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Steinmetz-Type Loss Modeling for Non-Linear Class II Multilayer Ceramic Capacitors

D. Menzi[1] , M. Heller[1], G. Kerridge[2], P. Marley[2], A. Ellmore[2], S. Ben-Yaakov[3], J.W. Kolar[1]

[1] Power Electronic Systems Laboratory (PES), ETH Zurich

[2] Knowles Precision Devices

[3] Ben-Gurion University of the Negev

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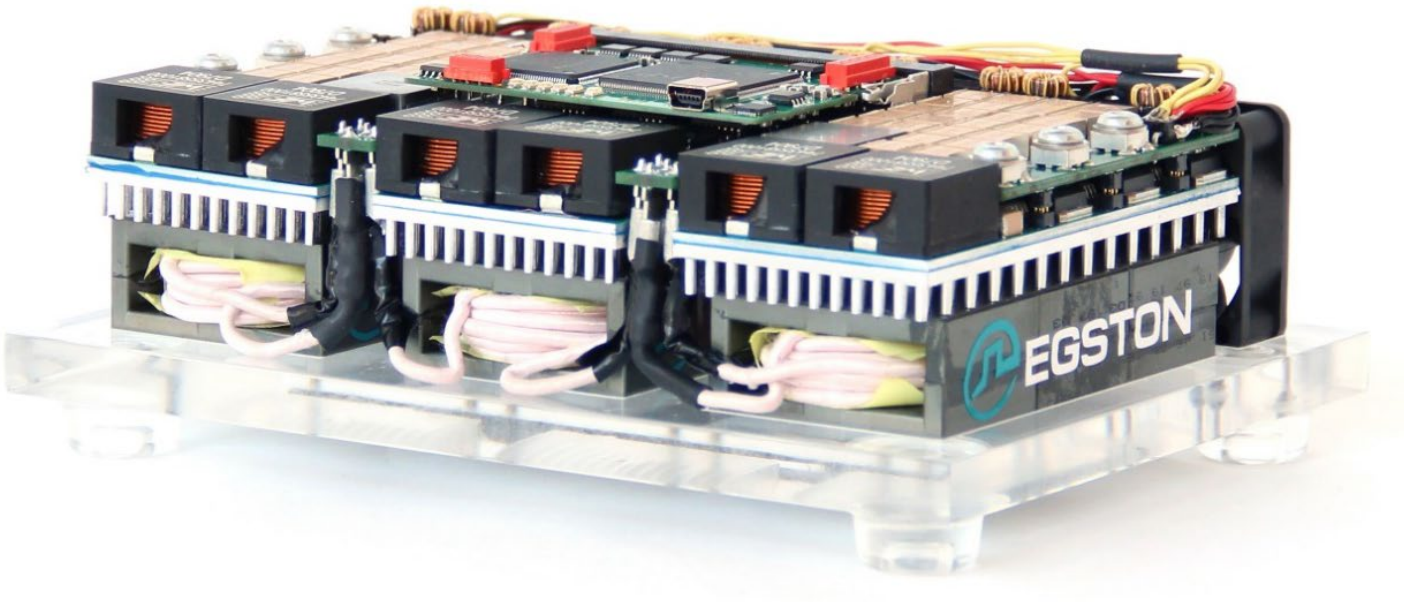
CLASS II MULTILAYER CERAMIC CAPACITORS (MLCCS)

- Research on next generation inverter motor drives

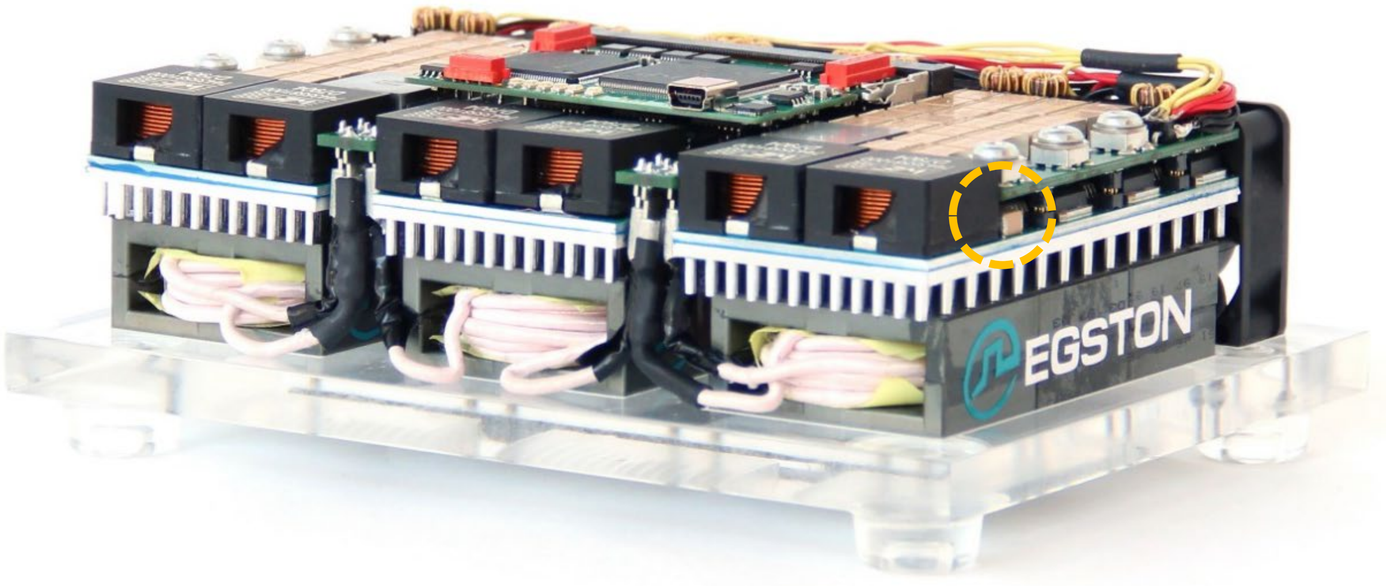


- 400…750V (DC) input voltage
- 0 .. 230V (AC, RMS) / 0…500Hz output voltages
- 11 kW nominal power

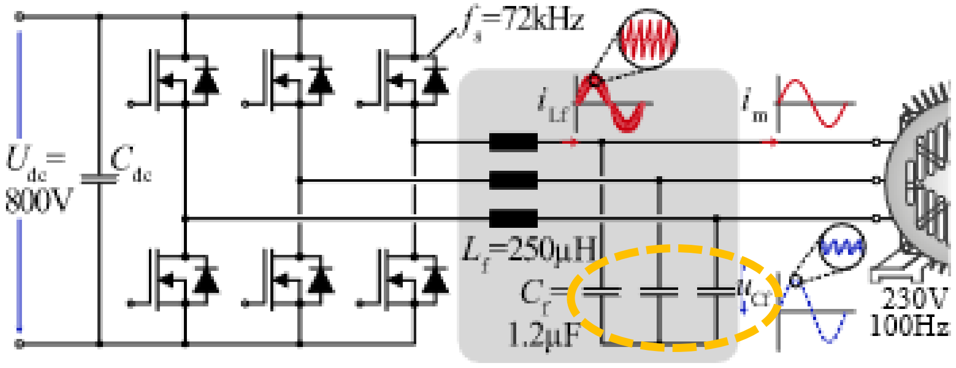
- Sinusoidal output voltages / unshielded motor cables
- Ultra compact converter realization (15kW/dm^3, 245W/in^3)

Class II Multilayer Ceramic Capacitors (MLCCs)

- Ferroelectric MLCCs with high energy density / low Dissipation Factor (DF)



▼ Class II MLCC applications



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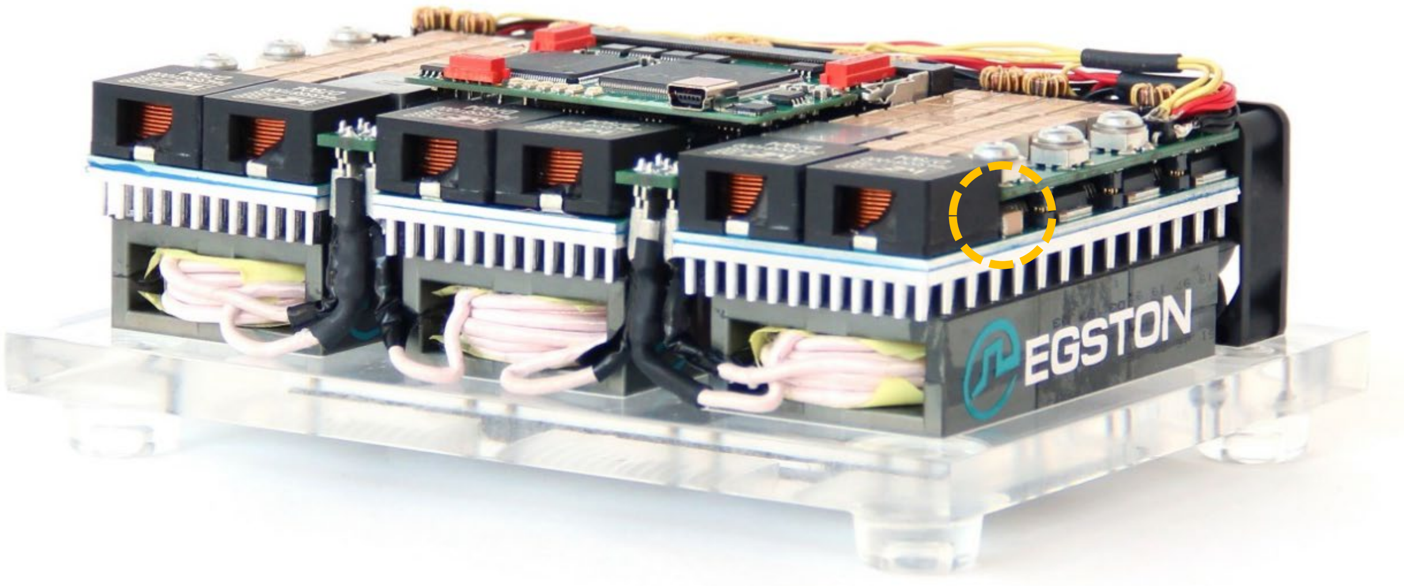
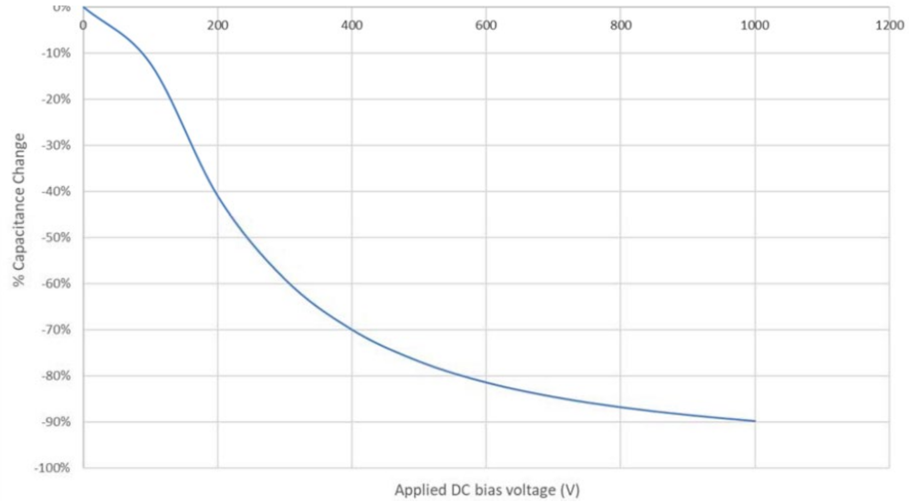
Class II Multilayer Ceramic Capacitors (MLCCs)

- Ferroelectric MLCCs with high energy density

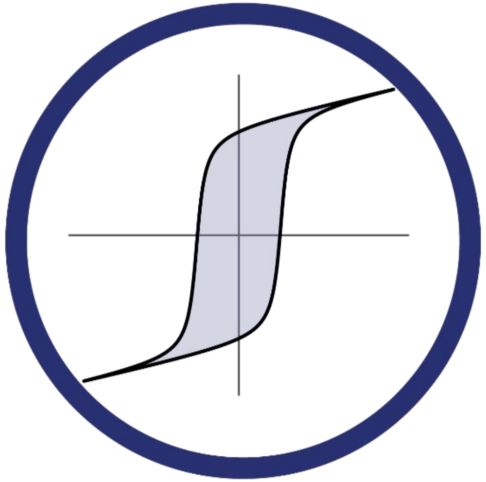


▼ Class II MLCC derating



- Non-linear dielectric constant / large-signal excitation losses
- Suitable measurement methods to record U-Q hysteresis?
- Suitable modeling techniques considering voltage amplitude, bias and frequency?

STEINMETZ-TYPE LOSS MODELING FOR NON-LINEAR CLASS II MULTILAYER CERAMIC CAPACITORS



Introduction

- Ferroelectric MLCCs
- Applications

Loss measurements

- Electric
- Calorimetric

Steinmetz loss models

- Fundamentals
- Macroscopic model
- Microscopic model

Overview: Measurement Techniques

- Impact of excitation amplitude / shape / bias / frequency + temperature

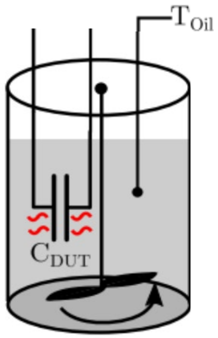
Electric

- Voltage/current
- Sawyer-Tower

→ Fast / waveform information

→ P/Q ratio is ill-conditioned (!)

Calorimetric



- Steady-state
- Transient

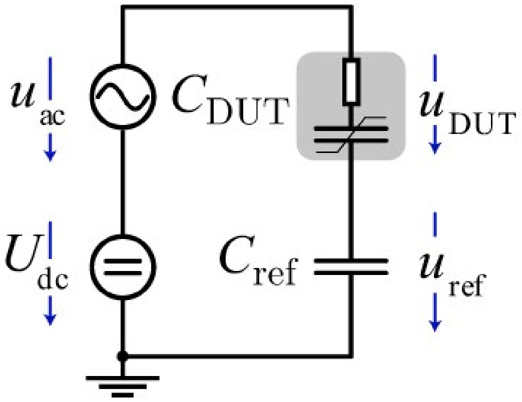
→ Slow / limited information

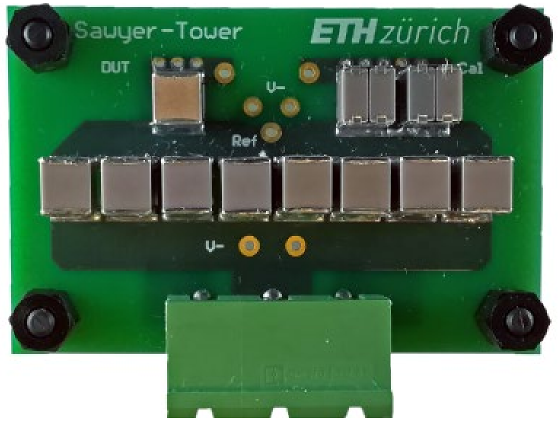
→ Extremely accurate

Sawyer-Tower MLCC Loss Measurement

- Impact of excitation amplitude / shape / bias / frequency + temperature

▼ Sawyer-Tower circuit / PCB





▼ Sawyer-Tower equations

$$Q_{DUT} = Q_{ref} = U_{ref} \cdot C_{ref}$$
$$E_{DUT} = \int U_{DUT}(Q)\,dQ_{DUT}$$
$$P_{DUT} = \frac{E_{DUT}}{T}$$

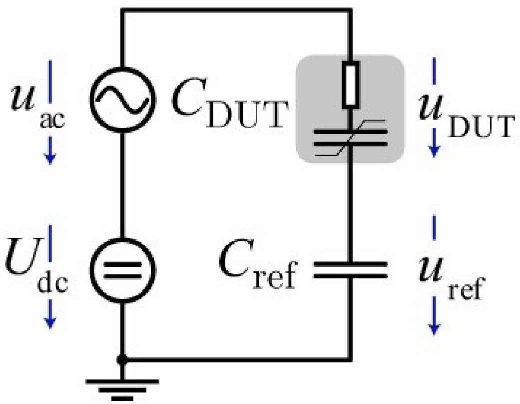
Hysteresis loop area (!)

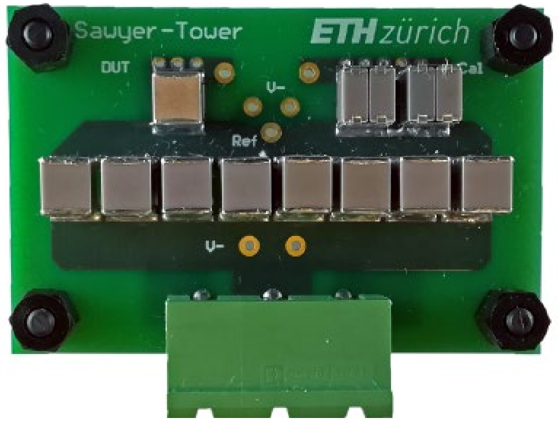
- Requirements for C_{ref}: → Linear dielectric / $C_{ref}(V)$=const
  → Small impedance (C_{ref} >> C_{DUT})
  → Low dissipation factor (DF_{ref} << DF_{DUT})

Sawyer-Tower MLCC Loss Measurement

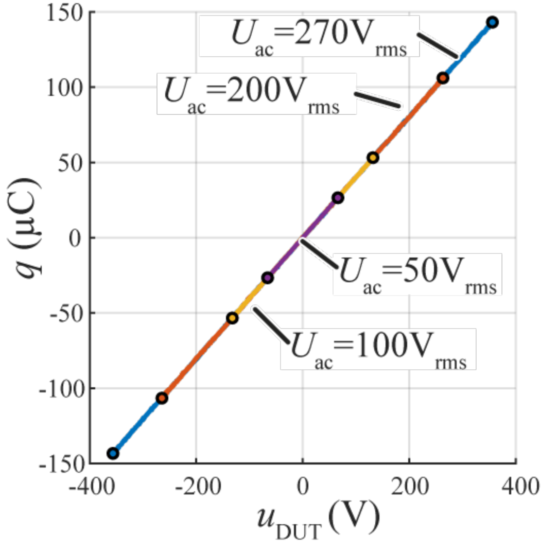
- Impact of excitation amplitude / shape / bias / frequency + temperature

▼ Sawyer-Tower circuit / PCB

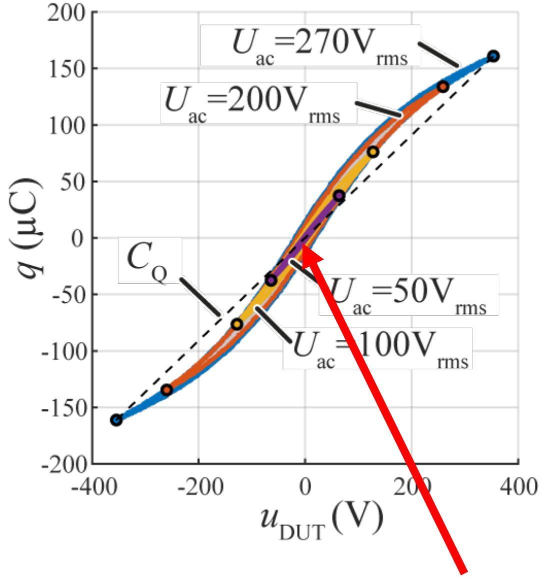




▼ C0G MLCC



▼ X7R MLCC



Hysteresis loop area (!)

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Steinmetz-Type Loss Modeling for Non-Linear Class II Multilayer Ceramic Capacitors

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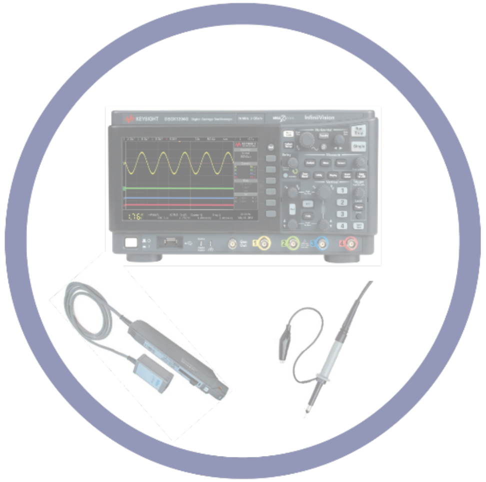
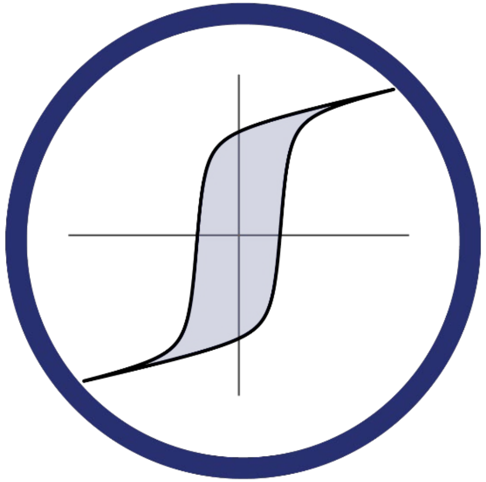


Loss measurements
- Electric
- Calorimetric

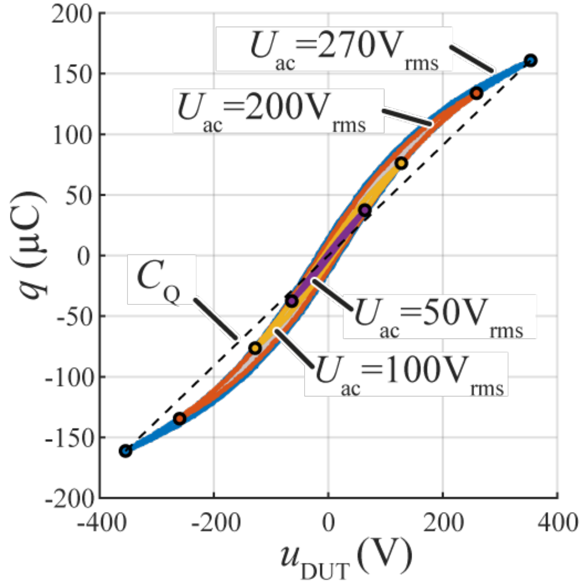


Steinmetz loss models
- Fundamentals
- Macroscopic model
- Microscopic model

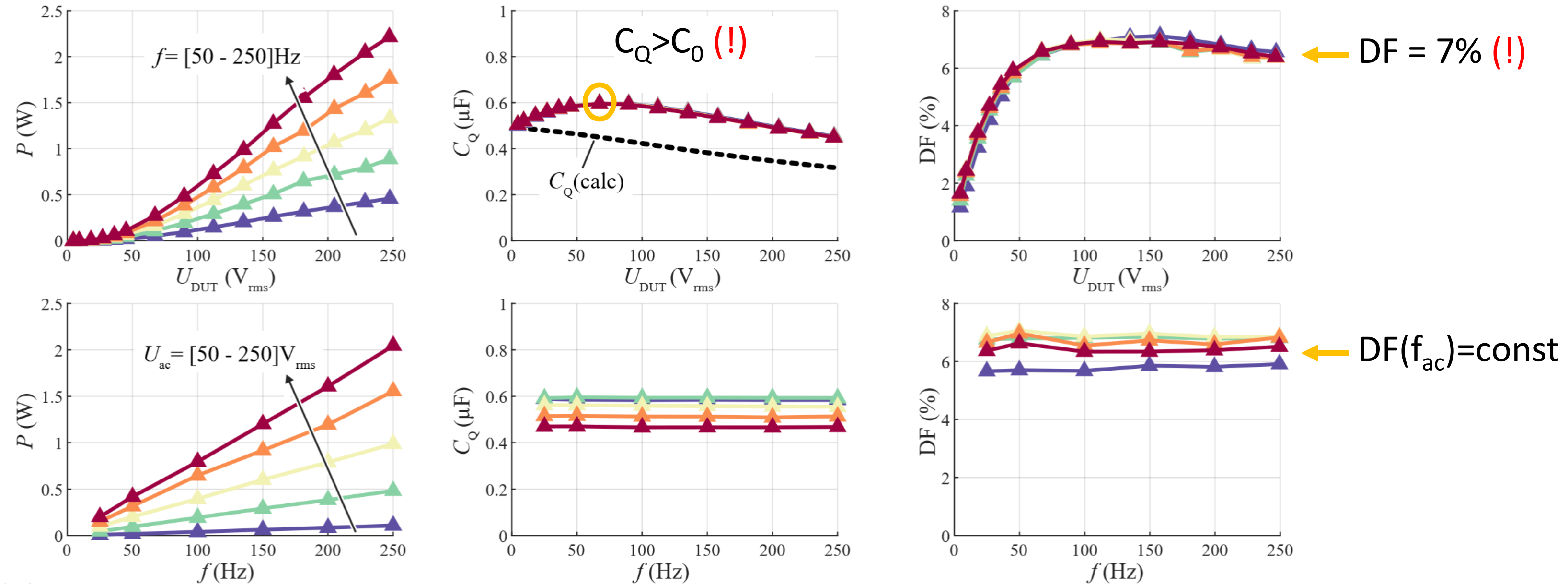
Macroscopic Steinmetz Loss Modelling

- Sawyer-Tower measurement results

▼ U-Q Hysteresis



▼ Impact of voltage and frequency

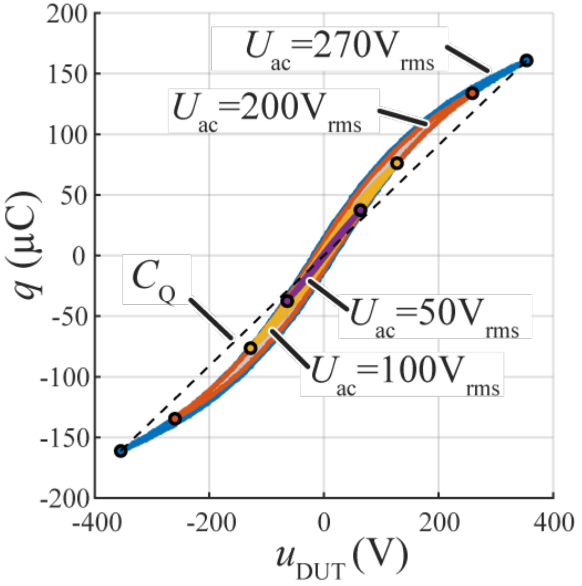


- Constant DF over frequency → linear loss increase
- Massive increase in DF with voltage → non-linear loss relationship

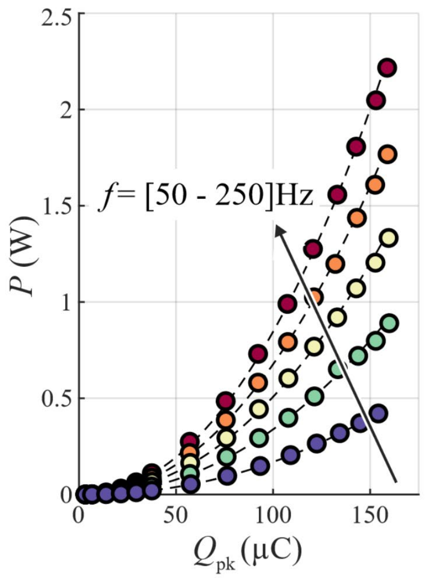
Macroscopic Steinmetz Loss Modelling

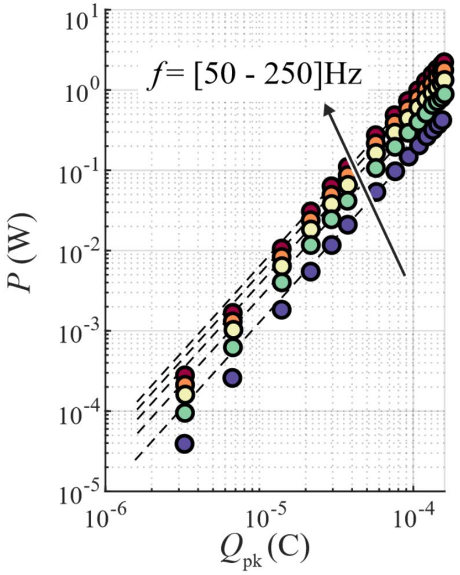
- Sawyer-Tower measurement results

▼ U-Q Hysteresis



▼ Impact of charge and frequency





▼ Steinmetz Model

$$P = k_Q \cdot f^{\alpha} \cdot Q_{pk}^{\beta}$$

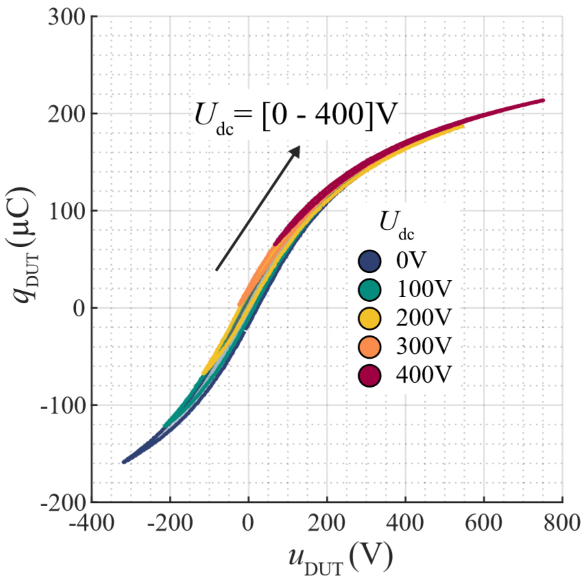
Q_{pk}	pk. charge
f	frequency
k_Q, α, β	Steinm. coefficients

- Power-law relationship between MLCC charge and losses
- Steinmetz loss model allows to predict losses

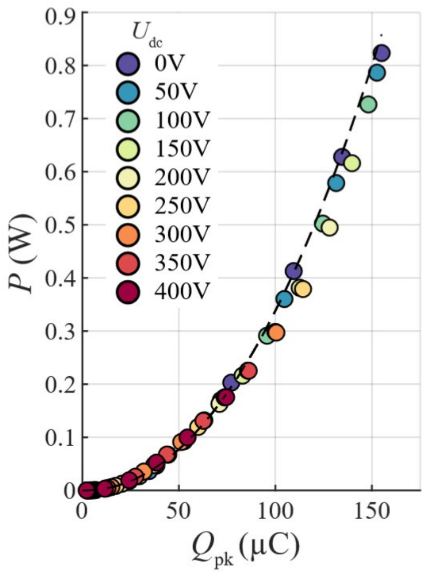
Macroscopic Steinmetz Loss Modelling

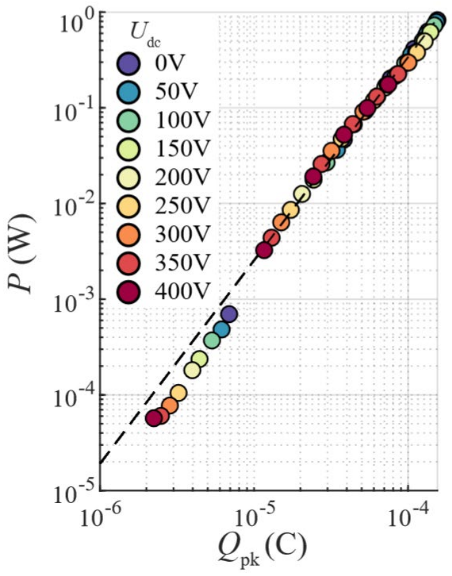
- Sawyer-Tower measurement results

▼ U-Q Hysteresis



▼ Impact of DC bias





▼ Steinmetz Model

$$P=k_Q \cdot f^{\alpha} \cdot Q_{pk}^{\beta}$$

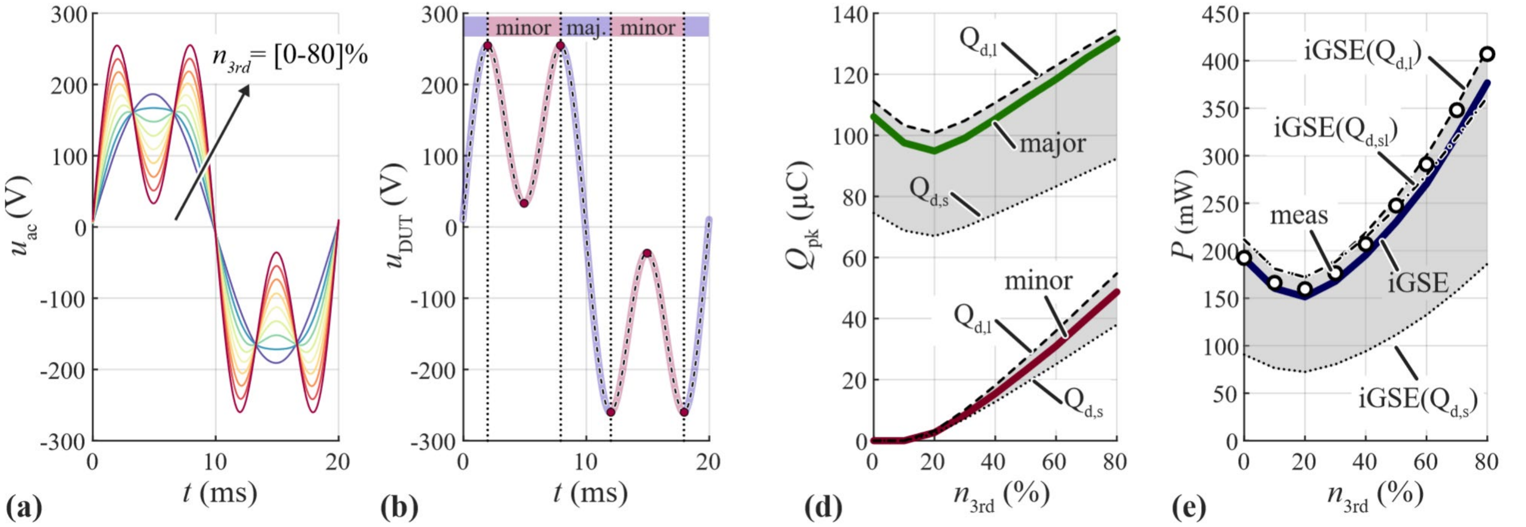
Q_{pk}	pk. charge
f	frequency
k_Q,α,β	Steinm. coefficients

- Power-law relationship between MLCC charge and losses
- Steinmetz parameters are DC-invariant

Macroscopic Steinmetz Loss Modelling

- Sawyer-Tower measurement results

▼ Major-minor loop splitting ▼ MLCC charge and losses ▼ iGSE-C Model



$$P = k_{\mathrm{i}} \cdot \Delta Q^{\beta-\alpha} \cdot \frac{1}{T}\int_0^T \left|\frac{dQ}{dt}\right|^\alpha dt$$

$$k_{\mathrm{i}} = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi} |\cos\theta|^\alpha 2^{\beta-\alpha}\, d\theta}$$

- Power-law relationship between MLCC charge and losses
- Losses described by improved Generalized Steinmetz Equation (iGSE-C)

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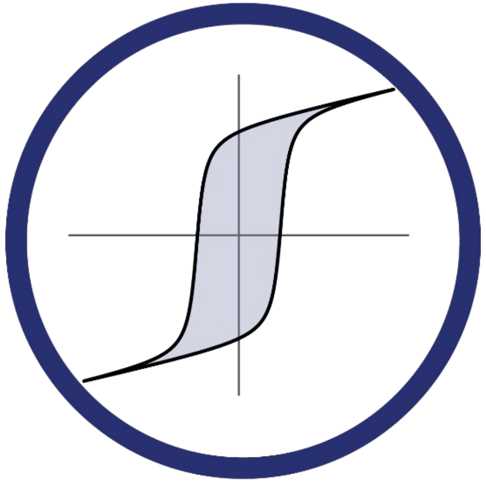

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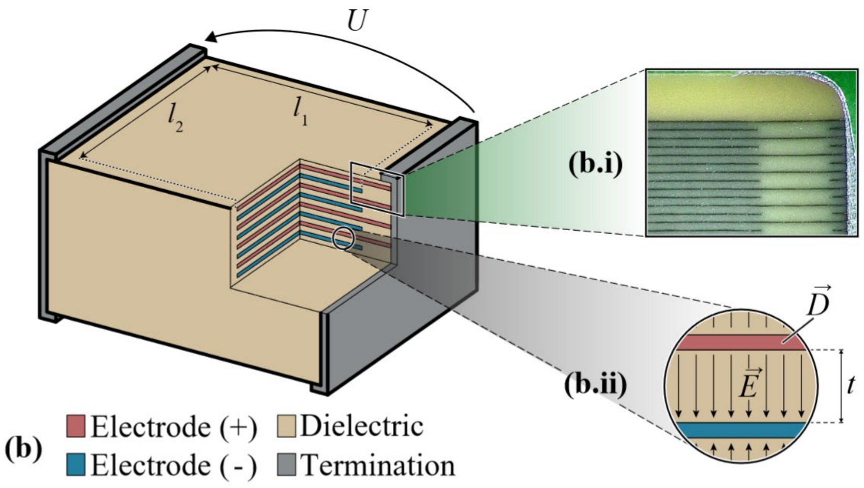
MICROSCOPIC STEINMETZ LOSS MODELLING

- iGSE-C limited to a specific MLCC

Ferromagnetic Core (iGSE)

- Material properties: k, α, β
- Geometry: A_c, V
- Loss Density $\rho = P / V = k f^{\alpha} B_{pk}^{\beta}$



Ferroelectric MLCC (iGSE-C)

Device Properties: k_Q, α, β

Unknown geometry

Losses $P = k_Q f^{\alpha} Q_{pk}^{\beta}$

Ferroelectric MLCC (iGSE-C$_D$)

Material properties: k_D, α, β

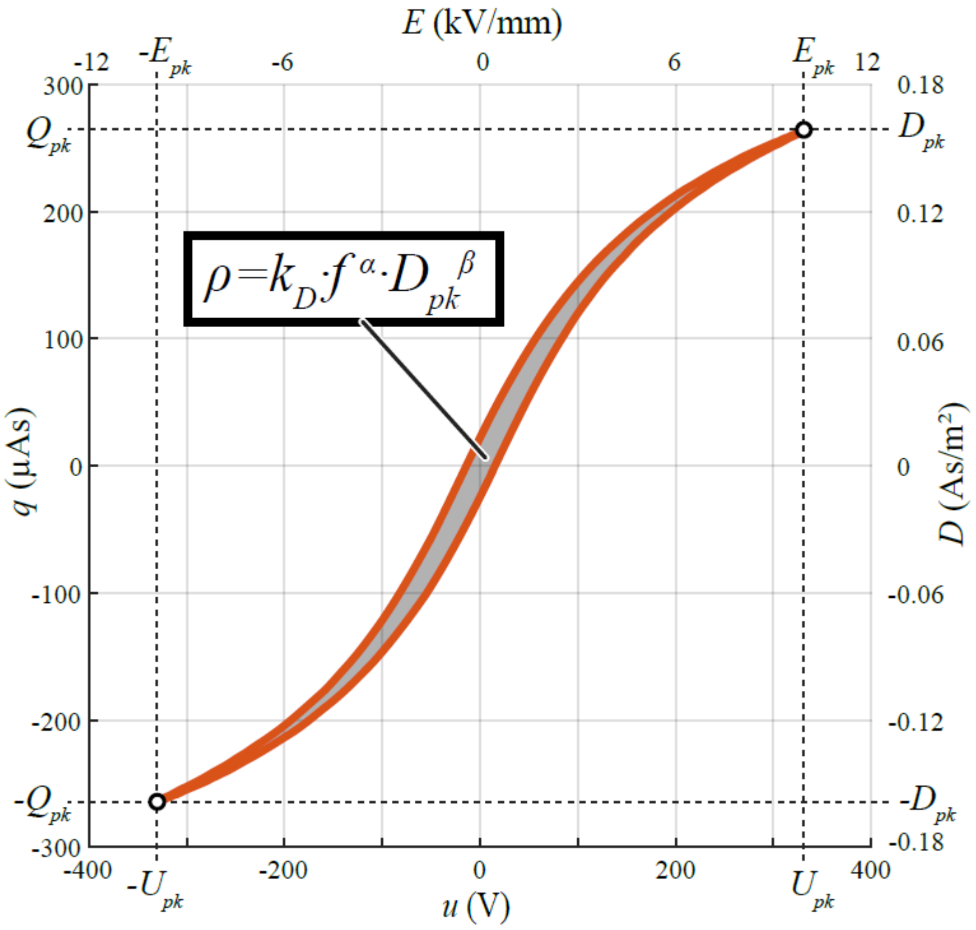
$k_D = k_Q A^{\beta} / V$

Geometry: A, V, t

Loss Density $\rho = P / V = k_D f^{\alpha} Q_{pk}^{\beta}$

Microscopic Steinmetz Loss Modelling

- iGSE-C_D applies to all MLCCs of the same dielectric



Ferroelectric MLCC (iGSE-C)

Device Properties: k_Q, α, β

Unknown geometry

Losses $P = k_Q f^{\alpha} Q_{pk}^{\beta}$

Ferroelectric MLCC (iGSE-C_D)

Material properties: k_D, α, β

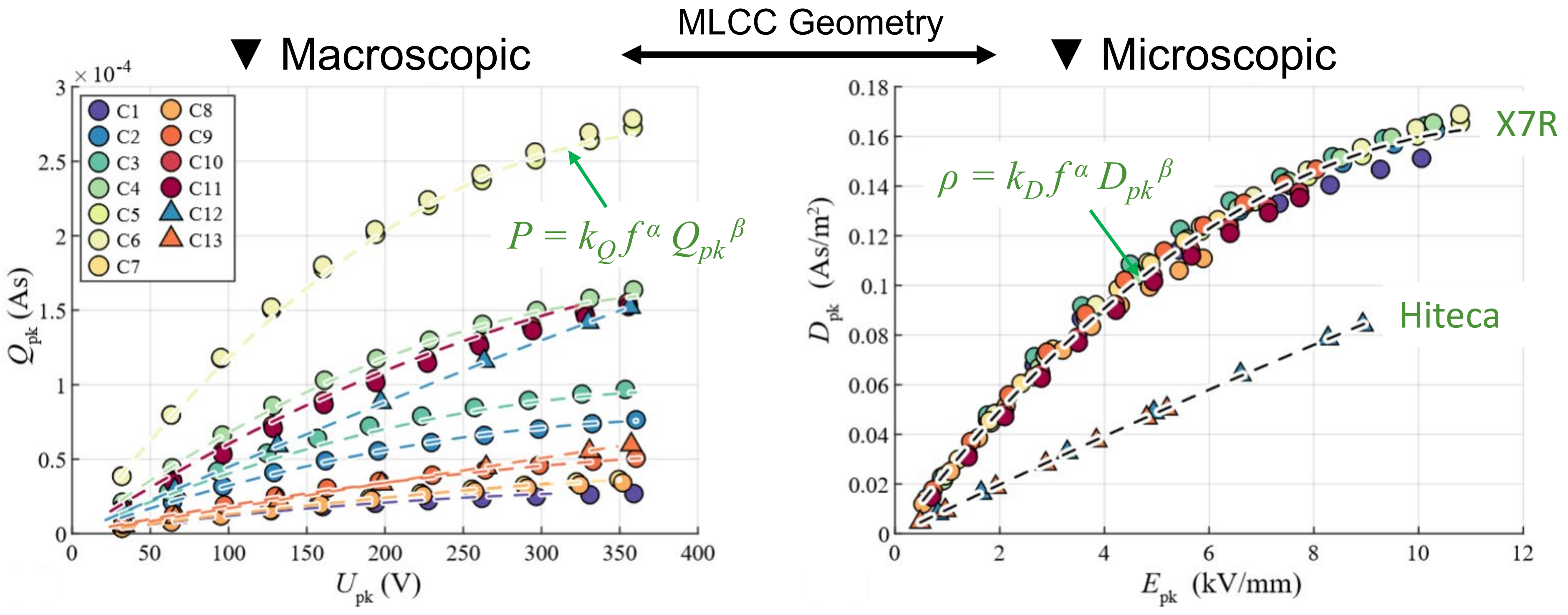
$k_D = k_Q A^{\beta} / V$

Geometry: $A,\ V,\ t$

Loss Density $\rho = P / V = k_D f^{\alpha} Q_{pk}^{\beta}$

Microscopic Steinmetz Loss Modelling

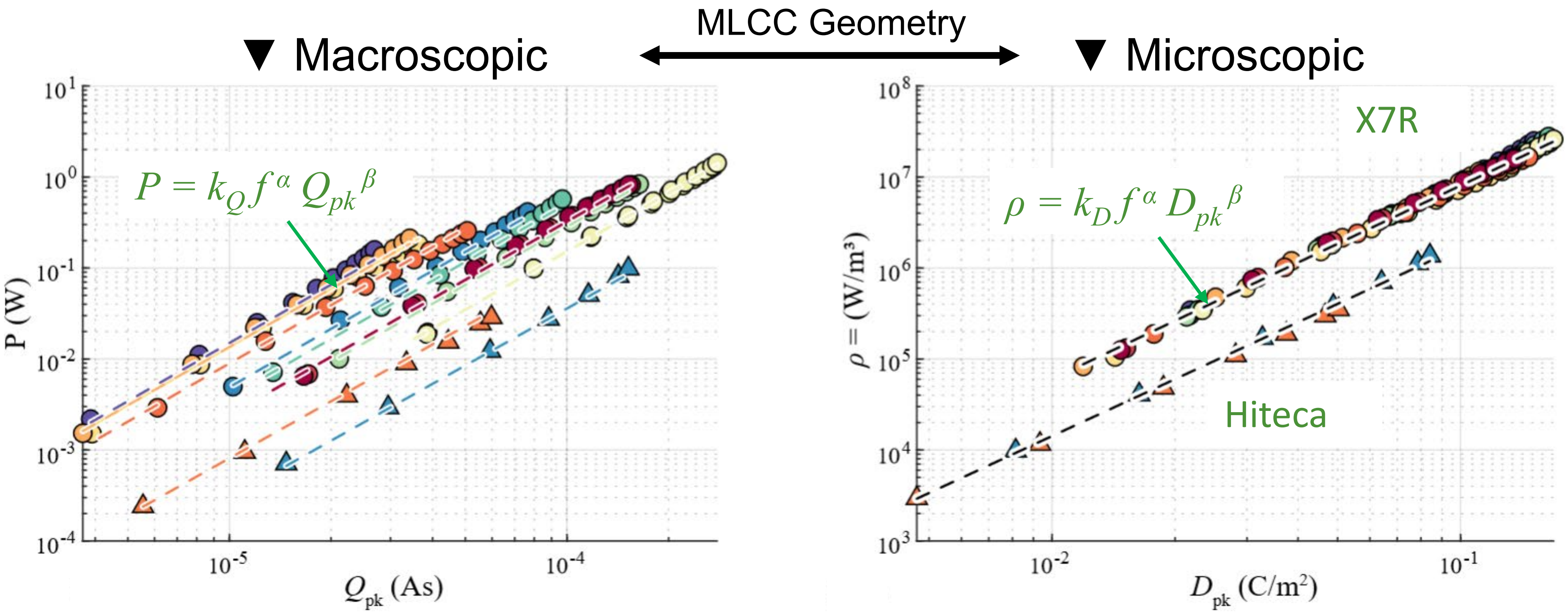
- iGSE-C_D applies to all MLCCs of the same dielectric



- Consistent E-D-field relationship for a given dielectric material

Microscopic Steinmetz Loss Modelling

- iGSE-C_D applies to all MLCCs of the same dielectric



- Consistent D-field-loss-density relationship for a given dielectric material

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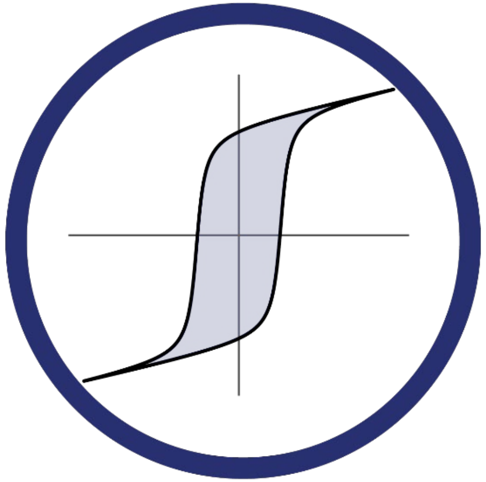

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Class II Multilayer Ceramic Capacitors (MLCCs)

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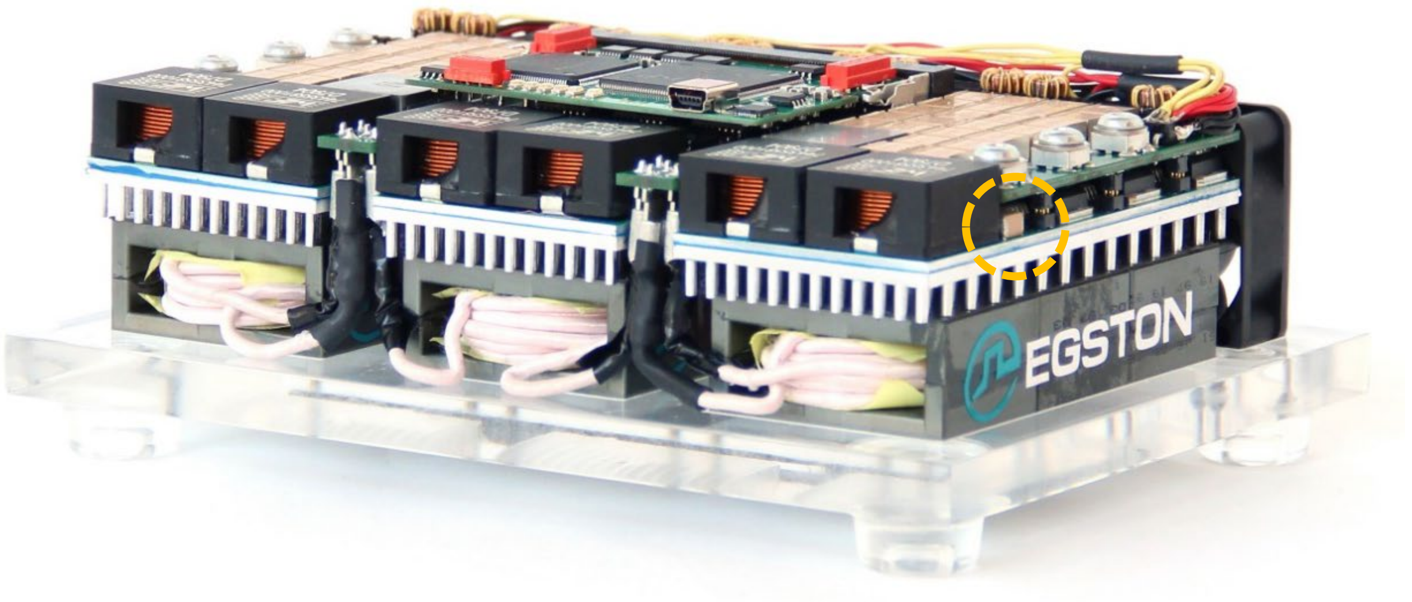

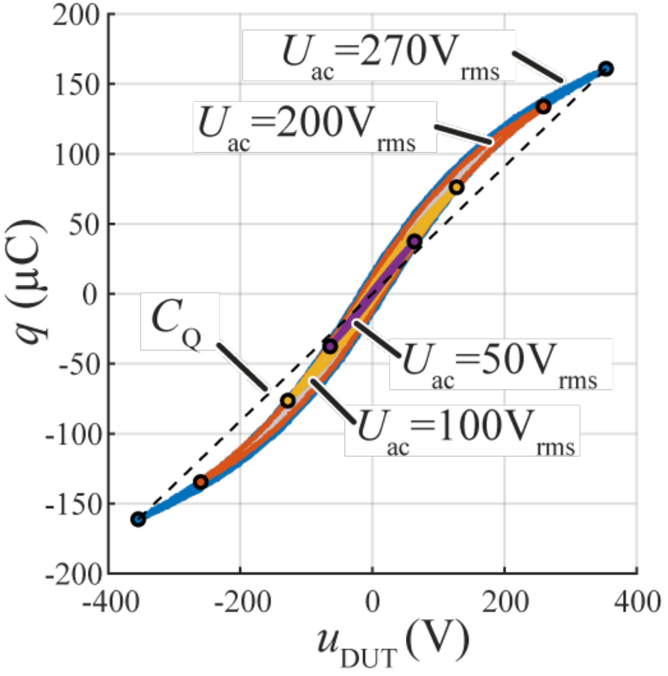

- Non-linear dielectric constant / large-signal excitation losses
- Material-specific / microscopic Steinmetz loss model

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