YAGEO GROUP

Imagine low ESL

Developing Film
Capacitor with Bode100

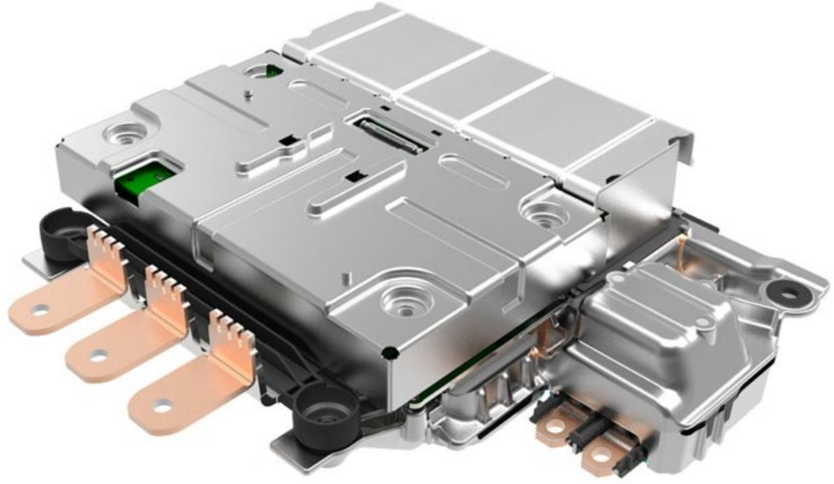
2025-04-09

Agenda

- Short introduction – why
- The object – the film capacitor
- The measurement setup
- Results
- Outlook

Electro Mobility and EMI aspects

- Broadcast cellphone 5G = 0.2W
- 87 Mio Inhabitents in Germany do a cell call at the same time = 16.4MW
- 60,7 Millionen vehicles (Jan 2024)
- Imagine all are BEVs and 10%driving at the same time
- operating up to 850 V / 450 A peak
- f = 5kHz … 200kHz



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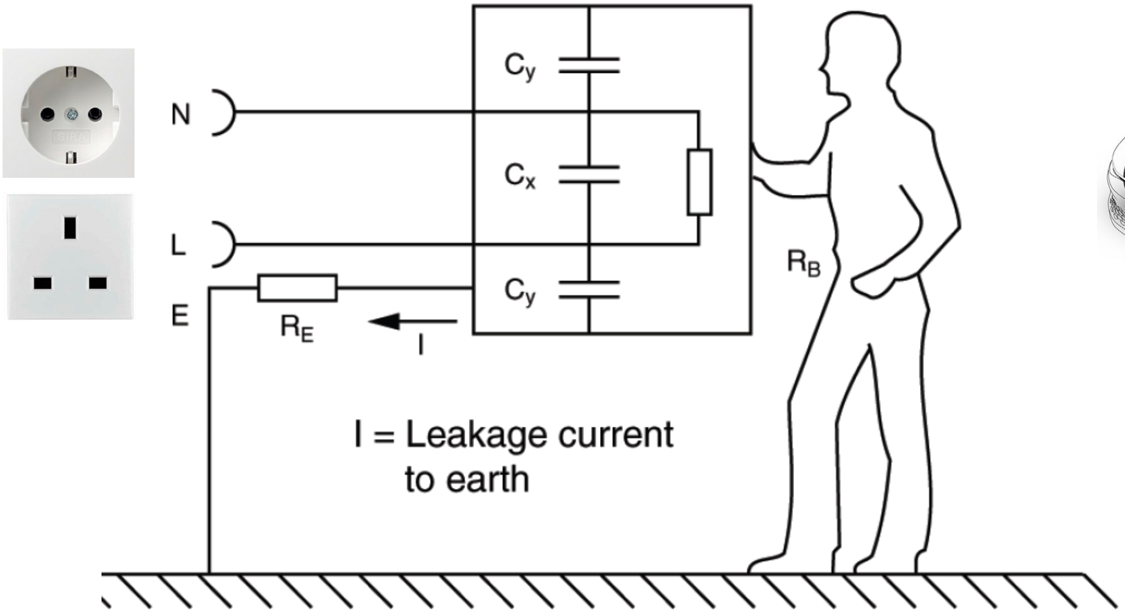
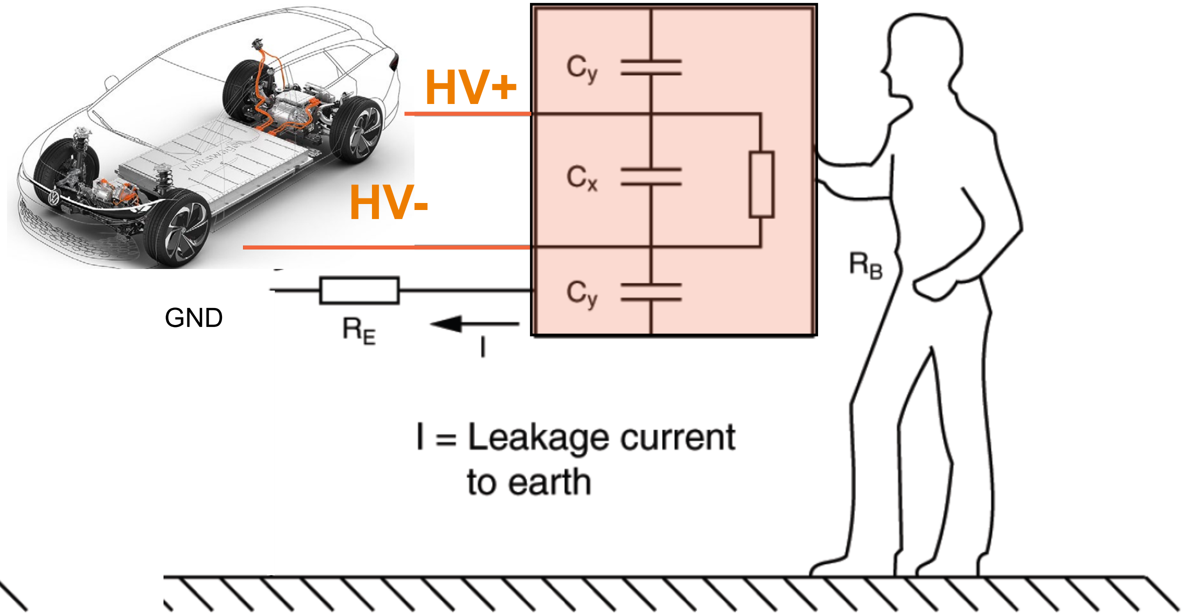
What is behind TESLA?

What is an EMI or X/Y capacitor ?

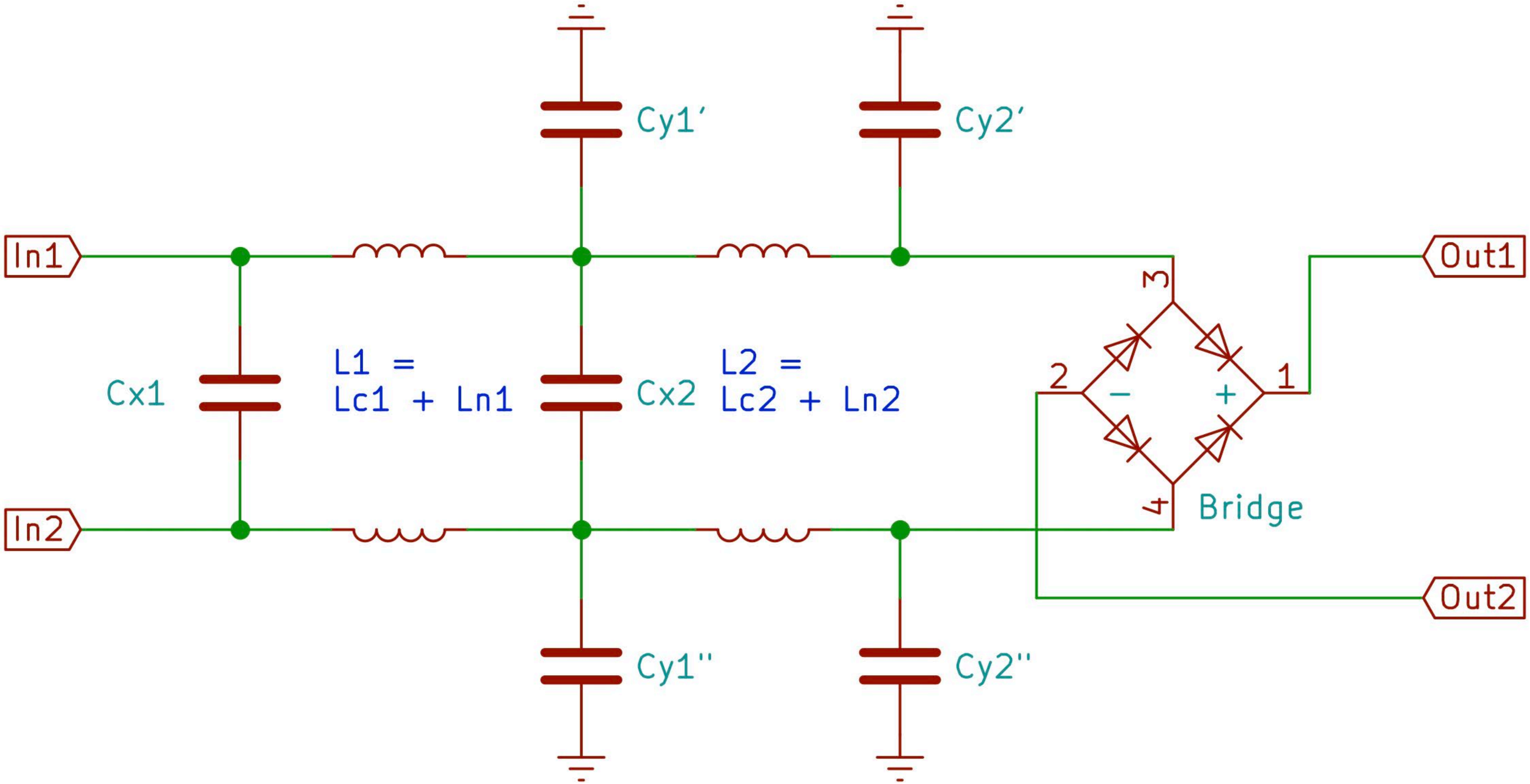
- aka “Funkentstörer”, Safety capacitor, IEC60384-14, Y-Capacitor, X-Capacitor
- Use in grid applications (230VAC, 110VAC) and BEV (400V/800V)
- was originally developed catching transients not for DC

AC (Grid)	DC (BEV)





EMI Filter



Cy1′
Cy2′
In1
Out1
3
L1 =
Lc1 + Ln1
L2 =
Lc2 + Ln2
2
1
Cx1
Cx2
−
+
4
Bridge
In2
Out2
Cy1''
Cy2''

Standards

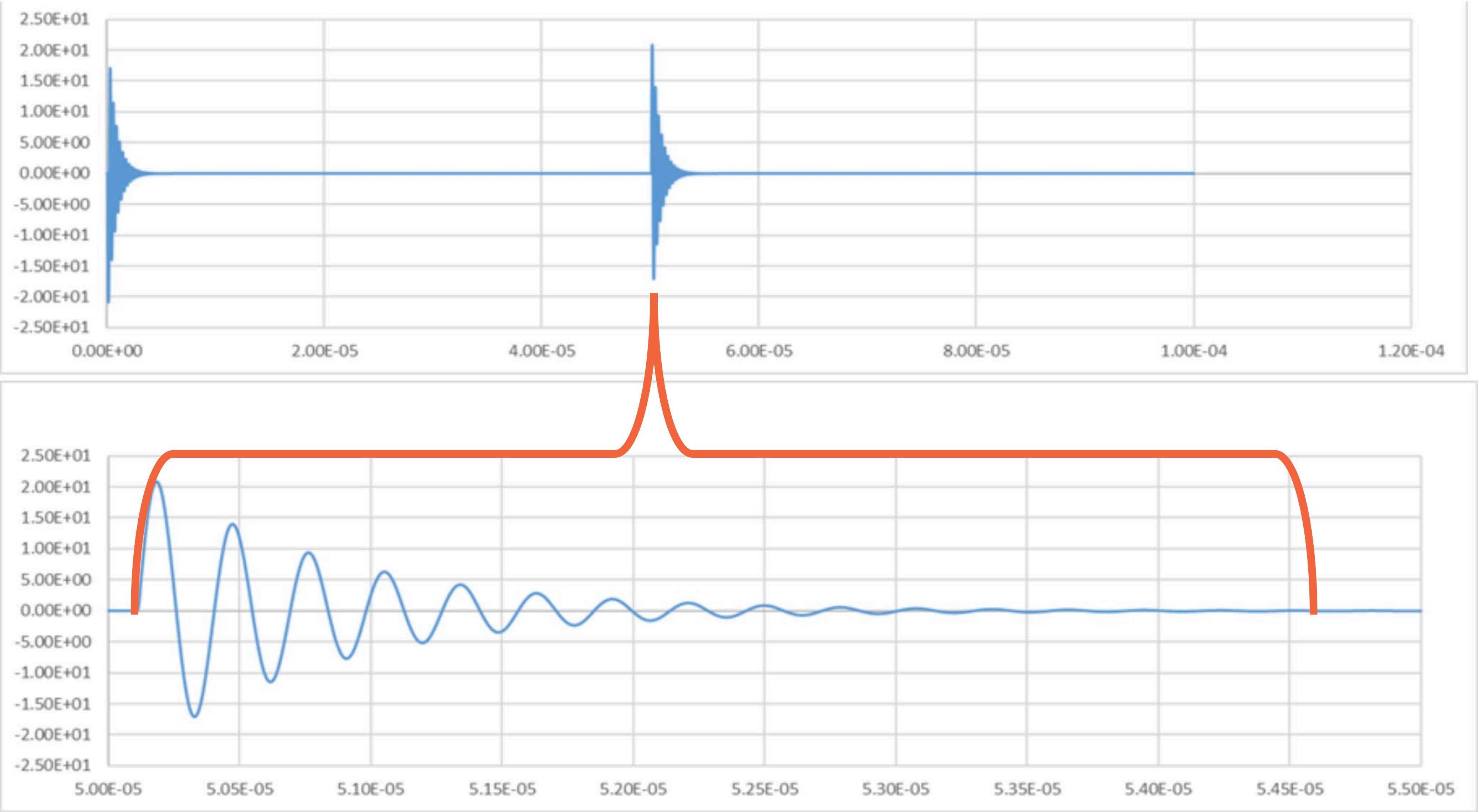
- Capacitance is defined 1kHz / 1Vrms **no** DC-bias
- DF is also defined at 1kHz
- ESR is determined at 100kHz
- There is **no** standard for ESL measurements
- Definition of inductance :
  The area inside the current loop defines inductance
  The component is only a part of the whole loop

	Frequency	Trace 1	ESR	Trace 2	ESL
Cursor 1	30 kHz	11,997 mΩ	12,142 mΩ	5,822 µH	5,813 µH
Cursor 2	200 kHz	8,918 mΩ	5,75 mΩ	124,848 nH	125,358 nH
Cursor 3	500 kHz	11,011 mΩ	10,381 mΩ	15,05 nH	15,353 nH
Cursor 4	1 MHz	14,432 mΩ	14,253 mΩ	264,714 pH	72,002 pH

Why low ESL an

- Film capacitor widely used for DC-Link capacitors, Snubber and X/Y caps
- ESL cause
  - Impact filter performance due shift of resonance frequency
  - Ringing in switched application (Inverter, PFC)

Ringing $I = f(t)$

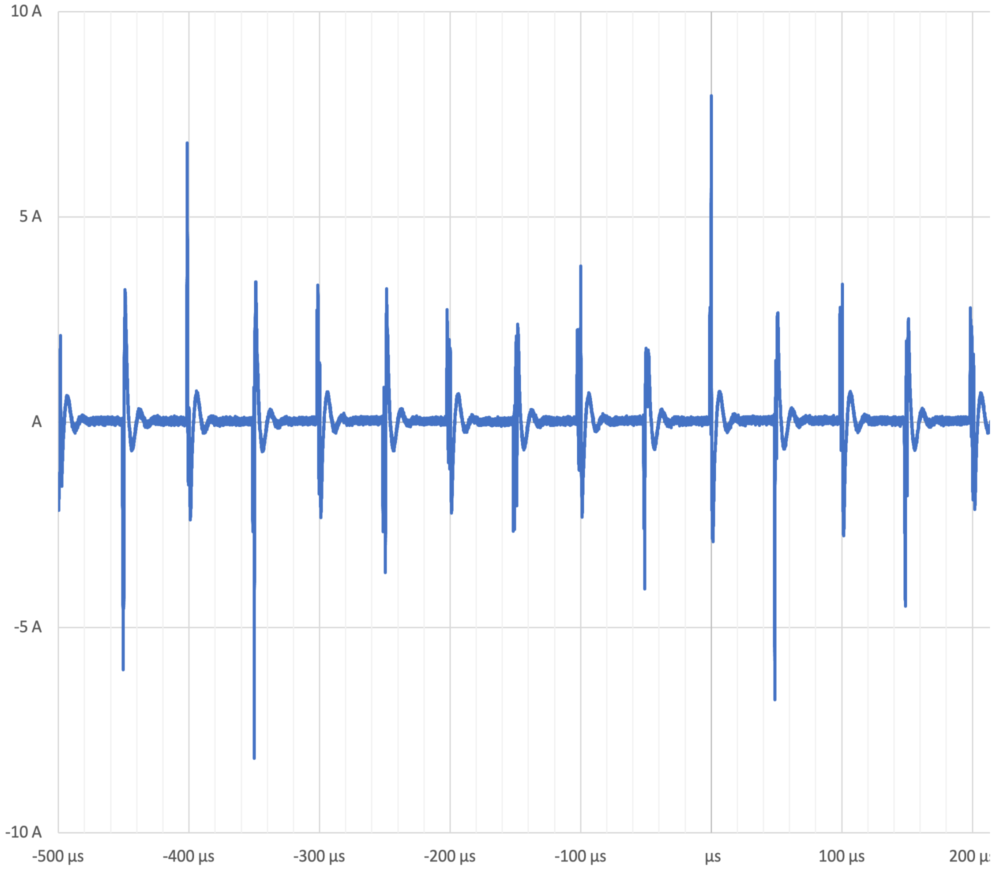


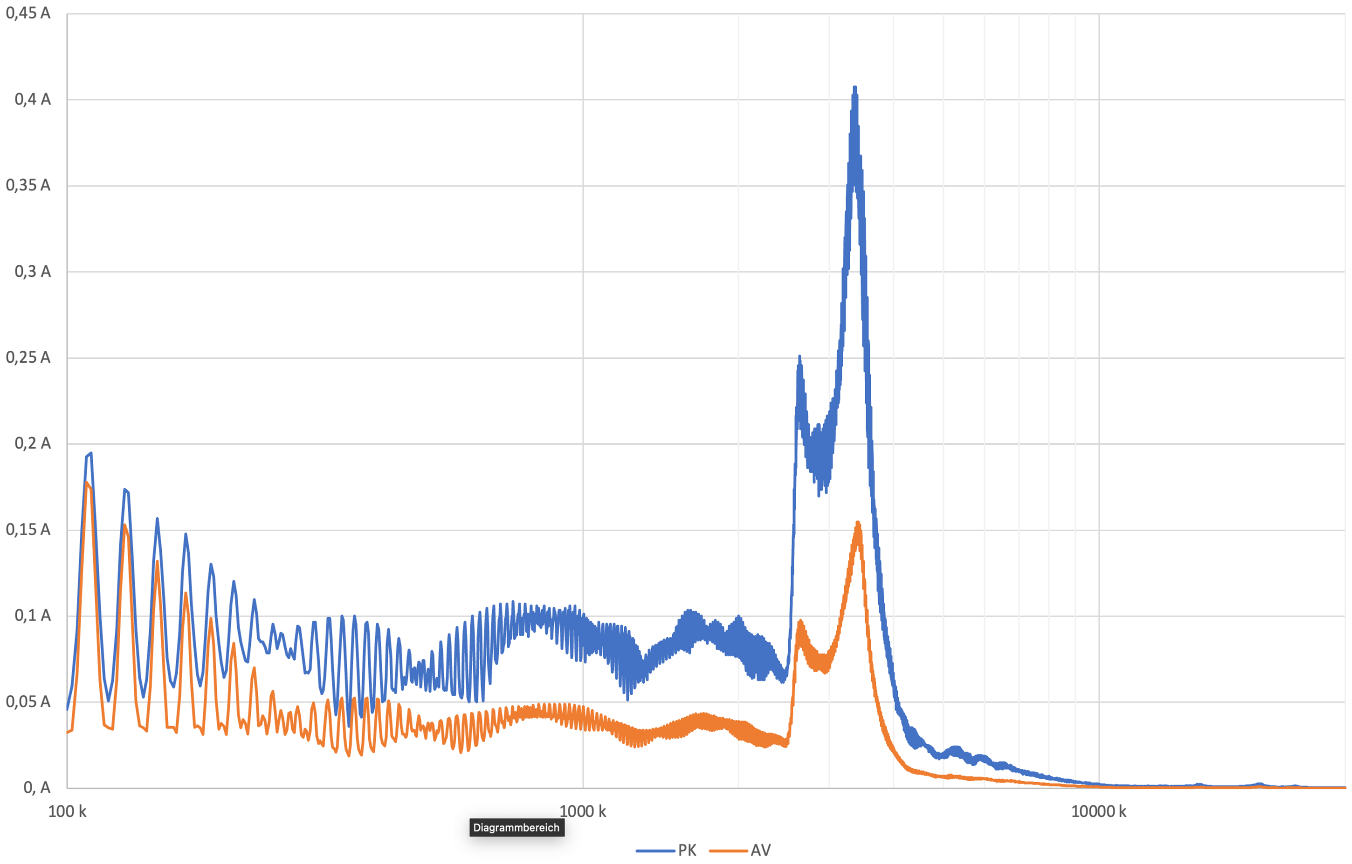
2.50E+01
2.00E+01
1.50E+01
1.00E+01
5.00E+00
0.00E+00
-5.00E+00
-1.00E+01
-1.50E+01
-2.00E+01
-2.50E+01
0.00E+00
2.00E-05
4.00E-05
6.00E-05
8.00E-05
1.00E-04
1.20E-04
2.50E+01
2.00E+01
1.50E+01
1.00E+01
5.00E+00
0.00E+00
-5.00E+00
-1.00E+01
-1.50E+01
-2.00E+01
-2.50E+01
5.00E-05
5.05E-05
5.10E-05
5.15E-05
5.20E-05
5.25E-05
5.30E-05
5.35E-05
5.40E-05
5.45E-05
5.50E-05

Ripple current : time variant and frequency domain

$$dT = I_{rms}^{2} \cdot ESR(f,T) \cdot R_{th}$$

I_rms Total	I_rms 7 Harmonics	Relation
2,622A	0,3355	13,5%





Film Construction

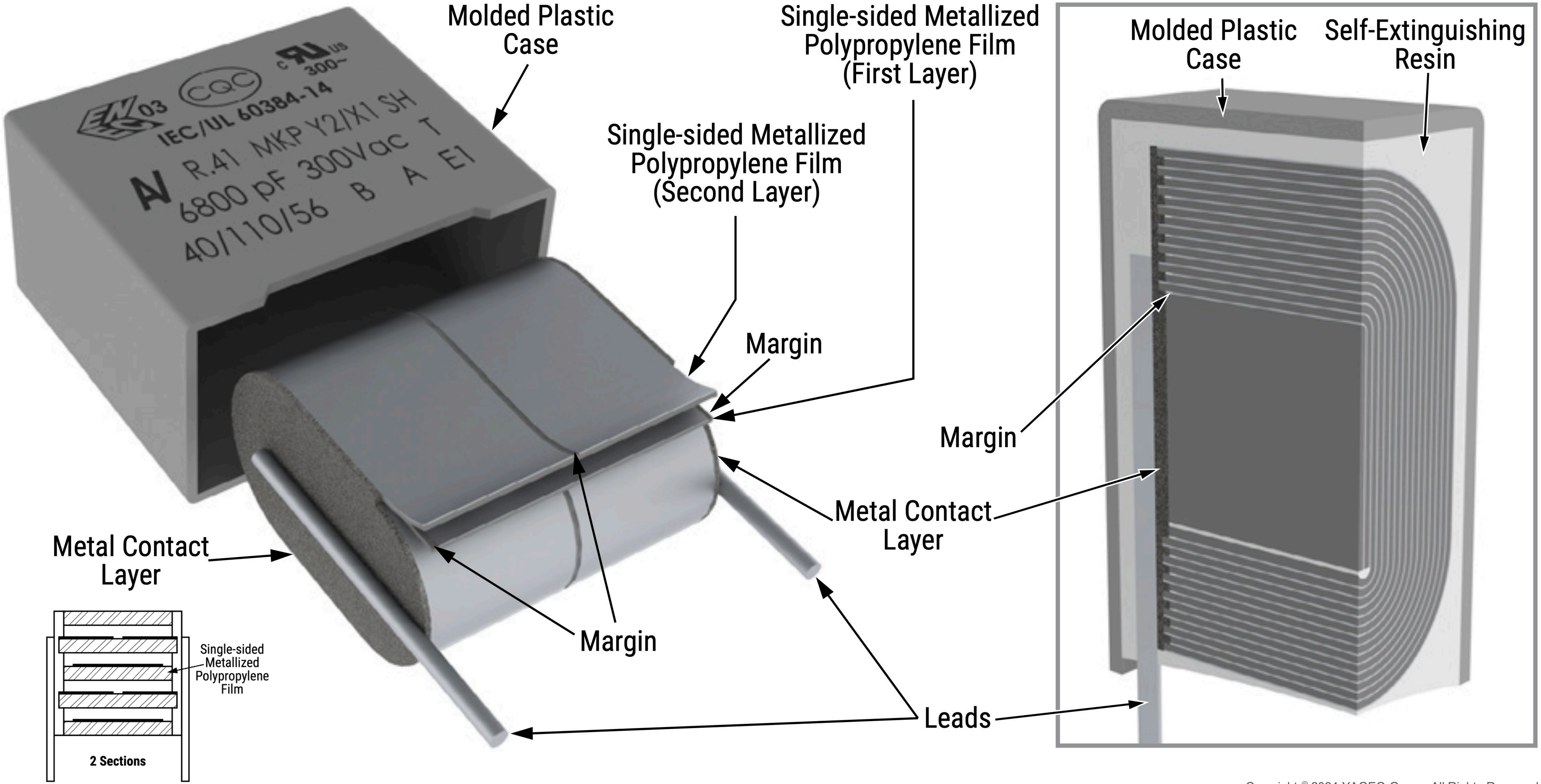
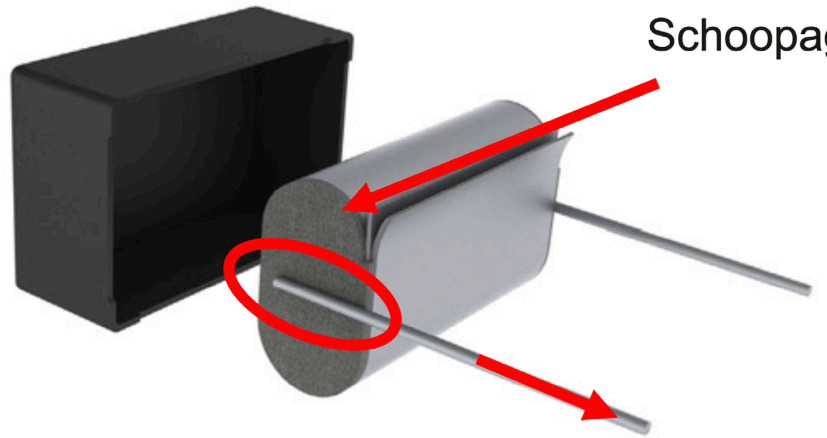


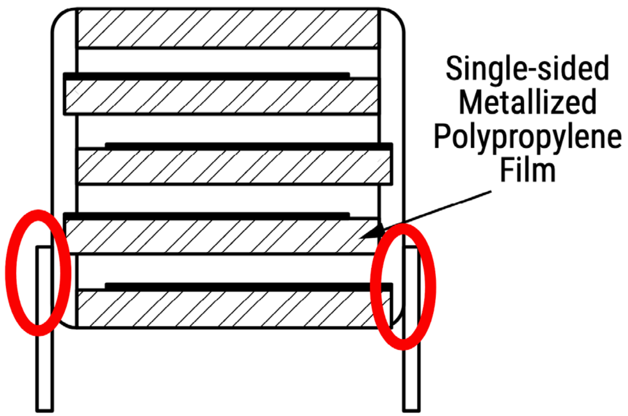
Table 1 – Ratings & Part Number Reference cont.

Cap Value (µF)	VDC	Dimensions (mm)					dV/dt	Ipkr	ESL	ESR 70°C at 10 kHz	Irms* 70°C at 10 kHz	Rth (HS/Amb)	Packaging Quantity	PART NUMBER
		T	H	L	S	S1	V/µs	Apk	nH	mΩ	Arms	(°C/W)		
V_{NDC} at 70°C = 1,100 VDC; V_{OP85} at 85°C = 900 VDC; V_{OP105} at 105°C = 700 VDC														
1.5	1,100	11	20	31.5	27.5	\	24	36	17	26.3	4.8	44	256	C4AQQBU4150A1WJ
2.7	1,100	13	25	31.5	27.5	\	24	65	22	15.3	6.9	36	234	C4AQQBU4270A1XJ
3.3	1,100	14	28	31.5	27.5	\	24	79	24	12.9	7.9	33	96	C4AQQBU4330A1YJ
5	1,100	19	29	31.5	27.5	\	24	120	25	9.1	10.1	29	72	C4AQQBU4500A11J
8	1,100	22	37	31.5	27.5	\	24	193	28	6.6	12.6	23	64	C4AQQBU4800A12J
12	1,100	20	40	42	37.5	10.2	16	190	12	6.3	14.4	20	58	C4AQQBW5120A3FJ
14	1,100	28	37	42	37.5	10.2	16	229	10	5.4	16.3	18	36	C4AQQBW5140A3JJ

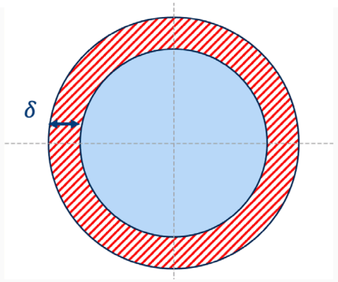
ESR impact by Wires – 0.8mm, 1.0mm and 1.2mm

- Loss in transition of Schoopage layer
- Additional loss due increasing resistance in lead wire due skin effect at higher frequencies





$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f}}$$



Wire diameter

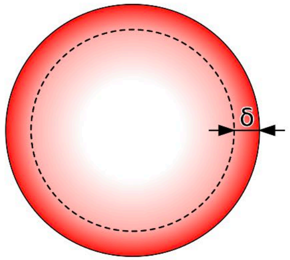
$$I_p = C \cdot \frac{dV}{dt}$$

$$P = \int_0^{t_r} I^2 \cdot ESR + \int_{t_f}^{t_{period}} I^2 \cdot ESR$$

Skin effect on Cu wires

- At 500kHz the x-section is only a half

$$\delta = \sqrt{\frac{2 \cdot \rho}{\omega\mu}}$$



$\delta = deepth\ of\ material$

$\rho = specific\ resistance$

$\omega = angular\ frequency = 2\pi\ freq$

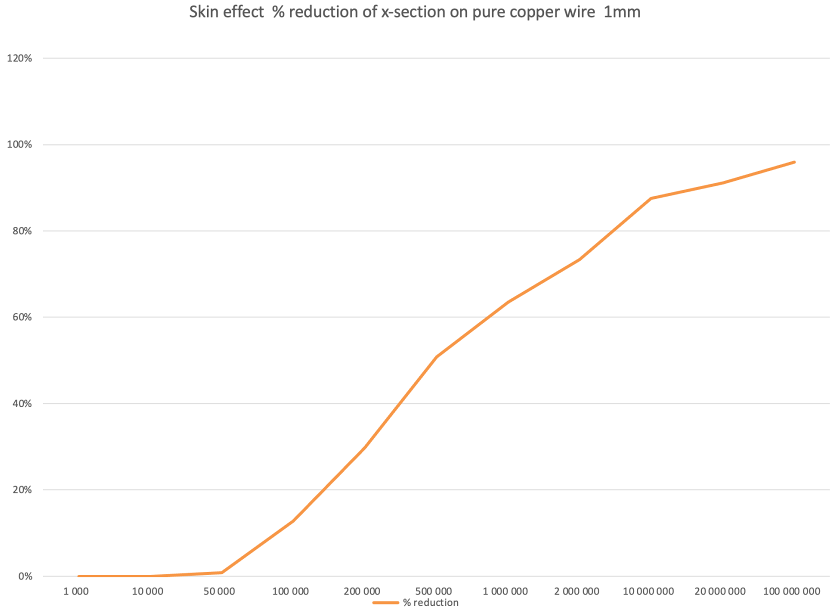
$\mu = permeability$

$$A = \pi(D^2 - (D - \delta)^2)$$

$A = wire\ cross - section$

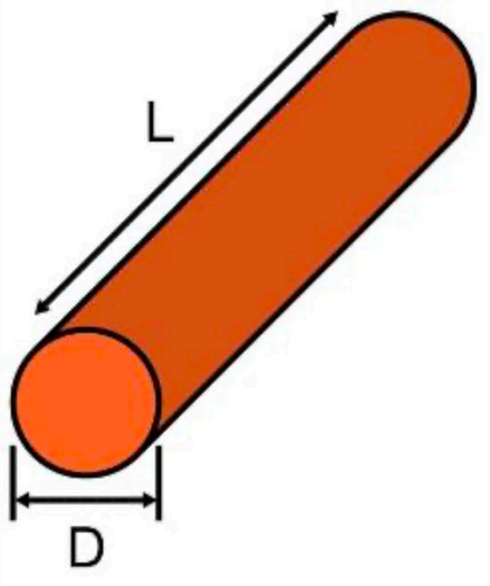
$D = wire\ diameter$

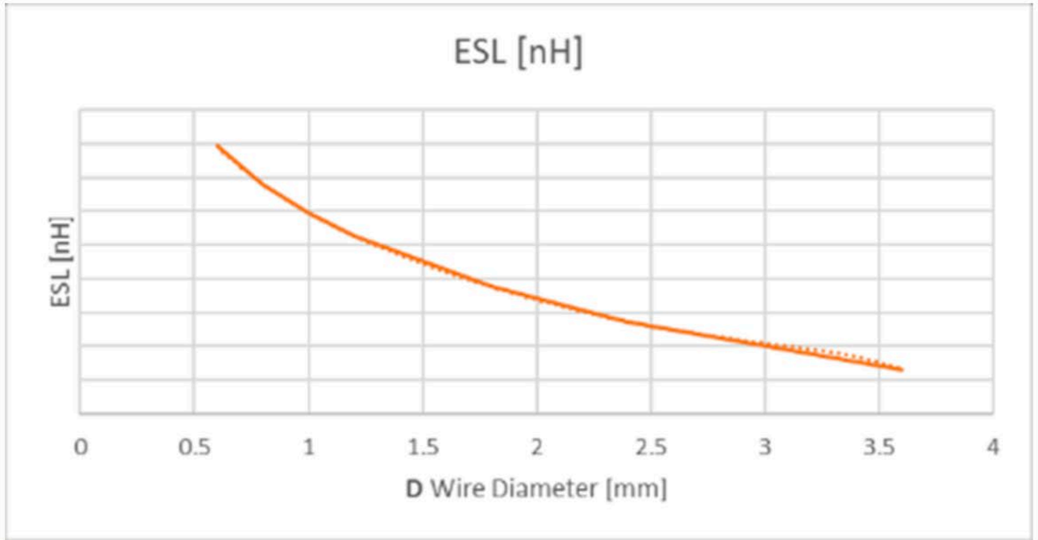
$\delta = deepth\ of\ material$

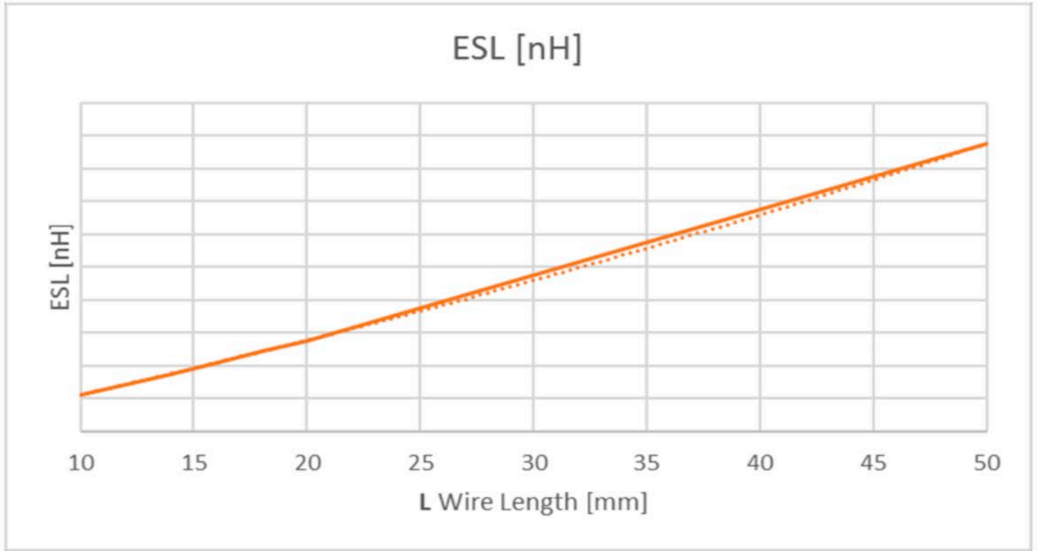


Frequency / kHz	Loss / %	Wire 1.0mm
10kHz	0%	1.0
50kHz	15%	0.85
100kHz	32%	0.68
200kHz	48%	0.52
500kHz	65%	0.45

ESL Value cersus Wire Ø and length







Specimen for our test

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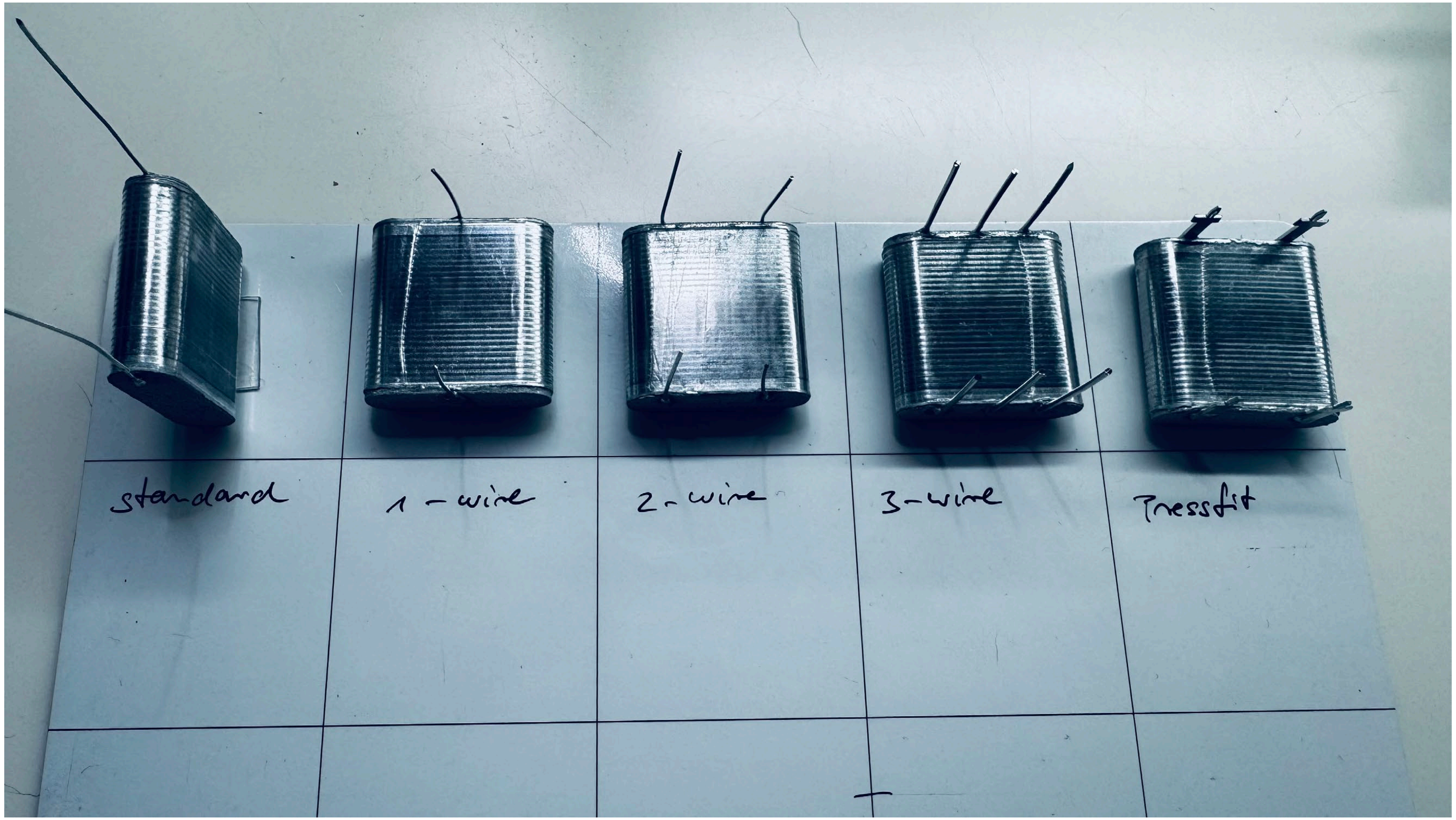
Wirethickness	0.8	1,0



Measurement Principle

$$\underline{Z} = \frac{\underline{U}}{\underline{I}}$$

$$\underline{Z} = |Z|\, e^{j\omega t+\varphi} \quad \varphi = arctan\left(\frac{X}{R}\right)$$

$$\underline{Z} = |Z|\left(cos(\varphi) + j\, sin(\varphi)\right)$$

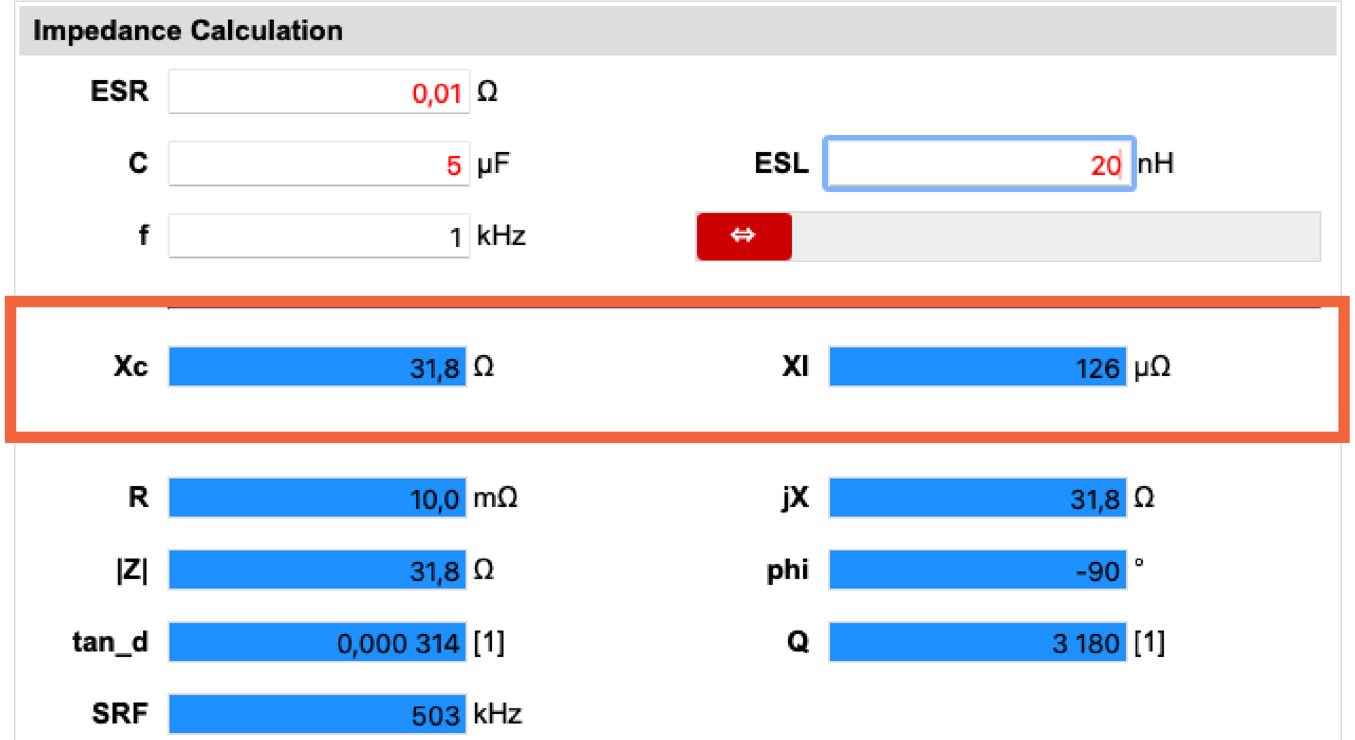
$$\underline{Z} = R + j(X_l + X_c)$$

$$3\ variables\ \ R, X_l, X_c\ \ but\ only\ two\ equations$$

$$R = |Z| \cdot cos(\varphi)$$

$$X = |Z| \cdot sin(\varphi)\ with\ X = X_l + X_c$$

Does it matter? C = 5µF, ESL = 20nH



	Xl	Xc
1kHz	0.000126	31.8
10kHz	0.00126	3.18
100kHz	0.0126	0.318
1MHz	0.126	0.0318

What we all know ..

- Real capacitor has **capacitance**, **resistance** & **inductance**

$$|Z| = \sqrt{ESR^2 + j\left(2 * \pi * f * L - \frac{1}{2 * \pi * f * C}\right)^2}$$

- ESL depends on length and width of the chip size
- ESL impacts the Self Resonance Frequency

$$SRF = \frac{1}{2 * \pi * \sqrt{L * C}}$$

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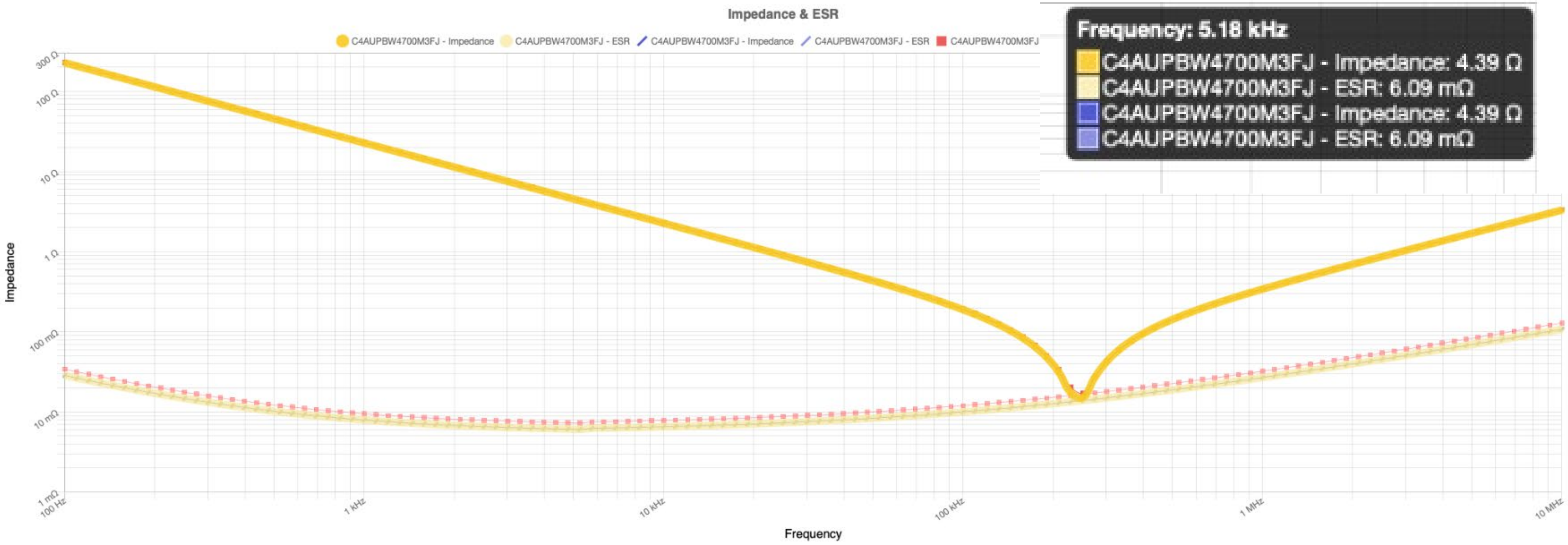
Where to start



Info	Legend	Tolerance	Part Number	Cap.	V_{DC}*	Dielectric	Qty.	Bias (V)	Amb. (°C)	Add	Remove
	●	n/a	**C4AUPBW4700M3FJ**	**7 uF**	**1200**	**PP**	1	0	25	+	✕
›	/	n/a	C4AUPBW4700M3FJ	7 uF	1200	PP	1	850	25		✕
	■	n/a	C4AUPBW4700M3FJ	7 uF	1200	PP	1	850	90		✕

Measurement methode PCB – criteria

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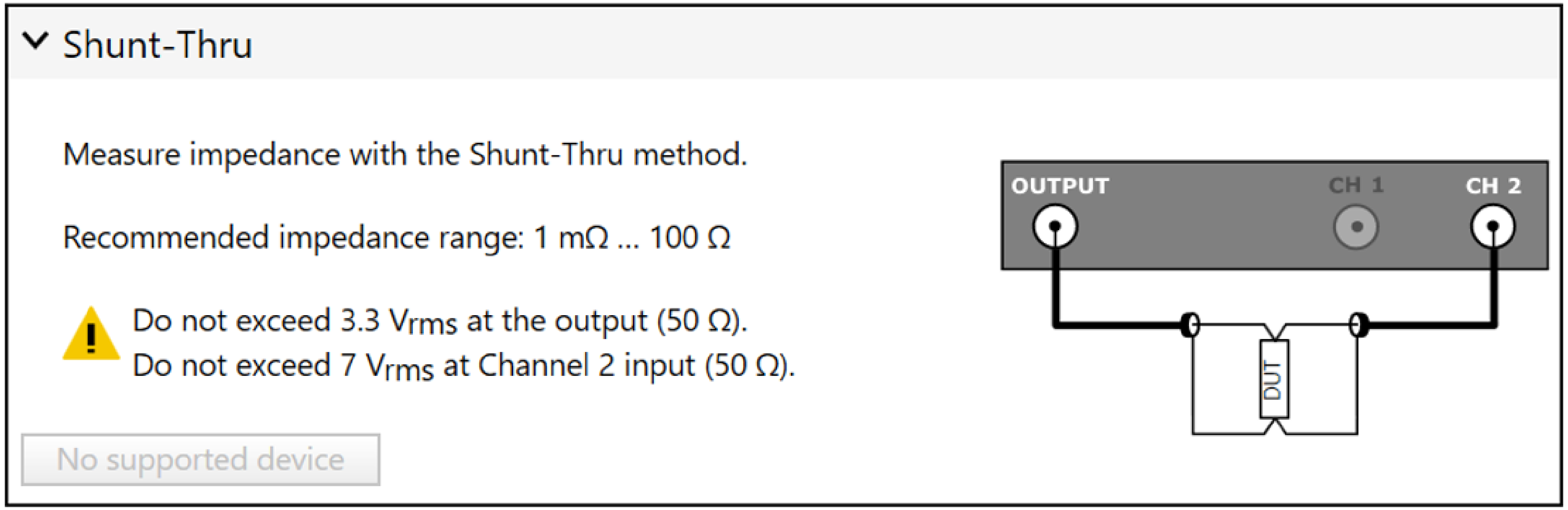
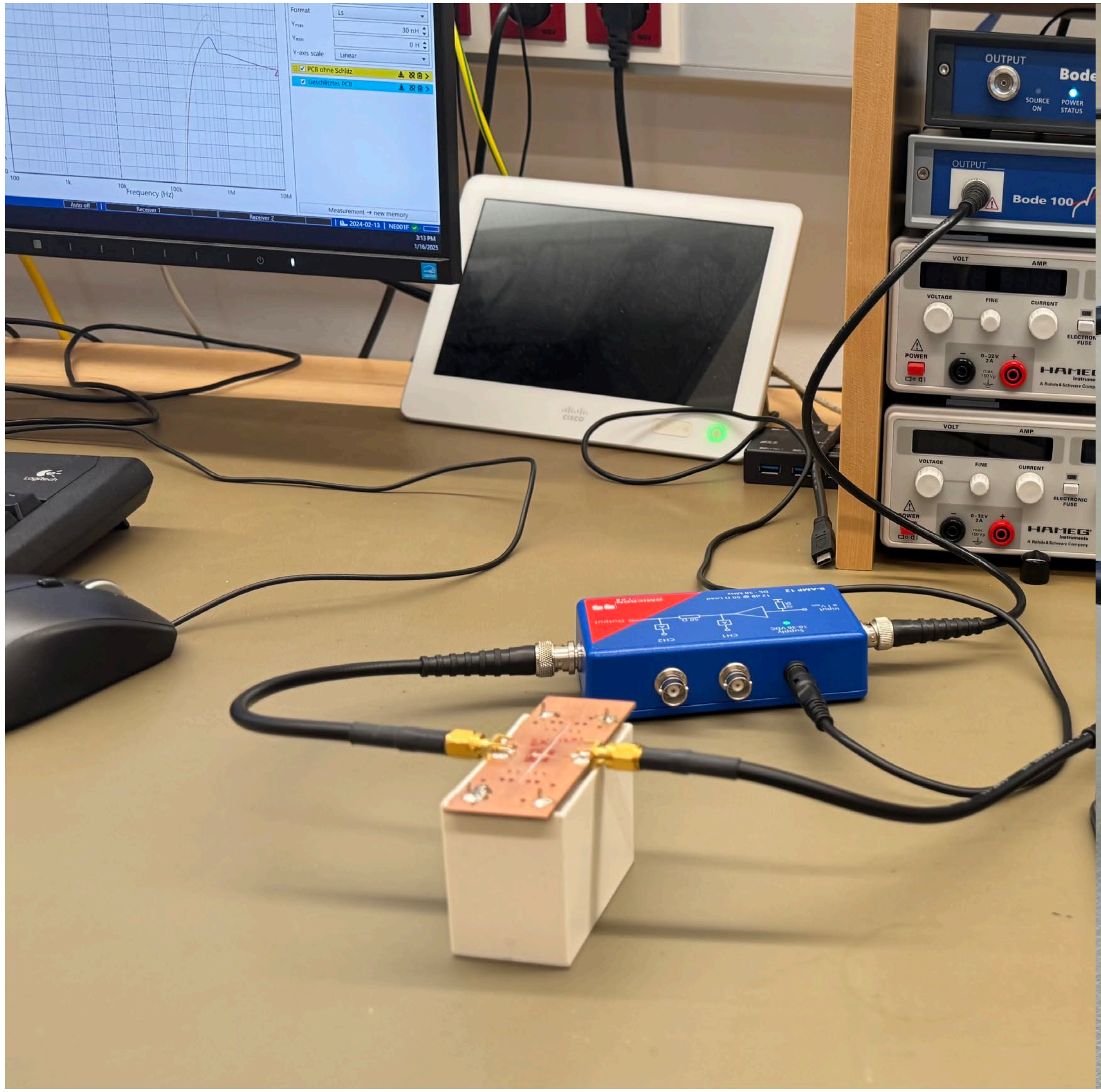
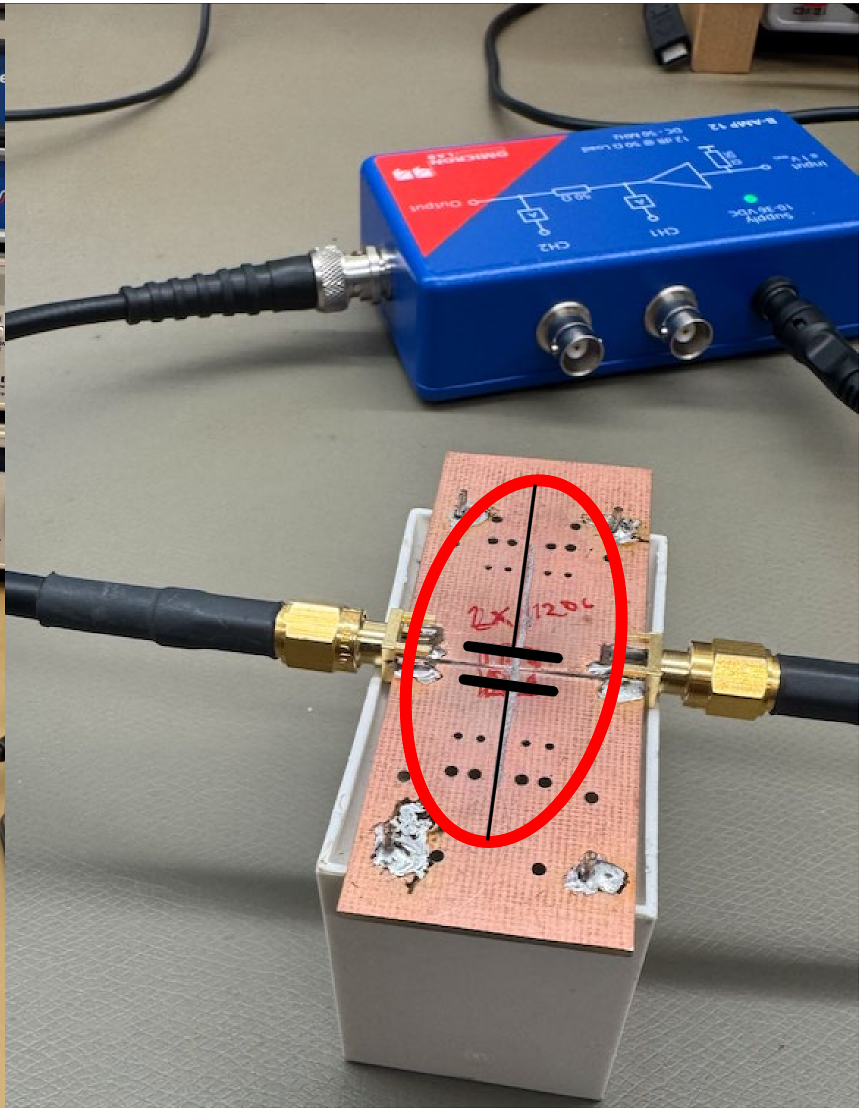
- Impedance is between 15mΩ .. 300Ω
- ESR is between 6mΩ and 100mΩ



- Z(226Hz) = 100Ω
- Z(10MHz) = 680mΩ

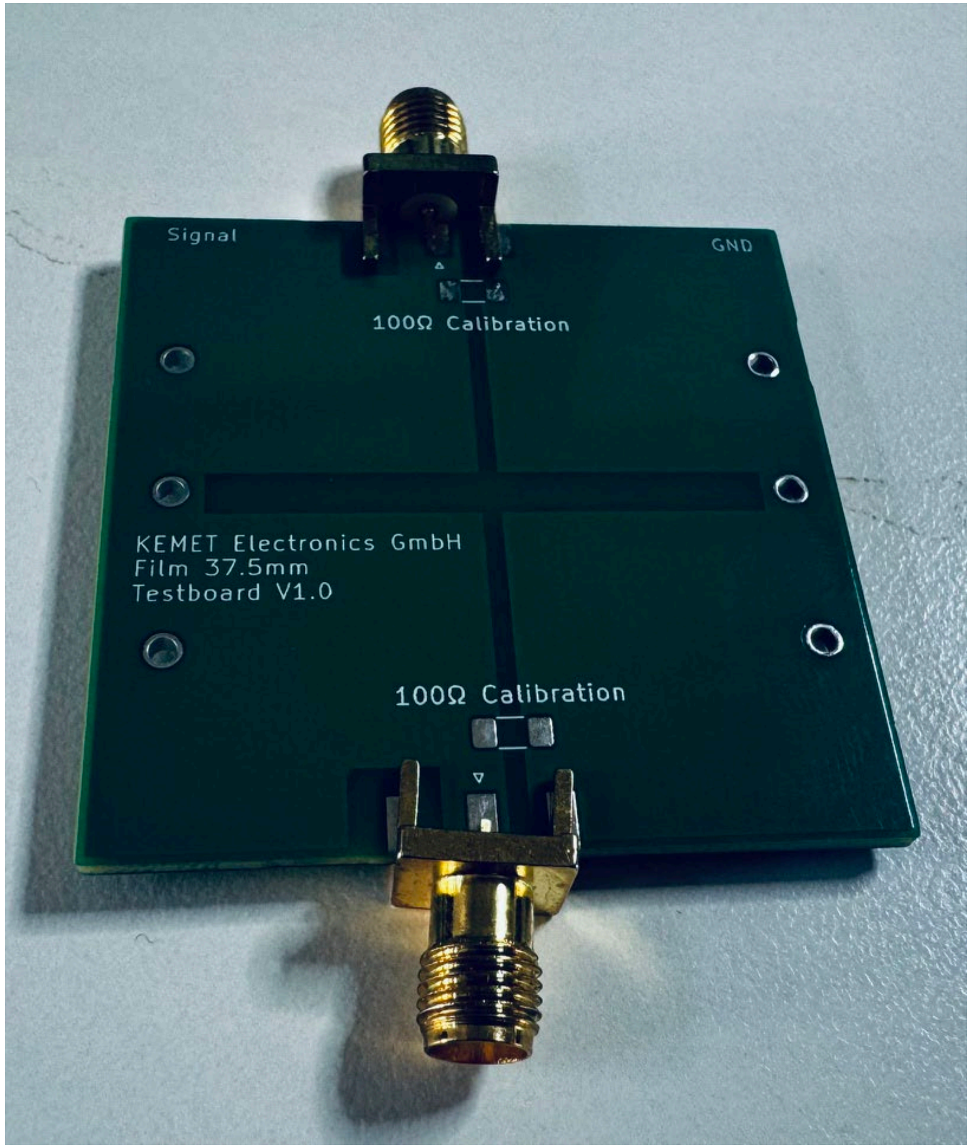
First shot





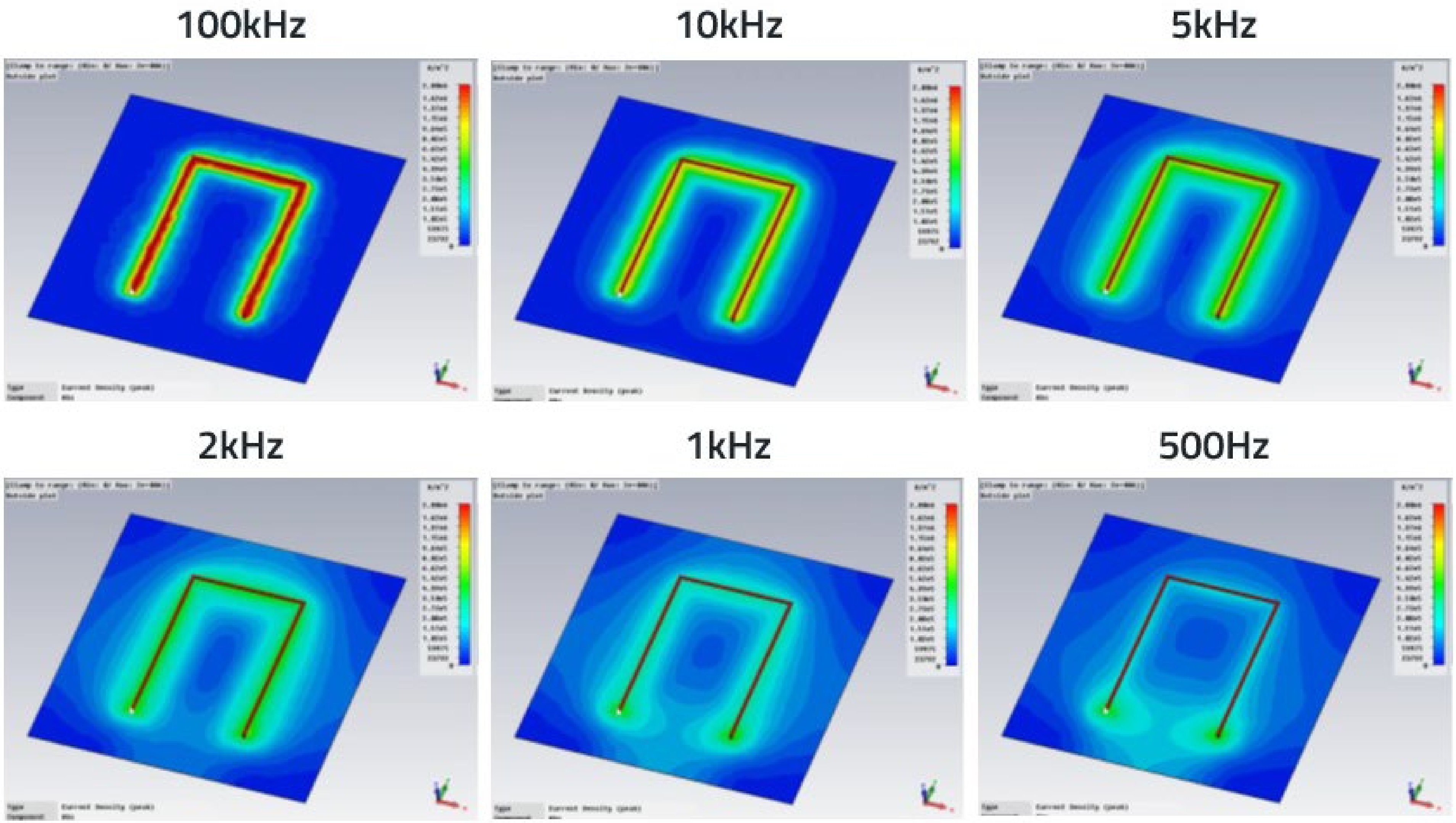
The Testboard

- Shunt-thru
- OSL (50Ω)
- Load is 2x 100Ω in parallel
- SMA – connector
- Symmetric layout

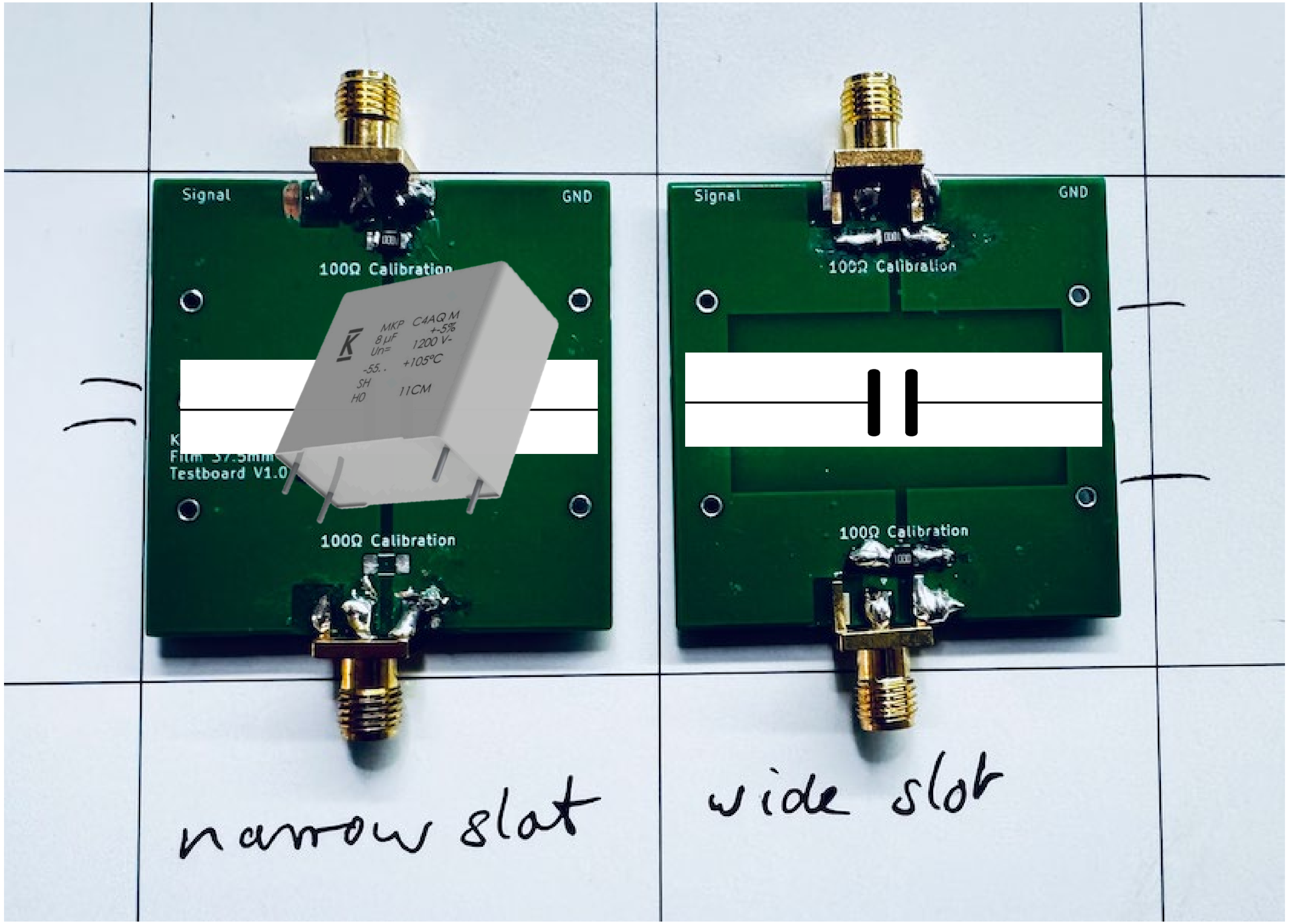


Coupling effects

Current path with a u shaped conductor simulated in CST EMS

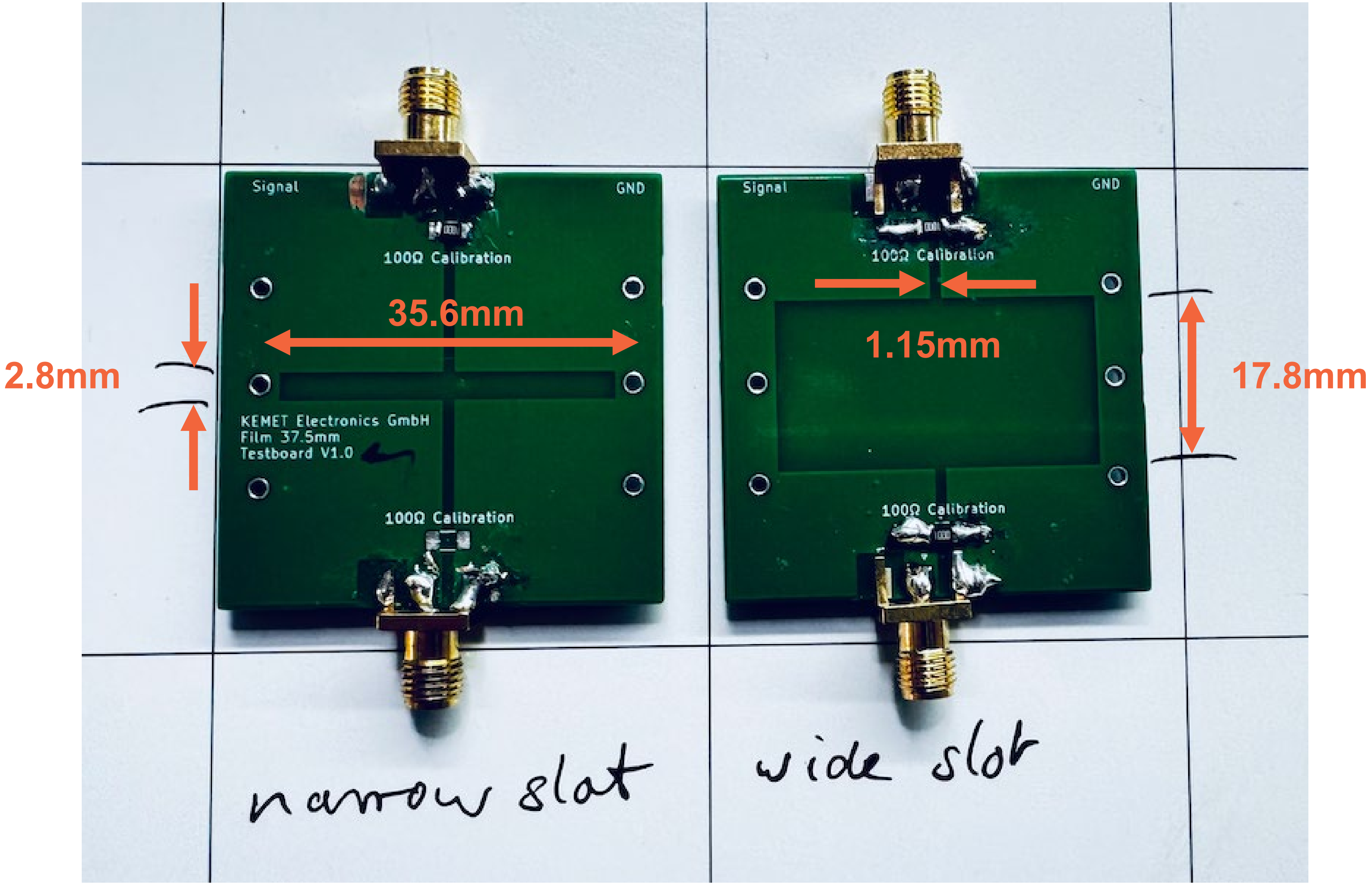


Testboards



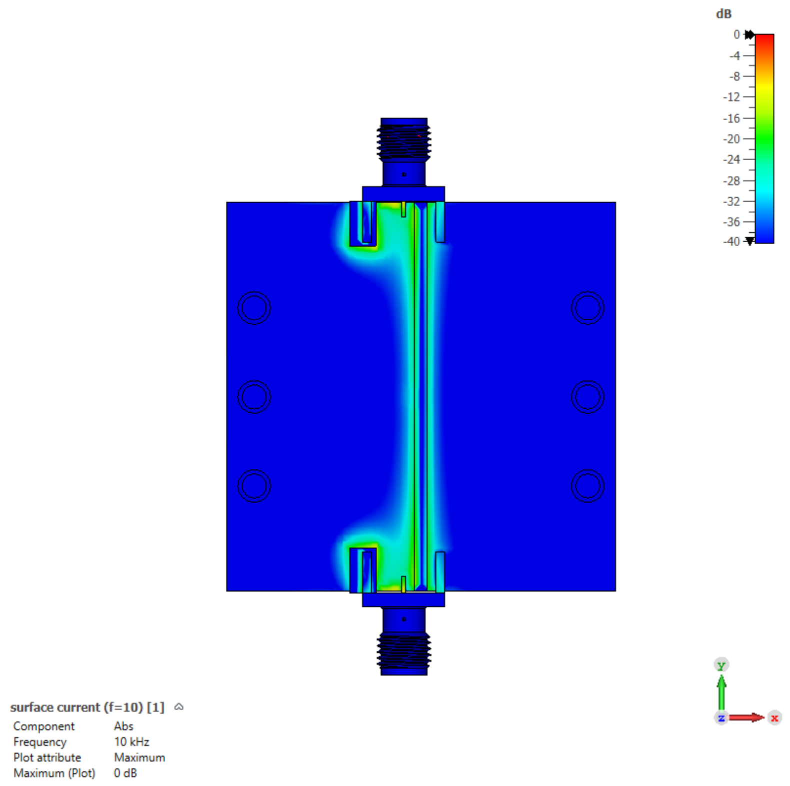
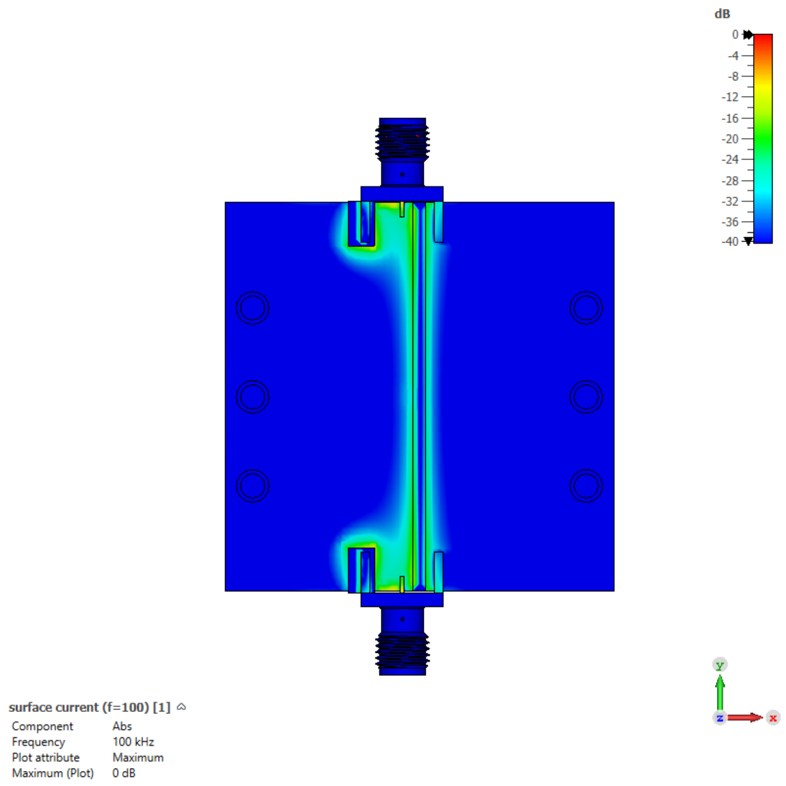
Signal
GND
100Ω Calibration
MKP C4AQ M
8 µF +-5%
Un= 1200 V-
-55.. +105°C
SH
H0 11CM
Testboard V1.0
100Ω Calibration
narrow slot
Signal
GND
100Ω Calibration
100Ω Calibration
wide slot

Testboards


Signal
GND
100Ω Calibration
35.6mm
2.8mm
KEMET Electronics GmbH
Film 37.5mm
Testboard V1.0
100Ω Calibration
narrow slot
Signal
GND
100Ω Calibration
1.15mm
17.8mm
100Ω Calibration
wide slot

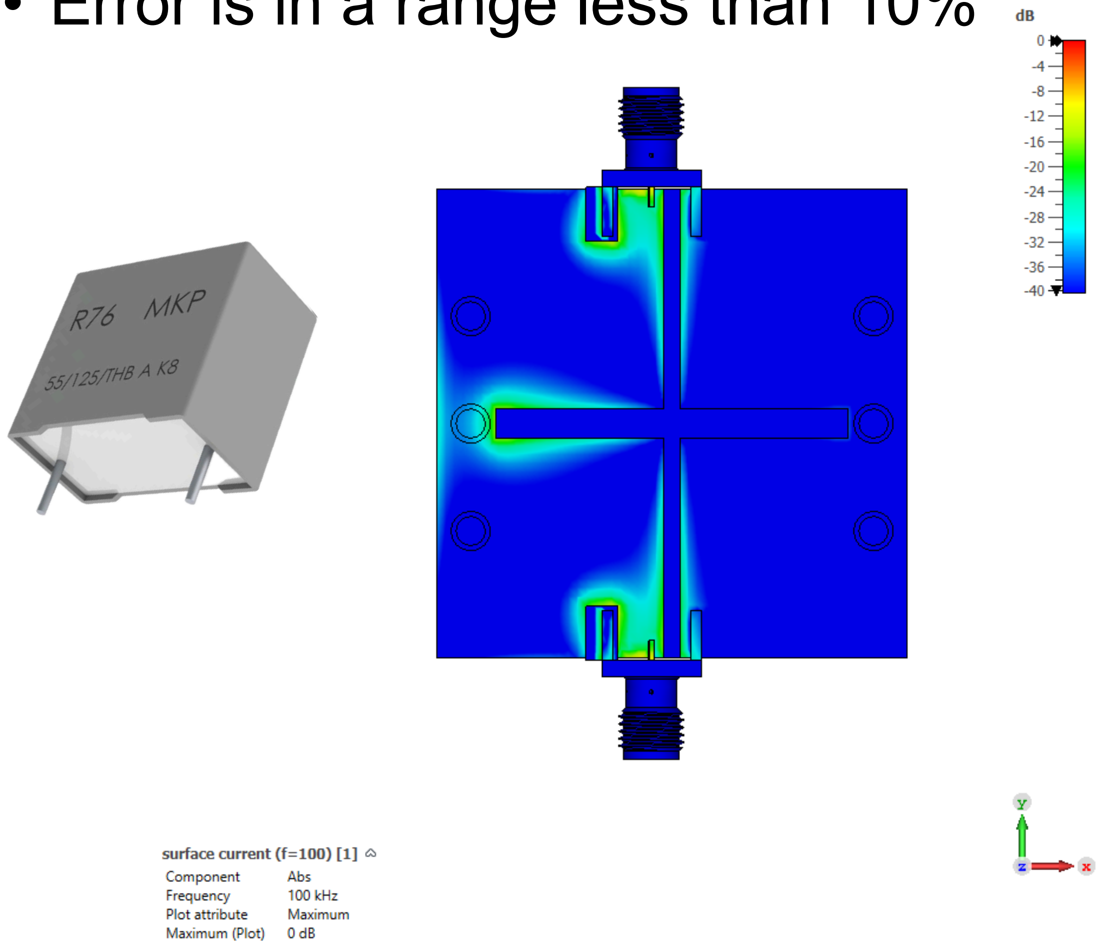
The simulation of the Test PCB

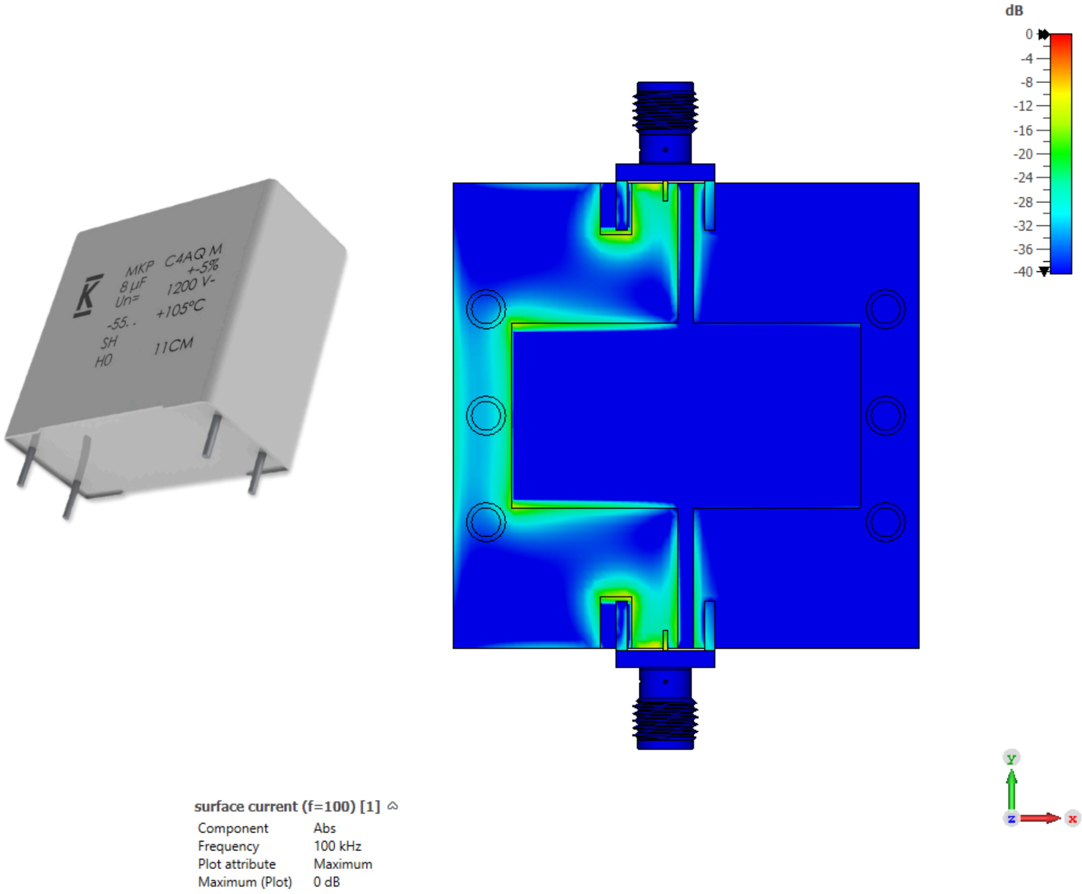
- Slot is necessary to drive the current thru the component
- Because of the dimension of the PCB the frequency doesn't really matter

10kHz	100kHz
	

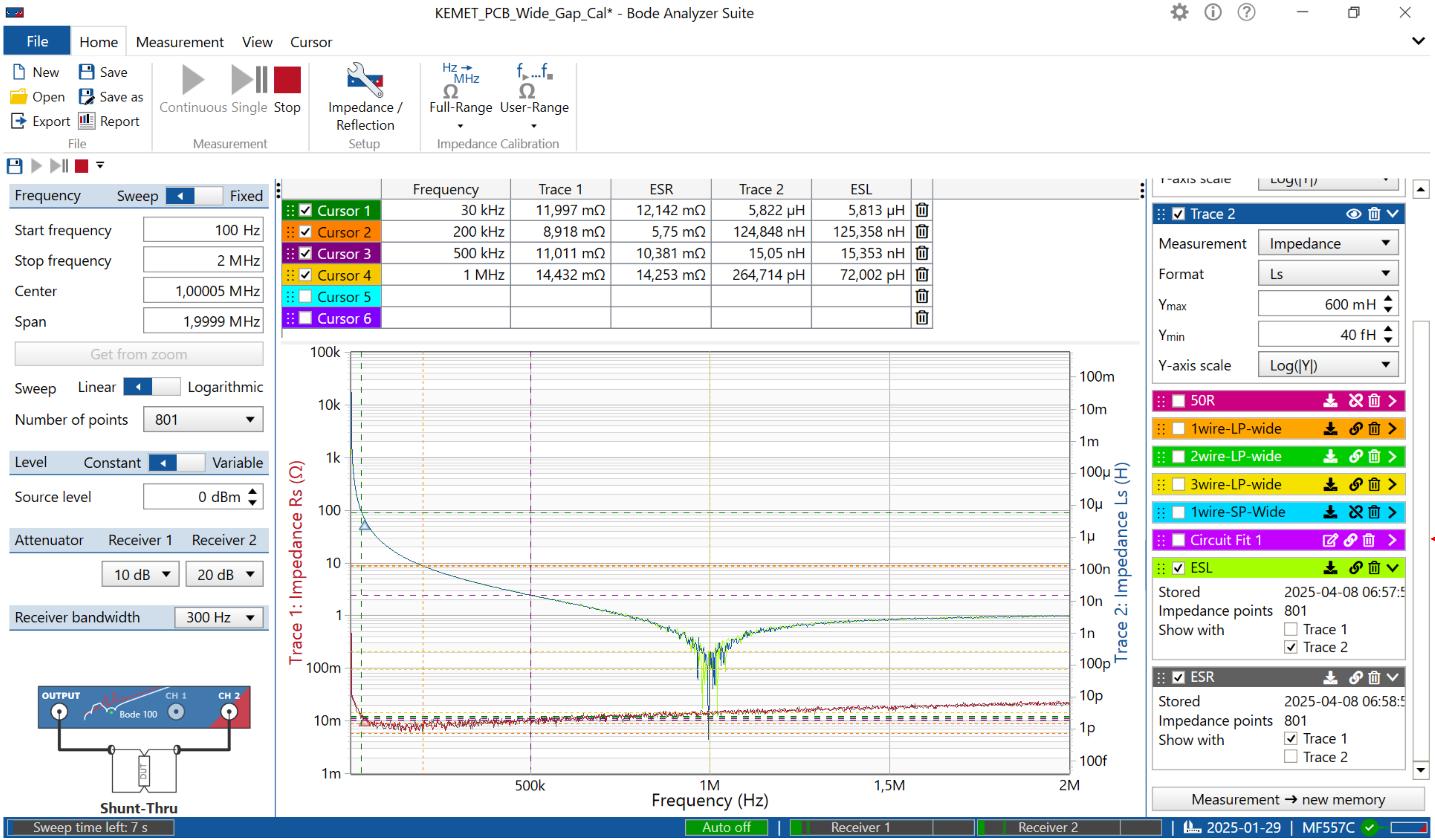
The simulation of the Test PCB (2)

- The width of the gap controls the current flow
- Adapt to the dimensiomal needs
- Error is in a range less than 10%



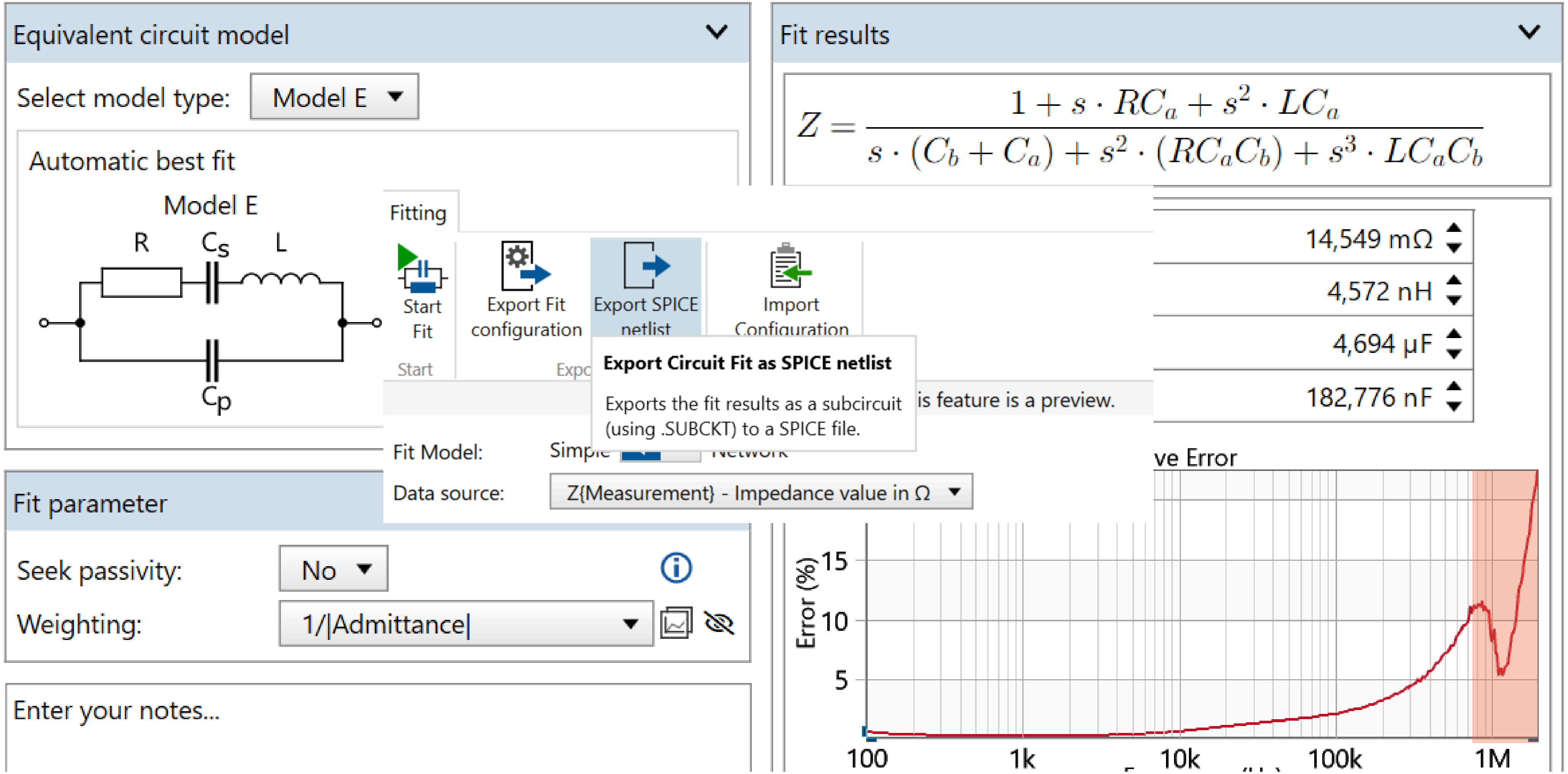


Measurement

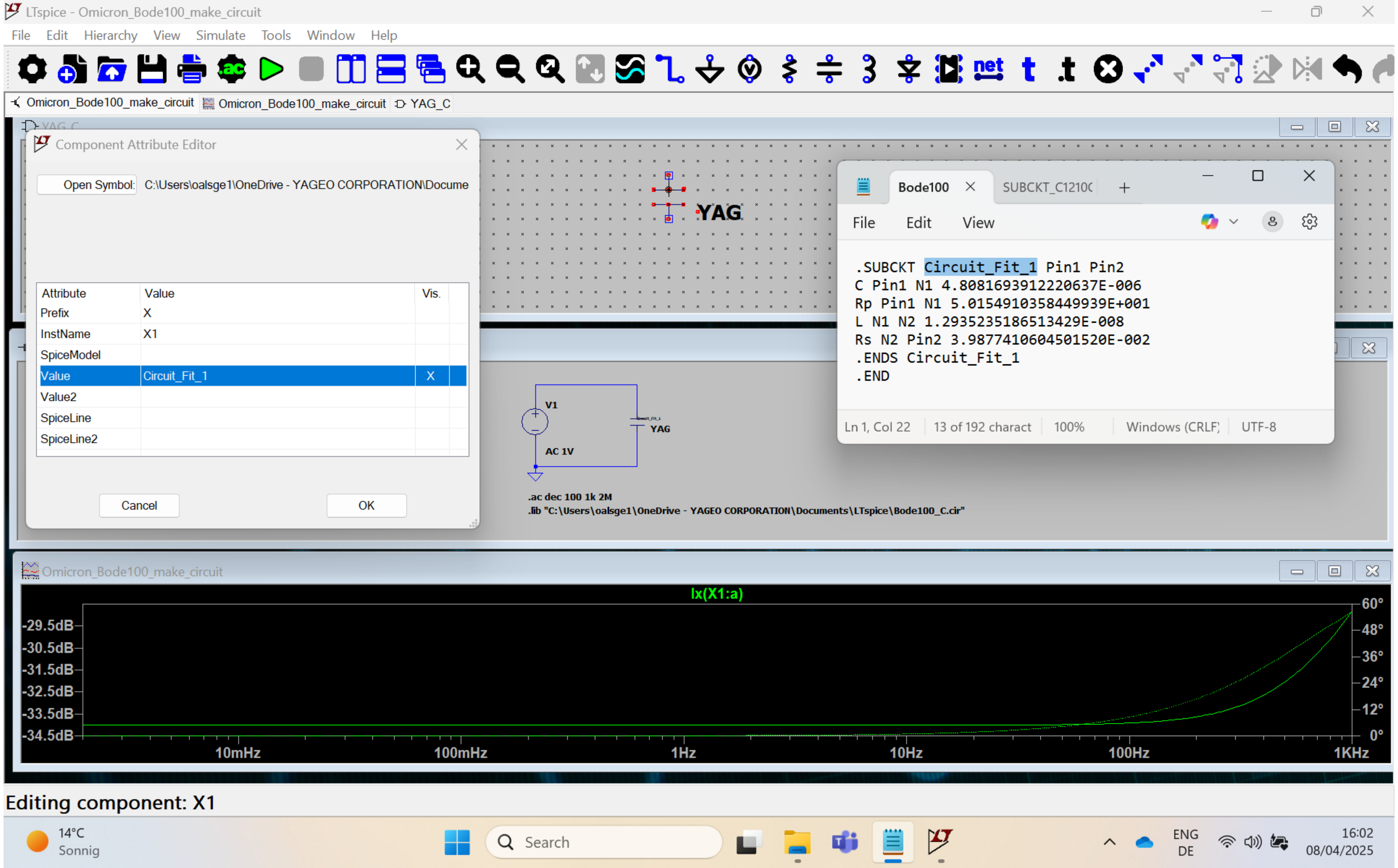


Measurement

- Try not to use beyond resonance frequency



Use in other programs



ESL reduction

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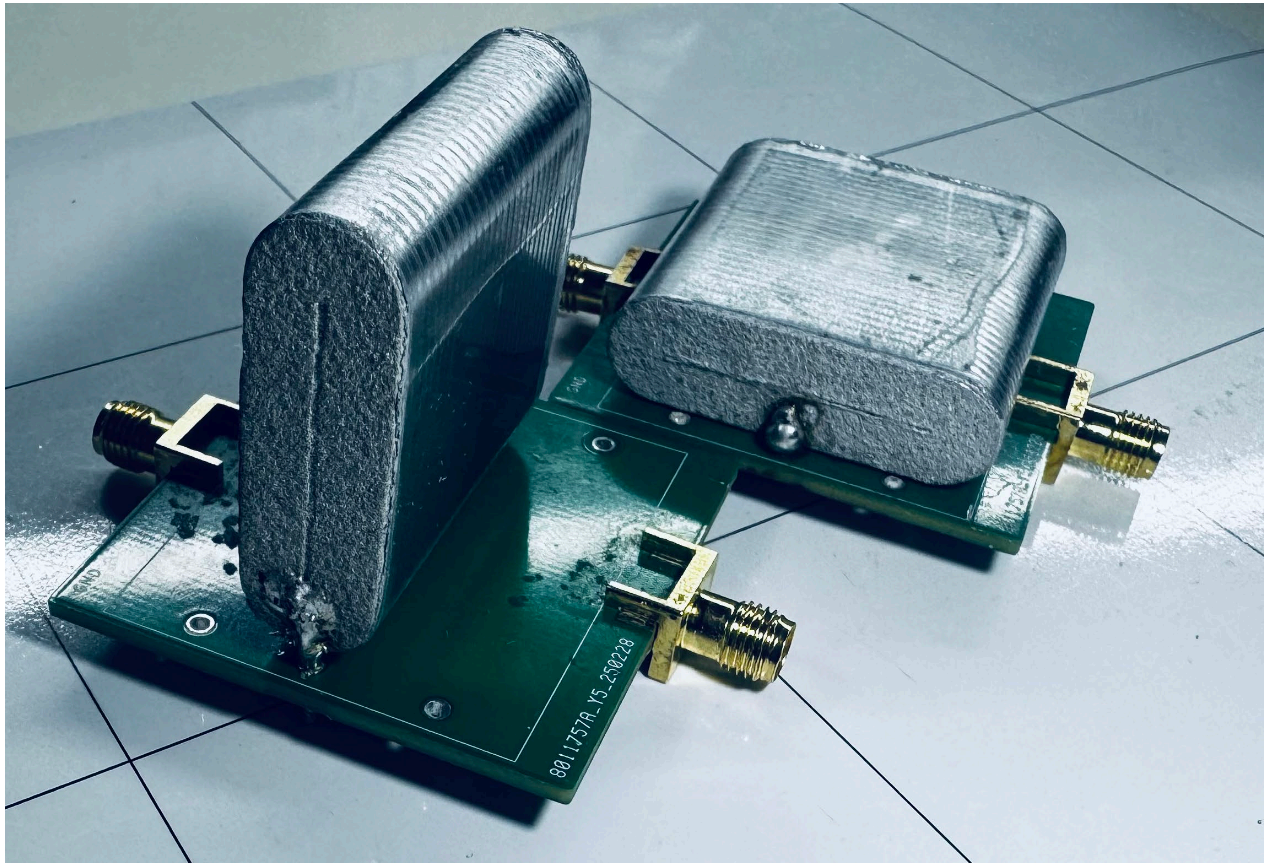
Capacitor Bobbin : 5uF 6,7um x 37,5 mm

	1 Wire/Standard Profile	1 Wire/Low Profile
ESL [nH]	12.1	5.3

56% less



Specimen for our test

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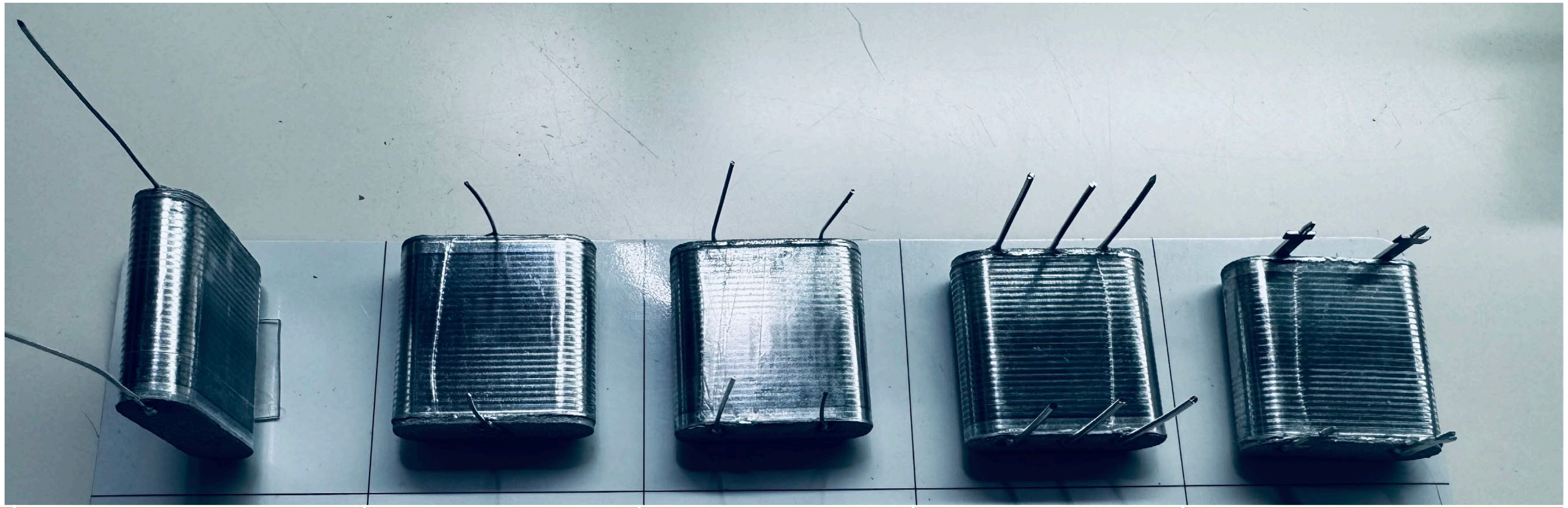
- More wires reduce ESL and ESR

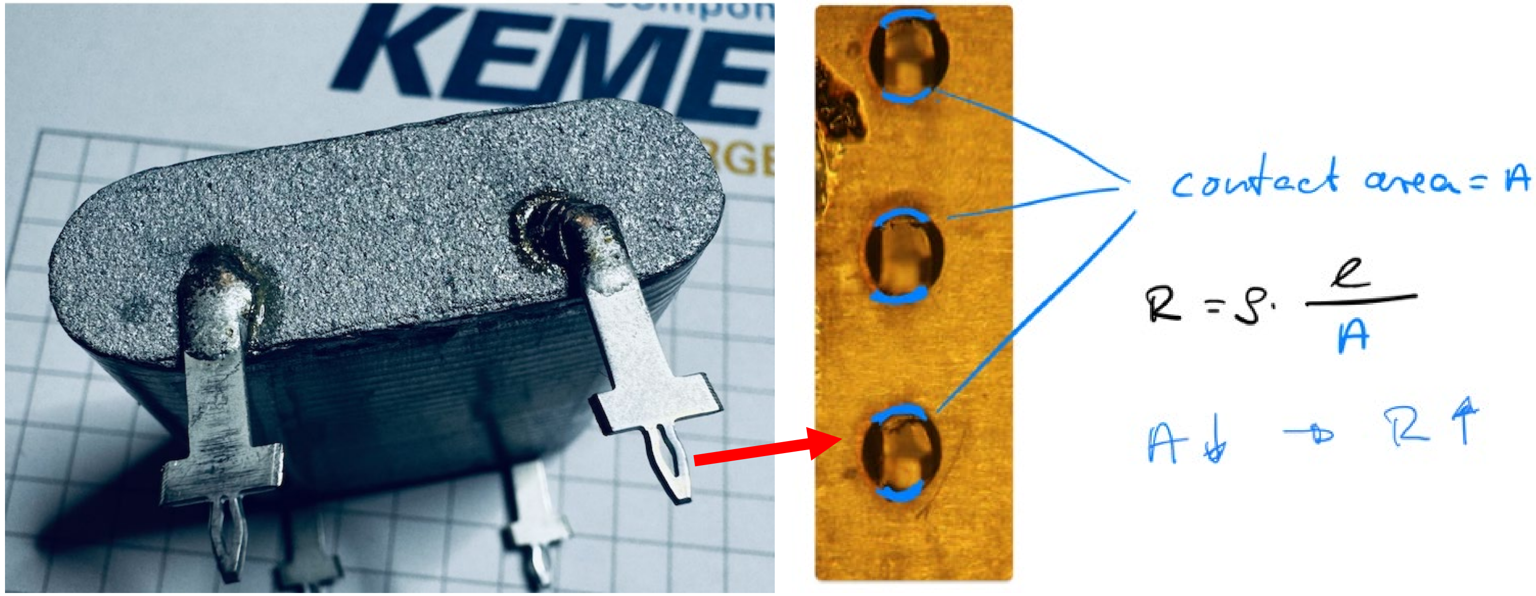


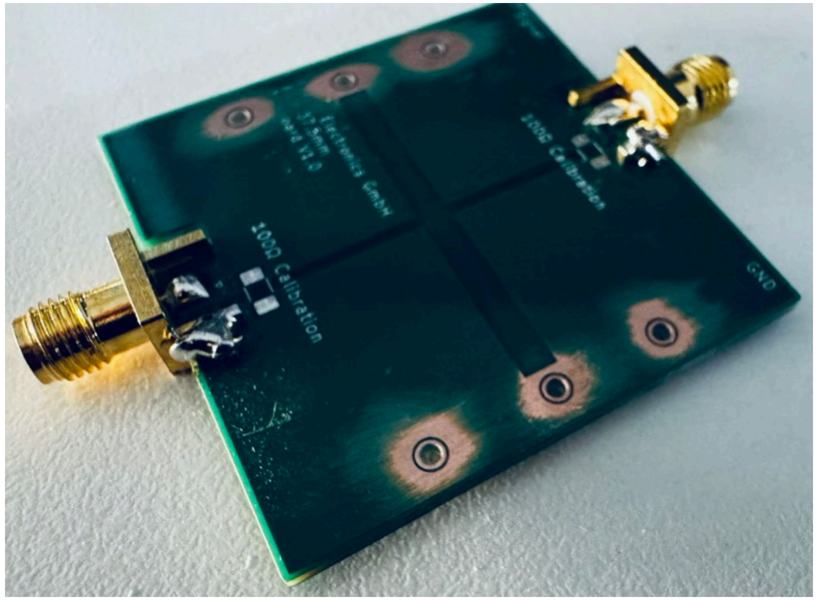
	1-wire SP	1-wire LP	2-wire LP	3-wire LP	2-PF LP
ESL/nH (2MHz)	12.1	5.3	4.7	3.1	./.
ESR/mΩ (100kHz)	7.8	4.2	3.1	2.4	./.
SRF/MHz	0.638	1.1	1.29[1)]	1.27	./.

1) Capacitance was at the lower limit

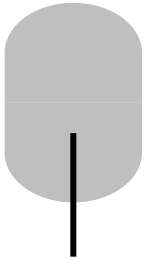
What about pressfit

- The restring disconnect the hole from the copper
- For wire use lots of solder
- Wire Pressfit contacts I messed it up – new PCB already ordered

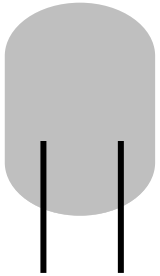




Low ESL: Low profile 4 pins DC Link



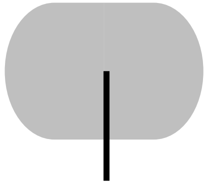
1 Wire



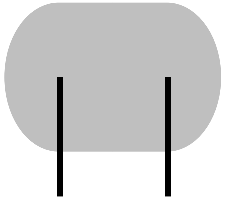
2 Wires

Table 1 – Ratings & Part Number Reference cont.

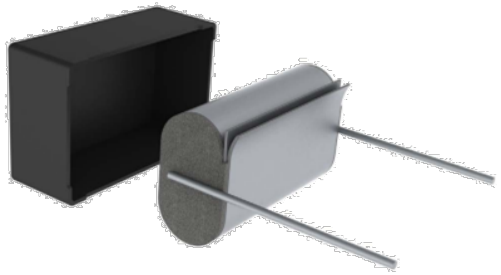
Cap Value (µF)	VDC	Dimensions (mm)					dV/dt	Ipkr	ESL	ESR_{typ} at 10 kHz	Irms* 95°C at 10 kHz	Rth (HS/Amb)	Packaging Quantity	PART NUMBER
		T	H	L	S	S1	V/µs	Apk	nH	mΩ	Arms	(°C/W)		
V_{NDC} at 85°C = 900 VDC; V_{OP105} at 105°C = 800 VDC; V_{OP125} at 125°C = 720 VDC														
1.2	900	11	20	32	27.5	\	40	48	17	35.0	3.8	44	256	C4AKOBU4120A3WJ
1.5	900	13	22	32	27.5	\	40	60	22	28.0	4.6	39	208	C4AKOBU4150A3BJ
2.7	900	14	28	32	27.5	\	40	108	24	16.0	6.6	33	96	C4AKOBU4270A3YJ
5	900	19	29	32	27.5	\	40	200	25	9.0	9.5	29	72	C4AKOBU4500A31J
8	900	22	37	32	27.5	\	40	320	28	6.1	12.8	23	64	C4AKOBU4800A32J
V_{NDC} at 85°C = 900 VDC; V_{OP105} at 105°C = 800 VDC; V_{OP125} at 125°C = 720 VDC														
1.5	900	21	12.5	32	27.5	\	40	60	11	28.6	4.1	46	192	C4AKOLU4150A31J
2.5	900	24	15	32	27.5	\	40	100	13	17.1	5.9	39	168	C4AKOLU4250A32J
4.8	900	31	19	32	27.5	\	40	192	16	9.2	9.1	30	80	C4AKOLU4480A39J
3.8	900	24	15	42	37.5	10.2	20	76	7	21.2	5.8	33	132	C4AKOLW4380A34J
5	900	24	19	42	37.5	10.2	20	100	8	16.2	7	29	88	C4AKOLW4500A33J
10	900	35	24	42	37.5	20.3	20	200	9	8.1	11	23	60	C4AKOLW5100A36J
14	900	43	25	42	37.5	20.3	20	280	9	5.9	14.3	19	48	C4AKOLW5140A38J



1 Wire
Low Profile



2 Wires
Low Profile



Wrap up

- It was fun to work on my own first testboard
- Very helpful to have a community and contacts you can talk with
- The pressfit will be investigate when the new boards arrive
- There a lot more to do on the components characterization and …

Enough material for future investigations

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- **Capacitors**
  - Aluminum
  - Ceramic
  - Film
  - Polymer
  - Supercapacitors
  - Tantalum
- **Resistors**
  - Carbon
  - Jumper
  - Metal
  - Metal Oxide Film
  - Platinum
  - Thick Film
  - Thin Film
  - Wirewound
- **Inductors**
  - Power
  - RF Signal
- **EMC**
  - Common Mode Choke - Power
  - Common Mode Choke - Signal
  - Differential Mode Choke - Power
  - Differential Mode Choke - Signal
  - Dual Mode Choke
  - EMI Filters
  - EMI Suppression
  - Ground Wire
  - Magnetic Materials
- **Transformers**
  - Isolation
  - Power
- **Signal Magnetics & Connectors**
  - Automotive Networks
  - Cages
  - Connectors
  - Ethernet (LAN)
  - Integrated Connector Modules (ICMs)
  - Telecom & Audio (WAN)
- **Sensors**
  - Current
  - Inductive & Capacitive Sensors
  - Limit Switches
  - Photoelectric Sensors
  - Resistance Temp. Detector (RTD)
  - Pressure Sensors
  - Pyroelectric Sensors
  - RFID Systems
  - Safety Sensors & Switches
  - Thermal Reed Switch
  - Ultrasonic Sensors
  - Vibration Sensors
- **Antenna, RF & Microwave**
  - Antennas
  - Connectors, Cables & Mounts
  - RF Filters
  - Couplers
  - Splitters
- **Circuit Protection**
  - Chip Fuse
  - Gas Discharge Tube
  - TNCs
  - PPTCs
  - Spark Gap Protectors
  - Thyristor Surge Suppressors
  - TVS Diodes
  - TVS Diodes – Low Capacitance
  - Varistors
- **Discrete Semi-conductors**
  - MOSFET
  - Rectifier Diode
  - Zener Diode
- **Magnets & Metal Materials**
  - Electromagnets
  - Memoalloy (Ni-Ti Wire)
  - Permanent Magnets
- **Piezoelectric Devices**
  - Piezo Ceramic Actuators
  - Piezo Ceramic Transducer
  - Piezo Ceramic Acoustic Modules
  - Piezo Film Haptic Modules
- **Power Supplies**
  - DC to DC
  - AC to DC
- **Electro-mechanical**
  - Lifting Magnets
  - Magnetic Coils
  - Relay Coils
  - Relays
  - Shock Absorber Coils
  - Solenoid Valves
  - Trigger Magnetics
- **Motor & Ignition Coils**
  - Ignition Coils
  - Motor Coils
- **Cable Harnesses**
  - Custom

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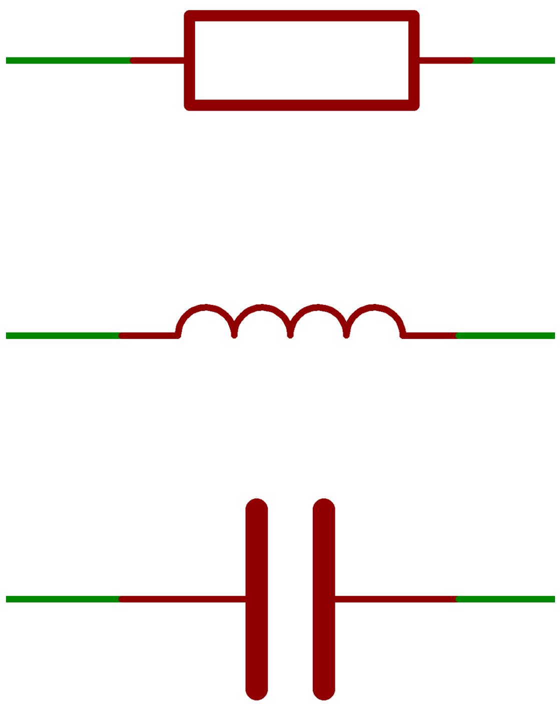
- Federico Fantini and Robert Airi YAGEO GROUP for the insight and samples

Thank you!謝謝你!



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Thank you!謝謝你!

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