3D Particle-In-Cell Simulation of Surface Flashover in Vacuum Interrupters

Svetlana Gossmann, Thomas Hammer
Siemens AG, Technology, Sustainable Energy & Infrastructure
Frank Graskowski, Andreas Lawall
Siemens AG, Smart Infrastructure

9th ITG International Vacuum Electronics Workshop 2024

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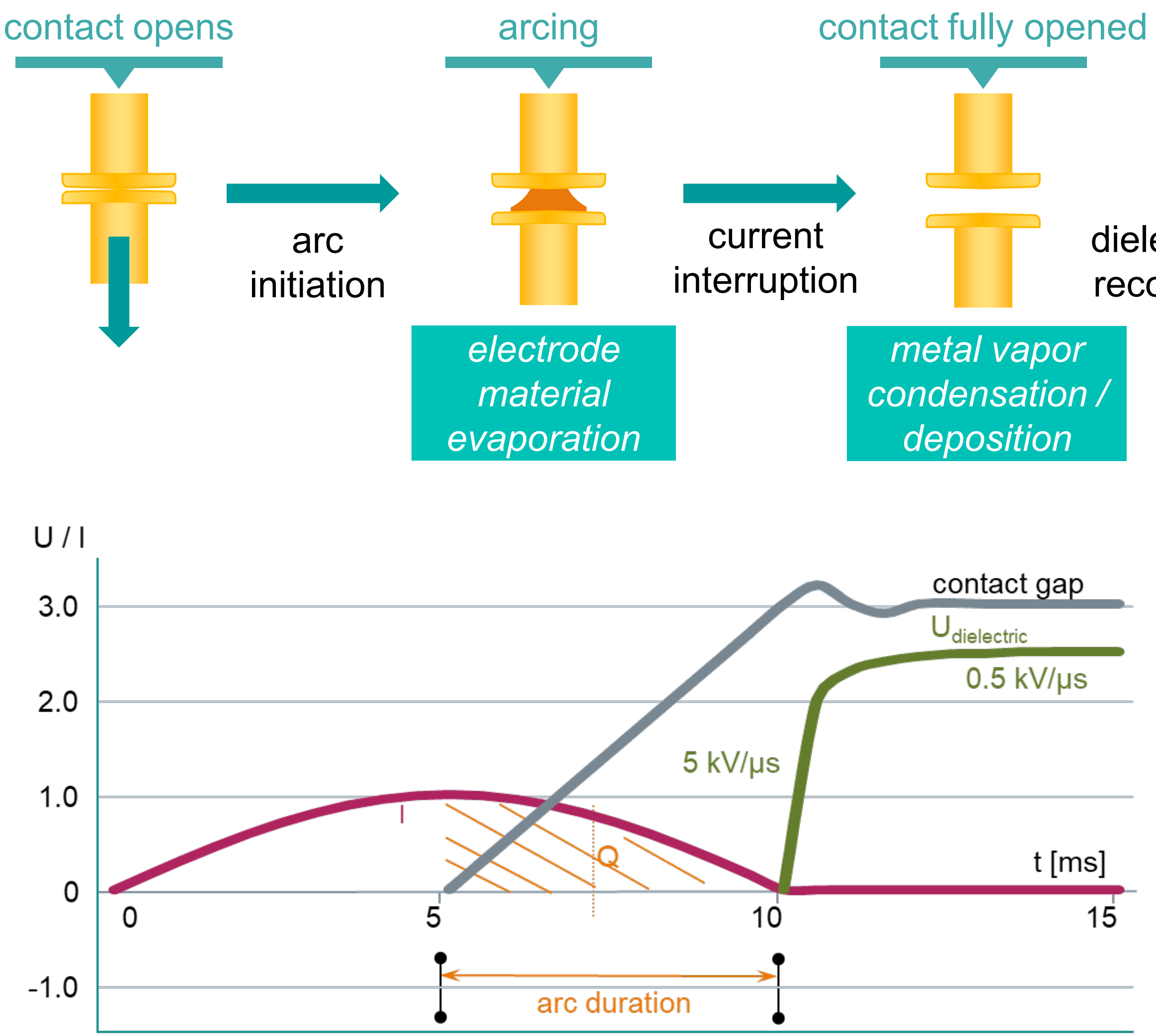
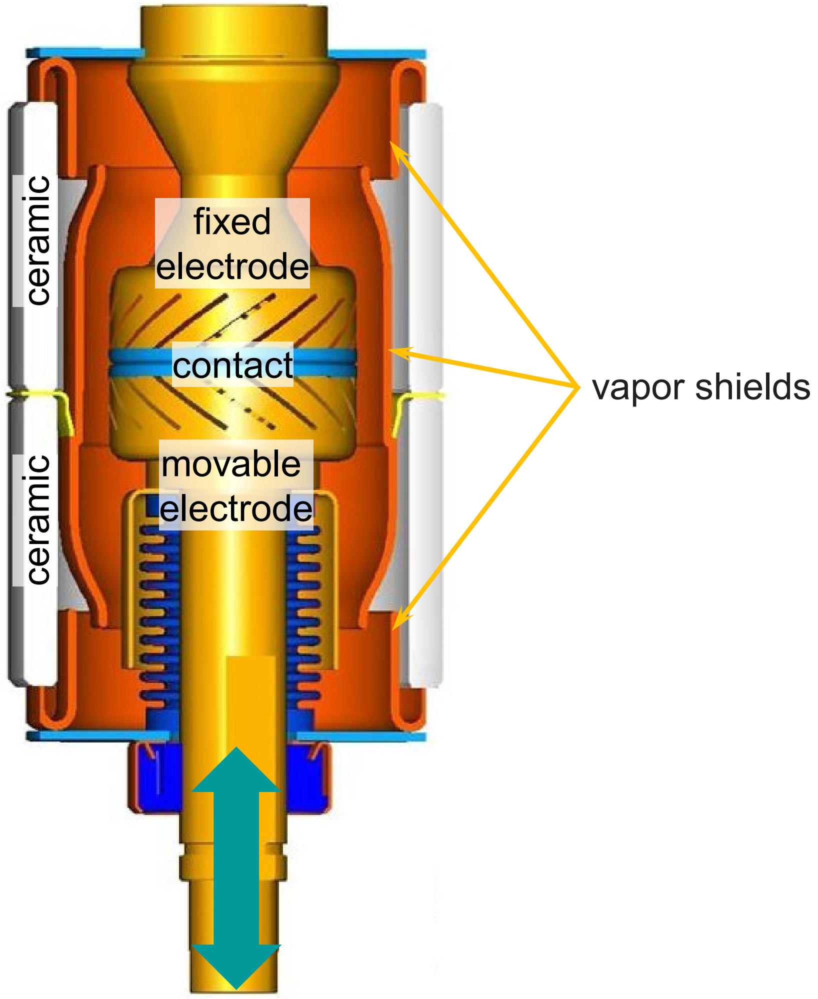
Vacuum Interrupter Design & Operation: Maintain Dielectric Strength





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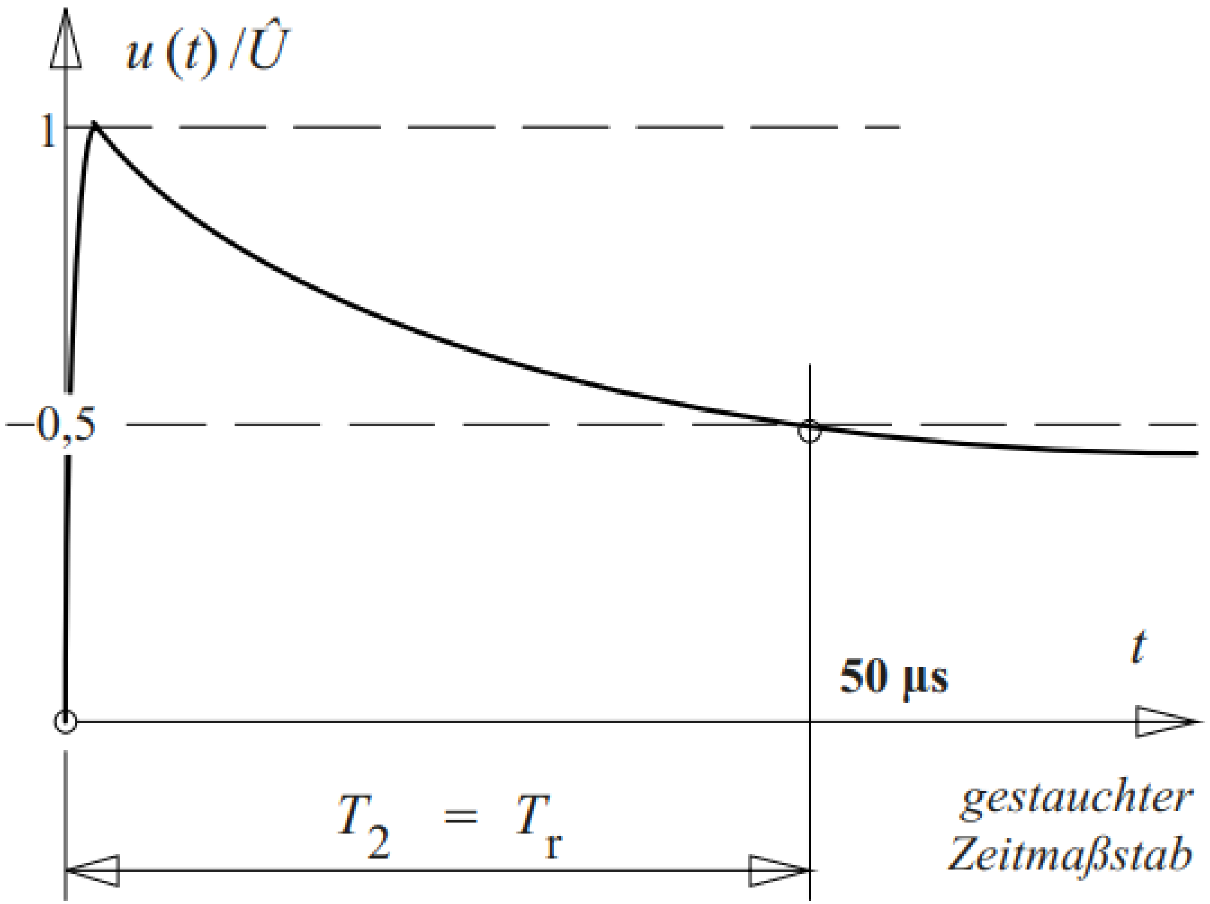
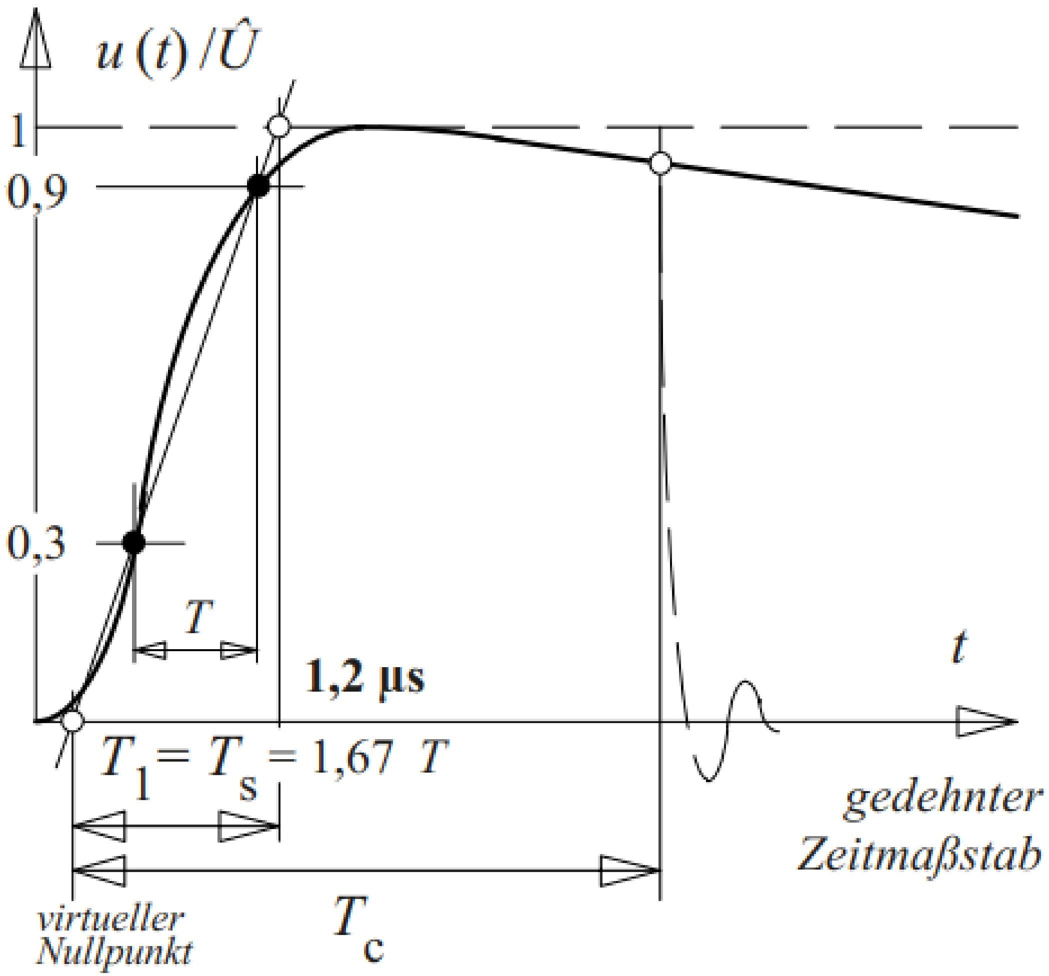
Waveform of Lightning Impulse Withstand Voltage





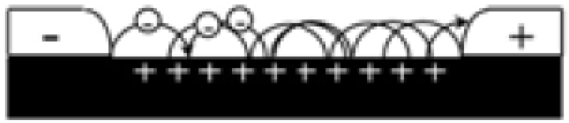
Andreas Küchler, Hochspannungstechnik Grundlagen, Technologie, Anwendungen, Springer Vieweg, 2017

Dielectric Breakdown in Vacuum Interrupters

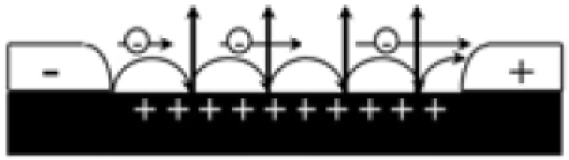
- Volume breakdown between contact electrodes (**E**xplosive **E**lectron **E**mission; µ-particle induced **S**livkov-**C**ranberg **C**lump **M**echanism)
- Volume breakdown between vapor shield and contact electrode (EEE, SCCM)
- Multistep breakdown involving insulator surface flashover

1


Field emission from cathode

2a


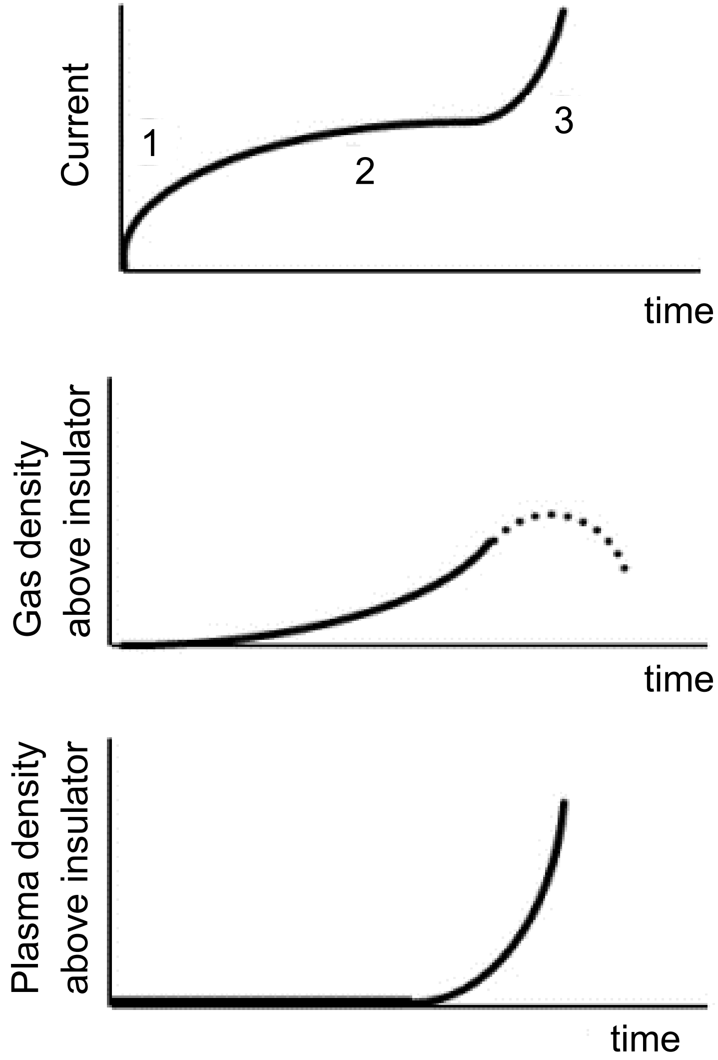
Secondary electron emission avalanche

2b


- Electron impact induced gas desorption
- Insulator heating ⇒ gas desorption

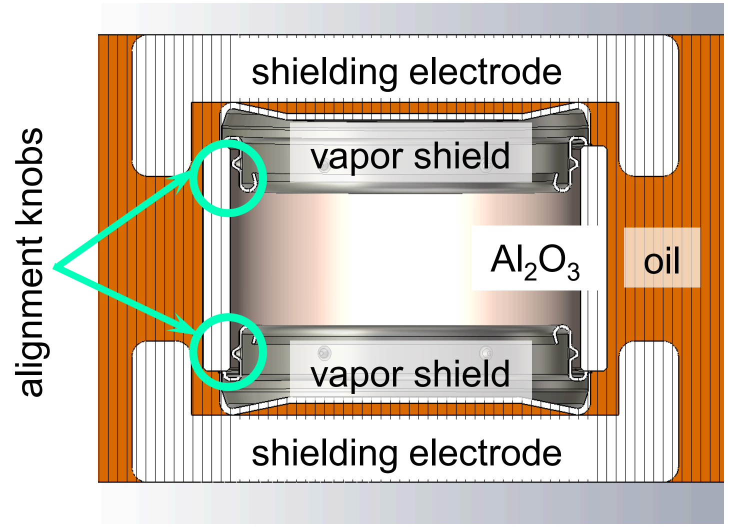
3


Breakdown in desorbed gas



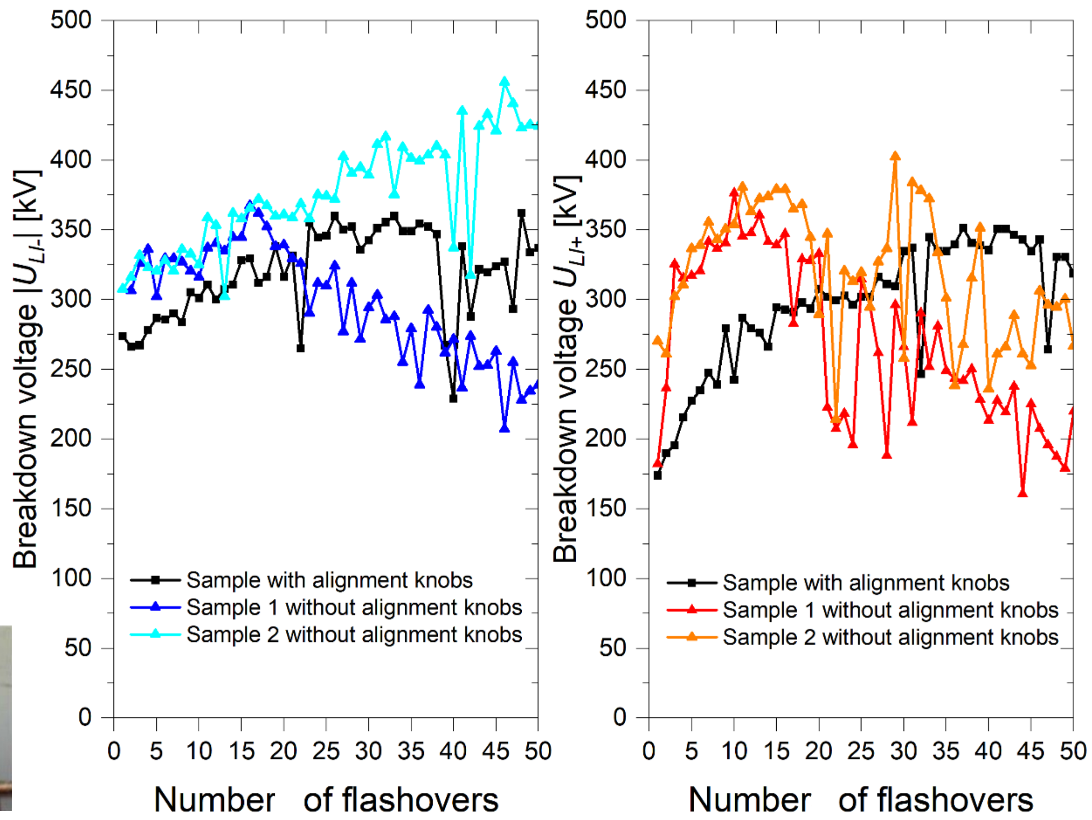
H. Craig Miller: Flashover of Insulators in Vacuum: The Last Twenty Years, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 22, No. 6; December 2015

Experimental Investigation: Influence of Vapor Shield Design and Conditioning on Vacuum Breakdown Voltage



Surface discharge traces on alumina ceramics

Conditioning, lightning impulse LI 1.2 µs / 50 µs



Torsten Psotta: Konditionierungsverhalten von Hochspannungsvakuumanordnungen bei inhomogener Feldverteilung, Doctoral Thesis, TU Darmstadt, 2017

Processes Considered in Simulation Model (I)

Field emission of primary electrons:
Fowler-Nordheim equation

$$j_{\phi\varepsilon} = a \cdot (\beta \cdot E)^2 \cdot exp\left(-\frac{b \cdot \Phi_{el}^{1.5}}{(\beta \cdot E)}\right)$$

Local E-Field $E(r)$, field enhancement factor β

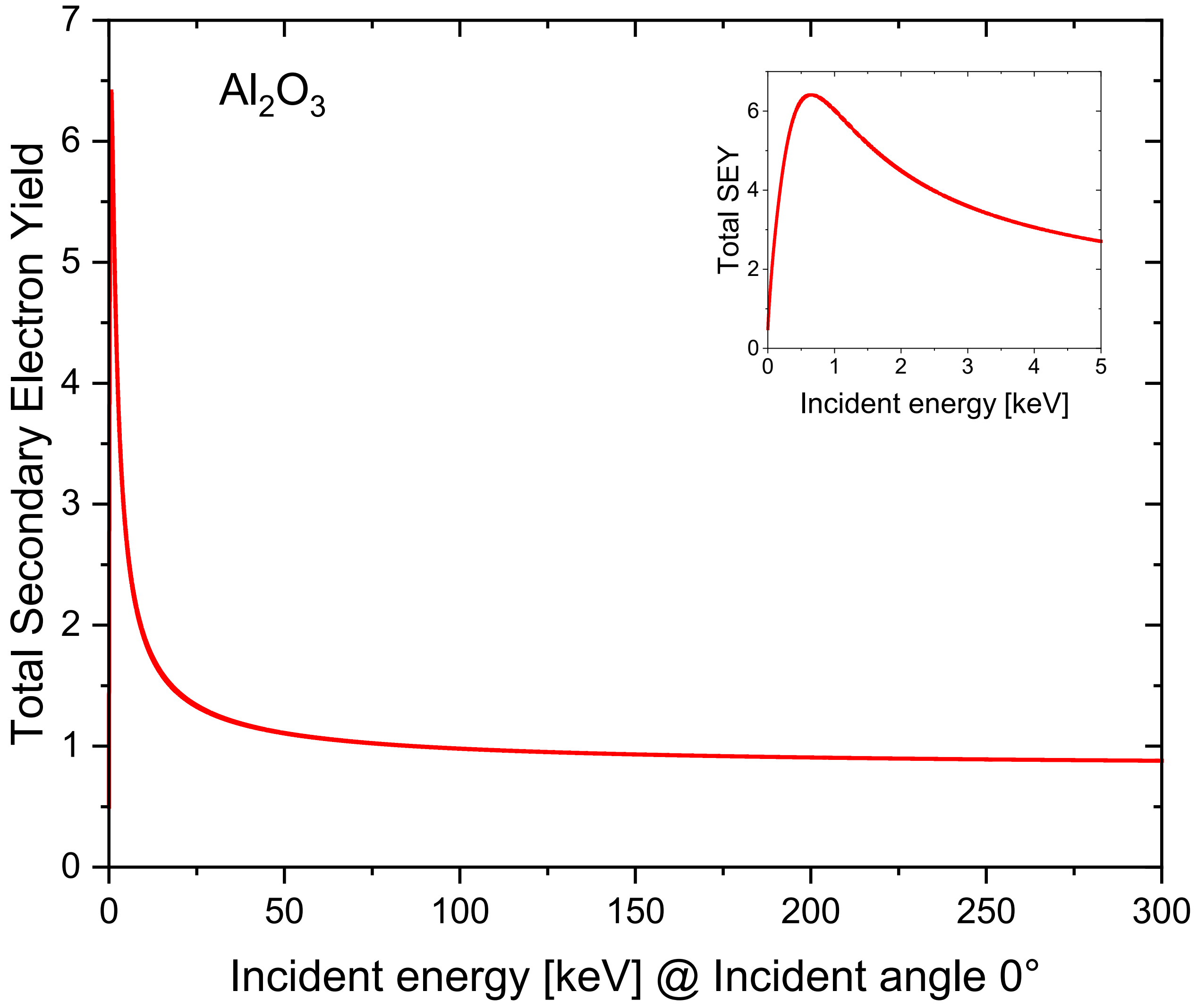
$a = 4.256 \cdot 10^{-7} \cdot \mathrm{A/V^2}$, $b = 2.84 \cdot 10^{9} \cdot \mathrm{V/m}$, electron work function $\Phi_{el} = 4.6\ (\mathrm{eV})$

Electron impact on alumina surface: Generation of **secondary electrons** described by **Furman model**

M. A. Furman, M. T. F. Pivi, "Probabilistic model for the simulation of secondary electron emission," Phys. Rev. Spec. Top. Accel Beams vol. 5 no. 12, p. 82-99, 2002.

Material parameters

Z. Insepov, V. Ivanov, H. Frisch, "Comparison of candidate secondary electron emission materials," Nucl. Instrum. Methods Phys. Res., Sect. B Vol. 268, p. 3315–3320, 2010.



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Processes Considered in Simulation Model (II):
Postprocessing of ES-PIC Results

Thermal gas desorption: Heating of the Al_2O_3-insulator described by 1-D heat diffusion equation

$$\rho \cdot c_p \cdot \frac{\partial T(x,t)}{\partial t} - k_{th} \cdot \frac{\partial^2 T(x,t)}{\partial x^2} = p_{el}(x)$$

mass density $\rho = 3.8 \cdot \mathrm{kg/l}$, specific heat $c_p = 880 \cdot \mathrm{J/(kg\ K)}$, thermal conductivity $k_{th} = 25 \cdot \mathrm{W/(m\ K)}$

Energy flux density due to electron impact

$$p_{el}(x) = j_e \cdot \frac{U_0}{d_p}, x < d_p$$

Thermal desorption rate coefficients increase with temperature T following Arrhenius equation

$$k_{des}(T) \sim \exp\left(-\frac{E_a}{R_0 T}\right)/\sqrt{R_0 T}$$

Electron impact induced desorption of H_2 molecules: Molecular flux density

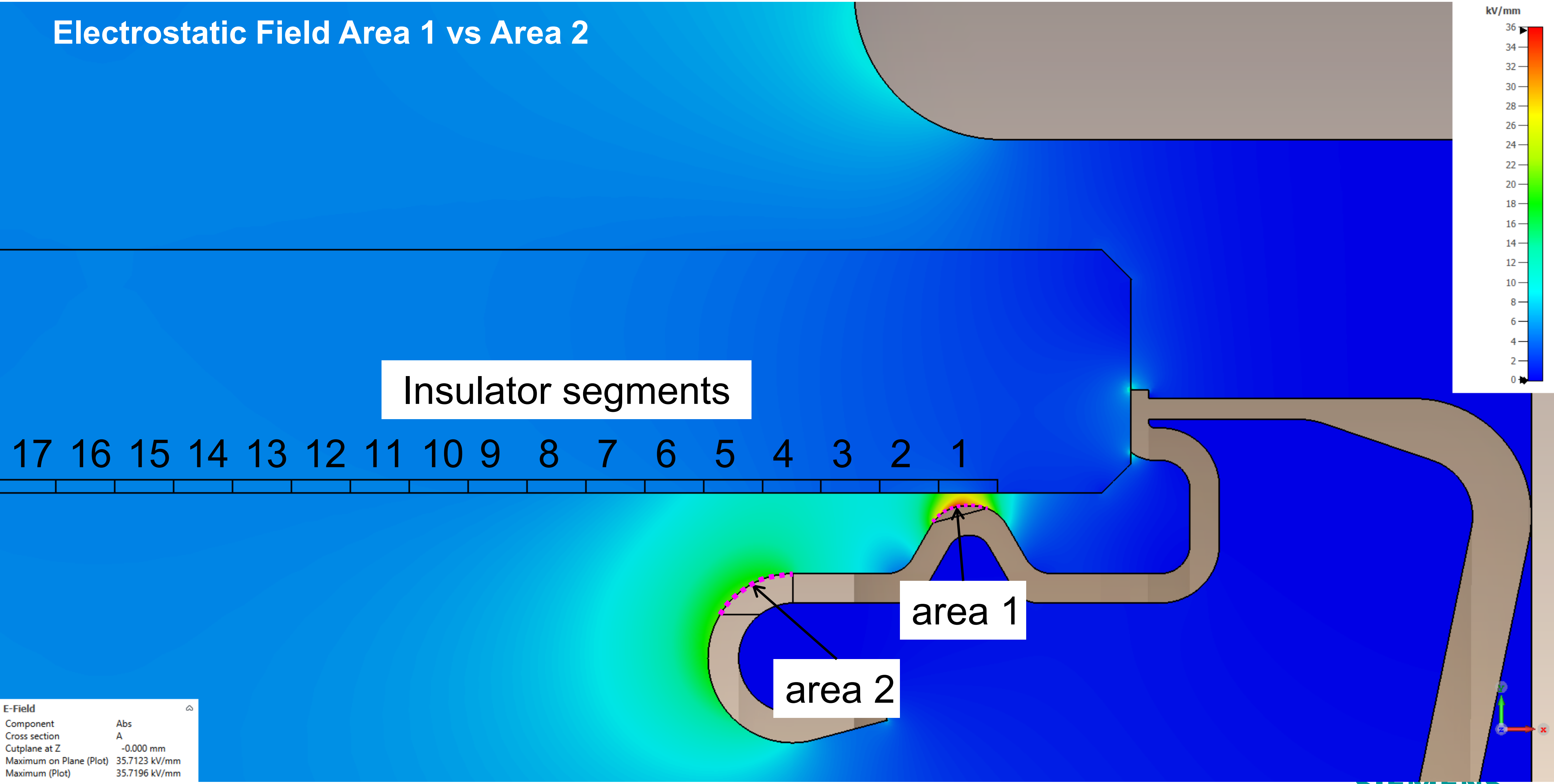
$$j_{des}(t) = \sigma \cdot n_{ads0} \cdot j_e/e_0 \cdot \exp(-\sigma \cdot j_e/e_0 \cdot t)$$

Electron impact desorption cross section for H_2-desorption from Al_2O_3

$$\sigma = 4 \cdot 10^{-22} \cdot \mathrm{m}^2$$

[12] V. Velthaus, B. Tietz, C. Trautmann, F. Völklein, M. Bender, “Desorption measurements of accelerator-related materials exposed to different stimuli,” Vacuum Vol. 194, 110608, 2021.
[13] Bai-Peng Song, Guo-Qiang Springer, Guan-Jun Zhang, J. Ikeda, Y. Yamano, “Electrons stimulated gas desorption of some dielectrics in vacuum,” 2016 IEEE International Power Modulator and High Voltage Conference (IPMHVC), p. 147 – 150, 2016.

Electrostatic Field Area 1 vs Area 2



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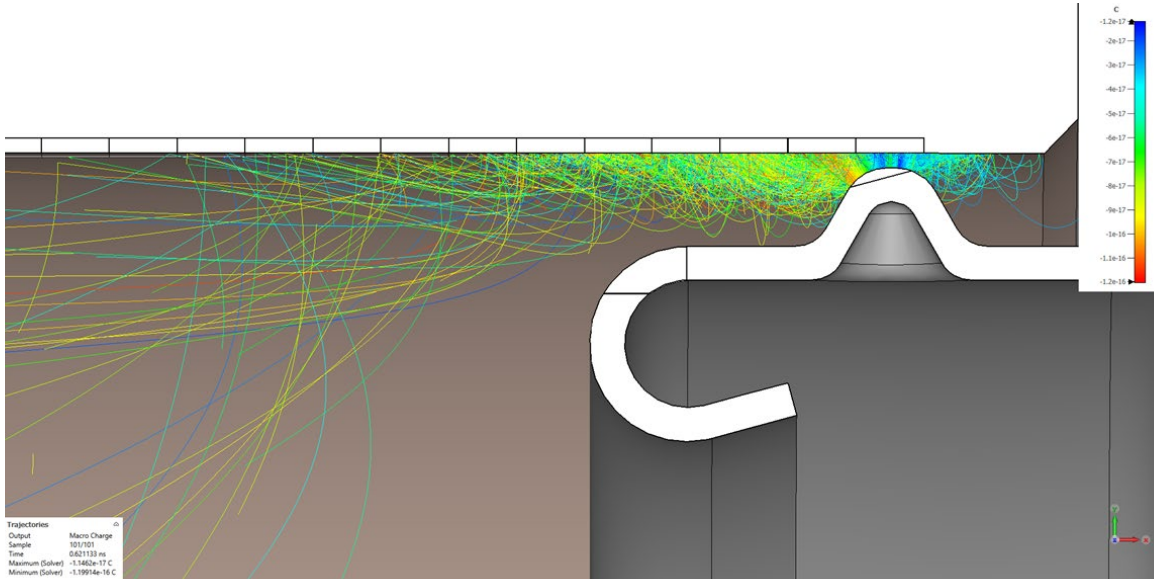
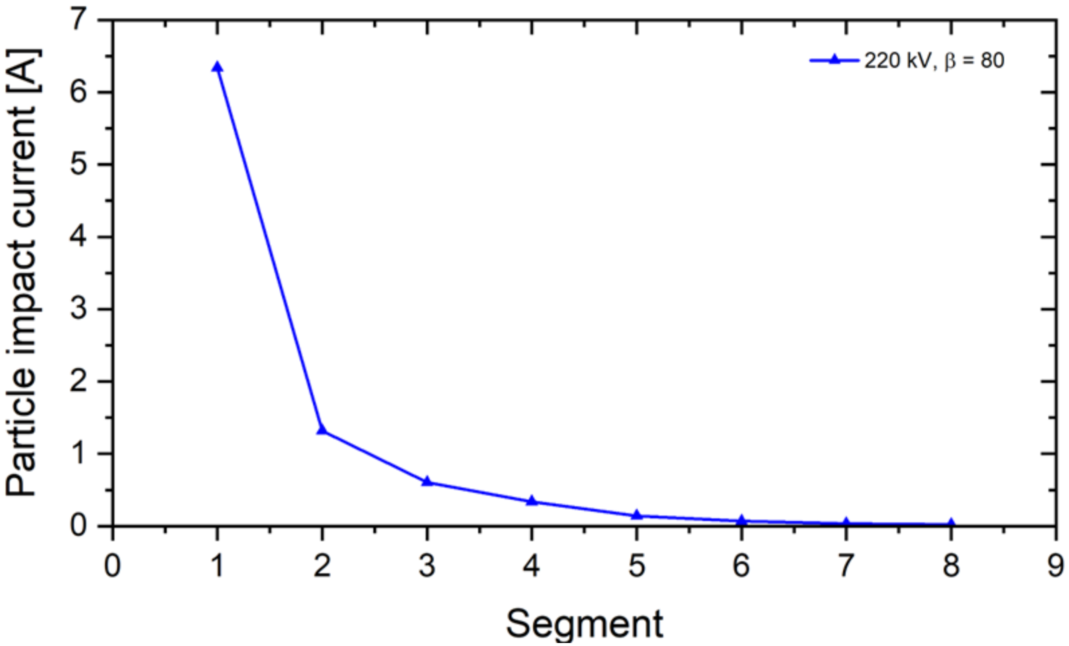
Electron Emission from Area 1 (Alignment Knob): Primary and Secondary Electron Current





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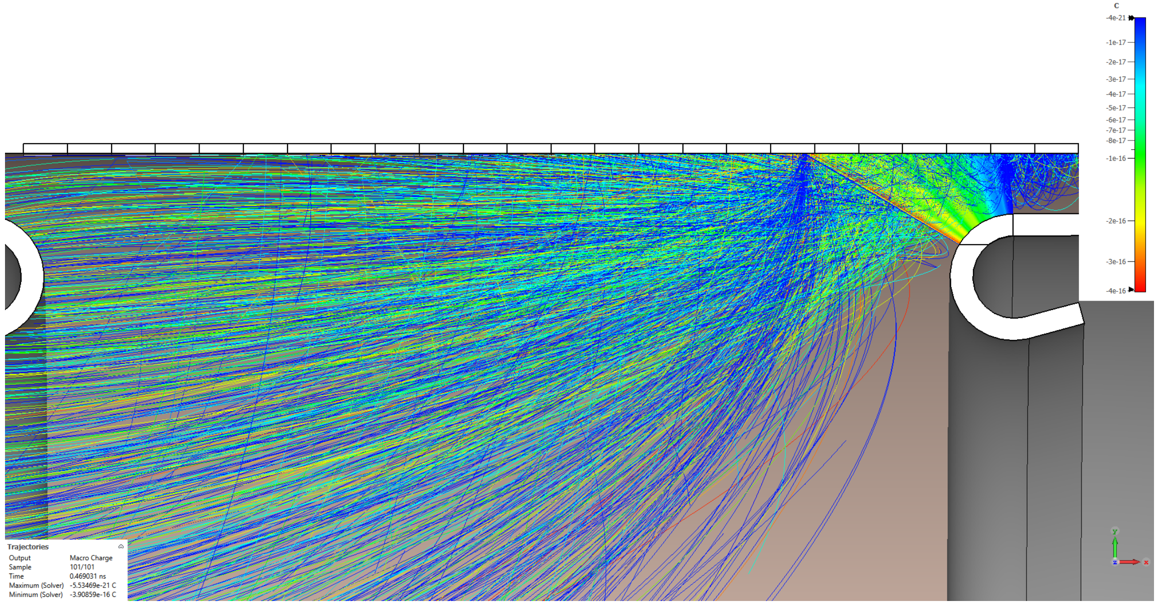
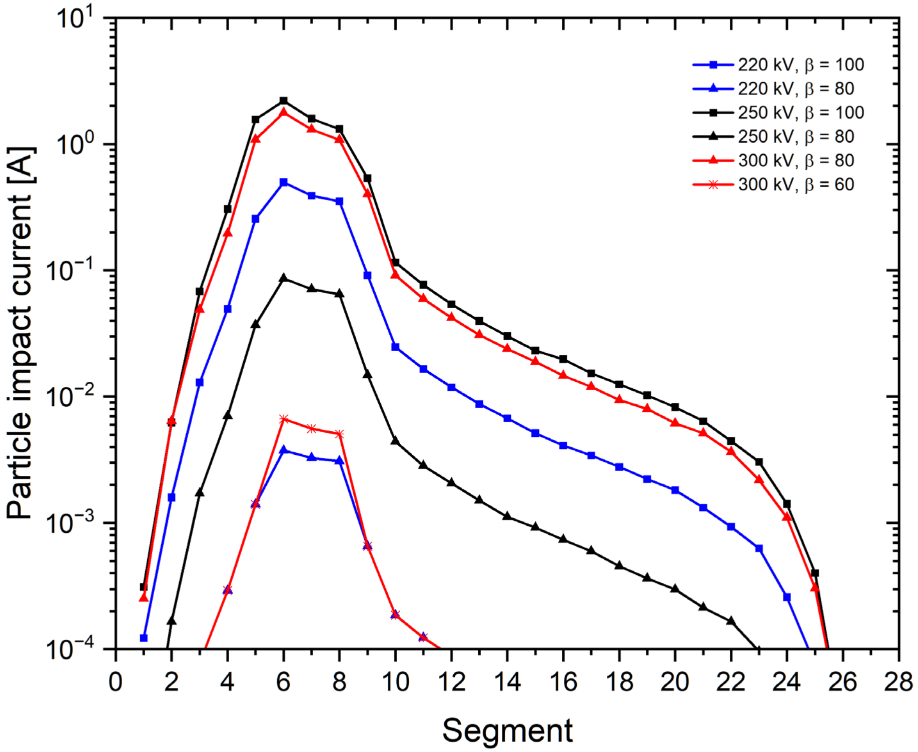
Electron Emission from Area 2 (Rim of Vapor Shield)





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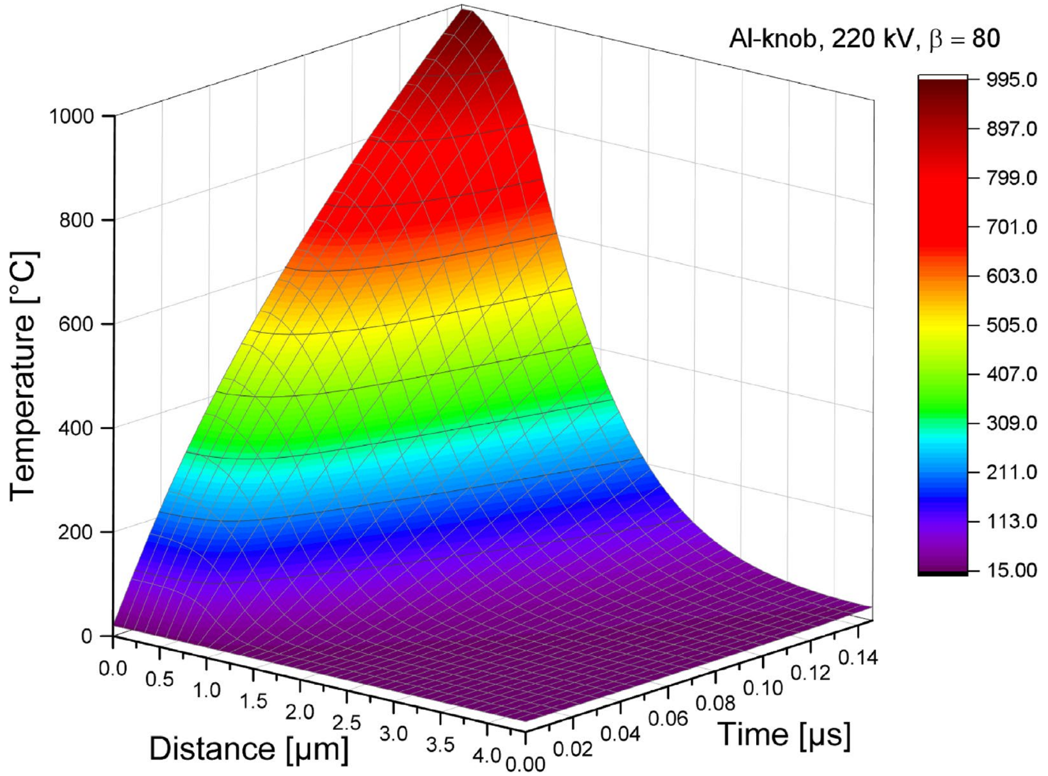
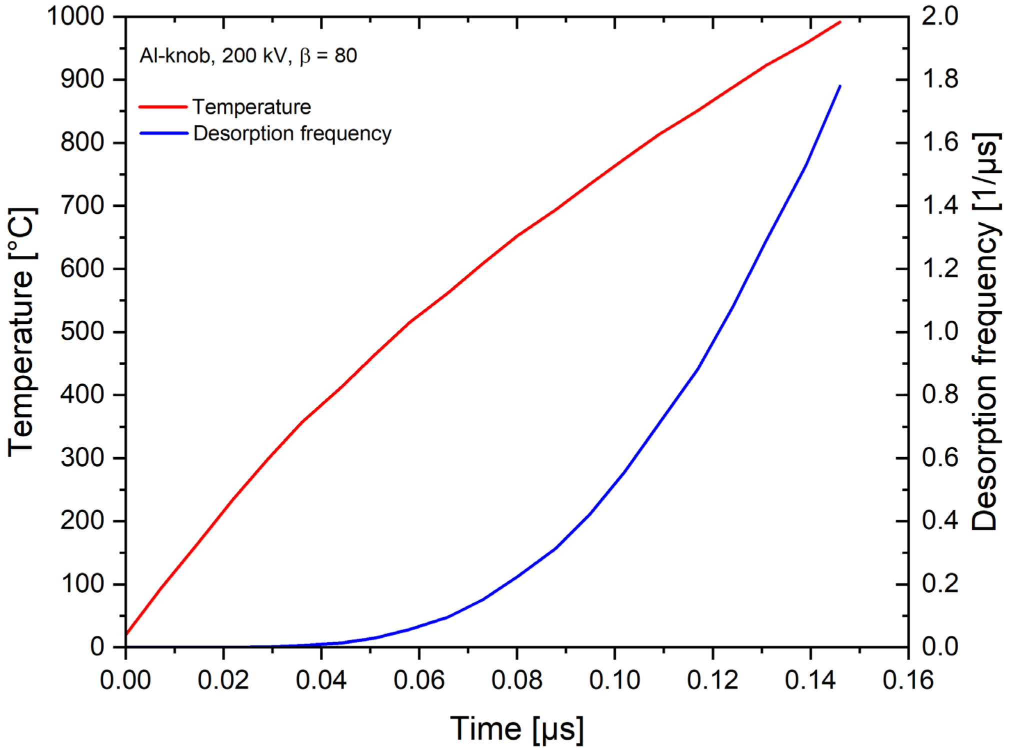
Insulator Temperature as a Function of Distance to Surface and Time

Segment 1: U_0 = 220 kV, β = 80, j_{av} = 0.13 A/m^2, ΔU_p = 10 kV, d_p = 0.88 µm





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$$k_{des}(T) \sim \exp(-\frac{E_a}{R_0 T}) / \sqrt{R_0 T}$$

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Gas Desorption: H_2 Number Density Above Insulator & Surface Coverage

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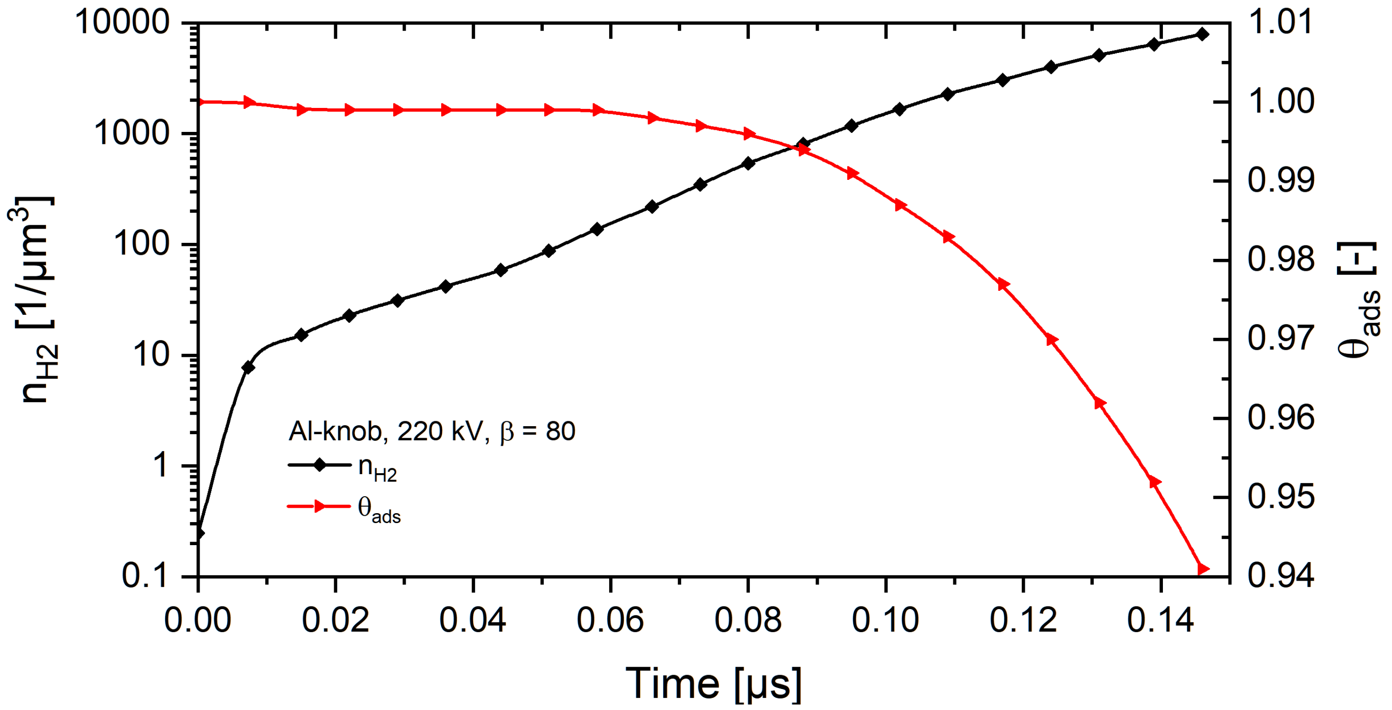

Thickness of gas layer: 50 µm

Initial gas density: $0.247 \cdot 10^{18}\mathrm{m}^{-3}$

Initial surface coverage: $6.775 \cdot 10^{18}\mathrm{m}^{-2}$

Vorgabe

$$\frac{d}{dz}\mathrm{nH2}(z) = \frac{1}{\mathrm{Lchar}}\cdot\left[(\mathrm{kdes}(z) + \sigma\mathrm{H2}\cdot\mathrm{jak})\cdot\mathrm{nads}(z) - \mathrm{kads}(z)\cdot\mathrm{nH2}(z)\cdot\left(1 - \frac{\mathrm{nads}(z)}{\mathrm{S0}}\right)\right] - \sigma\mathrm{iH2}\cdot\mathrm{nH2}(z)\cdot\mathrm{jak}$$

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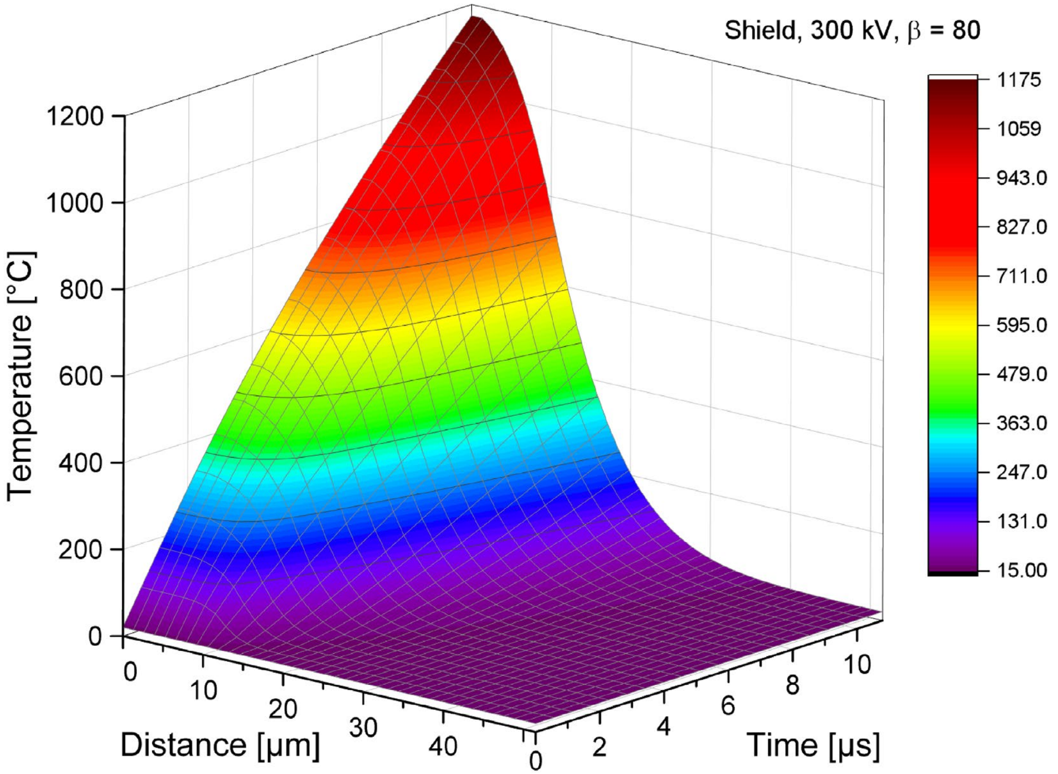
$$\frac{d}{dz}\mathrm{ni}(z) = \sigma\mathrm{iH2}\cdot\mathrm{nH2}(z)\cdot\mathrm{jak}$$

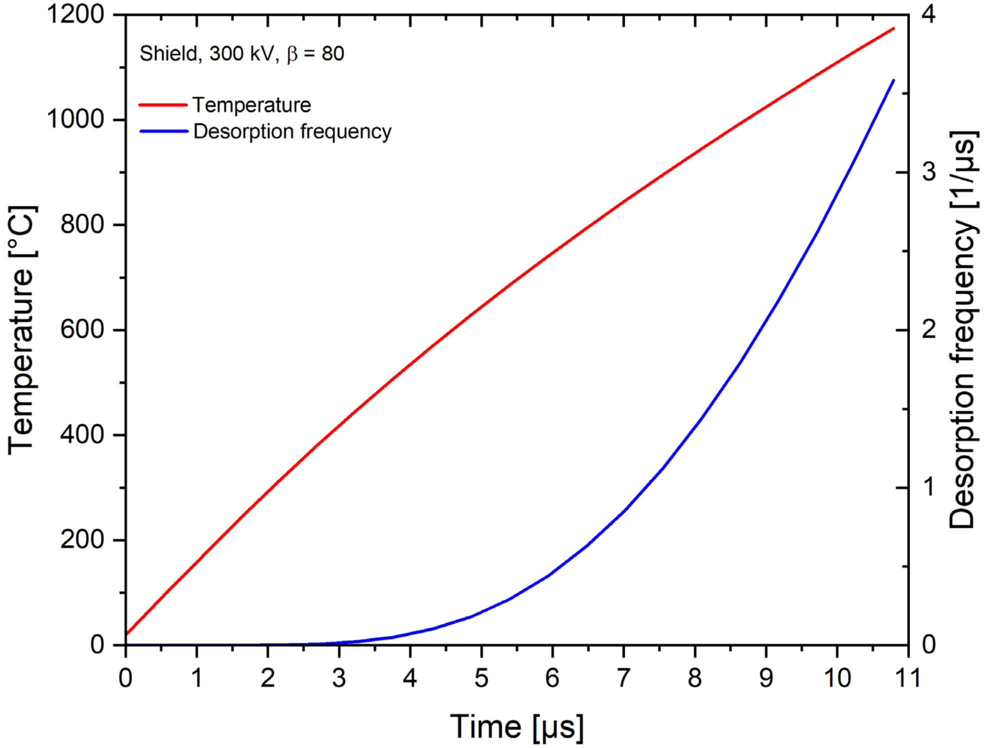
$$\mathrm{nH2}(0) = \mathrm{n0H2} \qquad \mathrm{nads}(0) = \mathrm{n0ads} \qquad \mathrm{ni}(0) = 0$$

$$\begin{pmatrix} n_{\mathrm{H2ti}} \\ n_{\mathrm{adsti}} \\ n_{\mathrm{i}} \end{pmatrix} := \mathrm{Gdgl\ddot{o}sen}\left[\begin{pmatrix} \mathrm{nH2} \\ \mathrm{nads} \\ \mathrm{ni} \end{pmatrix}, z, \mathrm{T0}, 2000\right]$$

Insulator Temperature as a Function of Distance to Surface and Time

Segment 6: U_0 = 300 kV, β = 80, j_{av} = 0.12 A/m², ΔU_p = 41 kV, d_p = 10 µm





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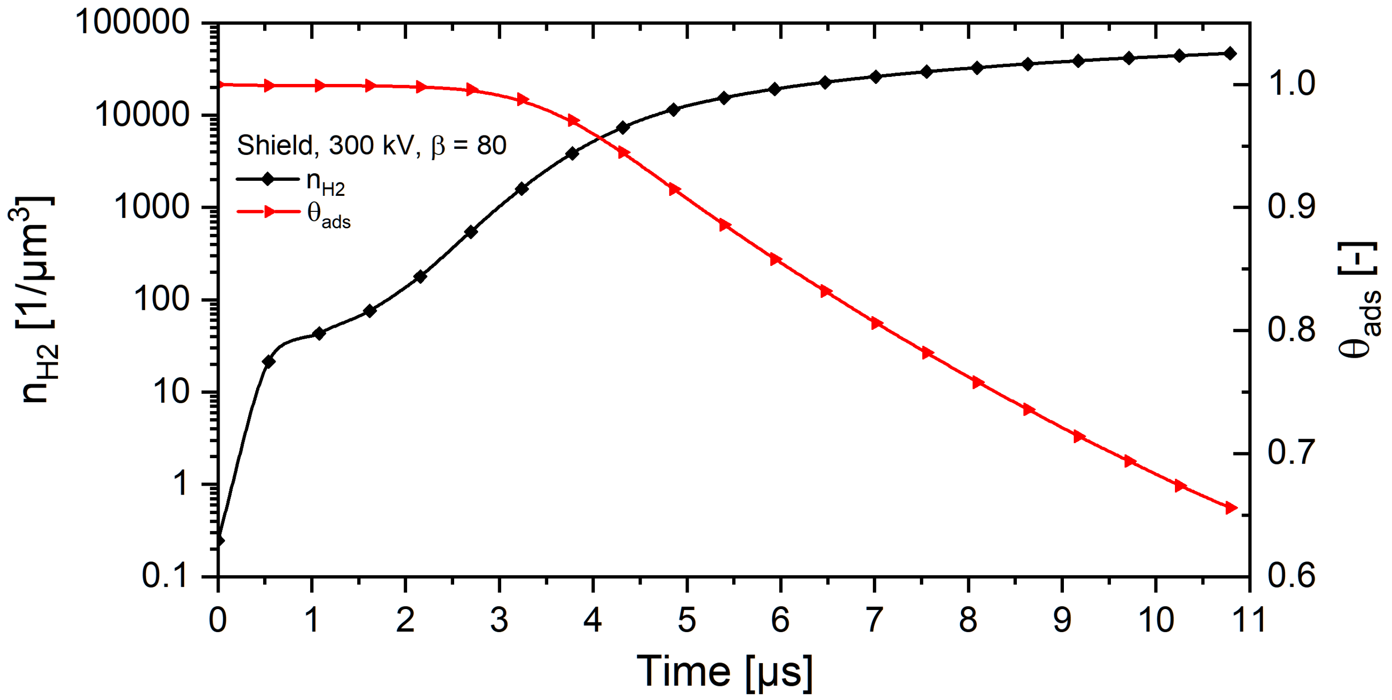

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$$\mathrm{nH2}(0) = \mathrm{n0H2} \qquad \mathrm{nads}(0) = \mathrm{n0ads} \qquad \mathrm{ni}(0) = 0$$

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Summary & Conclusions

- Initiation of insulator surface flashover in a VI test sample containing vapor shields has been investigated using ES-PIC and Particle Tracking Solver of CST Studio Suite 2023 (3D space charge limited field emission of primary electrons, secondary electron emission from insulator surface)
- Field emission current has beam-like character imaging the emission spots onto the insulator surface
- According to the Furman model there is scattered emission of secondary electrons carrying a substantial fraction of the energy provided by electron impact from the insulator surface.
- Since the E-field at the insulator surface is low, the secondary electron avalanche process suggested in literature here does not cause the vacuum breakdown.
- Post processing (1D): Electron impact induced gas desorption (EID), insulator heating, and thermal gas desorption
- Analysis of EIS using a kinetic description: EID rate by far too low to explain gas discharge breakdown
- Thermal desorption of gases chemisorbed at the insulator: Well explained by electron impact induced heating

- In conclusion, **electron impact induced heating** of the insulator essential for breakdown process in this VI test sample
- Vacuum breakdown simulation therefore should comprise electron impact induced heating of solids, gas desorption, gas dispersion under vacuum conditions, electron collision ionization of the gas, and ion transport.
- Further, insulator charging and the influence of temperature on secondary electron emission deserve investigation.

Thank you for your attention!

Contact

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Thomas Hammer
Senior Principal Research Scientist
Technology Sustainable Energy & Infrastructure
Schuckertstr. 2
91058 Erlangen
Germany

Phone +49 9131 17-33123
Mobile +49 172 84 02 196

E-mail thomas.hammer@siemens.com

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