EMI-FILTER
VON DER KOMPONENTE ZUM DESIGN

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Field Application Engineer

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

Reichs-Gesetzblatt.

№ 21.

Inhalt: Gesetz über das Telegraphenwesen des Deutschen Reichs. S. 467.

(Nr. 2015.) Gesetz über das Telegraphenwesen des Deutschen Reichs. Vom 6. April 1892.

Wir Wilhelm, von Gottes Gnaden Deutscher Kaiser, König von Preußen 2c.

verordnen im Namen des Reichs, nach erfolgter Zustimmung des Bundesraths und des Reichstags, was folgt:

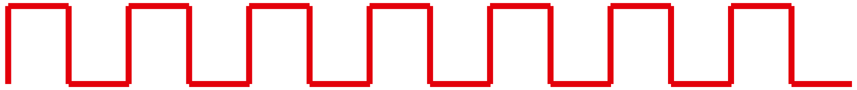
§. 12.

Elektrische Anlagen sind, wenn eine Störung des Betriebes der einen Leitung durch die andere eingetreten oder zu befürchten ist, auf Kosten desjenigen Theiles, welcher durch eine spätere Anlage oder durch eine später eintretende Aenderung seiner bestehenden Anlage diese Störung oder die Gefahr derselben veranlaßt, nach Möglichkeit so auszuführen, daß sie sich nicht störend beeinflussen.

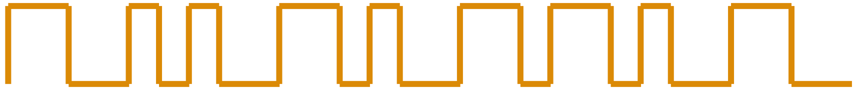
WO KOMMEN DIE STÖRER HER?

Origin of EMI

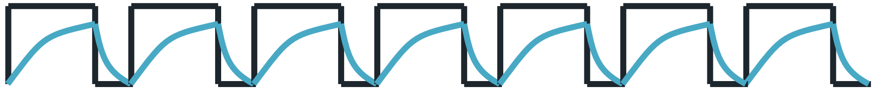
- Clock Signals
  - z.B. 25MHz, 2.6GHz



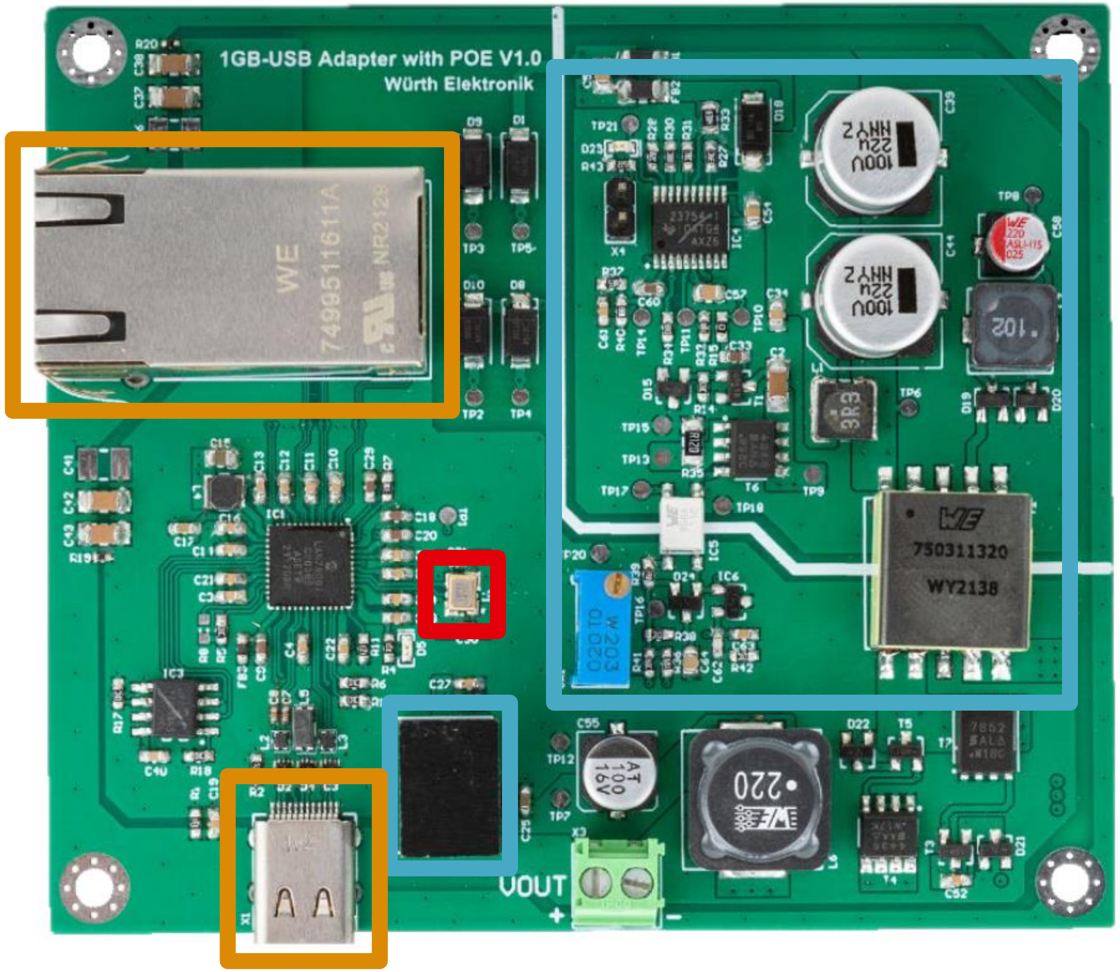
- Datalines
  - z.B. USB 2.0 480Mbps, SATA II 300Mbps



- DC/DC Converters
  - 150 kHz – 10 MHz



WE eiSos



Enstehung von Überspannung

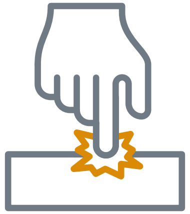
- Natürliche Phänomene
  - z.B.: indirekter Blitzschlag

- EN 61000-4-5
  - Surge mit hoher Energie

- Industrielle Entladungen
  - z.B.: Schalten induktiver Lasten

- EN 61000-4-4
  - EFT

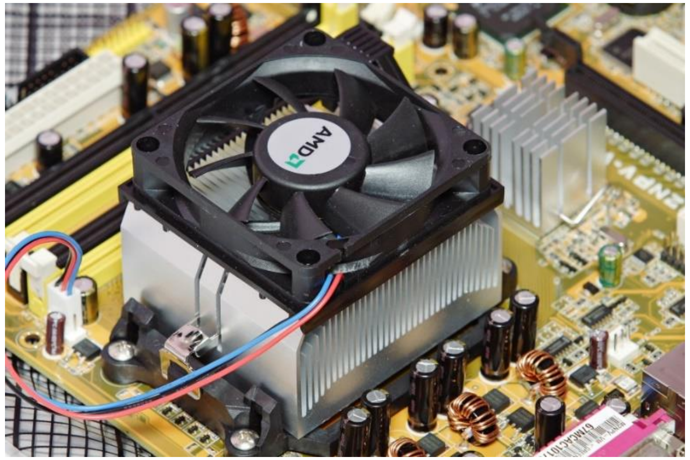
- Elektrostatische Entladung
  - z.B.: zwischen Mensch und Material



- EN 61000-4-2
  - ESD

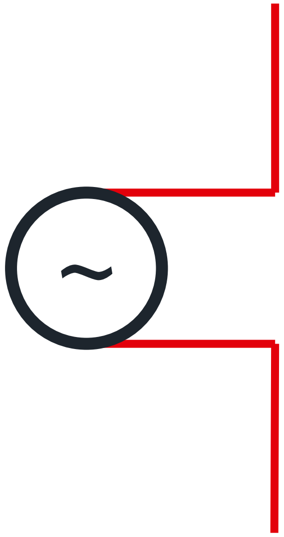
WIE VERBREITEN SICH DIE STÖRER?

Jeder Leiter ist eine Antenne

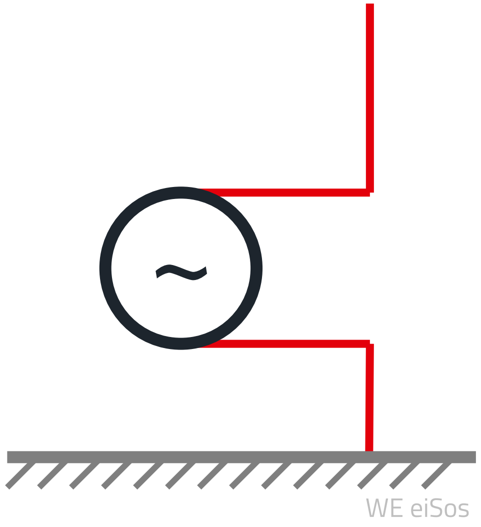


- Kabel
- Leiterzüge
- Bauteile
- ICs
- Kühlkörper
- Gehäuse

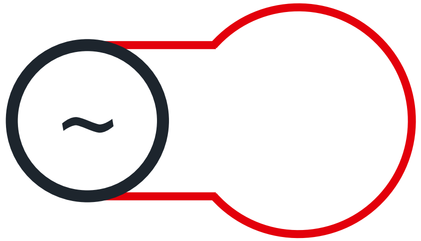
Jeder Leiter ist eine Antenne



Elektrische
Dipolantenne



Elektrische
Monopolantenne

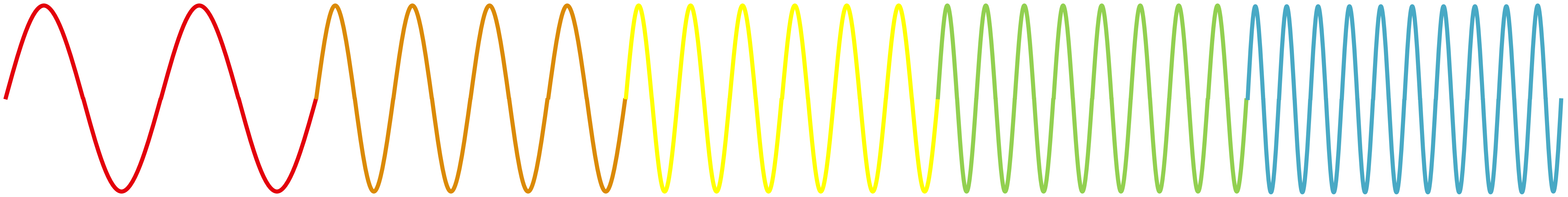


Magnetische
Rahmenantenne

Frequenz und Wellenlänge

$$c = \lambda * F$$

$$c = 300x10^6 \ {}^{m}/_{s}$$



Niedrige Frequenz

große Wellenlänge

Hohe Frequenz

kleine Wellenlänge

Netzfrequenz 50 Hz

λ = 6000 km

30 MHz

λ = 10 m

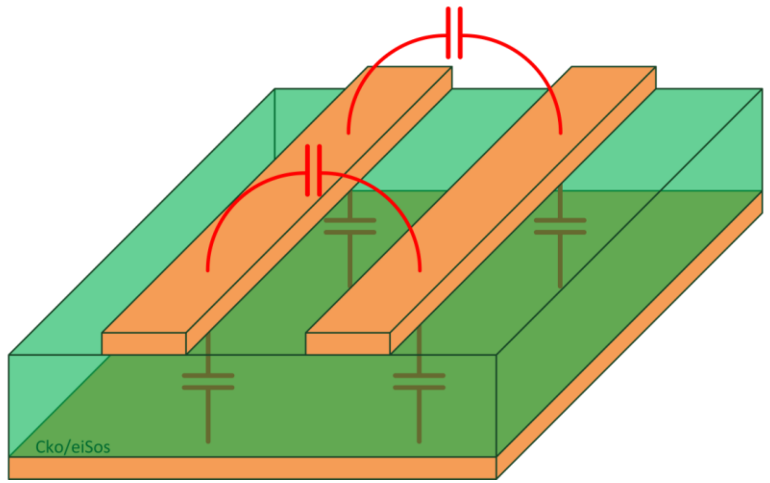
WLAN/ Bluetooth 2,4 GHz

λ = 12,5 cm

Capacitive Coupling

Origins

- Originates from high dU/dt
- Parallel conductors form a parasitic capacitance
- Coupling capacitance is directly proportional to the length of the parallel trace run



Isolating Components	typ. Coupling Capacitance
Optocoupler	0,5…5 pF
Solid State Relay	0,5…10 pF
Gate Drive Transformer	2…10 pF
Electromechanical Relay	10…100 pF
Digital Isolator	100…200 pF
Digital Isolator (int. SMPS)	300…600 pF
Transformers in SMPS	Up to 1000 pF

Capacitive Coupling

Effects

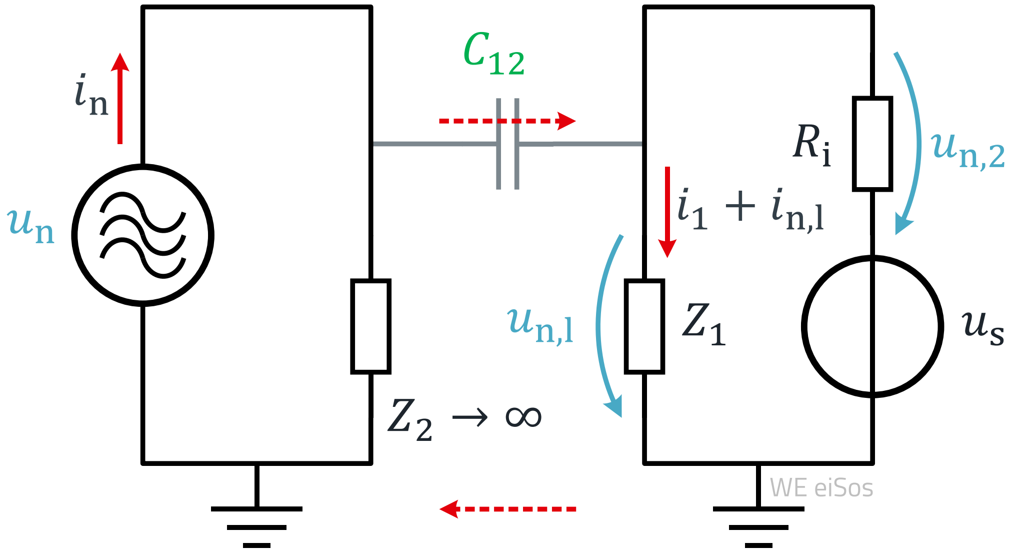
- Voltage interference at the load:

$$u_{n,l} = i_n \cdot \frac{R_i \cdot Z_1}{R_i + Z_1} = C_{12} \cdot \frac{du_n}{dt} \cdot \frac{R_i \cdot Z_1}{R_i + Z_1}$$

  - Laplace made easy: replace $\frac{d}{dt}$ by $j\omega$

$$U_{n,l} = U_n \cdot j\,\omega\, C_{12} \cdot \frac{R_i \cdot Z_1}{R_i + Z_1}$$

$$C_{12} = \varepsilon \cdot \frac{A}{d}$$

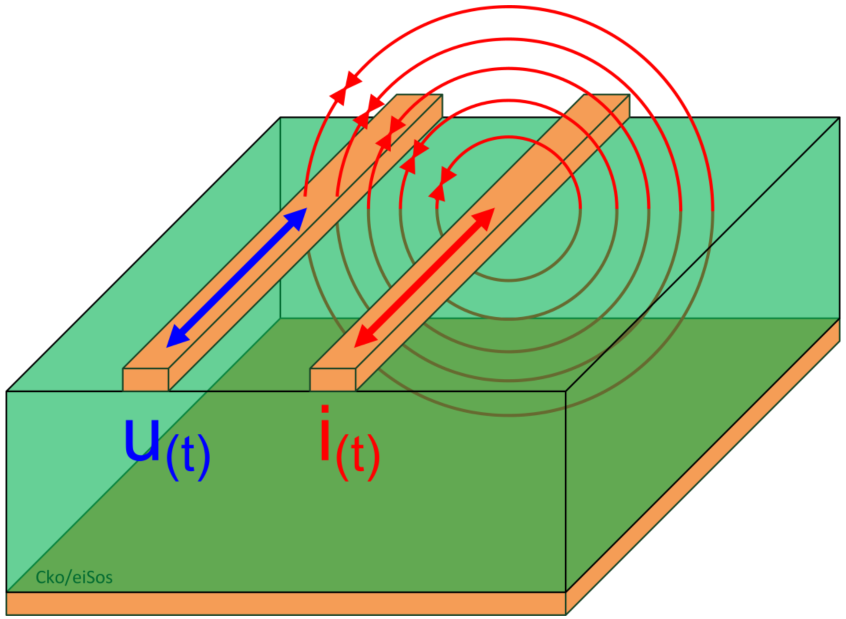


- Doubling the frequency doubles the crosstalk (+6 dB)
- Doubling the sink impedance (Ri||Z1) doubles the crosstalk

Inductive Coupling

Origins

- Originates from high dI/dt
- Parallel traces form a parasitic transformer
- Mutual Inductance increases with shorter distance



Inductive Coupling

Effects

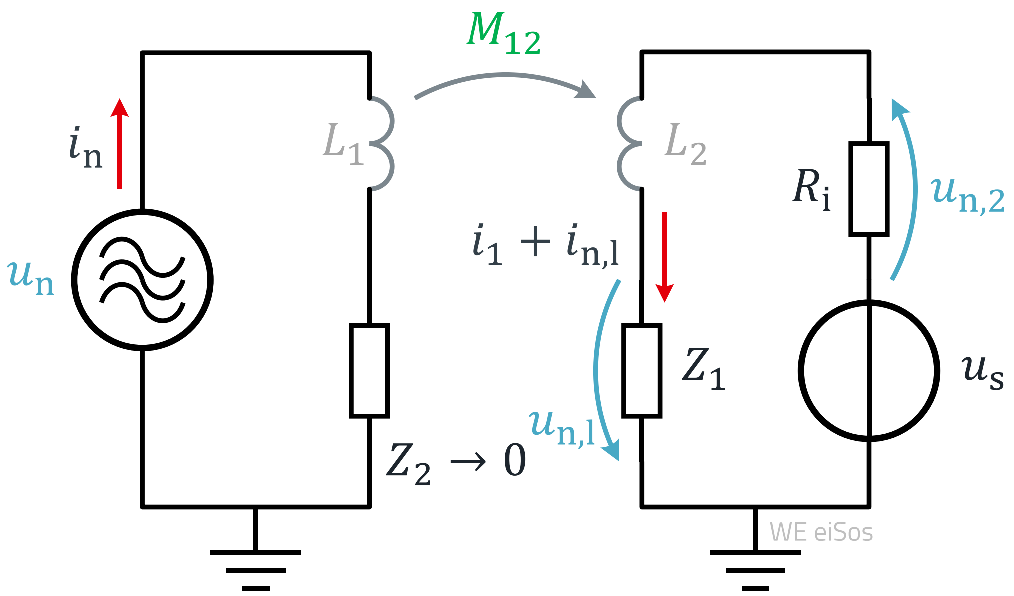
- Voltage interference at the load (Z1 = Near End):

$$u_{n,l} = M_{12} \cdot \frac{di_n}{dt} \cdot \frac{Z_1}{R_i + Z_1}$$

  - Lapace made easy: replace $\frac{d}{dt}$ by $j\,\omega$

$$U_{n,l} = I_n \cdot j\,\omega\, M_{12} \cdot \frac{Z_1}{R_i + Z_1}$$

$$M_{12} = \mu \cdot N_1 N_2 \cdot \frac{A}{l}$$



- Doubling the frequency doubles the crosstalk (+6 dB)
- Crosstalk increases with inductive loop dimensions

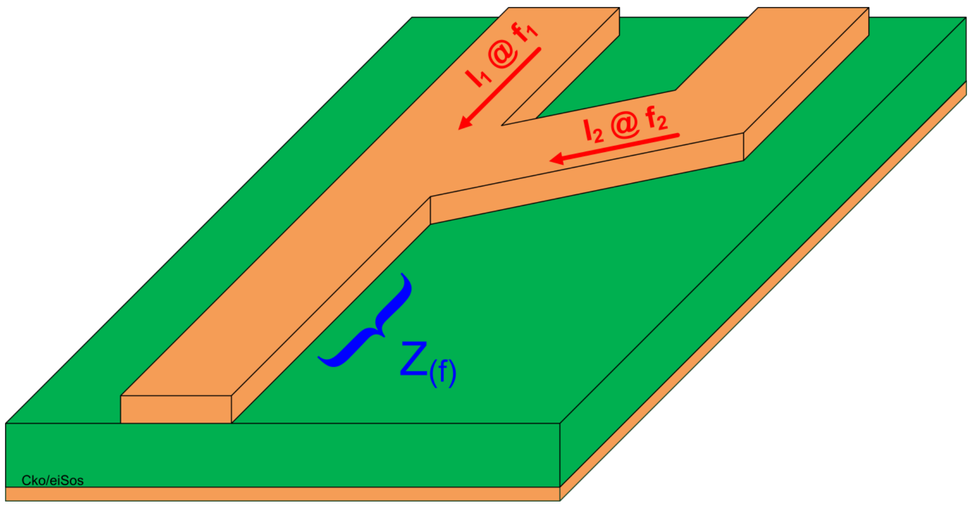
- Lenz's Law: Phase reversal of the induced current can be observed at the far end
- Voltage interference at the source (Ri = Far End):

$$U_{n,2} = -I_n \cdot j\,\omega\, M_{12} \cdot \frac{R_i}{R_i + Z_1}$$

Impedance Coupling

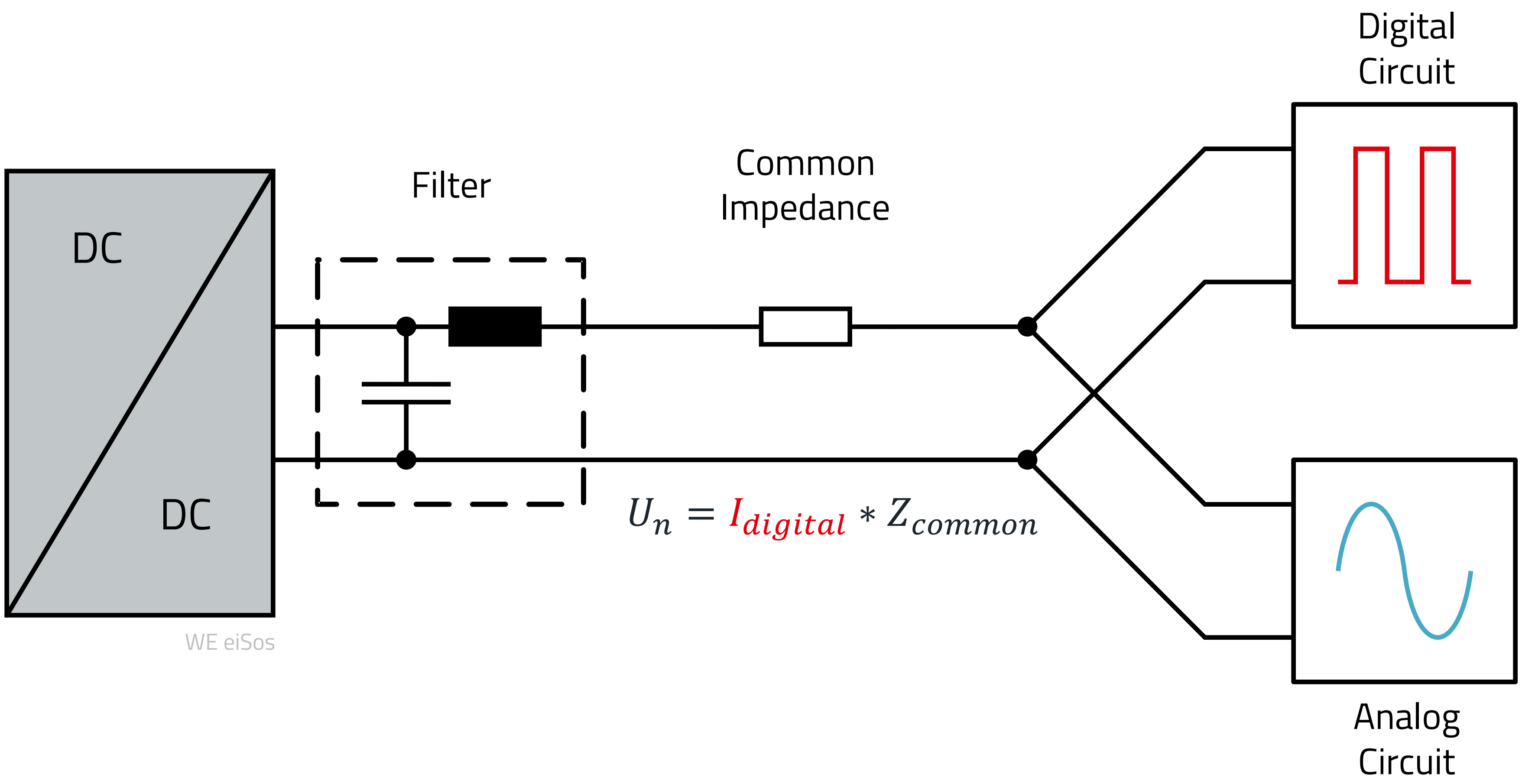
Origins

- Interference affects circuits with a mutual traces
- Circuits share an impedance and therefore the voltage across that impedance
- Main cause for high mutual impedances is self-inductance across copper traces

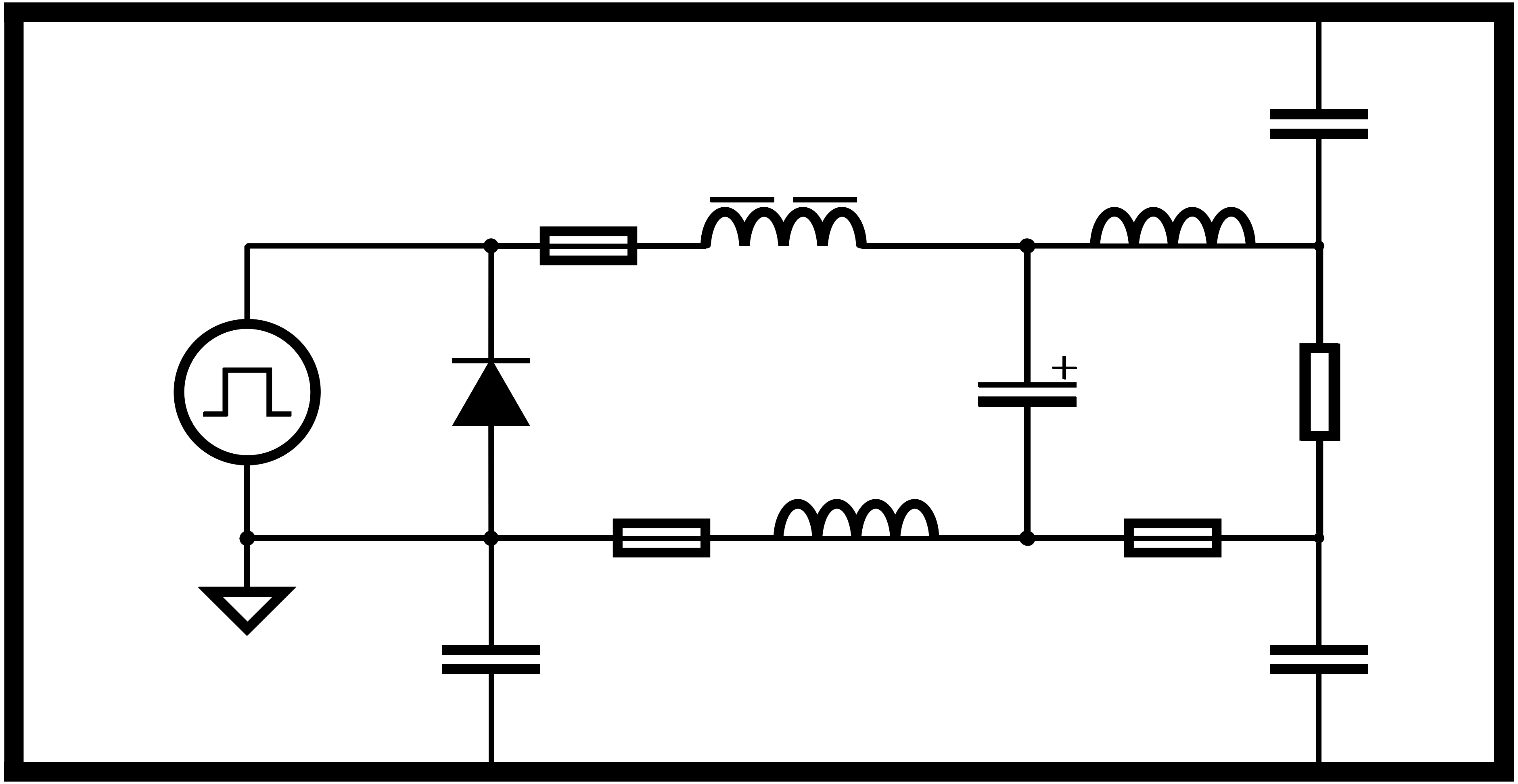


Impedance Coupling

A closer look



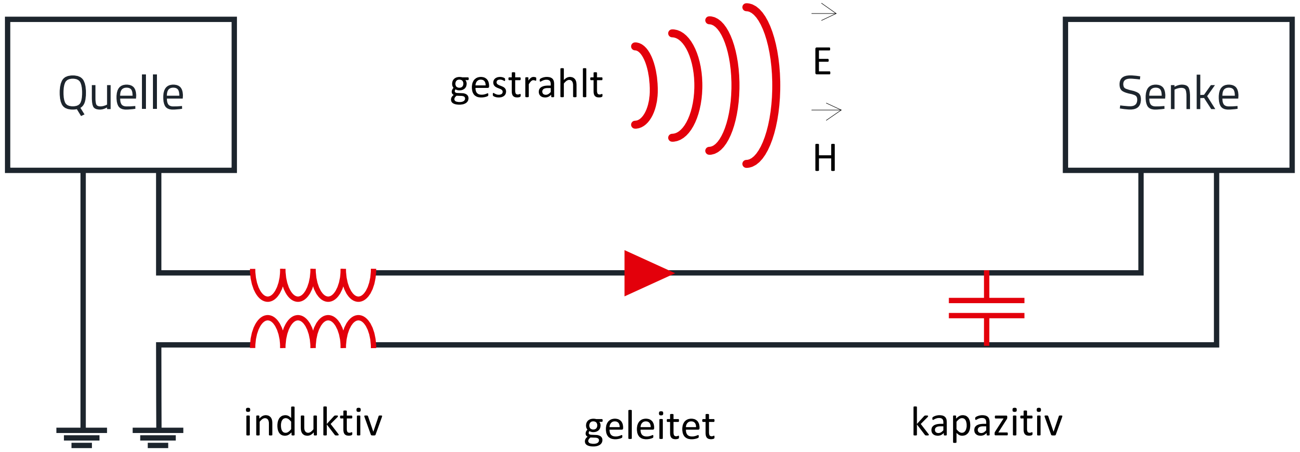
Plan und Resultat



WAS KANN ICH GEGEN STÖRER TUN?

EMV - Maßnahmen

- Ausreichende EMV lässt sich meist durch geeignete Maßnahmen an Sender, Pfad oder Empfänger erreichen.
  - **Primärmaßnahme** Emissionen des Senders minimieren
  - **Sekundärmaßnahme** Unterbrechung der Kopplungsmechanismen
  - **Tertiärmaßnahme** Störfestigkeit des Empfängers erhöhen



Capacitive Coupling

Measures to decrease coupling

- **Primary Measure**
  - Decrease dU/dt by selecting a slower signal edges
  - A Low pass filter to take off the edges

- **Secondary Measure**
  - Shorten/avoid parallel trace runs
  - Small areas for switched polygons (e.g. DC/DC switch node)
  - Increase distance between affected paths
  - Electrical shielding (Cable, PCB, Housing)

Inductive Coupling

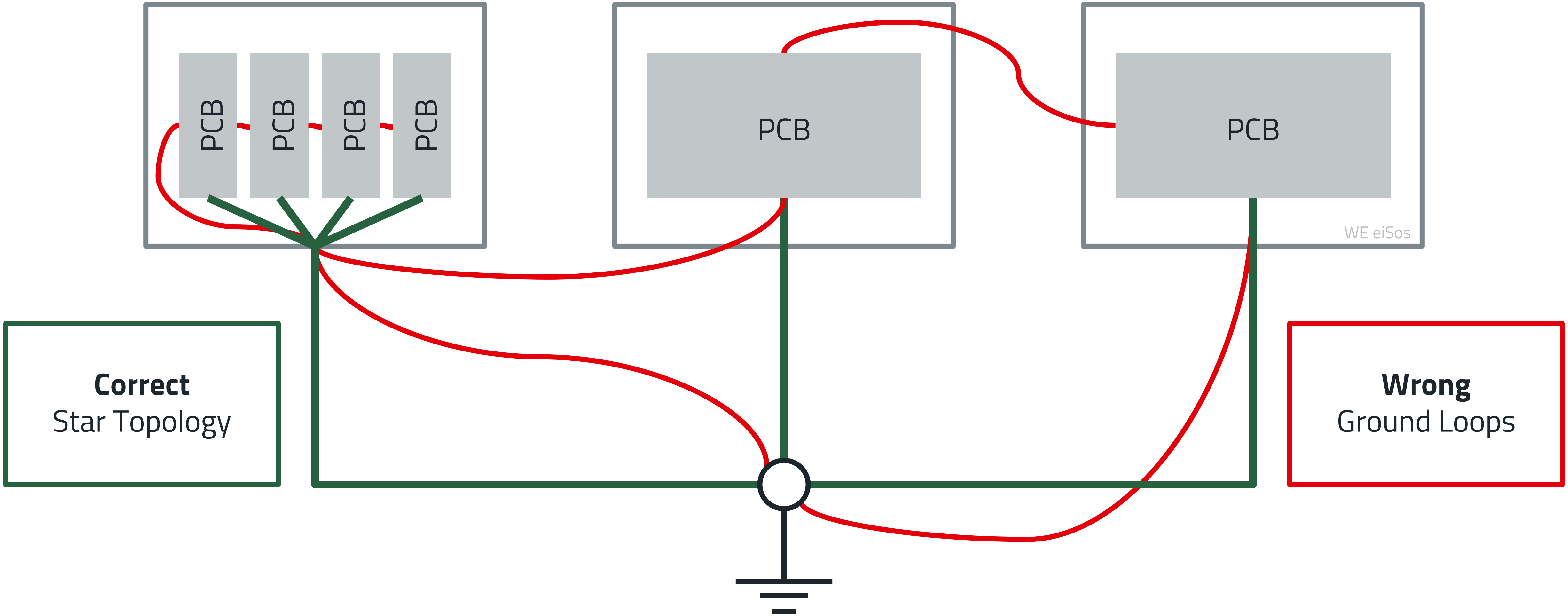
Measures to decrease coupling

- **Primary Measure**
  - Decrease dI/dt by selecting a lower switching frequency and slower signal edges
  - A filter Inductor/Ferrite to take off the edges

- **Secondary Measure**
  - Decrease magnetic loop area
  - Increase distance between affected circuits
  - Orthogonal component placement
  - Magnetic shielding with ferrite materials (soft permeability, high μ_r)

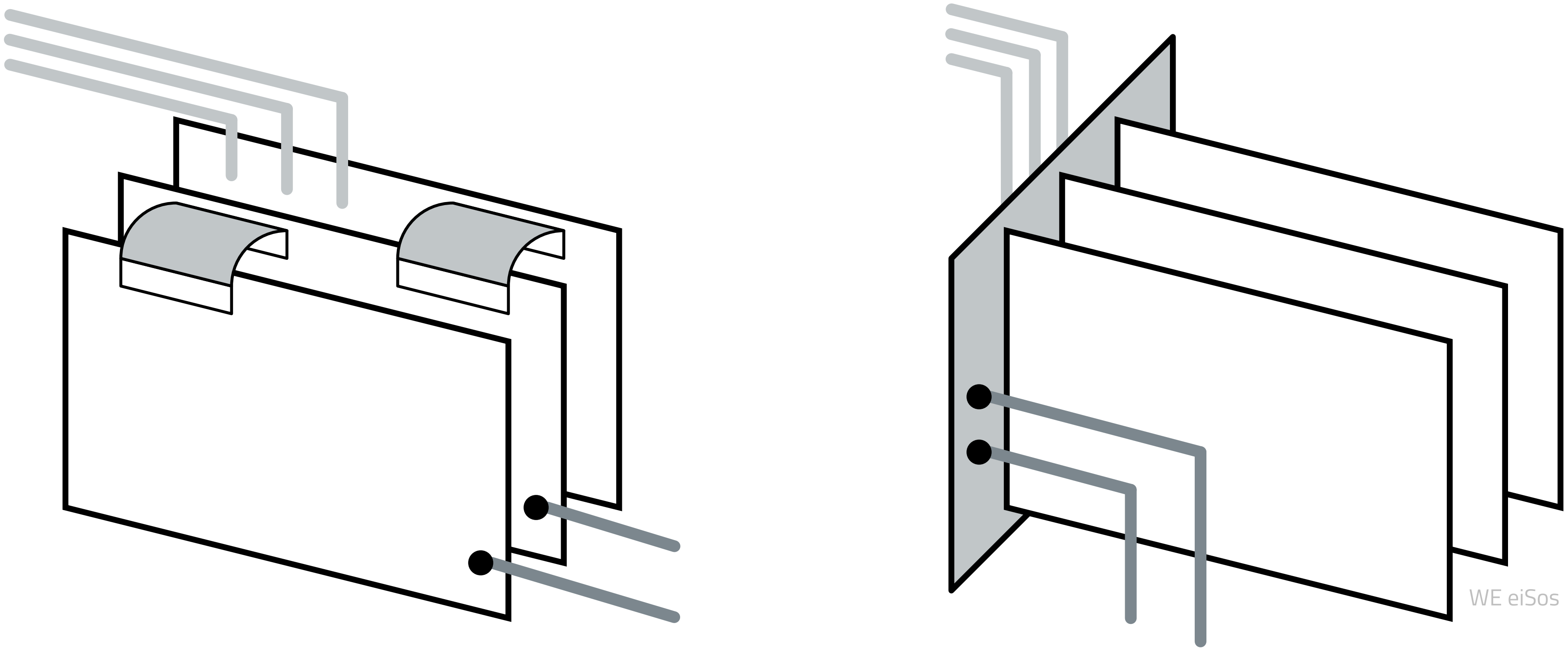
Ground Concept

Distribution across multiple PCBs



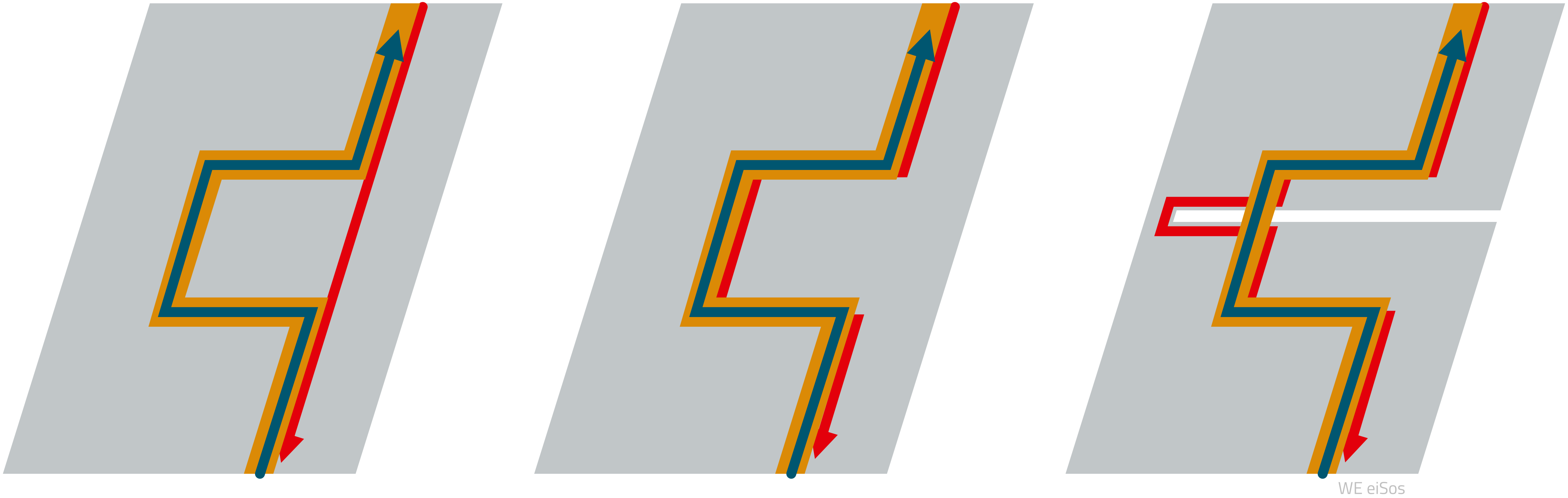
Ground Concept

Distribution across multiple PCBs



Changes in the Construction can make or break EMC

Path of least Impedance



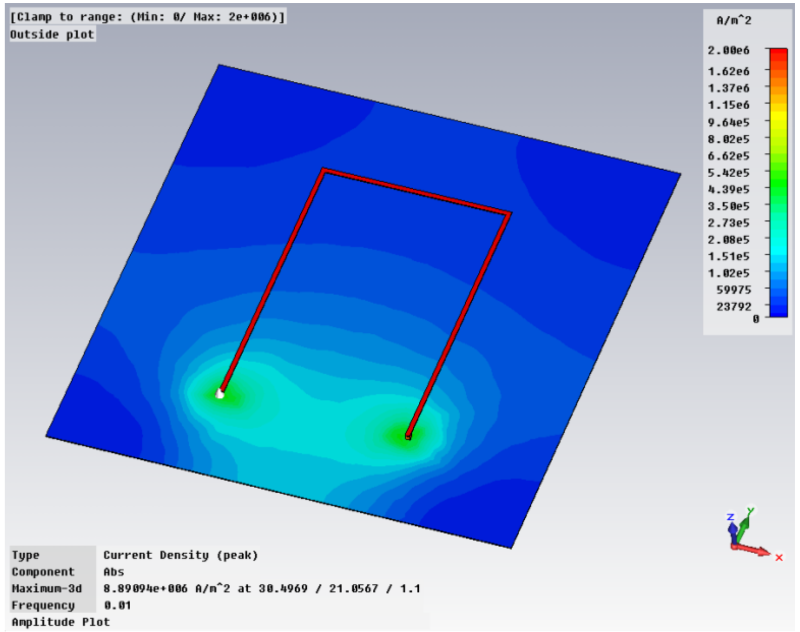
DC Return Path

AC Return Path

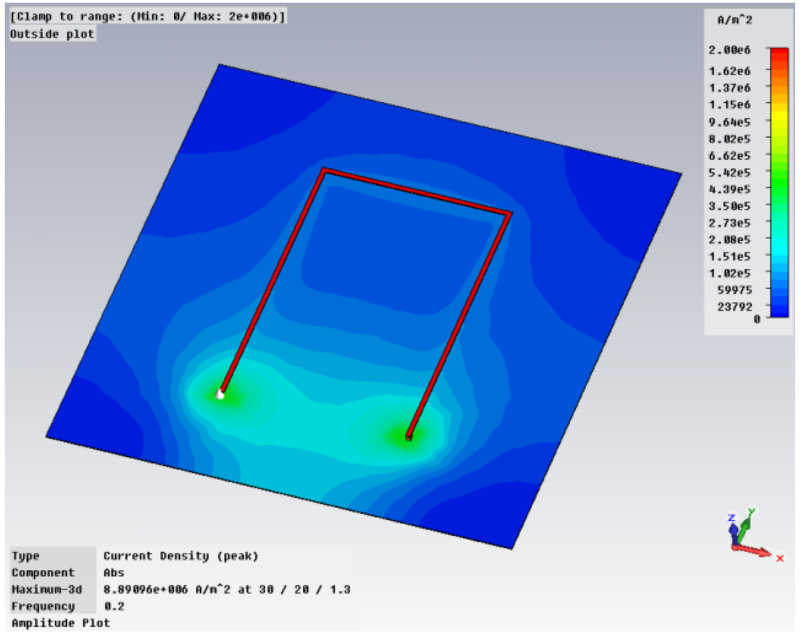
Slotted AC Return Path

Path of least Impedance

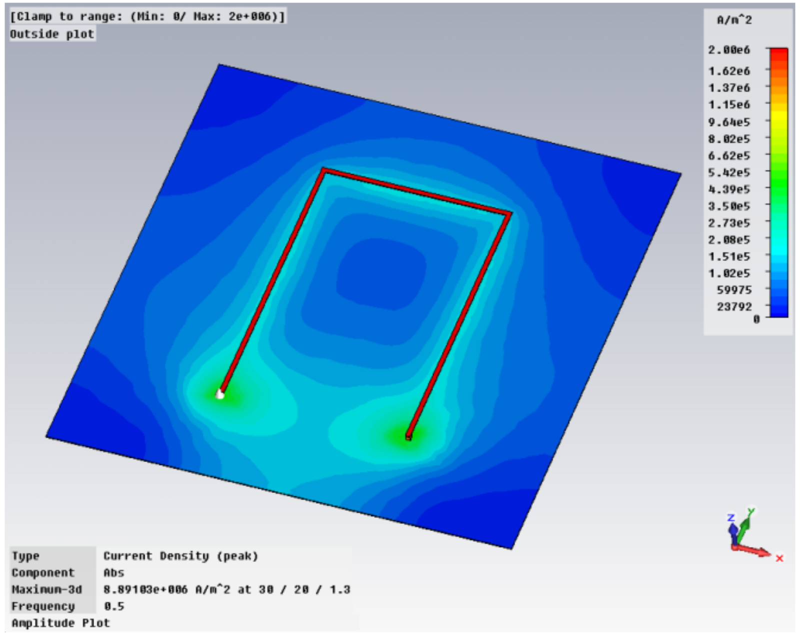
Simulation: Return Path depending on Frequency



10 Hz



200 Hz

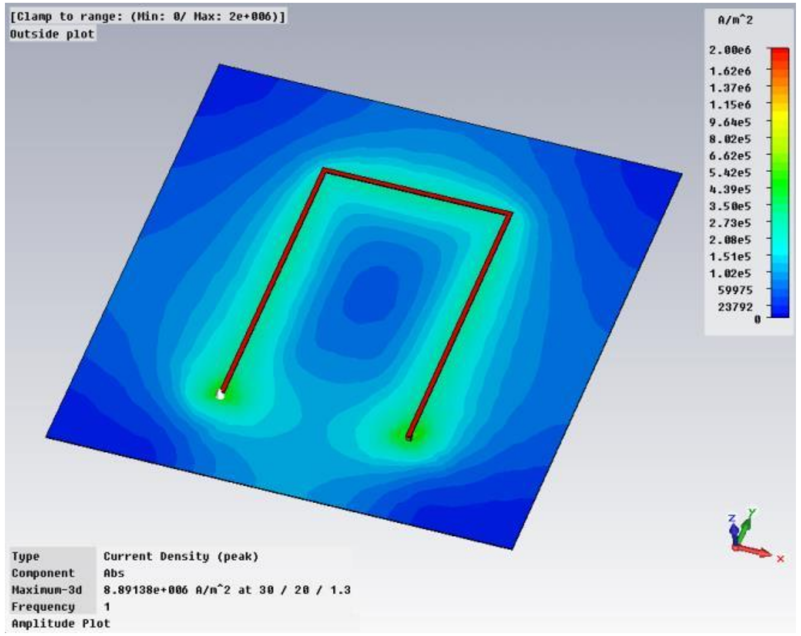


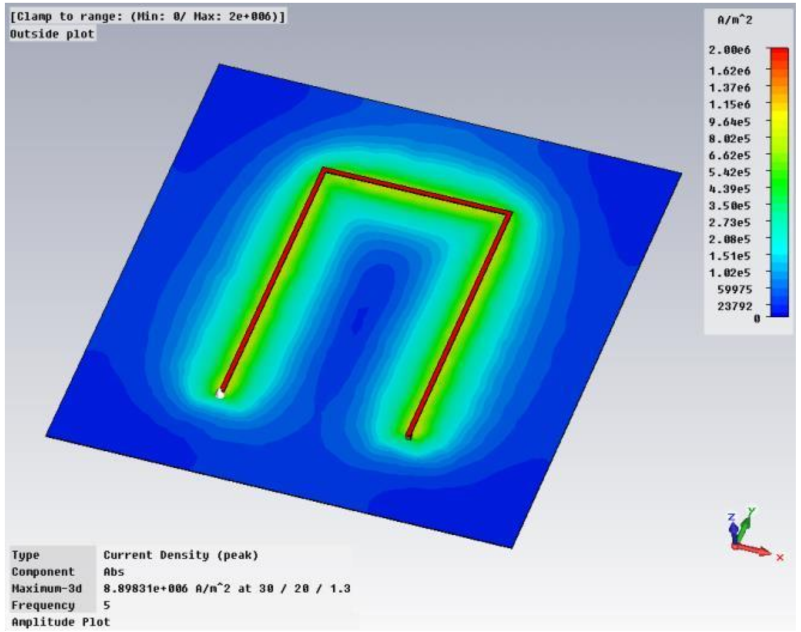
500 Hz

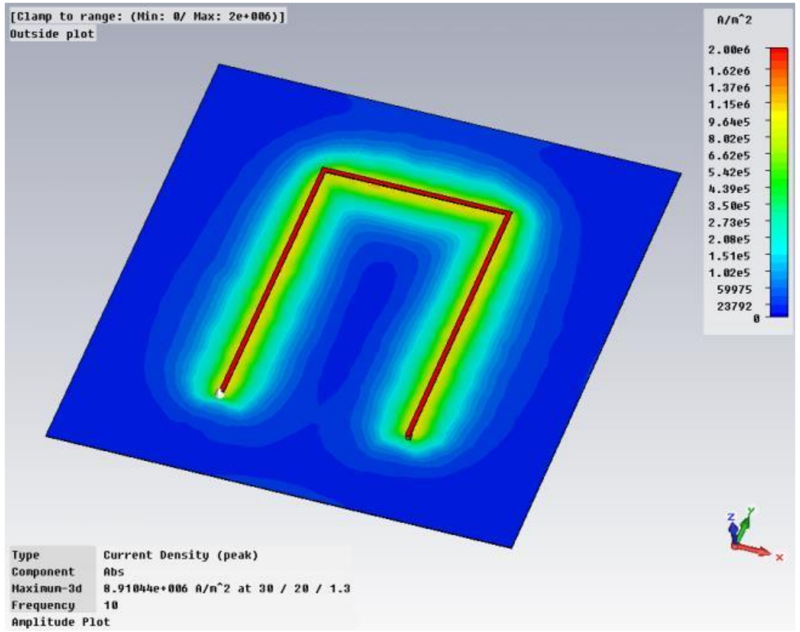
Path of least Impedance

Simulation: Return Path depending on Frequency

SEIBERSDORF LABORATORIES





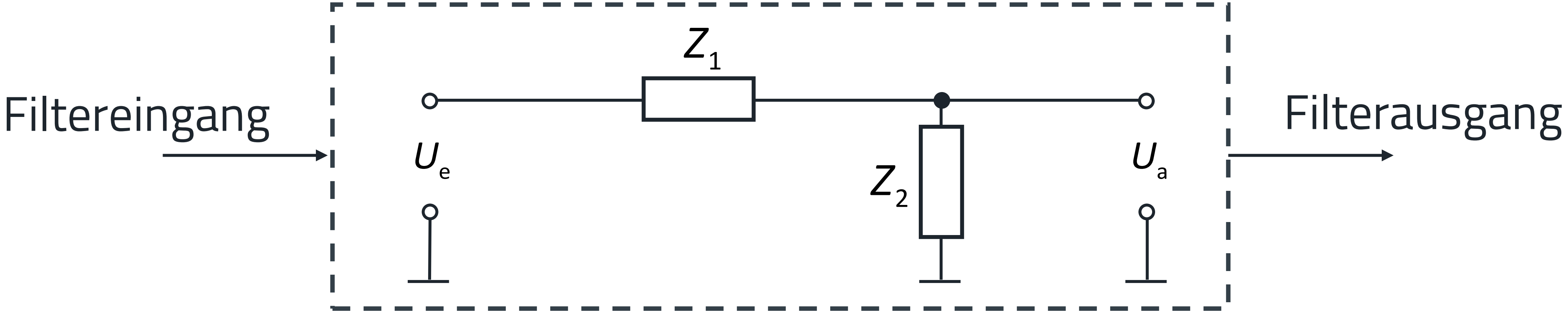


1 kHz | 2 kHz | 10 kHz

FILTERBAUTEILE

Prinzip der Filterung

- Definiertes Filter aus mindestens 2 Bauteilen
- mindestens ein Bauteil ist frequenzselektiv

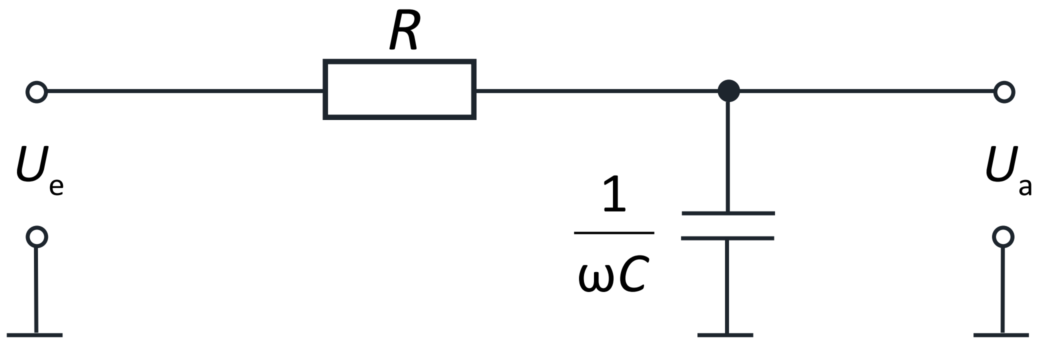


- Anpassung im Nutzfrequenzbereich
- Fehlanpassung im Störfrequenzbereich

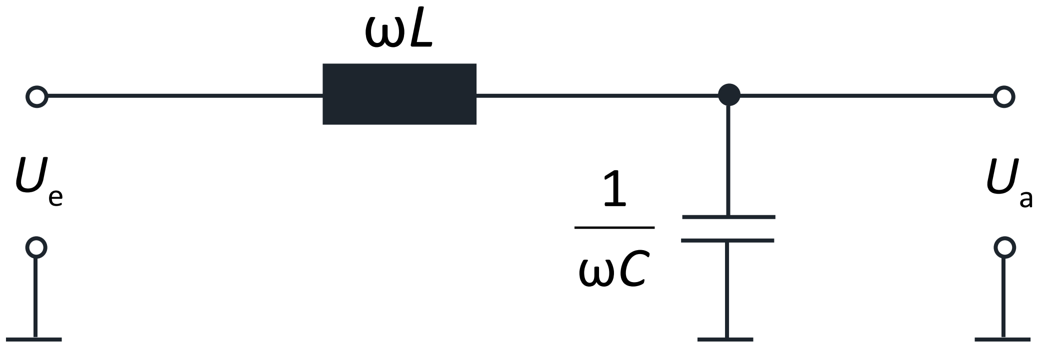
- **Filter sind frequenzabhängige Spannungsteiler**

Der Tiefpass

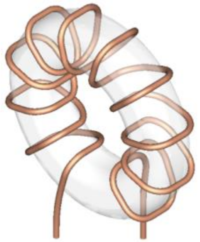
- **TP 1. Ordnung**
  - f↑ Z_C↓



- **TP 2. Ordnung**
  - f↑ Z_C↓
  - f↑ Z_L↑

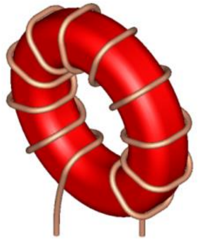


Impedanz einer Ringspule mit Ferritkern



Air-coil impedance $\underline{Z}_0$

Ferrite permeability $\underline{\mu}_\mathrm{r}$

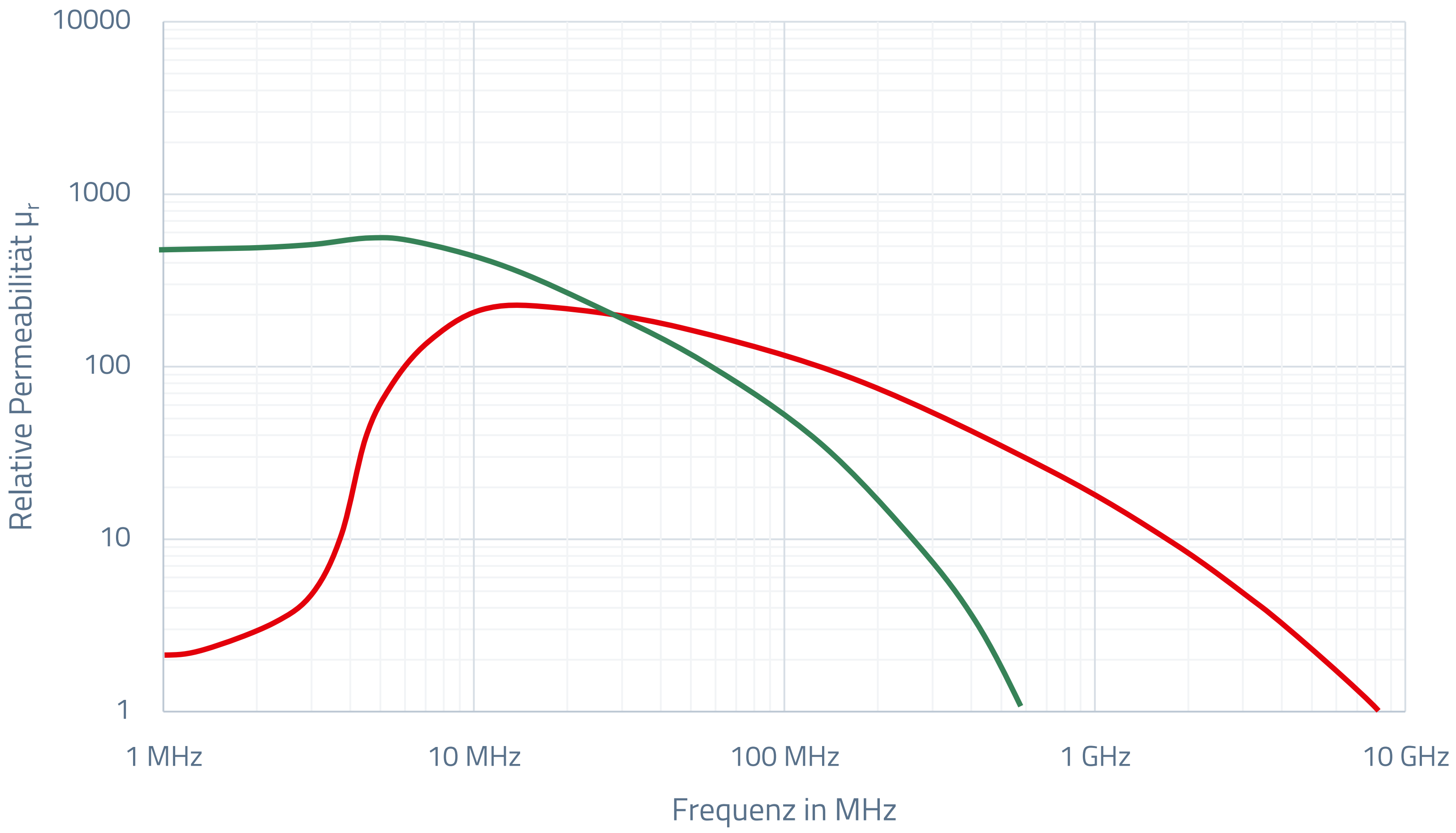


$$\underline{Z}(f) = \underline{Z}_0(f) \cdot \underline{\mu}_\mathrm{r}(f)$$
$$= \mathrm{j} \cdot 2\pi \cdot f \cdot L_0 \cdot [\mu'_\mathrm{r}(f) - \mathrm{j} \cdot \mu''_\mathrm{r}(f)]$$
$$= \mathrm{j} \cdot X_L(f) + R(f)$$

Pictures WE eiSos

Permeabilität

Frequenzabhängigkeit



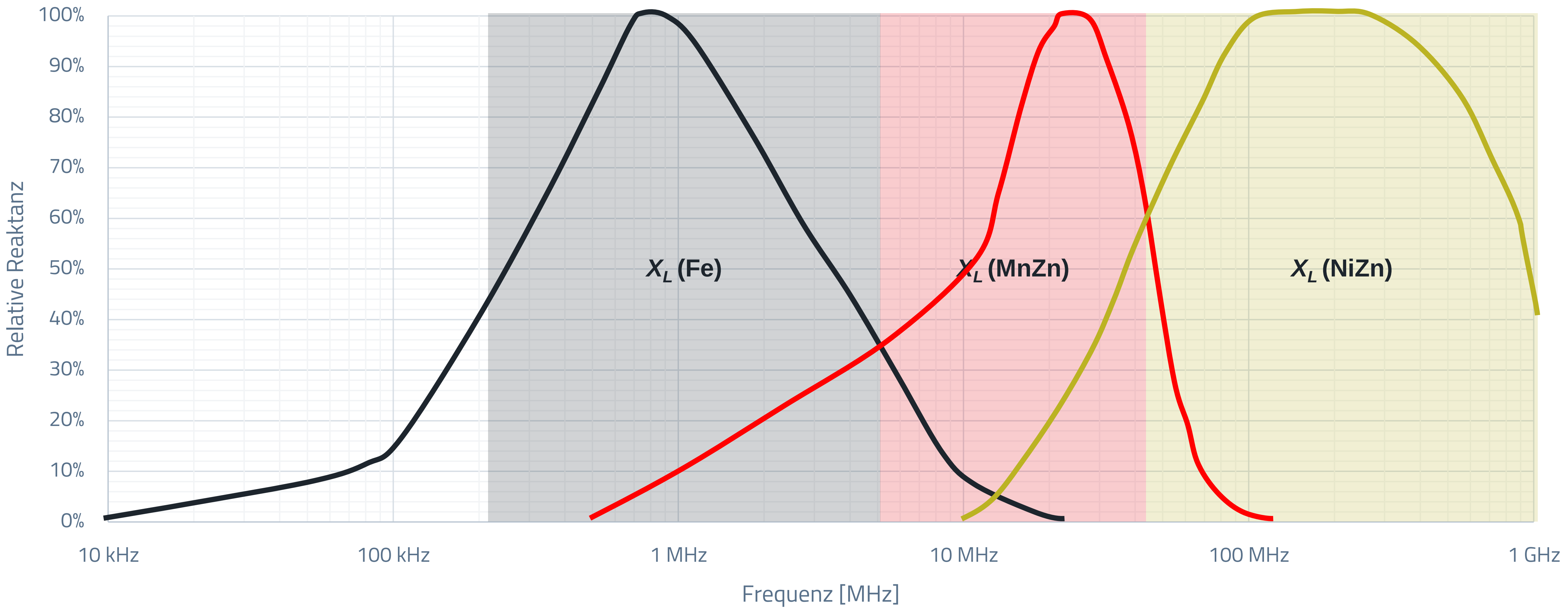
$$\bar{\mu} = \mu' - j\,\mu''$$
$$\bar{Z} = j\,\omega\,L_0 * (\mu' - j\,\mu'')$$
$$\bar{Z} = R + j\,X_L$$

$$X_L = \omega\,L_0\,\mu'$$
Frequenzabhängiger Magnetisierungsanteil

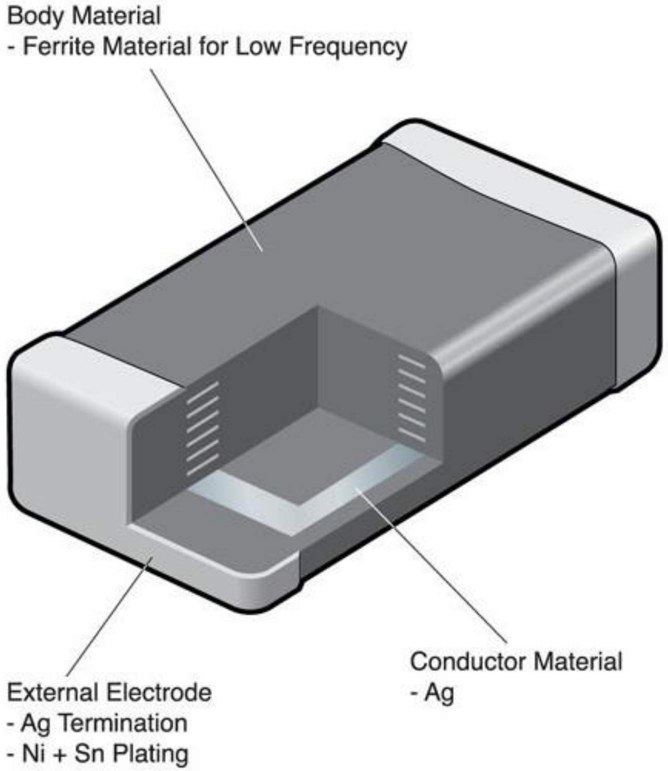
$$R = \omega\,L_0\,\mu''$$
Frequenzabhängiger Verlustanteil

Permeabilität

Verlustanteil

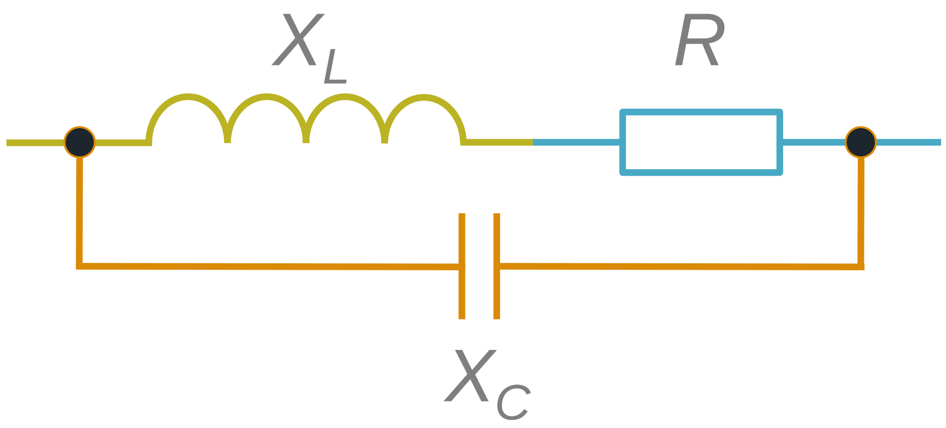


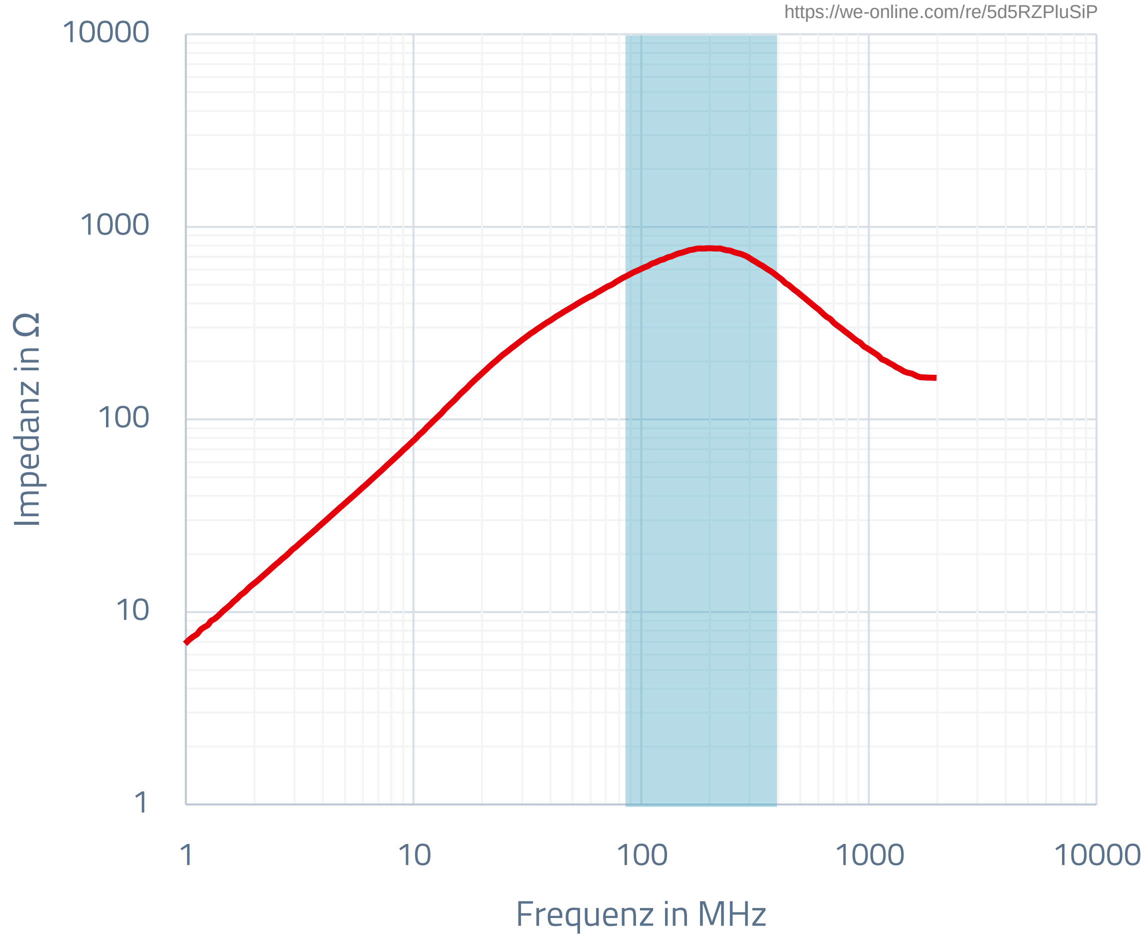
Aufbau Multilayer Ferrit



- als Ferritmaterial wird NiZn verwendet
- die Windungen in der Innenlage werden aus Silber im Siebdruckverfahren hergestellt
- Die Terminals bestehen aus Silber mit Nickel/Zinn Plating.

Frequenzverhalten eines Ferrits

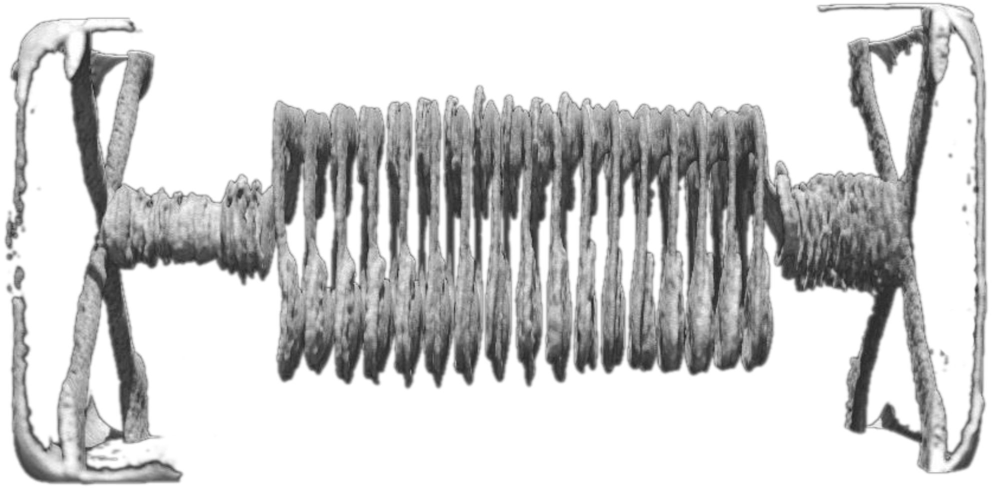




High Speed vs. Wideband

General Use vs. High Frequency

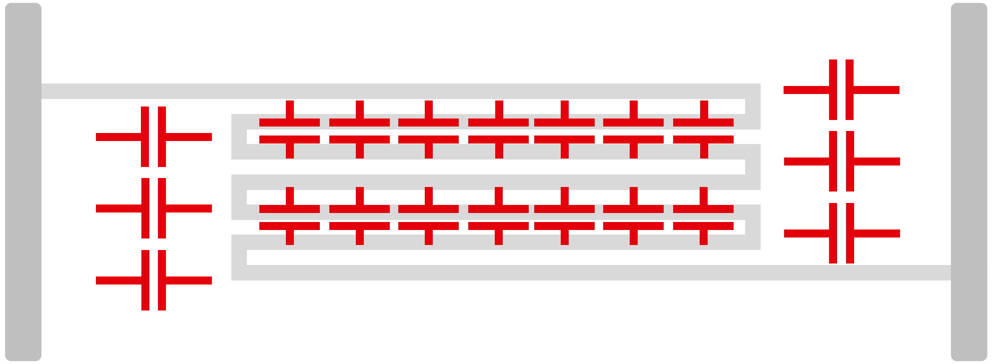
WE-CBF
Horizontale Anordnung der Lagen



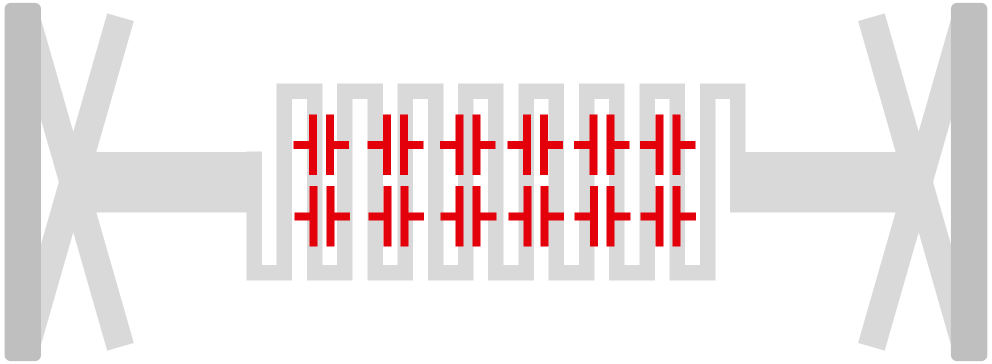
WE-CBF HF
Vertikale Anordnung der Lagen

General Use vs. High Frequency

$$\frac{1}{C_{sum}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_n}$$

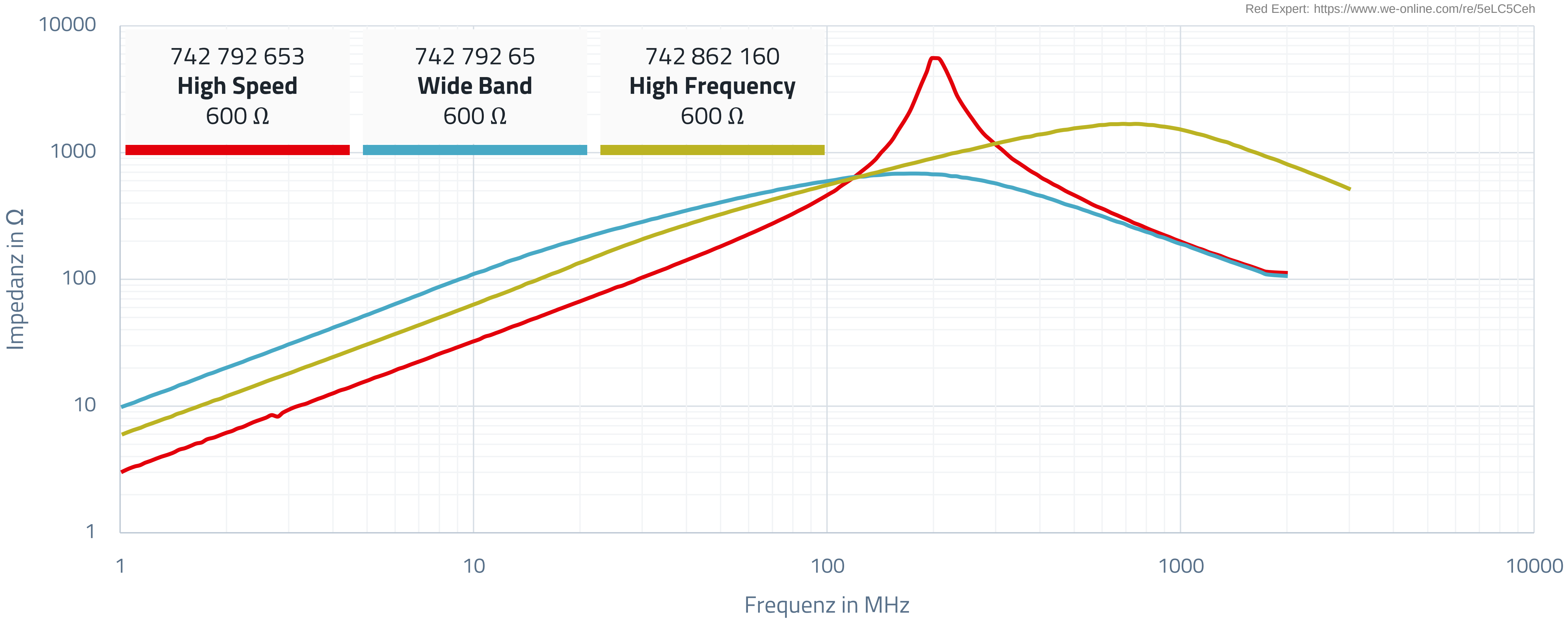


WE-CBF
Horizontale Anordnung der Lagen

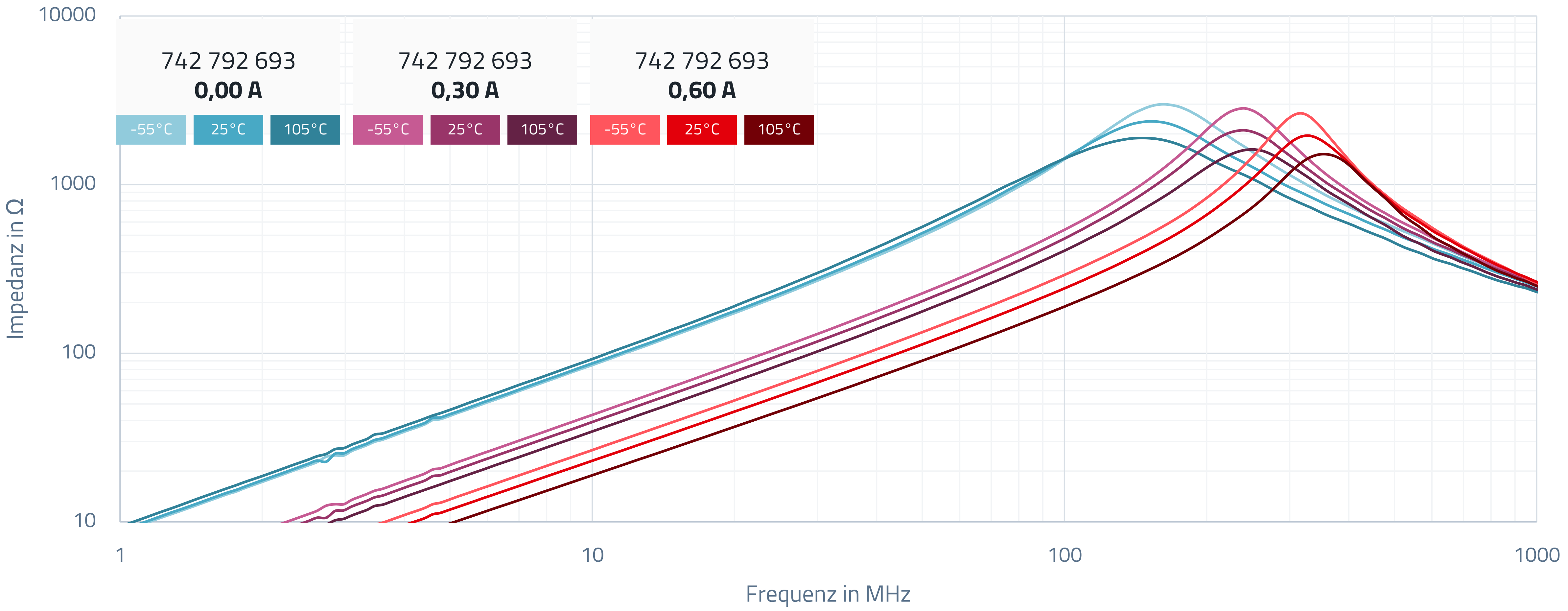


WE-CBF HF
Vertikale Anordnung der Lagen

Kategorien von SMD Ferriten



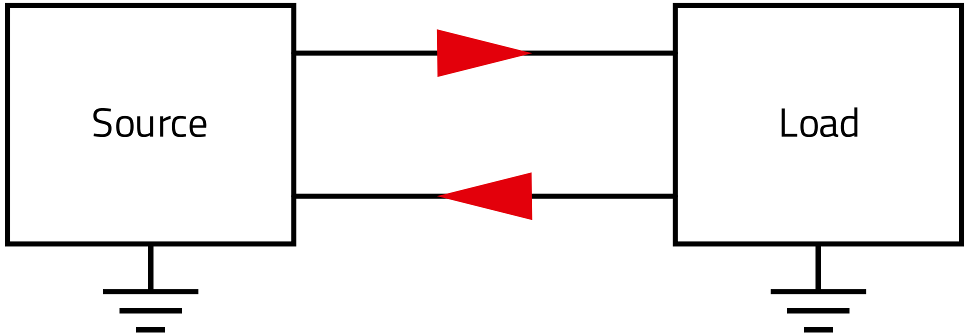
Verhalten der Impedanz unter Temperatur und Strom



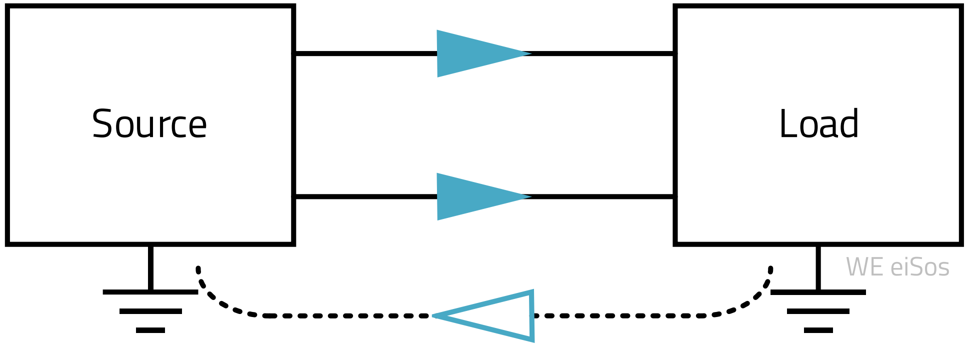
GLEICHTAKT, GEGENTAKT

Noise Transmission Modes

Differential Mode



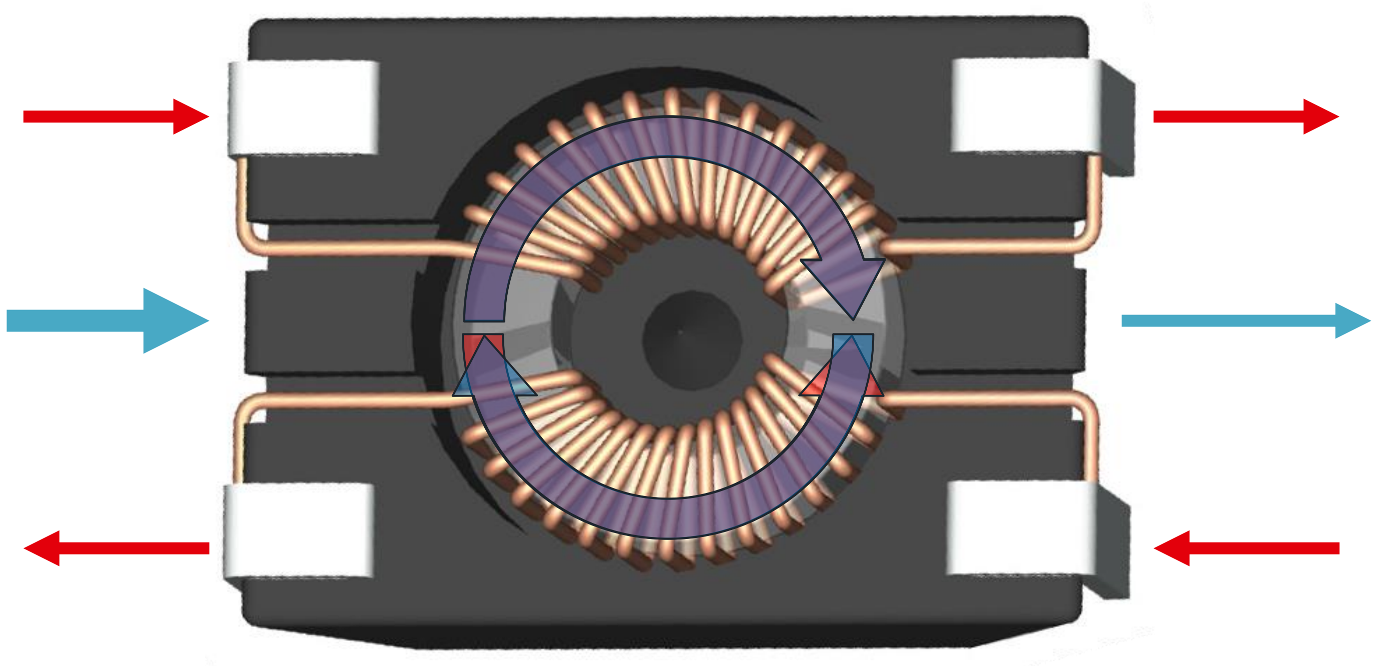
Common Mode



- Noise and useful signal use the same paths
- Earth is not affected

- Noise uses both lines in same direction
- Earth is used a return path

Common Mode Choke

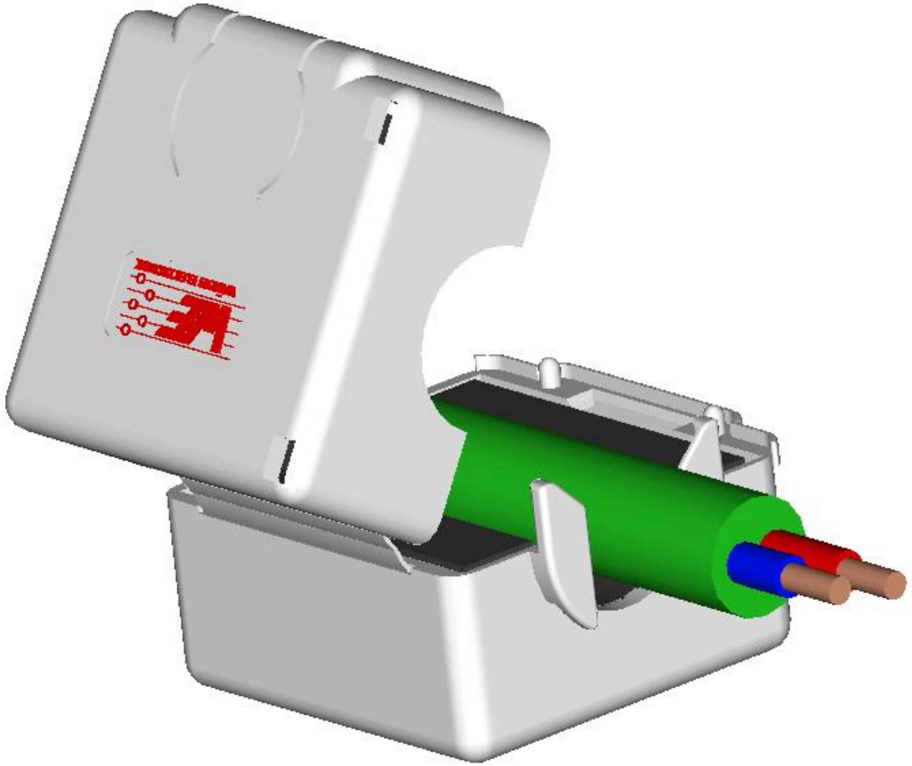


- **Compensation** of the **main magnetic flux** due to the differential-mode useful signal
- **Attenuation** of a **common-mode noise signal** by reflection and absorption

EXKURS:

REDEXPERT

Stromkompensierte Drossel – Klappferrit



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KONDENSATOREN

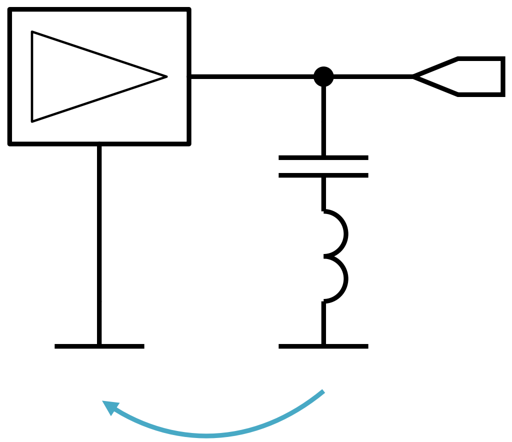
Filter Capacitors

General Considerations

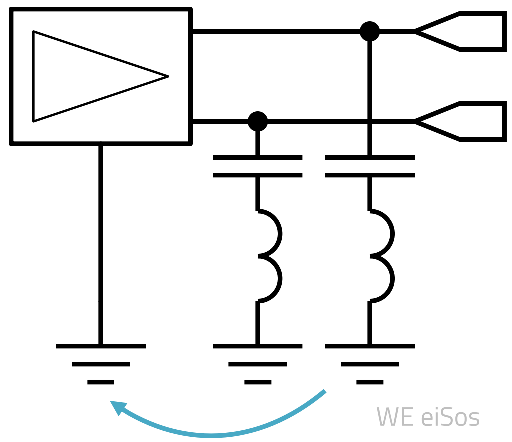
- For all capacitive Filters a low impedance connection to reference potential is key
  - For DM: (A/P) Ground
  - For CM: Earth / Chassis

- Additional Impedances decrease efficiency of RF short
  - THT contact pins
  - Inductance of PCB traces
  - Placement connection of steel spacers

Differential Mode Short

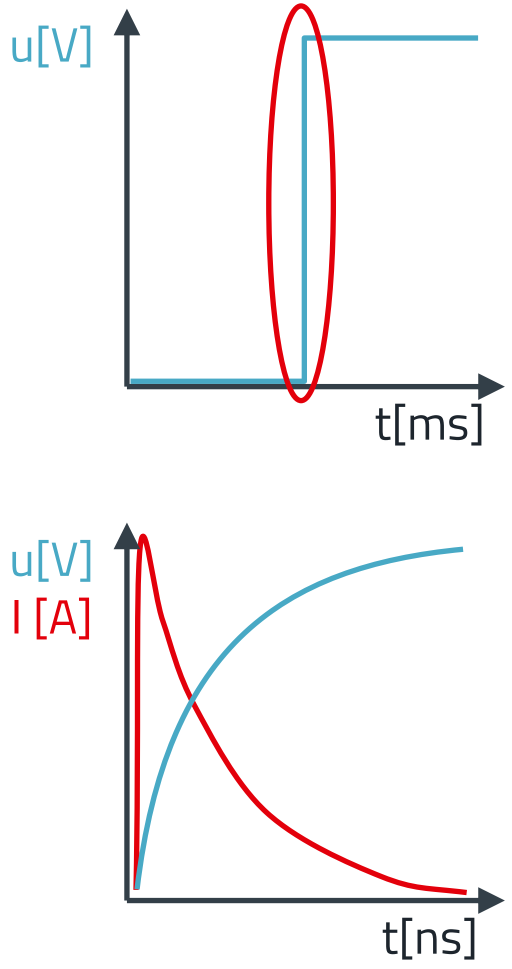


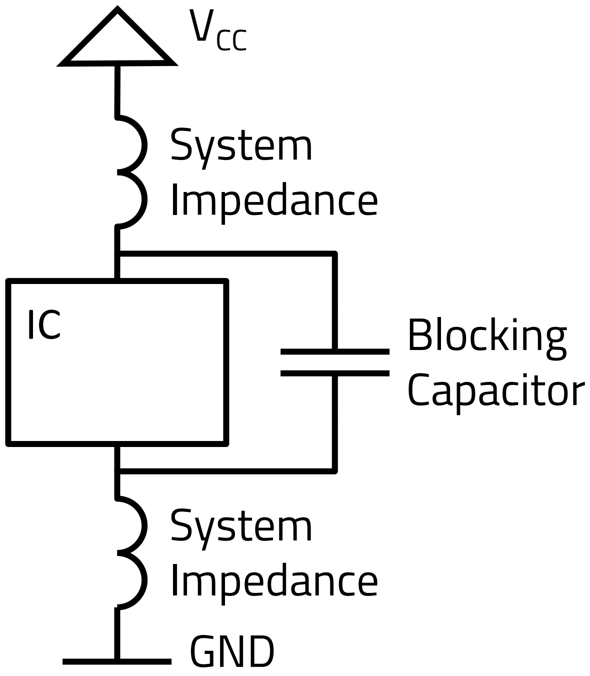
Common Mode Short

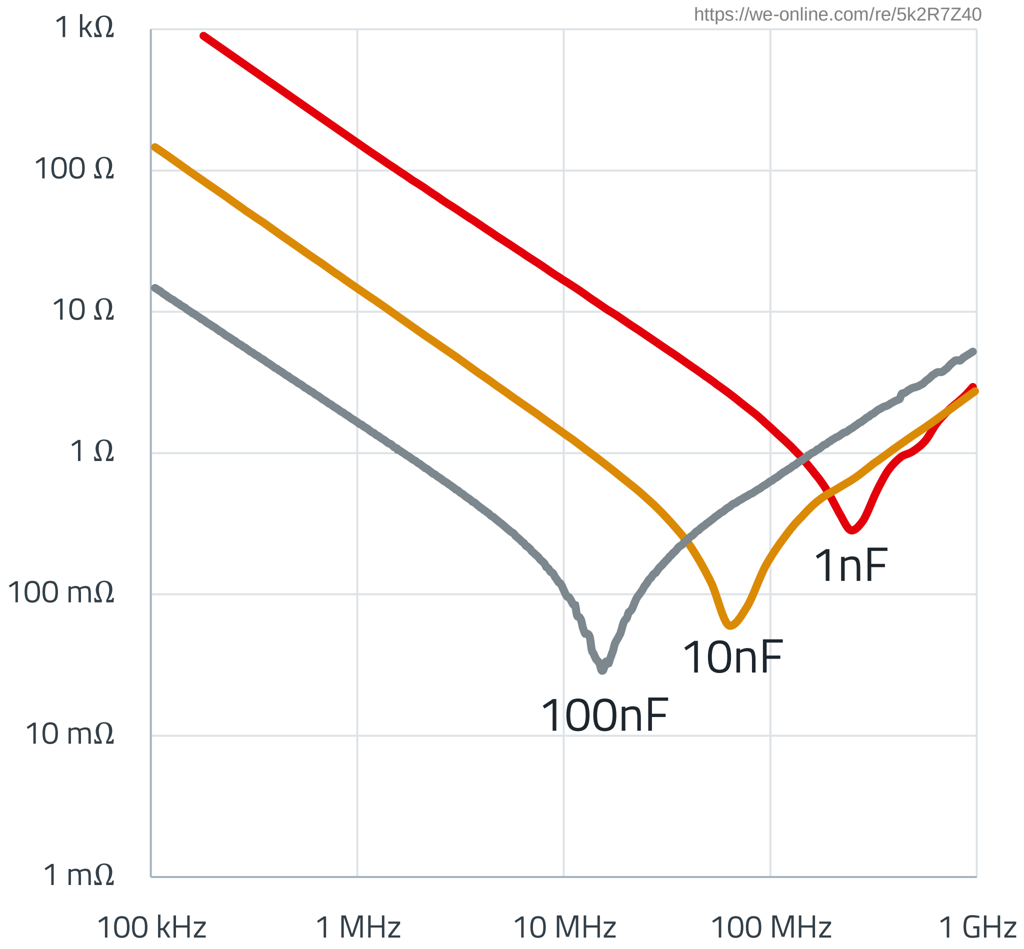


Blocking Capacitors

Mode of Operation and Selection Criteria

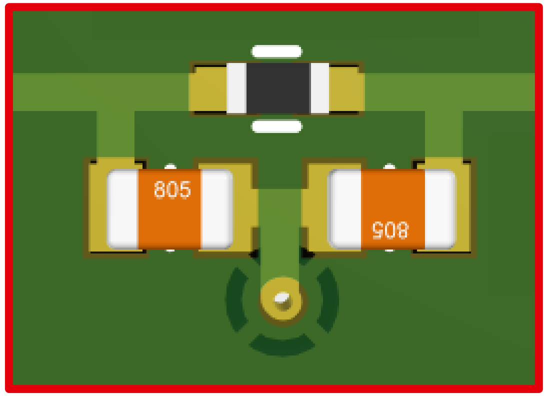




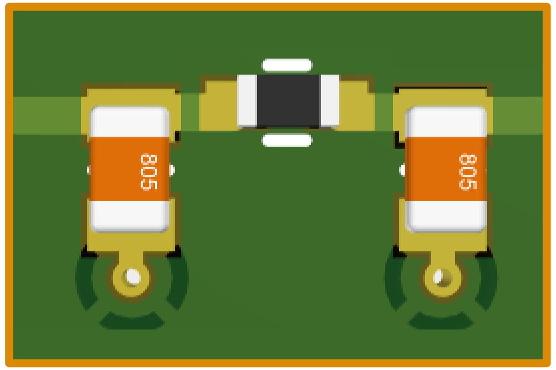


Filter Arrangement

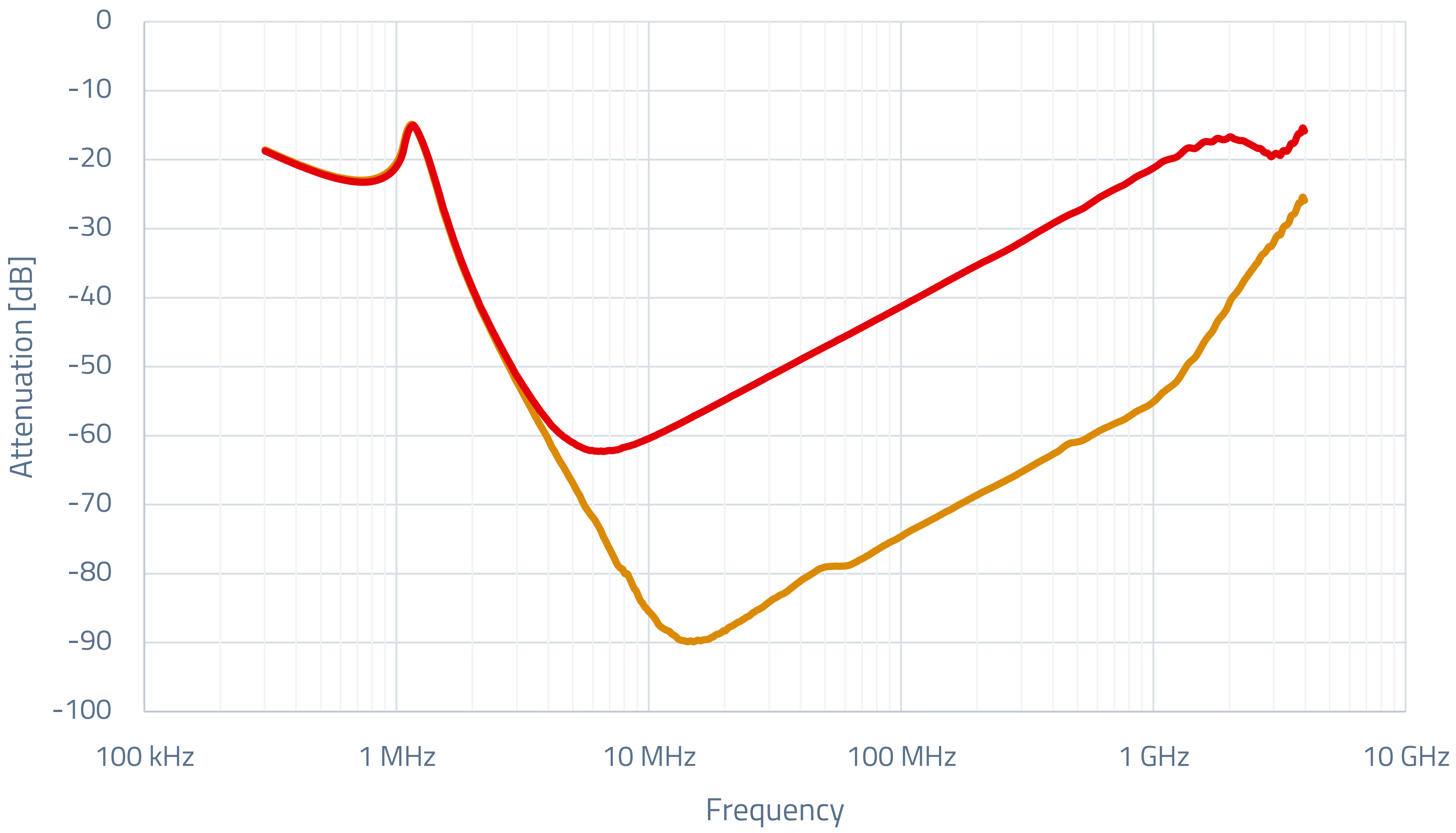
Layout: Influence on Insertion Loss



0805, Bad Layout



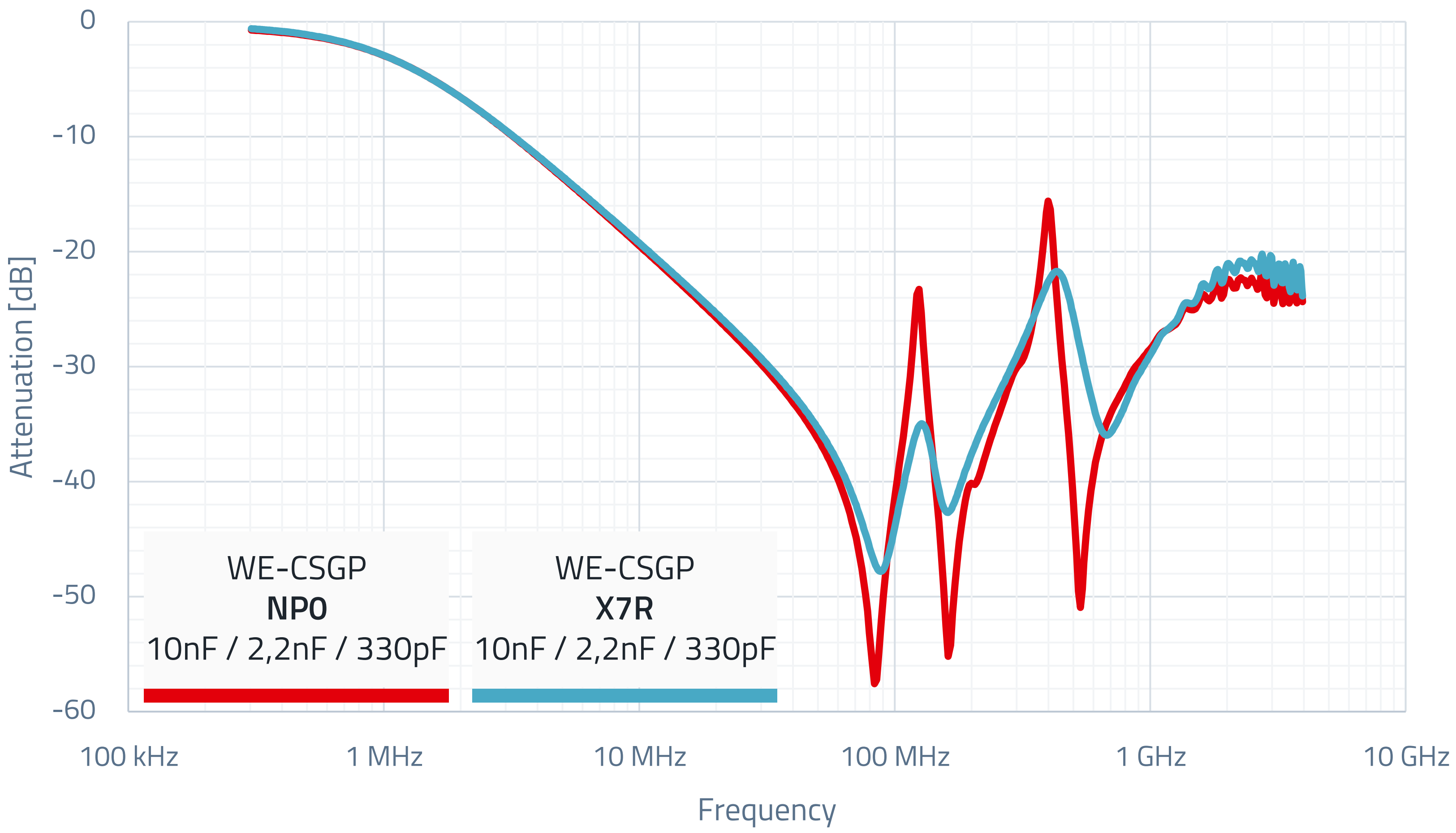
0805, Good Layout



Filter Capacitors

Selection Criteria

- Ceramic Class of the blocking capacitor affects performance
- NP0 with high Q tends to resonate strongly
- X7R provides a smoother curve but has its downsides:
  - DC Bias
  - Temperature Stability
  - Aging



WIE FINDE ICH DEN RICHTIGEN FILTER?

Dimensioning of a filter choke

Impedance vs. Attenuation

- A filter choke in series connection forms a **first-order low-pass Filter**

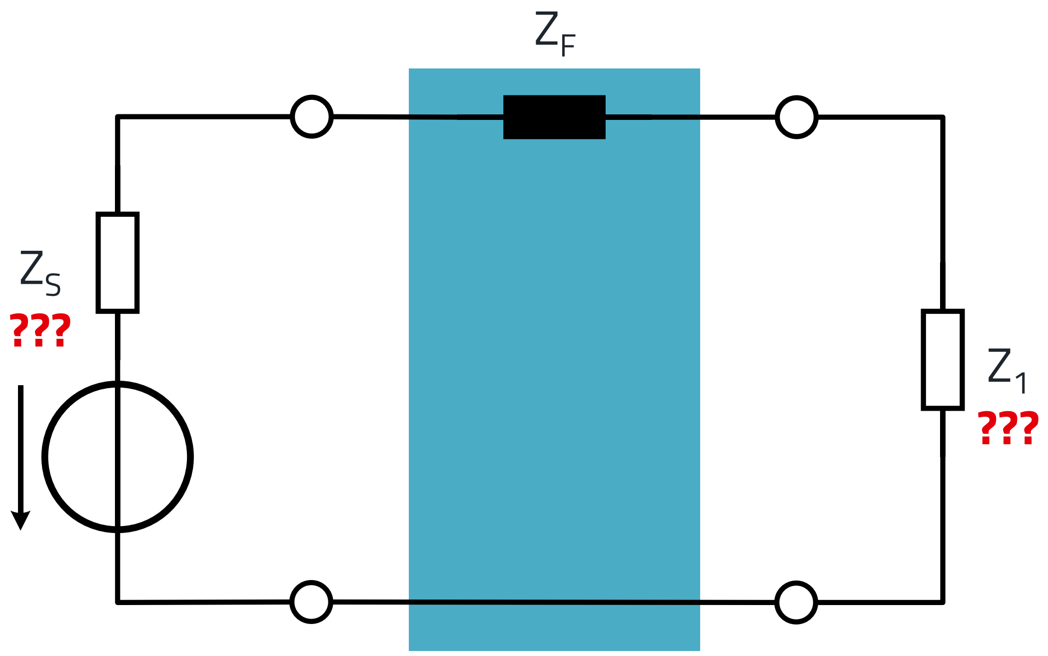
- **Insertion loss** in decibel:

$$A_{\mathrm{dm}} = 20 \cdot \log \left| 1 + \frac{Z_{\mathrm{F}}}{Z_{\mathrm{s}} + Z_{\mathrm{l}}} \right| \mathrm{dB}$$

- Minimum **filter impedance** at a noise frequency

$$Z_{\mathrm{filter}} = |Z_{\mathrm{s}} + Z_{\mathrm{l}}|_{f_{\mathrm{n}}} * (10^{\frac{A_{\mathrm{dm}}(f\mathrm{n})}{20}} - 1)$$

- For an exact calculation the source and load impedance for each noise frequency would have to be known.



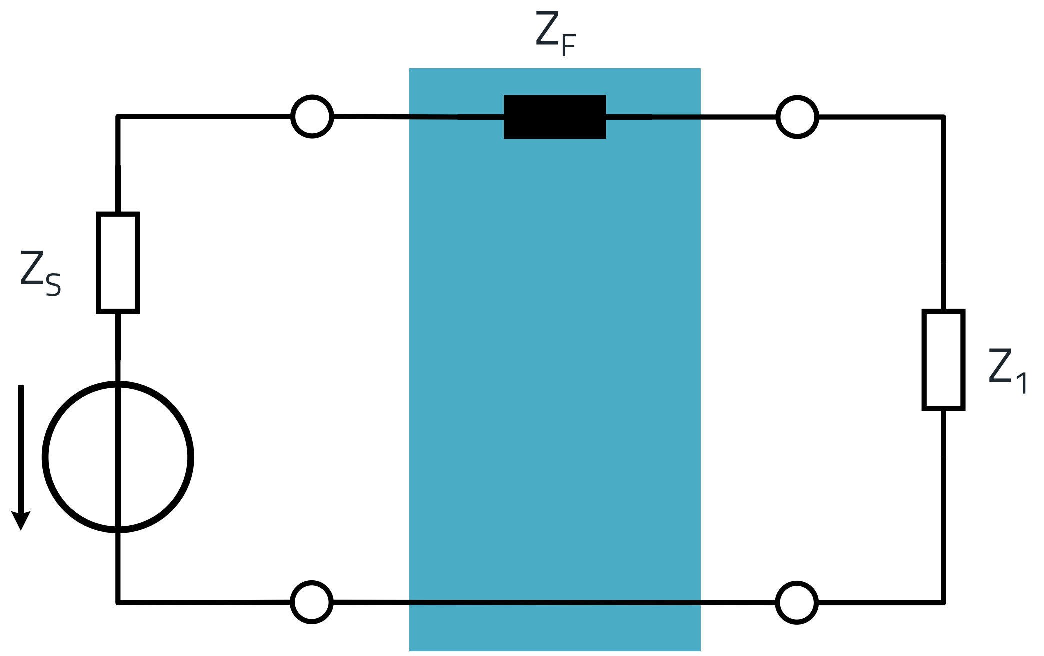
Dimensioning of a filter choke

Impedance vs. Attenuation

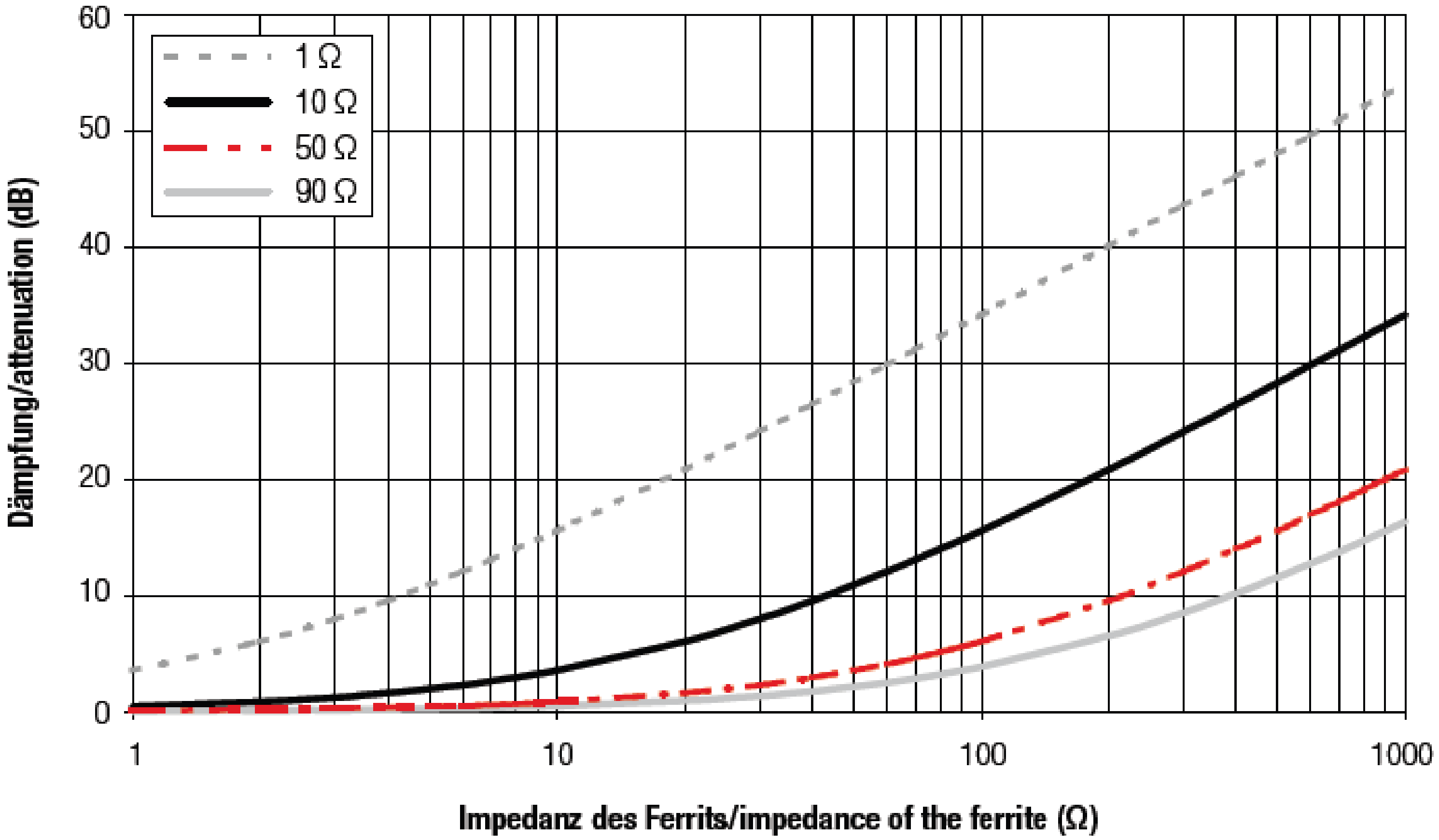
- Minimum **filter impedance** at a noise frequency

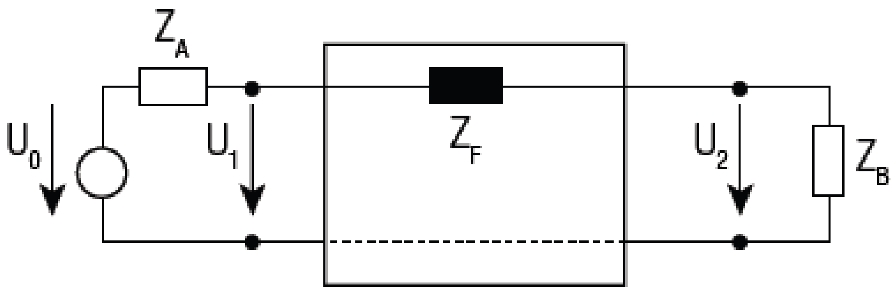
$$Z_{\text{filter}} = |Z_\text{s} + Z_\text{l}|_{f_\text{n}} \cdot \left(10^{\frac{A_{\text{dm}}(f_\text{n})}{20}} - 1\right)$$

- Empirical Values for system impedances
  - Ground 1 Ω
  - Power Supply 10 Ω
  - Clock-, Datalines 50…90 Ω
  - Long Datalines 90…150 Ω



Nomogram





$$|A|_{dB} = 20 * log_{10}\left(\frac{Z_A + Z_F + Z_B}{Z_A + Z_B}\right)$$

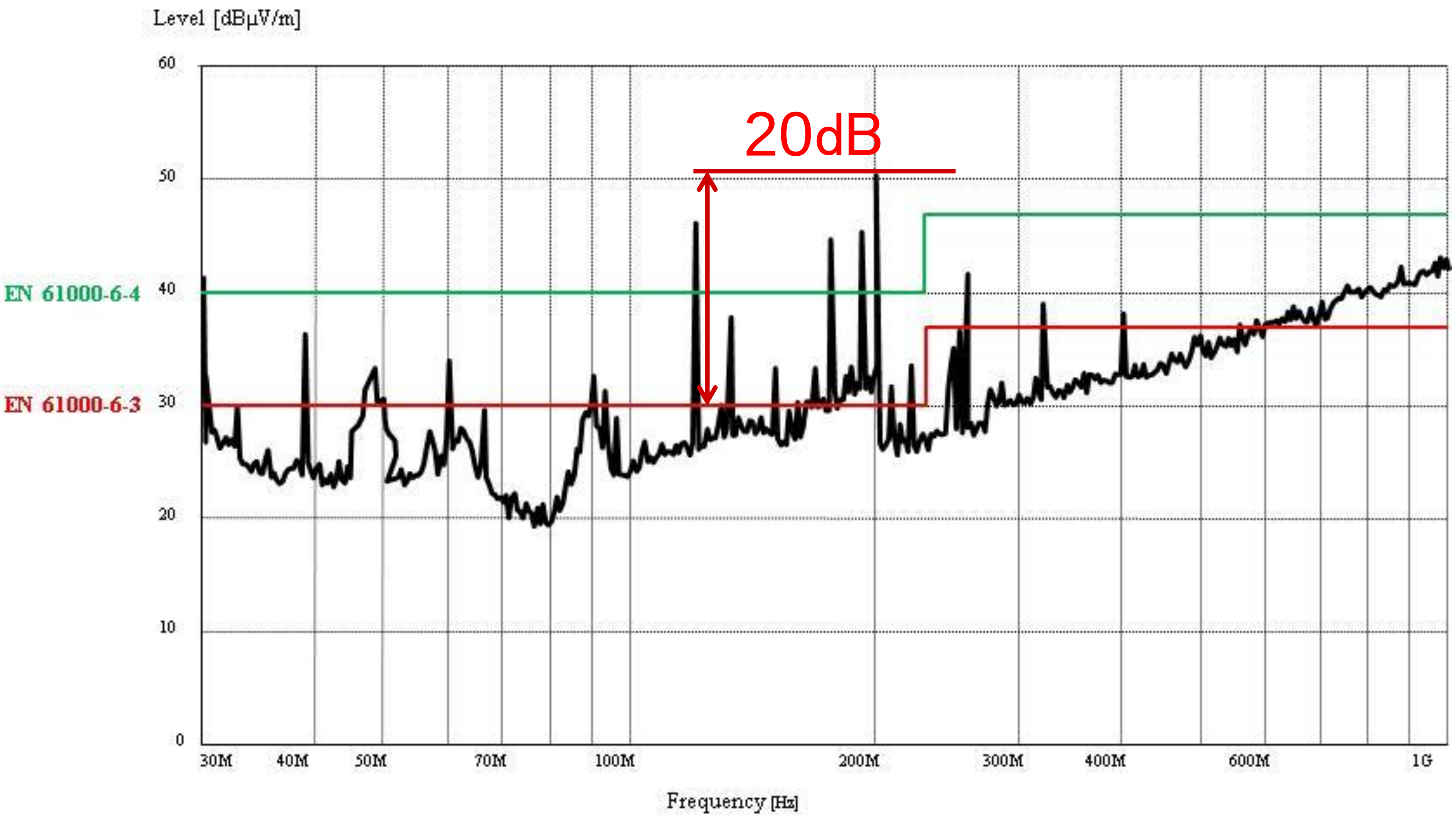
Auswahl eines Ferrits

- Stromversorgung mit 0,5A
- Einsatz im industriellen Umfeld

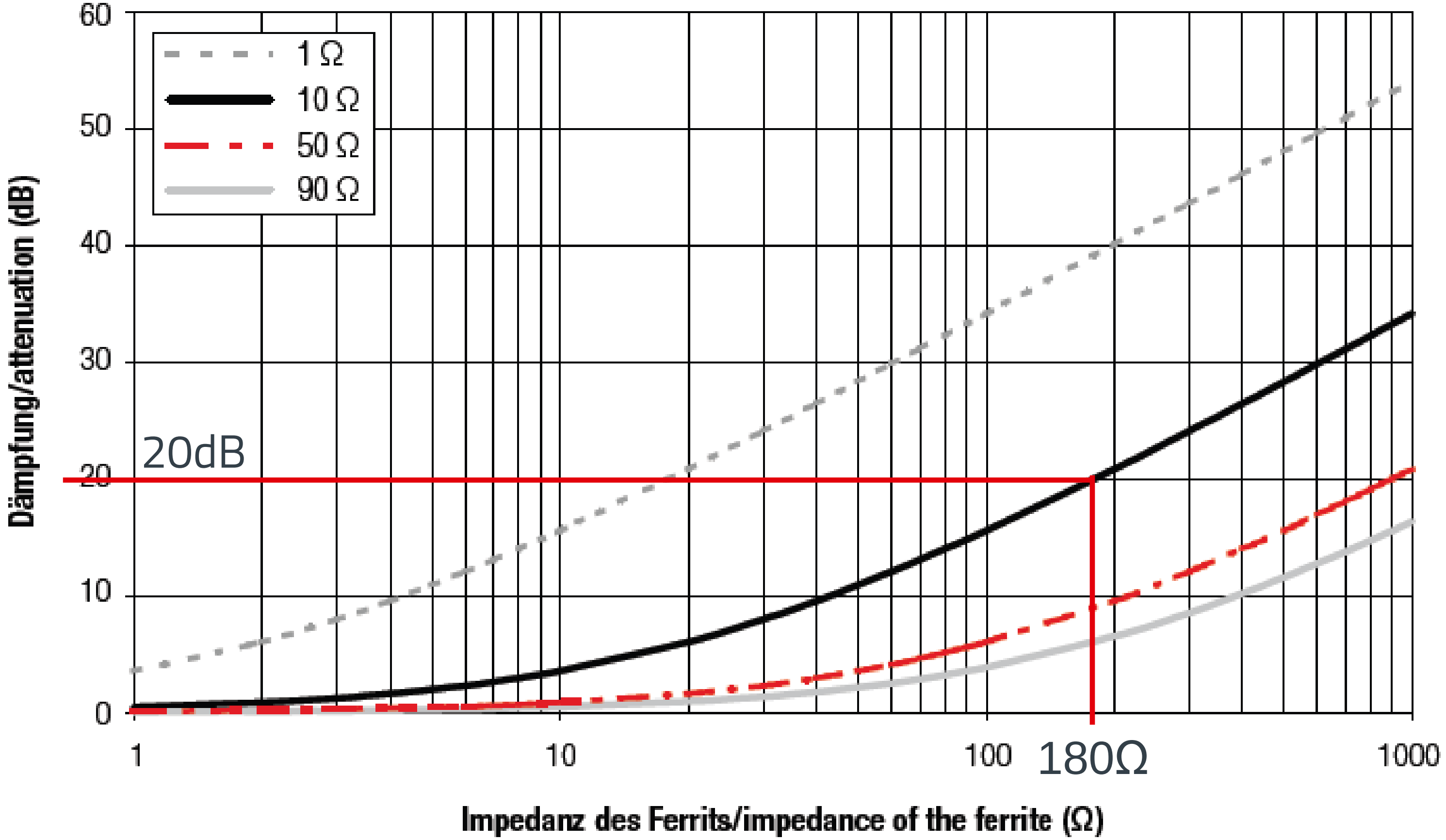
- EMV Test Ergebnis
  - Überhöhte Störausstrahlung

- Industrie
  - EN 61000-6-4

- Wohnbereich
  - EN 61000-6-3



Auswahl eines Ferrits - Katalog

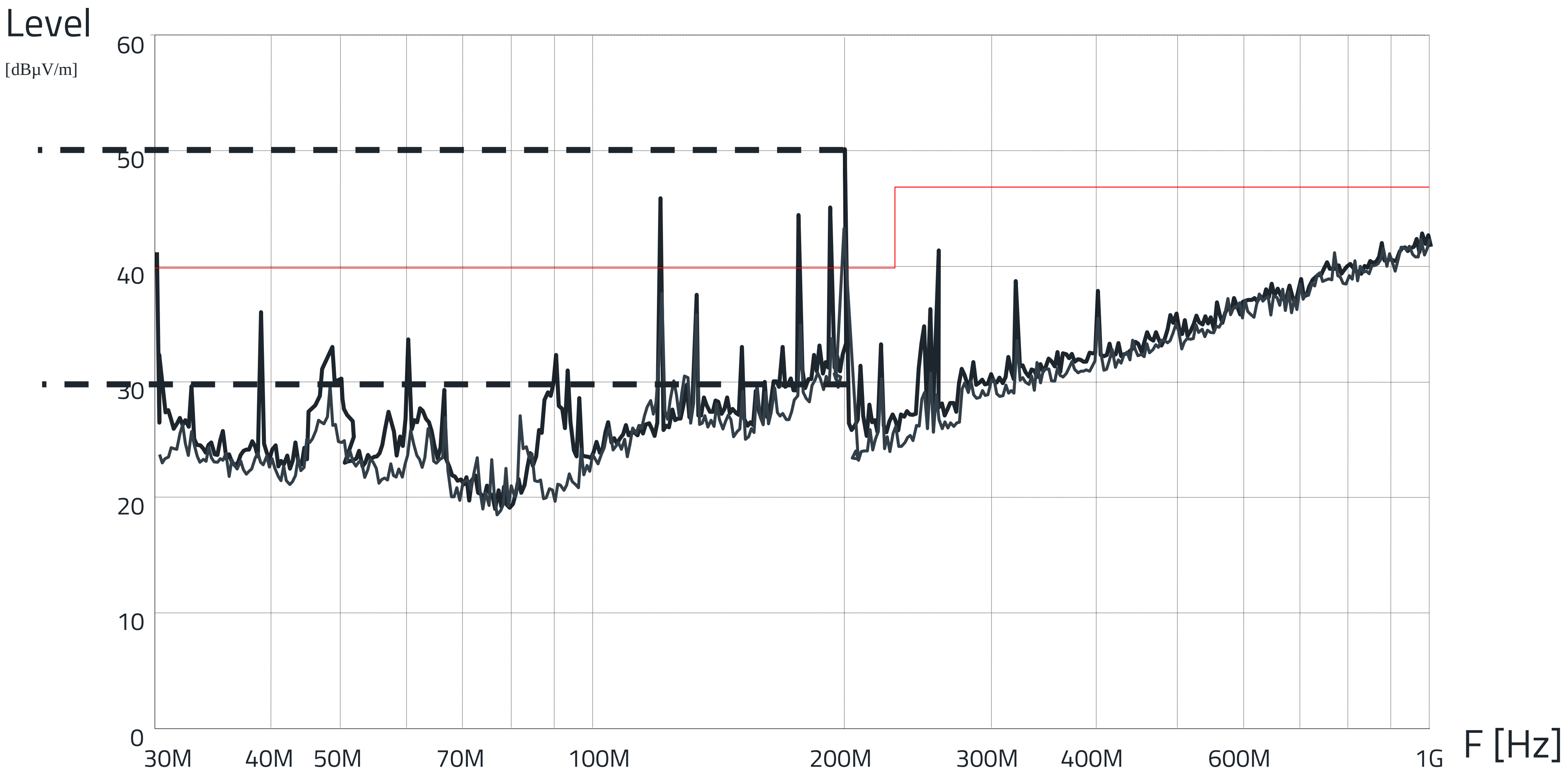


Anwendungsübersicht

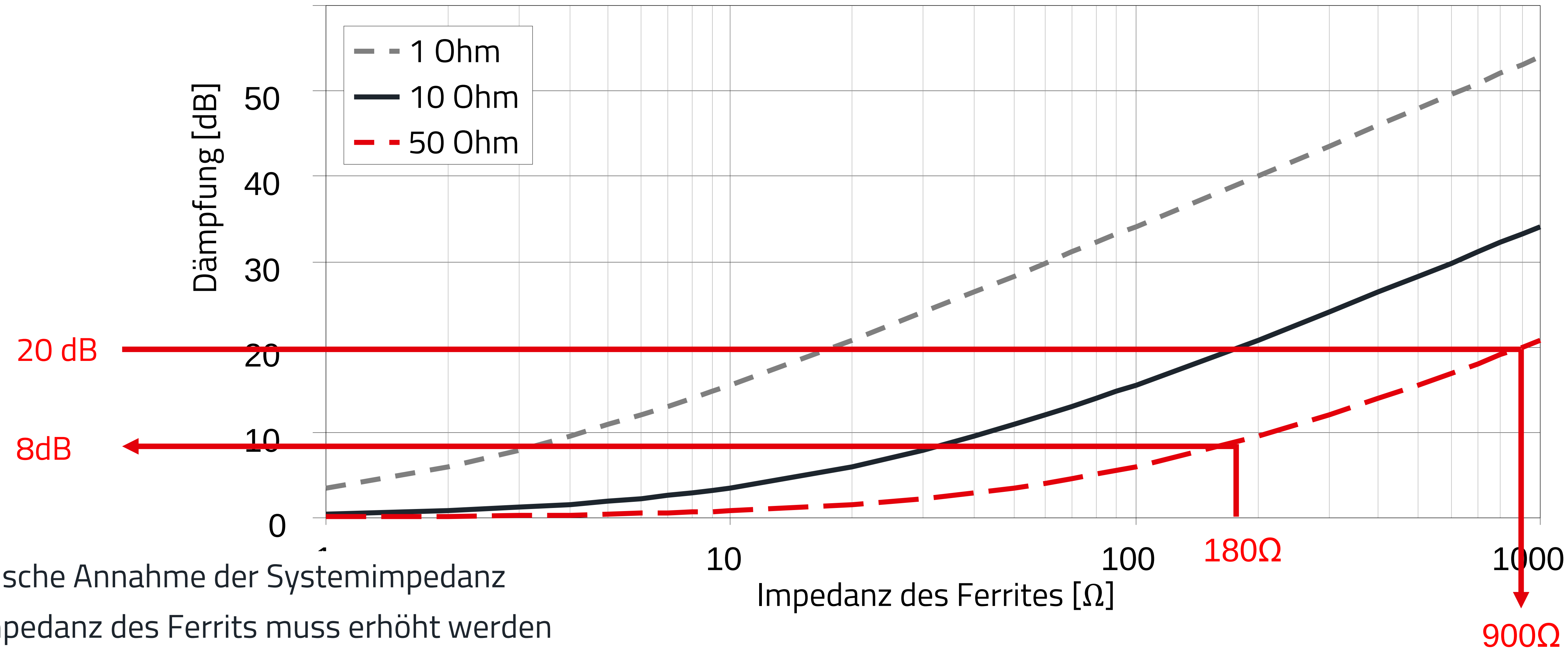
System-Impedanz	Anwendung
1 Ω	GND
10 Ω	V_{CC} Spannungsversorgung
50 Ω – 90 Ω	Datenleitungen: Videosignal, Takt, USB
90 Ω – 150 Ω	„lange“ Datenleitungen

Auswahl eines Ferrits - Redexpert

Einfügedämpfung – Beispiel

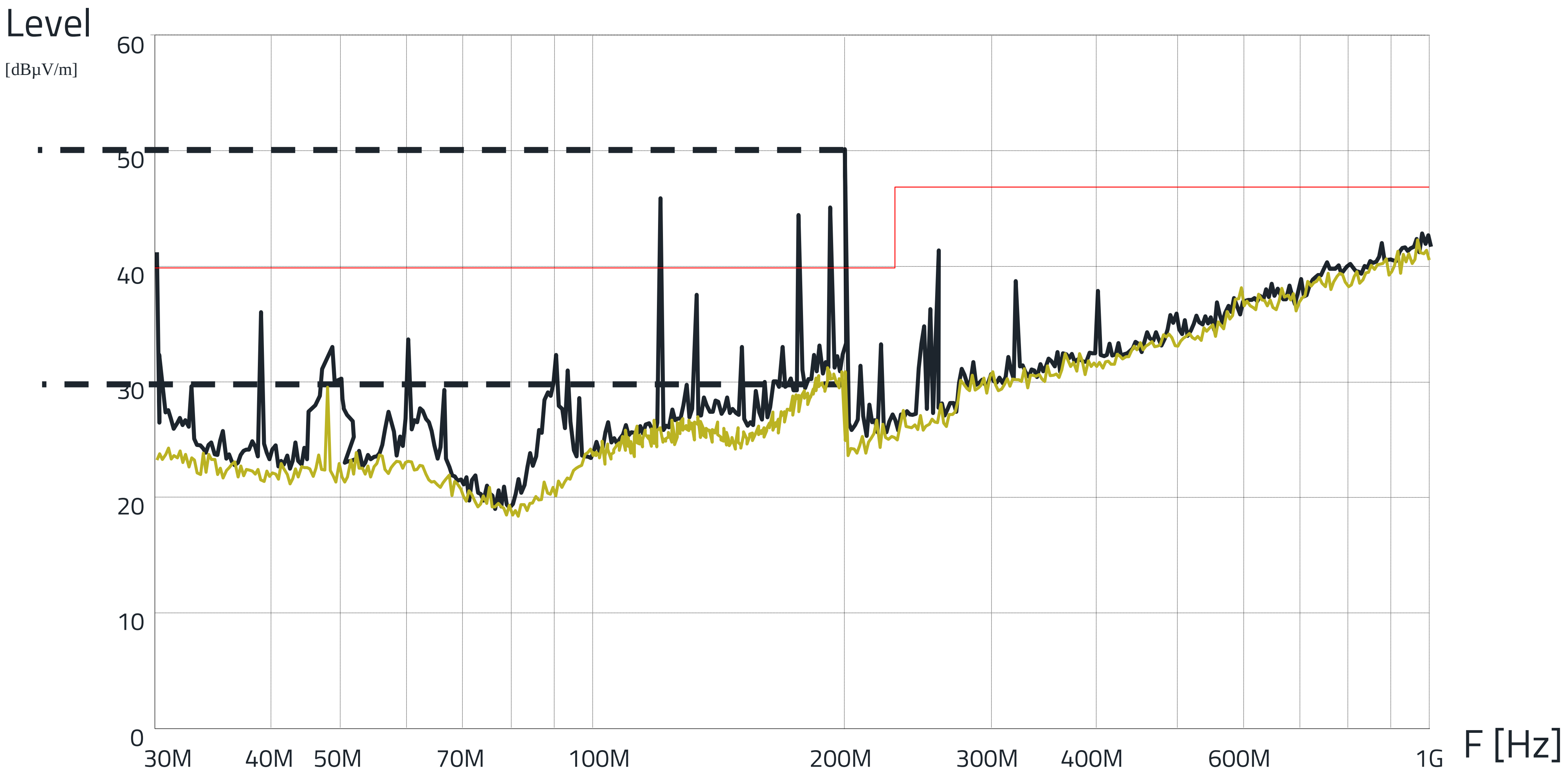


Einfügedämpfung – zu niedrig



- falsche Annahme der Systemimpedanz
- Impedanz des Ferrits muss erhöht werden

Einfügedämpfung – Beispiel



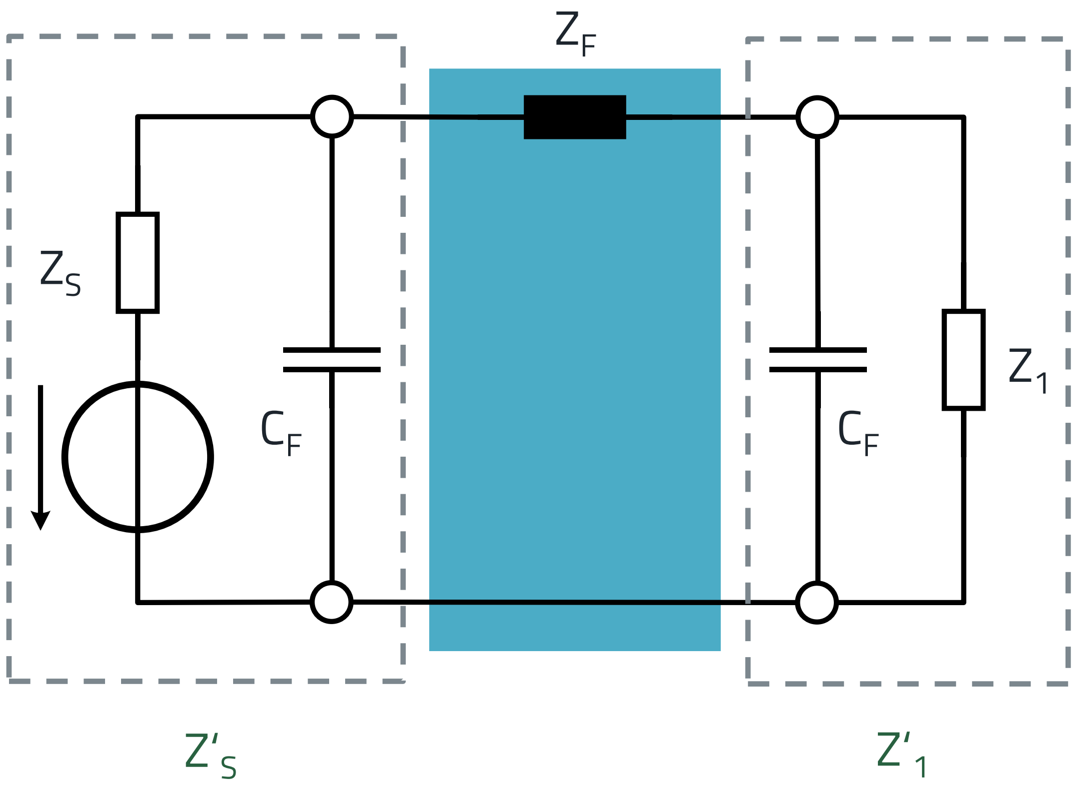
Dimensioning of a Filter

Adjusting the Operating Point with Capacitors

- Parallel Capacitors decrease System Impedance

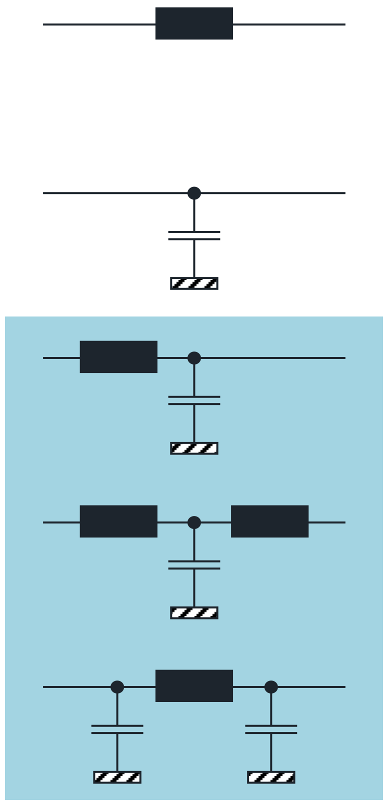
$$A_{\mathrm{dm}} = 20 \cdot \log \left| 1 + \frac{Z_{\mathrm{F}}}{Z'_{\mathrm{s}} + Z'_{\mathrm{l}}} \right| \mathrm{dB}$$

- Caps will also work as an RF Short to Ground
- Pay Attention to SRF of the Components
- 2nd order Filter Topologies can be adjusted to system impedances

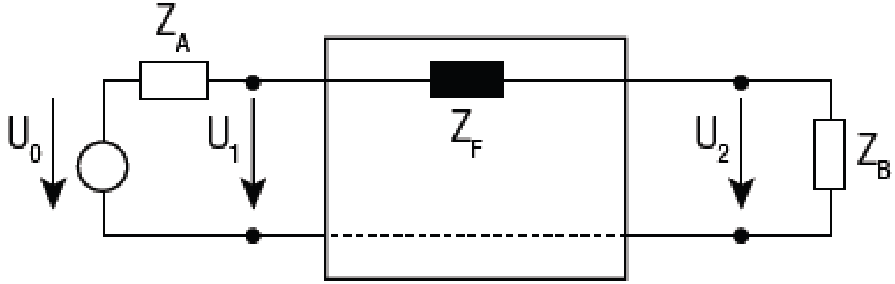


Empfohlene Topologien

Quellen-Impedanz	Senken-Impedanz
niedrig	niedrig
hoch	hoch
niedrig	hoch
unbekannt/ niedrig	unbekannt/ niedrig
unbekannt/ hoch	unbekannt/ hoch



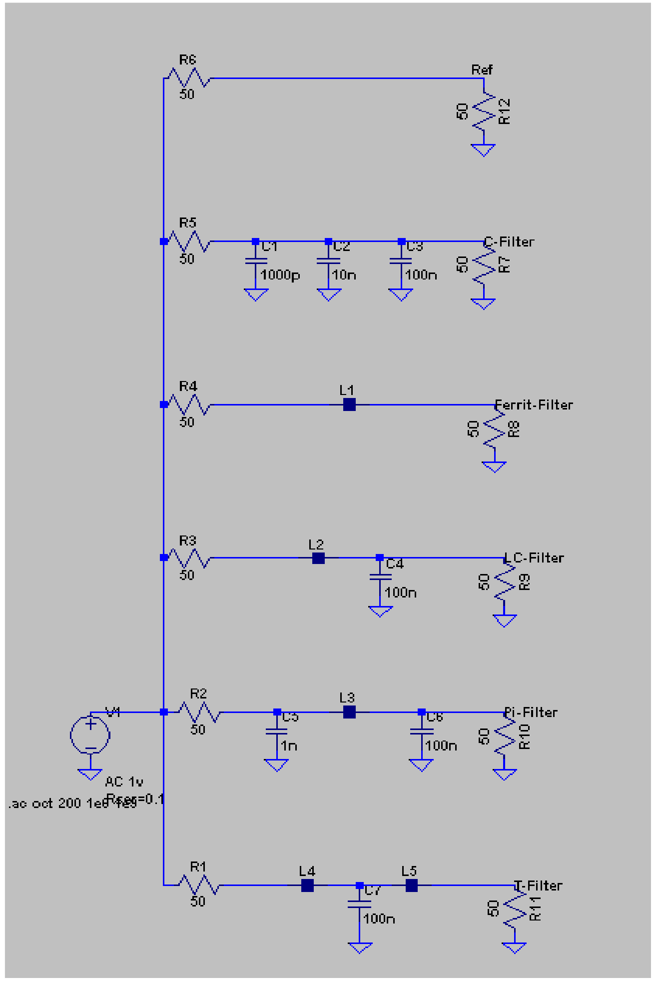
WE eiSos

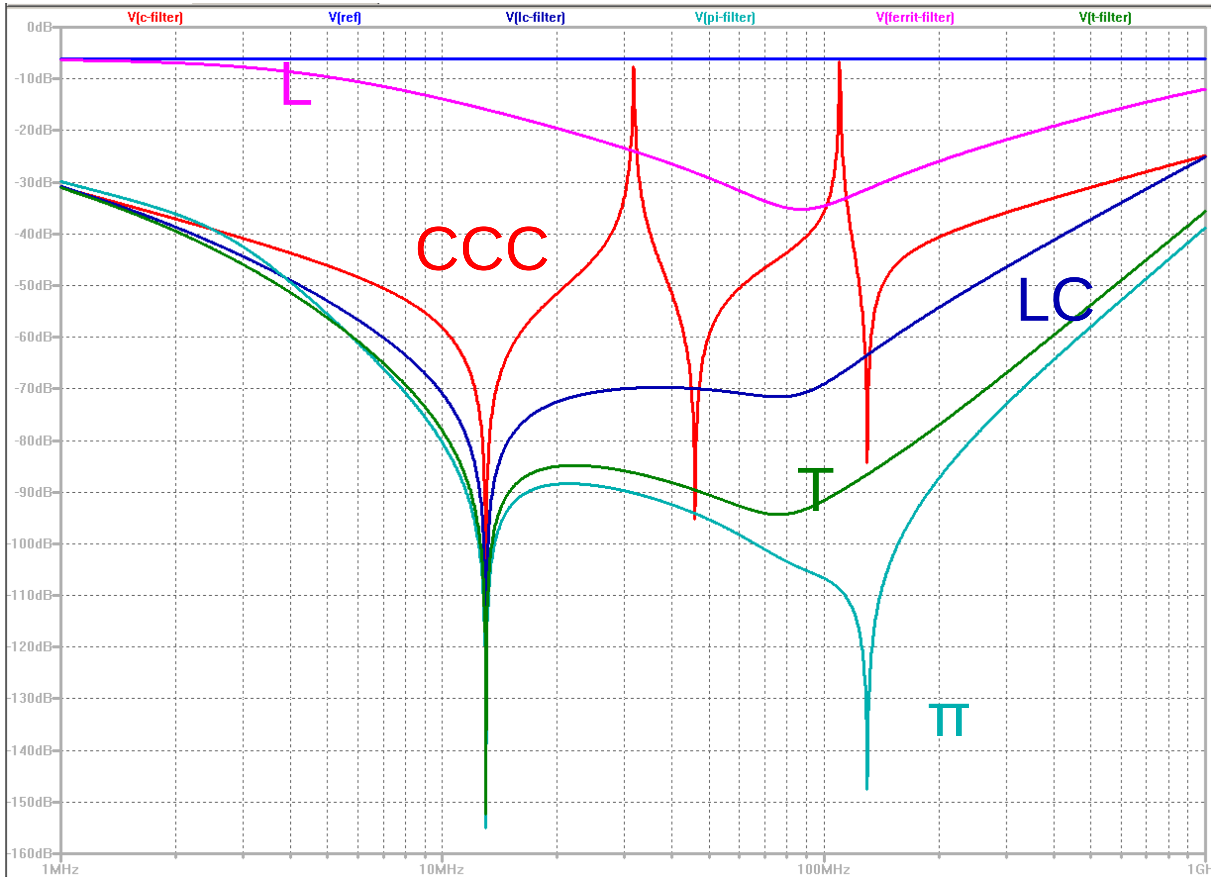


$$|A|_{dB} = 20 * log_{10}\left(\frac{Z_A + Z_F + Z_B}{Z_A + Z_B}\right)$$

Eigenresonanz der Bauteile beachten!

Filtertopologien - Dämpfung

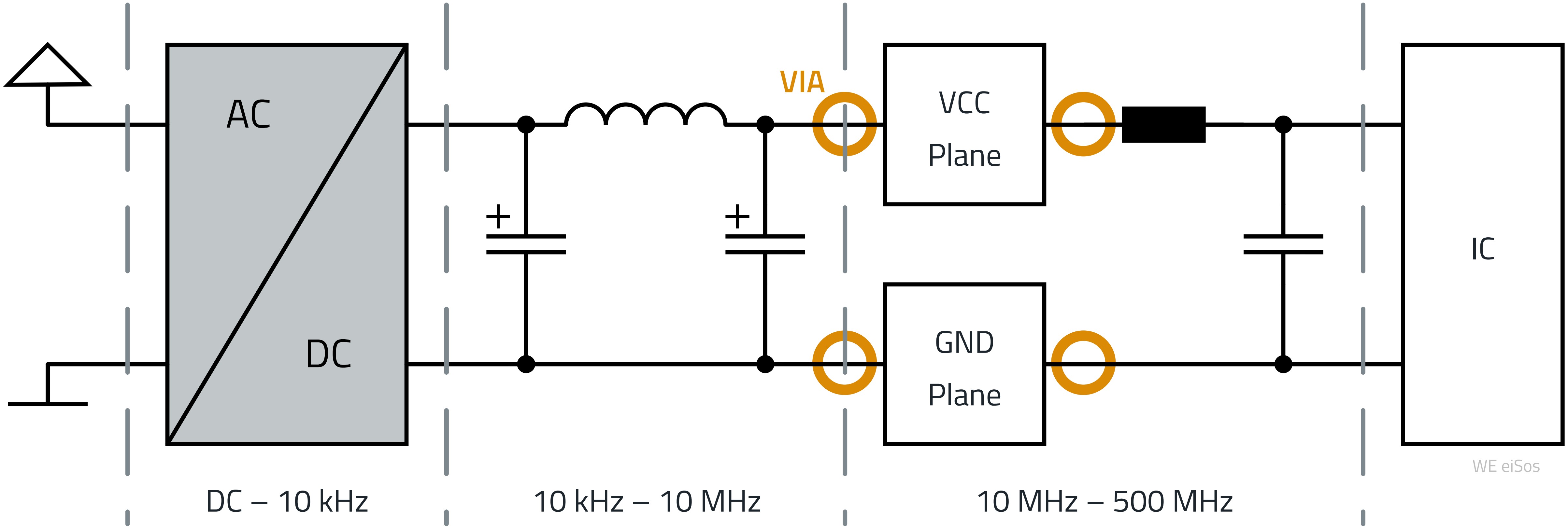




WOHIN MIT DEM FILTER?

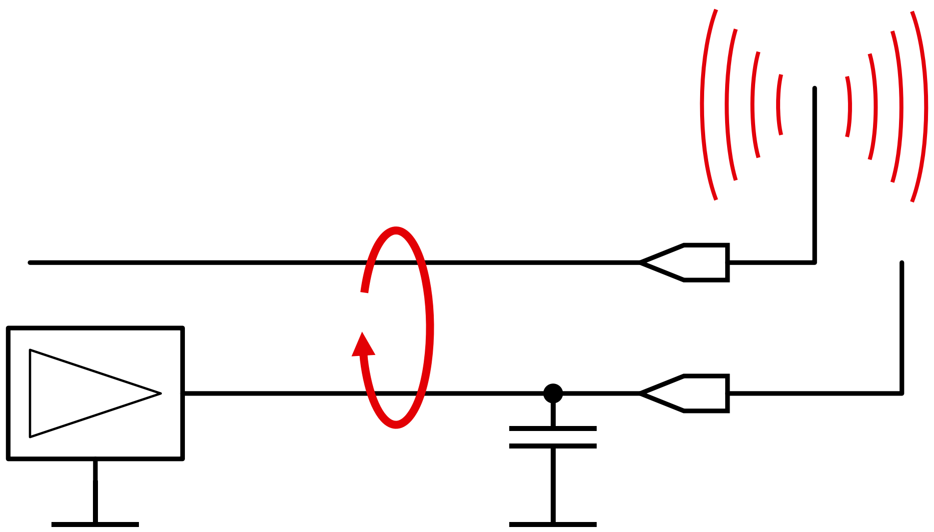
Filter Placement

Filter Bandwidth Requirements along the Power Path

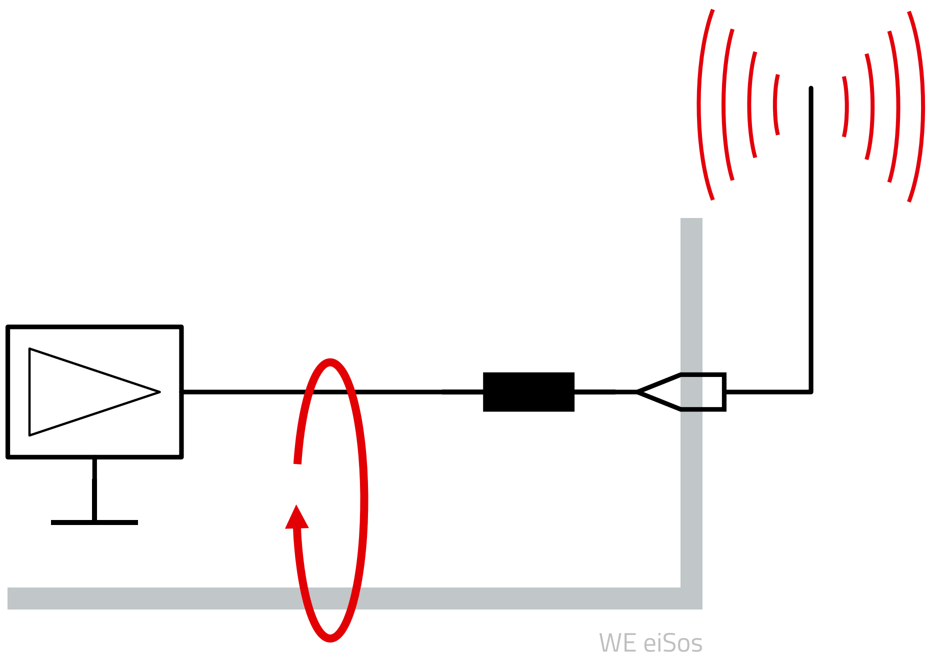


Filter Placement

Noise can bypass a misplaced Filter



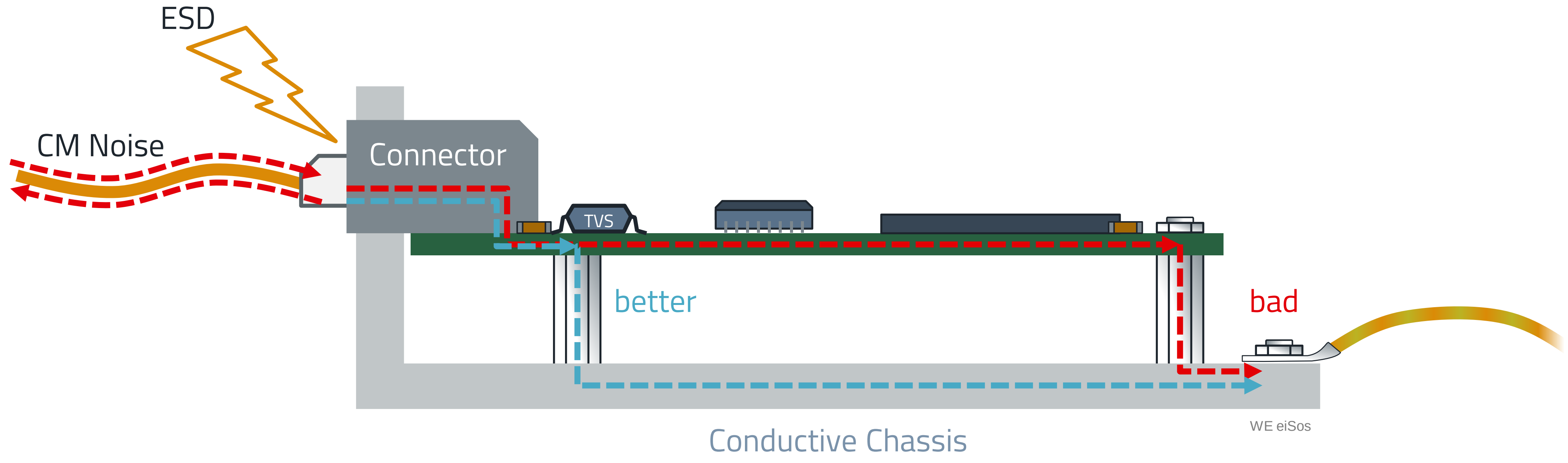
Bypassing via parallel Lines



Bypassing via chassis parts

Filter Placement

Diverting Noise to Earth



- Grounding studs have to placed so that disturbances don‘t affect the electronic parts
- Reference ground for ESD (and common mode noise) is earth potential