EMC Insights and Solutions:

DC/DC Converter EMC Troubleshooting

Livonia, MI EMC Lab

April 2022

Presenter Intro: Mark Malik

- Senior FAE supporting automotive OEM and Tier 1 customers in the Midwest region, based out of Livonia MPS office
- 20 years of experience in semiconductor field support, automotive/military hardware design and automotive OEM system level design
- Recently supporting OEM, Tier 1/2 customers with analog hardware design: power supplies, SERDES, motor control, LED control
- Passion for electronics and solving problems (that sometimes do not exist)
- Outside of work: married with children, snowboarding, electronics and other DIY activities

Agenda

- Approach to EMC Failure Troubleshooting
- Tools for EMC Troubleshooting
- Basics on Making Electrons Behave
- Examples with MPS Evaluation Boards
- Inductor Impact on EMC

Structured Troubleshooting:

- **Which EMC test is failed by DUT? (Radiated/Conducted Emission)**

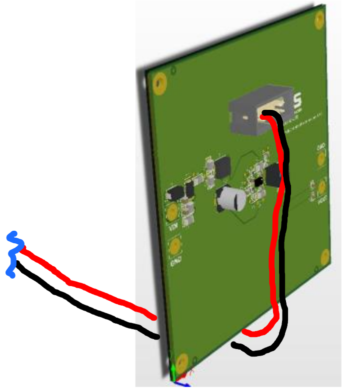
- **Or Immunity?**
- **What does the test set-up look like?**

- **Housing: metal or plastic?**
- **Are cables connected to the system?**
- **At which frequency does the DUT exceed the limits?**

- **Is it possible to identify the source clock(s)?**
- **Where are the DC/DC converters placed in the system?**

Structured Troubleshooting:

- **Are filter elements placed at each cable?**
- **What is the distance from DC/DC to the cable/connector?**
- **Identify and mark all high dV/dt and dI/dt circuit nodes!**
- **Check the routing of those circuit nodes for potential coupling!**
- **Use snap-on ferrites on cables, try to distinguish CM and DM noise!**
- **Place shielding over DC/DC converter block**



Tool Set for Troubleshooting:

- **Copper Foil: Used to create a shielding around certain areas or devices, modify ground. Low cost and versatile.**

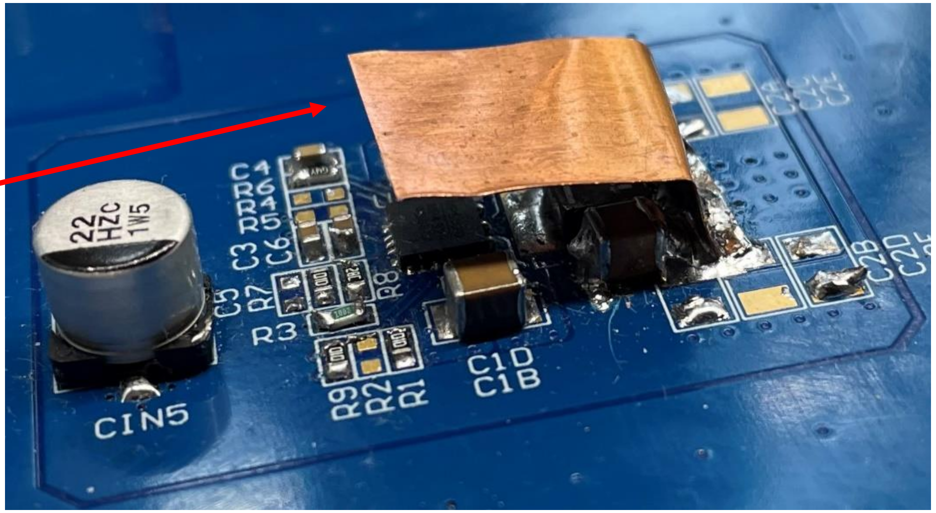
- **Snap-on Ferrites: Used to create impedance to high frequency signals travelling along a cable. Low cost, not as versatile.**

- **Field Probes: Used to identify areas of relatively high field strength on a circuit board. Note: identifying areas of high field strength may does not guarantee finding the source of the EMC problems, but those areas are much more likely to be causing problems than not. Medium cost and versatile.**

- **Current Probes: Can be used in conjunction with spectrum analyzer to look at differential and common mode currents. Can be useful to distinguish between common/differential modes. High cost, not as versatile.**

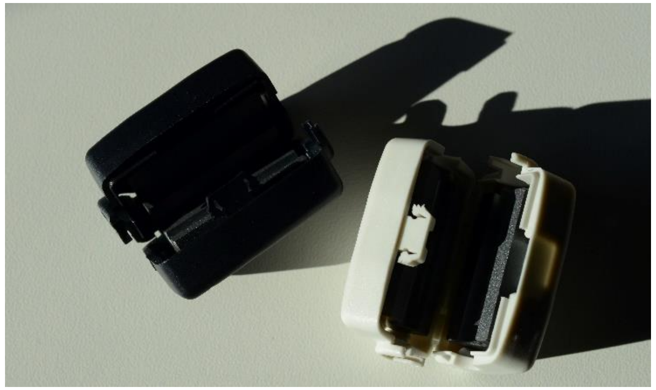
Use Cu-Foil

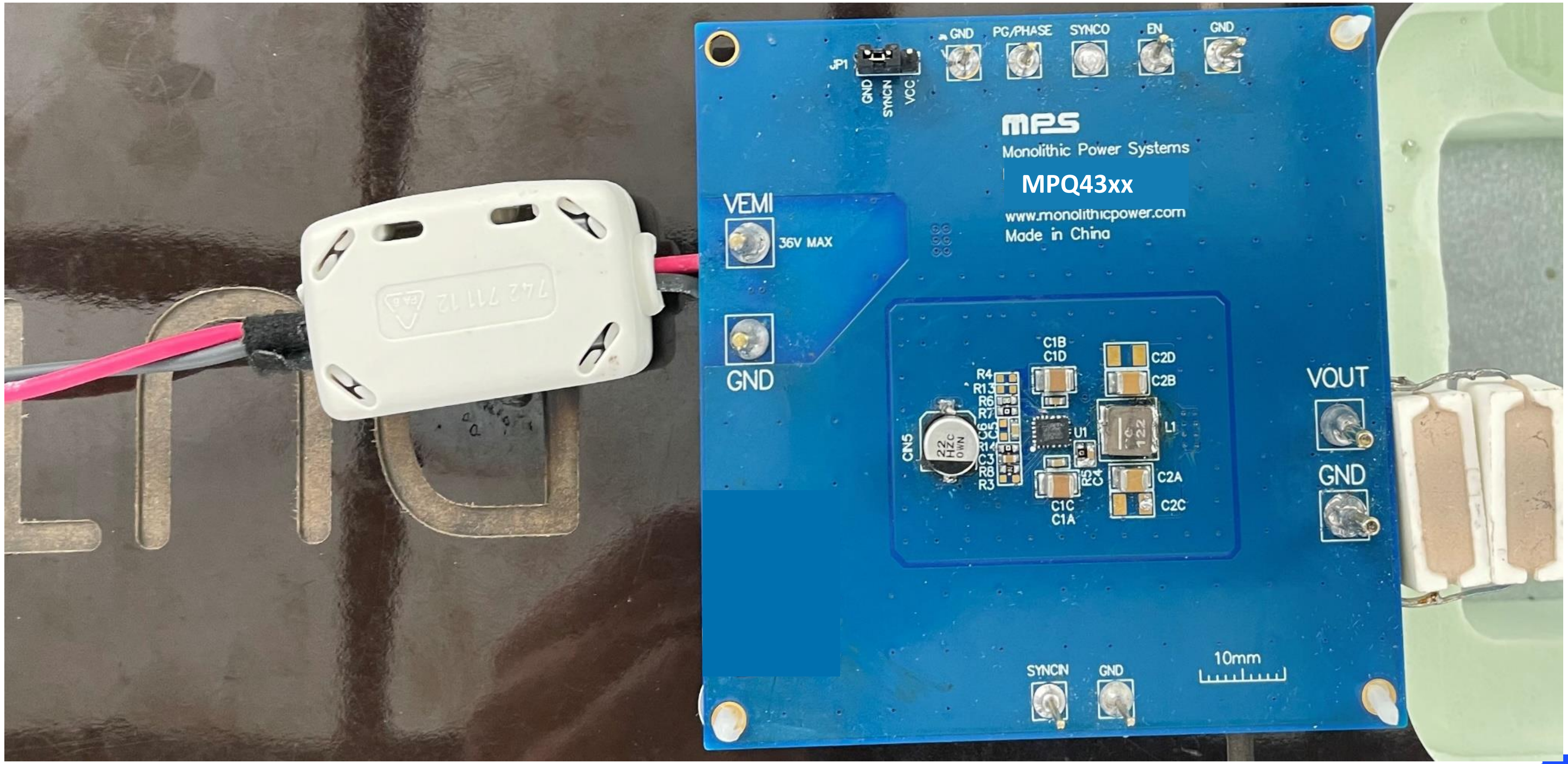
Start with DC/DC and Coil..



.... to part of the PCB

Use Snap-on Ferrite





Field Probes

H and E Field probes

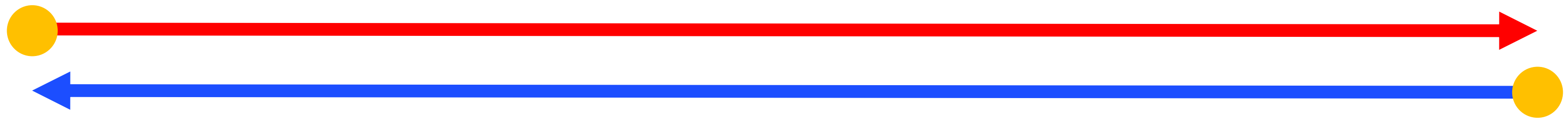
They can be used with Scope, Spectrum Analyzer or EMC Receiver

Basics on EMC

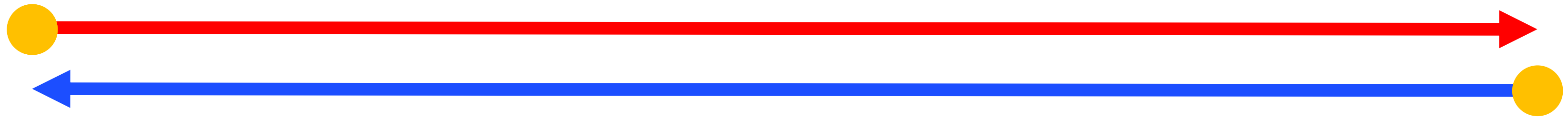
- **A moving charge generates an electromagnetic field – remember the Right Hand Rule**
- **Charges moving in opposite directions create opposing fields which cancel**
- **An electromagnetic field applied to a conductor causes free, charged particles to move**
- **Rise and fall times affect frequency content and amplitude – 5ns versus 10ns can be ~100 times different at 100MHz**
- **Drift Velocity of electrons in 18AWG wire with 1A current is approximately 74** $\frac{\mu m}{s}$
- **Emissions: 20dBµV → 200nA into 50Ω, Immunity: 0.2V ← 200nA into 1MΩ**
- **If every charge that leaves a source gets back to the source using the smallest possible path/loop, it will be a boring day in the ALSE chamber**

Basics on EMC

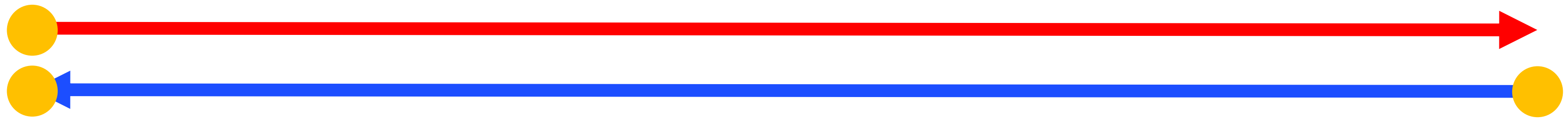
Case #1 – For every charge moving to the right there is a charge moving to the left



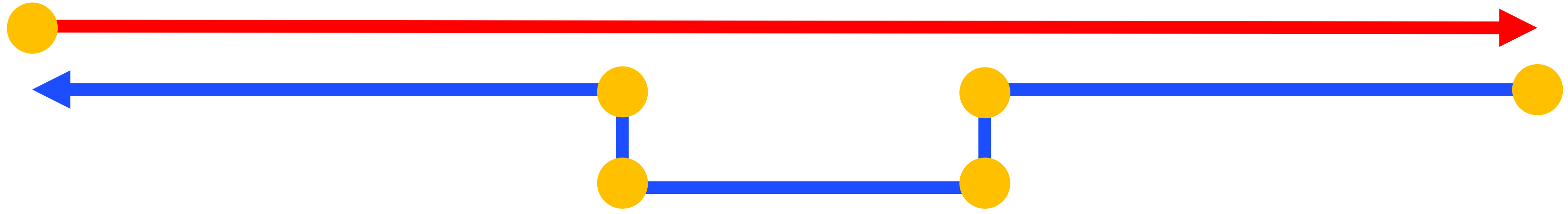
Case #2 – There is an unequal amount of charge moving in either direction



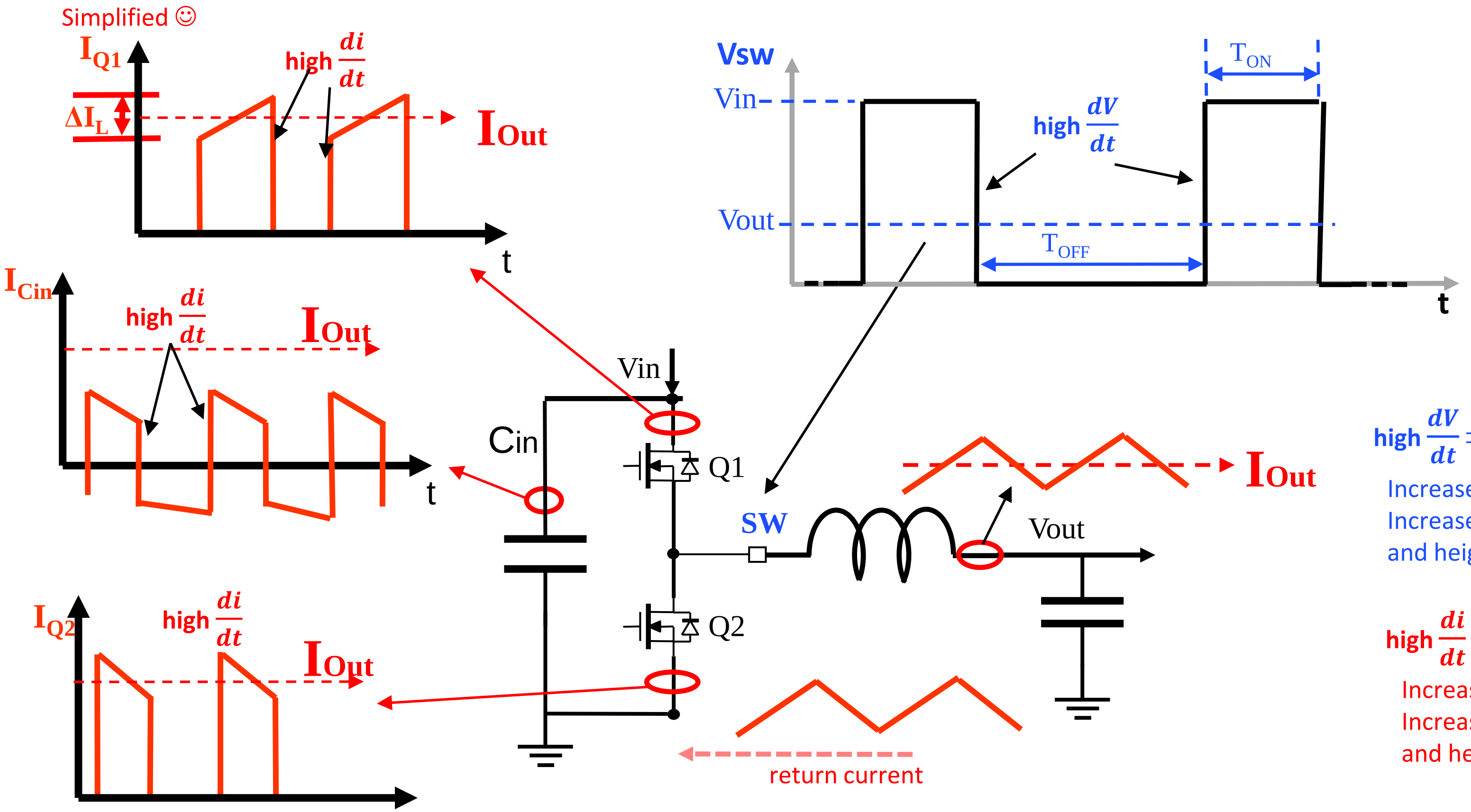
Case #3 – There are charges travelling in the same direction



Case #4 – There is equal charge flow in both directions, but the paths are different



Refresh: Buck Converter Voltage and Current Waveforms



high $\frac{dV}{dt} \Rightarrow E - Field$

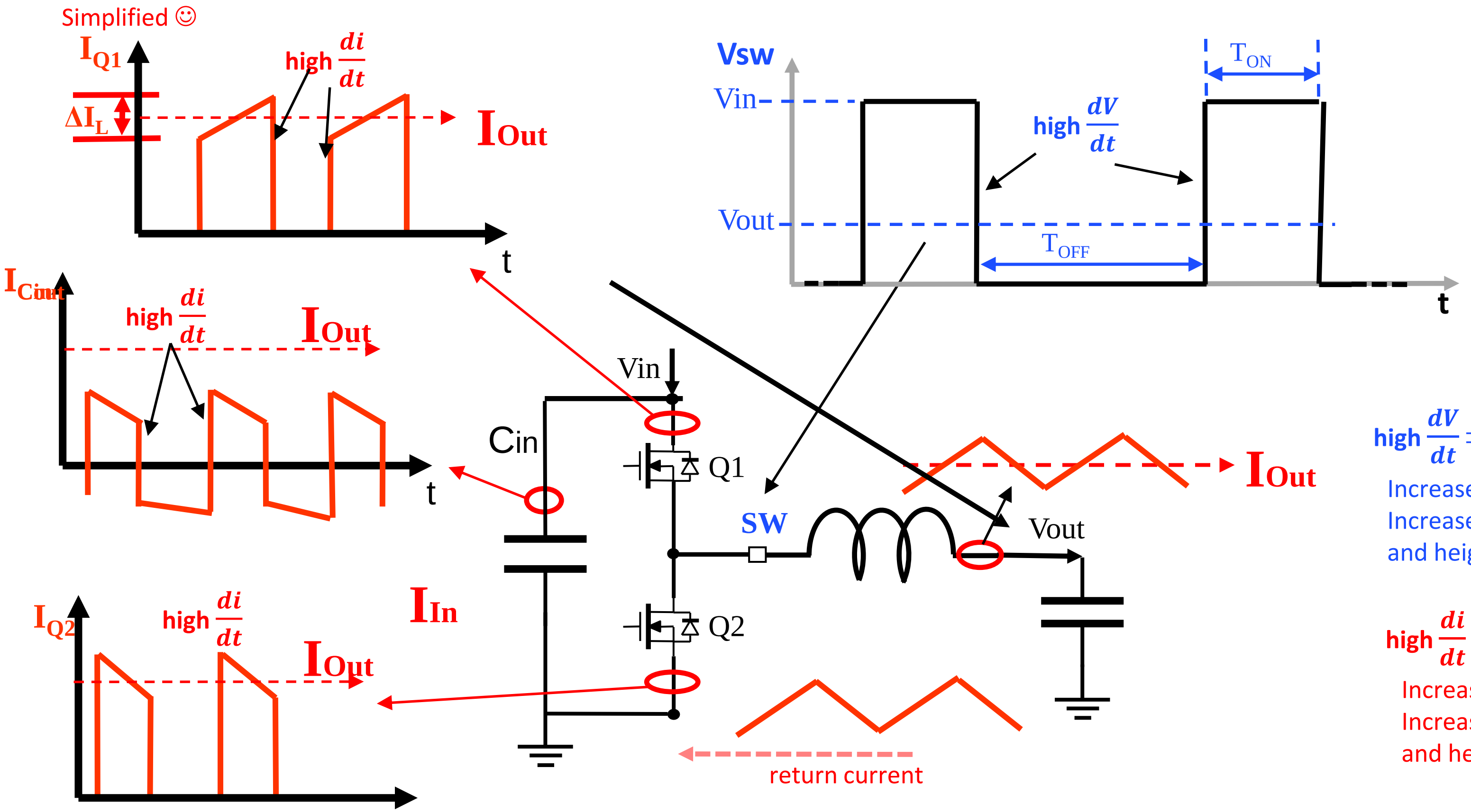
Increase with voltage
Increase with antenna size and height above PCB

high $\frac{di}{dt} \Rightarrow H - Field$

Increase with current
Increase with loop size and height above PCB

….and Boost Converter is just an mirror image.

Refresh: Boost Converter Voltage and Current Waveforms



high $\frac{dV}{dt} \Rightarrow E-Field$

Increase with voltage
Increase with antenna size and height above PCB

high $\frac{di}{dt} \Rightarrow H-Field$

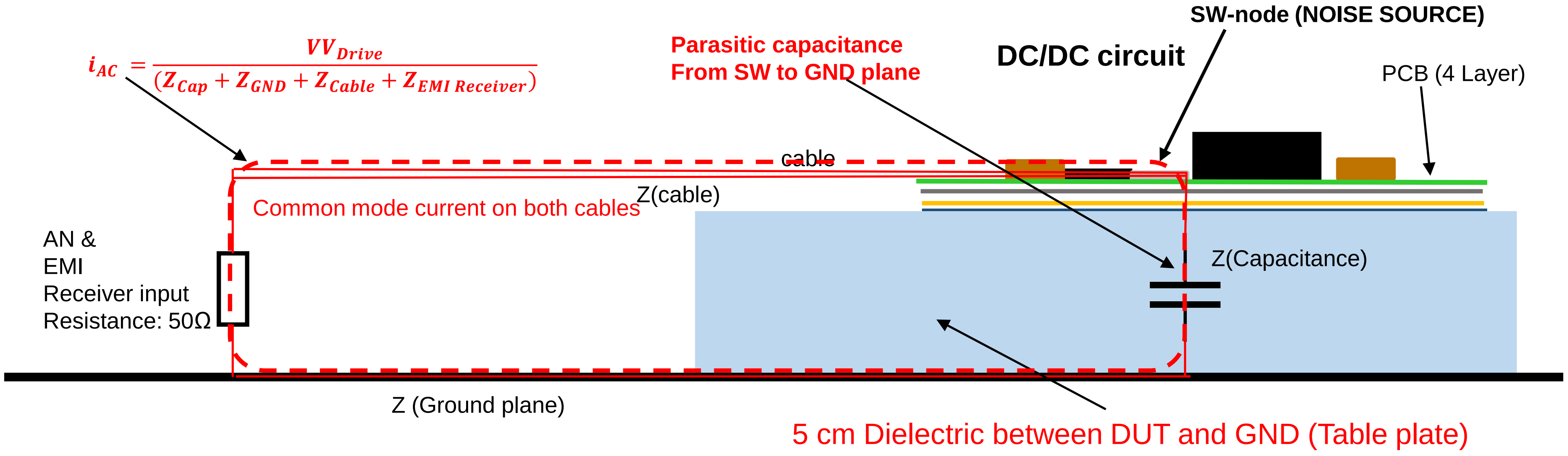
Increase with current
Increase with loop size and height above PCB

CE FM Band Common Mode Noise

Buck converter 13V input running at 2MHz
Drives ~260mV at 100MHz at SW

OEM AV Limit: 12dBµV which is 4µV at 50Ω input of EMI receiver
Current flowing in this AC loop at 100MHz has to be below 80nA

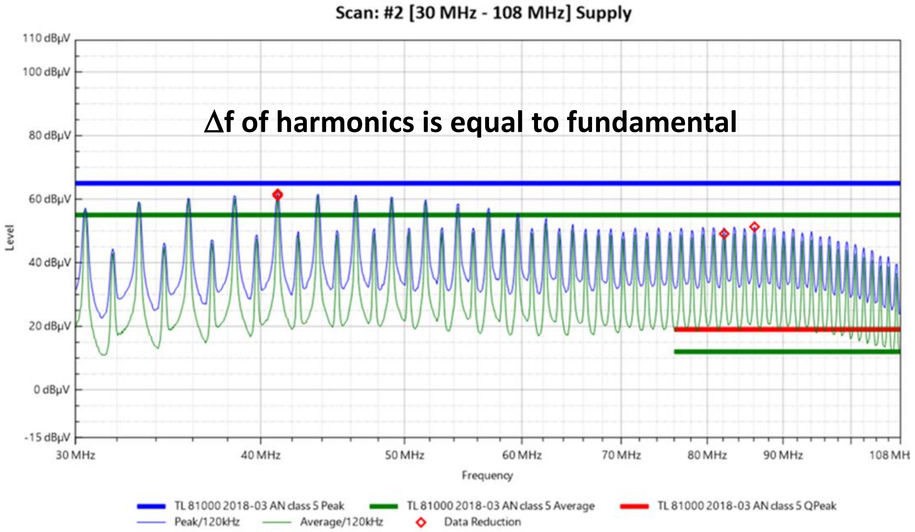
$$i_{AC} = \frac{VV_{Drive}}{(Z_{Cap} + Z_{GND} + Z_{Cable} + Z_{EMI\ Receiver})}$$



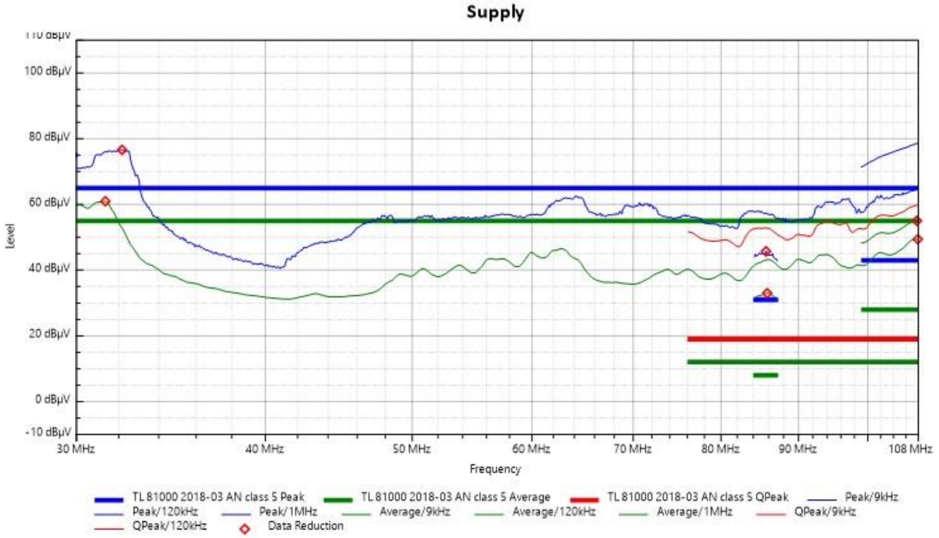
Identify the source:

Are discrete frequency lines above the limit or “mountains”?
Try to identify the source.

Sometimes the sources is obvious.



..and sometimes not …



Identify the source:

Which clocks are used in the system?
Measure exact frequencies of all clocks.
Create a table with the clocks, harmonics and mixing products.

	f1 [MHz]	f2 [MHz]	f2 - f1 [MHz]	f1+f2 [MHz]	f3 [MHz]	f3 + f1 [MHz]	f3 - f1 [MHz]
Fsw	0.489	1.93	1.441	2.419	20.03	20.519	19.541
2x	0.978	3.86	2.882	4.838	40.06	41.038	39.082
3x	1.467	5.79	4.323	7.257	60.09	61.557	58.623
4x	1.956	7.72	5.764	9.676	80.12	82.076	78.164
5x	2.445	9.65	7.205	12.095	100.15	102.595	97.705
6x	2.934	11.58	8.646	14.514	120.18	123.114	117.246
7x	3.423	13.51	10.087	16.933	140.21	143.633	136.787
8x	3.912	15.44	11.528	19.352	160.24	164.152	156.328
9x	4.401	17.37	12.969	21.771	180.27	184.671	175.869
10x	4.89	19.3	14.41	24.19	200.3	205.19	195.41
11x	5.379	21.23	15.851	26.609	220.33	225.709	214.951
12x	5.868	23.16	17.292	29.028	240.36	246.228	234.492
13x	6.357	25.09	18.733	31.447	260.39	266.747	254.033

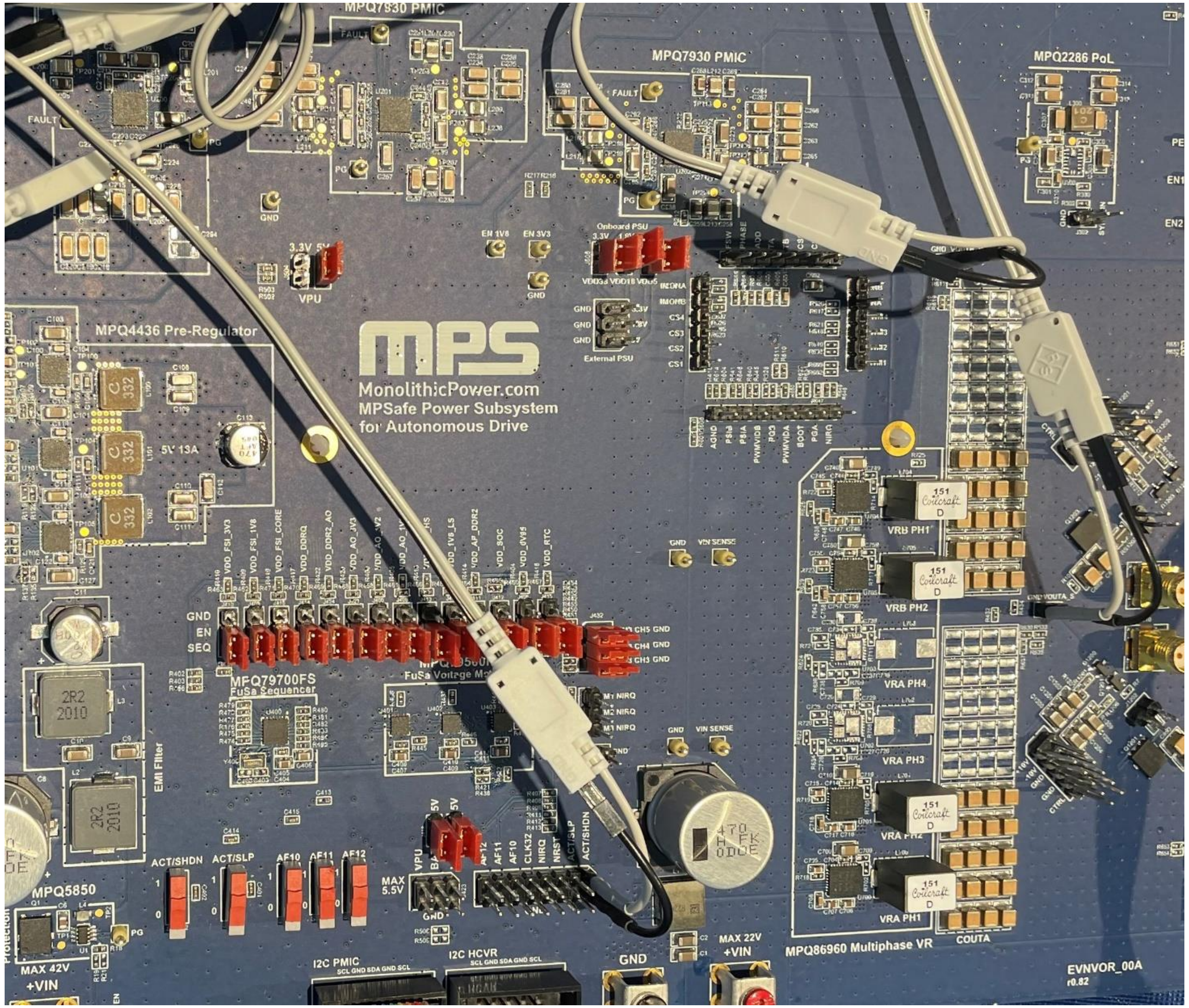
Try to find the path:

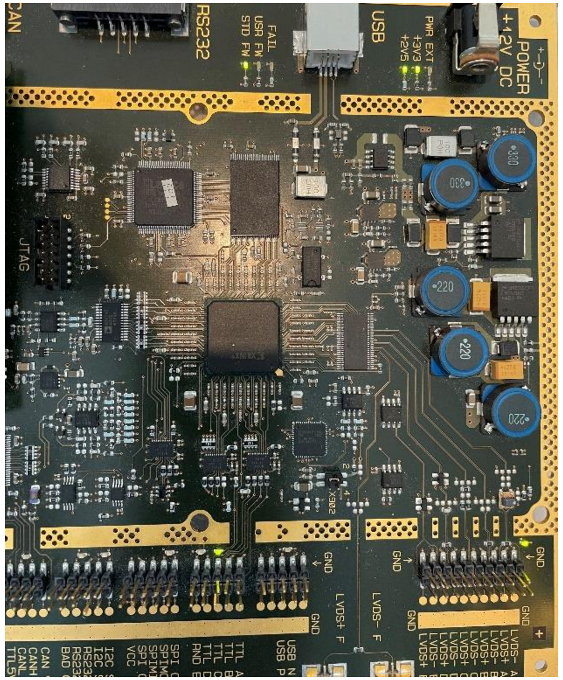
- **Increase Input Filter capacitors by 2x**
- **Increase Input Filter Coil by 2x**

- **What is the distance between Buck C_{IN} and Filter?**

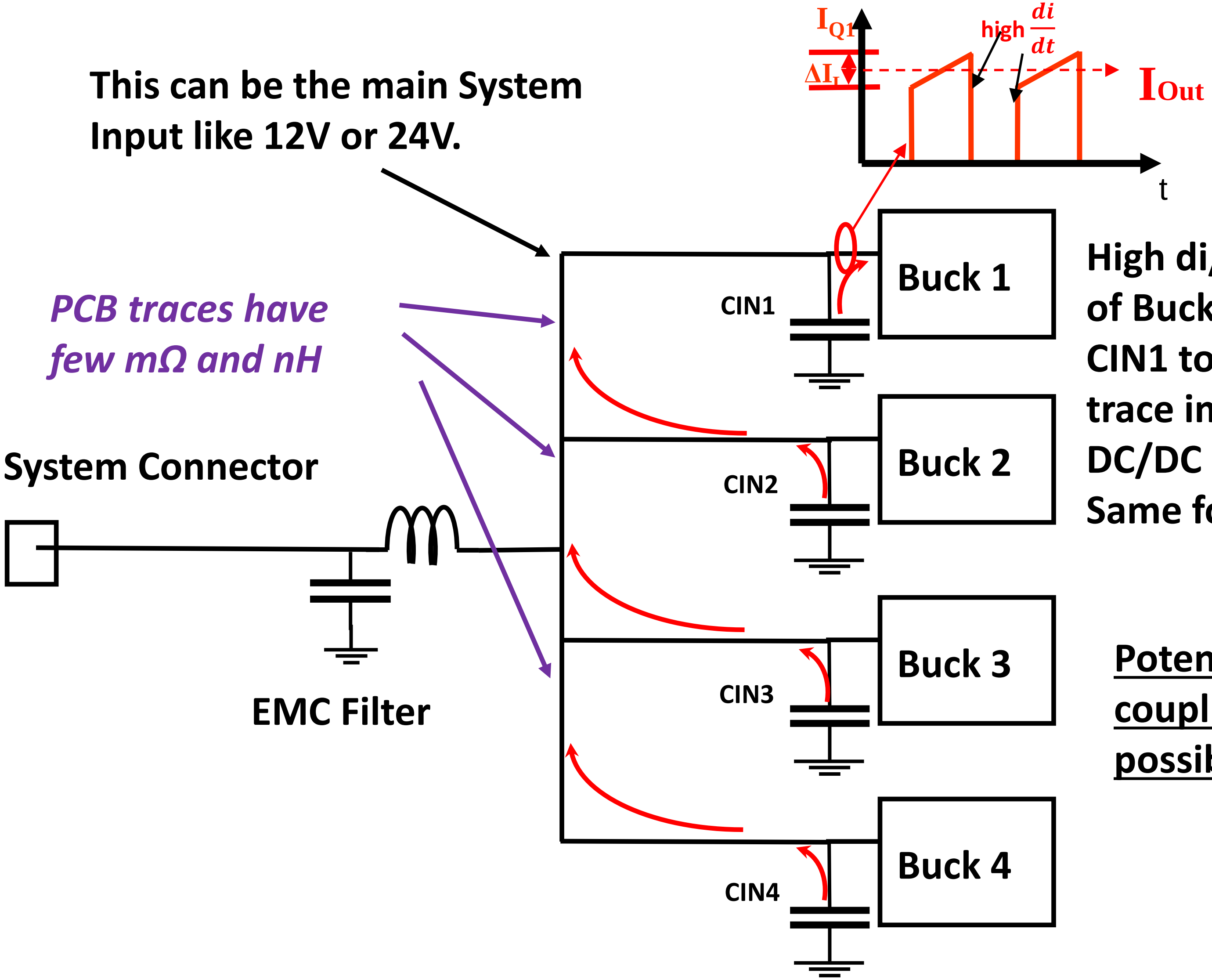
- **Is an OFF Board Filter effective?**

Large boards with many DC/DC power supplies:





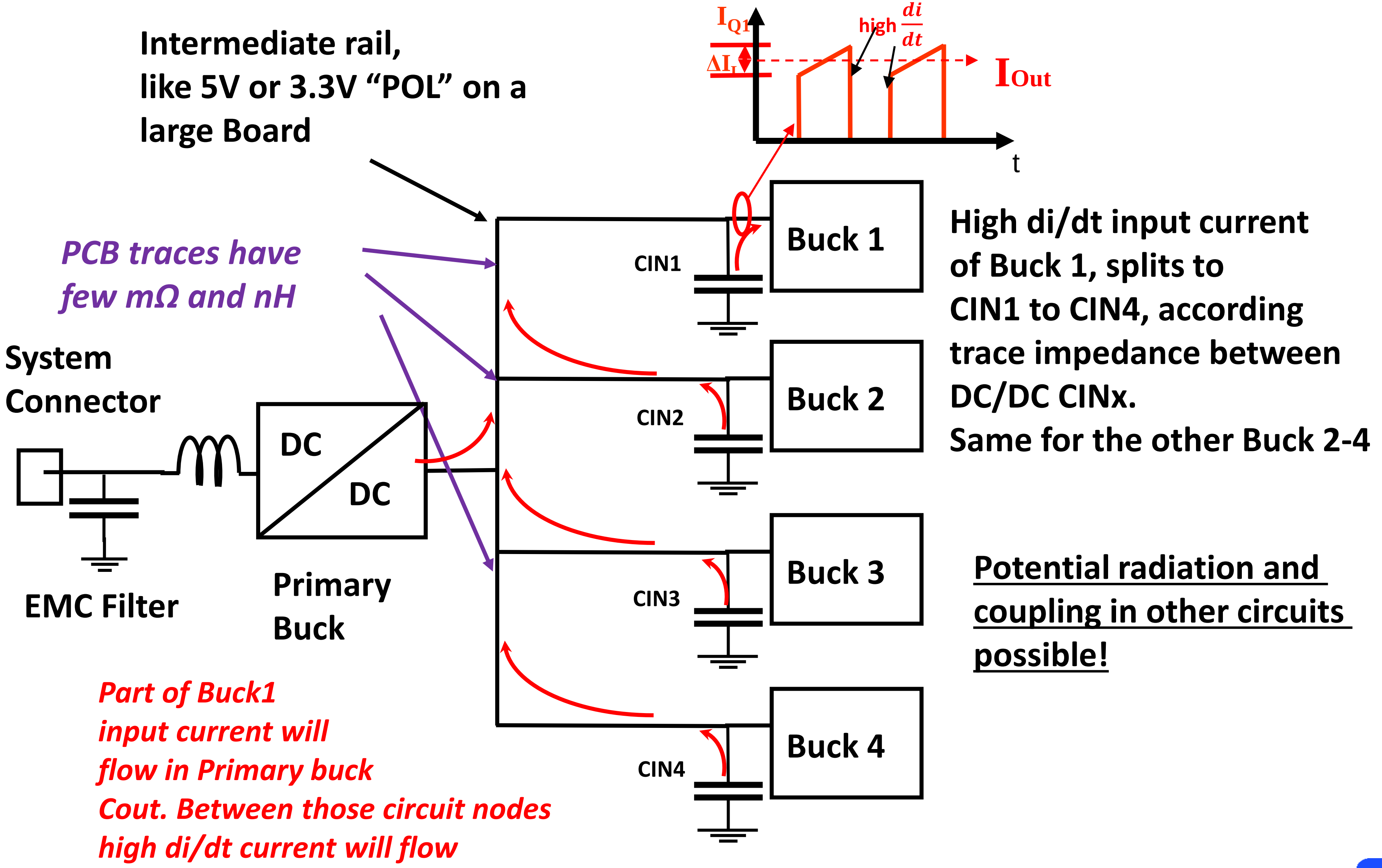
Several DC/DC Buck at one large Power Rail



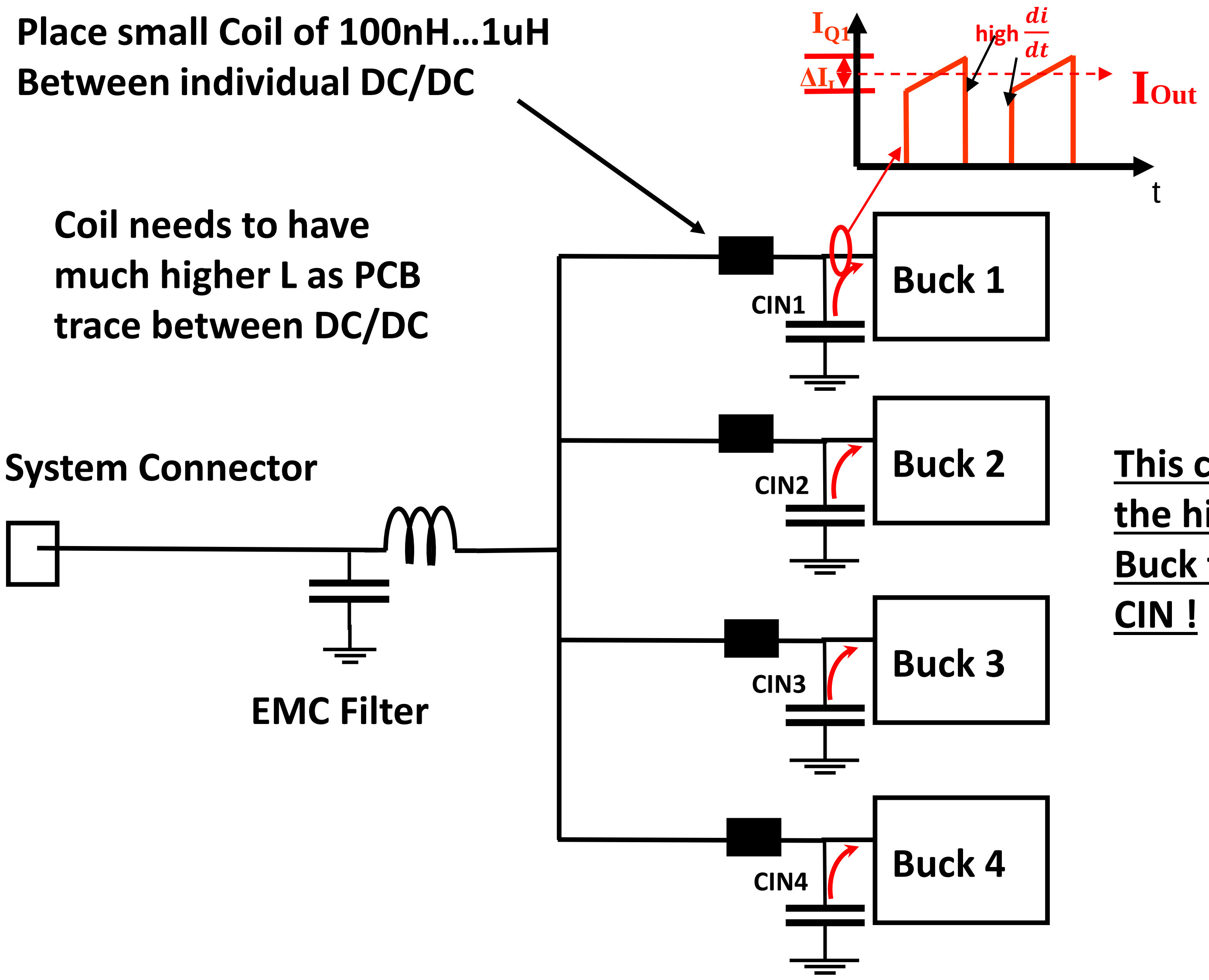
High di/dt input current of Buck 1, splits to CIN1 to CIN4, according trace impedance between DC/DC CINx.
Same for the other Buck 2-4

<u>Potential radiation and coupling in other circuits possible!</u>

Several DC/DC Buck at one large Power Rail

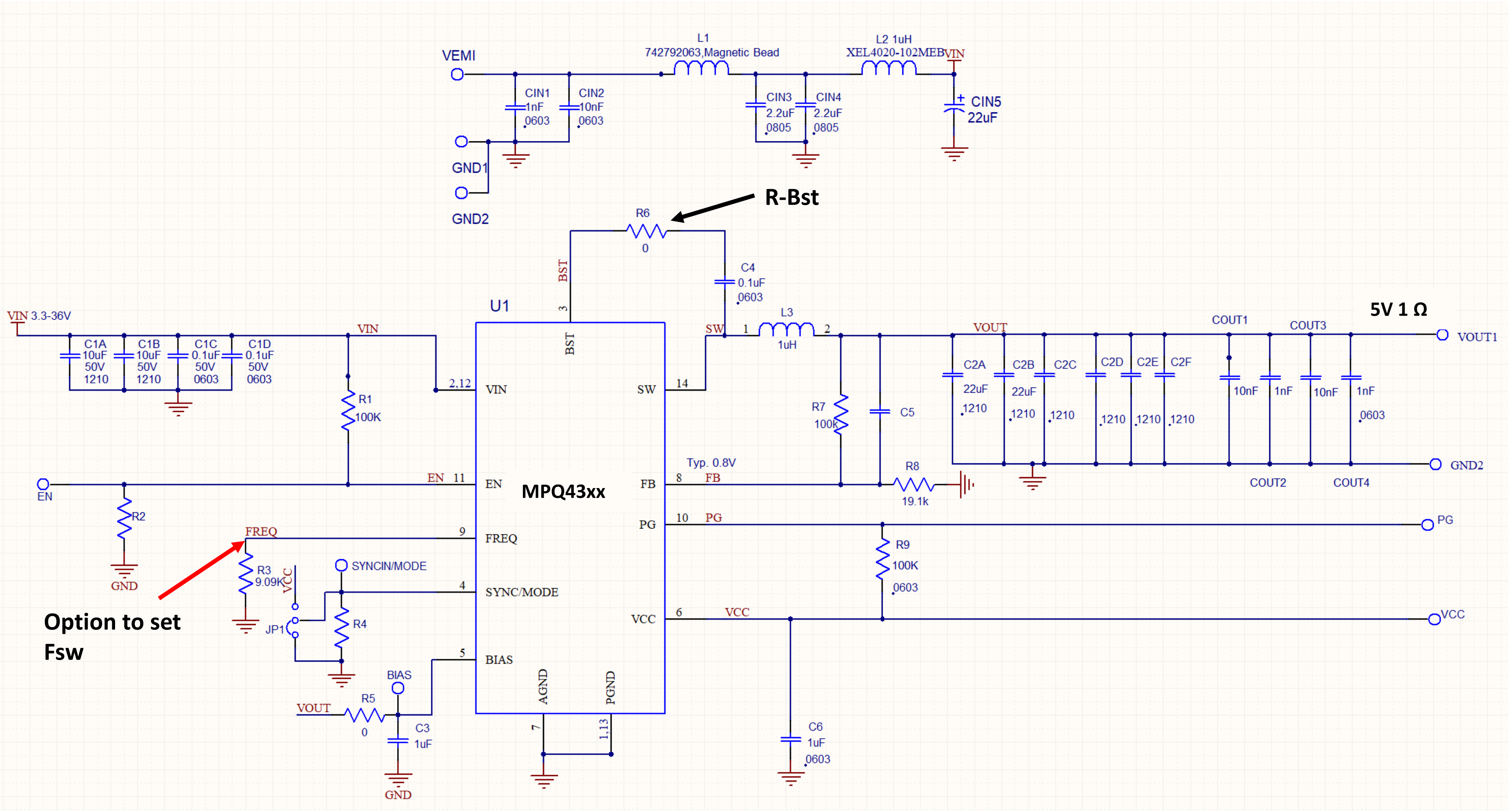


Several DC/DC Buck at one large Power Rail

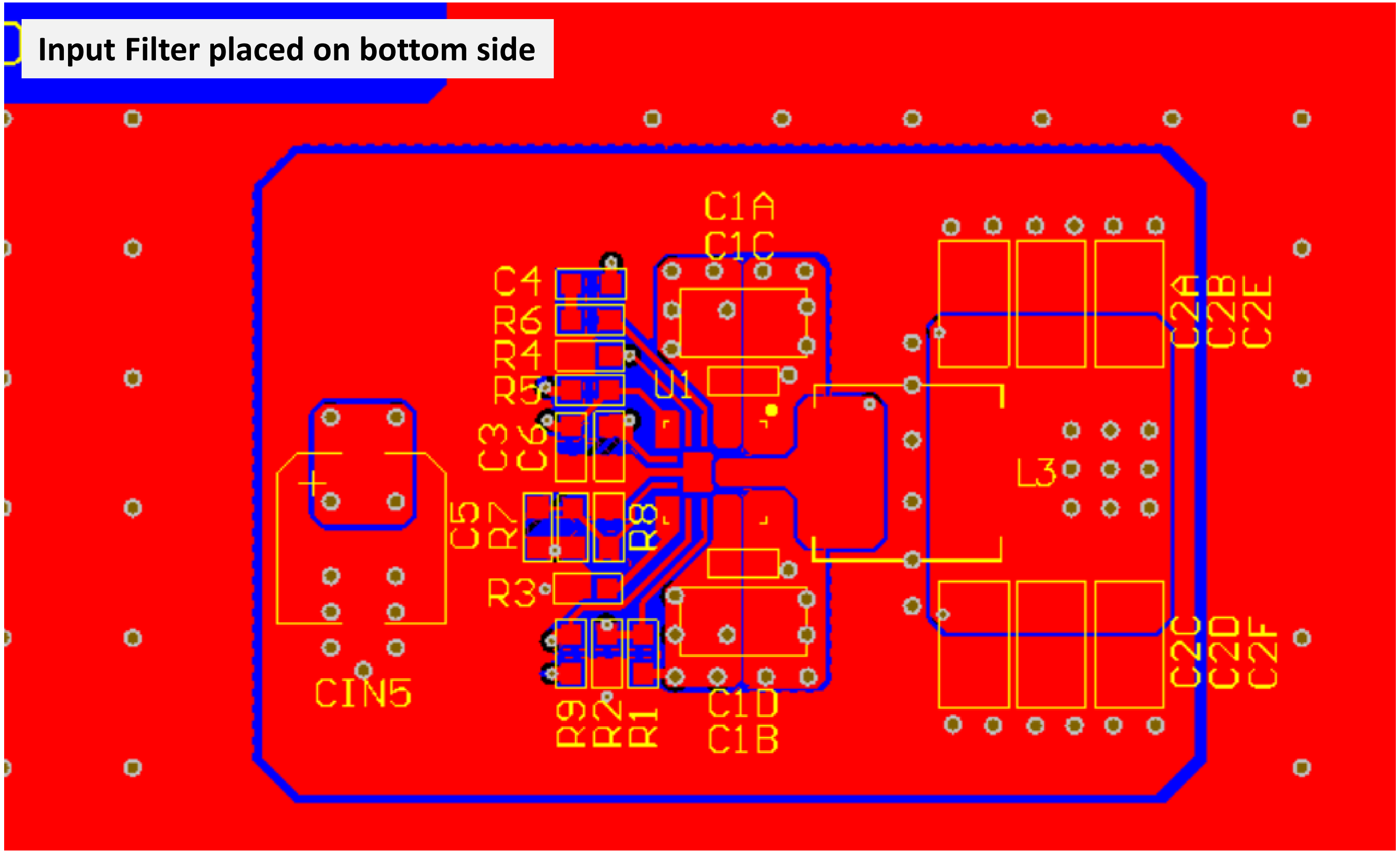


This configuration forces the high di/dt of each Buck to flow in its local CIN !

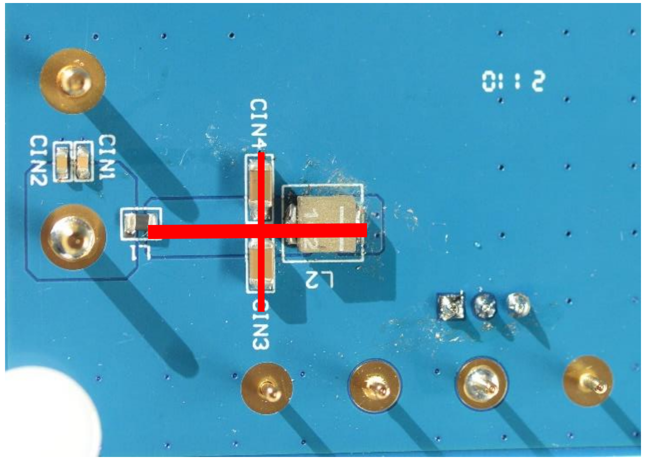
MPS Example #1: 5A Buck Fsw=2MHz

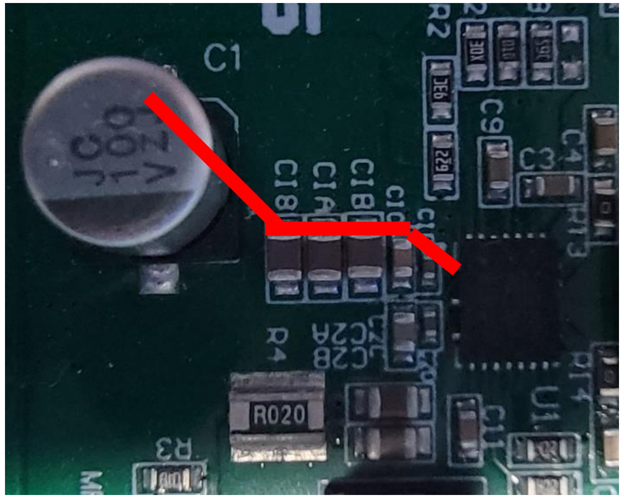


Top Layer


Input Filter placed on bottom side
C1A
C1C
C4
R6
R4
R5
U1
C3
C6
C5
R7
R8
R3
CIN5
R9
R2
R1
C1D
C1B
L3
C2A
C2B
C2E
C2C
C2D
C2F

“T” Capacitor Versus “I” Capacitor Design

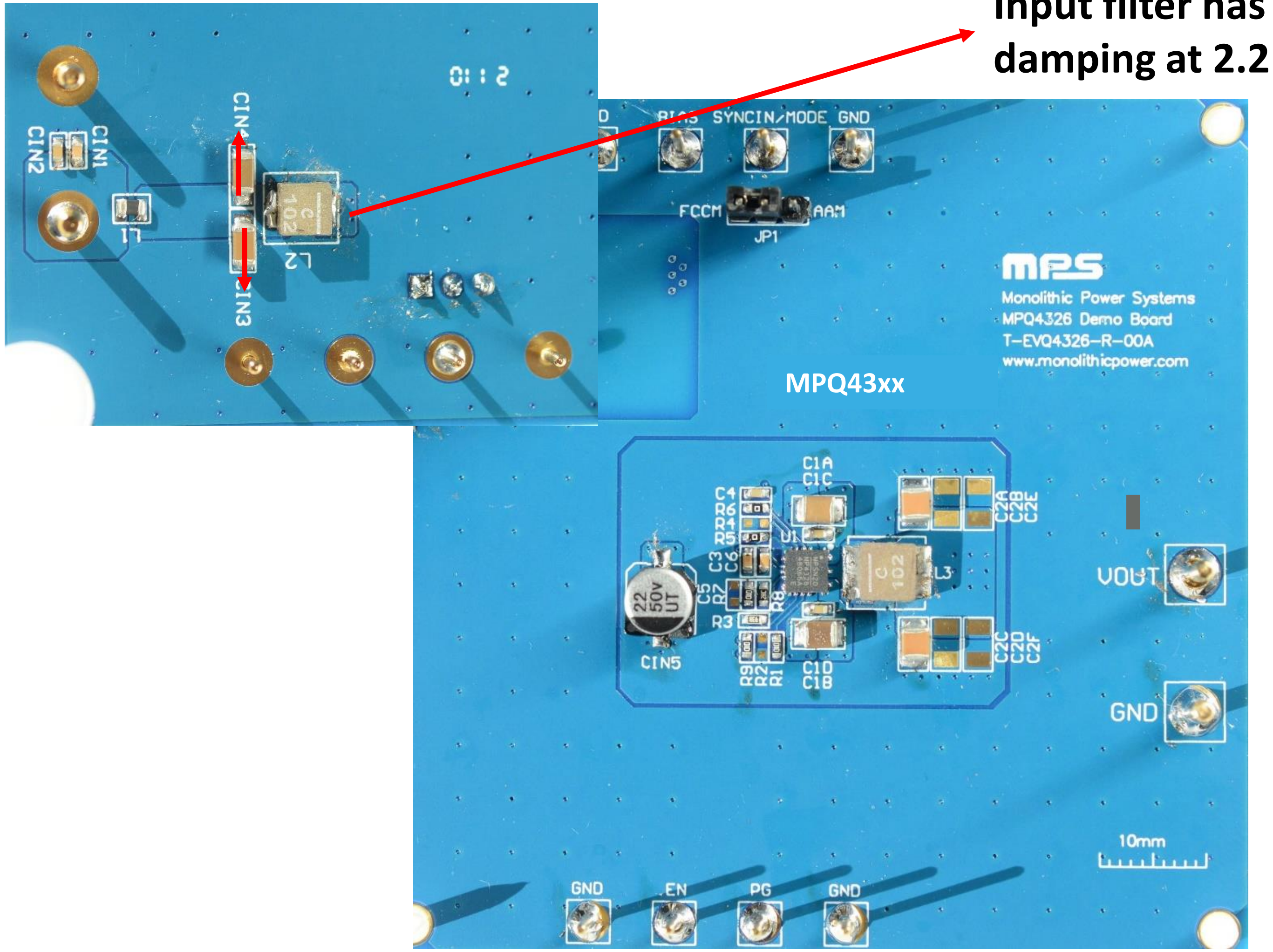




MPQ43xx 5V 5A Buck 2.2MHz with SSFM

Input Filter on Bottom

Input filter has around 50dB damping at 2.2MHz



Input L, C Filter – simplified 1-Stage vs. 2-Stage

Input EMC Filter: Single-Stage vs. Two-Stage

=Enter your parameter

Single Stage	Fundamental		1st Harm	2nd Harm	3rd Harm	4th	5th
Fsw:	2.20	MHz	4.40	6.60	8.80	11.00	13.20
Omega-Fsw	13.82	1/µs	27.65	41.47	55.29	69.11	82.94
L_single:	0.33	µH					
XL:	4.56	Ohm	9.12	13.68	18.25	22.81	27.37
C-effective:	0.70	µF					
XC:	0.10	Ohm	0.052	0.034	0.026	0.021	0.017
Damping	**-33.09**	**dB**	**-44.99**	**-52.00**	**-56.99**	**-60.86**	**-64.03**
Two stage filter design:							
1st L:	0.10	µH					
XL:	1.38	Ohm	2.76	4.15	5.53	6.91	8.29
1st C:	0.60	µF					
XC:	0.121	Ohm	0.060	0.040	0.030	0.024	0.020
Damping 1	-21.91	dB	-33.42	-40.36	-45.32	-49.18	-52.33
2nd L:	0.10	µH					
XL:	1.38	Ohm	2.76	4.15	5.53	6.91	8.29
2nd C:	0.40	µF					
XC:	0.181	Ohm	0.090	0.060	0.045	0.036	0.030
Damping 2:	-18.73	dB	-29.99	-36.88	-41.82	-45.67	-48.82
Total Damping:	**-40.65**	**dB**	**-63.40**	**-77.23**	**-87.13**	**-94.84**	**-101.16**

Simplified calculation: 20 log (Xc/(Xc + XL)) at Fsw, 2x Fsw etc…

- Murata has a filter simulator as part of their SimSurfing Suite
- Circuit simulation can also be done

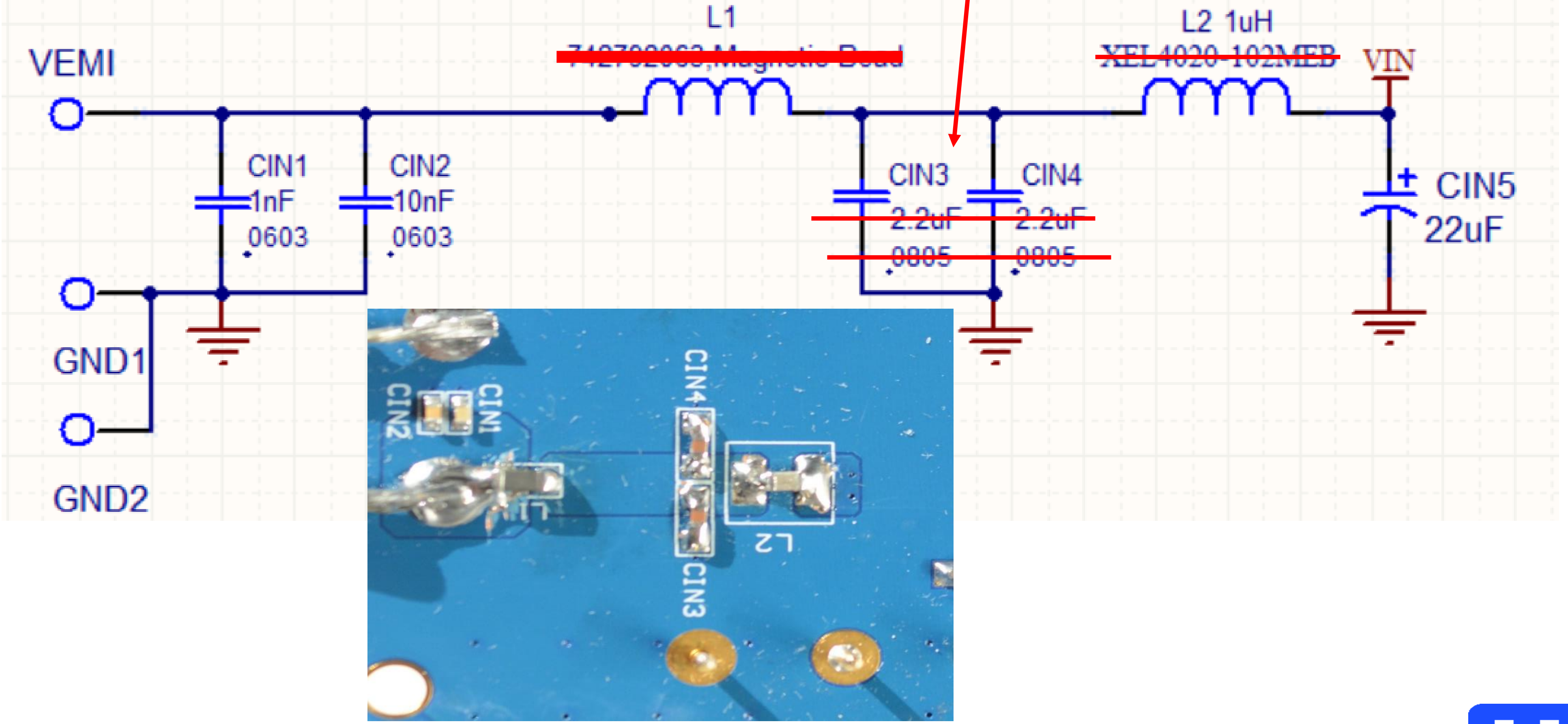
Reduced Input Filter for 2MHz with SSFM

This filter has ~ 33dB damping at 2.2MHz

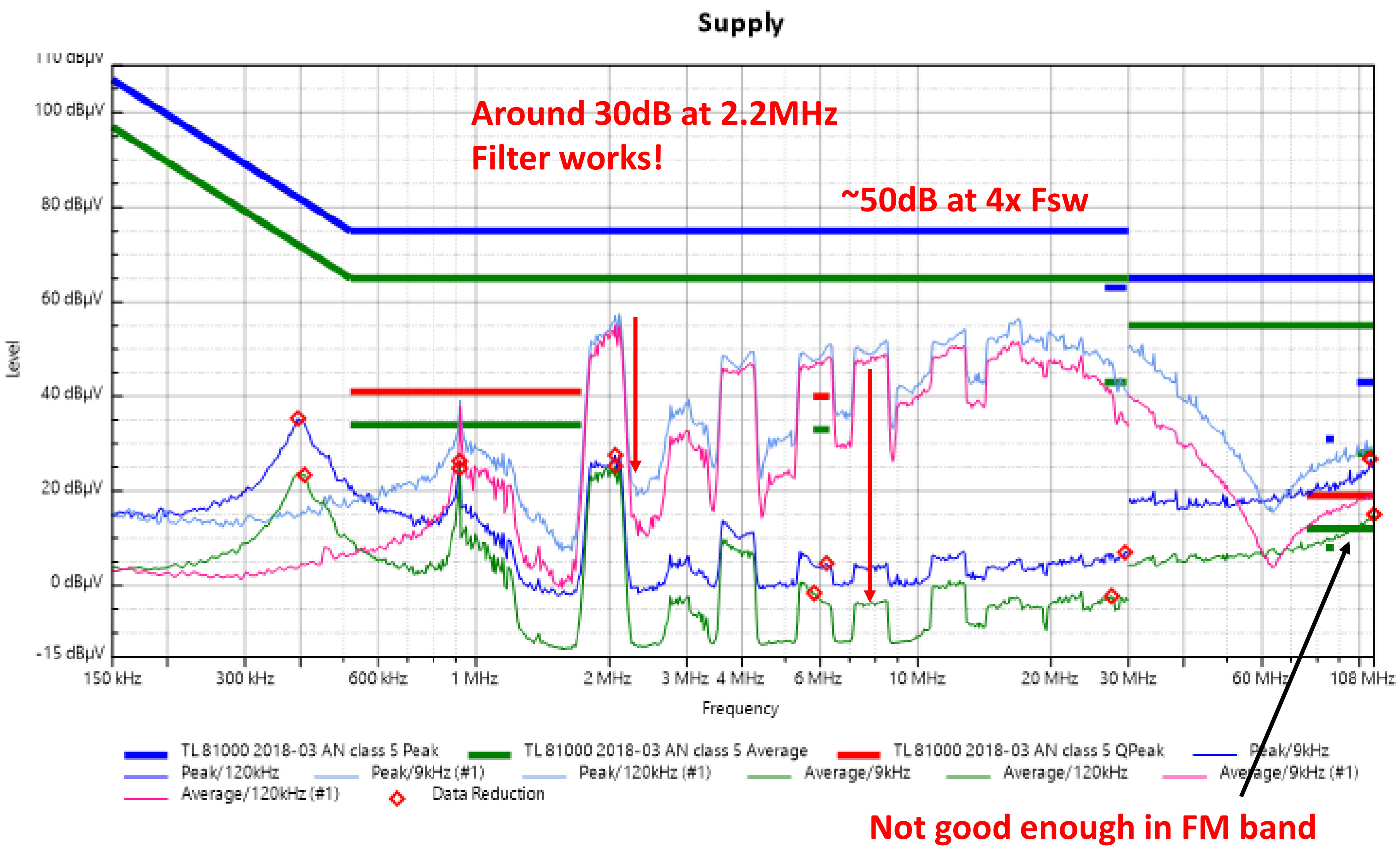
CIN3/4= 470nF 0603

L1: BLM or short

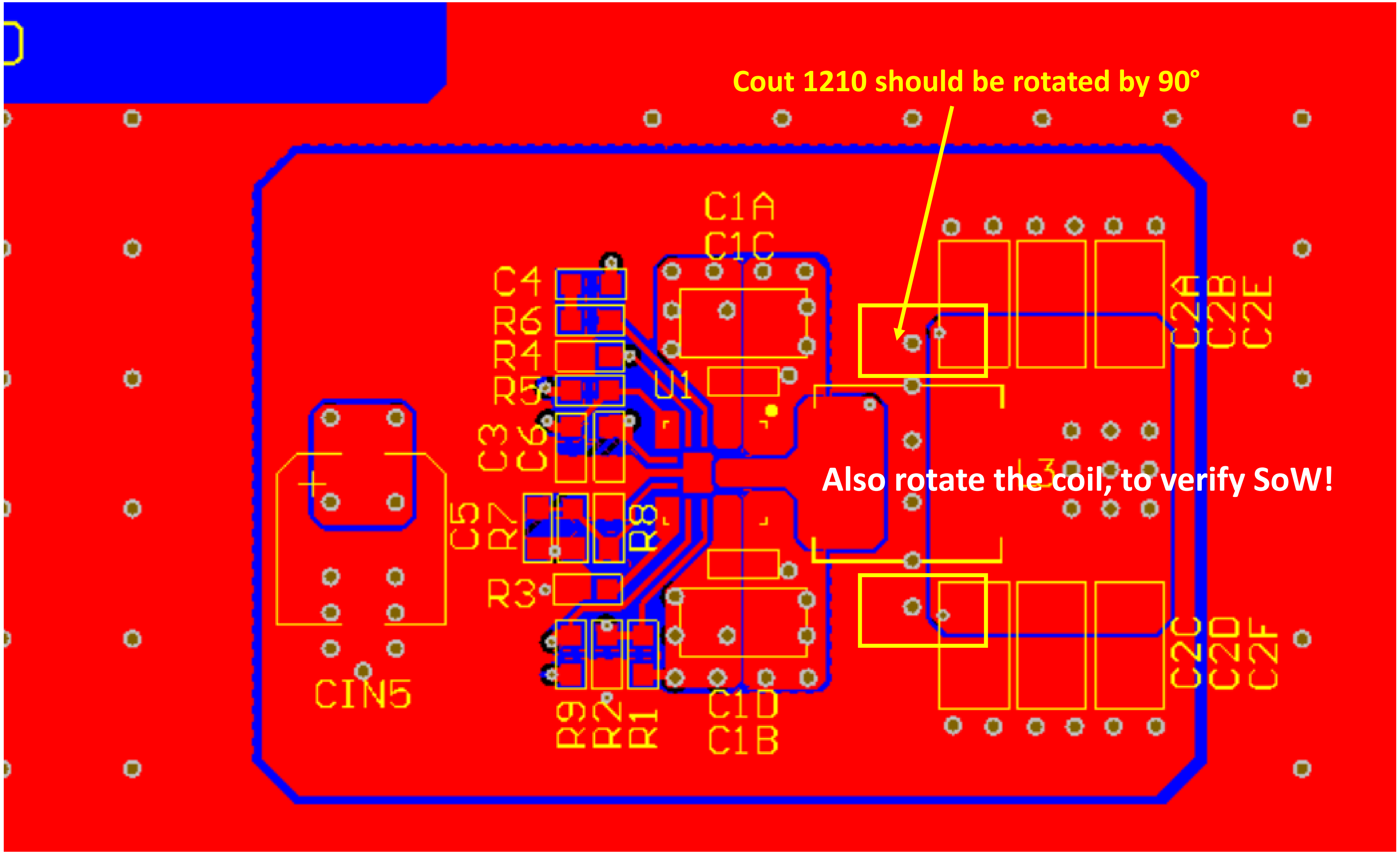
330nH 0805



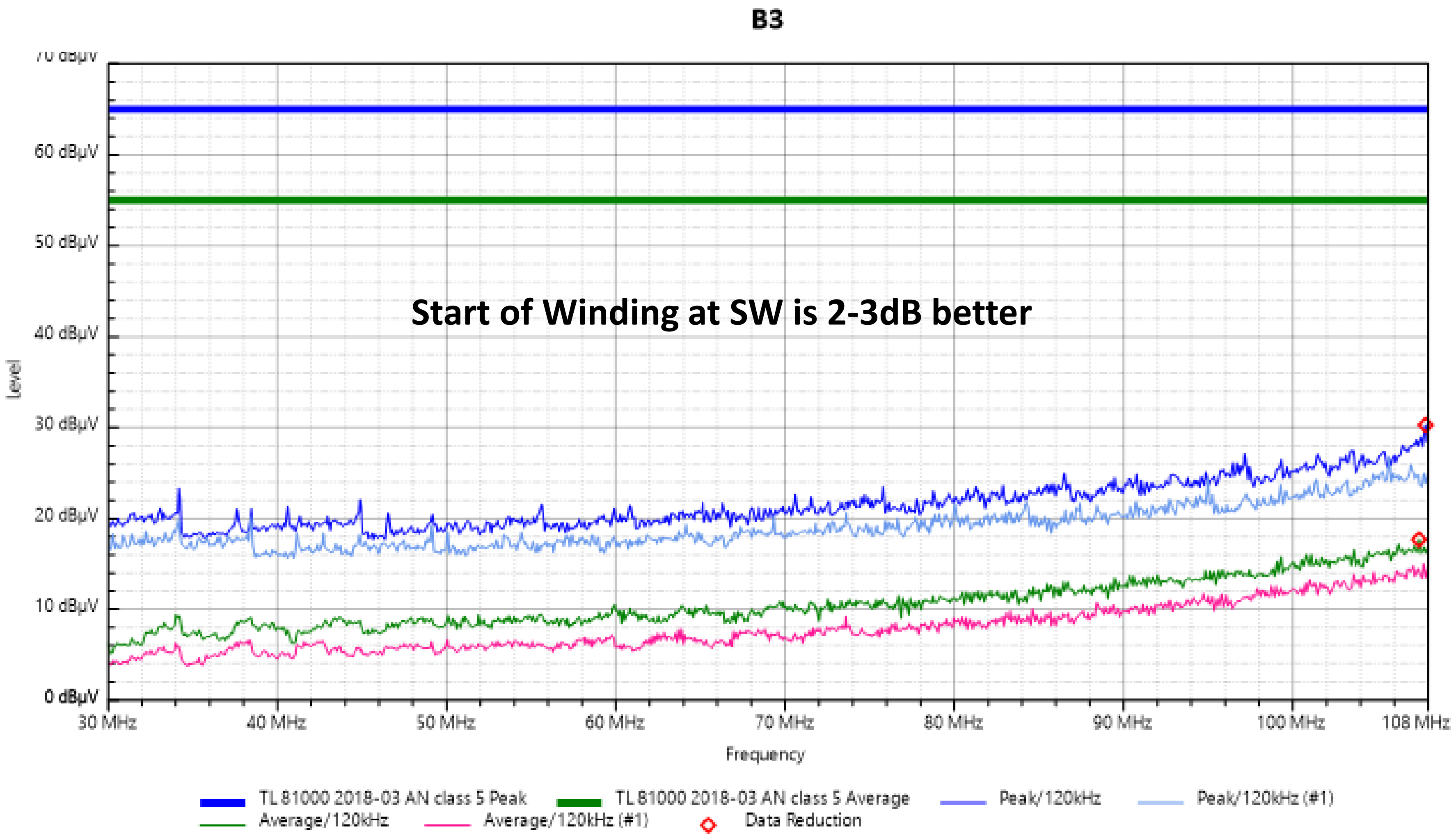
CE Test without and with reduced Input Filter



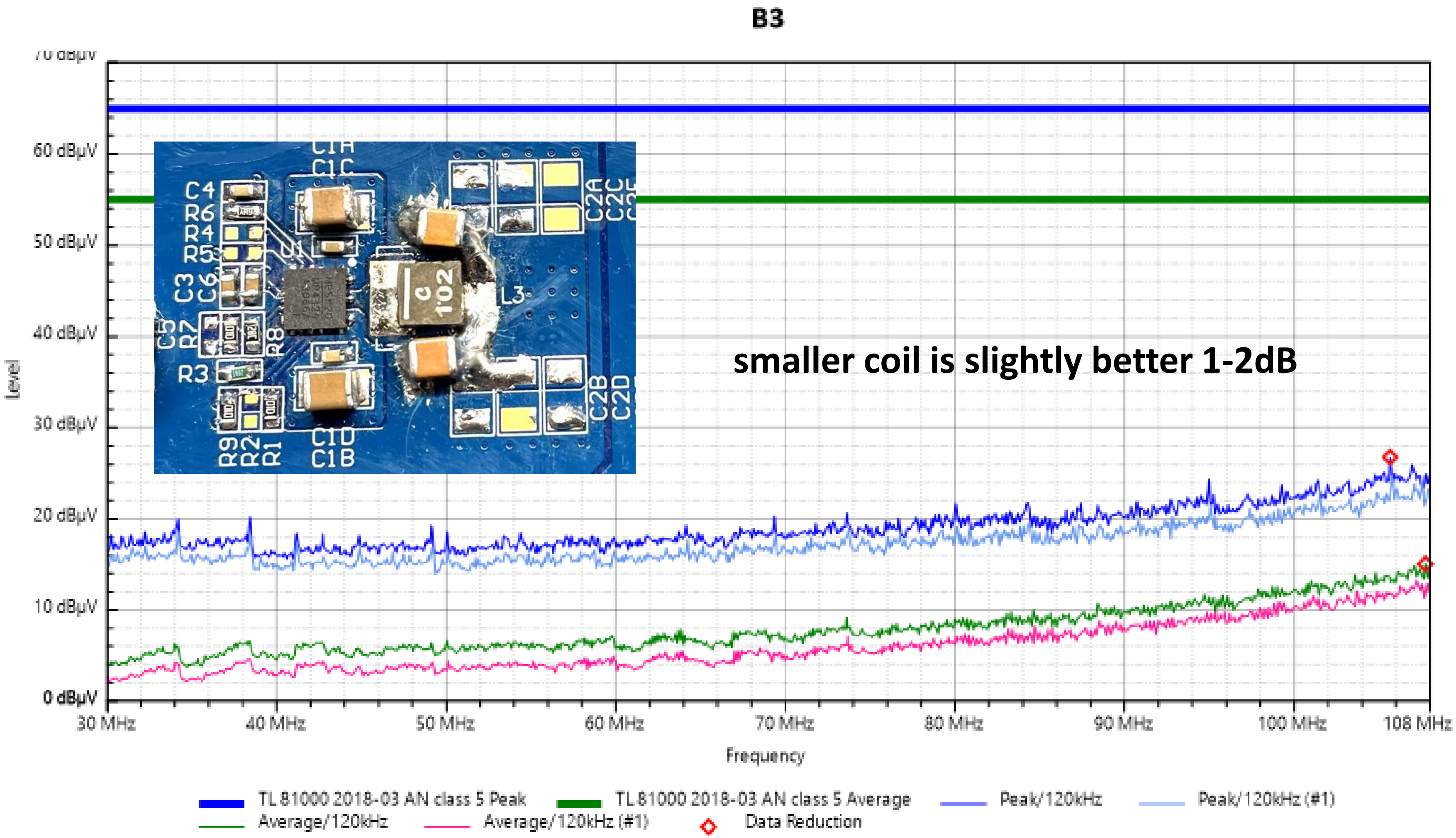
Top Layer - modification



XAL5030 1µH in both directions

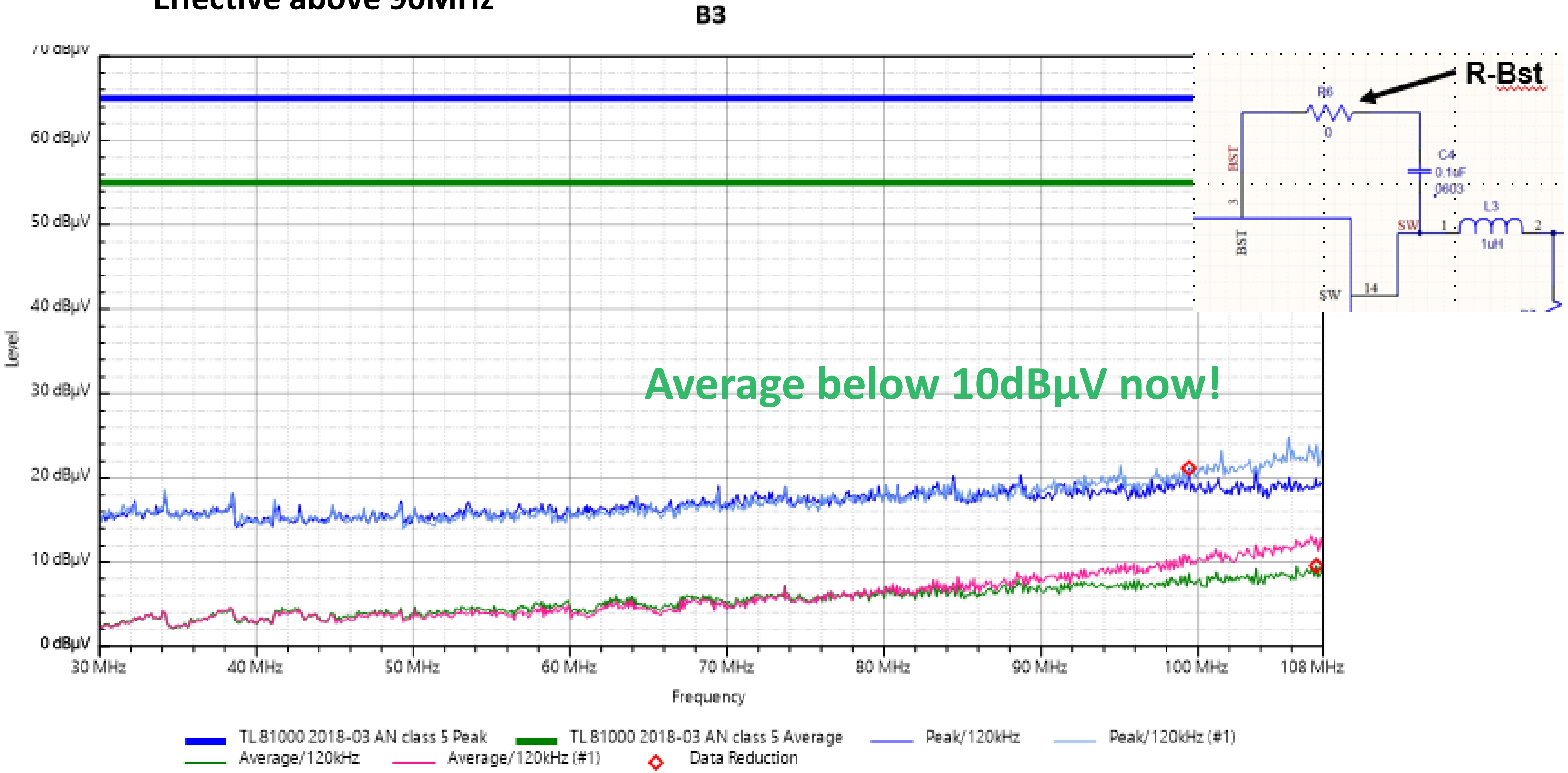


Replace XAL5030-1µH by XAL4020-1µH

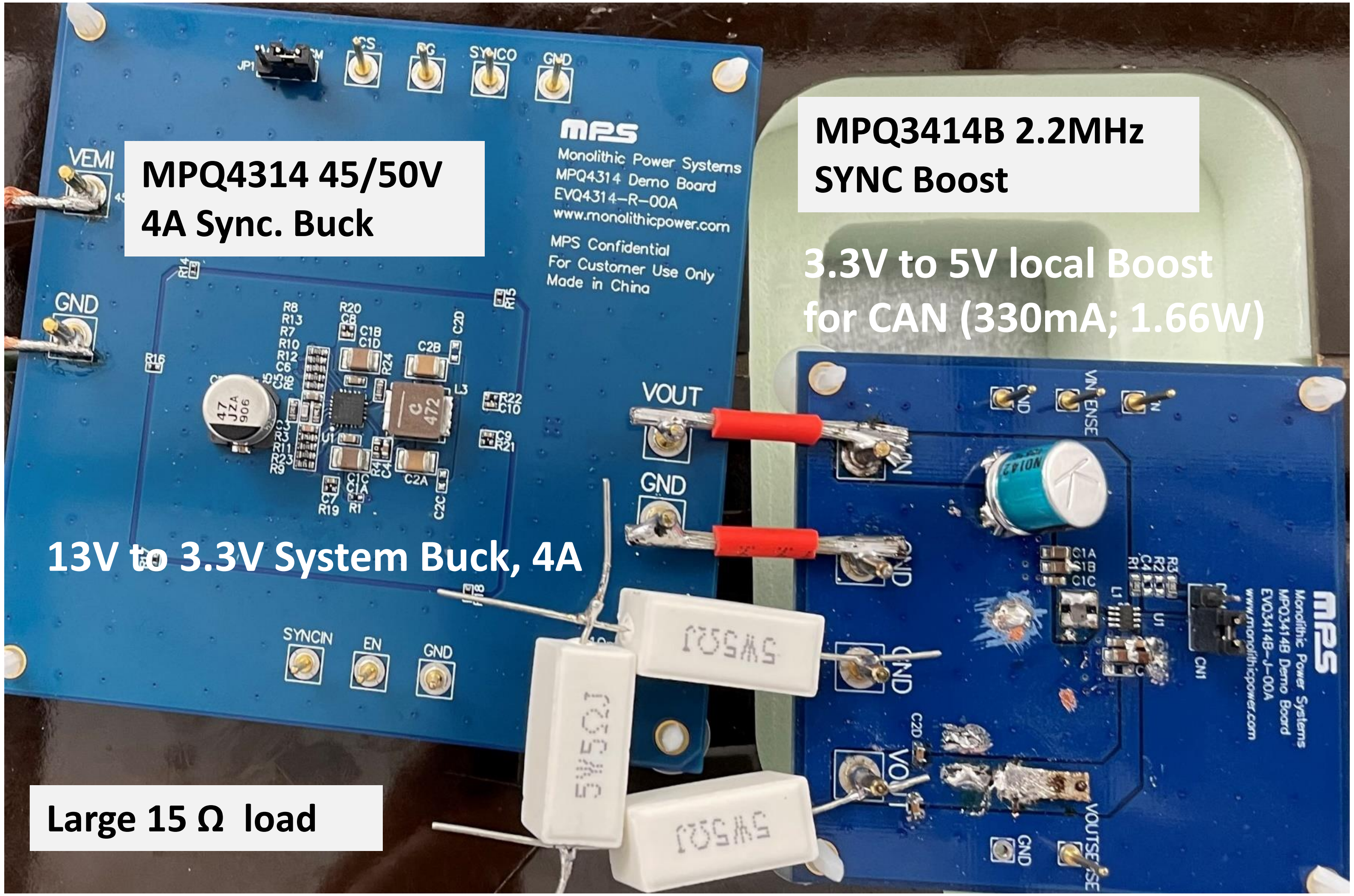


Add 4.7 Ω Into BST Circuit

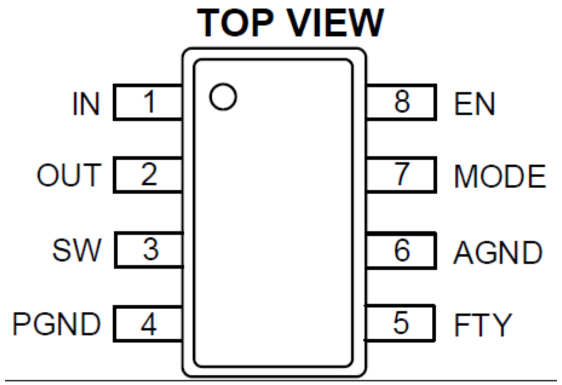
Effective above 90MHz



MPS Example #2

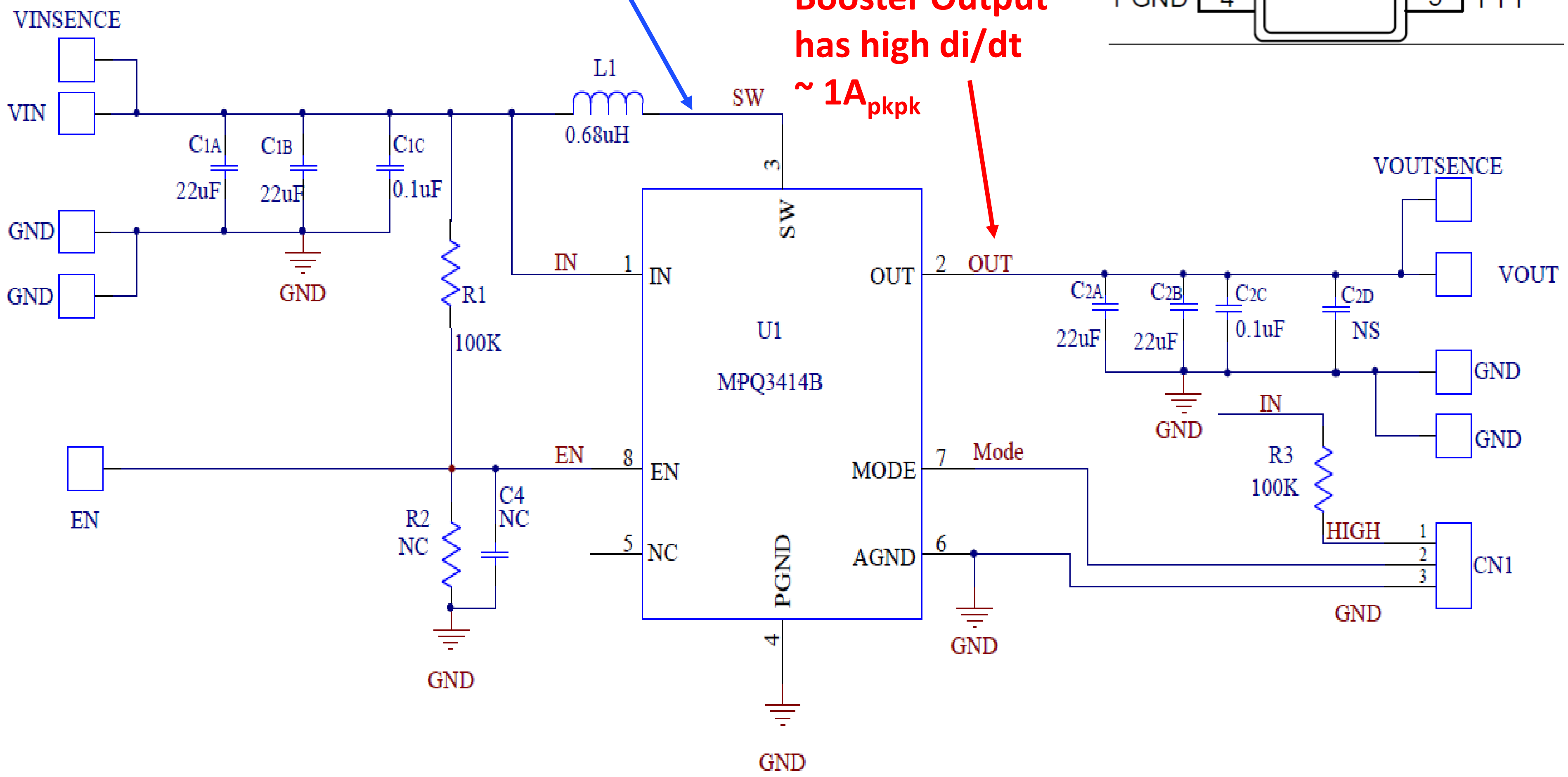


MPQ314B Boost Schematic



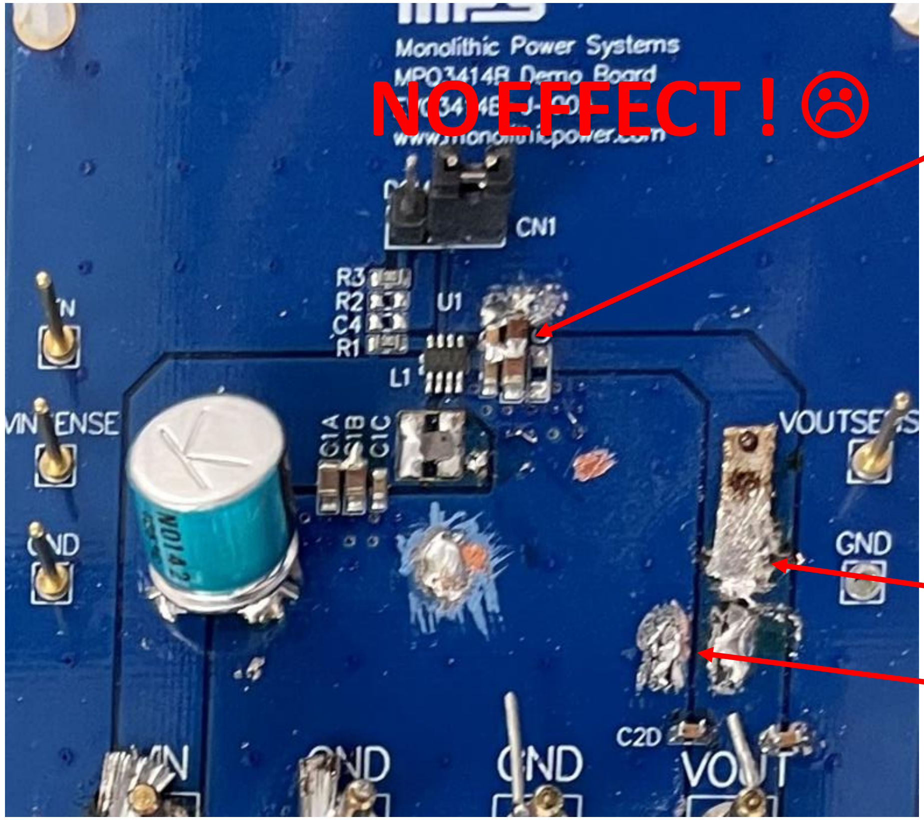
SW has 5V$_{pkpk}$ with fast dV/dt

Booster Output has high di/dt ~ 1A$_{pkpk}$



Circuit Modification

As large load resistor (Antenna!) is directly connected to Booster Output, the first modification was an L,C output filter.



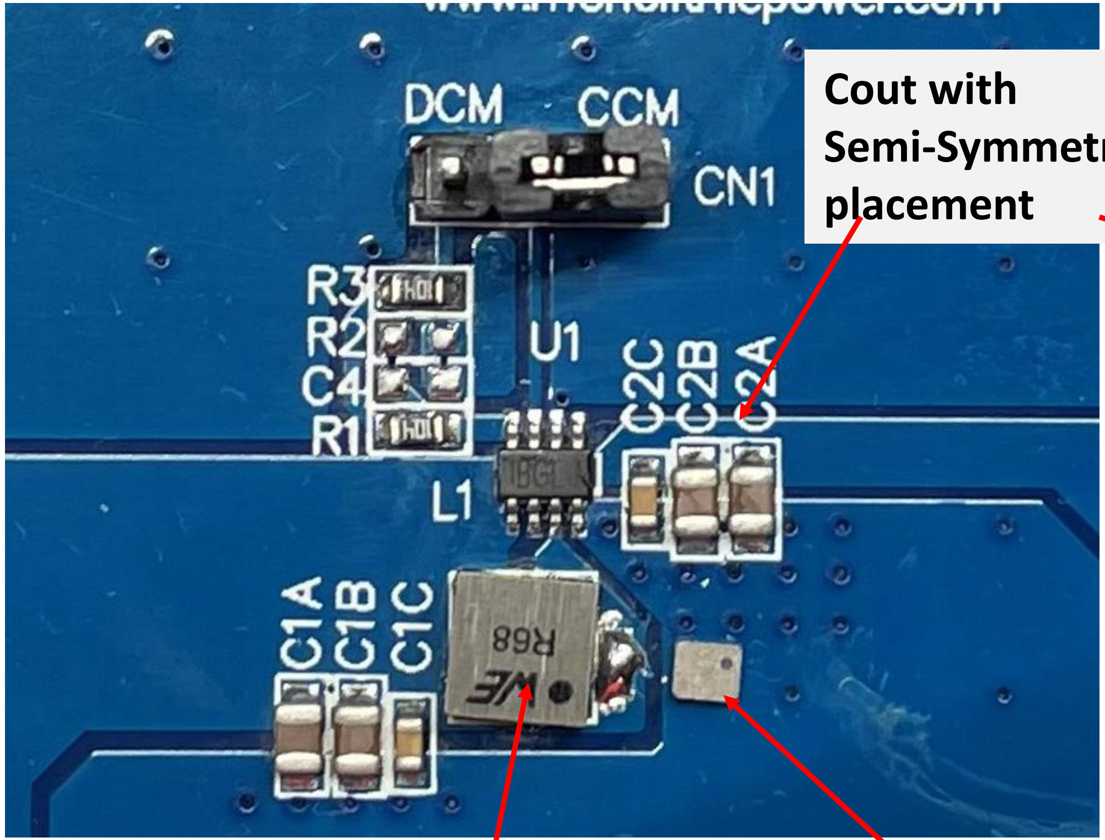
Second modification:
Cout with Semi-Symmetric placement

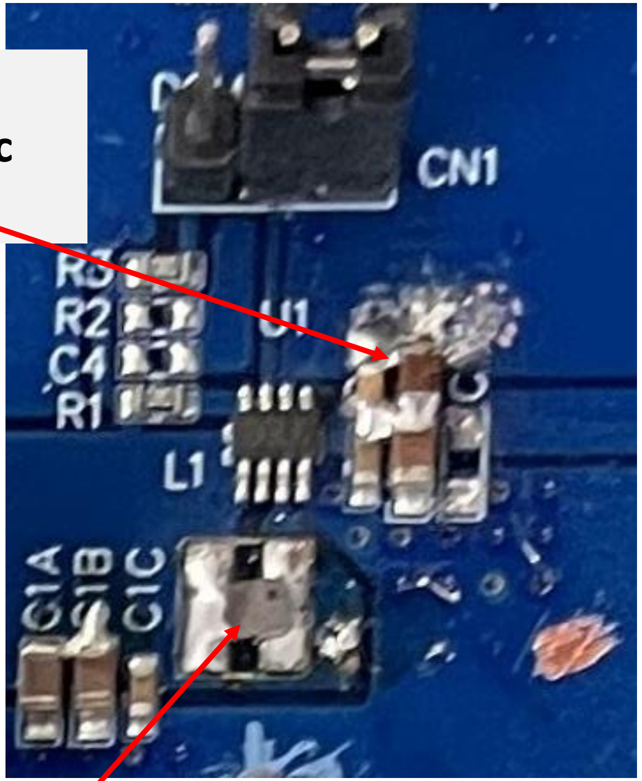
Small 330nH coil was placed here.
1µF MLCC here

Original MPS EV Board and modified board

Initial MAPI4020 I_{RMS}=8A and 8mΩ
4x4x2mm size

AT2010-R68 2x1.6x1mm
41mΩ I_{RMS}=3.5A; I_{SAT}=4.9A



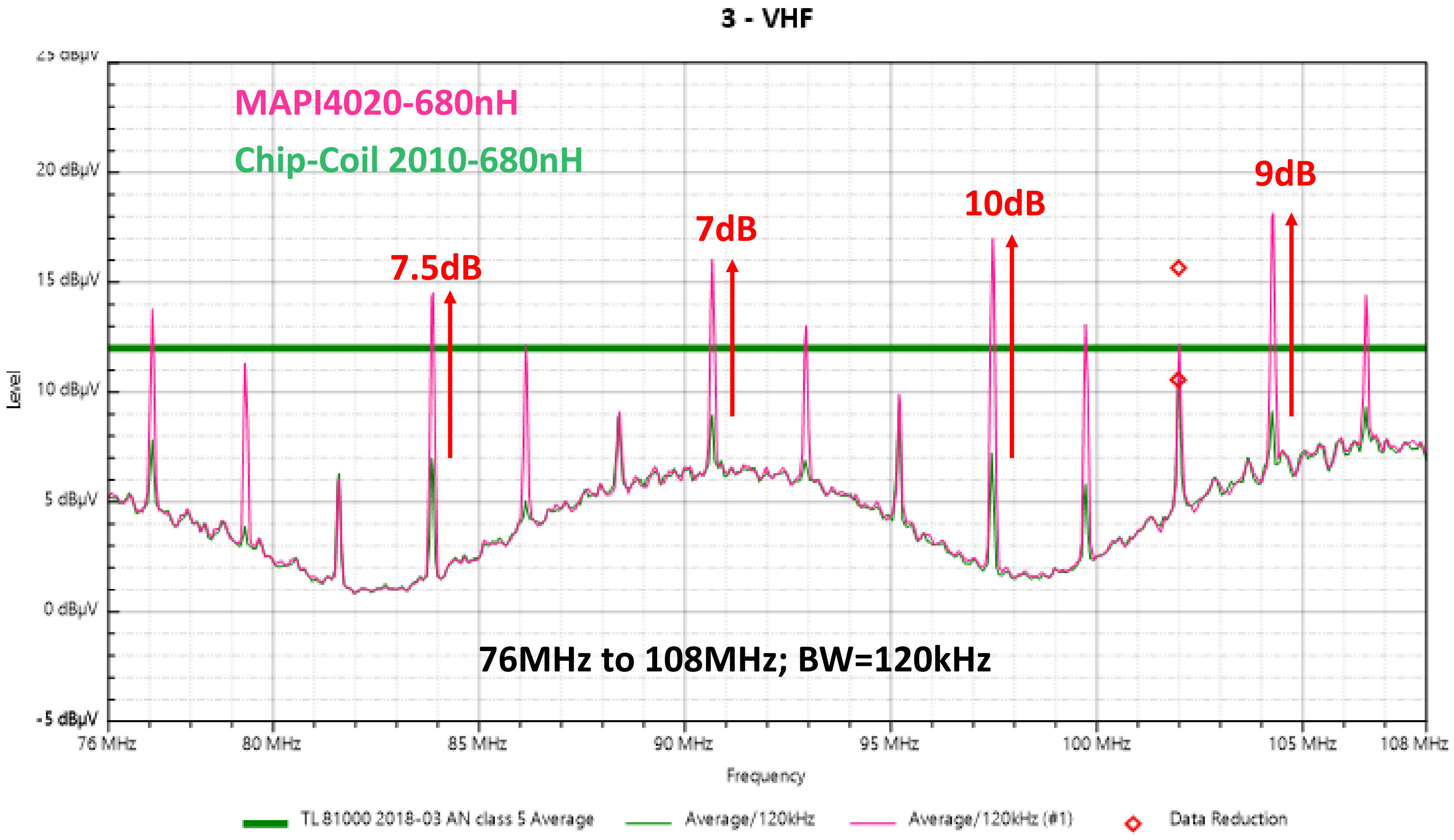


Cout with Semi-Symmetric placement

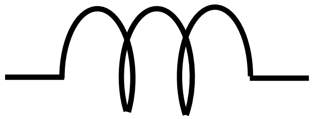
MAPI4020 680nH

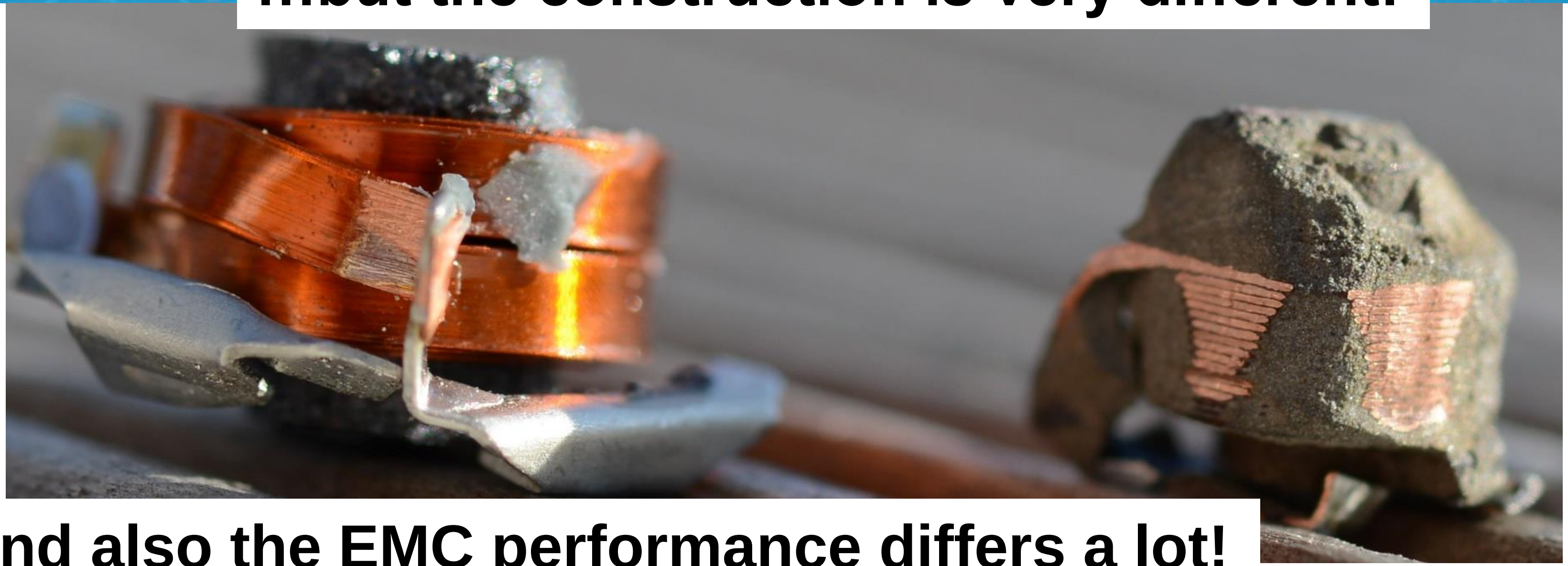
MPL-AT2010-R68

CE Average Test with OEM Limit



Power Inductors

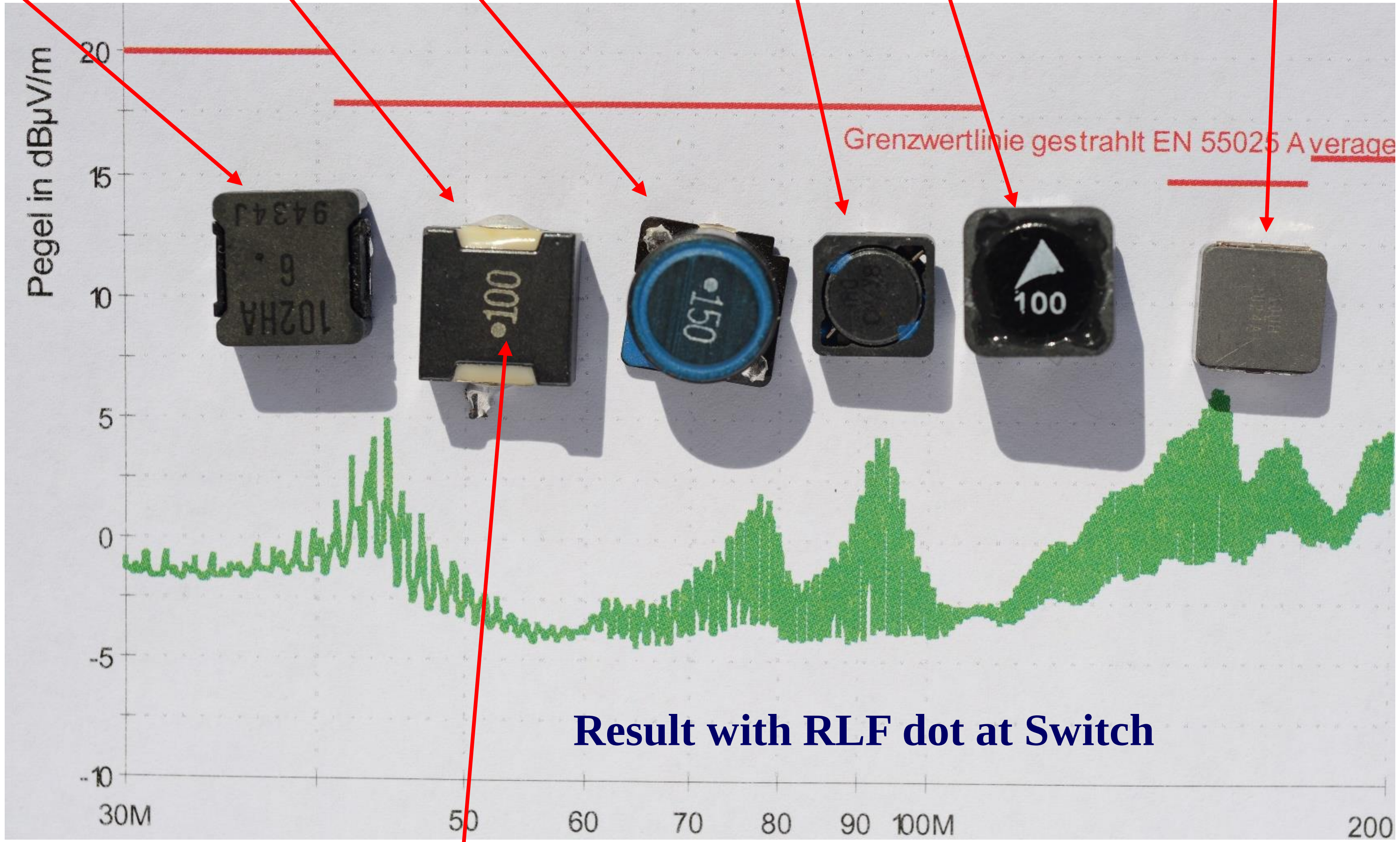




And also the EMC performance differs a lot!

MPS Case #3: More about Power Inductor and EMC

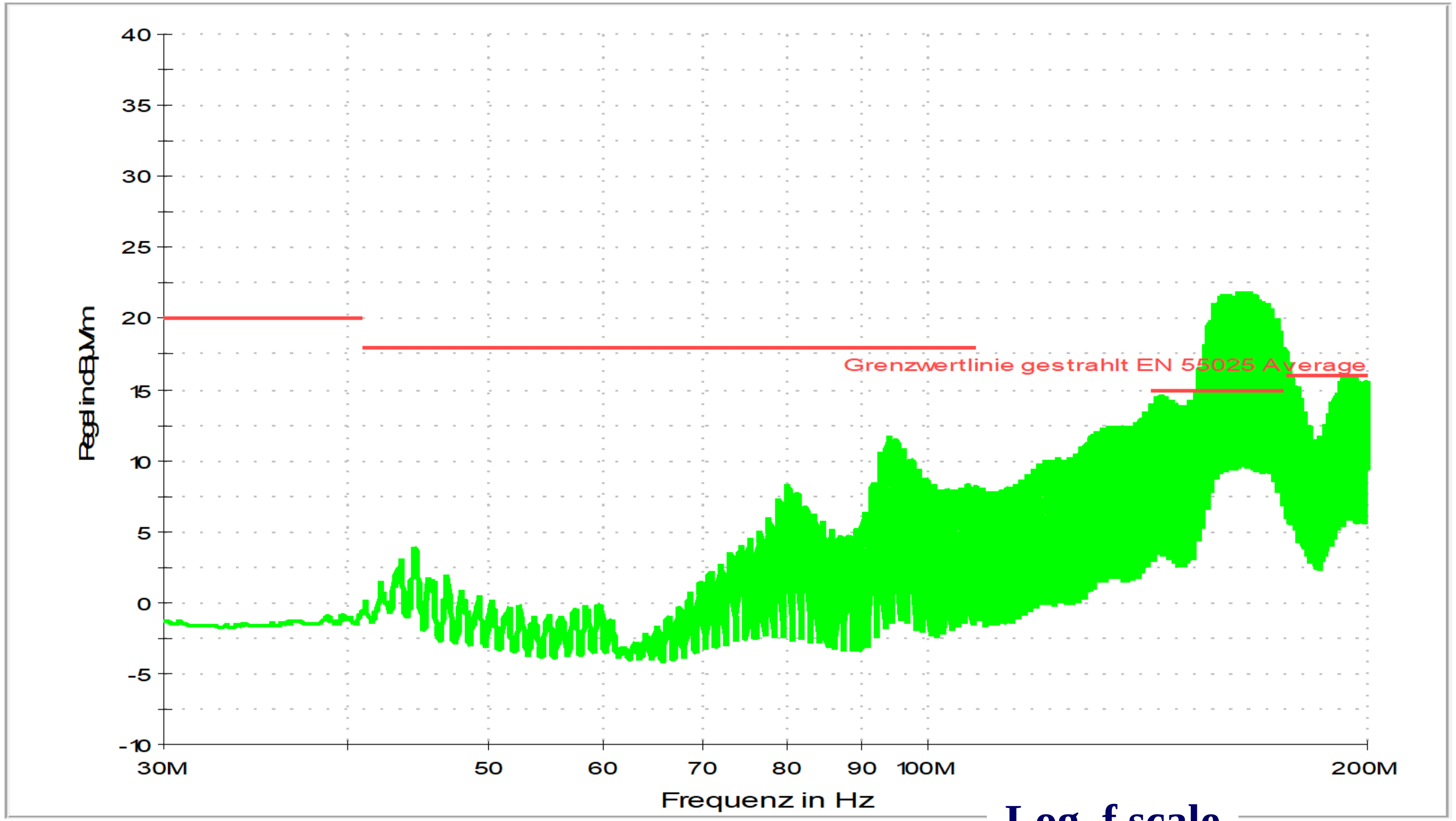
Panasonic; TDK RLF and SLF; Toko D104/124; Epcos & Vishay IHLP4040



Dot on coil indicates Start of Winding (SoW)

More about Power Inductors and EMC

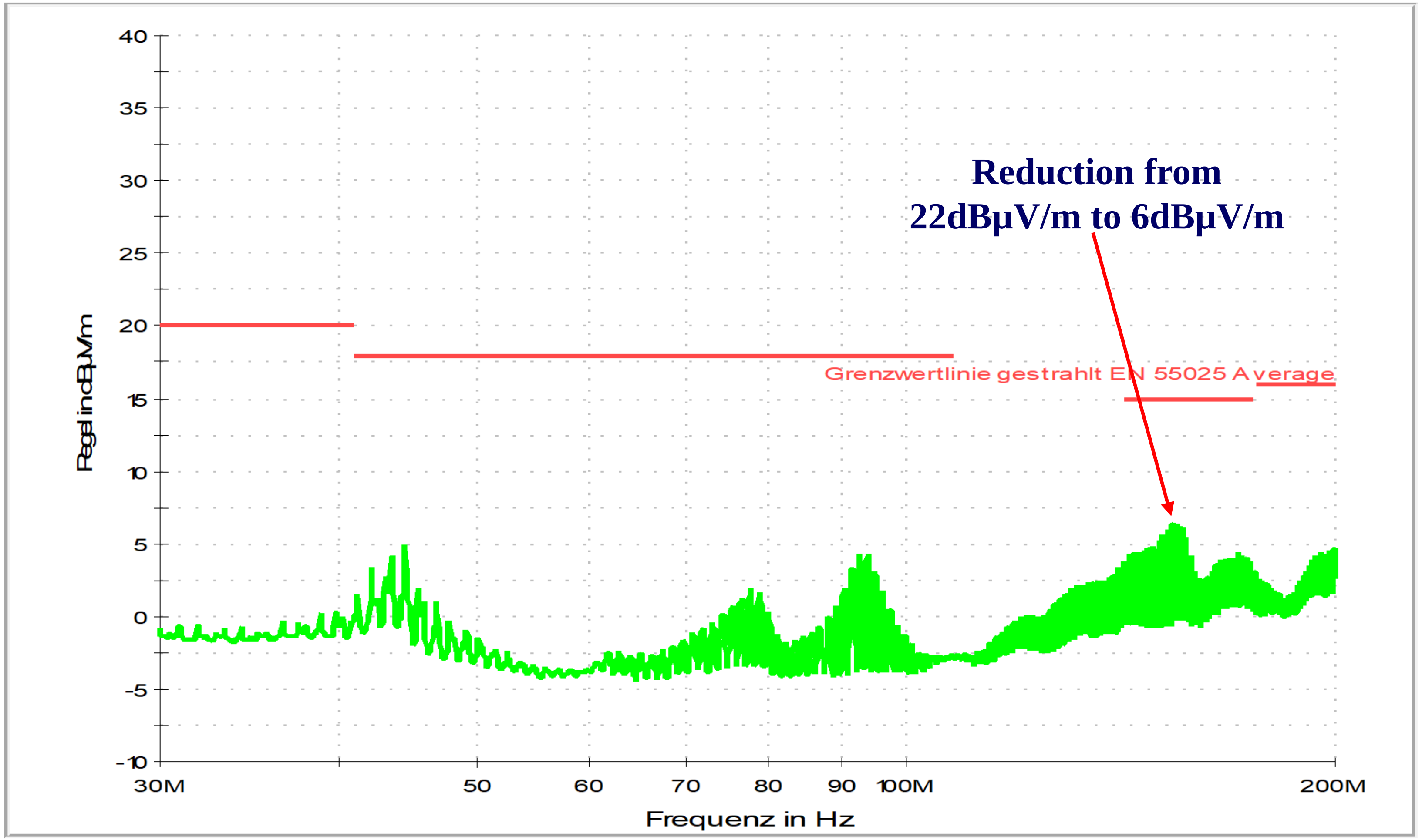
Molded inductor WE LHMI 10mm x 10mm



Log. f scale

More about Power Inductors and EMC

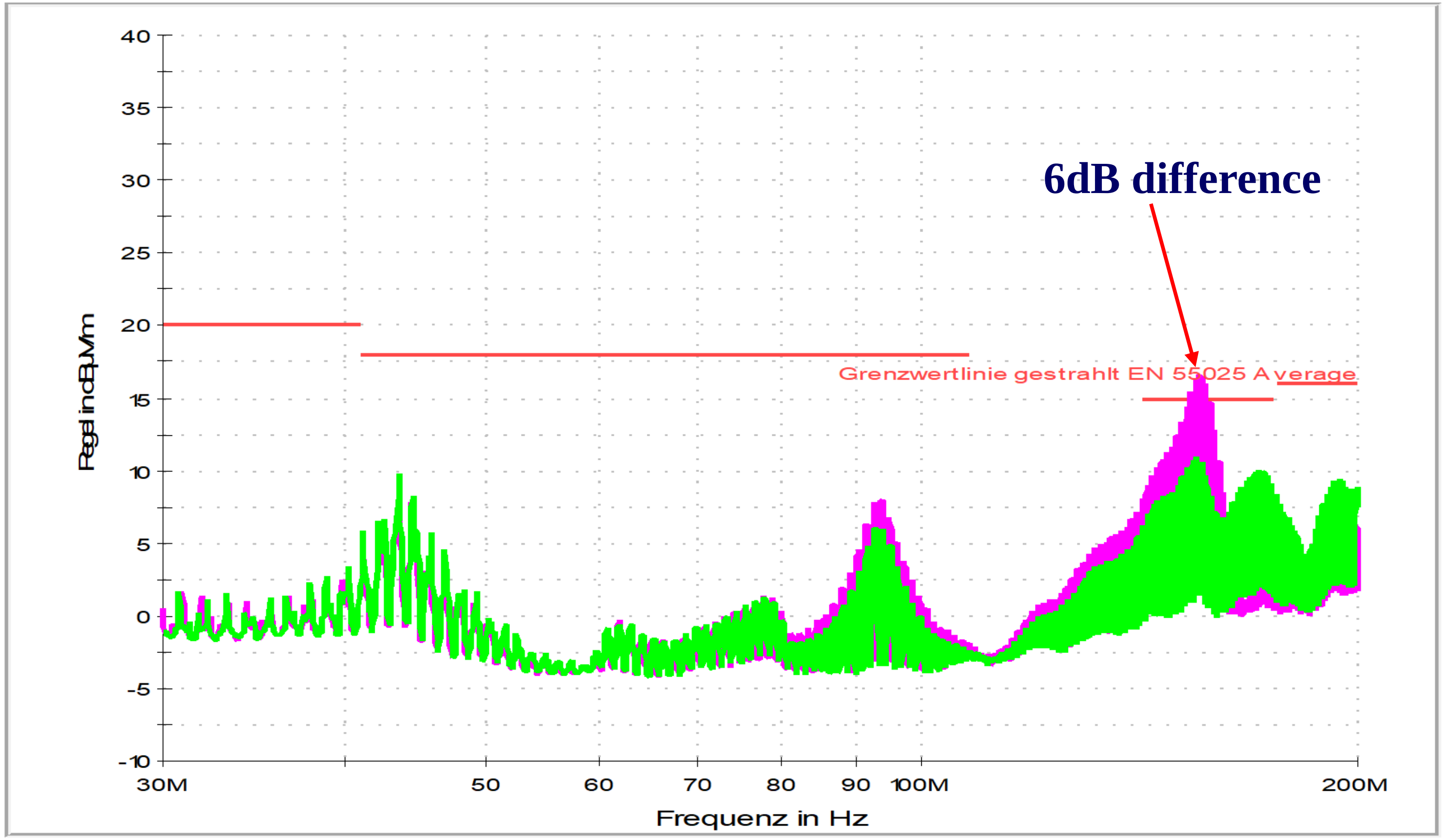
TDK SLF12575 SoW at Switch



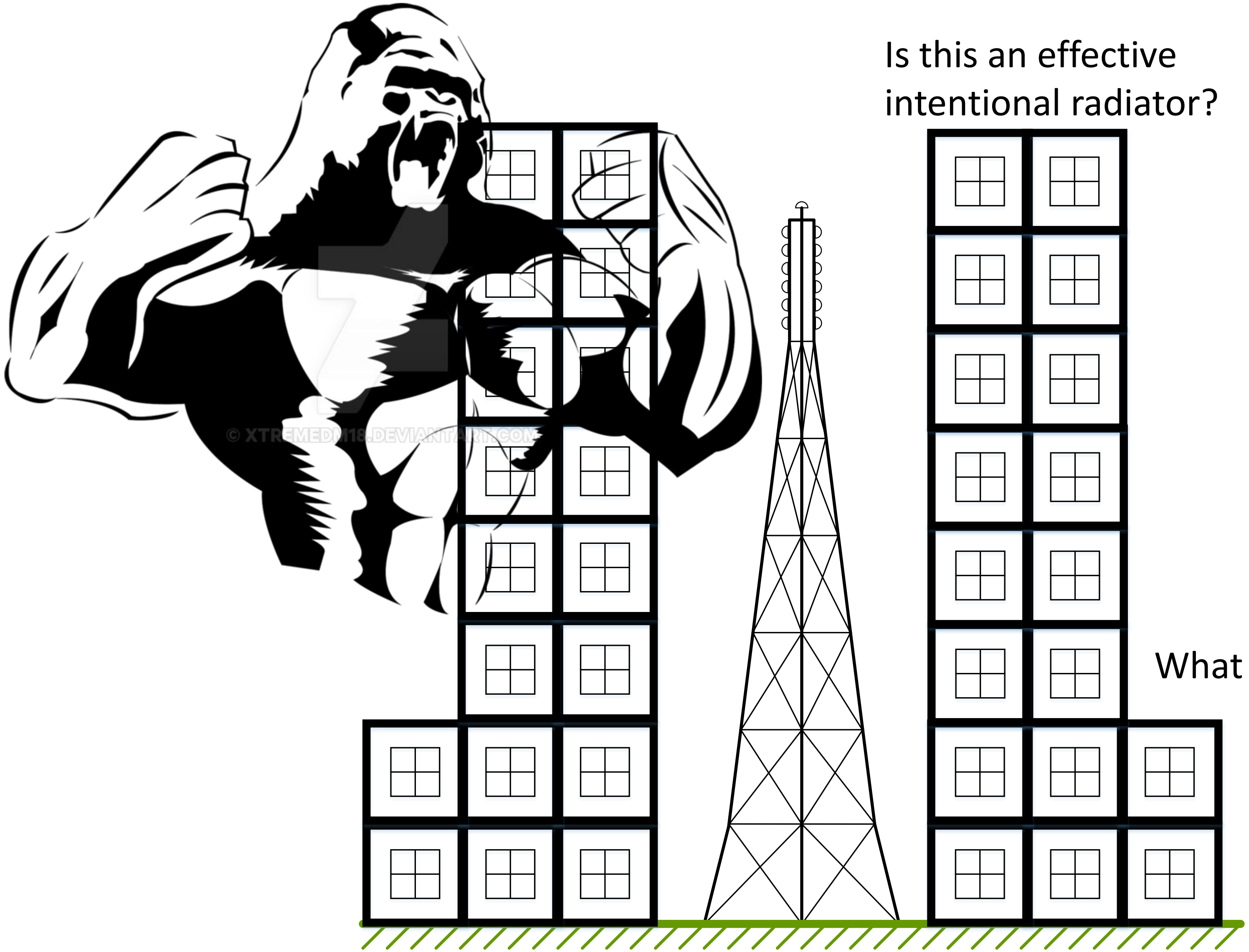
More about Power Inductors and EMC

Epcos Coil with MnZn Core SoW at SW (Pink) and SoW at Vout (green)

The core of this MnZn coil is conductive, this might be the reason for better Result with SoW at Vout.



More about Power Inductors and EMC

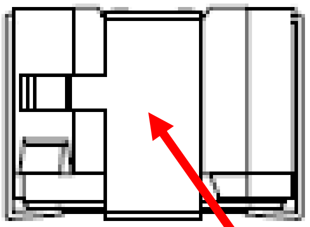


Is this an effective intentional radiator?

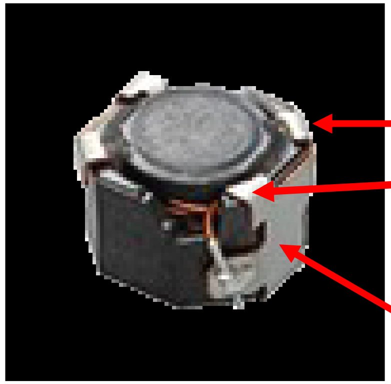
What about now?

More about Power Inductors and EMC

4.5mm Height



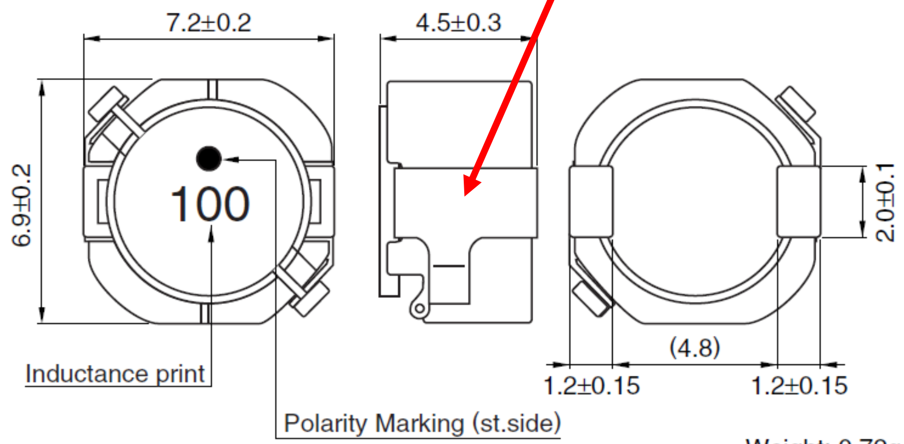
Contact metal acts as antenna for E-field from SW-node dV/dt



End of Winding side Contact metal with two clip into airgap for mechanical robustness

Even if S o W is at SW, plate will cause trouble

SHAPES AND DIMENSIONS

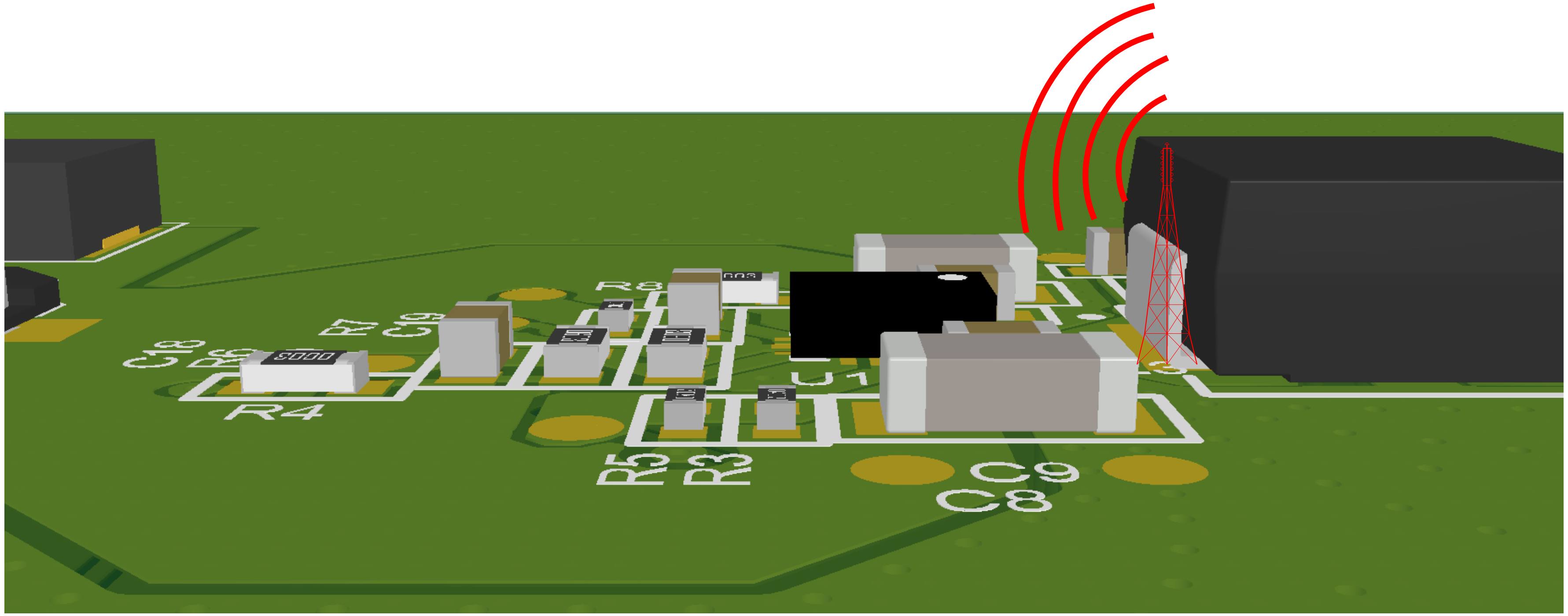


Weight: 0.72g

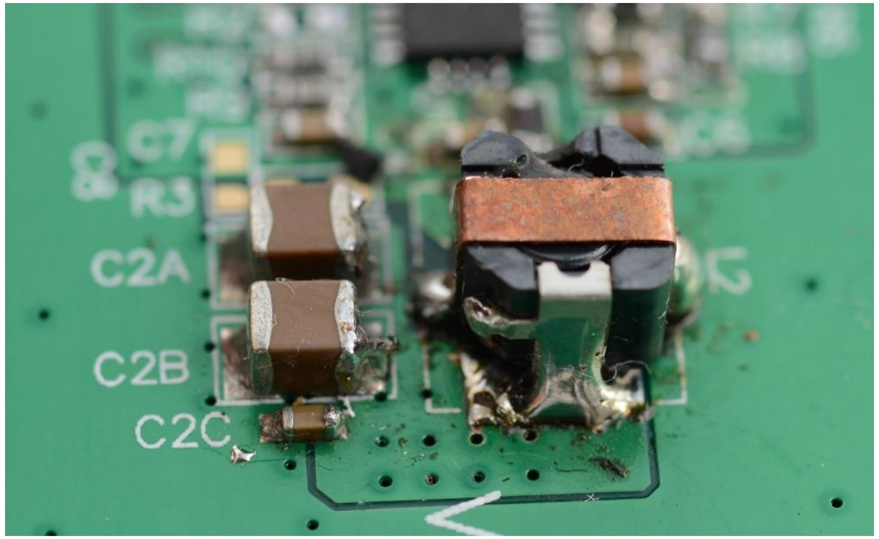
Dimensions in mm

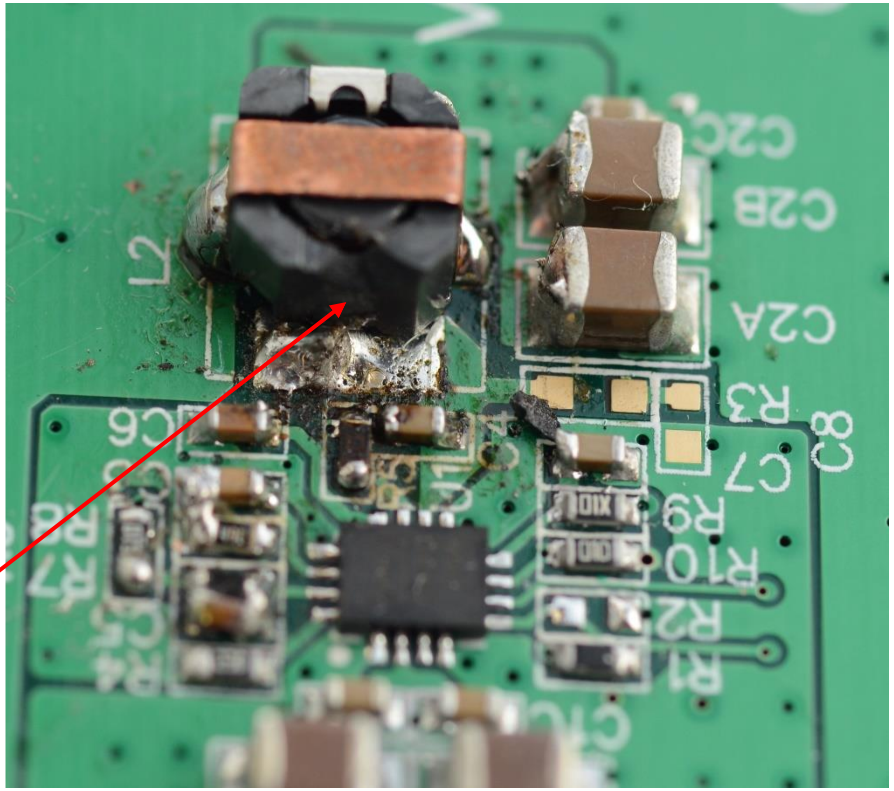
Example Drawings from Murata, TDK and ABC

More about Power Inductors and EMC



More about Power Inductors and EMC

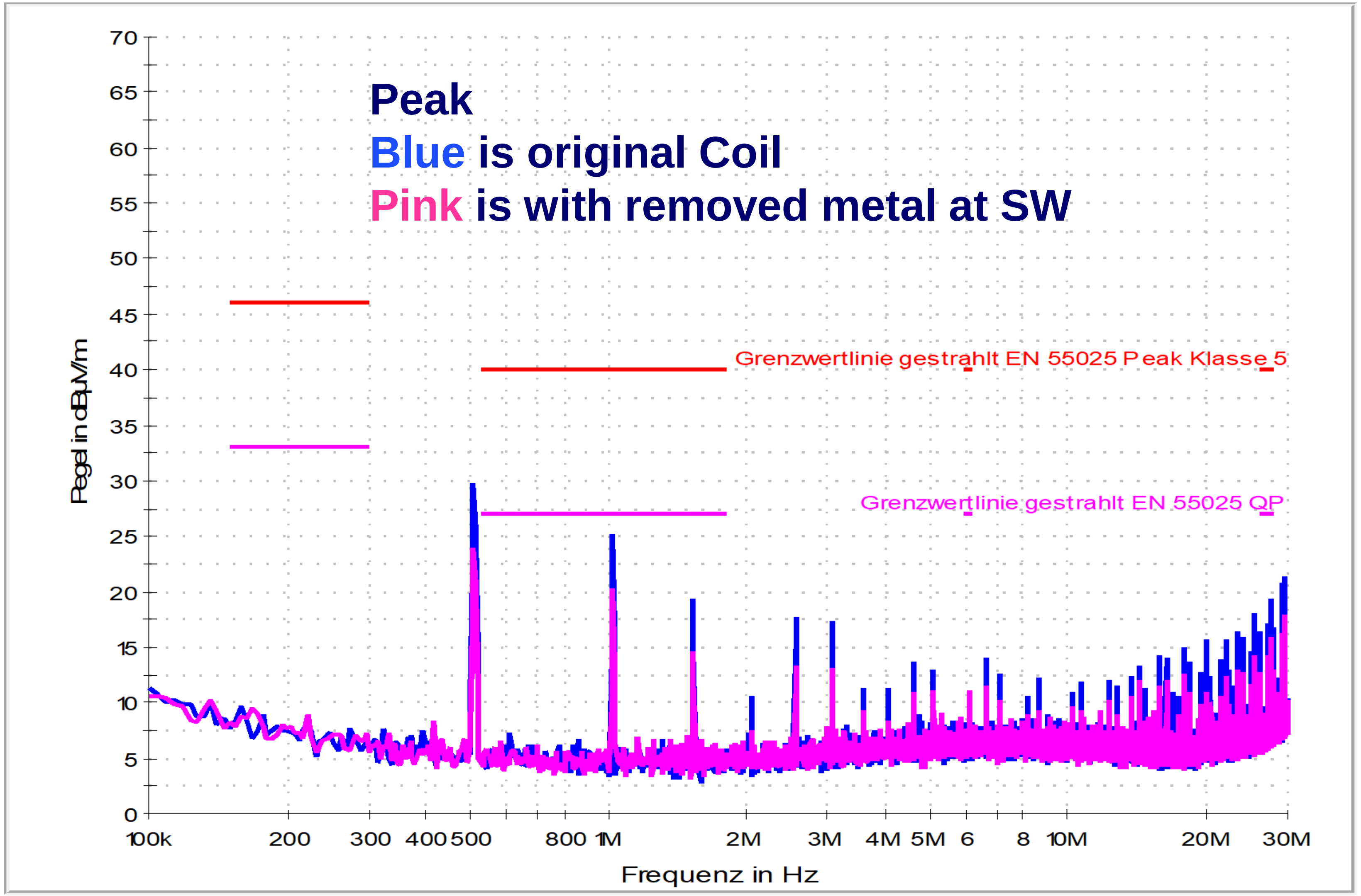




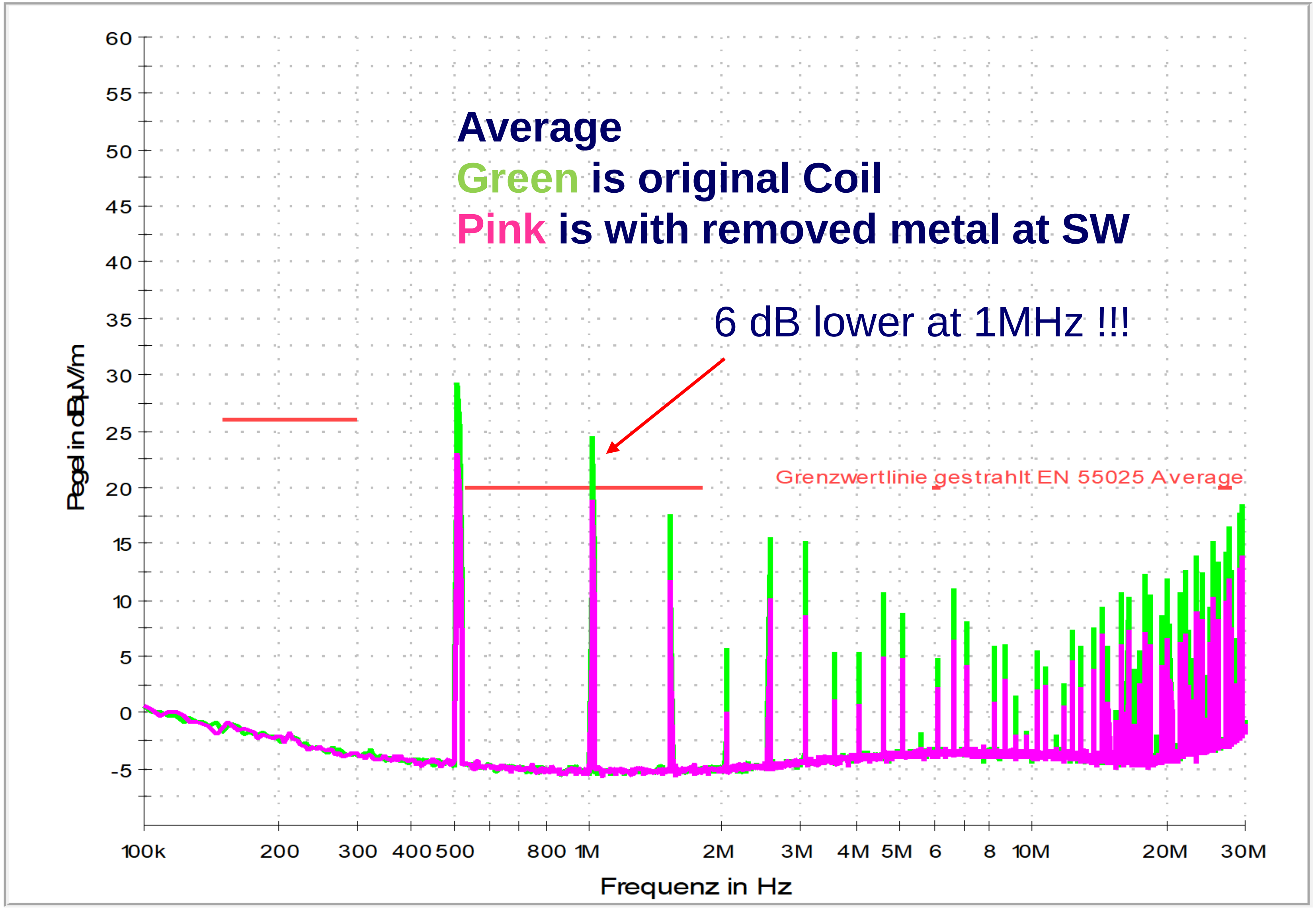
SW-node contact plate removed:
Winding soldered directly to PCB.
6 dB lower emissions at 1MHz
In Monopole Antenna Test

4.5mm height contact plate act as E-Field antenna for SW-node high dV/dt.
Optimum coil should have SW-contact at the bottom.

RE Monopole Test 0.1MHz to 30MHz

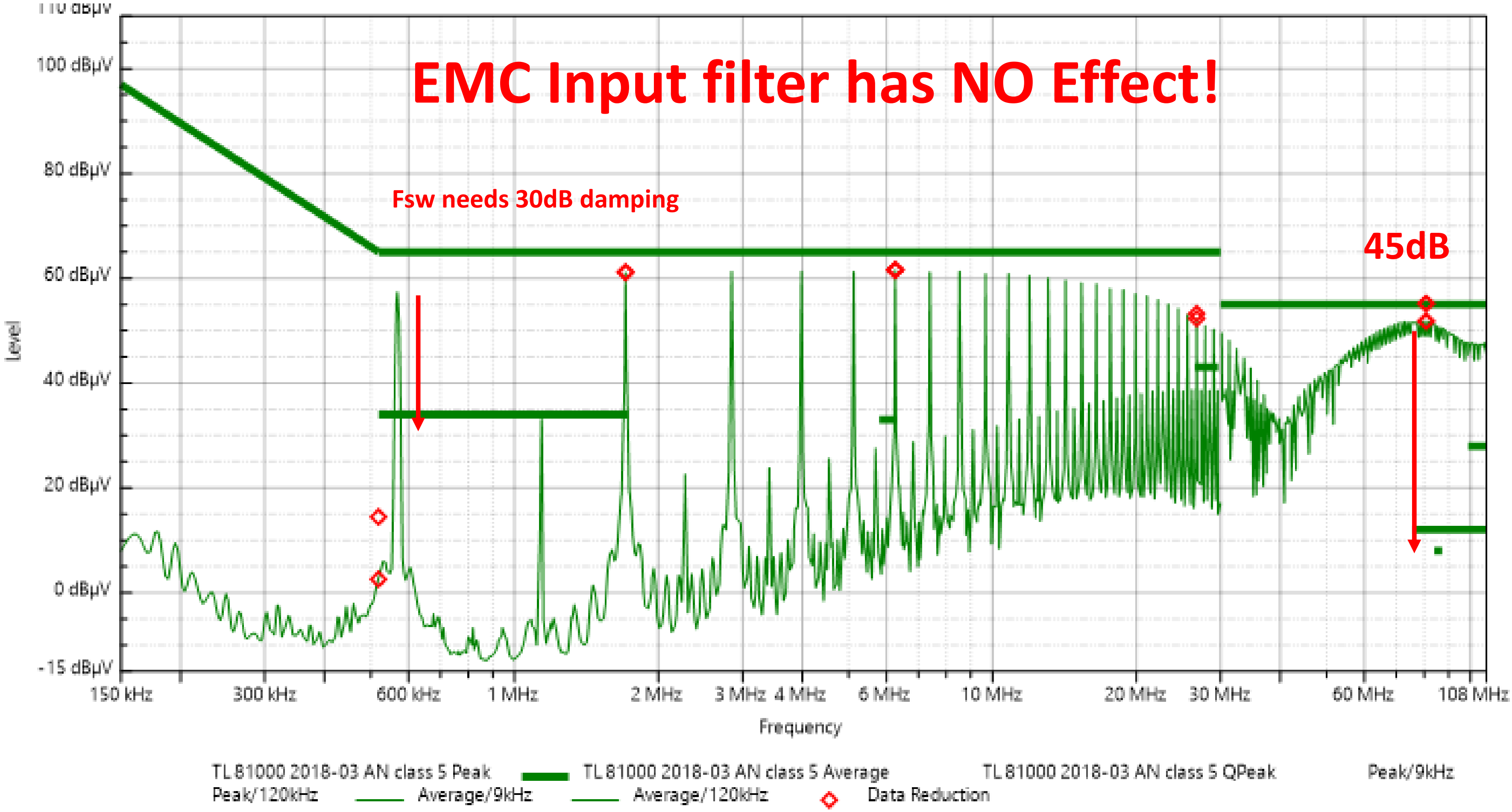


RE Monopole Test 0.1MHz to 30MHz



MPS Example #5:

Isolated DC/DC; 5W, Only CE Average is shown



MPS Example #5:

- Additional tests with Snap-ON Ferrite: No Improvement!
- Test with off Board EMC Filter: No Improvement!
- Copper Foil around circuit: some improvement!
- Add “Y”-Capacitor 2.2nF between primary and secondary GND **shows strong improvement**
- Additional circuit and Layout changes mainly on secondary needed.

Conclusion:

- Check EMC filter structure for effectiveness
- Review PCB layout for high di/dt circuit nodes:

  Loops have to be minimized!
- Review layout and components connected to high dV/dt nodes:

  High dV/dt area should be small and low profile!
- Try different inductors. Usually smaller and lower profile types radiate less.
- If distance between DC/DC and cable/connector is to small, use a local shield on top of DC/DC circuit.

Q&A

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