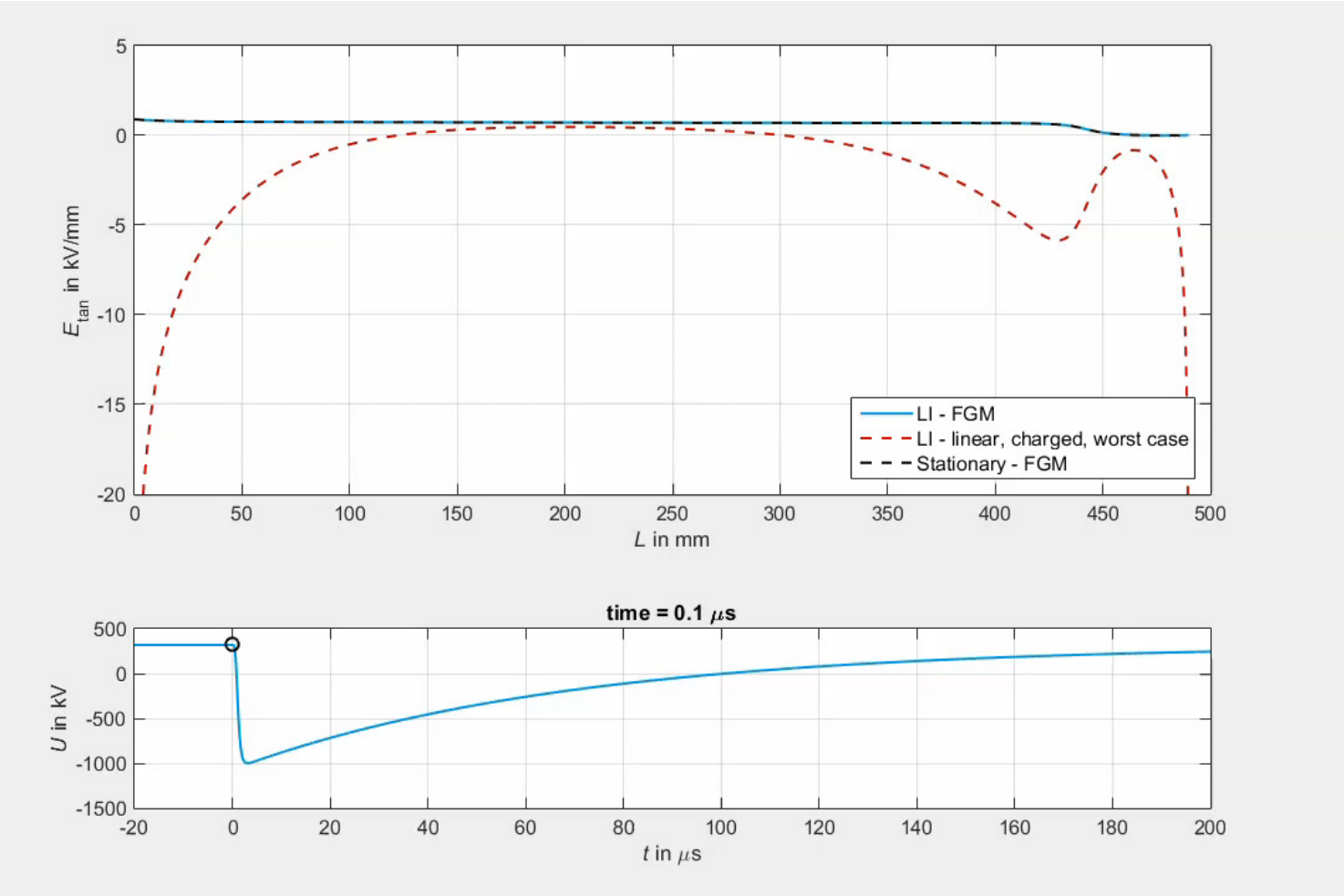
Base conductivity	$\kappa_0 \in [10^{-12}; 5 \cdot 10^{-9}] \frac{\mathrm{S}}{\mathrm{m}}$
Switching field strength	$E_1 = 0.7 \frac{\mathrm{kV}}{\mathrm{mm}}$
Slope of nonlinearity	$m = 4.7 \frac{\mathrm{mm}}{\mathrm{kV}}$
Saturation field strength	$E_2 = 1.1 \cdot E_{\mathrm{LI}} = 2.3 \frac{\mathrm{kV}}{\mathrm{mm}}$



- **Achieved Improvements**:
  - Desired dependency on electrical field strength over the full range
  - Approx. **10 times lower field stress** at triple point


10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
ϵ/τ_{LI}
ϵ/τ_{SI}
κ_0
E_1
E_{SI}
$E_2 = E_{LI}$
0
1
2
3
E in kV/mm


κ in S/m
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
ϵ/τ_{LI}
ϵ/τ_{SI}
κ_0
E_1
E_{SI}
$E_2 = E_{LI}$
0
1
2
3
E in kV/mm


5
0
-5
-10
-15
-20
E_{tan} in kV/mm
0
50
100
150
200
250
300
350
400
450
500
L in mm
LI - FGM
LI - linear, charged, worst case
Stationary - FGM
time = 0.1 μs
500
0
-500
-1000
-1500
U in kV
-20
0
20
40
60
80
100
120
140
160
180
200
t in μs

Application Example
Cable Joint

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Why significant?

- **High number of joints** per system necessary (land cable: one joint every 1…2 km)
- **Most critical point** of the cable system

Why interesting?

Shows most of the beformentioned challenges:

- **Triple points of different materials**
- **Temperature gradients**
- **Space charge accumulation**