Understanding Mitigation Methods to EMC issues

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MN EMC Event 2023

Mitigation Techniques

- Grounding
- Shielding
- Filters
- Ferrites

Ground

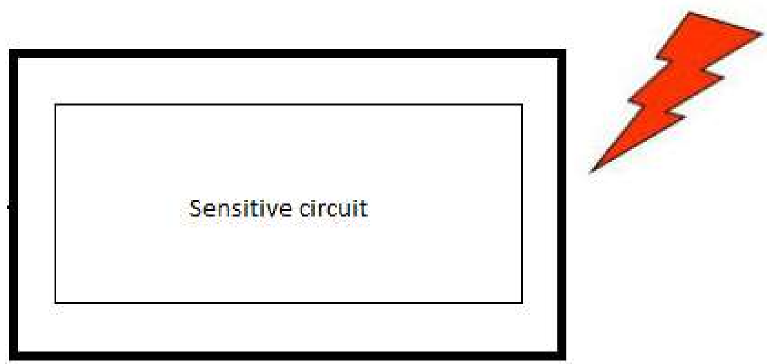
- What is ground?

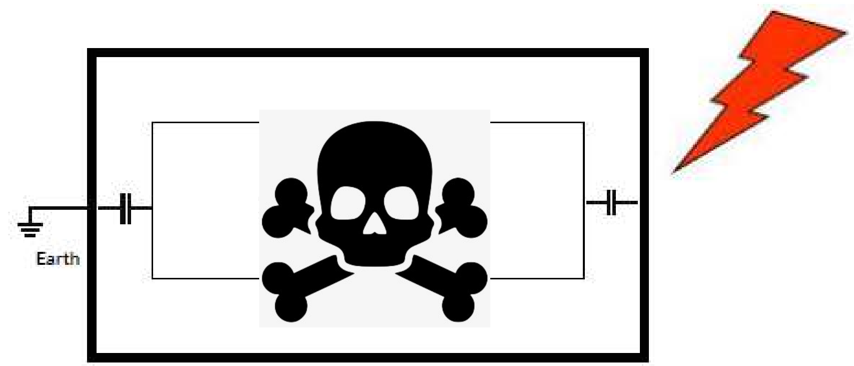
- What does a product actually need?
  - Signal return path
  - Controlled path for EMI (EMC ground structure)
  - Safety ground

- Earth ground is not needed for good EMC!

Grounding and Bonding

- "Grounding" isn't a universal fix for EMC issues

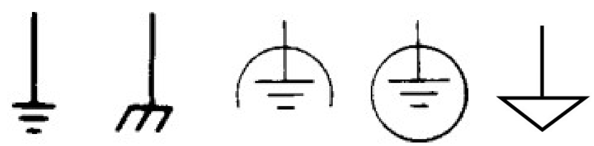




- Ground could be part of the problem!

Circuit Ground

- Different symbols specified for ground all the way back in 1975
  - IEEE 315-1975



- Grounds on a circuit diagram are often shorthand for current return path

Signal return path

- Signal return path needs to be low impedance
- A wire is not low impedance at high frequency
- Reference planes are the best option – but are not equipotential at high frequency!
- Return path can be on a supply voltage plane (AC signal return doesn't care about DC volts)

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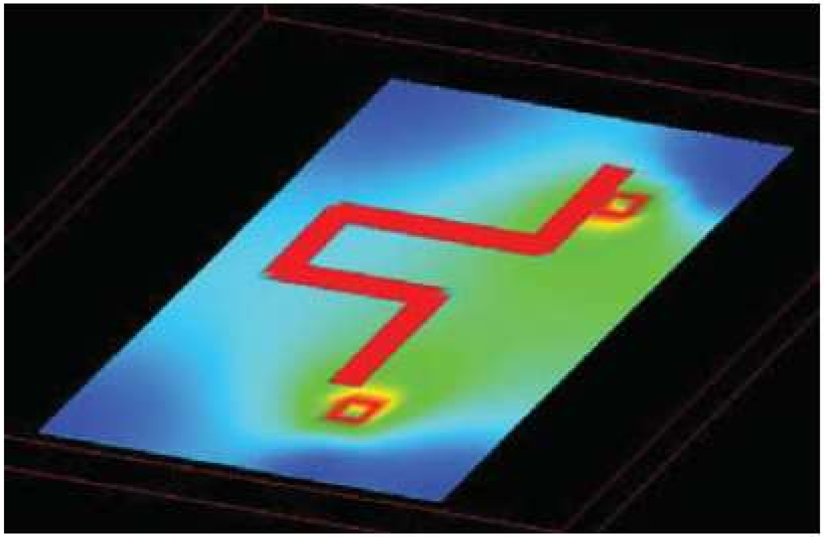
Controlling Return Current

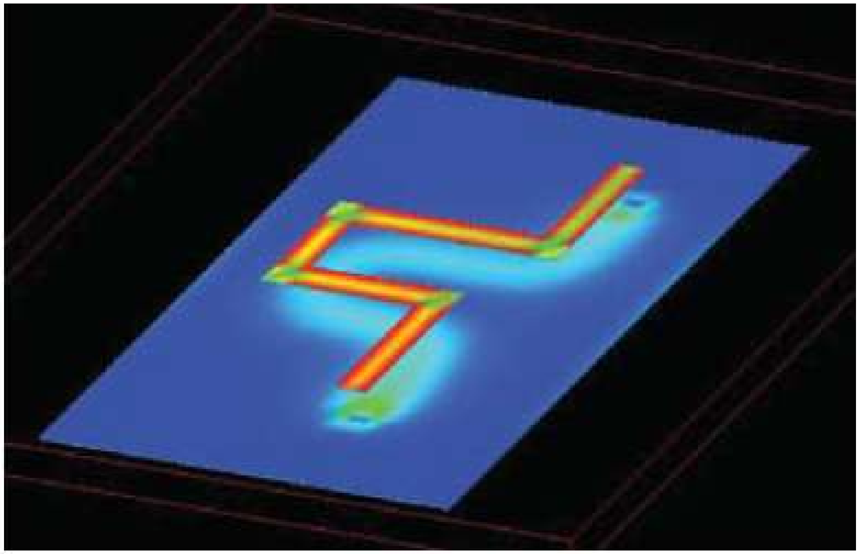
- Keep return planes solid – no moats, separations, etc.
- When splitting power planes use stitching capacitors for signals crossing them
- Don’t bring high frequency signals to a single point – take them back to return plane!

- Analog and Digital return planes can be isolated from each other to reduce Common Impedance Coupling

Current return path



(a) Frequency of 1 kHz



(c) Frequency of 1 GHz

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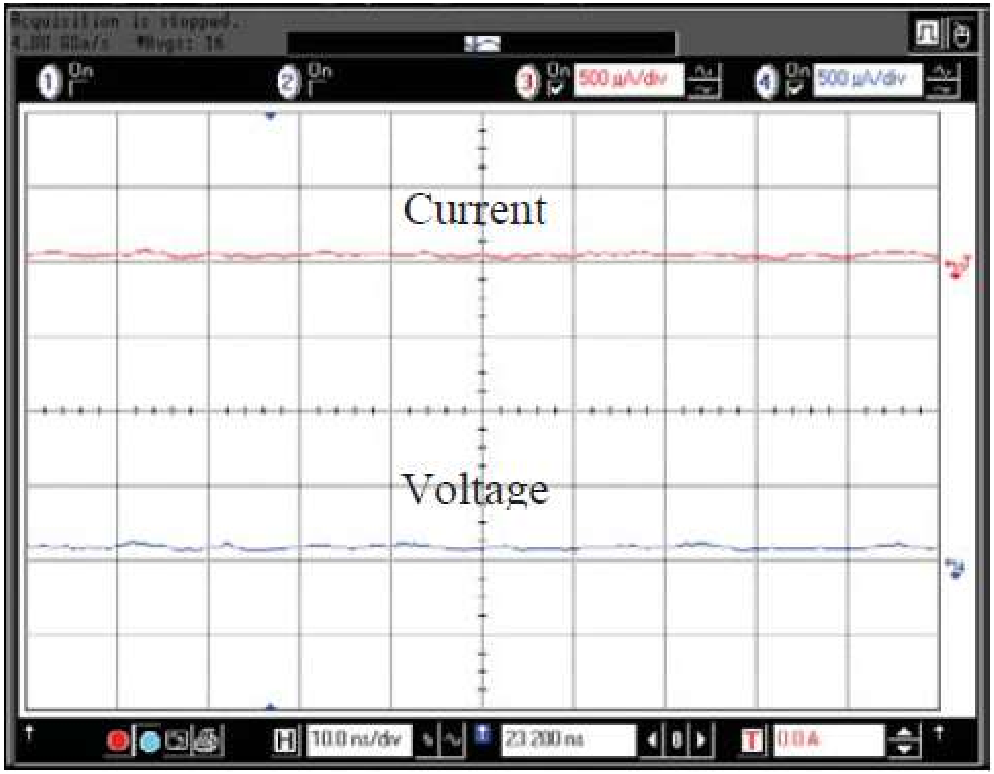
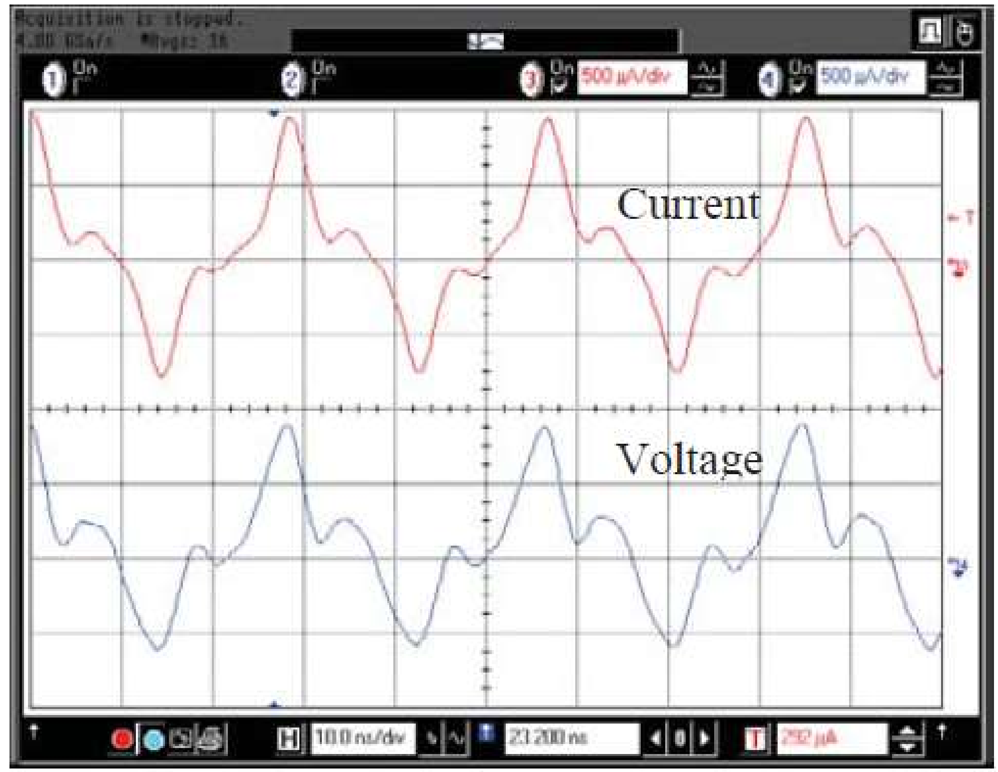
Gaps in Reference Planes





Images courtesy Doug Smith

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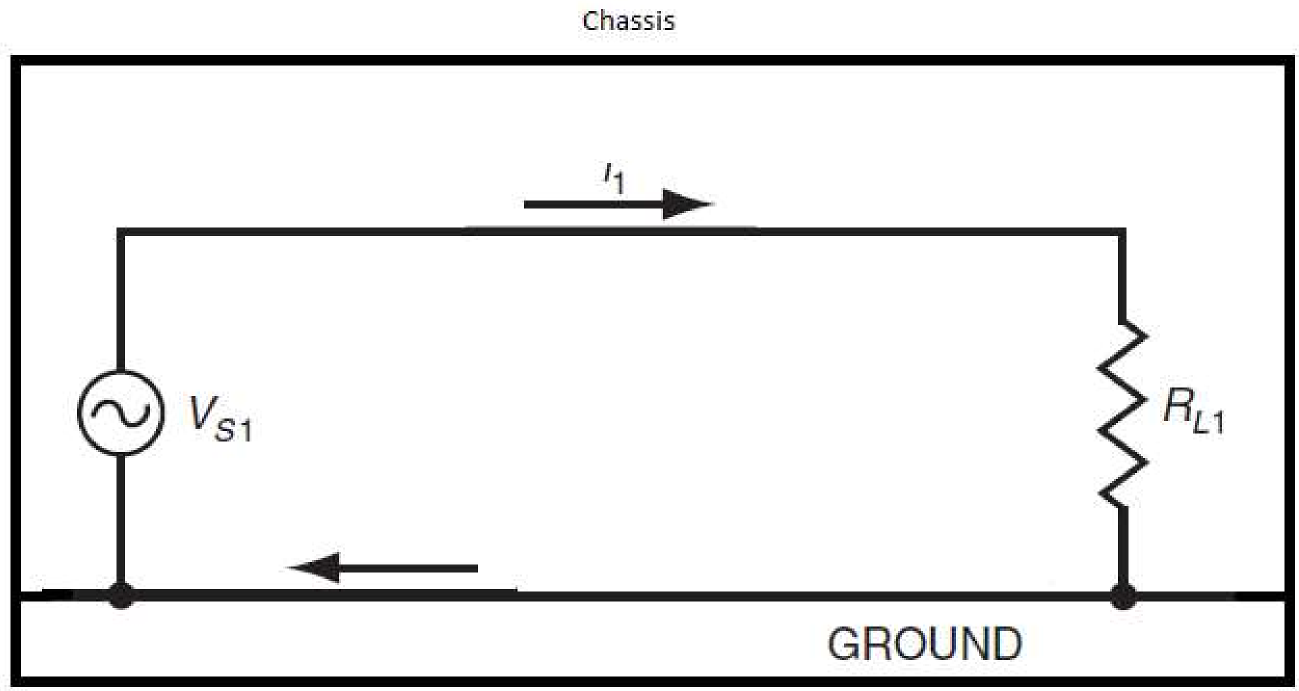
EMC ground structure

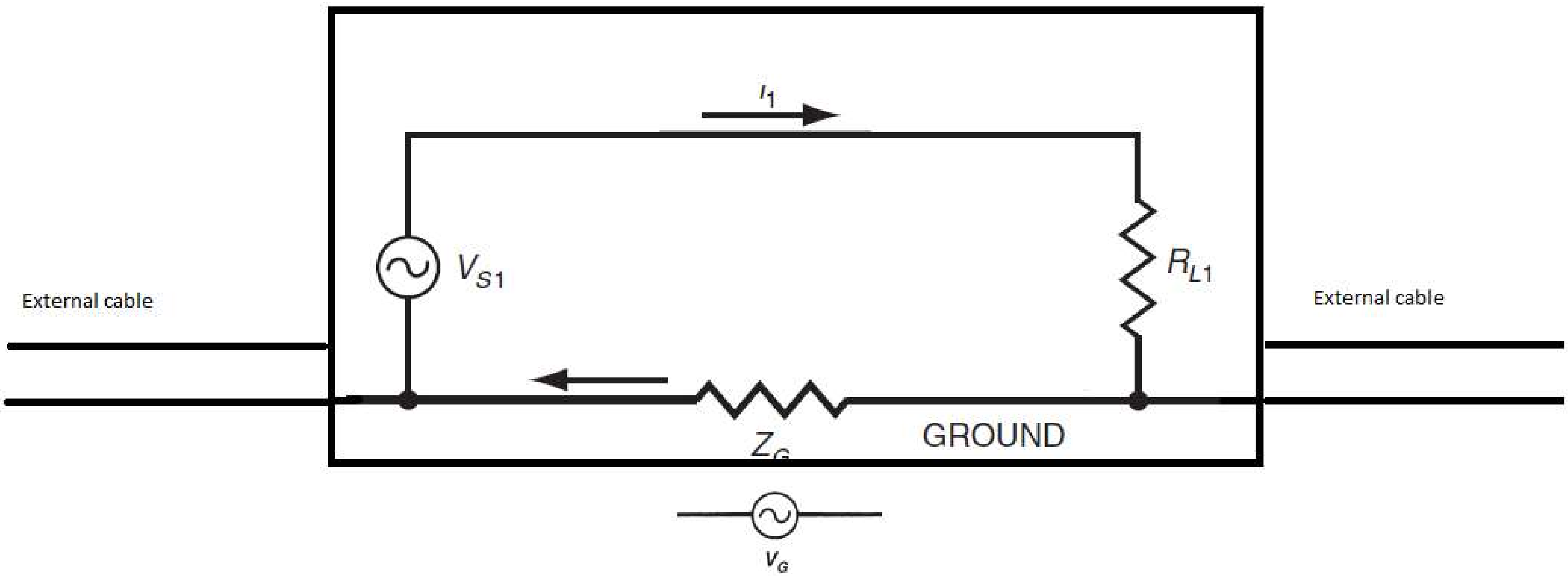
- Think of EMC ground like AC mains – ground is not intended to carry current except in fault conditions – your signal return path is supposed to do that!

- EMC ground structures
  - Do not carry return currents
  - Convenient to bond to for all parts of system
  - Can be:
    - Chassis
    - PCB plane

Circuit with ground return



Realistic Circuit



Connecting grounds

- Create grounding maps
- Star, hybrid, multi-point, single point all work in right circumstances
- Ground layout much less critical if return current paths are correctly designed. Don’t tie high frequency current returns together!
- Ground loops are an issue if you don’t control return current paths
- Isolate sensitive analog from noisy digital

- There is no one-size-fits-all solution to grounding!

Grounding map or tree

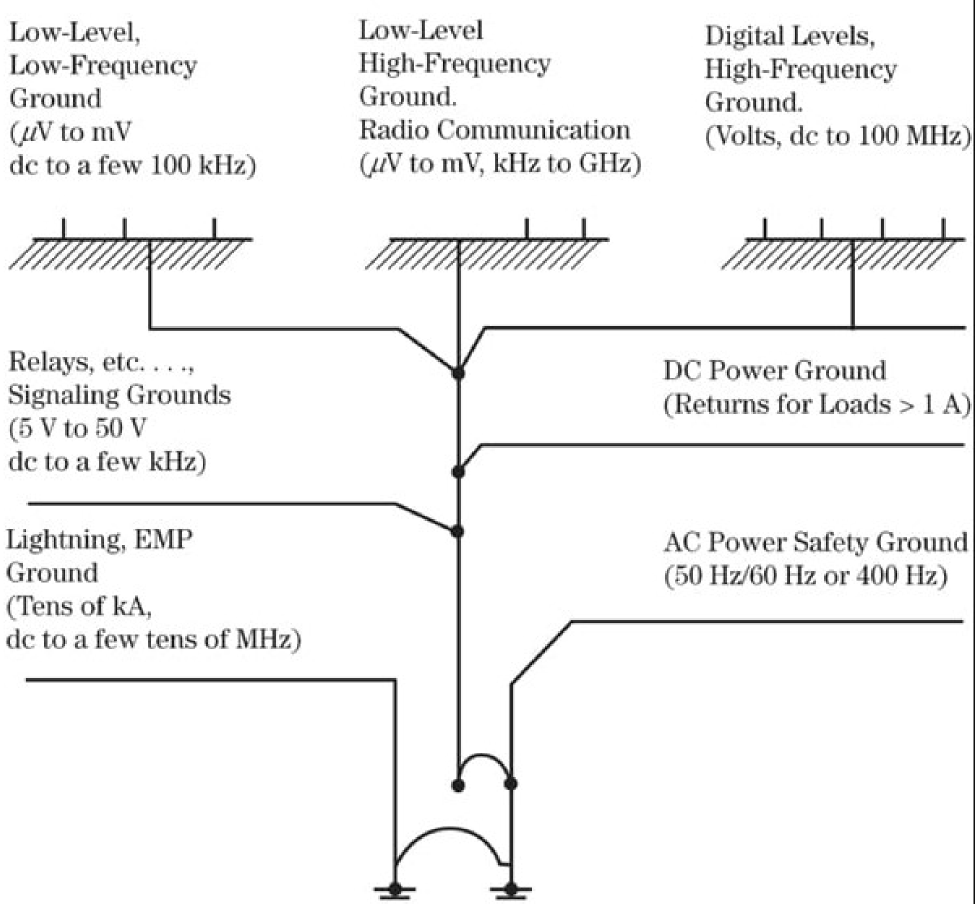
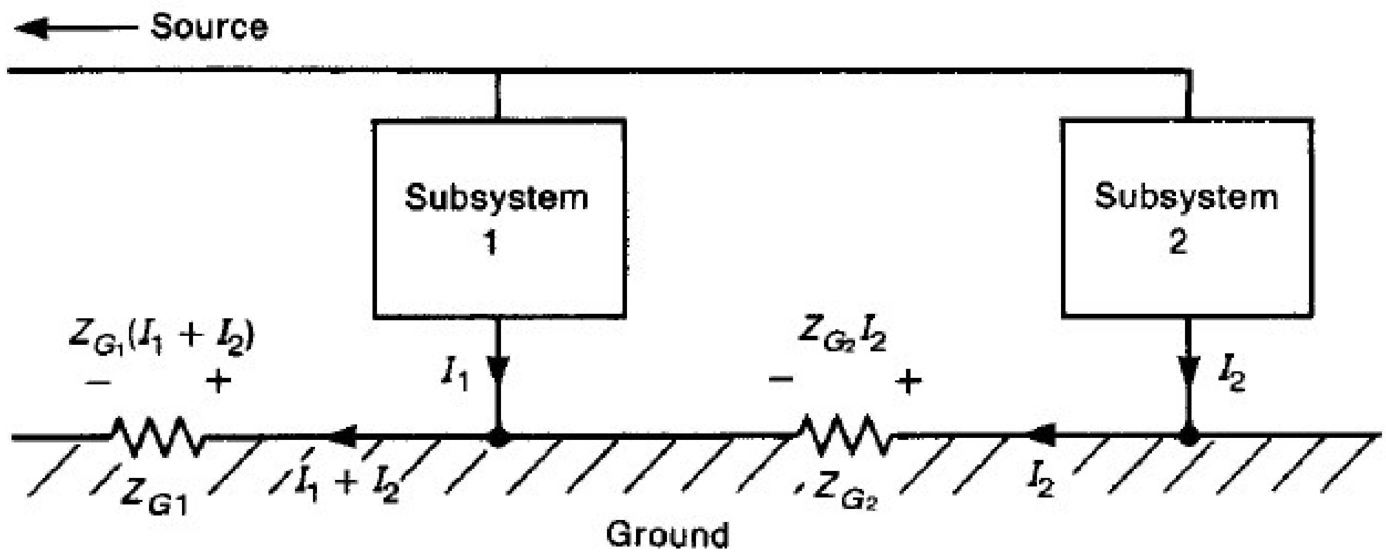


Image courtesy Dr. William Duff

Common Impedance Coupling



- Separate grounds in a system (e.g. analog vs digital) can improve common impedance coupling

Image from Introduction to Electromagnetic Compatibility by Clayton Paul

Design tips

- Define signal and EMC return paths during design
- Don’t tie analog and digital planes together more than once
- I/Os should by bonded to ground structure and all exit same side of board
- Ensure good bonding between different parts of the chassis(no paint or anodizing)
- Tie PCB circuit ground to chassis near I/O ports
- No splits in board reference planes

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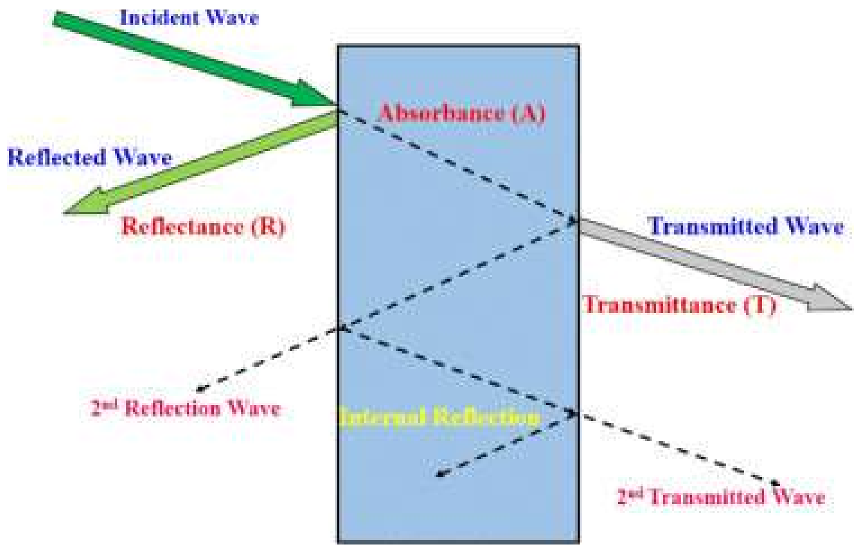
Shielding

- Shields create an impedance mismatch to reduce interference

- Absorption loss depends on material thickness, permeability, electrical conductivity, and frequency of the incident wave.
- Reflection loss depends on the distance of the EMI source to the material, material electrical conductivity, and frequency of the incident wave.

Reflection and Absorption



- Shielding effectiveness

  SE = R+A+M
- R and A depend on frequency and material
- Magnetic shielding requires material with high permeability
- Magnetic shields only effective above cutoff

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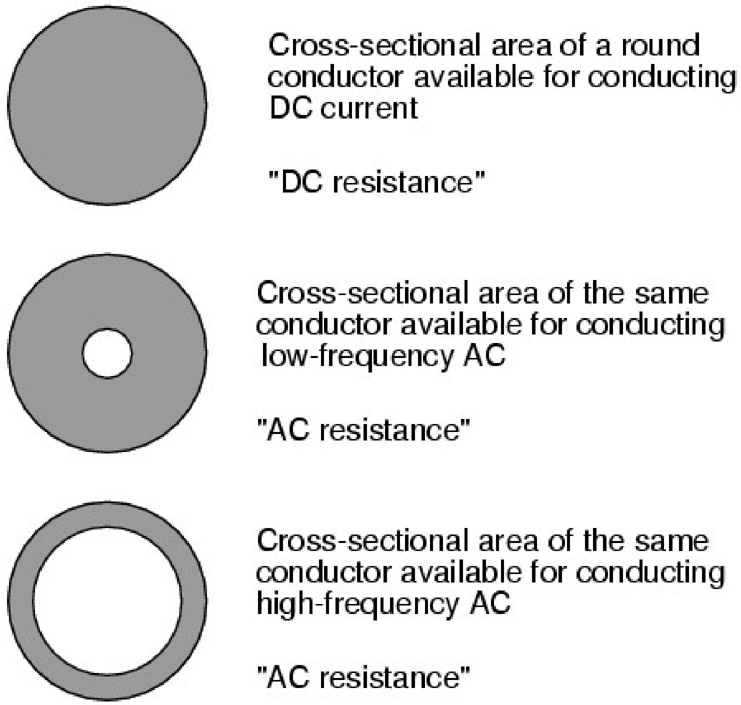
Skin Effect

- Skin effect – AC current flow along the skin of a shield
- Affects shield impedance
- E.g. Coaxial cables – noise current flows on outside of shield, return currents on inside of shield



Skin depth of copper

- Skin depth is depth where current is ~37% of surface current

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Where:

δ = skin depth (mm)

ω = angular (radian) frequency

μ = material permeability (4π x 10^{-7} H/m

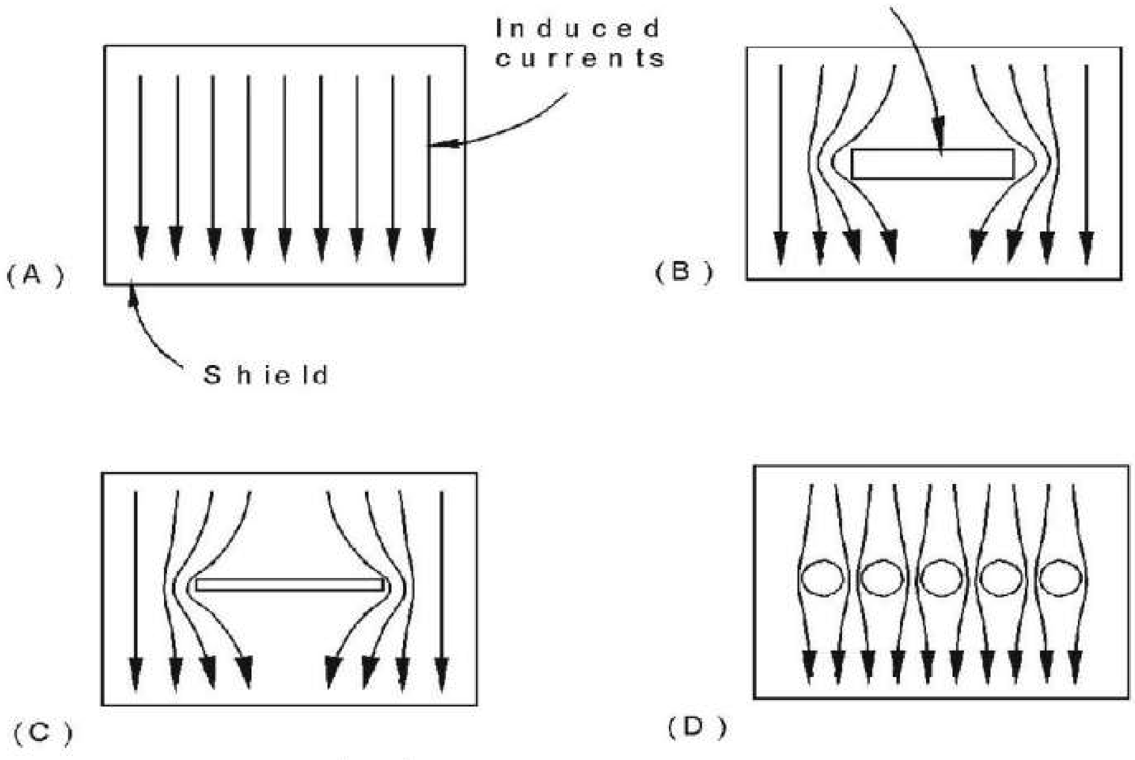
σ = material conductivity (5.82 x 10^{7} mho/m for Cu)

f = frequency (hertz)

f	δ (copper)
60 Hz	0.0086 in (8.6 mil, 2.2 mm)
100 Hz	0.0066 in (6.6 mil, 1.7 mm)
1 kHz	0.0021 in (2.1 mil, 0.53 mm)
10 kHz	0.00066 in (0.66 mil, 0.17 mm)
100 kHz	0.00021 in (0.21 mil, 0.053 mm)
1 MHz	0.000066 in (0.066 mil, 0.017 mm)
10 MHz	0.000021 in (0.021 mil, 0.0053 mm)
100 MHz	0.0000066 in (0.0066 mil, 0.0017 mm)
1 GHz	0.0000021 in (0.0021 mil, 0.00053 mm)

Apertures

- Current flow is disrupted
- Slot contains resistance and inductance
- Creates an electric field



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Multiple Apertures

- Multiple small apertures better than 1 large one
- Multiple aperture SE drops by approx. 10*Log(N)
  - i.e. 2 apertures = 3 dB loss, 4 = 6 dB
- Try and have circuits orthogonal to long apertures, or increase physical separation
- Depth of aperture matters

Waveguides

- Waveguide below cutoff
- Diameter determines cutoff freq
- Depth affects SE

- Cutoff freq

$$f_c = \frac{C}{2 \times W}$$

$$f_c = \frac{1.8412 \times C}{2 \times \pi \times r}$$

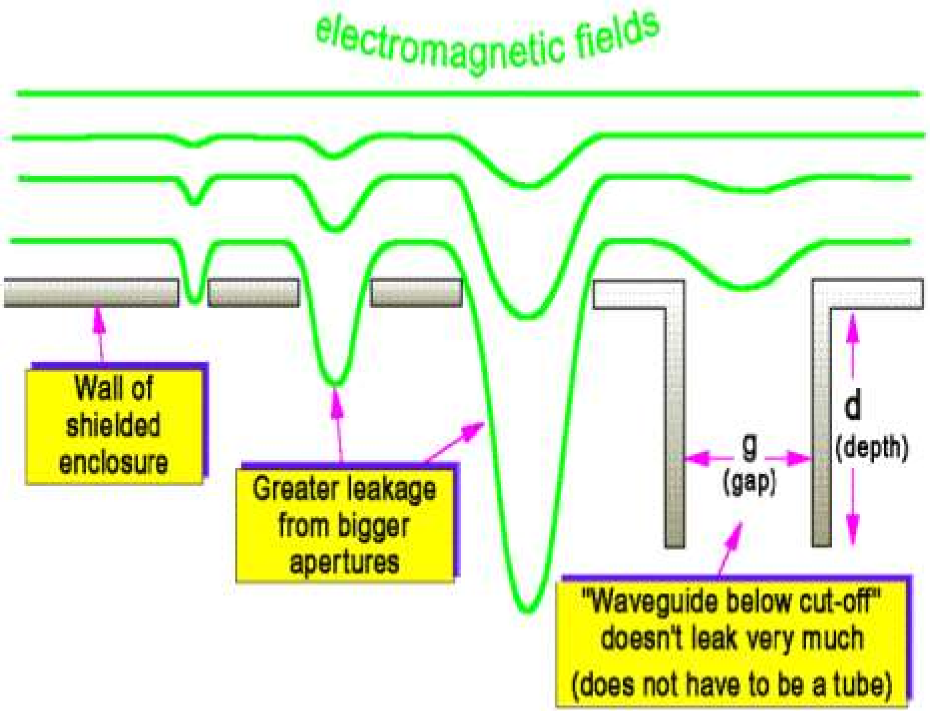
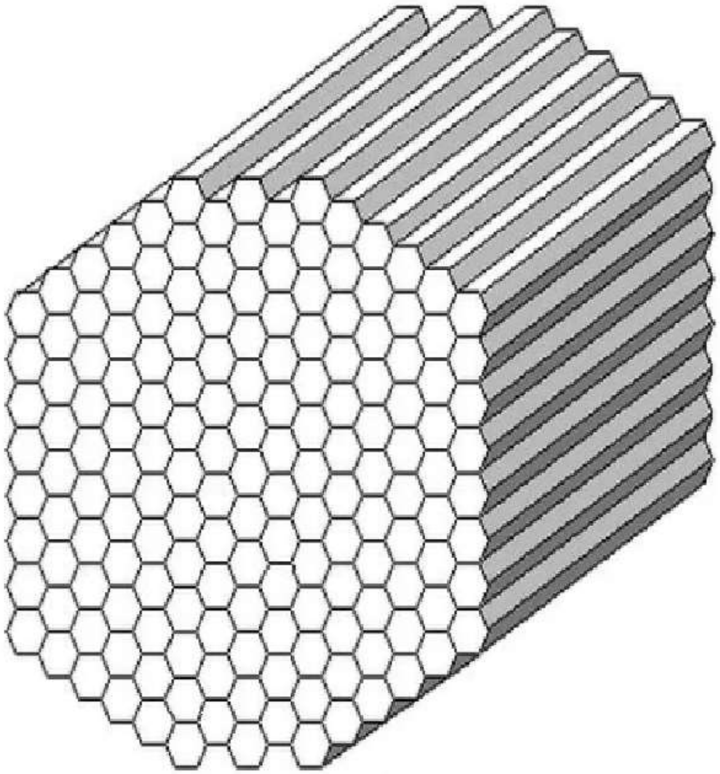


Image courtesy of Keith Armstrong

Honeycomb shield

- Note – shielding is better east west on diagram – intersecting tops instead of continuous bent seam
- Can do layers offset
- Reduces airflow, improves shielding



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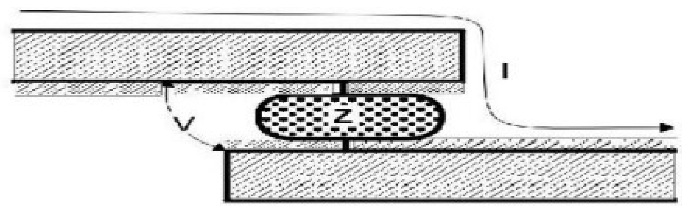
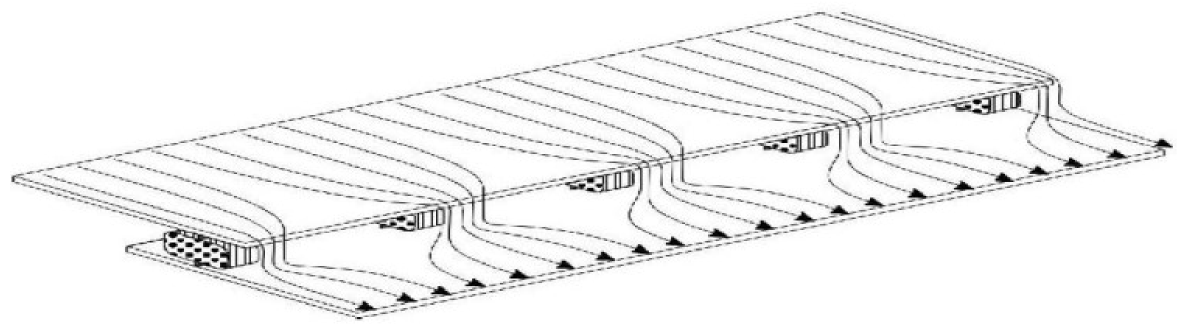
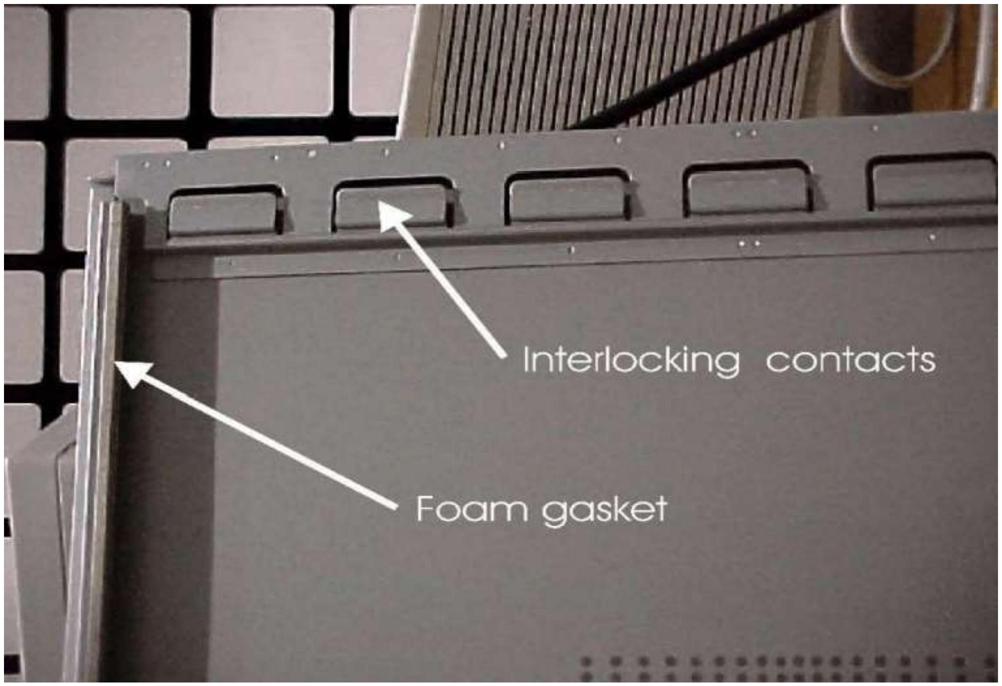
Joints and Seams

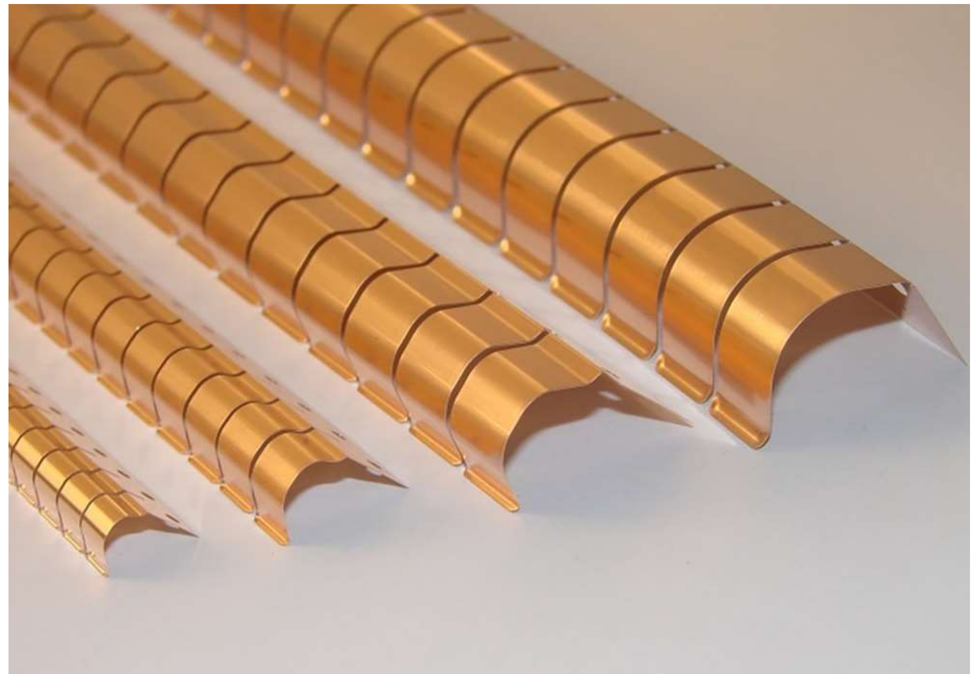
- Impedance between metals means an electric field
- Fixes:
  - More screws
  - Compression joints
  - Gasketing
  - Interconnects
  - Fingerstock





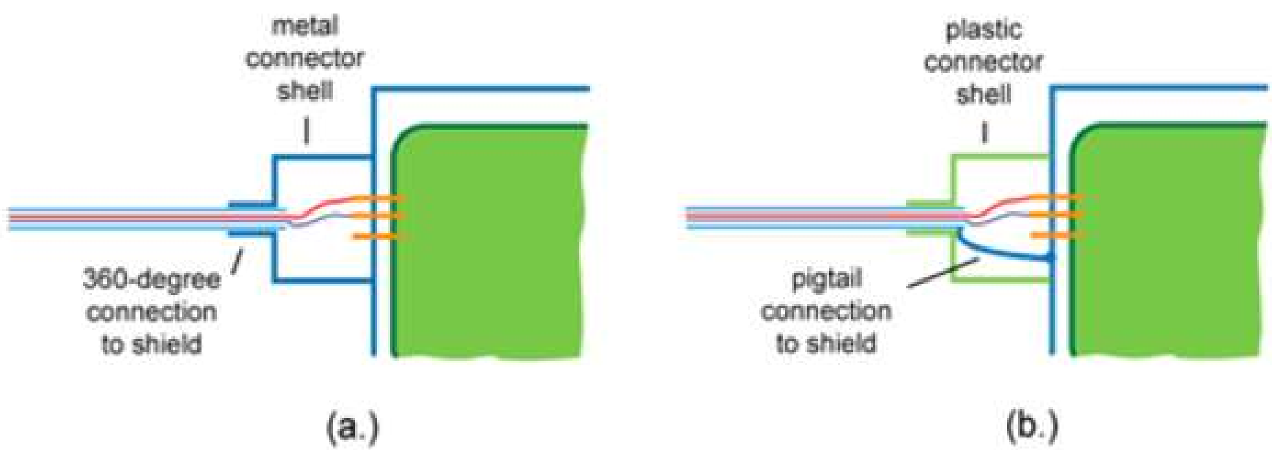
Seam Solutions





Cable Shielding

- Use standard practice RF protection
  - High coverage braid or foil over braid
  - Proper termination at enclosure and support equipment
  - 360 degree connection – no pigtails!



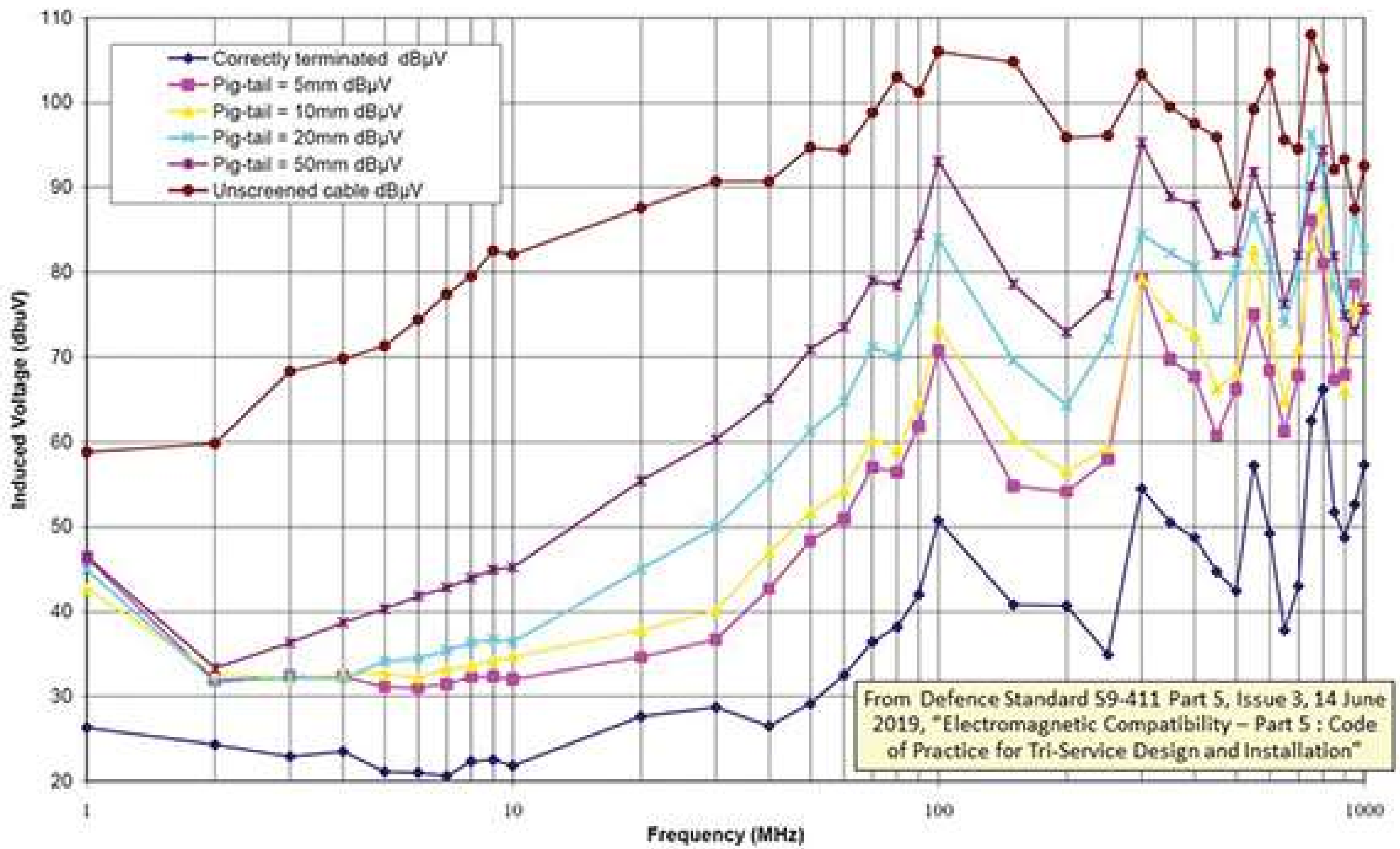


Figure 77 **Induced Voltage on a 0.6 m Cable from a 1 V/m Electric Field for Varying Lengths of Pigtail**

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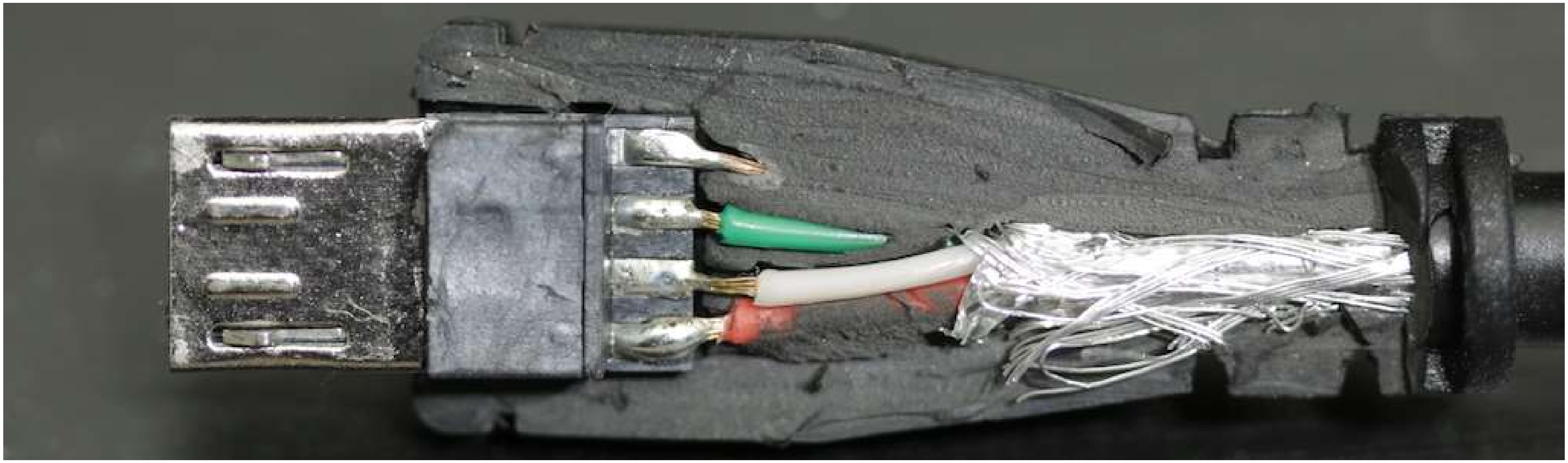
Penetrating enclosures

Shield termination

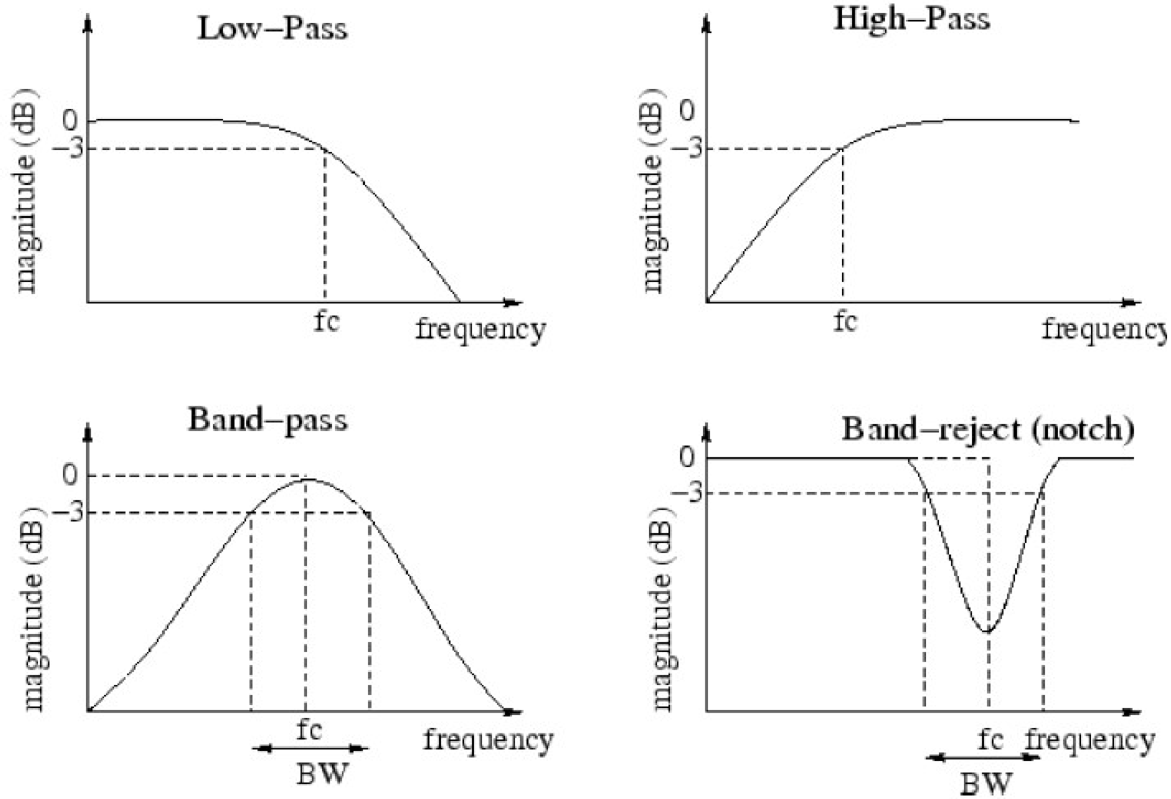
- Off the shelf USB cable



Filtering

- Ideal filter
  - Presents an open or short circuit to the frequency of interest
  - Has no loss in the passband
- Attenuation is driven by impedance mismatch
- Easiest solution for AC mains emissions/susceptibility
- Can be critical for signal lines

Four basic filter types



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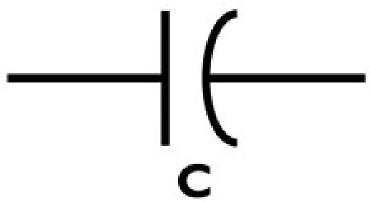
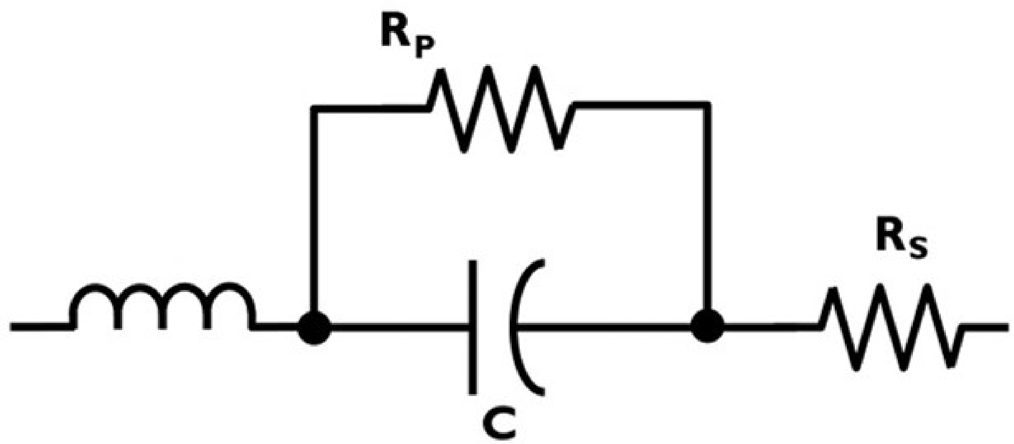
Real capacitors



Ideal Capacitor



“Real” Capacitor

Real Inductors

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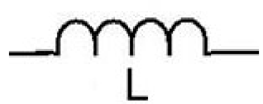
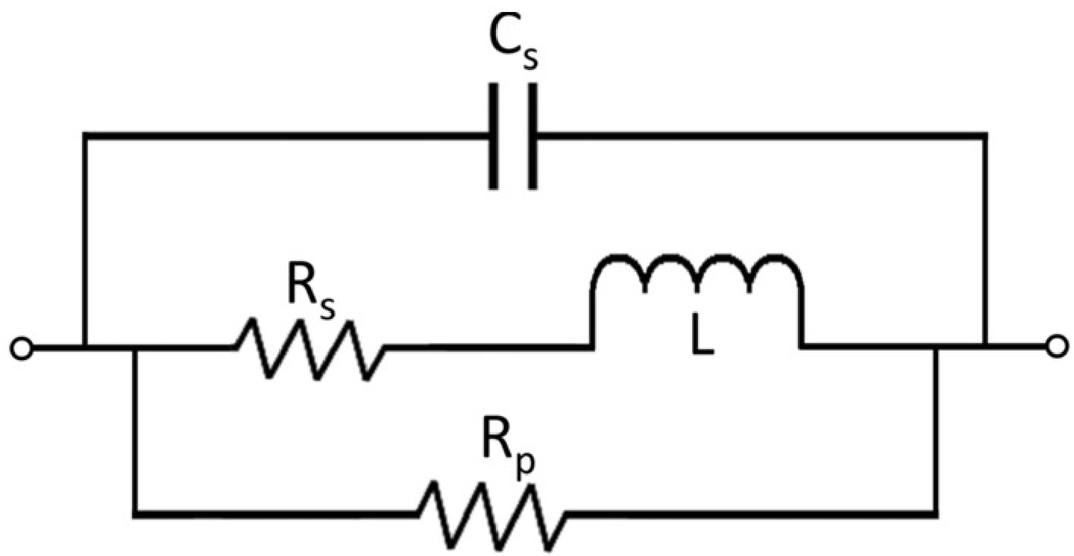
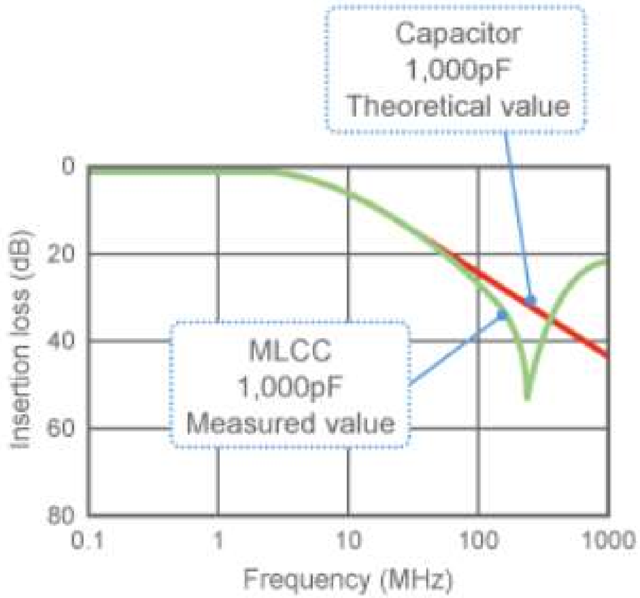


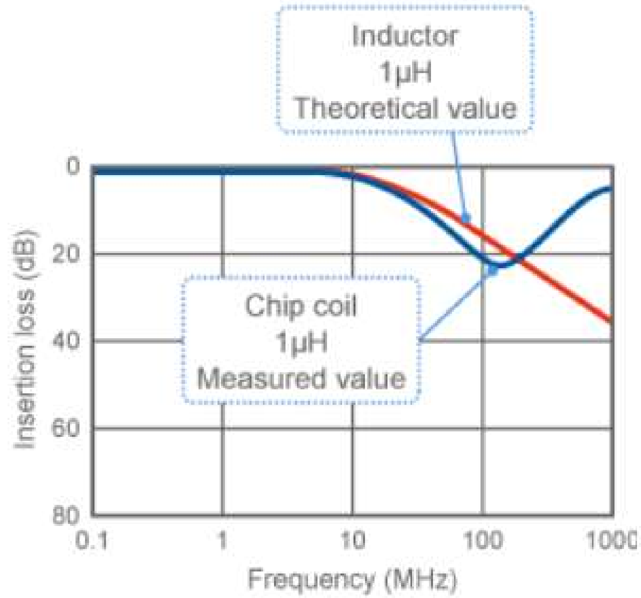


Component Resonance

- Capacitor resonance at Z = 1/(2π*C)
- Inductor resonance at Z = 2π*L



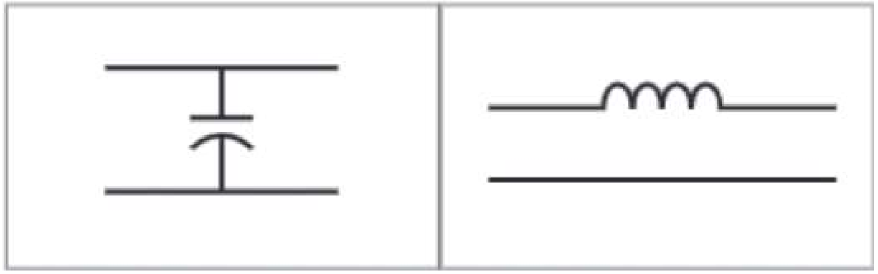
(a) Capacitor



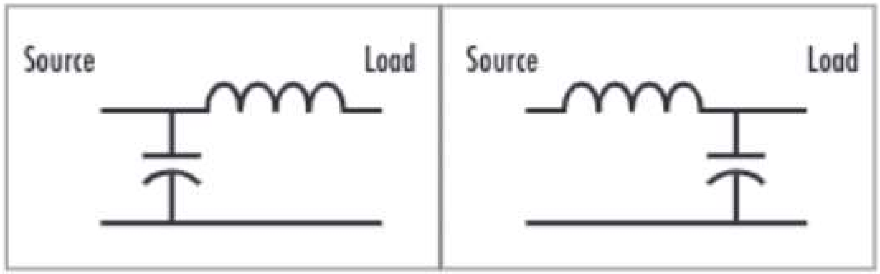
(b) Inductor

Filter orders

- First Order = 1 reactive component

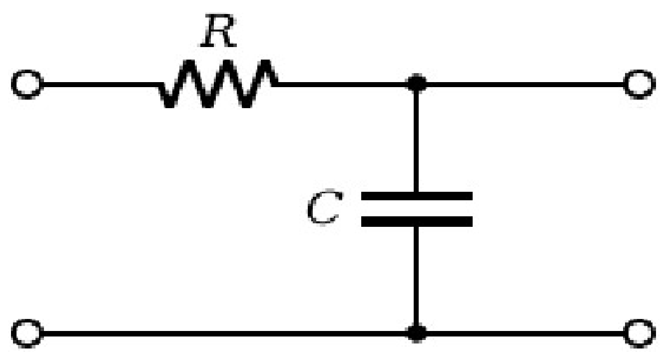


- Second Order = 2 reactive components

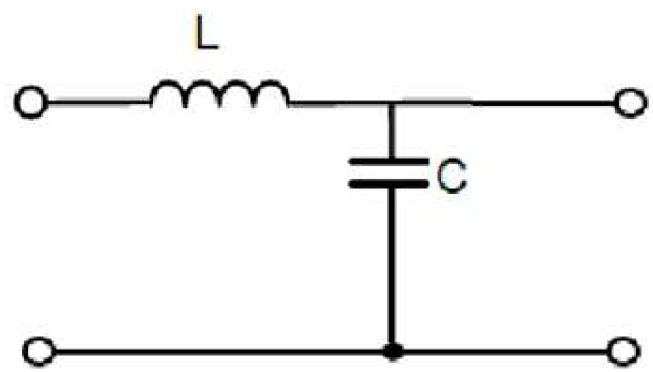


Basic L filter

- Basic RC filter



- Basic LC filter

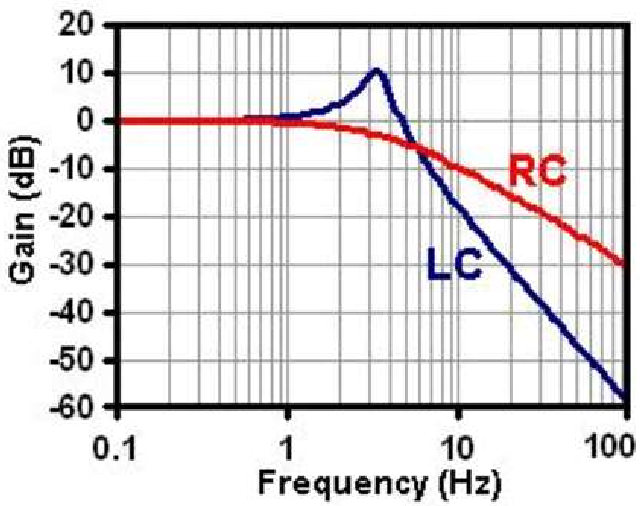


- Low pass has shunt capacitor
- High pass has series capacitor

$$f_c = \frac{1}{2\pi\sqrt{LC}}$$

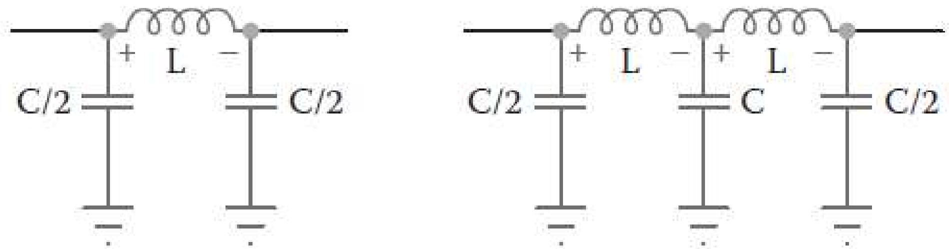
Low-Pass Passive filters

- Can use resistor, inductor, or ferrite as series element
- RC filter
  - Dissipates more power (causes V drop)
  - Single order, so slower roll off
- LC filter
  - Second order filter means better noise rejection
  - Steeper roll off
- FC
  - Wider bandwidth, risks of saturation

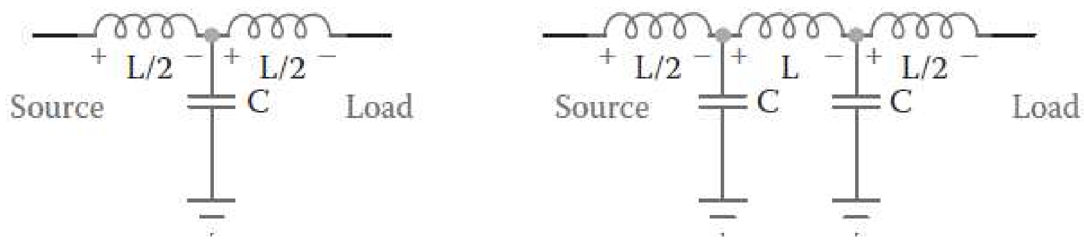


Multi-stage filters

- Increase roll off with additional stages
- Reduce matching concerns
- Consider resonances



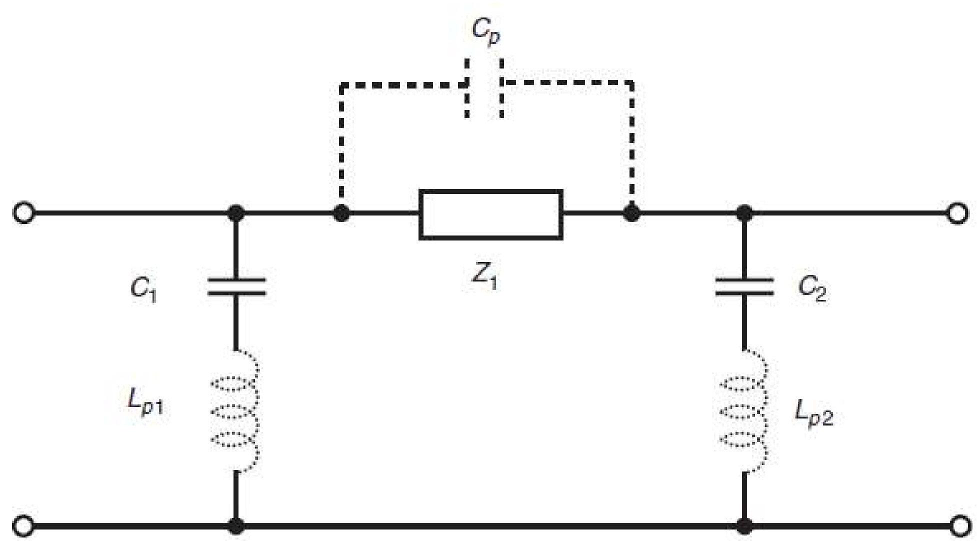
Pi and Double Pi



T and Double T

element

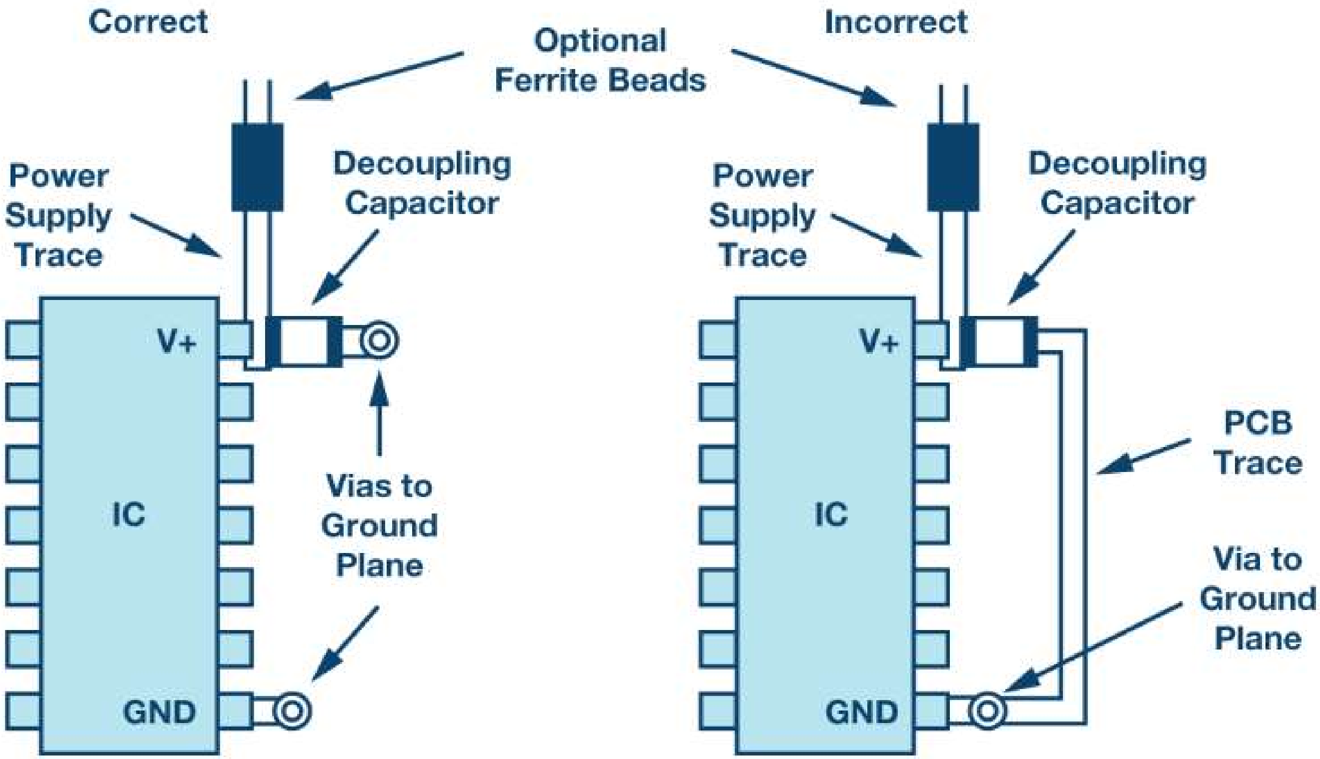
Real Low Pass Pi Filter



- Real filter has parasitic capacitance and inductance
- At high freq changes from low pass to high pass due to parasitics

Image from Henry Ott's Electromagnetic Compatibility Engineering

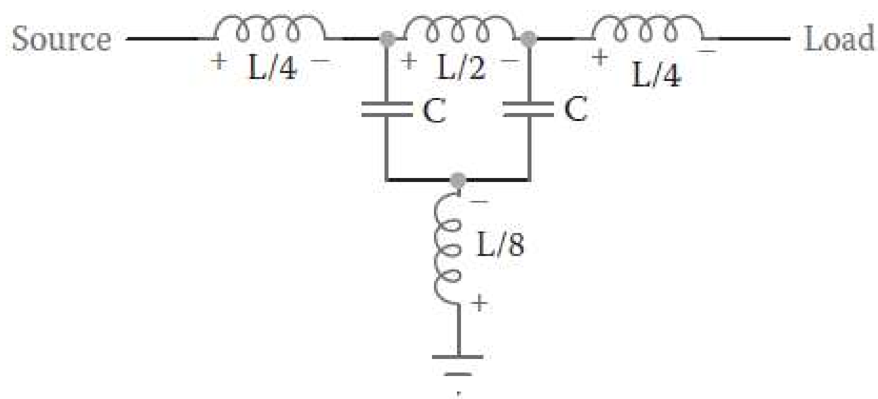
Layout



From Analog.com

Layout

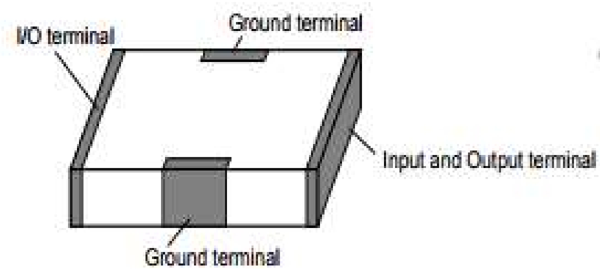
- Poorly grounded double T filter

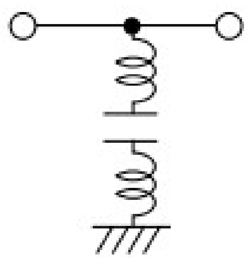


- Poor layout changes resonances and attenuation

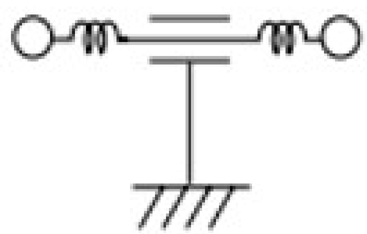
Three terminal capacitors

- Three terminal capacitors(feed through capacitors)
  - Shorter leads
  - Less inductance
  - Better high frequency performance





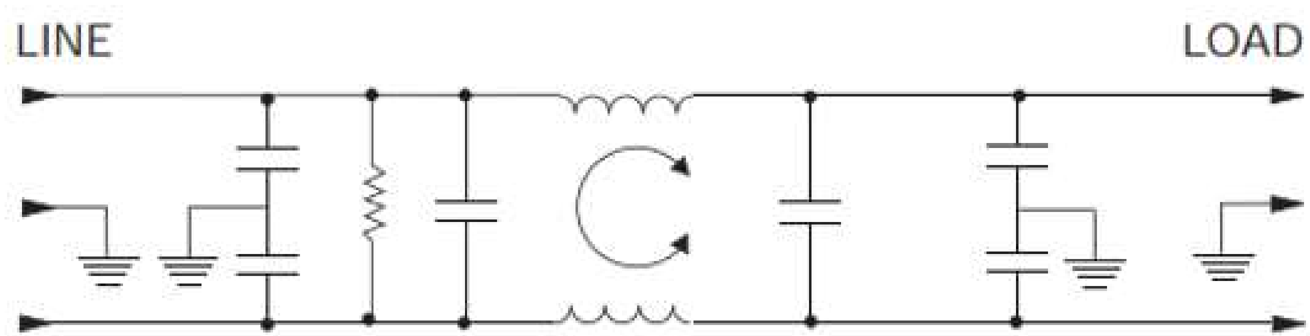
Two terminal cap circuit



Three terminal cap circuit

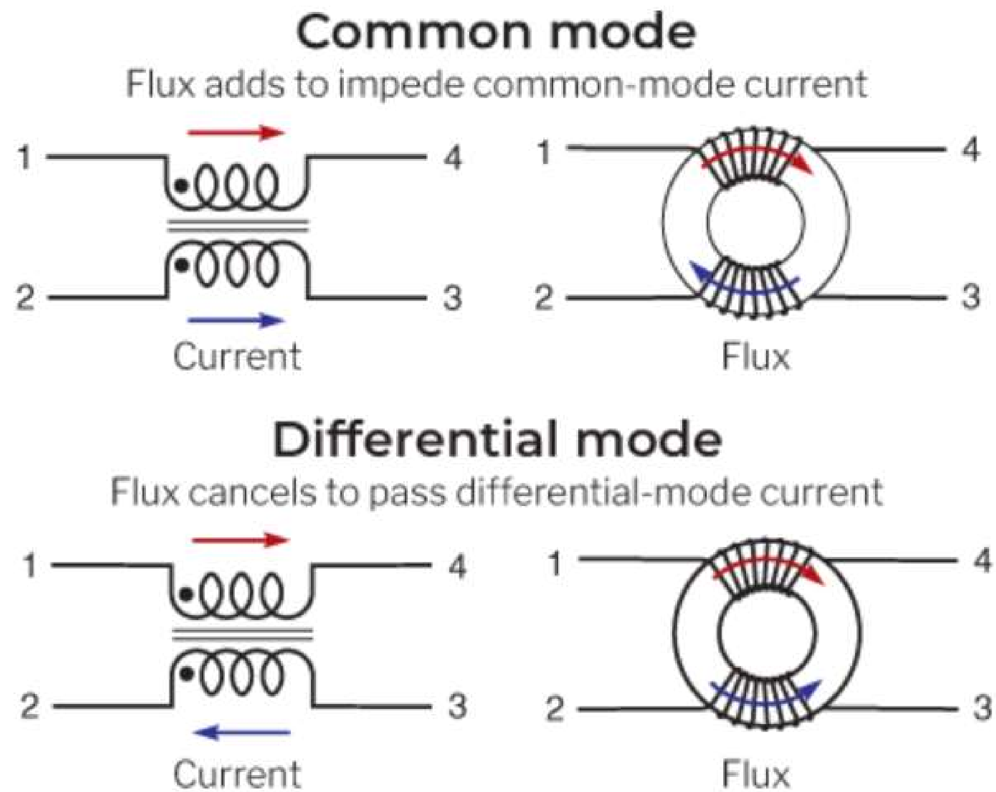
AC Mains Two Stage filter

- Two stage filter
- Two Y caps, a discharge resistor, X cap, common mode choke, an X cap, and two Y caps.



Common Mode Chokes

- Low differential mode impedance
- Used on mains and some data lines
- Risk of saturation



Two stage filter attenuation

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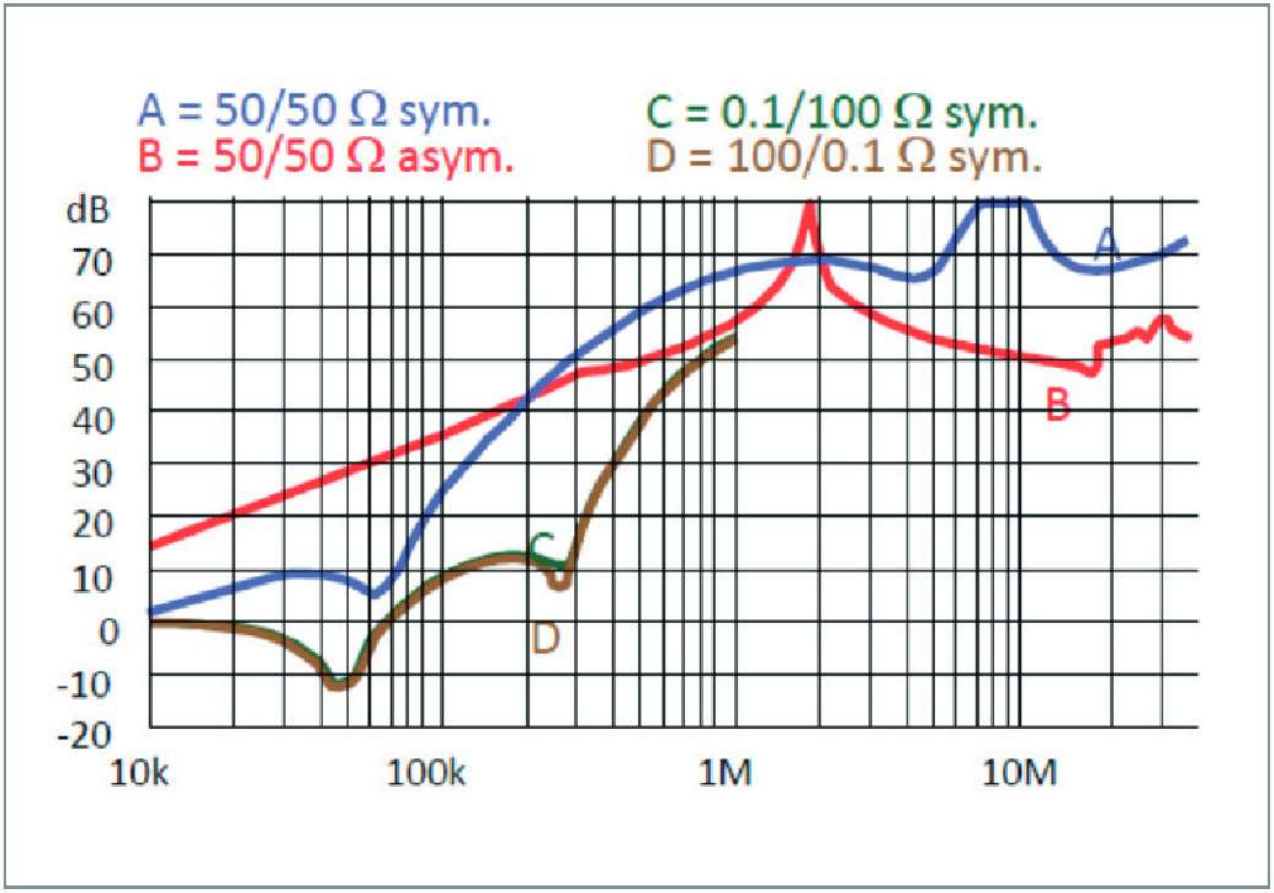
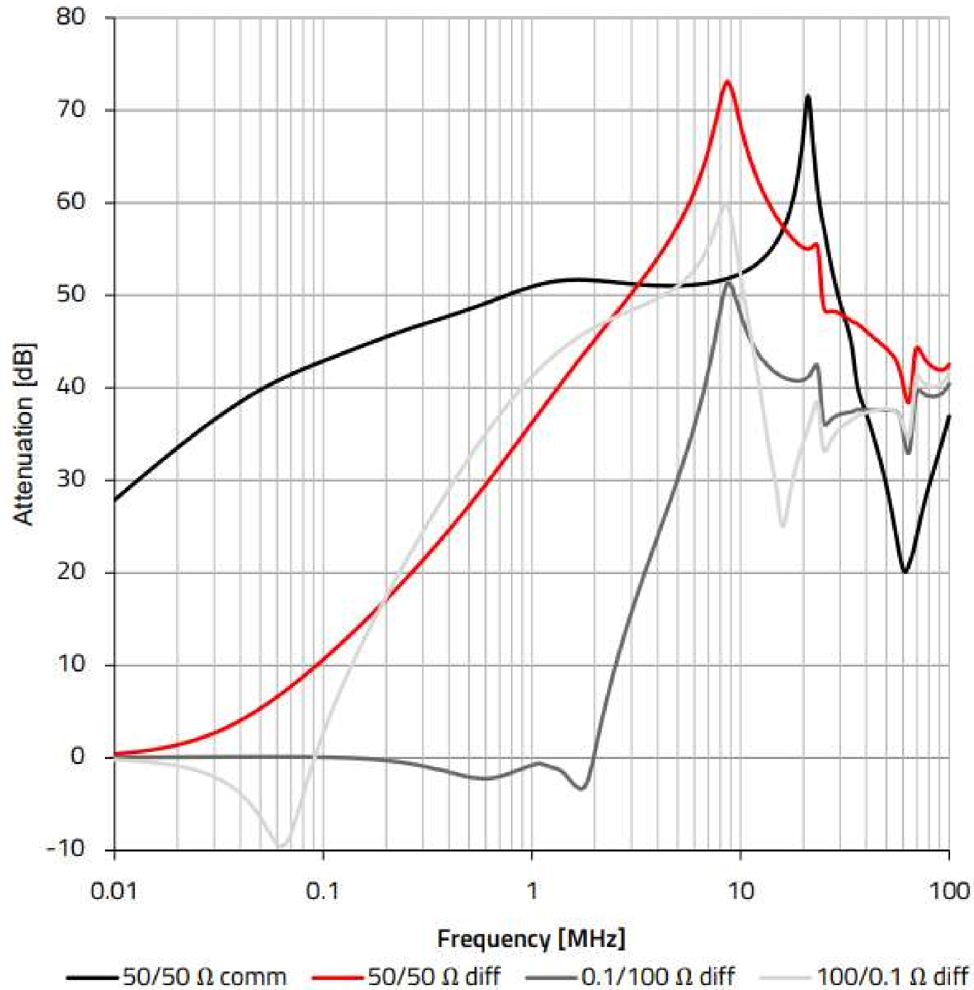


Single Stage Filter Attenuation



Mains filter sample

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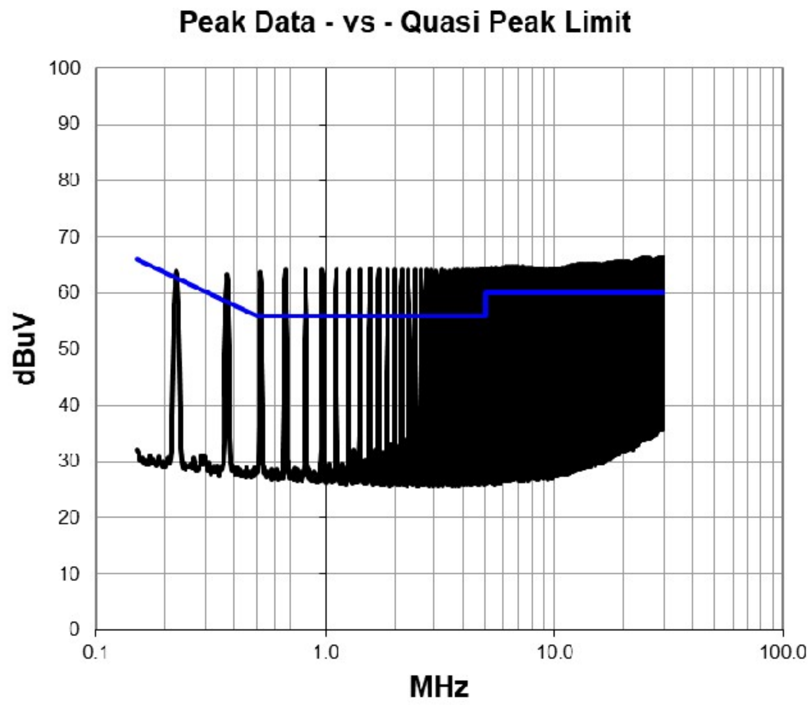

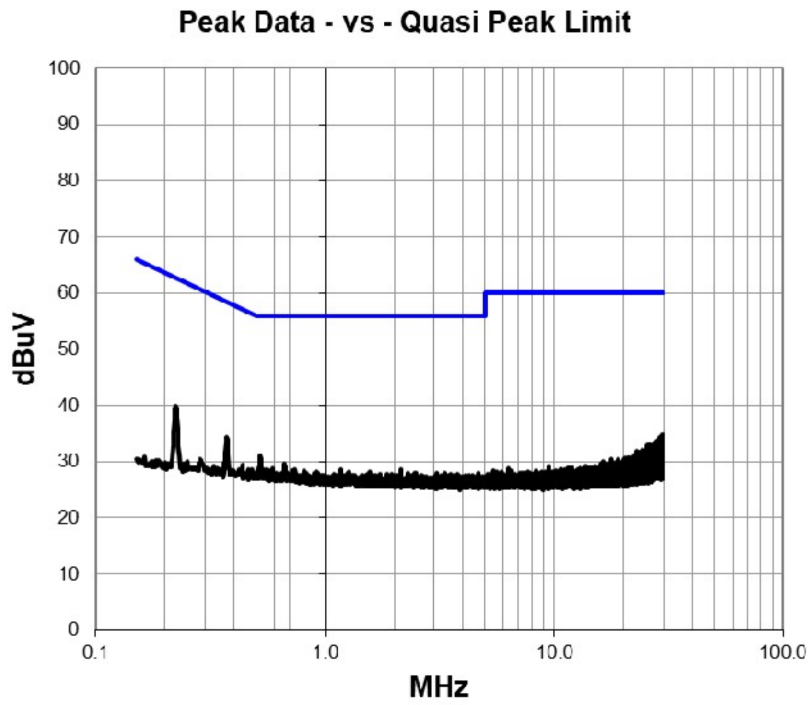

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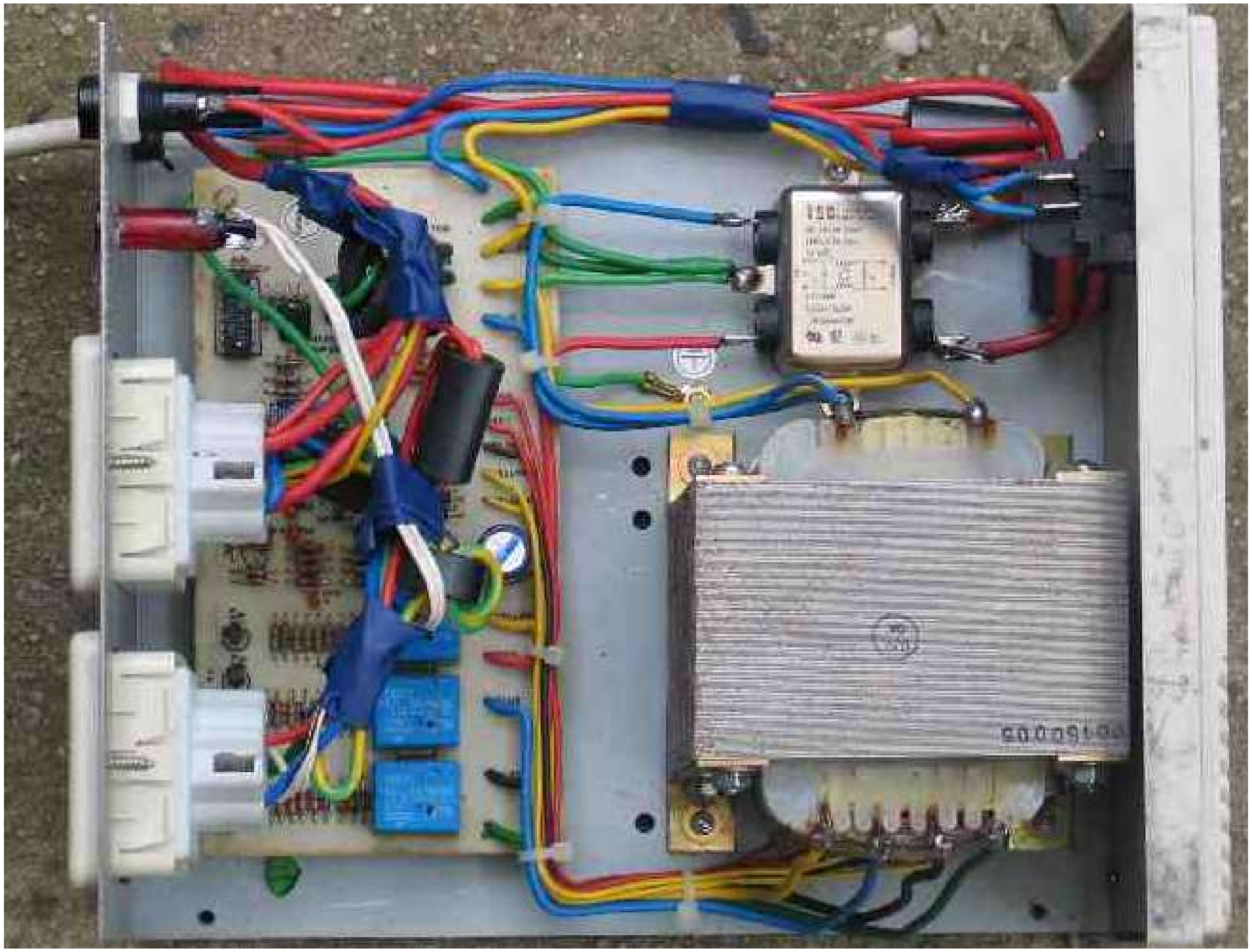
Mains filter limitations

- Limited value for transient suppression
- Leakage current limitations with Y caps
- X Caps limited by energy efficiency
- Choke saturation
- Follow installation guidelines

Poor filter installation



Poor filter installation

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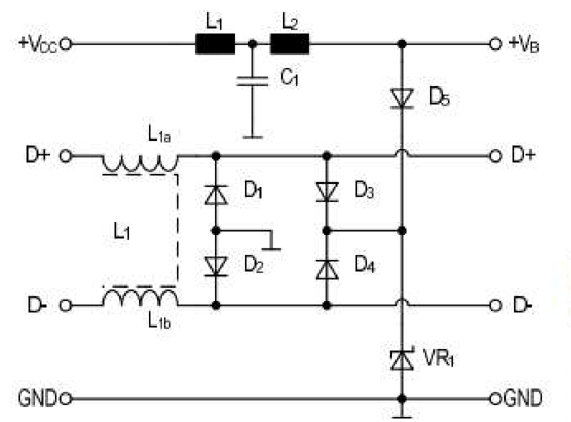
Off -the-shelf filter options

- Insert at connector

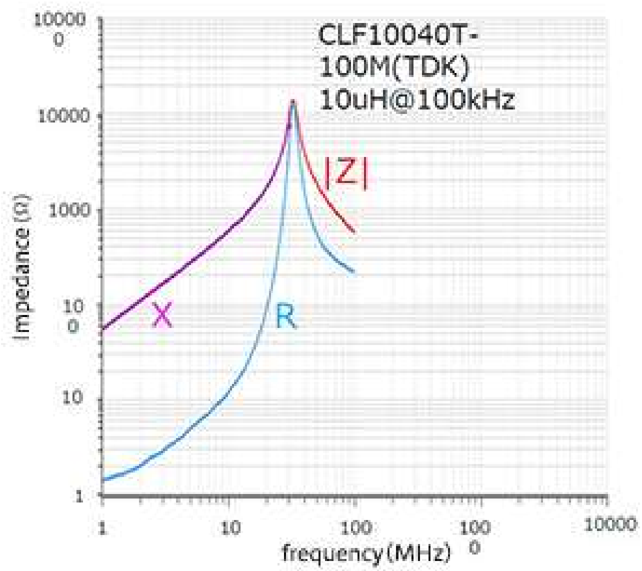


- Built into board connector

Ferrites

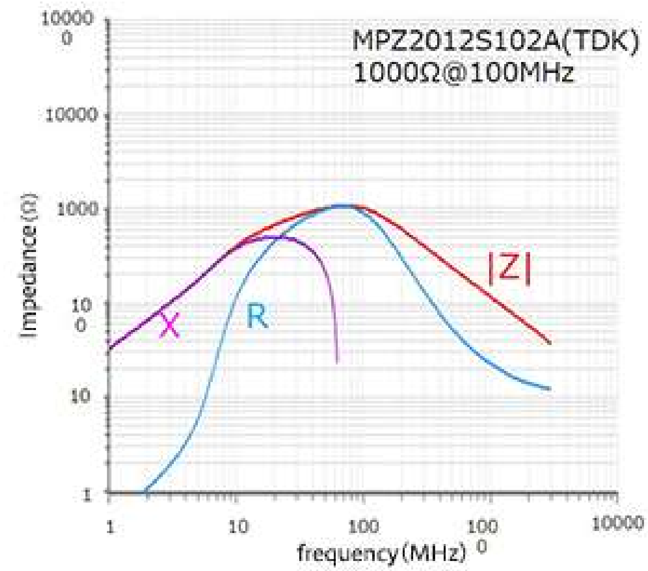
- Ferrite beads are conductors surrounded by magnetic material (ferrite)
  - Soft magnetic material can be easily magnetized and demagnetized
- Can be thought of as “frequency dependent resistance”
- Inductors and ferrite beads are both inductive components, but not always interchangeable

Inductor vs Ferrite



Inductor Impedance

- Low R component (loss).
- High Q.



Ferrite Bead Impedance

- High R component (loss).
- Low Q.

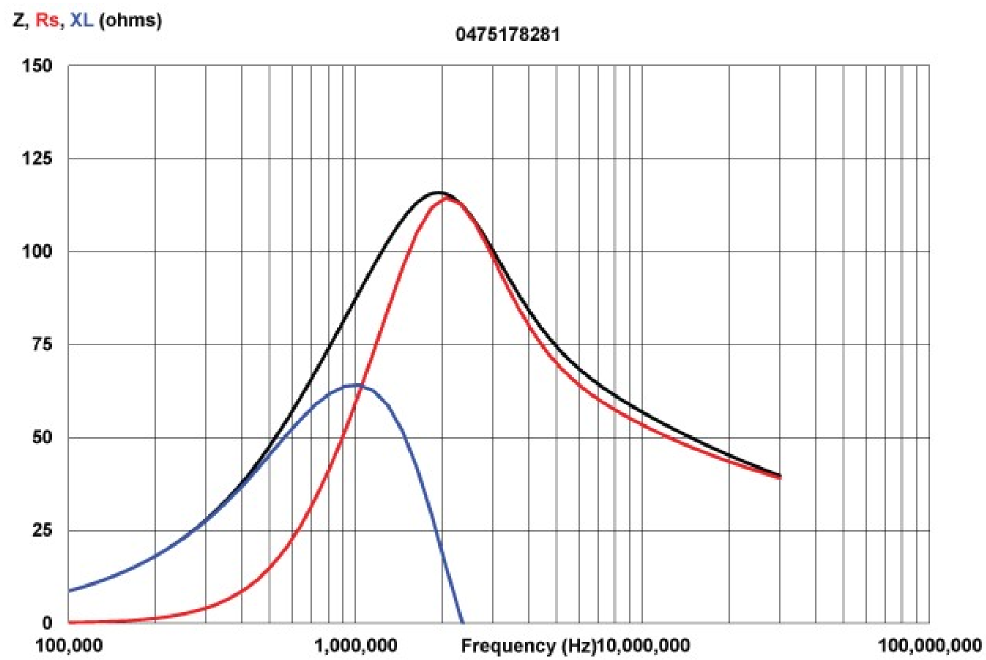
Ferrites

- Snap on, solid, or surface mount ferrites
- Most effective ~1-1000 MHz
- Quick fix, but can be costly
- Downsides
  - May adversely affect manufacturing
  - Adds impedance to signal lines
  - Adds cost
  - Bulky

element

Ferrite selection criteria

- Impedance curve
- DC Bias current rating
- Temperature
- Inner and outer diameters for cable beads
- Analog or digital circuit



DC bias

- DC current reduces impedance of ferrites

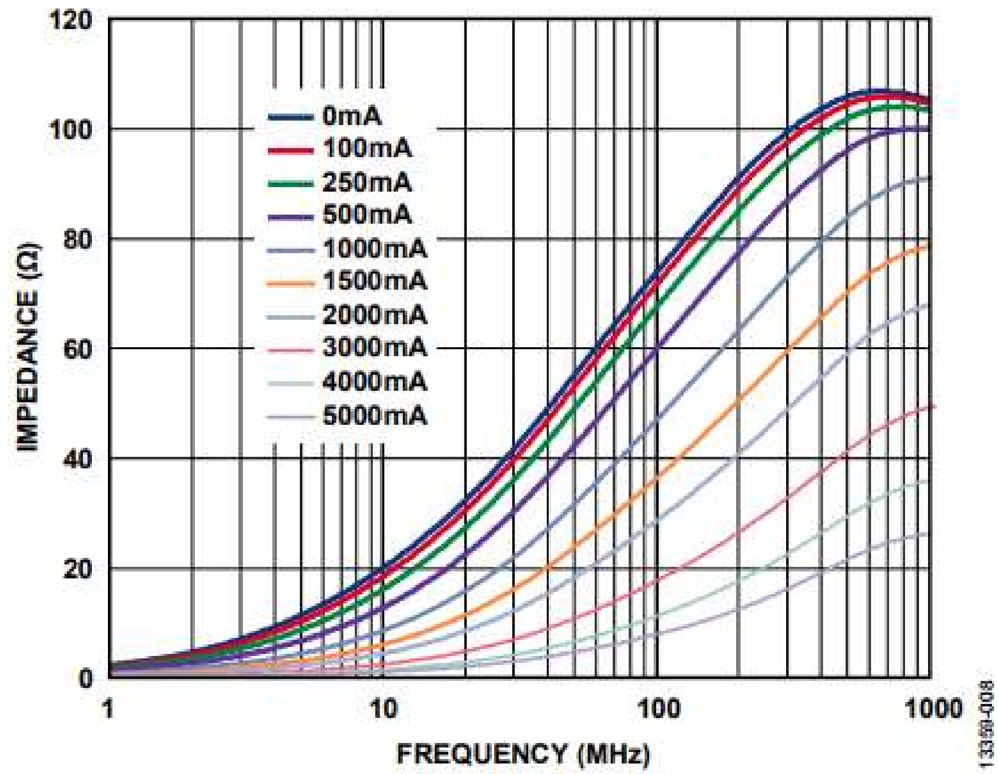
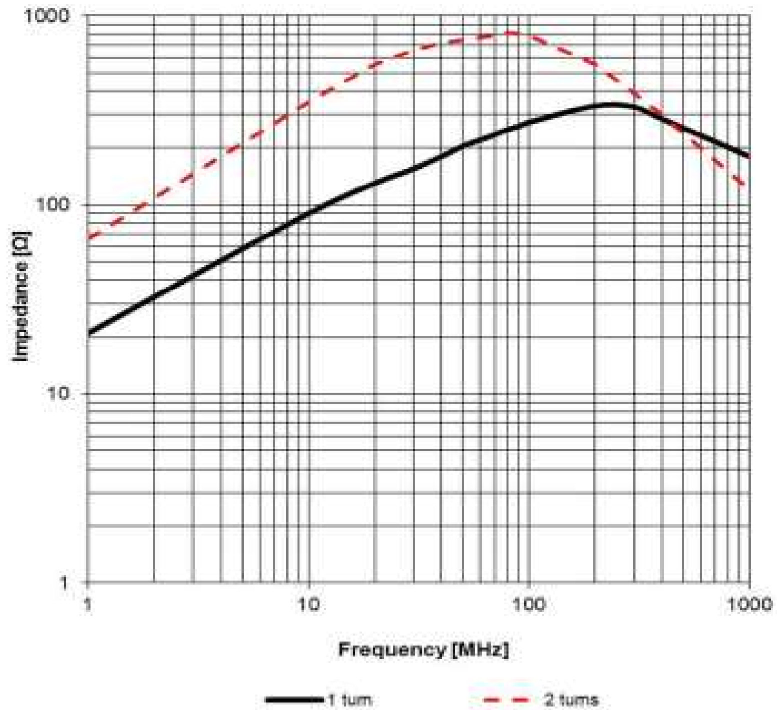
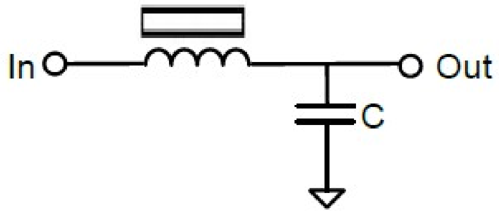


Figure 9. Wurth Elektronik 742 791 510 Impedance Curves with Respect to DC Bias Current

Ferrite usage

- Place snap-on ferrites close to where the cable enters the enclosure and surface mounts close to cable ingress and susceptible circuits
- Adding turns increases impedance, decreases resonant frequency, and increases risk of core saturation





Summary

- Reminder – all these fixes are more expensive when you get to the test stage. Design with EMC in mind!
- Think signal return paths, not just “ground”
- Plan an EMC return path
- Shields, filters, ferrites require analysis to be effective, and need proper installation

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Thank you!

Questions & Answers

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