General Equation to Determine Design Rules for Mitigating Partial Discharge and Electrical Breakdown in Power Module Layouts

Shilpi Mukherjee, Dr. Yarui Peng, and Dr. Alan Mantooth

University of Arkansas, Fayetteville, USA

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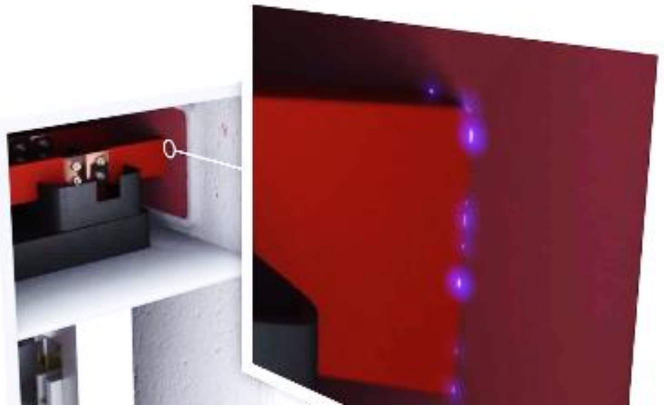
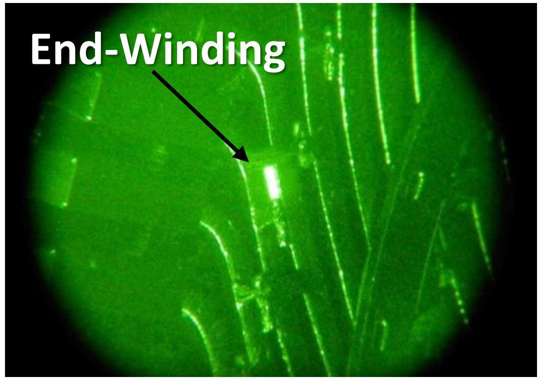
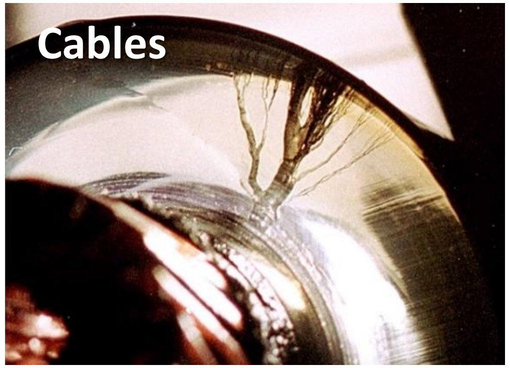
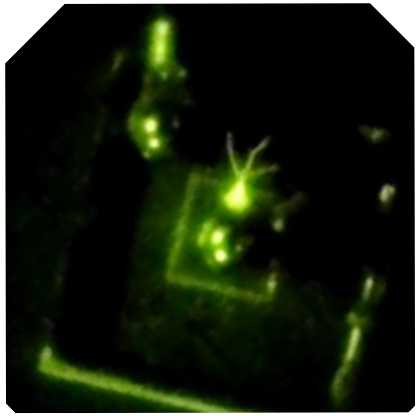
Partial Discharge

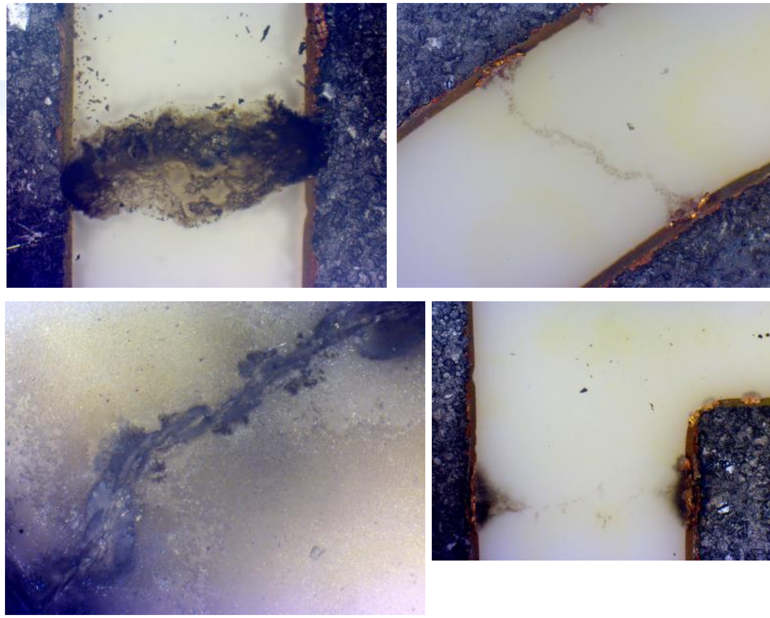


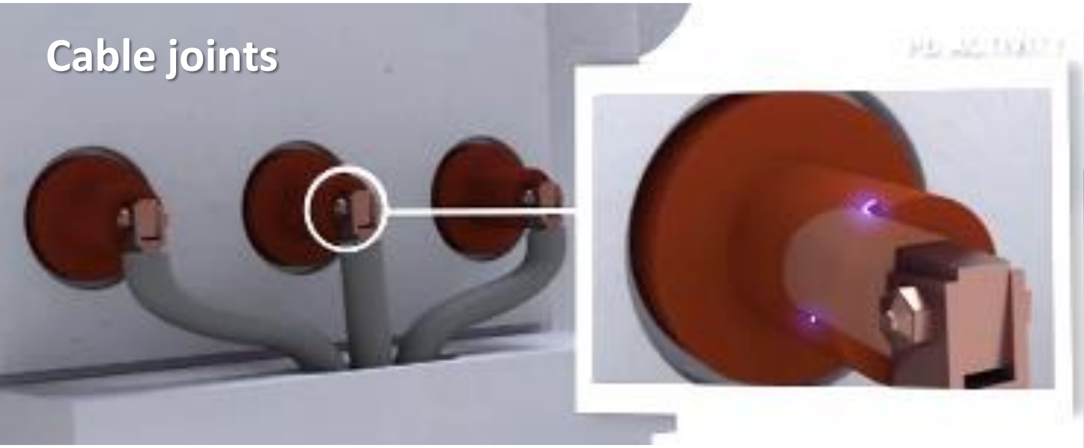




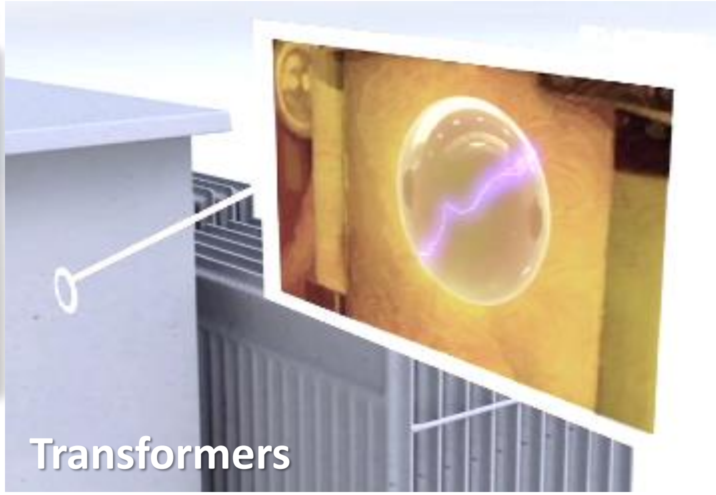
DBC test coupon







https://www.youtube.com/watch?v=QSivGicvtNM



Existing PD Models

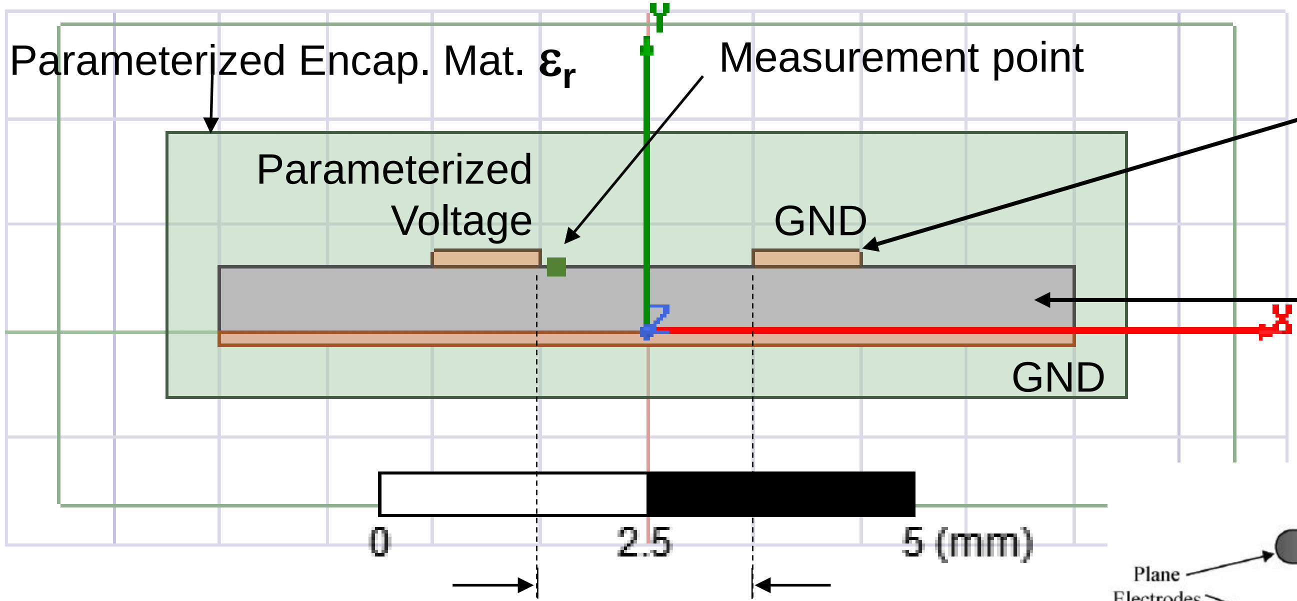
- Electrical Point of View

  Three-capacitor (ABC) model

- Field Point of View
  - Pederson's model – considers volume and surface charge density
  - Conductance model – considers current density
  - Niemeyer's model – considers avalanche and streamer propagation
  - Plasma model – fluid equations
  - Numerical simulation model – temporal and spatial distribution
- Other models

2D Simulations

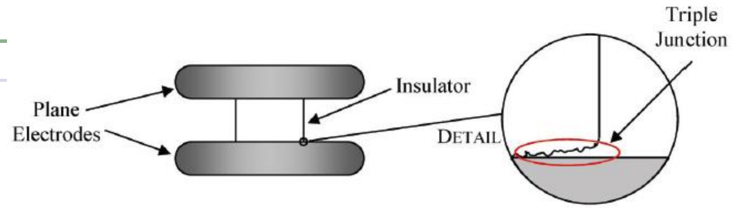
Model geometry



Metal traces, 0.125 mm thick

Ceramic Isolation, 0.625 mm thick

TRACE GAP parameterized



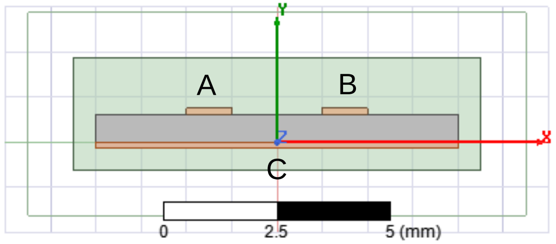
Triple point detail

Parameter range:

Trace gap: 0.5mm to 5.0mm ε_r : 1 to 10   Voltage: 5kV to 30kV

2D Simulations

Model geometry



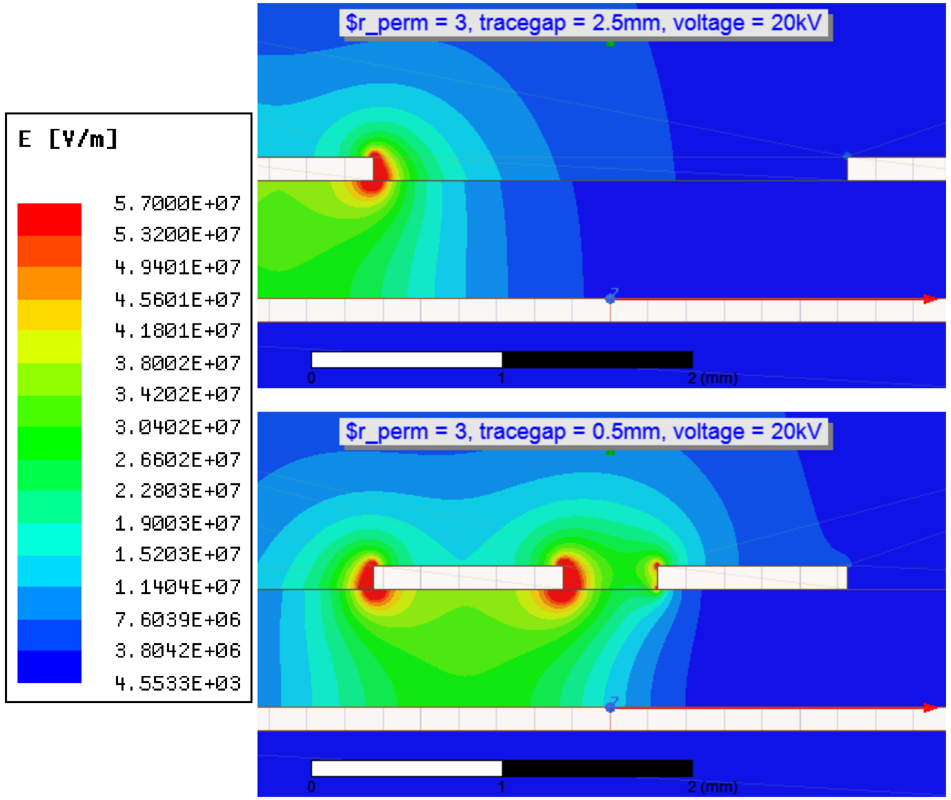
Parameter range:

Trace gap: 0.5mm to 5.0mm
step size: 0.5mm

ε_r : 1 to 10
step size: 1

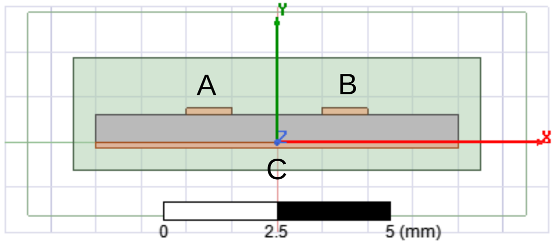
Voltage: 5kV to 30kV
step size: 5kV

E-field distribution



2D Simulations

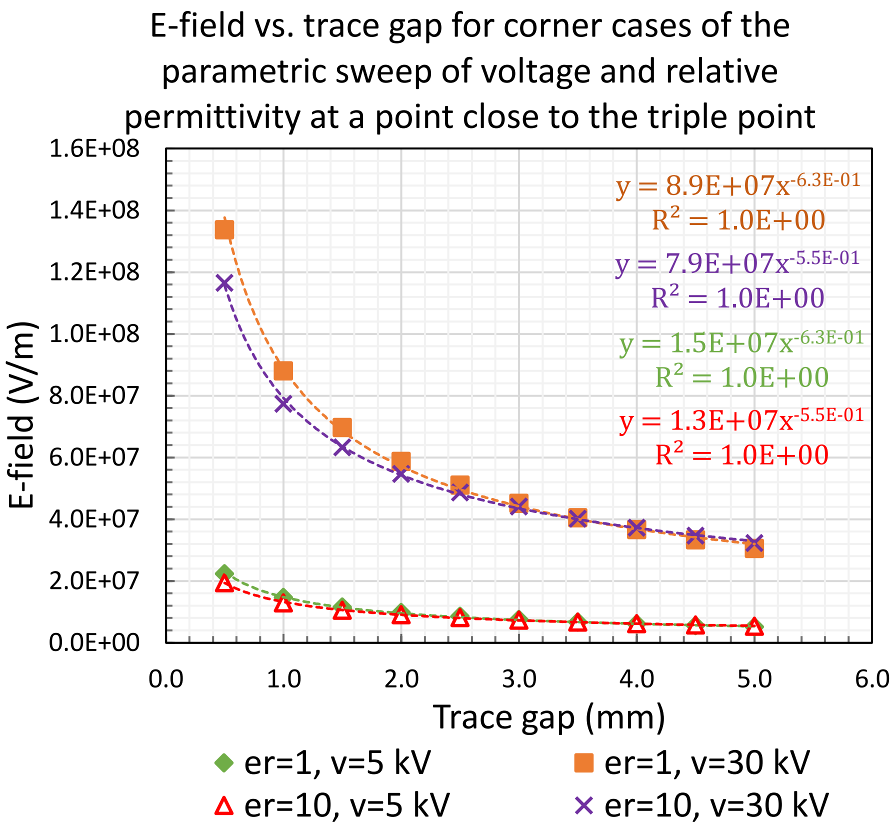
Model geometry



Parameter range:

Trace gap: 0.5mm to 5.0mm
step size: 0.5mm
ε_r : 1 to 10
step size: 1
Voltage: 5kV to 30kV
step size: 5kV

Power curves



2D Simulations

General form of equation

$$E = f(v, \varepsilon_r)\, x^{-g(v,\, \varepsilon_r)}$$

Where

E is the electric field in kV/mm,

v is the voltage in kV,

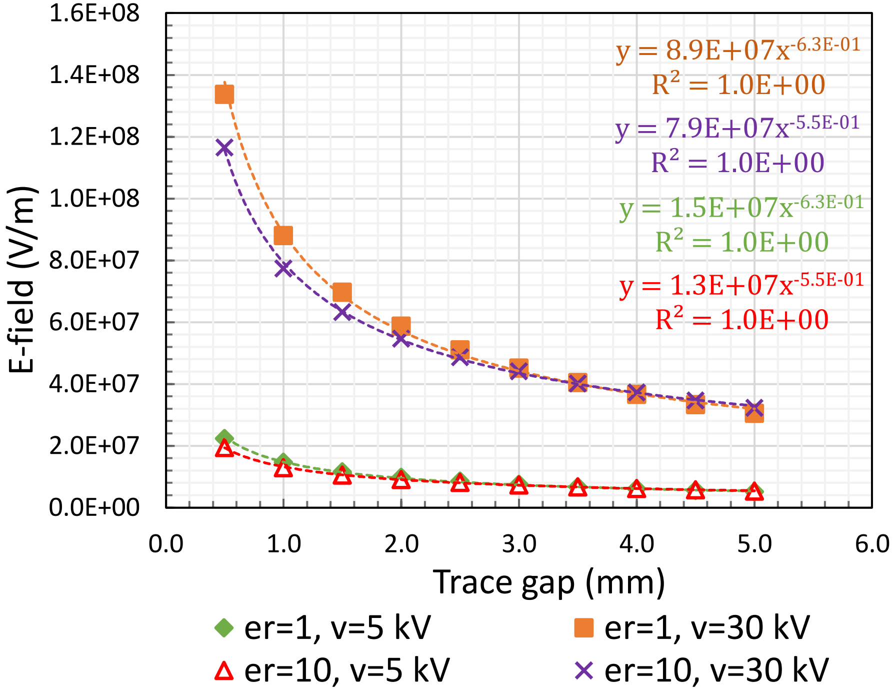
x is the gap between traces A and B in mm,

ε_r is the relative permittivity of the encapsulating material

f and g are functions of v and ε_r.

Power curves

E-field vs. trace gap for corner cases of the parametric sweep of voltage and relative permittivity at a point close to the triple point



2D Simulations

General form of equation

$$E = \frac{v}{5} f_{5kV}(\varepsilon_r)\, x^{-g(v,\,\varepsilon_r)}$$

Where

E is the electric field in kV/mm,

v is the voltage in kV,

x is the gap between traces A and B in mm,

ε_r is the relative permittivity of the encapsulating material

f and g are functions of (v and) ε_r.

Coefficient, $\frac{v}{5} f_{5kV}(\varepsilon_r)$ in mC/m^2

ε_r	5 kV	10 kV	15 kV	20 kV	25 kV	30 kV
1	1.48	2.96	4.43	5.91	7.75	8.87
2	1.48	3.02	4.27	5.75	7.60	9.11
3	1.41	2.94	4.23	5.61	7.51	9.11
4	1.38	2.77	4.15	5.74	7.17	8.30
5	1.62	2.90	4.24	5.48	7.22	8.64
6	1.39	2.78	4.07	5.51	6.88	8.18
7	1.35	2.69	4.03	5.38	6.80	8.20
8	1.35	2.72	4.05	5.41	6.80	8.11
9	1.33	2.67	4.00	5.35	6.66	8.01
10	1.32	2.64	3.96	5.29	6.61	7.92

Exponent, $g(v, \varepsilon_r)$

ε_r	5 kV	10 kV	15 kV	20 kV	25 kV	30 kV
1	0.63	0.63	0.63	0.63	0.66	0.63
2	0.56	0.55	0.51	0.55	0.53	0.53
3	0.57	0.54	0.49	0.51	0.57	0.53
4	0.56	0.56	0.51	0.60	0.56	0.51
5	0.53	0.61	0.56	0.54	0.56	0.55
6	0.54	0.53	0.54	0.55	0.53	0.56
7	0.52	0.53	0.53	0.53	0.54	0.54
8	0.54	0.54	0.54	0.55	0.56	0.56
9	0.55	0.55	0.55	0.55	0.55	0.54
10	0.55	0.55	0.55	0.55	0.55	0.55

3D Simulations

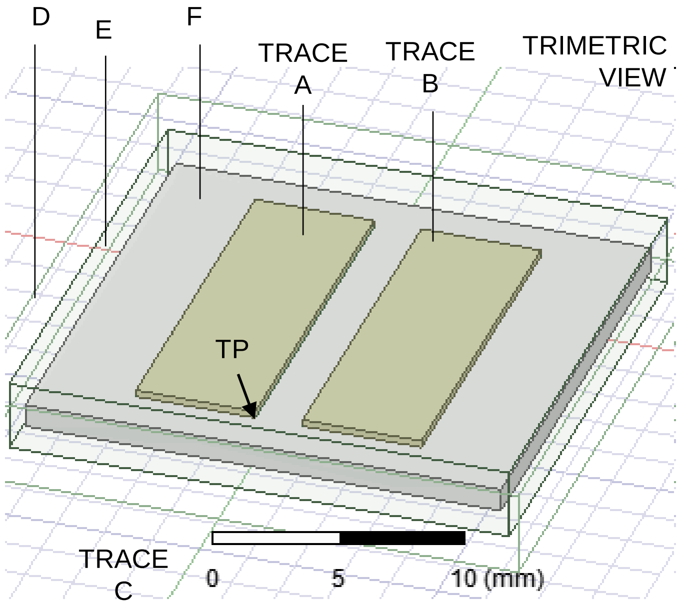
General form of equation

$$Q_s = f(v, \varepsilon_r)\, x'^{-g(v,\, \varepsilon_r)}$$

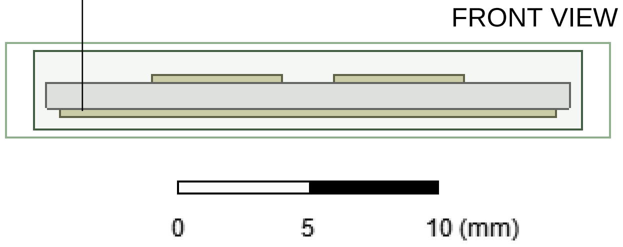
$$\rightarrow Q_s = \frac{v}{2.5} f(\varepsilon'_r)\, x'^{-g(\varepsilon'_r)}$$

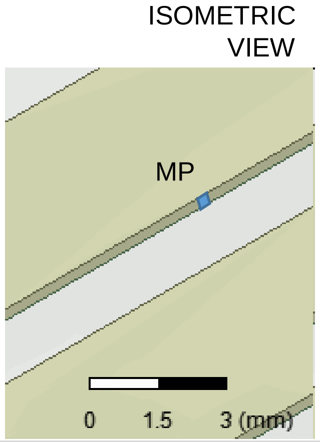
Where
Q_s is the surface charge density in mC/m^2,
v is the voltage in kV,
x' is the ratio of the gap between traces A and B, and the gap between traces A and C.
ε'_r is the relative permittivity of the encapsulating material relative to the relative permittivity of the ceramic,
f and g are functions of ε'_r.

Model geometry



A: Variable voltage Cu trace
B: 0 V Cu trace
C: 0 V back side Cu trace
D: Balloon boundary region
E: Encapsulant material
F: Ceramic (Al_2O_3)
TP: Triple point
MP: Measurement point
Ceramic thickness: 1mm
Metal thickness: 0.3mm

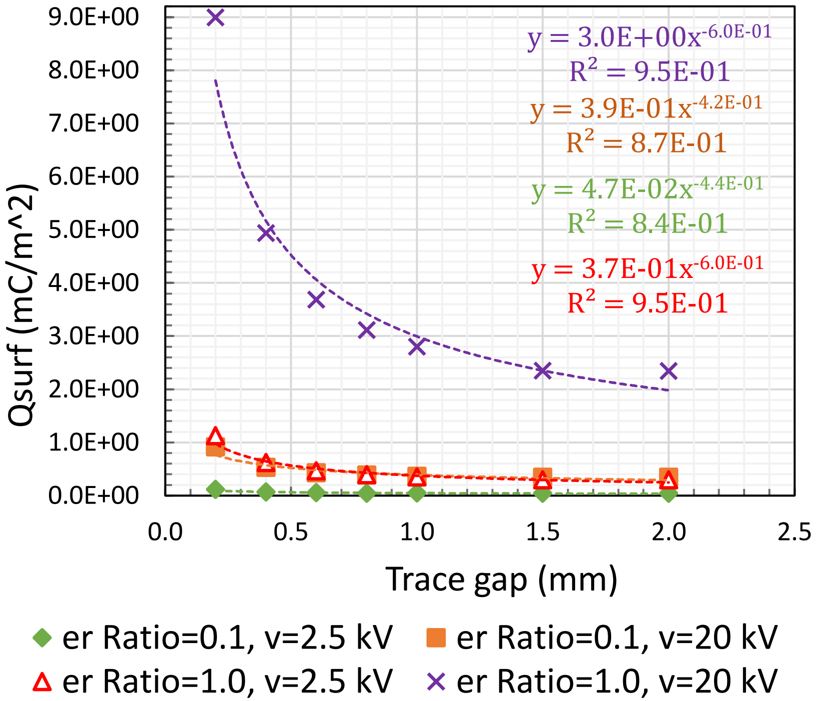




3D Simulations

Power curves

Surface charge density vs. trace gap for corner cases of the parametric sweep of voltage and relative permittivity



Coefficient, $[{}^{v}/_{2.5}\, f(\varepsilon'_r)]$ in mC/m²

ε_r	ε'_r	2.5 kV	5 kV	7.5 kV	10 kV	15 kV	20 kV
1	0.102	0.047	0.097	0.150	0.190	0.290	0.390
2	0.204	0.093	0.190	0.280	0.370	0.560	0.740
3	0.306	0.130	0.270	0.400	0.530	0.800	1.100
4	0.408	0.170	0.340	0.520	0.690	1.000	1.400
7	0.714	0.280	0.550	0.830	1.100	1.700	2.200
10	1.020	0.370	0.750	1.100	1.500	2.200	3.000

$$f = 0.35\varepsilon'_r + 0.02$$

Exponent, $g(\varepsilon'_r)$

ε_r	ε'_r	All voltages
1	0.102	0.42
2	0.204	0.45
3	0.306	0.48
4	0.408	0.50
7	0.714	0.56
10	1.020	0.60

$$g = 0.20\varepsilon'_r + 0.40$$

3D Simulations

General form of equation

$$Q_s = \frac{v}{2.5} f(\varepsilon'_r)\, x^{-g(\varepsilon'_r)}$$

$$\rightarrow\ x = e^{\left(\frac{1}{g}\ln\left(\frac{v}{2.5} f(\varepsilon'_r)\frac{1}{Q_s}\right)\right)}$$

$$\rightarrow\ x = e^{\left(\frac{1}{g}\ln\left(\frac{v}{2.5} f(\varepsilon'_r)\frac{1}{\varepsilon_0\varepsilon_r E*10^9}\right)\right)}$$

$$\rightarrow x = e^{\left(\frac{1}{0.20\,\varepsilon'_r + 0.40}\ln\left(\frac{v}{2.5}\left(0.35\,\varepsilon'_r + 0.02\right)\frac{1}{\varepsilon_0\varepsilon_r E*10^9}\right)\right)}$$

where

Q_s is the surface charge density in mC/m^2,

E is the electric field in kV/mm,

v is the voltage in kV,

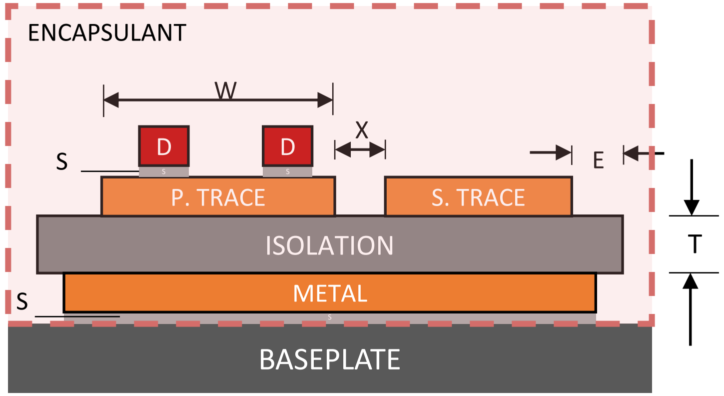
x is the ratio of the gap between traces A and B, and the gap between traces A and C. For ceramic thickness = 1mm, x gives trace-gap A-B in mm.

ε'_r is the relative permittivity of the encapsulating material relative to the relative permittivity of the ceramic,

f and g are functions of ε'_r.

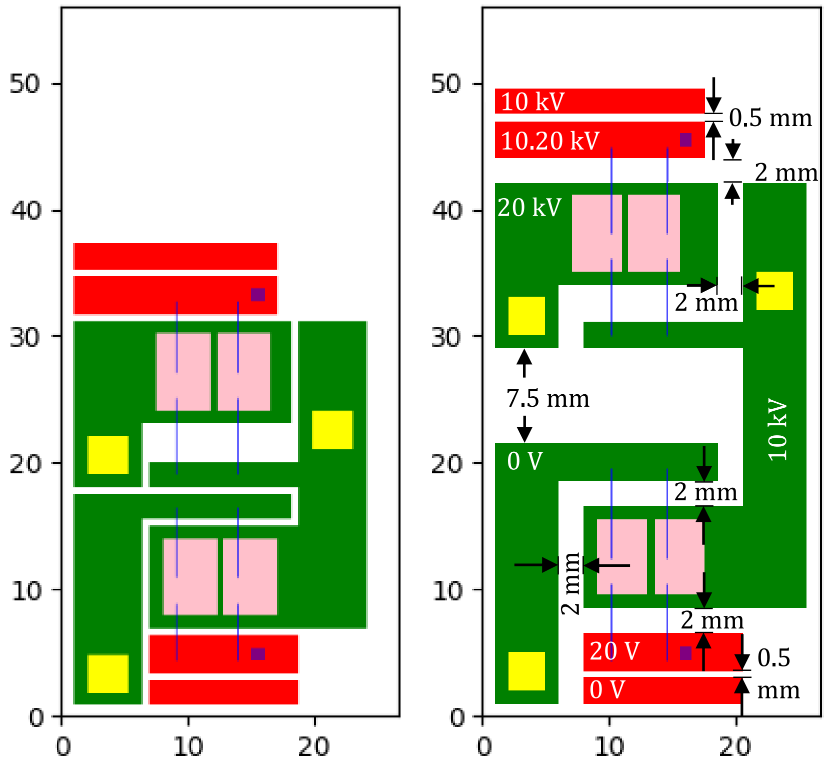
Implementation in PowerSynth

Manufacturing Design Kit (MDK) and Design Rule Check (DRC)

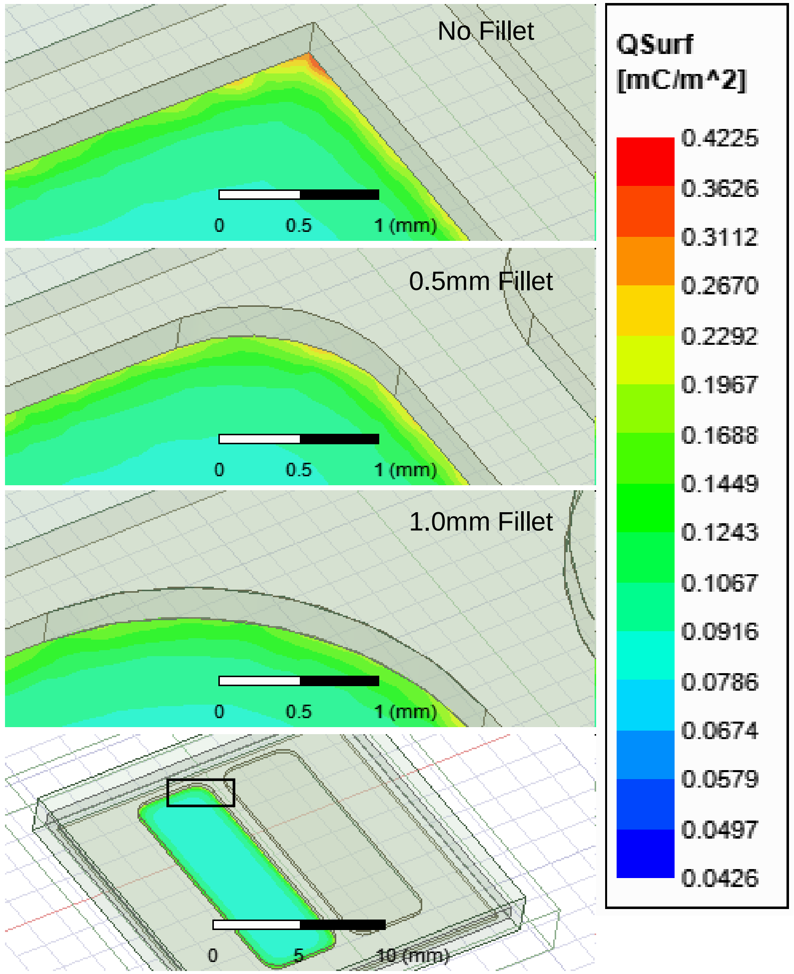


W: lateral width of trace
X: lateral trace gap
E: minimum enclosure
T: vertical thickness of a layer
D: device
P. trace: power trace; S. trace: signal trace
S: substrate attach or die attach

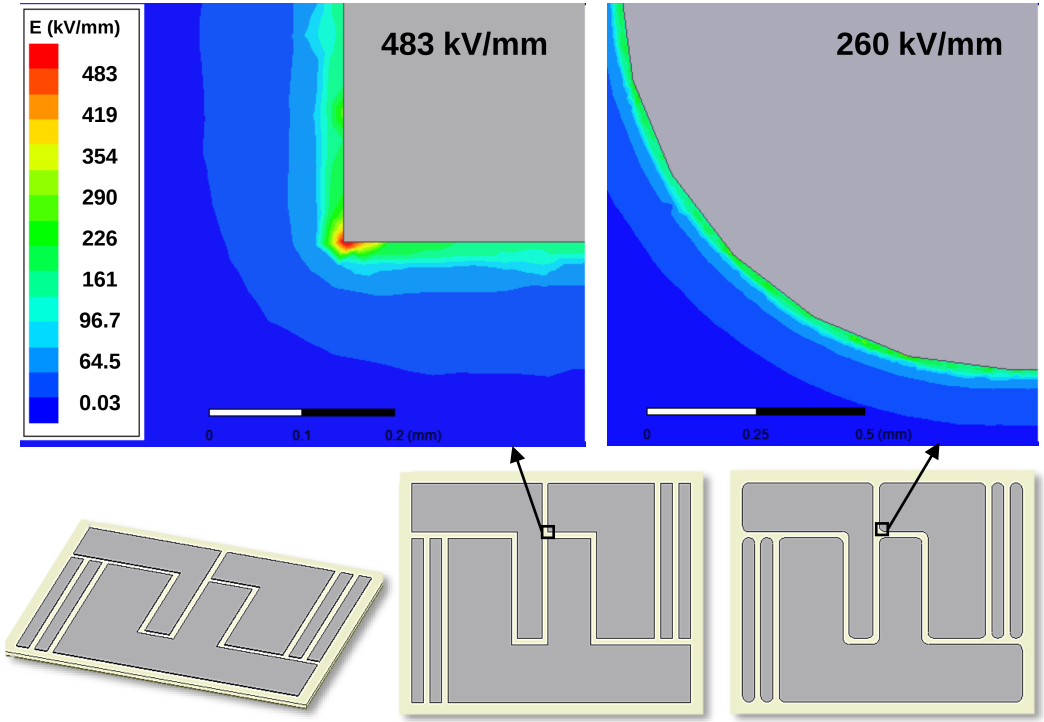
Default layout vs. Layout with design rules applied



Effect of filleting sharp corners



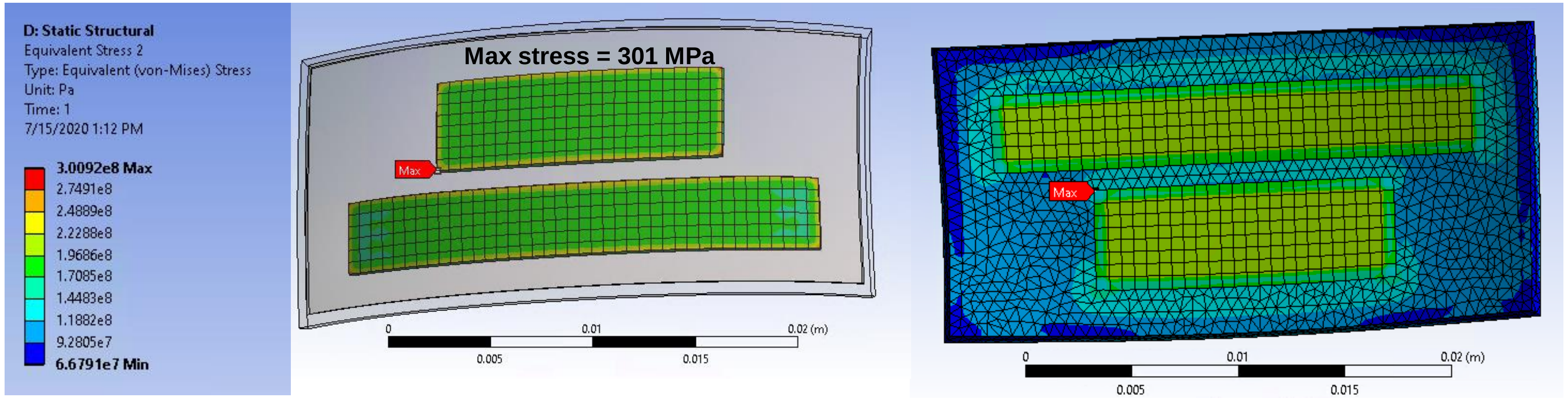
E-field and Q_s are almost halved



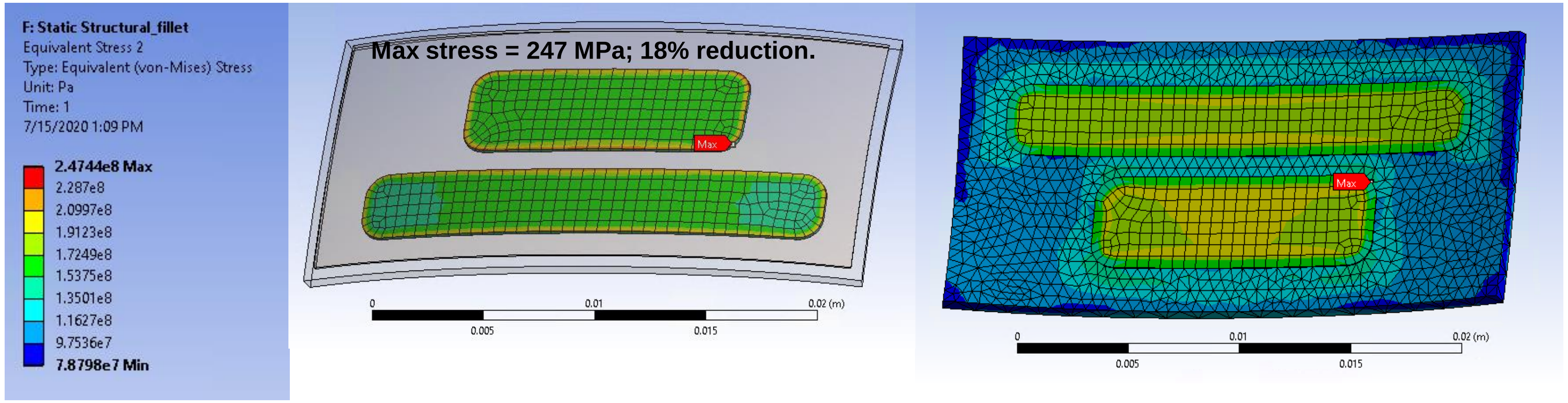
Filleting reduces mechanical stress

Bottom view | Top view

Sharp

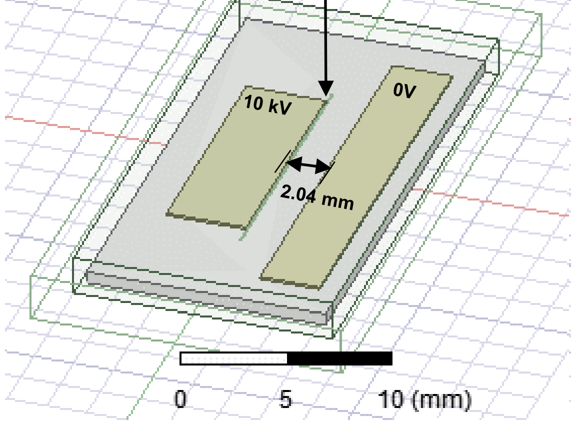


Fillet

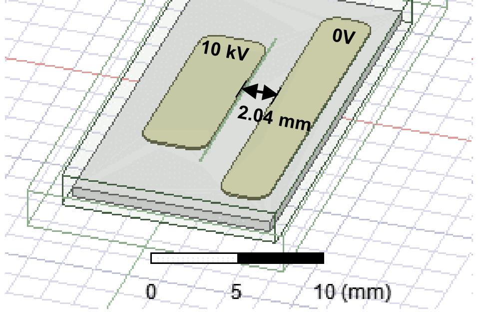


Effect of filleting sharp corners

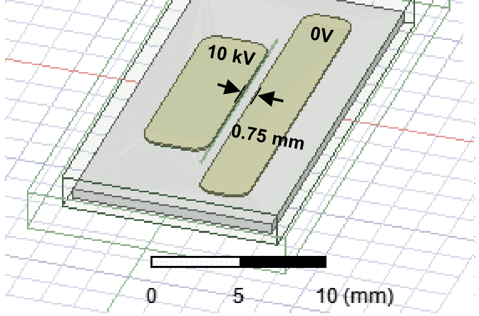
E = Emax; gap = 2.04 mm
No fillet



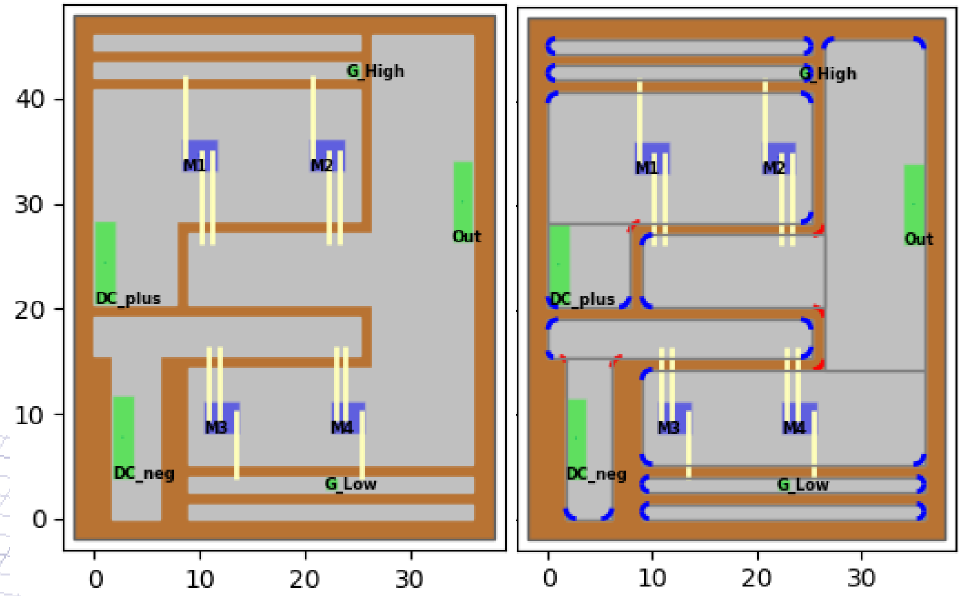
E = 0.65 Emax; gap = 2.04 mm
1 mm fillets



E = Emax; gap = 0.75 mm
1 mm fillets



Application of fillets in PowerSynth



← Gap can be reduced to about 40% of the original gap if fillets are applied.

Summary

- Partial discharge.
- 2D simulations of E-field focusing.
- 3D simulations of surface charge density.
- General equation developed for determining trace gap.
- Effect of filleting sharp corners.
- Implementation of trace-gap design rules and fillets in PowerSynth.

Coming up next…

- Enhancing the general equation with
  - Fillet factor,
  - Derating factor based on wet-etching profile of metal on ceramic,
  - Derating factor based on voltage profile, and
  - Metal thickness variation.
- Statistical analysis through partial discharge tests to determine a margin on design rules because PD is stochastic in nature.

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Authors:

Shilpi Mukherjee
sxm063@uark.edu

Dr. Yarui Peng
yrpeng@uark.edu

Dr. Alan Mantooth
mantooth@uark.edu

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