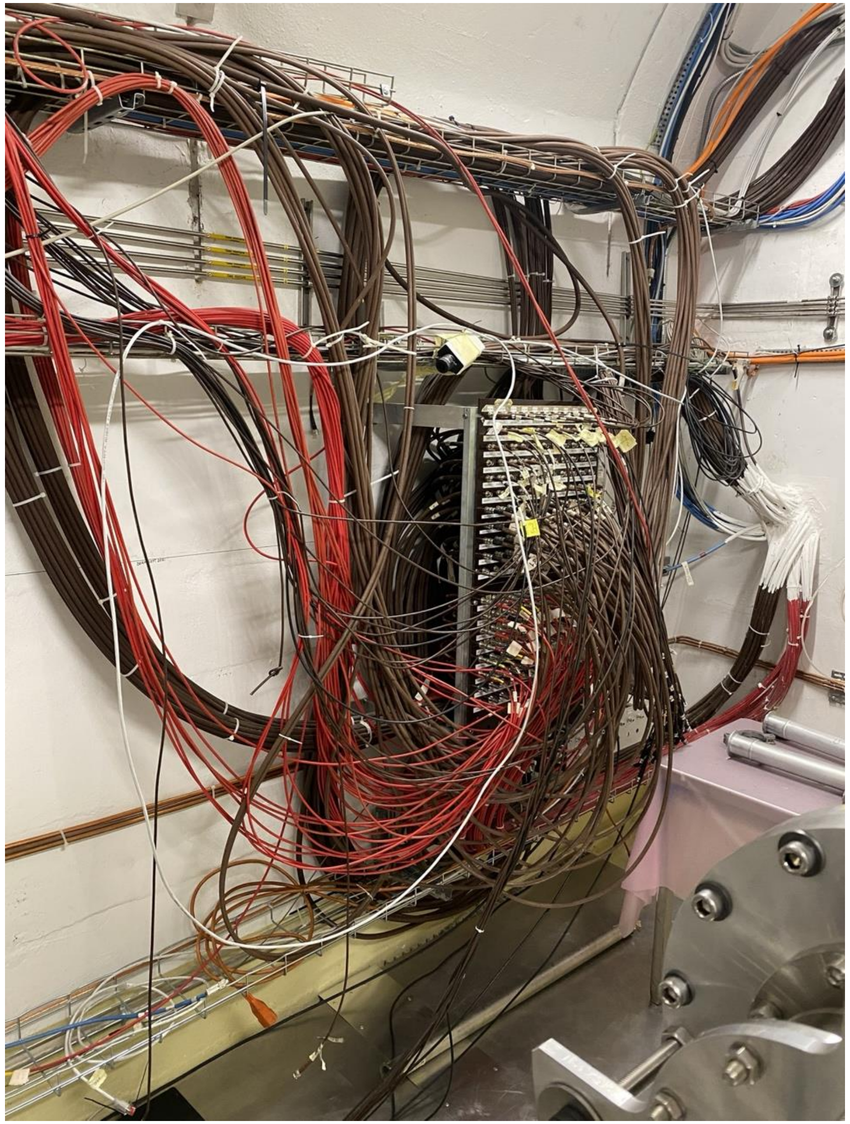
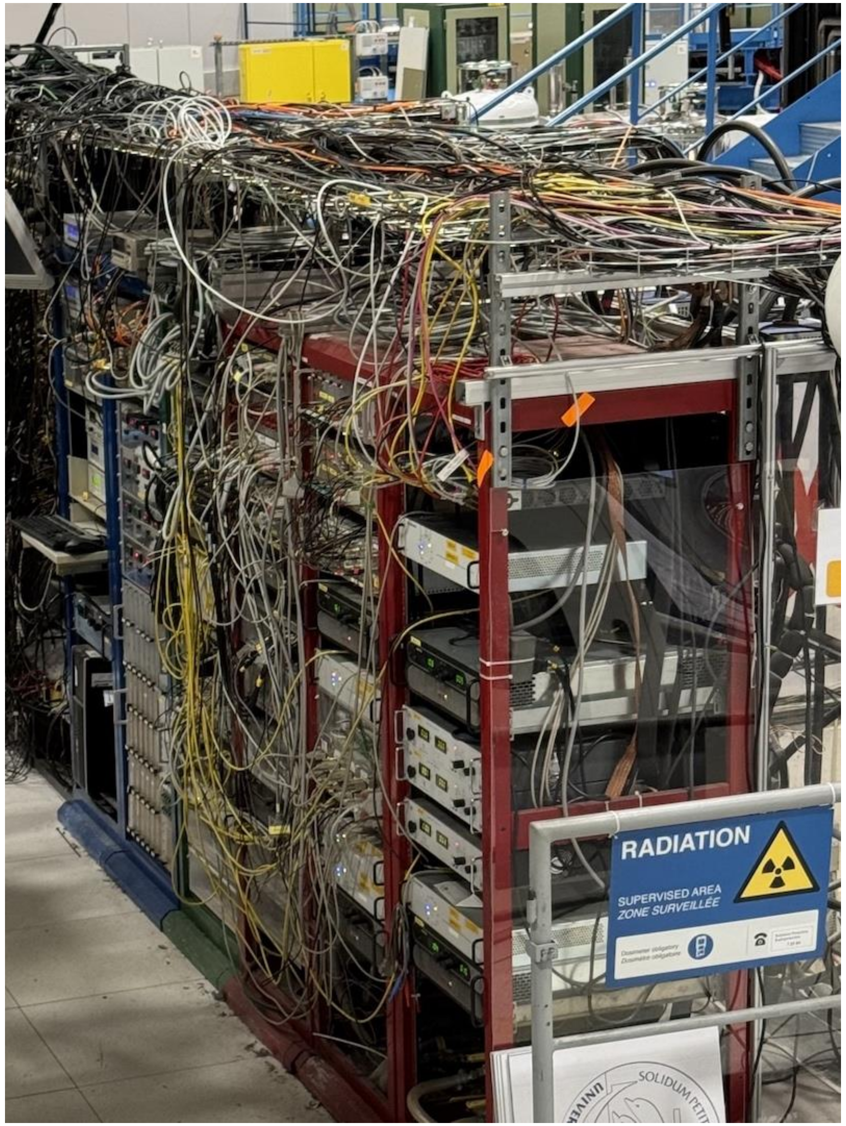
Electromagnetic compatibility. Does it matter when everything is digital anyway?

A 3-day lecture compressed into 50 minutes…

Daniel Valuch

A typical installation at CERN...





What is electromagnetic compatibility?

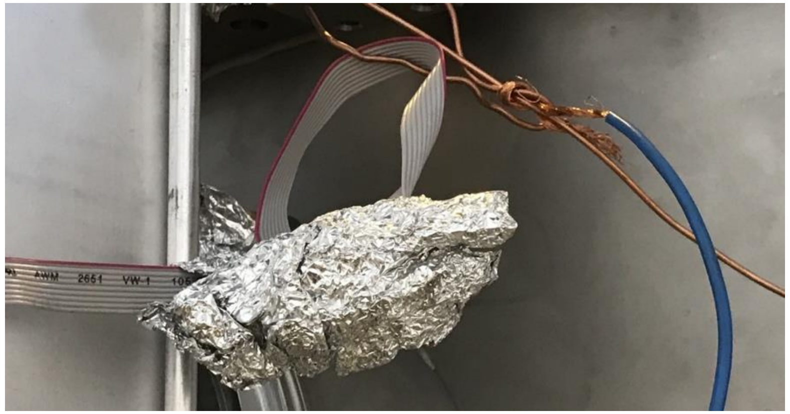
Electromagnetic compatibility [1]:

The ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbance to anything in that environment

[1] IEC50(161):(BS4727:Pt 1:Group09) Glossary of electrotechnical, power, telecommunication, electronics, lighting and colour terms: Electromagnetic compatibility

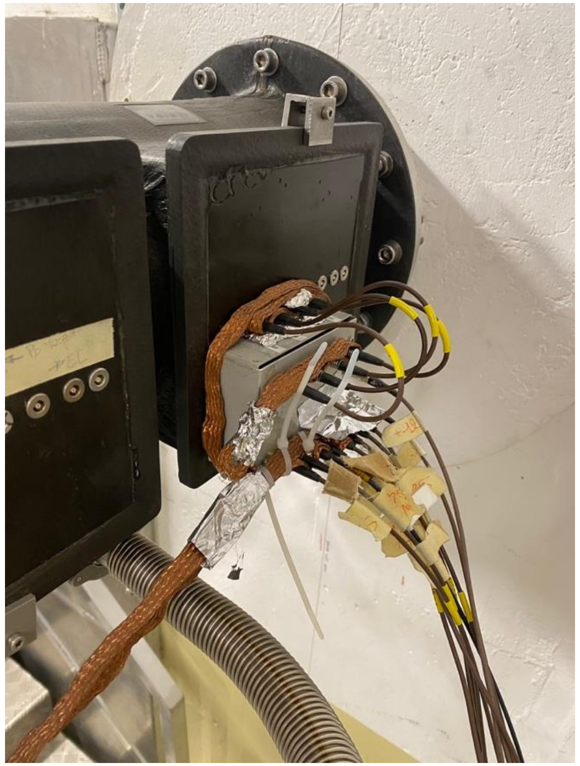
What is electromagnetic compatibility?

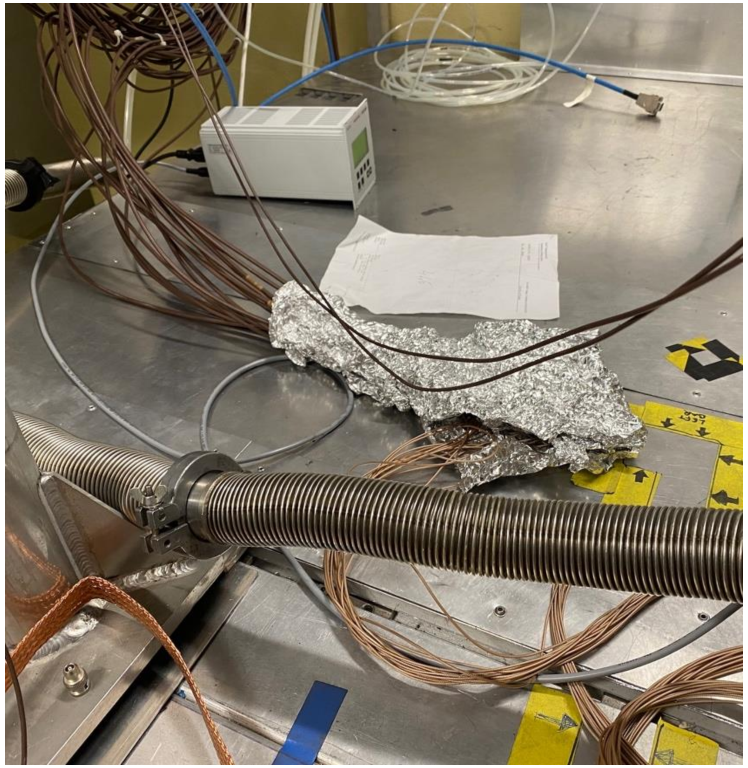
EMC is sometimes presented as black magic…

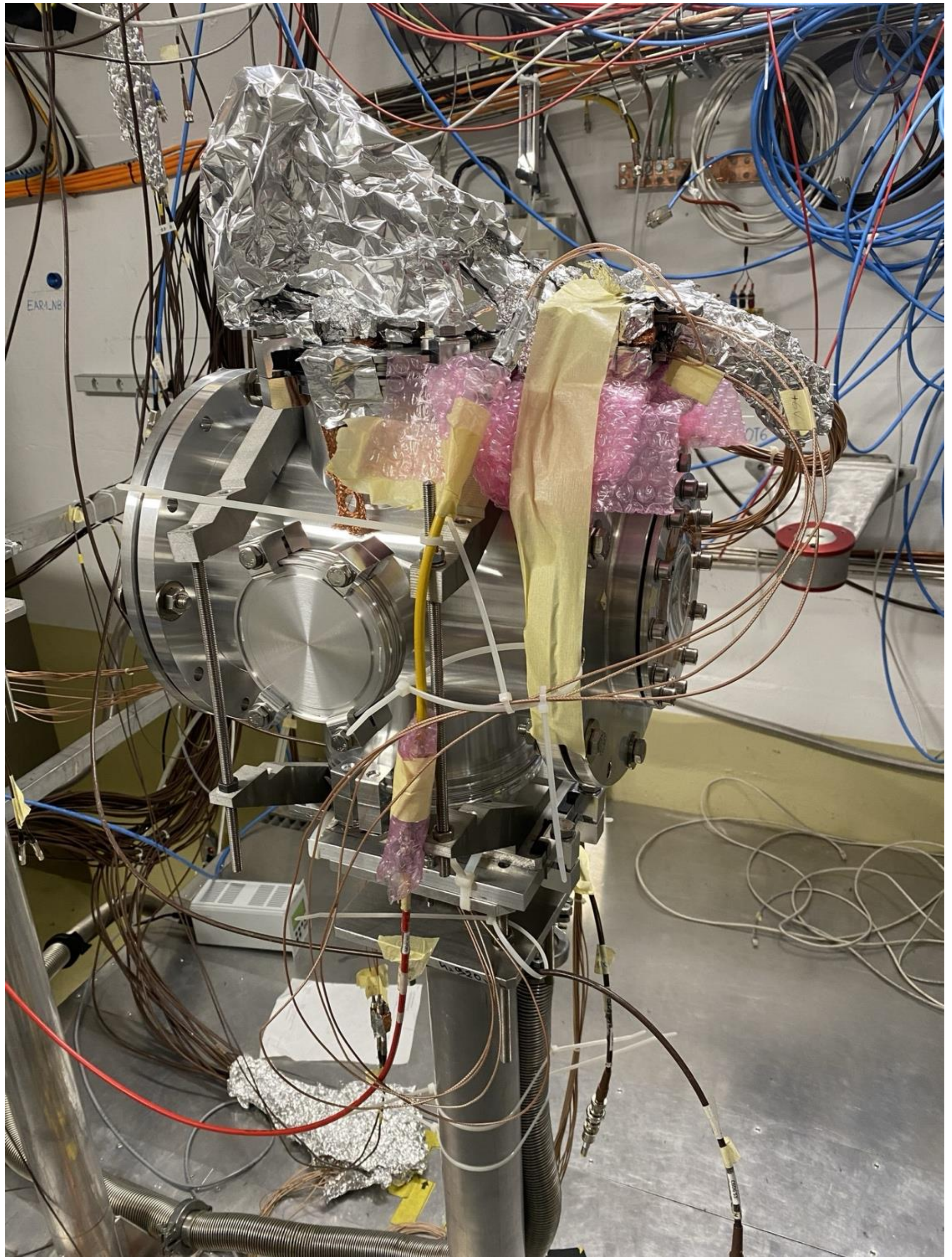


What is electromagnetic compatibility?

EMC is sometimes presented as black magic…







What is electromagnetic compatibility?

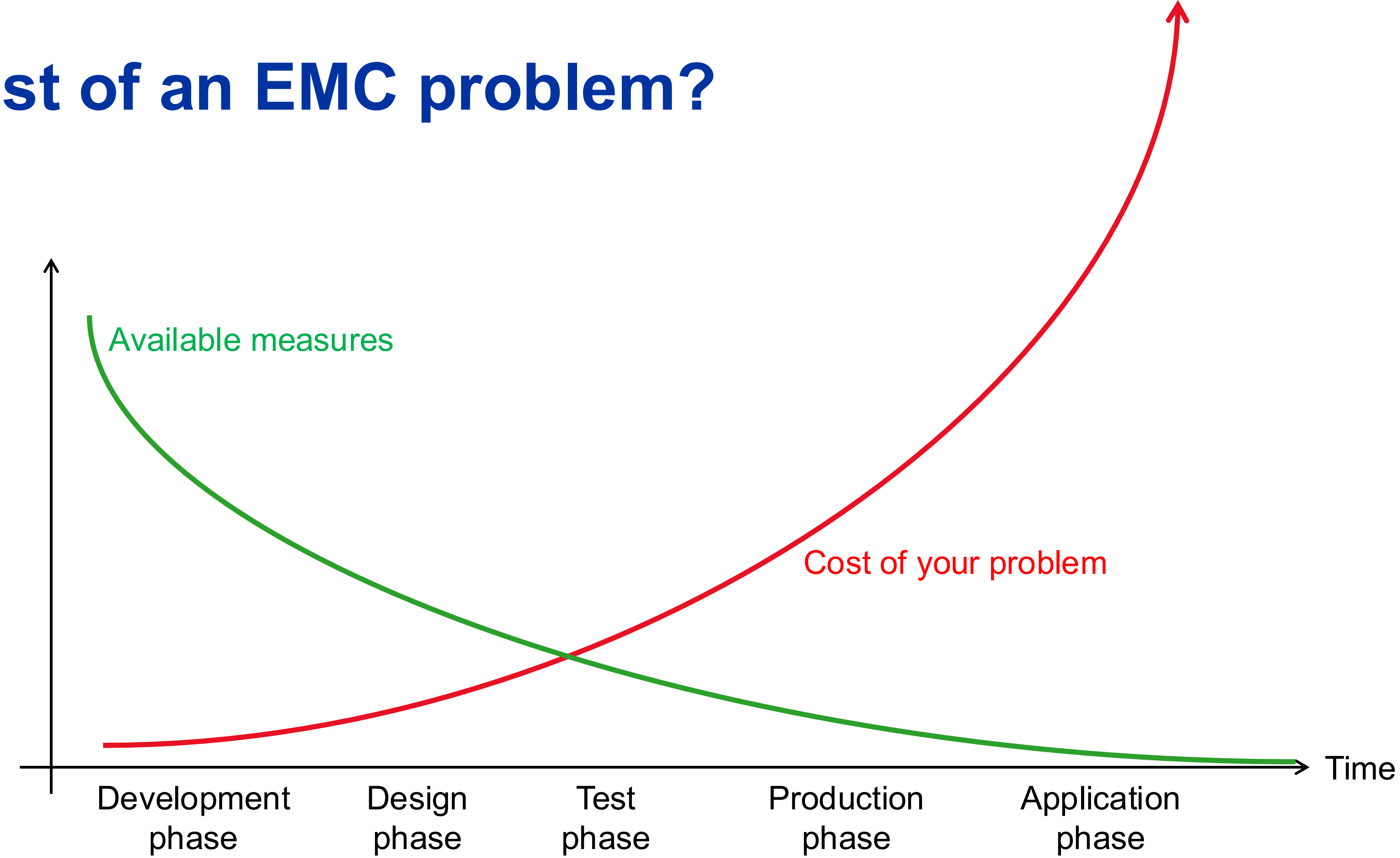
EMC is electrical engineering.

EMC scientists just add the invisible elements of the "schematic":

- Inductance of wires (self and mutual), magnetic coupling
- Capacitances, screen leakage
- Spurious signals, stray fields, man made noise
- Real world components, resonances, contact resistance
- Vicinity, common paths
- And many more

… and all that across 10 orders of magnitude

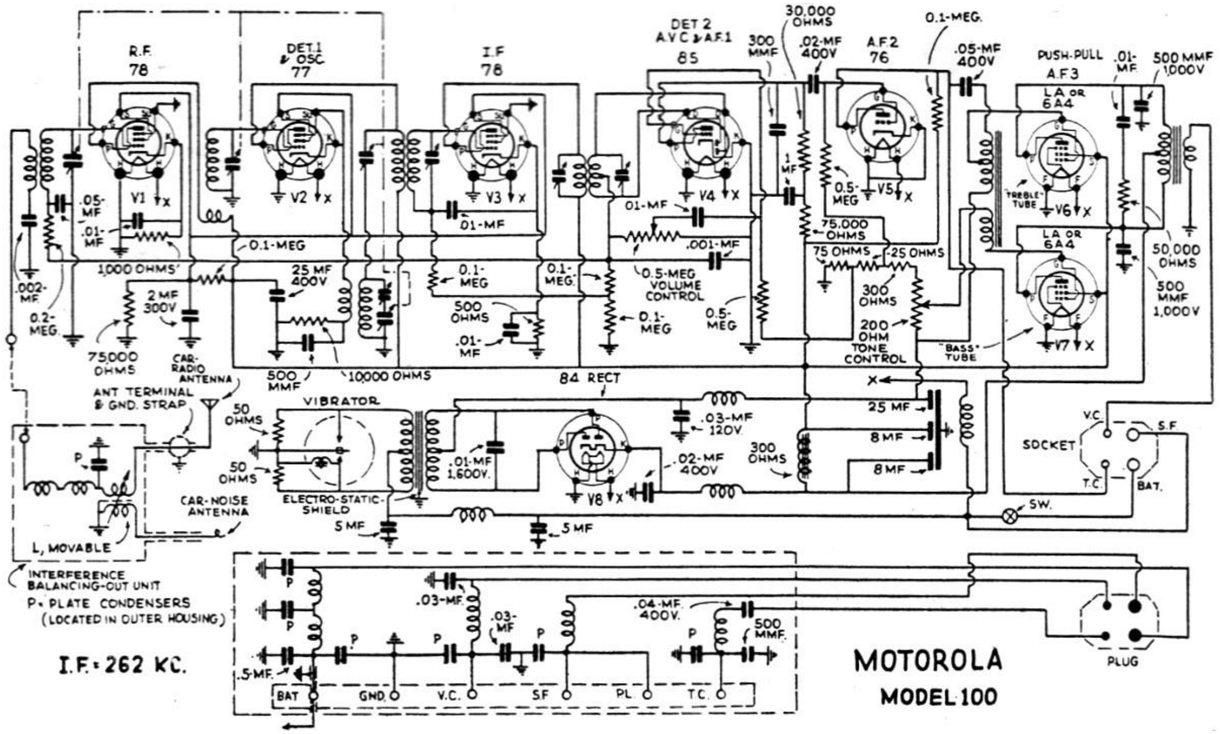
Cost of an EMC problem?



Prerequisites: basic components in an ideal world

“Wire”

In schematic, voltage all along the wire is the same, regardless the current, or signal shape. The outgoing current is exactly the same as the incoming one. It passes the wire in zero time.



Ground

Mythical electrical object that absorbs unlimited quantities of electrical current.
Ground exists in SPICE but nowhere else.
Radar engineers in the 1930s discredited the concept of ground as anything more than a good place to grow carrots and potatoes. [1]

[1] Dr. Howard Johnson: Manager's Guide to Digital Design
https://www.edn.com/managers-guide-to-digital-design/
[2] https://www.rfcafe.com/references/radio-craft/motorola-100-schematic-radio-craft-june-1935.htm

Legislation and standards

EMC Standards

EMC standards are technical documents – they define technical requirements, parameters, or testing and measurement methods.

EMC standards, however, do not tell you how you should do things properly

Two types exist:

- **Generic standards**
- **Equipment specific standards**

EMC Standards

- **IEC 61000-1-x General**
  - Basic concepts (fundamental principles, definitions, terminology), interference model
  - Functional Safety (what a safety function does and approaches of it being performed satisfactorily)
  - Measurement uncertainty
- **IEC 61000-2-x Environment**
  - Description of the environment
  - Classification of the environment
  - Compatibility levels
- **IEC 61000-3-x Limits**
  - Emission limits
  - Immunity limits
- **IEC 61000-4-x Testing and measurement techniques**
  - Measurement techniques (without specifying limits)
  - Testing techniques(without specifying limits)
- **IEC 61000-5-x Installation and mitigation guidelines**
  - Installation guidelines
  - Mitigation methods and devices
- **IEC 61000-6-x Generic Standards**
  - Generic emission and immunity requirements for residential/commercial and light-industrial environments (limits and minimum test levels)
  - Generic emission and immunity requirements for industrial environments (limits and minimum test levels)
- **CISPR 11-32 Specification of measurement equipment and methods for testing**

Example: Industrial Immunity EN 61000-6-2 (generic)

Table 1 – Immunity – Enclosure ports

	Environmental phenomena		Test specifications	Units	Basic standards	Remarks	Performance criterion
1.1	Power-frequency magnetic field		50, 60 30	Hz A/m	IEC 61000-4-8	a The test shall be carried out at the frequencies appropriate to the power supply frequency. Equipment intended for use in areas supplied only at one of these frequencies need only be tested at that frequency	A b
1.2	Radio-frequency electromagnetic field. Amplitude modulated		80 to 1 000 10 80	MHz V/m % AM (1 kHz)	IEC 61000-4-3 d	c The test level specified is the r.m.s. value of the unmodulated carrier	A
1.3	Radio-frequency electromagnetic field. Amplitude modulated		1,4 to 2,0 3 80	GHz V/m % AM (1 kHz)	IEC 61000-4-3 d	e The test level specified is the r.m.s. value of the unmodulated carrier	A
1.4	Radio-frequency electromagnetic field. Amplitude modulated		2,0 to 2,7 1 80	GHz V/m % AM (1 kHz)	IEC 61000-4-3 d	e The test level specified is the r.m.s. value of the unmodulated carrier	A
1.5	Electrostatic discharge	Contact discharge	±4 (charge voltage)	kV	IEC 61000-4-2	See basic standard for applicability of contact and/or air discharge tests	B
		Air discharge	±8 (charge voltage)	kV			B

Example: Industrial Immunity EN 61000-4-3: Selecting test levels

E.2 Test levels related to general purposes

The test levels and the frequency bands are selected in accordance with the electromagnetic radiation environment to which the EUT can be exposed when finally installed. The consequences of failure should be borne in mind in selecting the test level to be applied. A higher level should be considered if the consequences of failure are significant.

The following classes are related to the levels listed in Clause 5; they are considered as general guidelines for the selection of the corresponding levels.

– **Class 1:** Low-level electromagnetic radiation environment. Levels typical of local radio/television stations located at more than 1 km, and transmitters/receivers of low power.

– **Class 2:** Moderate electromagnetic radiation environment. Low power portable transceivers (typically less than 1 W rating) are in use, but with restrictions on use in close proximity to the equipment.

– **Class 3:** Severe electromagnetic radiation environment. **Portable transceivers (2 W rating or more) are in use relatively close to the equipment but not less than 1 m.** High power broadcast transmitters and/or ISM equipment may be located close by.

– **Class 4:** Portable transceivers are in use at a distance of 0,2 m and 1 m of the equipment. Other sources of significant interference may be within 1 m of the equipment.

– **Class x:** x is an open level which might be negotiated and specified in the product standard or equipment specification.

Example: Industrial Immunity EN 61000-6-2

4 Performance criteria

The variety and the diversity of the apparatus within the scope of this standard makes it difficult to define precise criteria for the evaluation of the immunity test results.

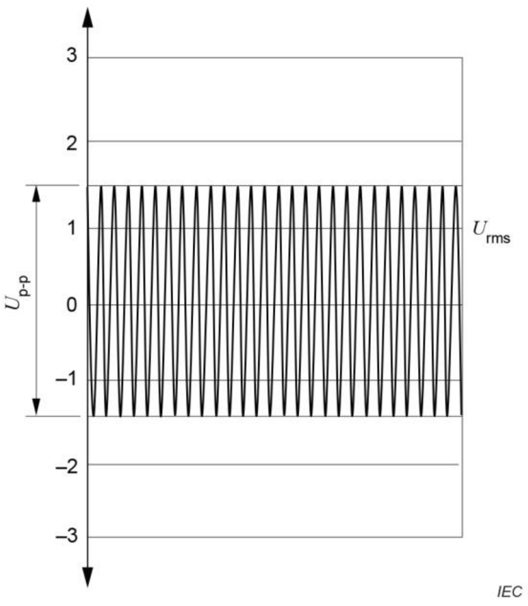
If, as a result of the application of the tests defined in this standard, the apparatus becomes dangerous or unsafe, the apparatus shall be deemed to have failed the test.

a) Performance criterion A: The apparatus shall continue to operate as intended during and after the test. **No degradation of performance or loss of function is allowed below a performance level specified by the manufacturer,** when the apparatus is used as intended. The performance level may be replaced by a permissible loss of performance. If the minimum performance level or the permissible performance loss is not specified by the manufacturer, either of these may be derived from the product description and documentation and what the user may reasonably expect from the apparatus if used as intended.

b) Performance criterion B: The apparatus shall continue to operate as intended after the test. No degradation of performance or loss of function is allowed below a performance level specified by the manufacturer, when the apparatus is used as intended. The performance level may be replaced by a permissible loss of performance. **During the test, degradation of performance is however allowed**. No change of actual operating state or stored data is allowed. If the minimum performance level or the permissible performance loss is not specified by the manufacturer, either of these may be derived from the product description and documentation and what the user may reasonably expect from the apparatus if used as intended.

c) Performance criterion C: **Temporary loss of function is allowed, provided the function is self-recoverable or can be restored** by the operation of the controls.

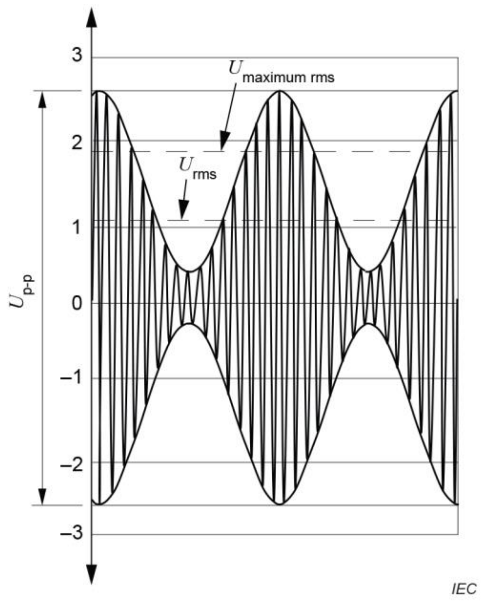
Example: Industrial Immunity EN 61000-4-3: Testing and measurement techniques



a) Unmodulated RF signal

$$U_{\text{rms,a}} = 1\text{ V}$$

$$U_{\text{p-p,a}} = U_{\text{rms,a}} \times \sqrt{2} \times 2 = 2{,}82\text{ V}$$

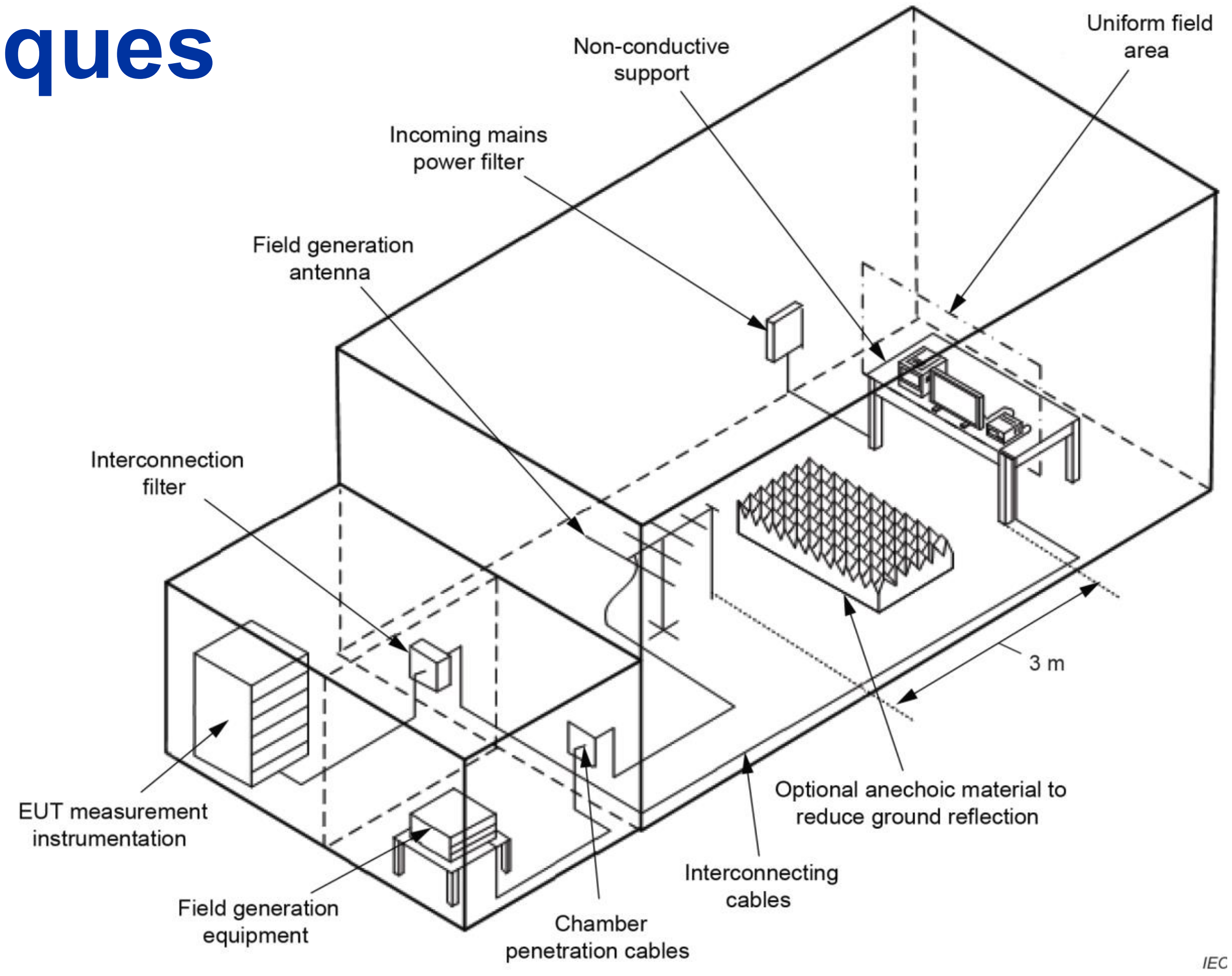


b) Modulated RF signal 80 % AM

$$U_{\text{p-p.max}} = U_{\text{p-p,a}} \times \frac{100+m}{100} = 5{,}09\text{ V}$$

$$U_{\text{p-p.min}} = U_{\text{p-p,a}} \times \frac{100-m}{m} = 0{,}57\text{ V}$$

$$U_{\text{rms,b}} = U_{\text{rms,a}} \times \sqrt{1+\frac{\left(\frac{m}{100}\right)^2}{2}} = 1{,}15\text{ V}$$



NOTE Anechoic lining material on walls and ceiling has been omitted for clarity.

Figure 2 – Example of suitable test facility

How do we specify?

On site, in accelerator tunnels and most experiments we are the only noise generators.

At the same time our own colleagues suffer from what is generated.

It is desirable to have a minimum set of EMC parameters for all equipment keeping in mind multiple apparatus in close vicinity

The EMC specification for purchased equipment is difficult even for experts

- **Overspecification leads to unnecessarily high cost**
- **Underspecification leads to potential problems**

Example of EMC specification for a pulsed 100 kW RF power amplifier tender

The system shall be compliant with the following EMC requirements and standards:

- Emissions according to CISPR-11, Class A, Group 1 equipment. The radiated emission limit at working frequency (101.28 MHz) is relaxed to 1.8 V/m at 3m (or equivalent 0.5 V/m at 10m). Recommended measurement distance for a device of expected physical size is 10 meters (by CISPR 16-2-3). As the device works with pulsed RF signal, the field values are considered peak.

- Conducted immunity according to IEC-61000-4-6, class 3, performance criteria A, tested on all interfaces except the output RF line

- Radiated immunity according to IEC-61000-4-3, class 3, performance criteria A. Required immunity at operating frequency 101.28 ± 2 MHz is as per class 4.

- Electrostatic discharge immunity according to IEC-61000-4-2, level 2, performance criteria B, tested on all user interfaces (screens, knobs, switches, LEDs...)

- Electrical fast transient/burst immunity test according to IEC-61000-4-4, level 3, performance criteria A on all interfaces except the output RF line

Items marked in orange are our specific requirements on top of the generic EMC standards

Coupling

Coupling mechanisms

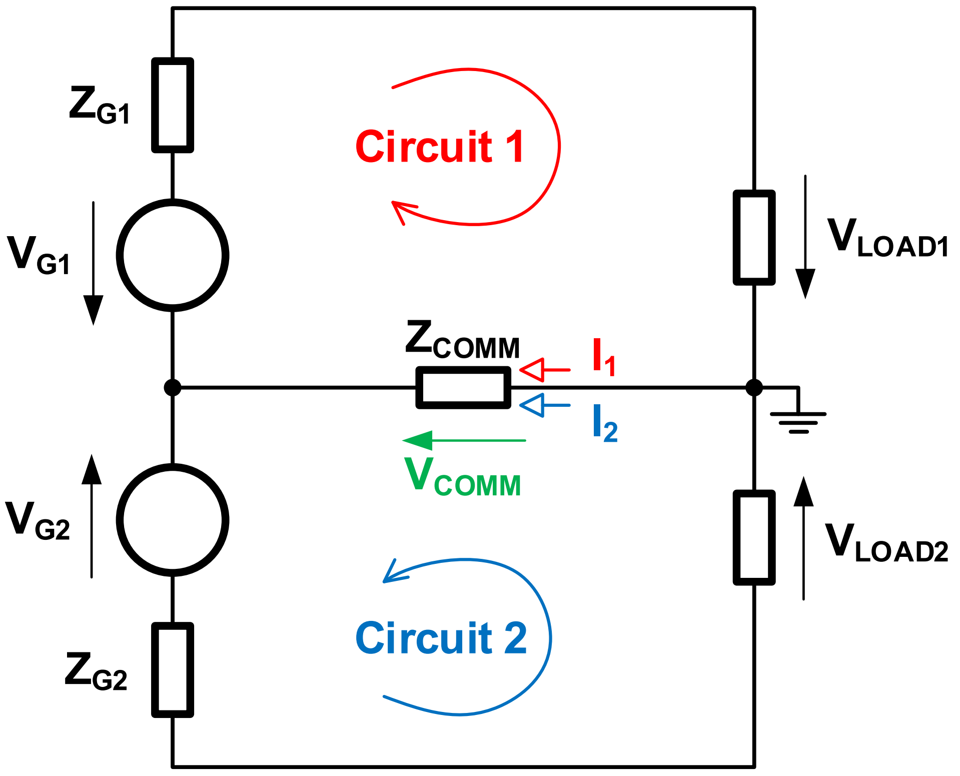
We recognize four main coupling mechanisms:

1. Conductive – via galvanic connection and common impedances
2. Capacitive – via near field, voltage-type, fast transients
3. Inductive – via near field, current type, loops and high currents
4. By radiation – far field, via electromagnetic field

5. Parametric coupling
6. Specific to accelerator facilities – beam related coupling

Coupling by common impedance

Mechanism requires a common impedance, which is shared by currents of the source and victim circuits.



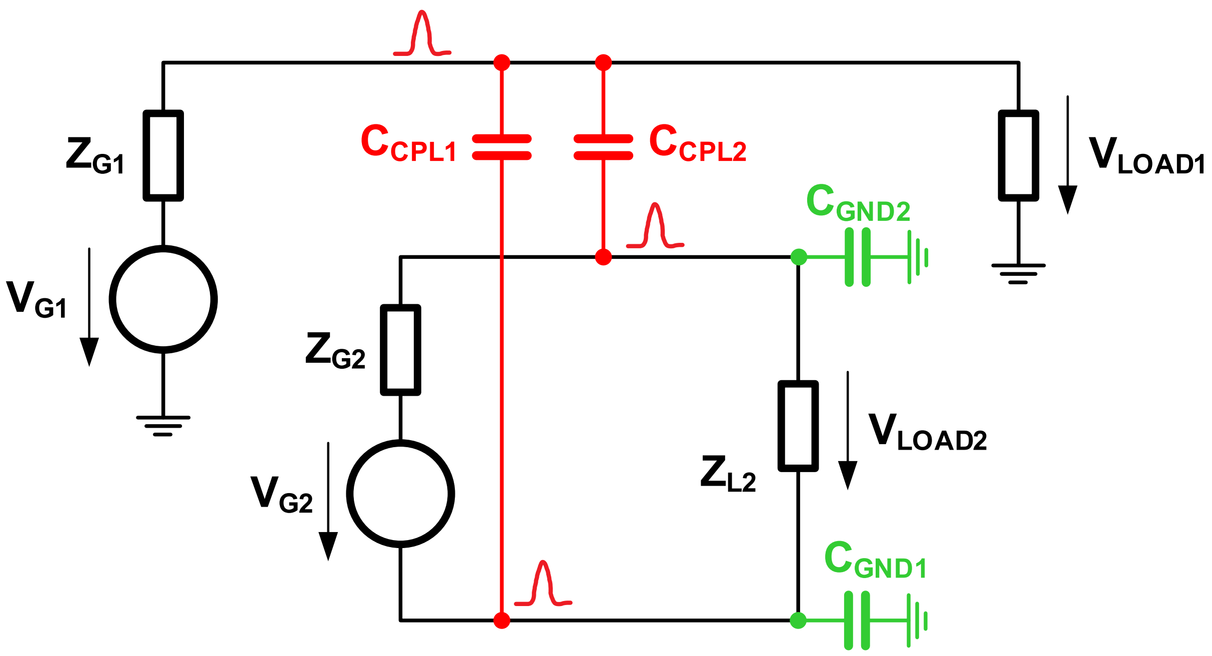
Mitigation tips:

- **Remove the common impedances (do not use cable screen as a signal return conductor)**
- **Do not share wiring between noisy and sensitive signals (use different cables for power and sensor, use multiple ground planes on a PCB for noisy and sensitive signals)**
- **Minimize the common impedances (sufficient cross-section, low impedance paths)**
- **Minimize the currents through common impedance (transformers, optocouplers)**

Capacitive coupling

Near field coupling. High pass phenomena. High impedance, high voltage.

Typically between conductors/equipment without screen

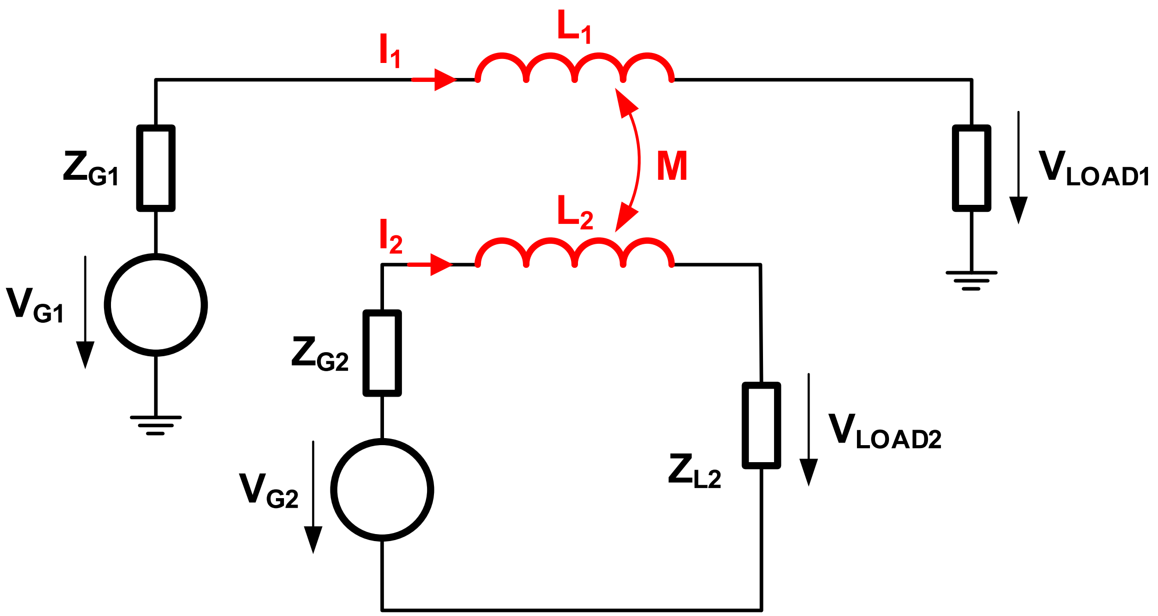


Mitigation of capacitive coupling:

- **Increase distance between the conductors.**
- **Lower the distance to GND (increase C_{GND}), wiring tied to chassis, use ground planes on PCBs**
- **Reduce the area of coupling**
- **Reduce operating voltage and/or frequency content of the signal**
- **Use electrostatic shielding**

Inductive coupling

Near H-field, high pass phenomena. Low impedance, high current phenomena



Mitigation of inductive coupling:

- **Reduce the loop size**
- **Reduce the coupling by orthogonal orientation of loops**
- **Reduce operating current and/or frequency content of the signal**
- **Use twisted pair conductors**
- **Use magnetic shielding**

Radiation coupling

Coupling by electromagnetic wave $E/H = Z_0 = 377\ \Omega$, coupling in the far field, $l > \lambda$

All effects on wavelengths that are comparable to the equipment size

Mitigation of radiation coupling:

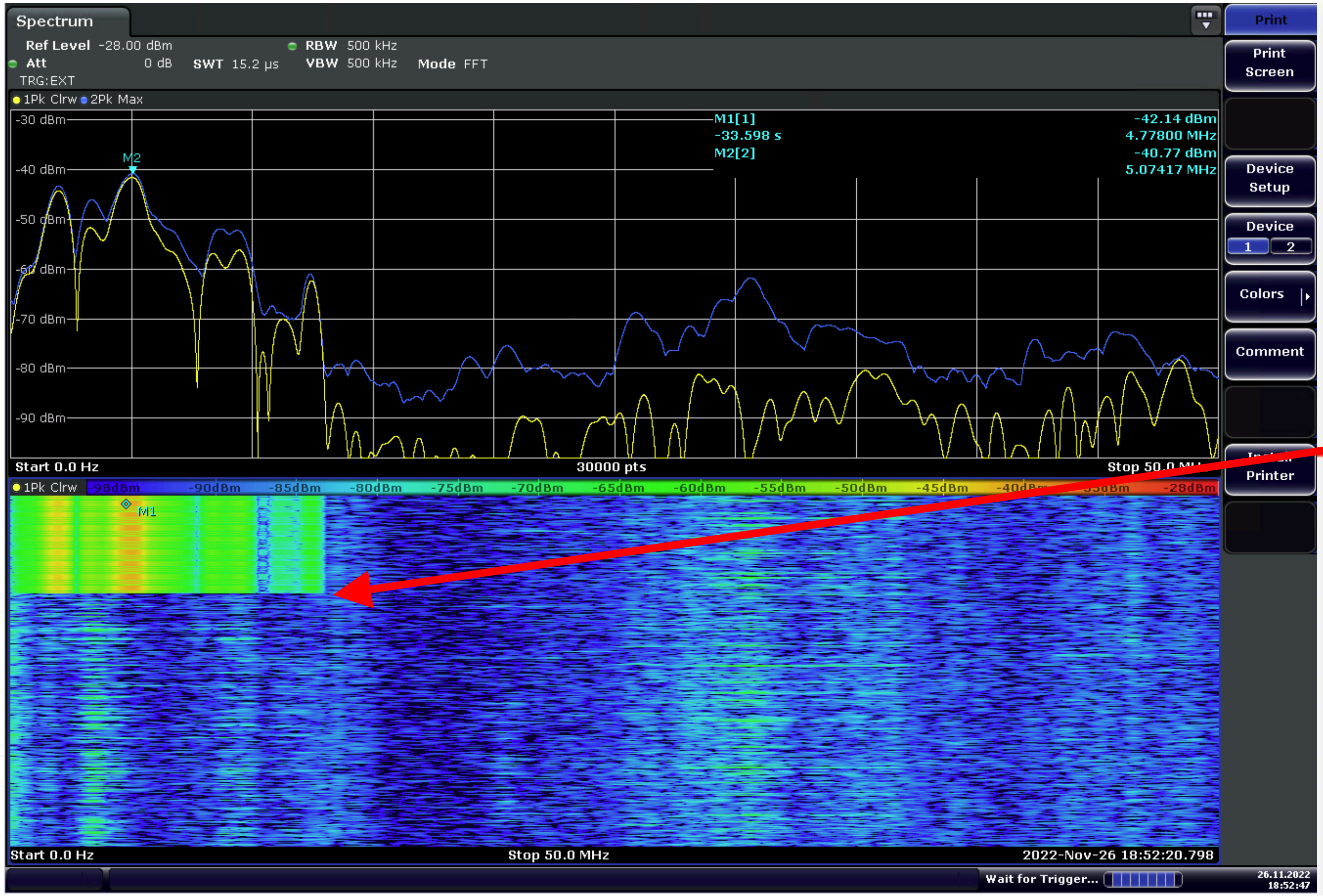
- Minimize the power level
- Minimize emissions: High quality transmission lines, tight RF joints, no open structures, RF tight ventilation openings, continuous leakage monitoring
- Increase immunity: Shielding, high quality coaxial cables, RF filters in equipment feedthroughs, going digital
- Faraday cage

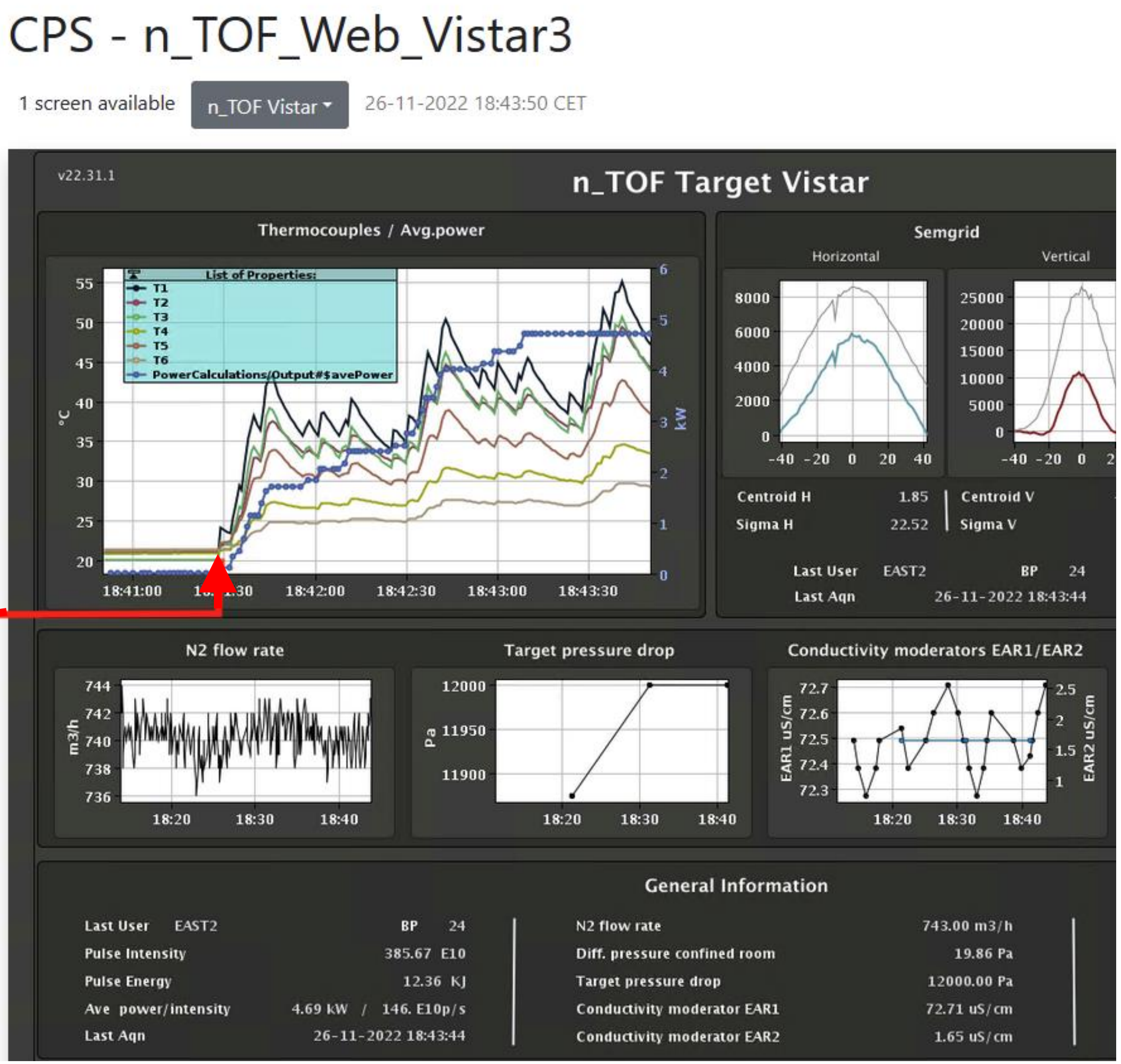
Parametric coupling

Relatively rare, but can be seen from time to time

- **Vibration of conductive components when in magnetic field**
- **Mechanical stress on components (e.g. capacitors, or precision resistors)**
- **Microphonics of all kinds**
- **Photo effect in glass encapsulated devices (e.g. diodes in glass package), or recently introduced package-less flip-chip ICs with**

Specific to CERN – beam induced EMC problems to equipment

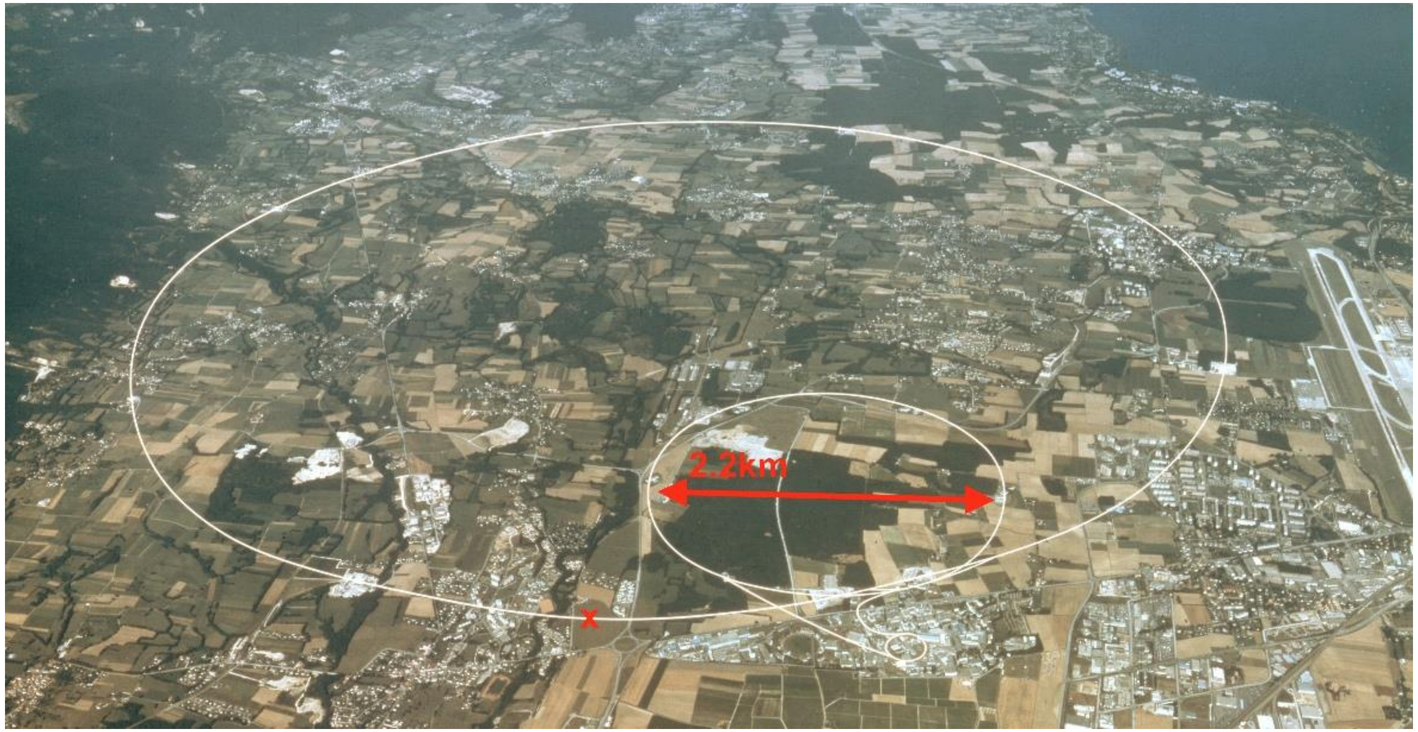


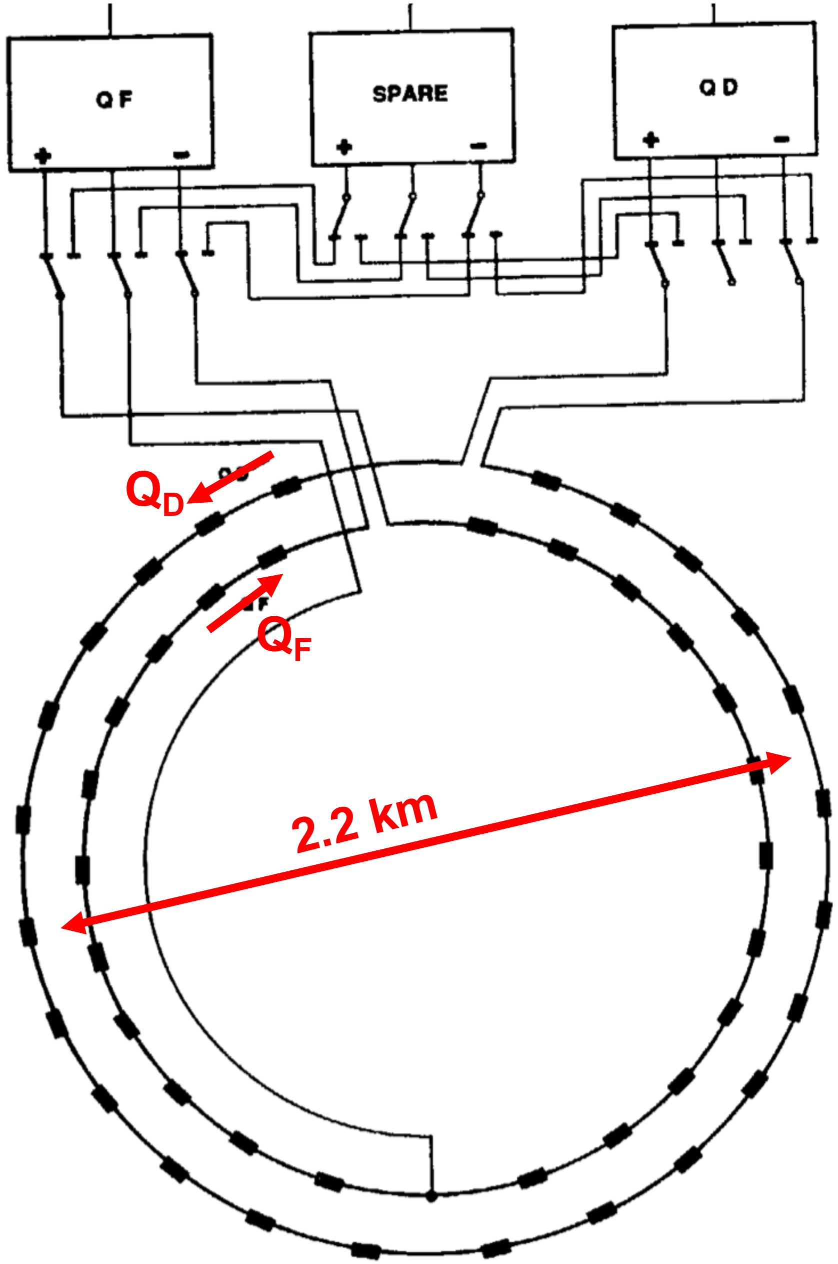


Specific to CERN – EMC induced problems to the beam

SPS lattice quadrupole circuits

$I_{nominal}$ = 2200 A, di/dt = 800 A/s

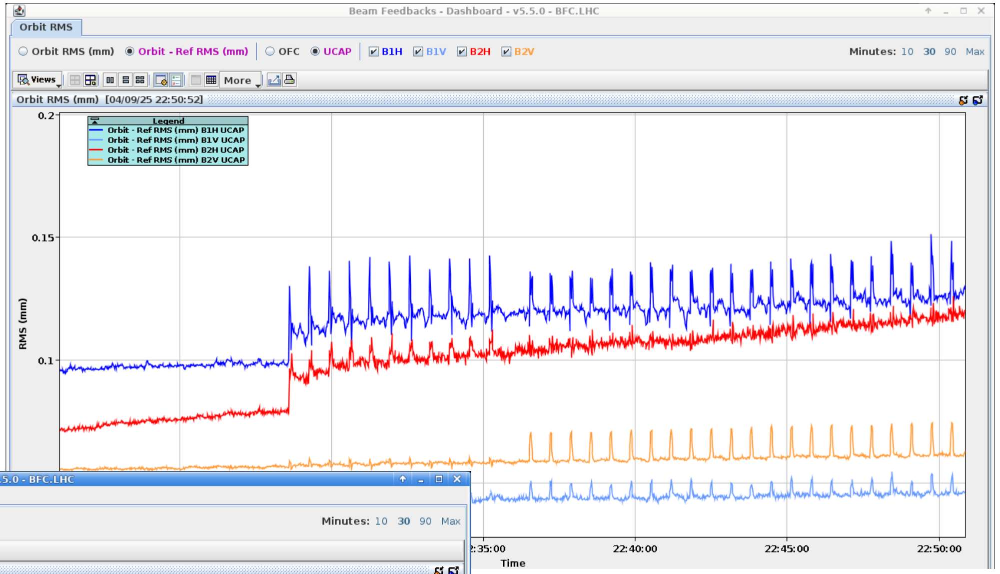


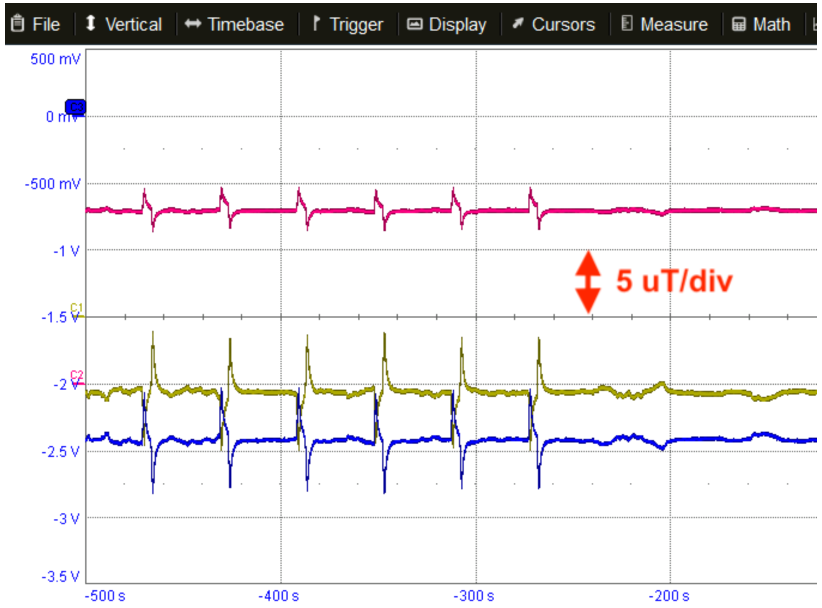


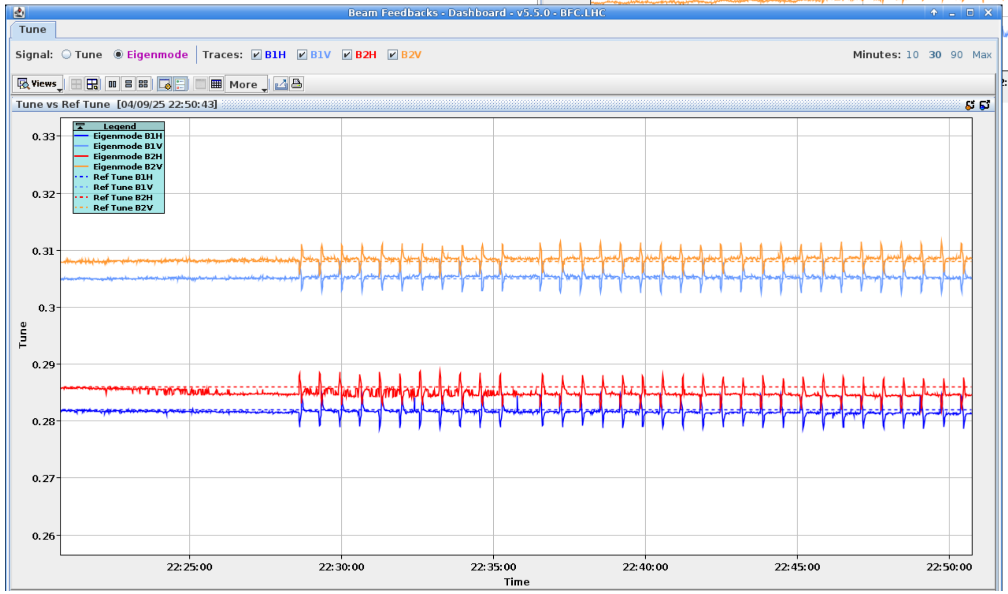
Specific to CERN – EMC induced problems to the beam

In the mean time 1 km away in LHC...

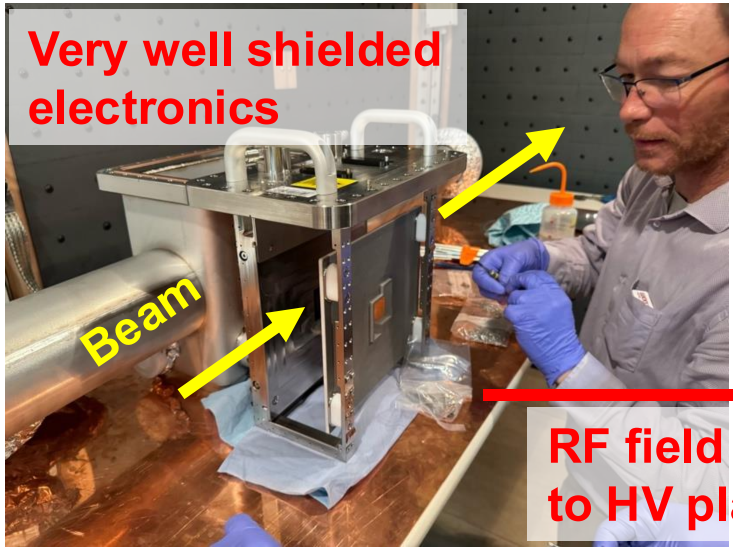
- Ambient magnetic field changes by 10 μT
- Machine tune changes by 5×10^{-3}
- RMS LHC orbit drifts by 20 μm





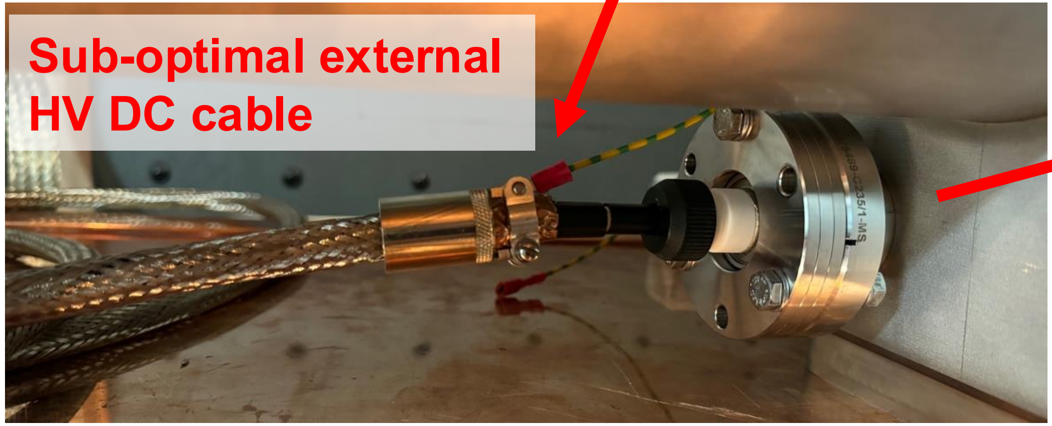


Coupling in reality - usually all coupling mechanisms combine. Very complex problems…

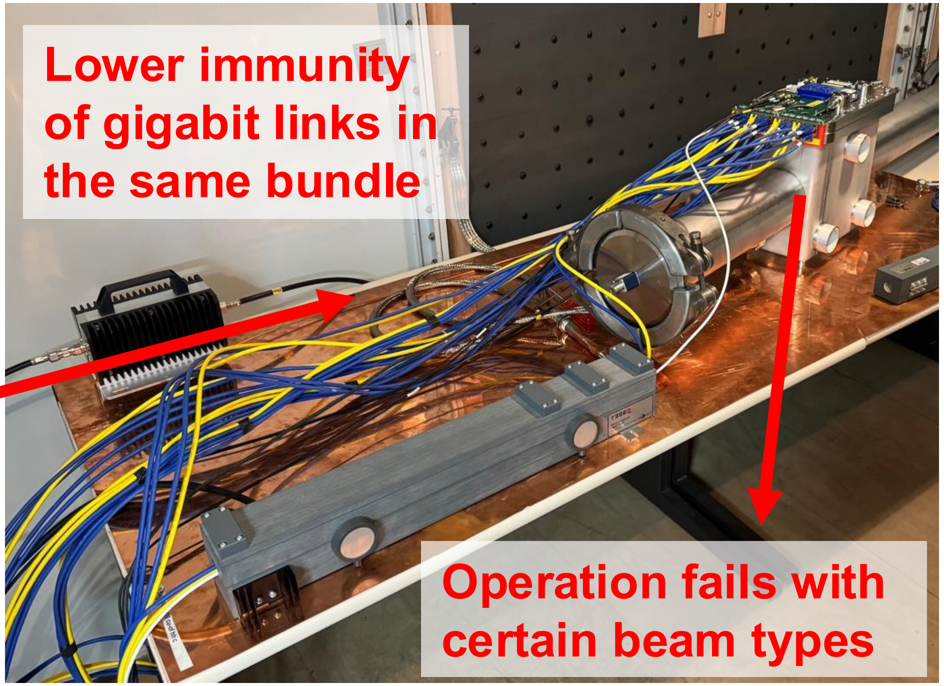


Very well shielded electronics

RF field coupling to HV plate



Sub-optimal external HV DC cable



Lower immunity of gigabit links in the same bundle

Operation fails with certain beam types

Bonding and equipotentiality

Grounding vs. equipotentiality

Two main purposes of grounding and equipotentiality:

- Personal safety
- Providing a defined potential for the system, including return path for currents

Electric potential of Earth is conventionally taken as zero

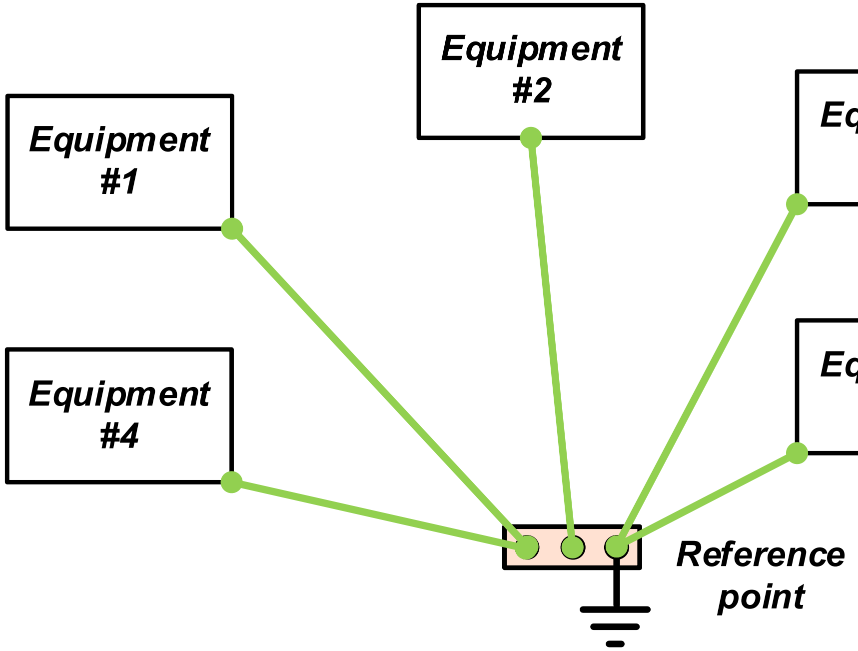
No circuit needs to be earthed in order to work. Faraday cage does not depend on earth connection

Equipotentiality, however, is what we really need (at all frequencies, starting from DC to several GHz)

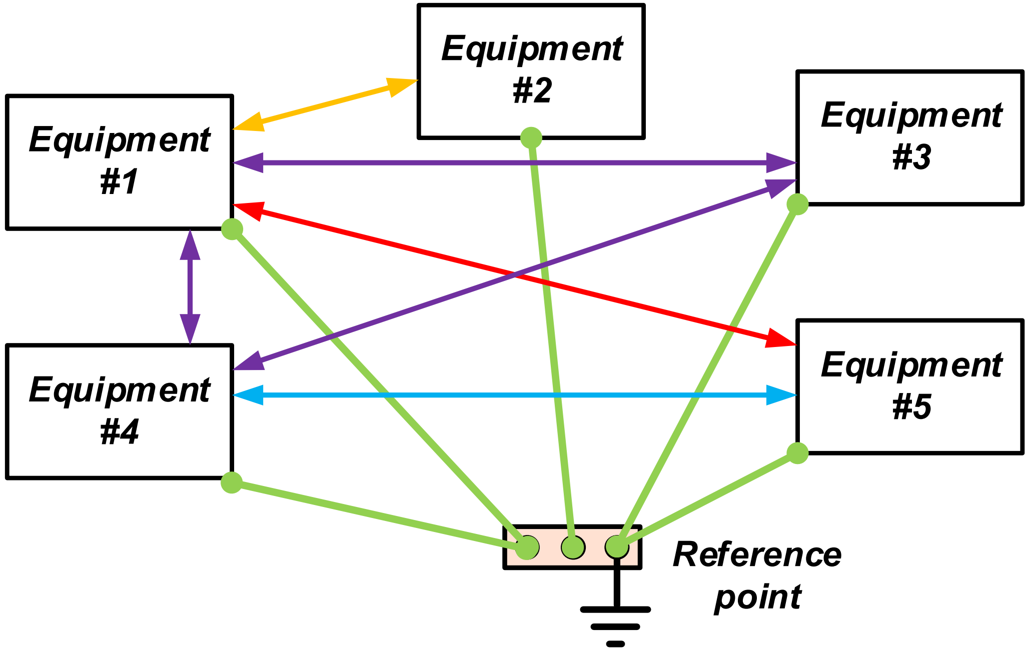
Grounding and equipotentiality

Star grounding:

on the drawing board



vs. in reality



Mesh bonding network

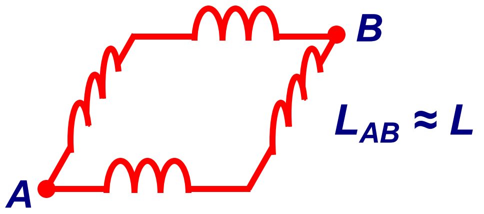
Bonding – the first step to true equipotentiality

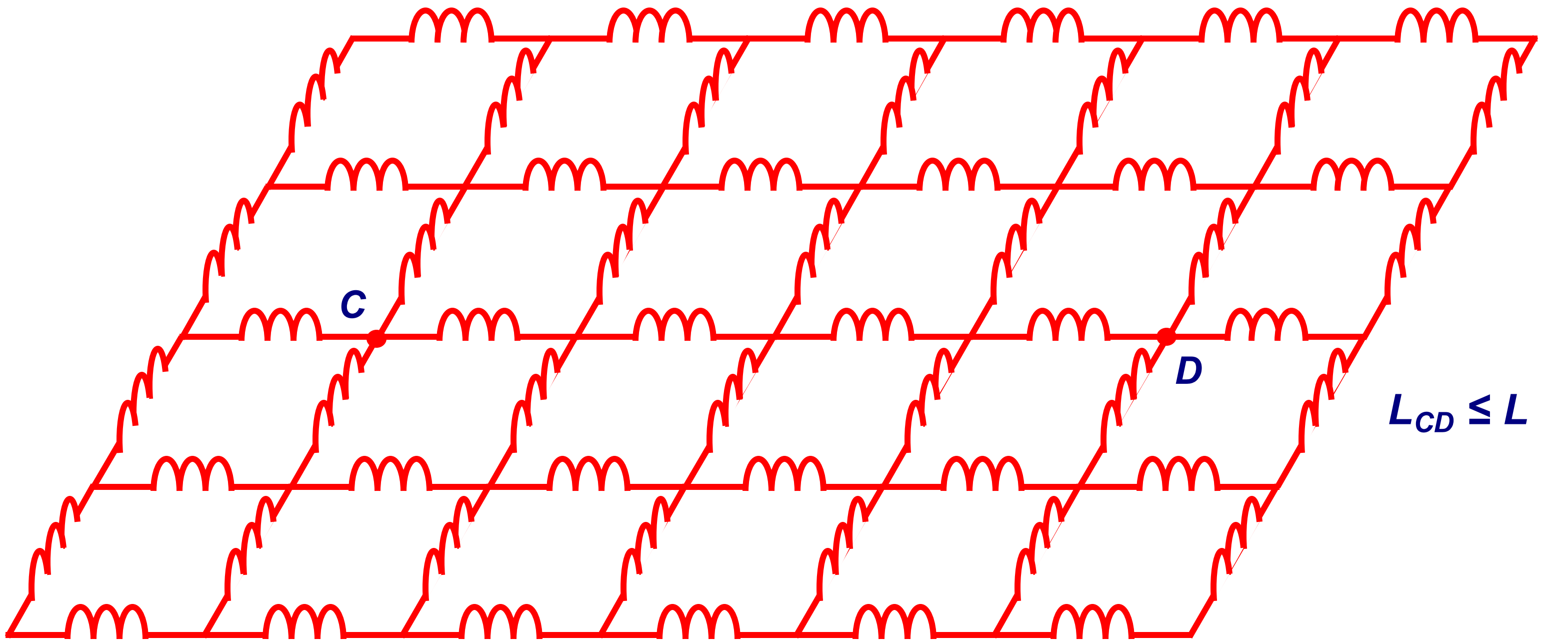
Bonding is the practice of interconnecting all accessible metalwork – whether associated with the electrical installation (known as exposed metalwork) or not (extraneous metalwork) – to the system "earth" (reference potential distribution network)

Sufficiently dense mesh bonding leads to equipotentiality

Impedance of a meshed network

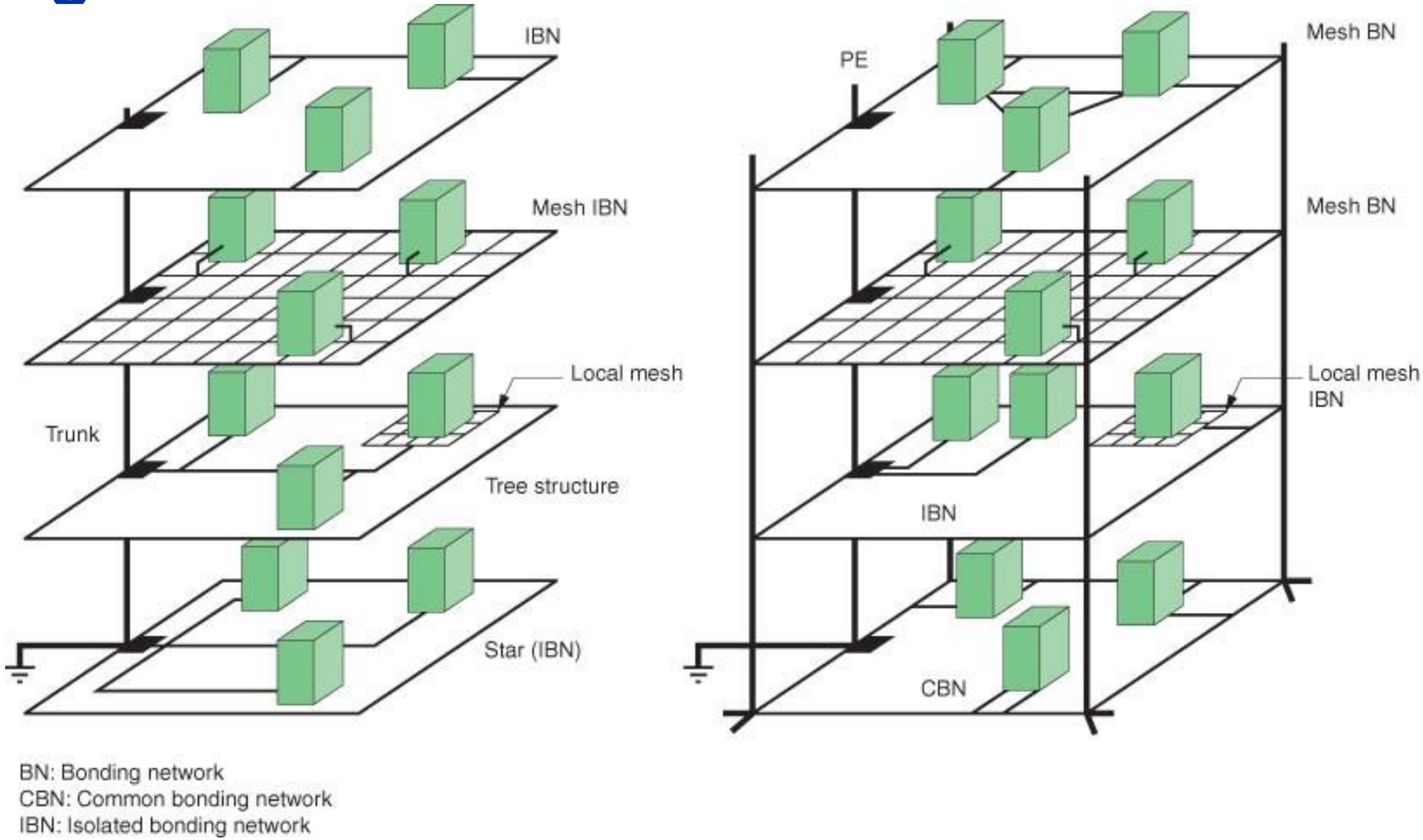
- For a conductor, impedance between the ends increases with its length 
- For a 2D grid, impedance between two points does not depend on distance
- For a 3D grid, impedance between two points decreases with size of the structure!





Mesh bonding network

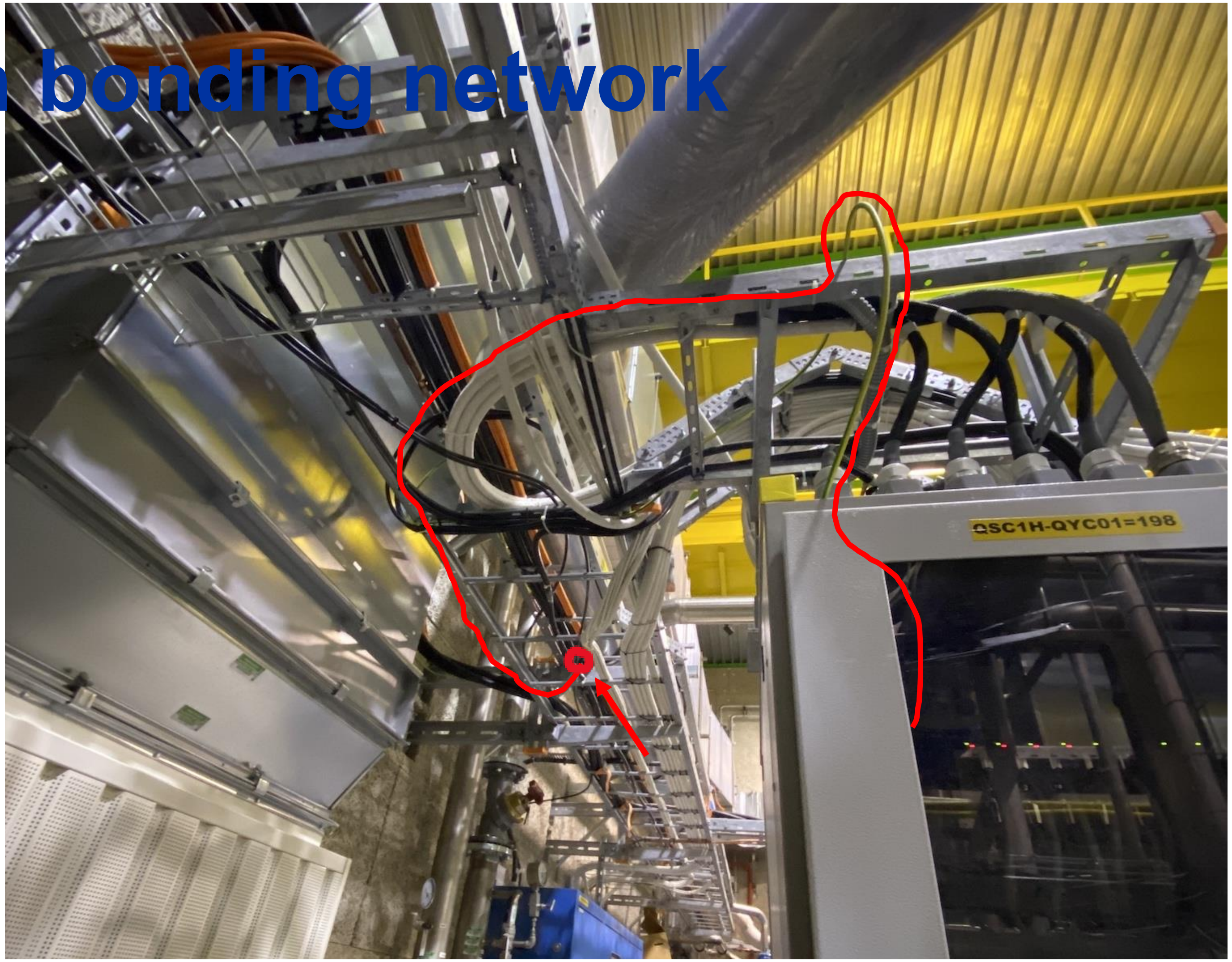
Bonding at a building level



Mesh bonding network

Bonding using the structural components

Mesh bonding network



Connection to a reference potential by an insulated green-yellow PE conductor. OK for 50 Hz, but completely useless for EMC…

Mesh bonding network

Bonding using the racks and chassis

Use the rack as a conducting structure

Careful with the old types which are all covered by paint

Introduce a well conducting path

Interconnect all racks at multiple points

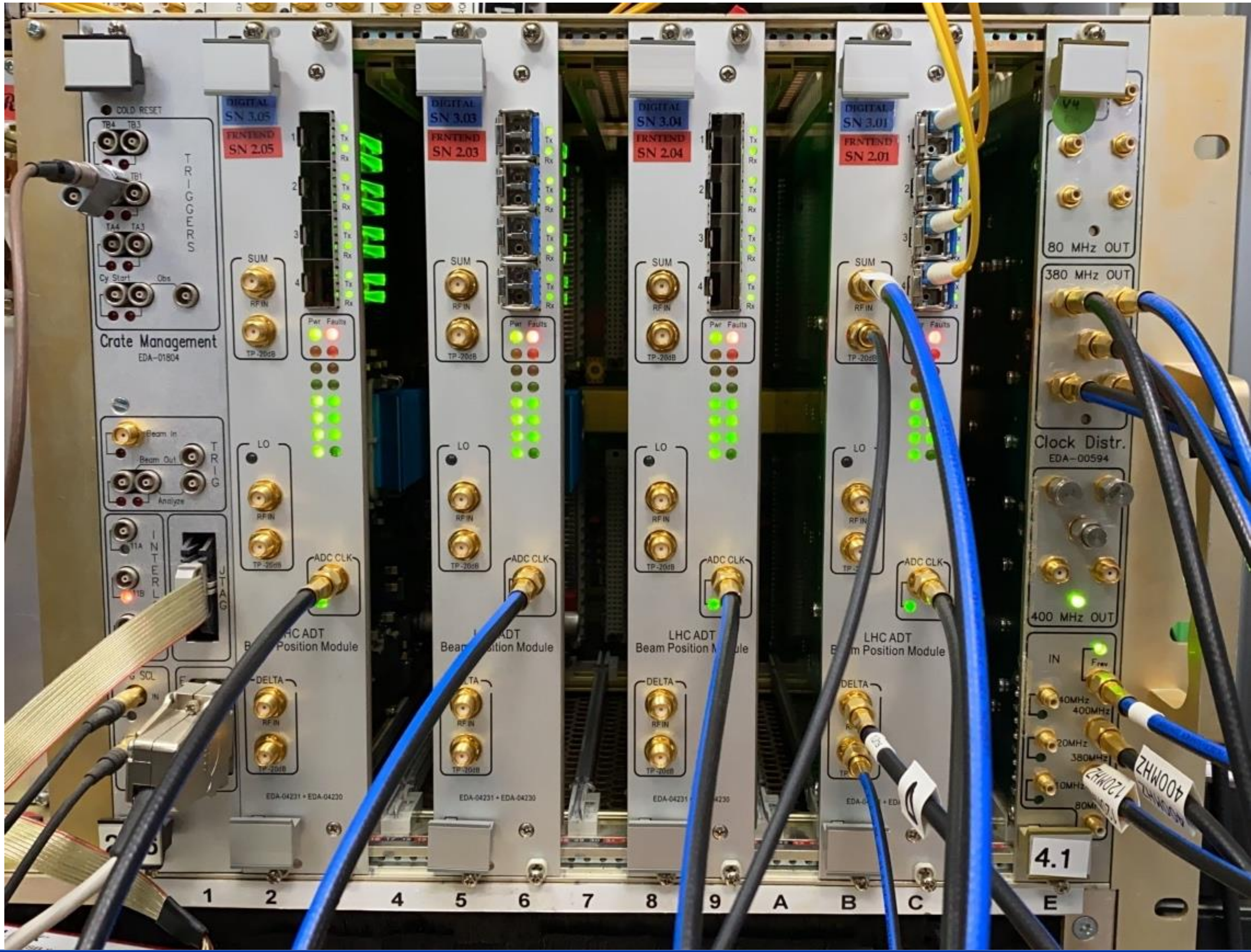
Mesh bonding network

Bonding within a chassis/crate

Use conducting panels

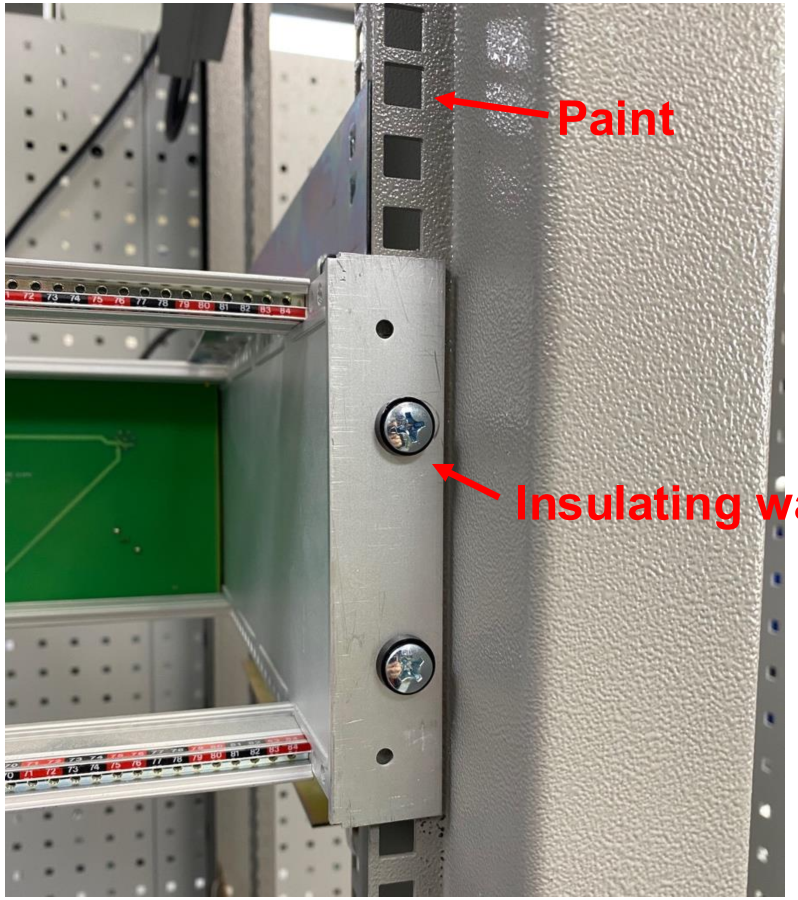
Use electromagnetic gaskets, or RF fingers for better contact

Tighten all screws, do not use plastic washers

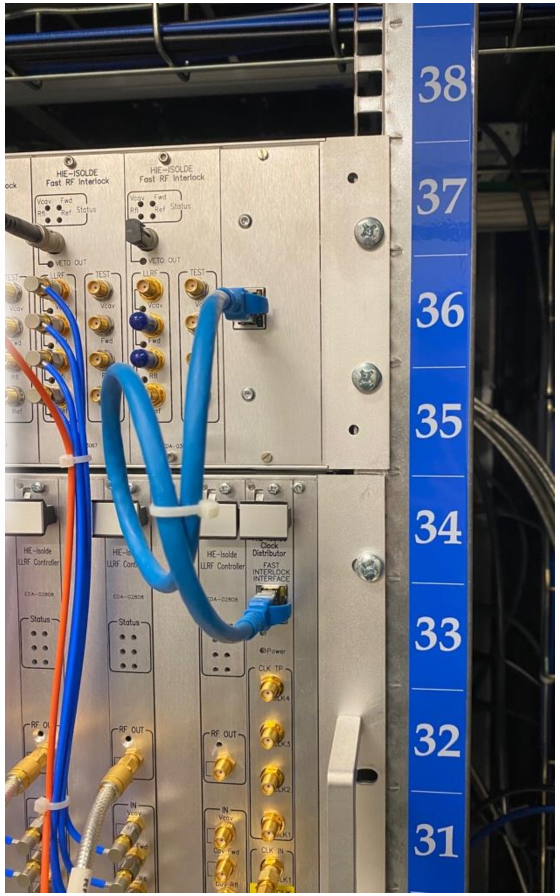


Mesh bonding network

Bad practice:
Insulated rack, insulated screws. Connection to the reference only via PE conductor of mains cable



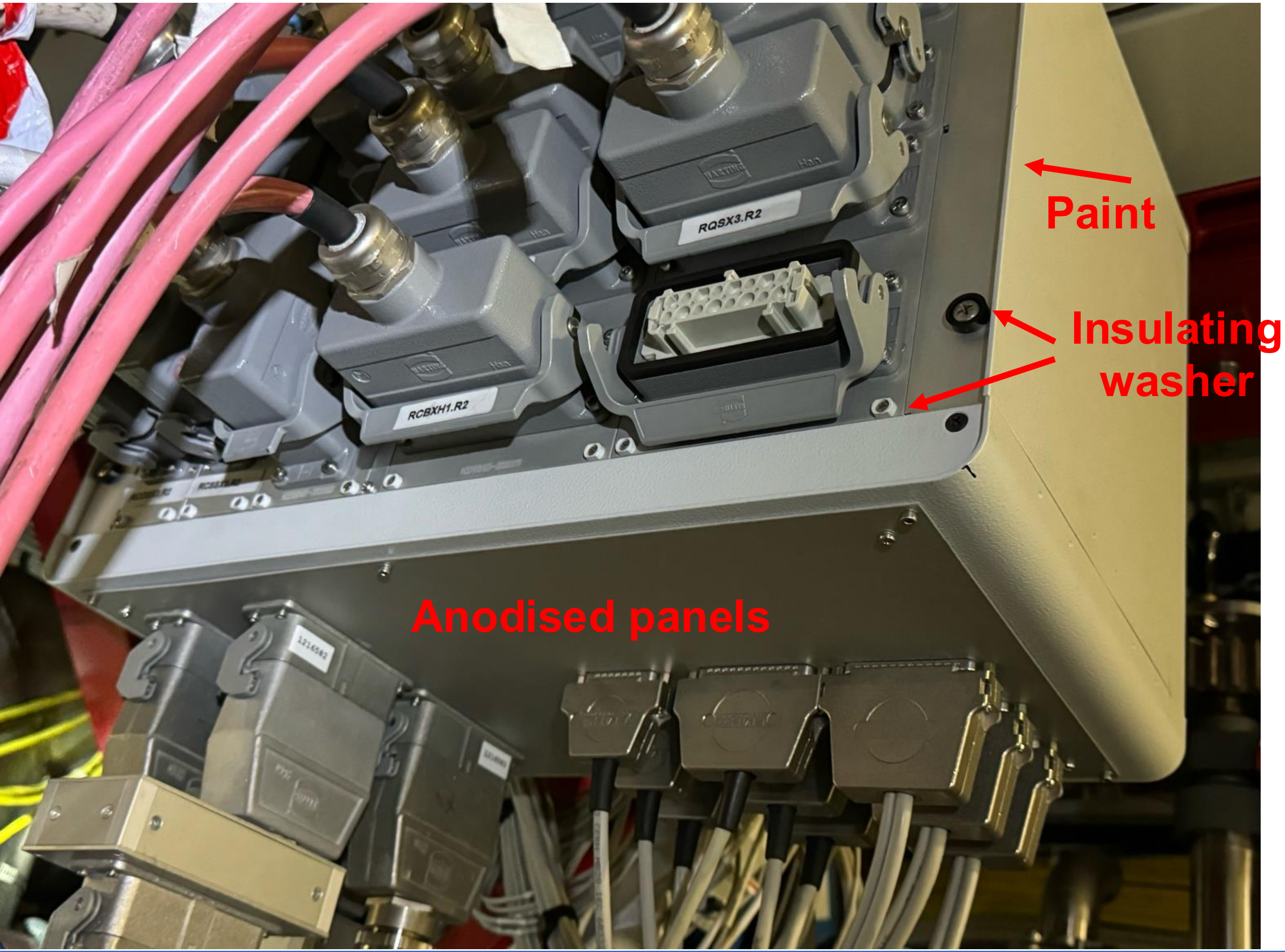
Good practice:
Conductive rack, conductive screws, conductive panels. Connection to the reference via large, low impedance surfaces.

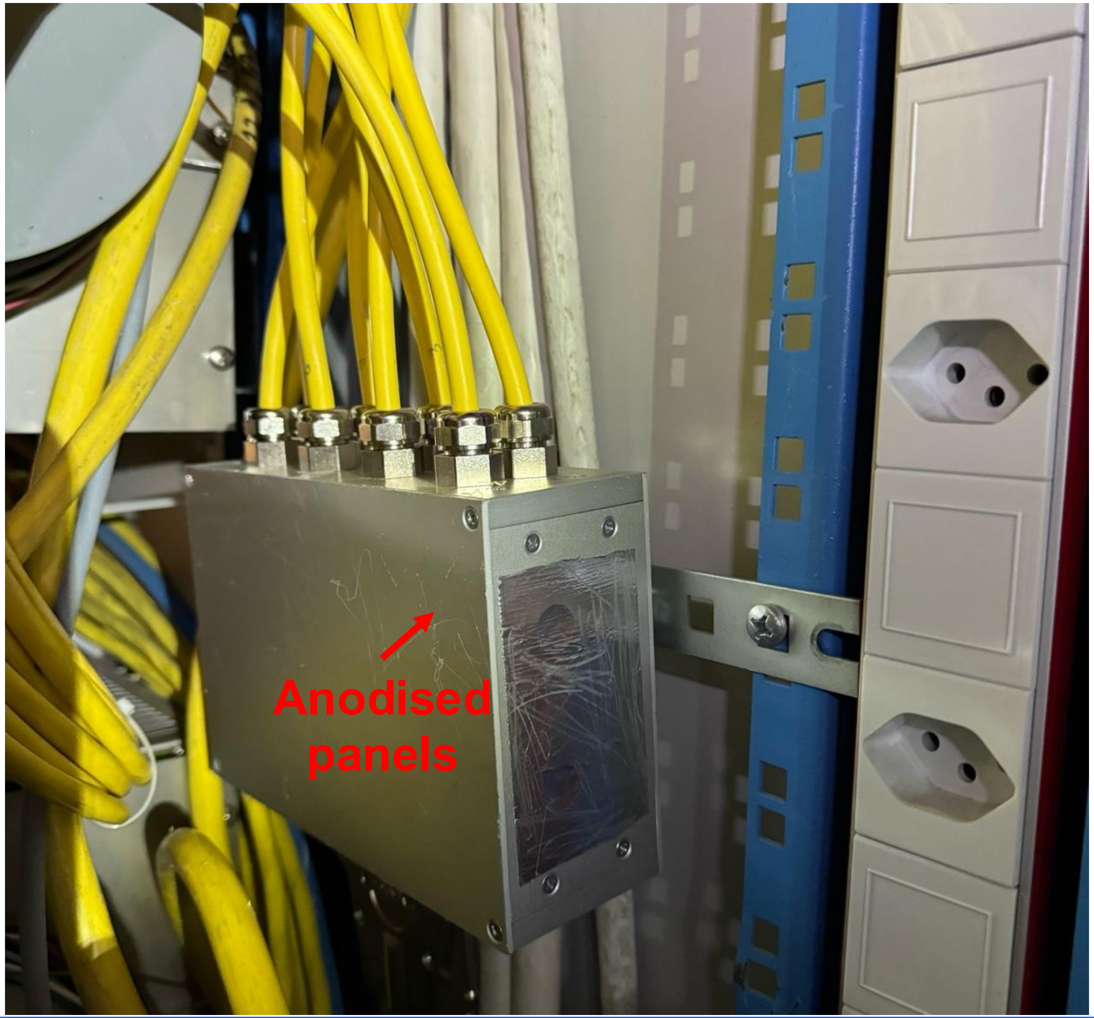


Mesh bonding network

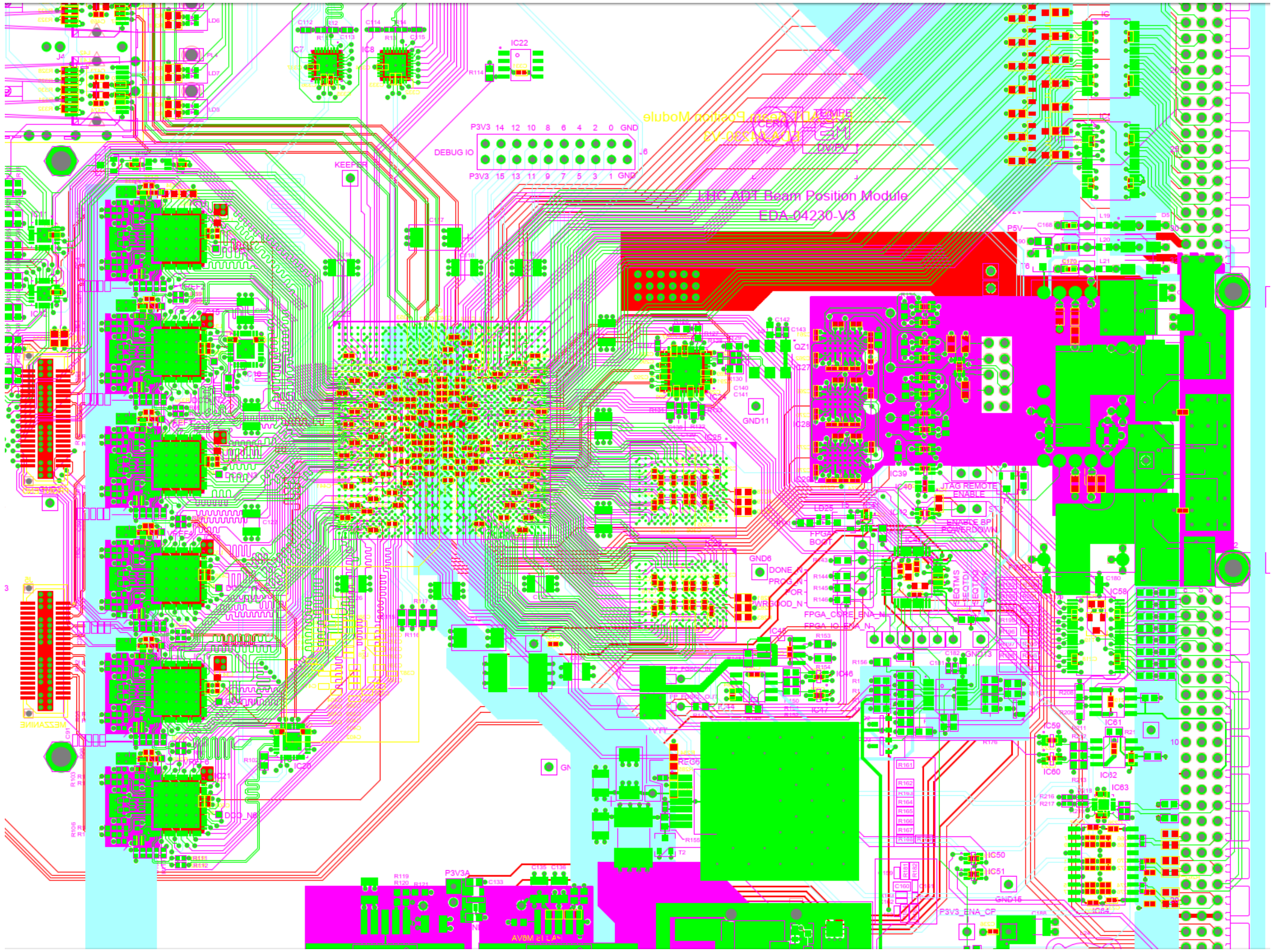
Bad practice:

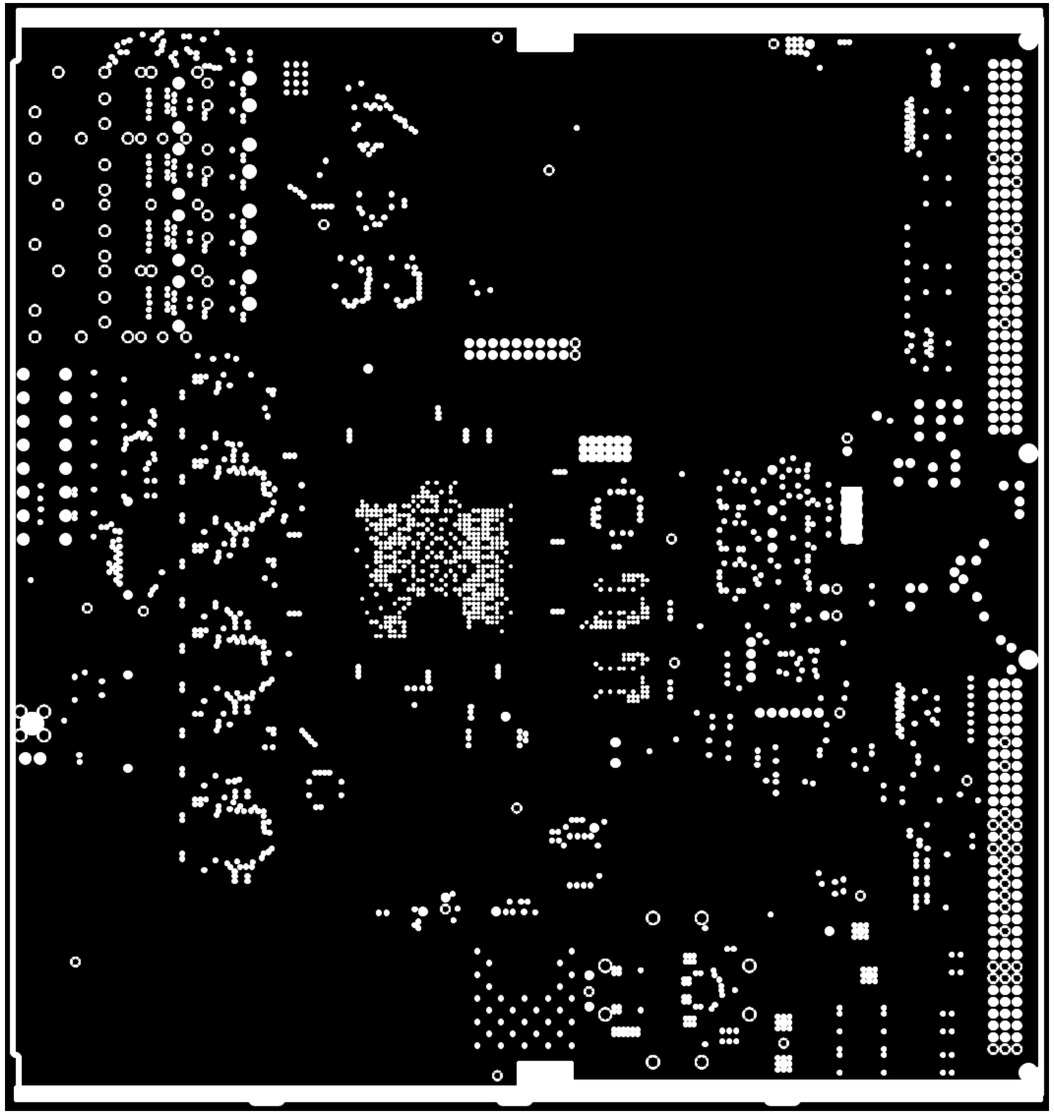
Painted chassis, anodised panels, insulating washers.





Printed circuit boards and equipotentiality





Shielding

Shielding principles

Shielding does not destroy, nor consume the noise. Shielding:

- **improves the immunity by keeping the noise away from the sensitive equipment**
- **lowers the emissions by keeping the noise contained at the source**

We recognize the following principal shielding methods:

- **Electric field AC/DC**
- **Magnetic field DC**
- **Magnetic field AC**
- **Electromagnetic field**

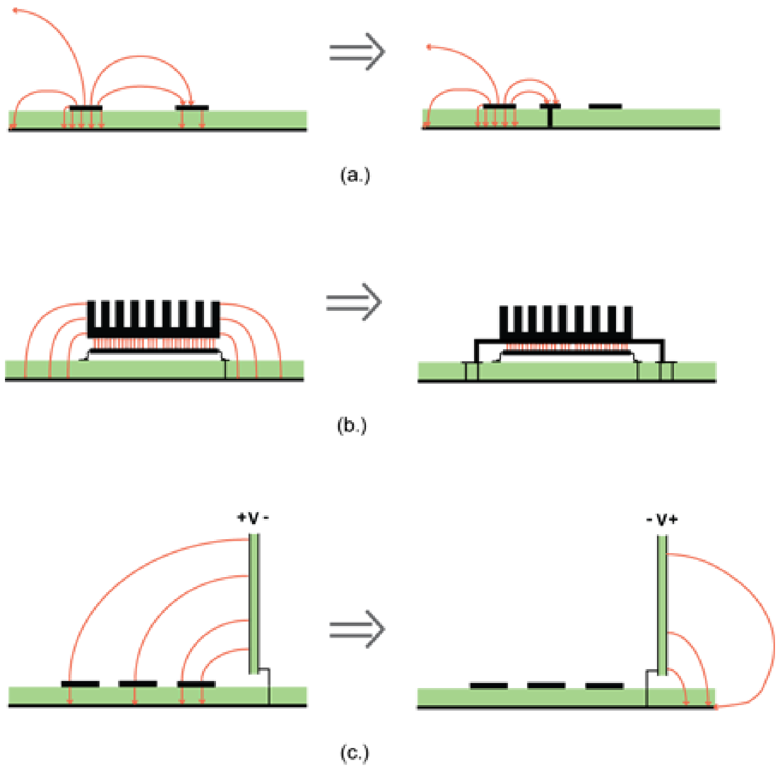
Shielding DC/AC electric field

Electric field can be easily shielded by a conductive material connected to a reference potential (e.g. earthed).

Examples:

- PCB plane
- Sheet of metal
- A metallic mesh, or grid

Static field shielding by a conductive mesh. Window to the former Linac II HV room (750 kV)



Shielding at a PCB level
Picture: https://learnemc.com/practical-em-shielding

Shielding AC magnetic field

For AC magnetic field we can profit from induction, or eddy currents.

The induced voltage is a function of magnetic flux intensity, frequency, loop size and coupling.

Think about skin depth and how thick the shielding must be at a given frequency

Cable screens do not help against ELF induction!

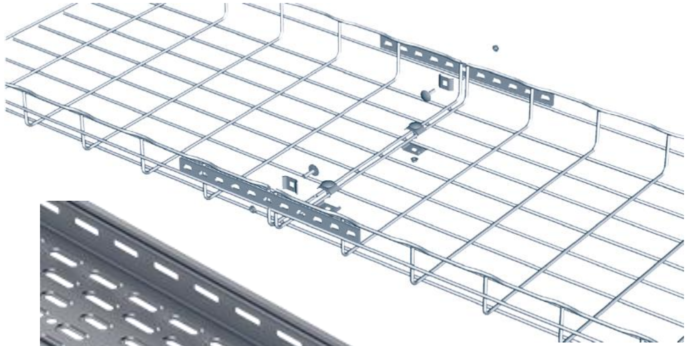
x/δ	J_x/J_0
0 (surface)	1.00000
1.0	0.36787
2.0	0.13533
3.0	0.04978
4.0	0.01831
5.0	0.00673

Frequency (Hz)	Silver	Copper	Alumi-nium	Iron
0	∞	∞	∞	∞
50	8.96 mm	9.22 mm	11.6 mm	1.30 mm
1k	2.00 mm	2.06 mm	2.59 mm	0.292 mm
30k	0.366 mm	0.376 mm	0.473 mm	0.053 mm
1M	63.4 μm	65.2 μm	82 μm	9.22 μm
30M	11.6 μm	11.9 μm	15.0 μm	1.68 μm
1G	2.00 μm	2.06 μm	2.59 μm	0.292 μm

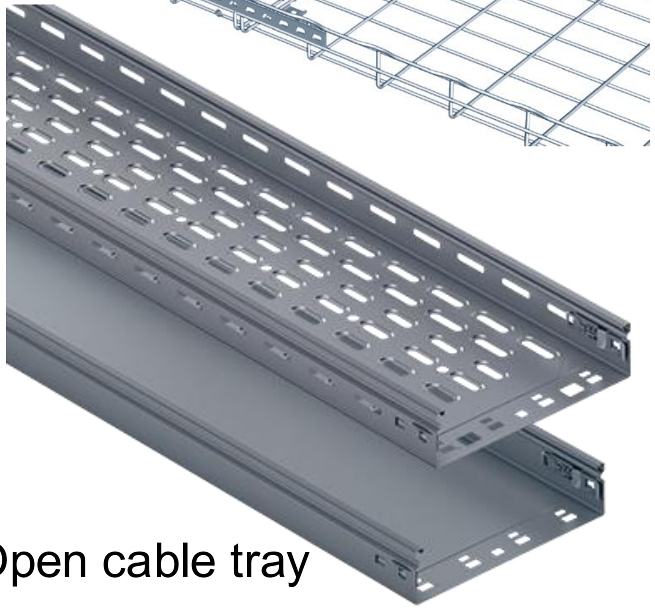
Cables in cable trays

Metallic cable trays offer additional shielding and help to form additional CBN

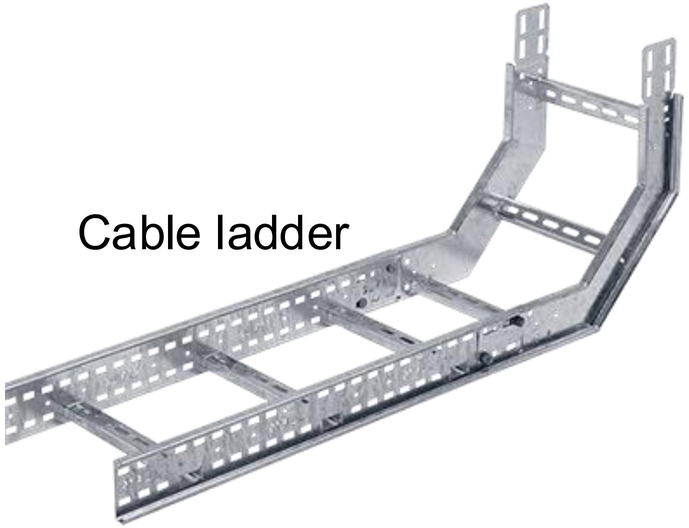
Wire mesh cable tray



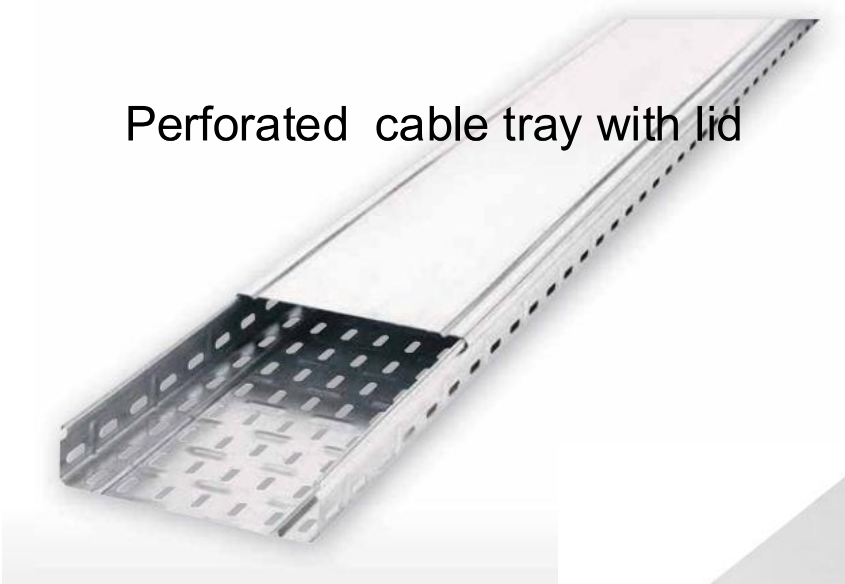
Open cable tray



Cable ladder



Perforated cable tray with lid

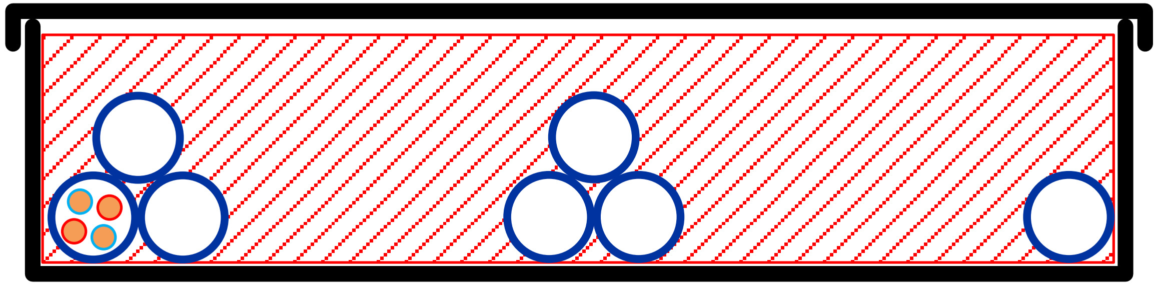


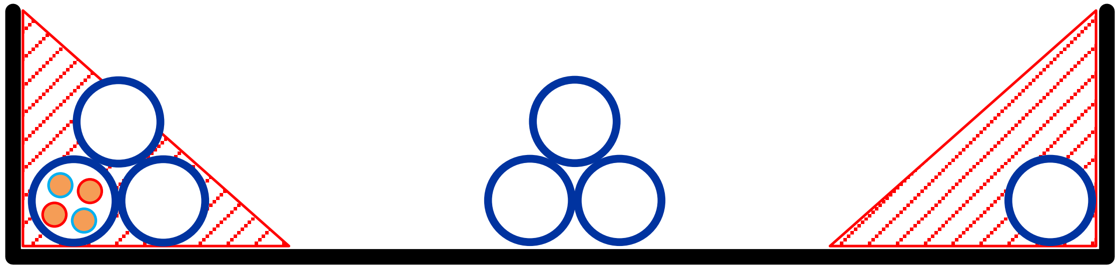
Closed cable tray

Cables in cable trays

Metallic cable trays offer additional shielding and help to form additional CBN

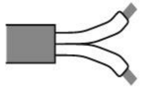
Install sensitive (or offending) cables close to the metallic walls



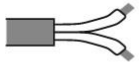


Cables in cable trays

Organization of cables in cable trays Combine compatible types…

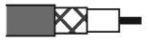


Class 4 Noisy: AC power and return, chassis ground, high-power RF and wideband signals; power inputs, outputs and DC links of adjustable speed motor drives, welding equipment, and similar electrically noisy equipment

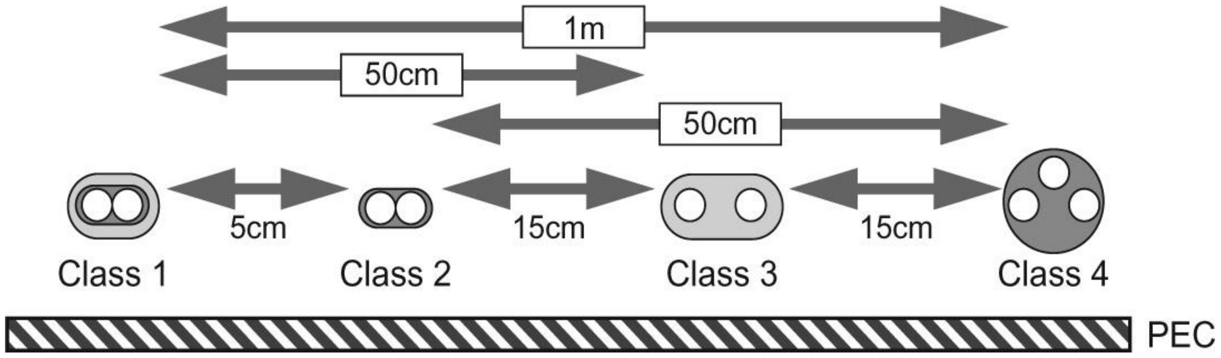


Class 3 Slightly Noisy: DC power, suppressed switched loads, filtered AC; externally supplied low-voltage AC or DC power which does not also supply other noisy equipment, contactor and solenoid coil circuits

Class 2 Slightly Sensitive: low-power low frequency signals, low bit rate digital data; analogue instrumentation (e.g. 4–20 mA, 0–10V) and slow digital bus communications (e.g. RS232, RS422, RS485, Centronics); switched I/O such as limit switches, encoders, and the outputs of internal DC power supplies



Class 1 Sensitive: low-level analogue signals such as thermocouples, thermistors, RTDs, strain gauges, load cells, microphones; also wideband digital and analogue communications such as Ethernet, video, RF receiver inputs; and all other signals with full-scale range less than 1V or 1mA, or with a source impedance > 1kΩ, or signal frequency > 1MHz



Williams T.: EMC for product designers.
https://catalogue.library.cern/literature/3en3f-khz31

Cables in cable trays – what you find

Some signal cables

More power cables

Computer network cables in iron shielding gland

Optical fibres

Most sensitive coax cables with 10MHz signals from the atomic clock

High current power cables

Clean and dirty box approach

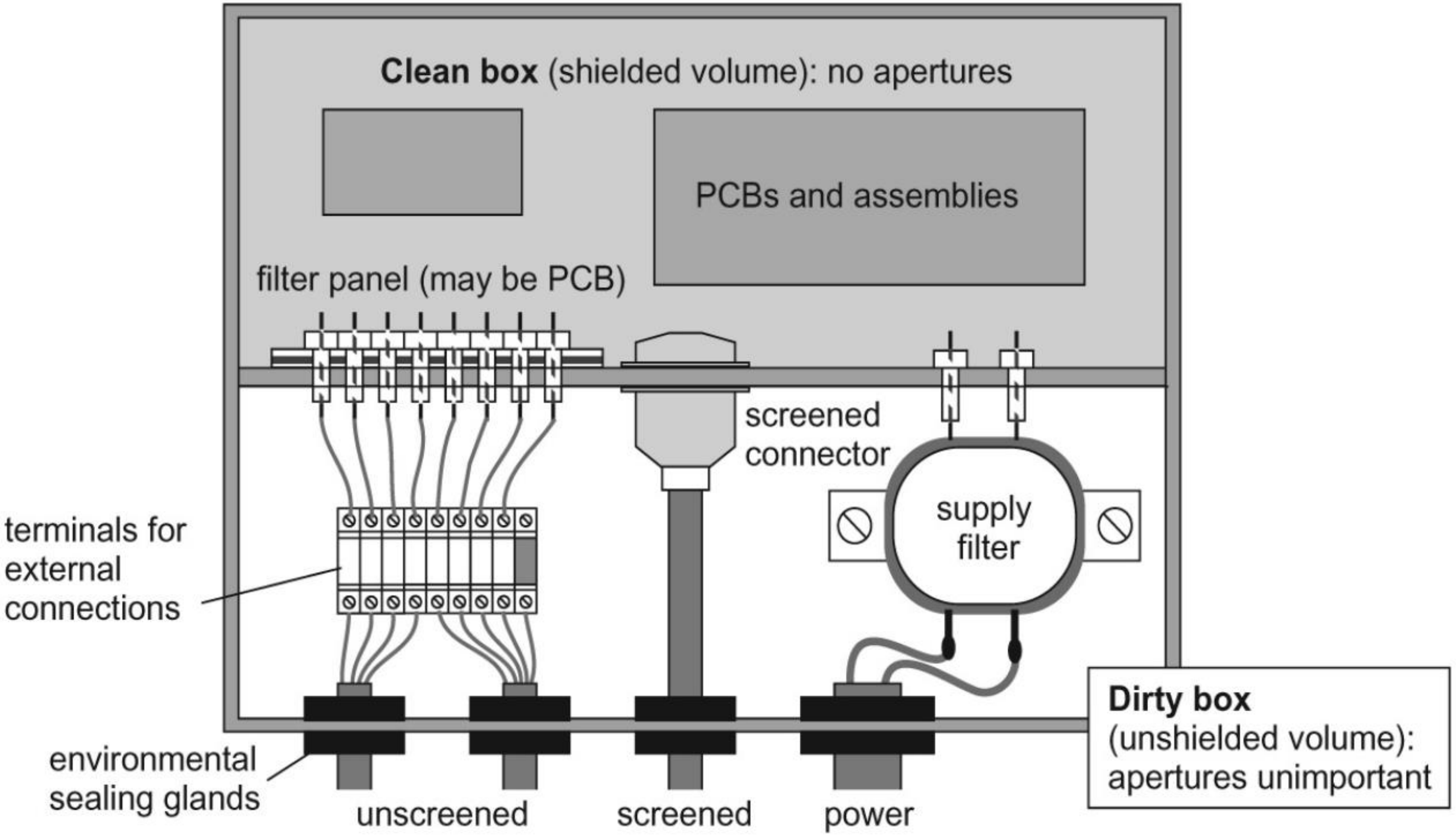


FIGURE 16.7 The “clean/dirty” segregated shielded cabinet

Williams T.: EMC for product designers.
https://catalogue.library.cern/literature/3en3f-khz31

Shielding, cable entry

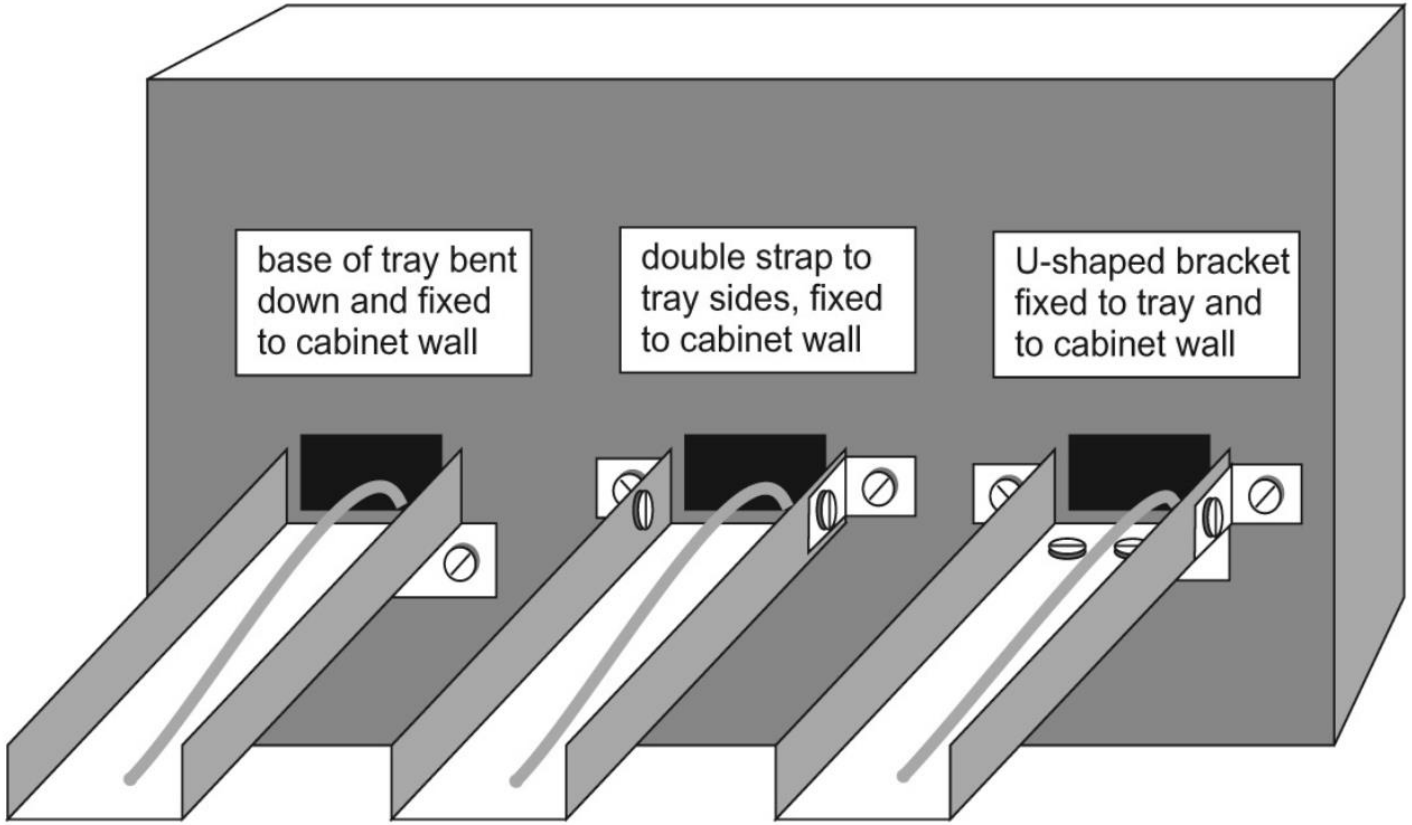
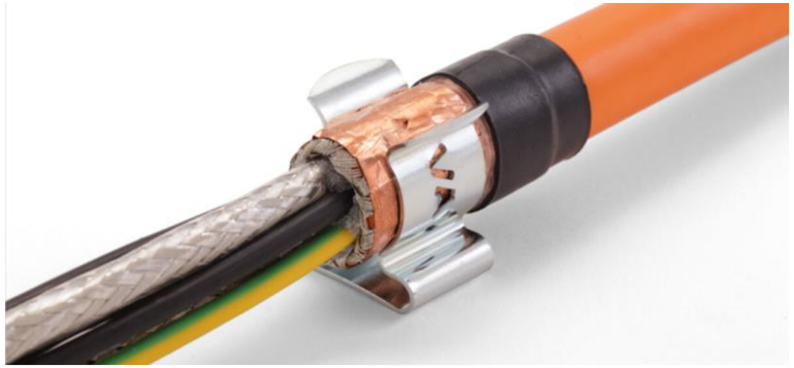


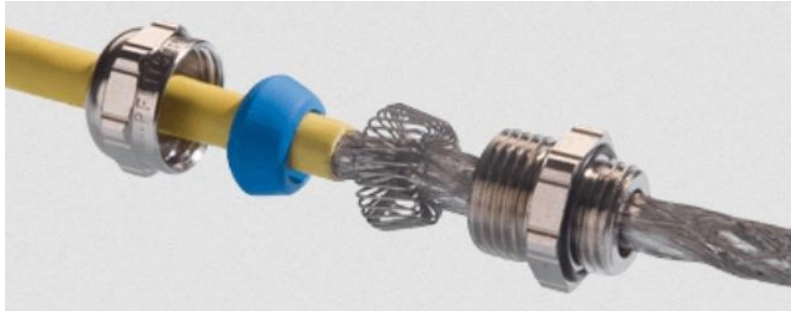
FIGURE 16.4 Methods of bonding cable trays and ducts to equipment cabinets

Williams T.: EMC for product designers.
https://catalogue.library.cern/literature/3en3f-khz31

Shielding, cable entry

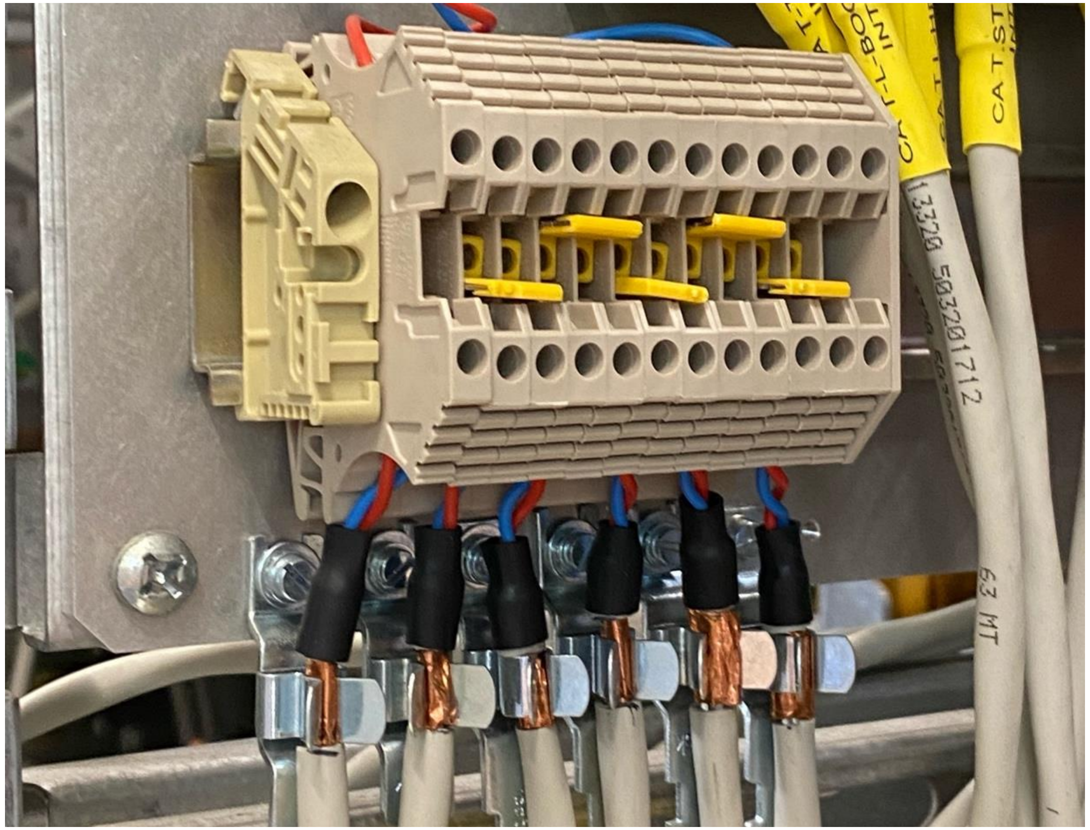
Leave the noise currents “outside”

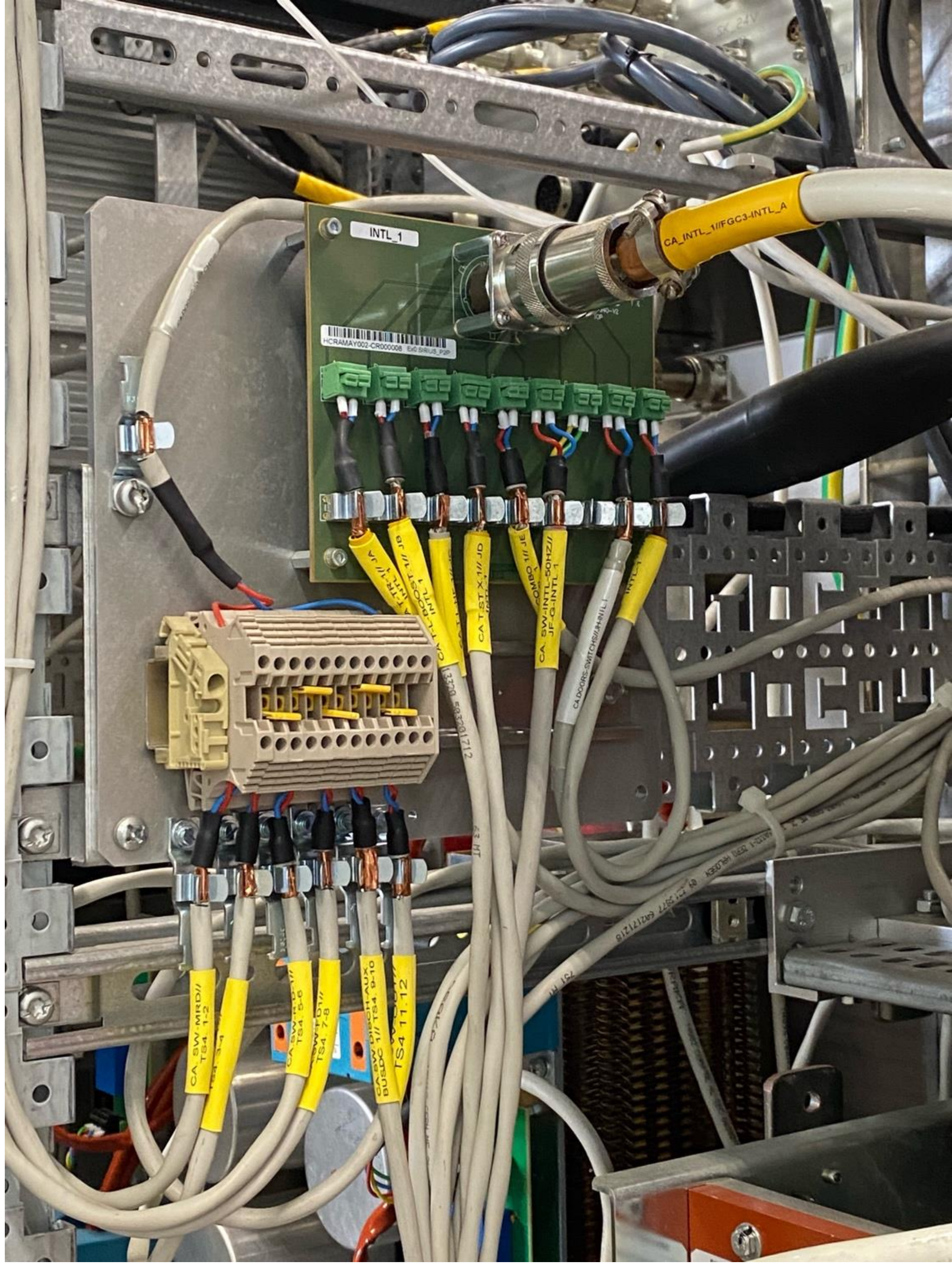




Shielding, cable entry

Leave the noise currents "outside"





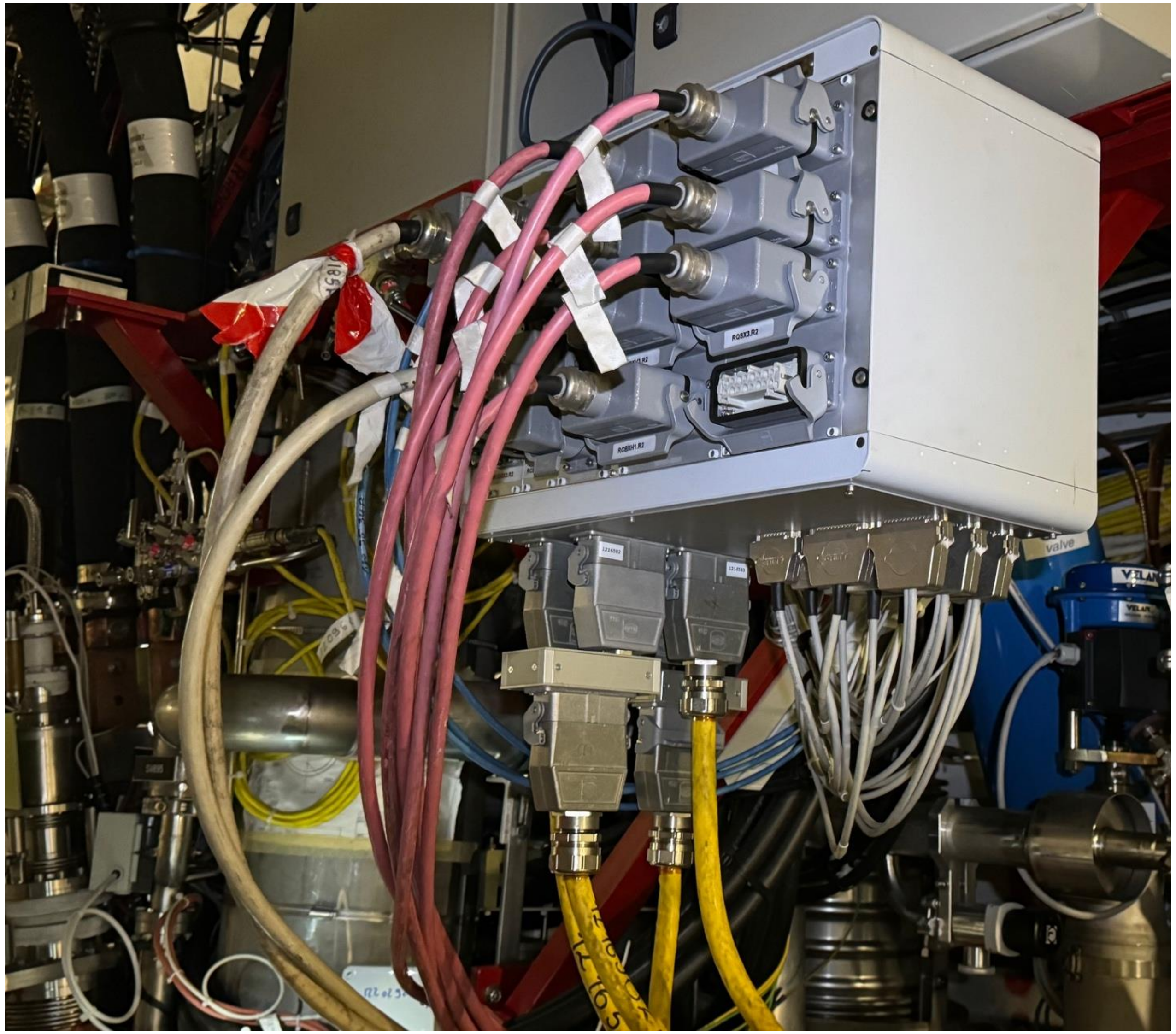
Improper cable entry – bringing all the noise inside

Cable shielding has 360° contact to the connector body, but…

- **Anodised panels**
- **Painted chassis**
- **Insulating screws**

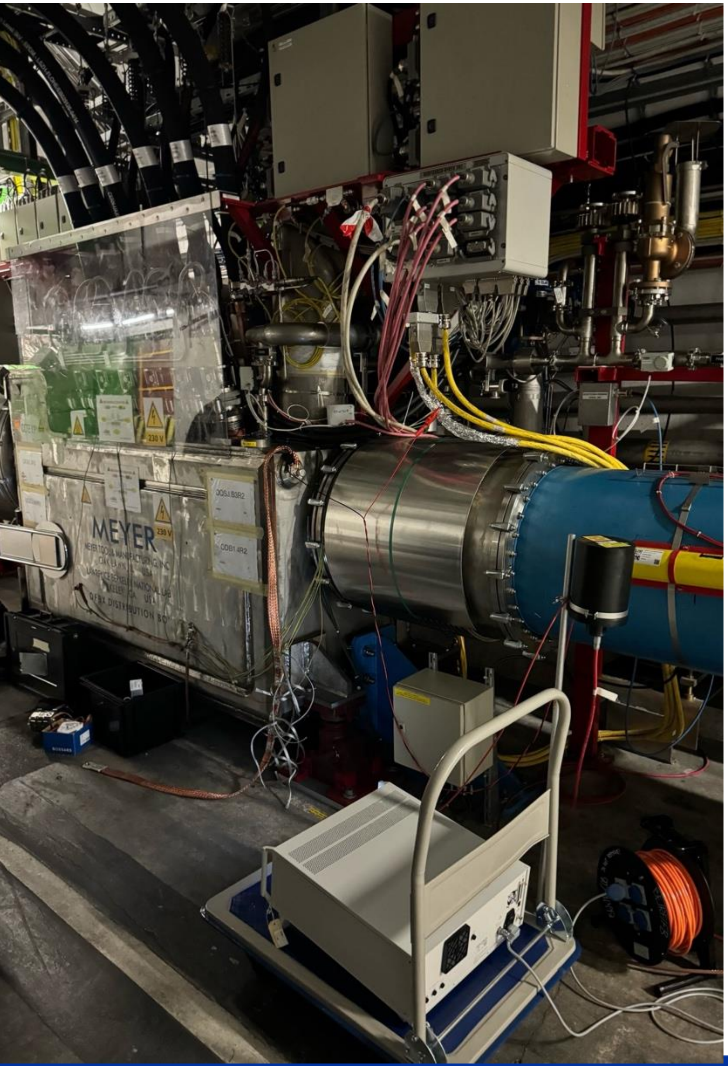
Result:

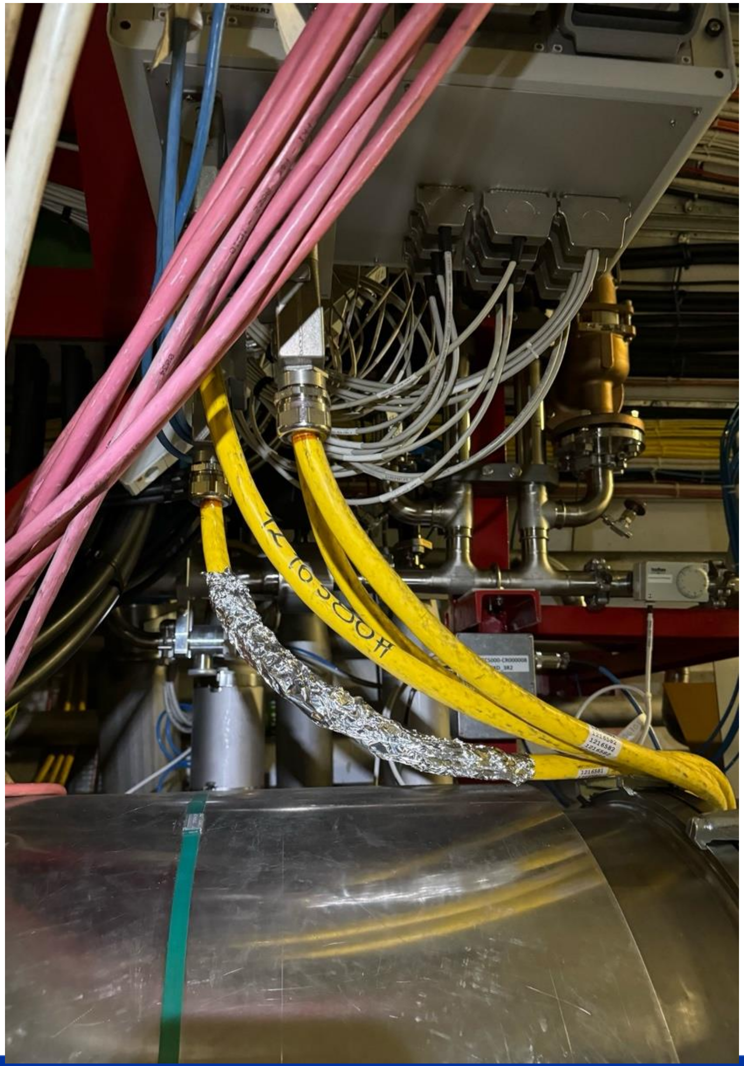
Noise currents are directly guided into the protected volume by “GND pigtails”

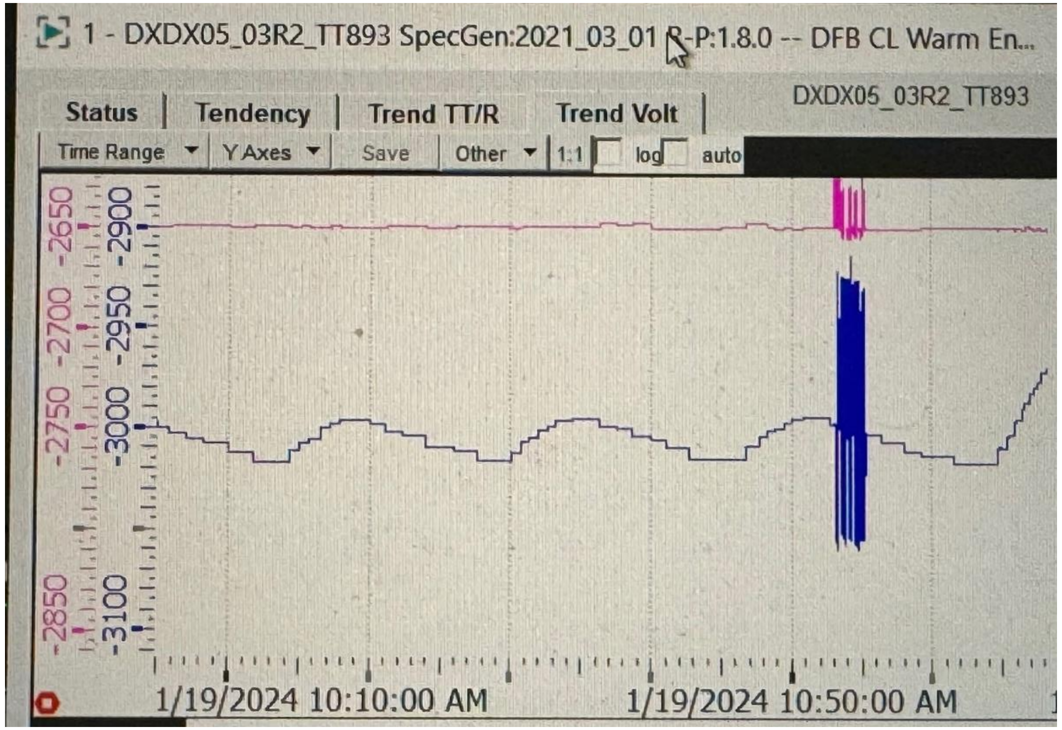


Improper cable entry – bringing all the noise inside

Testing the hypothesis…







Shielding RF electromagnetic fields

RF fields (full electromagnetic field) are usually high frequency, so the skin depth is very small with respect to size of the structural components used

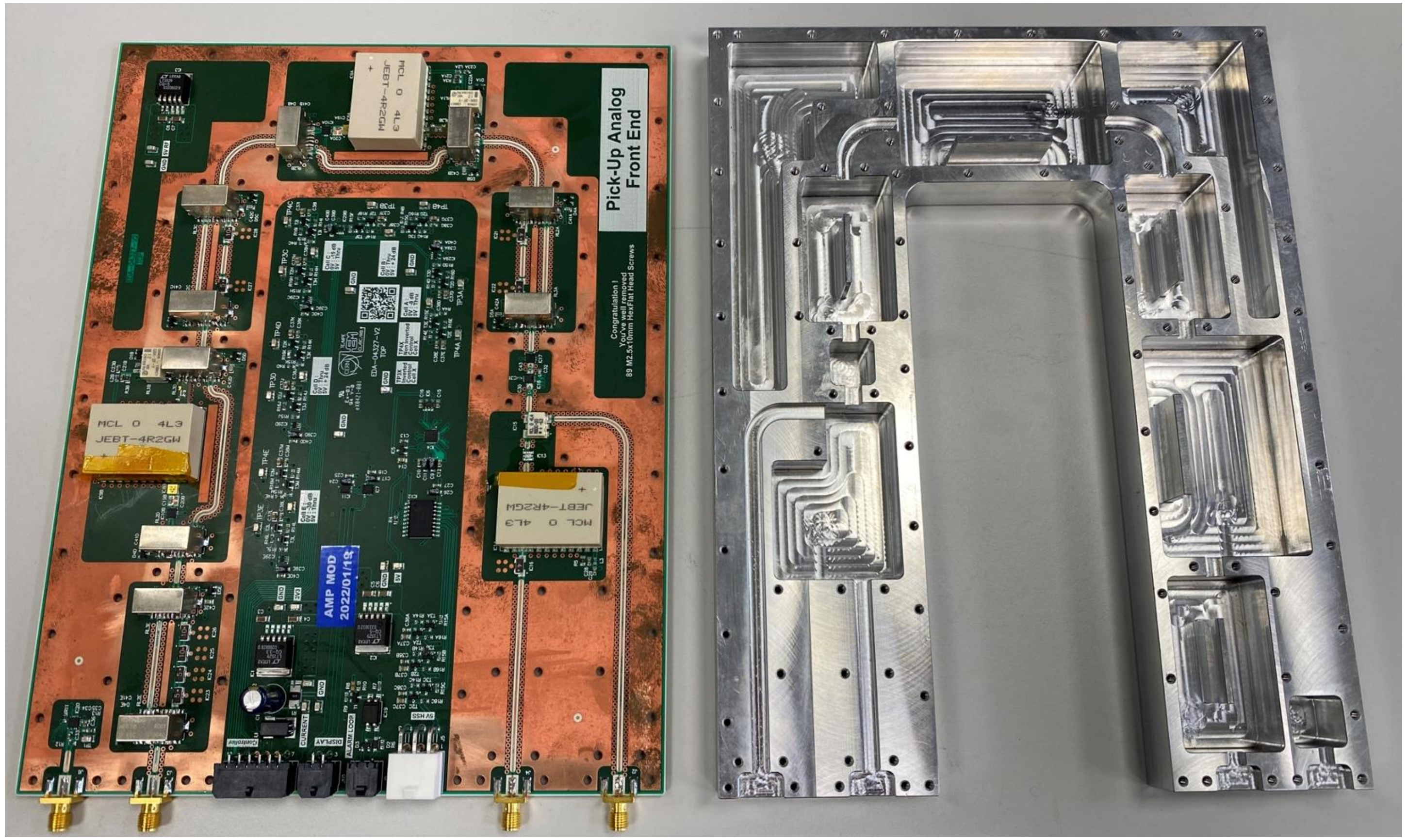
RF fields can be shielded by seamlessly connected conductive planes forming a fully closed enclosure

Sometimes we call it a "Faraday cage"

Tricky part: the seamlessness

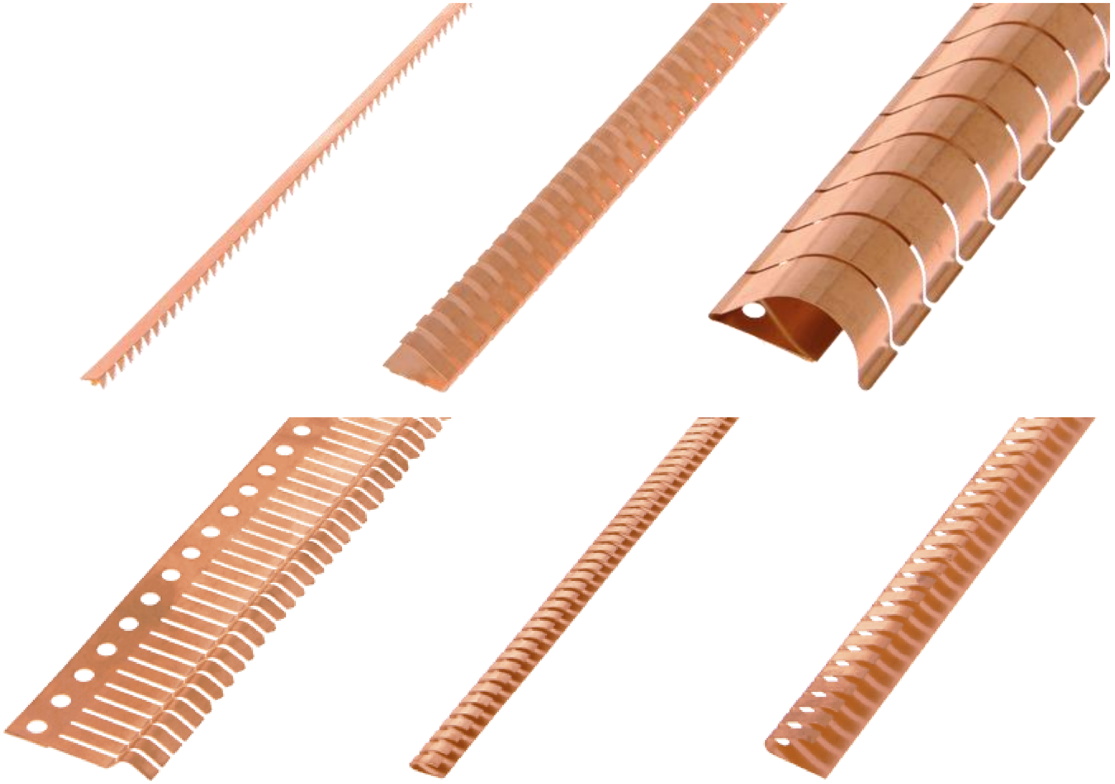
Shielding RF electromagnetic fields

Example: RF shielding at a circuit level

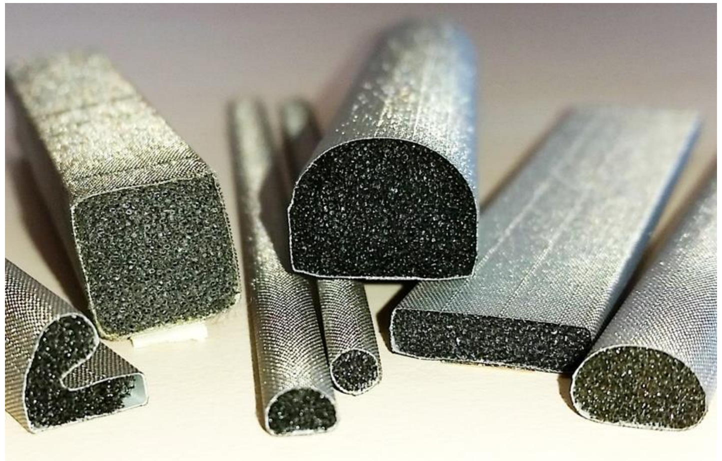


Shielding RF electromagnetic fields

RF fingers, of RF gaskets



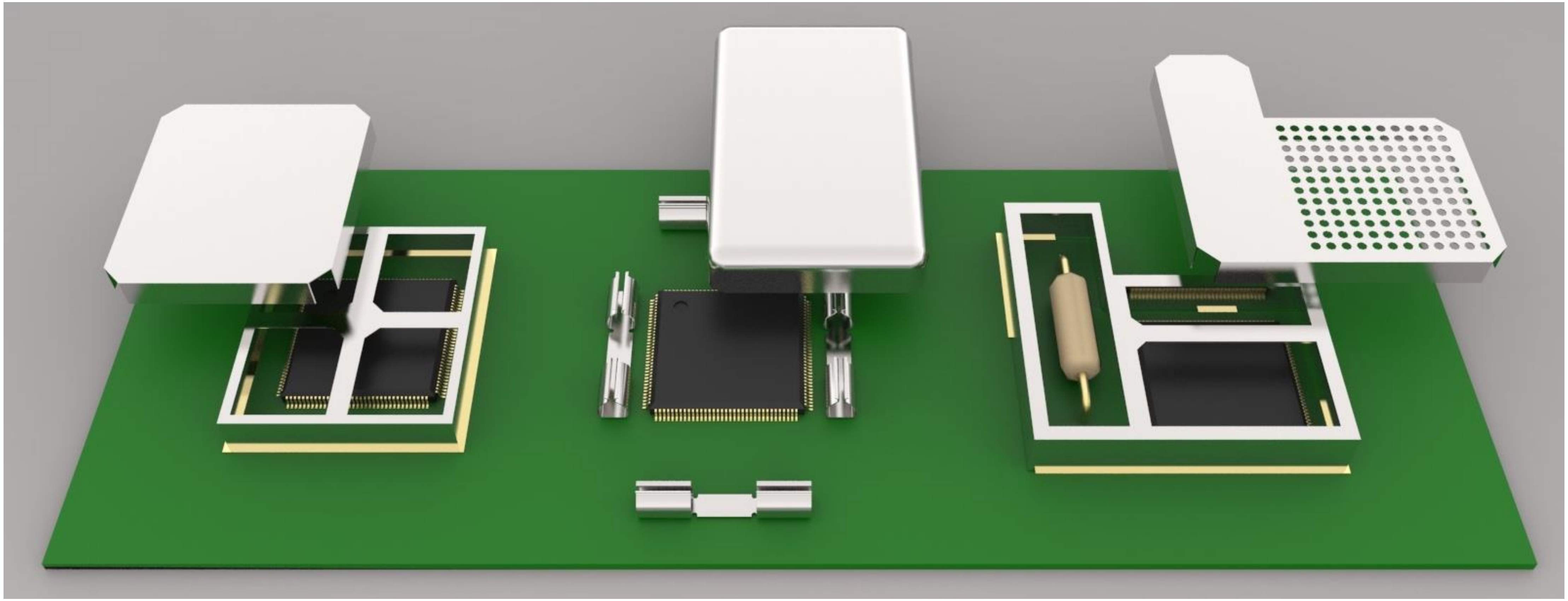
https://hollandshielding.com/Contact-fingers-series



https://www.compelma.com/products/soft-emi-rfi-shielding-gasket

Shielding RF electromagnetic fields

Board level, or component level RF shielding



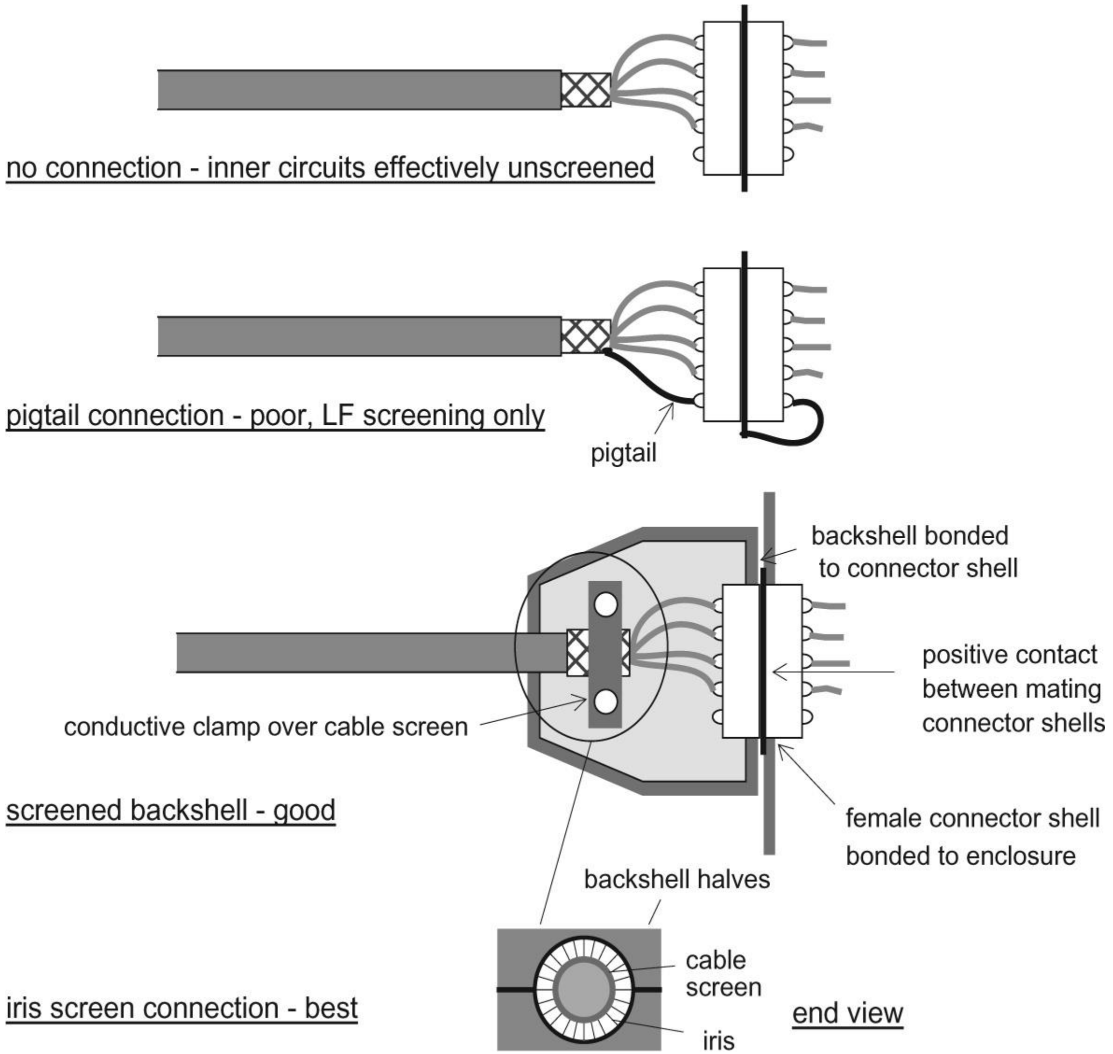
https://www.compelma.com/products/board-level-shielding-emi-cover-and-frame-for-pcb

Cables and connectors

Cable-connector-enclosure transition

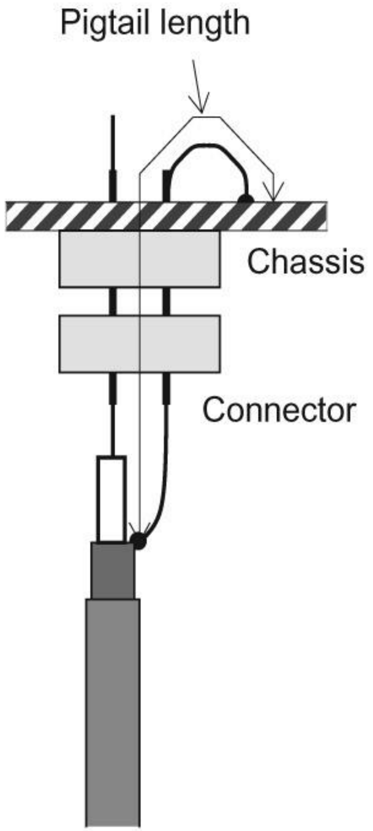
Keep the screen continuous, make the connection to the enclosure "seamless" to provide screen currents a low-impedance path to CBN

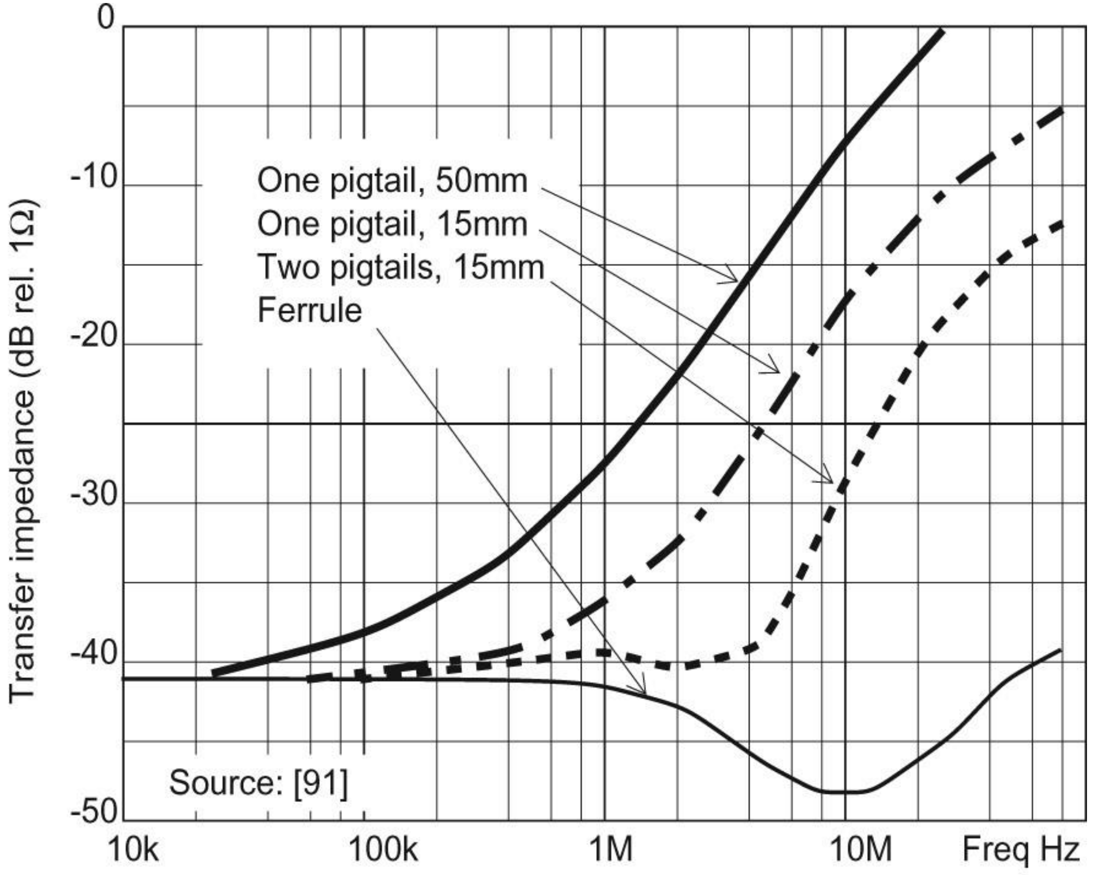
Avoid creating pigtails

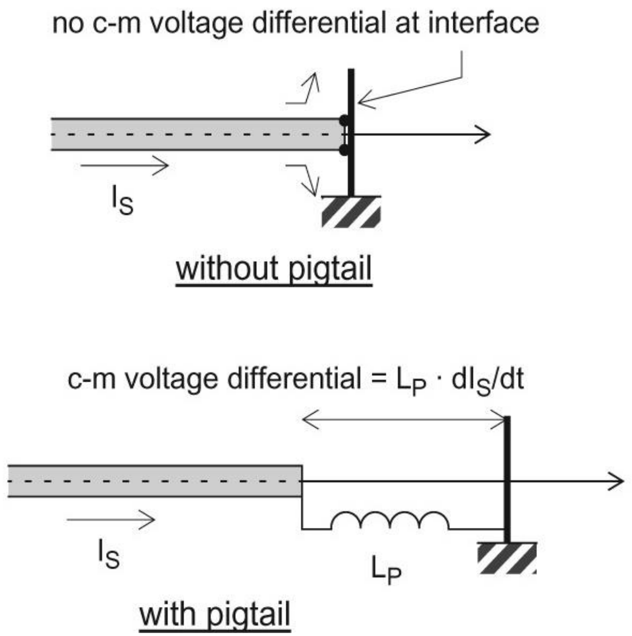


Cable-connector-enclosure transition

Effect of pigtails



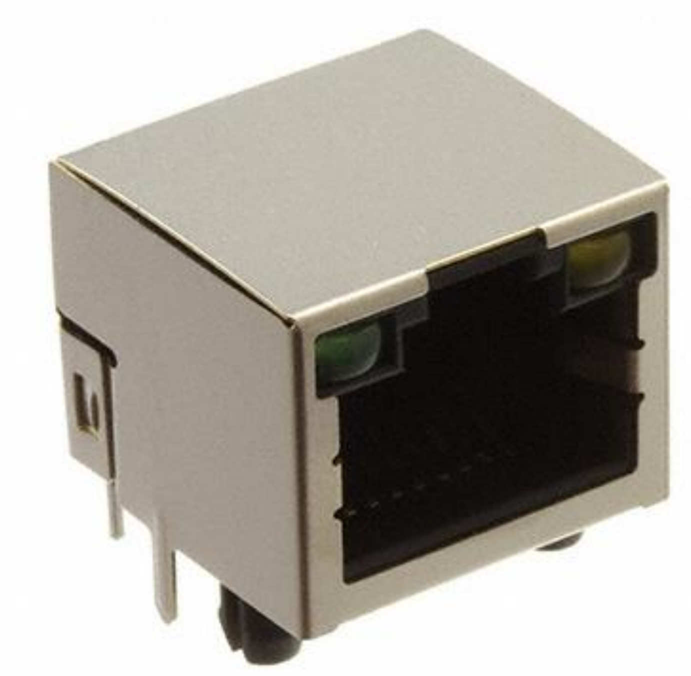




[91] Jones J.W.E. *Achieving Compatibility in Inter-Unit Wiring,* In: Portsmouth Poly, 6th Symposium on EMC, Zurich; March 5-7 1985.

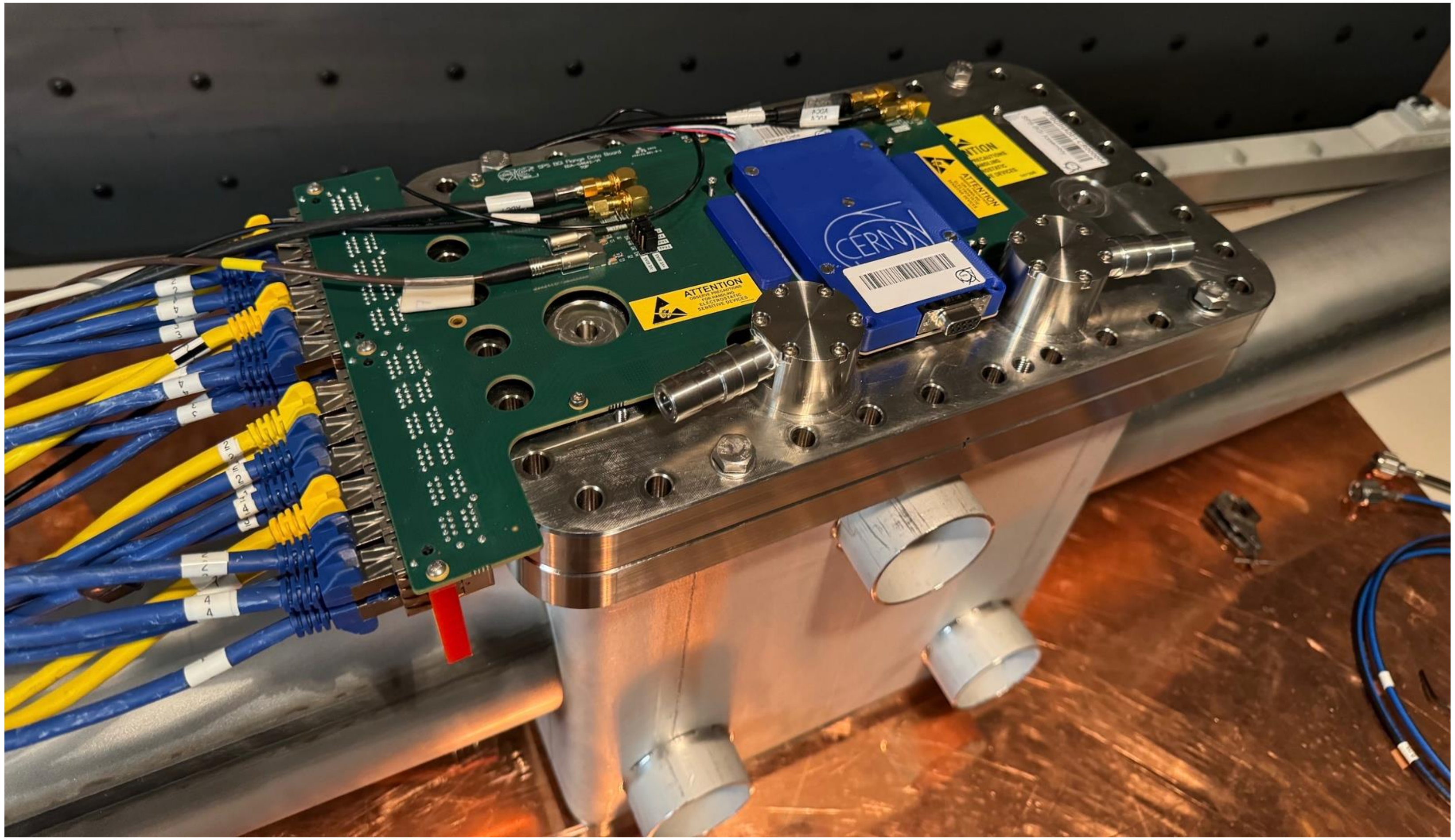
Cable-connector-enclosure transition

Effect of cable screen connection.



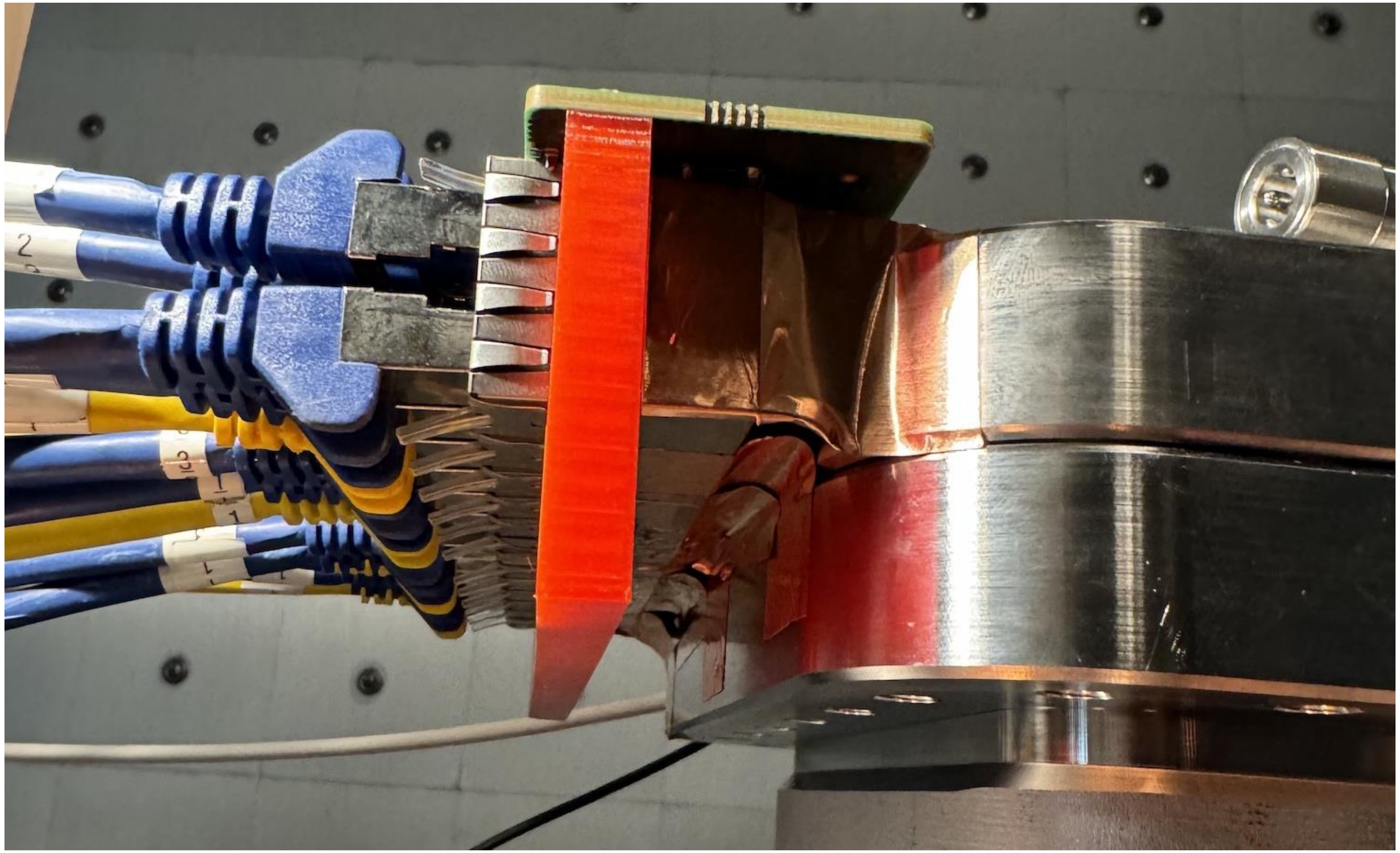
Cable-connector-enclosure transition

Effect of cable screen connection.



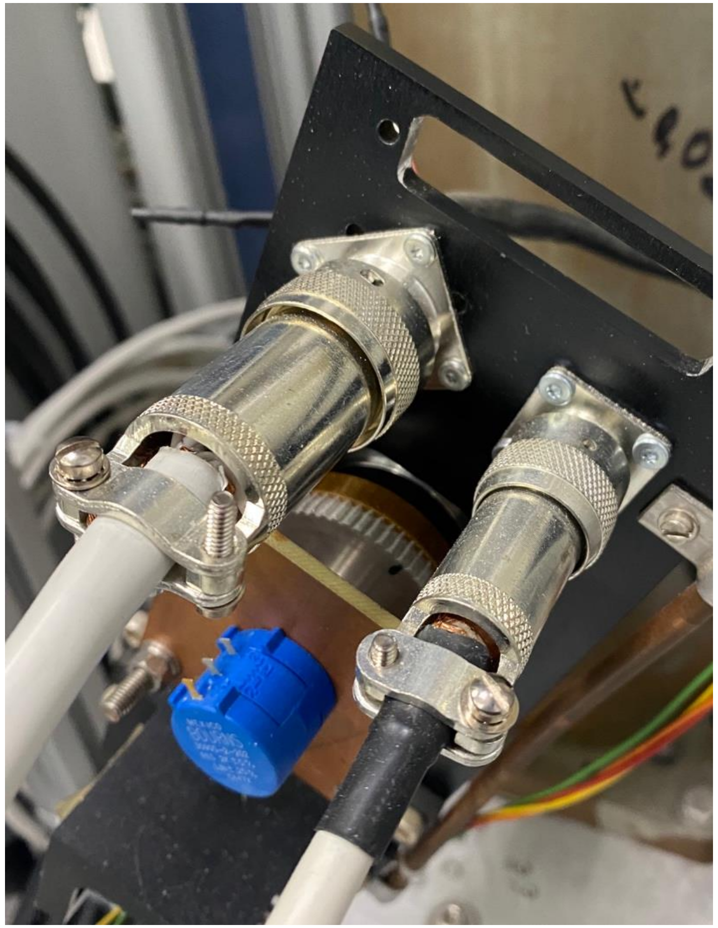
Cable-connector-enclosure transition

Effect of cable signal screen connection.



Cable assembly procedure

Cable screen connected to the connector body by a long pigtail.



Cable screen is either fully floating, or connected to the connector body by a long pigtail.

Cable screen has a good contact with the connector body.

Industrial connectors for EMC performance

Types of hood/housing

Standard hoods/housings for industrial connectors

Field of application	For excellent mechanical and electrical protection in demanding environments, for example, in the automobile and mechanical engineering industries also for process and regulation control applications
Distinguishing feature	Hoods/housings colour-coded grey (RAL 7037)
Material of hoods/housings	Die-cast light alloy
Locking levers	Han-Easy Lock®
Cable entry protection	Optional special cable clamp for hoods with strain relief, bell mouthed cable fitting and anti-twist devices

Han® M hoods/housings for more demanding environmental requirements

Field of application	For all applications where aggressive environmental conditions and extreme climatic atmospheres are encountered
Distinguishing feature	Hoods/housings colour-coded black (RAL 9005)
Material of hoods/housings	Die-cast light alloy, corrosion resistant
Locking levers	Corrosion resistant stainless steel
Cable entry protection	Special cable clamp for hoods with strain relief, bell mouthed cable fitting and anti-twist devices

Han® EMC hoods/housings for higher EMC requirements

Field of application	For sensitive interconnections that have to be shielded against electrical, magnetic or electro-magnetic interferences
Distinguishing feature	Electrically conductive surface, internal seal
Material of hoods/housings	Die-cast light alloy
Locking levers	Han-Easy Lock®
Cable entry protection	EMC cable clamp in order to connect the cable shielding to the hood without interruption of the shielding

Han® HPR hoods/housings for harsh outdoor environments

Field of application	For external electrical interconnections in vehicles, in highly demanding environments and wet areas, as well as for sensitive interconnections that have to be shielded
Distinguishing feature	Hoods/housings colour-coded black, internal seal (RAL 9005)
Locking parts	Stainless steel
Material of hoods/housings	Die-cast light alloy, corrosion resistant
Cable entry protection	Optional universal cable clamp for hoods with strain relief, or special cable clamp with bell mouthed cable fitting and anti-twist devices (use of adapter is necessary)

Han-INOX® hoods/housings for harsh environments

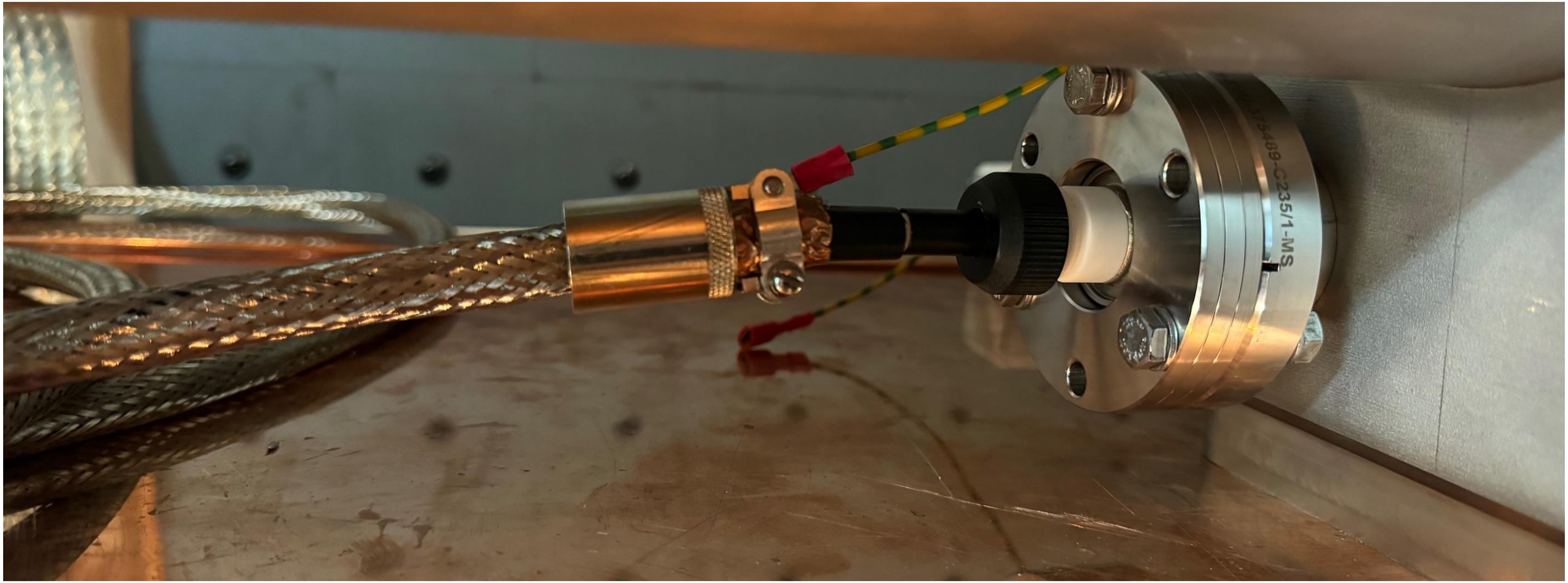
Field of application	For excellent mechanical and electrical protection in demanding environments, for example, in the food, automobile and mechanical engineering industries also for process and regulation control applications
Distinguishing feature	Matt-finished metal surface
Material of hoods/housings	Stainless steel
Locking levers	Stainless steel
Cable entry protection	Standard cable gland (stainless steel)

Han-Eco® – Lightweight hood/housing made of high-performance plastic

Field of application	Industrial environments, outdoor applications
Distinguishing feature	Black plastic hoods / housings
Material of hoods/housings	Polyamide (glass-fibre reinforced)
Locking levers	Double locking lever / single locking lever (10 A / 16 A) (polyamide, glass-fibre reinforced)
Cable entry protection	Integrated plastic cable gland (optional) for sizes 6 B, 10 B, 16 B, 24 B / 10 A, 16 A

https://b2b.harting.com/files/livebooks/en/PRD0200000100046/downloads/livebook.pdf#page=677

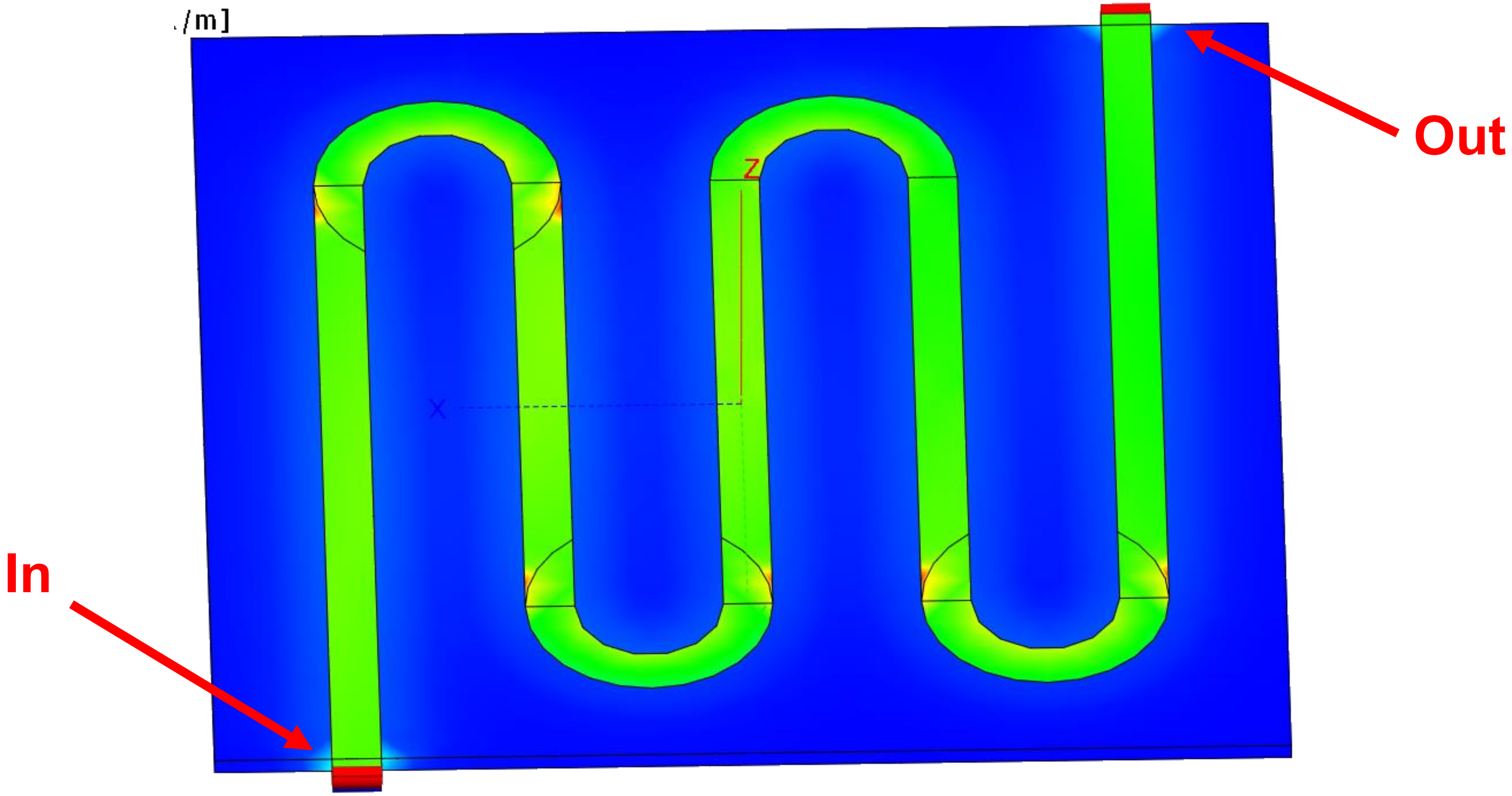
Feedthrough to cable transition…
High Voltage DC signal assumed



Printed boards

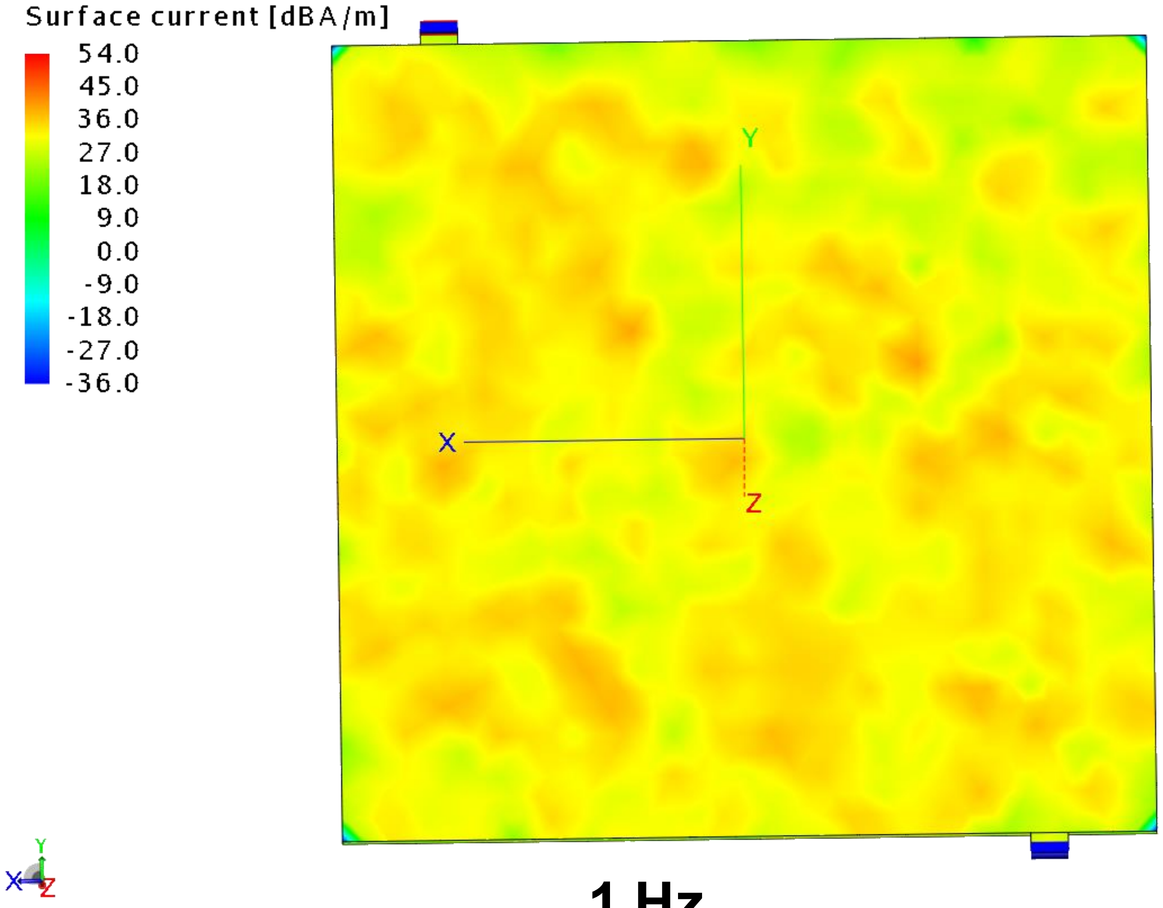
Where does the current flow?

Assume we have a double sided printed board, with meander on top layer and a ground plane at the bottom layer

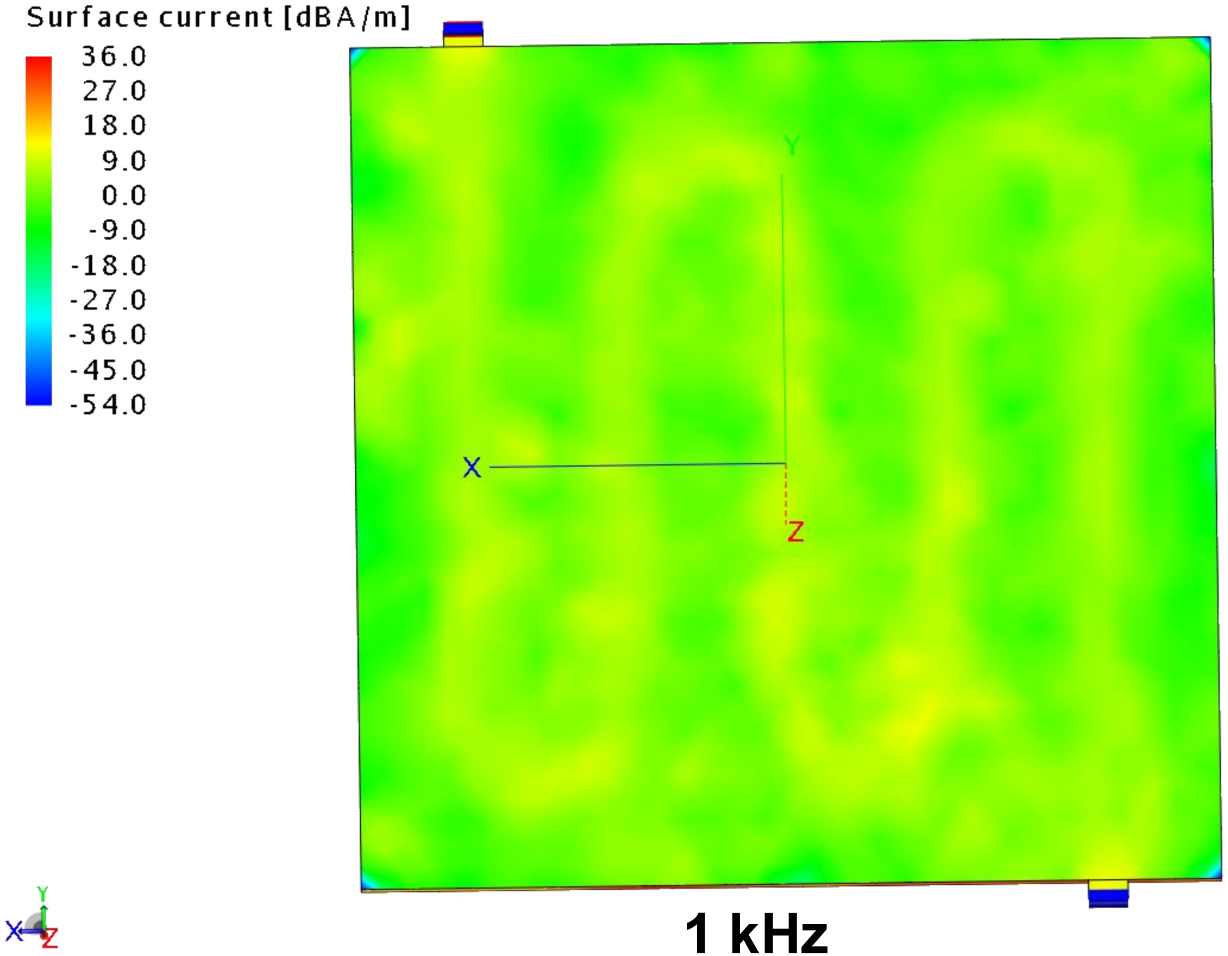


Where does the current flow?

Bottom (gnd) plane current distribution



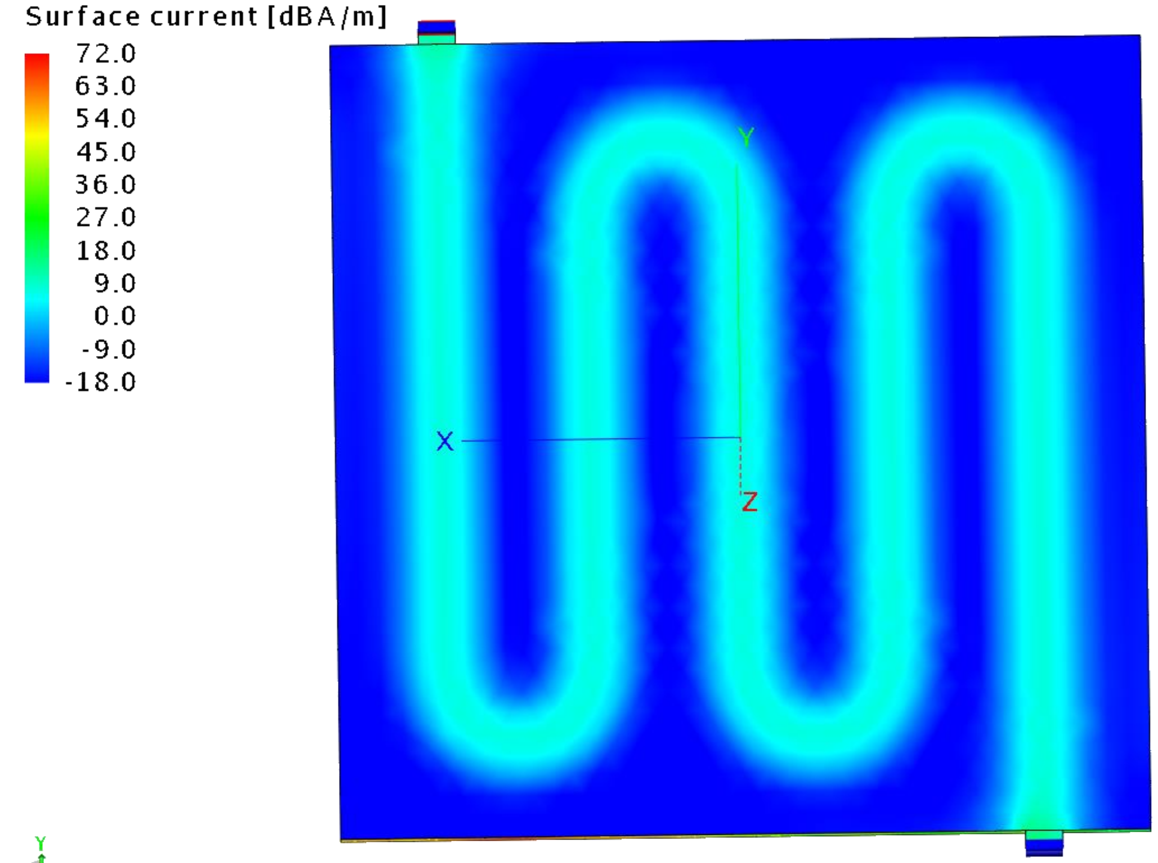
1 Hz



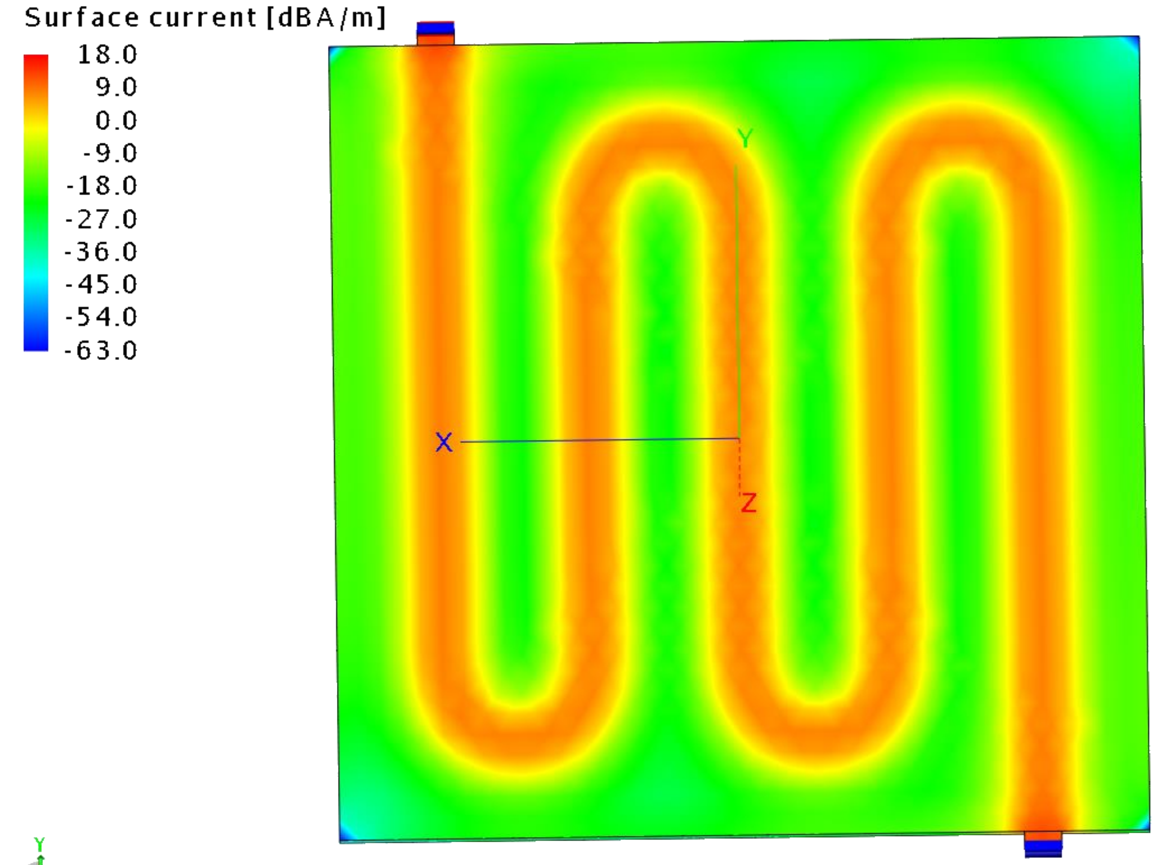
1 kHz

Where does the current flow?

Bottom (gnd) plane current distribution



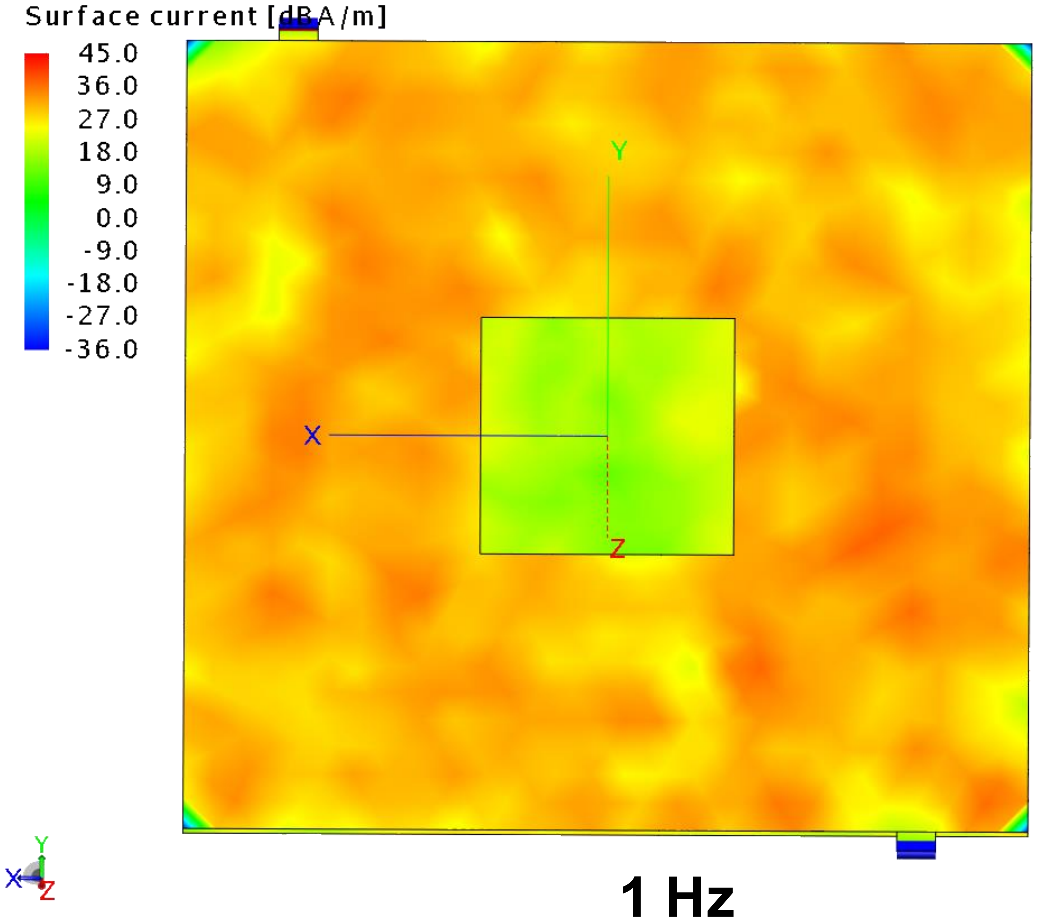
1 MHz



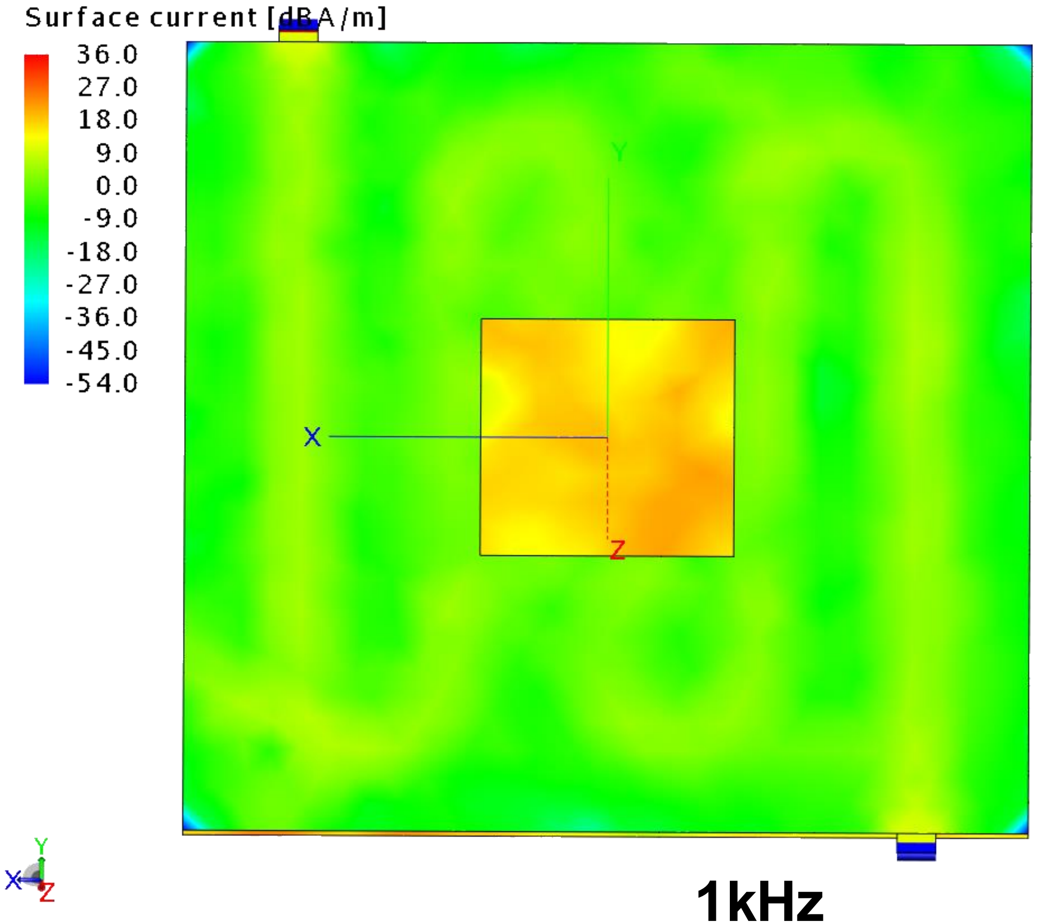
100 MHz

Where does the current flow?

Let us introduce a square hole in the GND plane



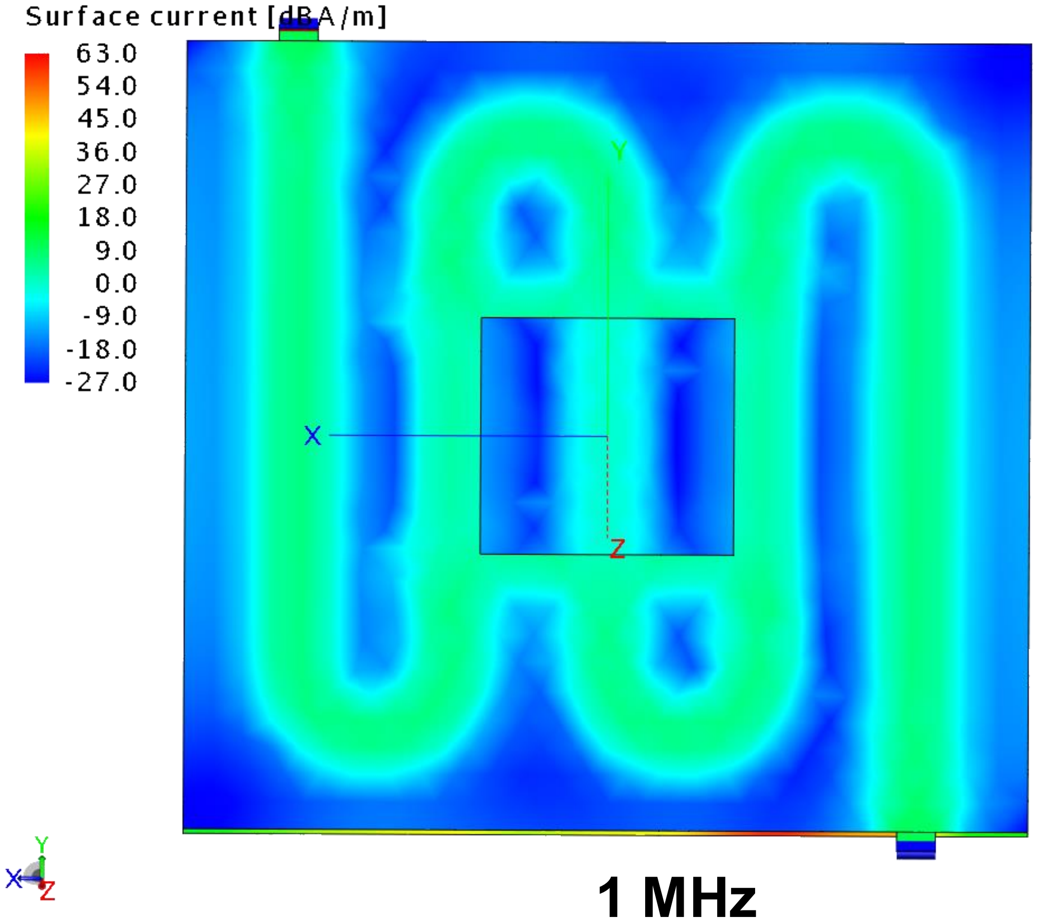
1 Hz



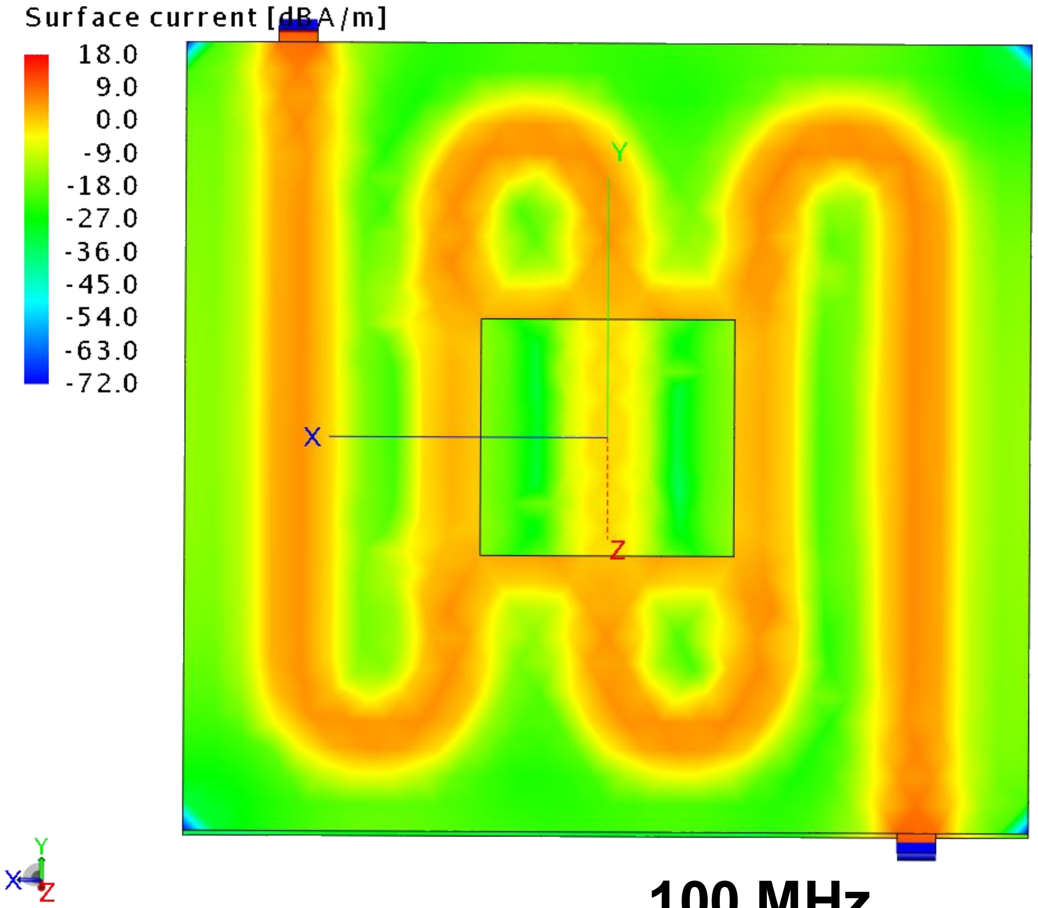
1kHz

Where does the current flow?

Let us introduce a square hole in the GND plane



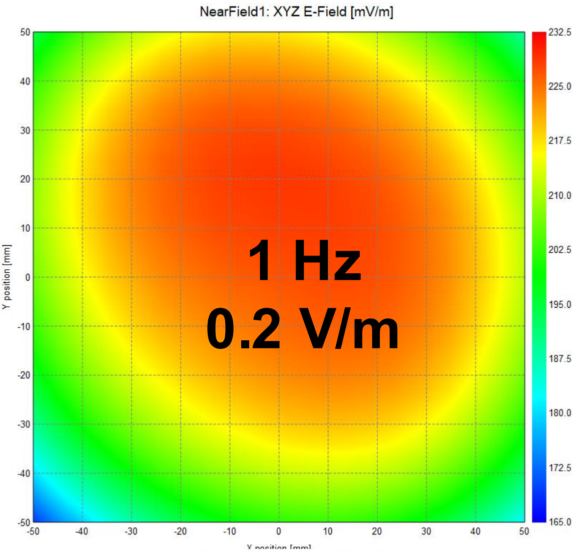
1 MHz

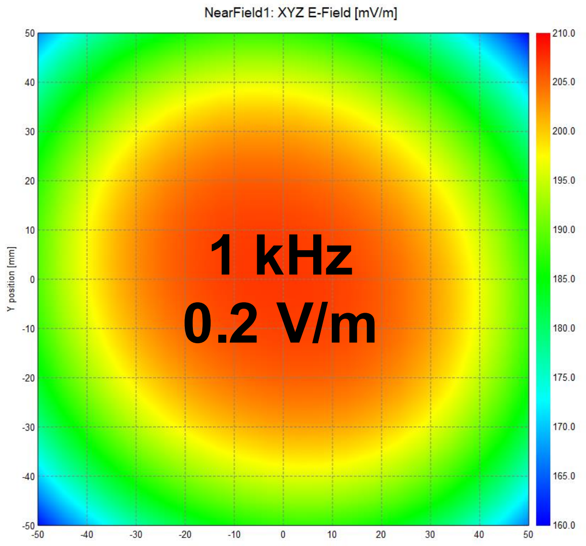


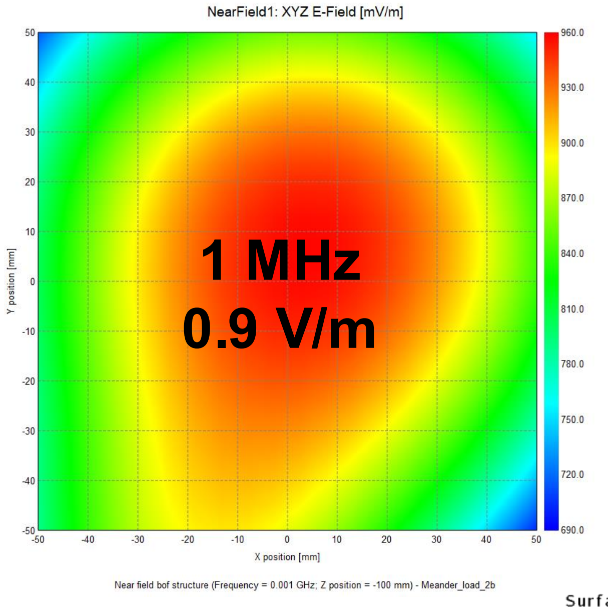
100 MHz

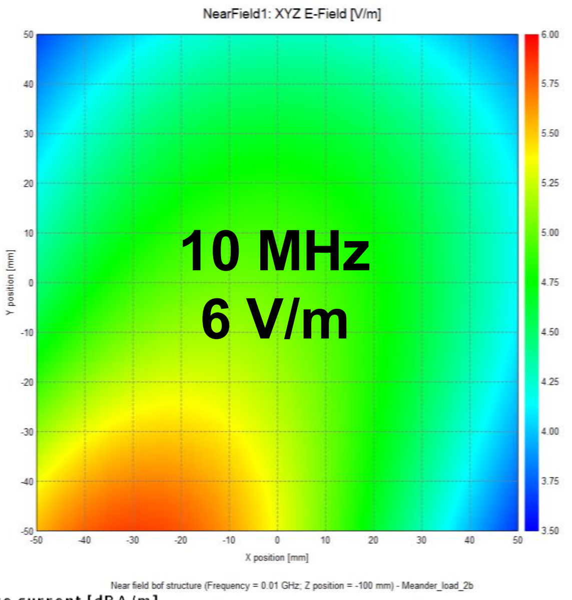
Where does the current flow?

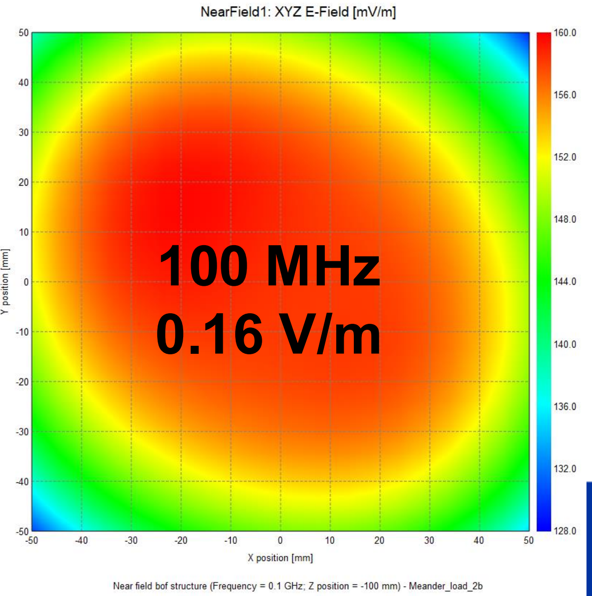
Let us introduce a square hole in the GND plane. Look at the E-field emissions

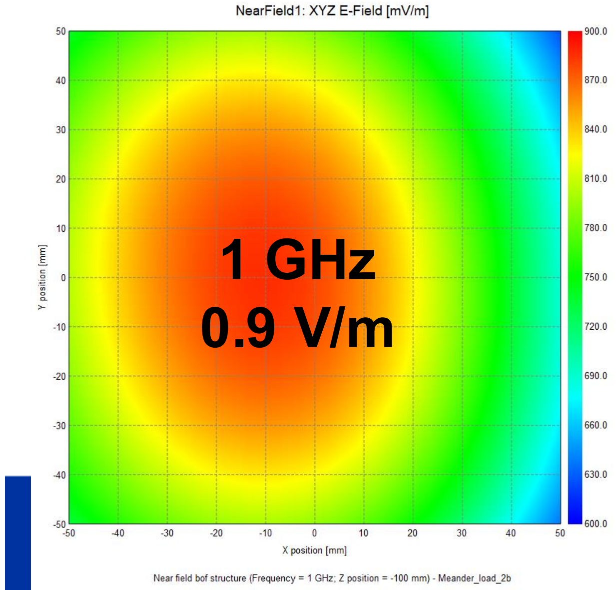


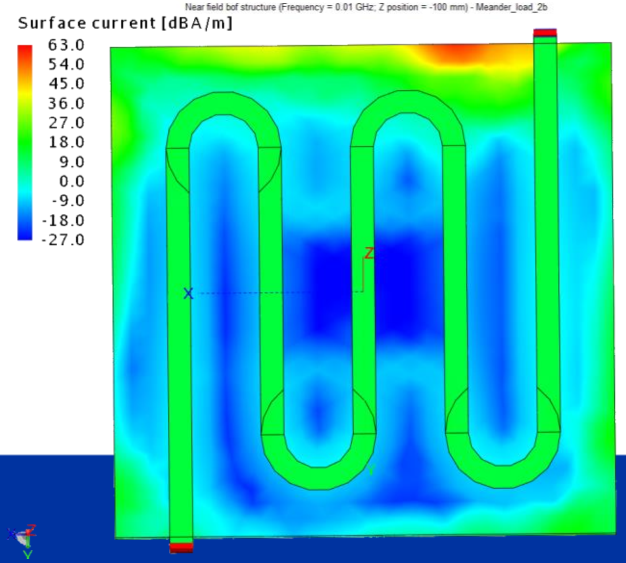




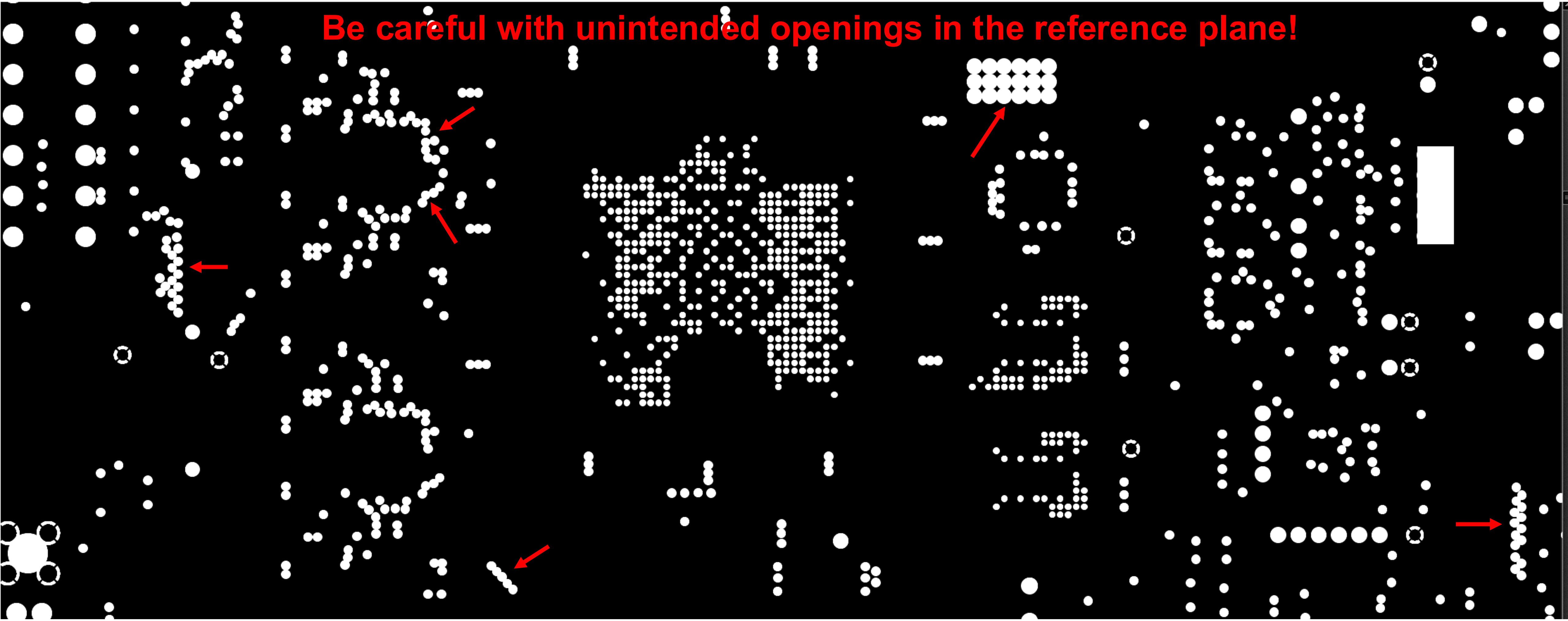




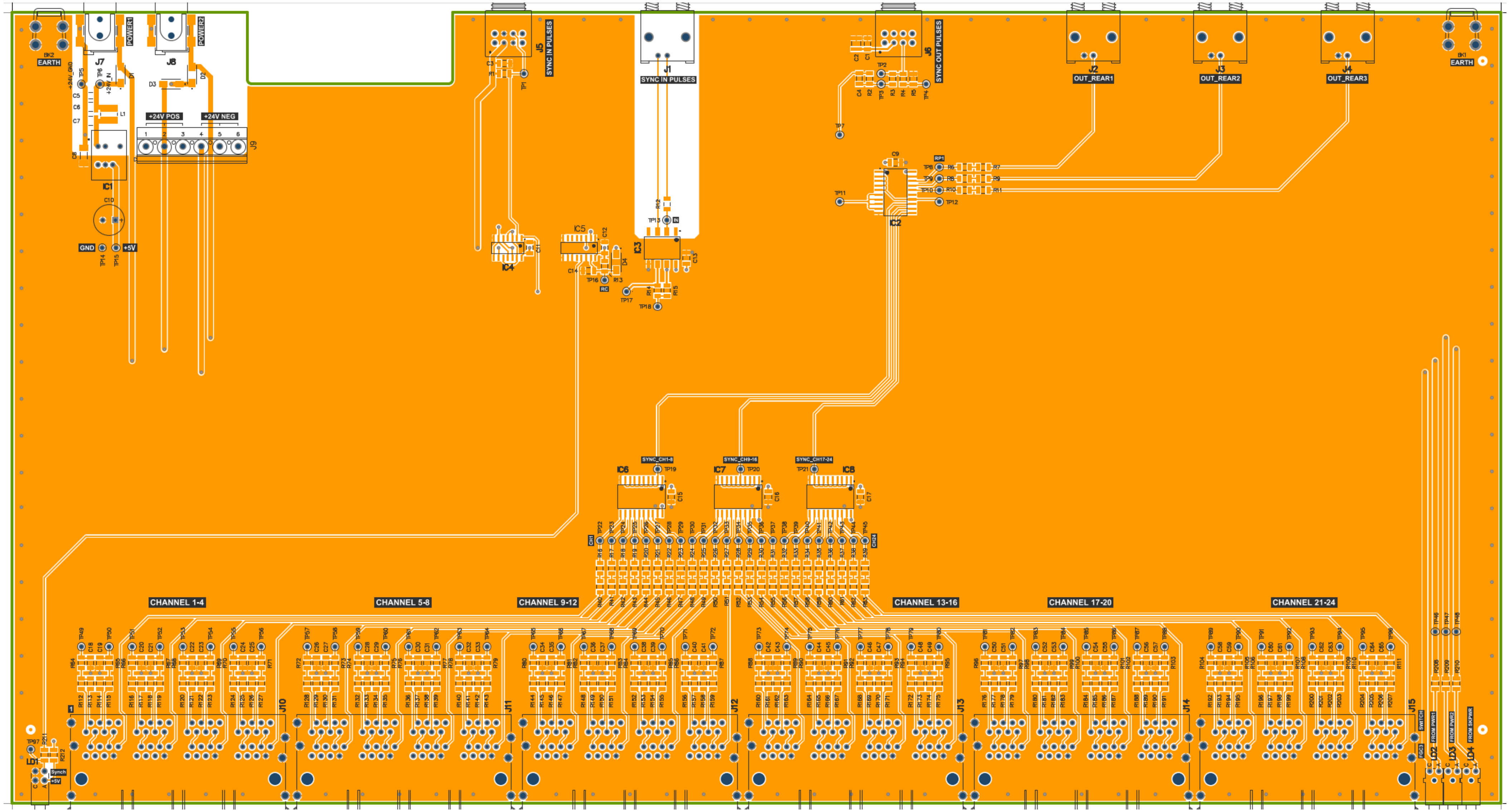




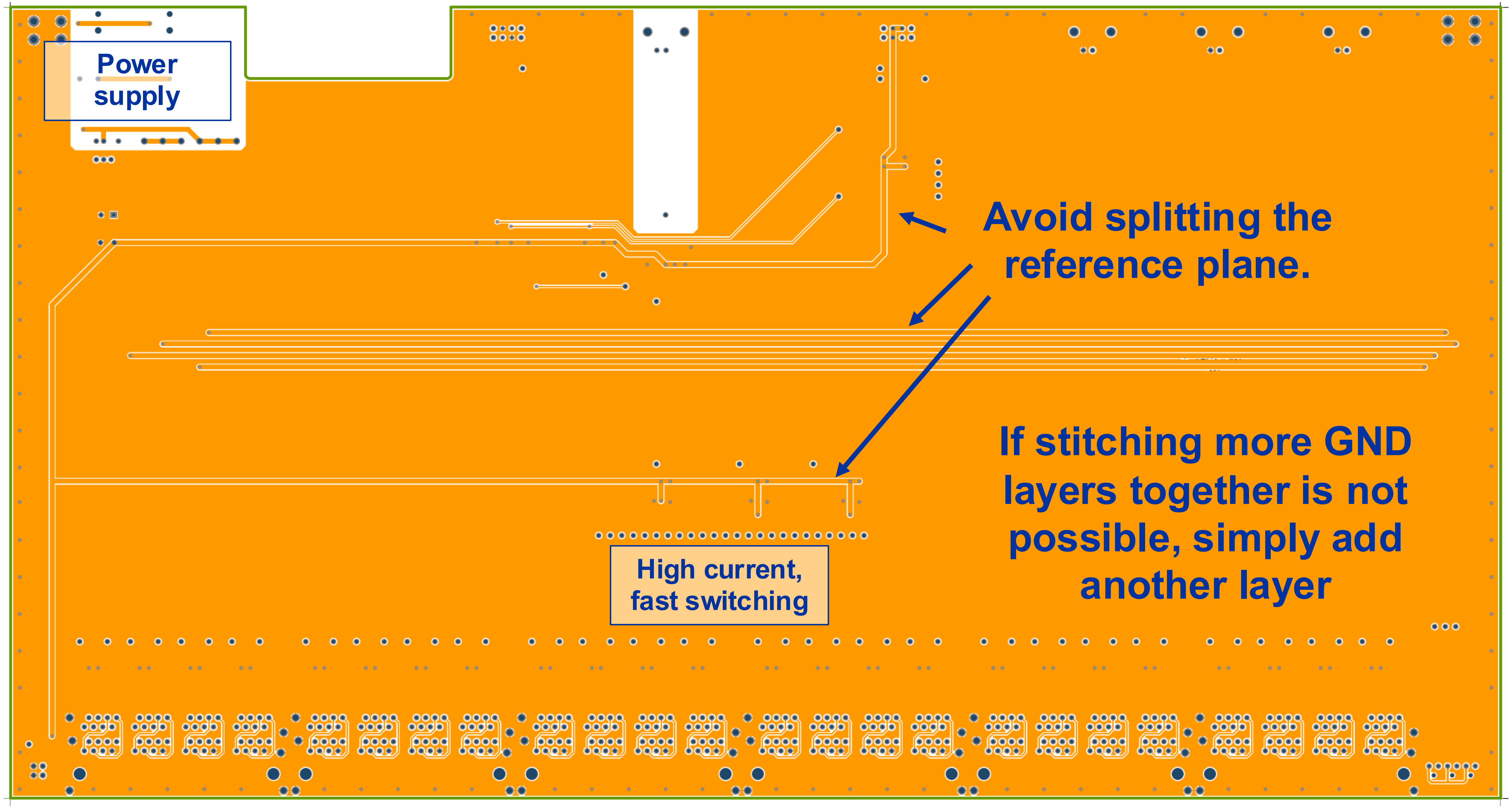
Where does the current flow?



Where does the current flow?



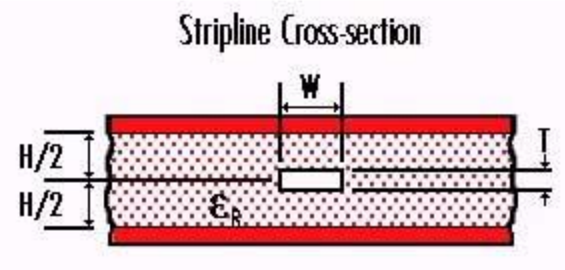
Where does the current flow?



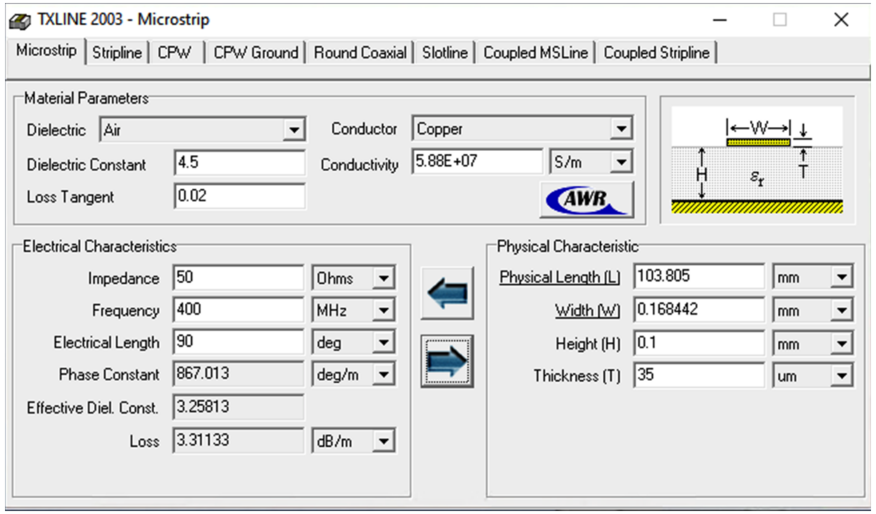
Impedance controlled lines/designs

RF, or high-speed digital designs call for "impedance controlled lines"

Traces need to be treated as RF transmission lines with defined impedance. Size must be carefully calculated, board materials properly chosen, PCB manufacturing process tightly controlled.



$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4H}{0.67\pi W\left(0.8+\frac{t}{W}\right)}\right]$$

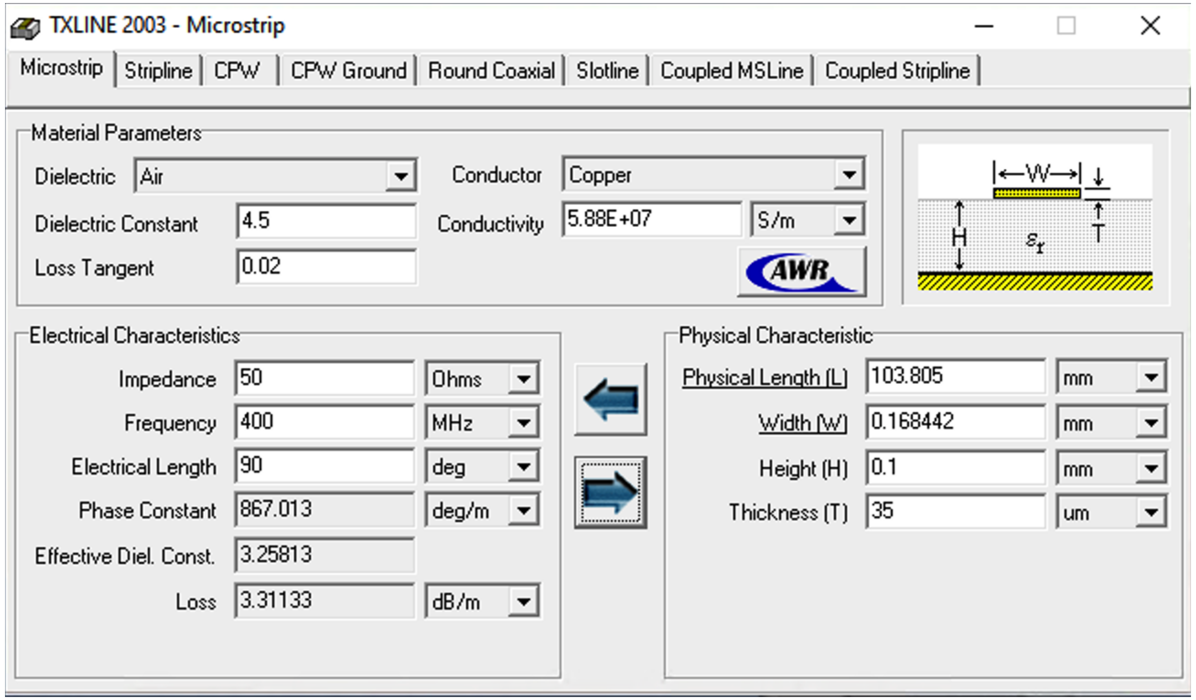


LAYER IDENTIFICATION		NOMINAL COPPER THICKNESS	CONTROLLED IMPEDENCE +/- 10%	DIELECTRIC THICKNESS *=CRITICAL
TOP LAYER	SIGNAL LAYER	35 um	50 Ohms	
				*0.1 mm
LAYER 2	GND PLANE	35 um	xx Ohms	
				0.2 mm
LAYER 3	POWER PLANE	35 um	xx Ohms	
				0.2 mm
LAYER 4	POWER PLANE	35 um	xx Ohms	
				. mm
LAYER 5	SIGNAL LAYER	35 um	xx Ohms	
				0.2 mm
LAYER 6	SIGNAL LAYER	35 um	xx Ohms	
				0.2 mm
LAYER 7	GND PLANE	35 um	xx Ohms	
				*0.1 mm
BOTTOM LAYER	SIGNAL LAYER	35 um	50 Ohms	
FINISHED BOARD THICKNESS +/-10%:				1.6 mm

Impedance controlled lines/designs

The board stack-up needs to be defined, so the trace width for 50 Ohm lines can be calculated. We need 160 micron traces for 50 Ohm microstrip.

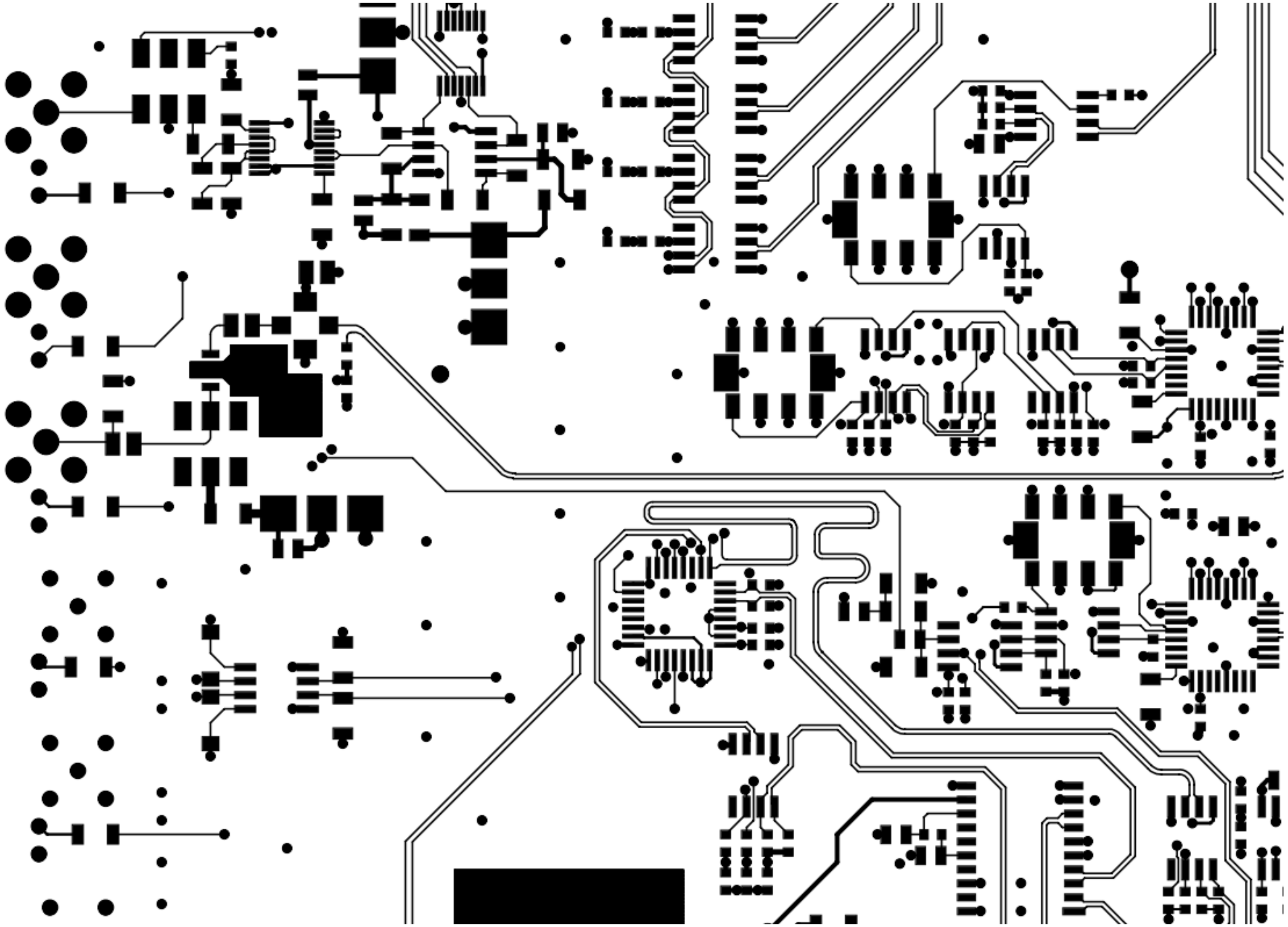
What were the assumptions and parameters?

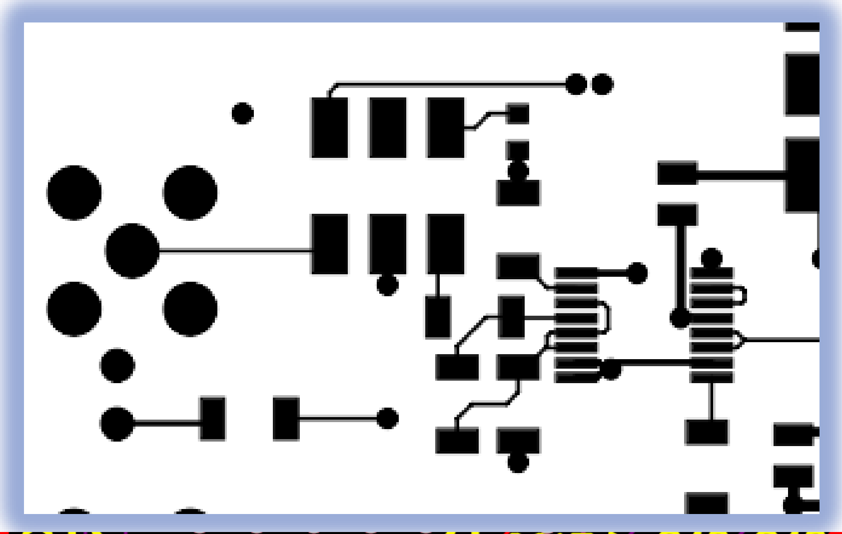


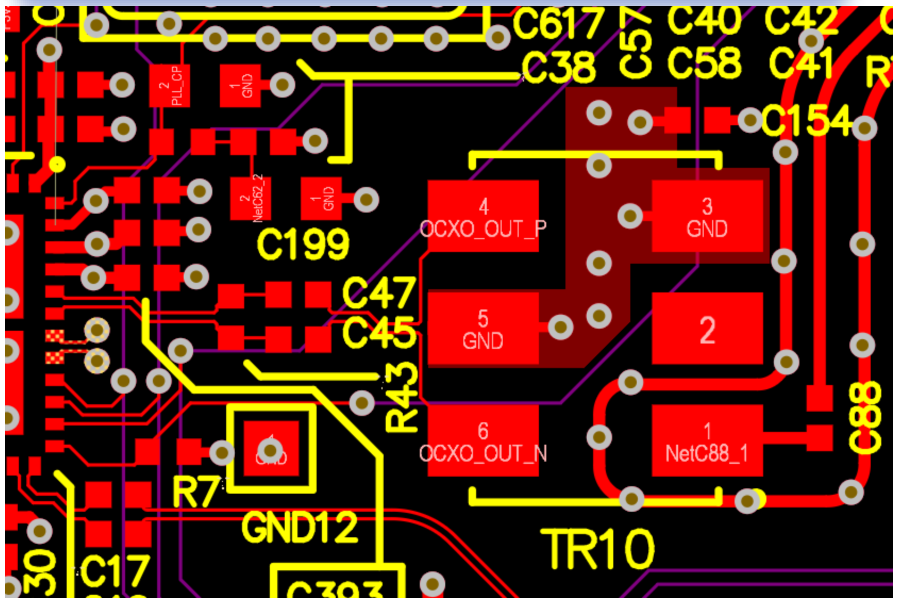
LAYER IDENTIFICATION		NOMINAL COPPER THICKNESS	CONTROLLED IMPEDENCE +/- 10%	DIELECTRIC THICKNESS *=CRITICAL
TOP LAYER	SIGNAL LAYER	35 um	50 Ohms	*0.1 mm
LAYER 2	GND PLANE	35 um	xx Ohms	0.2 mm
LAYER 3	POWER PLANE	35 um	xx Ohms	0.2 mm
LAYER 4	POWER PLANE	35 um	xx Ohms	*.* mm
LAYER 5	SIGNAL LAYER	35 um	xx Ohms	0.2 mm
LAYER 6	SIGNAL LAYER	35 um	xx Ohms	0.2 mm
LAYER 7	GND PLANE	35 um	xx Ohms	*0.1 mm
BOTTOM LAYER	SIGNAL LAYER	35 um	50 Ohms	
FINISHED BOARD THICKNESS +/-10%:				1.6 mm

Impedance controlled lines/designs

And the final design… What is VERY wrong here?

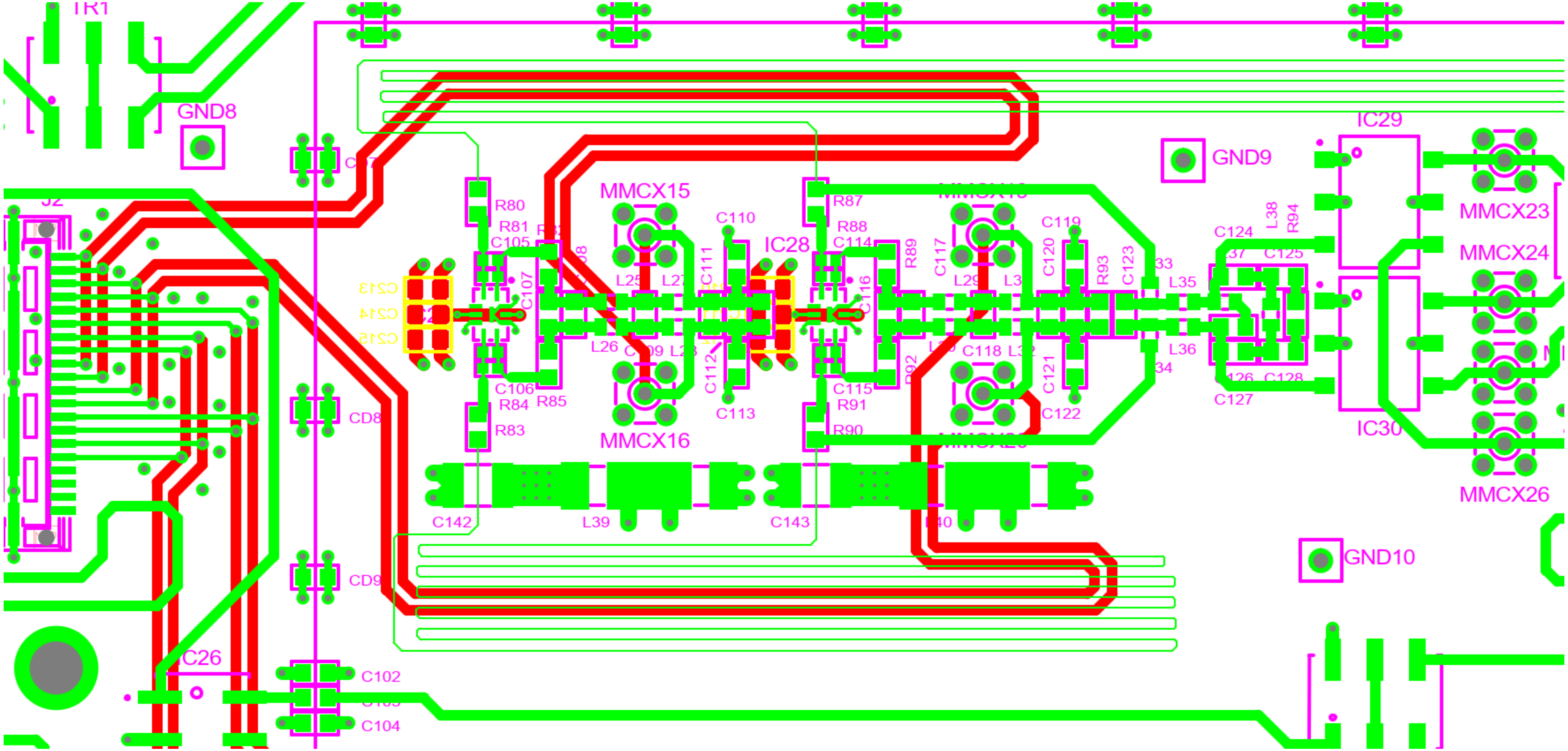






Impedance controlled lines/designs

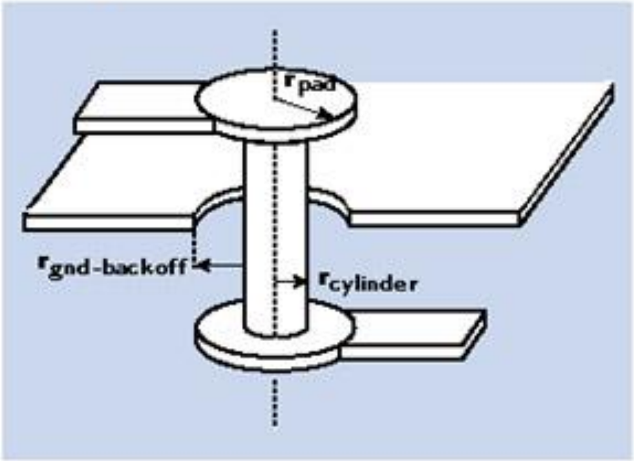
Make the traces compatible with your components. May require unusual layer stackup



PCB vias

Via is a plated interconnect between layers. It has its electrical parameters too…

Fig. 1 A via connecting two microstrip transmission lines.



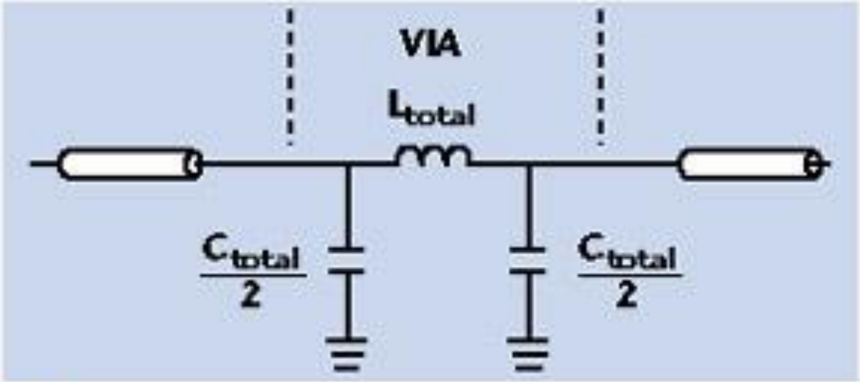
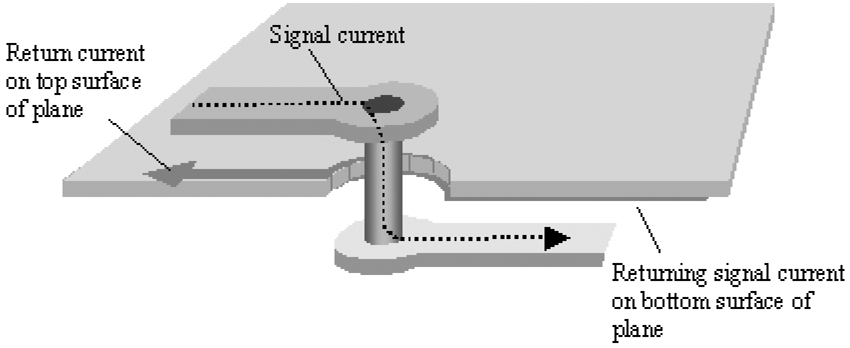


Fig. 2 Via equivalent circuit.

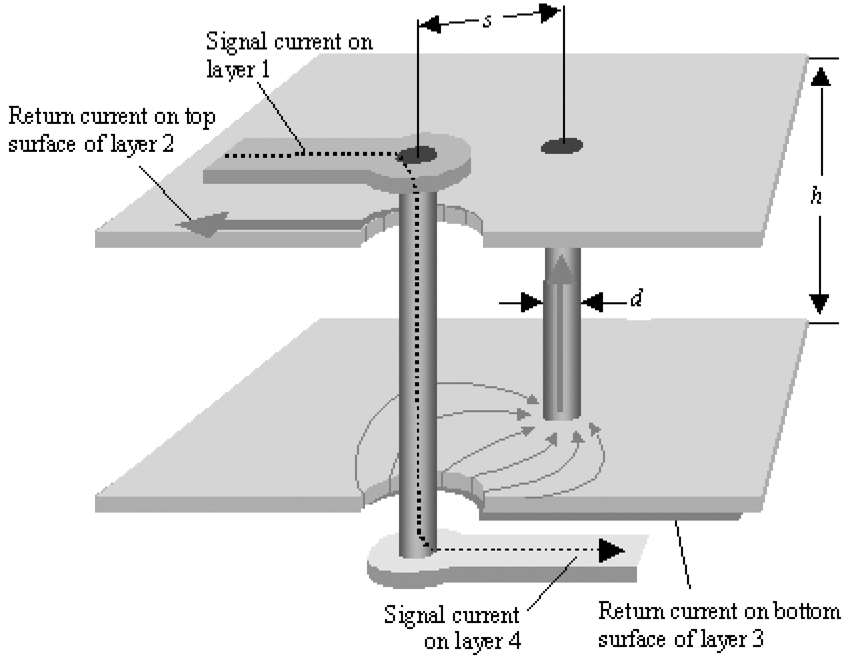
Brock J. LaMeres and T.S. Kalkur: Time Domain Analysis of a Printed Circuit Board Via. Microwave Journal, November 2000. https://www.microwavejournal.com/articles/3082-time-domain-analysis-of-a-printed-circuit-board-via

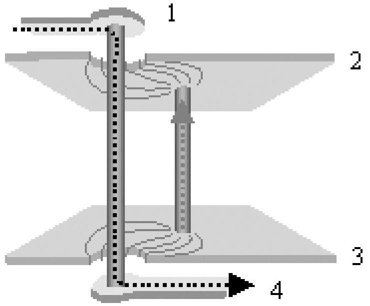
Crossing reference planes

Signal traces adjacent to the same reference plane.



Signal traces adjacent to different reference planes.

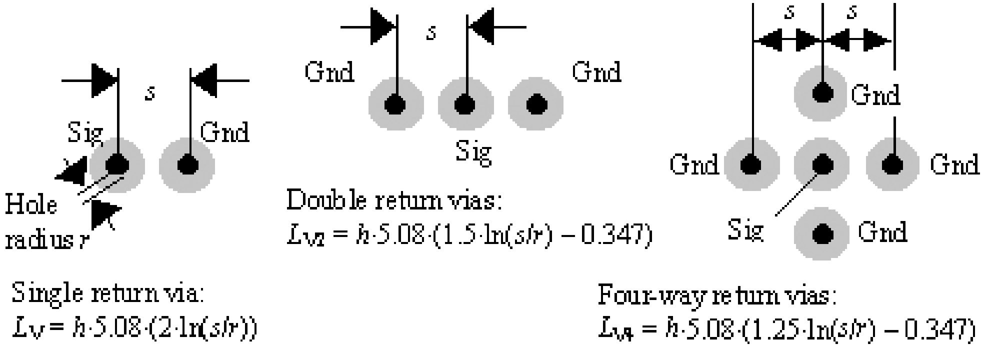




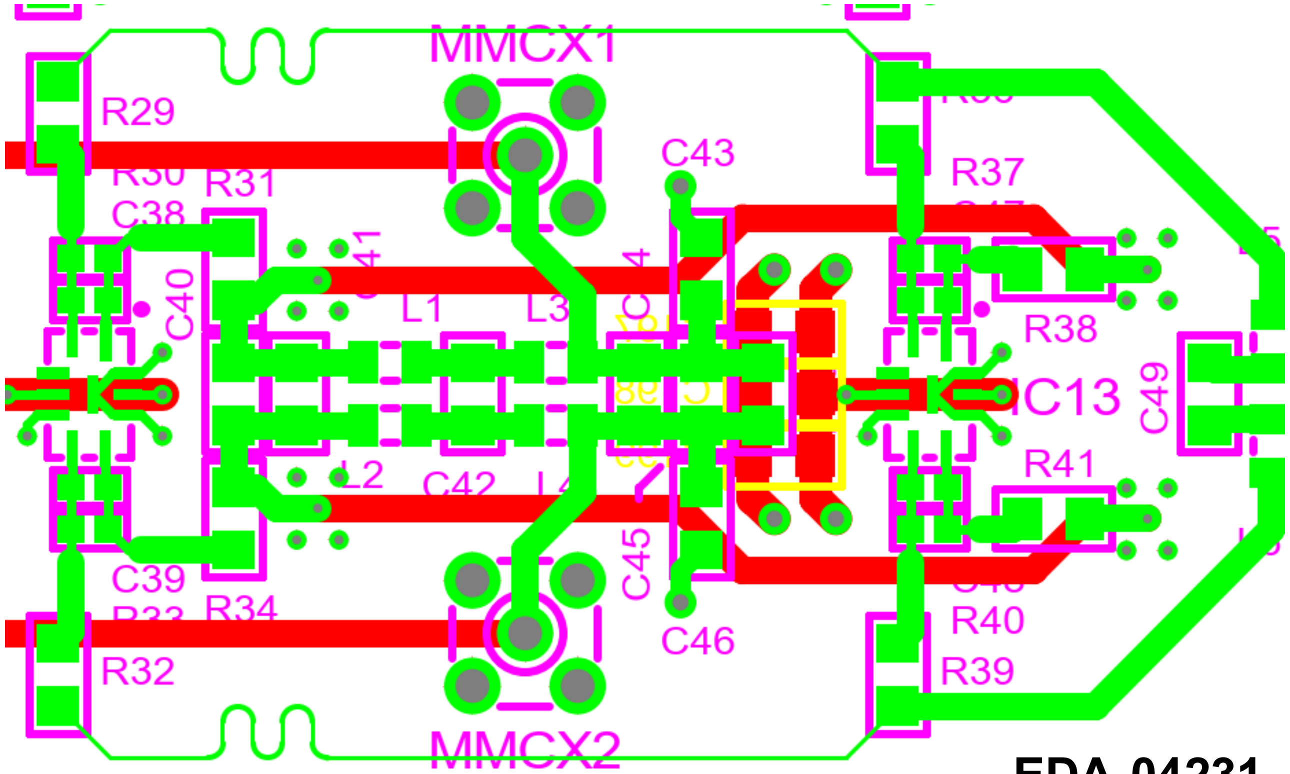
https://flylib.com/books/en/1.389.1/modeling_vias.html

Crossing reference planes

Crossing reference planes



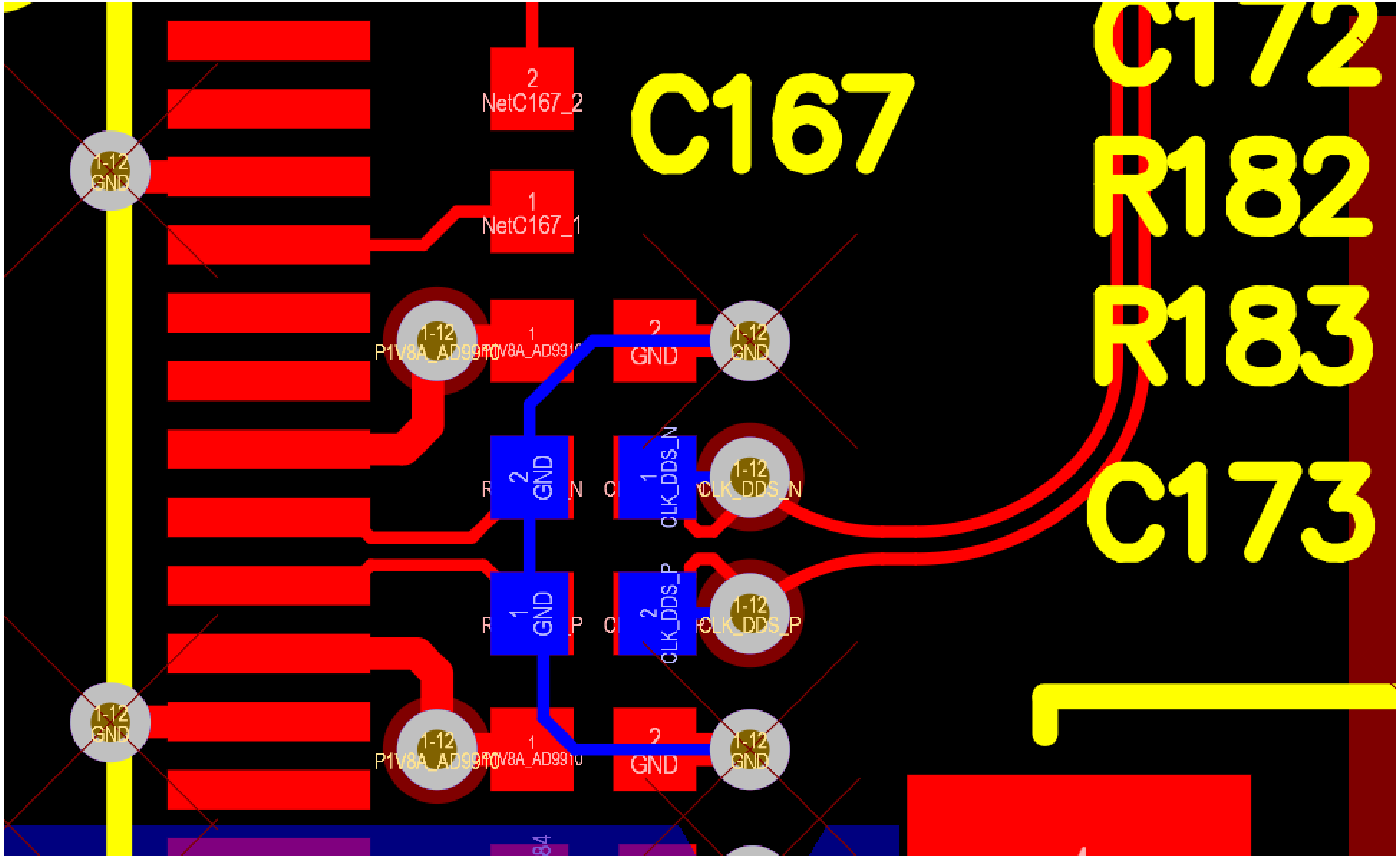
Where:
L_V via interplane inductance
h, s, r dimensions in inch (sorry)



EDA-04231

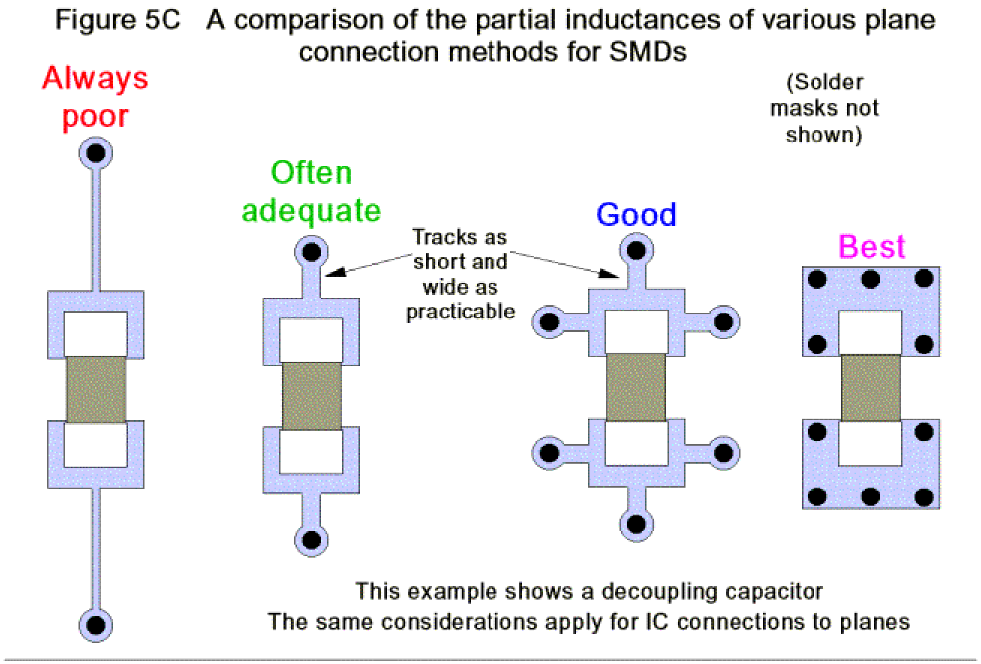
https://flylib.com/books/en/1.389.1/modeling_vias.html

Crossing reference planes

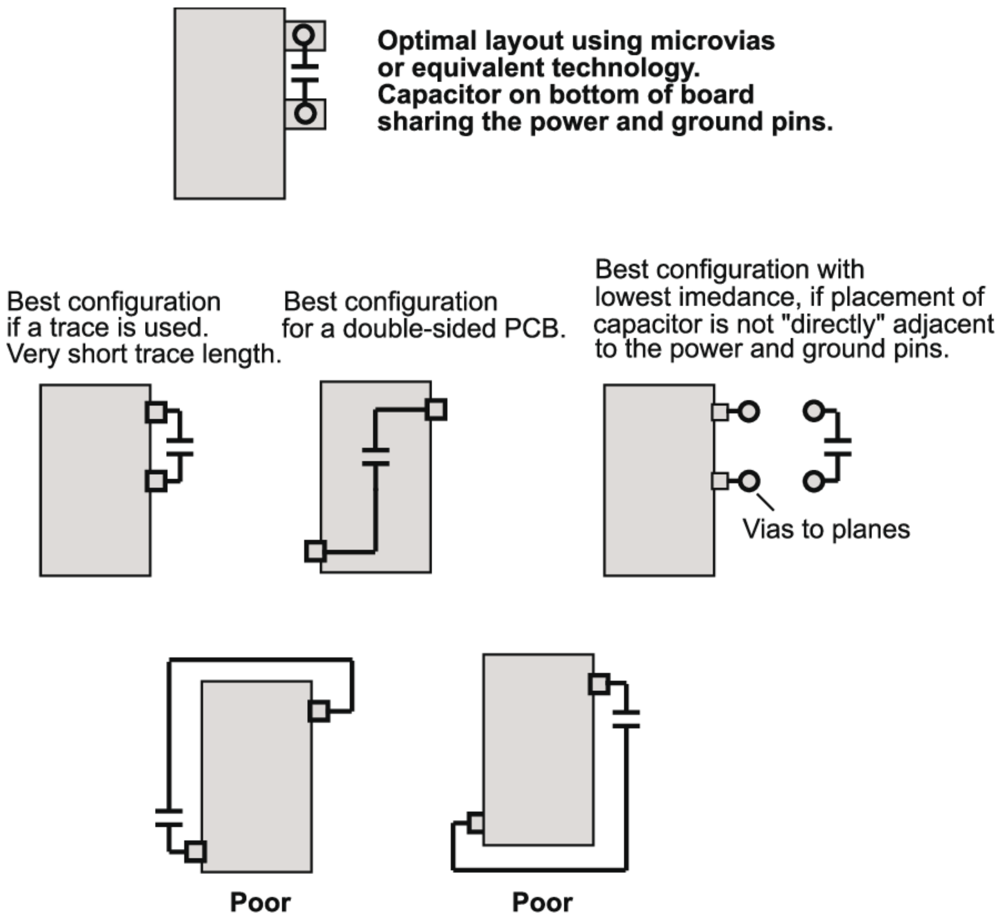


Decoupling capacitors and power plane RF impedance

Power distribution networks on PCB require very low impedance



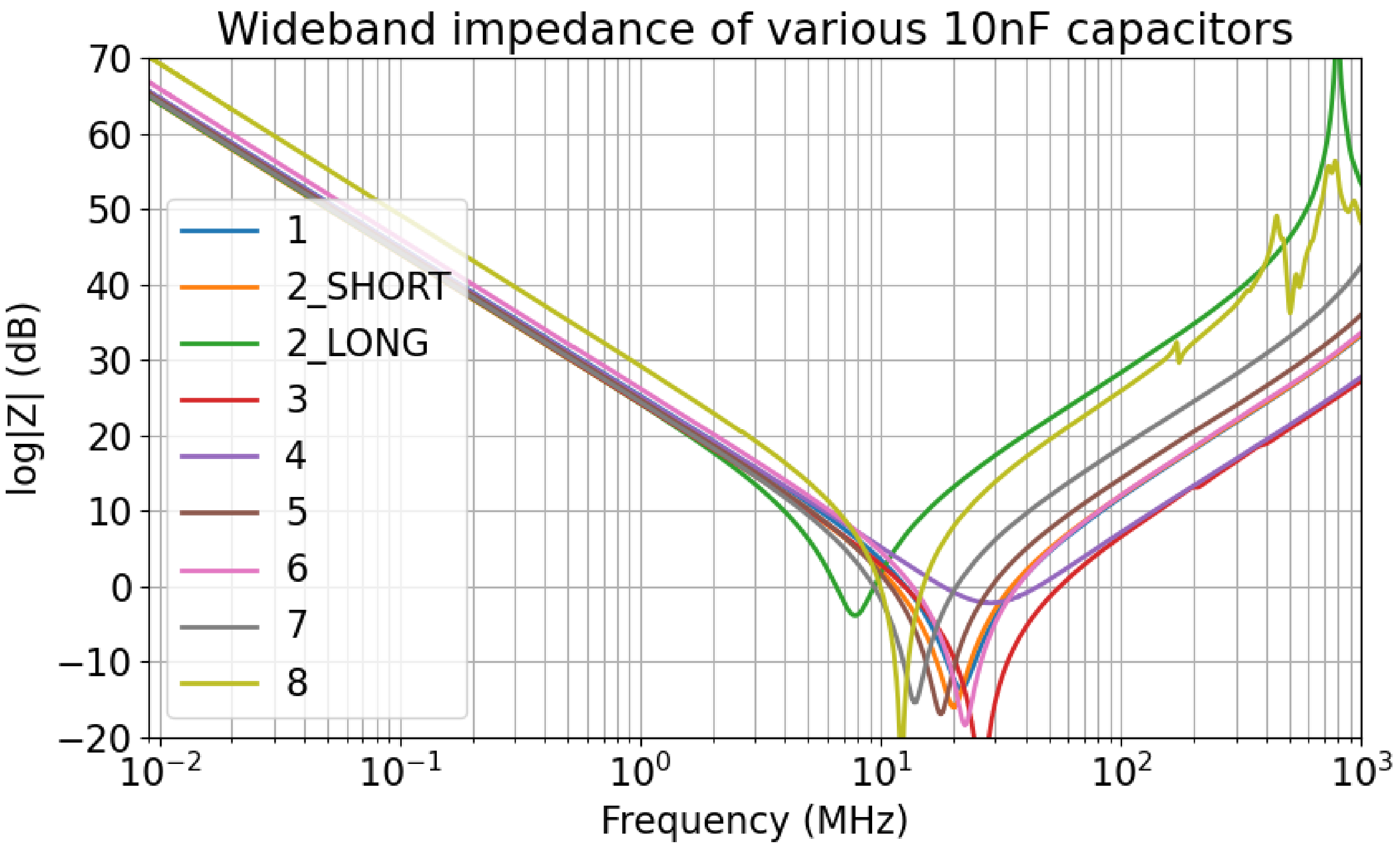
https://www.nutwooduk.co.uk/archive/keitharmstrong/design_techniques5.html

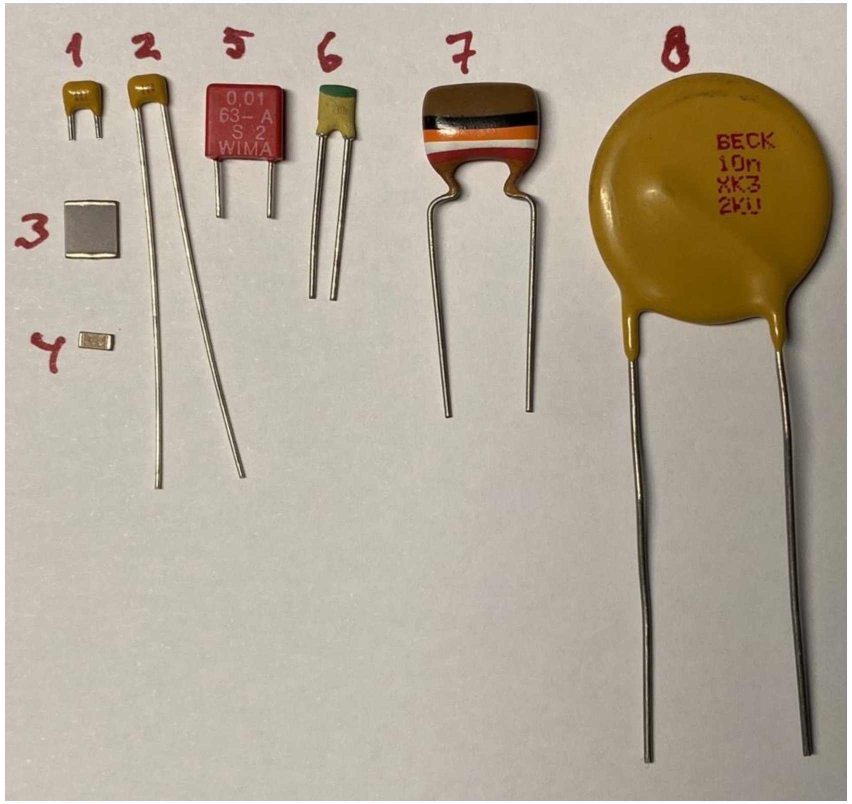


M. Montrose: Decoupling capacitors as a cause of radiated EMI: an analysis of capacitor placement

A real world capacitor

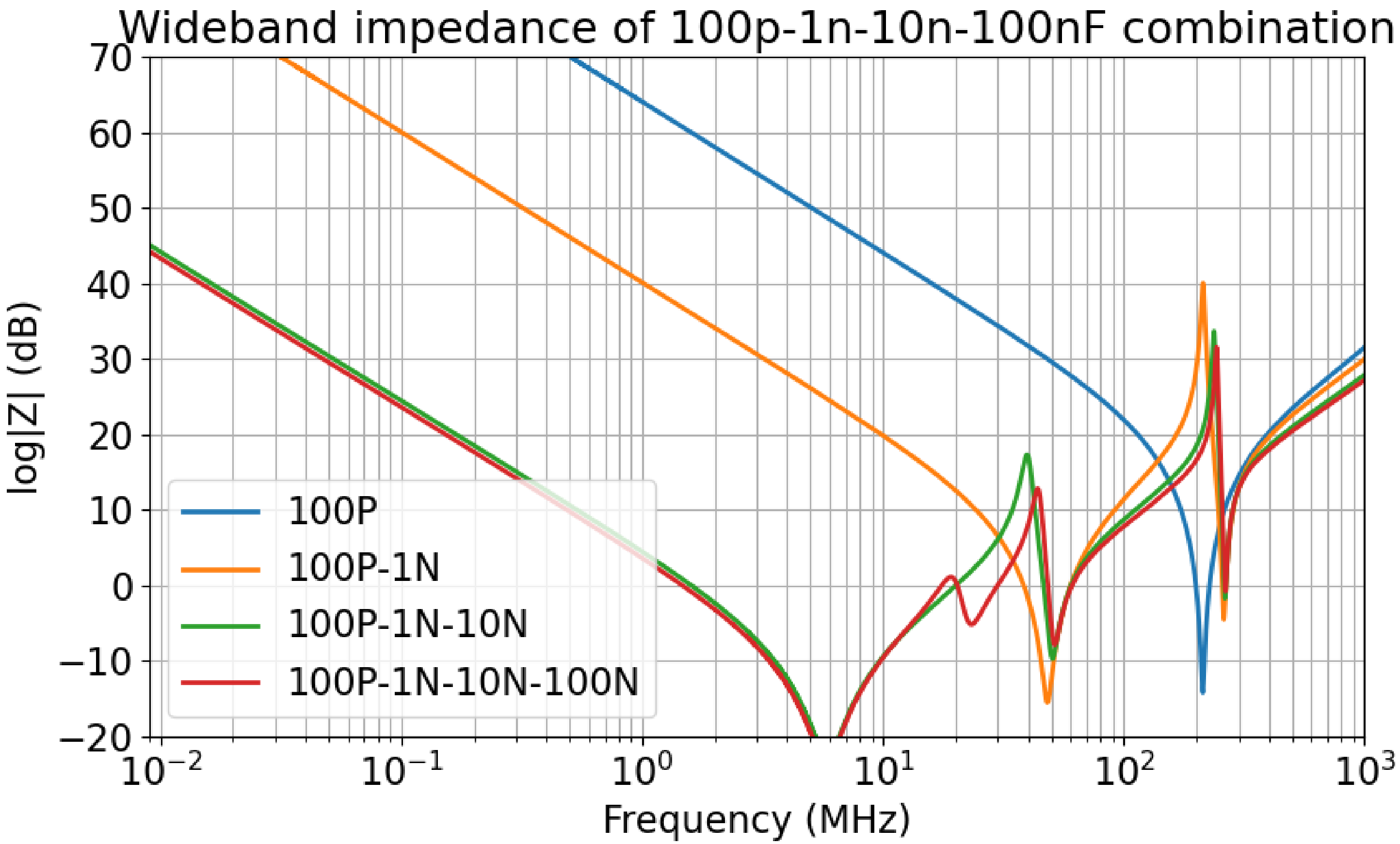
10 things they do not teach at university: #8 there is at least 10 types of capacitors…





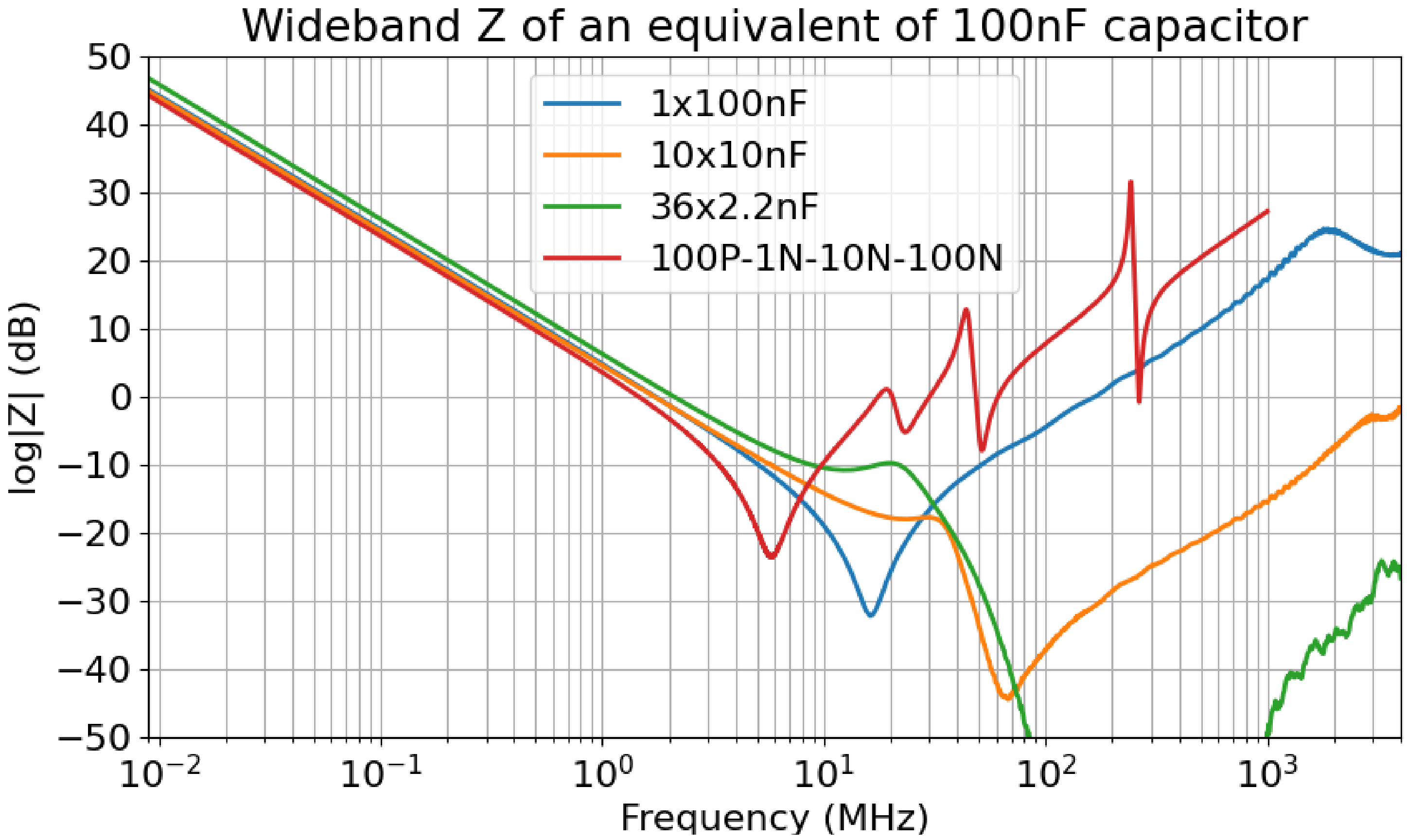
A real world capacitor

What to do if we need a wideband low-impedance?

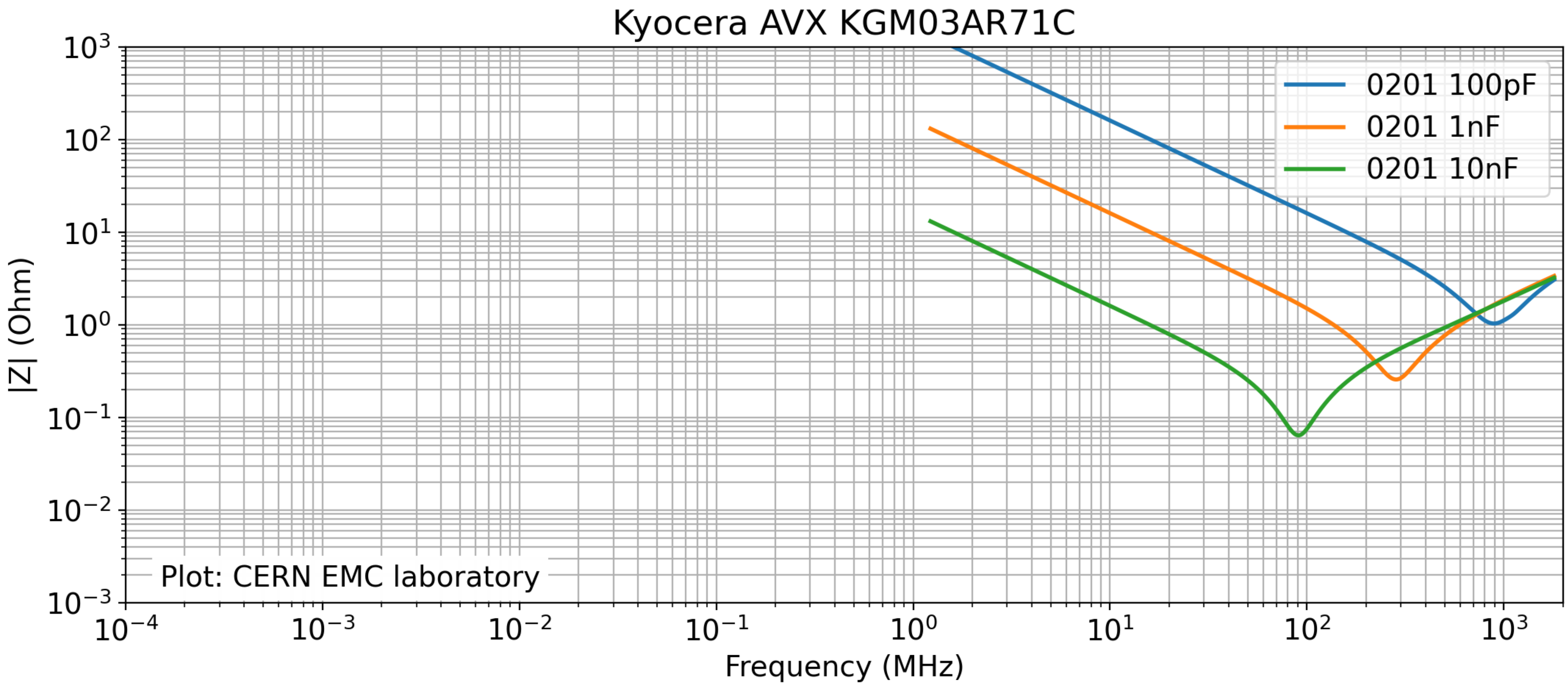


A real world capacitor

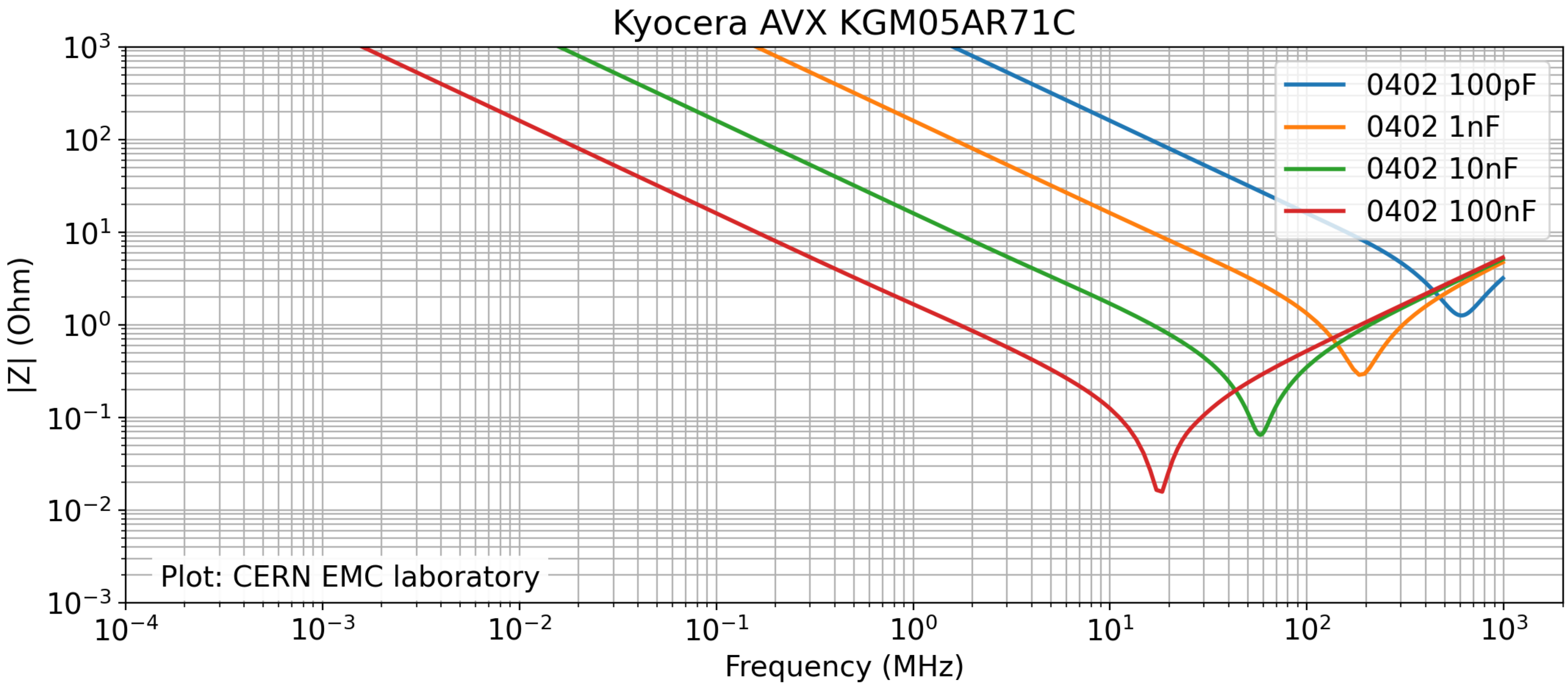
An alternative way – use many same value/type capacitors in parallel. For certain cases the wideband performance is better



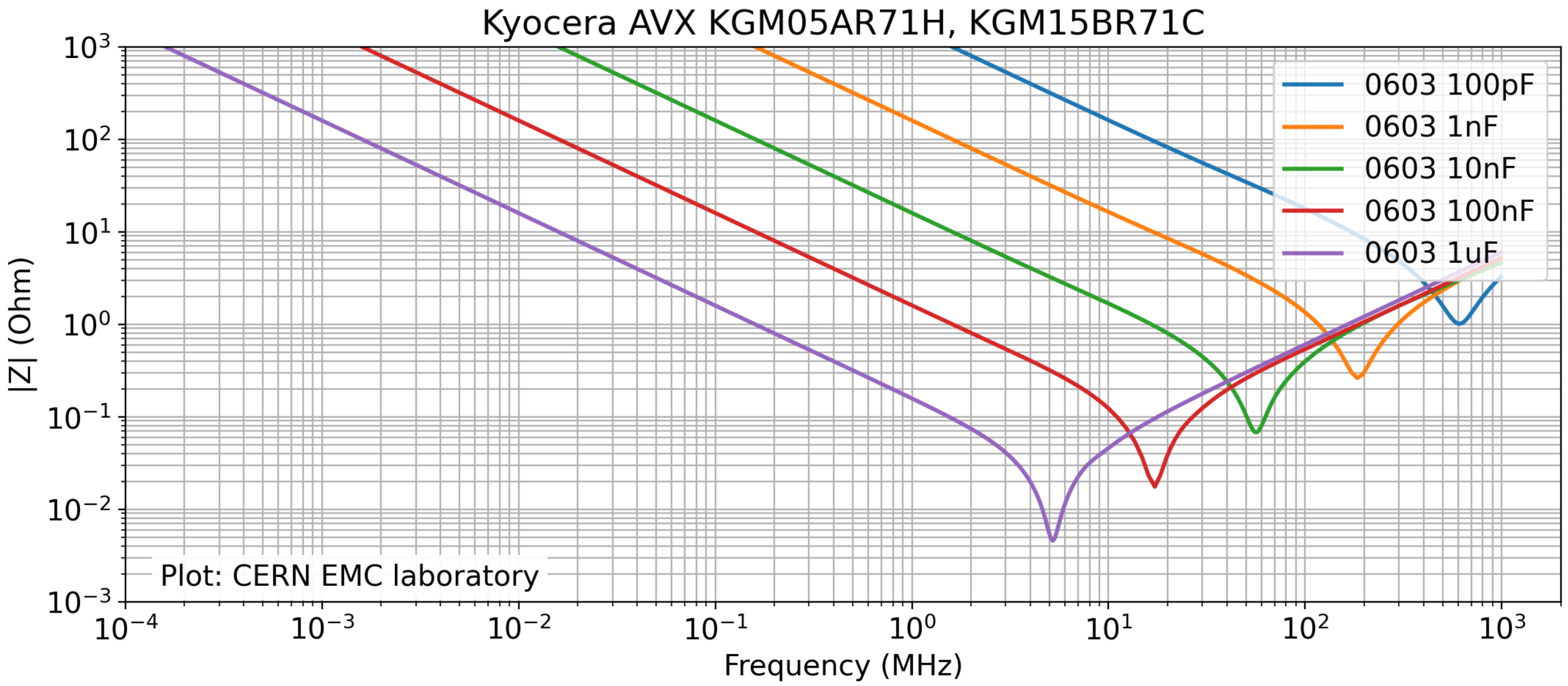
Power rail decoupling – properties of standard MLCC capacitors



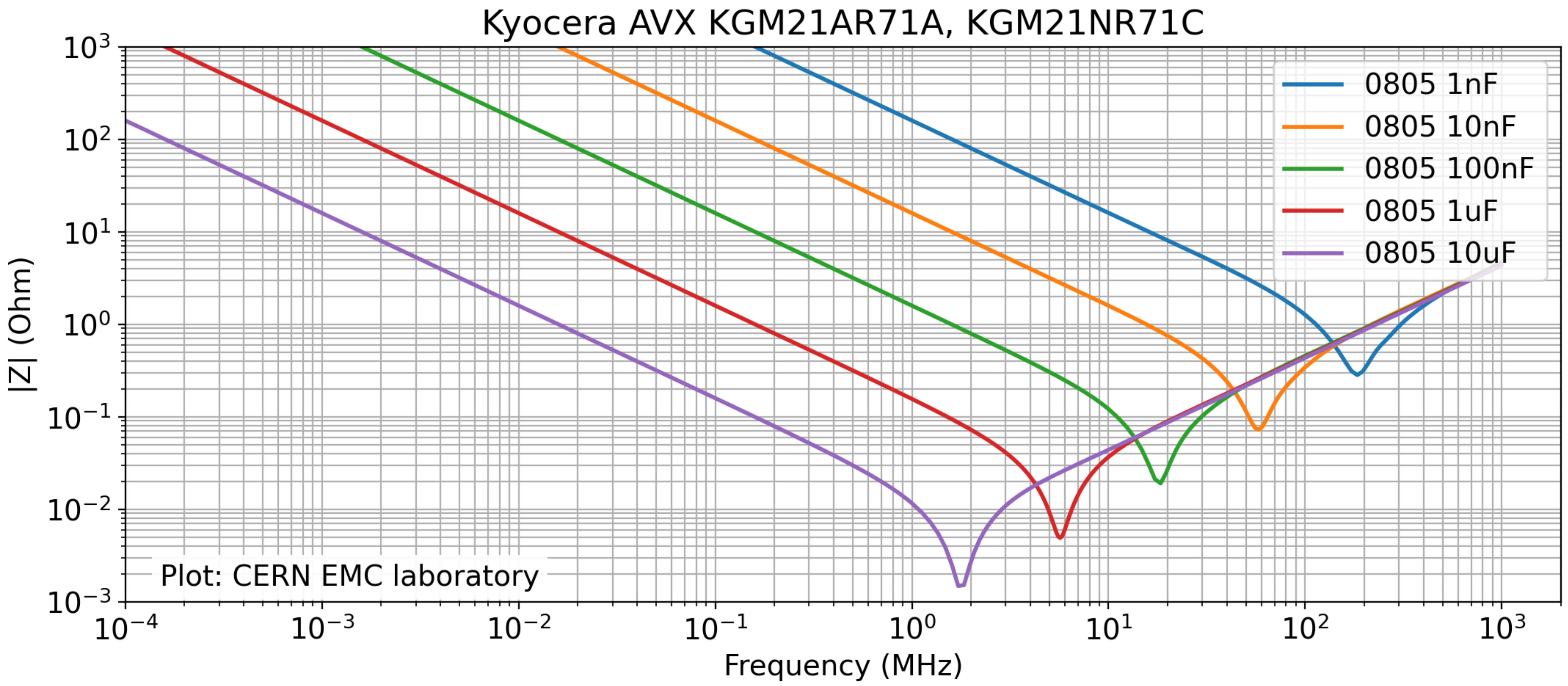
Power rail decoupling – properties of standard MLCC capacitors



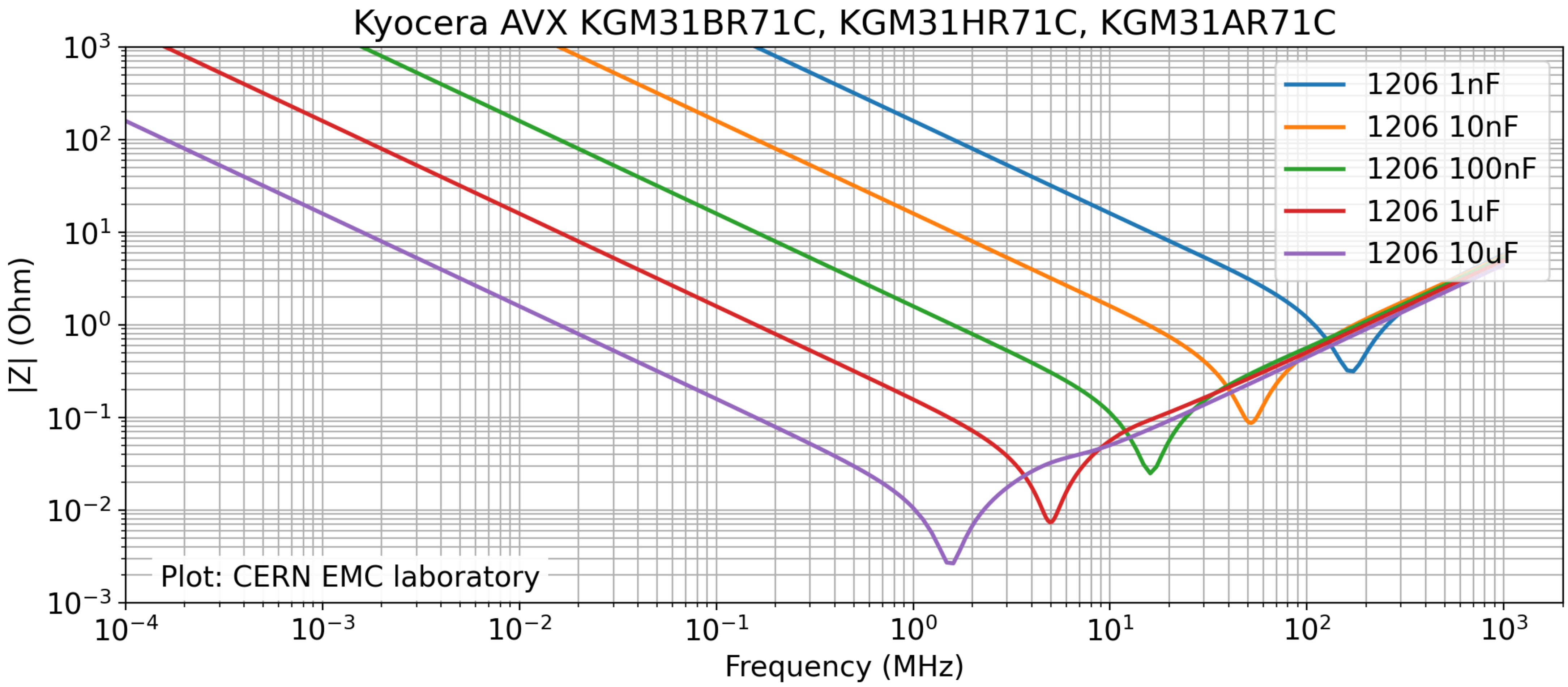
Power rail decoupling – properties of standard MLCC capacitors



Power rail decoupling – properties of standard MLCC capacitors

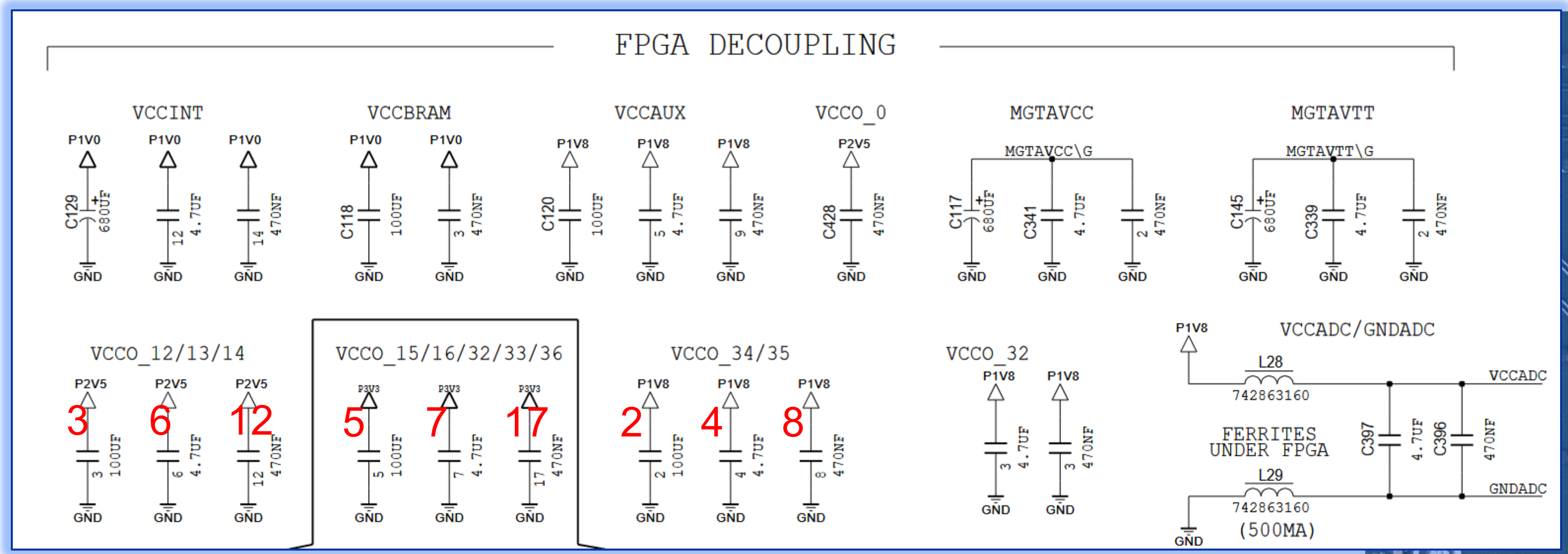


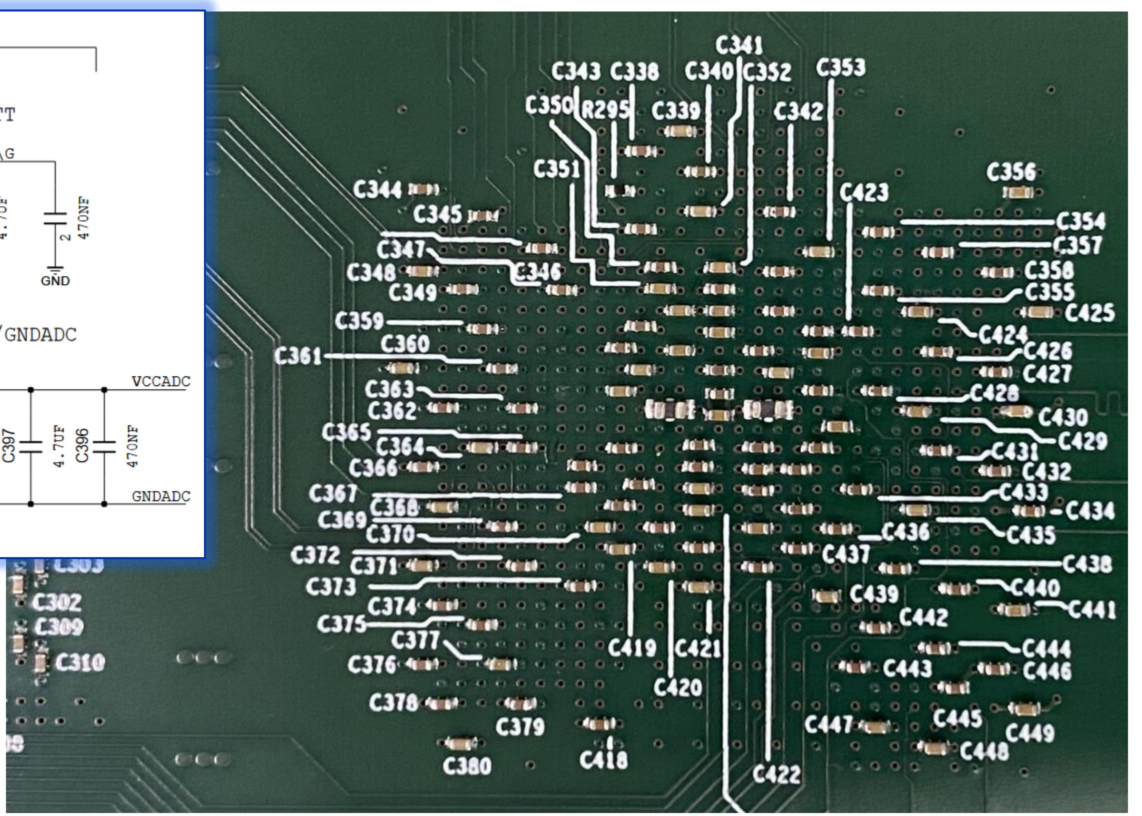
Power rail decoupling – properties of standard MLCC capacitors



Power rail decoupling

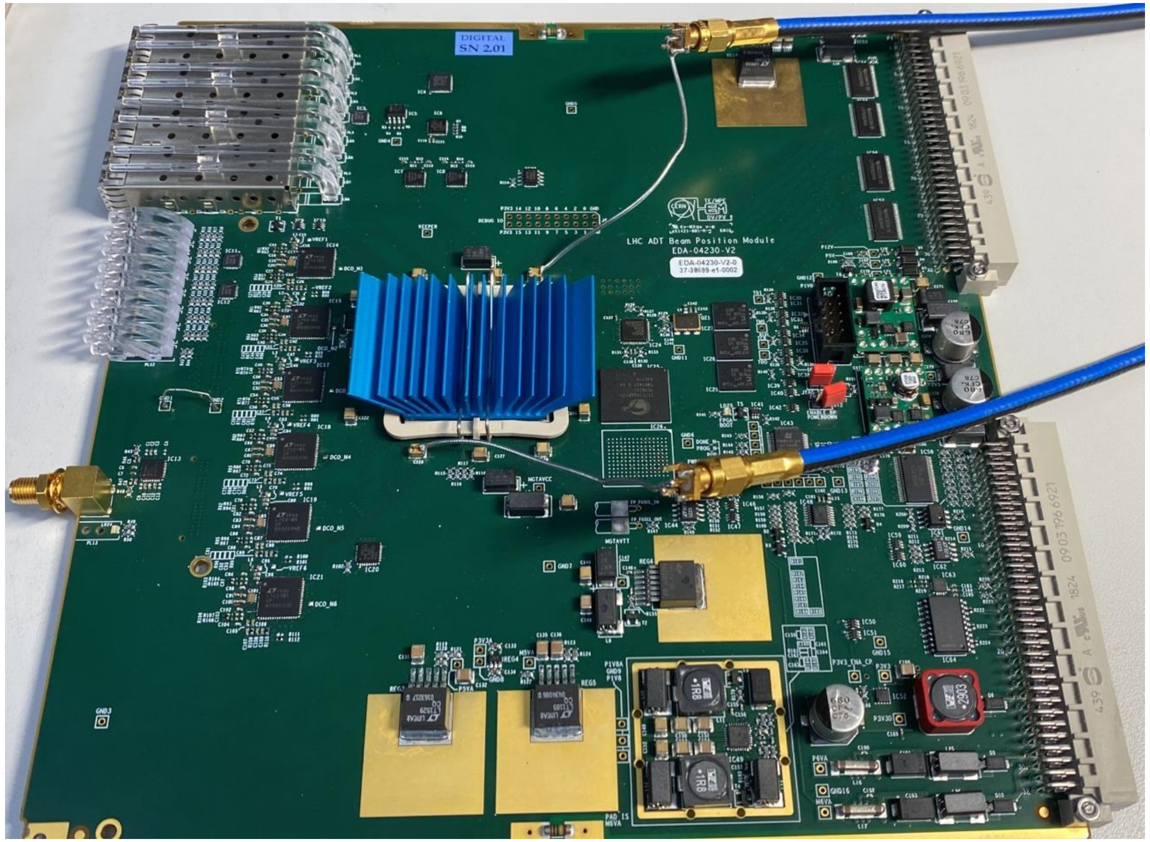
What to do if we need a wideband low-impedance? Massive parallel combination of multiple capacitor values with carefully chosen resonant frequencies….

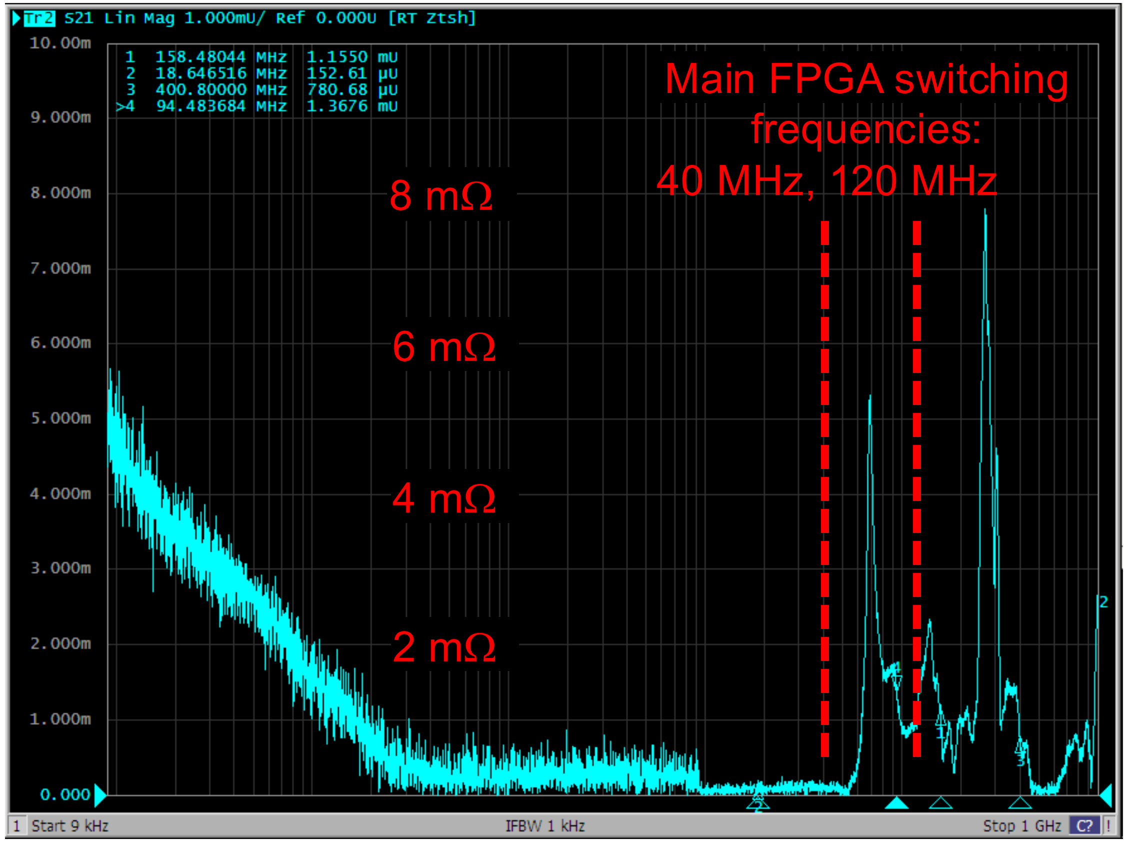




Power rail decoupling

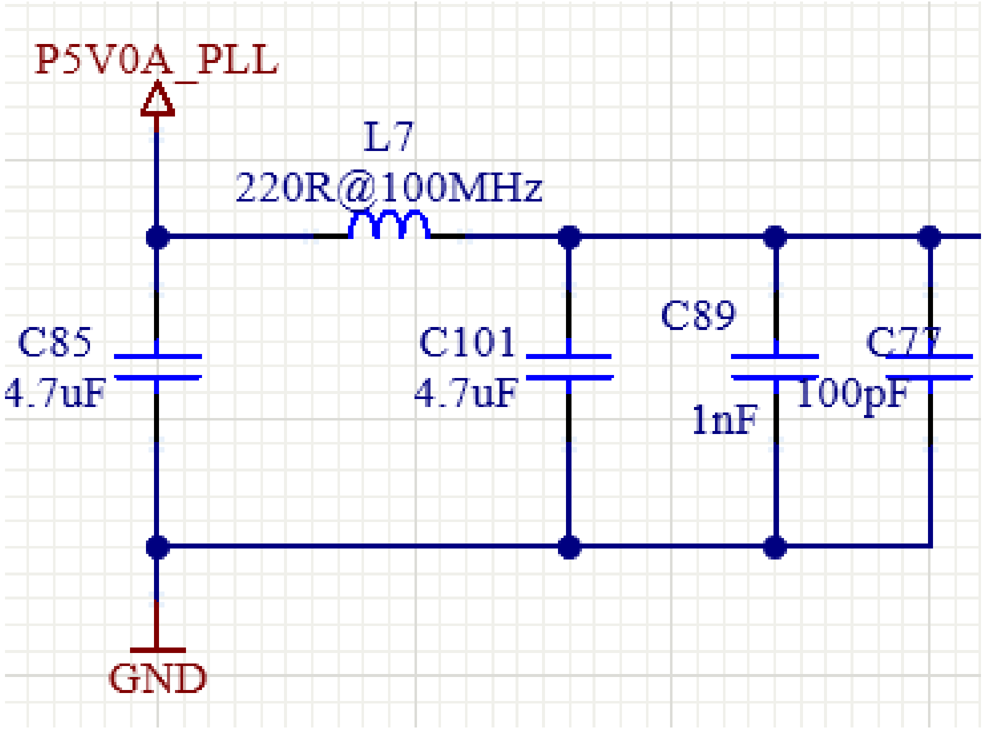
What to do if we need a wideband low-impedance? Massive parallel combination of multiple capacitor values with carefully chosen resonant frequencies….

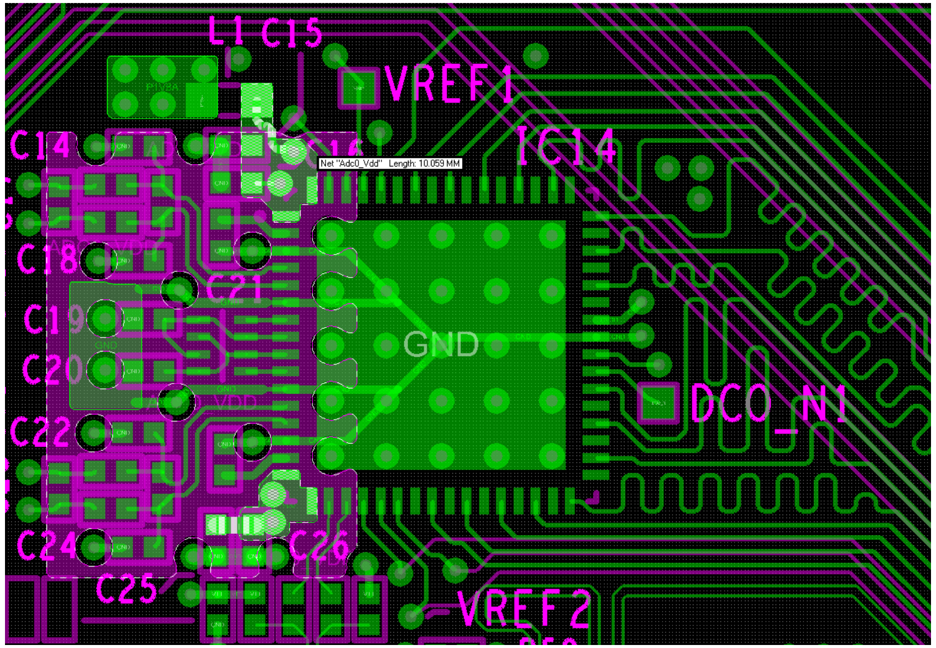




Power rail decoupling

I have this great idea for noise suppression. Let's add a filter to the power rail!



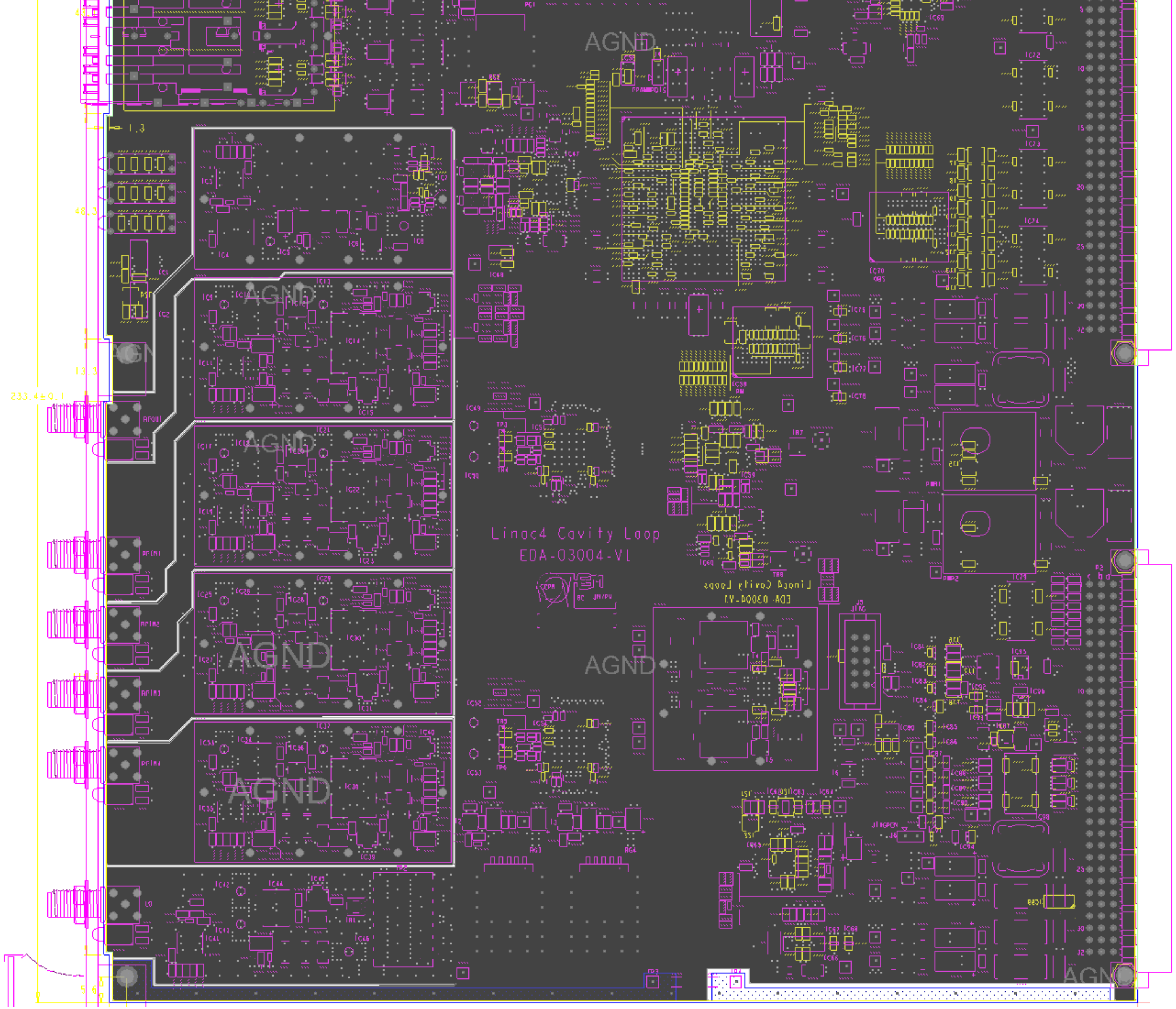


“All bad practices in one” design example

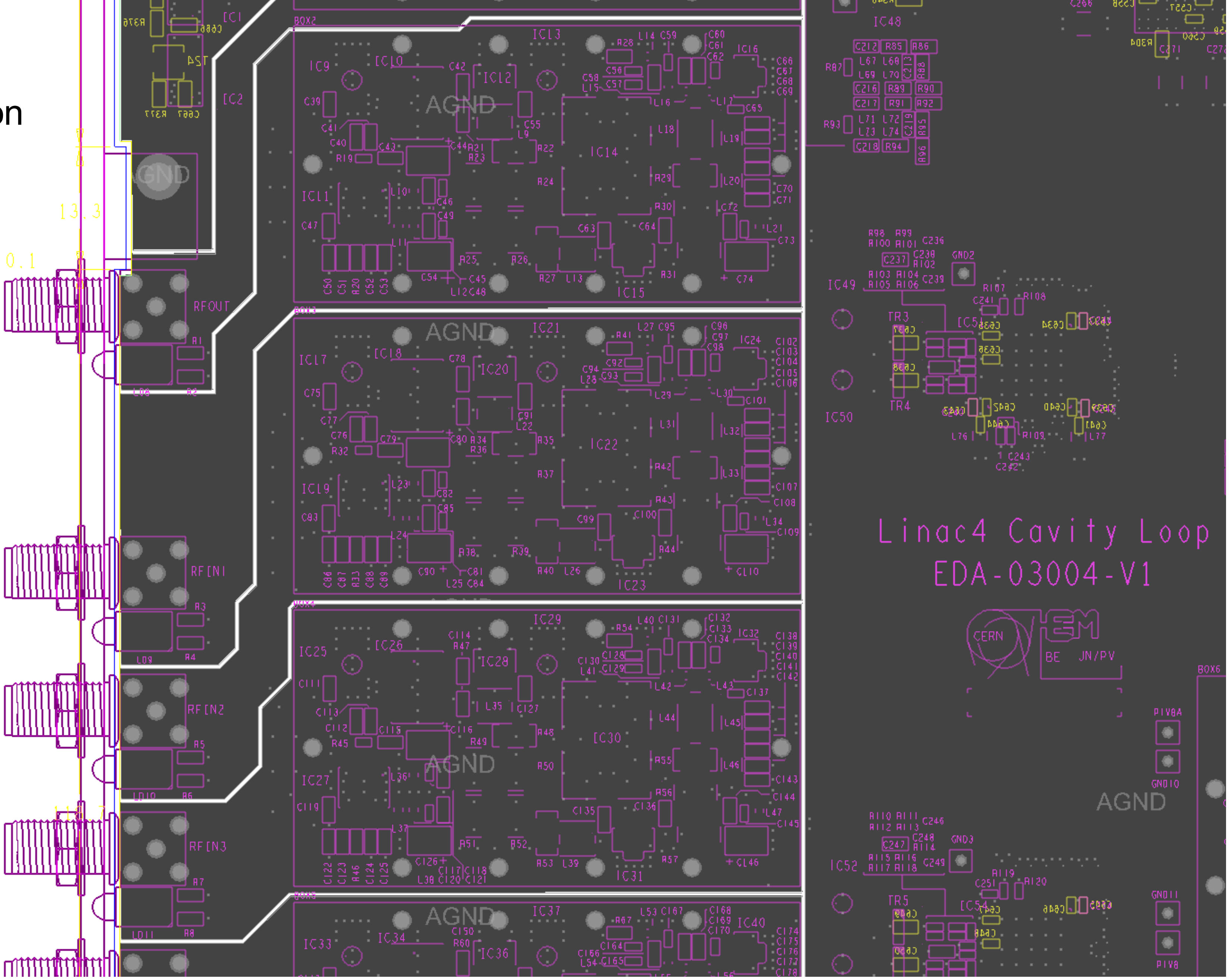
Mixed signal board RF+digital

- **RF inputs 352 MHz**
- **Local oscillator distribution at 10-20 dBm level**
- **Intermediate frequency ~20 MHz**
- **Sampling by fast ADCs**
- **Large FPGA**
- **RF drive signal generation at 352 MHz**

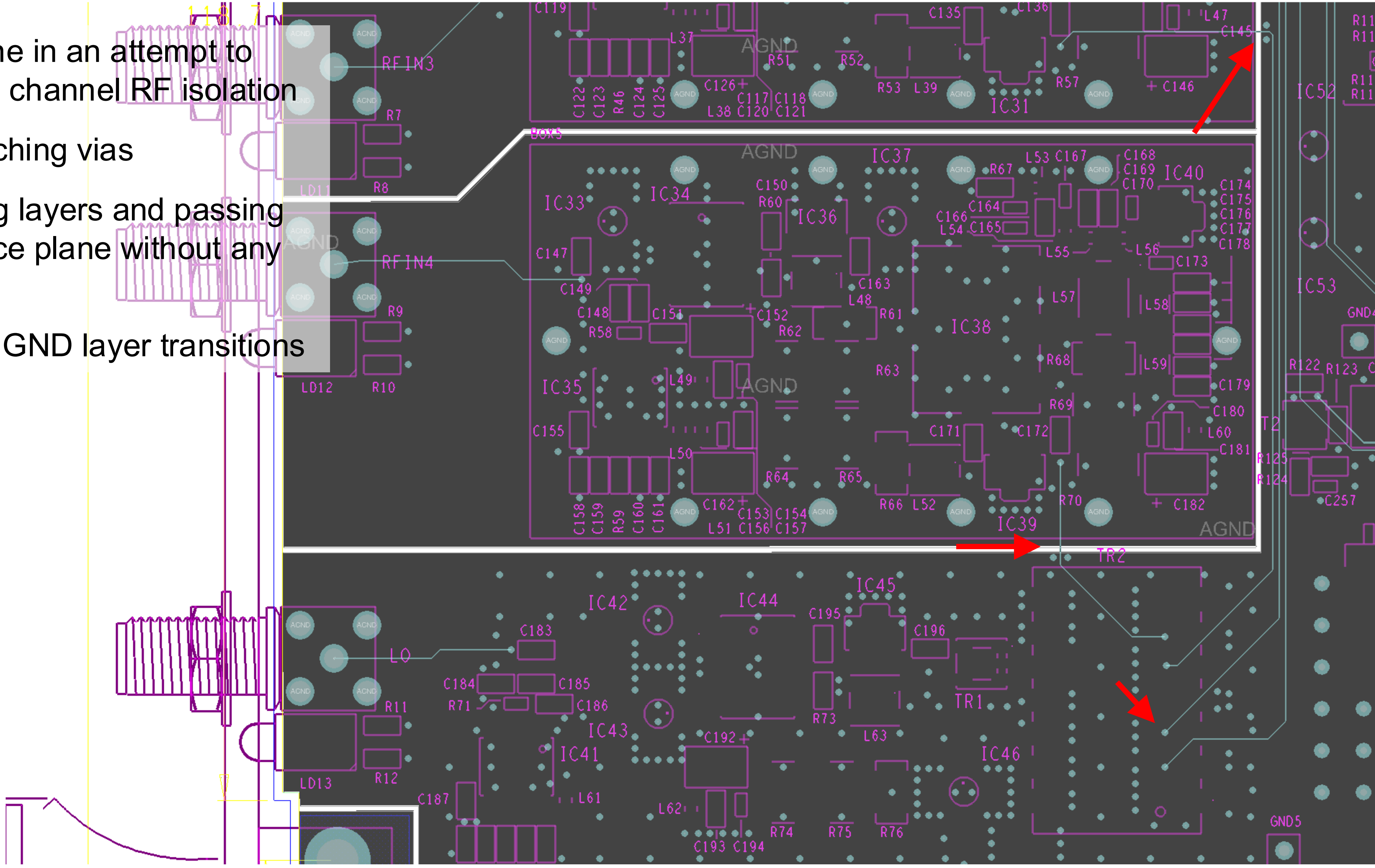
- Split reference plane in an attempt to improve channel to channel RF isolation



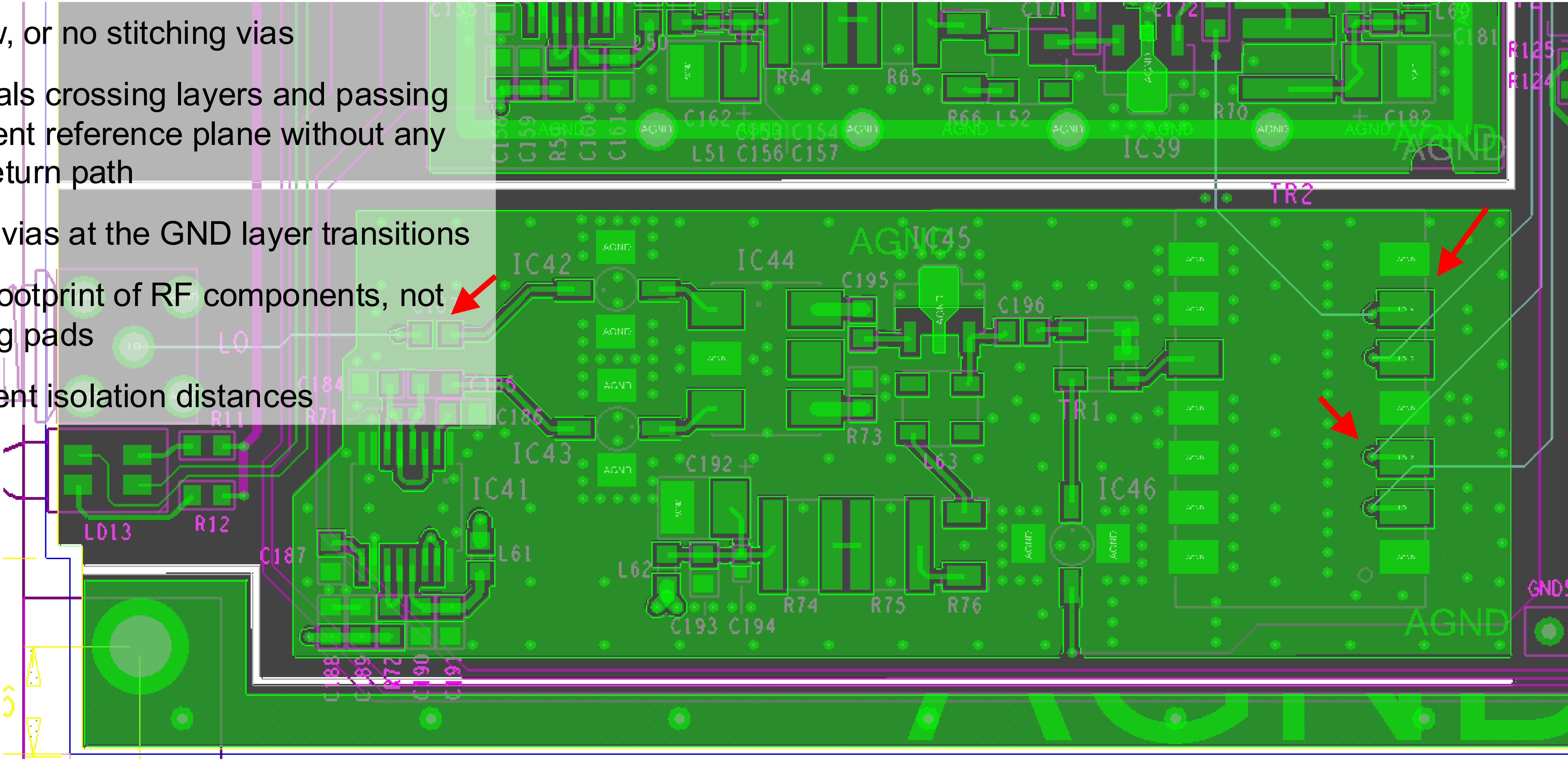
- Split reference plane in an attempt to improve channel to channel RF isolation
- Very few, or no stitching vias



- Split reference plane in an attempt to improve channel to channel RF isolation
- Very few, or no stitching vias
- RF signals crossing layers and passing to different reference plane without any signal return path
- Missing vias at the GND layer transitions

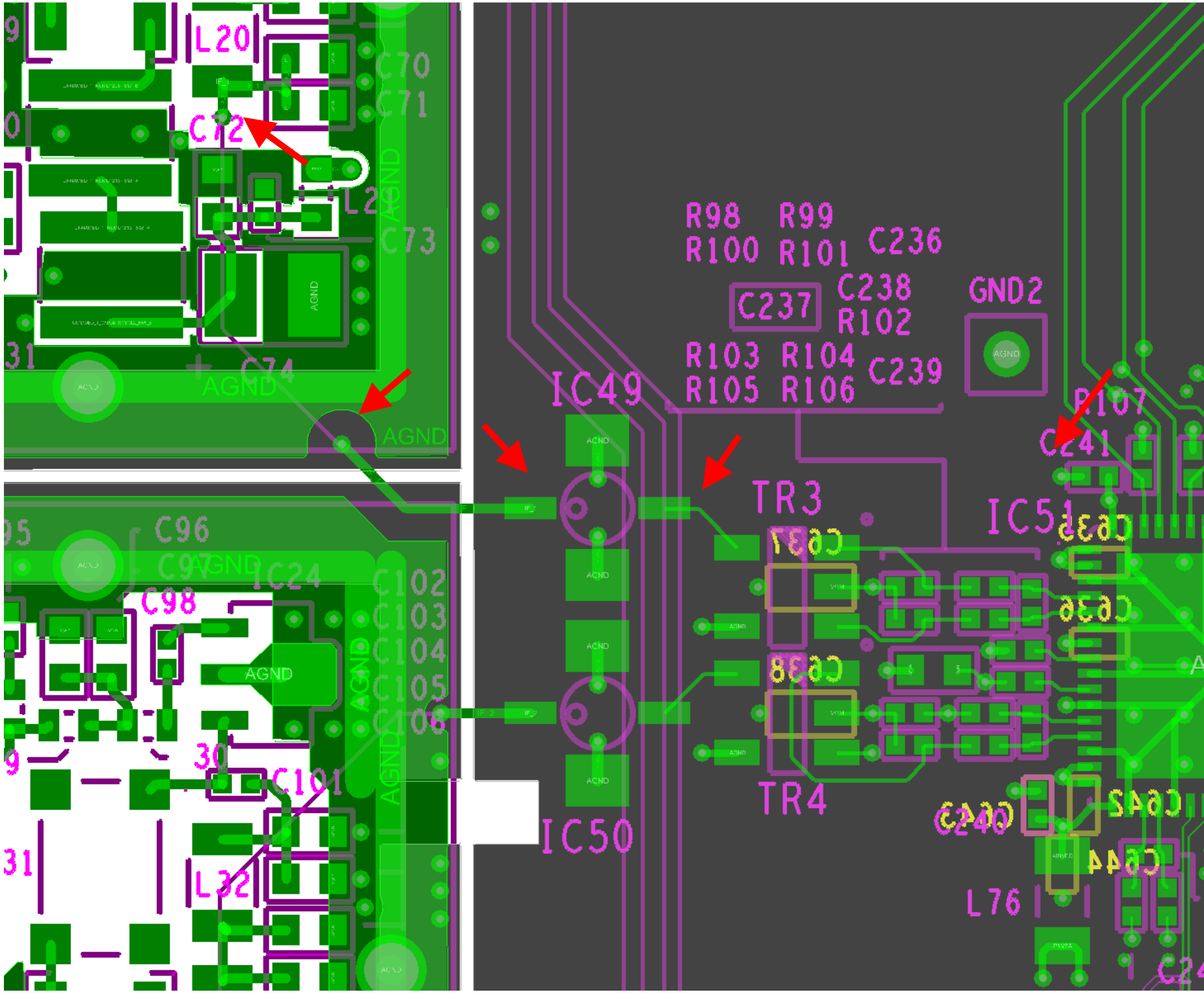


- Split reference plane in an attempt to improve channel to channel RF isolation
- Very few, or no stitching vias
- RF signals crossing layers and passing to different reference plane without any signal return path
- Missing vias at the GND layer transitions
- Wrong footprint of RF components, not matching pads
- Insufficient isolation distances



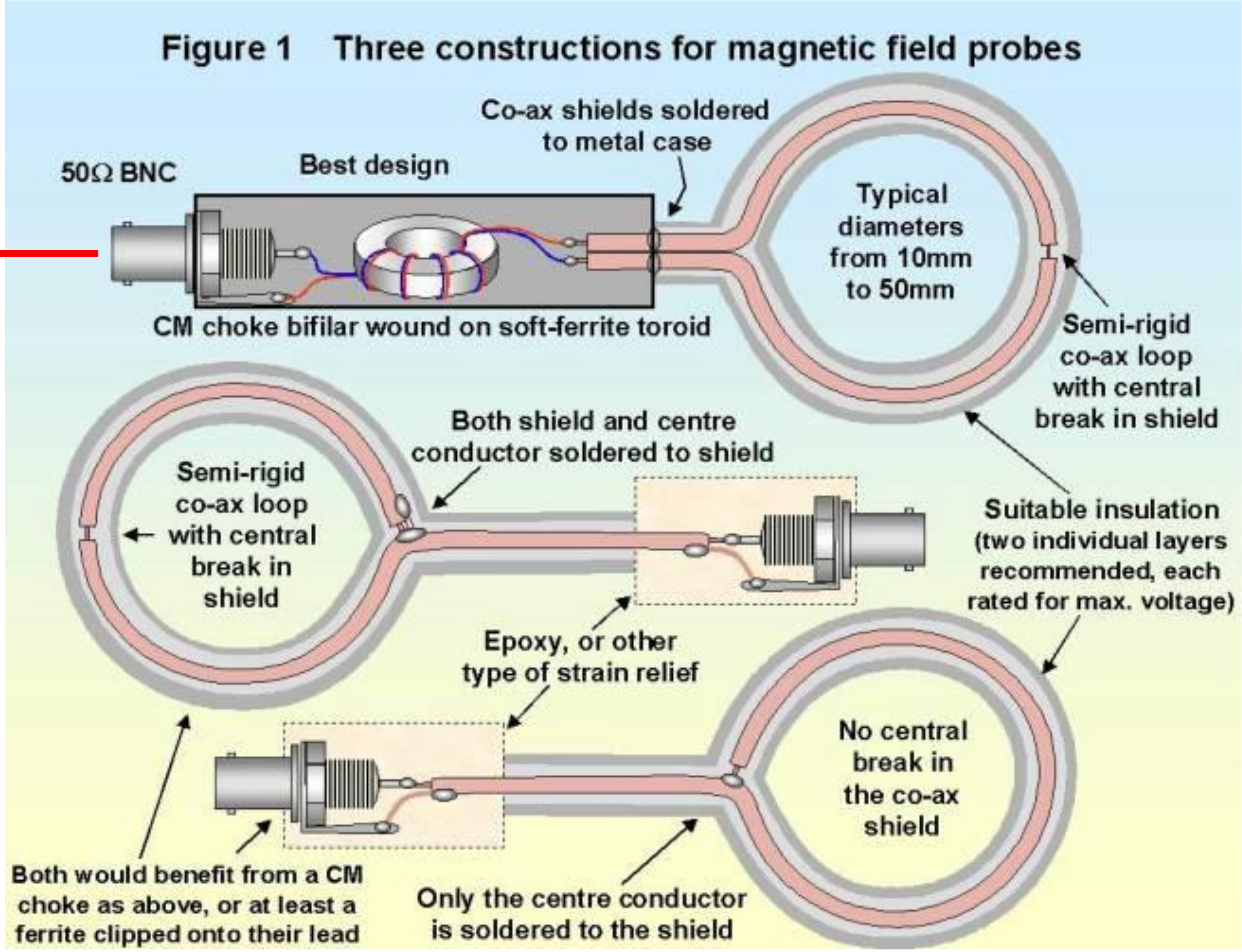
- Split reference plane in an attempt to improve channel to channel RF isolation
- Very few, or no stitching vias
- RF signals crossing layers and passing to different reference plane without any signal return path
- Missing vias at the GND layer transitions
- Wrong footprint of RF components, not matching pads
- Insufficient isolation distances
- Crossing reference planes without return path
- Impedance controlled tracks
- Single vias to reference plane

- ***Problems fixed by complete redesign***

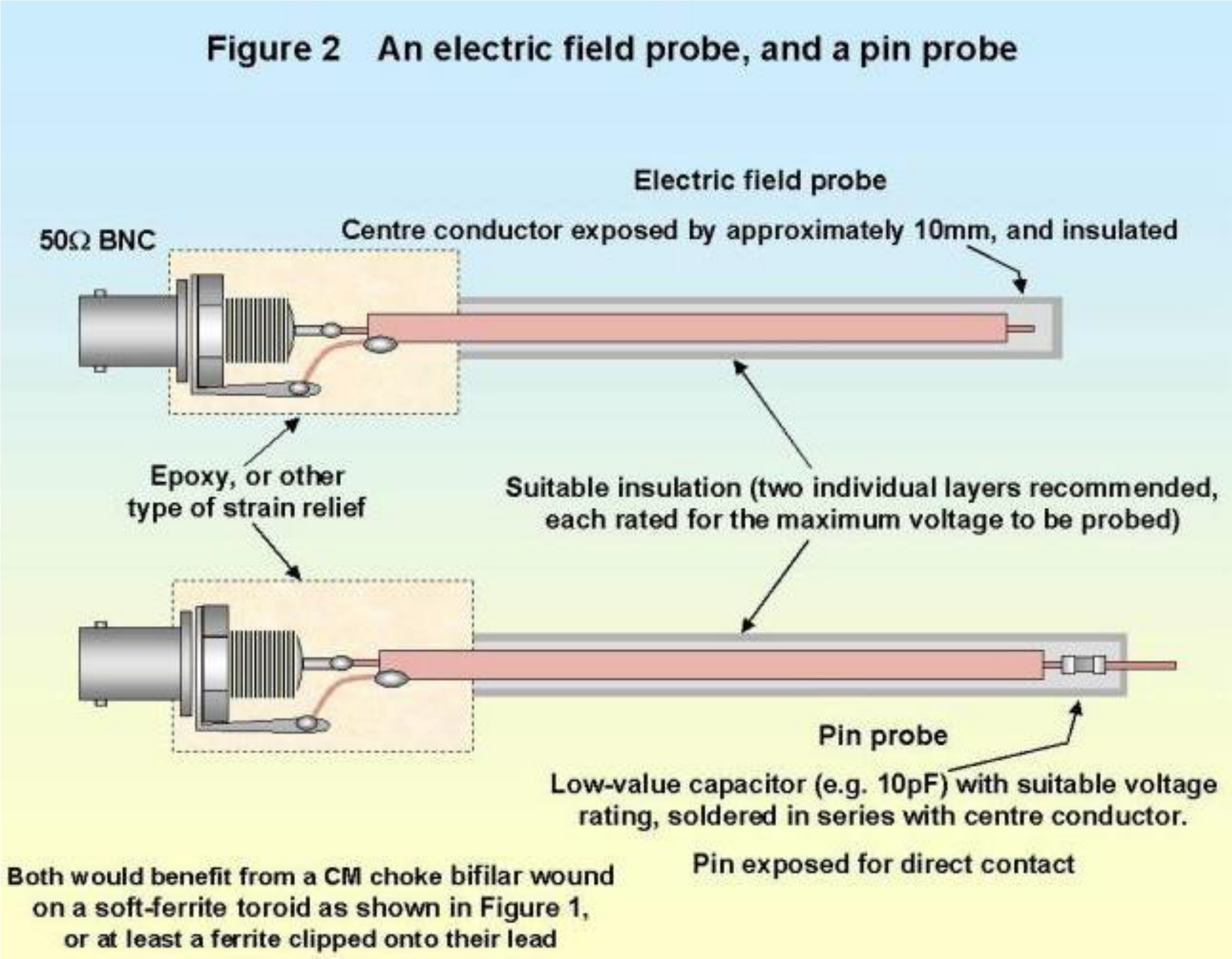


DIY measurement of near fields

To spectrum analyzer



DIY measurement of near fields

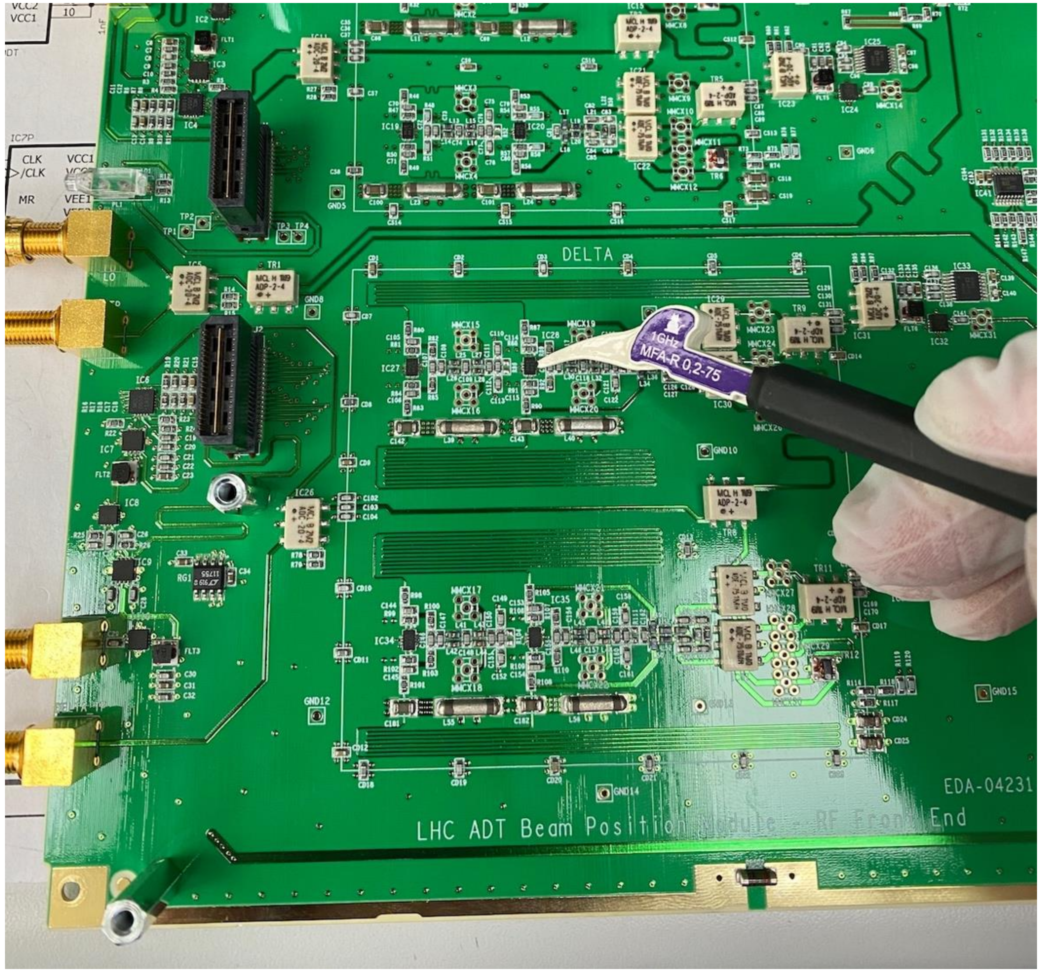


Measurement of near fields

Example of probes used in the CERN ATS EMC laboratory:

A combined 3D E/H probe with field meter

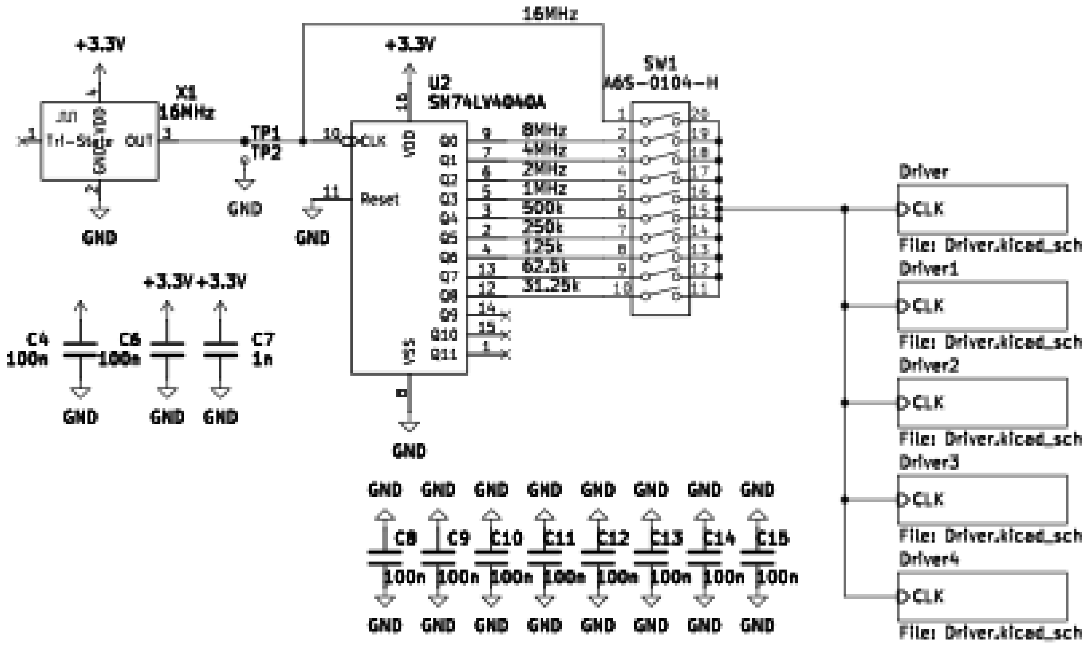
Microprobe for PCB trace level measurements

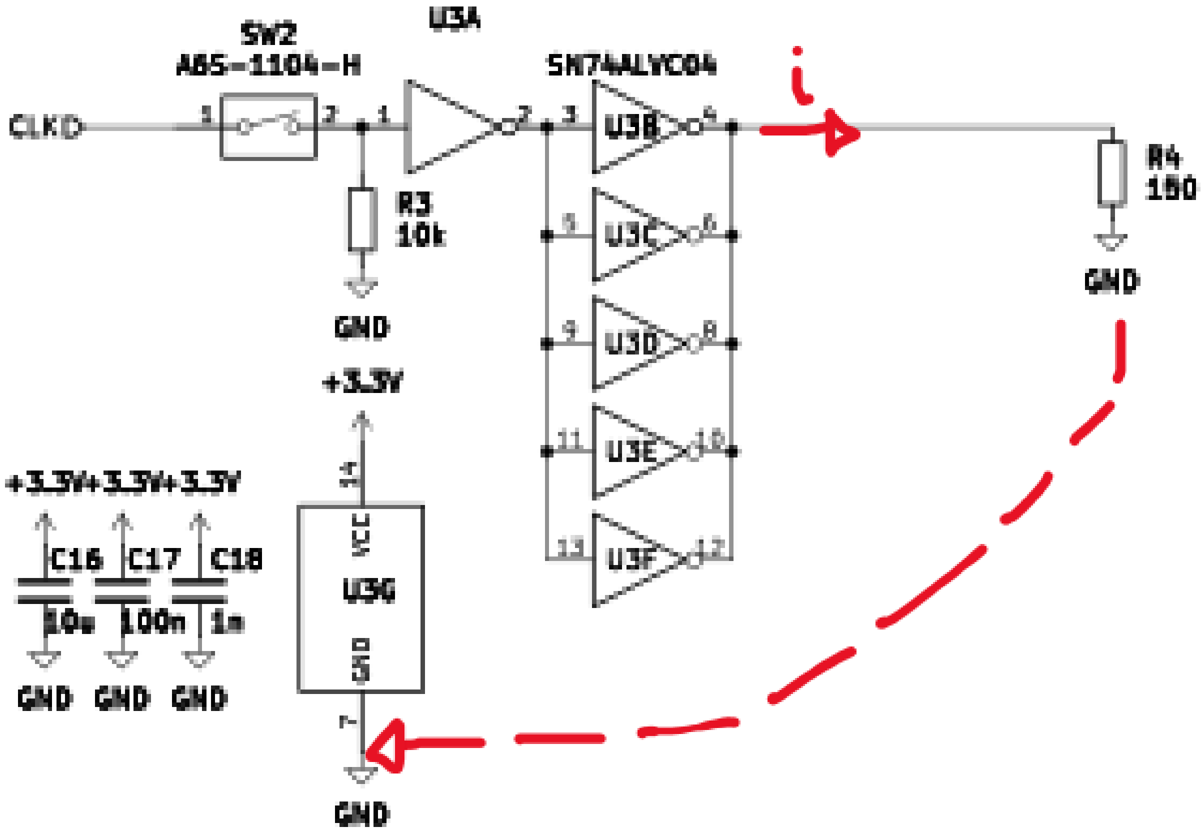


Measurement of near fields

Experiment 1 – return path and routing

- **Investigate emissions of a differently routed 25 mA current loop**

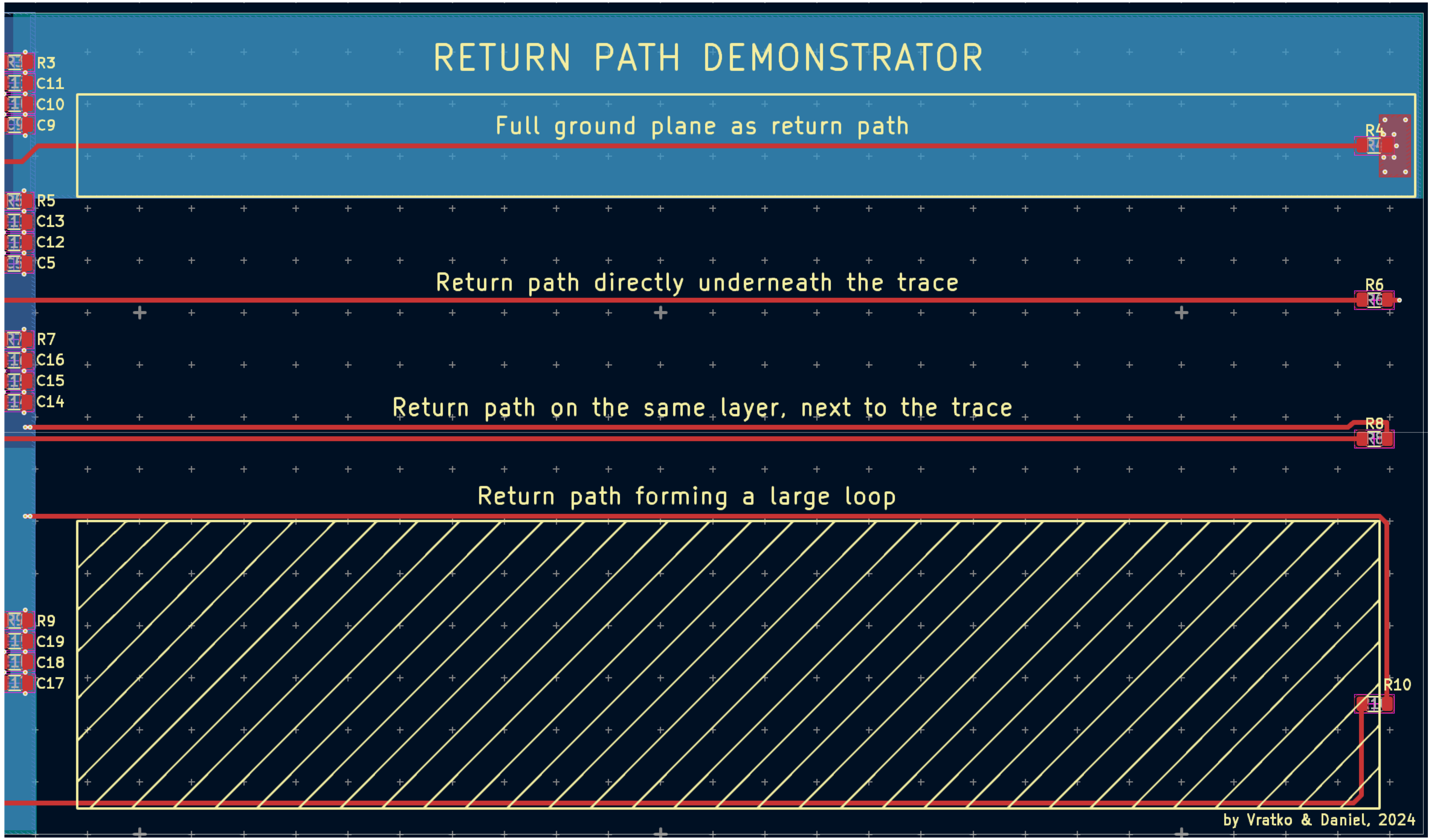




Help with designs and realisation:
V. Hajdučík, V. Štovčík. Thank you!

Experiment 1 – return path and routing

- **Investigate emissions of a differently routed 25 mA current loop**



Full GND plane

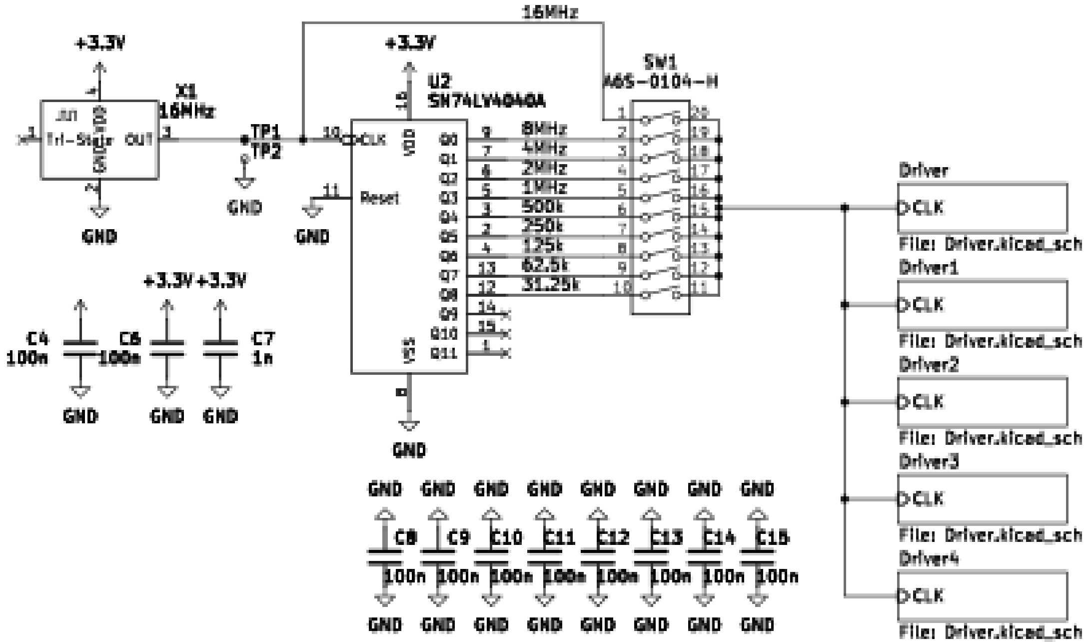
Return path directly under the trace

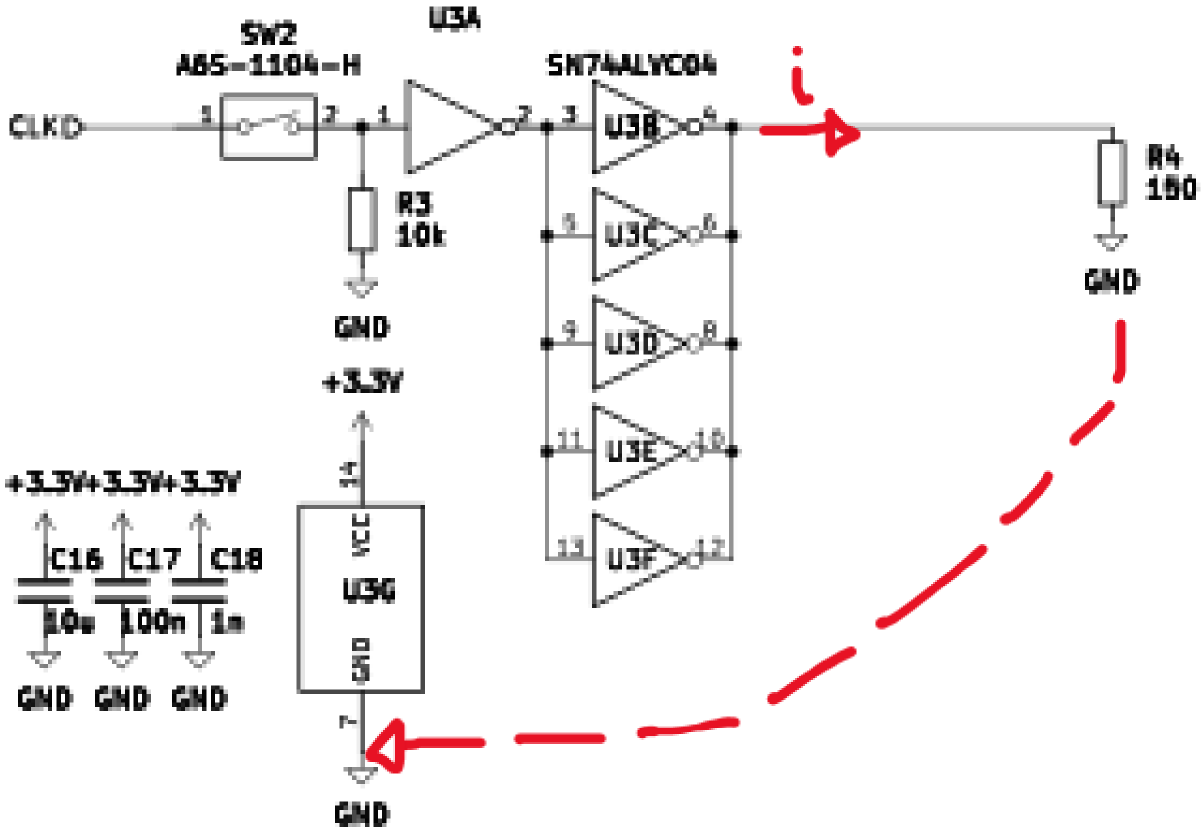
Return next to the trace

Return path 35 mm from the inward path forming a 35x160 mm^2 loop.

Experiment 2 – return path and crossing layers

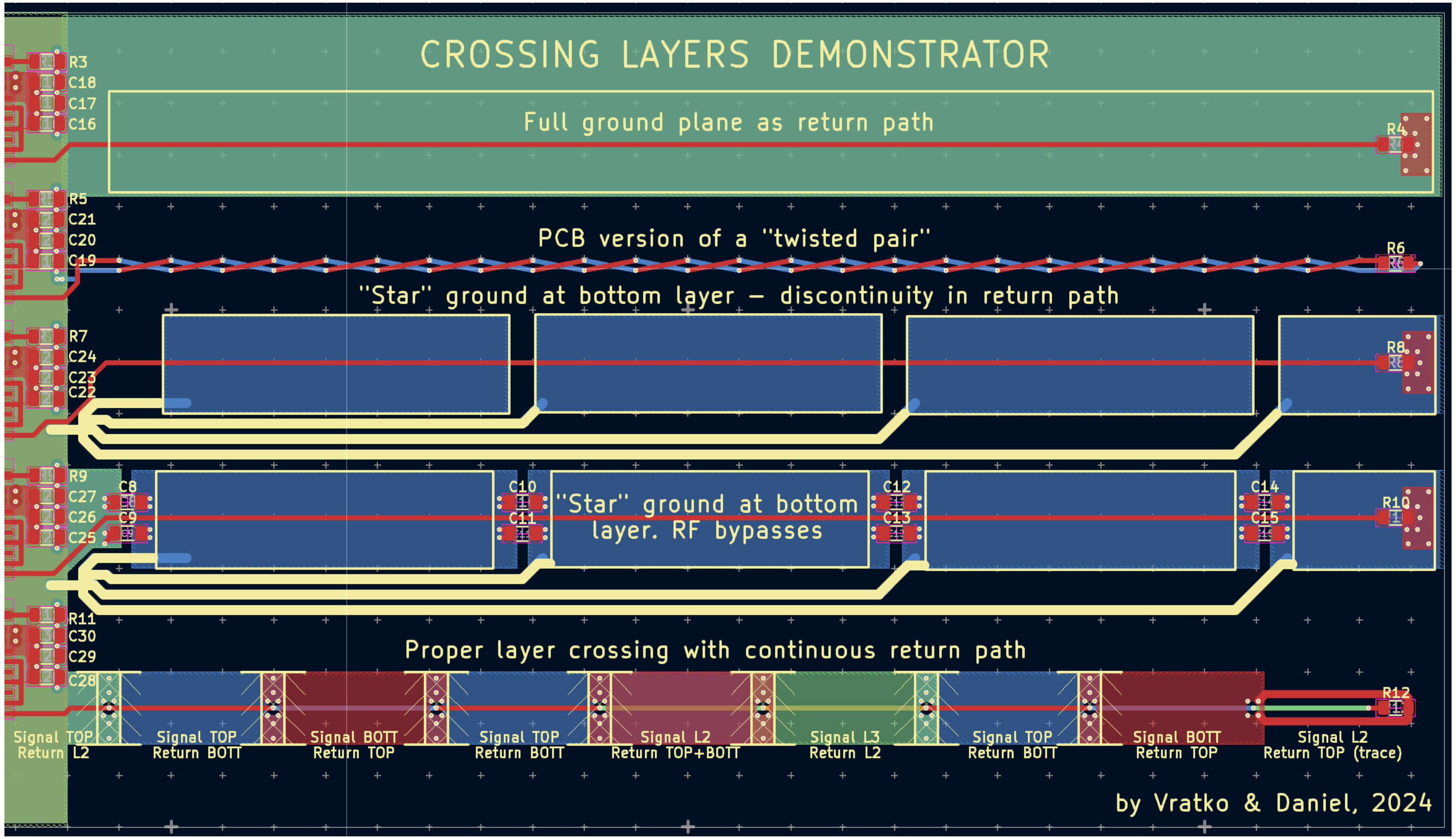
- Investigate emissions of a trace carrying 25 mA with different return path and layer crossing configurations





Experiment 2 – return path and crossing layers

- **Investigate emissions of a trace carrying 25 mA with different return path and layer crossing configurations**



Full GND plane

Equivalent of twisted pair

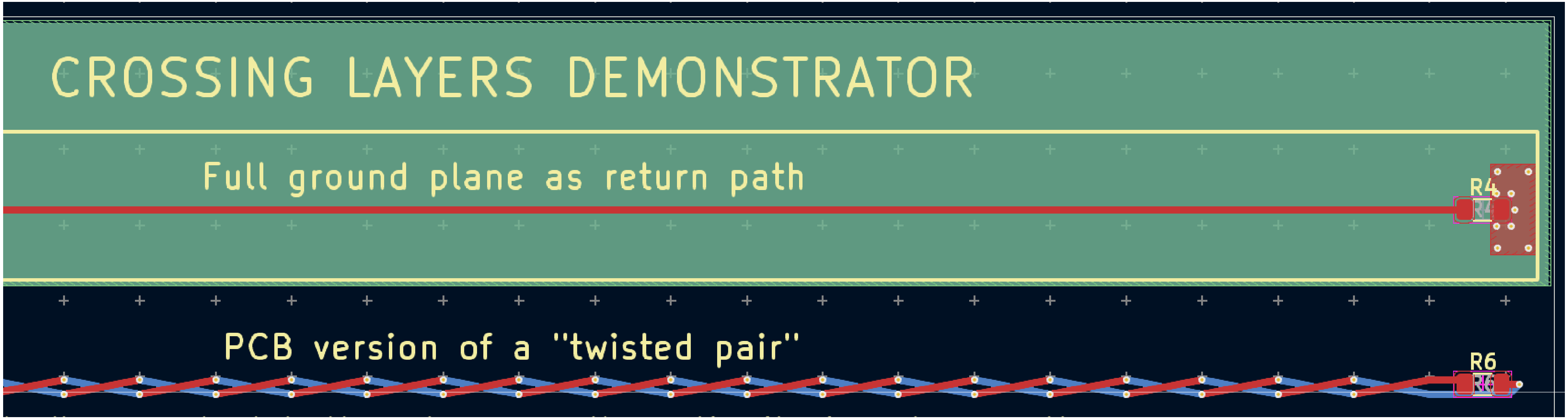
Star ground

Star ground with RF bypasses

Layer crossing with continuous return path

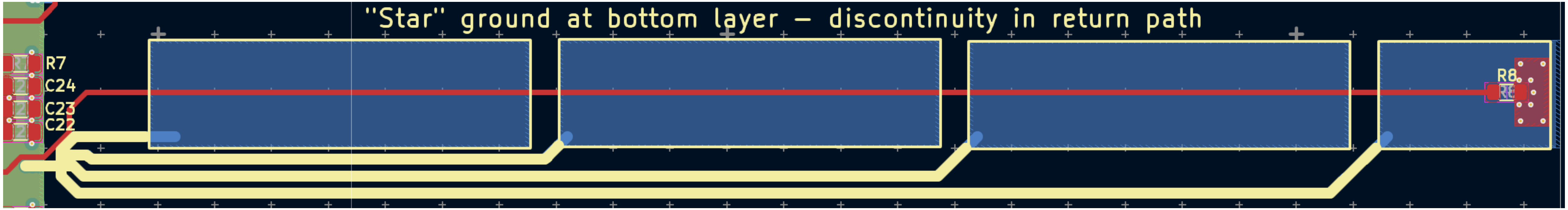
Experiment 2 – return path and crossing layers

- **Investigate emissions of a trace carrying 25 mA with different return path and layer crossing configurations**



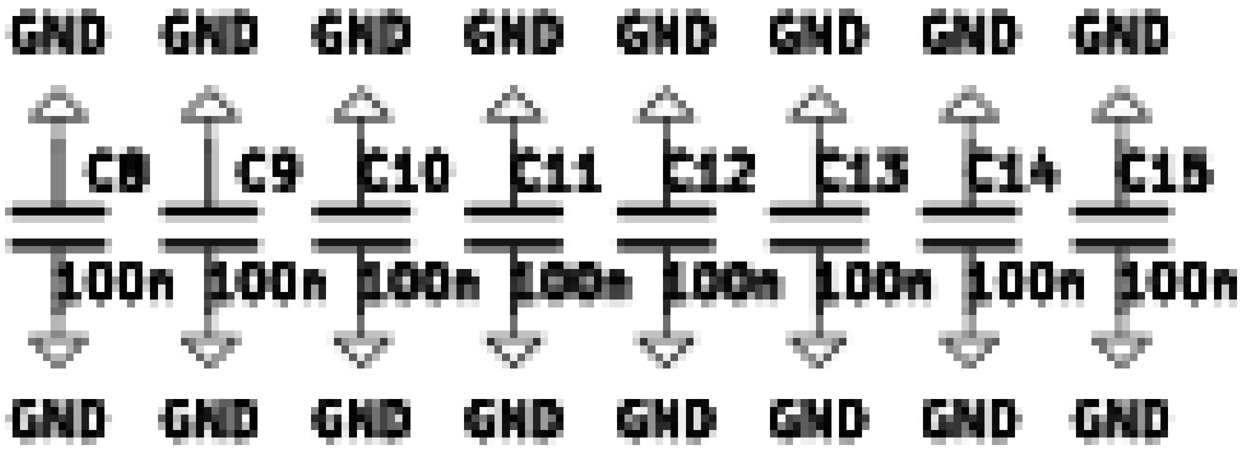
Experiment 2 – return path and crossing layers

- **Investigate emissions of a trace carrying 25 mA with different return path and layer crossing configurations**



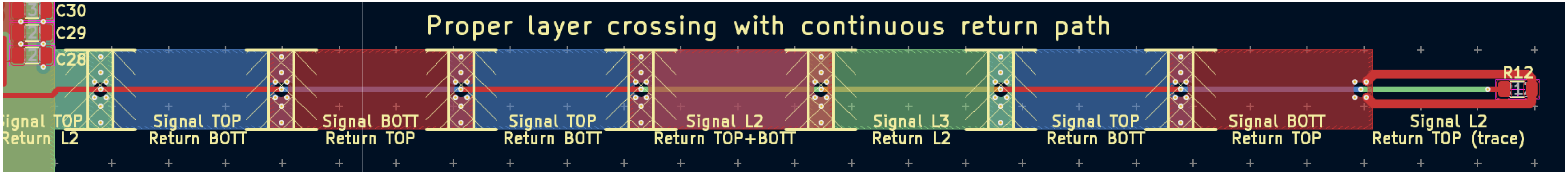
Experiment 2 – return path and crossing layers

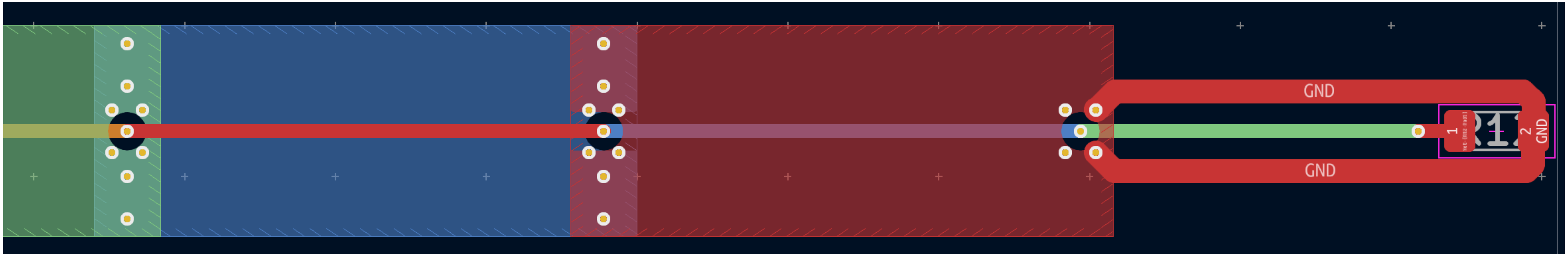
- **Investigate emissions of a trace carrying 25 mA with different return path and layer crossing configurations**



Experiment 2 – return path and crossing layers

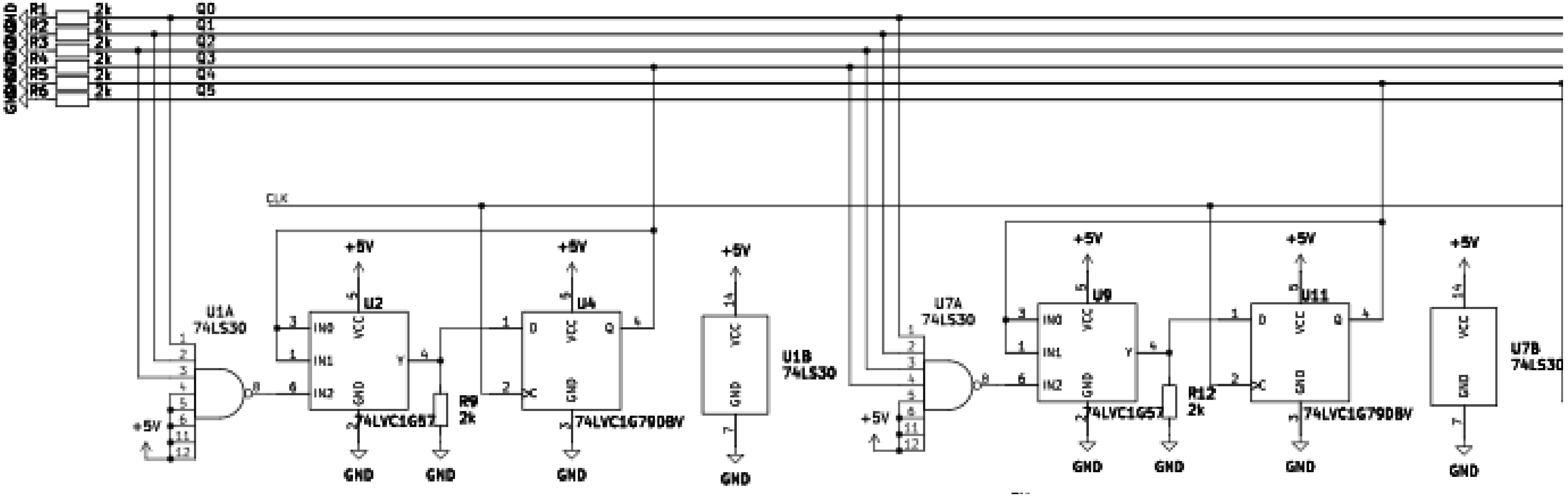
- **Investigate emissions of a trace carrying 25 mA with different return path and layer crossing configurations**

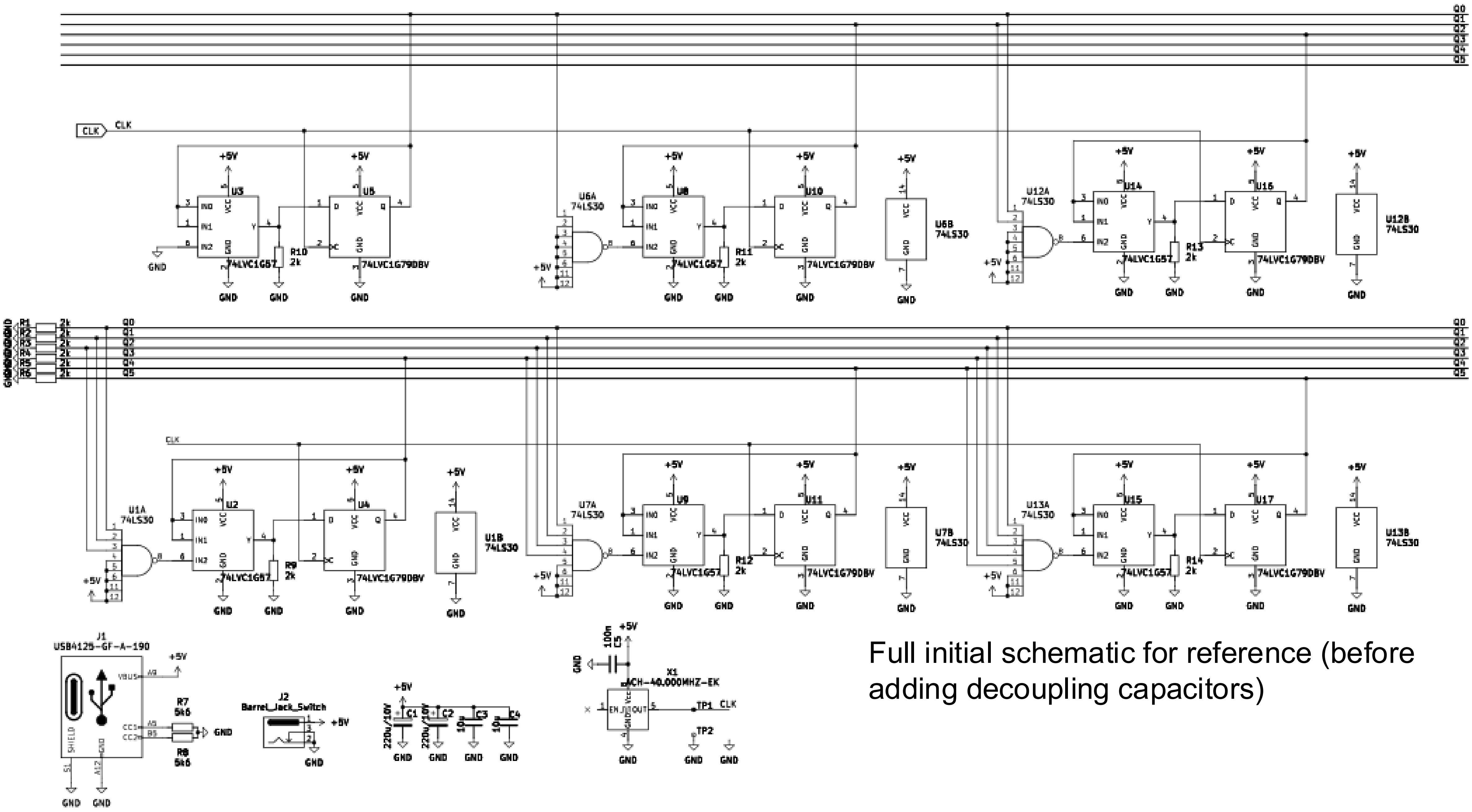




Experiment 3 – routing and decoupling

- 6 bit synchronous counter realized with discrete logic.
- 10 MHz oscillator, 74LVC and 74LS logic (tr ~ 2…4 ns)
- Two designs on a 2 layer board, one design on a 4 layer board
- **Instruction to the designers:** "add what-ever components you think are important"

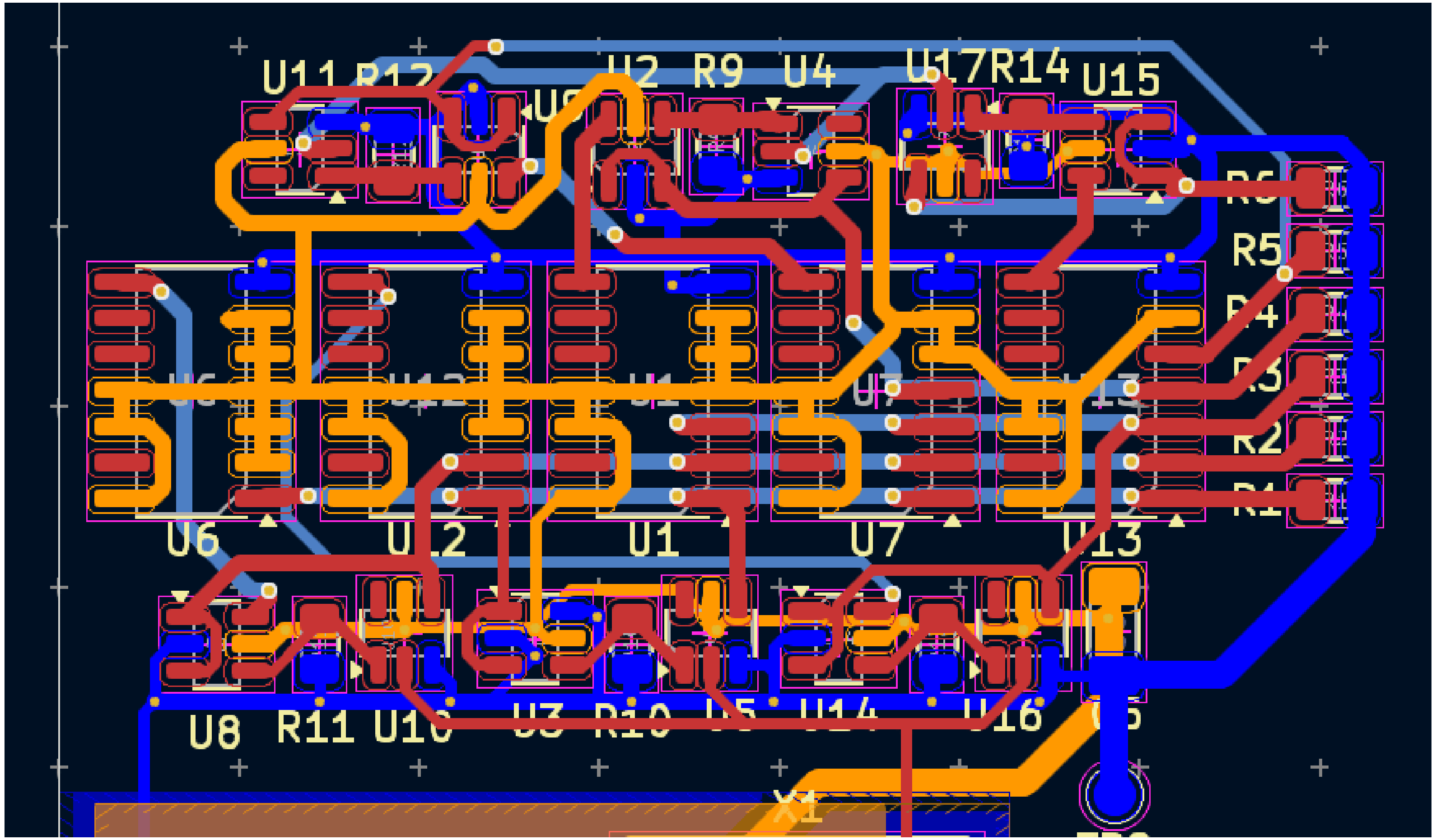




Full initial schematic for reference (before adding decoupling capacitors)

Experiment 3 – routing and decoupling (Exhibit A)

- **2 layer board, no dedicated power buses, everything routed as "nets"**
- **"add what-ever components you think are important" no decoupling capacitors added**



Legend:

GND

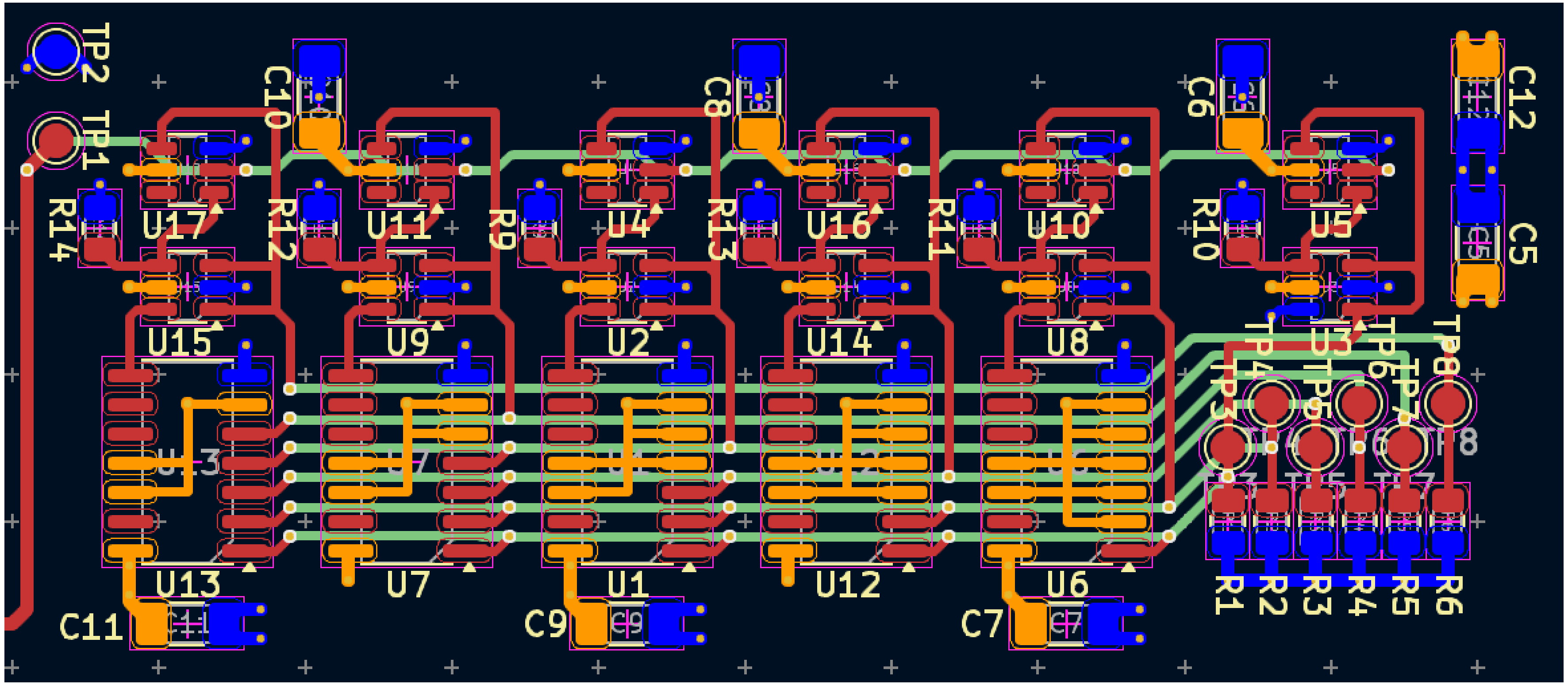
+5V

Signal nets (top)

Signal nets (bott)

Experiment 3 – routing and decoupling (Exhibit B)

- 4 layer board, dedicated GND/+5V layer, two signal layers
- Decoupling capacitors added (3x 100nF, 3x 10uF)
- Signals are not crossing power planes



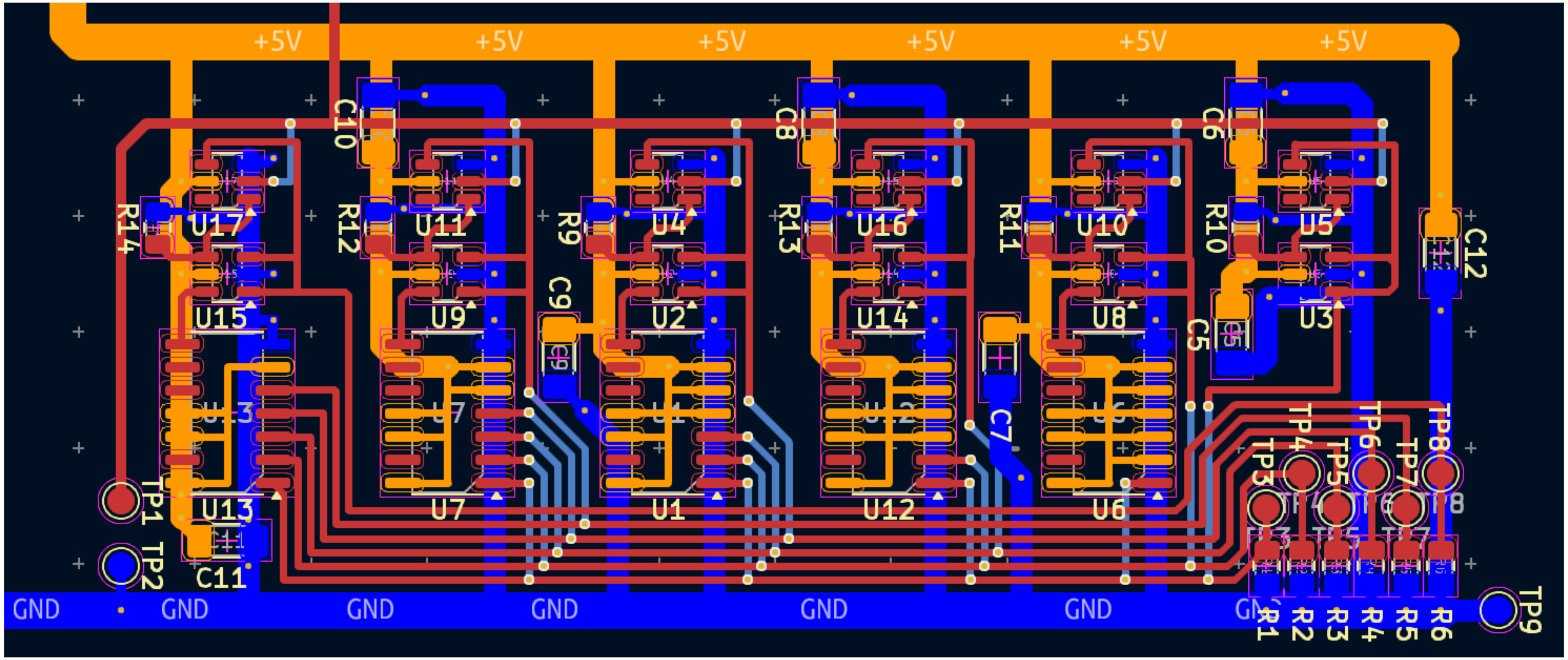
Legend/layer stackup:

Top	signal nets
L2	signal nets
L3	GND
Bottom	+5V

Experiment 3 – routing and decoupling (Exhibit C)

- **Is it possible to route it “properly” on 2 layers only?**

- **Dedicated power buses**
- **Decoupling capacitors added (3x 100nF, 3x 10uF)**



Legend:

GND

+5V

Signal nets (top)

Signal nets (bott)