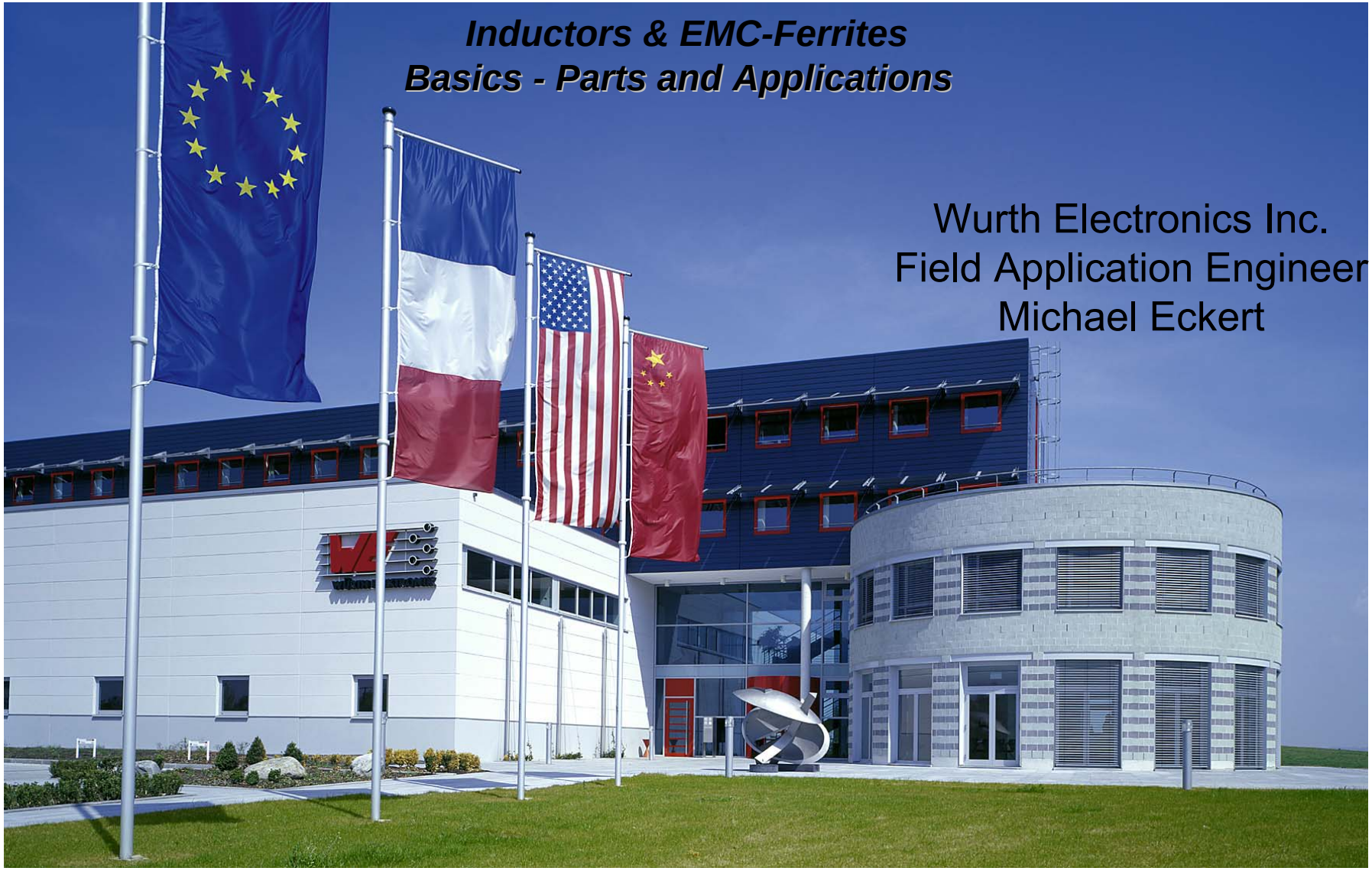
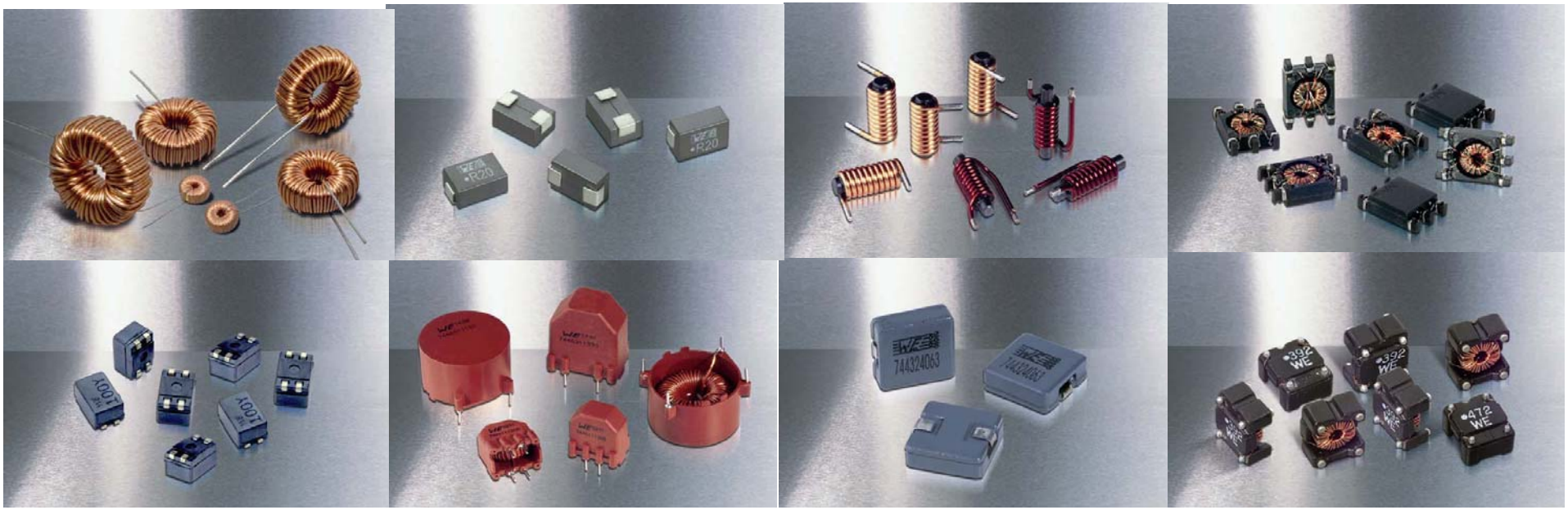
Welcome!


Inductors & EMC-Ferrites
Basics - Parts and Applications
Wurth Electronics Inc.
Field Application Engineer
Michael Eckert

What is an Inductor ?

technical view:

- a piece of wire wounded on something
- a filter
- an energy-storage-part (short-time)
- examples:



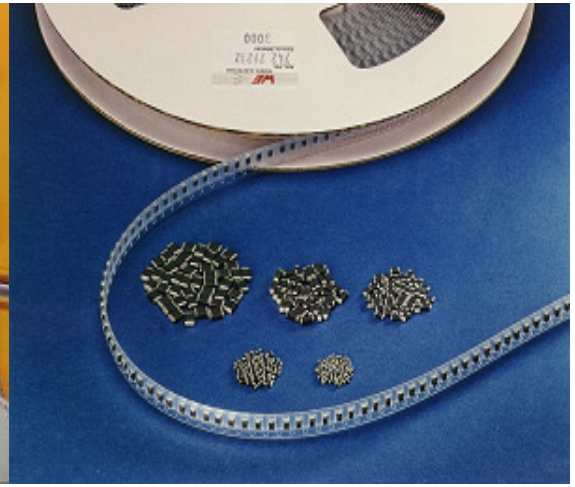
What is an EMC-Ferrite ?

Technical view:

- Frequency dependent filter
- Absorber for RF-energy
- examples:

EMC Snap-Ferrites

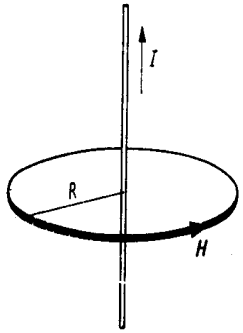
EMC-Ferrites for Flatwire



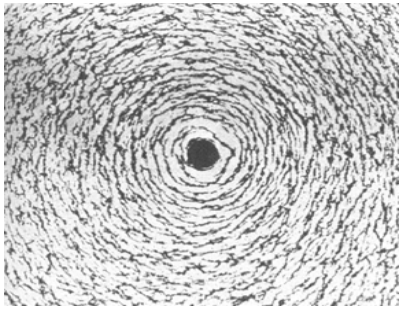
SMD-Ferrites

Magnetic Field Strenght *H* of some configurations

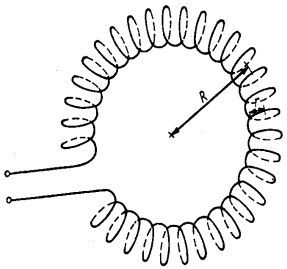
long, straight wire



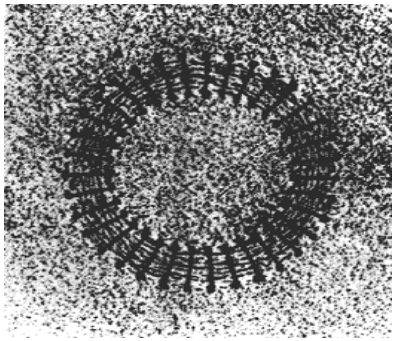
$$H = \frac{I}{2 \cdot \pi \cdot R}$$



Toroidal Coil

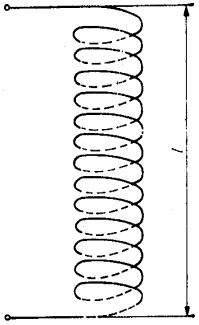


$$H = \frac{N \cdot I}{2 \cdot \pi \cdot R}$$

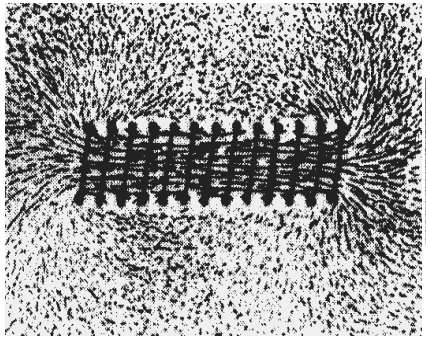


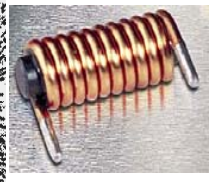
Long solenoid

(e.g. rod core indcutor)



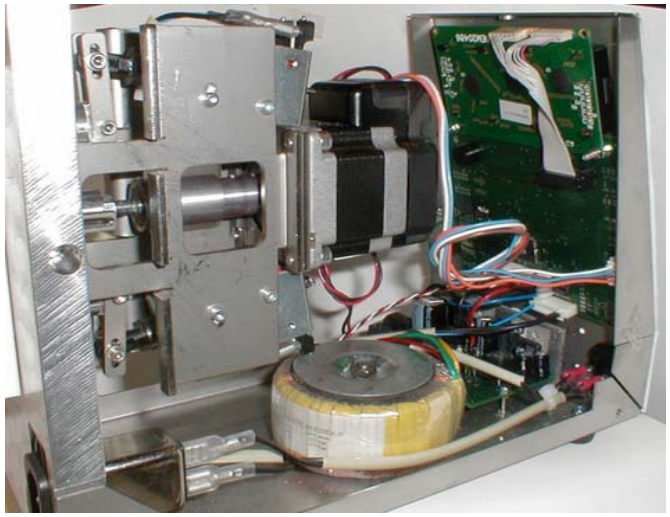
$$H = \frac{N \cdot I}{l}$$

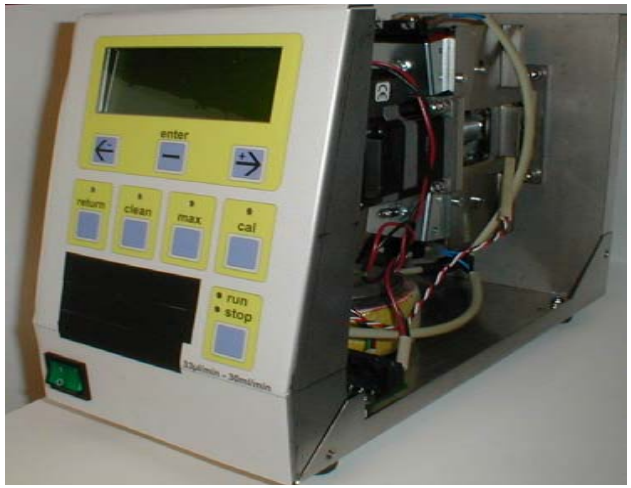


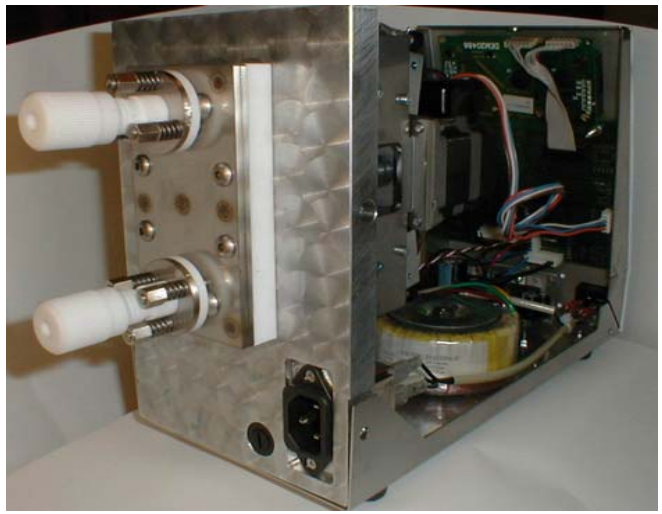


Example: Conducted Emission Measurement

- Dosing pump for chemicals industry.







Conducted Emission Measurement

- Power supply V 1.0

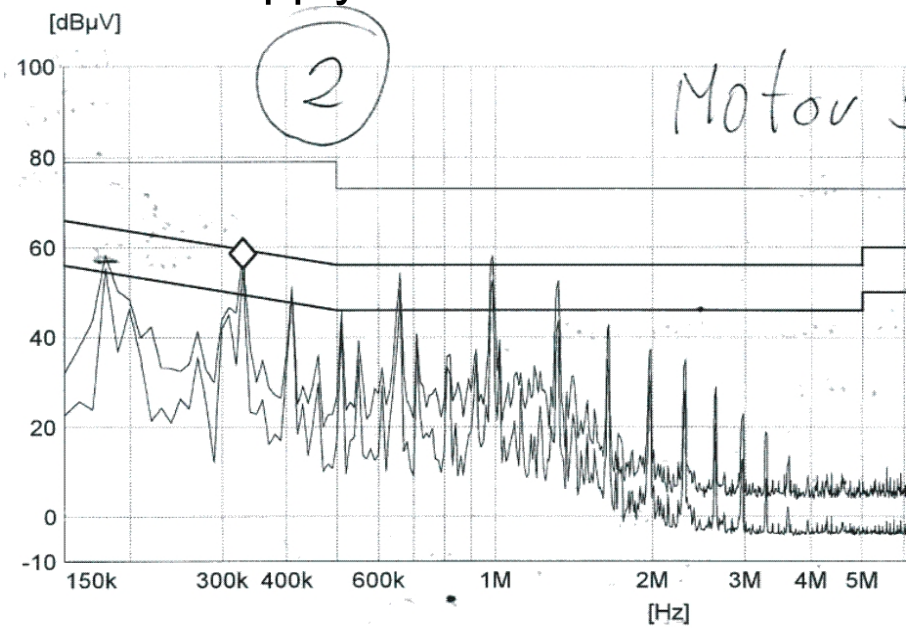
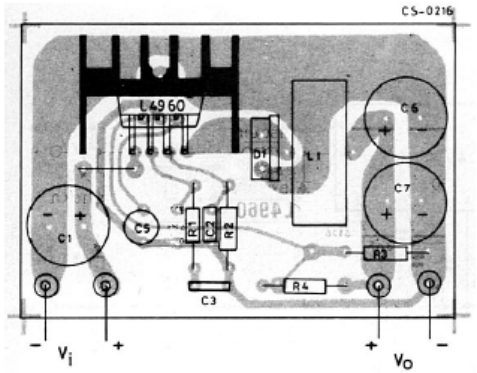
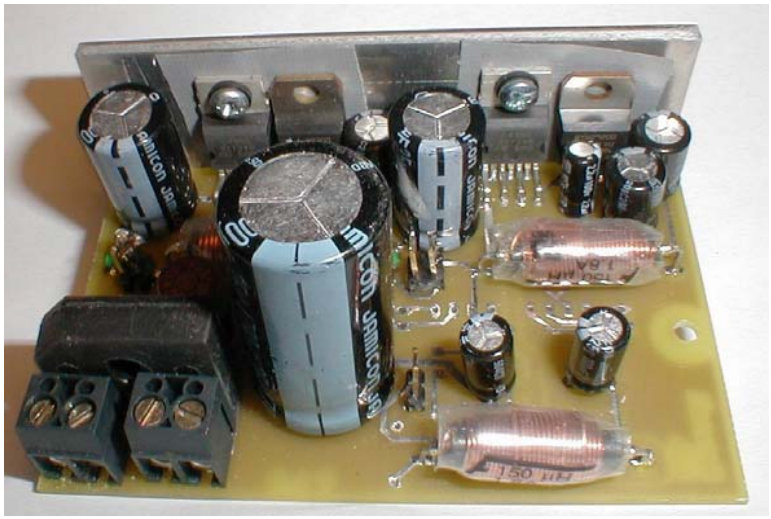
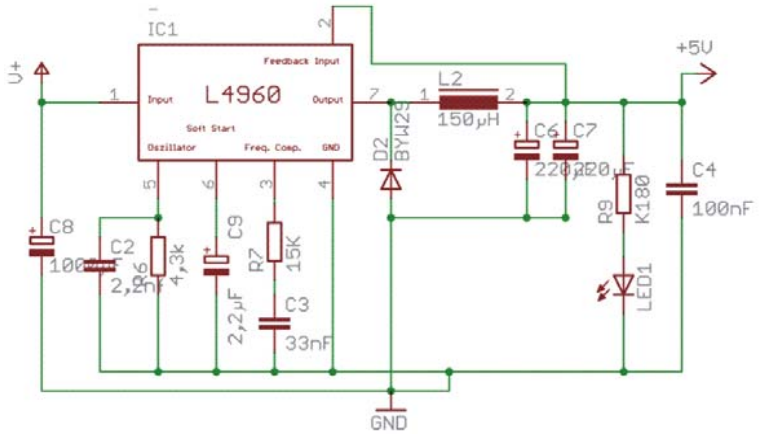


Figure 25. P.C. board and component layout of the Fig. 24 (1 : 1 scale)





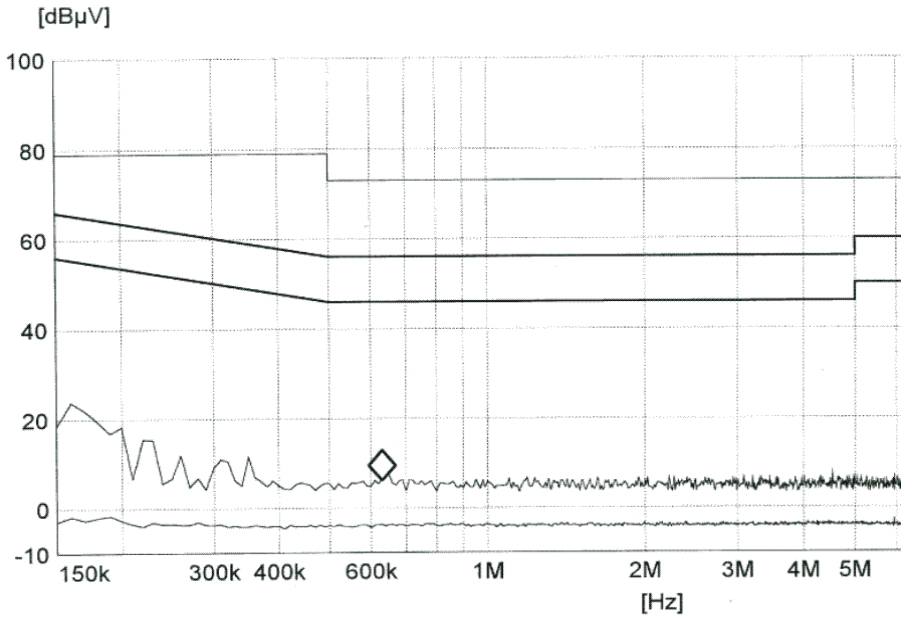
PCB

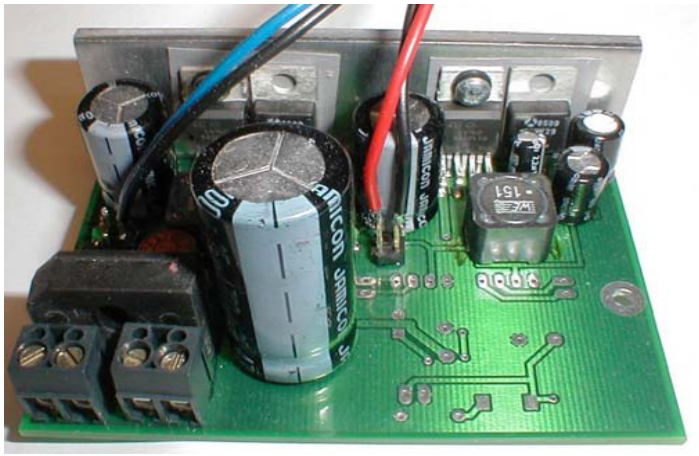


Buck Converter ST L4960/2.5A/fs 85-115KHz

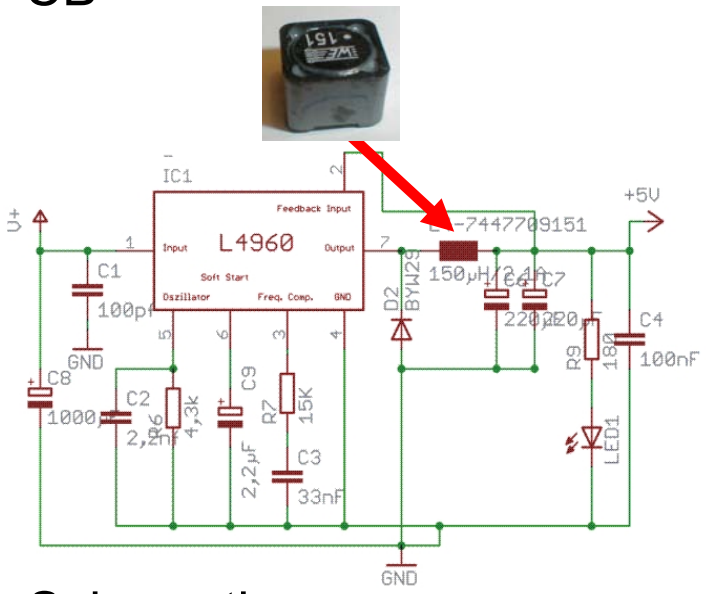
Conducted Emission Measurement

- Power supply V 1.1





PCB



Schematic

Awareness:

- **Select the right parts for your application**
- **Do not always look on cost**

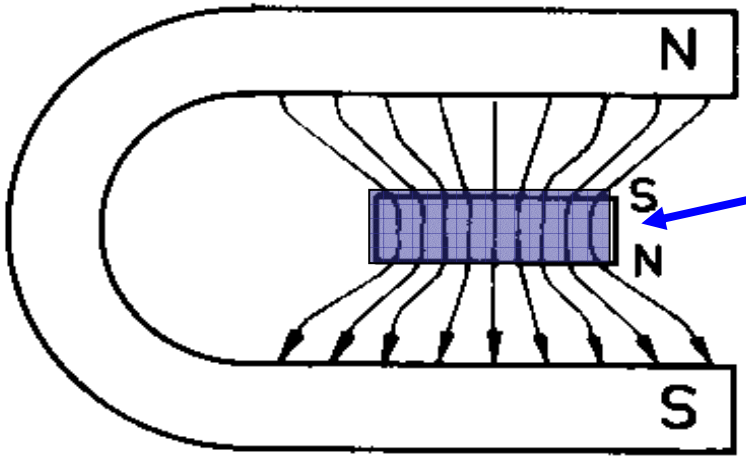
Very easy solution with a dramatic result!!!

Choke before

Choke after

or

What is permeability [u_r]?



– **Permability** (μr): **describe the capacity of concentration of the magnetic flux in the material.**

typical permeabilities [μr] :

- Iron powder / Superflux : 50 ~ 150

- Nickel Zinc : 40 ~ 1500

- Manganese Zinc : 300 ~ 20000

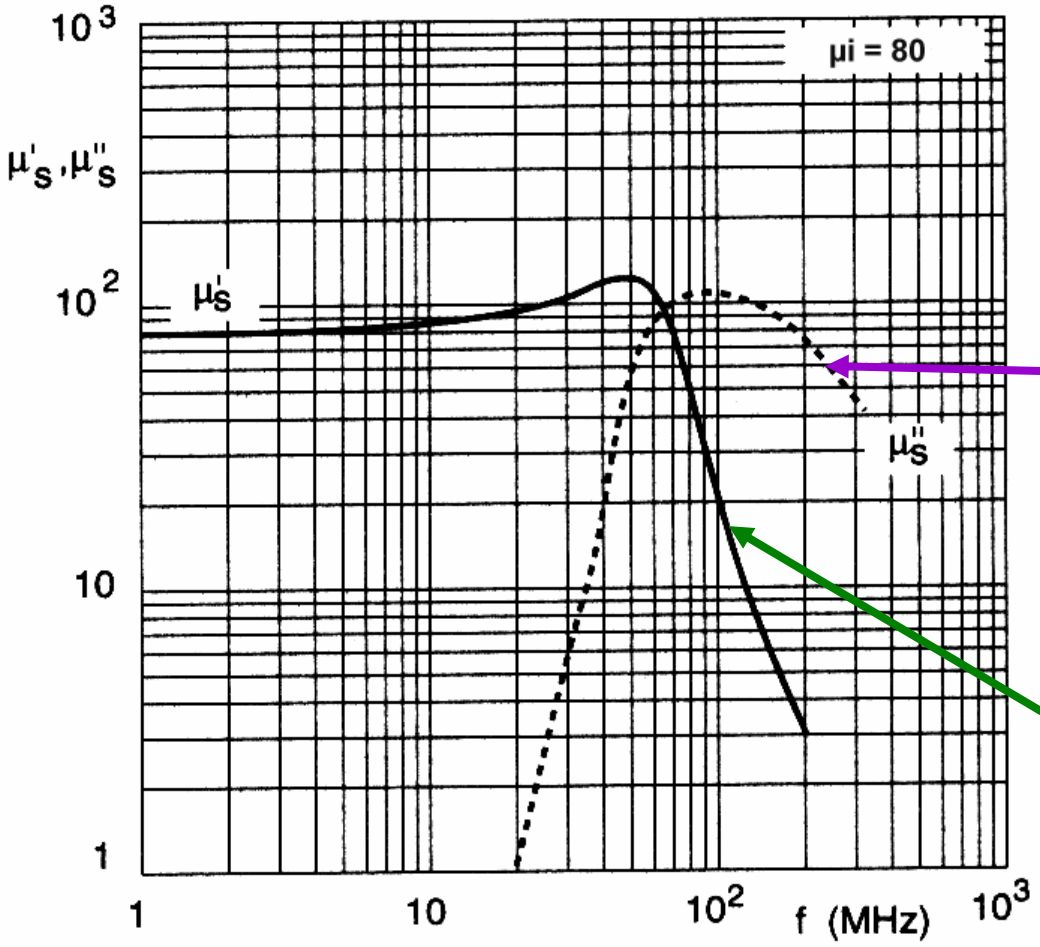
Magnetic induction in ferrite:

$$B \neq \mu_0 \cdot \mu_r \cdot H$$

Non-Linear Function (μ_r!)

The relative permeability is dependent on frequency……

Frequency dependent Permeability



$$\text{Tan}\delta = \frac{R}{X_L}$$

Loss factor

$$R = \omega L_0 \mu''$$

resistive component (material it self)

frequency dependent core losses

$$X_L = j\omega L_0 \mu'$$

„ideell“ (without material) inductive component

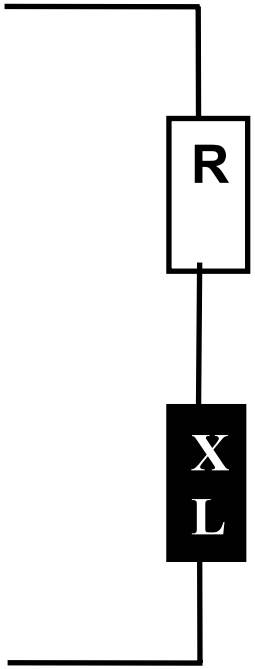
frequency dependent inductive portion

complex permeability

Measurement of Core Material Properties

Core Material (Fe / MnZn/ NiZn/ …)

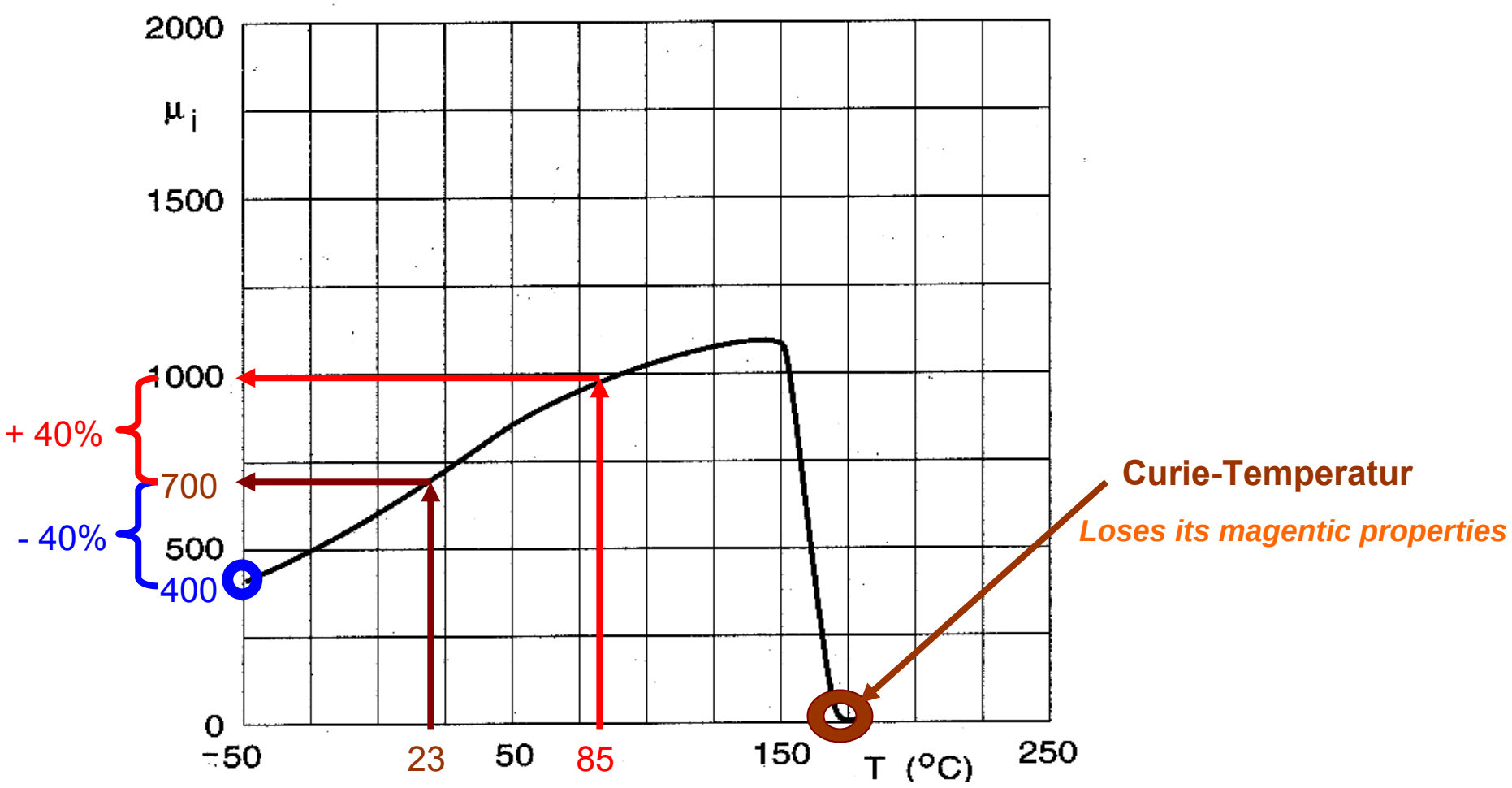
Impedance Analyser



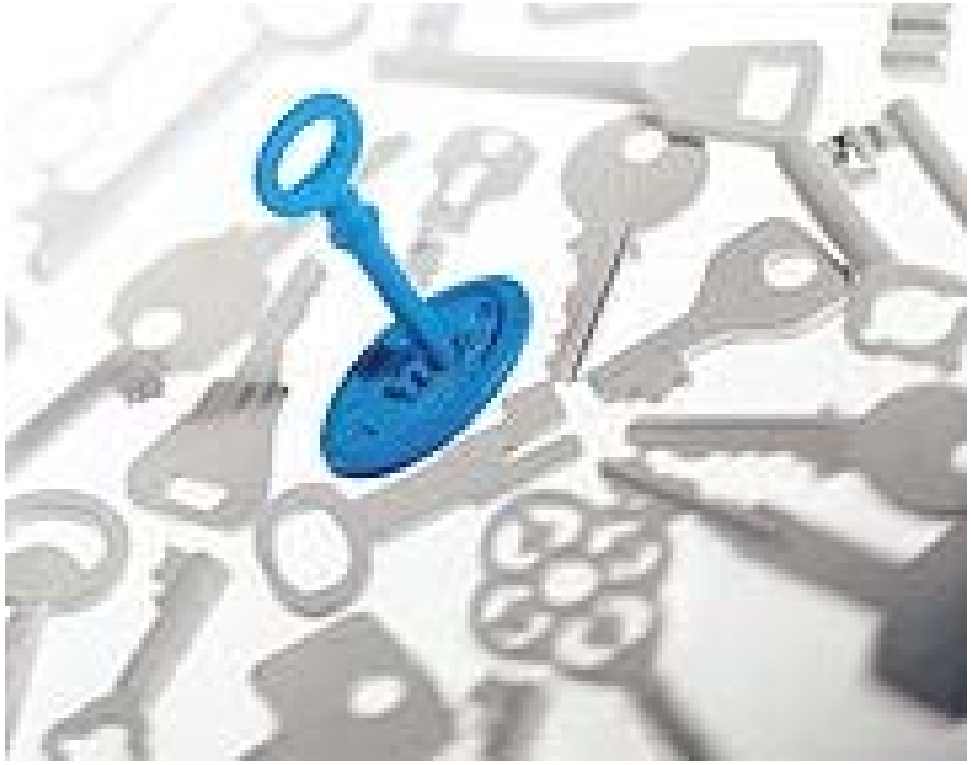
Core Material Parameter

$$Z = \sqrt{R^2 + X_L^2}$$

Permeability vs. Temperature

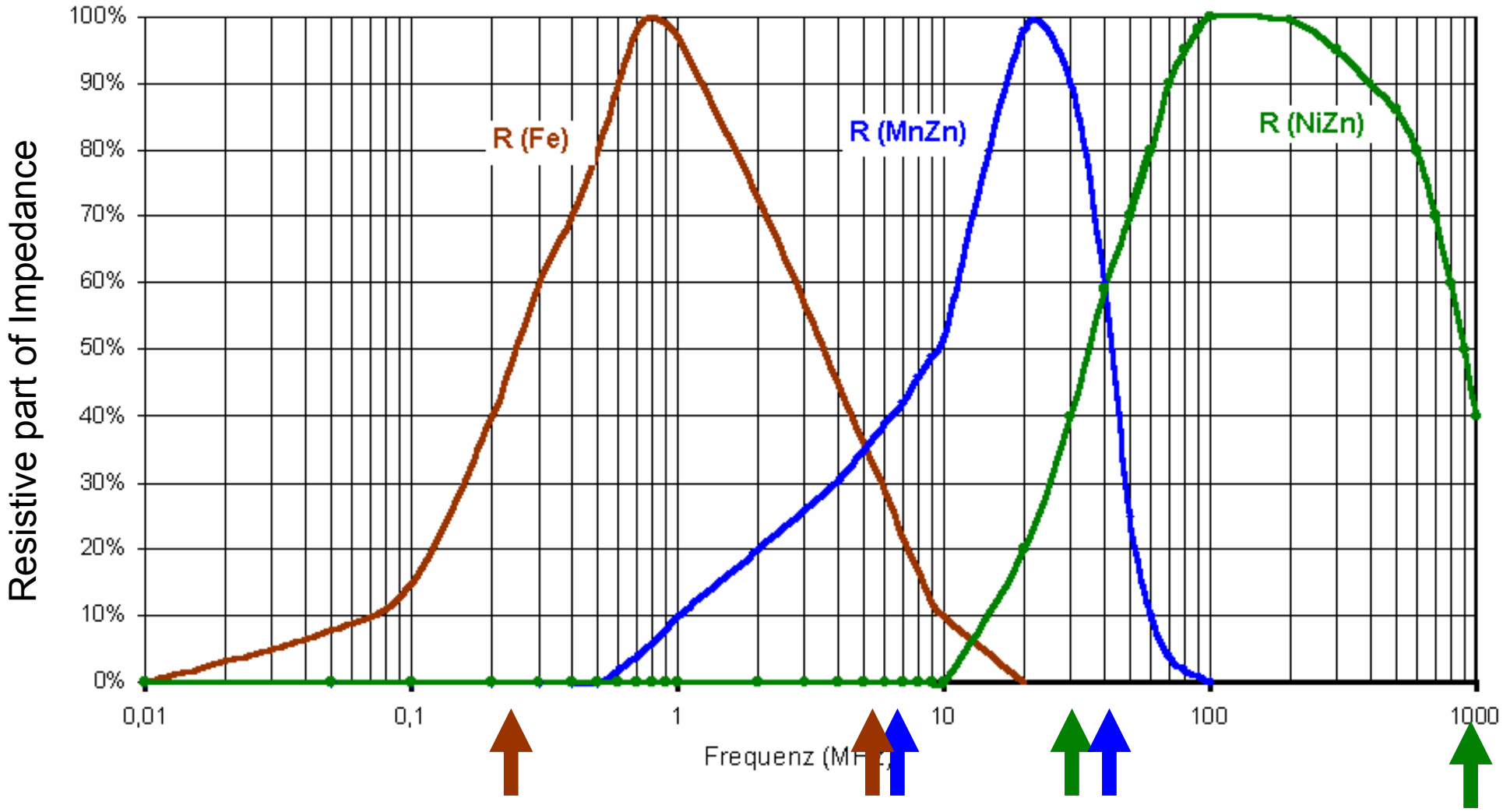


How to find the best part for my application ?



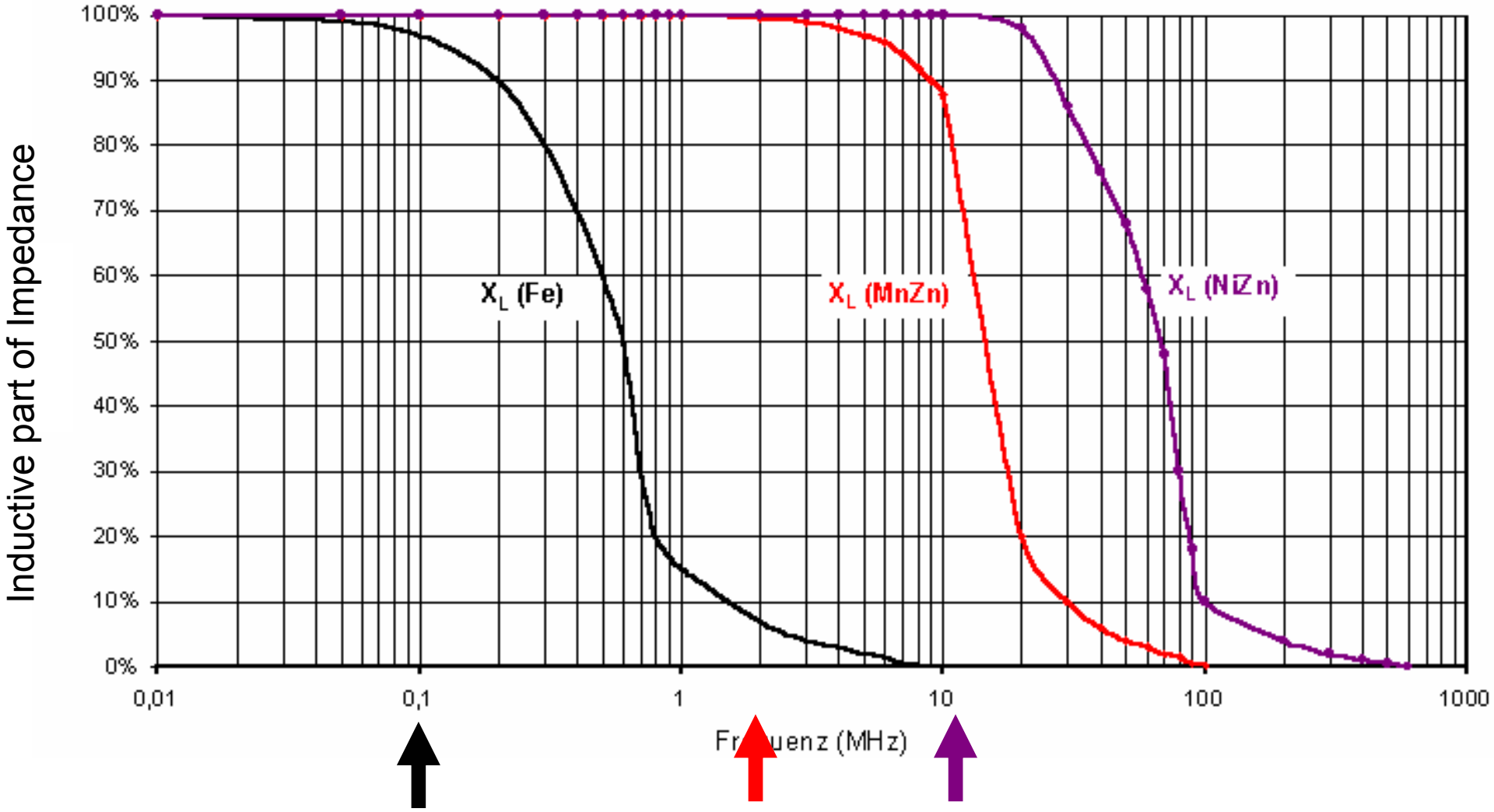
Core Material Comparison

When to use which type of material for filtering ?



=> It depends on frequency-range to filter !

When to use which material for store energy



=> It depends on application frequency for EACH Core-Material !

When to use an Inductor ?
When to use an EMC-Ferrite ?

WÜRTH ELEKTRONIK

=> Application Storage Choke:

Request: **lowest possible losses** at application frequency

high Q-factor

=> Application as absorber-filter:

Request: **highest losses possible** at application frequency range

low Q/factor

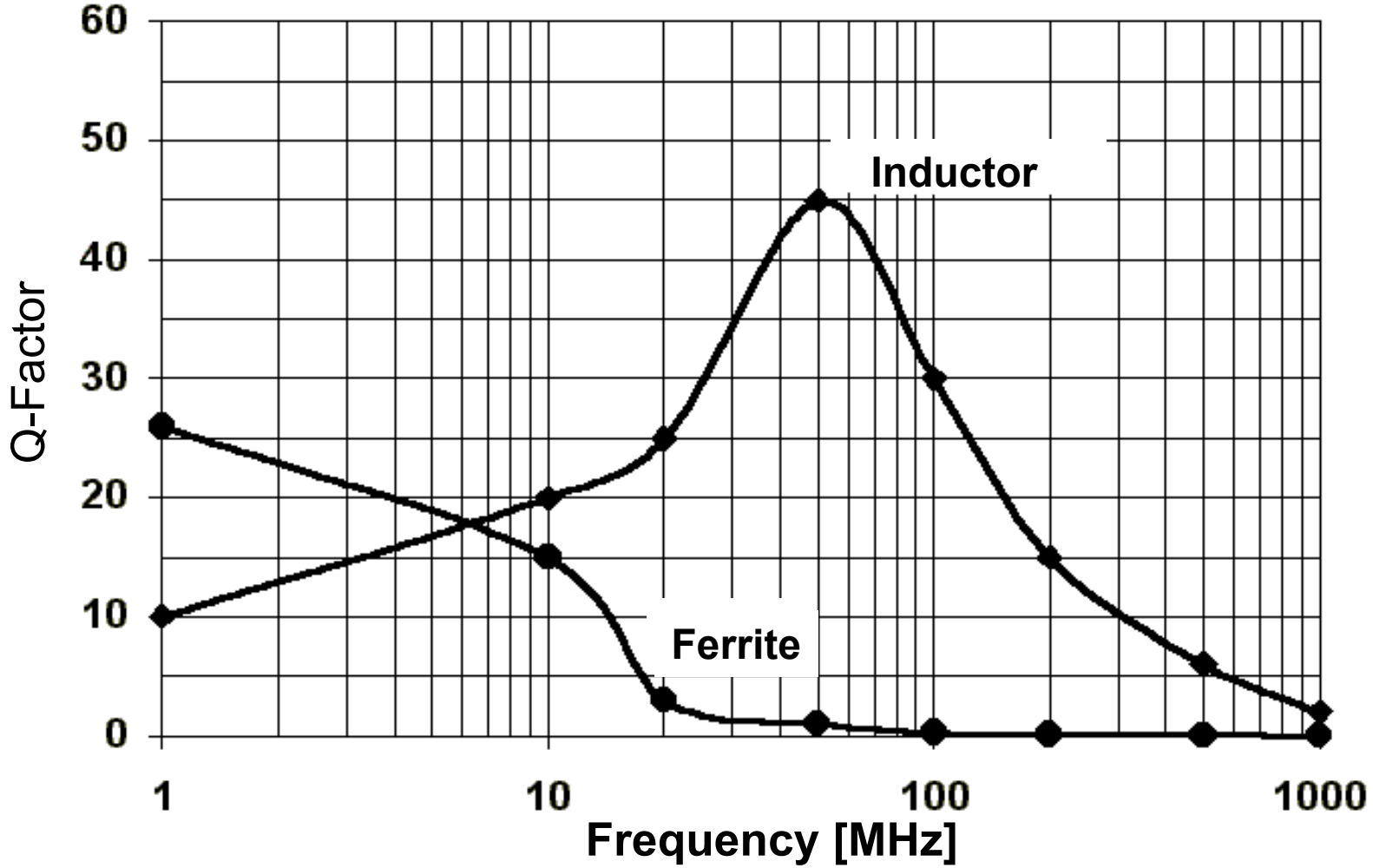
Inductor vs. EMI-Ferrit:

WÜRTH ELEKTRONIK

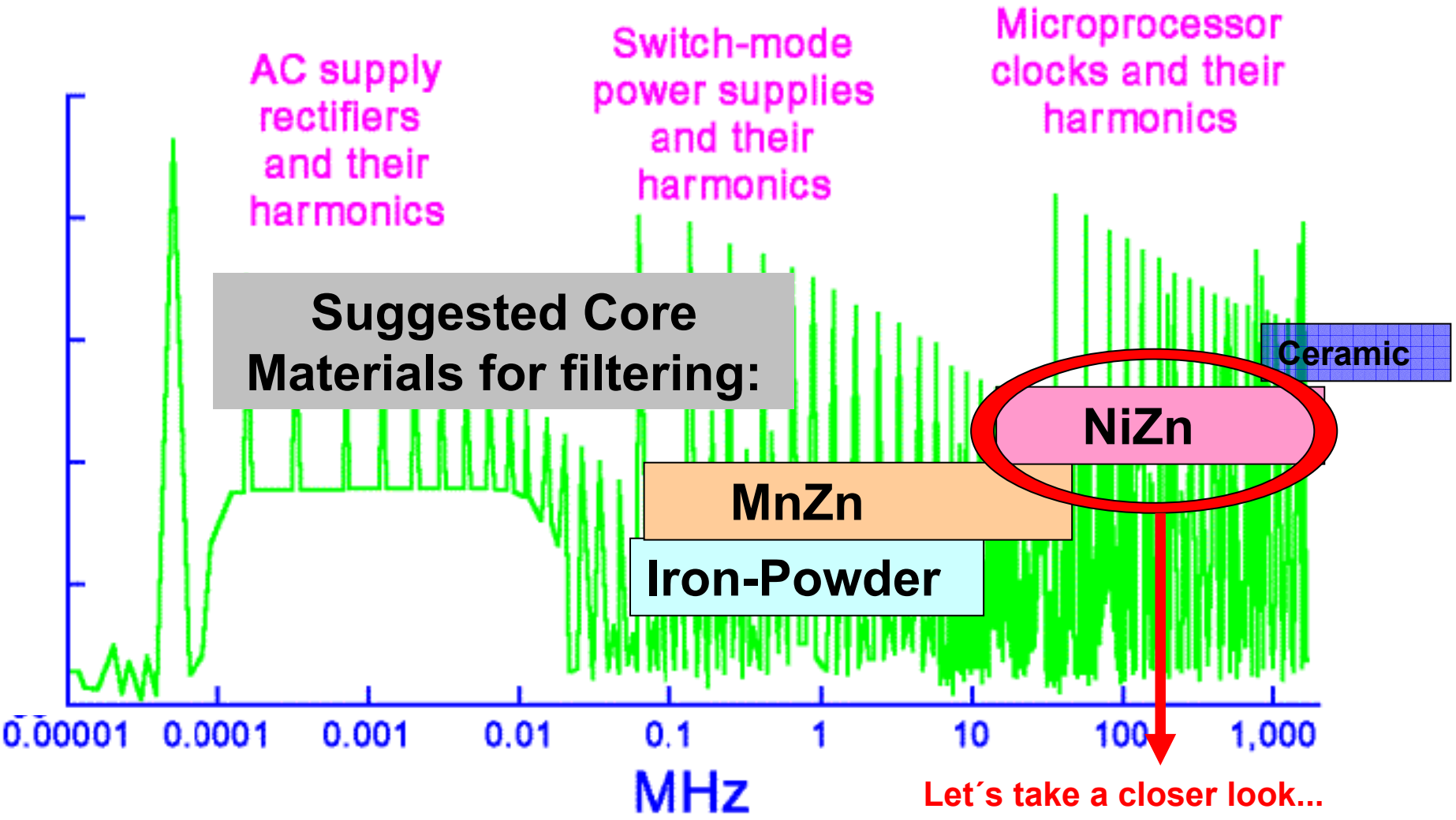
Comparison Q-Factor: Ferrite vs. Inductor

$$Q = \frac{XL}{R}$$

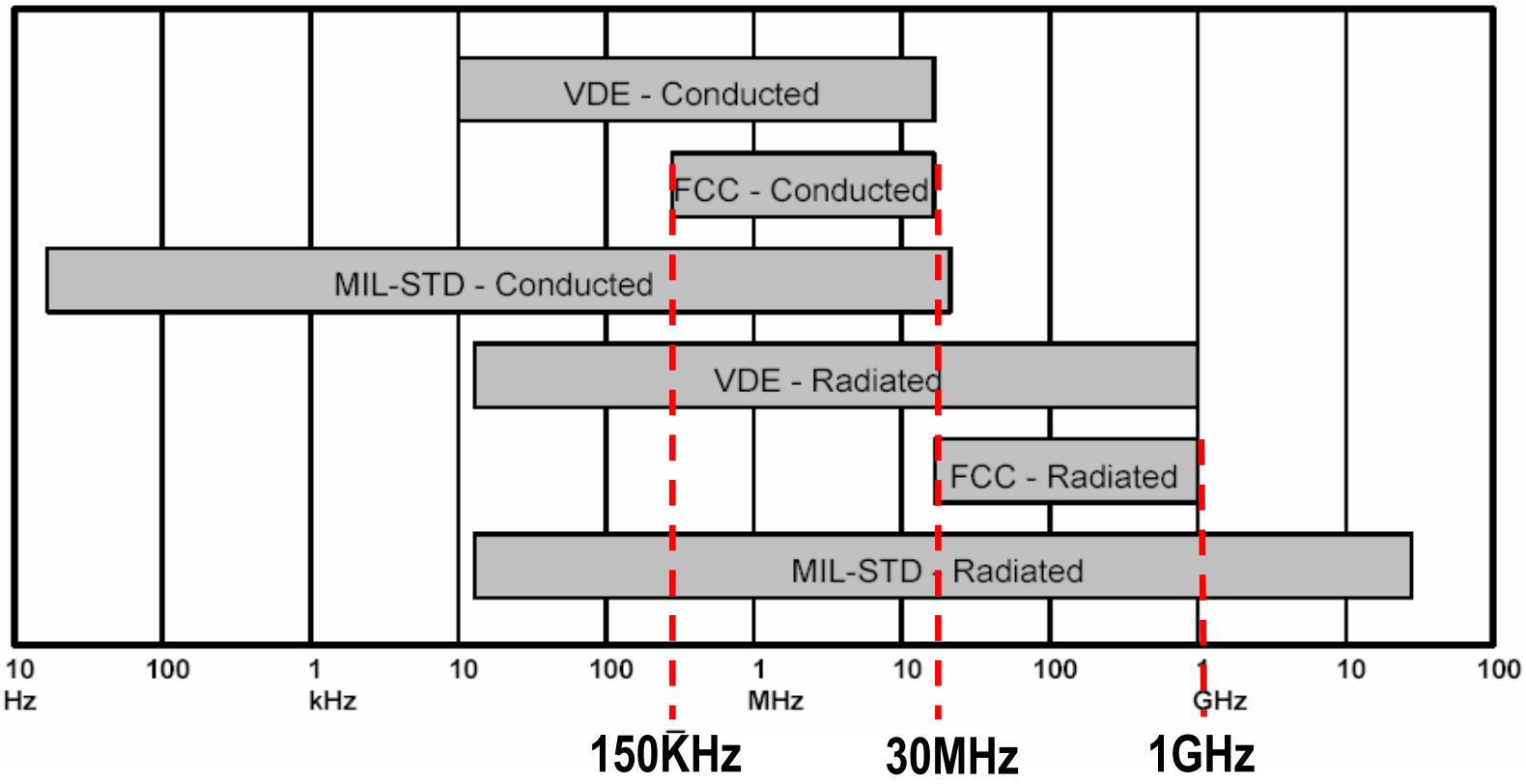
Losses



Frequency-Spectrum and suggested Core Materials

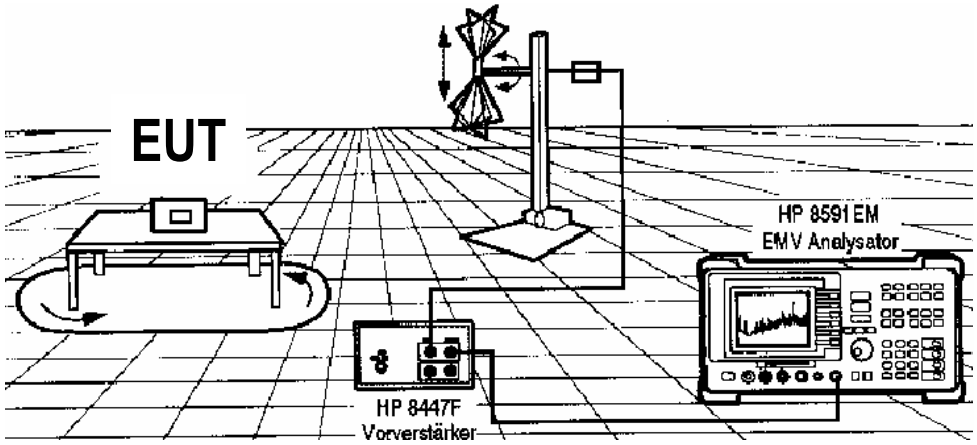


Frequency range for EMI tests

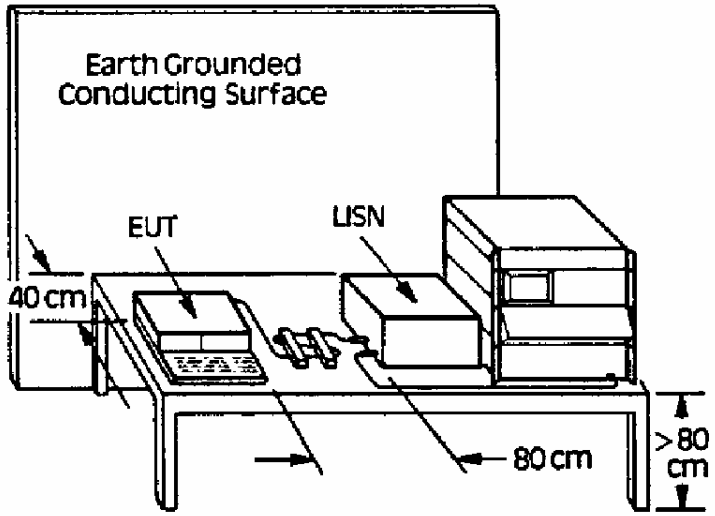


Overview FCC Tests

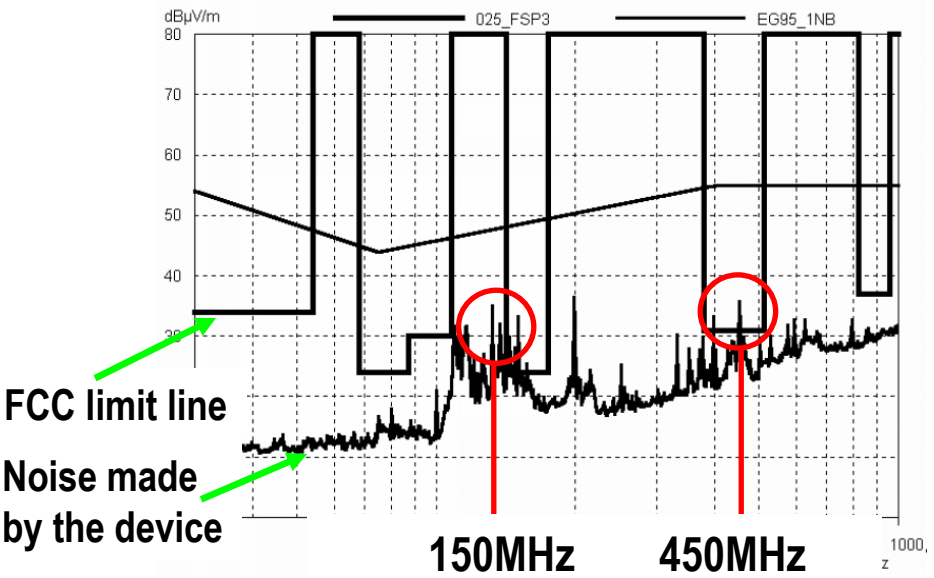
Radiated Configuration

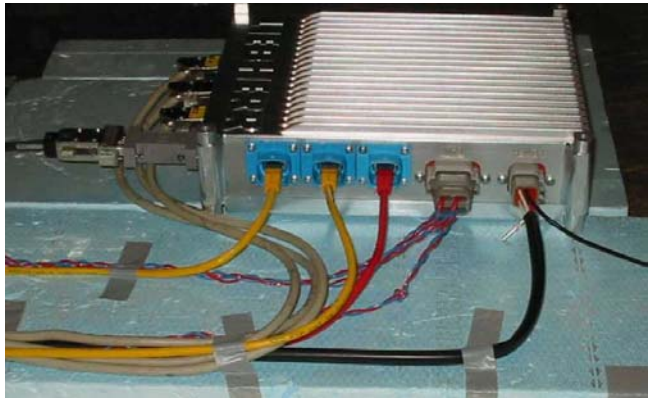


Conducted Configuration

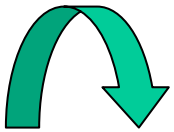


Noise Spectrum

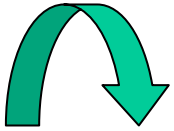




What‘s the main Interference we see on the board level?



Common Mode Interference (asym. Interference)



Differential Mode Interference (sym. Interference)

How can we find out what interference we have on the PCB‘s?

Take a Snap Ferrite and fix it on the cable
(both lines e.g. VCC and GND)

noise reduction
or „noise immuntiy increase“

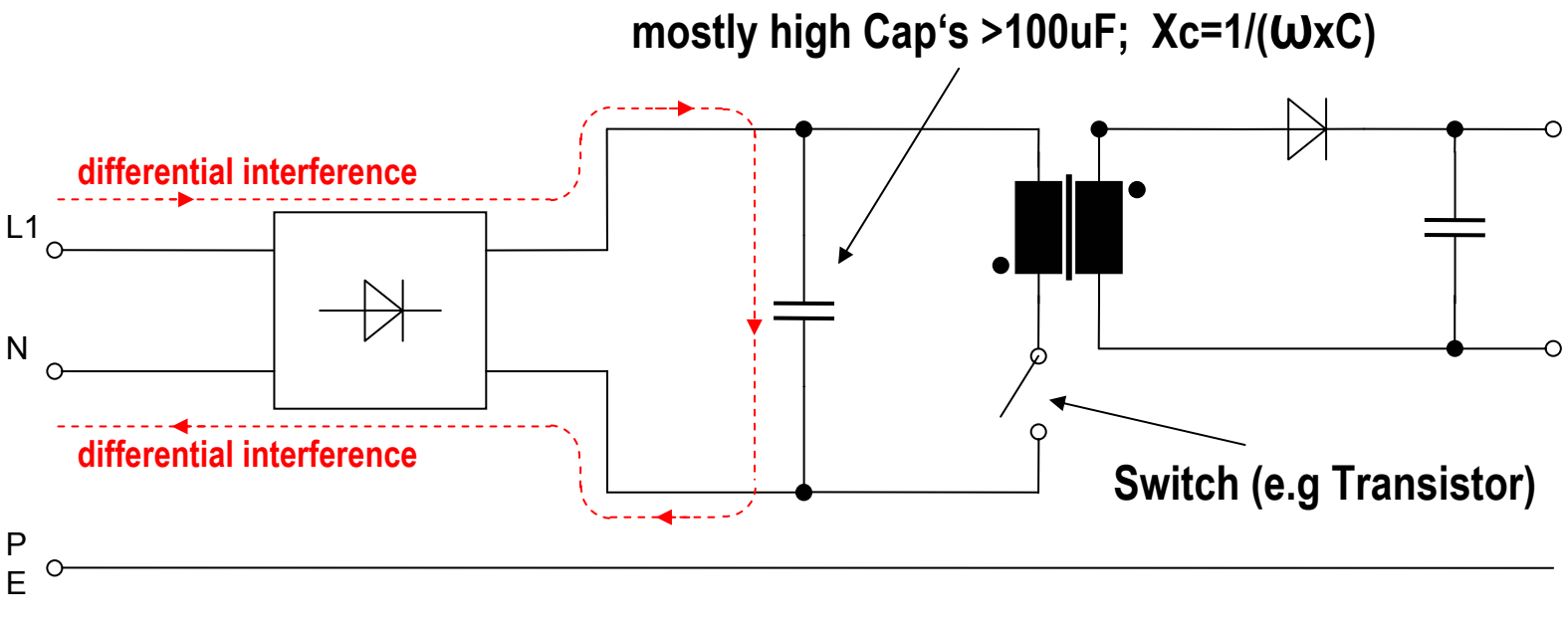
you have Common Mode Interference

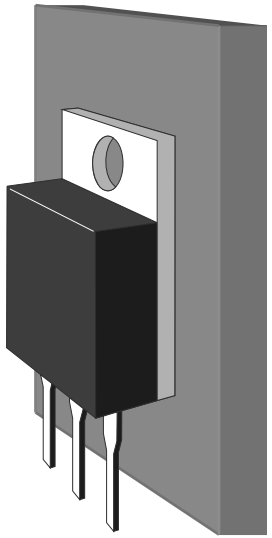
if not

you have Differential Mode Interference

Example: Flyback Converter

Appearance of ***differential noises*** on the input line of a Flyback Converter

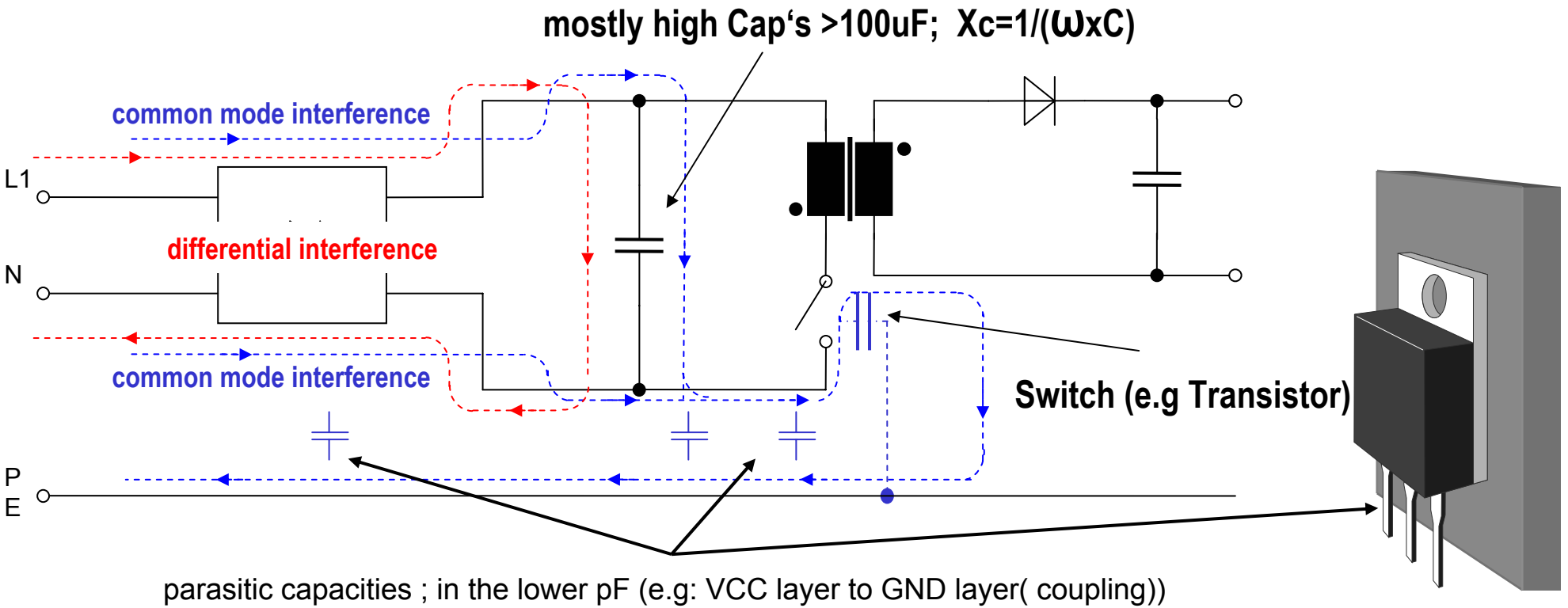




differential interference occurs mainly at *lower* frequencies

Example: Flyback Converter

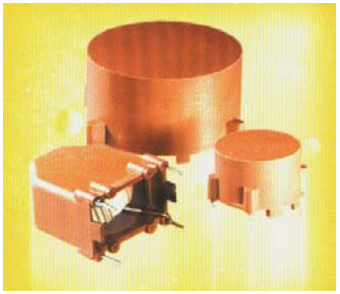
Appearance of ***common mode noises*** on the input line of a Flyback Converter

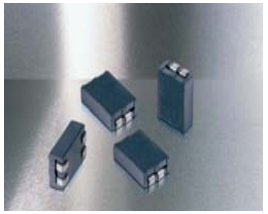


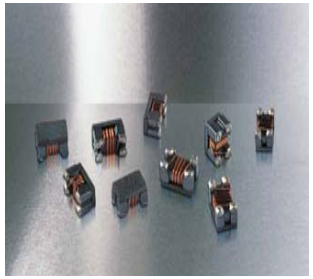
parasitic capacities ; in the lower pF (e.g: VCC layer to GND layer(coupling))

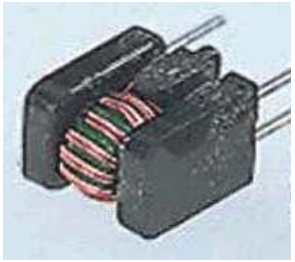
common mode interference occurs mainly at *higher* frequencies

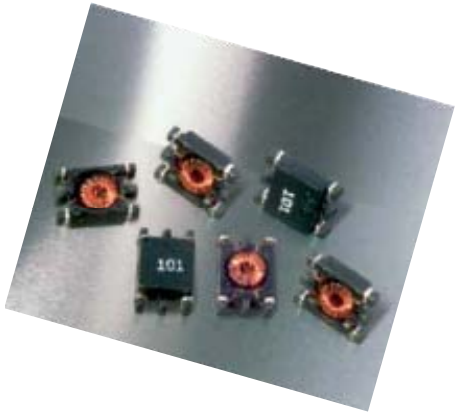
Current Compensated Chokes

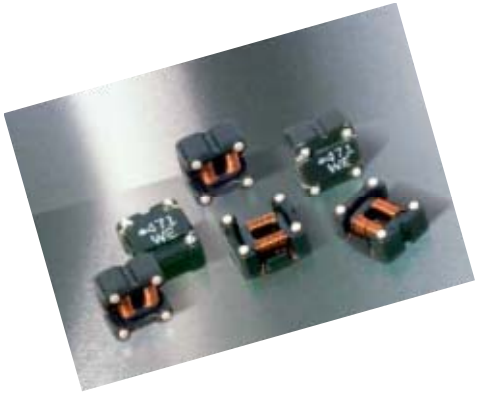


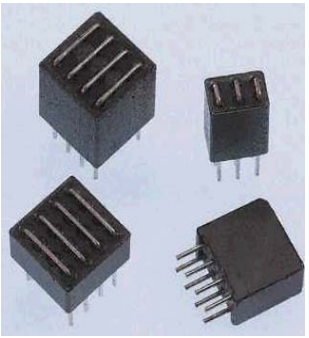




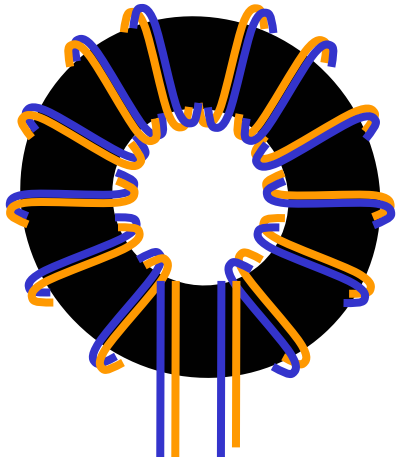


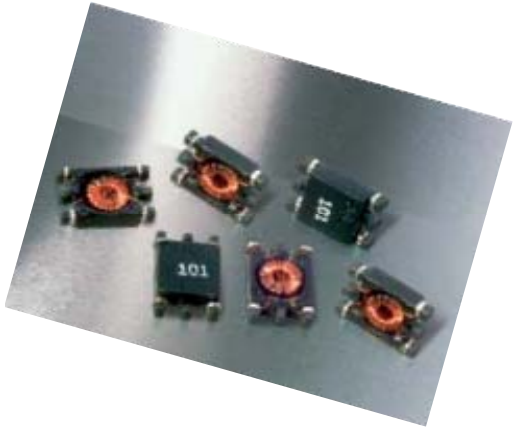






Replace a „Snap Ferrit“ by a common choke ?



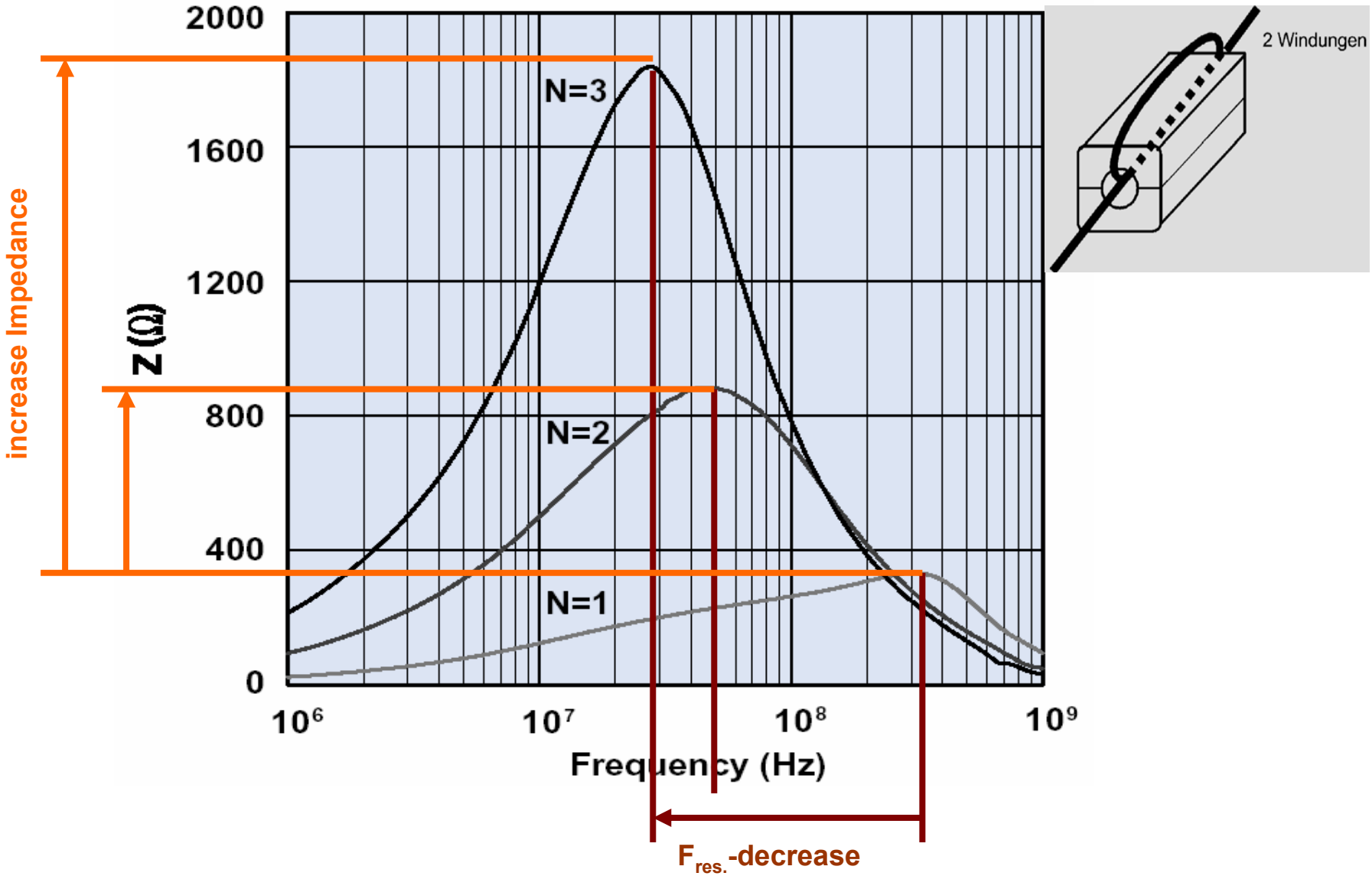


We can replace ferrite by common mode choke

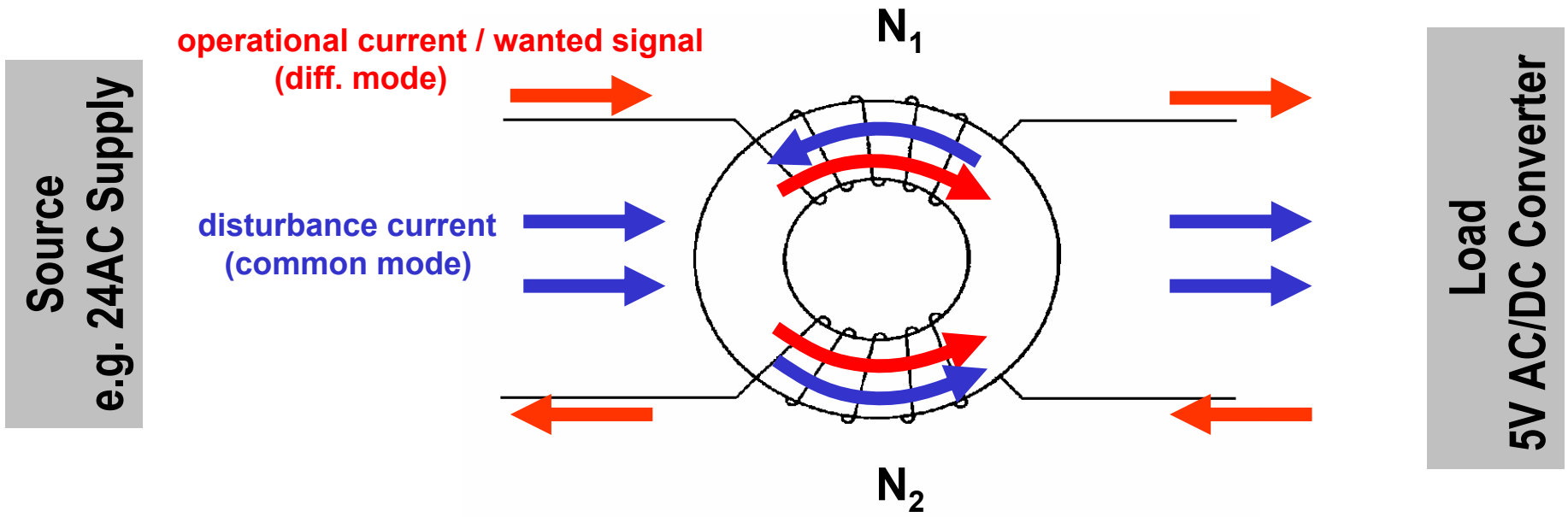
Both are common mode filters !

First check for the technologie and look the impedance curve

Impedance increase vs. numbers of turns



Functionality of a common mode choke:

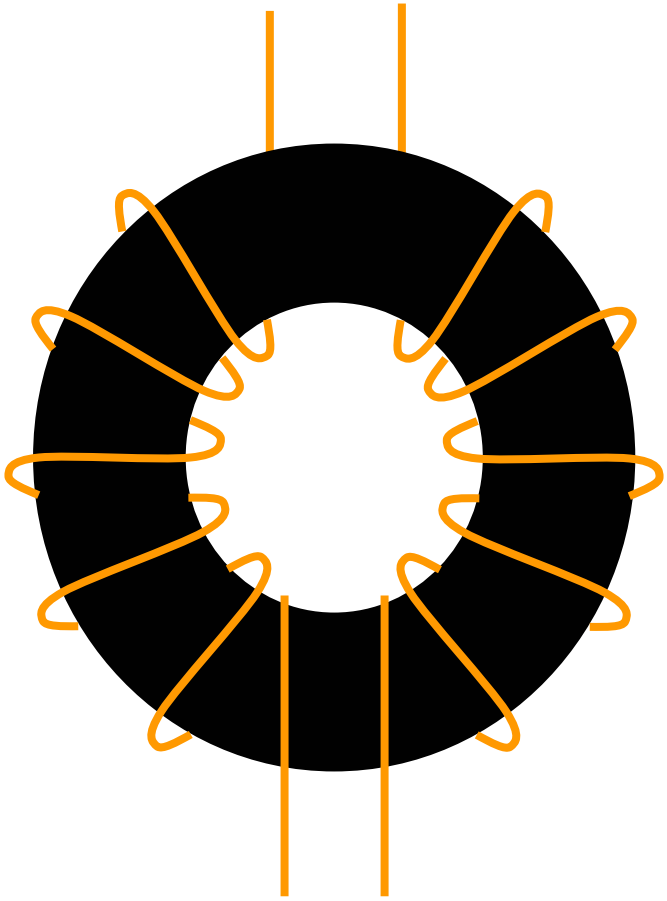


The operational current (diff. mode) is routed by all relevant conductors through the core (e.g. +/- or L/N).
That´s why the magnetic fields of these two conductors compensate each other to zero => no influence on the wanted signal

The disturbance current flows on both wires in the same direction and generates a magnetic field in the toroidal core => the choke is able to filter unwanted noises.

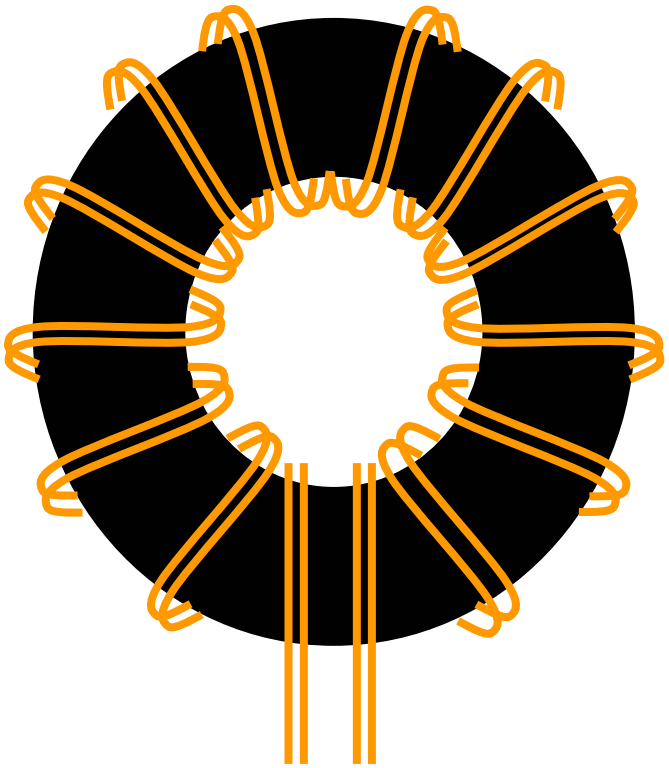
Common Mode Choke

sectional winding



< advantage? >

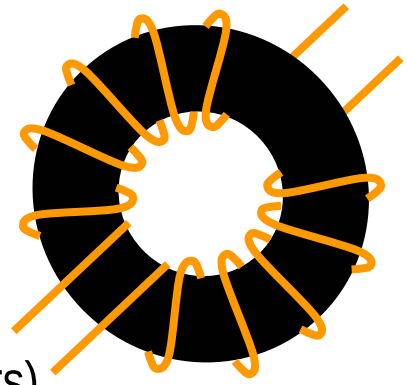
bifilar winding



Why bifilar / sectional winding ?

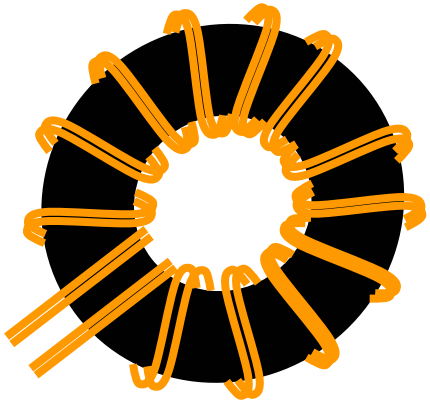
sectional winding:

- Same number of windings placed opposed on the toroidal core
- In addition to the common mode suppression (asym. noises) the high leakage inductance also allows filtering of differential interferences (sym. noises)



bifilar winding:

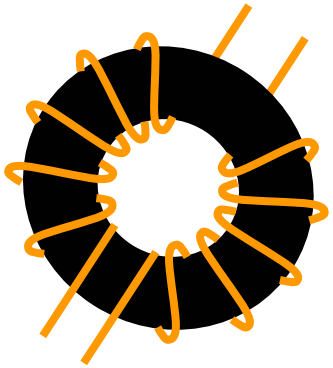
- Parallel wiring around the core (in most cases we use wires with different colors)
- Small leakage inductance and therefore less attenuation of high-frequency differential noises



Sectional winding:

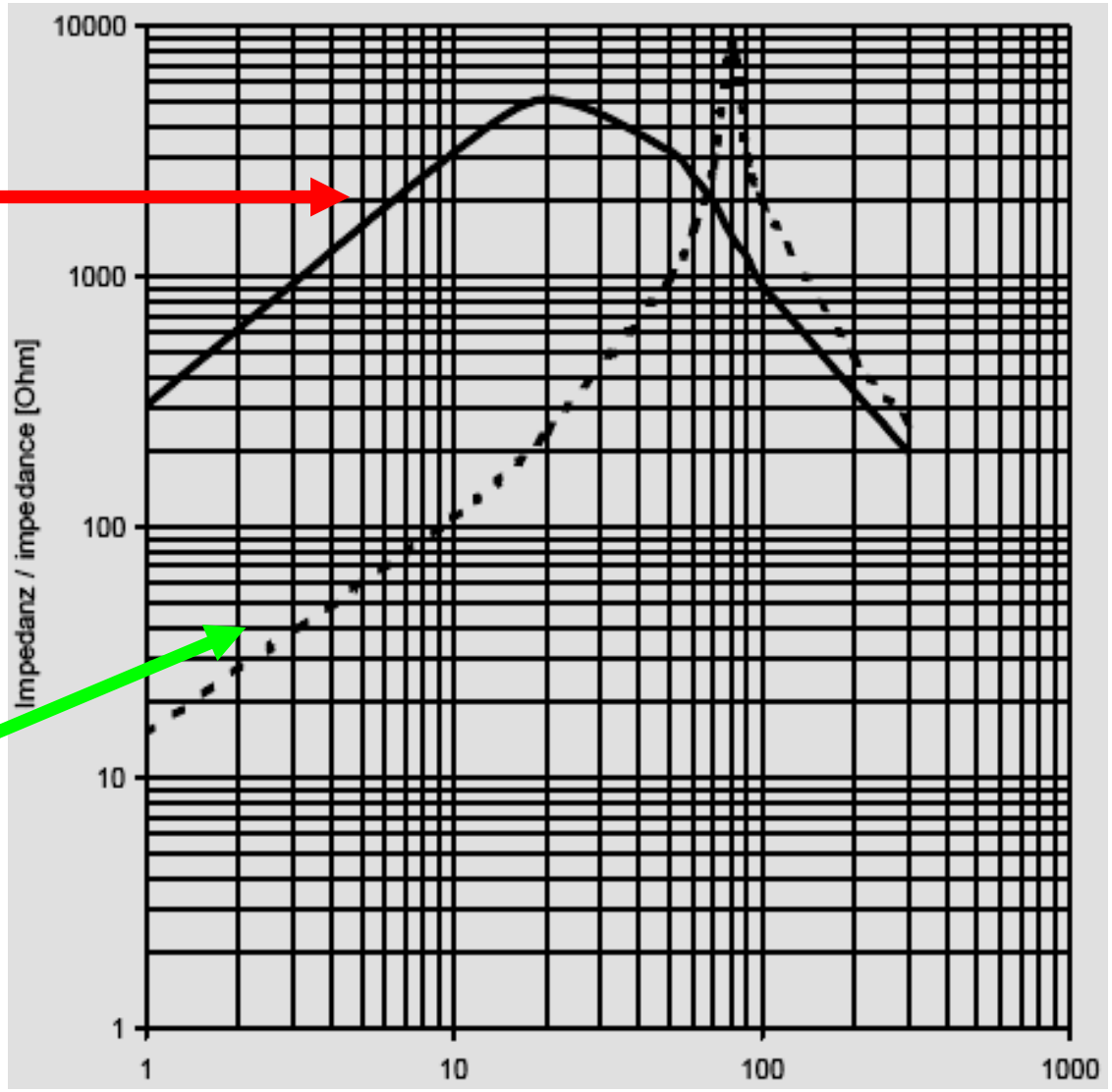
For example: WE-SL2 744227S

Common Mode suppression



Differential Mode suppression

is high!



ATTENTION:

SECTIONELL WINDING MUST BE USED ON MAIN-POWER SUPPLY !

Bifilar winding vs. Sectional winding

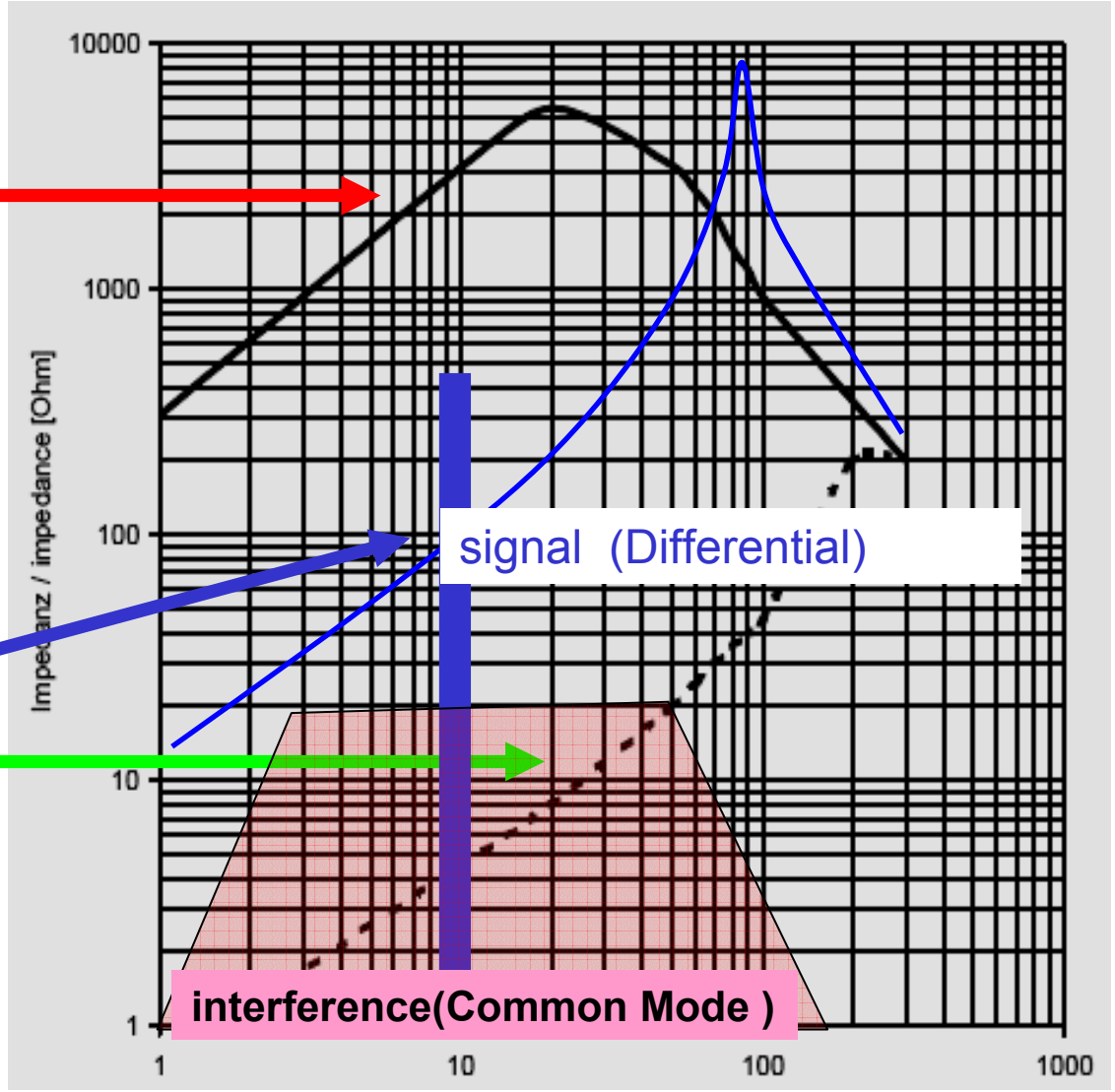
For example: WE-SL2 744227

Common Mode suppression

Differential Mode S-Type

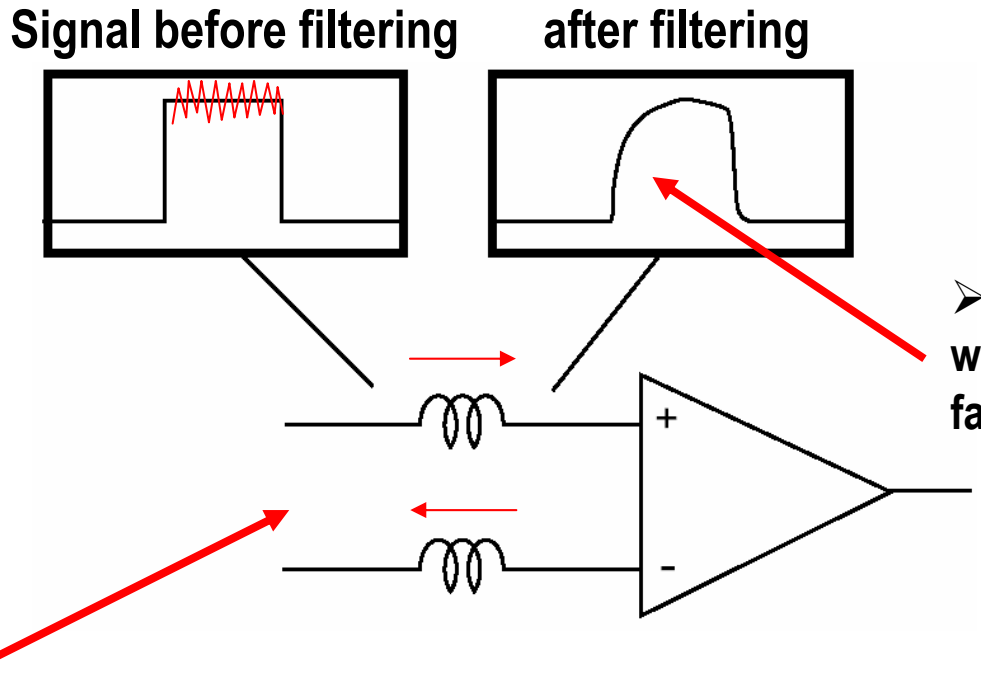
Differential Mode suppression

is low!



Advantage of a Common Mode Choke

Filtering with two inductors or ferrites



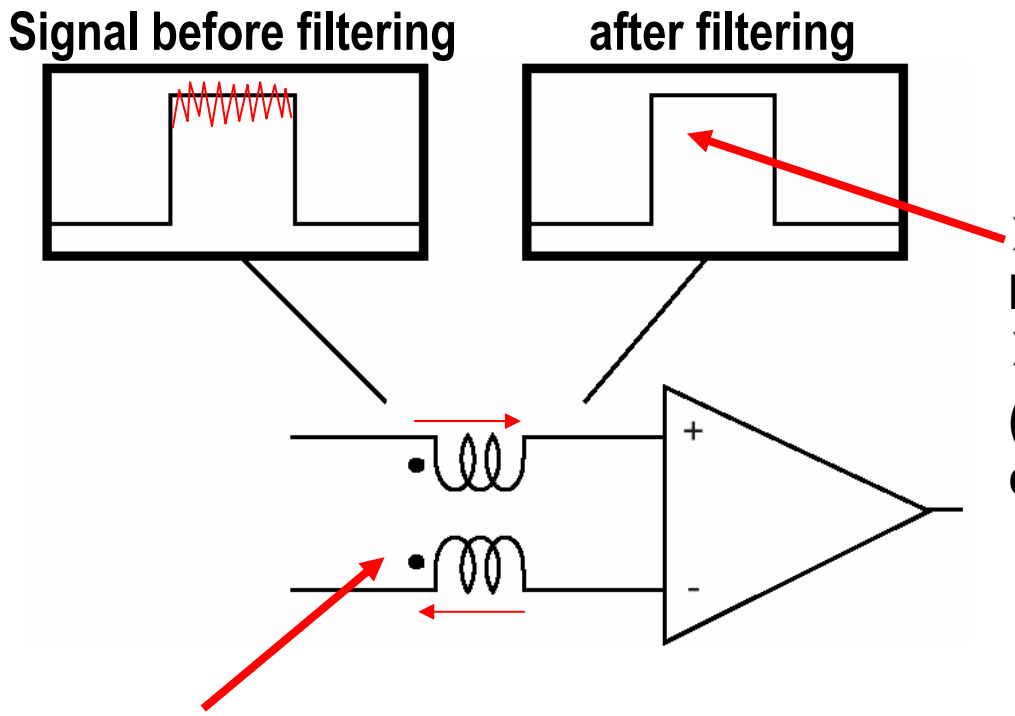
➢Rise-time of the signal is affected, which could cause problems for fast data and signal lines

which occurs from the DC current the filtering performance is shortened.

➢because of the pre-magnetization (saturation)

Advantage of a Common Mode Choke

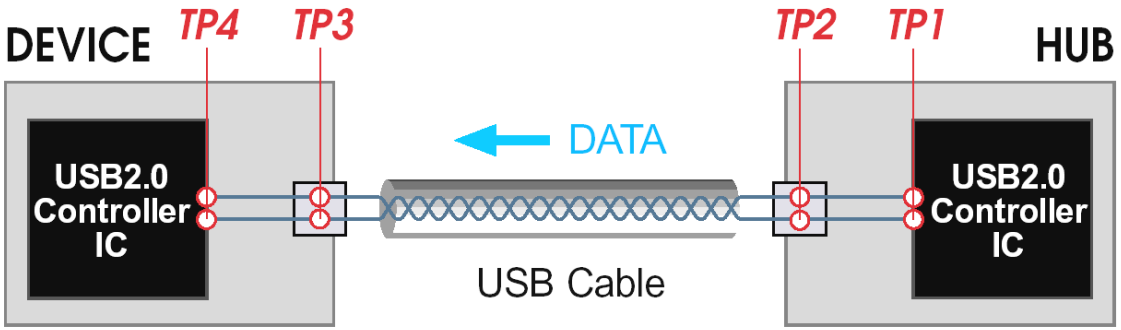
Filtering with a Common Mode Choke

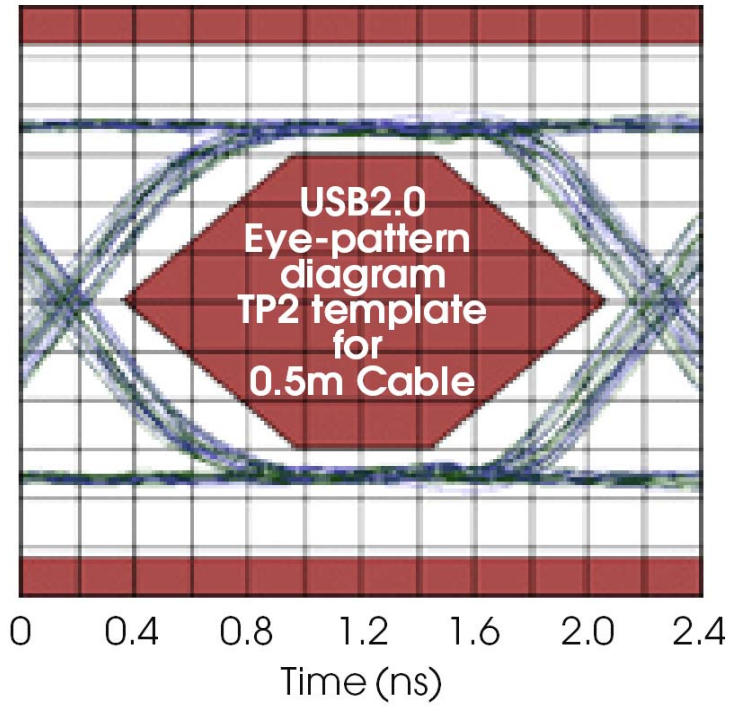


➢ no affect on the signal rise-time, because of magnetic field compensation
➢ no influence of the wanted signal (the two windings are magnetically coupled)

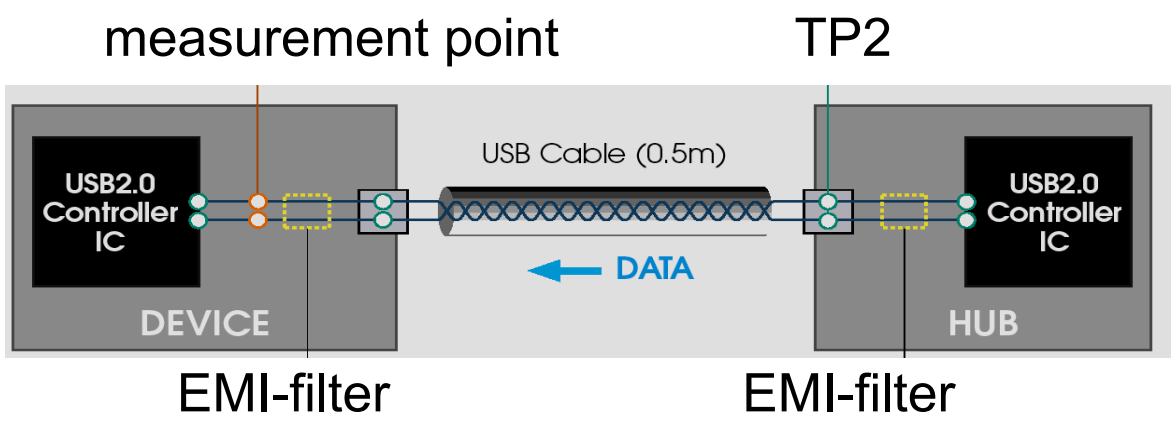
➢ no pre-magnetization (saturation) occurs from the DC current, because of magnetic coupling
➢ much better performance vs. two separate inductors or ferrites

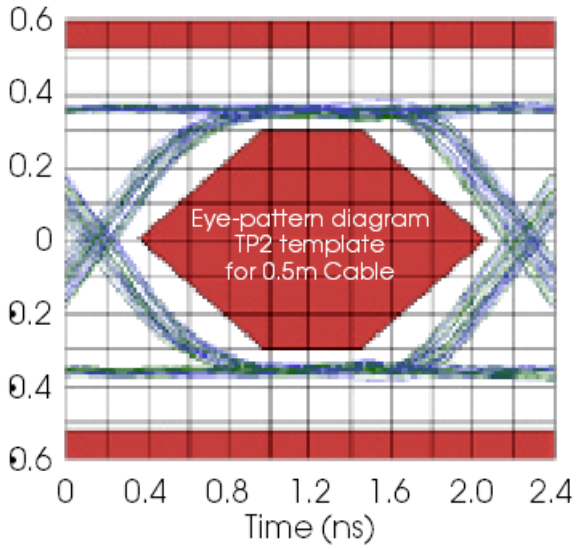
Filtering the USB 2.0 interface via CMC



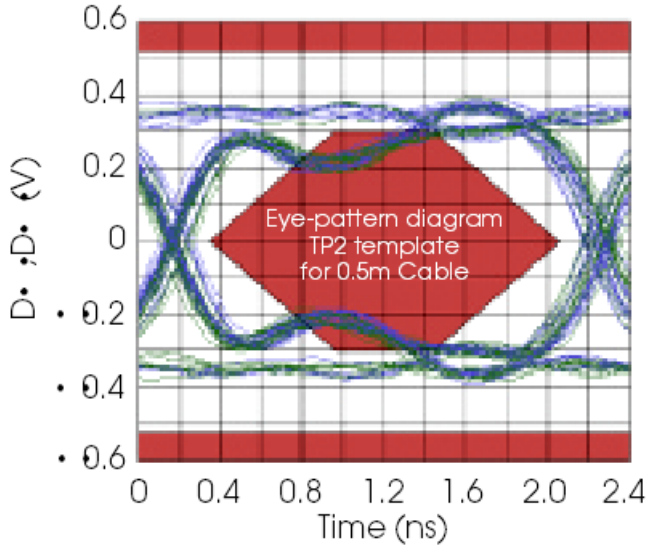


USB 2.0 Filtering via WE-CNSW

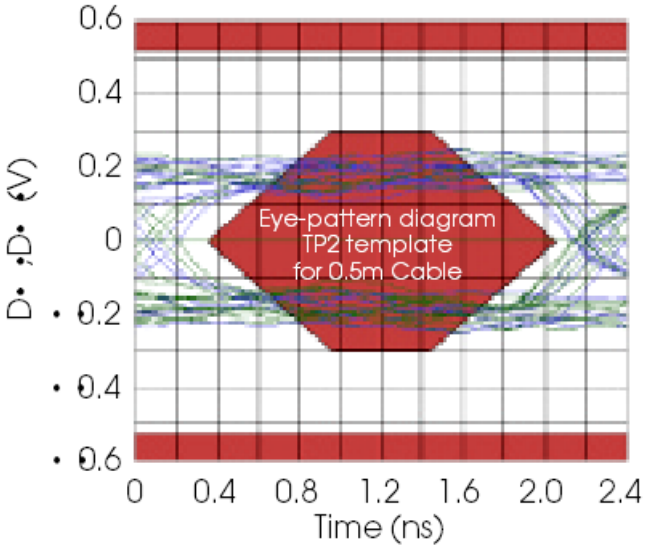




90 Ohm @ 100 MHz C.M.
20 Ohm @ 240 MHz D.M.

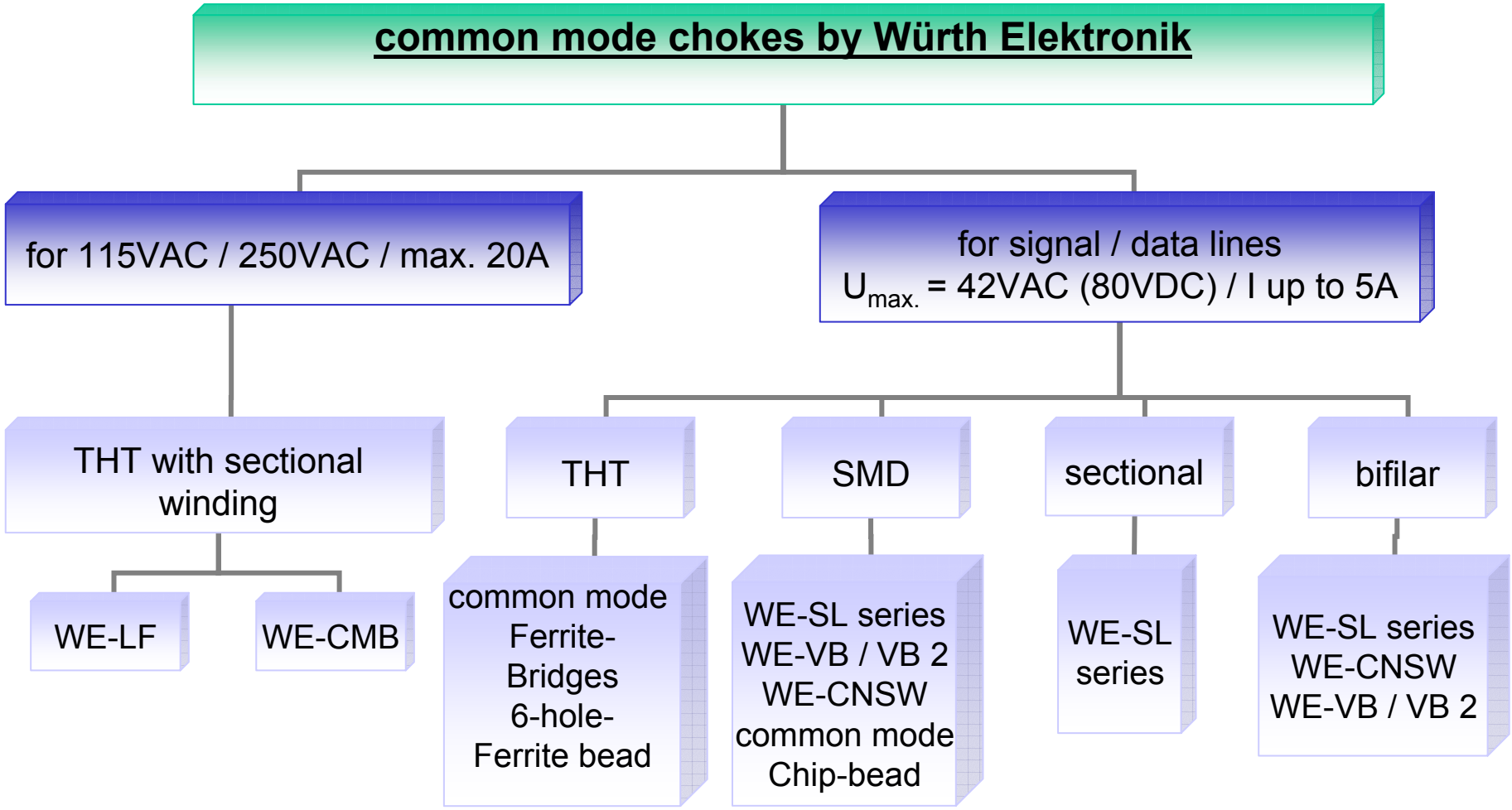


600 Ohm @ 100 MHz C.M.
40 Ohm @ 240 MHz D.M.

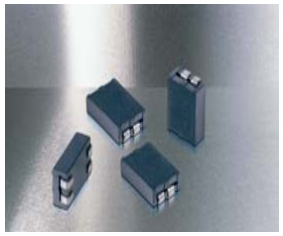


WE-CBF
120 Ohm @ 100 MHz

Portfolio of eiSos:



Common mode chokes in SMD:



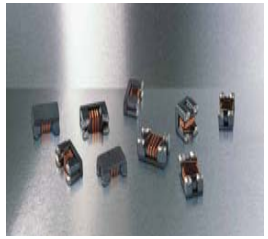
WE-CMS for signal / data lines up to I_{max} = 5 A

NiZn Z = 52 Ohm @ 100 MHz

WE-SL for signal / data lines up to I_{max} = 5,6 A

MnZn (für L > 60uH)	NiZn (für L < 100uH)

L ~ 10 µH ... ~ 47 mH

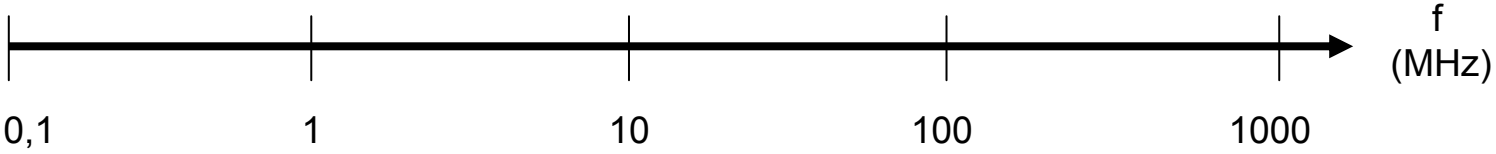


WE-CNSW for signal / data lines up to I_{max} = 0,4 A

NiZn Z = 67–2200 Ohm @ 100 MHz

WE-VB2 for signal / data lines up to I_{max} = 0,5 A

NiZn L~ 15 uH… ~ 80 uH

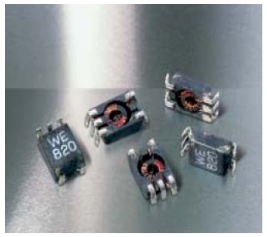


Common mode chokes in SMD:

WE-SL2 for signal / data lines up to I_{max} = 1,6 A

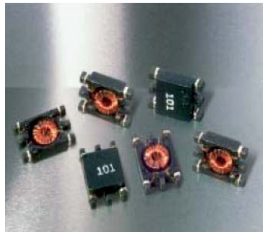
MnZn (für L < 250uH)	NiZn (für L > 51uH)

L ~ 25 µH ... ~ 47 mH



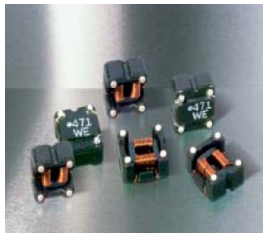
WE-SL1 for signal / data lines up to I_{max} = 0,3 A

NiZn L ~ 10 µH… ~ 330 µH



WE-SL3 for signal / data lines up to I_{max} = 0,7 A

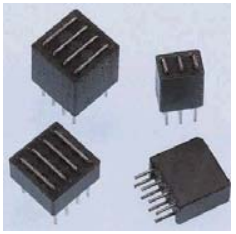
NiZn L ~ 20 uH… ~ 100 uH



WE-SL5 for signal / data lines up to I_{max} = 2,5 A

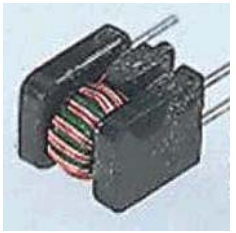
NiZn L ~ 120 uH… ~ 4,7 mH

Common mode chokes for THT:



Ferrite bridge für V_{CC}-lines, signal / data lines up to I_{max} = 16 A
(WE-MLS)

NiZn Z = 264 – 334 Ohm



WE-VB for V_{CC}-lines, signal / data lines up to I_{max} = 1,6A

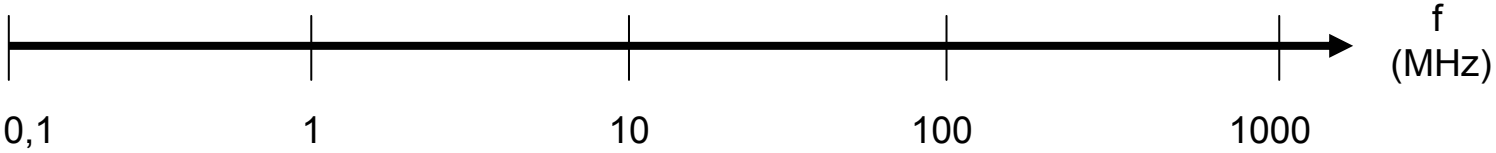
NiZn L ~ 10 µH… ~ 100 µH

WE-LF for 115 / 230VAC up to I_{max} = 6 A

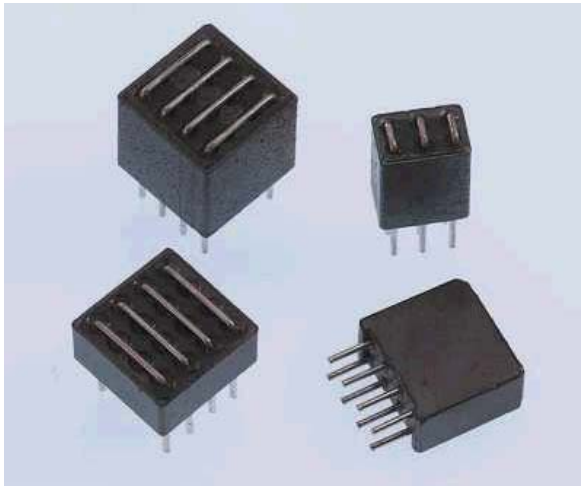
MnZn L ~ 1 mH… ~ 47 mH

WE-CMB for 115 / 230VAC up to I_{max} = 15 A

MnZn L ~ 150 uH… ~ 39 mH

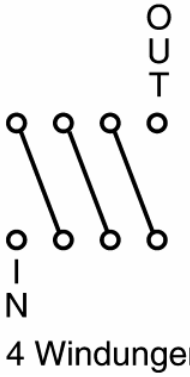


Ferritebridge WE-MLS:



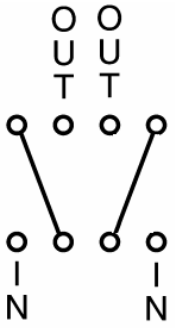
With an adequat PCB layout it´s possible to realize up to 5 applications with only 1 standard component !

Examples:



4 Windungen

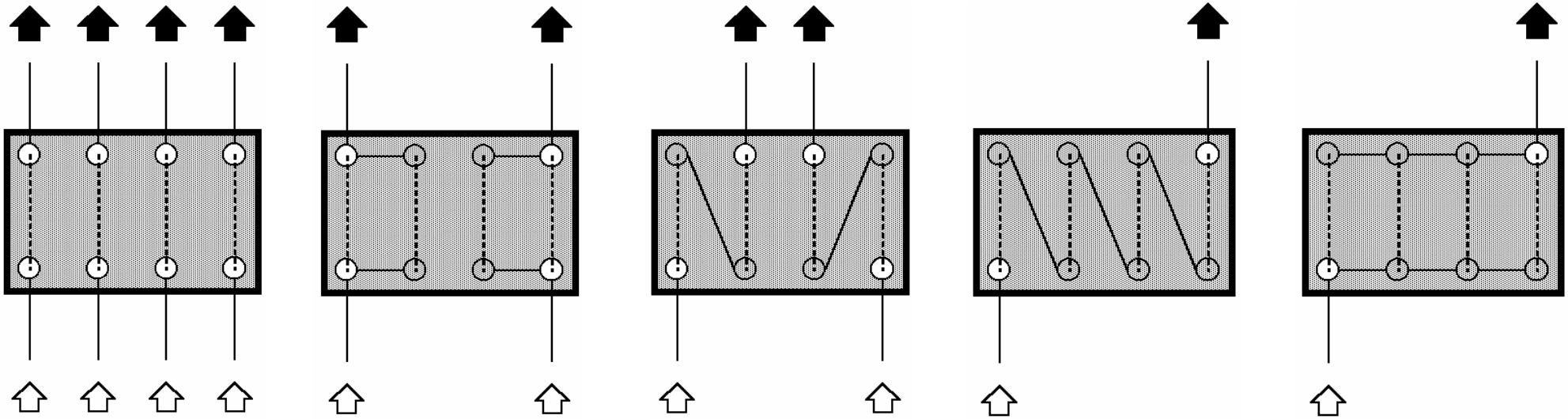
Replacement for 6-Hole Ferrite-Bead



2 x 2 Windungen

Dual common mode choke; 4A

Applications with the WE-MLS:



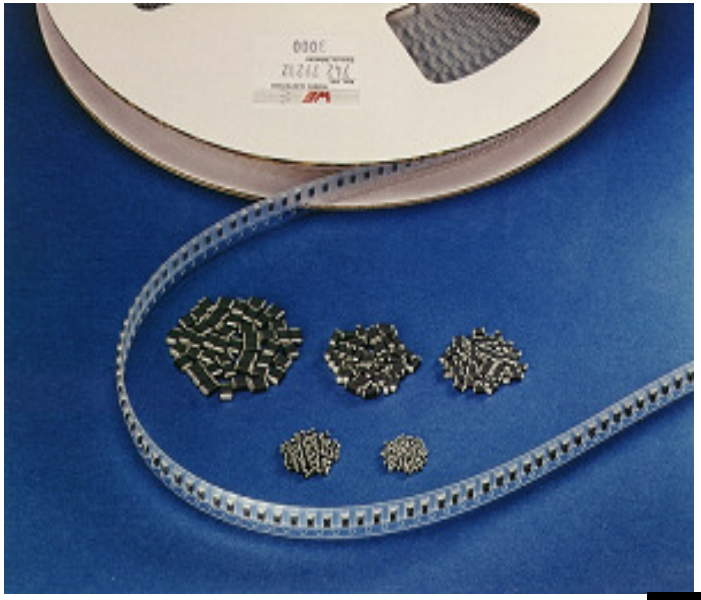
Dual CM choke	Single CM choke	Single CM choke	4 windings	Single winding
Z ~ 170 .. 350 Ω @ 100 MHz	Z ~ 170 .. 350 Ω @ 100 MHz	Z ~ 600 .. 900 Ω @ 100 MHz	Z ~ 900 .. 1500 Ω @ 100 MHz	Z ~ 170 .. 350 Ω @ 100 MHz
I = 4 A	I = 8 A	I = 4 A	I = 4 A	I = 16 A
RDC < 2 mΩ	RDC < 1 mΩ	RDC < 4 mΩ	RDC < 10 mΩ	RDC < 1 mΩ

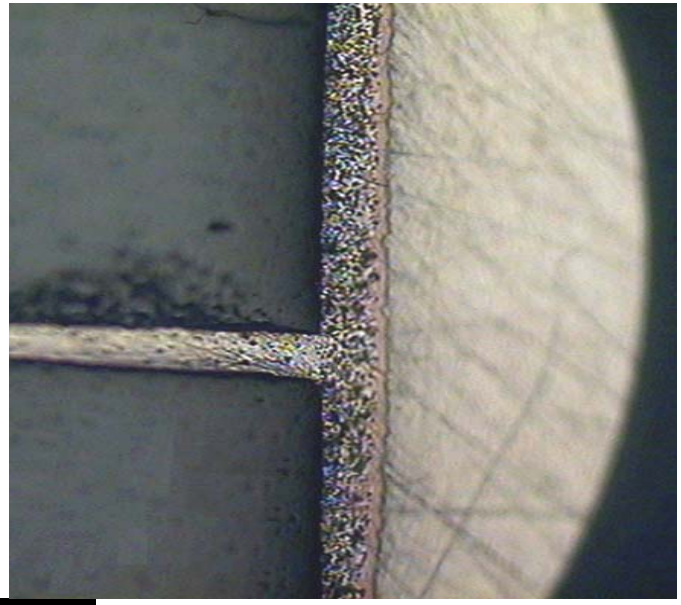
optimal for e.g. filtering in power supplies (U < 60VDC), charger or sensor technology

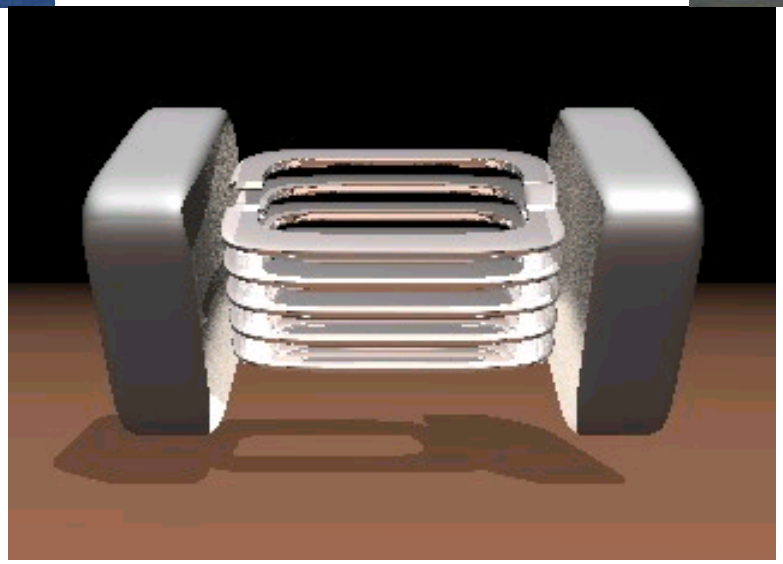
Common mode chokes for SMD:

		Size [mm]	Impedance [Ω]	Current [A]	Application
WE-CNSW		2.0 x 1.2 x 1.2 3.2 x 1.6 x 1.9	130 – 910 60 – 400	0.28 – 0.4 0.20 – 0.37	USB 2.0 Firewire/ high speed dataline
WE-SL		12.7 x 10.5 x 5,75	1100 – 14400	0.20 – 2.70	ISDN Telecom Applications
WE-SL 1 NEW 744212xxx		6.5 x 3.6 x 1.65	300 – 2000	0.30	PCMCIA cards
WE-SL 2		9.2 x 6.0 x 5.0	1000 – 20000	0.40 – 1.60	VCC Power & Datalines
WE-SL 3 NEW 744252/253xxx		9.2 x 6.6 x 2.5	1250 – 5000	0.50 – 0.70	VCC Power & Datalines higher current ratings
WE-SL 5 NEW 744272xxx		10.0 x 8.2 x 6.5	290 – 13000	0.35 – 2.50	VCC Power Lines

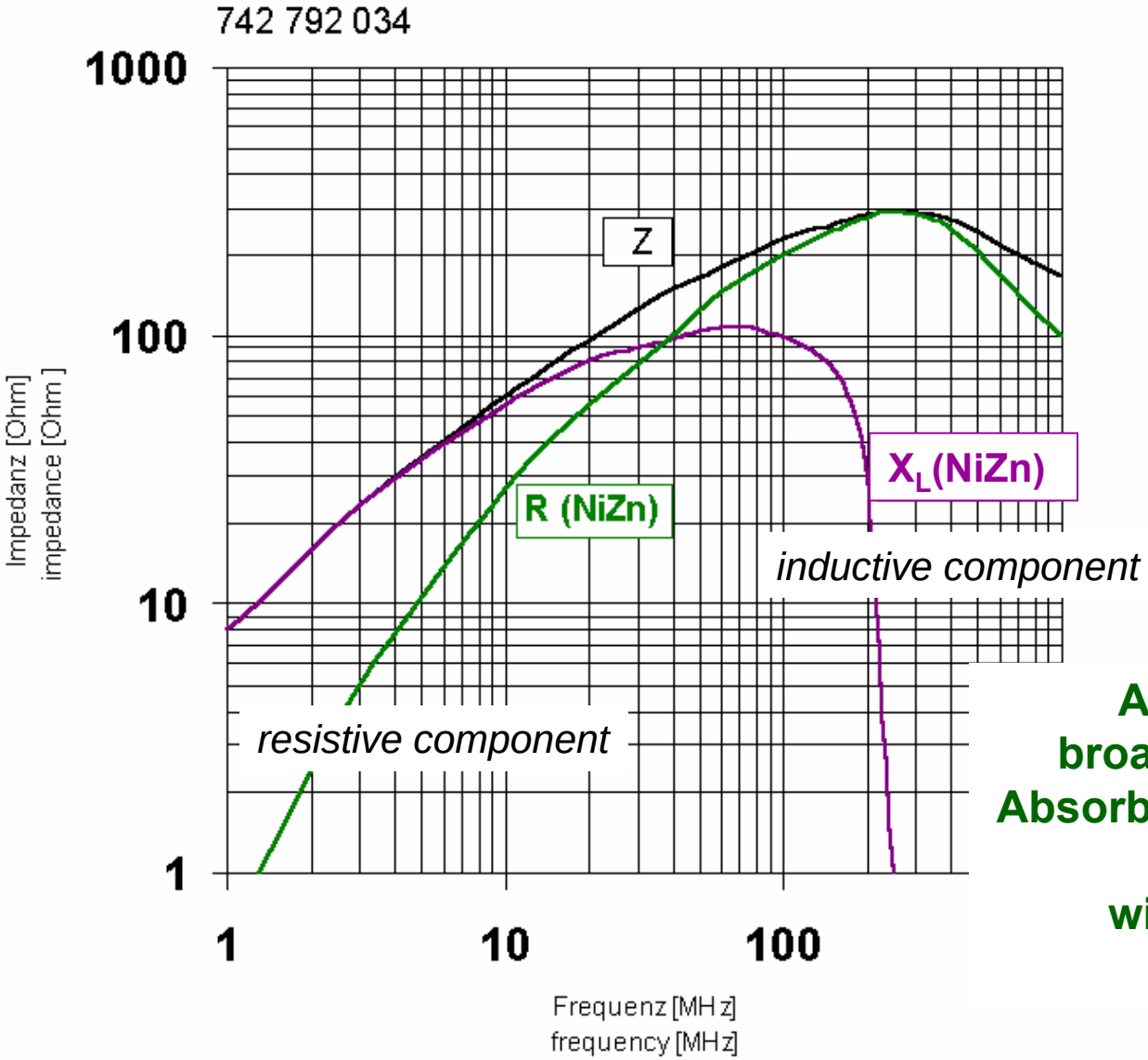
Differential Mode suppression : SMD-Ferrit WE-CBF

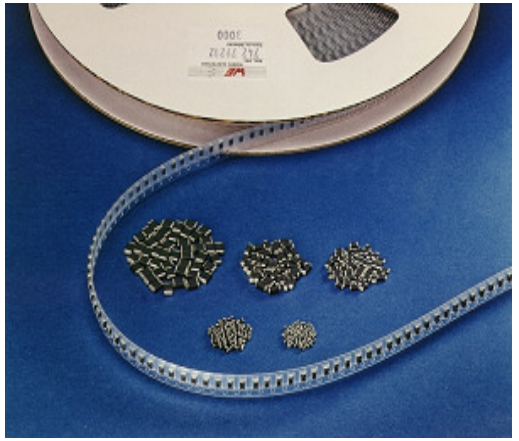






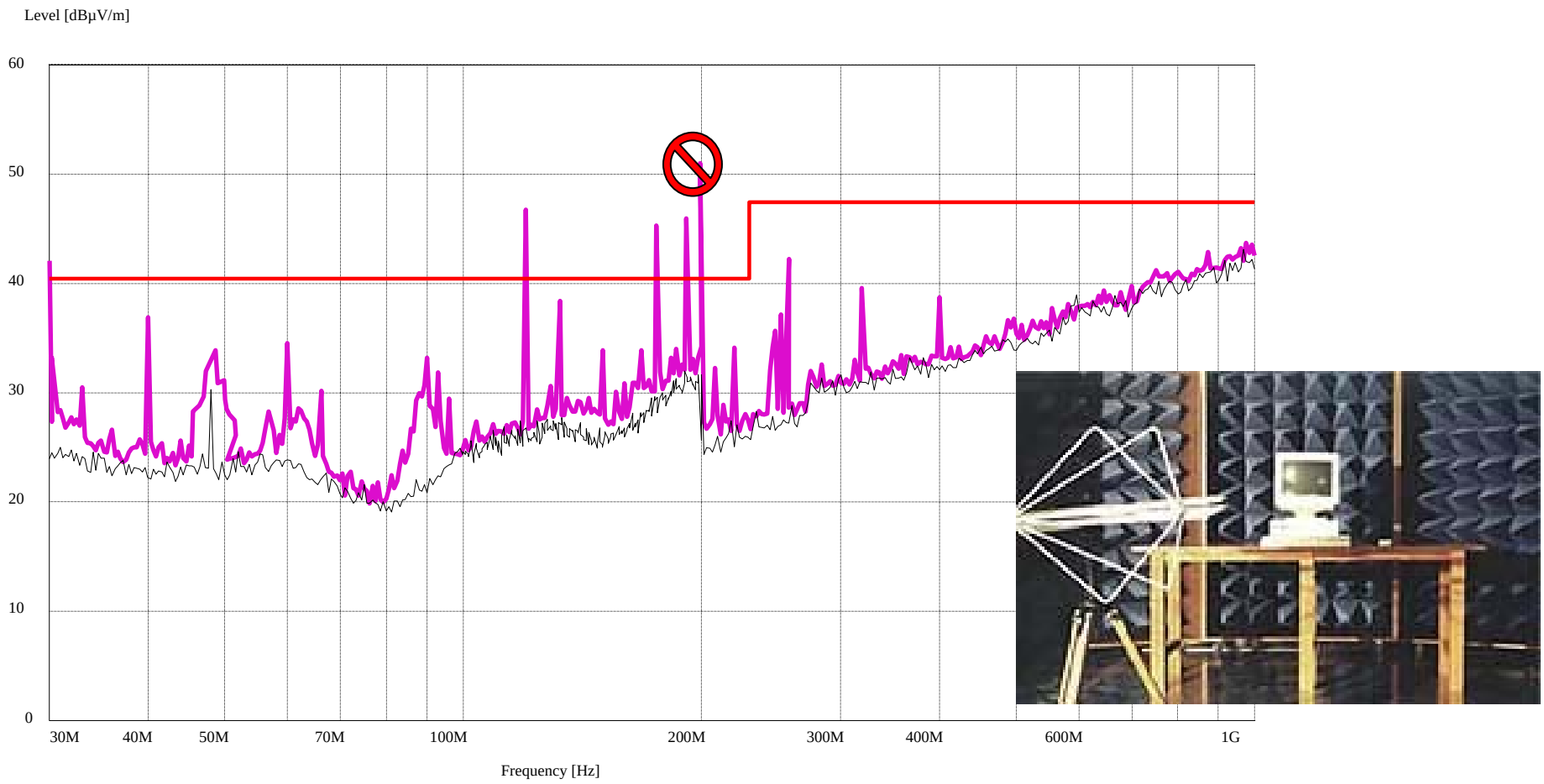
Impedance: SMD-Ferrite (Chip Bead)



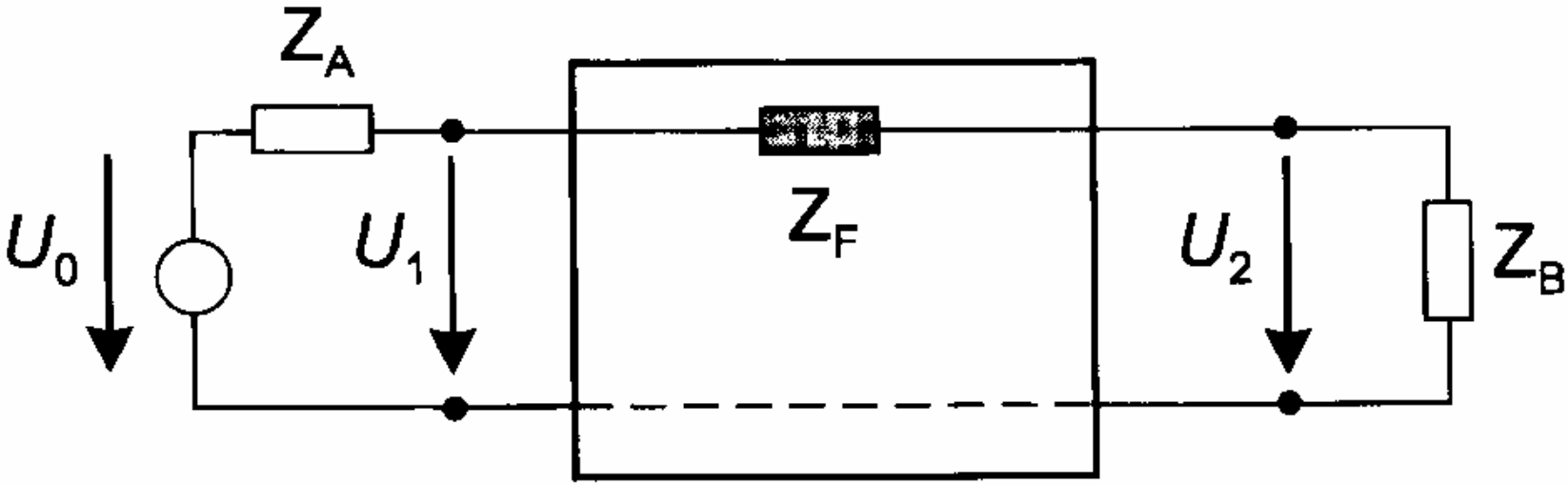


Advantage of SMD-Ferrites:
broadband, frequency-dependent Absorber for RF-noise in the frequency range 10 MHz ... > 1GHz
with very low DC-Resistance
(< 0,8 Ohm max. !)

Which impedance do we need ?



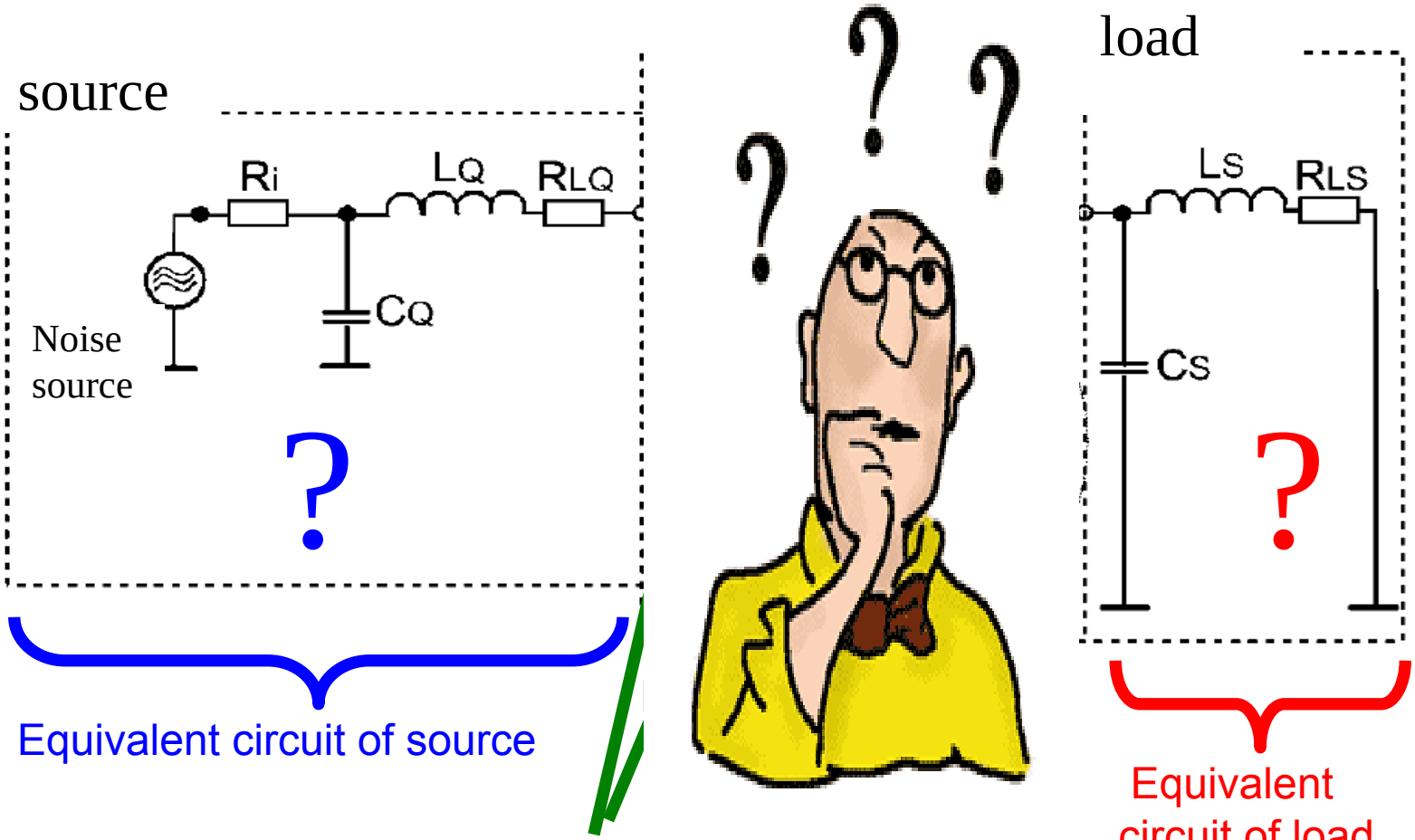
Insertion Loss Model



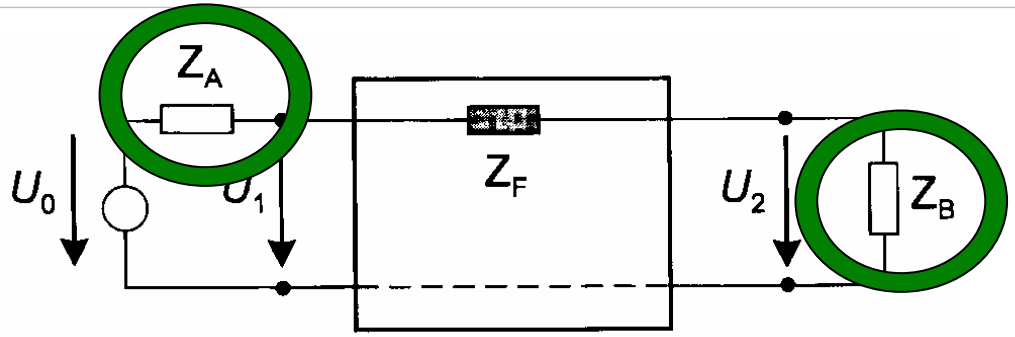
Insertion Loss =>

$$A = 20\log\frac{Z_A + Z_F + Z_B}{Z_A + Z_B} \quad in \quad (dB)$$

The real world..... !



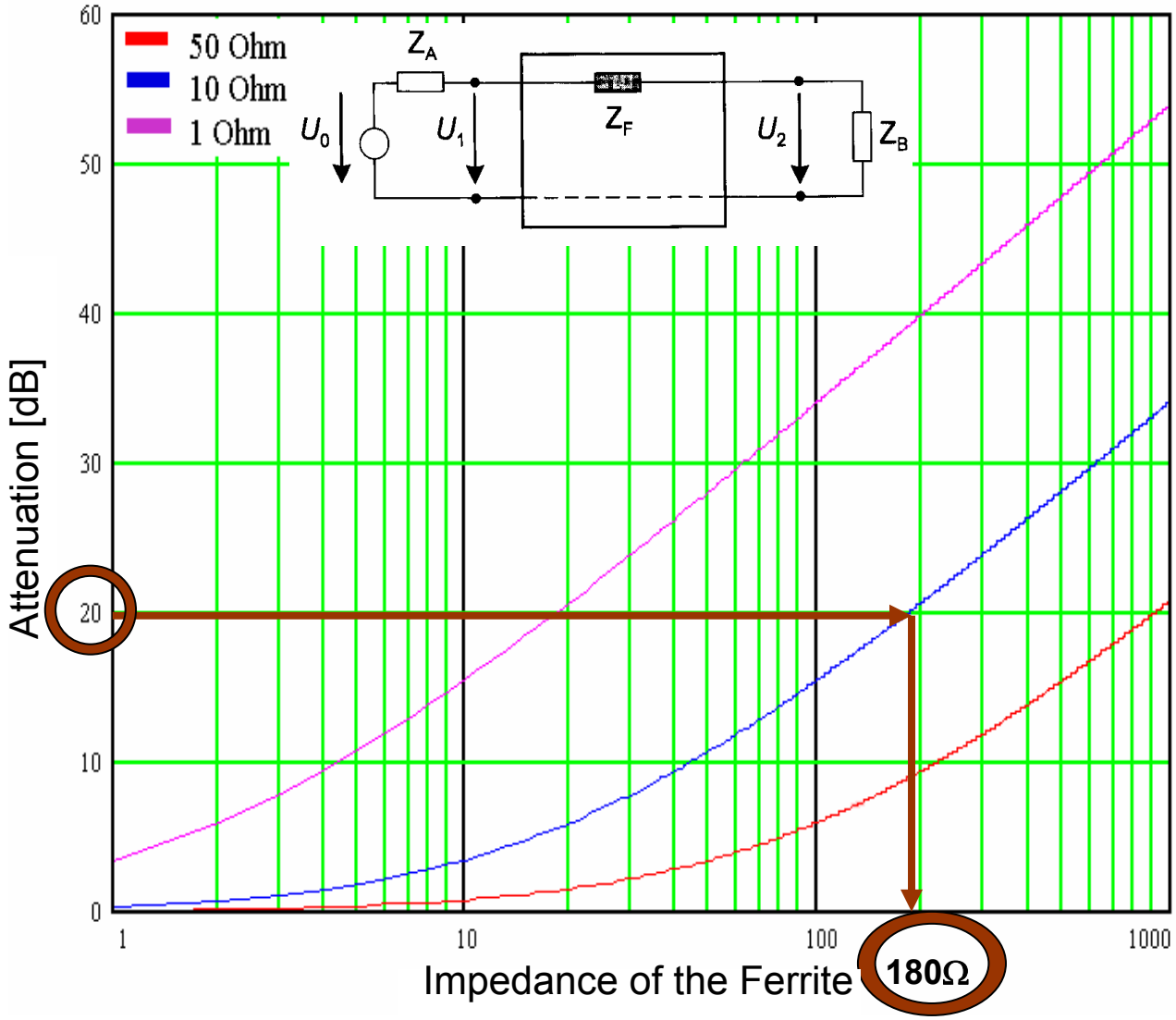
Starting Point: Practical figures for Z_A / Z_B



* **Groundplanes :** **Impedance range 1 ... 2 Ω**
* **VCC-Distribution:** **Impedance range 1 ... 2 Ω**
* **Video-/ Clock-/ Dataline:** **Impedance range 50 ... 90 Ω**
* **Long Datalines:** **Impedance range 90 ... >150 Ω**

With this we can make a first decision of a Ferrite-Impedance Z_F which would suppress noise in our application :

Which Impedance Z_F is needed ?



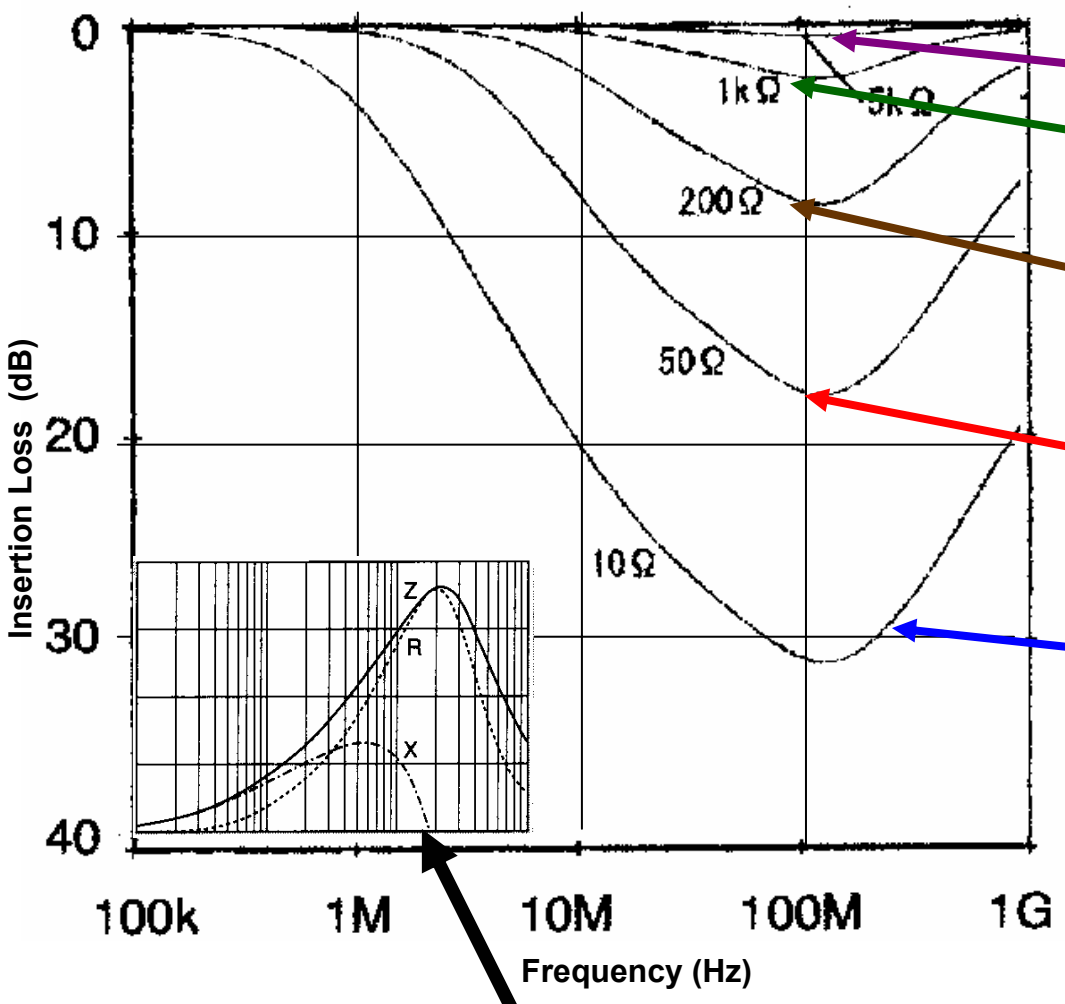
Example 1: required attentuation = 20dB @ 200 MHz

VCC-Distribution

=> goto Nomogramm:

180 Ω => chosen: 220 Ω

Insertion Loss vs. Impedance of Source/ Load (Z_A / Z_B)



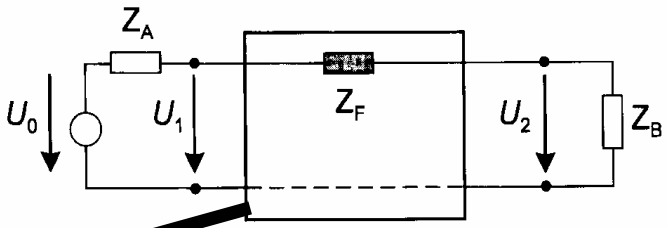
with $Z_A = Z_B = 5000\ \Omega$ =constant
no effect in filtering !

A = - 3 dB max.
with $Z_A = Z_B = 1000\ \Omega$ = constant

A = - 8 dB max.
with $Z_A = Z_B = 200\ \Omega$ = constant

A = -18 dB max.
with $Z_A = Z_B = 50\ \Omega$ = constant

A = -32 dB max.
with $Z_A = Z_B = 10\ \Omega$ = constant



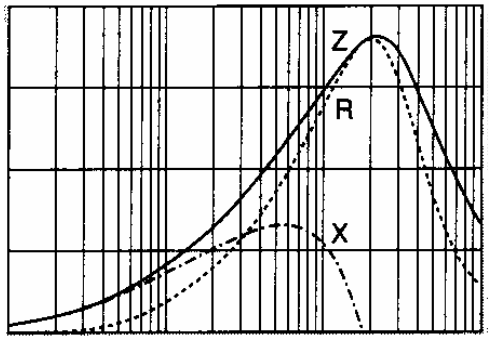
SMD-Ferrite Z_F = 600 Ohm @ 100 MHz

Simulation with RF Sim 99 or SWITCHER CAD III

Demostration

a) via equivalent circuit

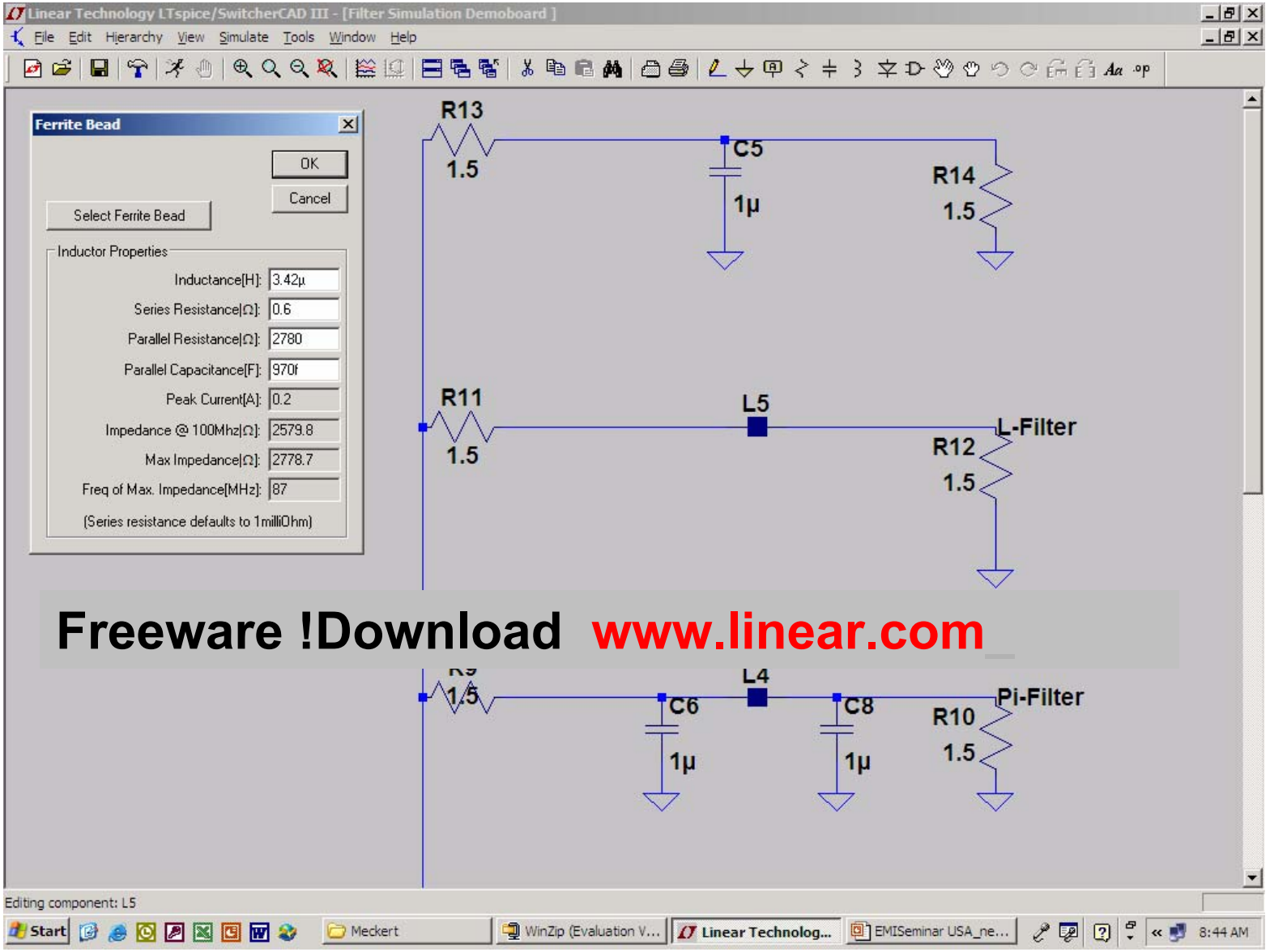
b) via S-Parameters



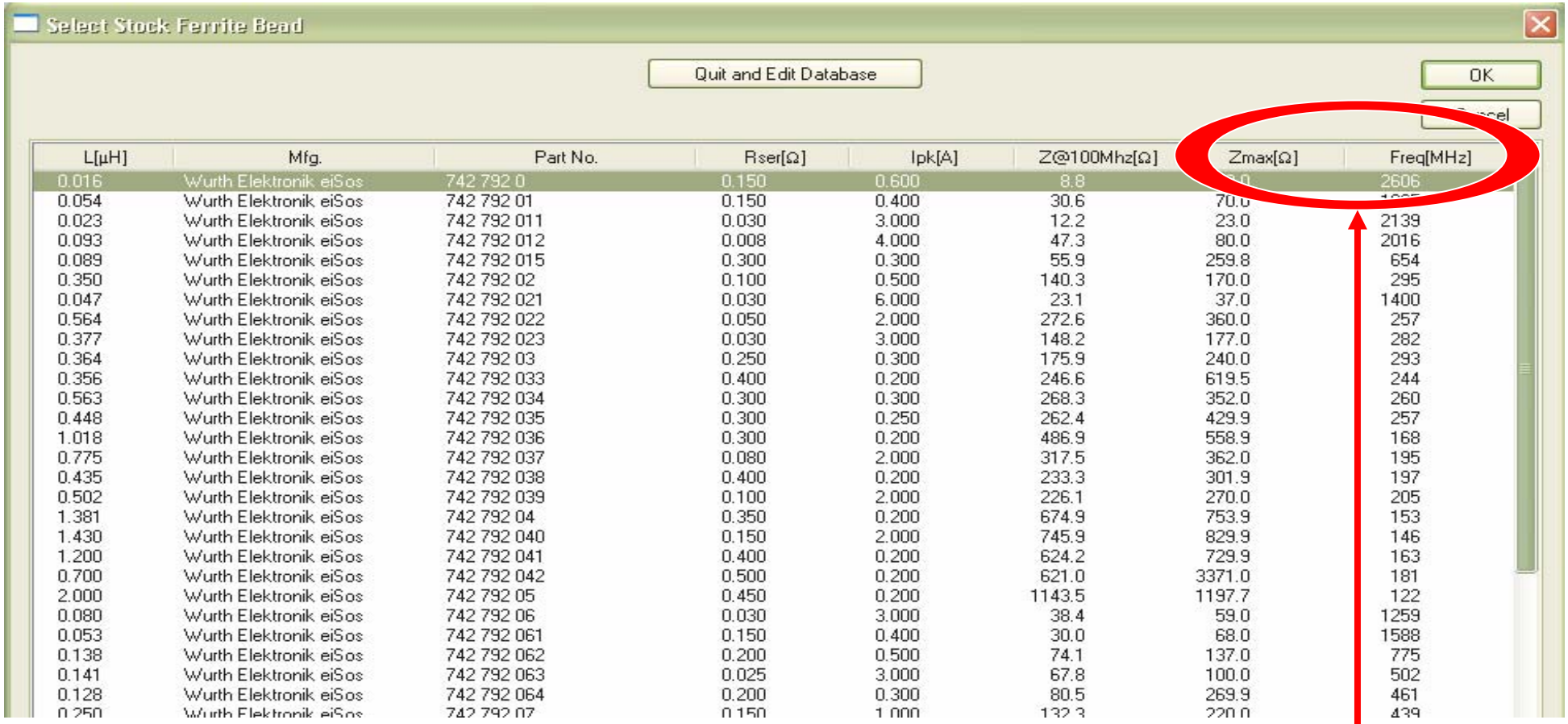
Insertion Loss => $A = 20 \log \frac{Z_A + Z_F + Z_B}{Z_A + Z_B} \quad in \quad (dB)$

S-parameters are available on our homepage

SMD-Ferrite listed in LTSpice/SwitcherCADIII



SMD-Ferrites LTSpice/SwitcherCADIII



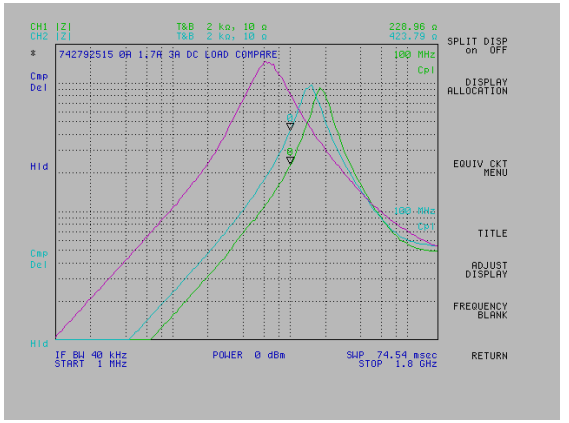
L[µH]	Mfg.	Part No.	Rser[Ω]	Ipk[A]	Z@100Mhz[Ω]	Zmax[Ω]	Freq[MHz]
0.016	Wurth Elektronik eiSos	742 792 0	0.150	0.600	8.8		2606
0.054	Wurth Elektronik eiSos	742 792 01	0.150	0.400	30.6	70.0	
0.023	Wurth Elektronik eiSos	742 792 011	0.030	3.000	12.2	23.0	2139
0.093	Wurth Elektronik eiSos	742 792 012	0.008	4.000	47.3	80.0	2016
0.089	Wurth Elektronik eiSos	742 792 015	0.300	0.300	55.9	259.8	654
0.350	Wurth Elektronik eiSos	742 792 02	0.100	0.500	140.3	170.0	295
0.047	Wurth Elektronik eiSos	742 792 021	0.030	6.000	23.1	37.0	1400
0.564	Wurth Elektronik eiSos	742 792 022	0.050	2.000	272.6	360.0	257
0.377	Wurth Elektronik eiSos	742 792 023	0.030	3.000	148.2	177.0	282
0.364	Wurth Elektronik eiSos	742 792 03	0.250	0.300	175.9	240.0	293
0.356	Wurth Elektronik eiSos	742 792 033	0.400	0.200	246.6	619.5	244
0.563	Wurth Elektronik eiSos	742 792 034	0.300	0.300	268.3	352.0	260
0.448	Wurth Elektronik eiSos	742 792 035	0.300	0.250	262.4	429.9	257
1.018	Wurth Elektronik eiSos	742 792 036	0.300	0.200	486.9	558.9	168
0.775	Wurth Elektronik eiSos	742 792 037	0.080	2.000	317.5	362.0	195
0.435	Wurth Elektronik eiSos	742 792 038	0.400	0.200	233.3	301.9	197
0.502	Wurth Elektronik eiSos	742 792 039	0.100	2.000	226.1	270.0	205
1.381	Wurth Elektronik eiSos	742 792 04	0.350	0.200	674.9	753.9	153
1.430	Wurth Elektronik eiSos	742 792 040	0.150	2.000	745.9	829.9	146
1.200	Wurth Elektronik eiSos	742 792 041	0.400	0.200	624.2	729.9	163
0.700	Wurth Elektronik eiSos	742 792 042	0.500	0.200	621.0	3371.0	181
2.000	Wurth Elektronik eiSos	742 792 05	0.450	0.200	1143.5	1197.7	122
0.080	Wurth Elektronik eiSos	742 792 06	0.030	3.000	38.4	59.0	1259
0.053	Wurth Elektronik eiSos	742 792 061	0.150	0.400	30.0	68.0	1588
0.138	Wurth Elektronik eiSos	742 792 062	0.200	0.500	74.1	137.0	775
0.141	Wurth Elektronik eiSos	742 792 063	0.025	3.000	67.8	100.0	502
0.128	Wurth Elektronik eiSos	742 792 064	0.200	0.300	80.5	269.9	461
0.250	Wurth Elektronik eiSos	742 792 07	0.150	1.000	132.3	220.0	439

You can sort database by :
Part.Nr.; RDC; Current ; Impedance @100MHz
or
maximum Impedance @ which Frequency

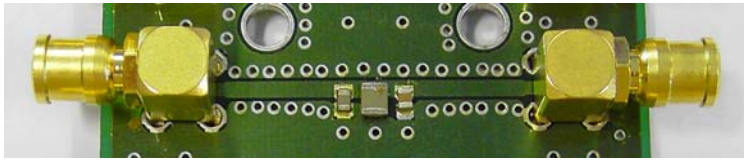
SwCAD III.lnk

Design-In mistakes of Ferrites

Examples:

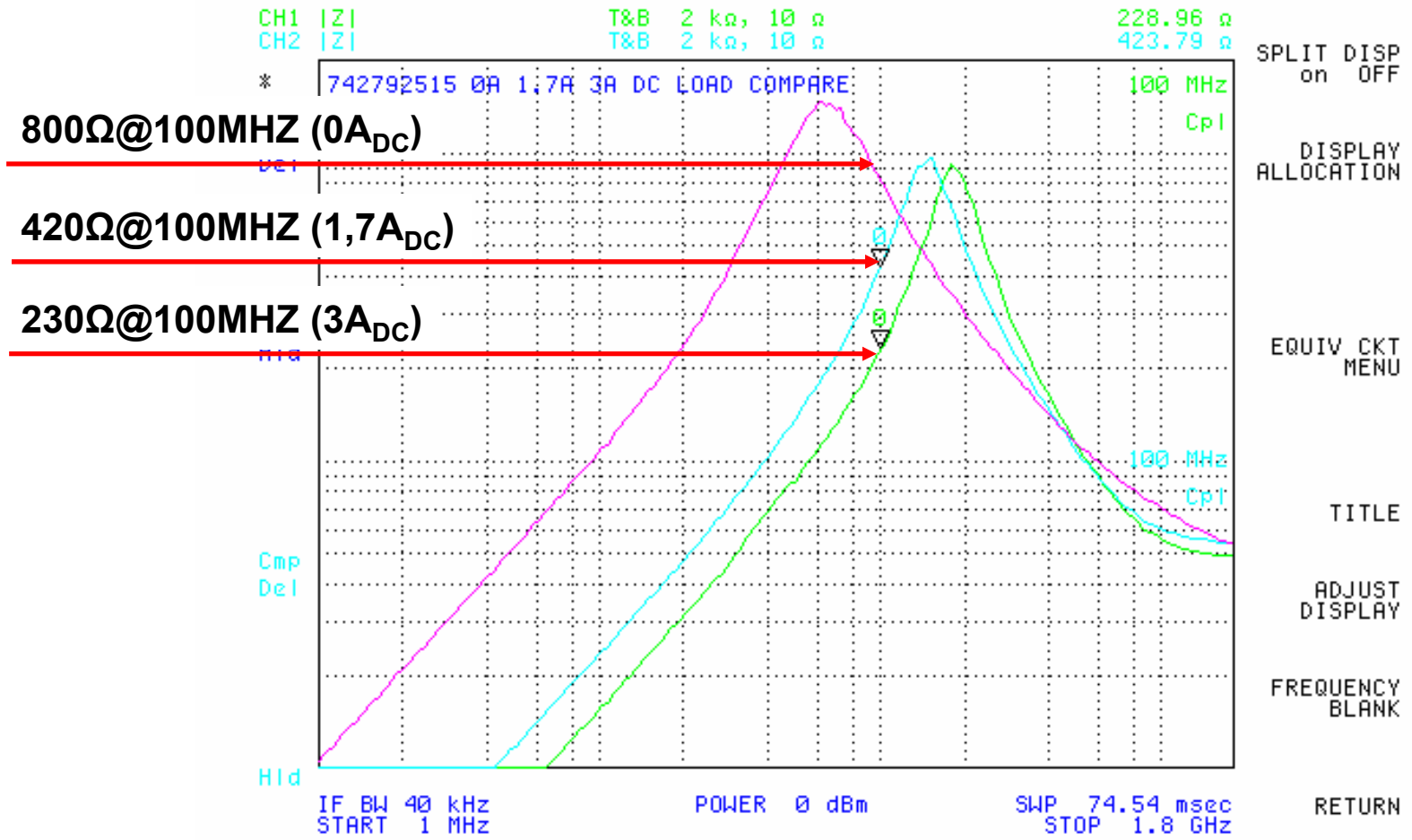


- **Saturation of the ferrite (Impect of DC-bias (magnetize))**
- **To high inrush current (switch on current)**
- **Wrong layout of the filter circuit (noise coupling)**
- **Wrong compination of components (Lsrf = Csrf >> no wideband suppression)**



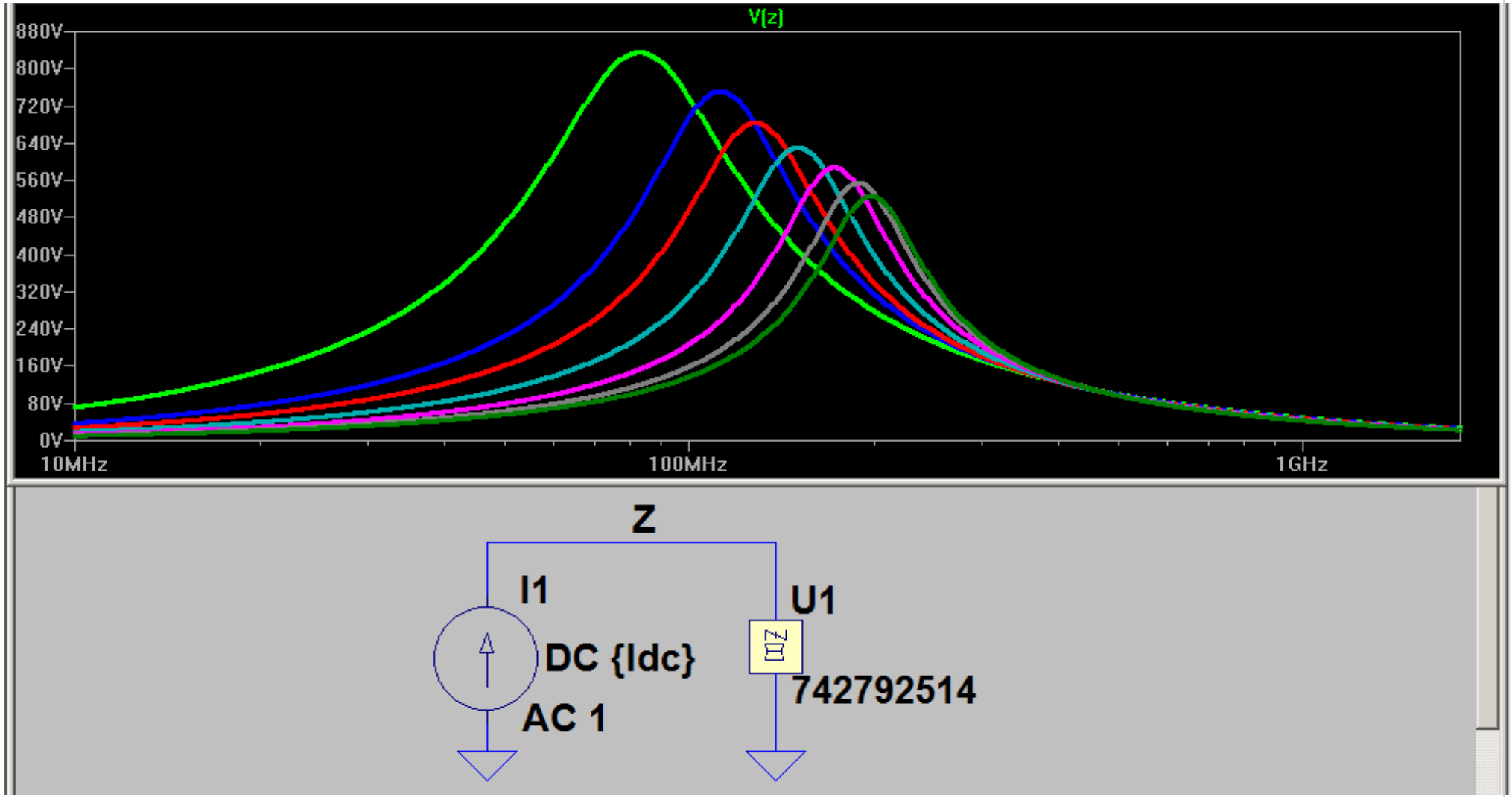
Design-In mistakes of Ferrites

Impect of DC-bias (pre-magnetization (saturation)



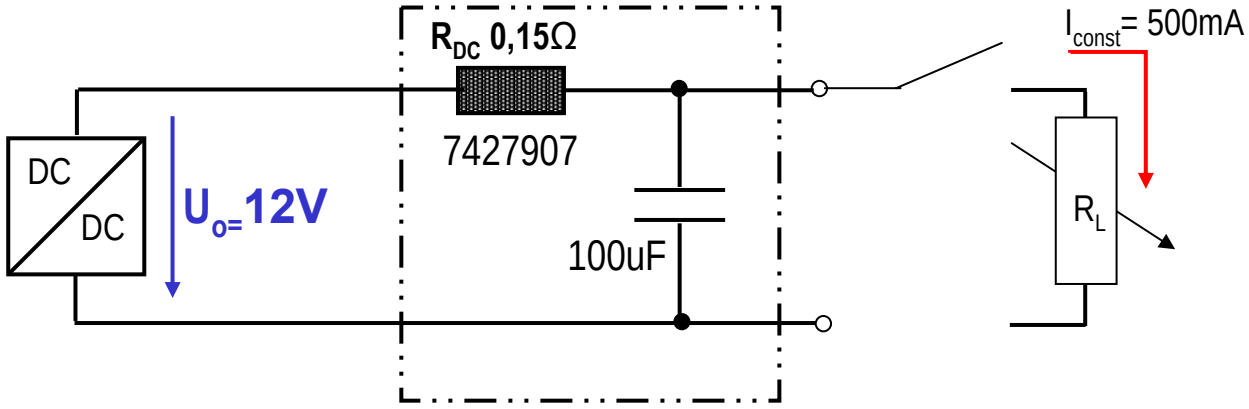
742792515 (3A typ)

Impect of DC-bias (pre-magnetization (saturation)



Design-In mistakes of Ferrites

Destroy the ferrite due over current/inrush current



$$I_o = Uo/ (R_{DC\ ferrite} + R_{ESR\ capacity})$$

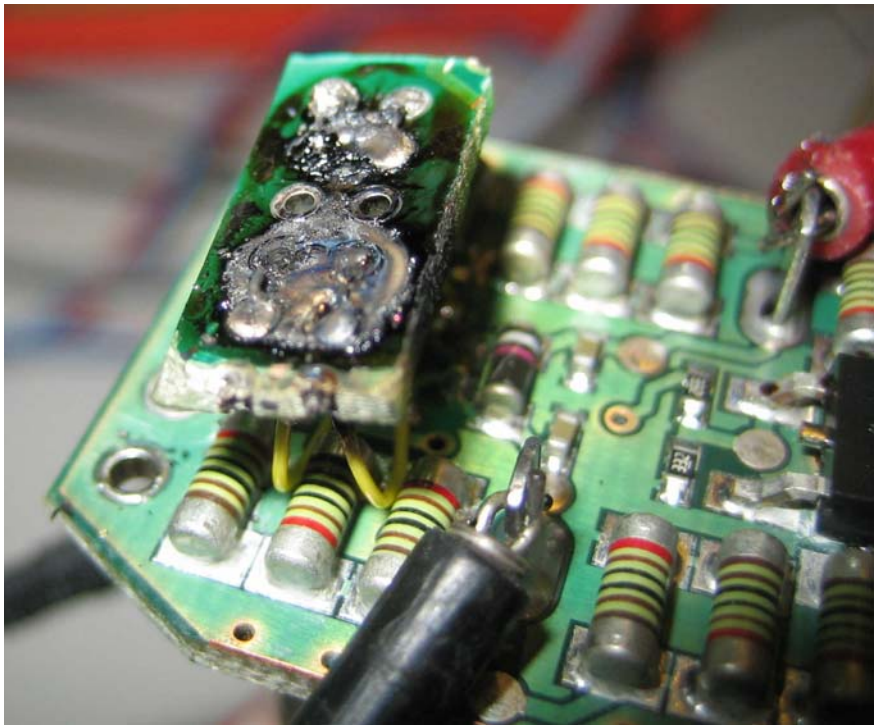
$$= 12V / (0{,}15\Omega + 0{,}5\Omega) = 18A$$

→ 18 time higher current

Ferrite can be destroyed , muss not fail directly.
„creeping process“

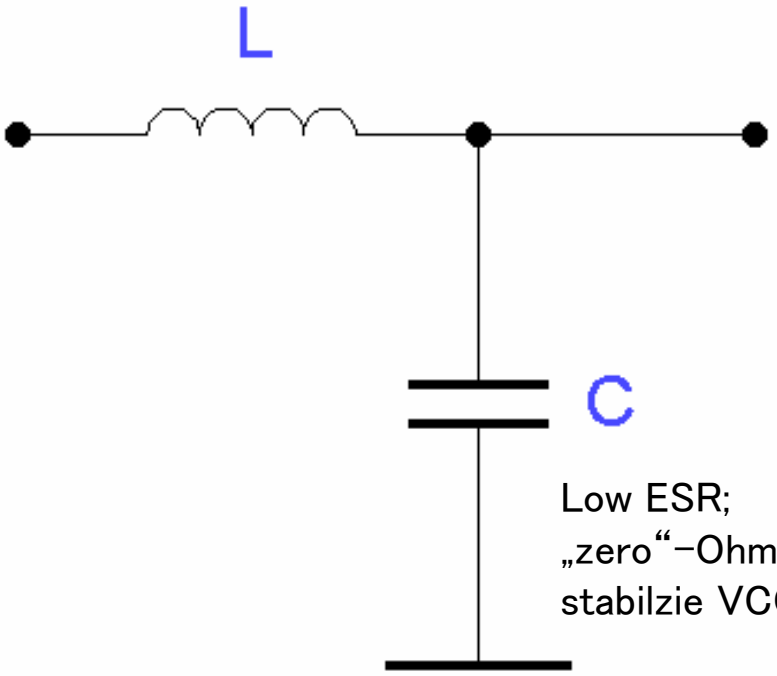
Design-In mistakes of Ferrites

Destroy the ferrite due switch on current
(no current limitation was done by the customer)



Basic Design-Rules of EMC-Filters

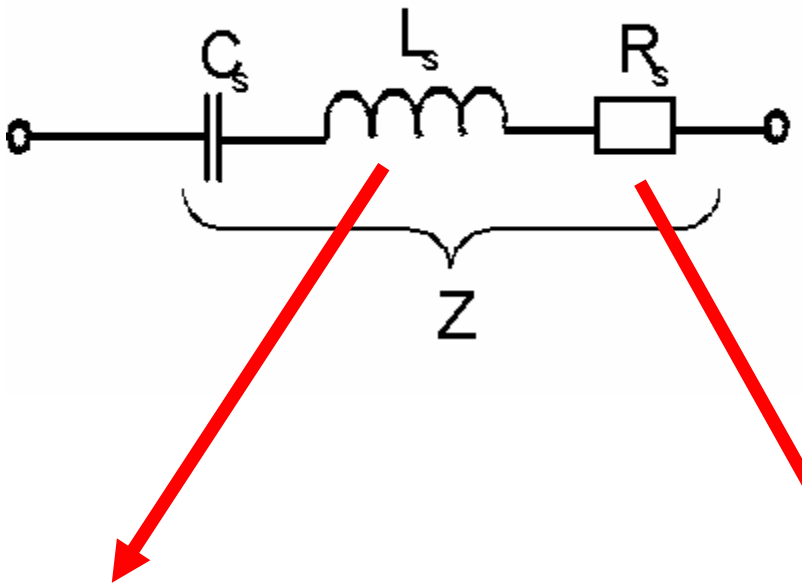
Low DC-Resistance; high Absorption for RF-noise; no SRF-Point

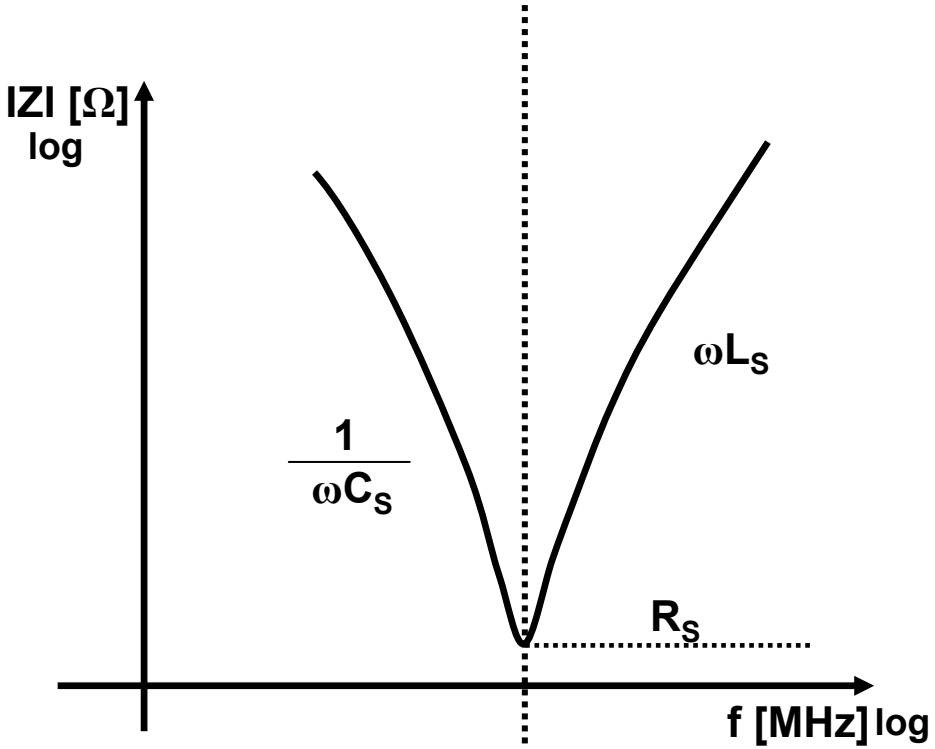


Low ESR;
„zero"-Ohm-Path to GND for RF-noise
stabilzie VCC for Pulse-Currents

Basic Design-Rules of EMC-Filters

Equivalent Circuit: Capacitor





Inductance of connection:

SMD-types 1 nH ... 5 nH

wired 10 nH ... 50 nH !

ESR:

SMD-types 20 mΩ ... 300 mΩ

up to 1 Ω

(see Datasheet)

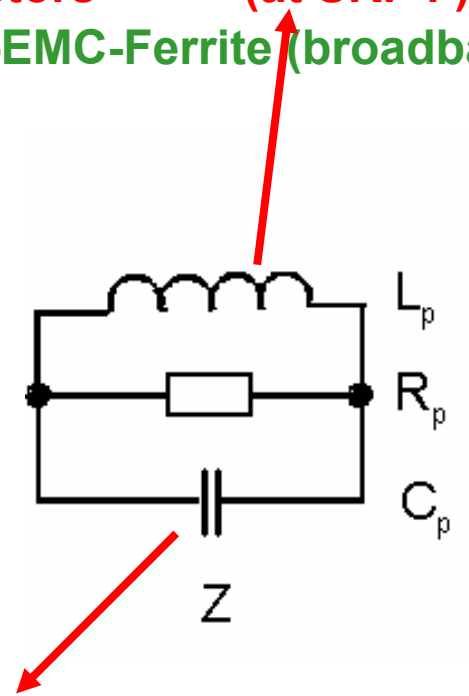
Basic Design-Rules of EMC-Filters

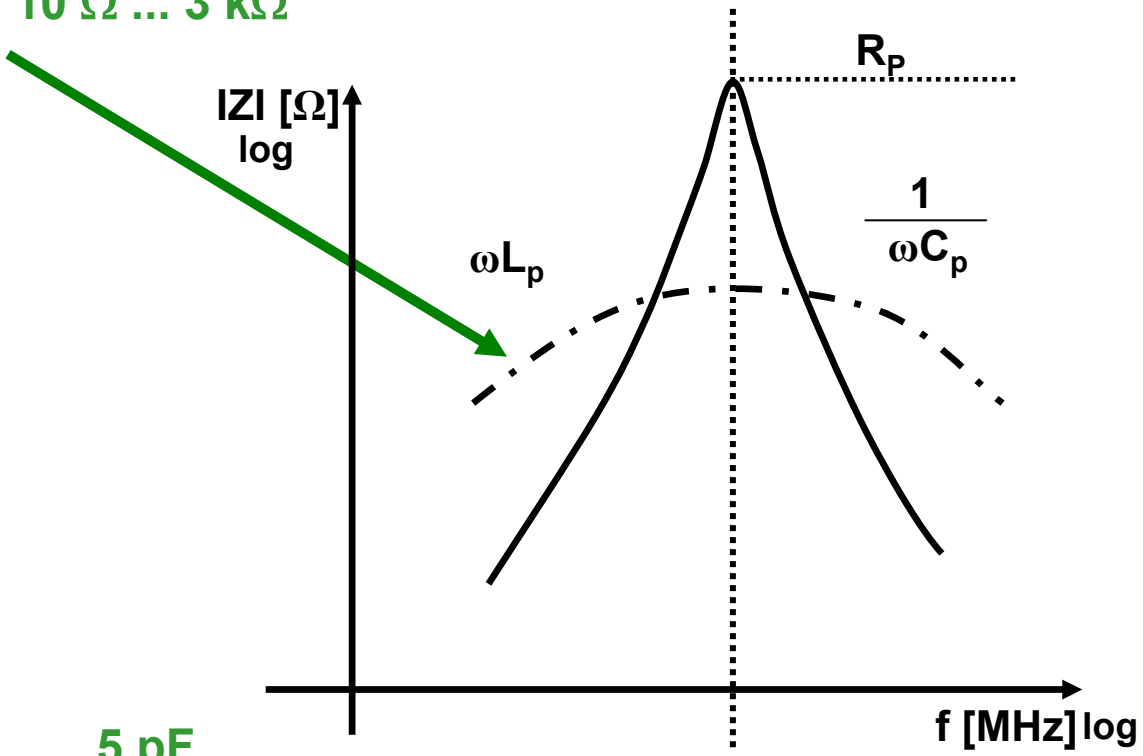
Equivalent circuit : Inductor /Ferrite

Losses:

Inductors **(at SRF !)** **up to 30 kΩ**

SMD-EMC-Ferrite (broadband !) **10 Ω ... 3 kΩ**



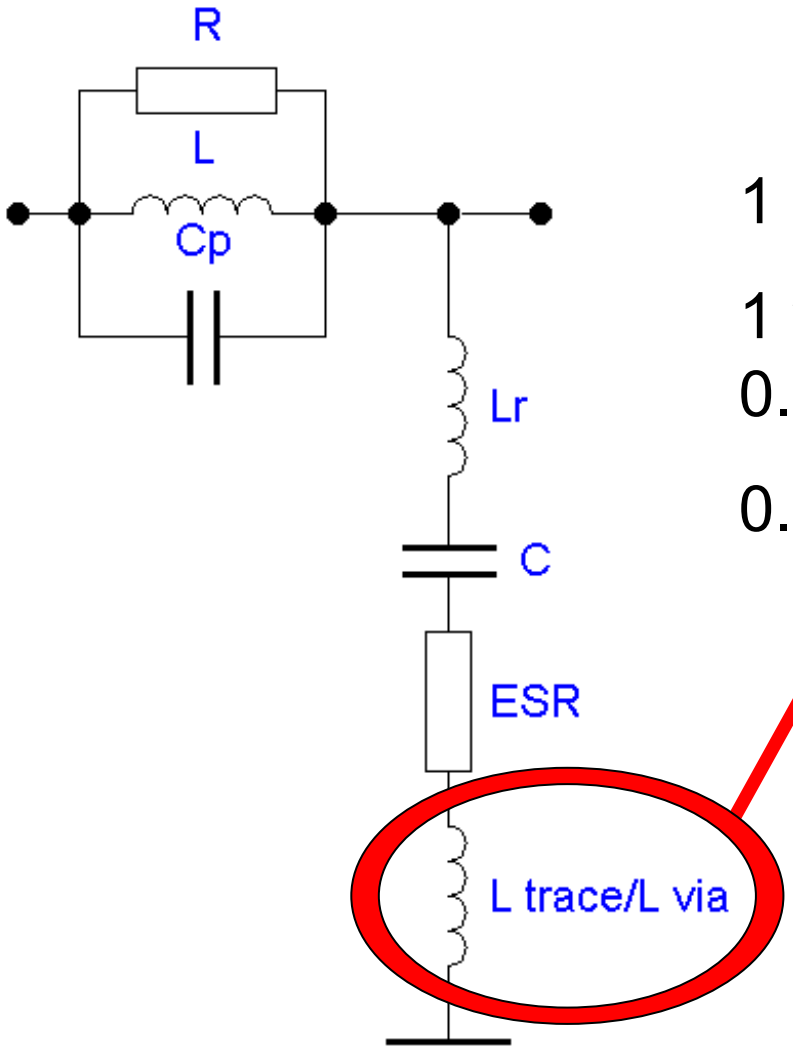


Parasitic Capacitance:

SMD-EMC-Ferrite **5 fF ... 5 pF**

winded Inductors 10 pF ... 500 pF !

Basic Design-Rules of EMC-Filters



1 mm ~ 1nH

1 via ~ 0.5 nH
0.5 nH @ 100 MHz = 0.314 Ω

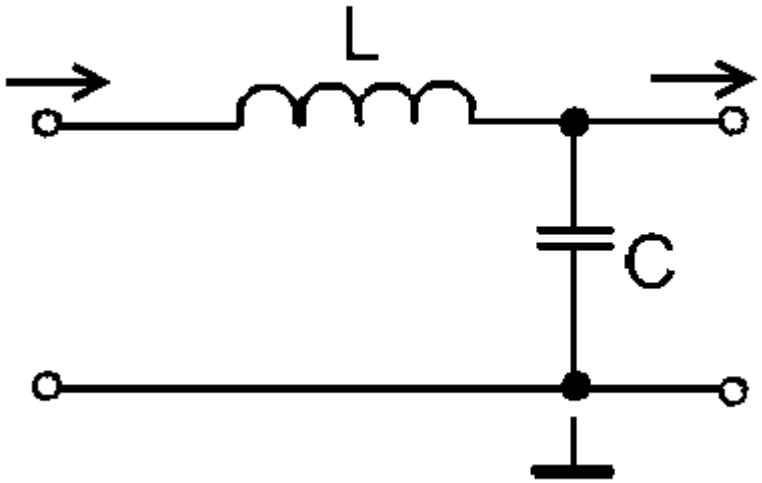
0.5 nH @ 1 GHz = 3.14 Ω !

Zges: ESR+Lr (2nH)+Lvia(0,5nH)

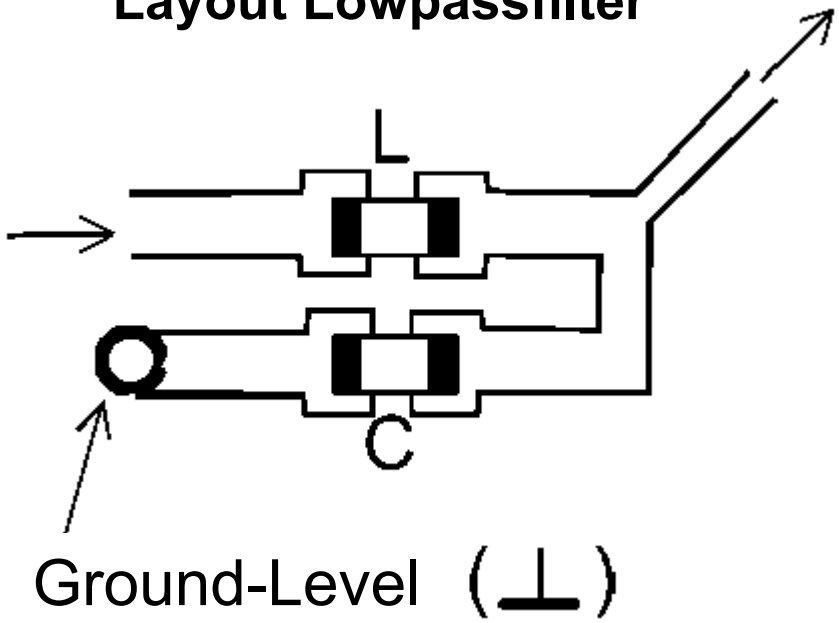
100nF= 0,2Ω+1,2Ω+0,3Ω= 1,7Ω@100MHz
Size: 0603/X7R

Grounding / Layout

LC-Lowpassfilter



Layout Lowpassfilter

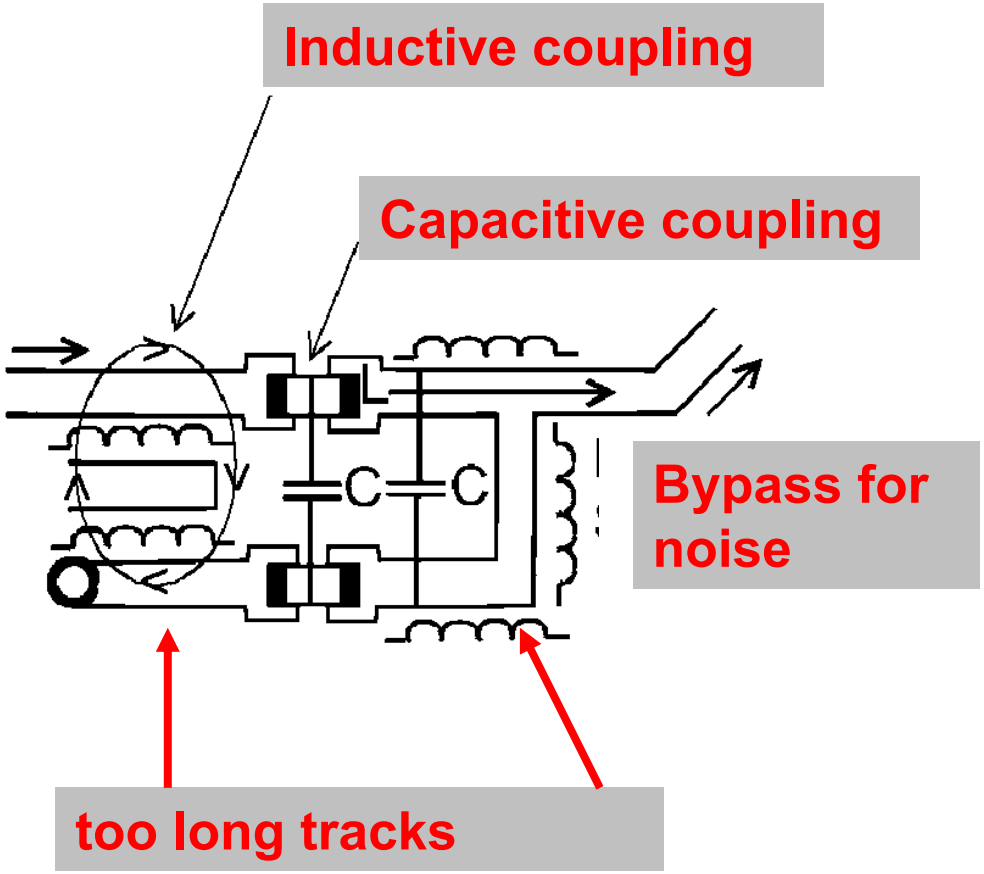


Why will this Filter not work properly at RF-Frequencies ?

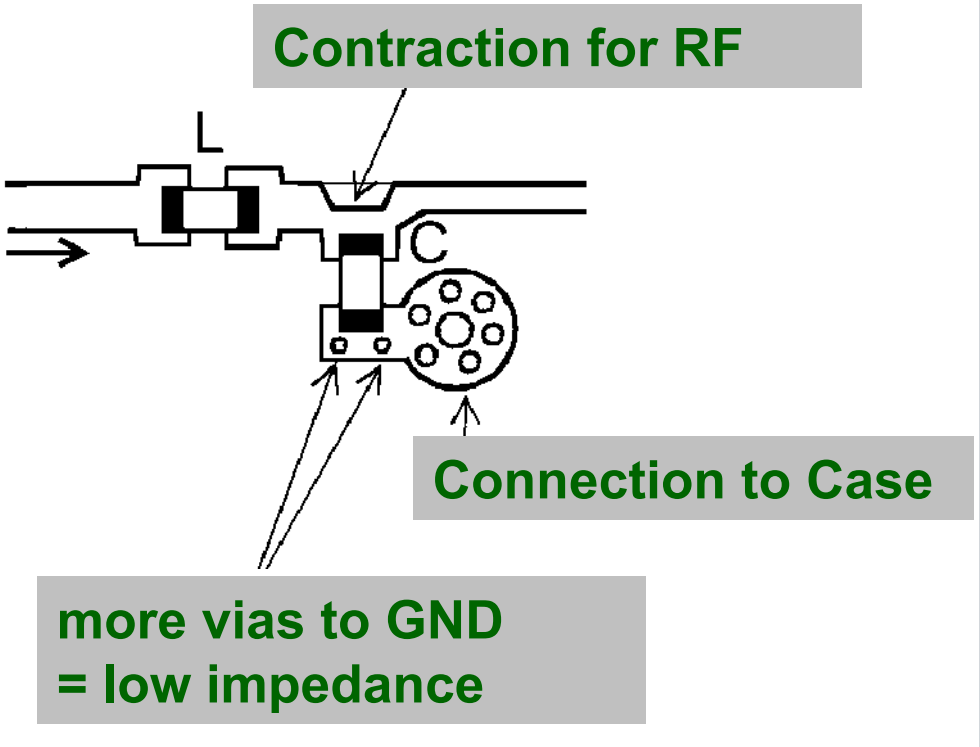
Grounding / Layout

WÜRTH ELEKTRONIK

bad solution

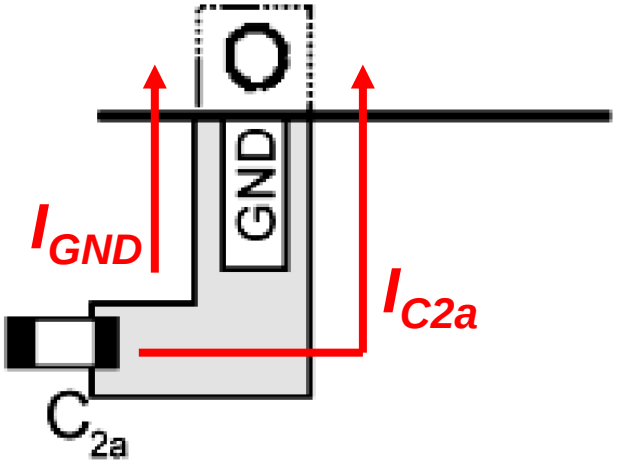


optimized

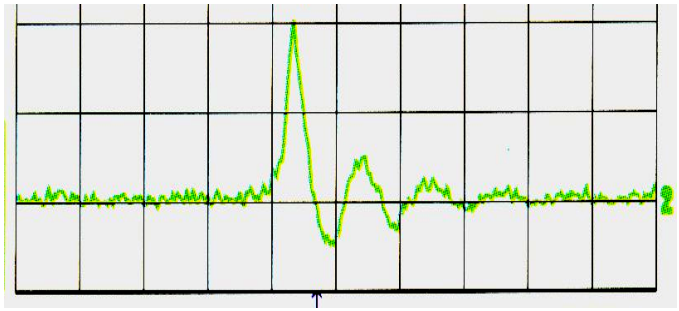


Layout for Ground

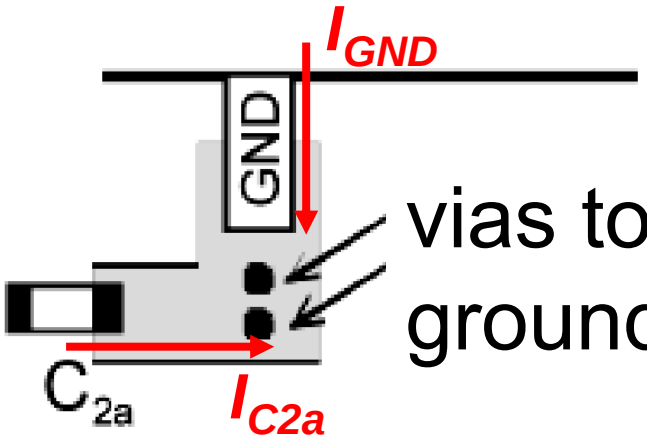
bad



The GND-Potential is affected by current driven through ground-pin of semiconductor !



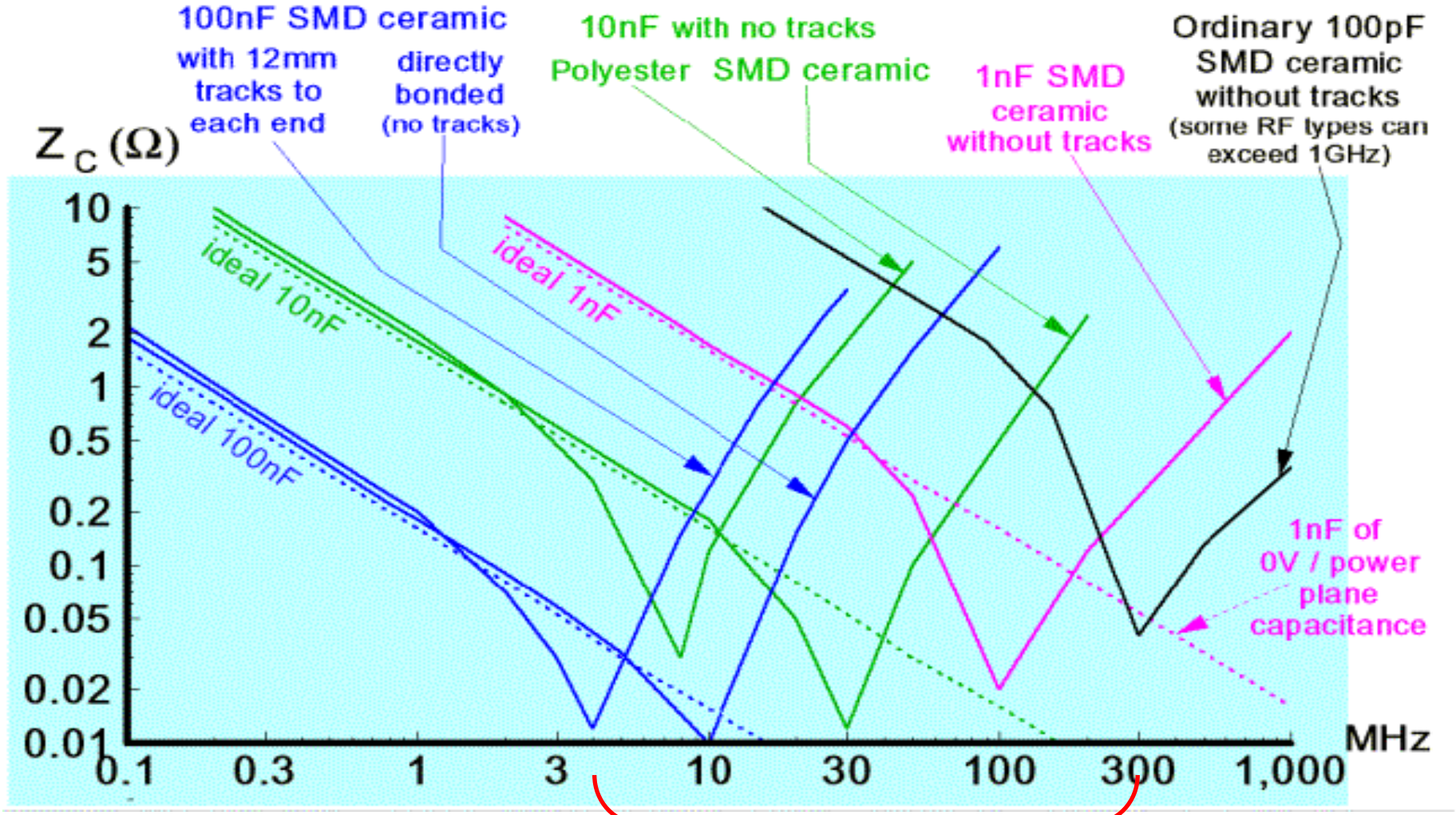
good



Separated ways for RF-current of C2a and semiconductor

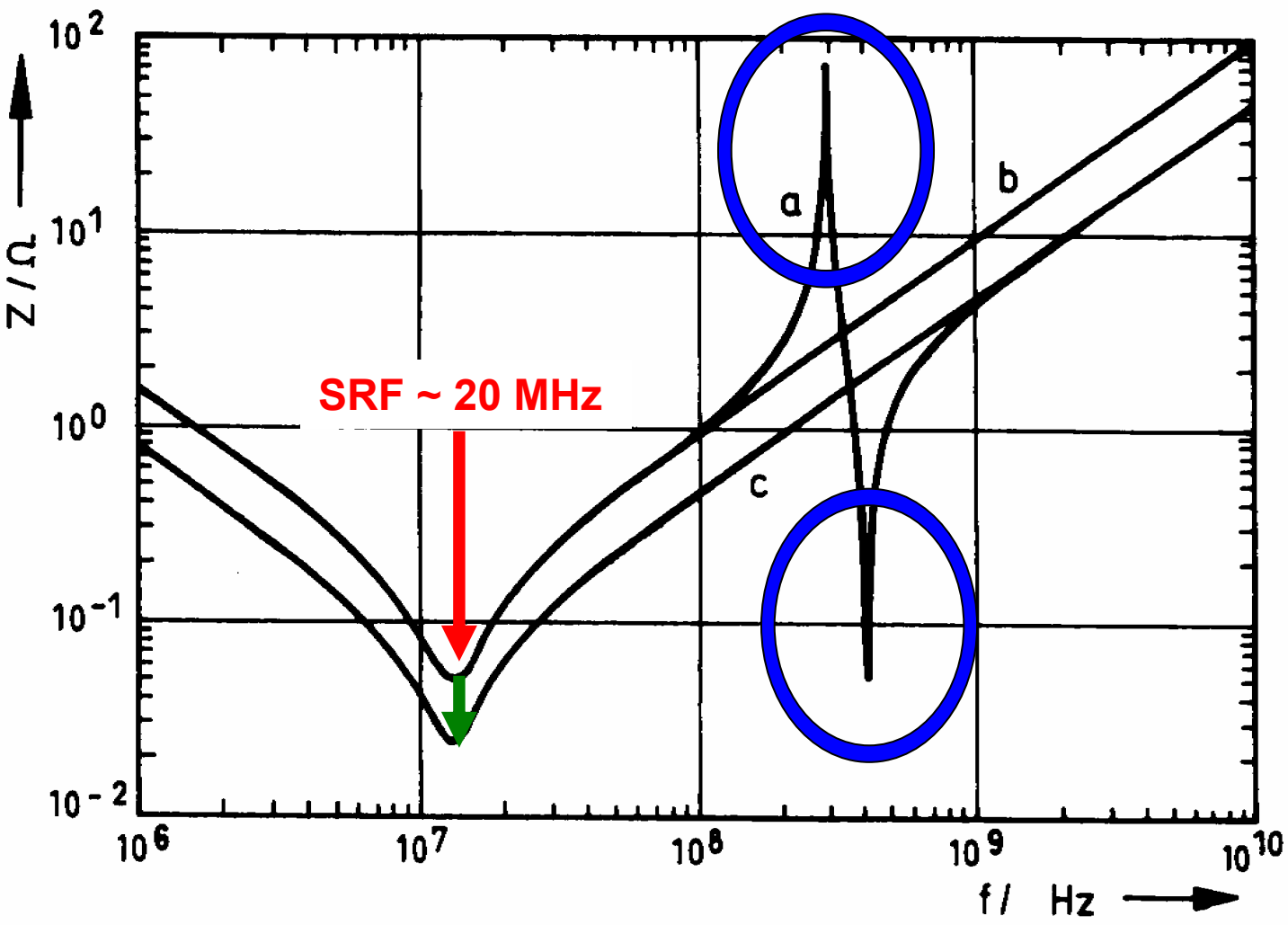
More vias = smaller DCR/L

Impedance vs. Frequency of Capacitors



3/4 parts are needed to,,,,,,,,,,, !!

Paralleled Capacitors



a:

100nF // 100 pF
(without Ferrite !)
Attention !

Resonant Circuit !!

b:

1 x 100nF

c:

2 x 100nF paralleled
lower Impedance

Simulation with RF Sim 99 or SWITCHER CAD III

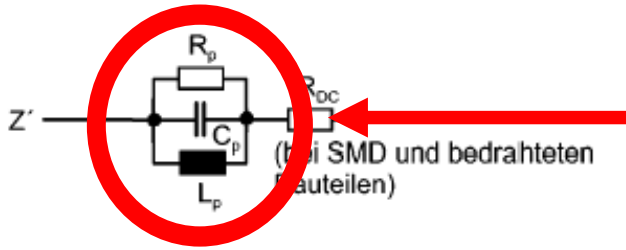
➢ Simulation of parallel resonance due to the wrong choice of Cap‘s (100nF; 1nF; 100pF)

➢ Correct choice of parallel Cap‘s (100nF; 22nF; 5nF)
Attenuation of at least 12dB in the range of 1 MHz to 500MHz

➢ Optimal solution: (100nF; SMD Ferrit)
Wideband attenuation of the complete frequency range

Simulation-Modell for EMC-Ferrites and Power Inductors

Tabelle und Beispieldiagramme



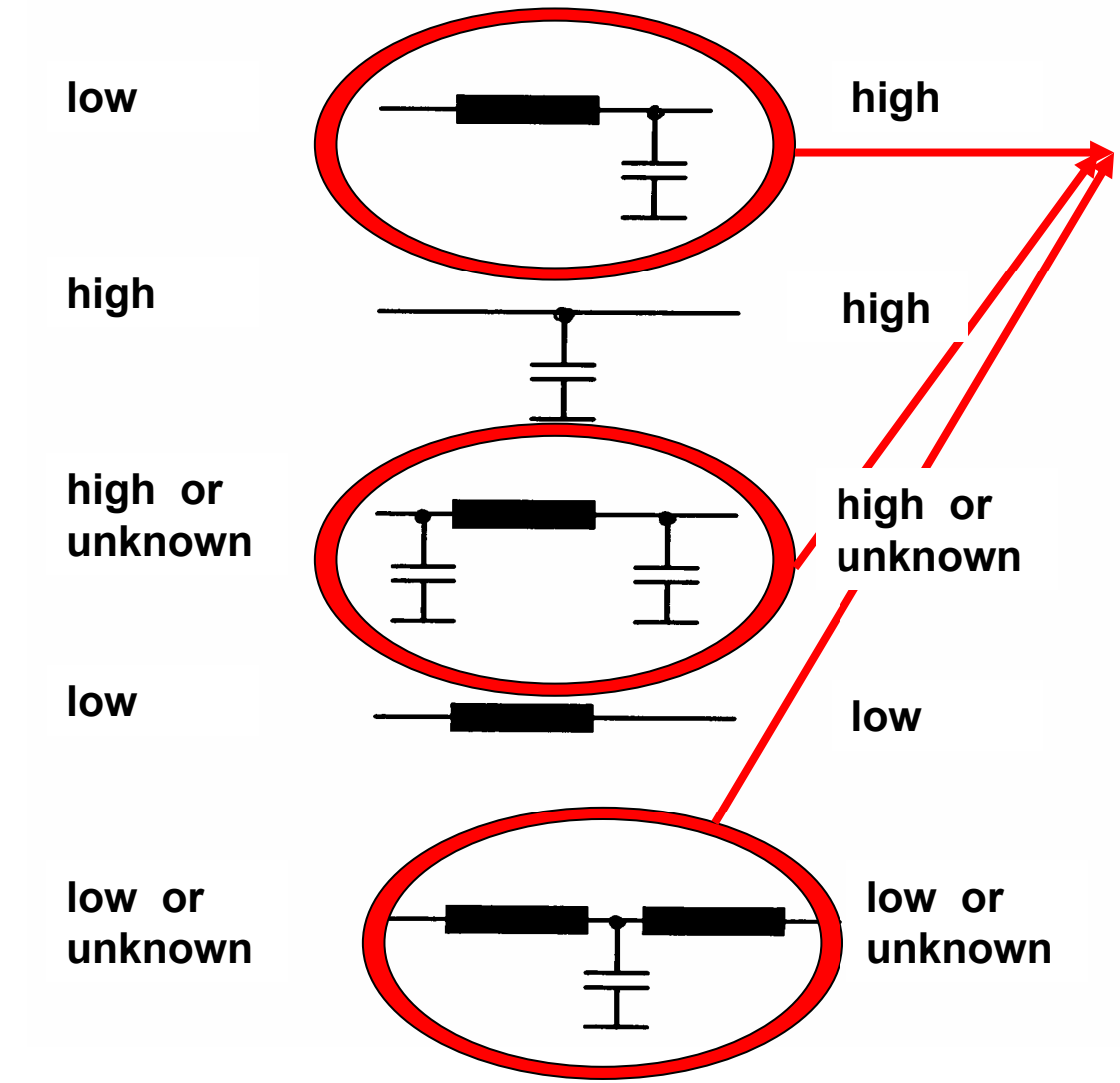
Artikelnummer	Bezeichnung	Rp in Ω	Lp in uH	Cp in pF
	SMD-Ferrit 0402	180	0,4662	0,5071
742 792 71	SMD-Ferrit 0402 120 Ω	180	0,4662	0,5071
742 792 72	SMD-Ferrit 0402 300 Ω	380	0,9394	0,5487
	SMD-Ferrit 0603			
742 792 68	SMD Ferrit 0603 15 Ω	58	0,0260	0,3747
742 792 601	SMD Ferrit 0603 30 Ω	43	0,0600	0,6647
742 792 60	SMD Ferrit 0603 40 Ω	68	0,0917	0,1202
742 792 67	SMD Ferrit 0603 60 Ω	115	0,1500	0,0926
742 792 61	SMD Ferrit 0603 80 Ω	448	0,1938	0,4323
742 792 62	SMD Ferrit 0603 120 Ω	190	0,2935	0,3991
742 792 621	SMD Ferrit 0603 140 Ω	360	0,1992	0,8710
742 792 621	SMD Ferrit 0603 180 Ω	310	0,4454	0,6666
742 792 63	SMD Ferrit 0603 2200 Ω	300	0,4425	0,6584

Model as Parallel-Circuit with *constant* Parametern for Rp / Lp / Cp

can be used in any Simulationprogram (like P-SPICE or Electronics Workbench, ...) !

Datas: see Book *„Trilogy of Inductors“ Seite 113ff*

Recommended Filtercircuits



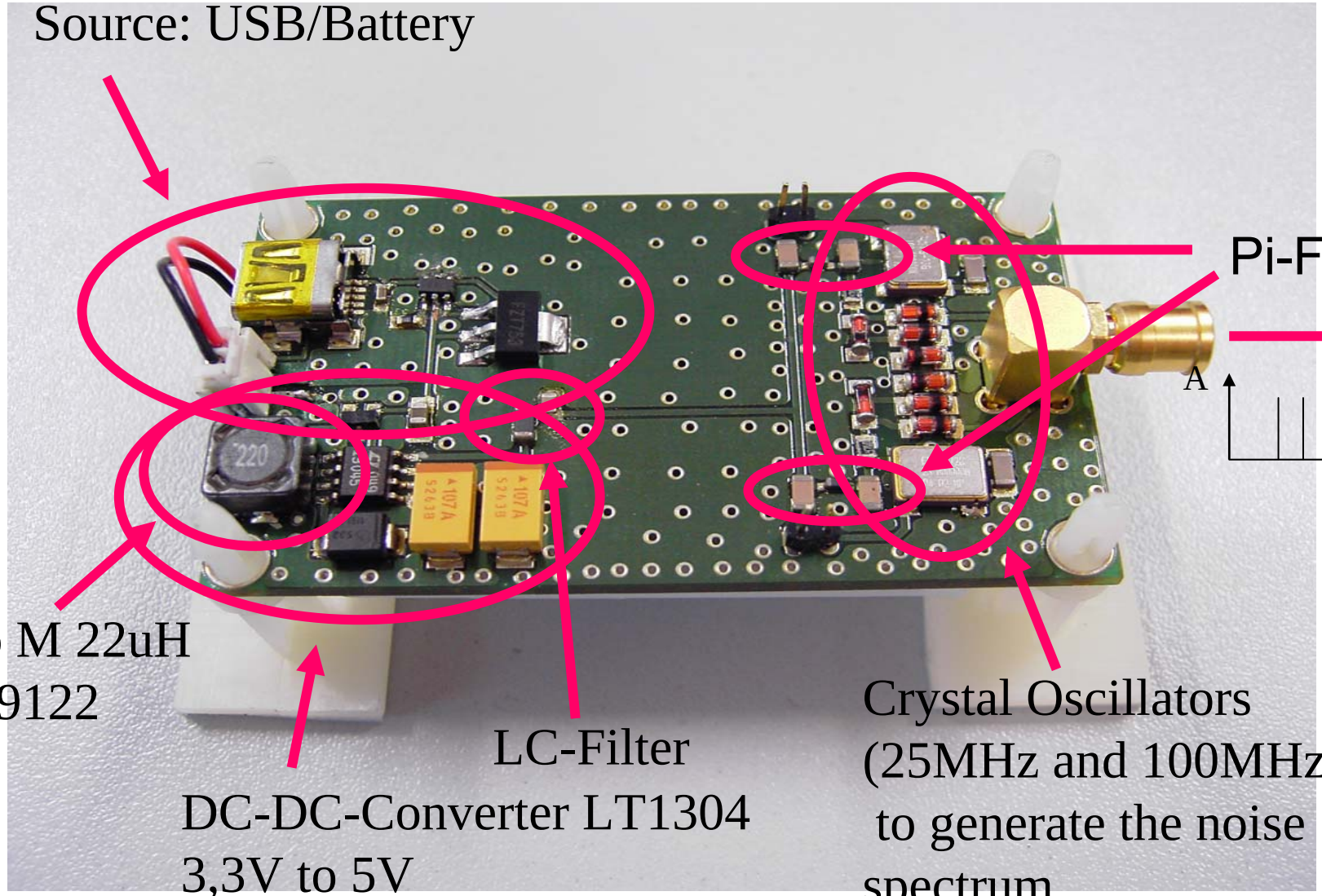
Suggested Circuits

ATTENTION !
Self-Resonant-Frequency of Components !!!

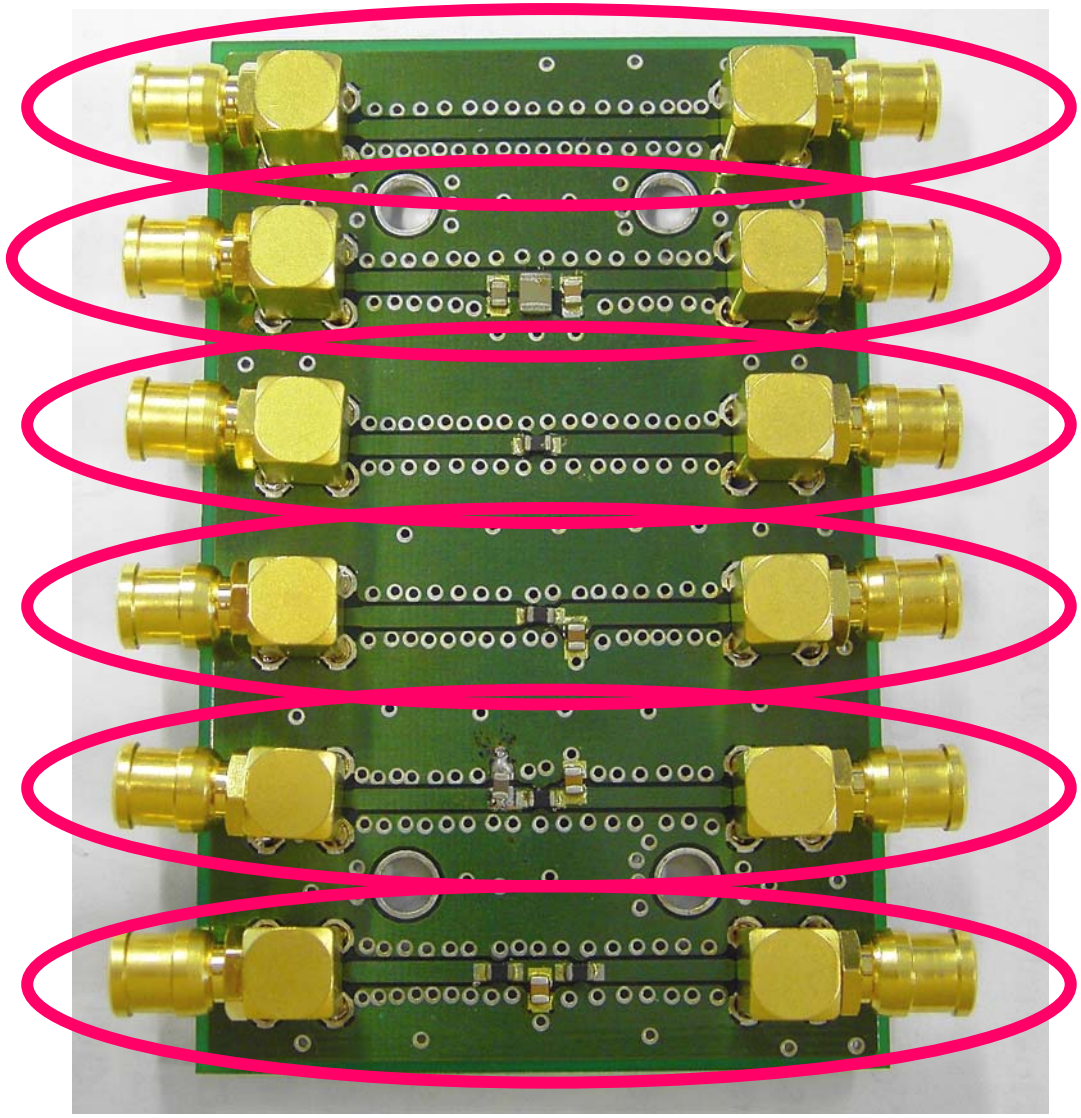
smaller C = higher SRF

If you choose SMD-Ferrite instead of Inductor L
= no Resonance with C
= broadband filtering

Noise source



Filter Topologies



50 Ohm Ref. Line

3xC Capacitance Filter

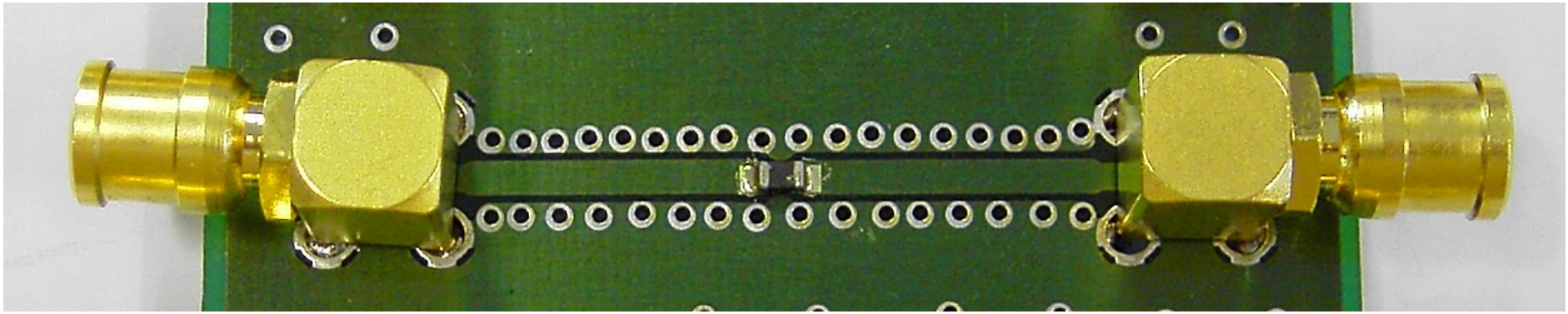
„L“Filter with SMD Ferrite

„L-C“ Filter with SMD Ferrite und Capacitor

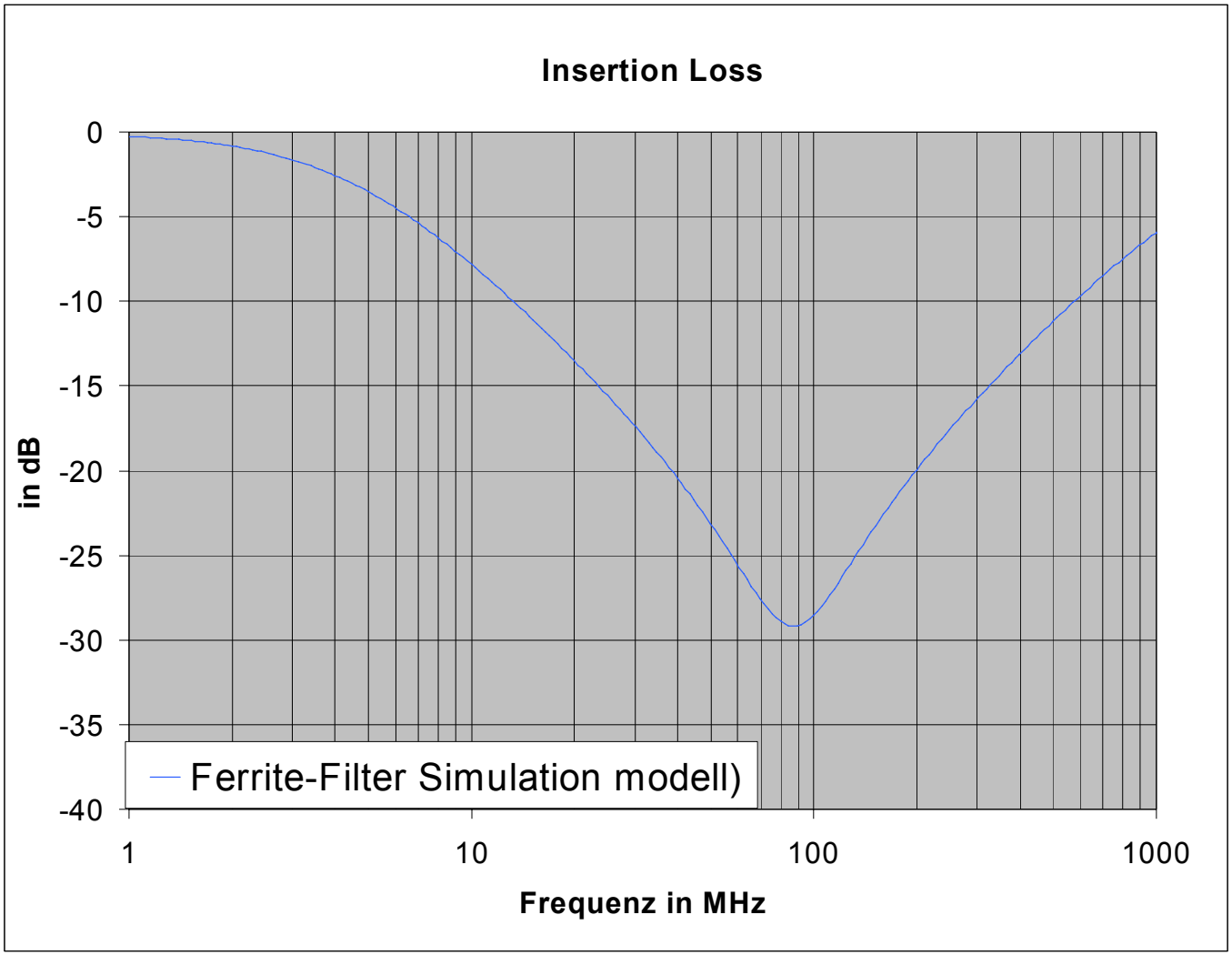
„PI“ Filter

„T“ Filter

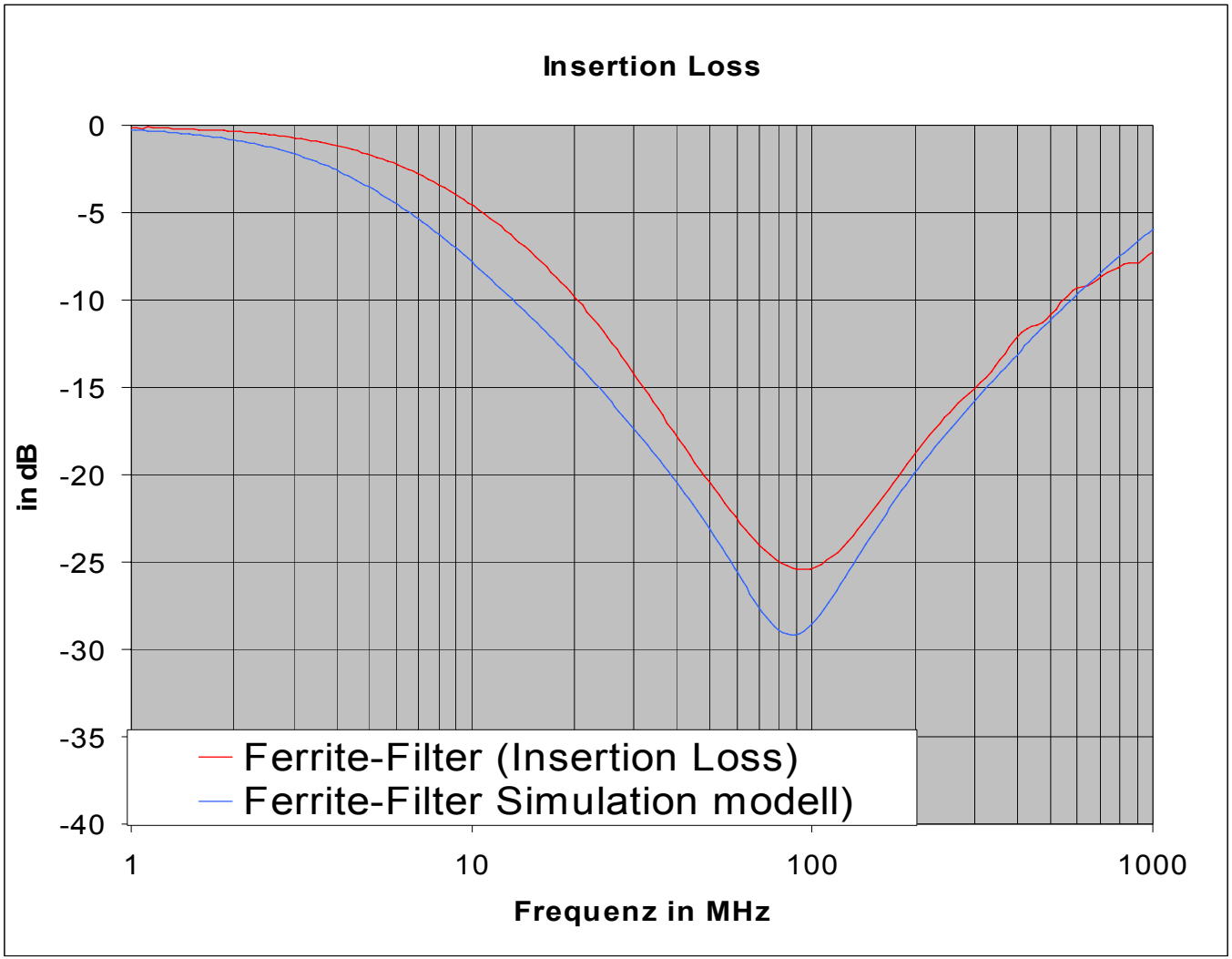
The „L“ Ferrite –Filter



The „L“ Ferrite –Filter



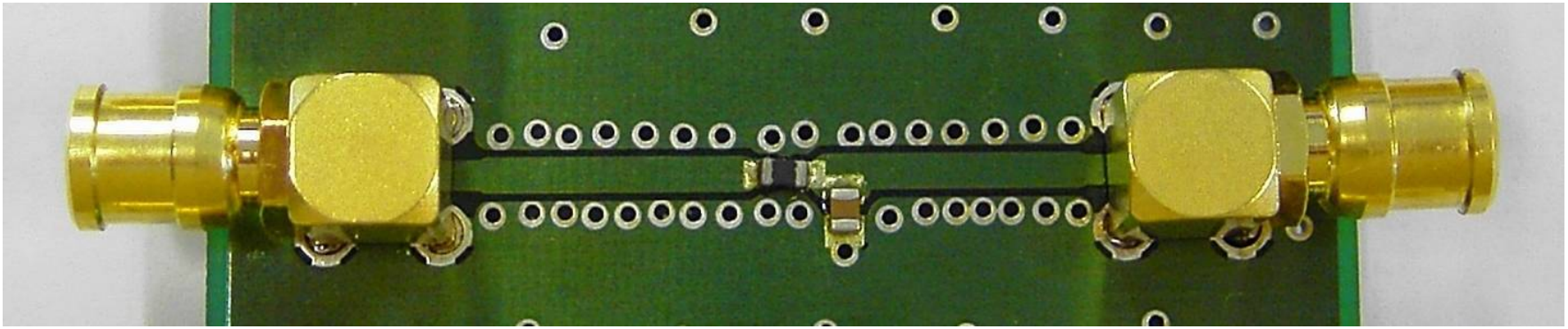
Ferrite –Filter: Measurement vs. Simulation



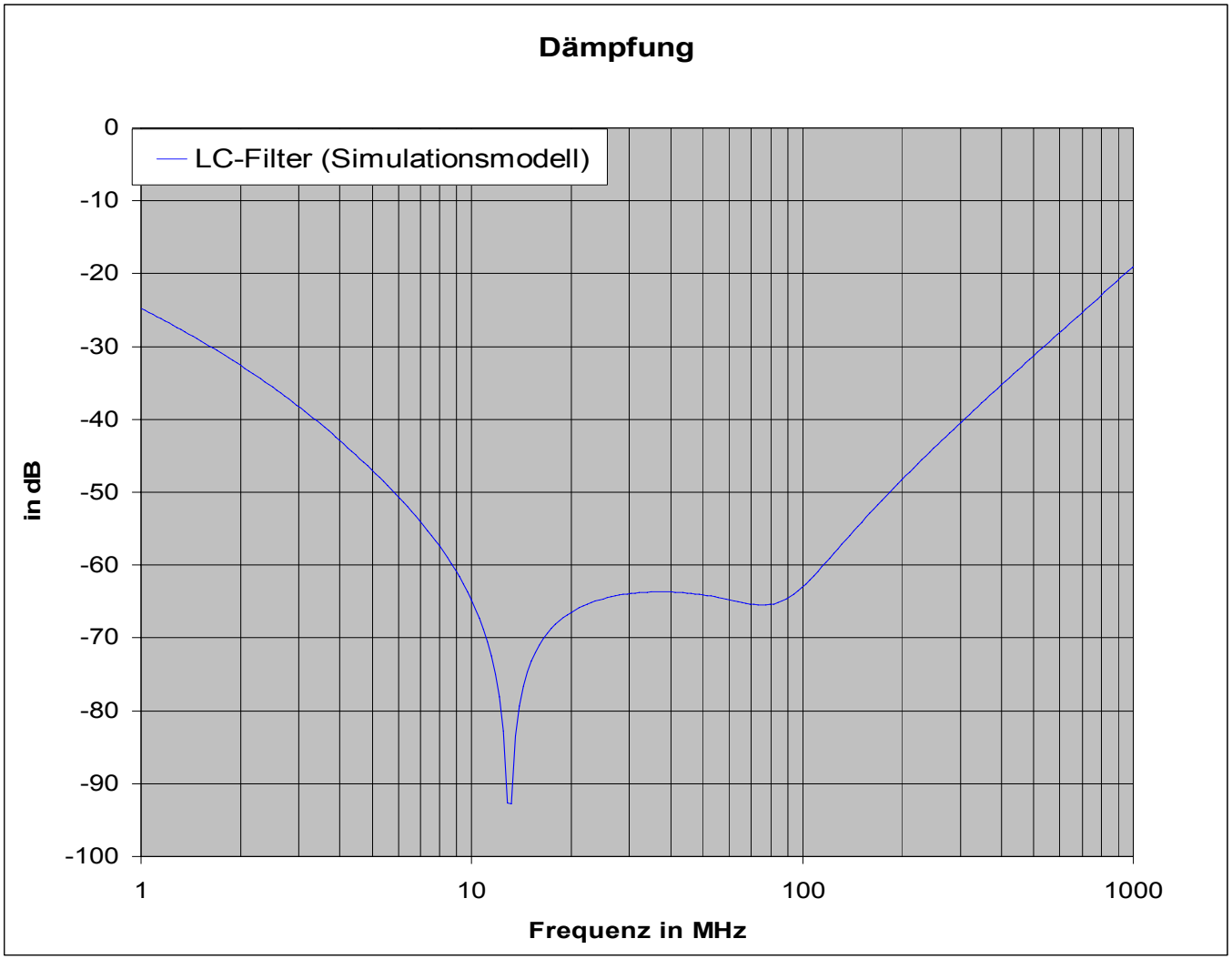
LC-Filter

L=742 792 093

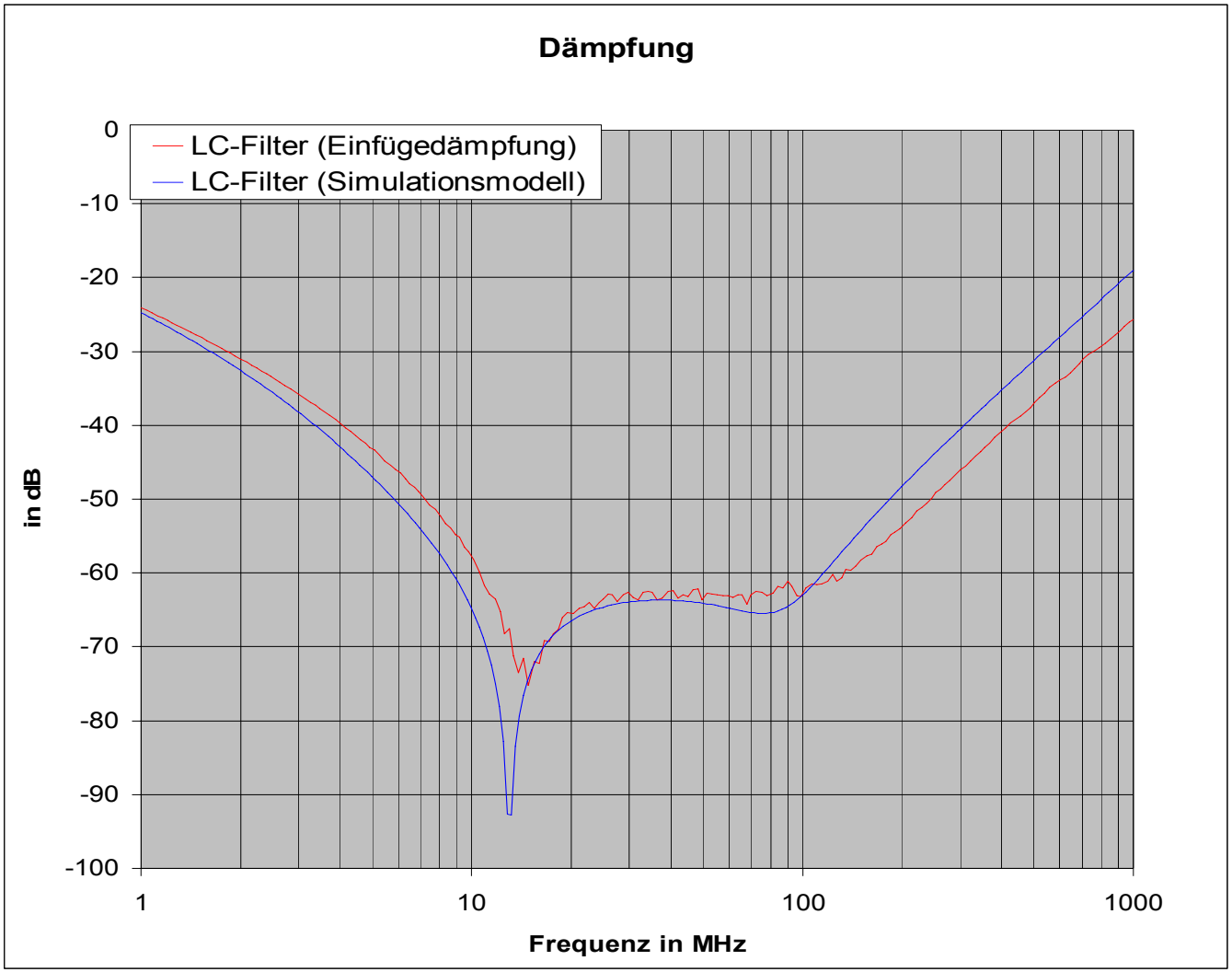
C=100nF



LC-Filter


Dämpfung
LC-Filter (Simulationsmodell)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
in dB
1
10
100
1000
Frequenz in MHz

LC-Filter: Measurement vs. Simulation

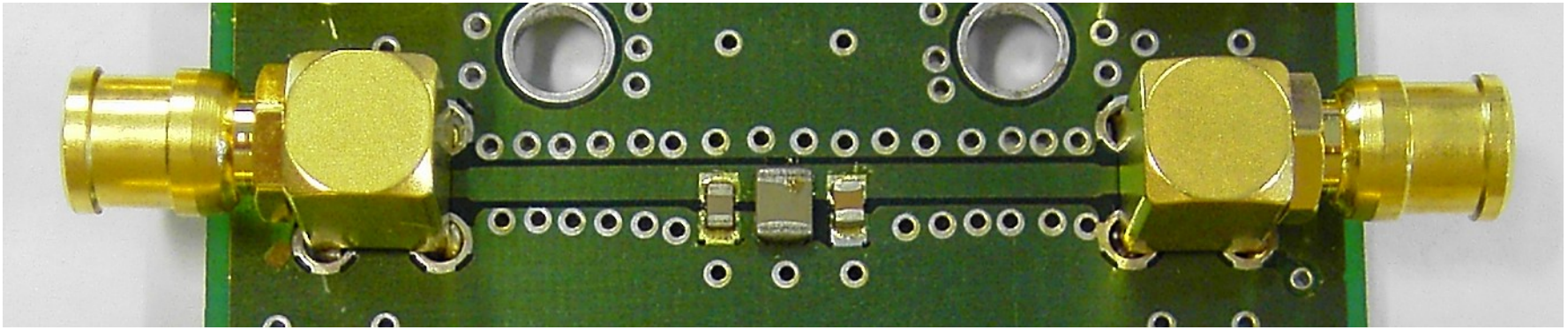


Parallel capacitors

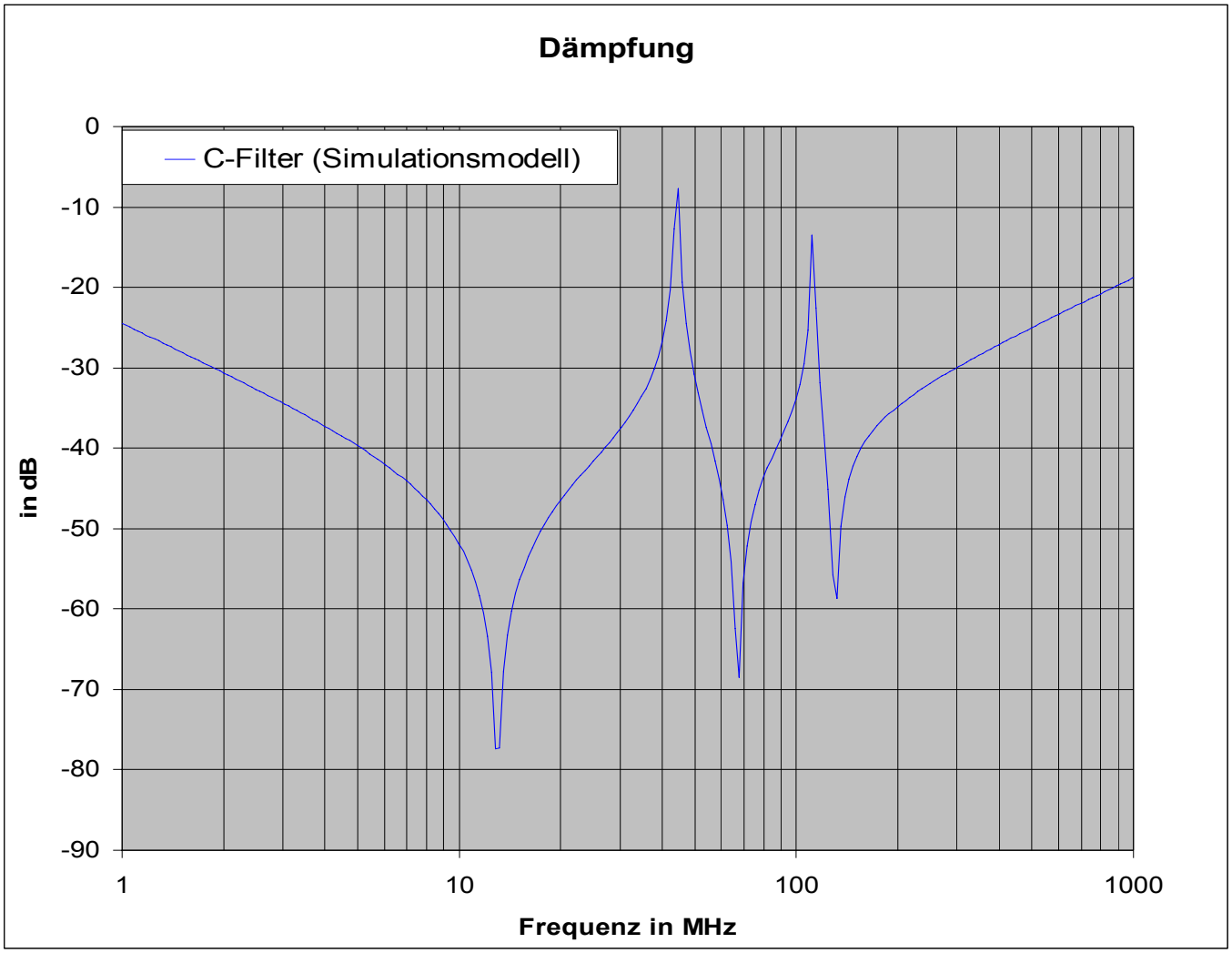
C_1= 1nF

C_2=10nF

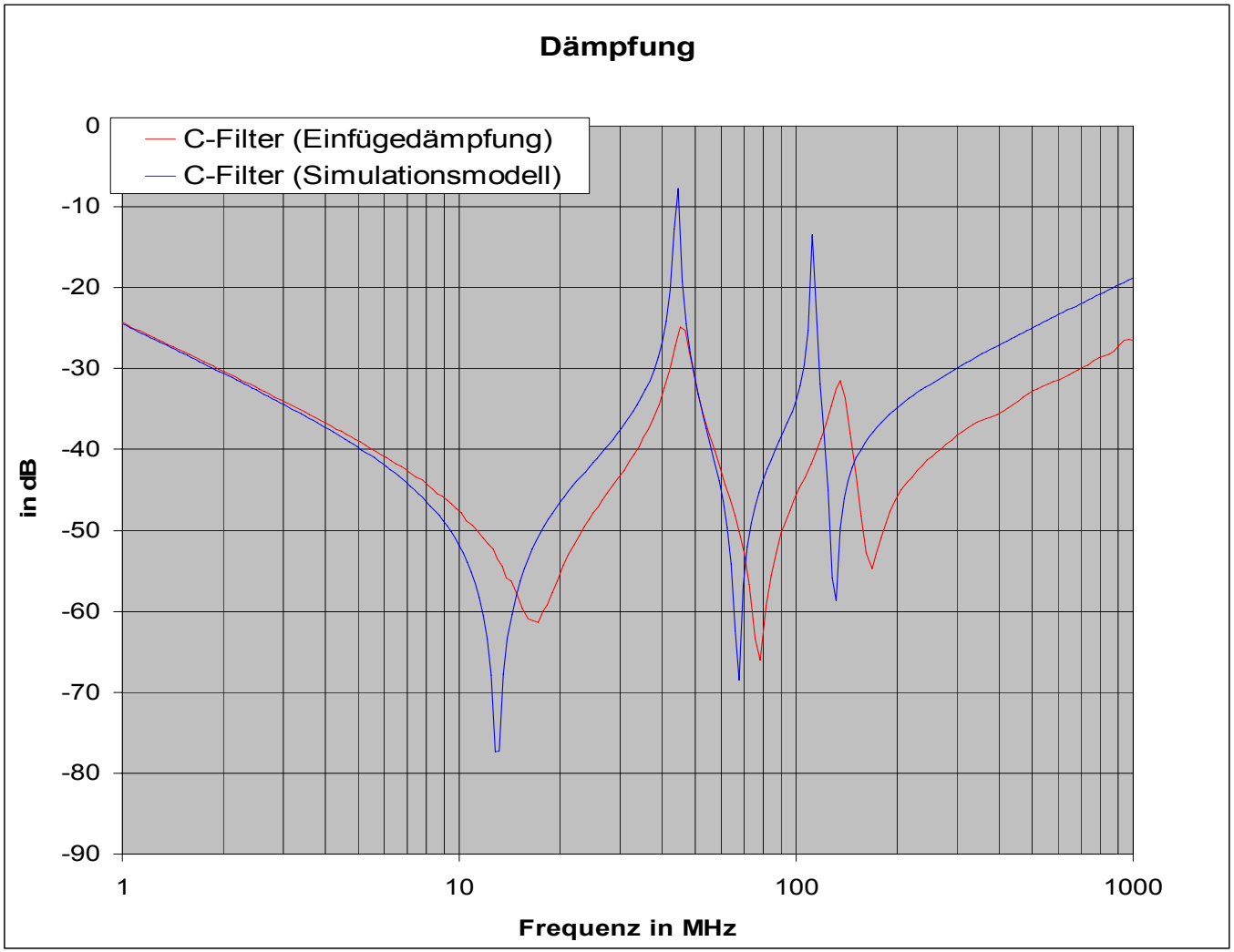
C_3=100nF



Parallel capacitors



C-Filter: Measurement vs. Simulation

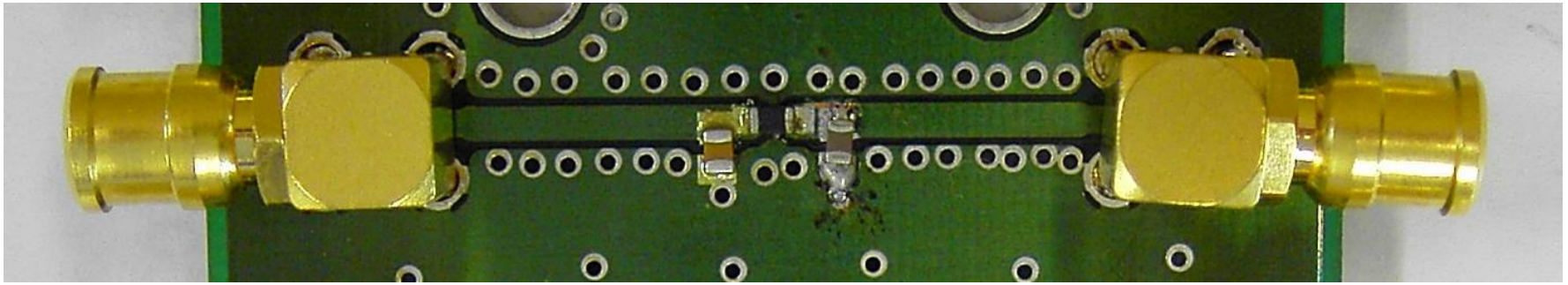


Pi-Filter

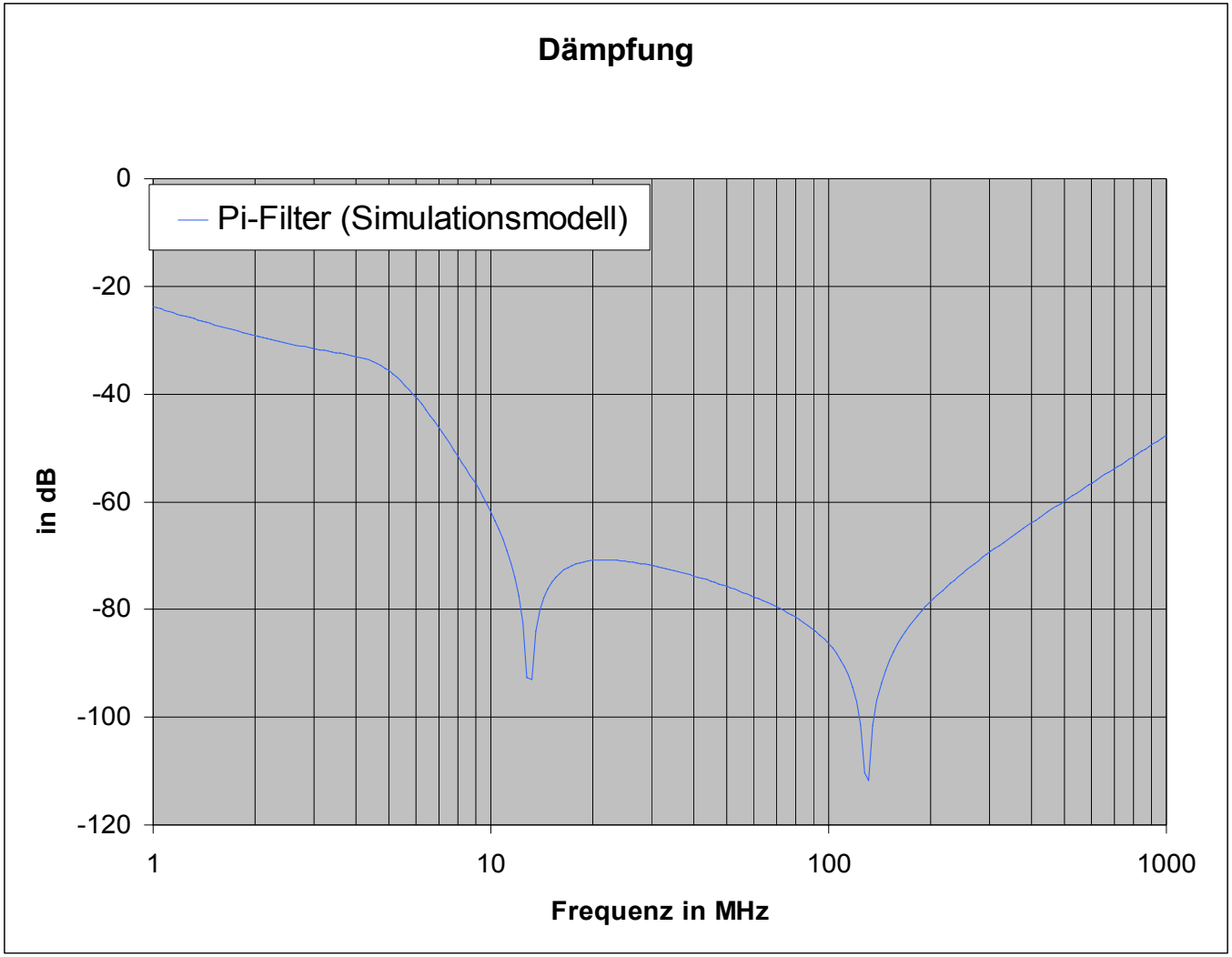
C_1=1nF

L=742 792 093

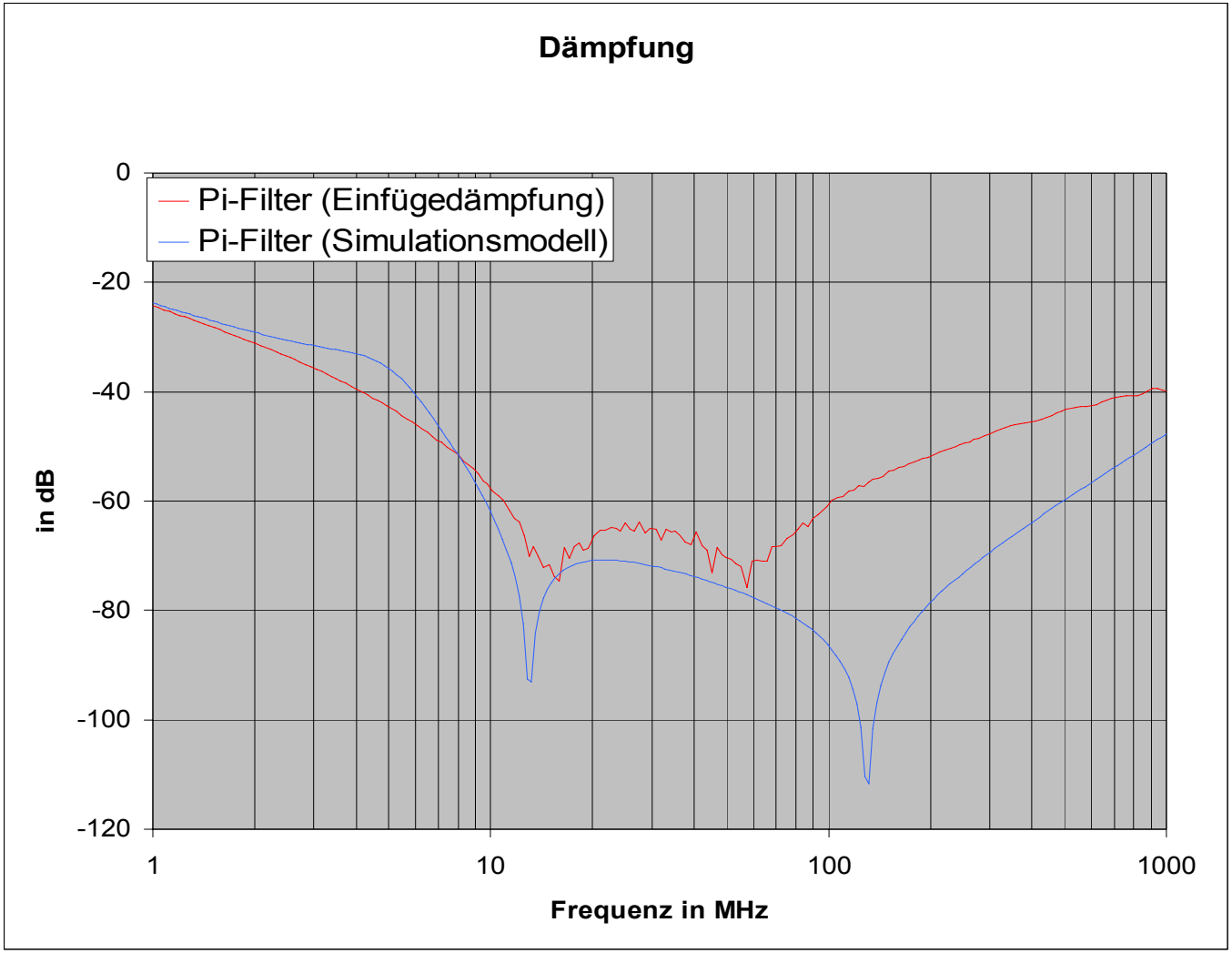
C_2=100nF



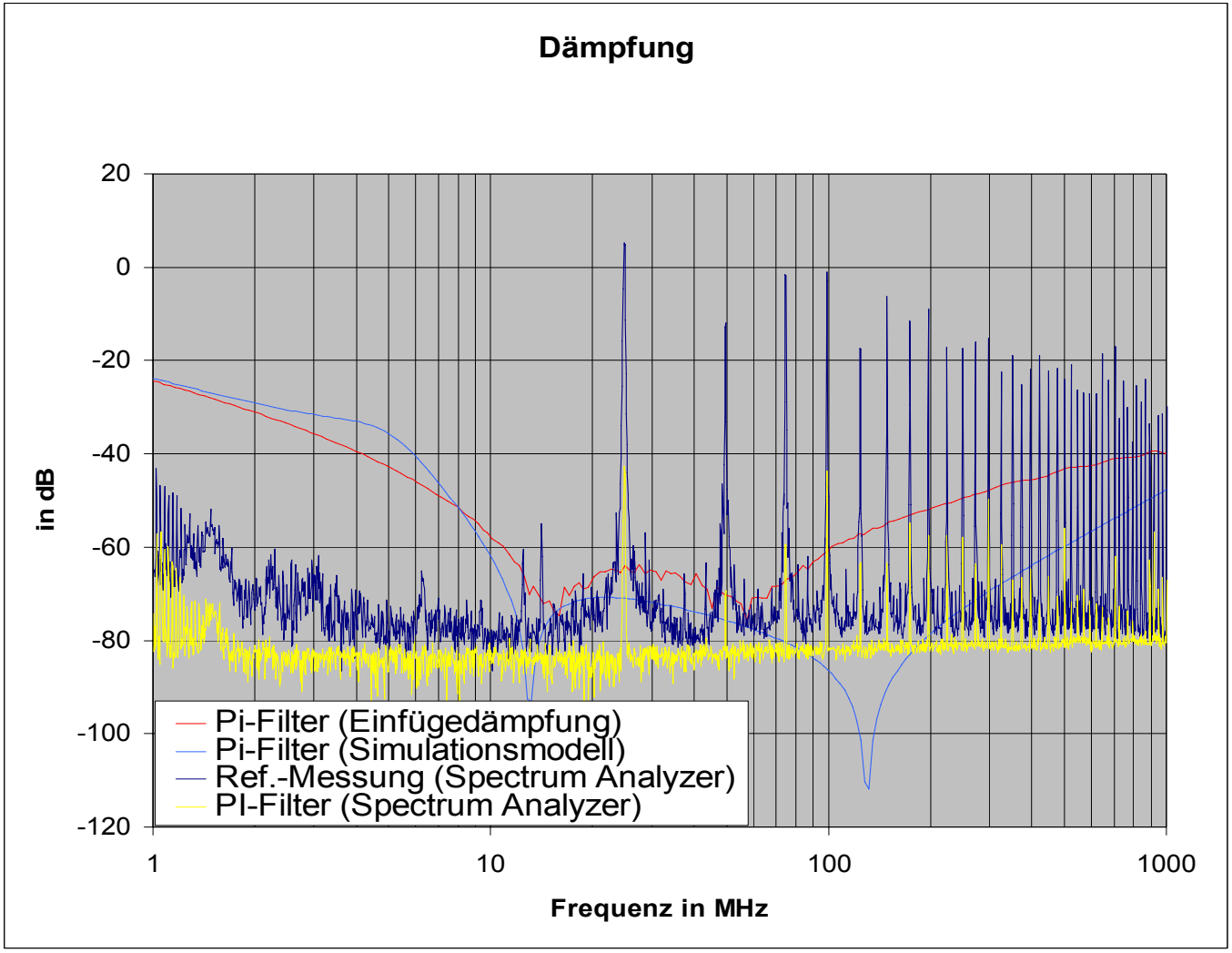
Pi-Filter


Dämpfung
Pi-Filter (Simulationsmodell)
0
-20
-40
-60
-80
-100
-120
in dB
1
10
100
1000
Frequenz in MHz

Pi-Filter: Measurement vs. Simulation



Pi-Filter: Measurement vs. Simulation

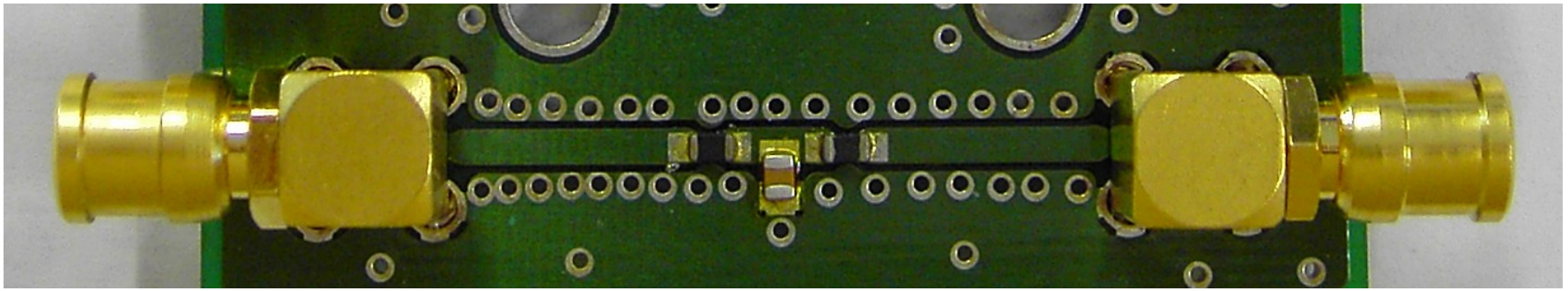


T-Filter

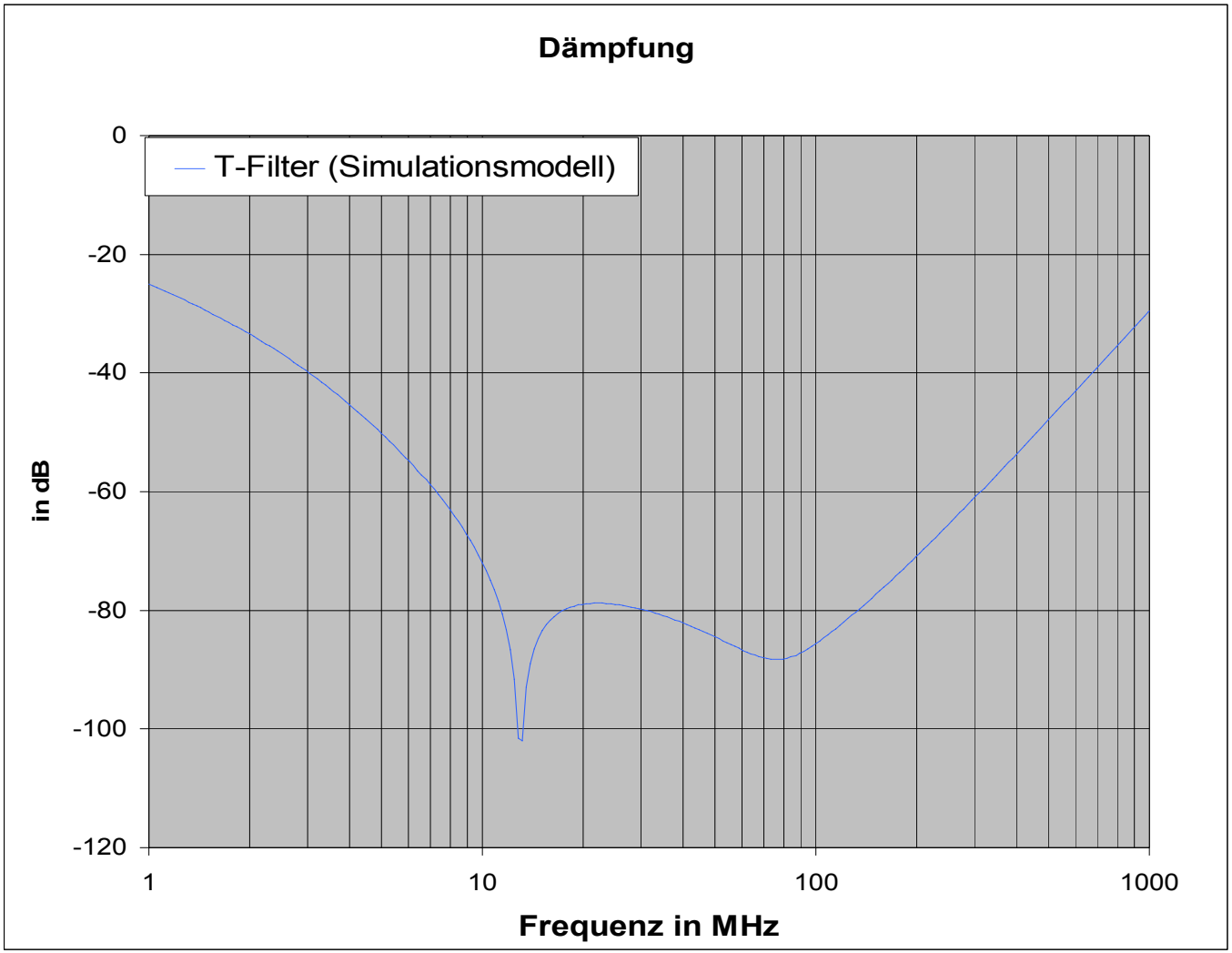
L_1=742 792 040

C=100nF

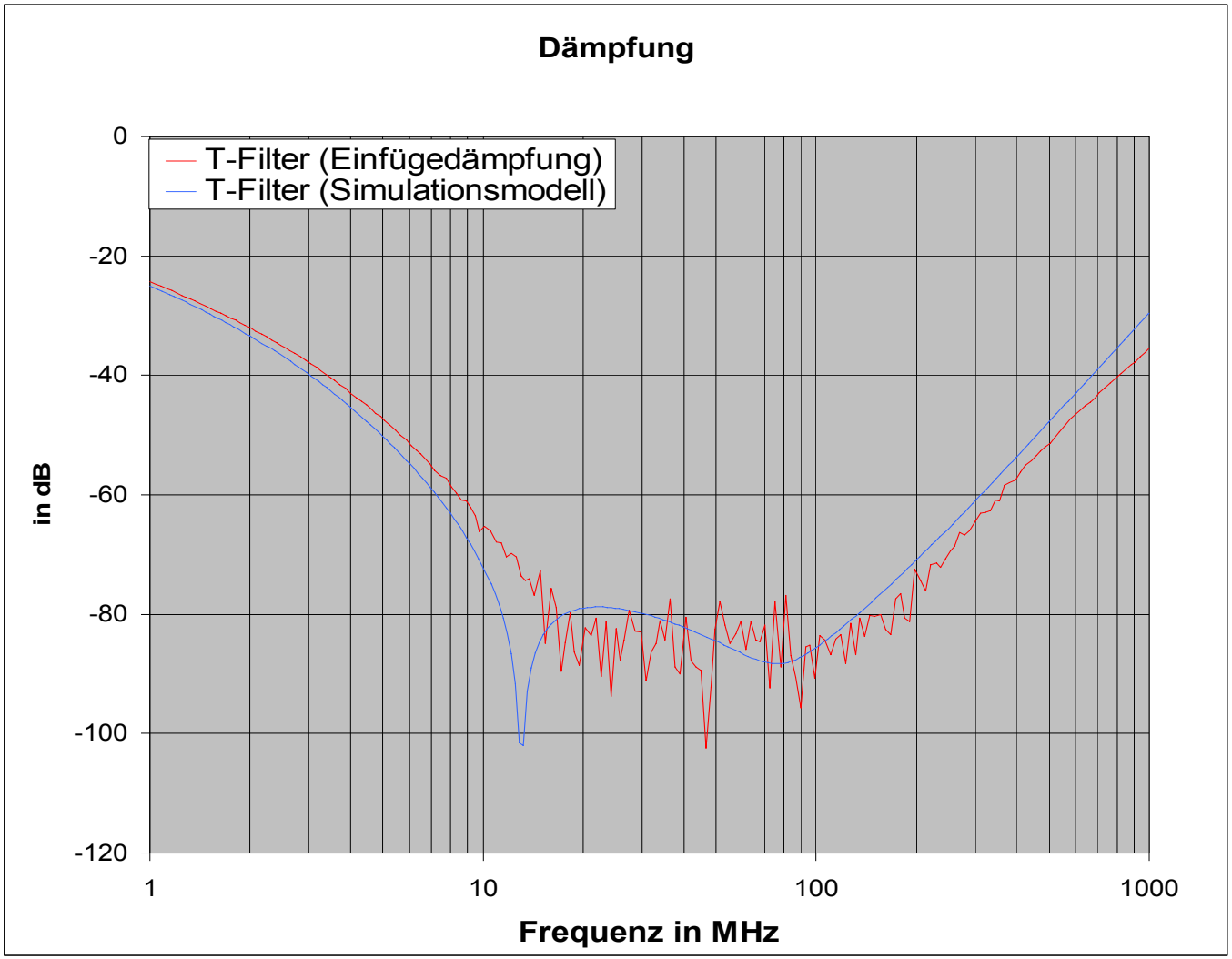
L_2=742 792 092



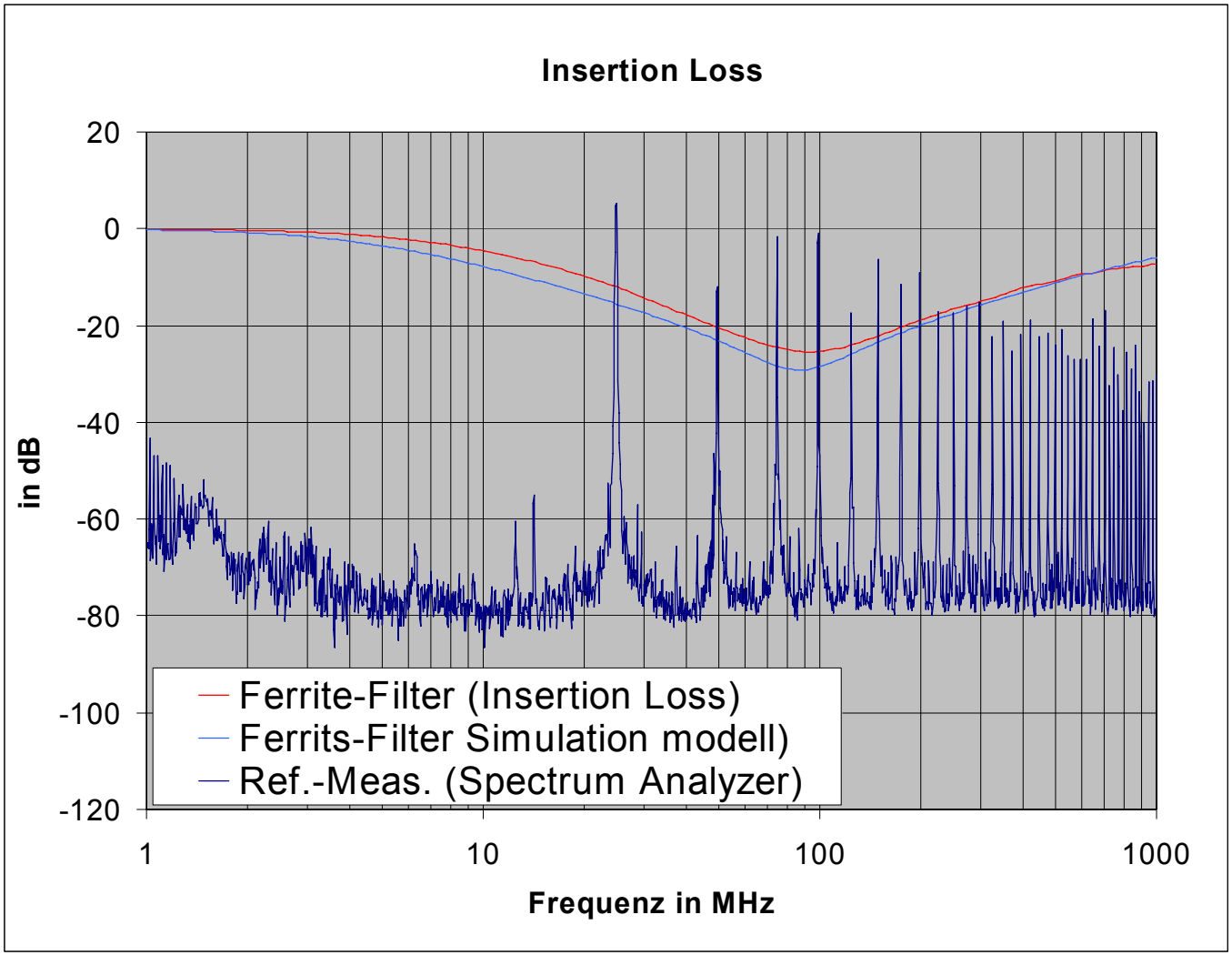
T-Filter


Dämpfung
T-Filter (Simulationsmodell)
0
-20
-40
-60
-80
-100
-120
in dB
1
10
100
1000
Frequenz in MHz

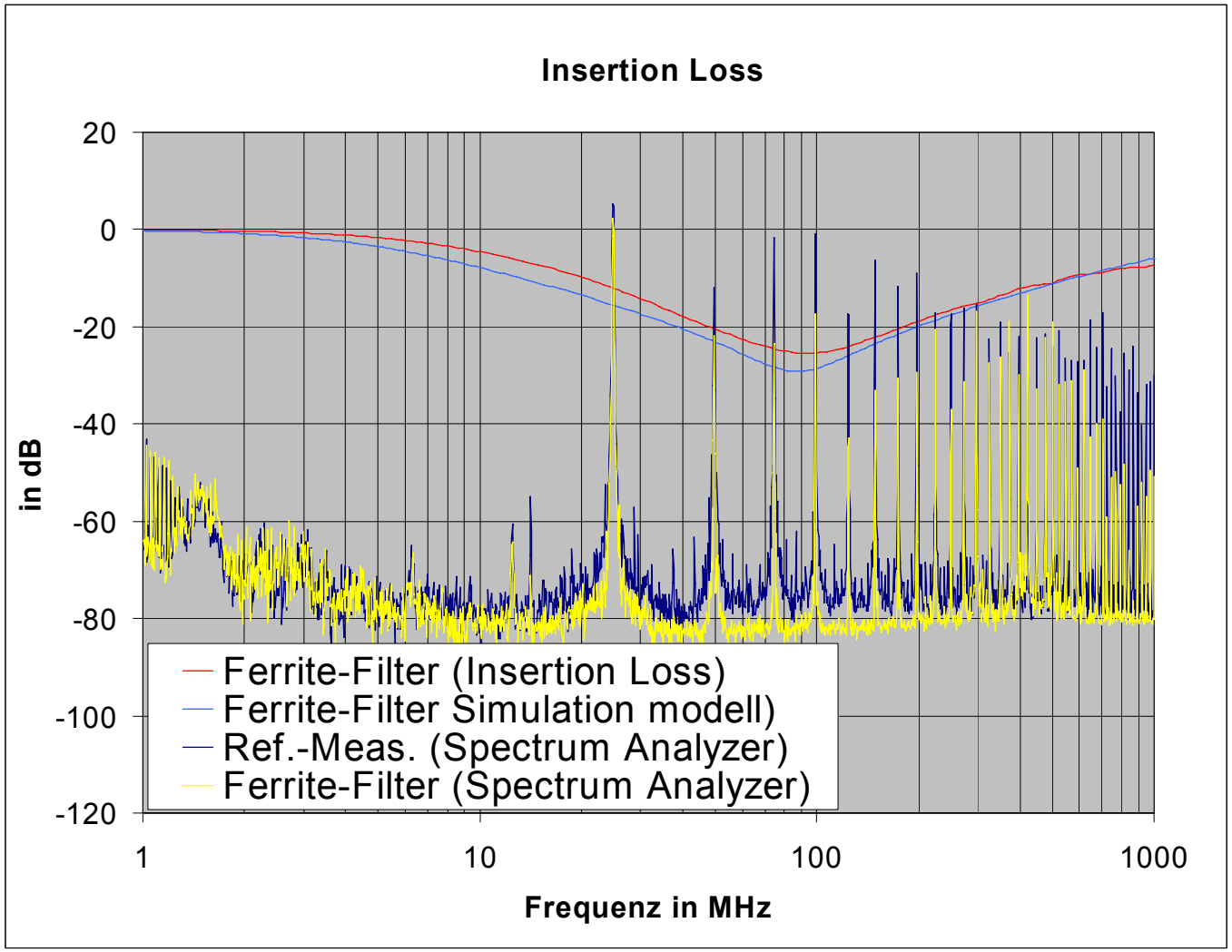
T-Filter: Measurement vs. Simulation



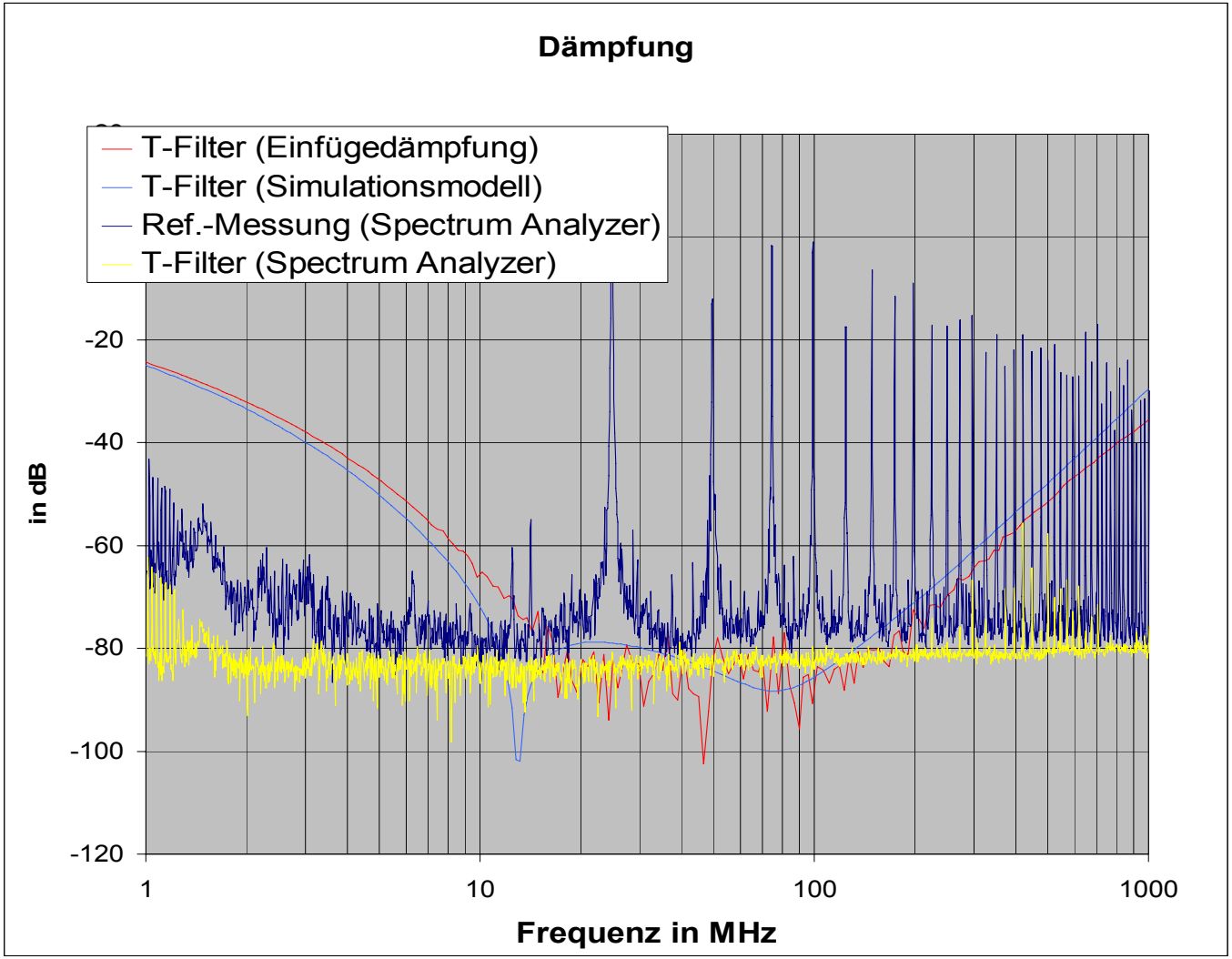
Ferrite –Filter: Measurement vs. Simulation



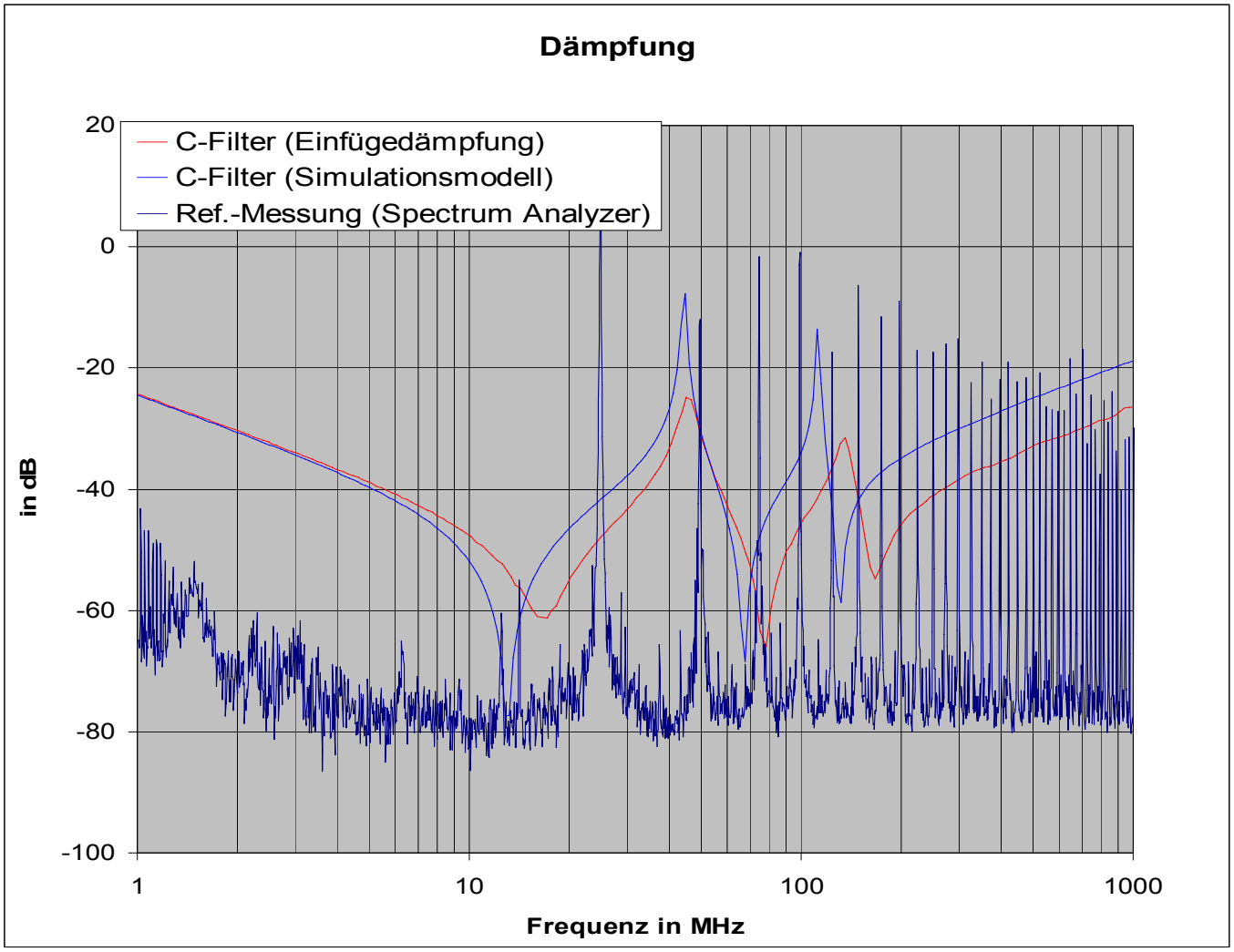
Ferrite –Filter: Measurement vs. Simulation



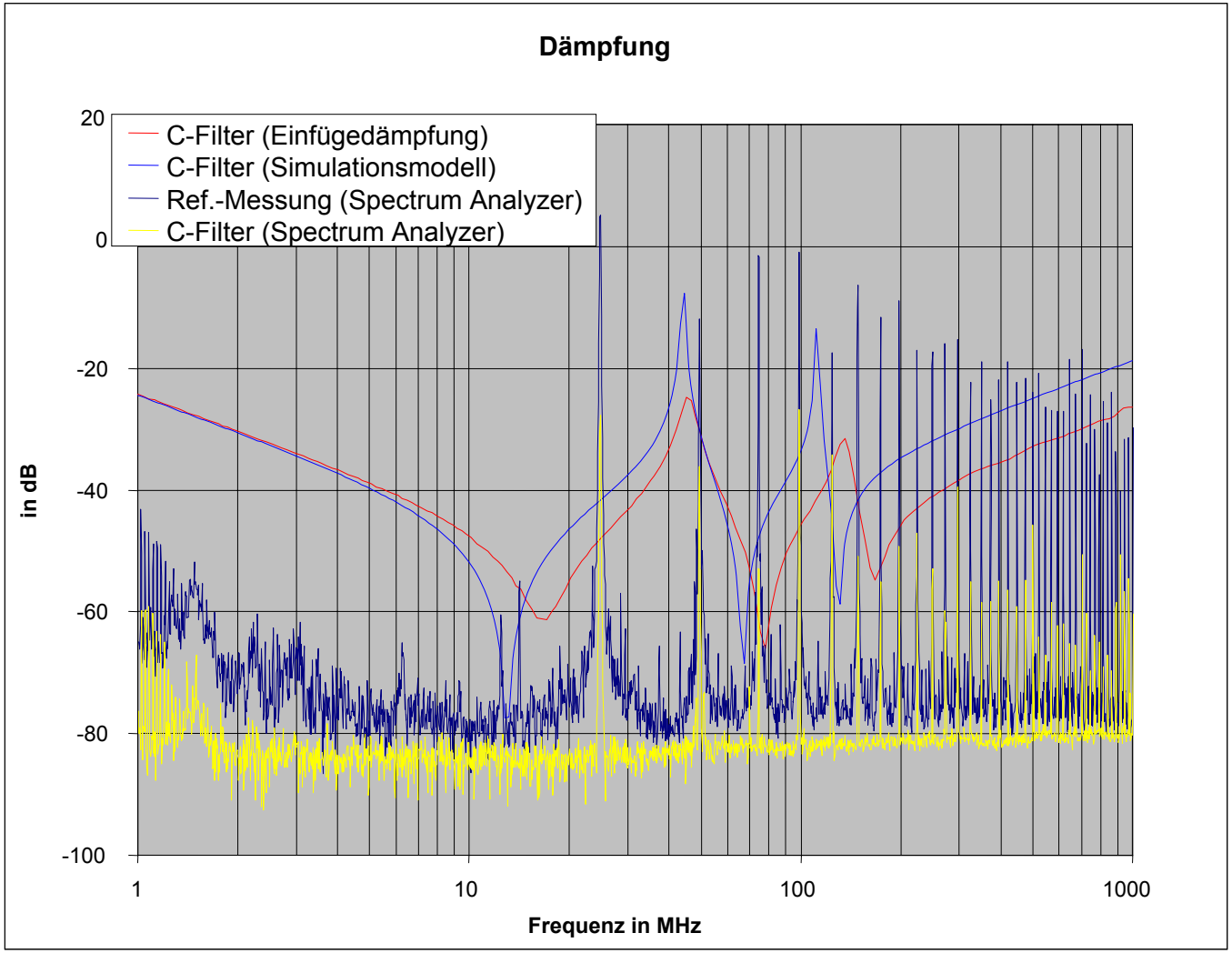
T-Filter: Measurement vs. Simulation



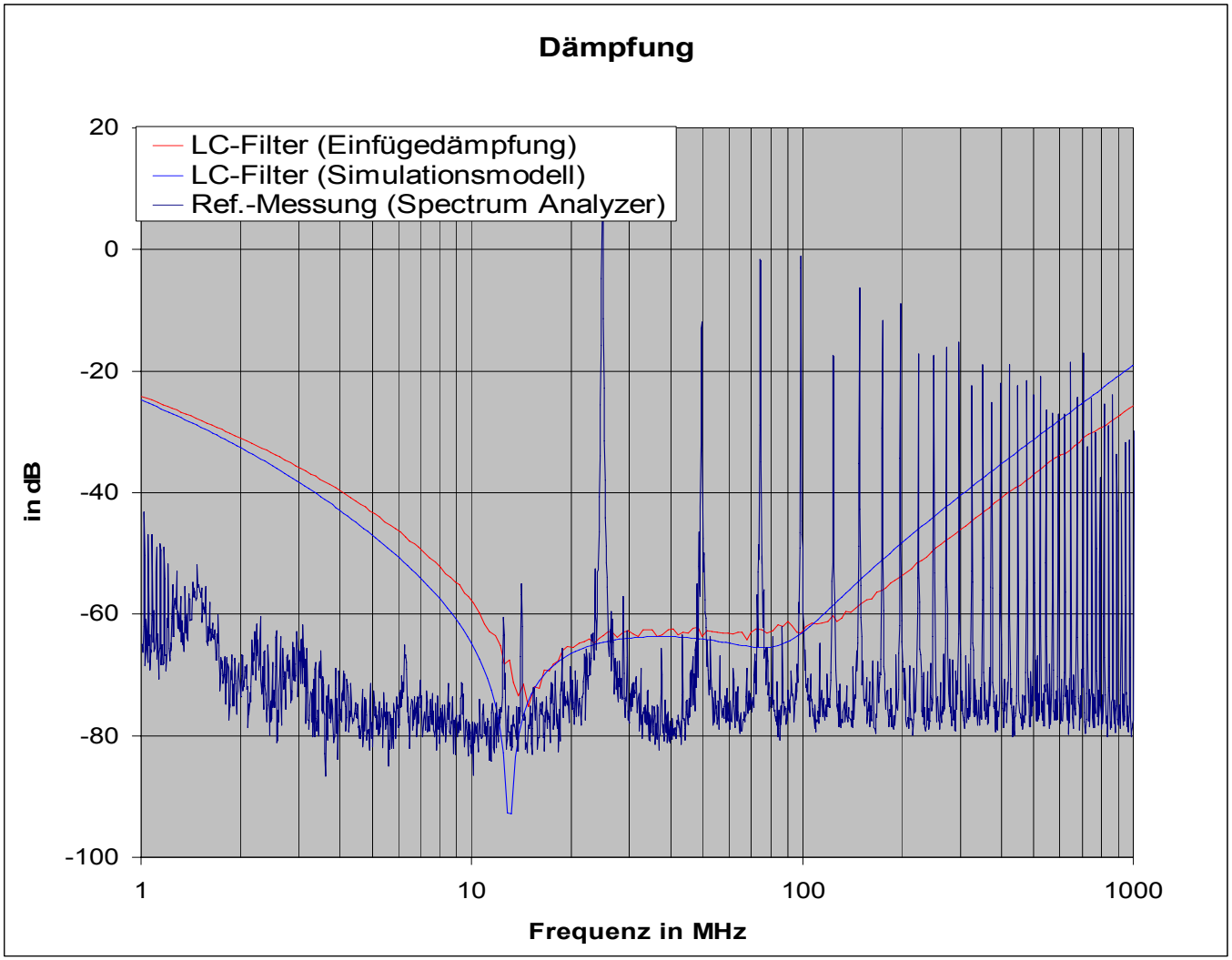
C-Filter: Measurement vs. Simulation



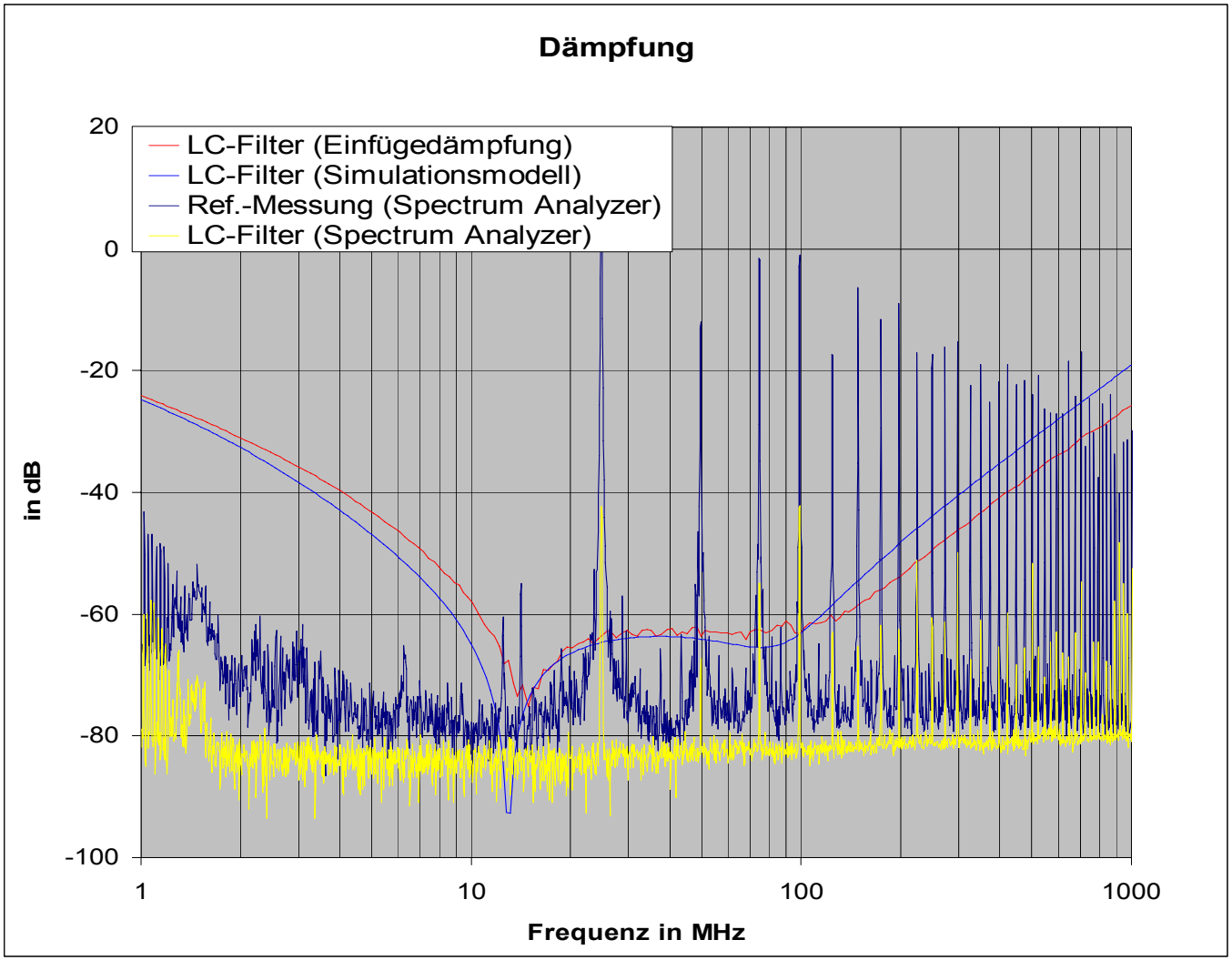
C-Filter: Measurement vs. Simulation



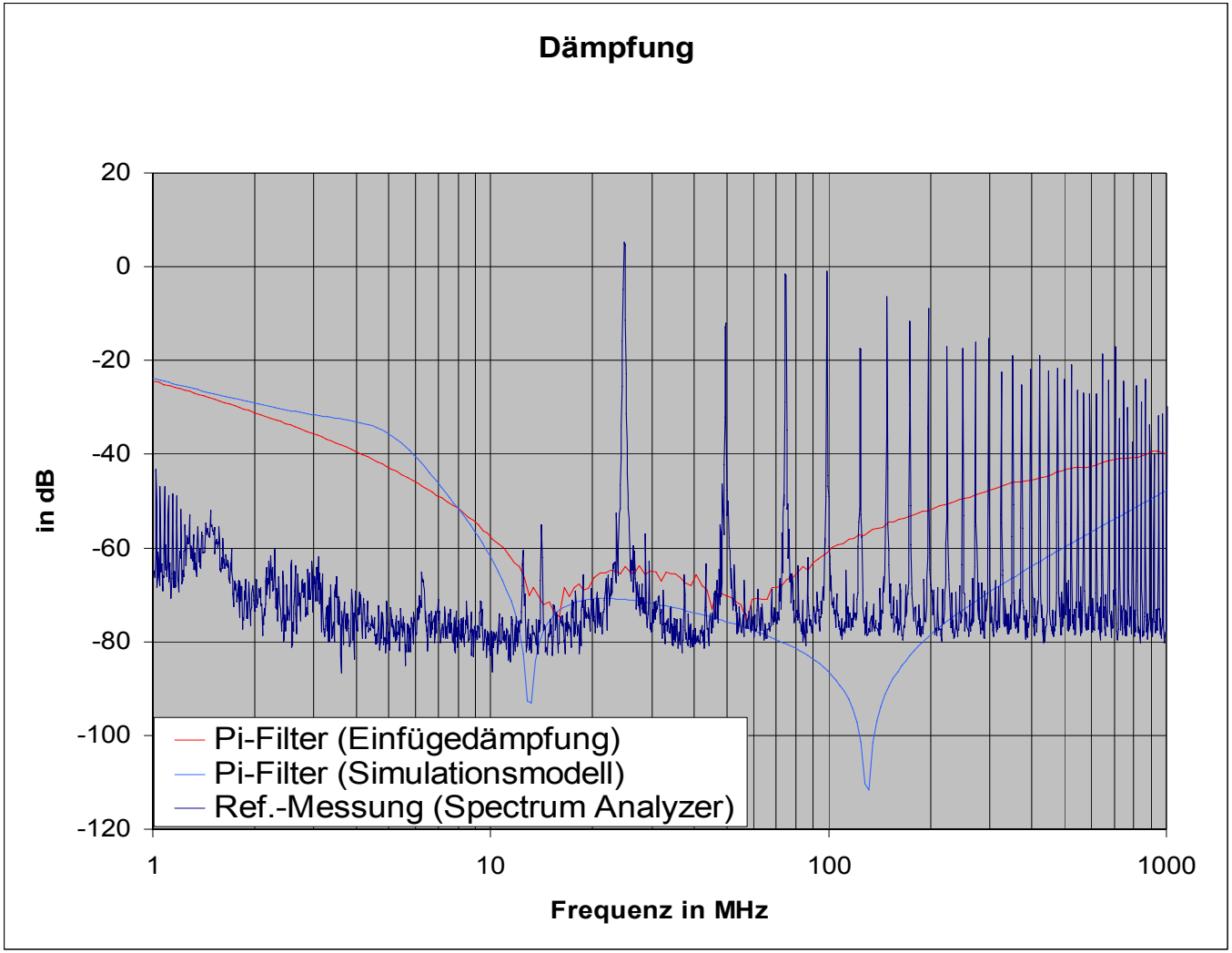
LC-Filter: Measurement vs. Simulation



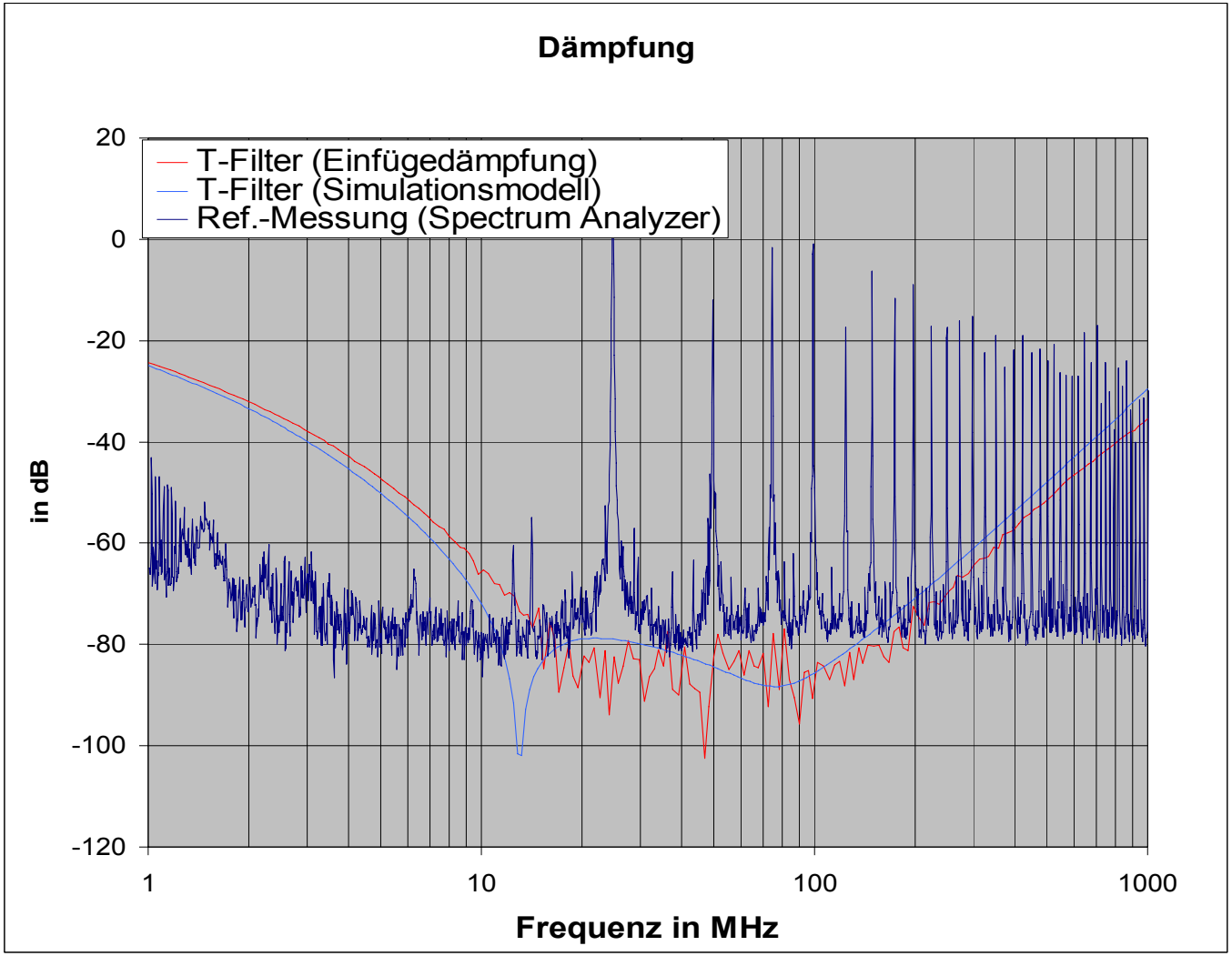
LC-Filter: Mesaurement vs. Simulation



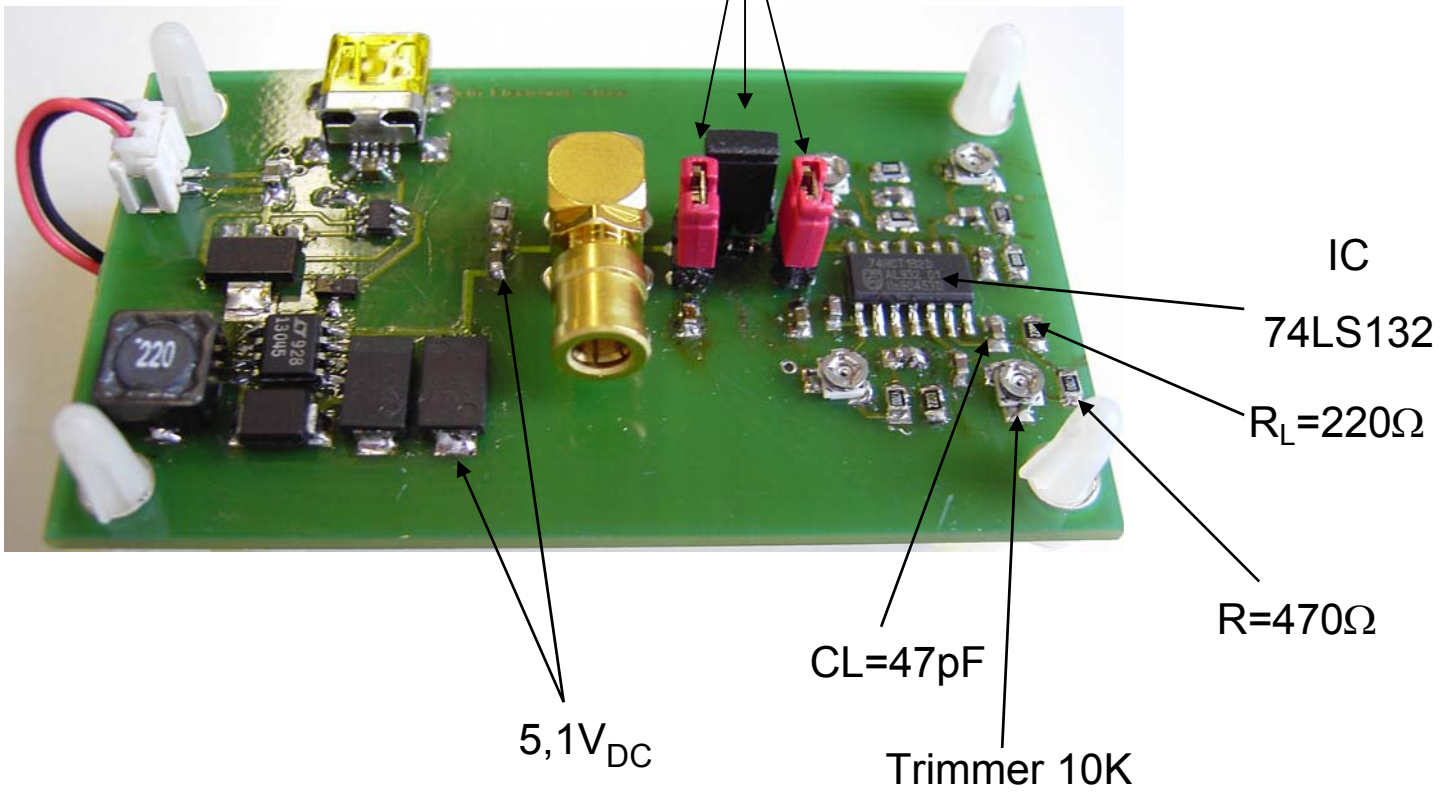
Pi-Filter: Measurement vs. Simulation



T-Filter: Measurement vs. Simulation

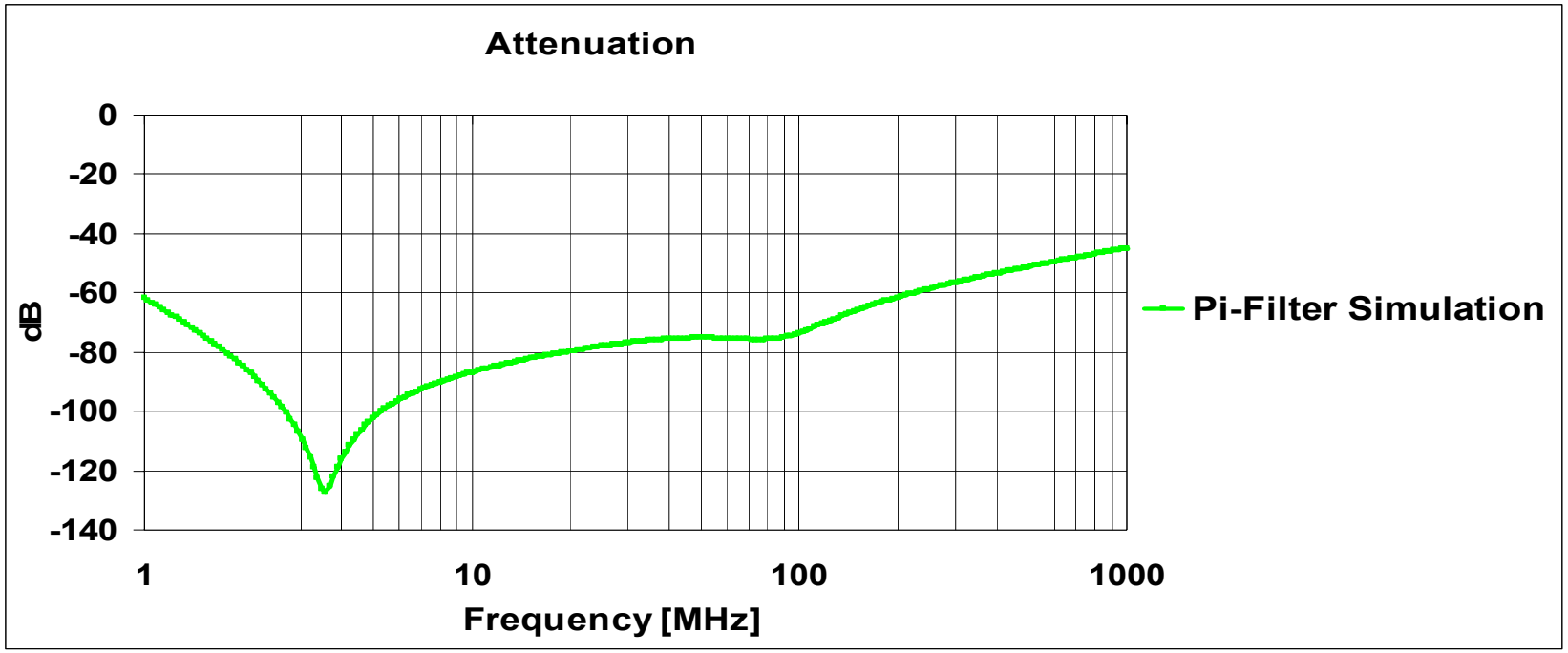


Testboard V_{CC}-decoupling

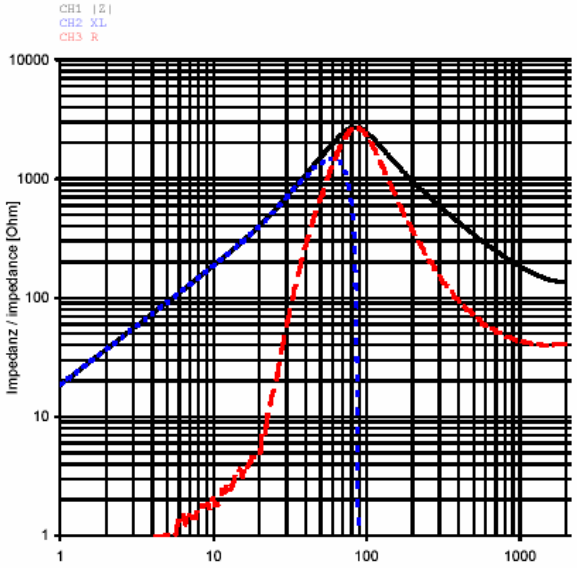


V_{CC}- decoupling via discrete π-Filter

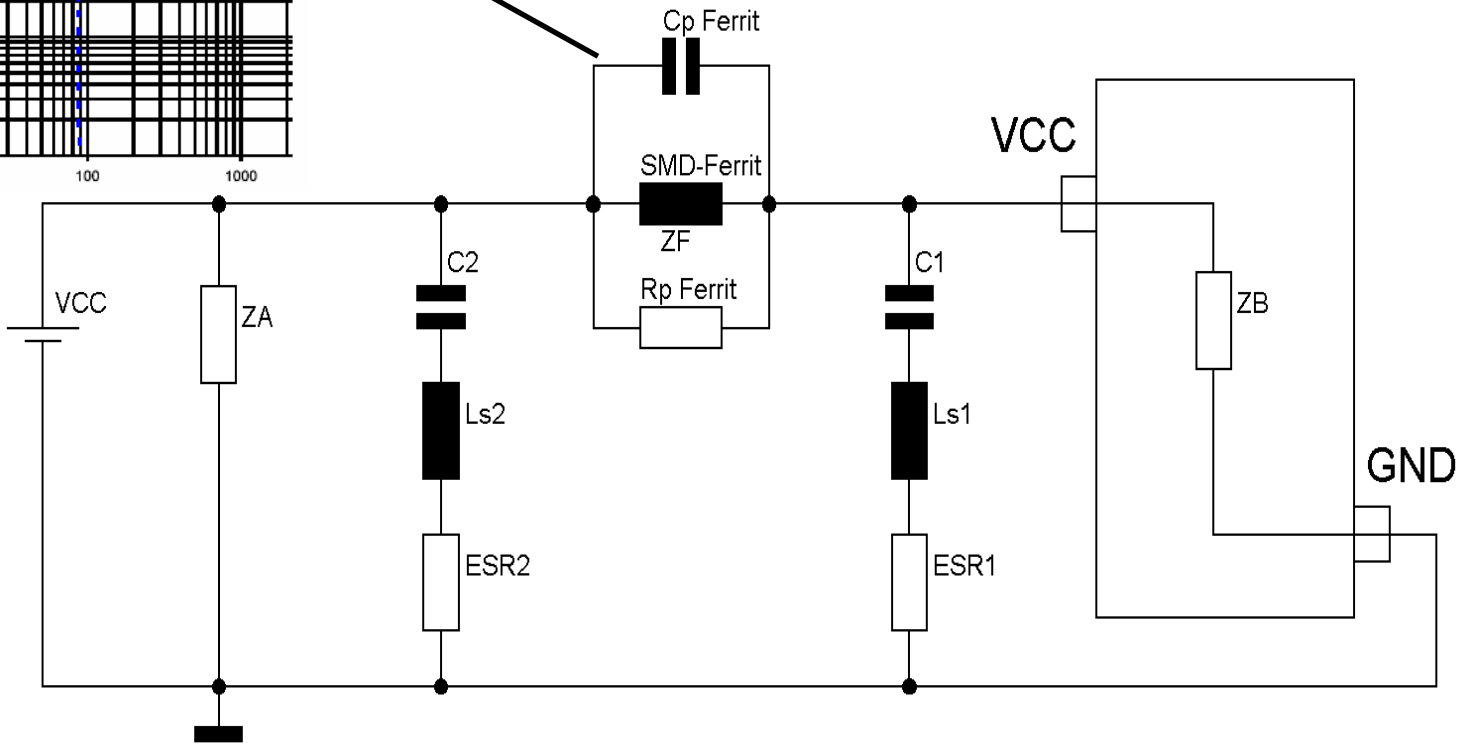
π-Filter: 1uF-742792093-1uF



Filter Circuit Simulation: VCC- π -Filter



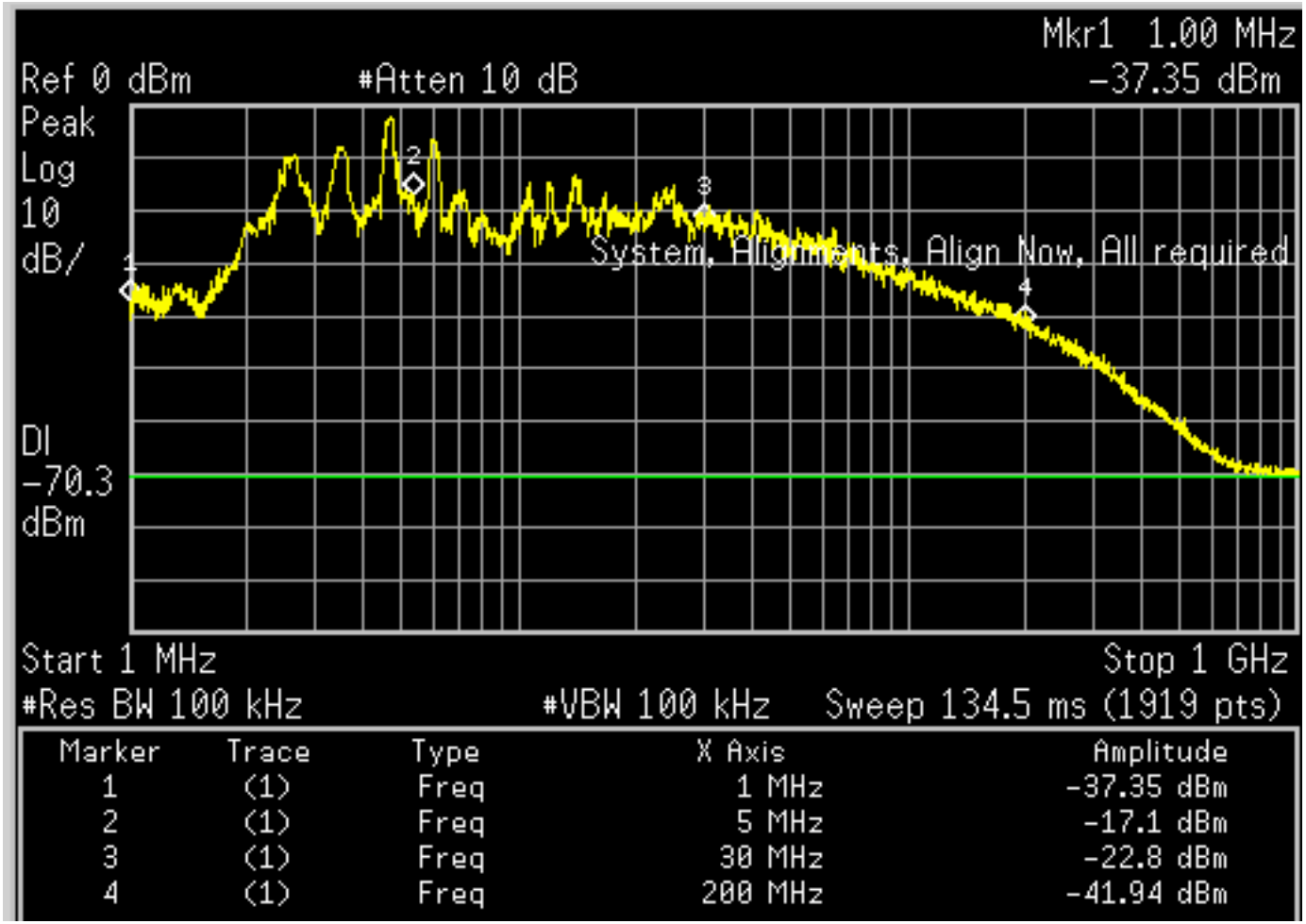
Impedance Characteristic Zmax@100MHz
742792093



SwCAD III.lnk

Noise-Spectrum on V_{CC}

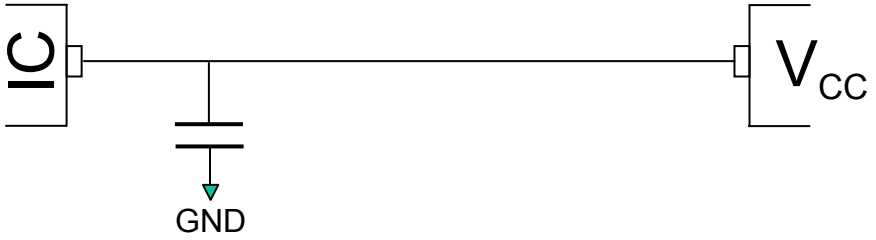
no filtering on Vcc
(condition: max. Hold)

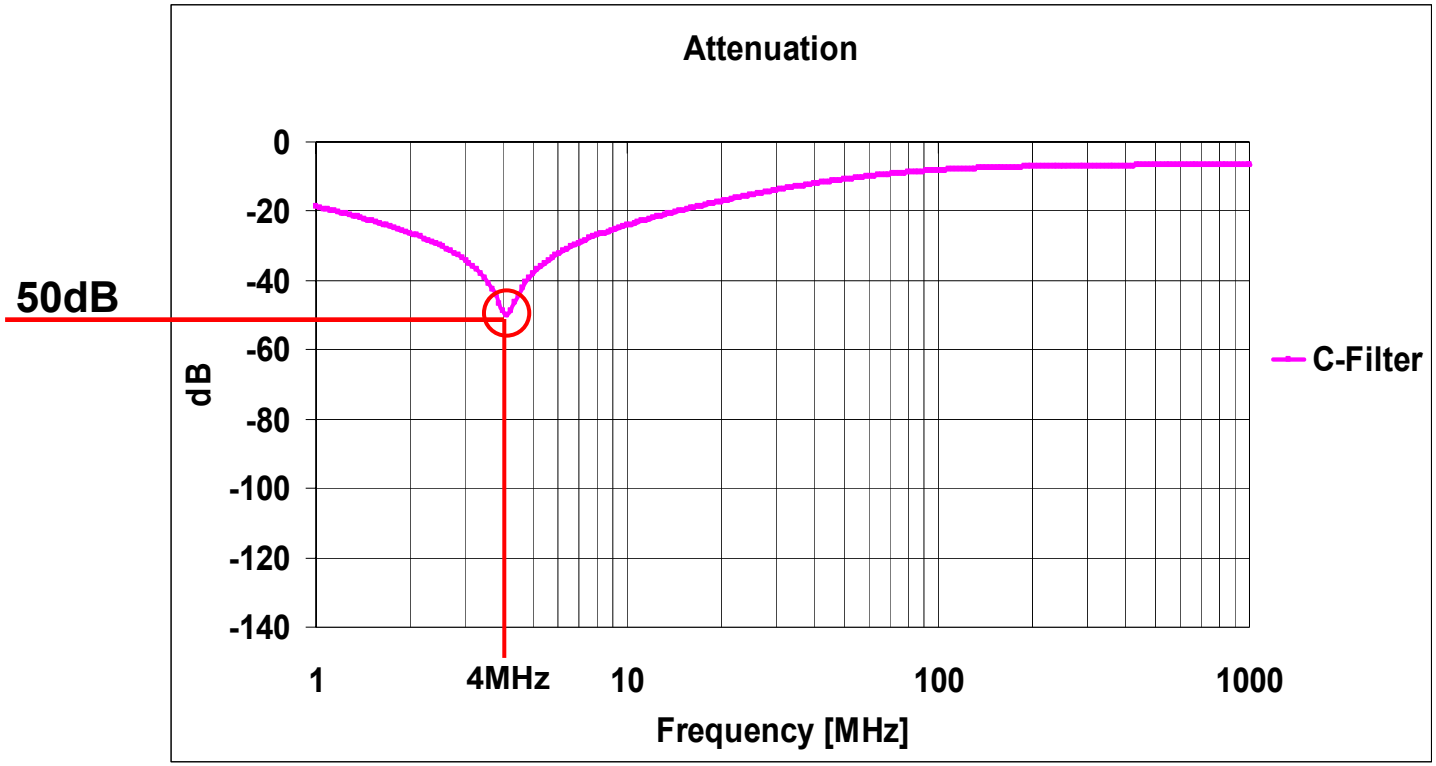


Simulation V_{CC} decoupling 1uF

Step 1:
1uF Cap.

C-Filter with 1uF

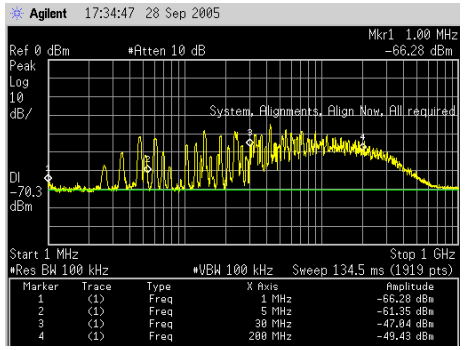


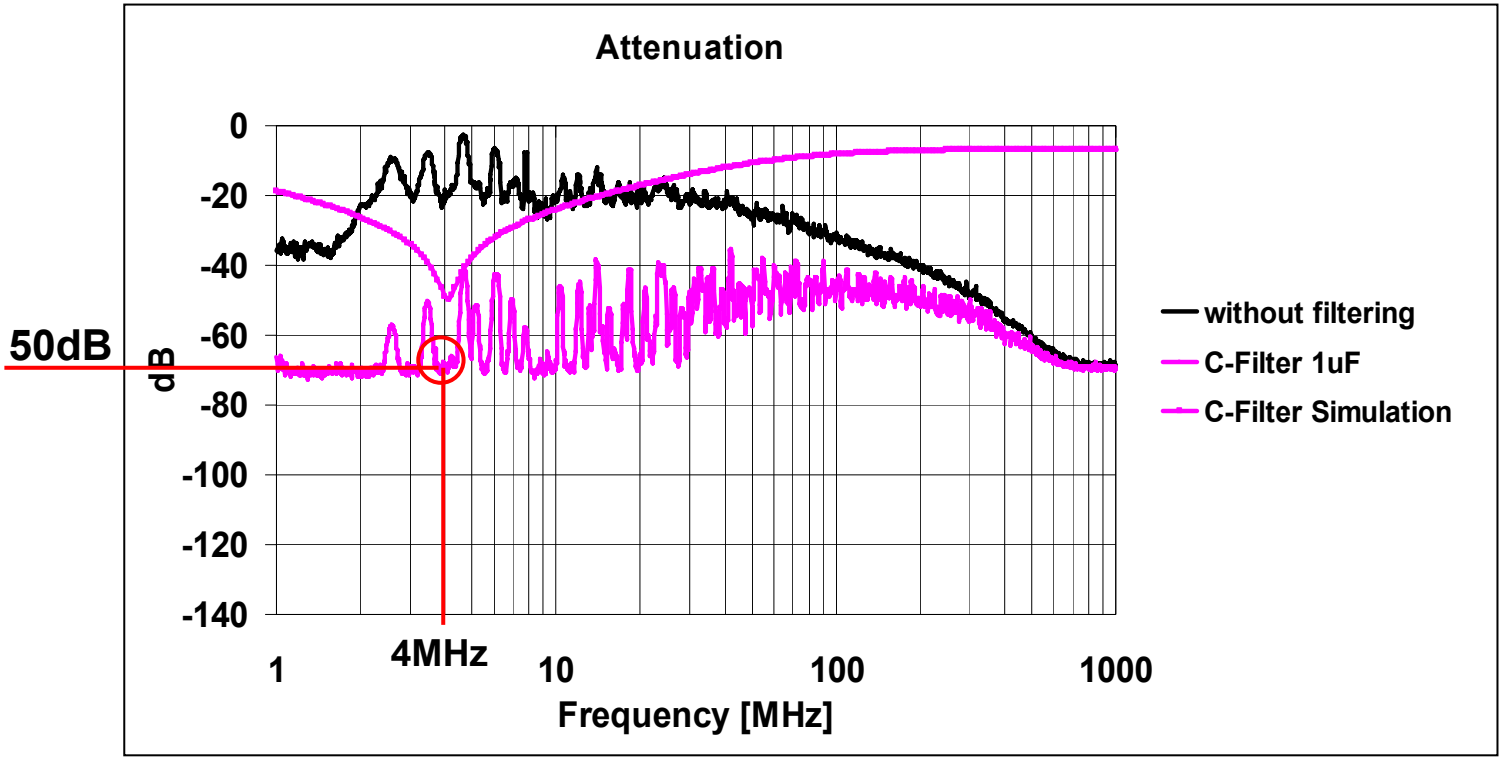


Simulation V_{CC} decoupling 1uF

Step 1:
1uF Cap.

C-Filter: 1uF

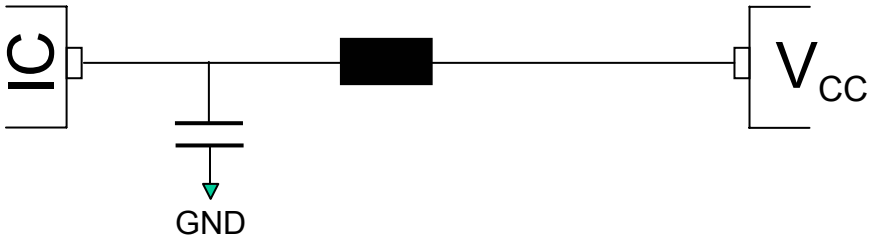


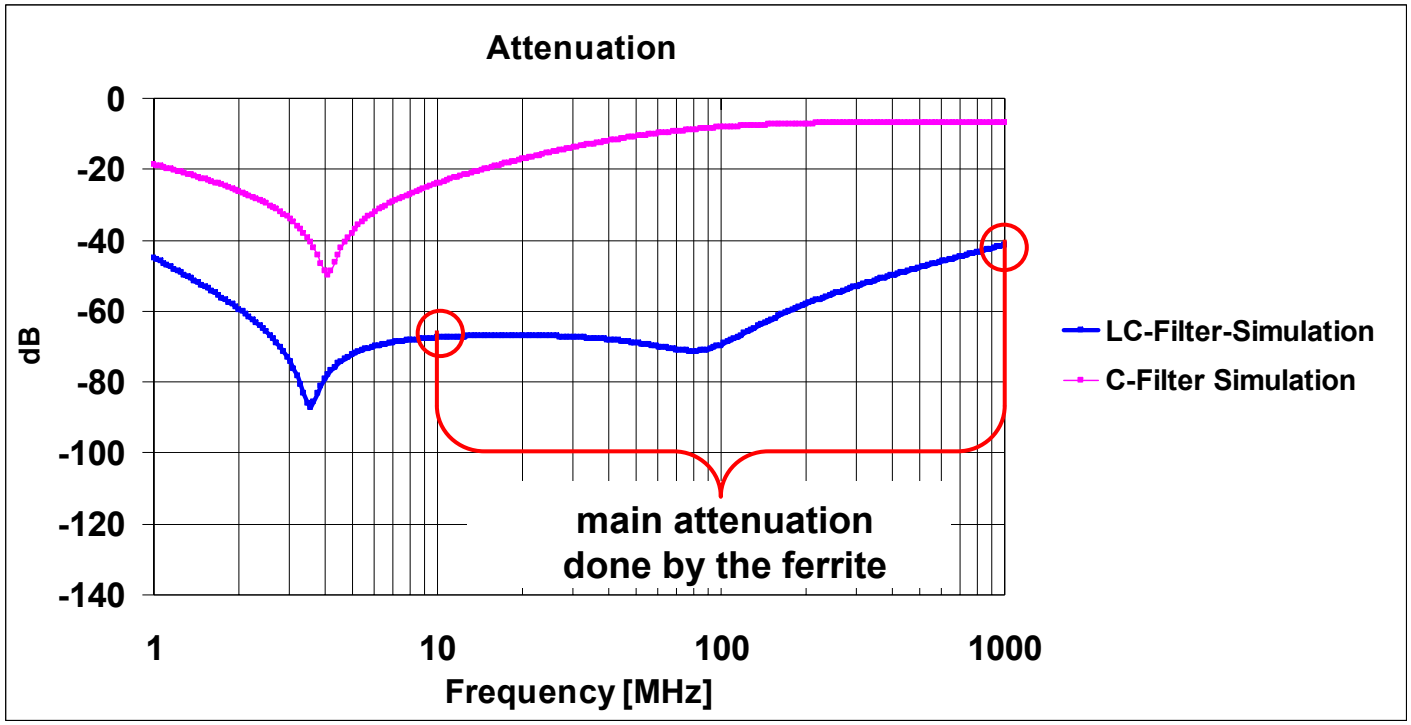


Simulation V_{CC} decoupling 1uF - Ferrite

Step 2:
1uF Cap.
& Ferrite

LC-Filter: 1uF-742792093

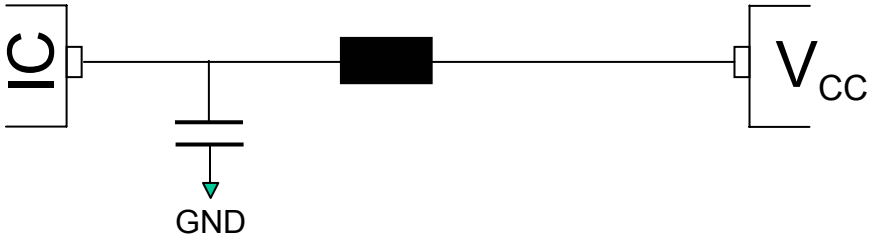


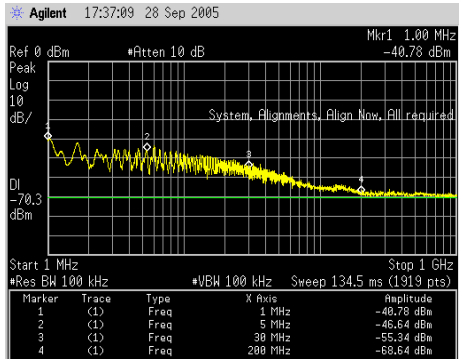


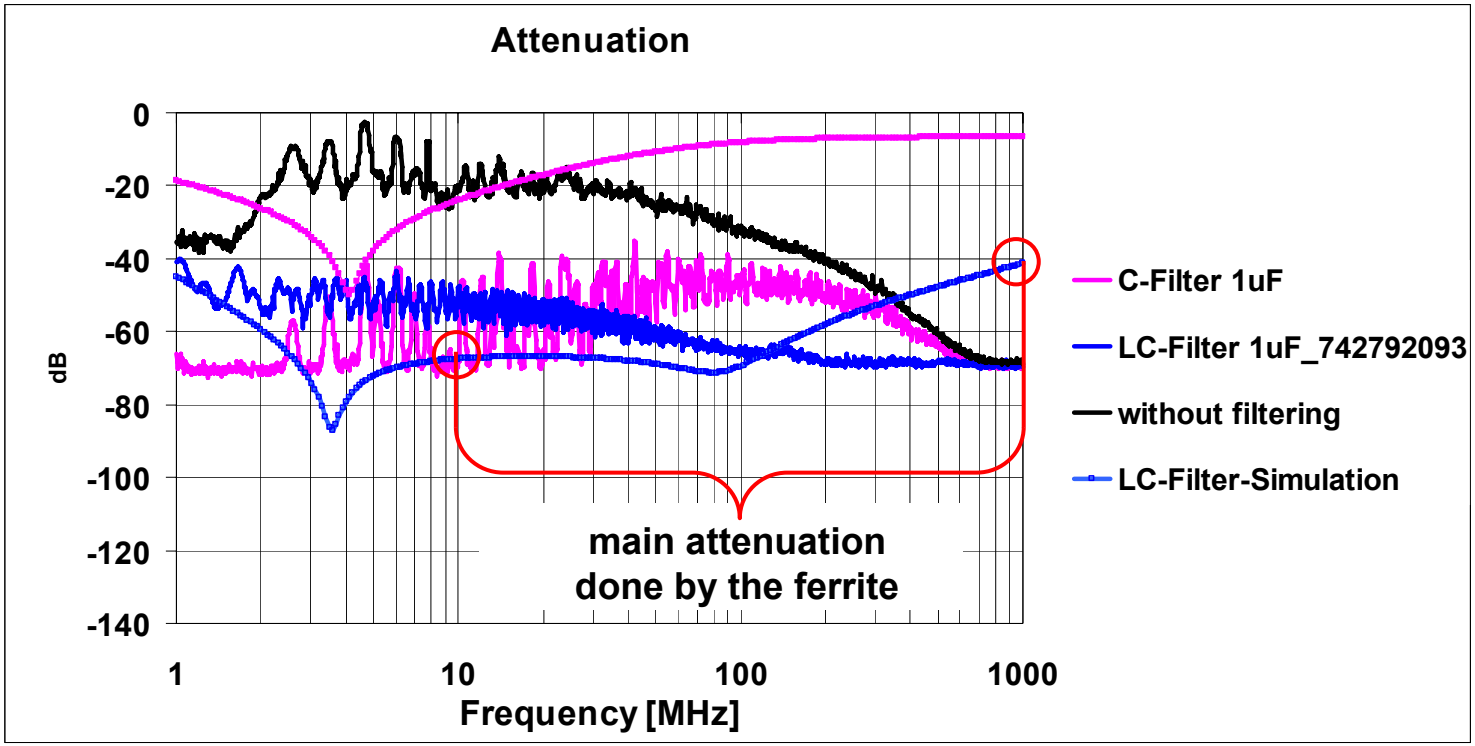
Simulation V_{CC} decoupling 1uF - Ferrite

Step 2:
1uF Cap.
& Ferrite

LC-Filter: 1uF-742792093



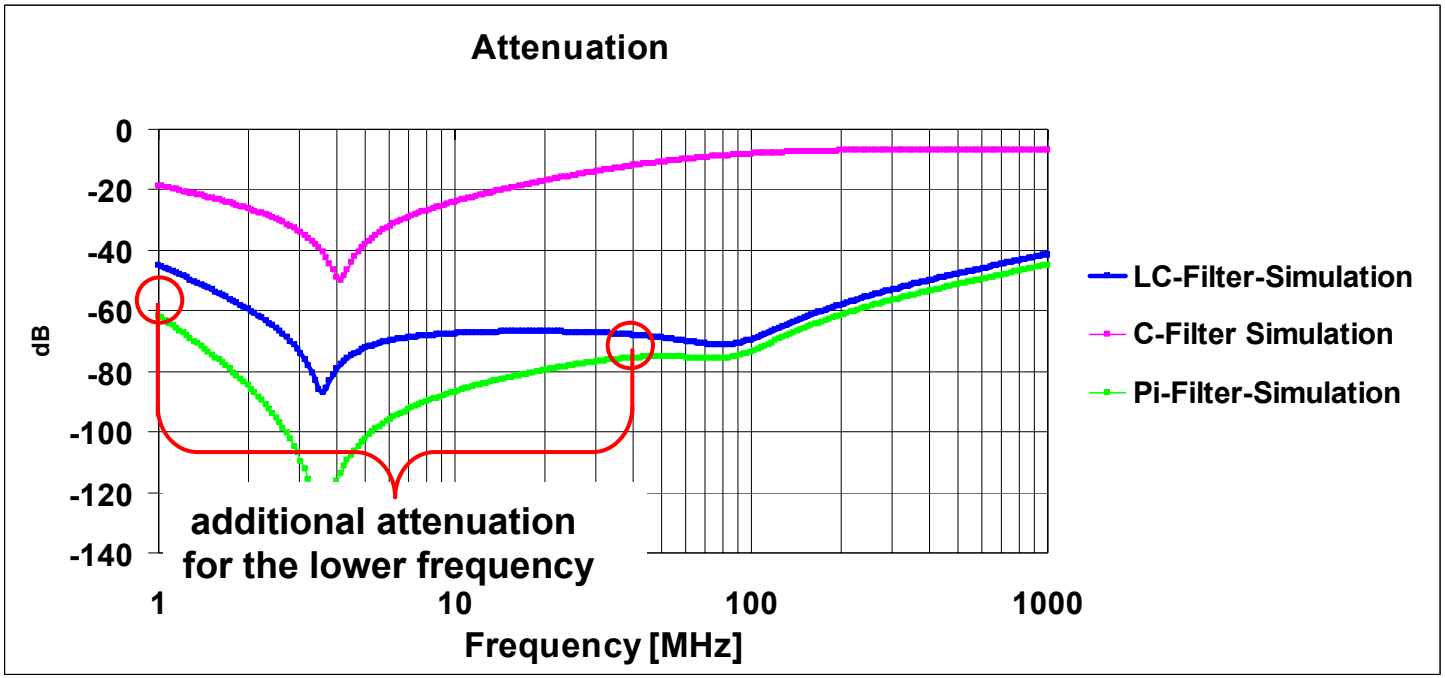




Simulation V_{CC} decoupling 1uF - Ferrite

Step 3:
1uF//1uF Cap.
& Ferrite

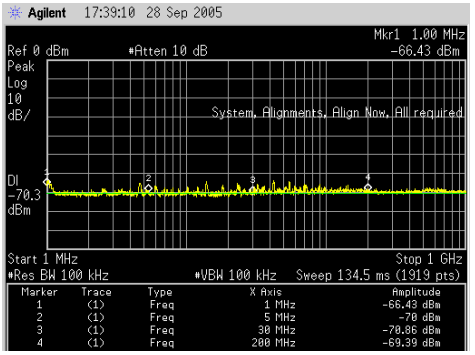
π-Filter: 1uF-742792093-1uF

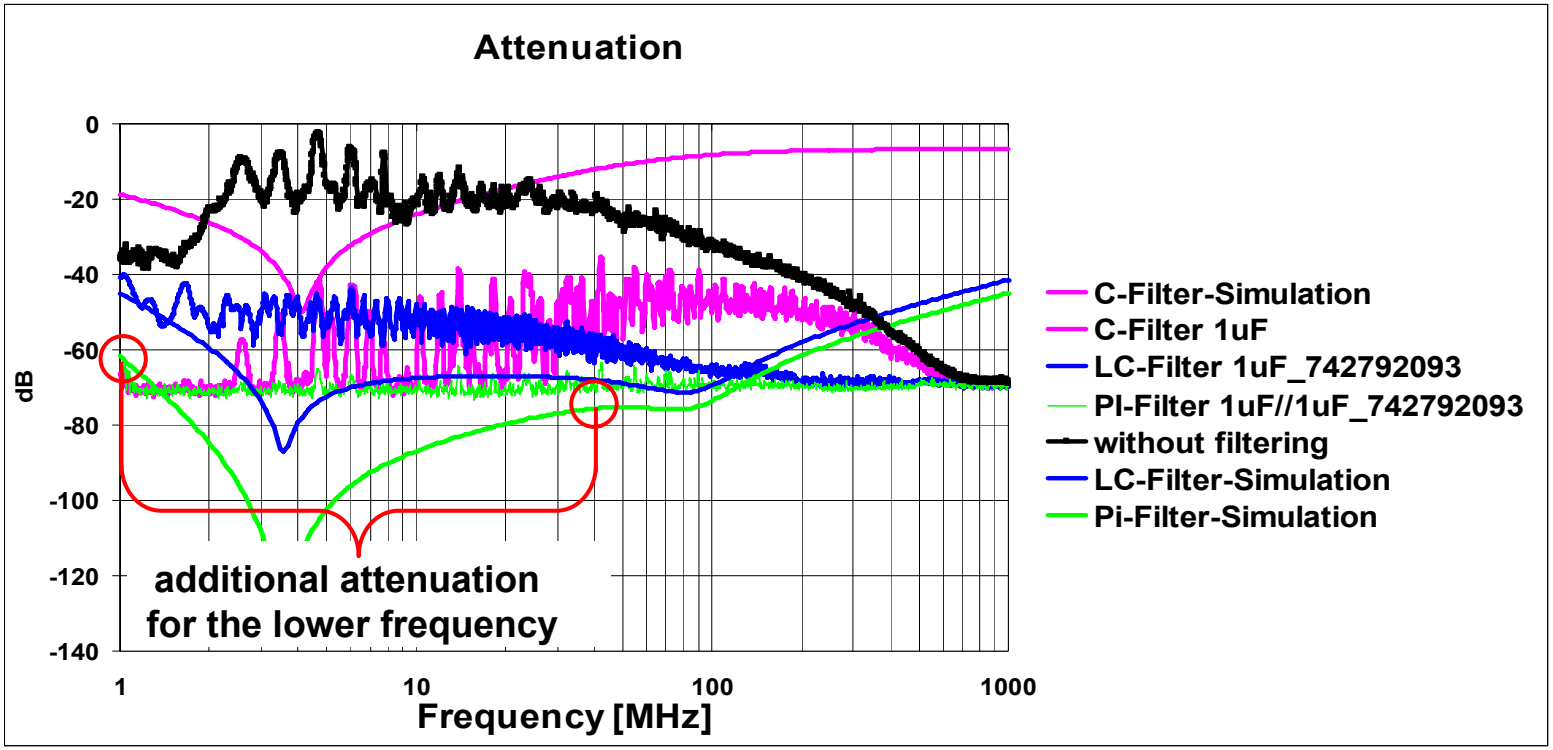


Simulation V_{CC} decoupling 1uF – Ferrite – 1uF

Step 3:
1uF//1uF Cap.
& Ferrite

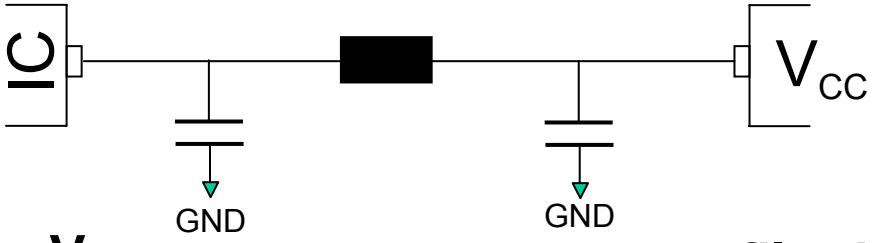
π-Filter: 1uF-742792093-1uF



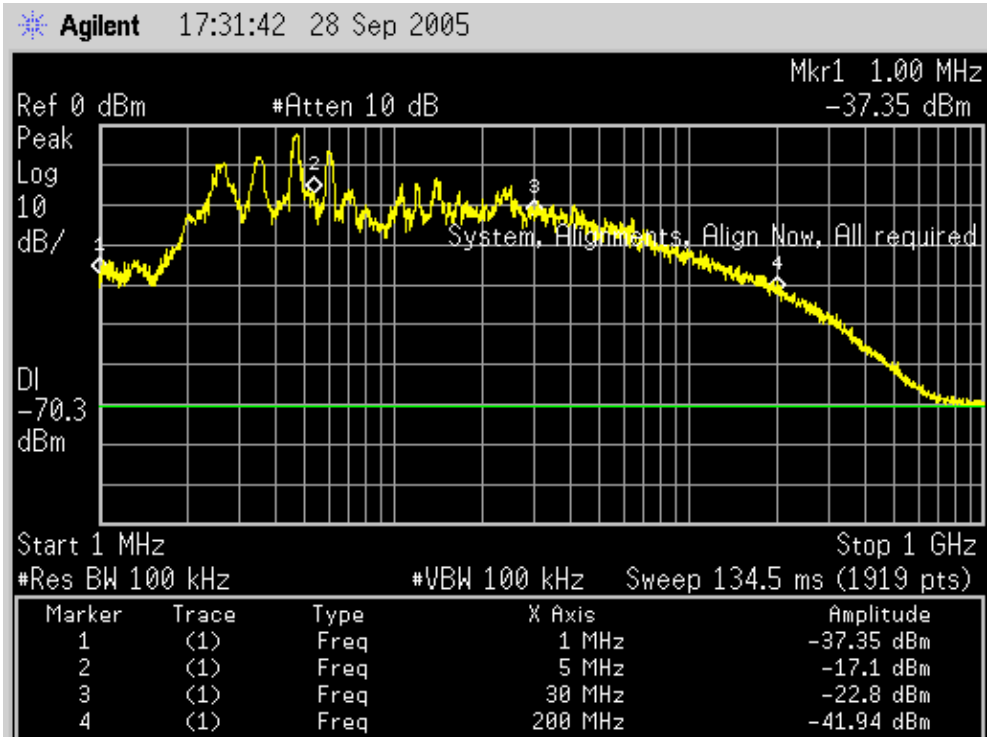


Final Result

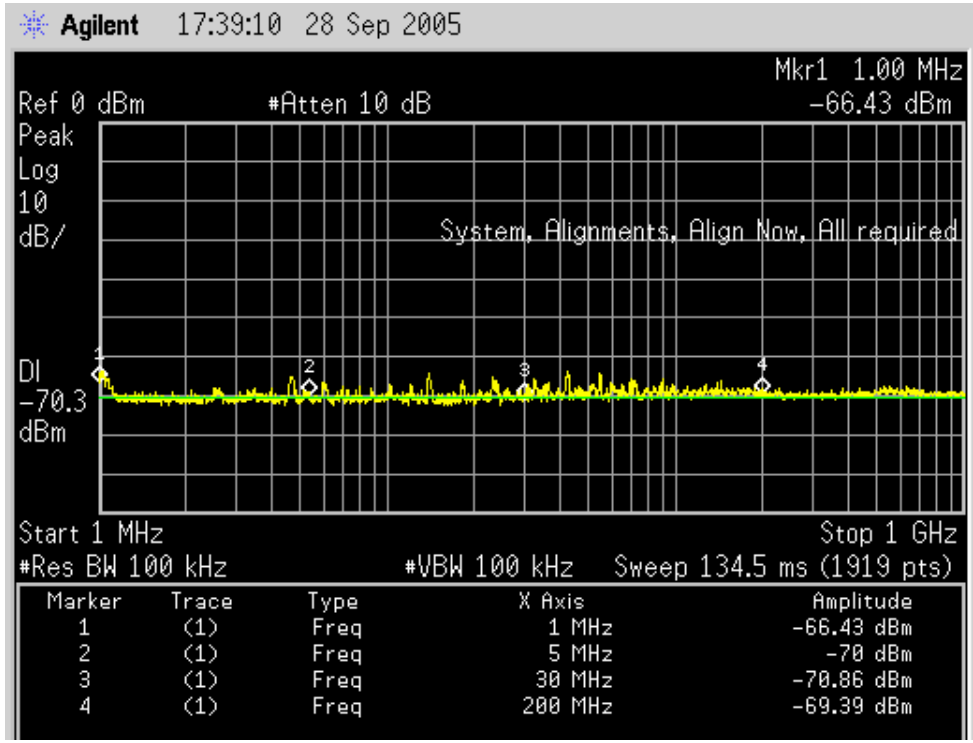
π-Filter: 1uF-742792093-1uF



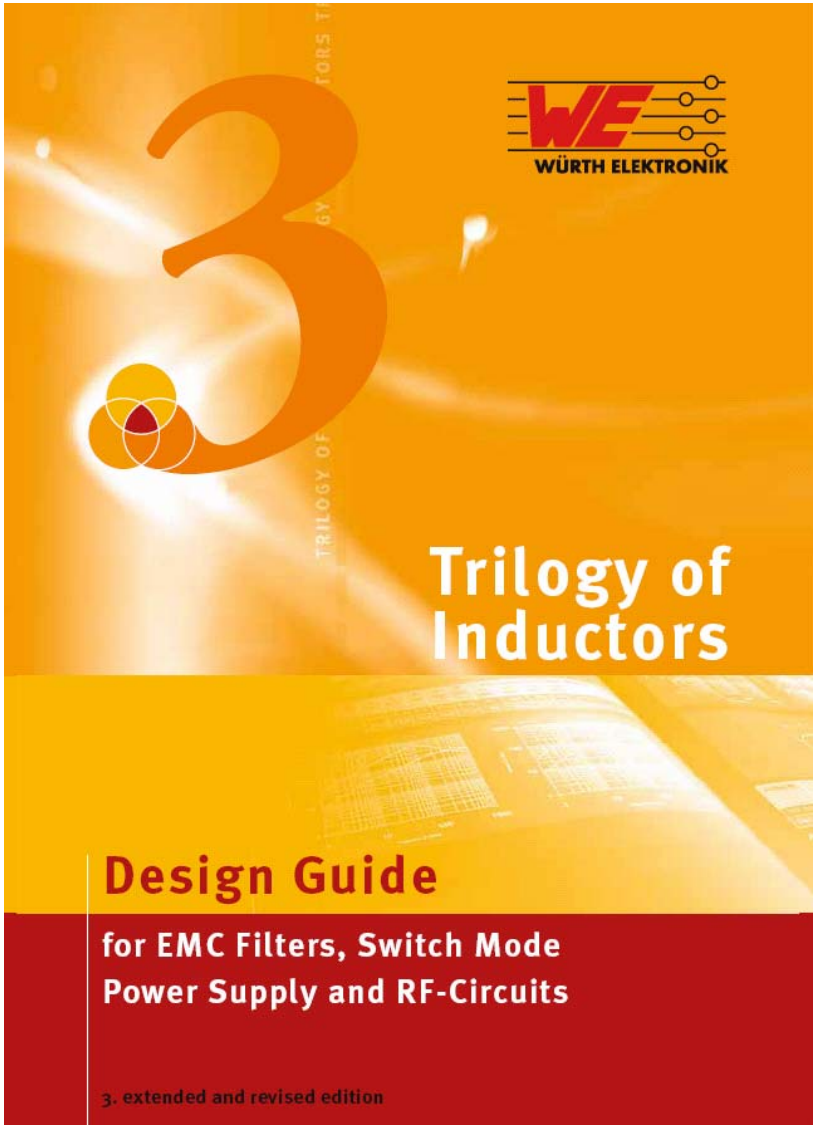
no filtering on Vcc



filtering on Vcc



You want to know more ??



Look at our Book:

Chap.1: Basics
keep it simple, stupid

Chap.2: Components
Descriptions, Applications, Simulation Models and many more

Chap.3: Filter-Circuits
Design, Grounding, Layout, Tipps

Chap.4: Applications
Circuit, suggested parts, Layout

Chap.5: Appendices
from A to Z

Online:

WÜRTH ELEKTRONIK