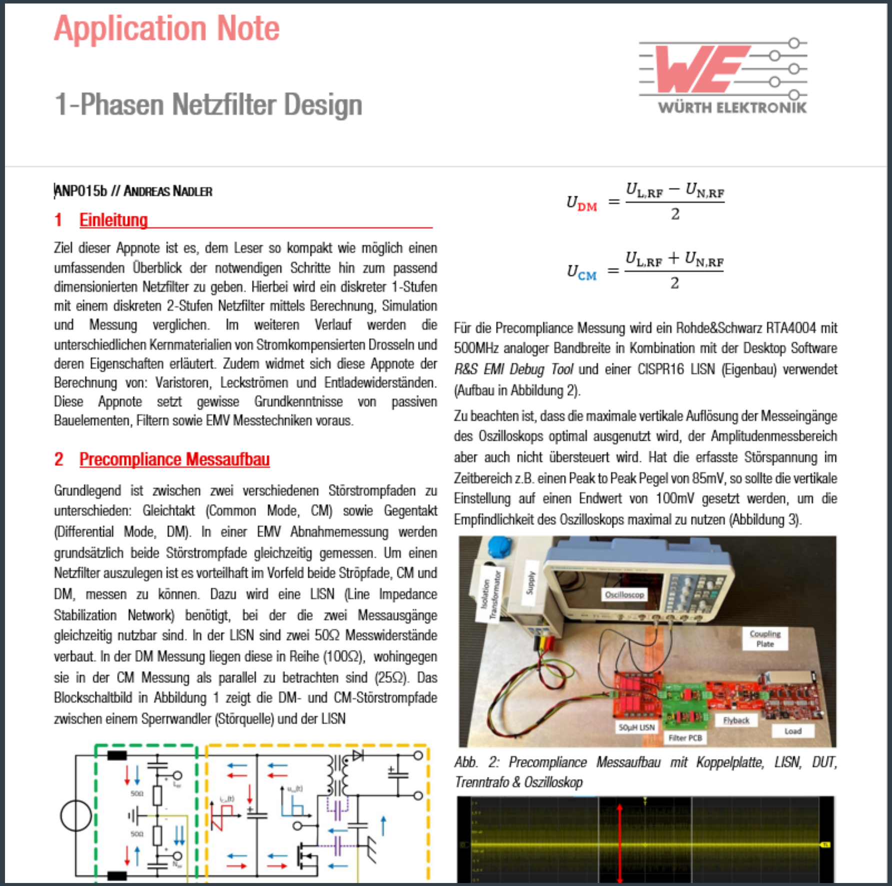
DIGITAL WE DAYS 2024

CALCULATION, DESIGN & LT SPICE SIMULATION OF AC LINE FILTERS

Andreas Nadler

1-PHASE FILTER DESIGN

Related Appnote: ANP015



Application Note

1-Phasen Netzfilter Design

ANP015b // Andreas Nadler

1 Einleitung

Ziel dieser Appnote ist es, dem Leser so kompakt wie möglich einen umfassenden Überblick der notwendigen Schritte hin zum passend dimensionierten Netzfilter zu geben. Hierbei wird ein diskreter 1-Stufen mit einem diskreten 2-Stufen Netzfilter mittels Berechnung, Simulation und Messung verglichen. Im weiteren Verlauf werden die unterschiedlichen Kernmaterialien von Stromkompensierten Drosseln und deren Eigenschaften erläutert. Zudem widmet sich diese Appnote der Berechnung von: Varistoren, Leckströmen und Entladewiderständen. Diese Appnote setzt gewisse Grundkenntnisse von passiven Bauelementen, Filtern sowie EMV Messtechniken voraus.

2 Precompliance Messaufbau

Grundlegend ist zwischen zwei verschiedenen Störstrompfaden zu unterschieden: Gleichtakt (Common Mode, CM) sowie Gegentakt (Differential Mode, DM). In einer EMV Abnahmemessung werden grundsätzlich beide Störstrompfade gleichzeitig gemessen. Um einen Netzfilter auszulegen ist es vorteilhaft im Vorfeld beide Ströpfade, CM und DM, messen zu können. Dazu wird eine LISN (Line Impedance Stabilization Network) benötigt, bei der die zwei Messausgänge gleichzeitig nutzbar sind. In der LISN sind zwei 50Ω Messwiderstände verbaut. In der DM Messung liegen diese in Reihe (100Ω), wohingegen sie in der CM Messung als parallel zu betrachten sind (25Ω). Das Blockschaltbild in Abbildung 1 zeigt die DM- und CM-Störstrompfade zwischen einem Sperrwandler (Störquelle) und der LISN

$$U_{DM} = \frac{U_{L,RF} - U_{N,RF}}{2}$$

$$U_{CM} = \frac{U_{L,RF} + U_{N,RF}}{2}$$

Für die Precompliance Messung wird ein Rohde&Schwarz RTA4004 mit 500MHz analoger Bandbreite in Kombination mit der Desktop Software *R&S EMI Debug Tool* und einer CISPR16 LISN (Eigenbau) verwendet (Aufbau in Abbildung 2).

Zu beachten ist, dass die maximale vertikale Auflösung der Messeingänge des Oszilloskops optimal ausgenutzt wird, der Amplitudenmessbereich aber auch nicht übersteuert wird. Hat die erfasste Störspannung im Zeitbereich z.B. einen Peak to Peak Pegel von 85mV, so sollte die vertikale Einstellung auf einen Endwert von 100mV gesetzt werden, um die Empfindlichkeit des Oszilloskops maximal zu nutzen (Abbildung 3).

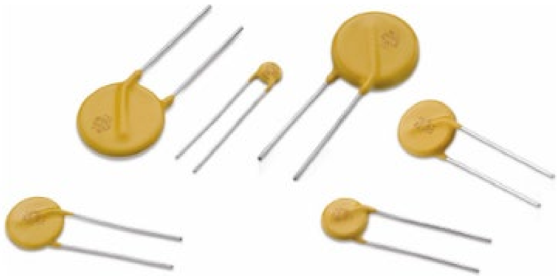
Abb. 2: Precompliance Messaufbau mit Koppelplatte, LISN, DUT, Trenntrafo & Oszilloskop

AGENDA

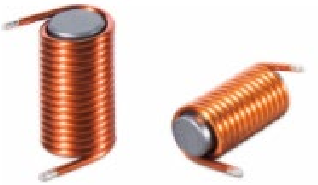
- Sources of interference
- Components for filtering
- 1-stage filter design
- 2-stage filter design
- Calculation and simulation
- Measurements of interference suppression
- Y-Cap placement and PE connection style

WE Portfolio for AC Filter

- Varistors min. 14mm! (WE-VD surge protection)
- X capacitors (WCAP-FTXX)
- Y capacitors (WCAP-CSSA & FTY2)
- Current-compensated chokes (WE-CMBx)
- Longitudinal filter chokes (WE-TIHV / WE-SD)
- Complete line filters (WE-CLFS)





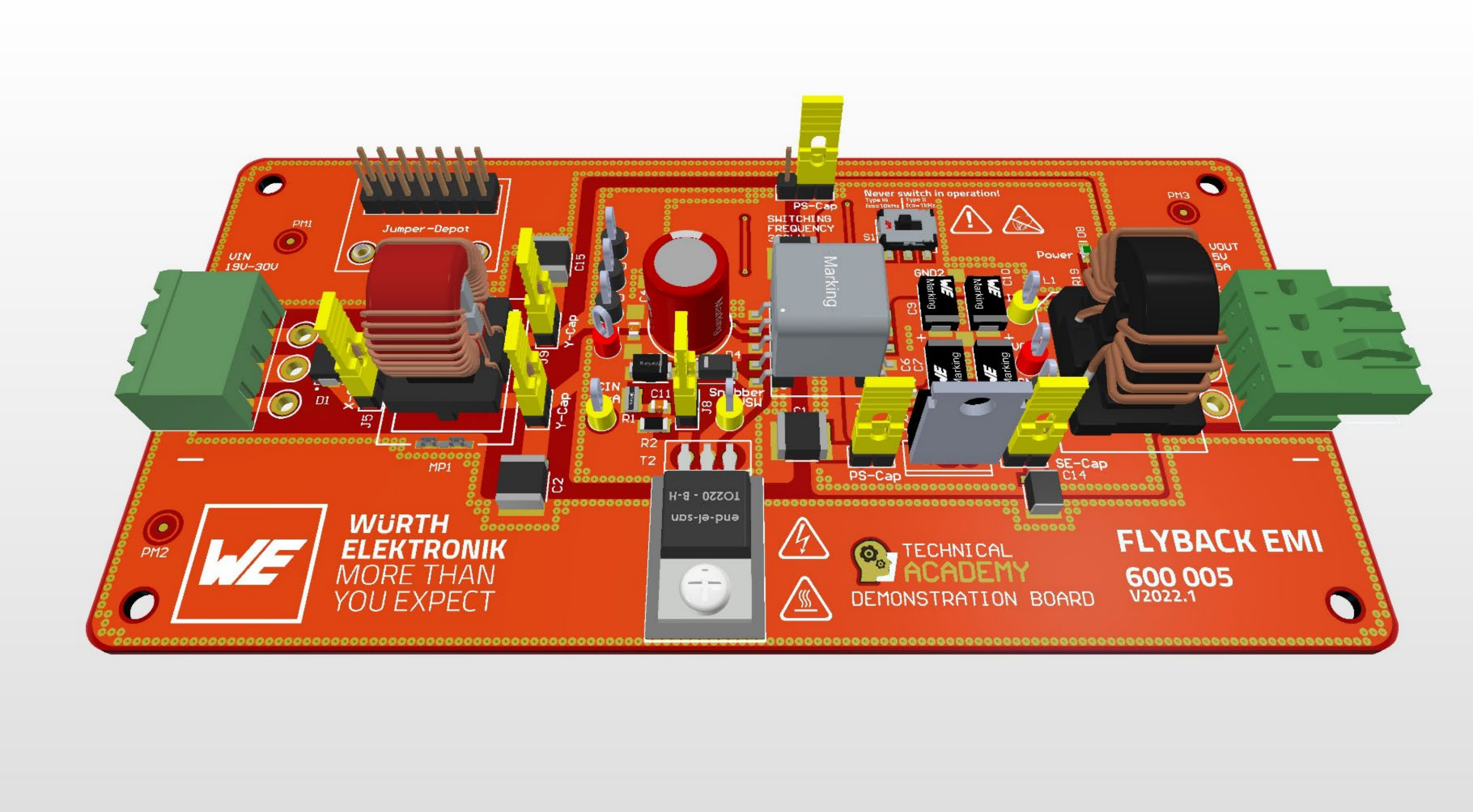

Technical specification noise source

- DC/DC Flyback-Converter CCM (Forced Continuous Conduction Mode)
  - U_{in} = 24V (19-30V)
  - U_{out} = 5V
  - $I_{out,max}$ = 5A (25W)
  - f_{sw} ≈ 300kHz
  - Efficiency ≈ 90%

- IC: ADP1071-2 (Analog Devices)
  - with synchronous rectifier

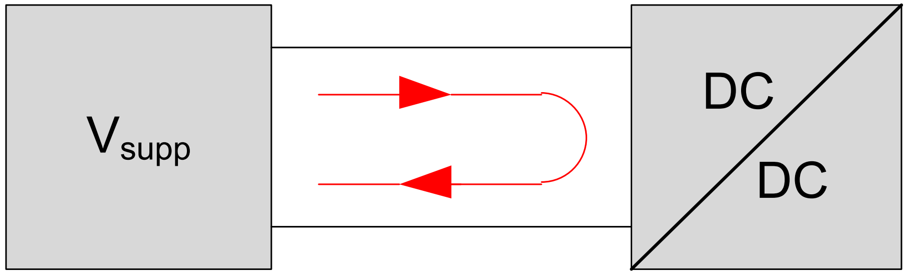
- Transformer: 749119550

- MOSFETs in TO220-package

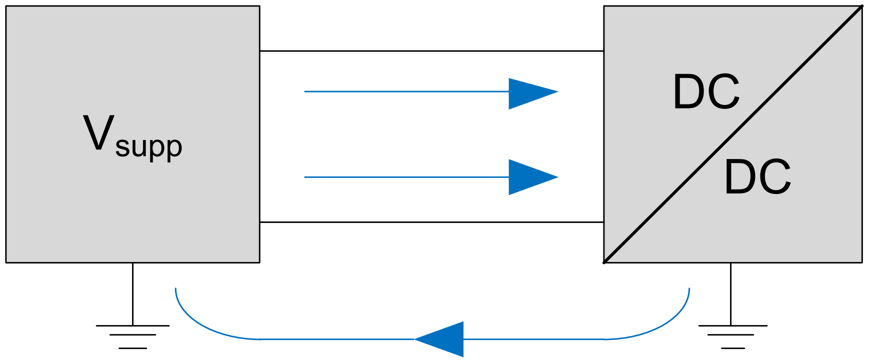


Differntial Mode & Common Mode

Differential Mode



Common Mode



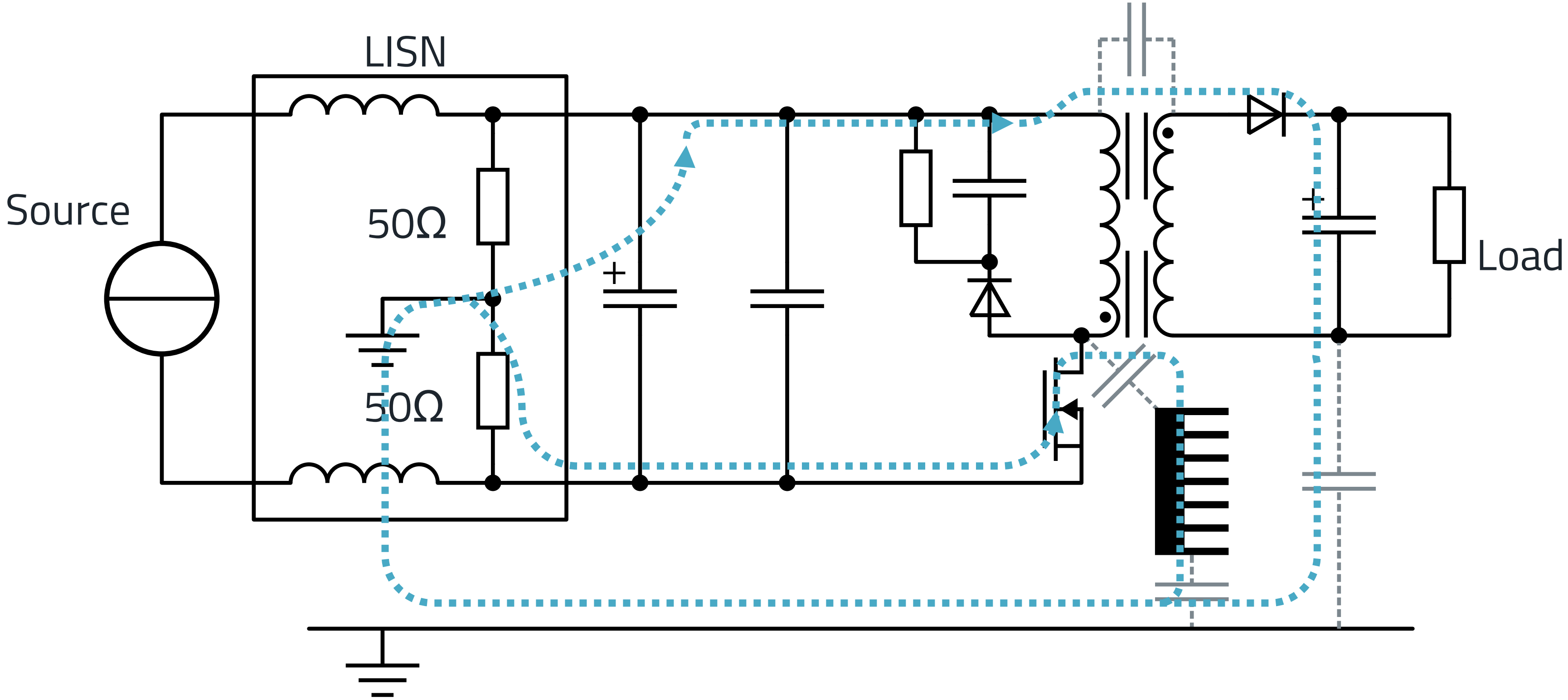
CM & DM comparisson

- **Differential mode currents**
- Current path as in circuit diagram
- Easy to follow paths
- Return current path very close
- Relatively large currents
- Filtering with LC , π , T topologies
- dI / dt is dominant cause
- Conducted EMI problem

- **Common-mode currents**
- Unexpected current path
- Current flows via parasitic paths
- Return current path very large
- Relatively small currents (μA)
- Filtering with CMC and Y-caps
- dU / dt is dominant cause
- Radiated & conducted EMI problem

Introduction - Capacitive Coupling in a Flyback Converter

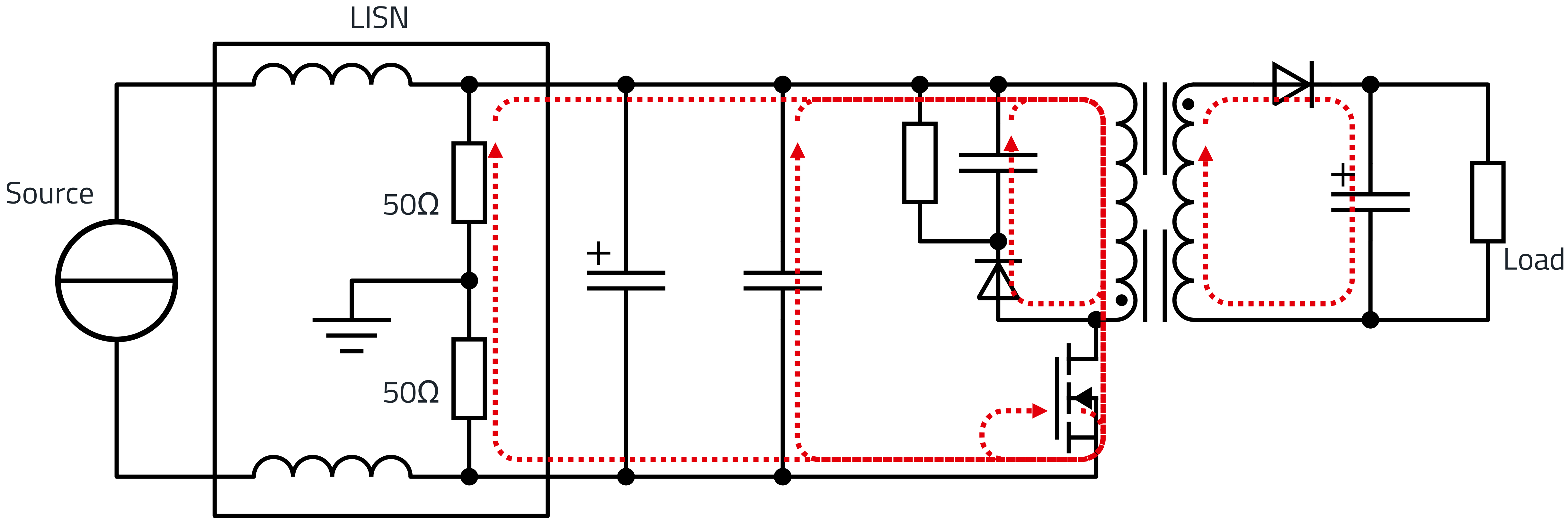
Common mode current paths



High du/dt common mode currents through parasitic capacitances (electric dipole and monopole antennas)

Introduction - Inductive Coupling in a Flyback Converter

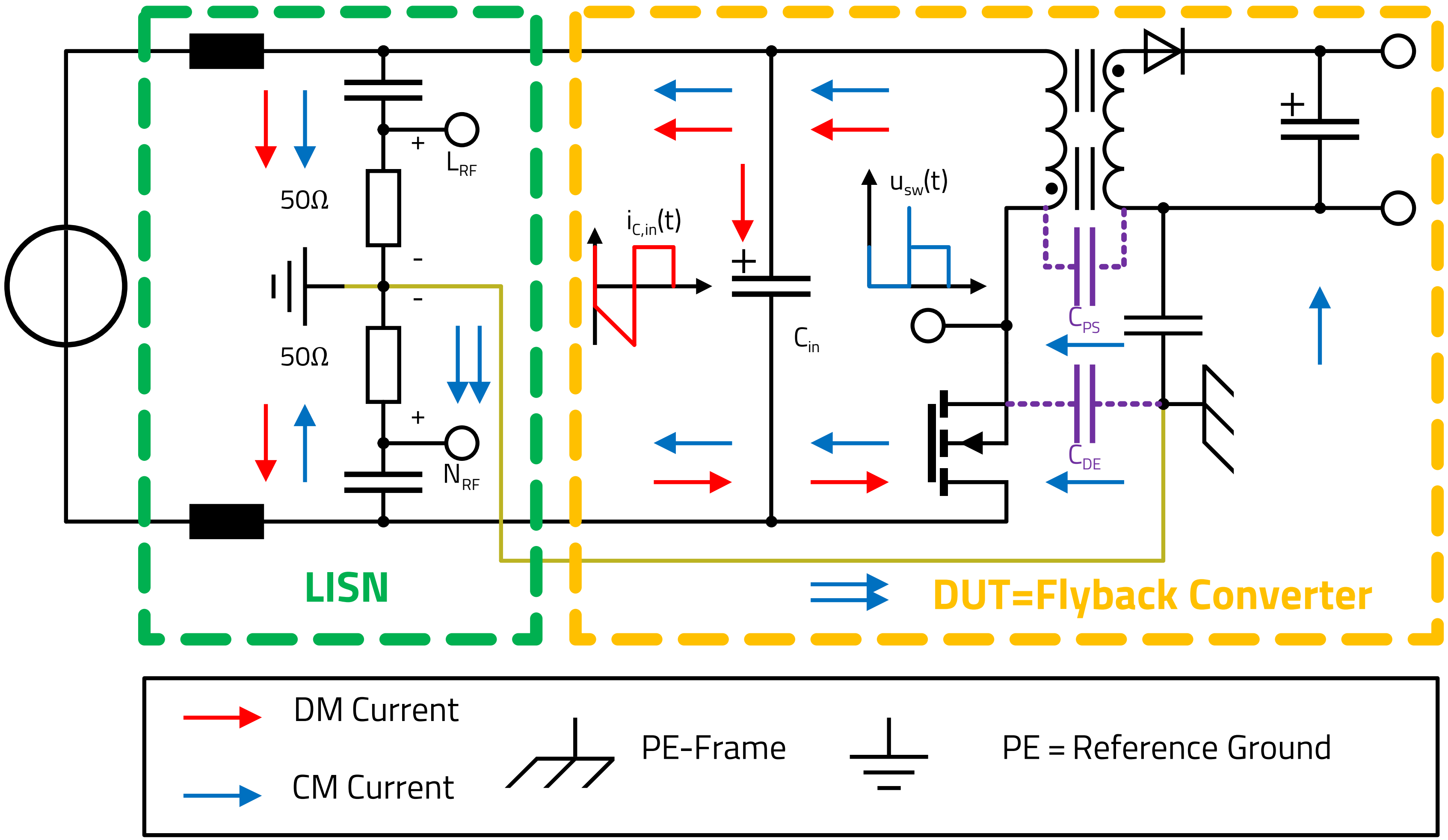
Differential mode current paths



Inductive coupling caused by high di/dt differential mode currents (magnetic loop antennas)

Test#3: Background - Noise categories

Theory: DM and CM noise path in a flyback converter



$$U_{L,RF} = U_{CM} + U_{DM}$$

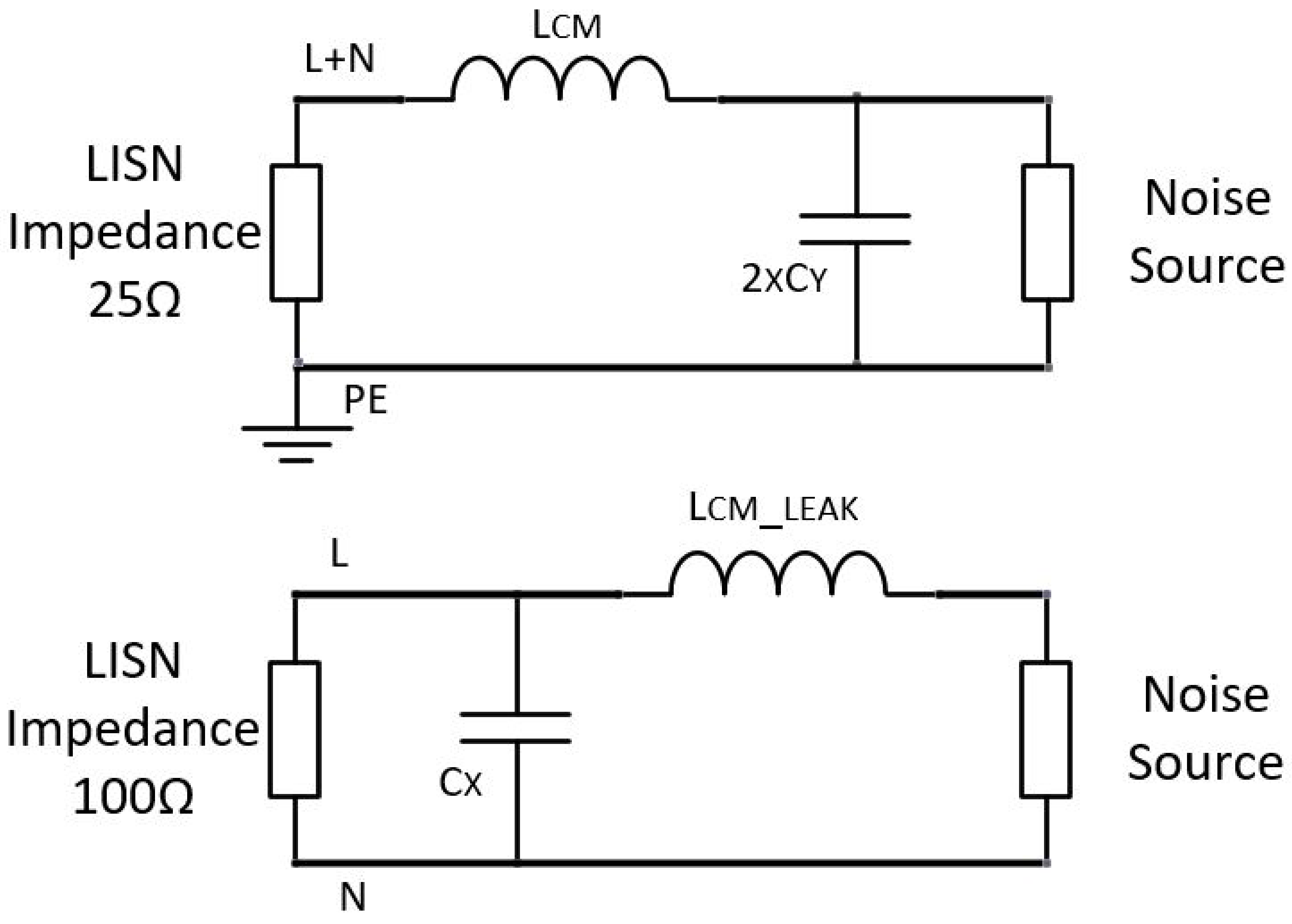
$$U_{N,RF} = U_{CM} - U_{DM}$$

$$U_{DM} = \frac{U_{L,RF} - U_{N,RF}}{2}$$

$$U_{CM} = \frac{U_{L,RF} + U_{N,RF}}{2}$$

CM & DM Filter Equivalent

Effective LISN Impedance and Component Arrangement



Common mode chokes

Core materials

- If the CM insertion loss of the calculated 1-stage line filter with MnZn CMC core is not sufficient for the higher frequency range (from approx. 10MHz - 100MHz), a second CMC with NiZn or nanocrystalline core must also be used

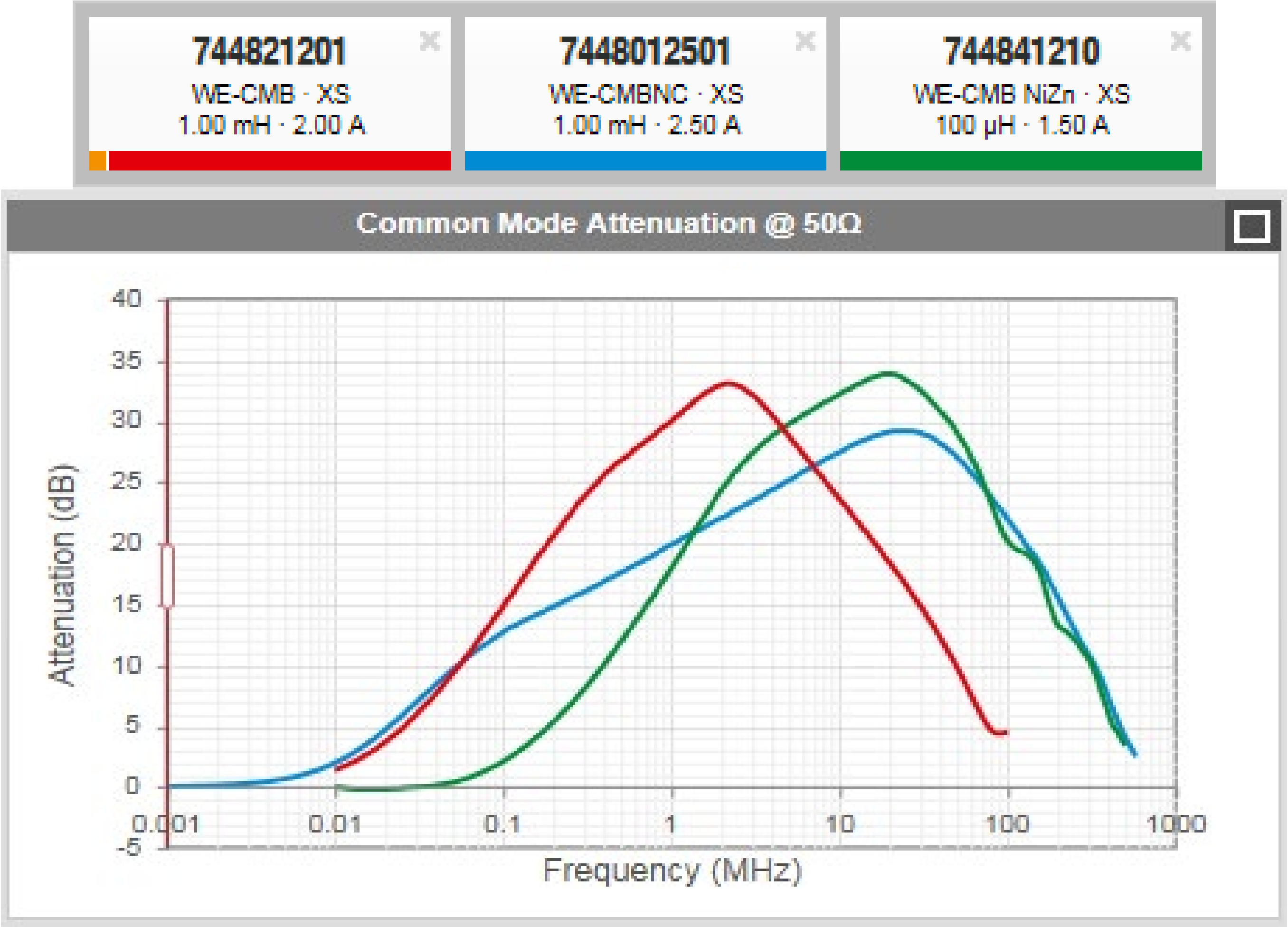
- MnZn cores
- 10kHz to 10MHz

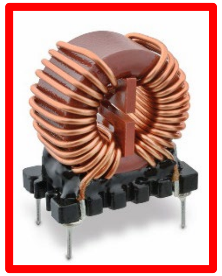
- NiZn cores
- 5MHz to 200MHz

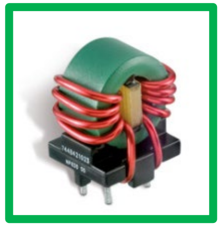
- Nanocrystaline cores
- 1kHz to 300MHz

Core materials comparisson

MnZn, NC, NiZn

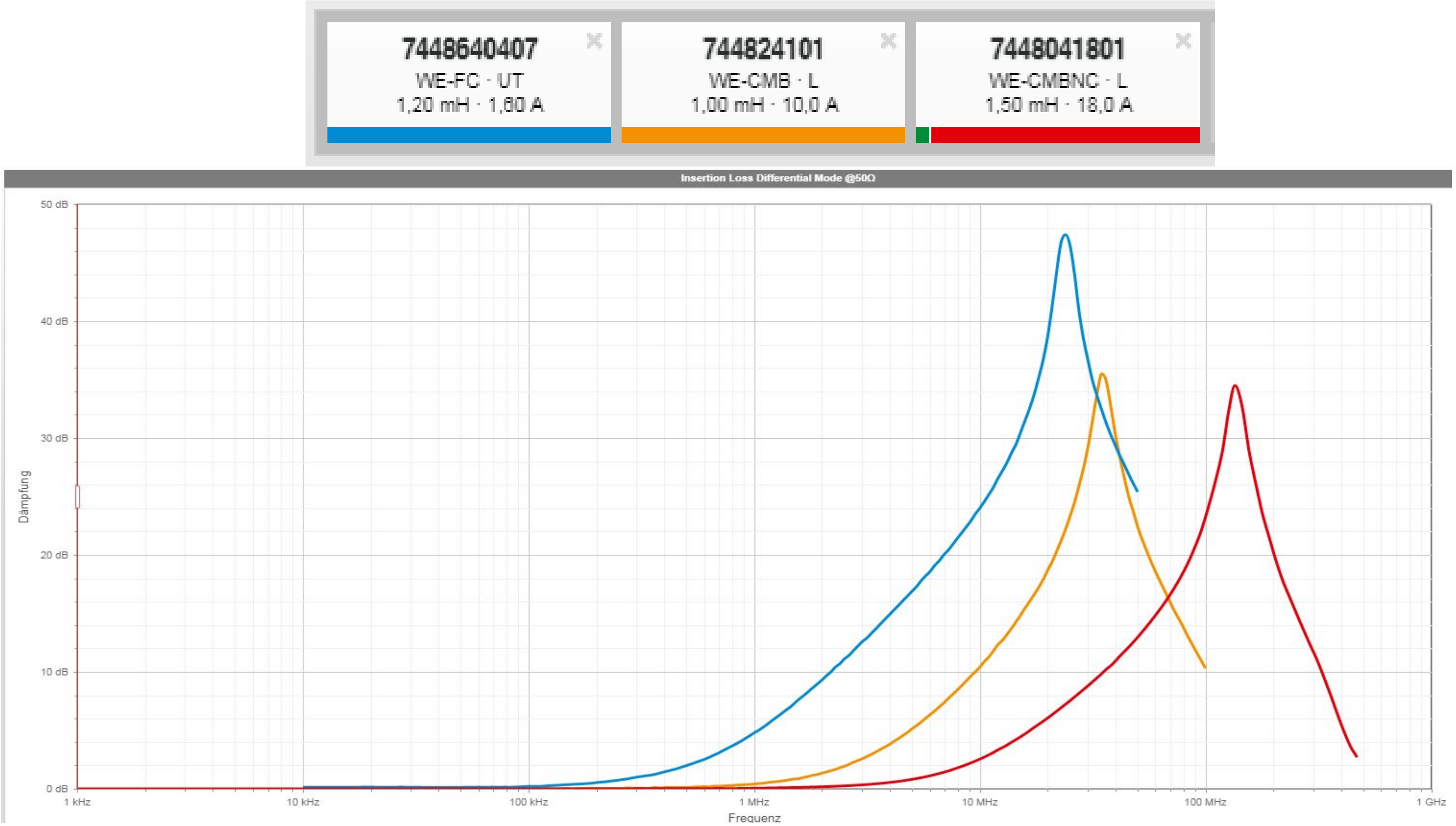


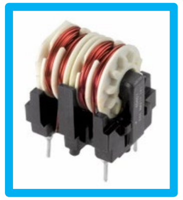


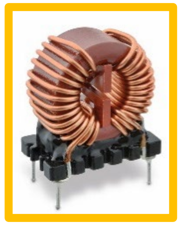


Leakage inductance

Is mainly determined by the geometry of the winding body

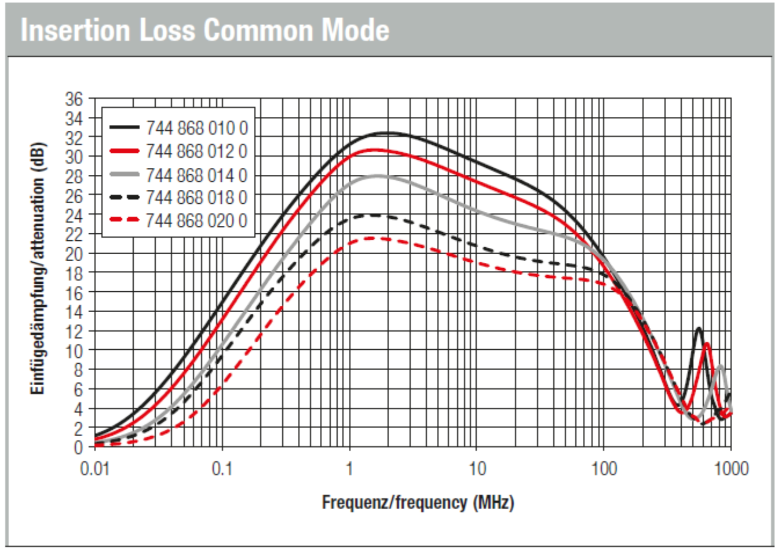


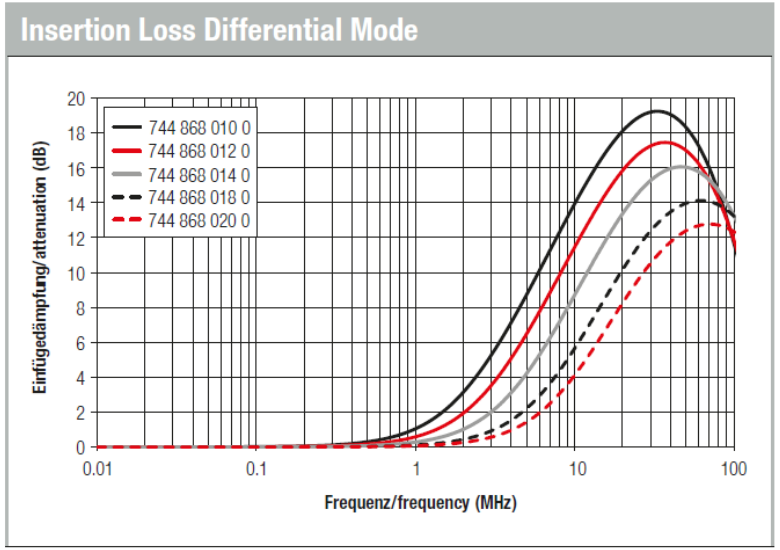




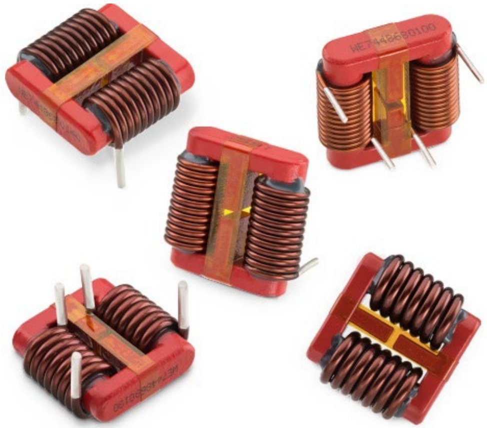
CMC with airgap

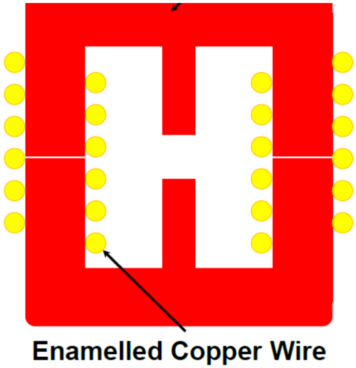
- Flat CMC with defined air gap WE-LPCC (up to 24A)
- Broadband attenuation from 100kHz to 300MHz
- Less maximum attenuation compared to cores without air gap





WE-LPCC

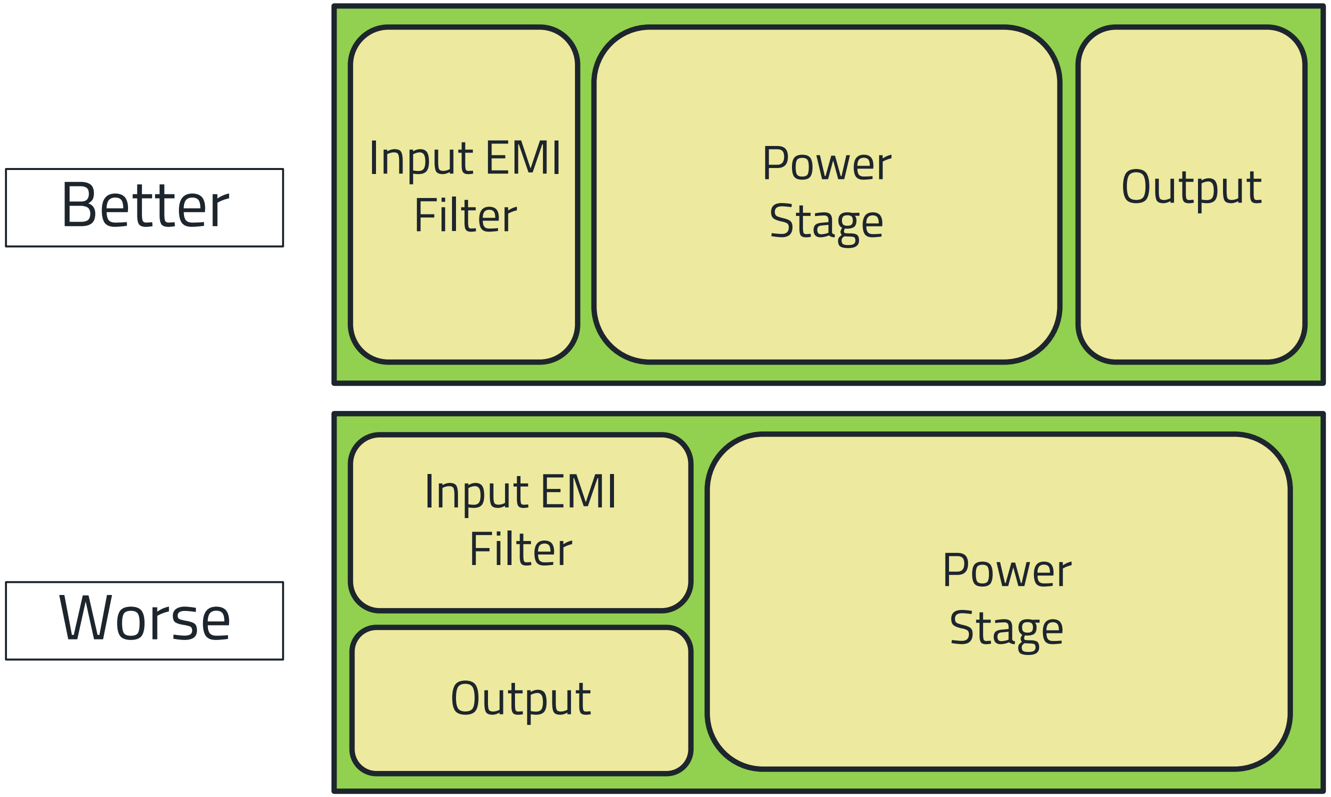




WE-LPCC

Geometric arrangement of filters

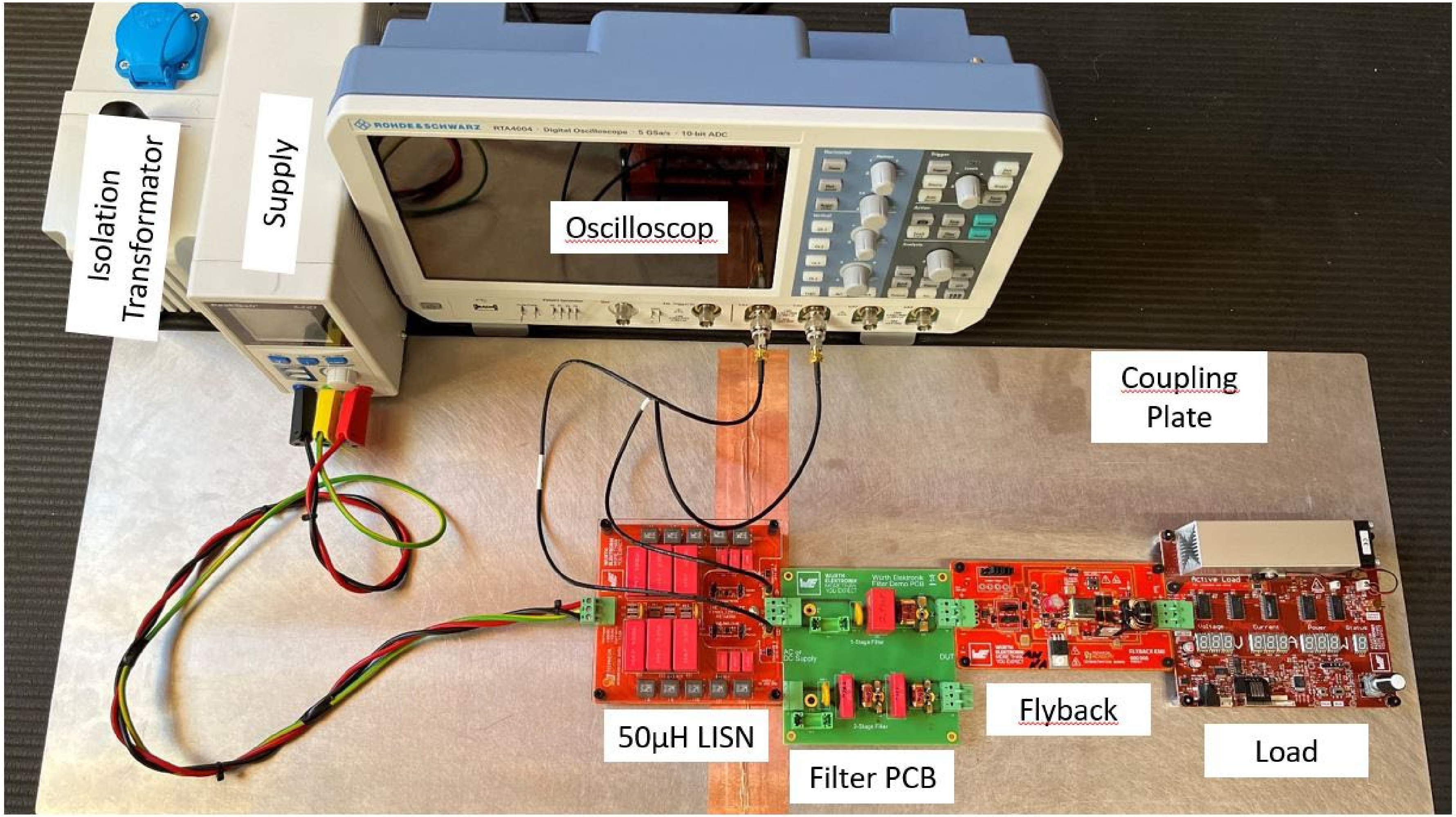
- Correct placement of the filters for maximum interference suppression effect is crucial
- Avoidance of parallel structures/coupling of I/Os



MATH

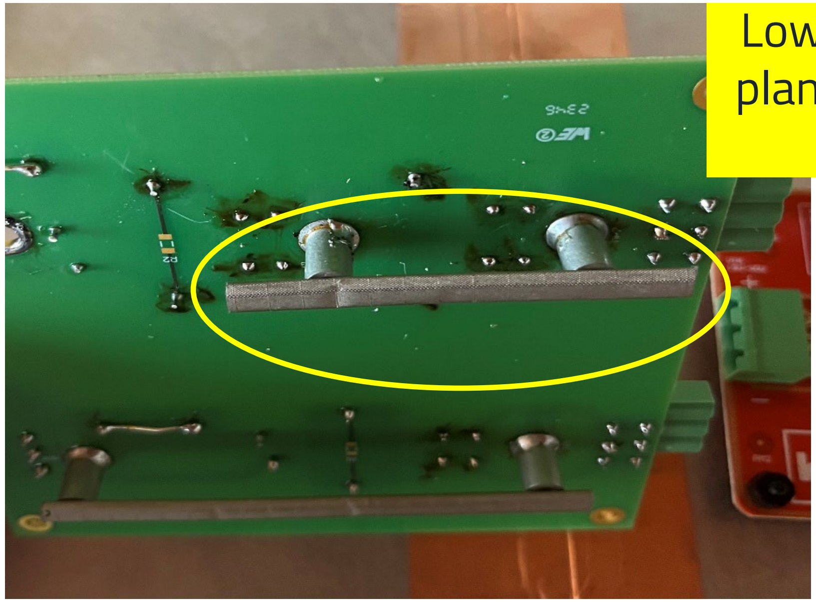
First: Measure DM and CM separate without filter

Mandatory: LISN with two RF outputs which can be used simultaniosly

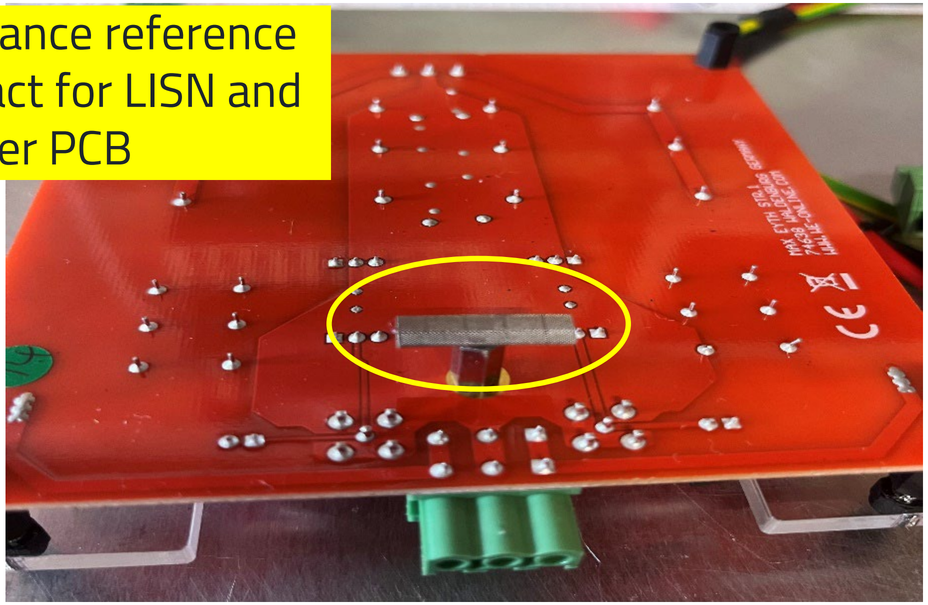


Setup

External filter PCB with 1- & 2-stage CM/DM filter

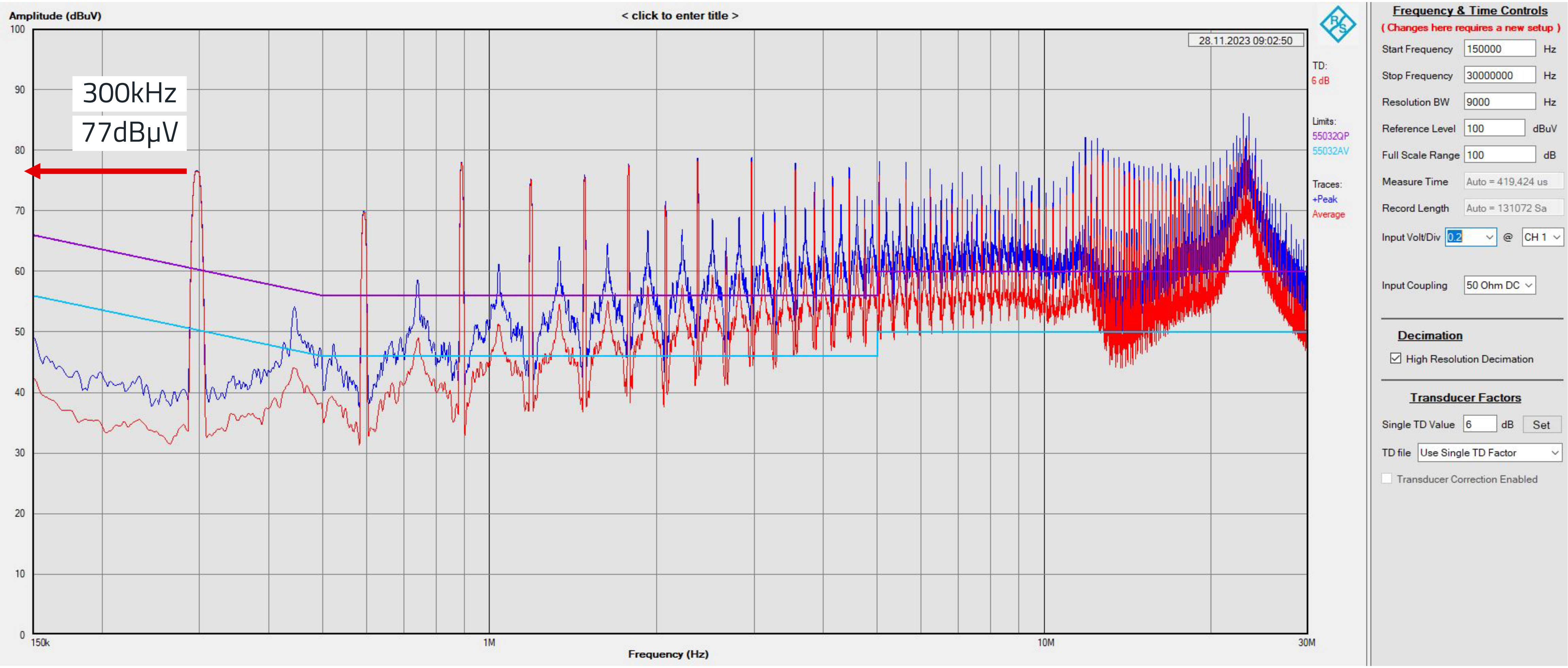


Low impedance reference plane contact for LISN and filter PCB



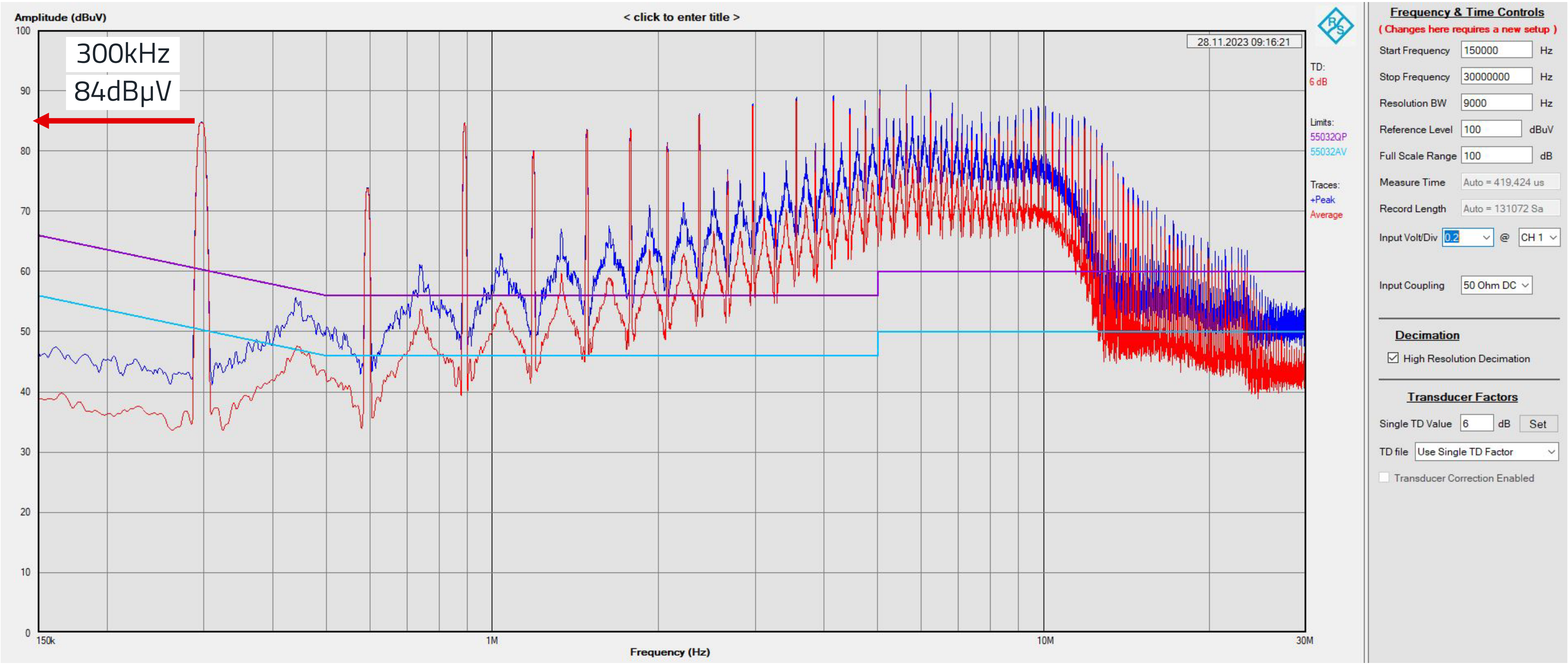
Conducted Spectrum 50uH LISN

DM no filter



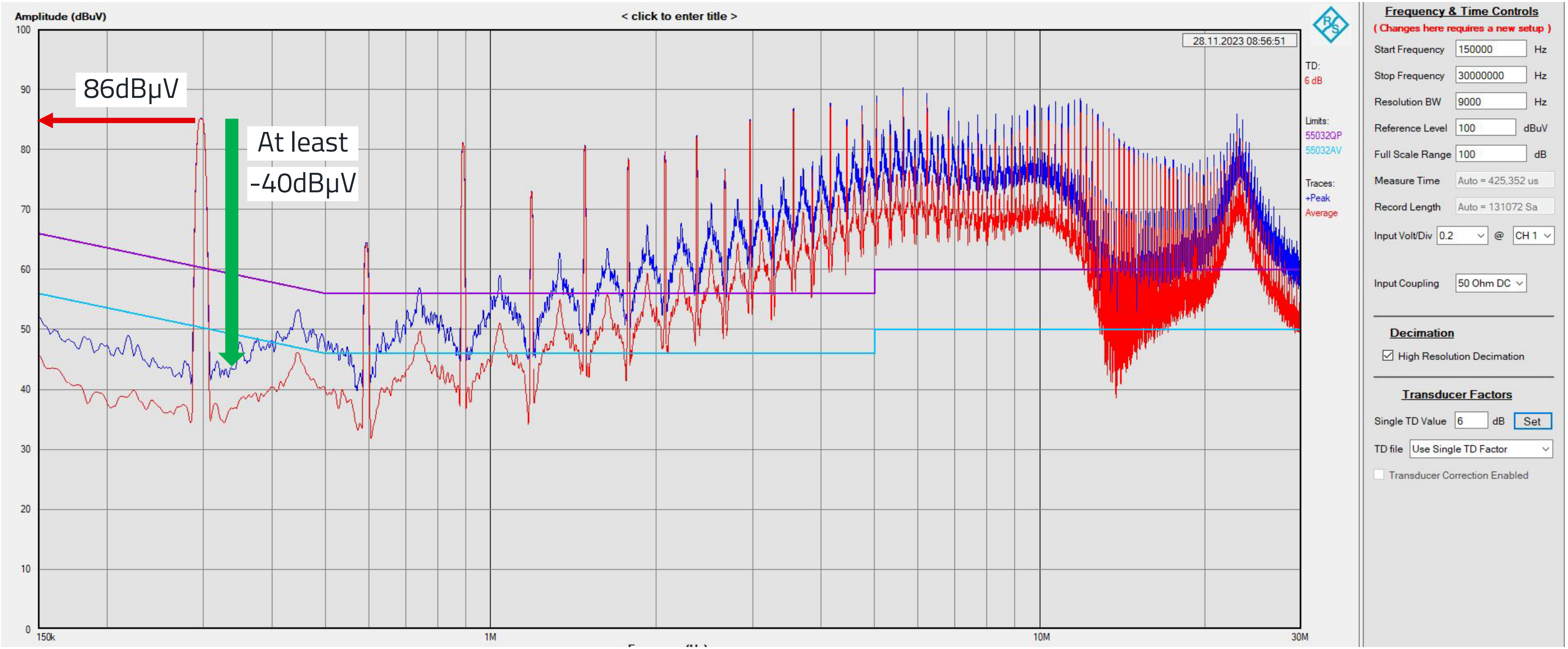
Conducted Spectrum 50uH LISN

CM no filter



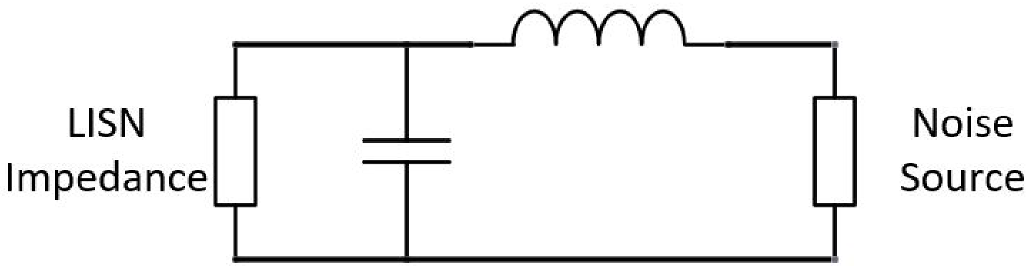
Conducted Spectrum 50uH LISN

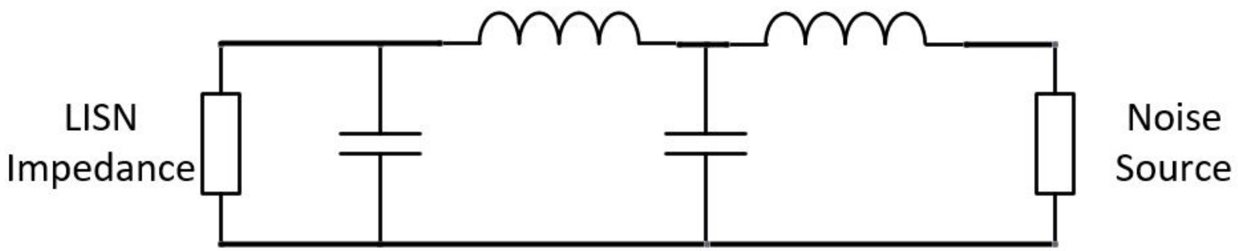
CM + DM no Filter



Corner Frequency for desired Attenuation at fsw = A_fsw

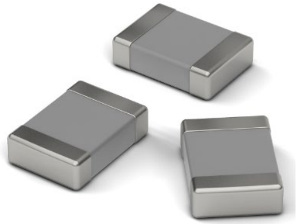
1-Stage LC	2-Stage LC
$A_{\mathrm{fsw}} = \log\left(\frac{f_{sw}}{f_{co}}\right) \cdot 40dB$	$A_{\mathrm{fsw}} = \log\left(\frac{f_{sw}}{f_{co}}\right) \cdot 80dB$
$f_{co} = \frac{f_{sw}}{10^{\frac{A_{fsw(dB)}}{40dB}}}$	$f_{co} = \frac{f_{sw}}{10^{\frac{A_{fsw(dB)}}{80}dB}}$

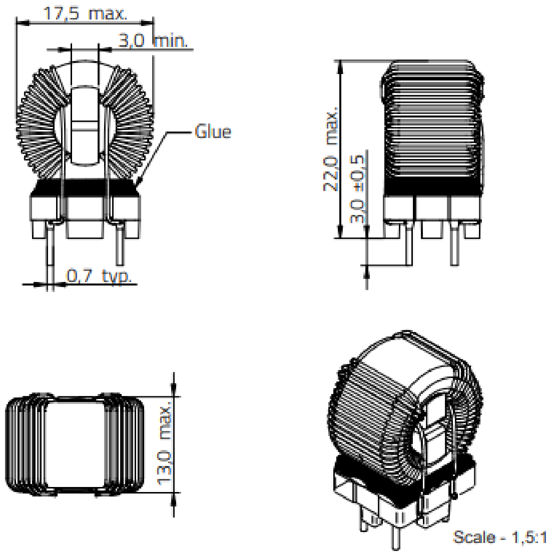


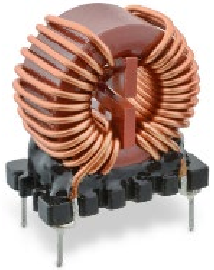


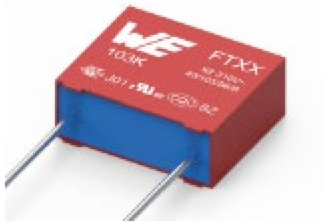
1-Stage Calculation

Desired damping CM&DM = 40dB @ fsw(300kHz) → fc= 30kHz







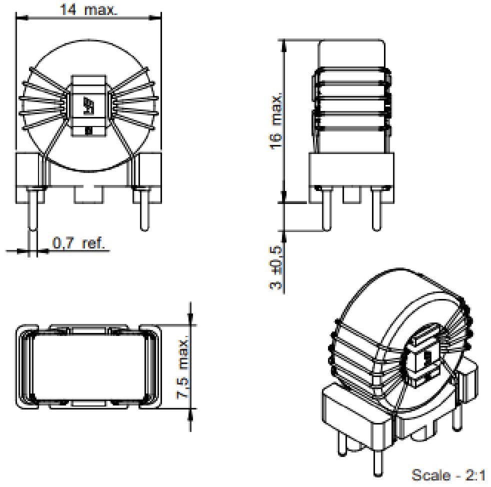


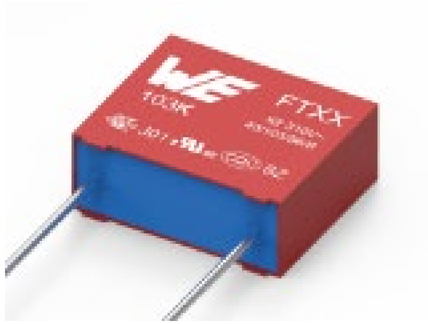
1. „LC“ = 40dB/Dec
2. Filter corner frequency: fc = 30kHz → 1/10 of fsw → 40dB @ 300kHz damping
3. Define Y-caps → 4,7nF x 2 → **9,4nF** total Cy
4. Define L_cm for fc = 30kHz → $L_{cm} = \frac{1}{(2\pi f c)^2 C_y} = \frac{1}{(2\pi \cdot 30kHz)^2 \cdot 9{,}4nF} = 3mH$ → **3,3mH** chosen (744822233)
5. $Actual\ f_{cm} = \frac{1}{2\pi\sqrt{L_{cm}Cy}} = \frac{1}{2\pi\sqrt{3.3mH \cdot 9{,}4nF}} = 28{,}5kHz \longrightarrow A_{fsw\ cm} = log\left(\frac{300kHz}{28{,}5kHz}\right) \cdot 40dB = \mathbf{41dB}$
6. Calc. L_dm → XL = 92Ω@1MHz → $L_{dm} = \frac{XL}{2\pi f} = \frac{92\Omega}{2\pi \cdot 1MHz} = \mathbf{14{,}6\mu H}$ (use REDEXPERT for help)
7. Define Cx → $C_x = \frac{1}{(2\pi f c)^2 L_{dm}} = \frac{1}{(2\pi \cdot 30kHz)^2 \cdot 14{,}6\mu H} = 1{,}92\mu F$ → **2,2µF** chosen (890334026034CS)
8. $Actual\ f_{dm} = \frac{1}{2\pi\sqrt{L_{dm}Cx}} = \frac{1}{2\pi\sqrt{14{,}6\mu H \cdot 2{,}2\mu F}} = 28kHz \longrightarrow A_{fsw\ dm} = log\left(\frac{300kHz}{28kHz}\right) \cdot 40dB = \mathbf{41dB}$

2-Stage Calculation

Desired damping DM&CM = 40dB @ fsw(300kHz) → fco= 95kHz

1. „2nd LC" = 80dB/Dec
2. Filter corner frequency: fc = 95kHz → 40dB @ 300kHz damping
3. Define Y-caps → 2,2nF x 2 → **4,4nF** total Cy (8853622110151)
4. Define L_cm for fc = 95kHz → $L_{cm} = \frac{1}{(2\pi f c)^2 C_y} = \frac{1}{(2\pi \cdot 95kHz)^2 \cdot 4{,}4nF} = 0{,}64mH$ → **1,0mH** chosen (744821201)
5. $Actual\ f_{cm} = \frac{1}{2\pi\sqrt{L_{cm}Cy}} = \frac{1}{2\pi\sqrt{1mH \cdot 4{,}4nF}} = 75kHz \dashrightarrow A_{fsw_{cm}} = log\left(\frac{300kHz}{75kHz}\right) \cdot 80dB = \mathbf{48dB}$
6. Calc. L_dm → XL = 41Ω@1MHz → $L_{dm} = \frac{XL}{2\pi f} = \frac{41\Omega}{2\pi \cdot 1MHz} = \mathbf{6{,}5\mu H}$ (use REDEXPERT for help)
7. Define Cx → $C_x = \frac{1}{(2\pi f c)^2 L_{dm}} = \frac{1}{(2\pi \cdot 95kHz)^2 \cdot 6{,}5\mu H} = 0{,}43\mu F$ → **560nF** chosen (890334026018CS)
8. $Actual\ f_{dm} = \frac{1}{2\pi\sqrt{L_{dm}Cx}} = \frac{1}{2\pi\sqrt{6{,}5\mu H \cdot 560nF}} = 83kHz \dashrightarrow A_{fsw_{dm}} = log\left(\frac{300kHz}{83kHz}\right) \cdot 80dB = \mathbf{45dB}$
9. Additional DM capacitance: Varistor ~ 420pF & $({}^1/_2 \cdot Cy) = 3.3nF$





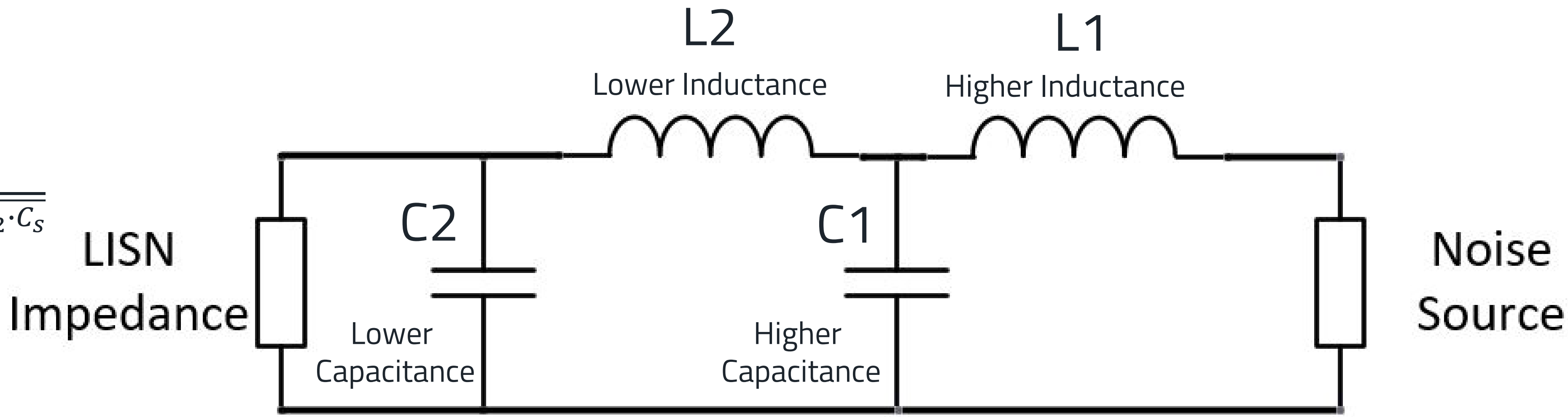
2-Stage Calculation

If the values of the filter components differ **greatly** (DM example)

- If the size of the inductors are different in size, then there are two pairs of poles: High & Low frequency pole
- In this example has L1 the bigger inductance and C1 the bigger capacitance

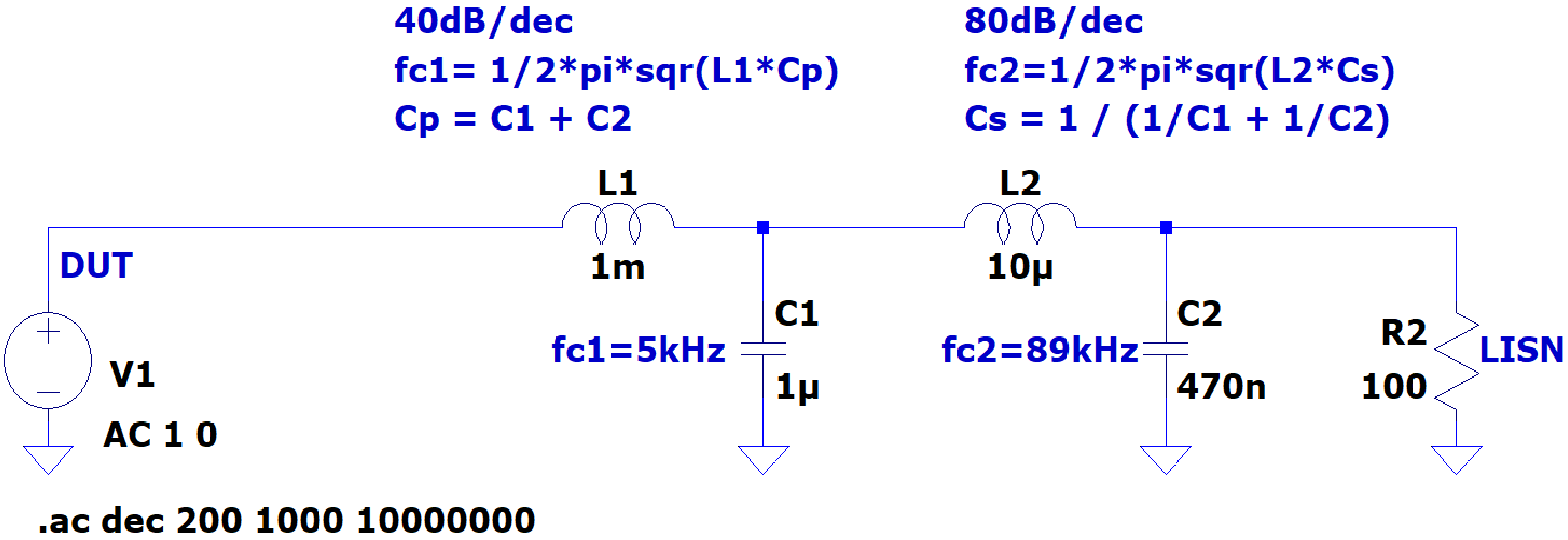
- $\Delta s = \left[1 + \frac{s}{\omega_L Q_L} + \frac{s^2}{{\omega_L}^2}\right] \cdot \left[1 + \frac{s}{\omega_H Q_H} + \frac{s^2}{{\omega_H}^2}\right]$
- $\omega_L = \frac{1}{\sqrt{L_1 \cdot C_p}} \rightarrow f_{CL} = \frac{1}{2\pi\sqrt{L_1 \cdot C_p}}$
- $C_p = C_1 + C_2$
- $\omega_H = \frac{1}{\sqrt{L_2 \cdot C_S}} \rightarrow f_{CH} = \frac{1}{2\pi\sqrt{L_2 \cdot C_S}}$
- $C_S = \frac{1}{\left(\frac{1}{C_1} + \frac{1}{C_2}\right)}$

L1>>L2
C1>>C2



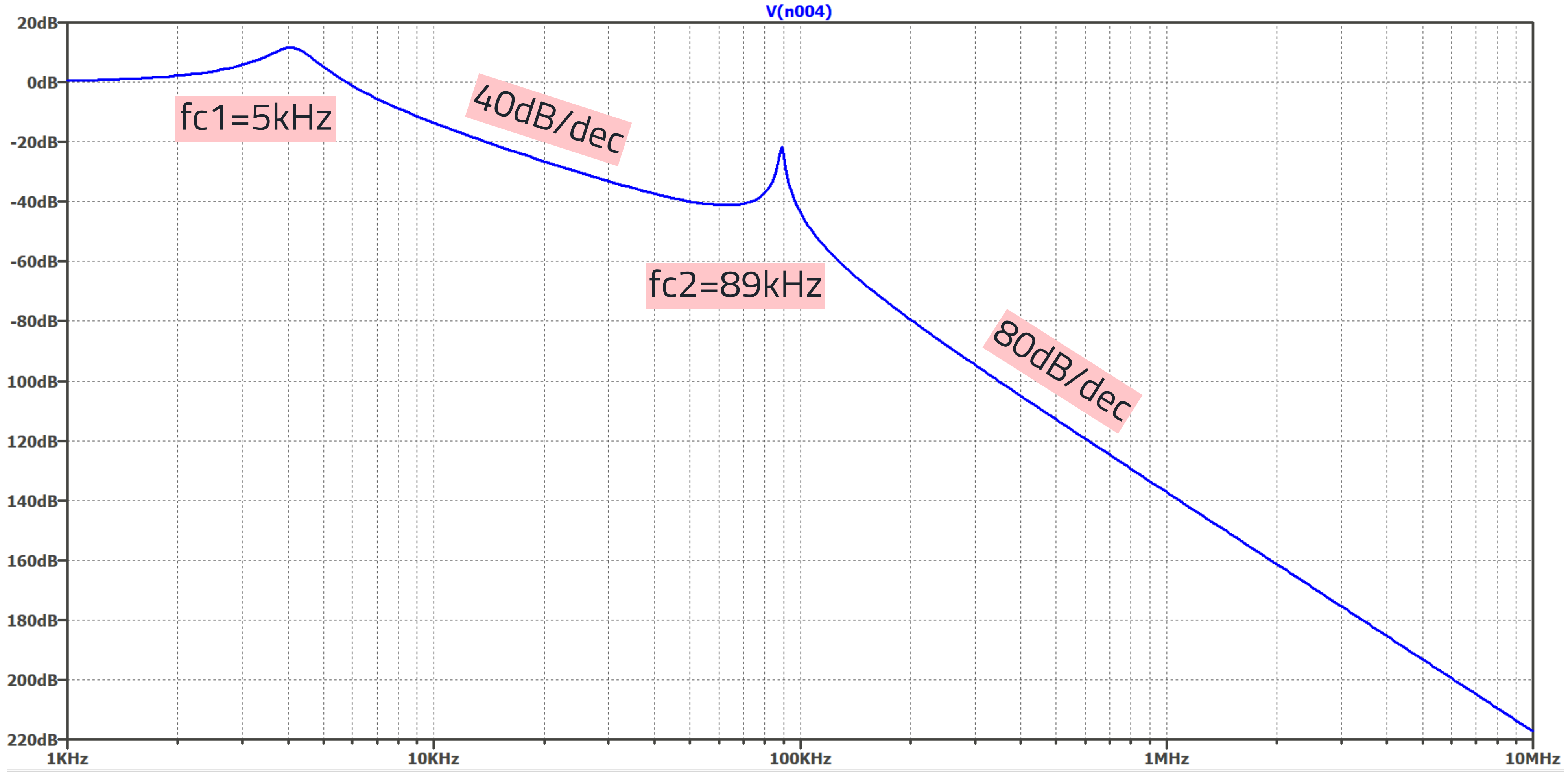
2-Stage Simulation Example

If the values of the filter components differ greatly



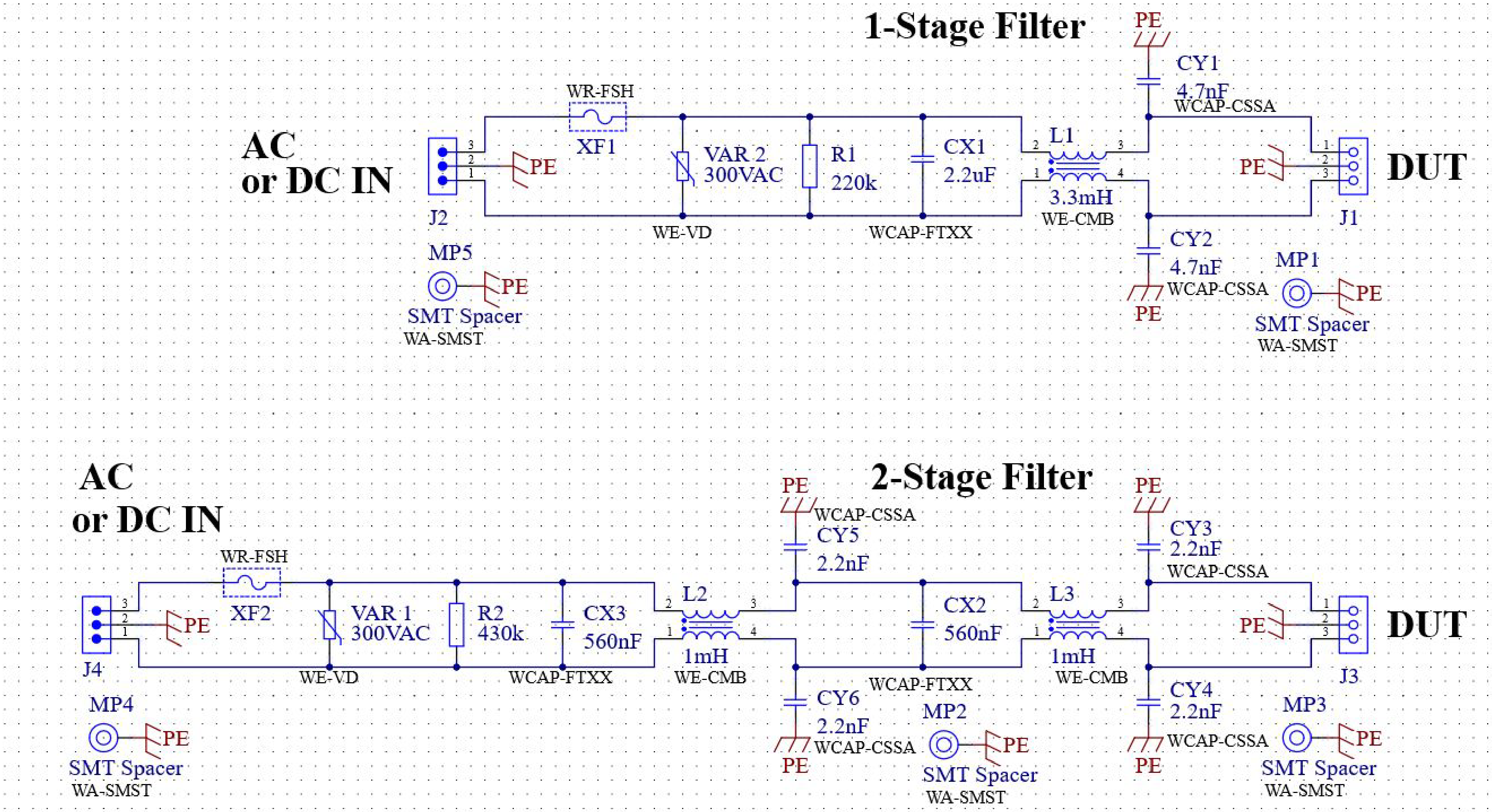
2-Stage Calculation Example

If the values of the filter components differ greatly

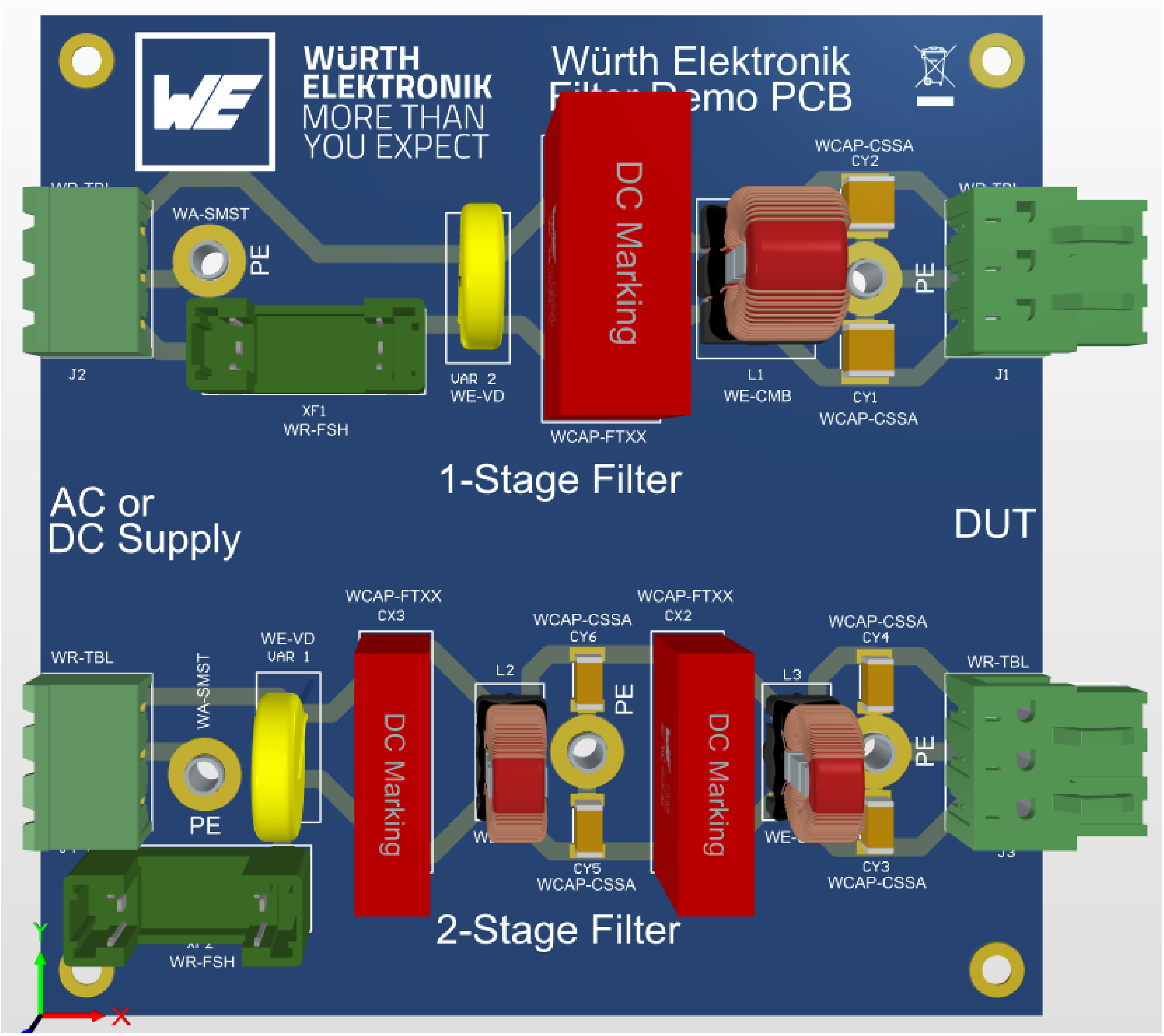


FILTER SCHEMATIC & PCB

Altium Schematic



Altium PCB

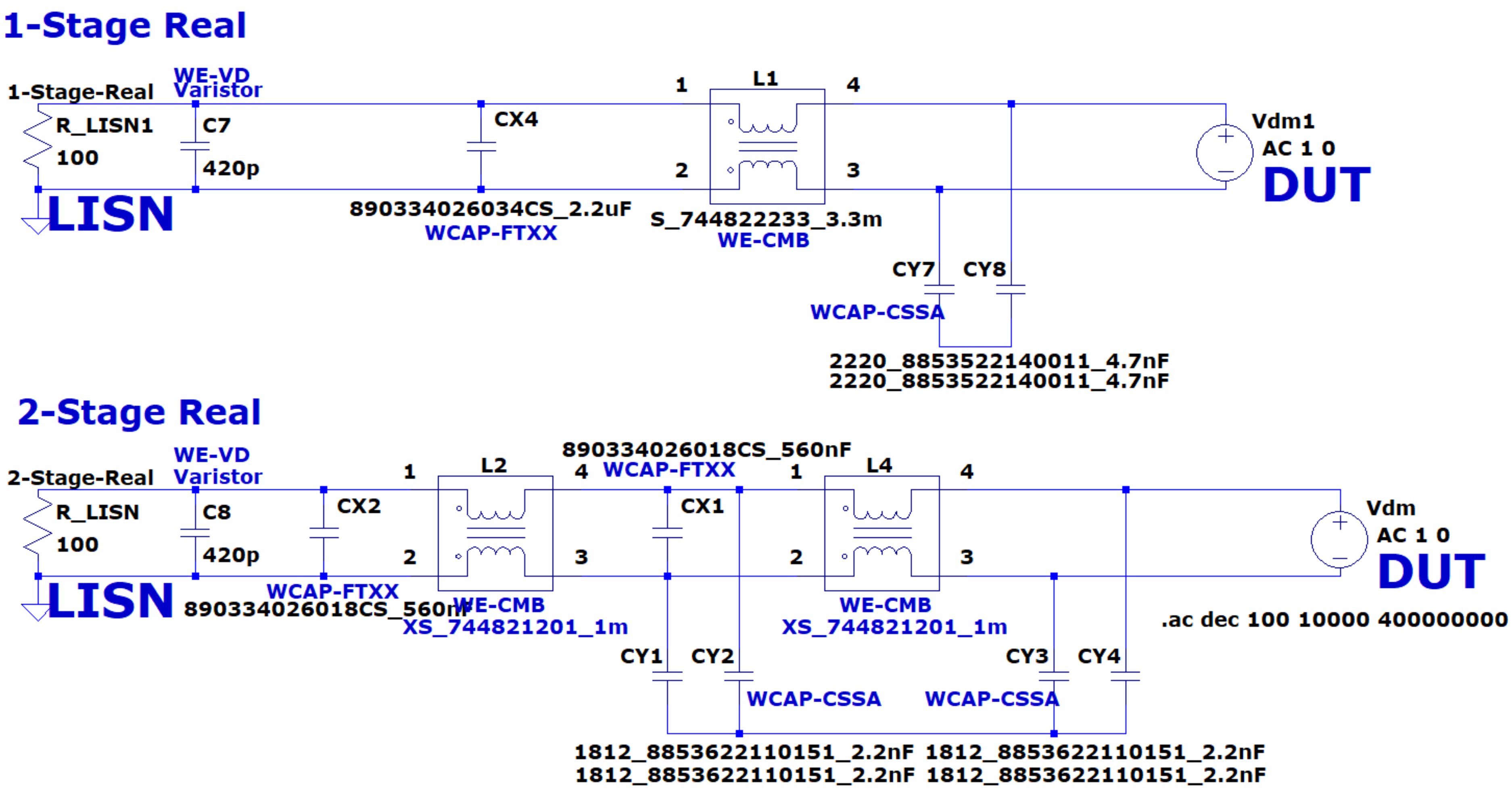


WÜRTH ELEKTRONIK
MORE THAN YOU EXPECT
Würth Elektronik
Filter Demo PCB
WA-SMST
PE
J2
XF1
WR-FSH
VAR 2
WE-VD
DC Marking
WCAP-FTXX
L1
WE-CMB
WCAP-CSSA
CY2
CY1
J1
1-Stage Filter
AC or
DC Supply
DUT
WCAP-FTXX
CX3
WCAP-CSSA
CY6
CX2
CY4
WR-TBL
WE-VD
VAR 1
L2
L3
CY5
CY3
WR-FSH
2-Stage Filter
Y
X

SIMULATIONS

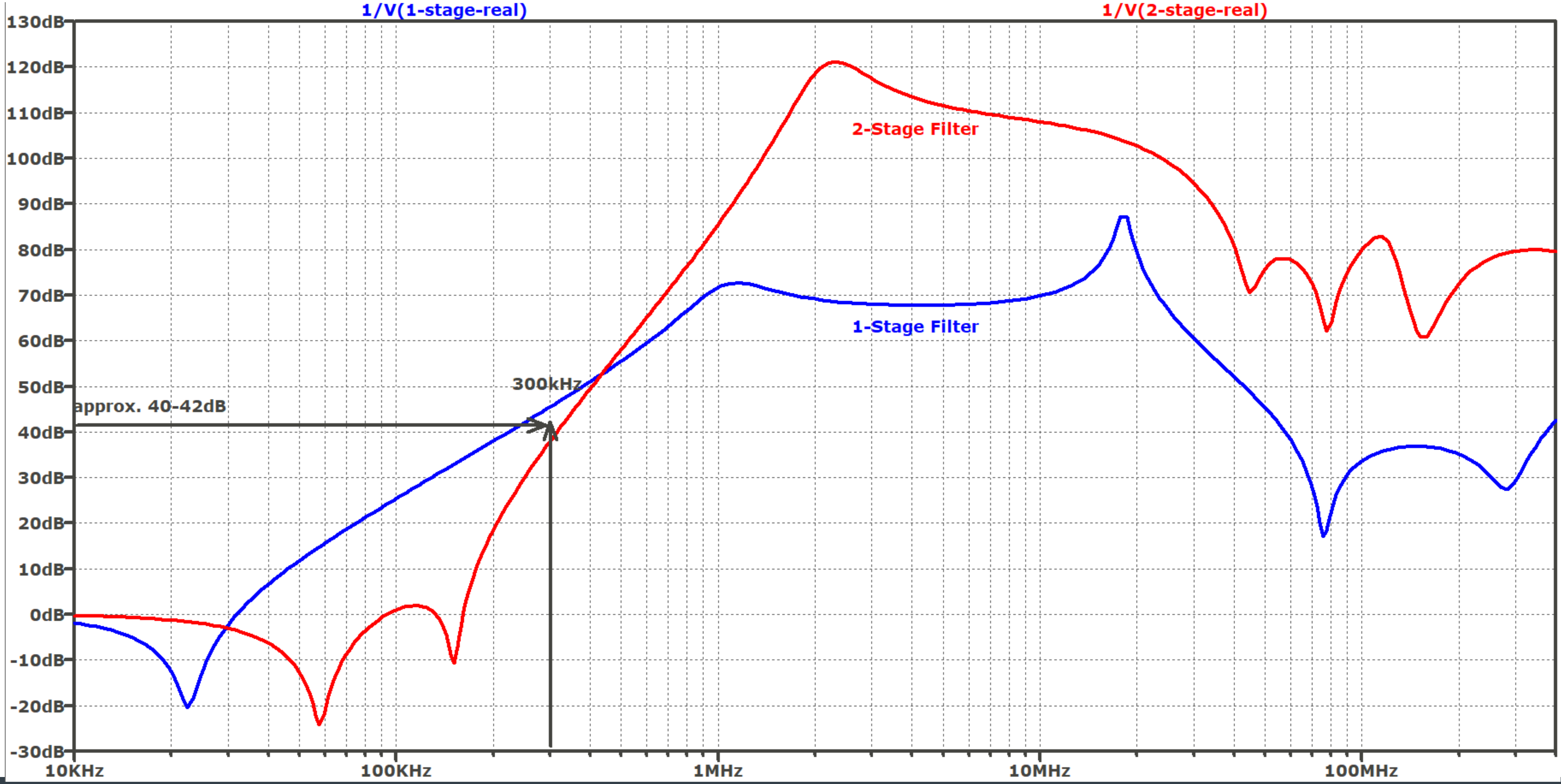
LT Spice

DM simulation



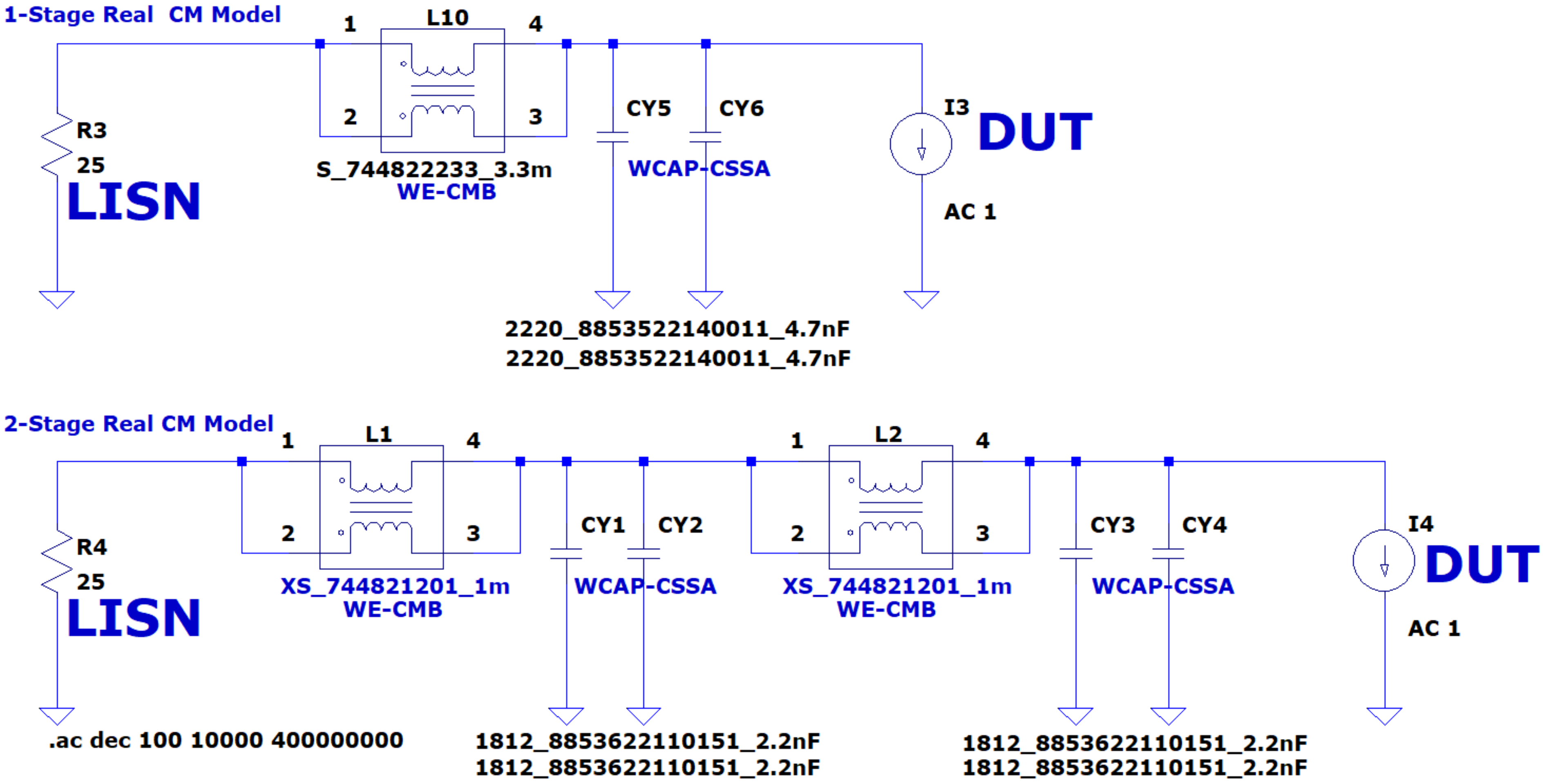
LT Spice

DM simulation



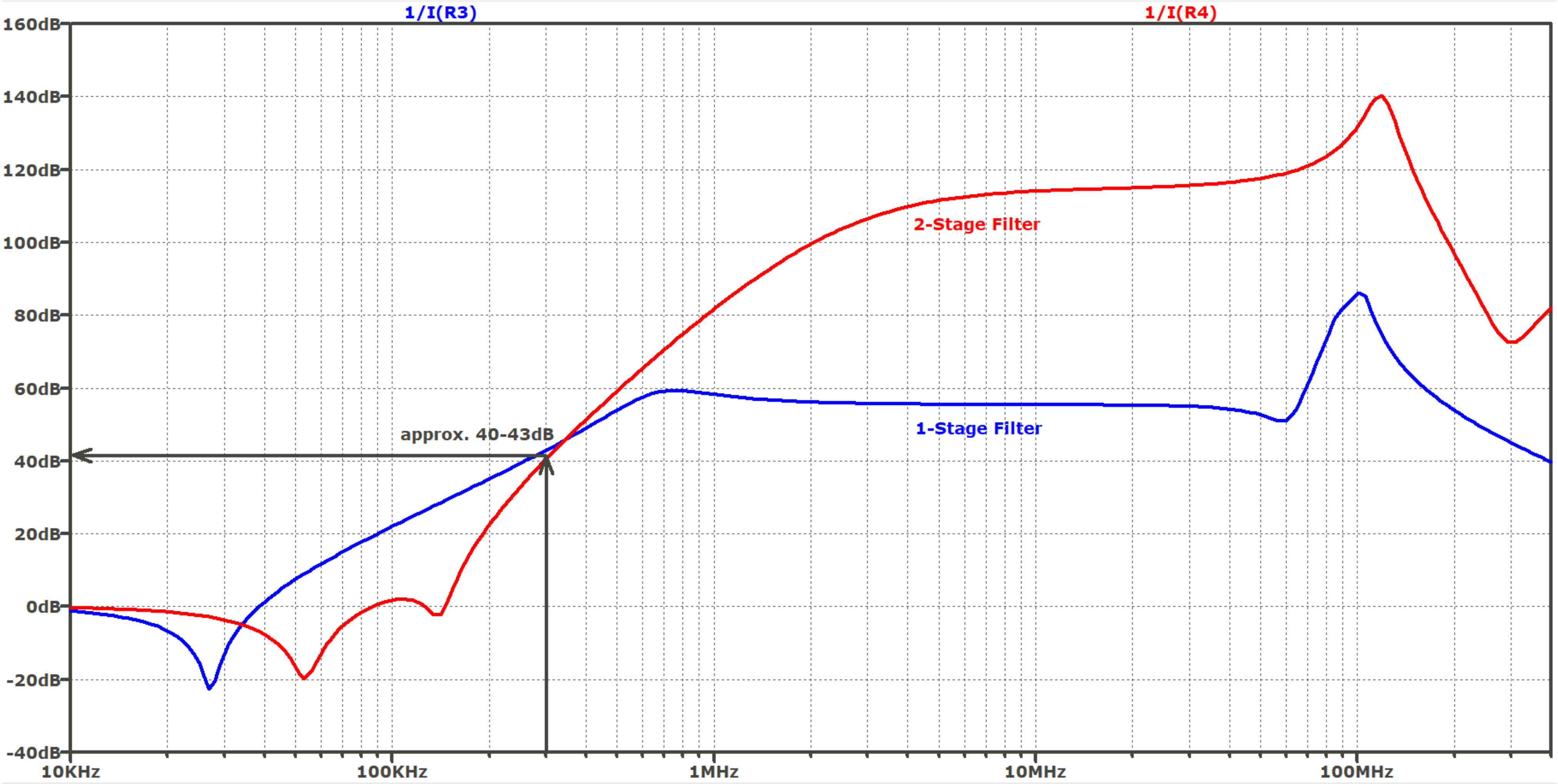
LT Spice

CM simulation



LT Spice

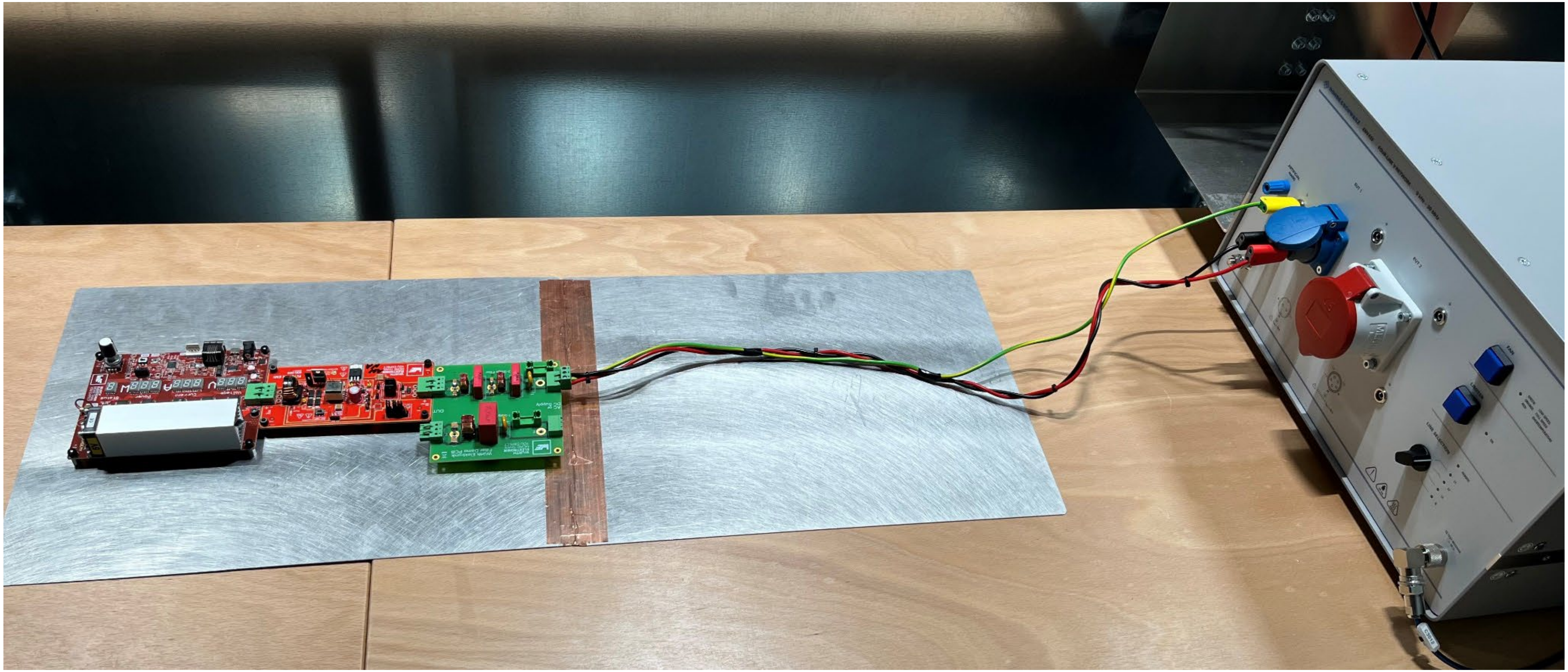
CM simulation



MEASUREMENTS FROM EMC LAB

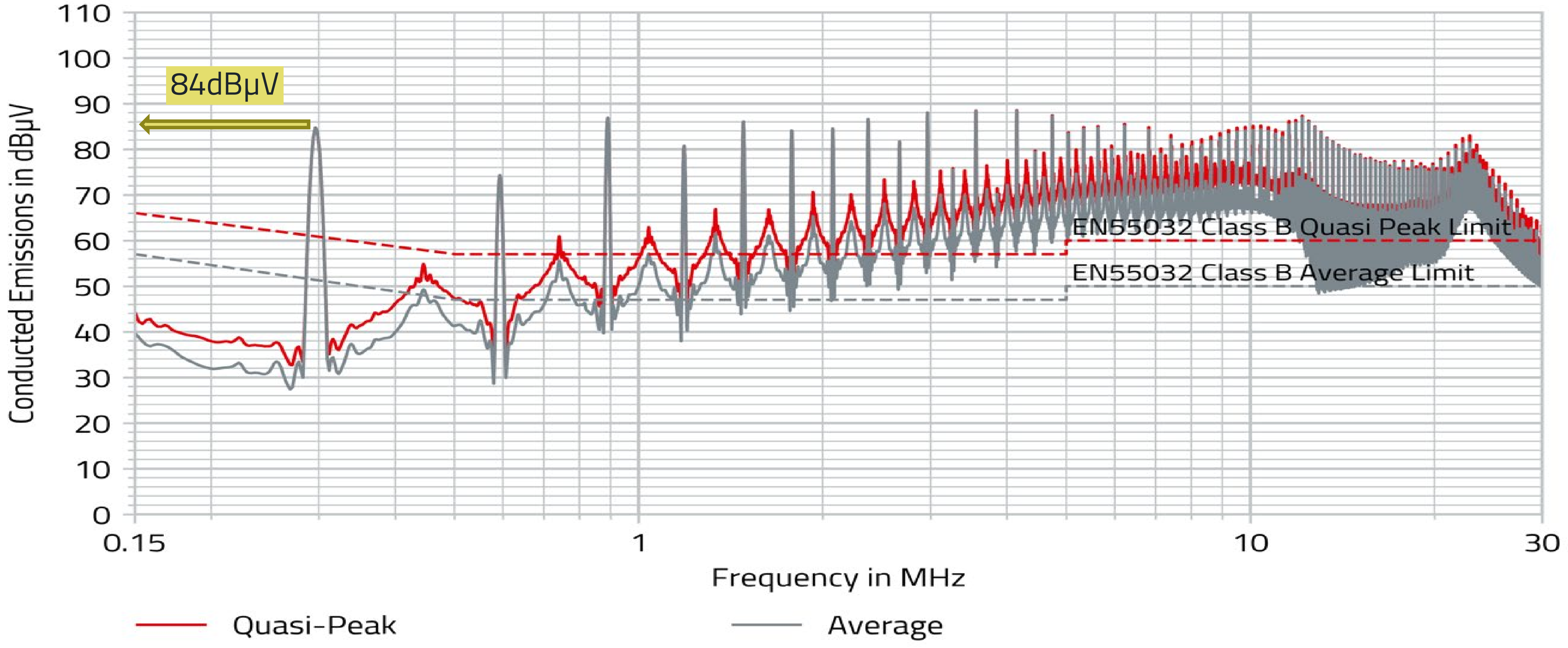
Test side: Würth Elektronik HIC Freiham

Test Setup Conducted



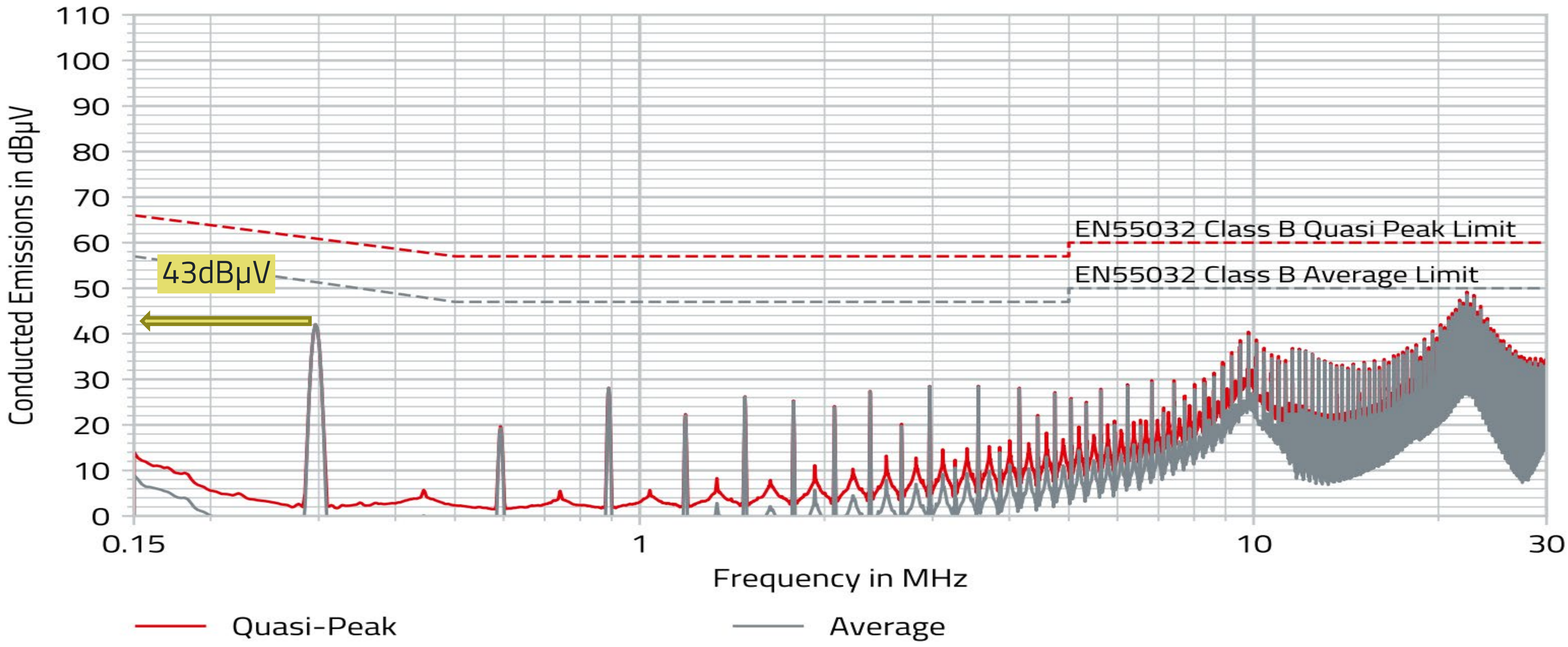
Conducted CM+DM

No Filter



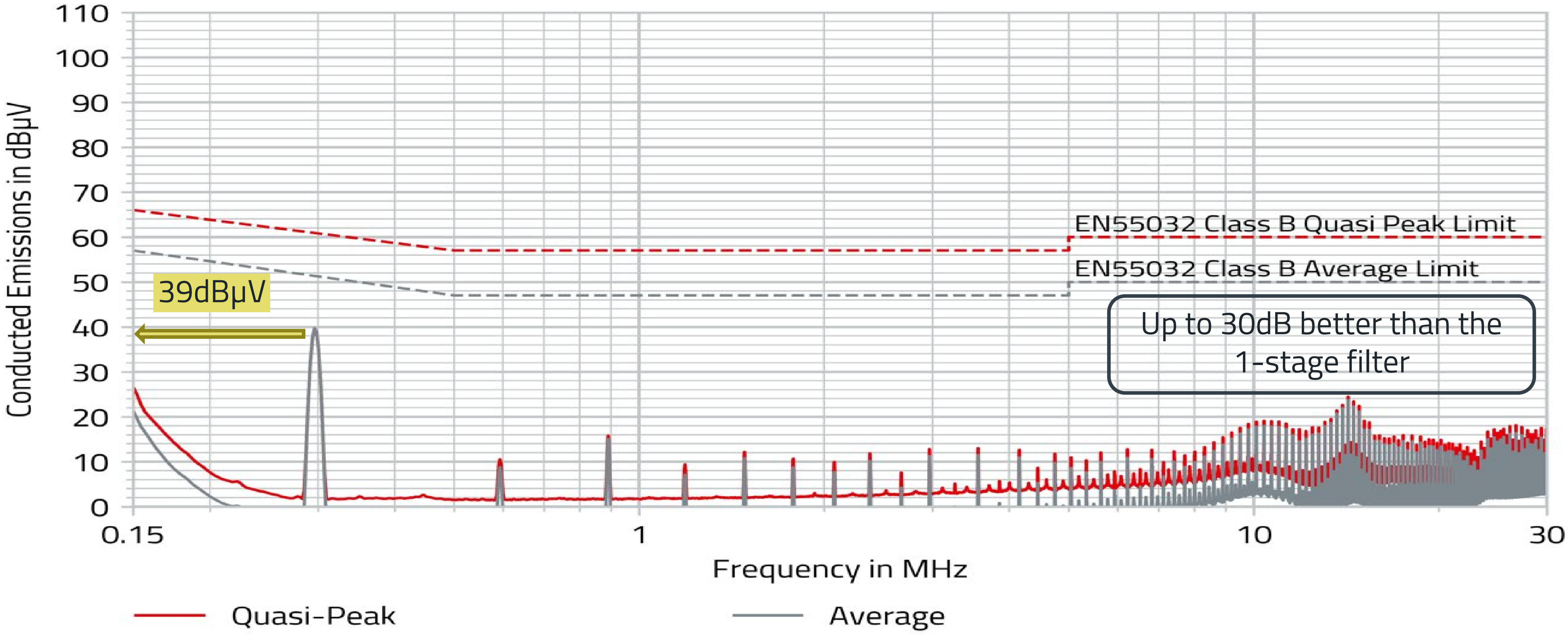
Conducted CM+DM

1-Stage Filter→ approx. 41dB damping *(41dB CM & 41dB DM was calculated)*

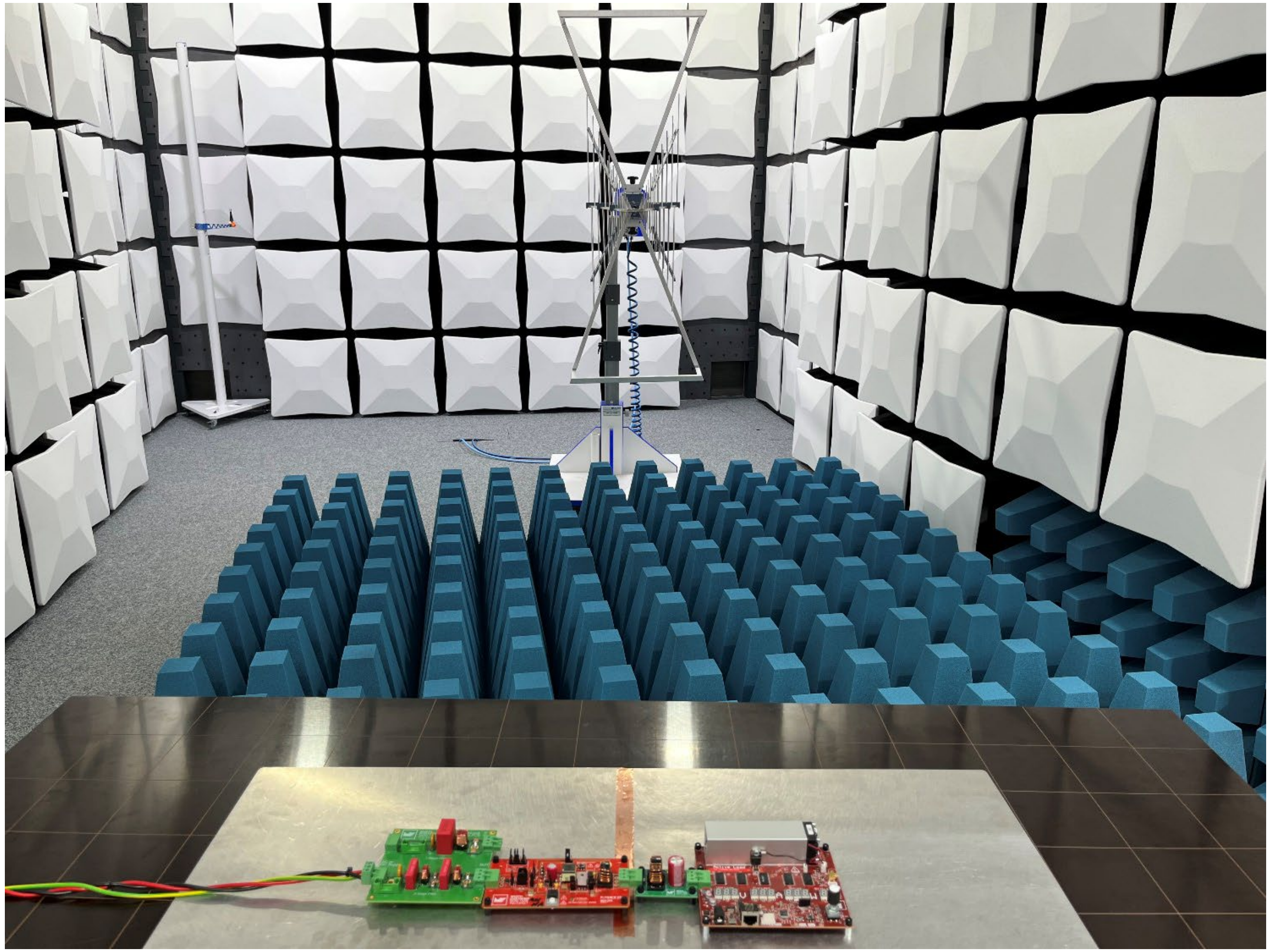


Conducted CM+DM

2-Stage Filter → approx. 45dB damping *(48dB CM & 45dB DM was calculated)*

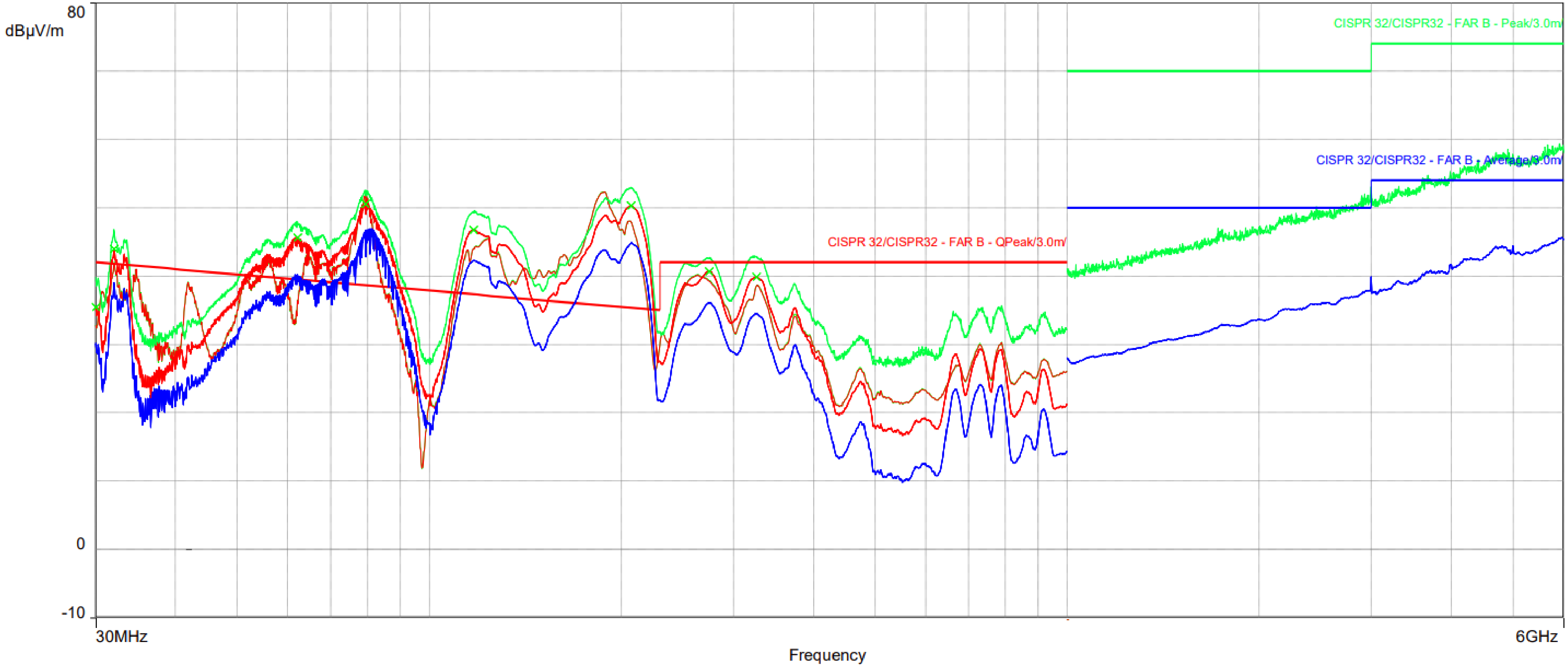


Test Setup Radiated



Radiated

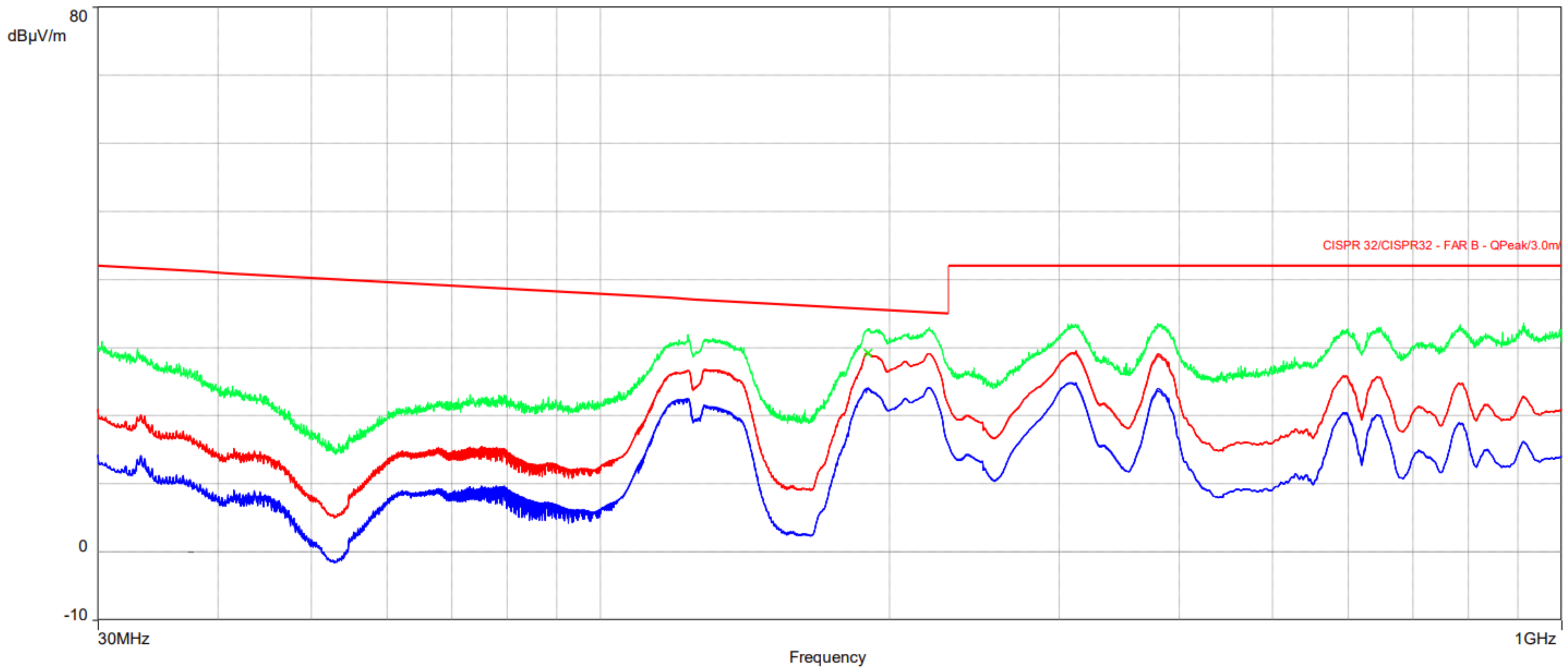
- No Filter



Radiated

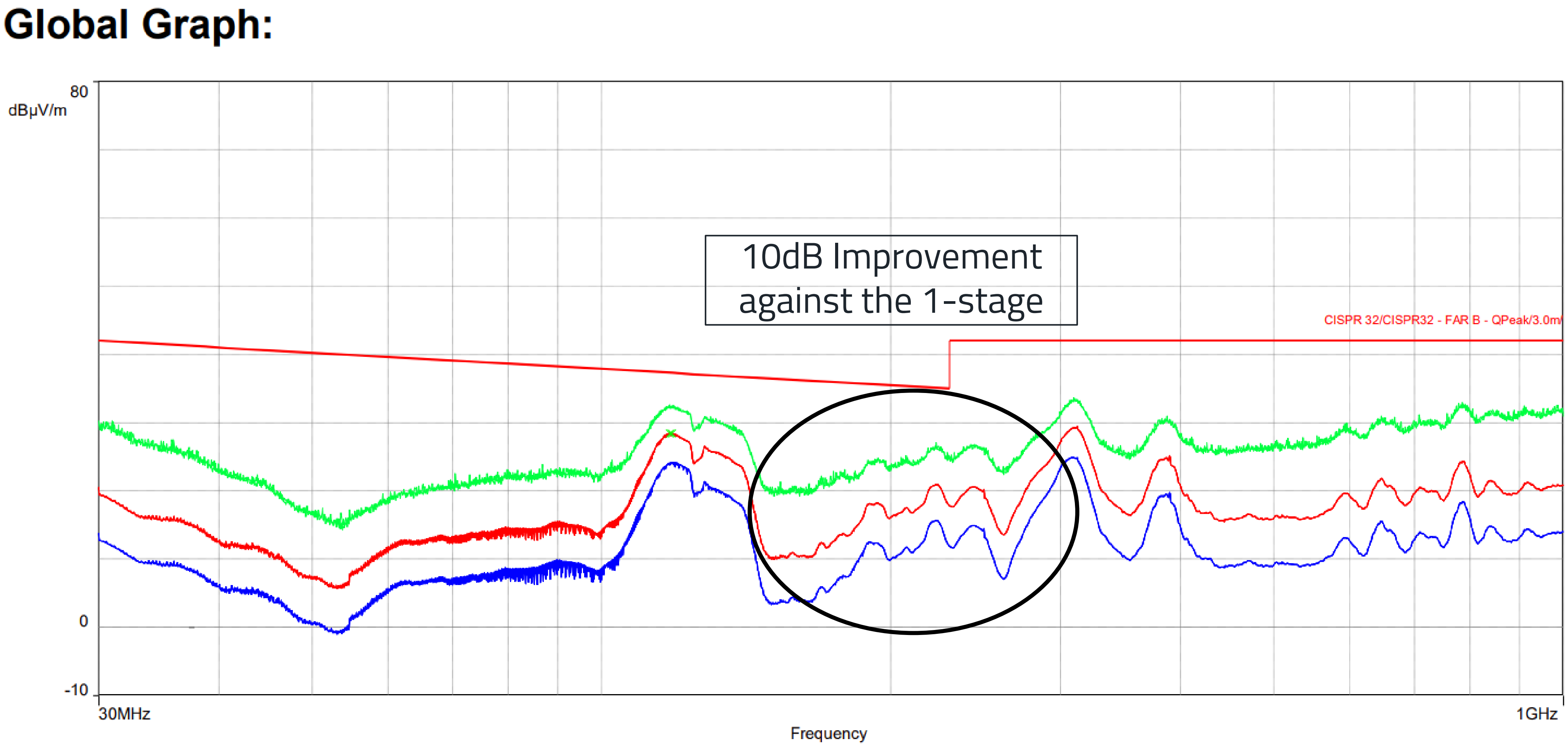
1-Stage Filter

Global Graph:



Radiated

2-Stage Filter



Possible Deviations

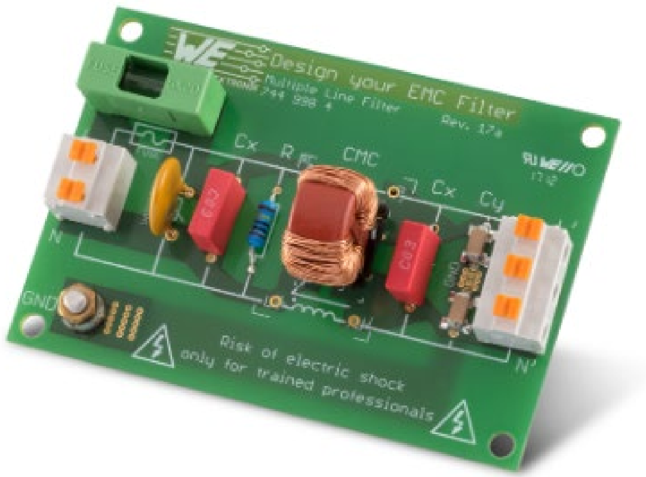
Measurement vs Math vs Simulation

- Inductance of supply wires
- Inaccuracy of simulation models
- Tolerance of the inductive and capacitive components
- Grounding of Y-caps
- CMC saturation effects
- ESL of filter PCB
- Parasitic inductive & capacitive couling between the filter components
- Varistor capacitance

Ready to use Filte PCBs

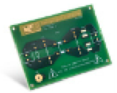
AC & DC versions

Order Code 7449984

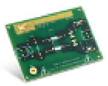


Order Code 744998

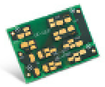
Filter Evaluation Boards



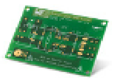
Evaluation Board Line Filter **NEW**



Evaluation Board Differential Filter **NEW**



Evaluation Board DC 2stepCMC Filter **NEW**



Evaluation Board Multiple Line Filter **NEW**

Questions

& Answers

We are here for you now!
Ask us directly via our chat or via E-Mail.

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Andreas.Nadler@we-online.de