EMC on Tour 2016
October 19, 2016, Eindhoven

EMC on Tour

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Contents

Acknowledgements

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THALES

Environmental Competence Centre

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Rijksdienst voor Ondernemend Nederland

EMC on Tour has received funding from Agentschap NL, now part of RVO

EMC on tour has been organized starting in 2010 to provide practical demonstrations at universities of applied sciences where students and interested employees of small and medium sized companies are explicitly invited to witness:

- Practical examples of EMC effects

and

- The results of measures proposed

This session of EMC on Tour was organized by the Dutch EMC-ESD association

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Definition of EMC

“The ability of the System to Operate according to its Specifications in its Intended Electromagnetic Environment” **[IMMUNITY]**

Source: YouTube

“Without generating Unacceptable Electromagnetic Disturbances into that Environment” **[EMISSION]**

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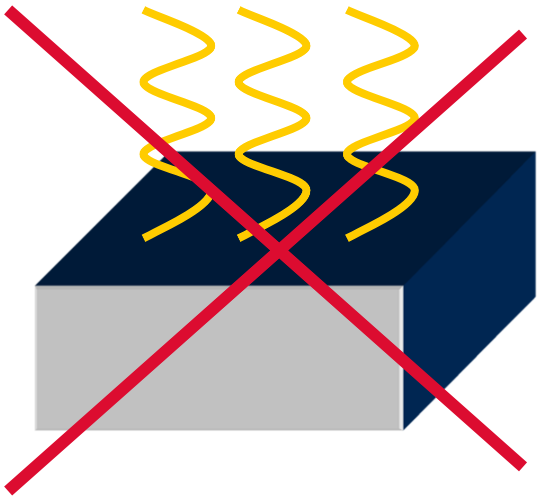

1. No (intolerable) emissions into the environment

2. Operate satisfactorily in its EM environment

Source: YouTube

3. Not cause interference with itself

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Systems Perspective: Performance Criteria

what happens when immunity threshold levels are approached?

A
System continues to work according to specification
Degradation not acceptable
Generally applies to all interference with a continuous nature

B
Temporary degradation acceptable, auto recovery.
Usually applies to sporadic interference
to a non-critical function.

C
Degradation acceptable. Recovery after manual RESET.
e.g. at mains interruptions. Only for non-critical functions.

An UNSAFE situation is never acceptable!

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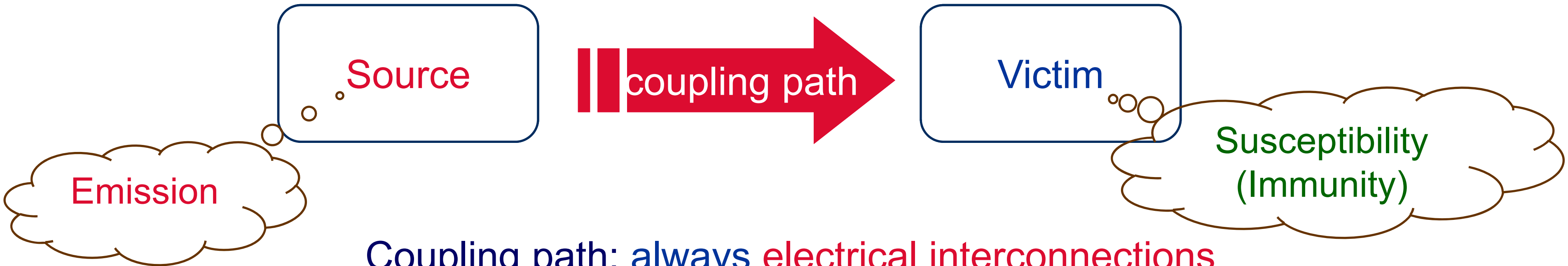
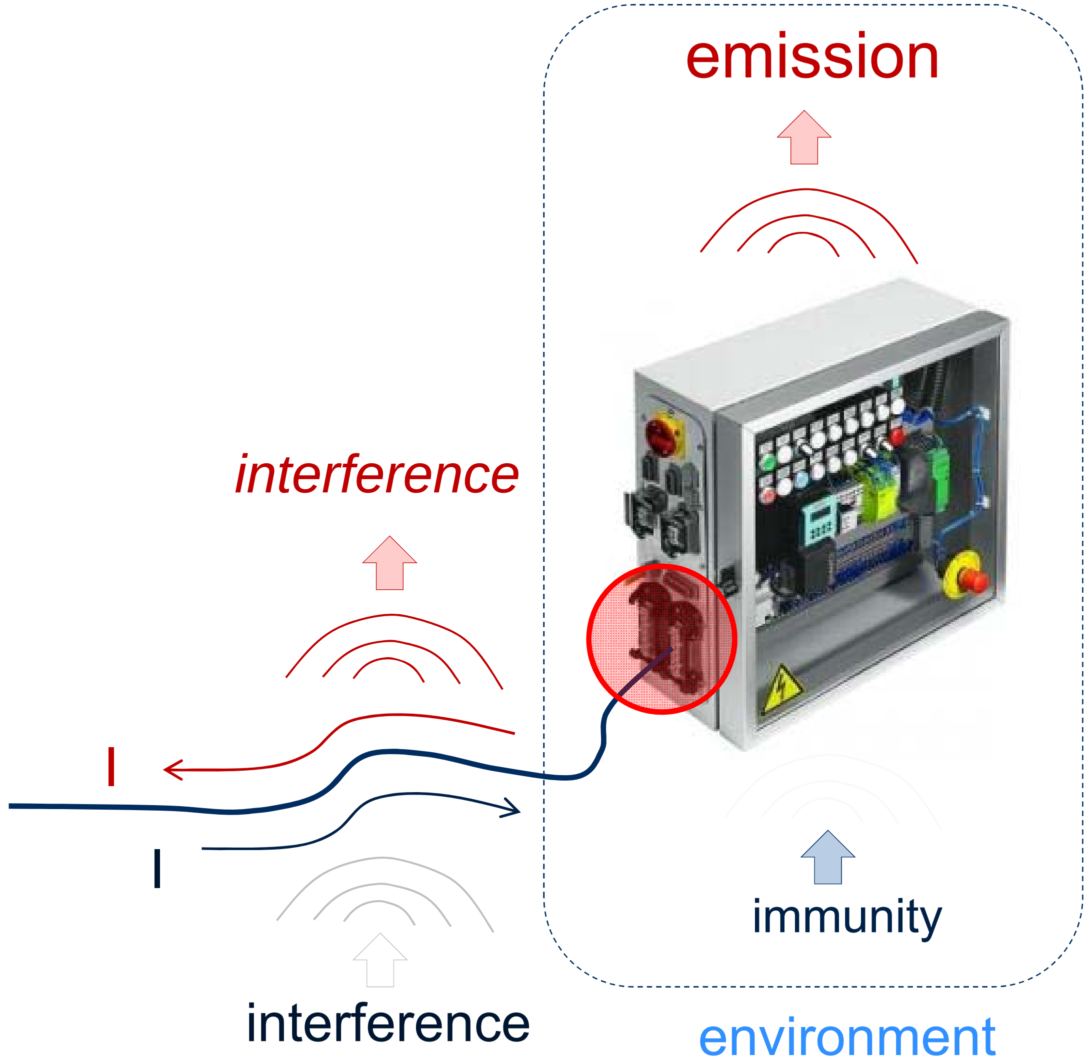
EMI, ElectroMagnetic Interference model: source – victim and coupling path



Coupling path: always electrical interconnections

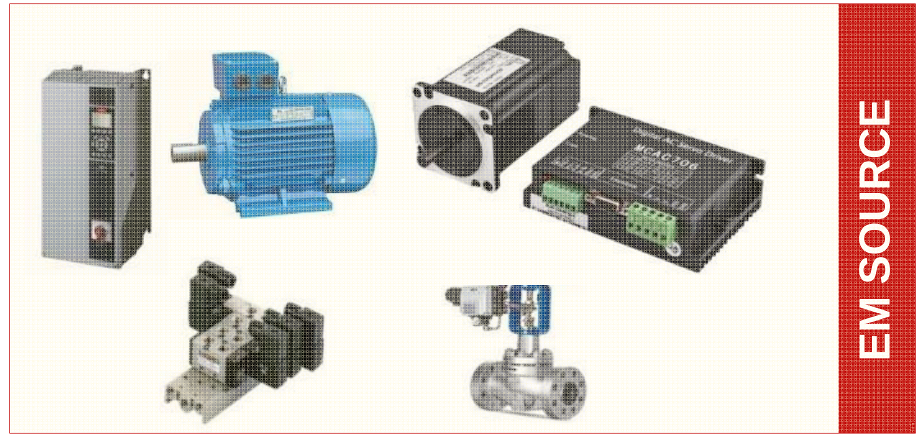
Effects appear
at any scale
(relative to wavelength)

Very large….


emission
interference
I
I
immunity
interference
environment

EMC characteristics of LARGE installations

- SMPS, variable speed drives (frequency converters, servo drives)
- Switched applications (electrical motors, pneumatics, hydraulics)
- Measurement and control
- Datacommunication (fieldbus, ethernet)



EMC?

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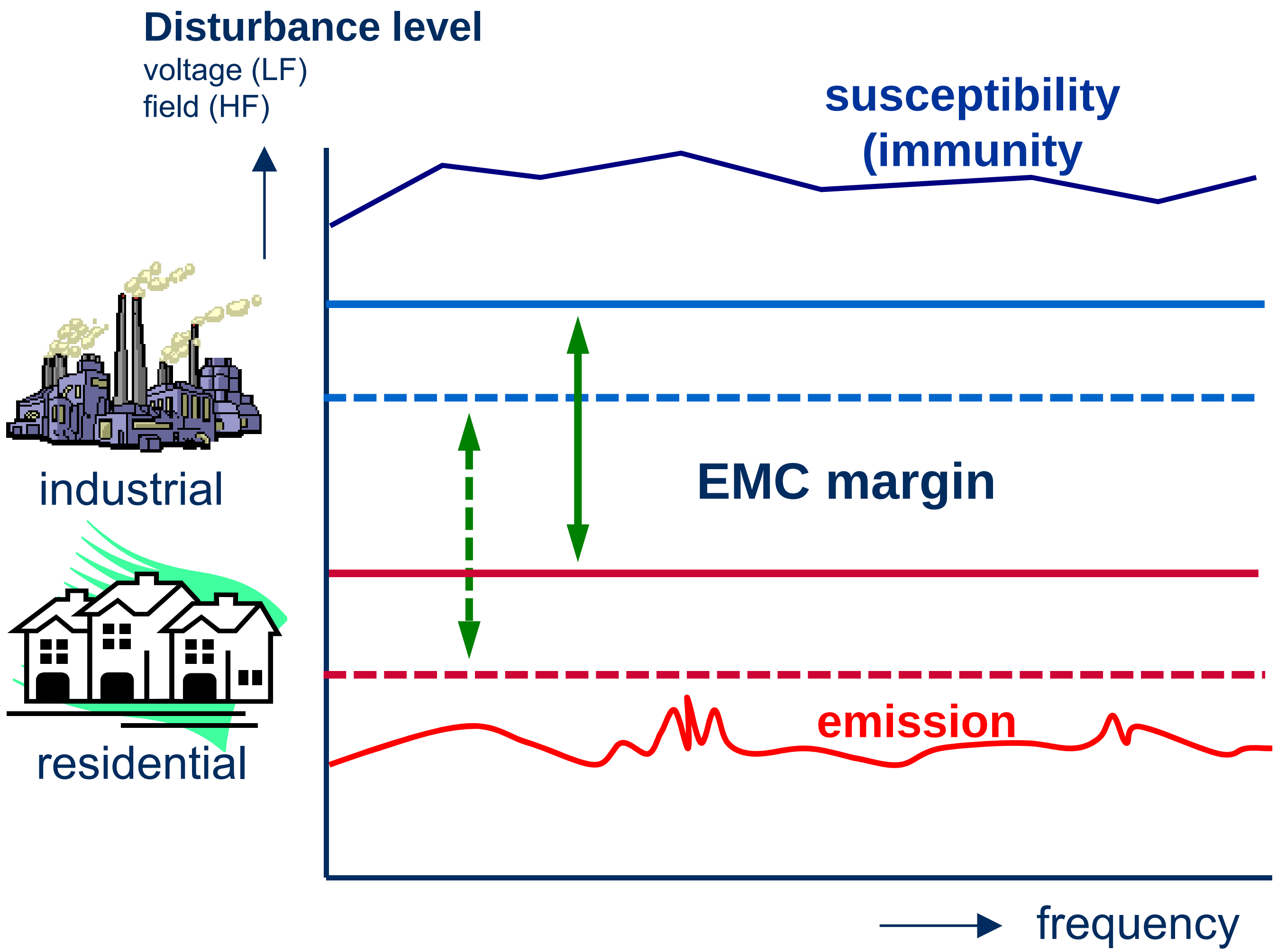
EMC as per the requirements



Generic standards

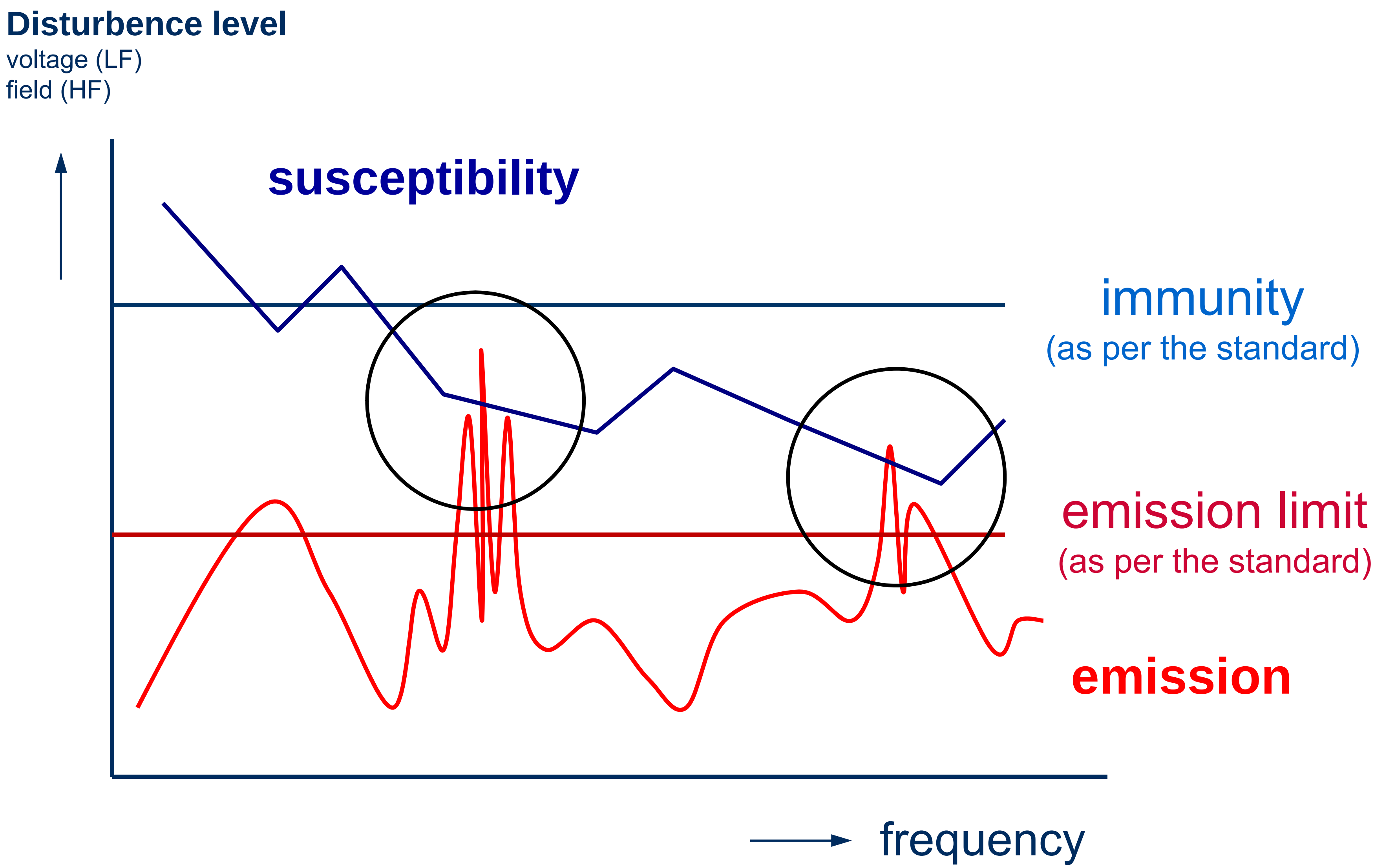
industrial immunity
EN-IEC 61000-6-2

residential immunity
EN-IEC 61000-6-1

industrial emission
EN-IEC 61000-6-4

residentieal emission
EN-IEC 61000-6-3

Lack of EMC: EMI = EM Interference



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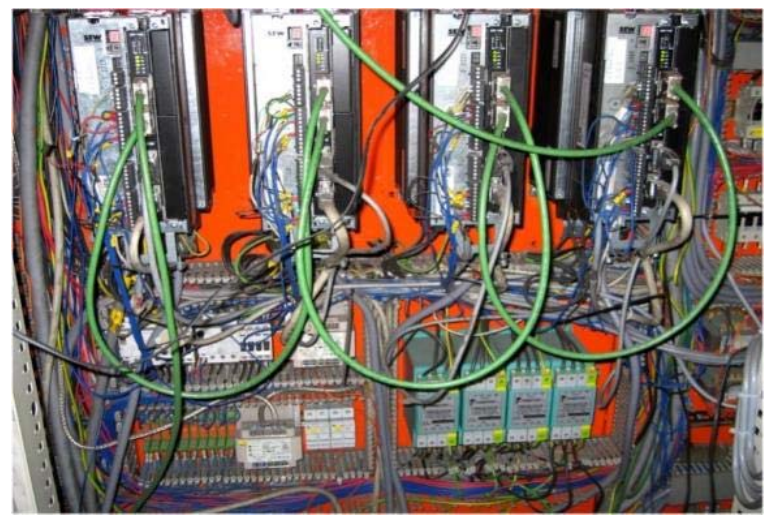
- Large number of apparatus
- Deviations in EM levels, gaps in technical standards

> **Warning**
> This product complies with the requirements in accordance with product standard IEC 61800-3. In a domestic environment, this product may cause radio interference, in which case supplementary mitigation measures may be required.

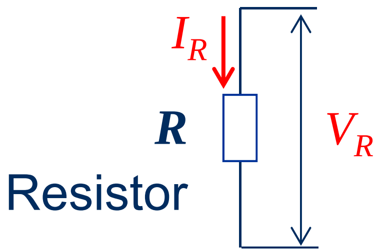
- Different environments
- Different installation practices

> **WARNING:** Screened cables must be used with this equipment in order to comply with the EMC Directive 2004/108/EC regulations

- Very high EMC margin →



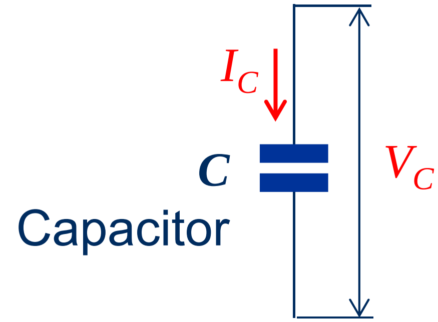
passive components and their *(ideal)* behavior in the time domain



described by
(behavioral model)

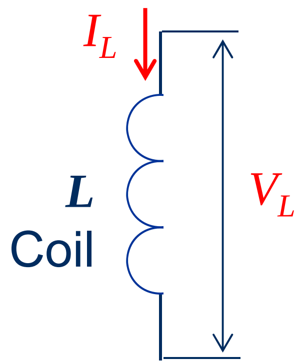
$$V_R = IR \cdot R$$

Ohm's Law



described by

$$I_C = C \cdot \frac{dV_C}{dt}$$



described by

$$V_L = L \cdot \frac{dI_L}{dt}$$

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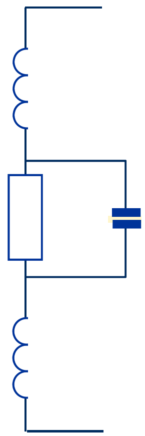
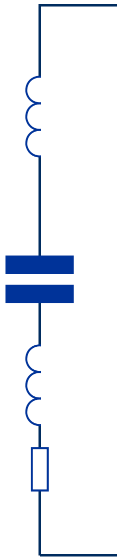
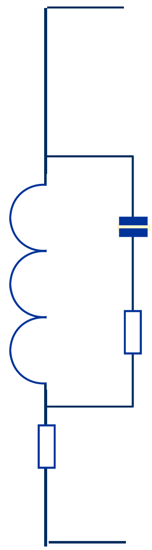
all components have, so called, "parasitics"







LTSpice IV (free on the Internet): http://www.linear.com/designtools/software/

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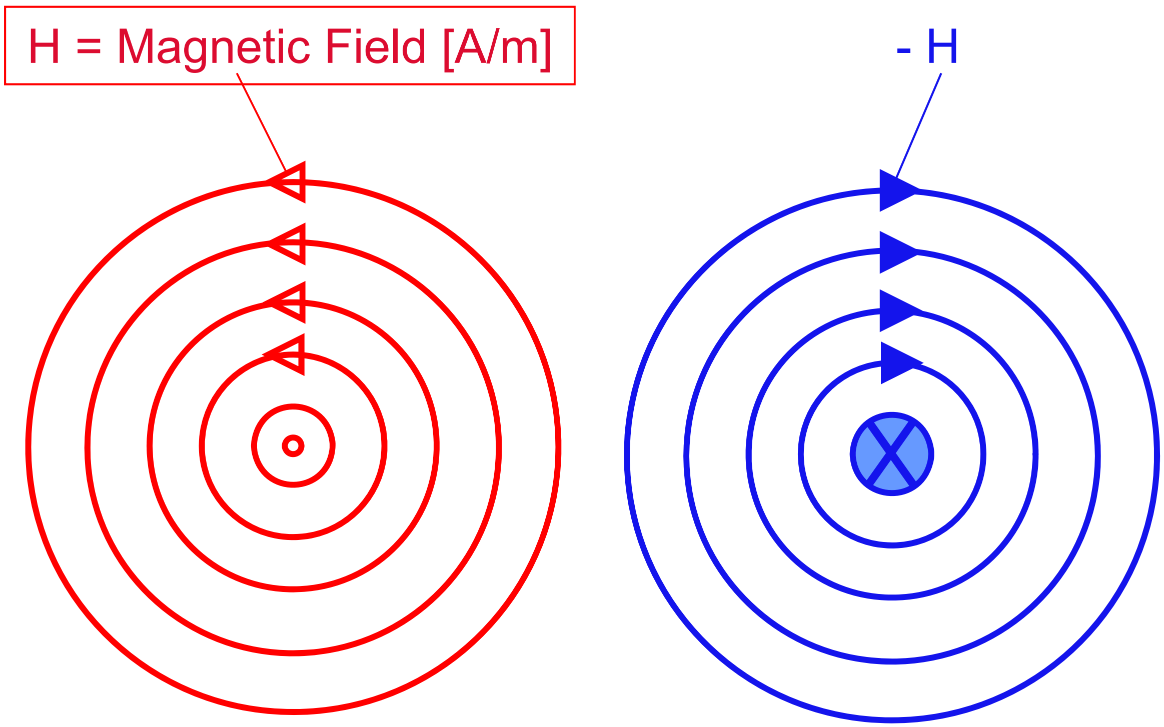
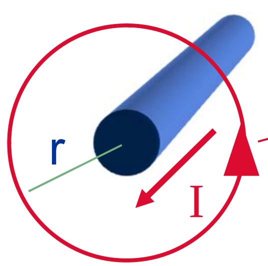
Any current needs a magnetic field!

field of the return conductor is identical but opposite (if geometry is identical)



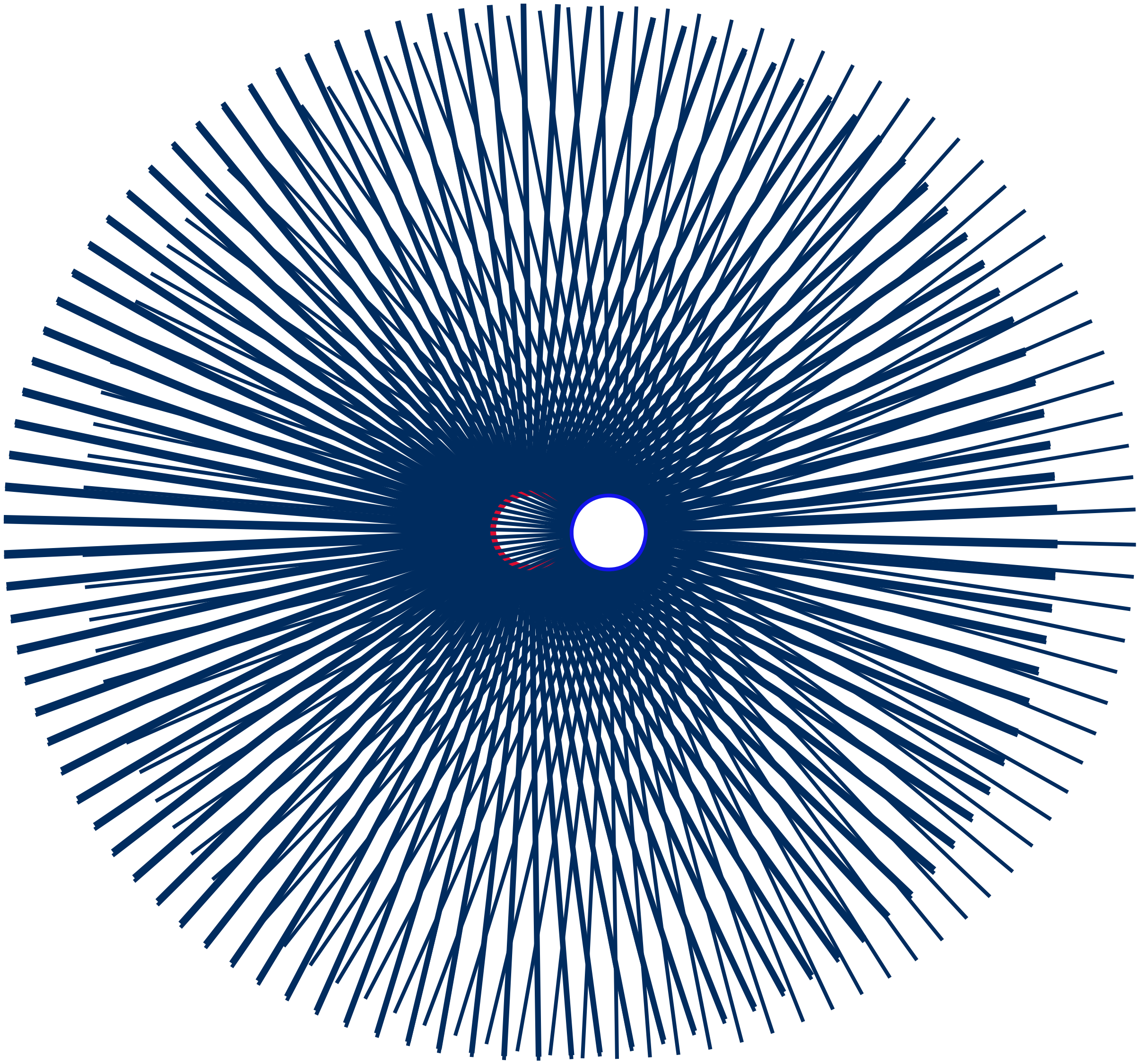
Biot Savart's Law:



$$H \approx \frac{I}{2\pi \cdot r}$$

Current carrying conductor always exhibits H-field

minimize fields by aligning conductors (not possible for twin wires)



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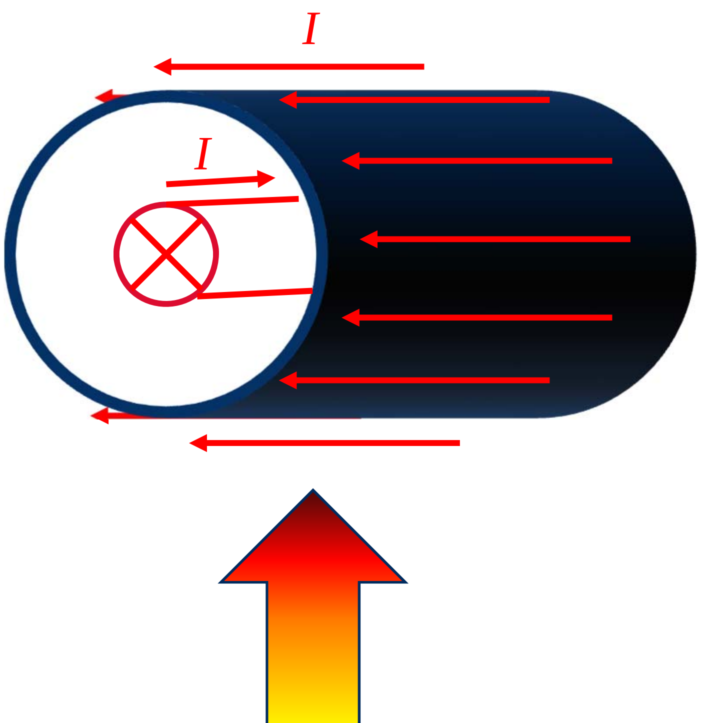
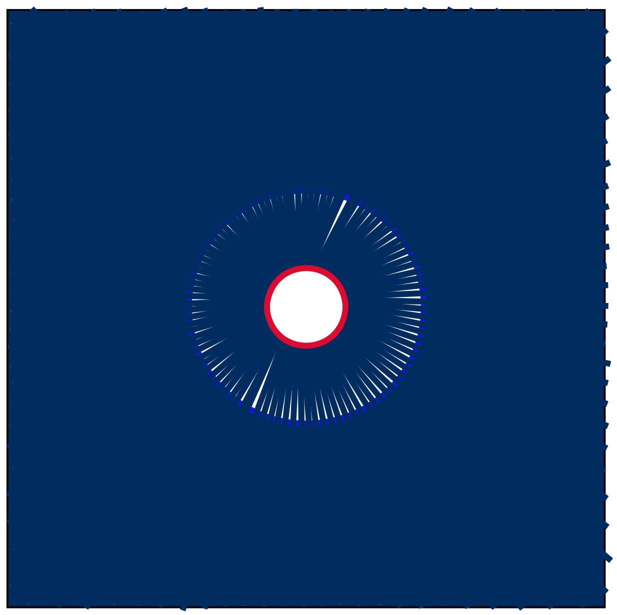
COAX produces less fields than twin wires (under conditions)





ONLY if shield current uniformly distributed over 360°

Special care when mounting connectors or glands!

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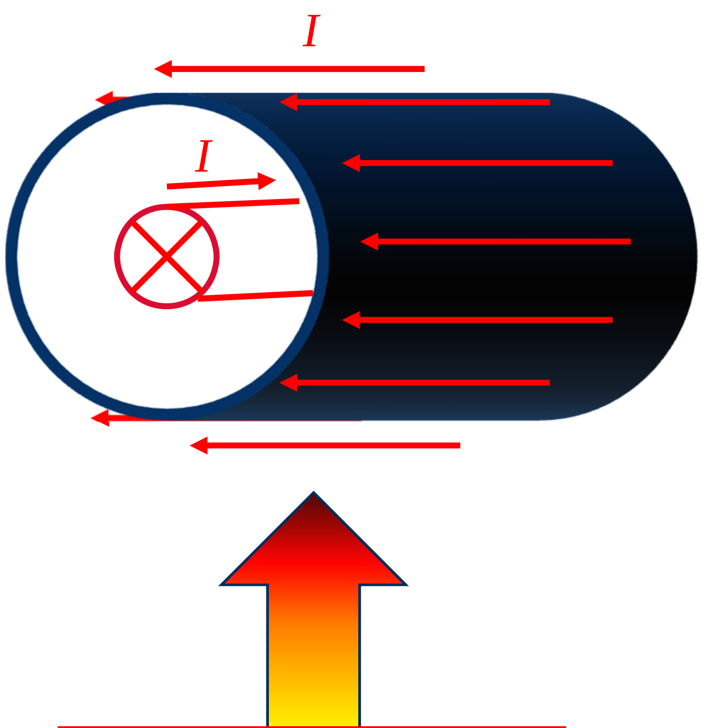
make sure, current over shield can be uniformly distributed over 360°



EMC gland with provision for 360° contact

ONLY if shield current uniformly distributed over 360°

Source: **Smythe W.R.**
"Static and Dynamic Electricity"
p. 278. McGraw Hill, 1950

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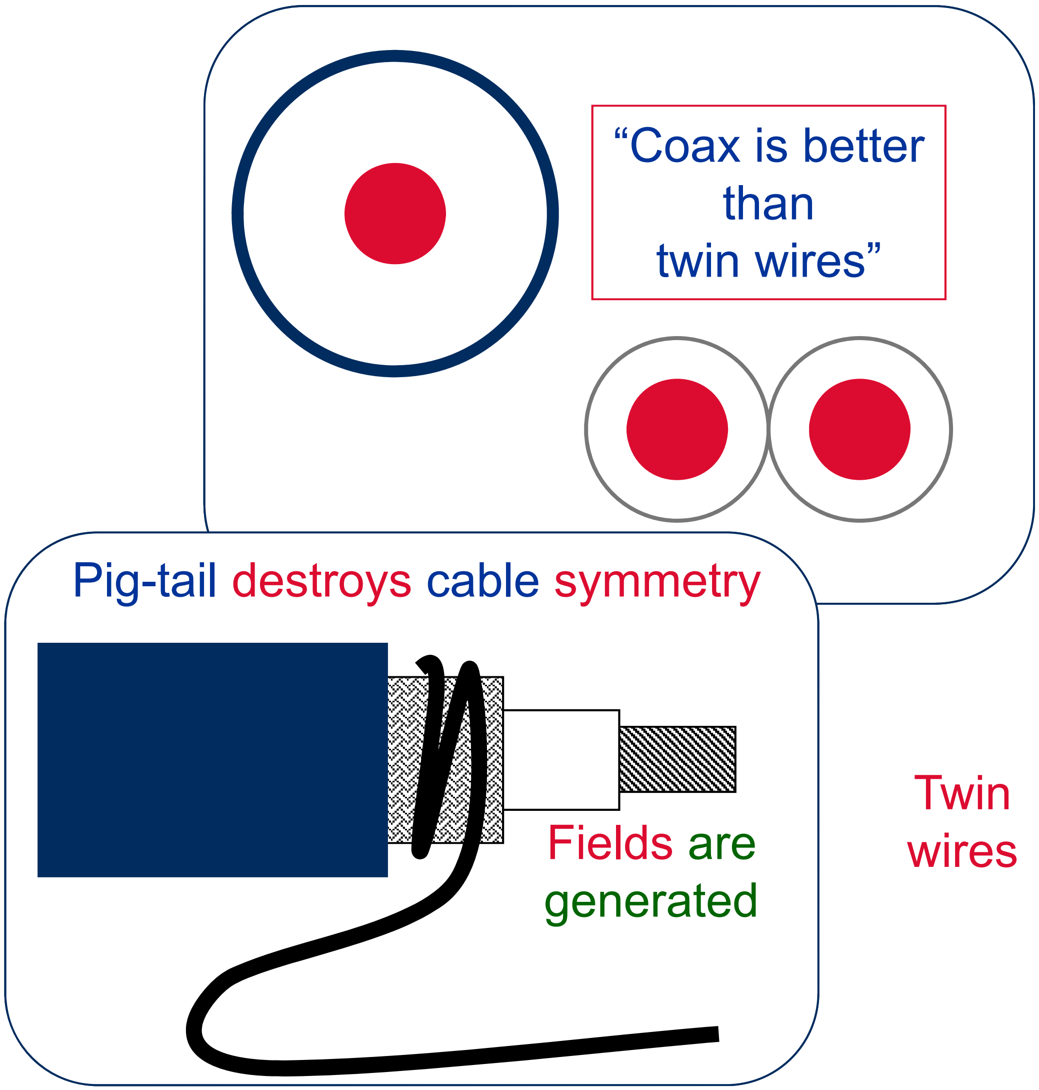
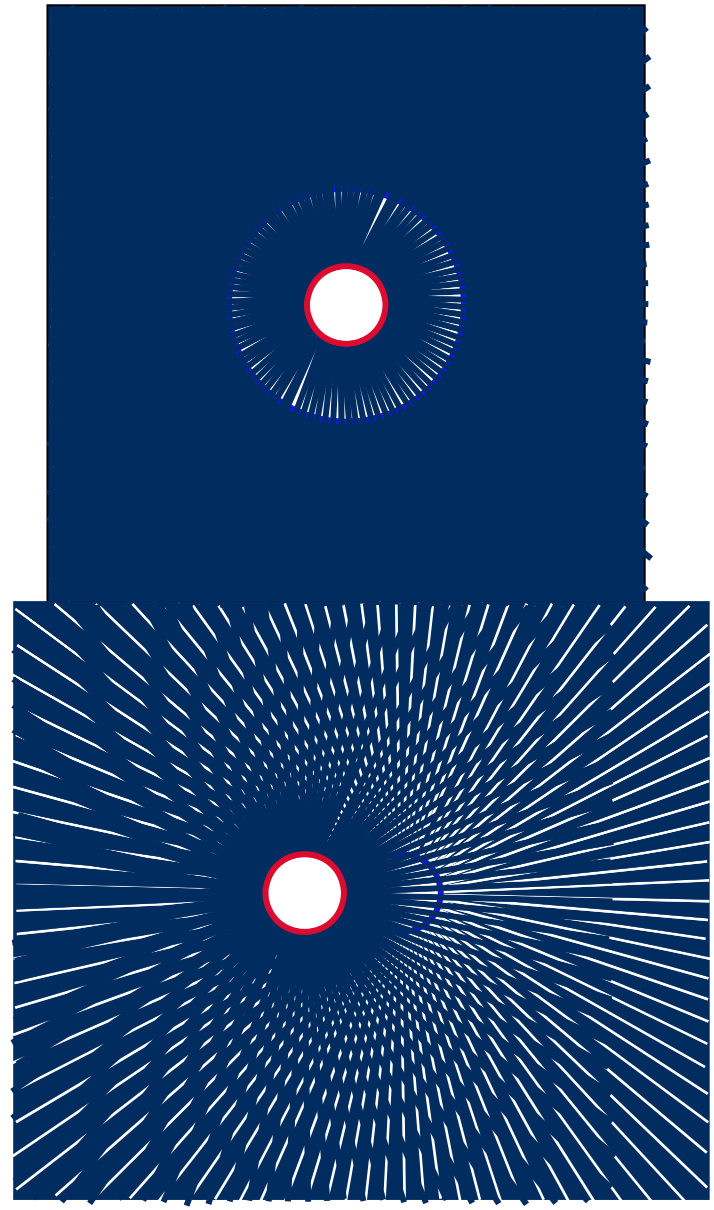
"Pig-tails" Destroy Good Coax Properties

effect of geometry changes: fields outside interconnections; CM currents

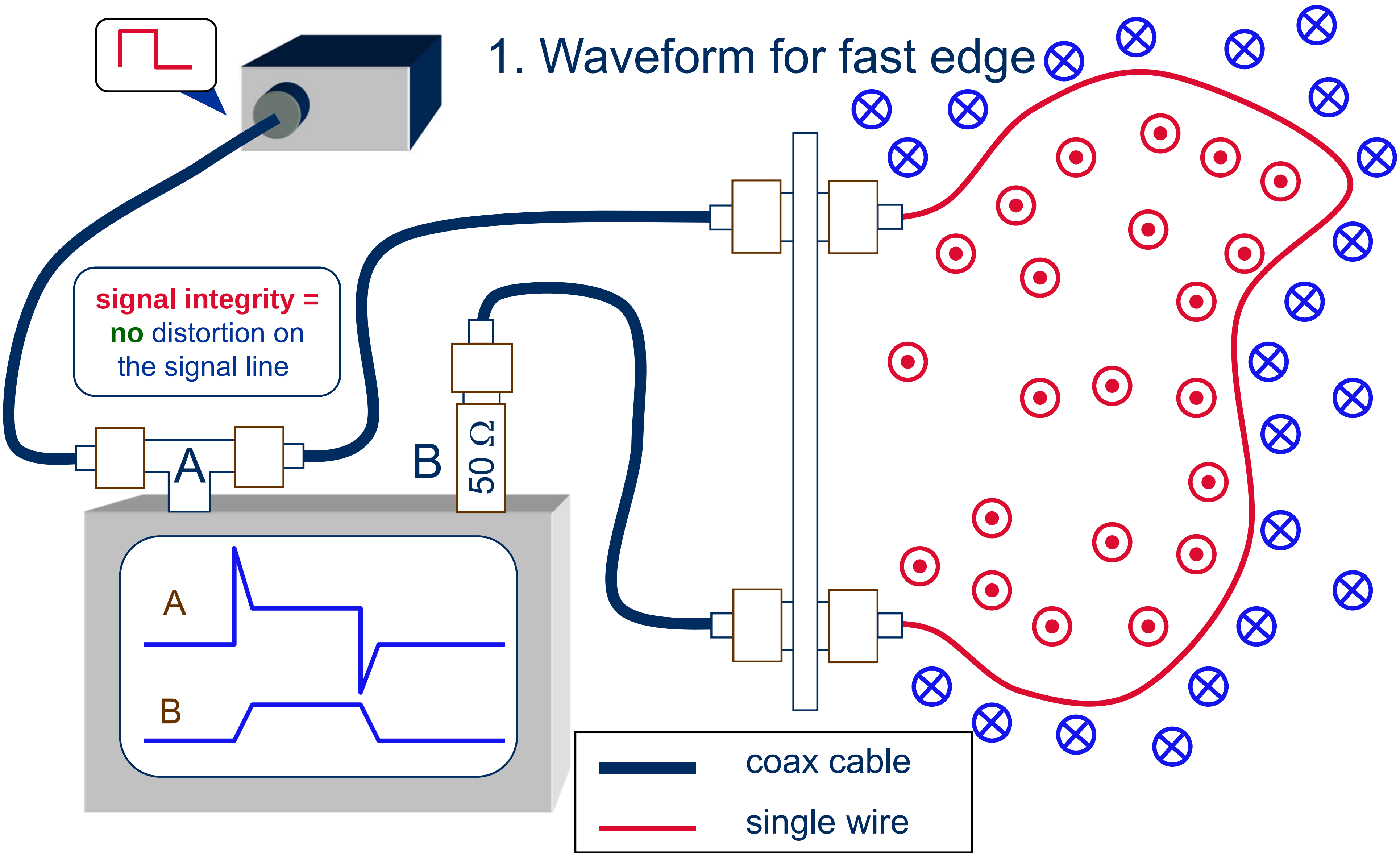




Coax

Twin wires

current in a conductor is only possible when a magnetic field exists



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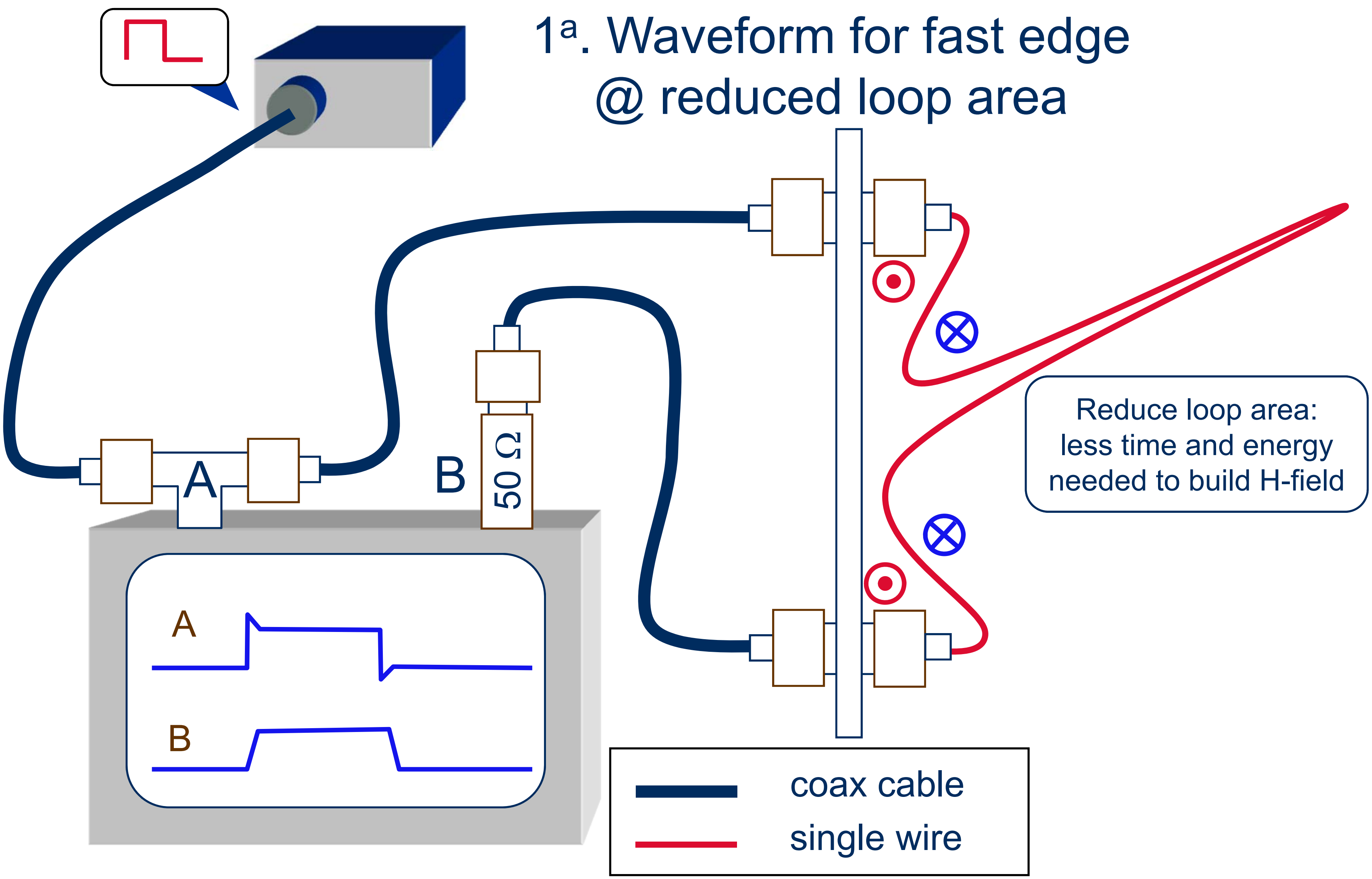
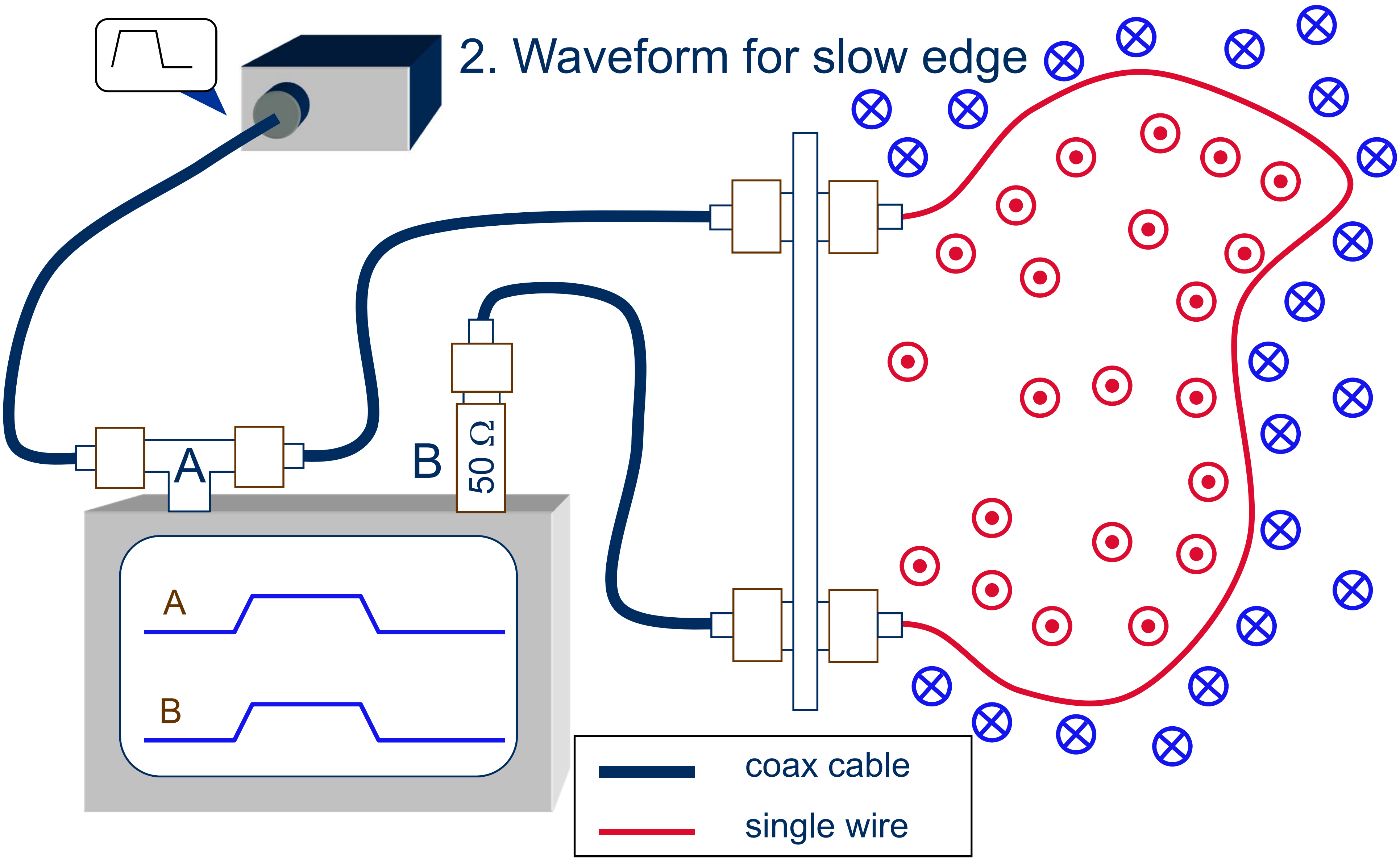
current in a conductor is only possible when magnetic field exists

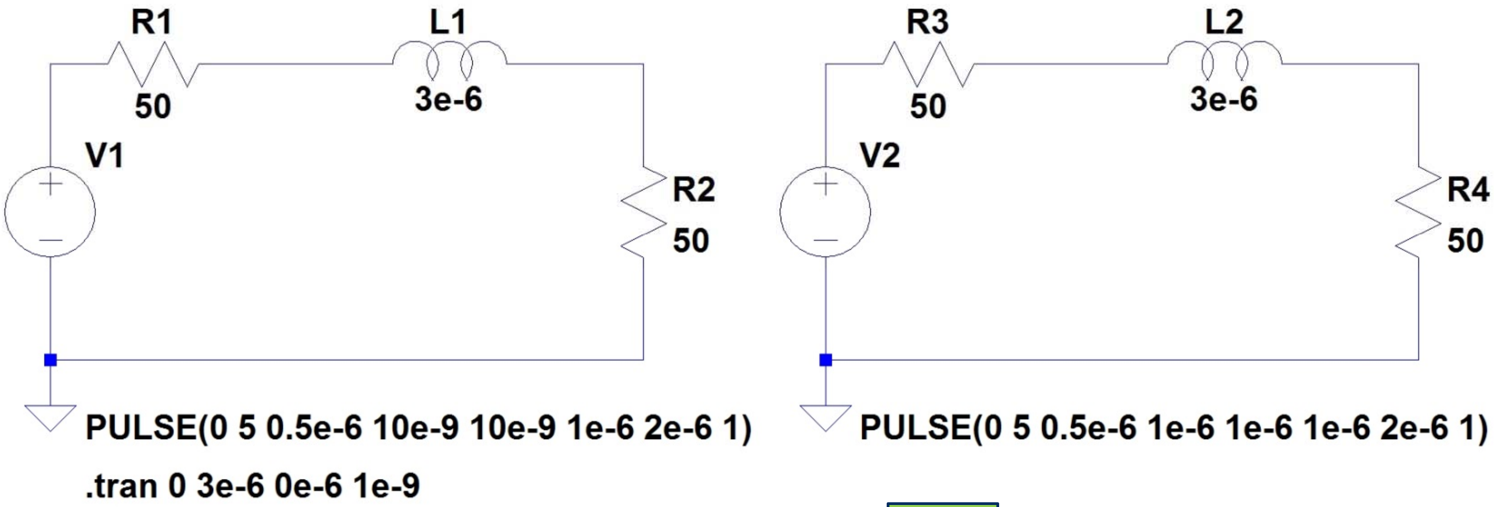


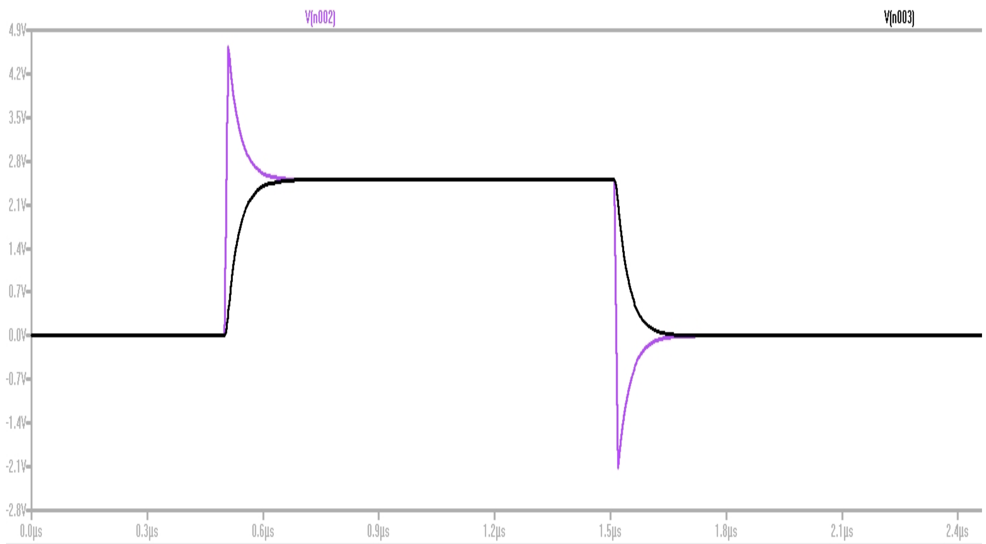
current in a conductor is only possible when magnetic field exists

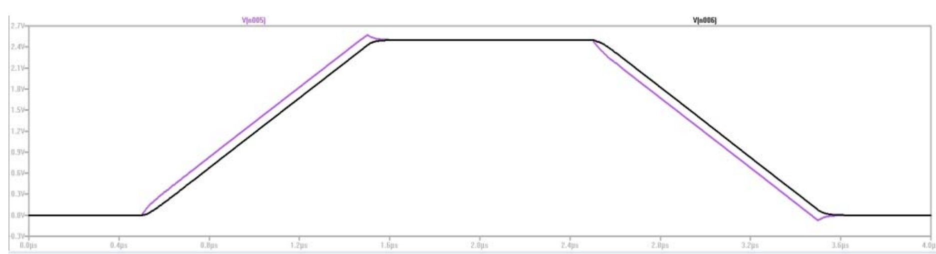


Simulation of Wire Inductance Demonstration

in LTSpice IV

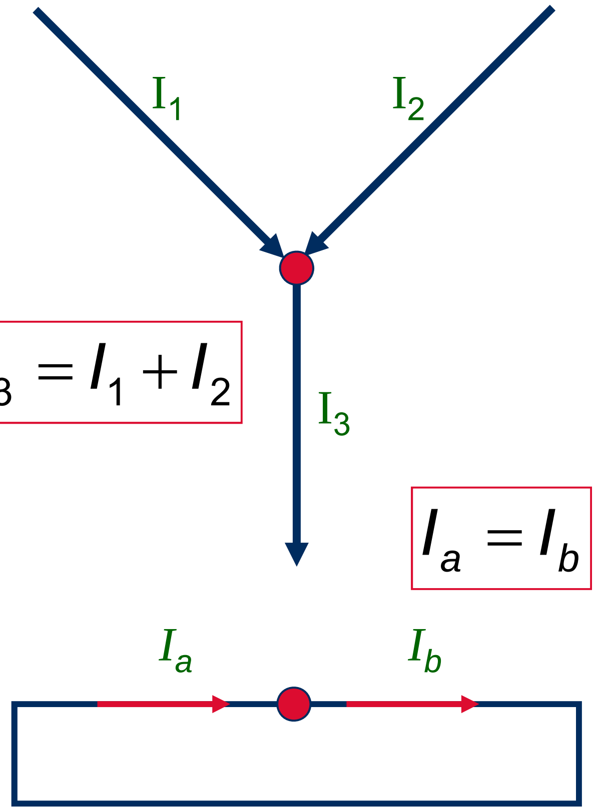






Kirchhoffs Current Law: basic for the design of component networks

Kirchhoff’s electrical current law



$I_3 = I_1 + I_2$

$I_a = I_b$

Every current must have a return path!

As a Designer,

ask yourself:

Where does my

Return Current

Flow?

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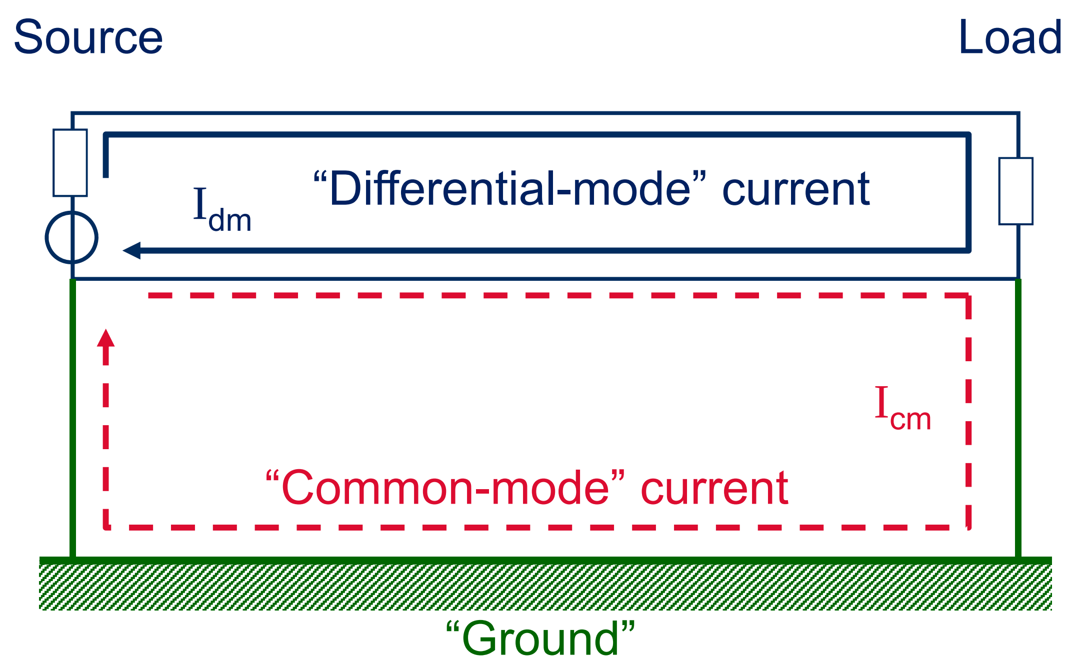
Common-mode currents dominate the EMC arena

currents, generated by cables' "desired currents" into CM or ground-loop



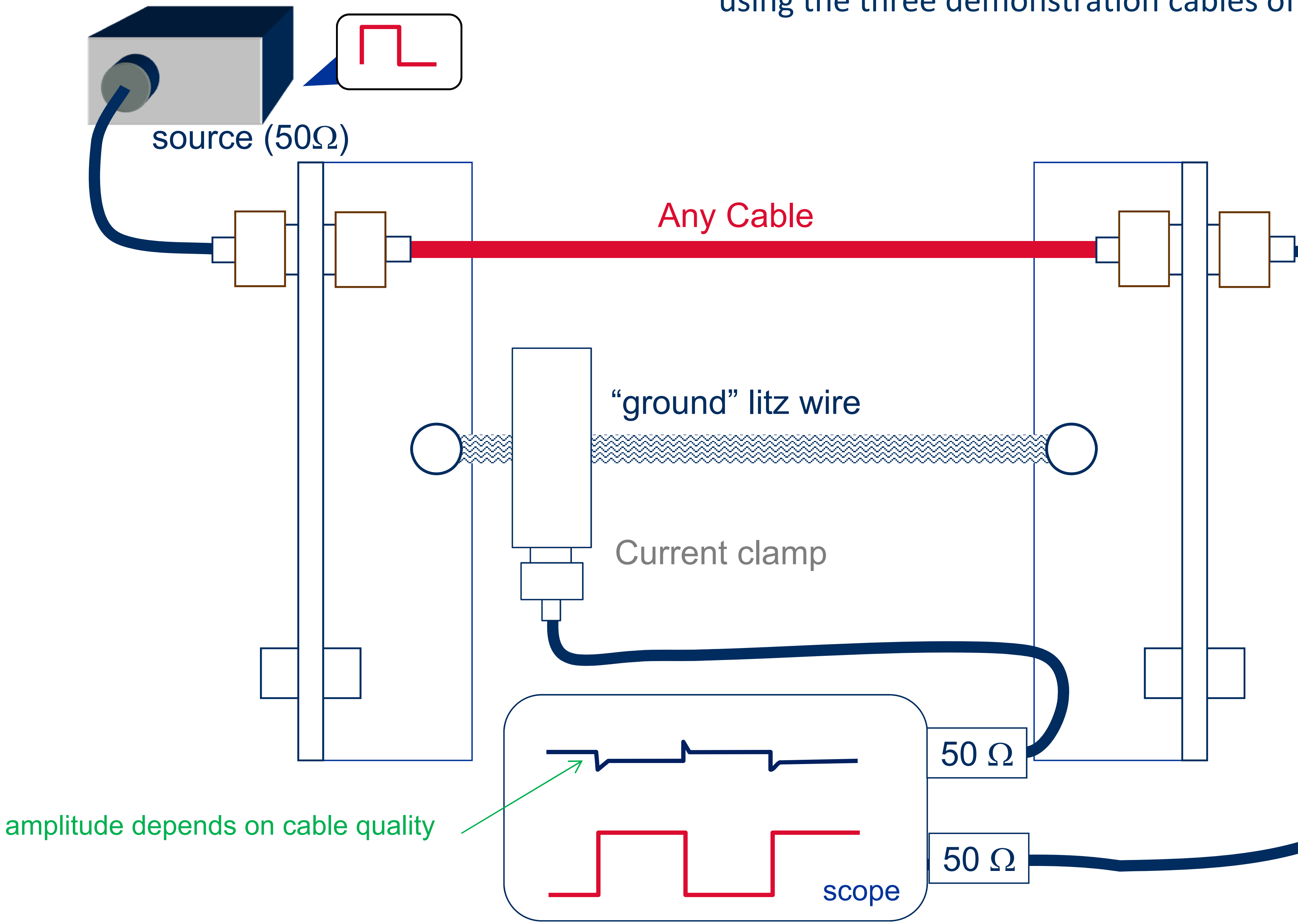
CM: **99%** of all EMI problems!

Common-mode current is that part of the return current which follows a different path than the designers intended route

CM-currents can be created "elsewhere"

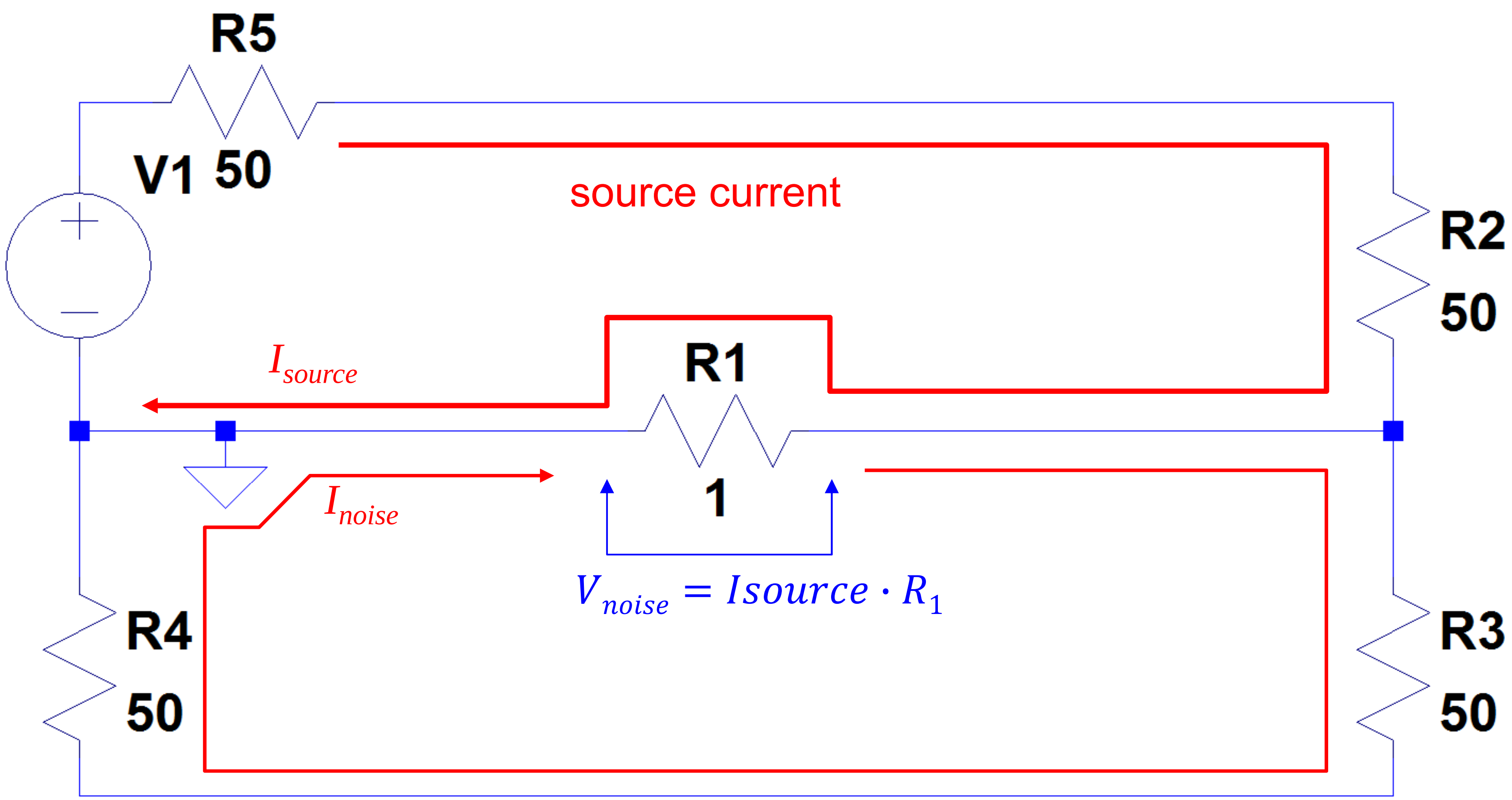
Demonstration of the Common Mode Current

using the three demonstration cables of slide 1

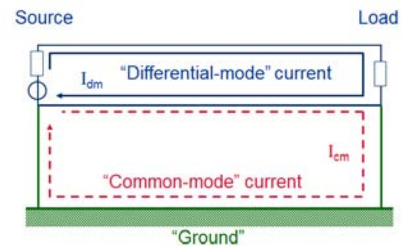


"Common-Resistance" Crosstalk

resistance in the common return path of two loops (SPICE model)

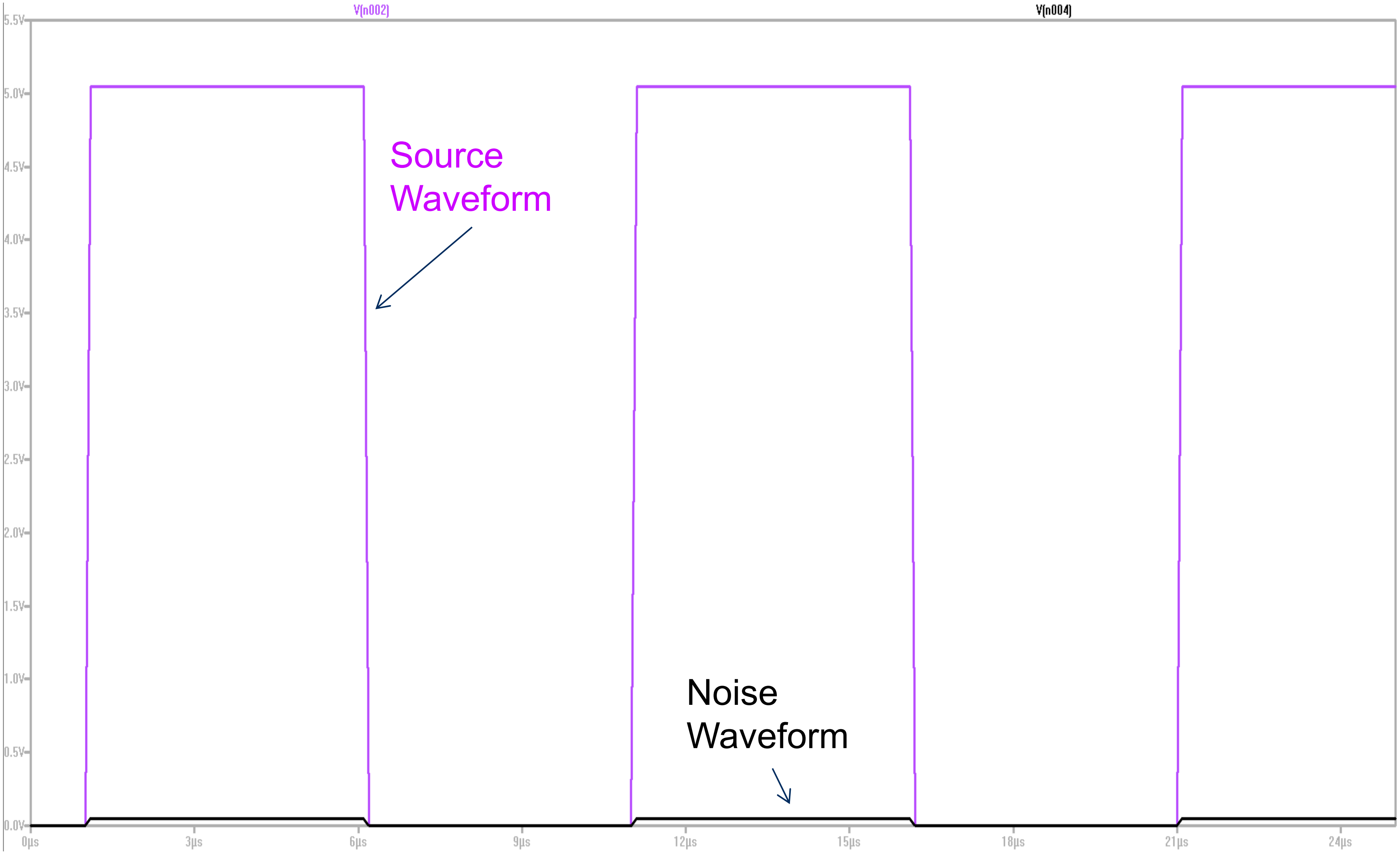


PULSE(0 10 1e-6 100e-9 100e-9 5e-6 10e-6 5)
.tran 0 25e-6 0 1e-8



Resistive Crosstalk Waveform

linear operation: noise signal shape is identical to source waveform



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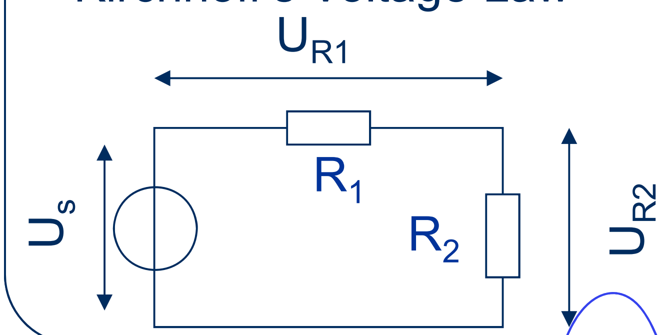
assumes all fields are *inside* the circuits components

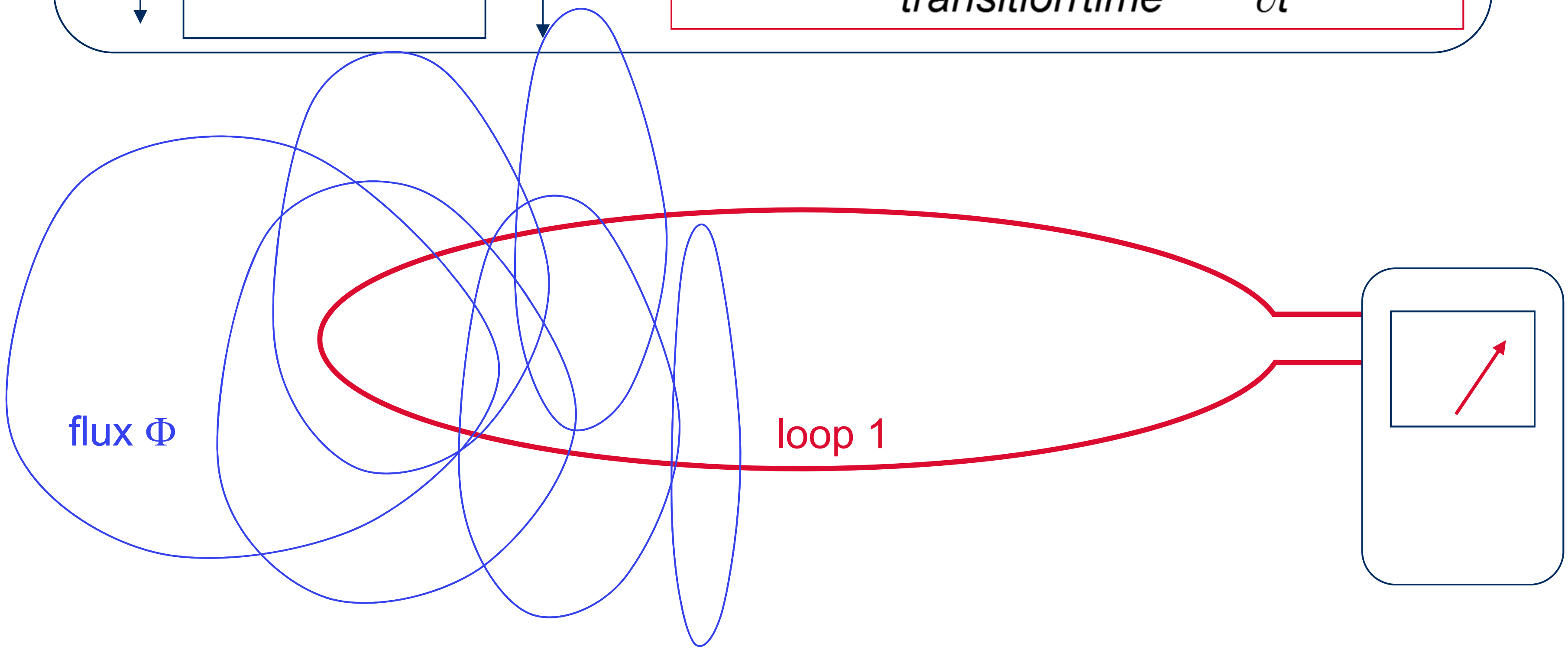
Kirchhoff's Voltage Law



$$U_S + U_{R1} + U_{R2} = 0 \leftarrow ?$$

Faraday's Law:

$$Voltage = -\frac{flux\ change}{transition\ time} = -\frac{\partial \Phi}{\partial t} = -j\omega\Phi$$



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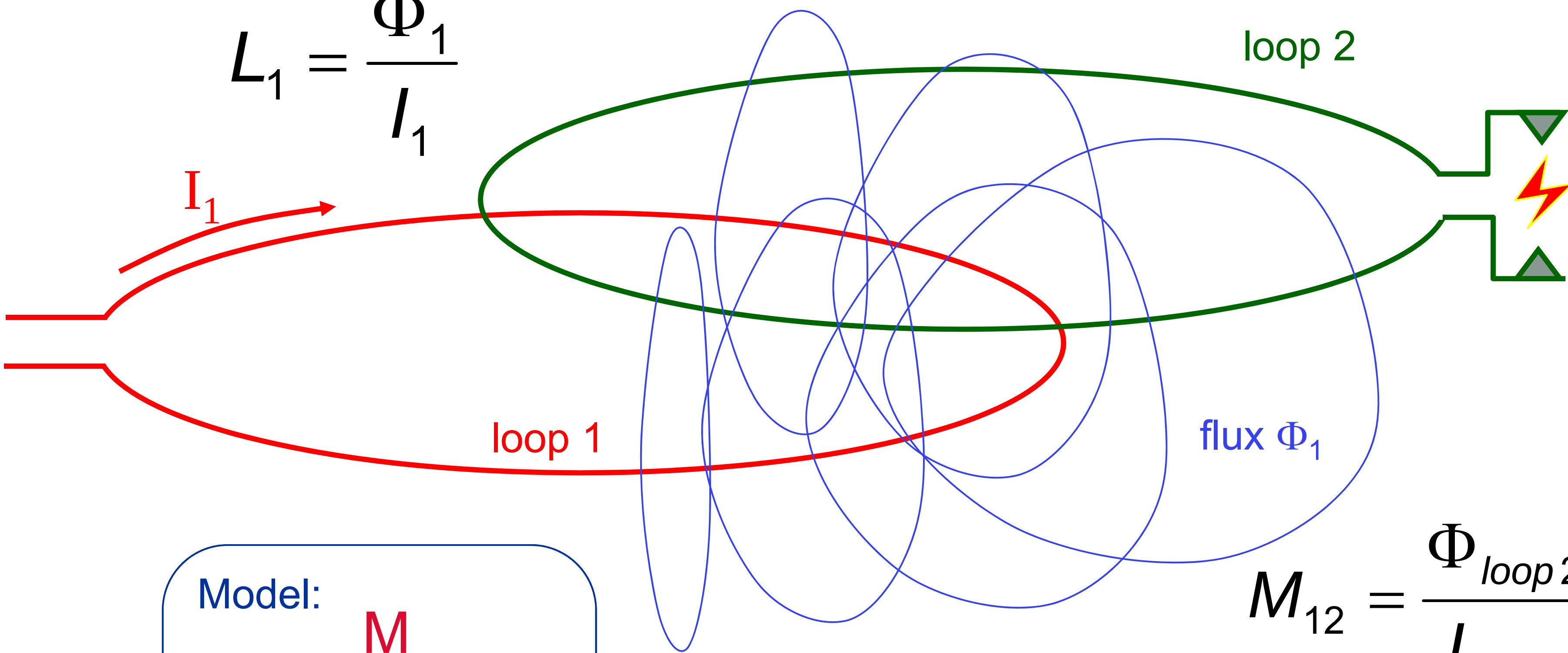
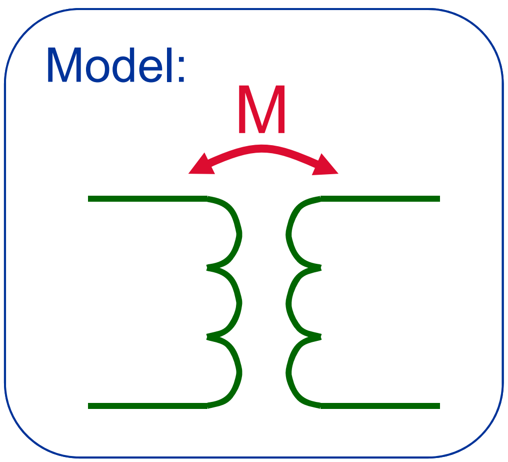
Mutual induction: coupling of circuits (loops)

Field loop 1 induces voltage in loop 2 (“Crosstalk”- or: transformer)

$$L_1 = \frac{\Phi_1}{I_1}$$



$$M_{12} = \frac{\Phi_{loop\,2}}{I_{loop\,1}}$$



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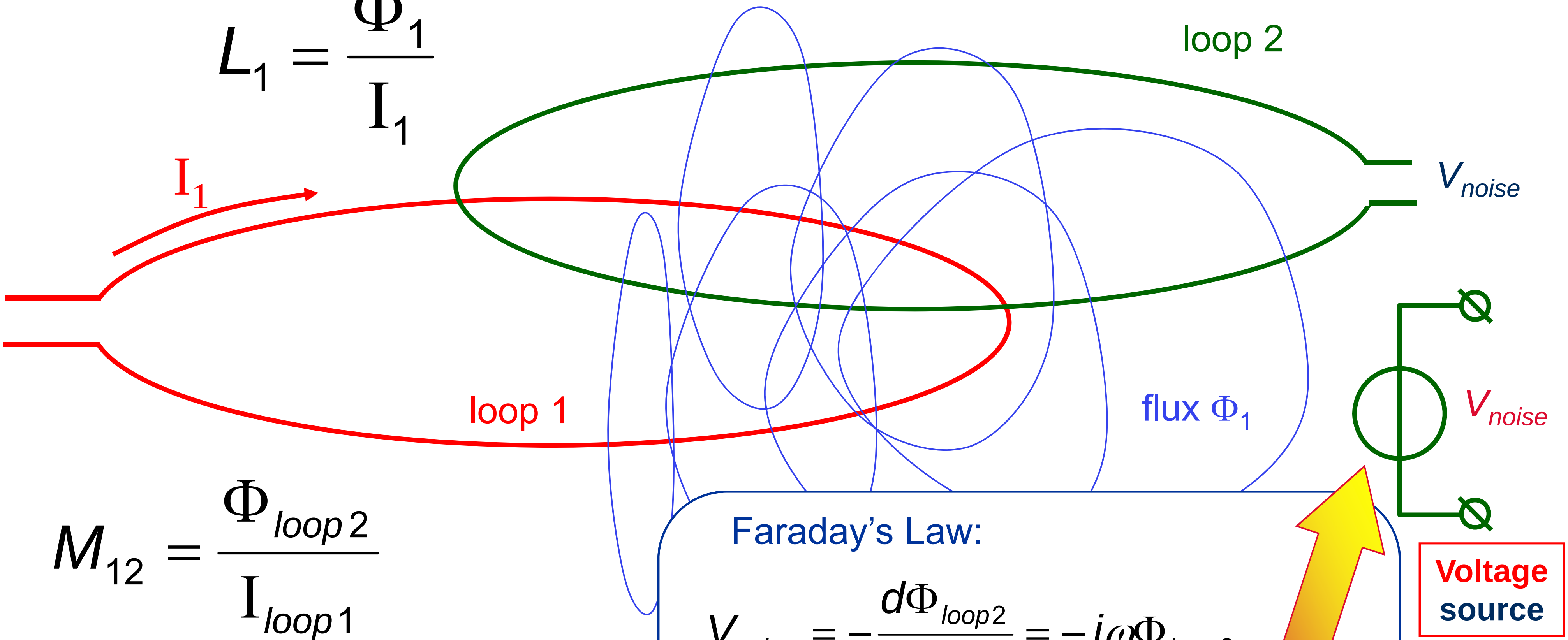
Substitute source model for inductive crosstalk

Faraday's Law expressed in the time and frequency domain

$$L_1 = \frac{\Phi_1}{I_1}$$



$$M_{12} = \frac{\Phi_{loop\,2}}{I_{loop\,1}}$$

$$\Phi_{loop\,2} = M_{12} \cdot I_{loop\,1}$$

Note: capacitive model yields current source

Faraday's Law:

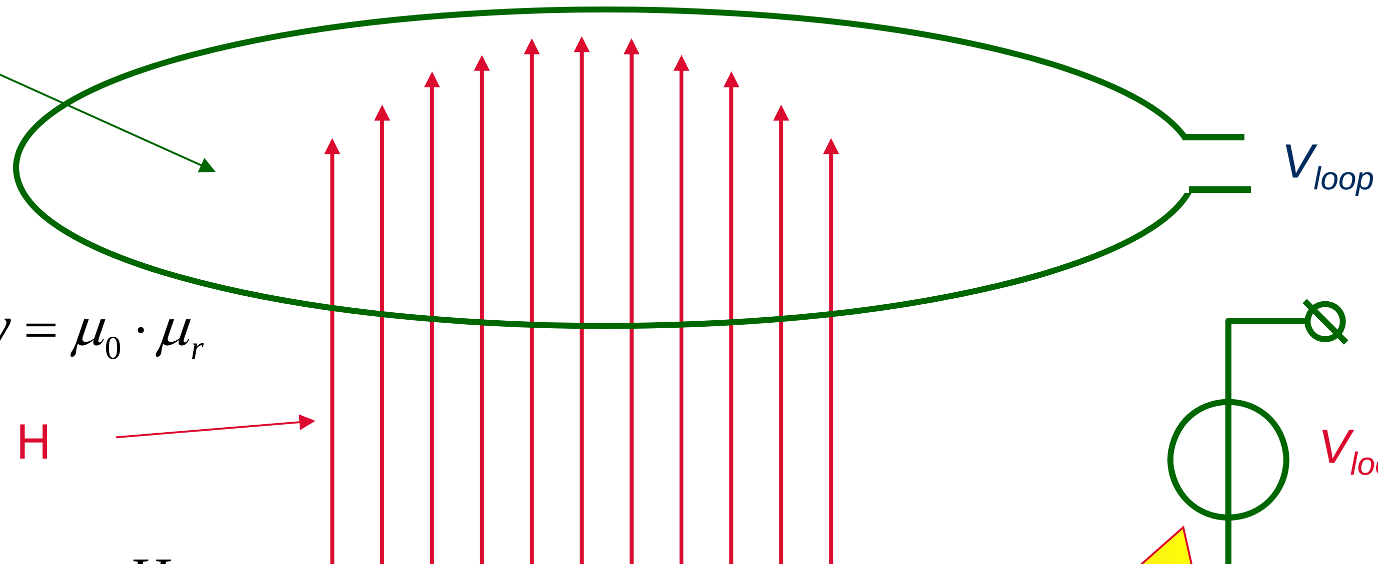
$$V_{noise} = -\frac{d\Phi_{loop2}}{dt} = -j\omega\Phi_{loop2}$$

or

$$V_{noise} = -\frac{dM_{12} \cdot I_{loop1}}{dt} = -j\omega M_{12} \cdot I_{loop1}$$

Substitute source model for inductive probes

Faraday's Law for a Loop Probe



$$Medium\ Permeability = \mu_0 \cdot \mu_r$$

$$Flux\ Density = B = \mu_0 \cdot \mu_r \cdot H$$

$$\mu_{r,air} = 1 \quad \mu_0 = 4\pi \cdot 10^{-7} \left[\frac{H}{m}\right]$$

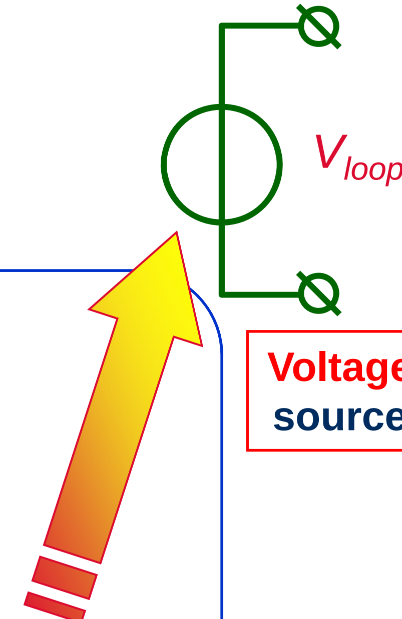
$$Flux = \Phi_{loop} = B \cdot A_{loop}$$

Faraday's Law:

$$V_{loop} = -\frac{d\Phi_{loop}}{dt} = -j\omega\Phi_{loop}$$

or

$$V_{loop} = -\frac{d\mu \cdot H \cdot A_{loop}}{dt} = -j\omega\mu \cdot H \cdot A_{loop}$$



Voltage source

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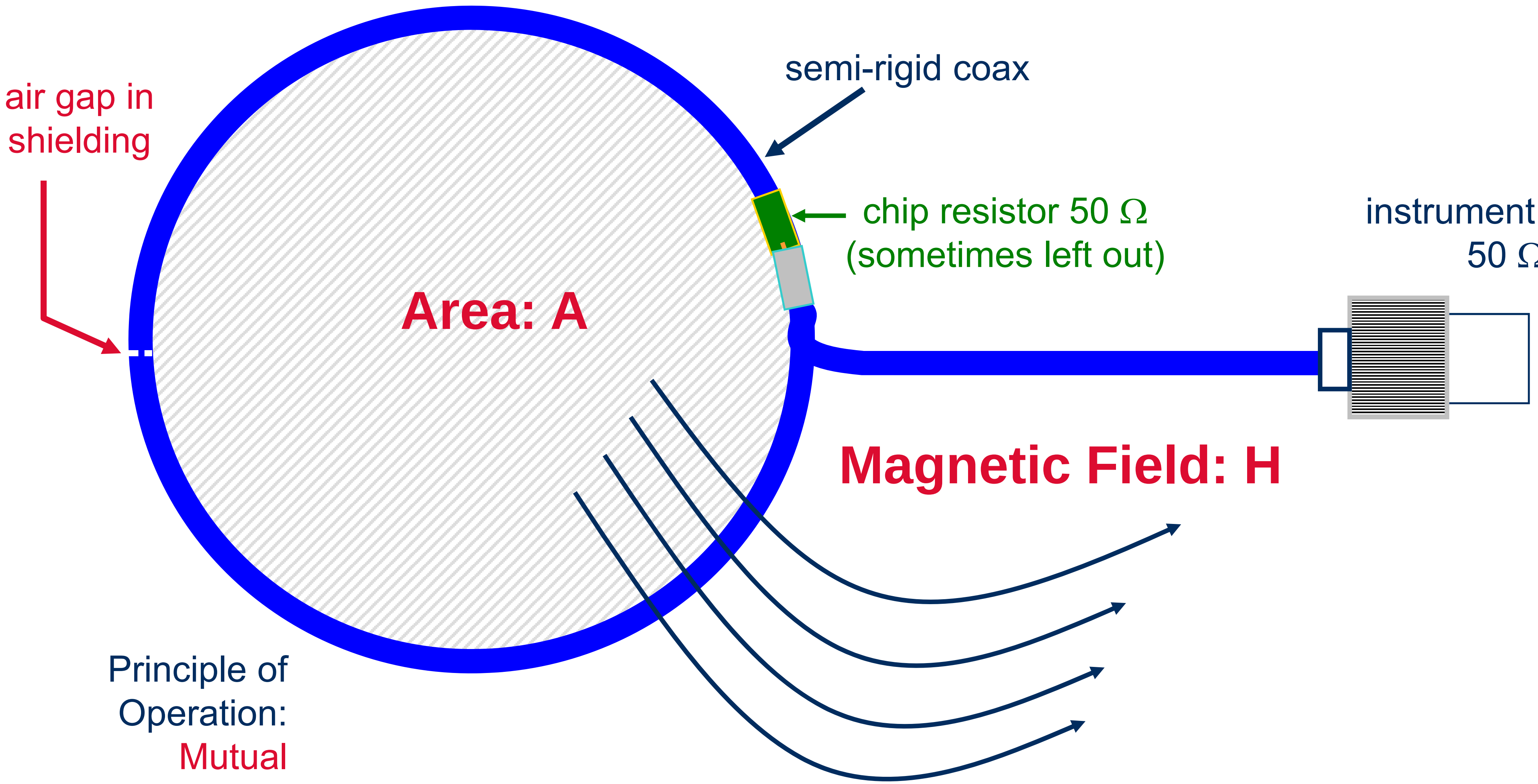
Inductive probe for Magnetic Fields: the Model

derivation using a substitute voltage source



Principle of Operation:
Mutual Induction

$$Flux\ Density = B = \mu \cdot H$$

$$Coupled\ \ Flux = \Phi = B \cdot A$$

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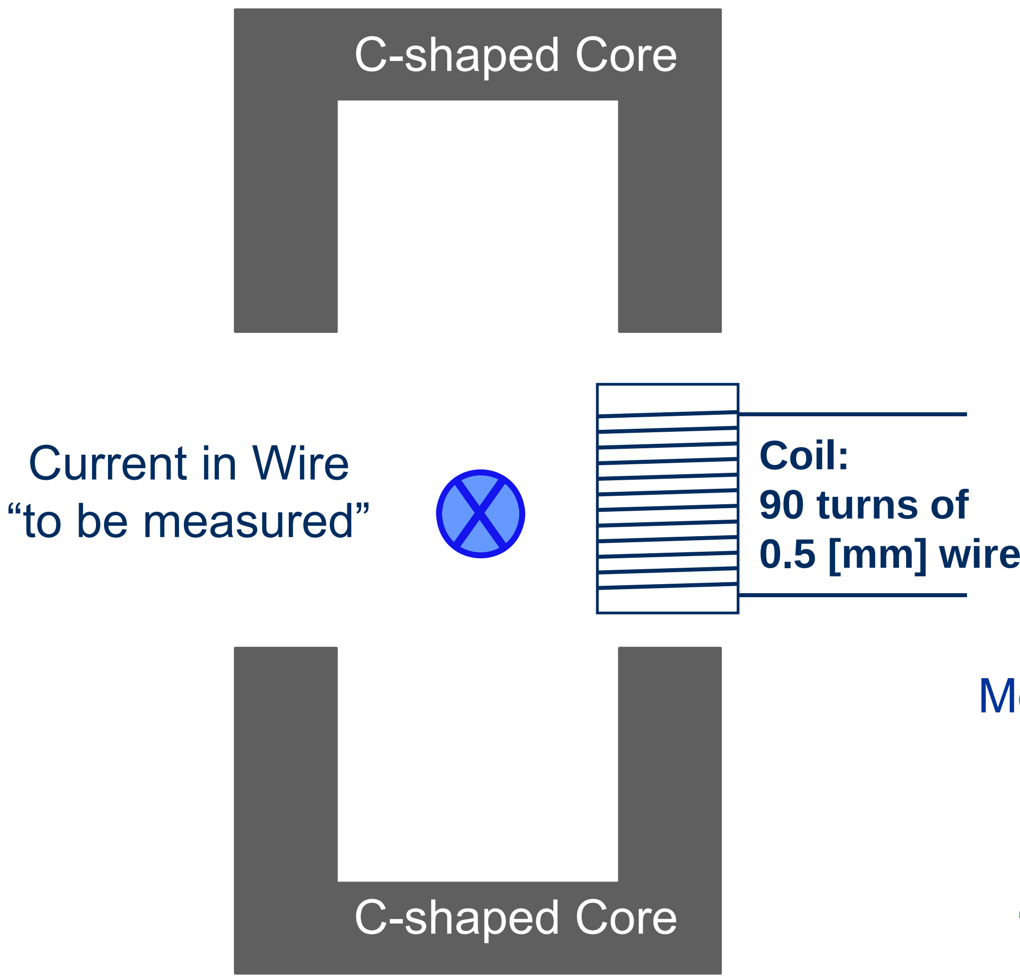
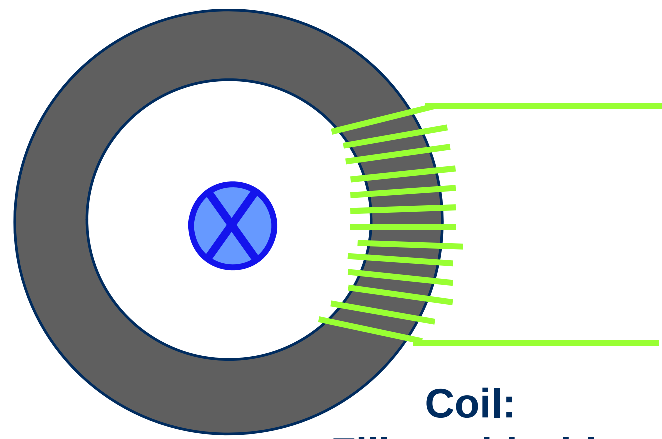
Alternative Shape: Current Clamps/Probes

current clamps use ferrite cores to guide magnetic field through coil



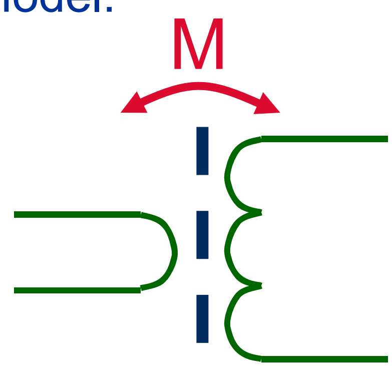
Both cores are clamped together around the current conductor to be measured

Conductor/Current to be measured must be led through toroid



Coil:
Fill toroid with wire turns
(Most sensitive)

Model:



Principle of Operation: Mutual Induction

$$Coupled\ \ Flux = M \cdot I$$

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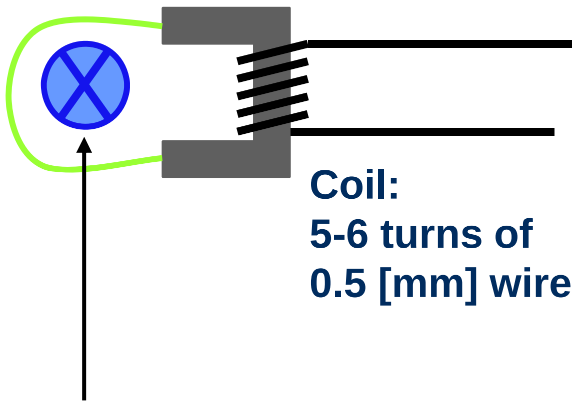
Small Magnetic Sniffer Probe

5-turn loop probe using ferrite to concentrate flux lines



Usable for lower frequencies:
- more sensitive than single loop probe
- ferrite concentrates magnetic field lines

Note for Loop and Sniffer Probe

The probe output voltage is proportional to $\frac{\partial B}{\partial t}$ or $\dot{B}$

Hence, the MIL-STD-461 calls it a “B-dot” probe

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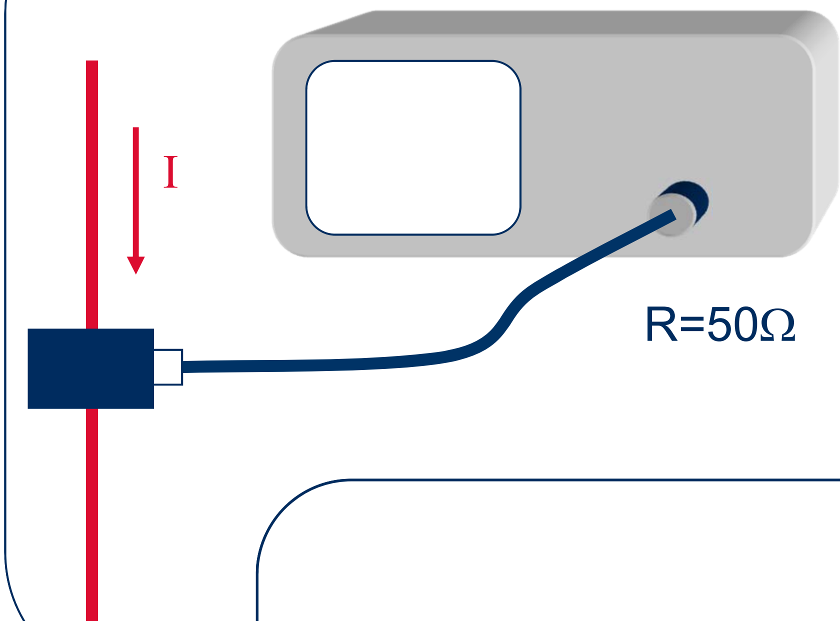
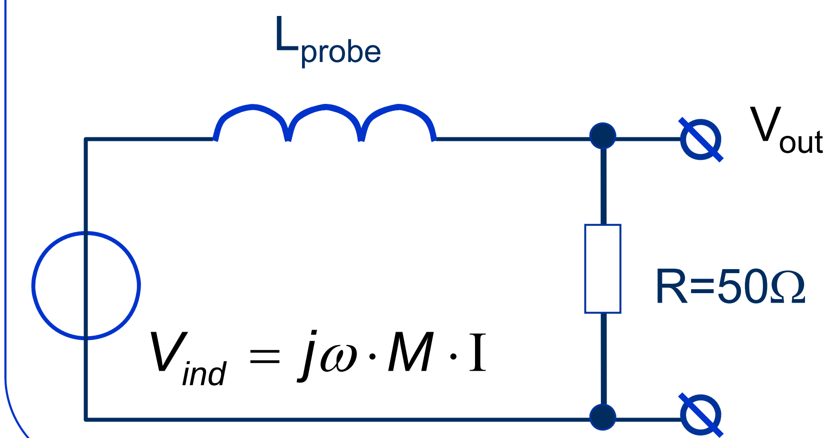
derivation using a substitute voltage source

Measurement setup:



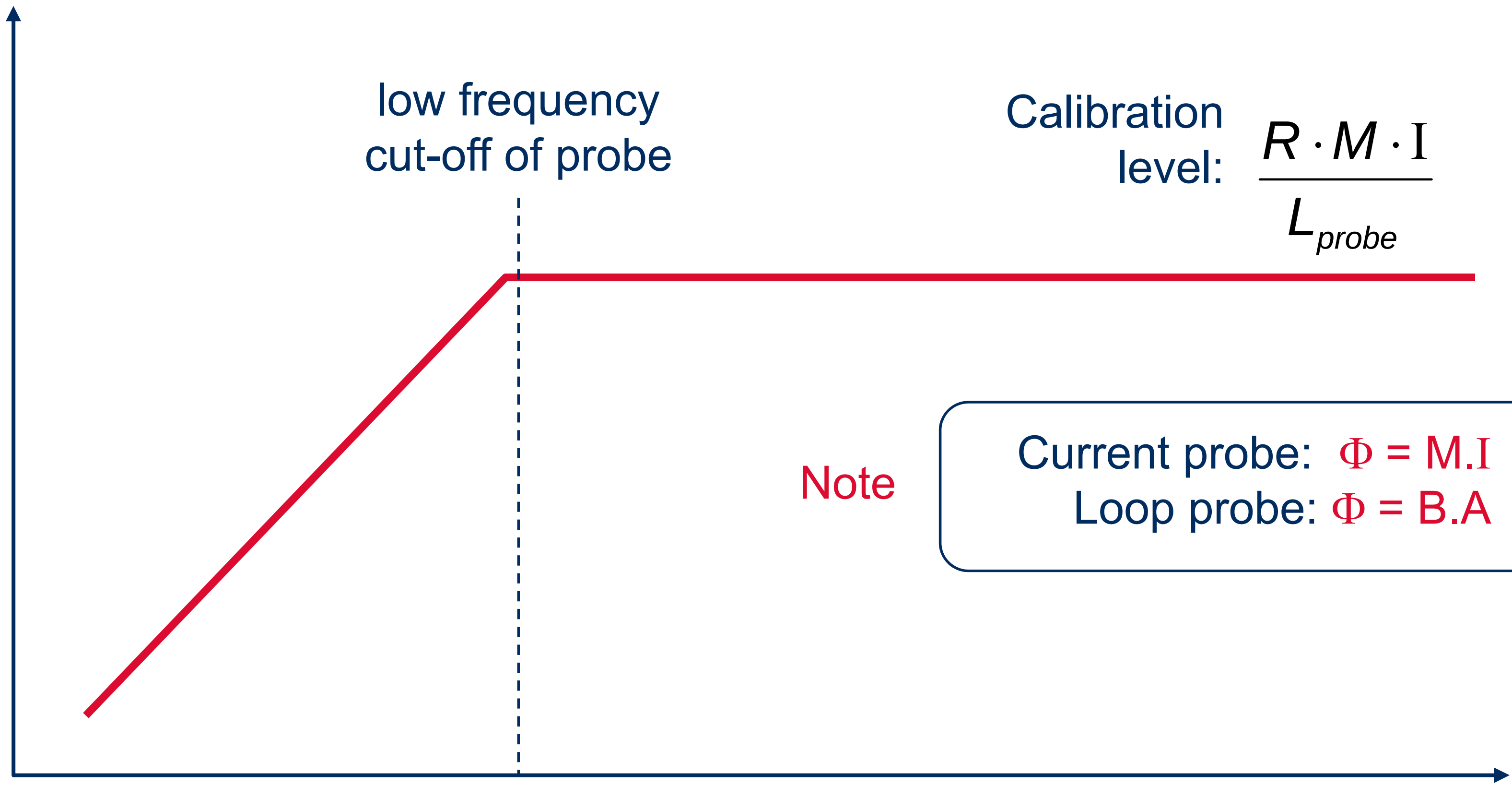
Equivalent circuit diagram:



$$V_{out} = j\omega \cdot M \cdot I \cdot \frac{\frac{R}{L_{probe}}}{j\omega + \frac{R}{L_{probe}}} \begin{cases} \omega \ll \frac{R}{L_{probe}} & V_{out} = j\omega \cdot M \cdot I \\ \omega \gg \frac{R}{L_{probe}} & V_{out} = \frac{R}{L_{probe}} \cdot M \cdot I \end{cases}$$

Operation of the current probe

graphical representation of results



Note

Current probe: $\Phi = M.I$
Loop probe: $\Phi = B.A$

$$\omega_C = \frac{R}{L_{probe}}$$

R = 50 Ω
Measure L_{probe}
Calculate ω_C

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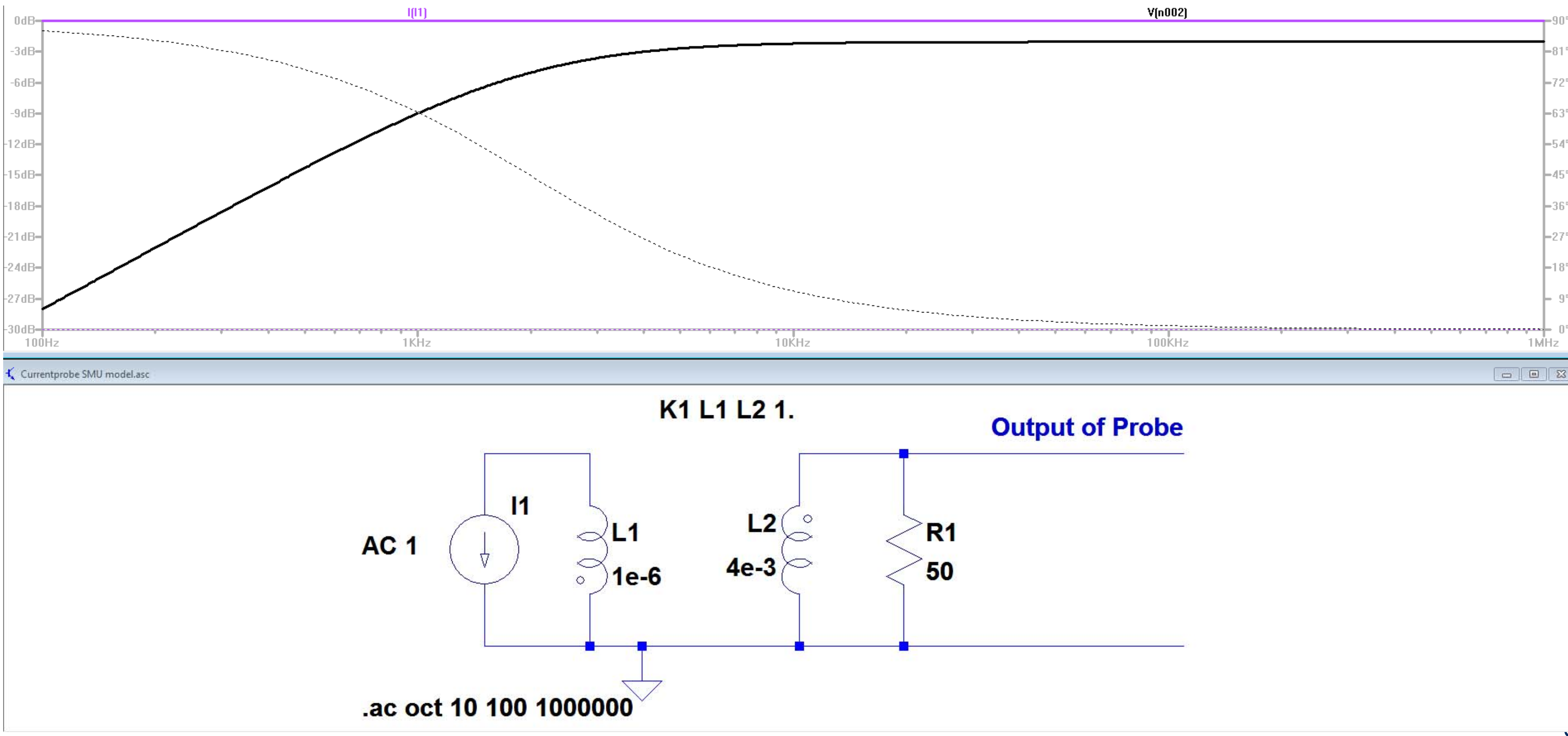
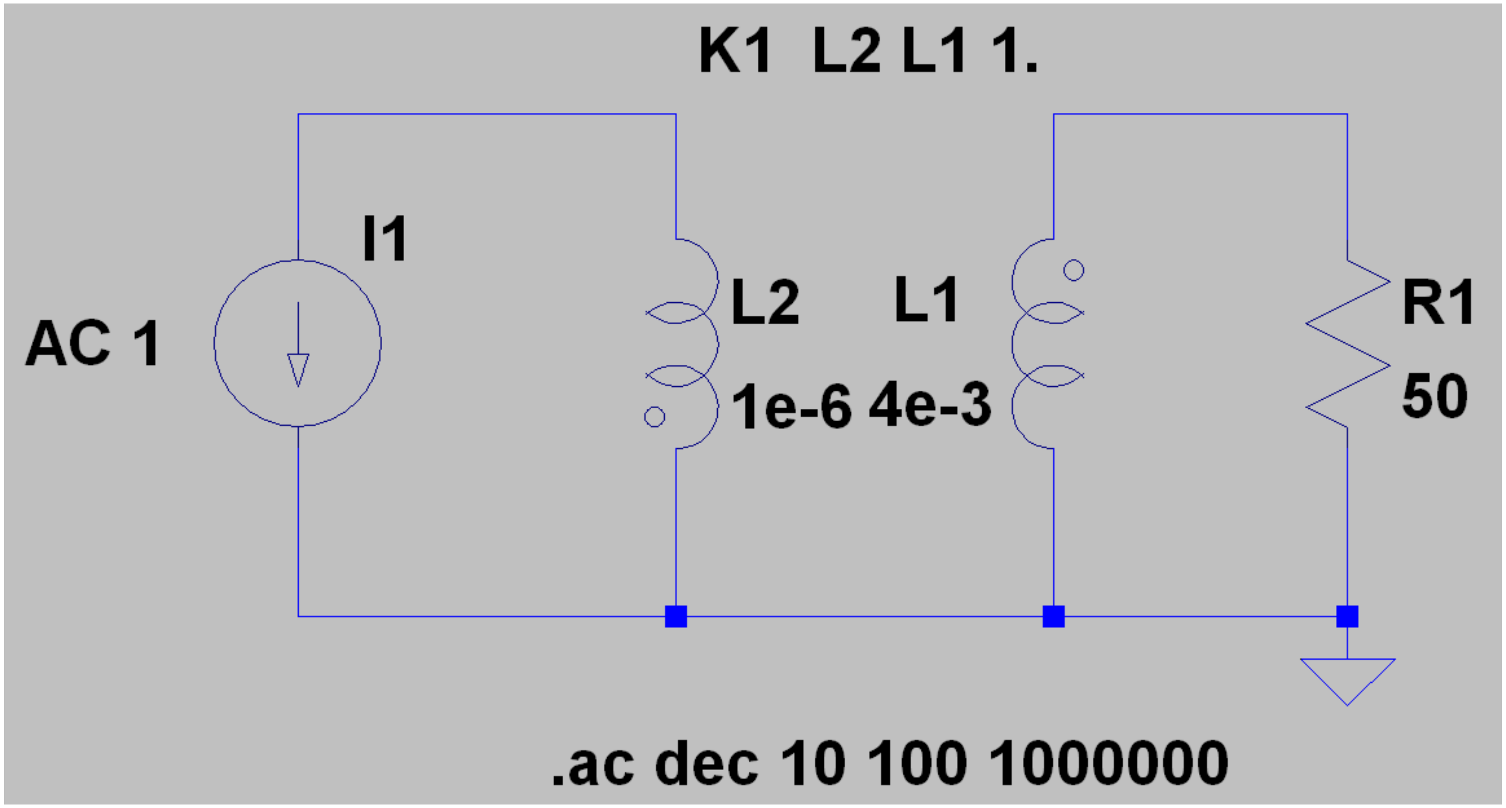
SPICE Simulation of an Inductive Probe

With LTSpice IV



model the frequency dependent source using a transformer

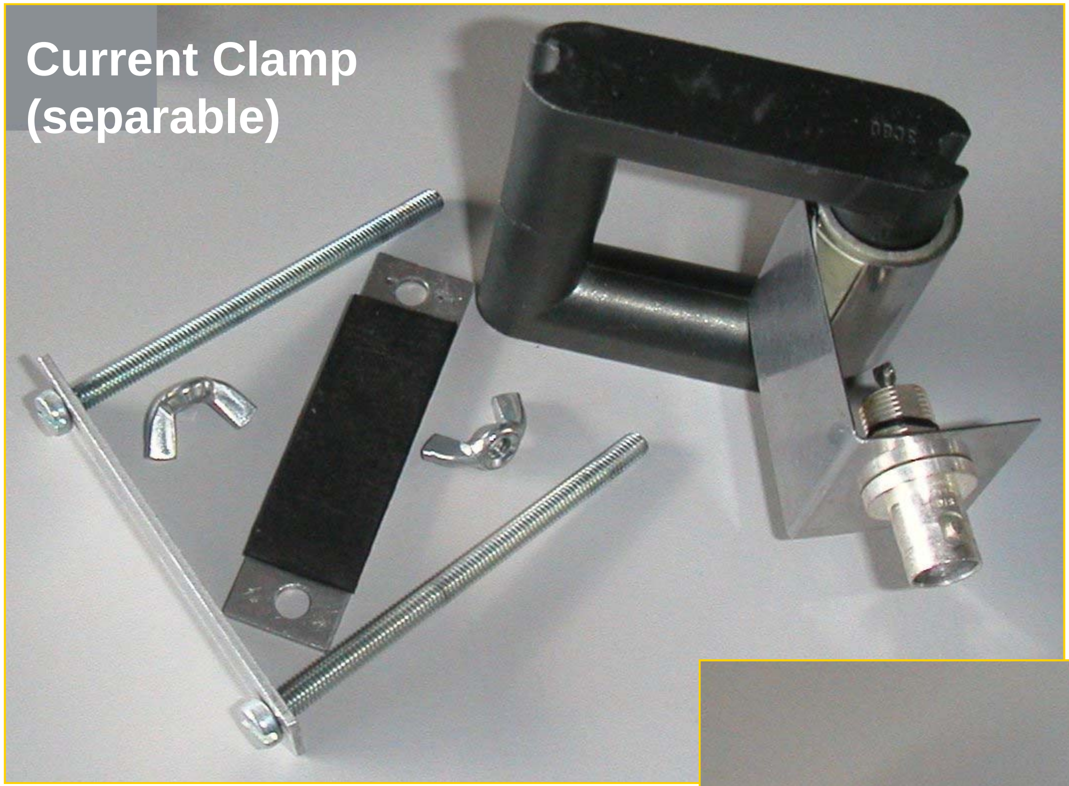


The source I1 is the "current to be measured", set as 1 Amp (no DC)

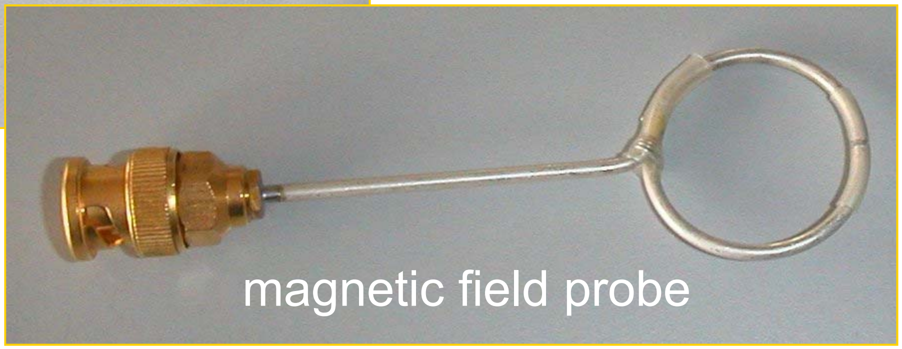
A transformer is used to model the "frequency dependent source"
Coupling Factor K1 = 1

Examples of “home made” magnetic field probes

useful if professional equipment is unavailable



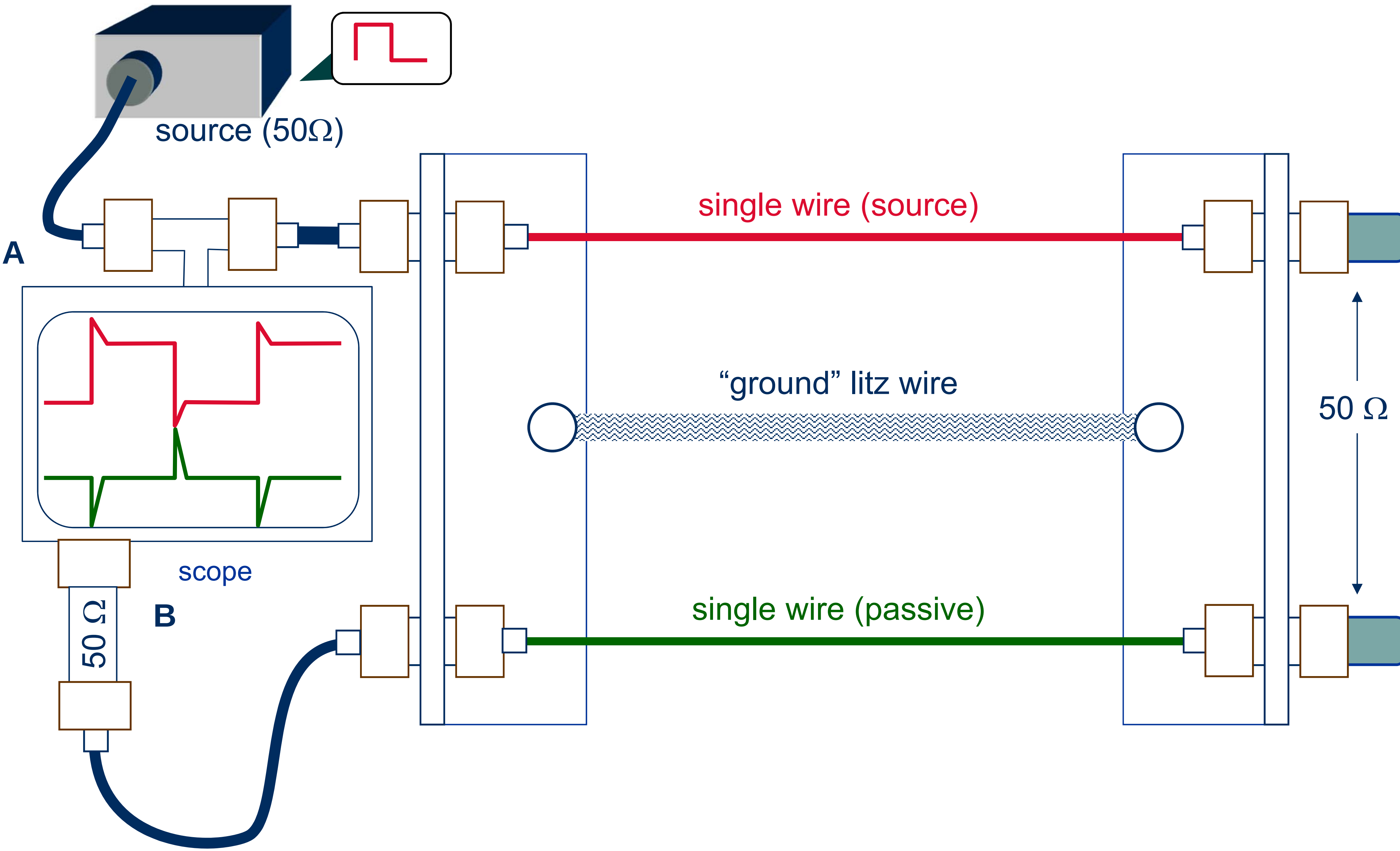
Current Clamp (fixed)



October 19, 2016

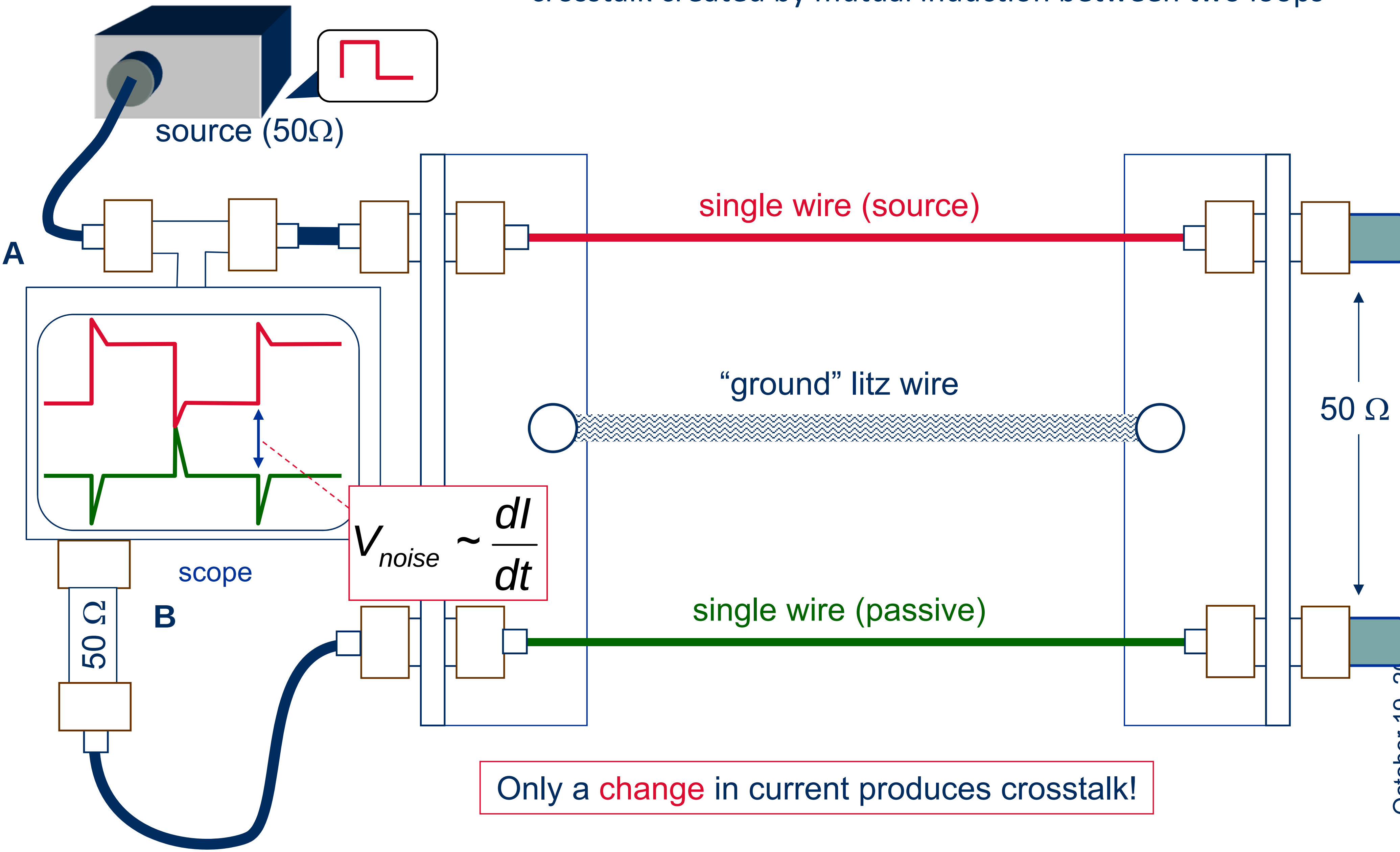
Mutual induction in practice

two circuits with a common return ("ground") conductor



Mutual induction in practice

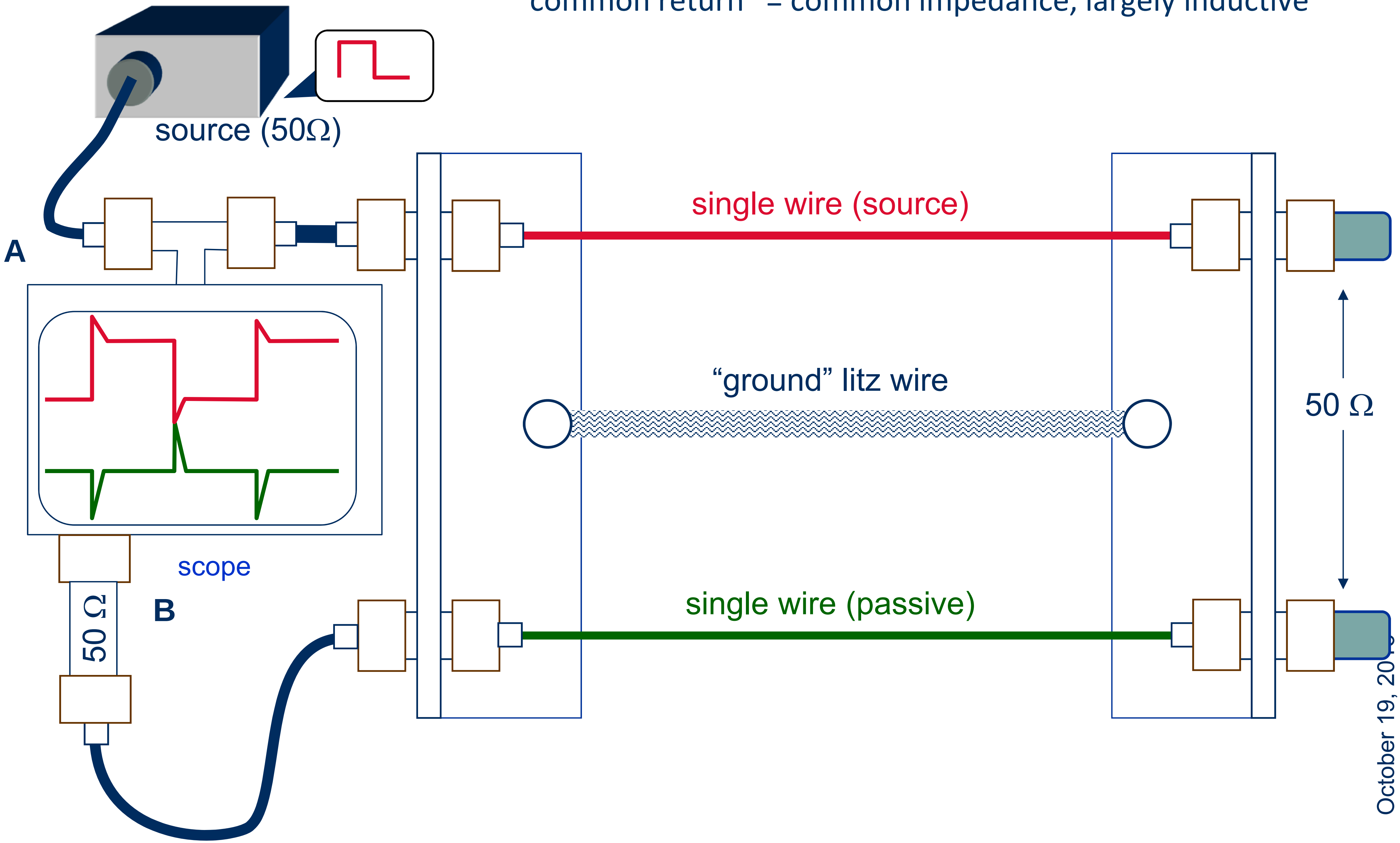
crosstalk created by mutual induction between two loops



Only a change in current produces crosstalk!

Mutual induction in practice

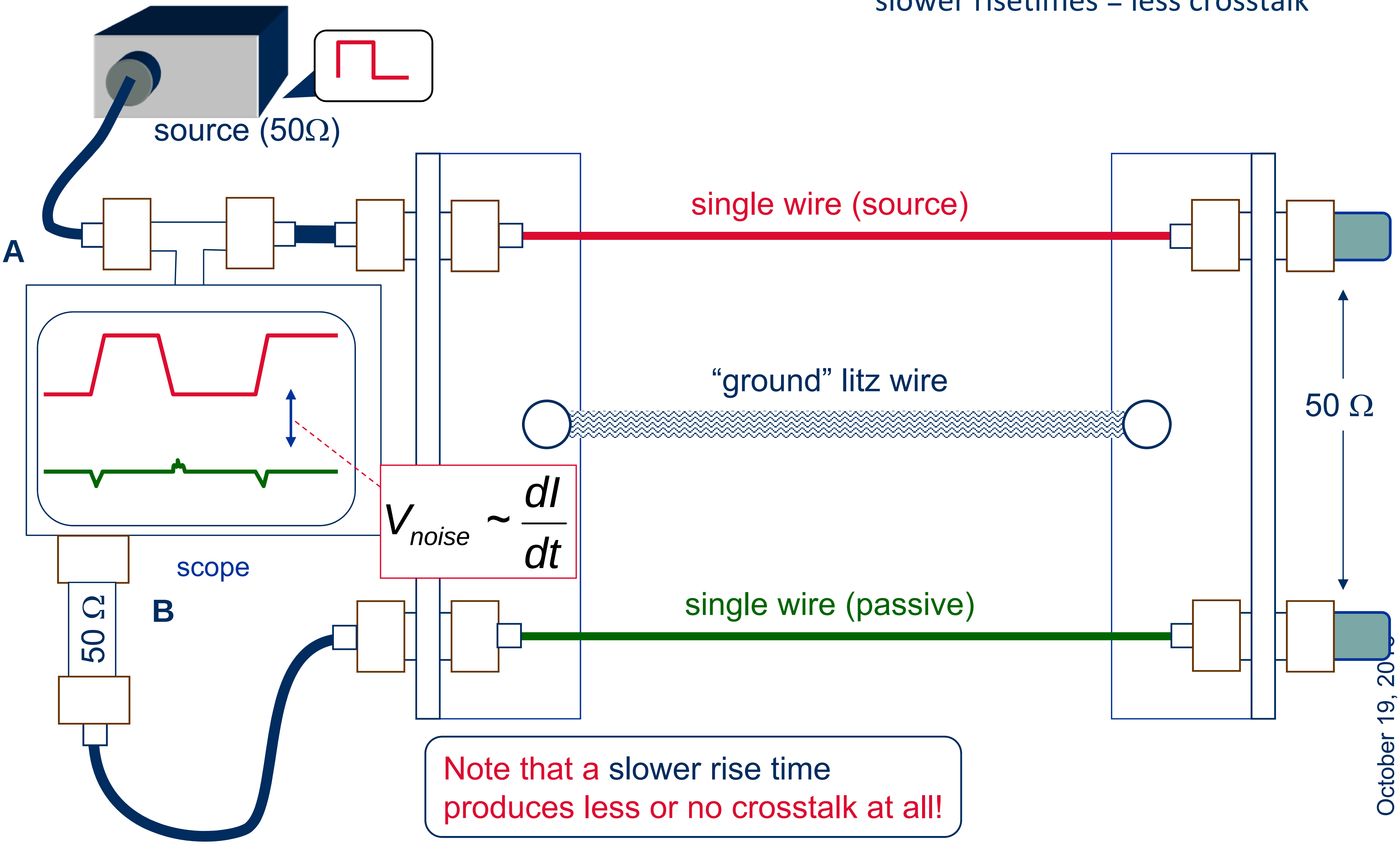
"common return" = common impedance, largely inductive



October 19, 20…

Mutual induction in practice

slower risetimes = less crosstalk

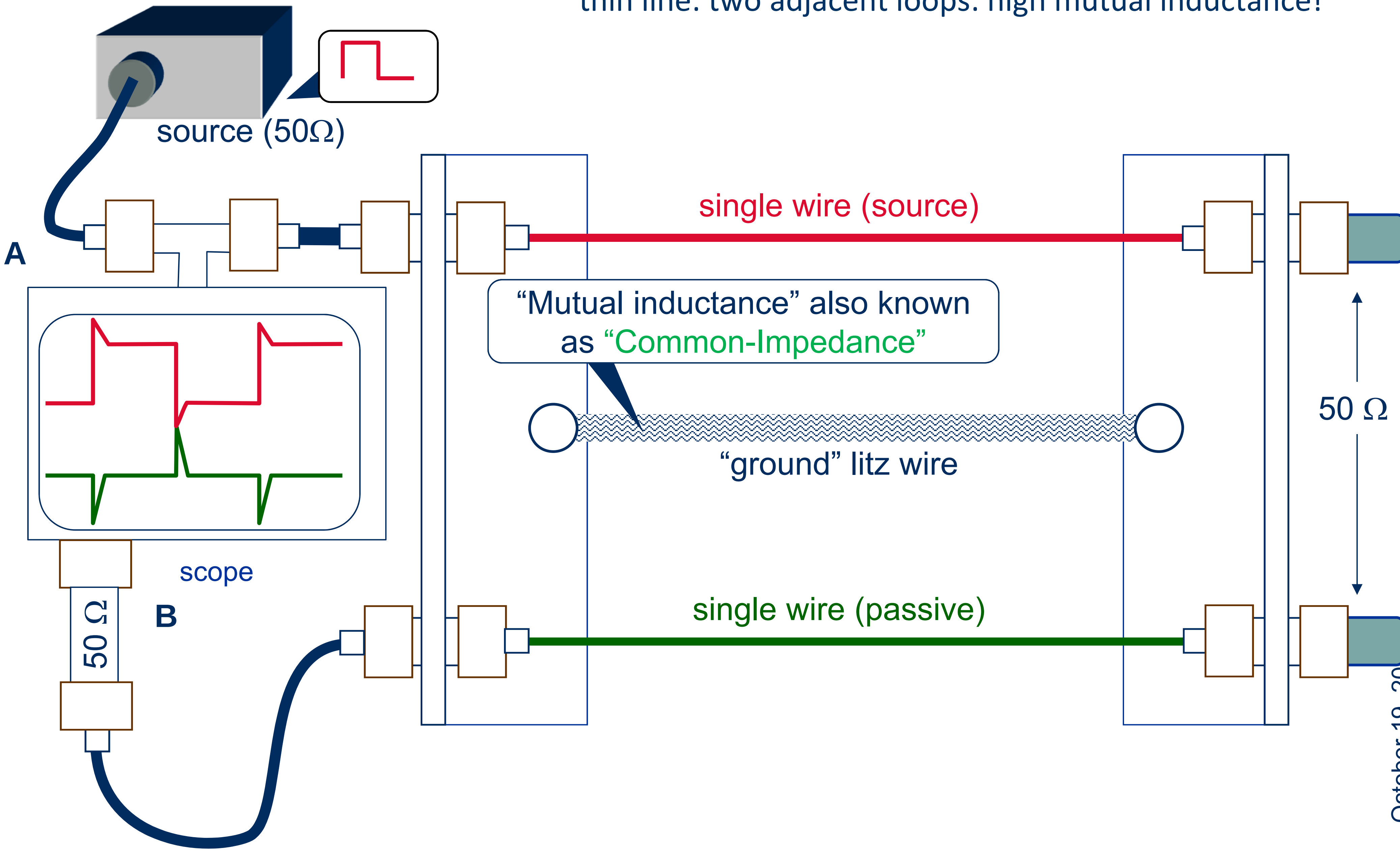


Note that a slower rise time produces less or no crosstalk at all!

October 19, 20

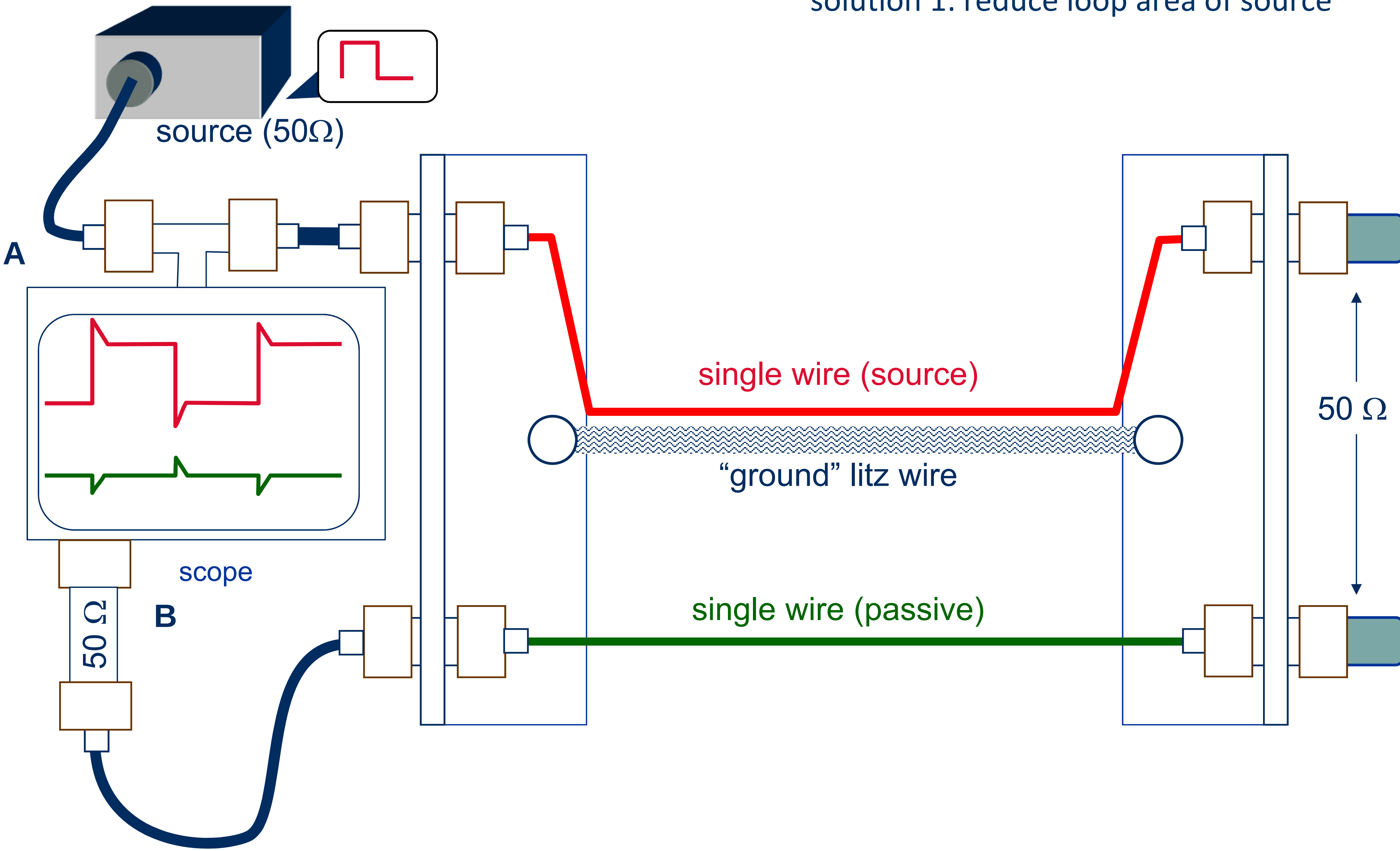
Mutual induction in practice

thin line: two adjacent loops: high mutual inductance!



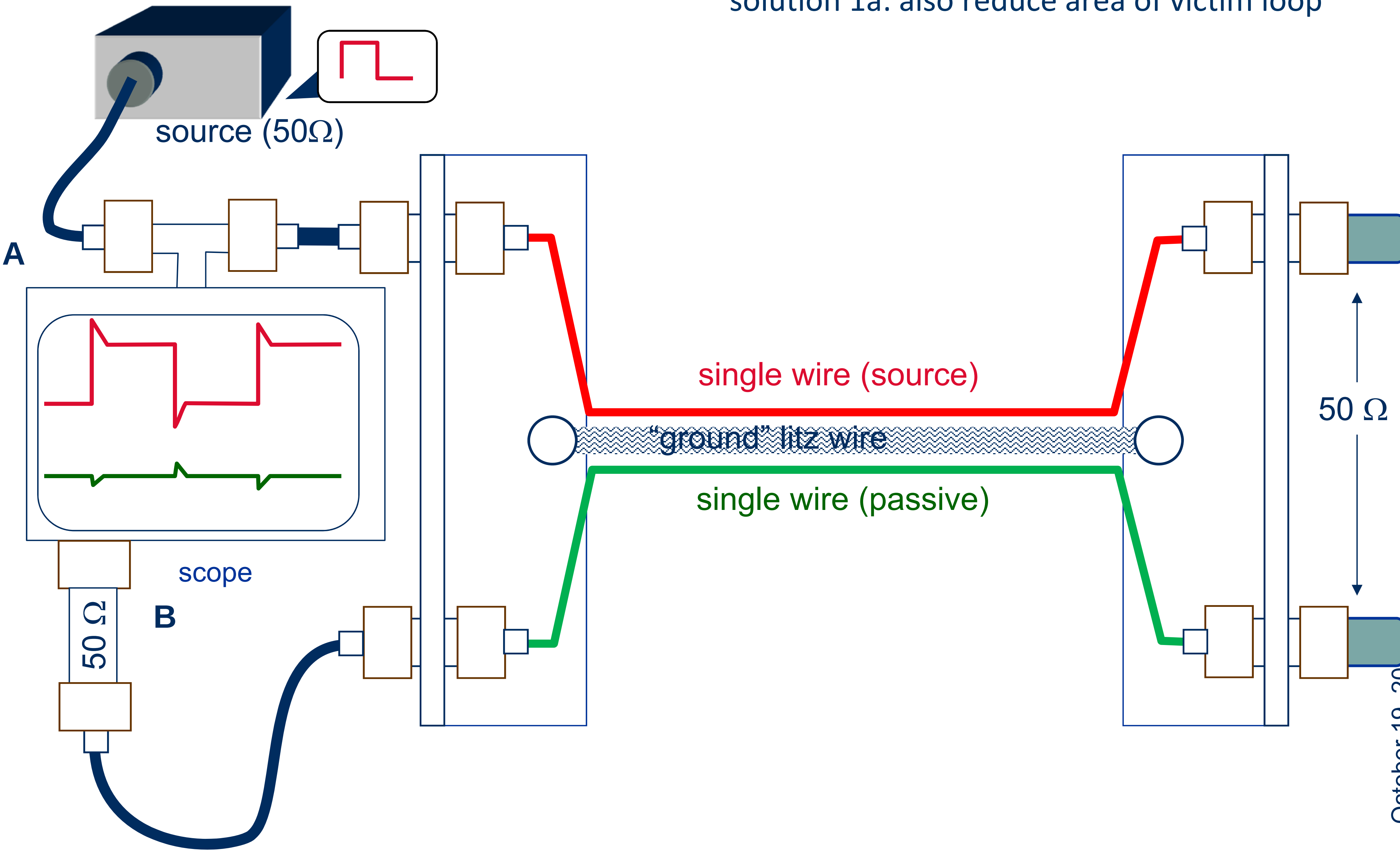
October 19, 20…

solution 1: reduce loop area of source



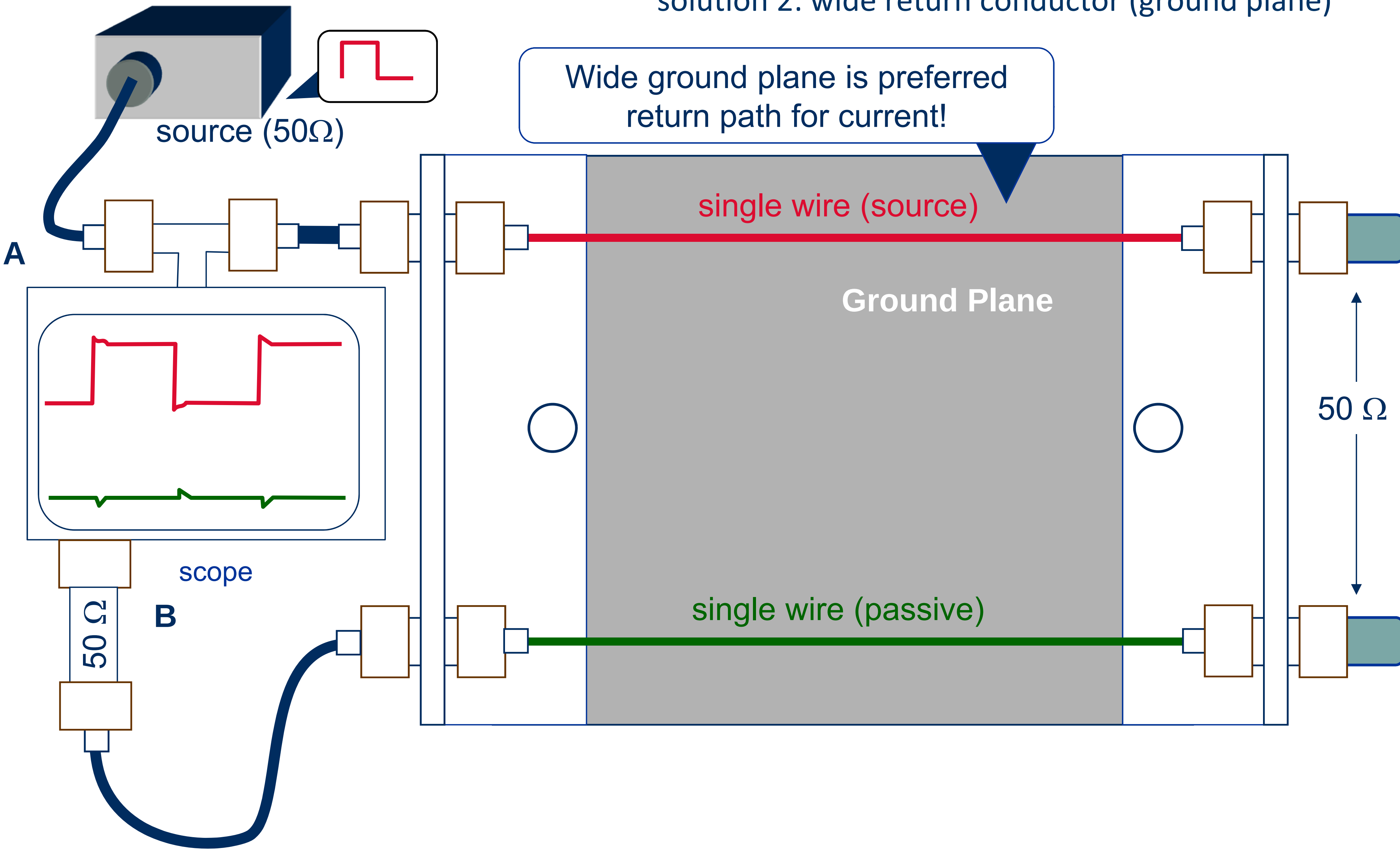
Mutual induction in practice

solution 1a: also reduce area of victim loop



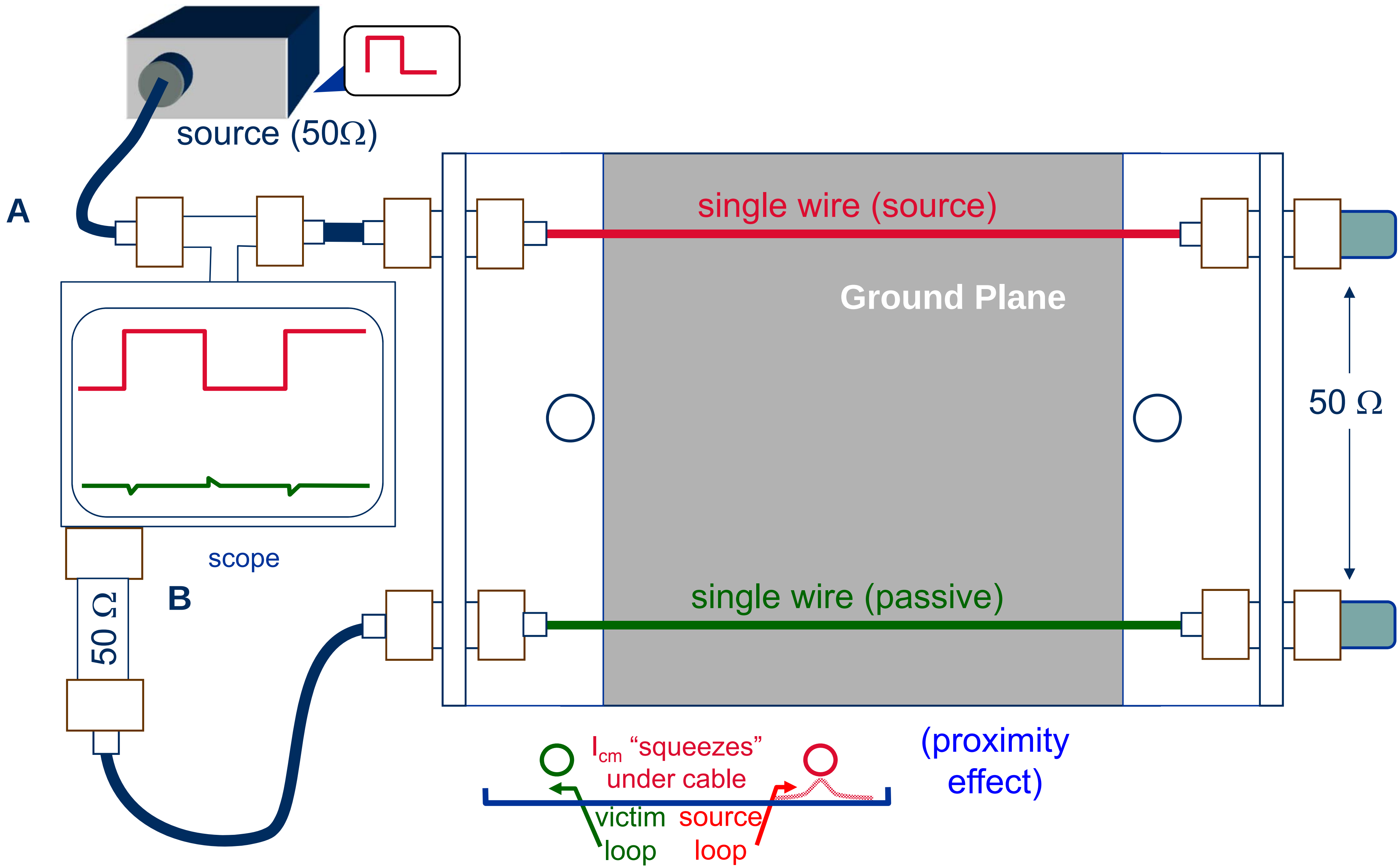
Mutual induction in practice

solution 2: wide return conductor (ground plane)

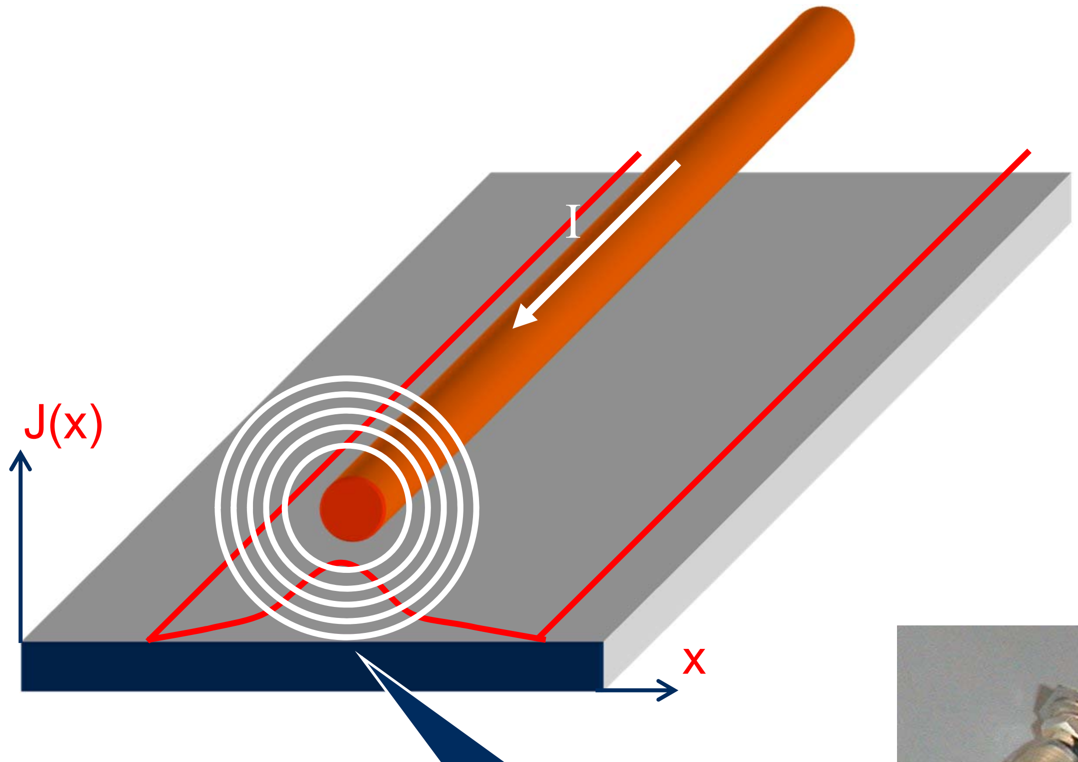


Mutual induction in practice

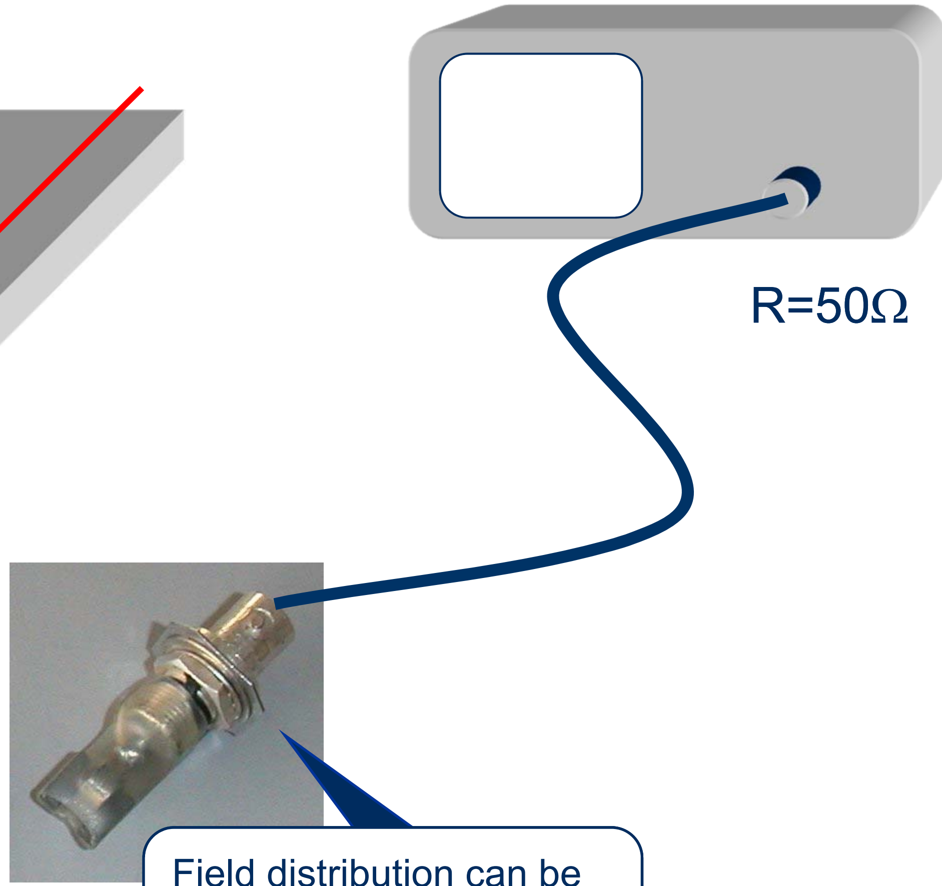
proximity effect: return current concentrates under "red" wire



current concentrates under conductor, minimizing loop inductance



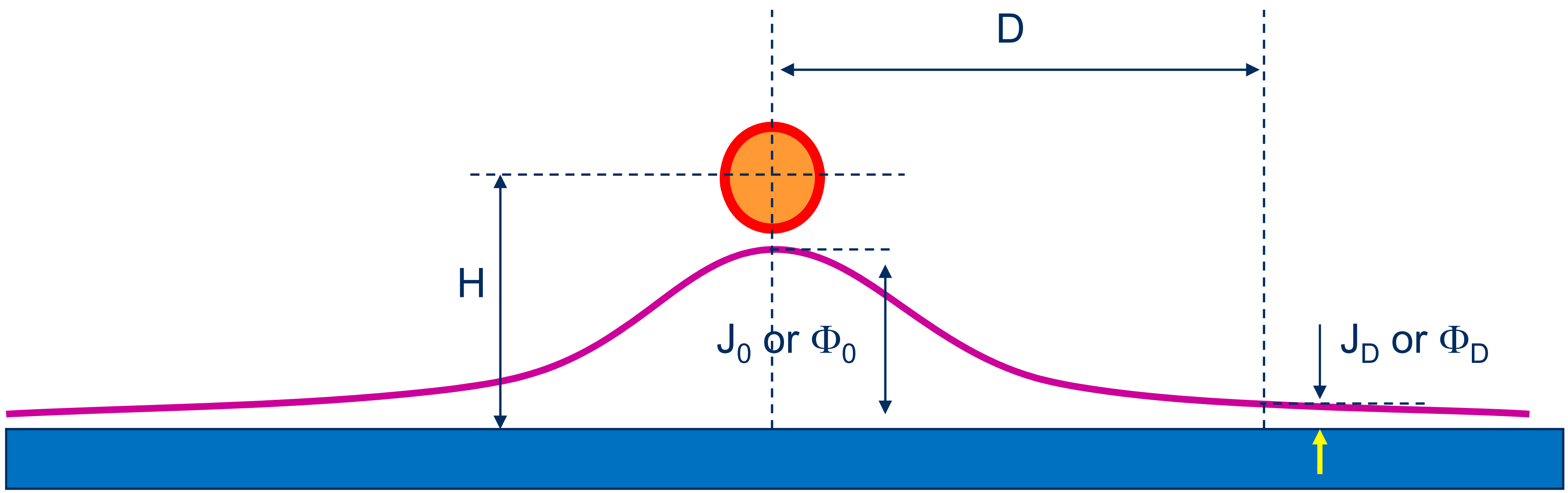
Current concentrates under conductor (proximity effect)



Field distribution can be measured with small sniffer probe

Return Current Distribution Magnitude in Ground Plane

lowering the wire reduces volume "filled with flux"



Source:
Johnson, H
"High-Speed Digital Design"
1993

$$\frac{J_D}{J_0} = \frac{\Phi_D}{\Phi_0} \approx \frac{1}{1+\left(\frac{D}{H}\right)^2}$$

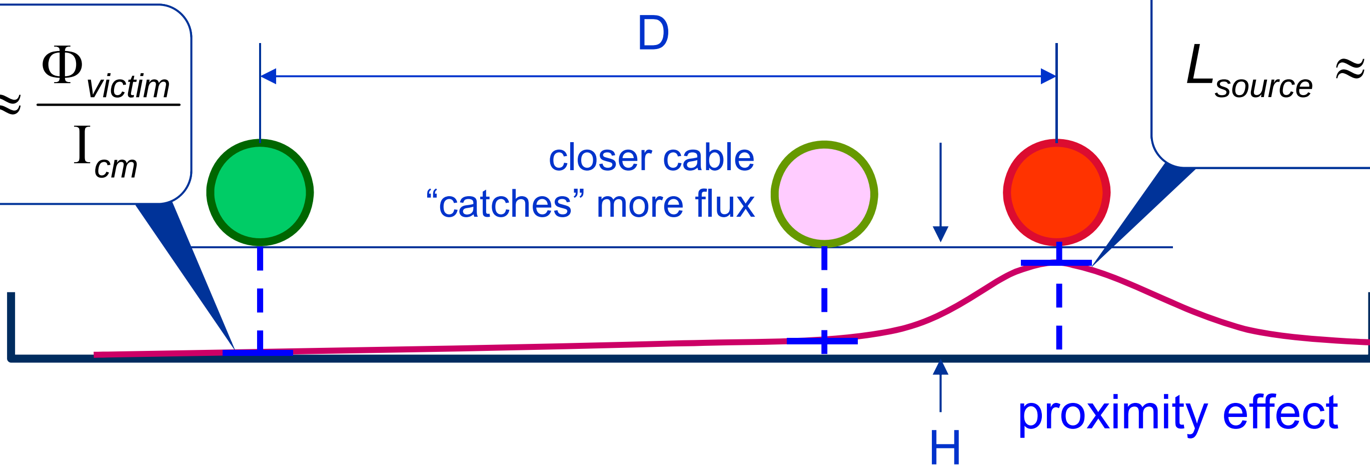
October 19, 2016

Wire /cable (!) distance is important

once a metal plane is used for separation

Current distribution of I_{cm} in cable guide is measure of flux density, Φ, coupling into cable: at source ~L, at victim ~M!

$$M_{\frac{source}{victim}} \approx \frac{\Phi_{victim}}{I_{cm}}$$



$$L_{source} \approx \frac{\Phi_{source}}{I_{cm}}$$

COUPLING FACTOR: k

$$M \approx \frac{L_{source}}{1+\left(\frac{D}{H}\right)^2}$$

$$k = \frac{M}{L_{source}} = \frac{1}{1+\left(\frac{D}{H}\right)^2}$$

Source:
Johnson, H
“High-Speed Digital Design”
1993

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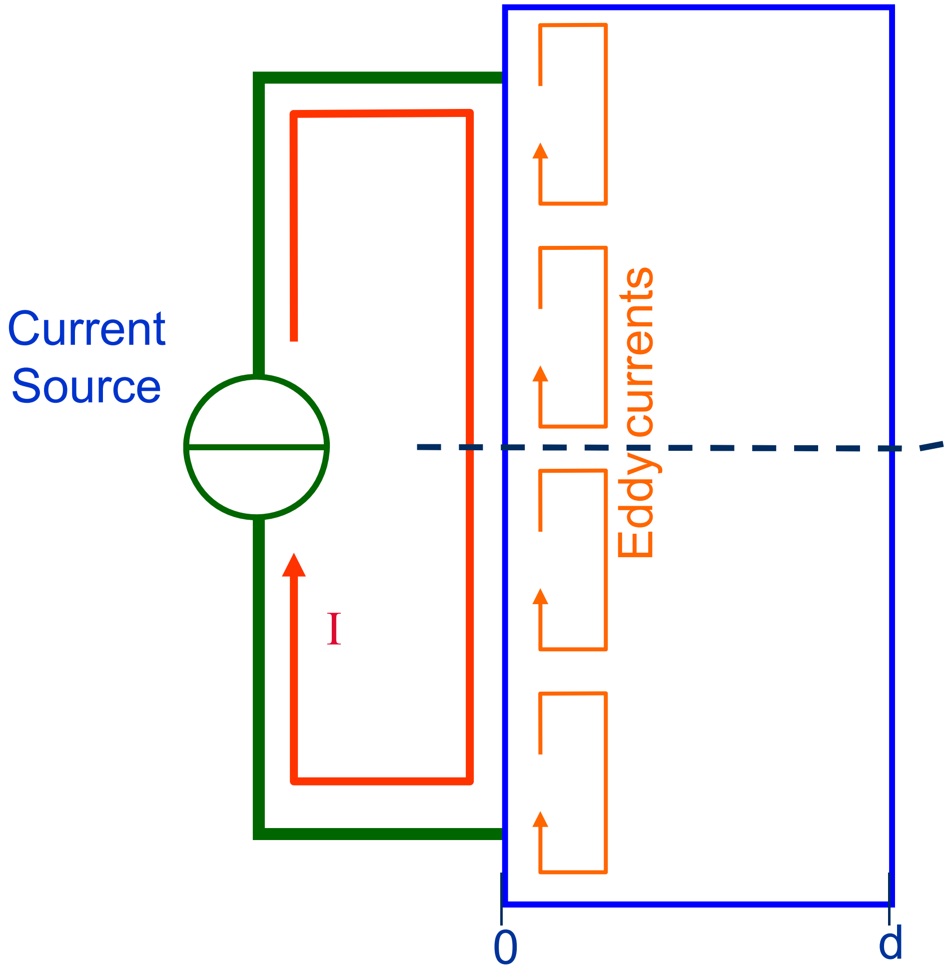
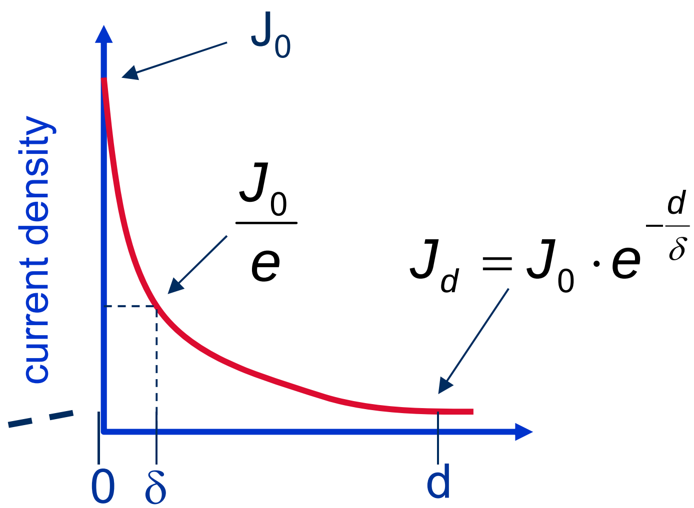
Wide metal also features: the Skin Effect

Lenz'Law and the basis for shielding effects





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

f = frequency [Hz]
σ = conductivity [S/m]
μ = permeability [H/m]

Induced Eddy currents oppose direction of external current (Lenz' Law)

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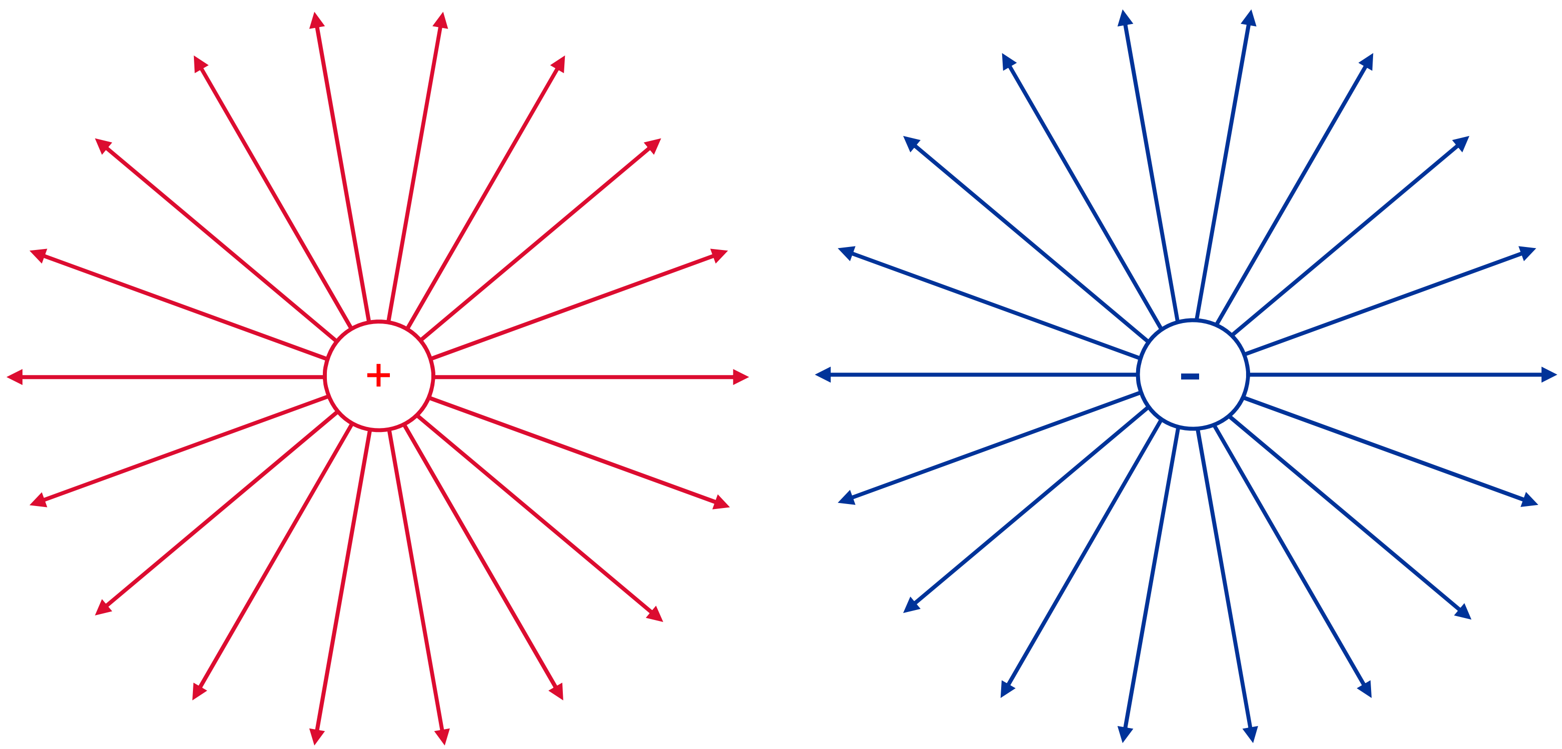
Any Voltage needs an Electric Field!

Two conductors in an interconnection each have an individual field pattern



(Electric Force lines)

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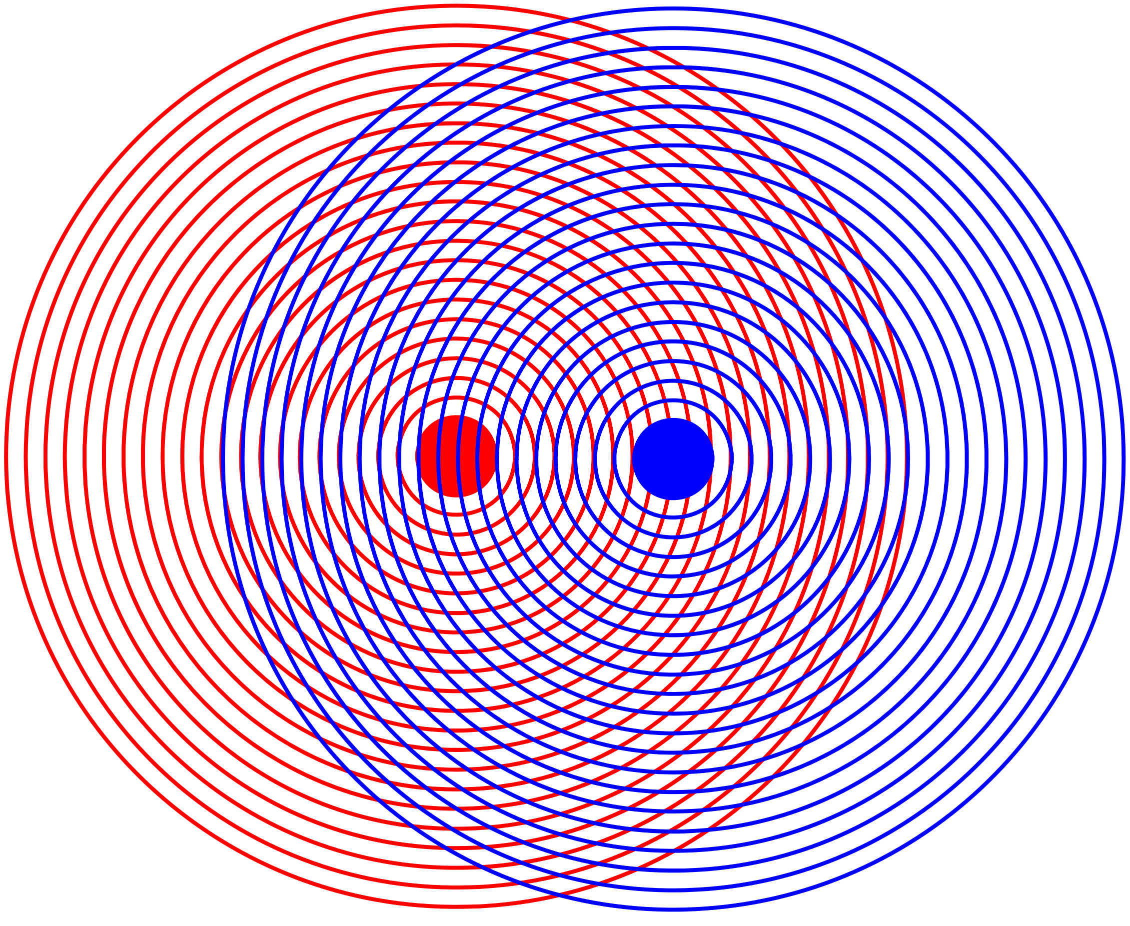
Combined Electric Field Pattern

concentric circles model the actual E-field pattern of two conductors



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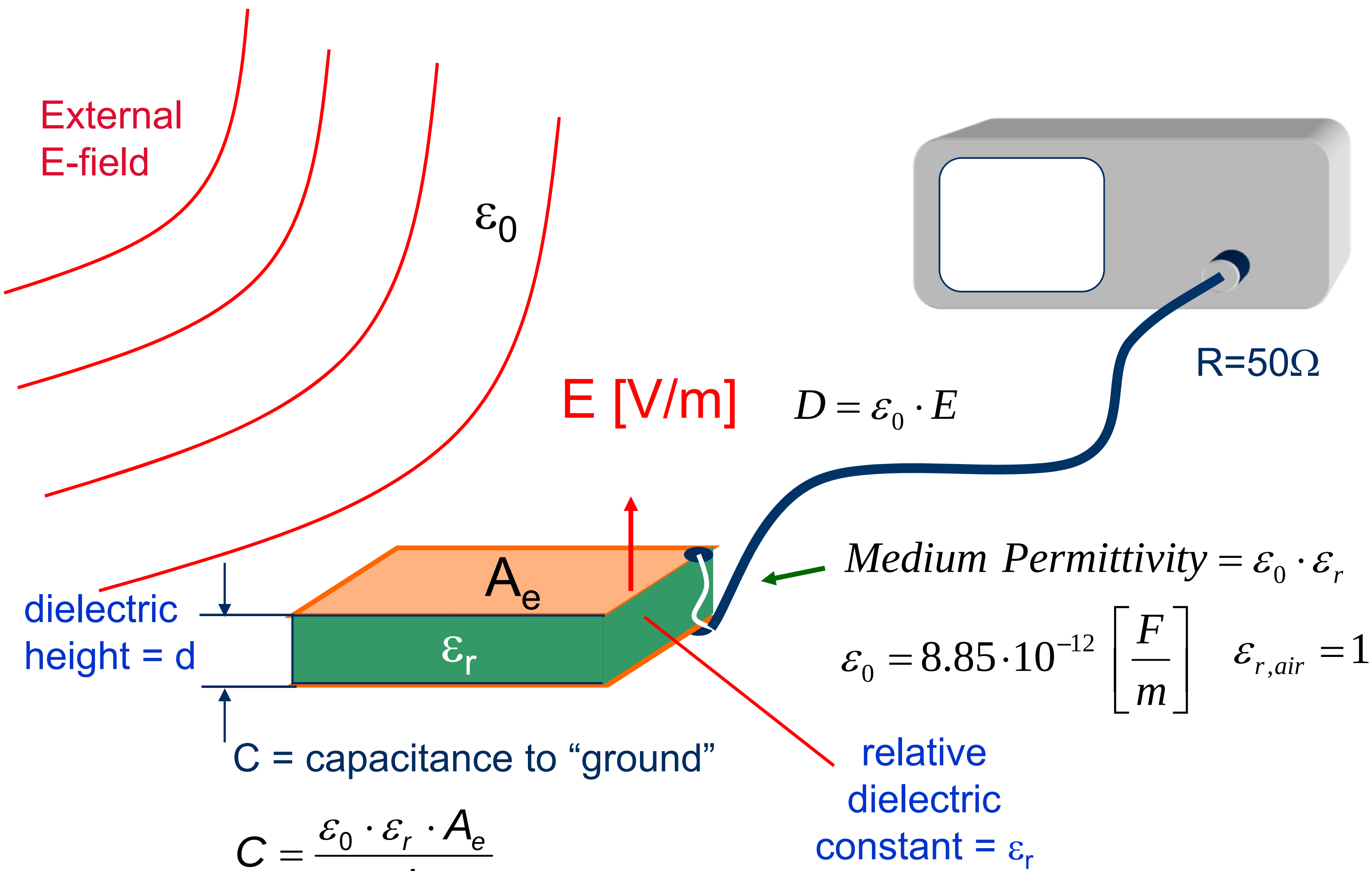
Capacitive Probe for Electric Fields, the Model

derivation using a substitute current source



$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A_e}{d}$$

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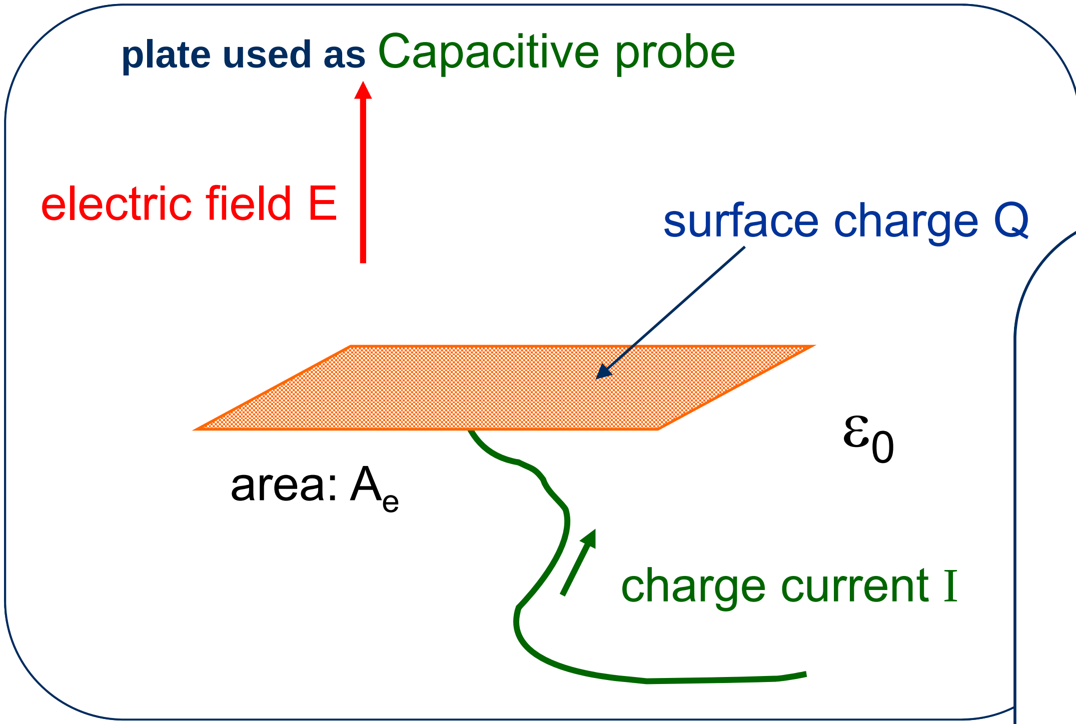
Substitute source for capacitive probe

a current source, based on Gauss' Theorem



$$Q = A_e \cdot \varepsilon_o \cdot E \quad \text{(Gauss)}$$

$$I = \frac{\partial Q}{\partial t} \quad \text{(time domain)}$$

or

$$I = j\omega Q \quad \text{(frequency domain)}$$

$$\boxed{I = j\omega \cdot A_e \cdot \varepsilon_o \cdot E}$$

Note

$$\varepsilon_0 \cdot E = D \quad \text{(Dielectric Displacement)}$$

$$I = \frac{\partial Q}{\partial t} = A_e \cdot \frac{\partial D}{\partial t} \quad or \quad \boxed{A_e \cdot \dot{D}}$$

The MIL-STD-461 hence calls this device a "D-dot probe"

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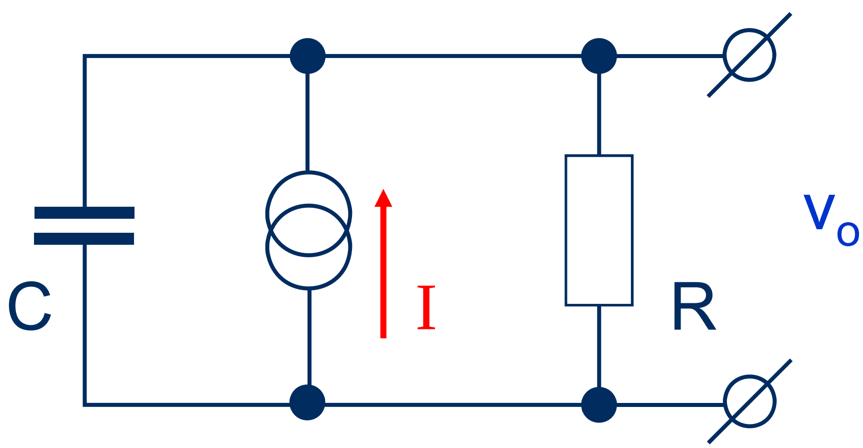
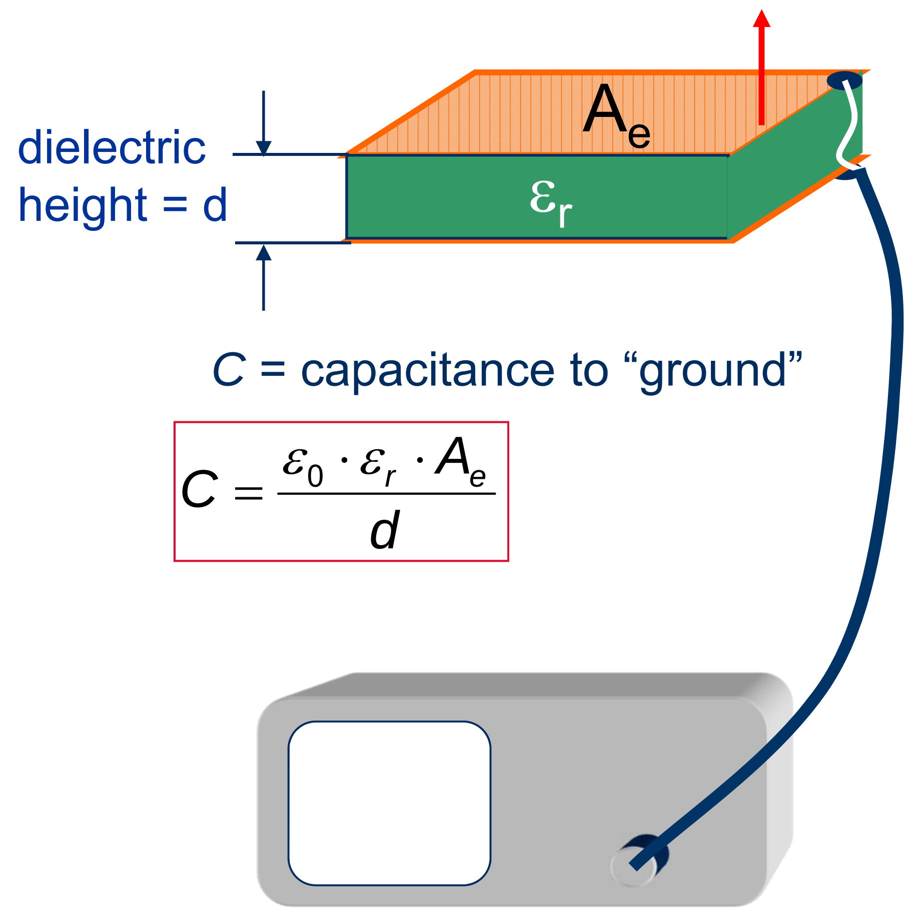
Equations for the measurement circuit

when loaded with a resistor

Equivalent Circuit Model:



$$I = j\omega \cdot A_e \cdot \varepsilon_o \cdot E$$



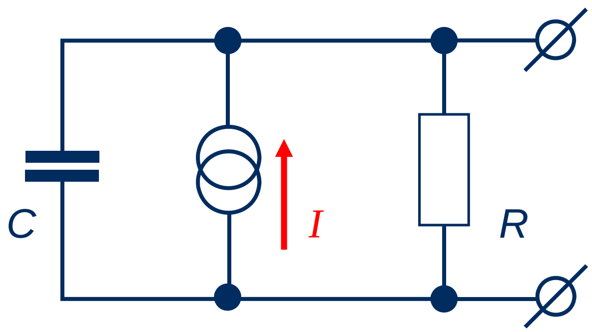
C = capacitance to “ground”

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A_e}{d}$$

R=50Ω

Using a Capacitive Probe for Voltage Measurements

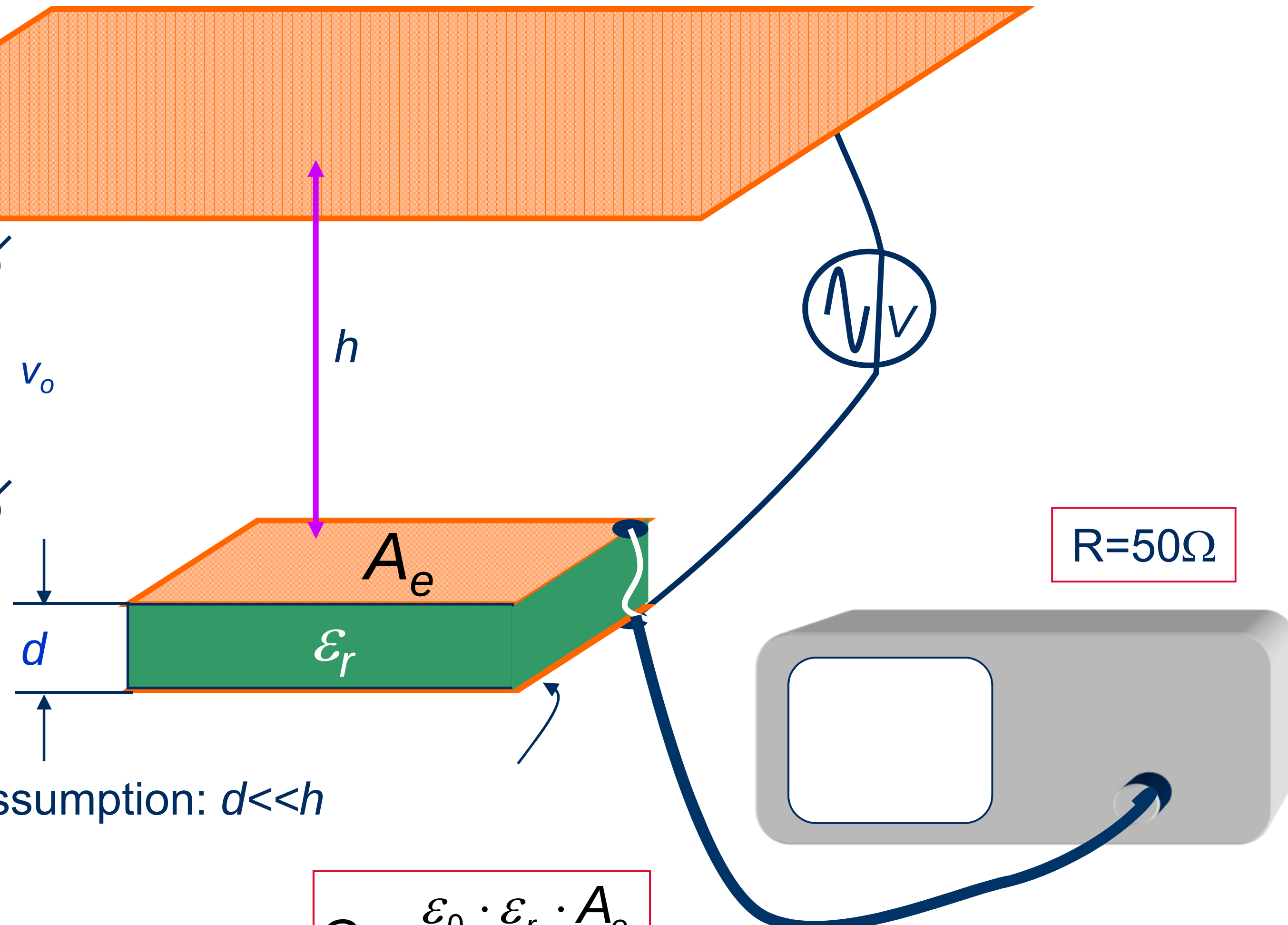
replace *E* by *V* (Voltage) divided by *h* (distance)



$$I = j\omega \cdot A_e \cdot \varepsilon_o \cdot \frac{V}{h}$$

Gauss rewritten:

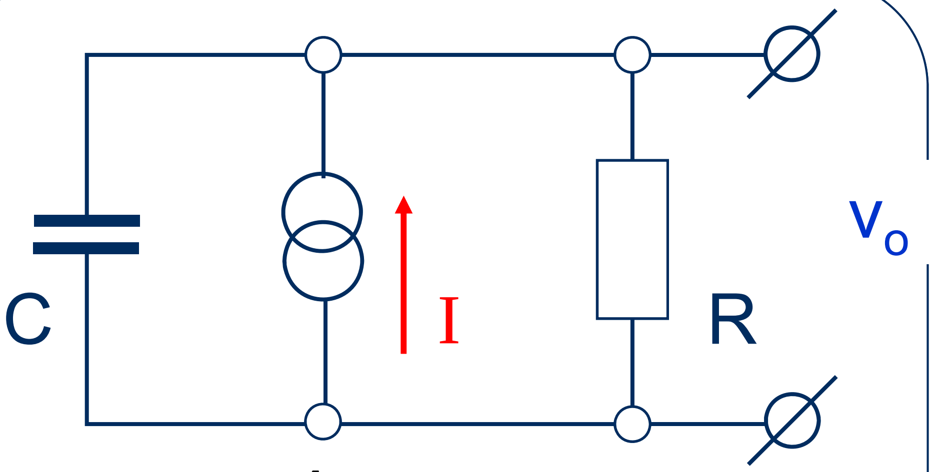
$$Q = C_{Mutual} \cdot V$$



$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A_e}{d}$$

Equations for the measurement circuit

when loaded with a resistor



$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A_e}{d}$$

$$v_o = \mathrm{I} \cdot \frac{R}{j\omega RC + 1}$$

$$\mathrm{I} = j\omega \cdot A_e \cdot \varepsilon_o \cdot E$$

$$v_o = j\omega \cdot \frac{d \cdot E}{\varepsilon_r} \frac{1}{j\omega + \frac{1}{RC}}$$

LF: $\omega < \frac{1}{RC}$

$$v_o = j\omega R \cdot A_e \cdot \varepsilon_o \cdot E$$

HF: $\omega > \frac{1}{RC}$

$$v_o = \frac{d \cdot E}{\varepsilon_r}$$

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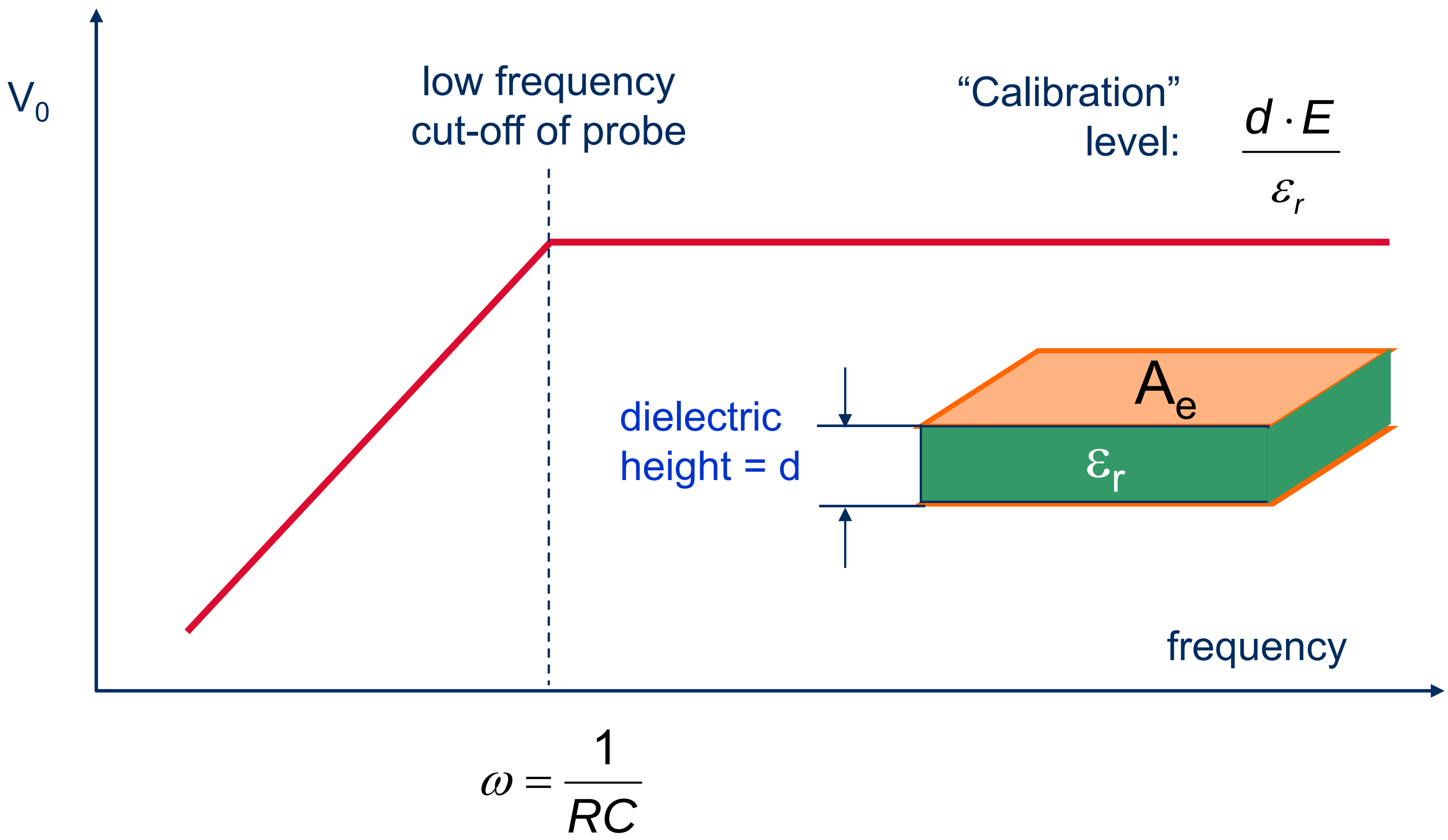
Operation of the capacitive probe

graphical representation of results



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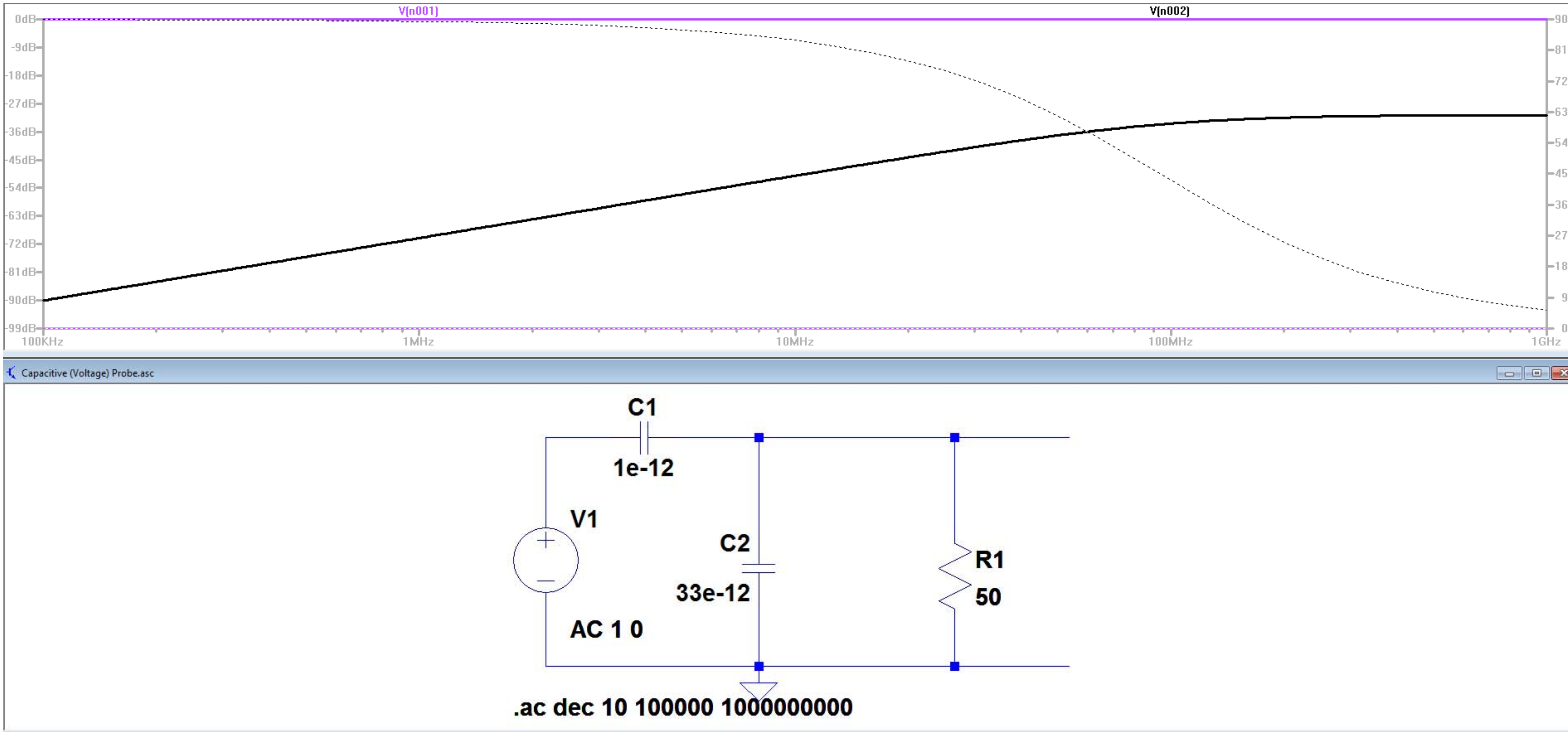
SPICE Simulation of a Capacitive Probe

Using LTSpice IV



LTSpice IV: http://www.linear.com/designtools/software/

October 15, 2015

Example of some electric field probes

useful if professional equipment is unavailable

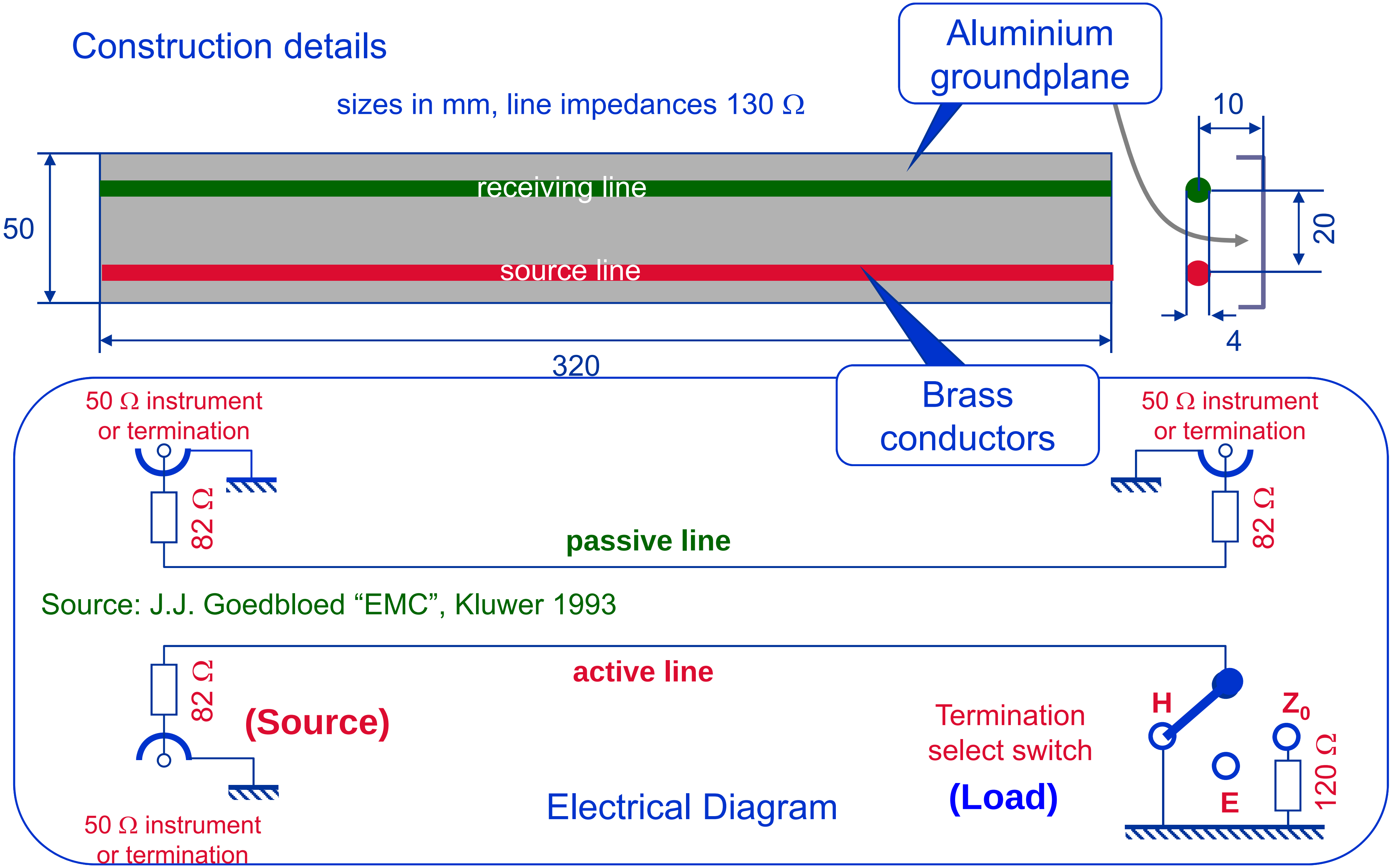
Insulate!

Can sense E-fields
and generate them!

October 19, 2016

Combination of capacitive and inductive crosstalk

depending on load of source line, capacitive or inductive effects dominate



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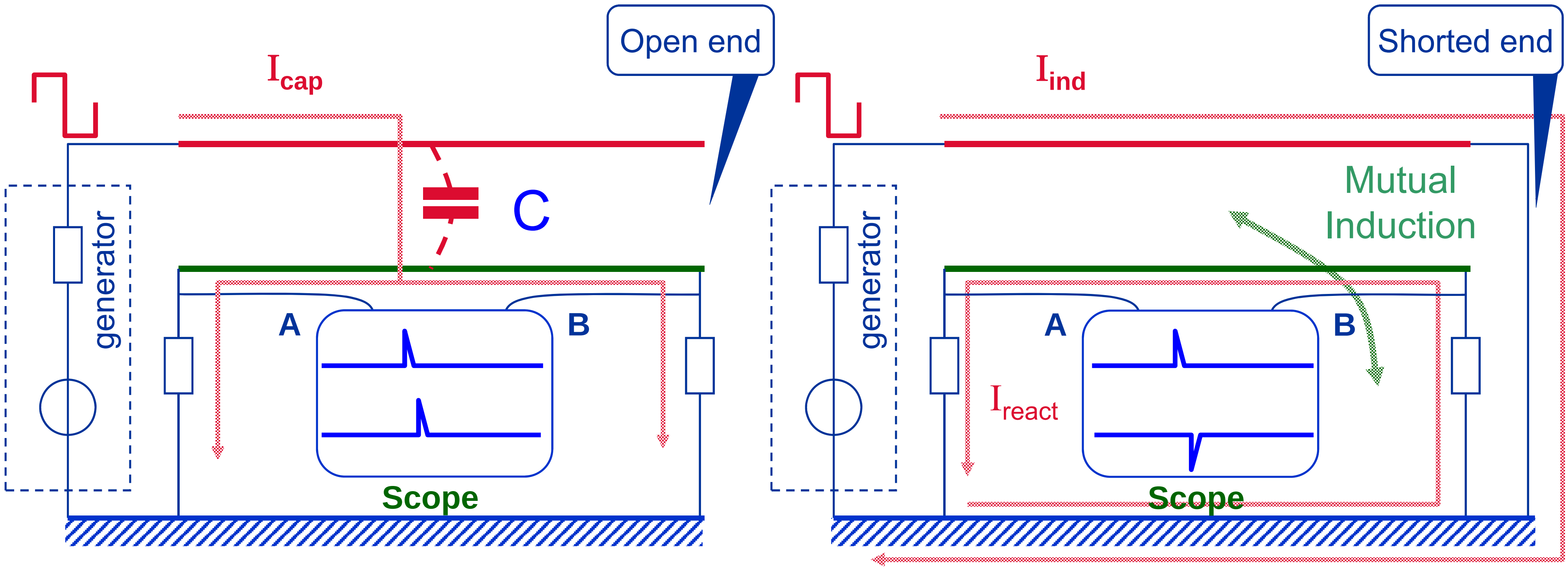
Flow of currents determines crosstalk behaviour

always look for the current paths, inductive and capacitive



Capacitive situation

Crosstalk "in phase"

Inductive situation

Crosstalk "in anti-phase"

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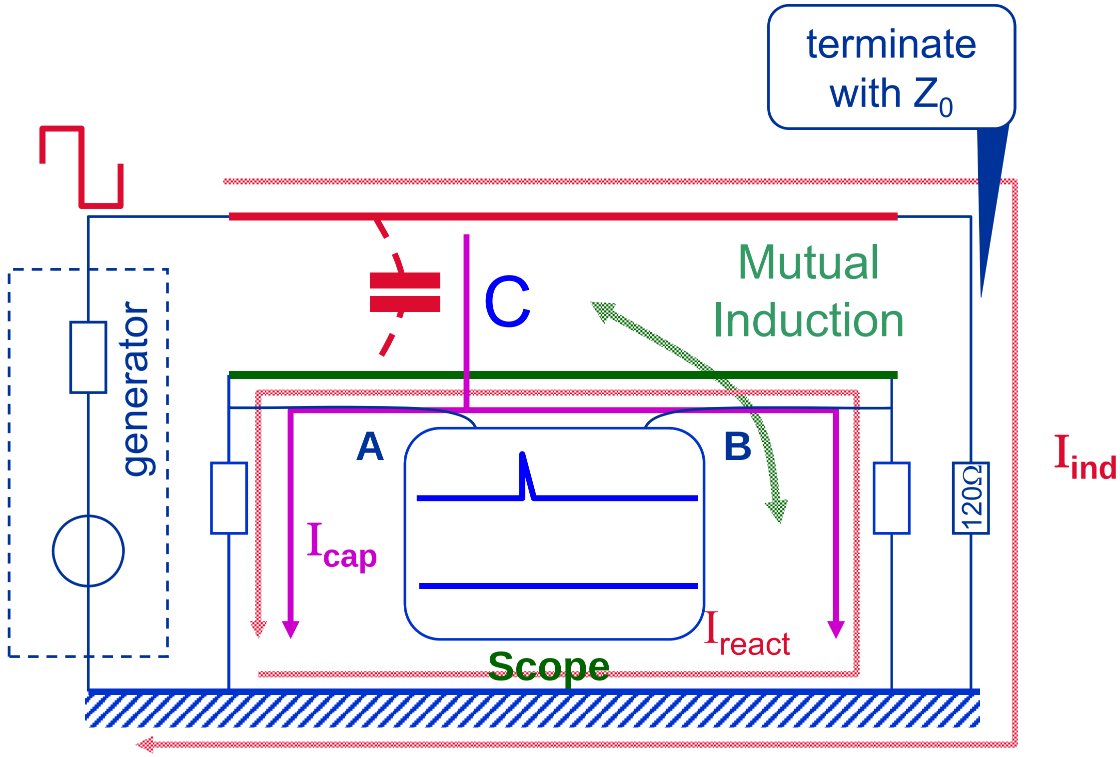
Balancing capacitive and inductive crosstalk

terminating the source line with its characteristic impedance



Z_0 terminated situation

Crosstalk far end “balanced”

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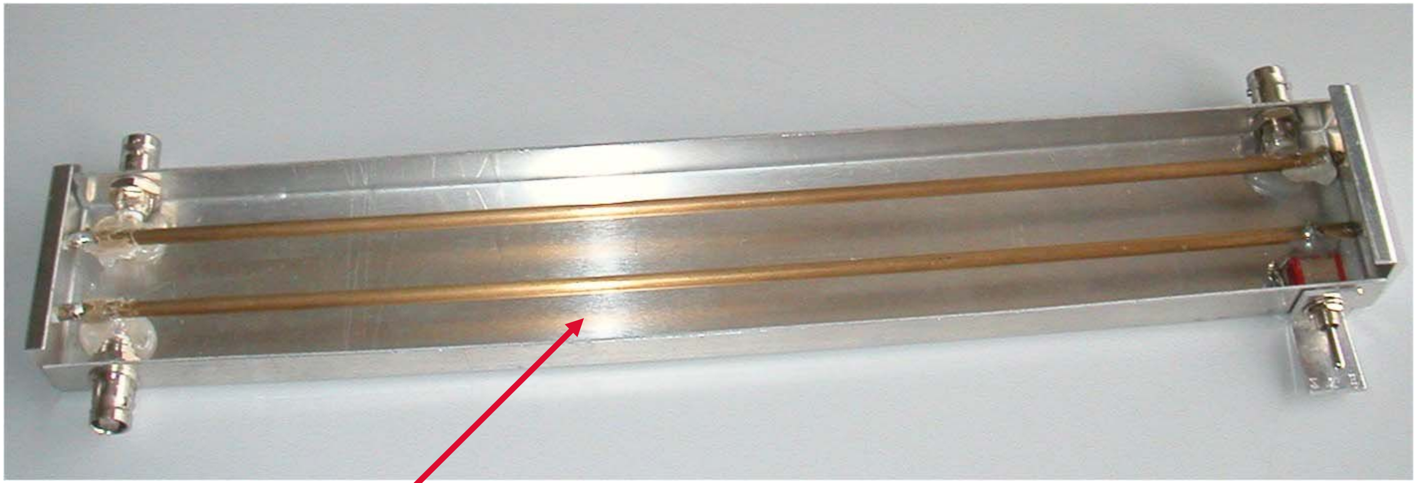
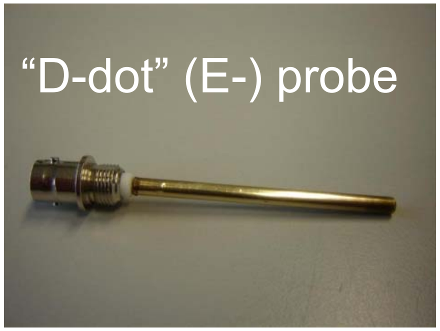
Capacitive or Inductive Sniffer Probe shows Field

magnetic field (shorted source line) or electric field (open source line)





Note
Terminated Line:
Both Field Types

Use probe near source line

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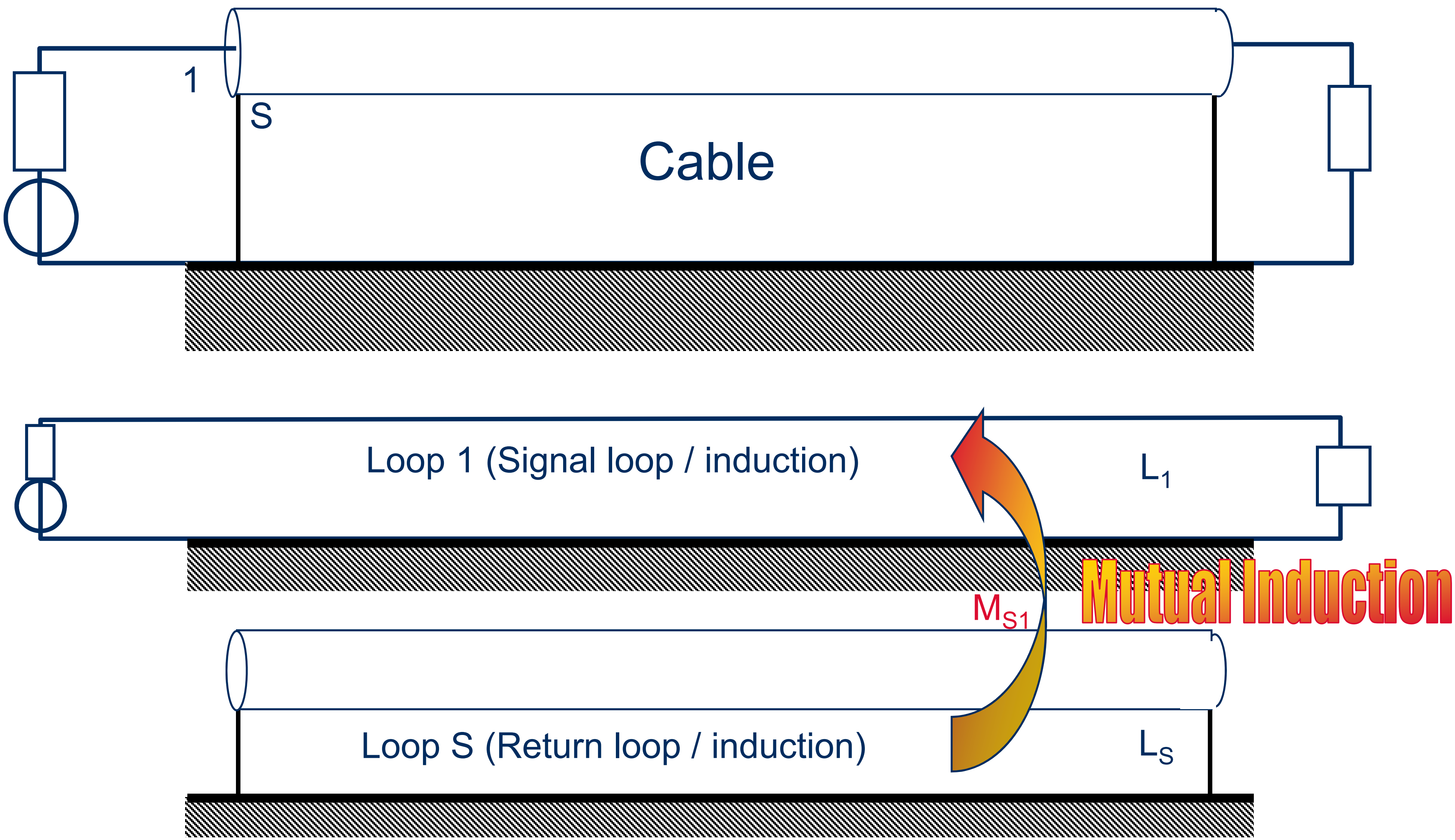
Cable Shielding: Signal/Return Circuit have Mutual Induction

screen and centre wire form a transformer



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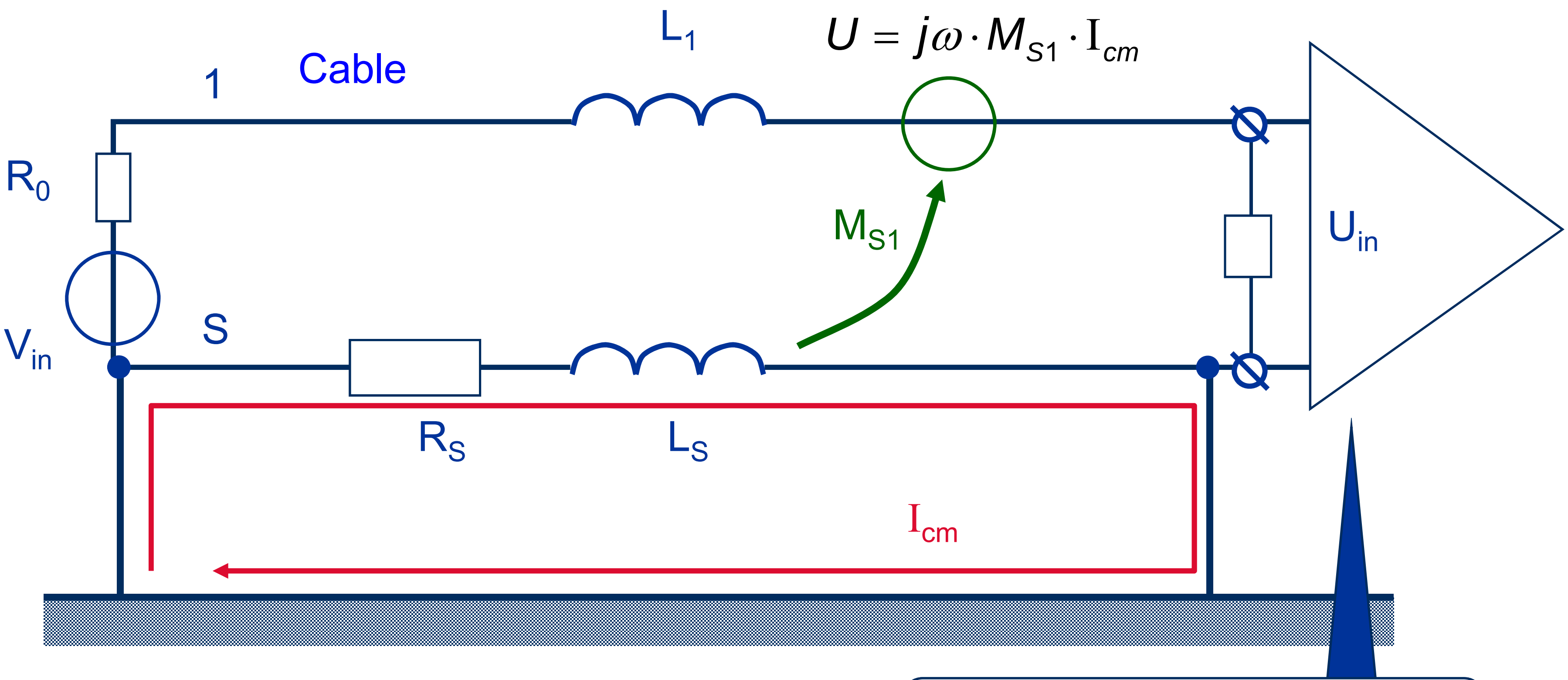
Mechanism of Shielding

common-mode noise current flows on shield (return impedance)



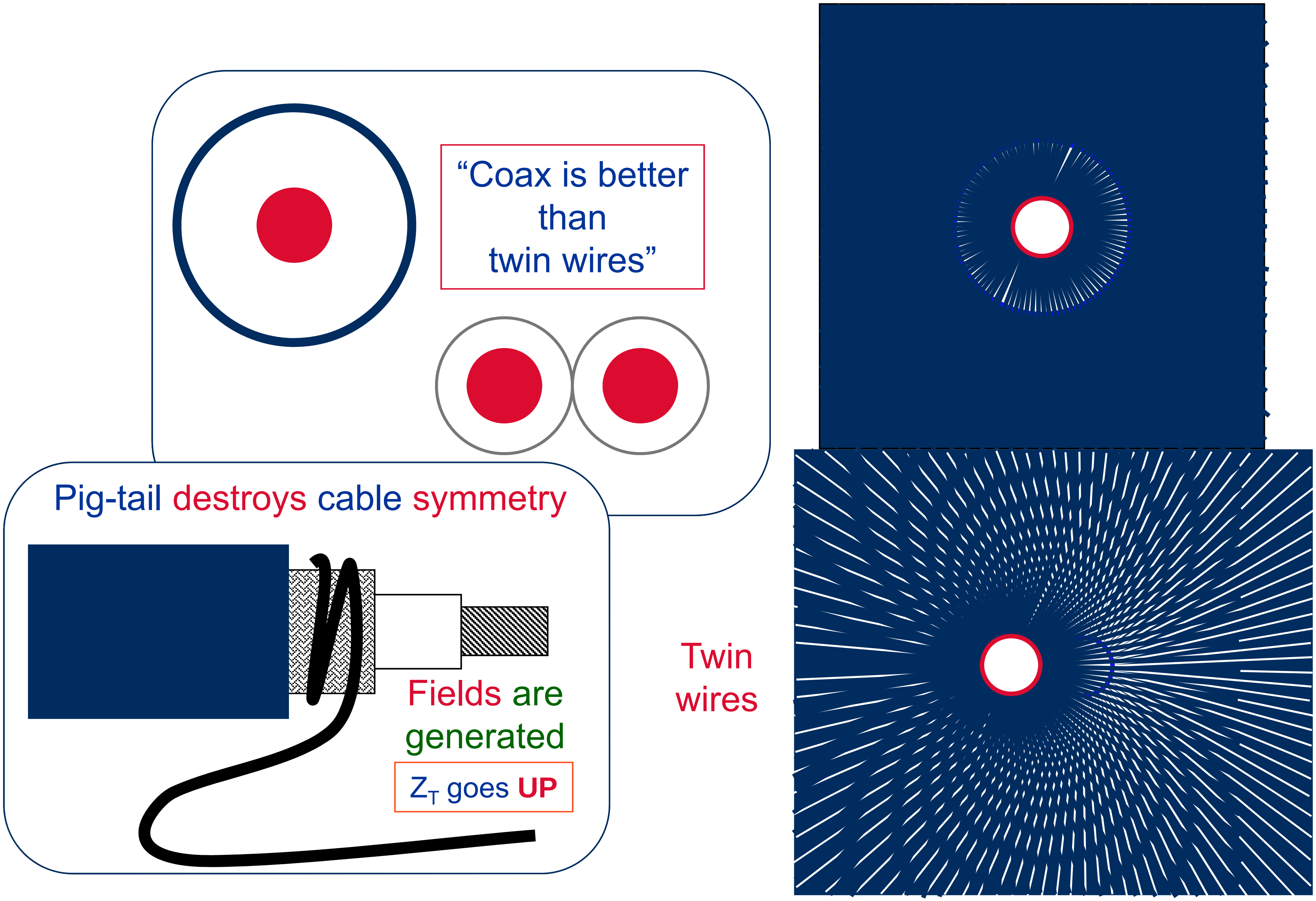
$$U_{in} = I_{cm}\left(R_S + j\omega\left(L_S - M_{S1}\right)\right)$$

Transfer Inductance (L_T)

(Don White)

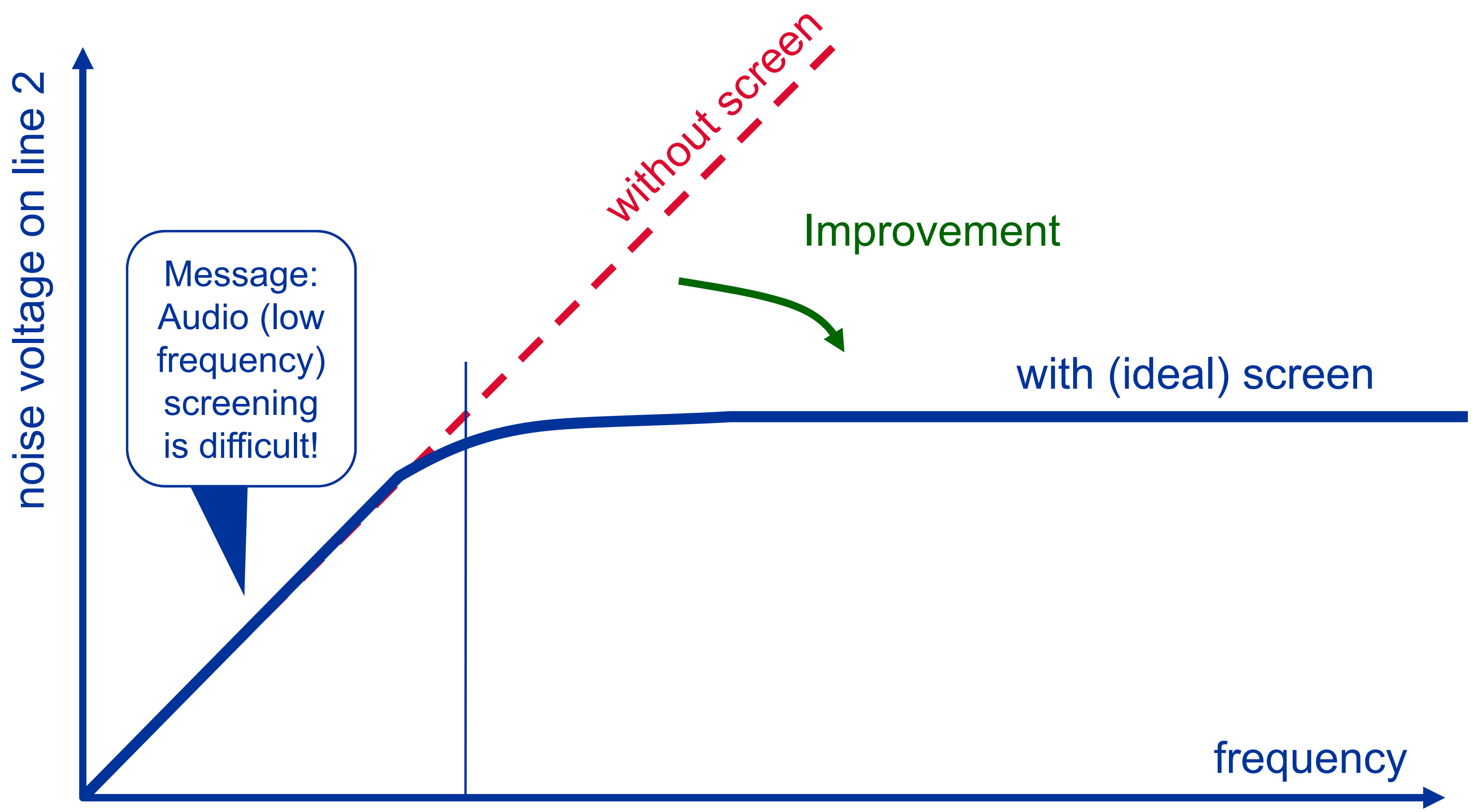
In addition come the "Pig-tails"

effect of geometry changes: fields outside interconnections; CM currents



Graphic representation of screening effect

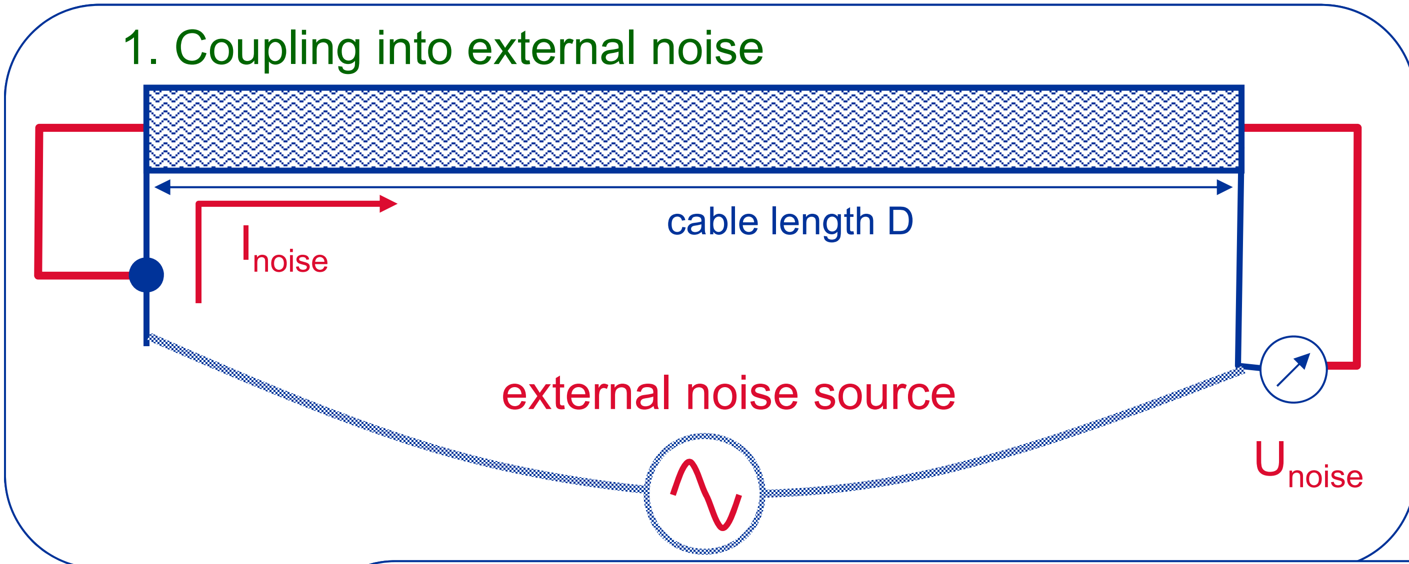
in relation to the crosstalk in the unscreened situation



$$\omega_{SC} = \frac{R_S}{L_S}$$ (screen cut-off frequency)

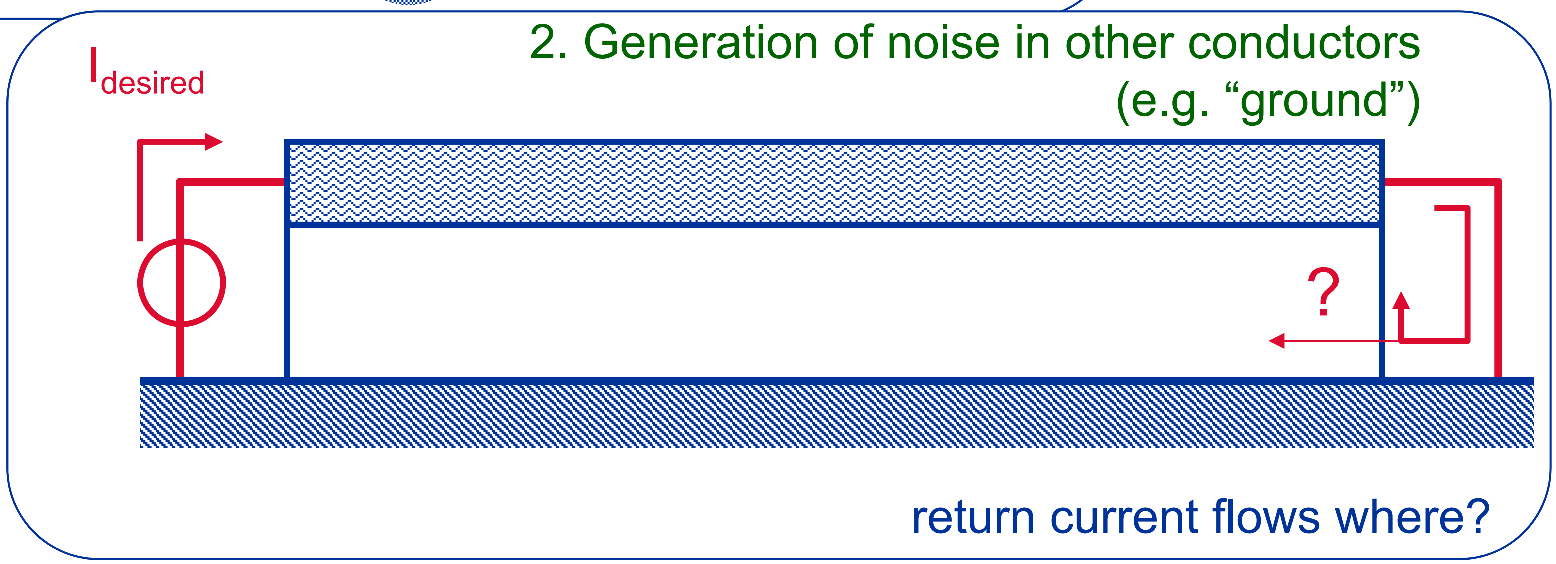
Properties of cables: Transfer Impedance Z_T

cable may produce or pick up common mode currents



$$Z_T = \frac{U_{noise}}{I_{noise} \cdot D}$$

[Ohm per meter]



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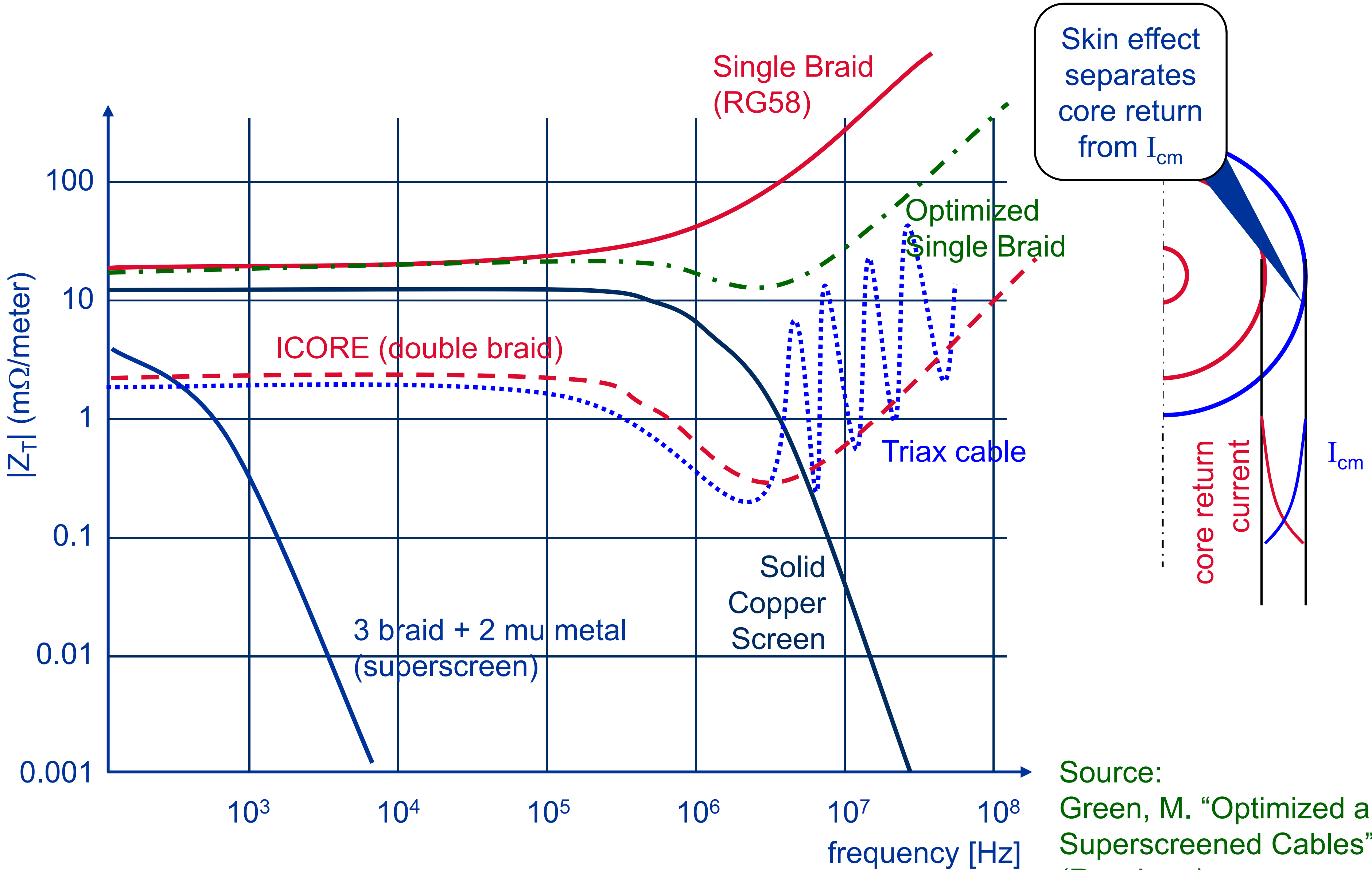
Examples of Transfer Impedance

addition of the skin effect as important aspect of screening

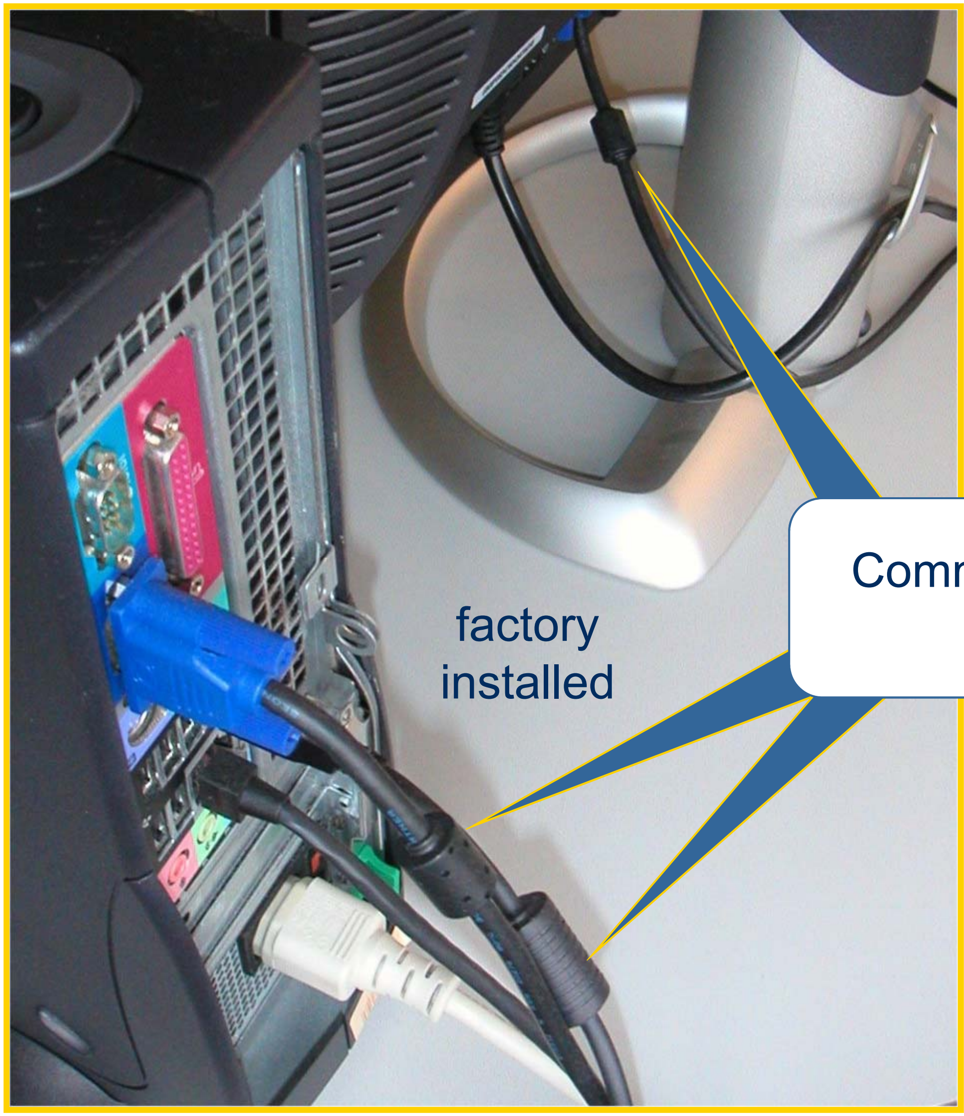


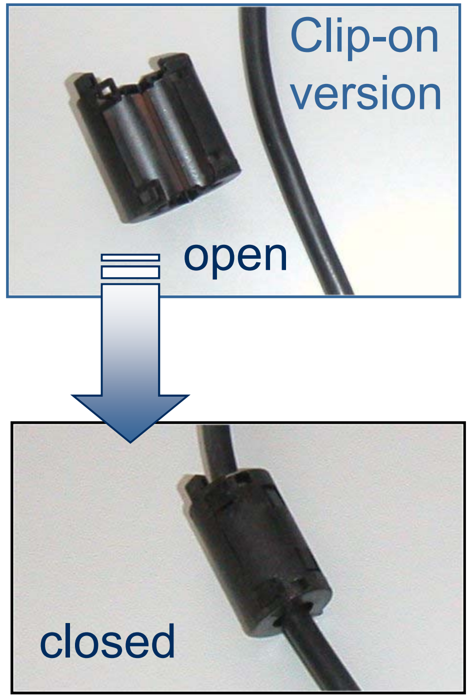
Source:
Green, M. “Optimized and Superscreened Cables” (Raychem)

October 19, 2016

The Common-mode Coil

appearances: from factory installed to self made

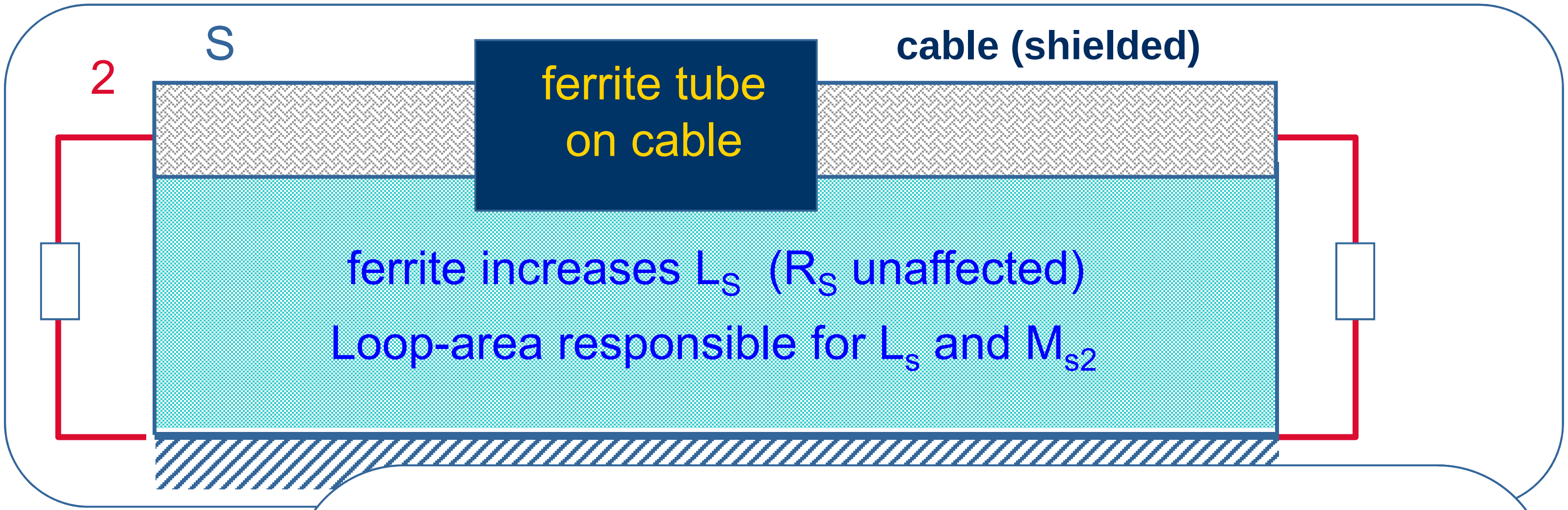


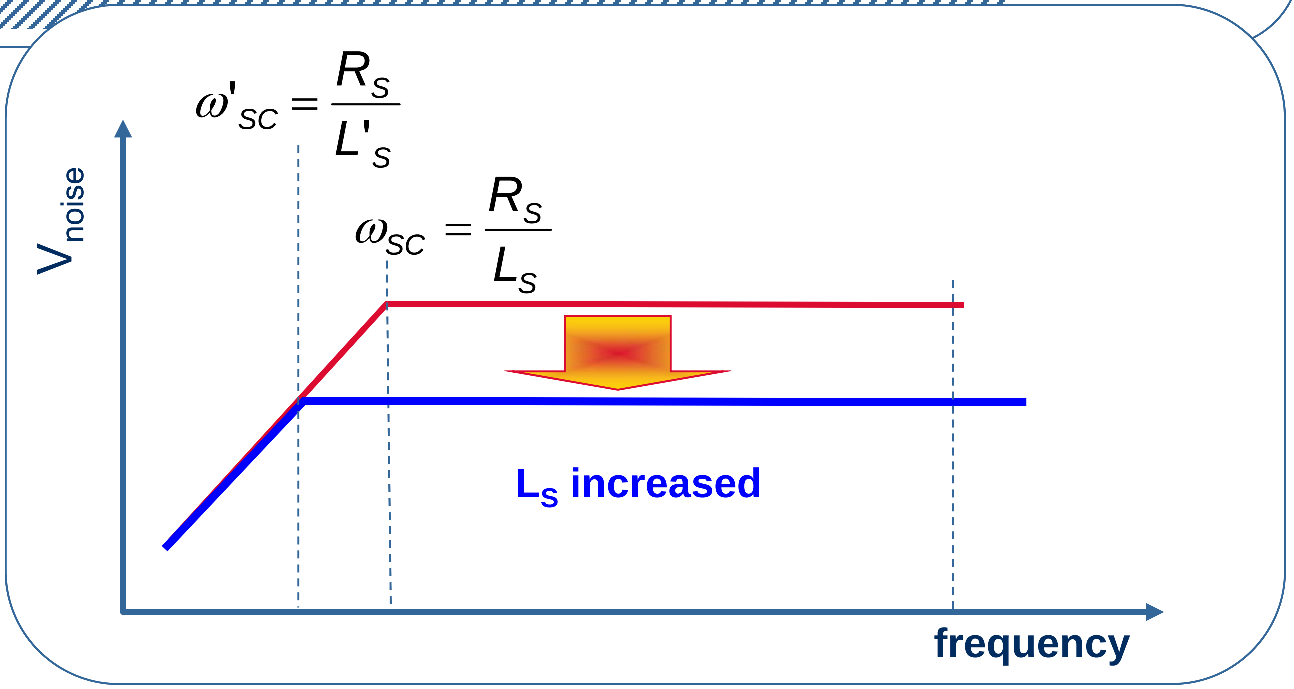


UTP cable
wound on
ferrite ring

October 19, 2016

improve, essentially, the low frequency behaviour of a cable





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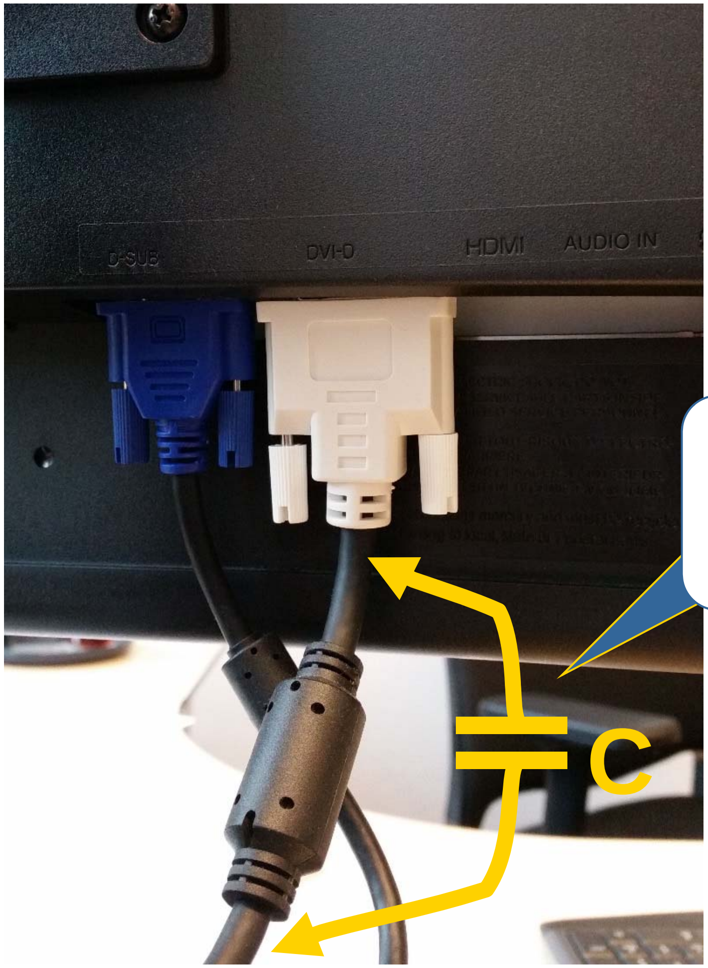
The Common-mode Coil

drawback: does not work at very high frequencies (fields travel around it)



Input and output "see" each other (for high frequencies)

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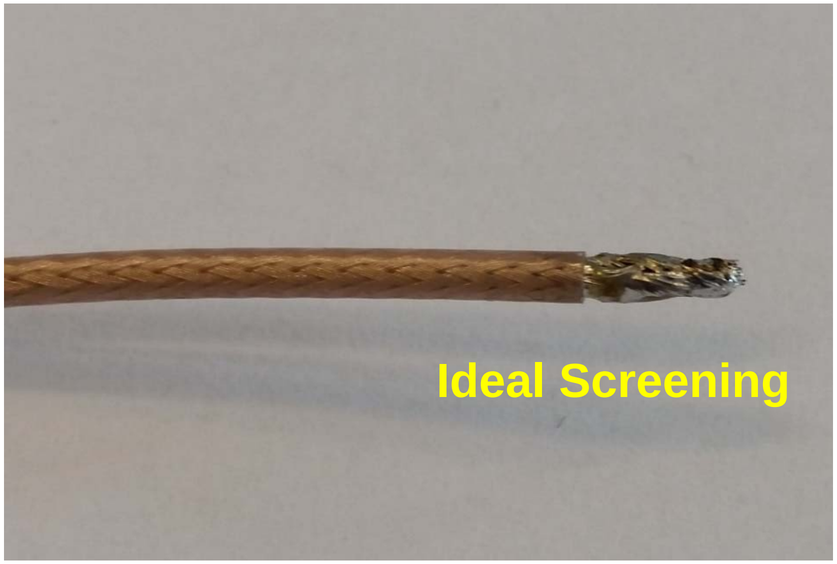
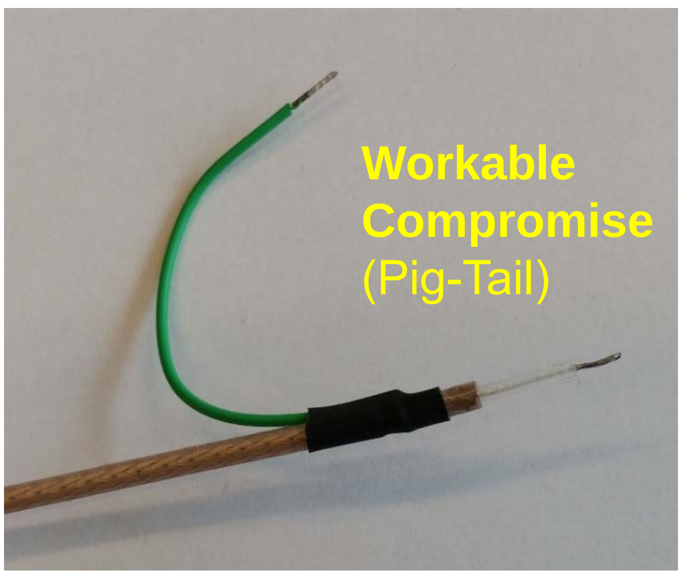
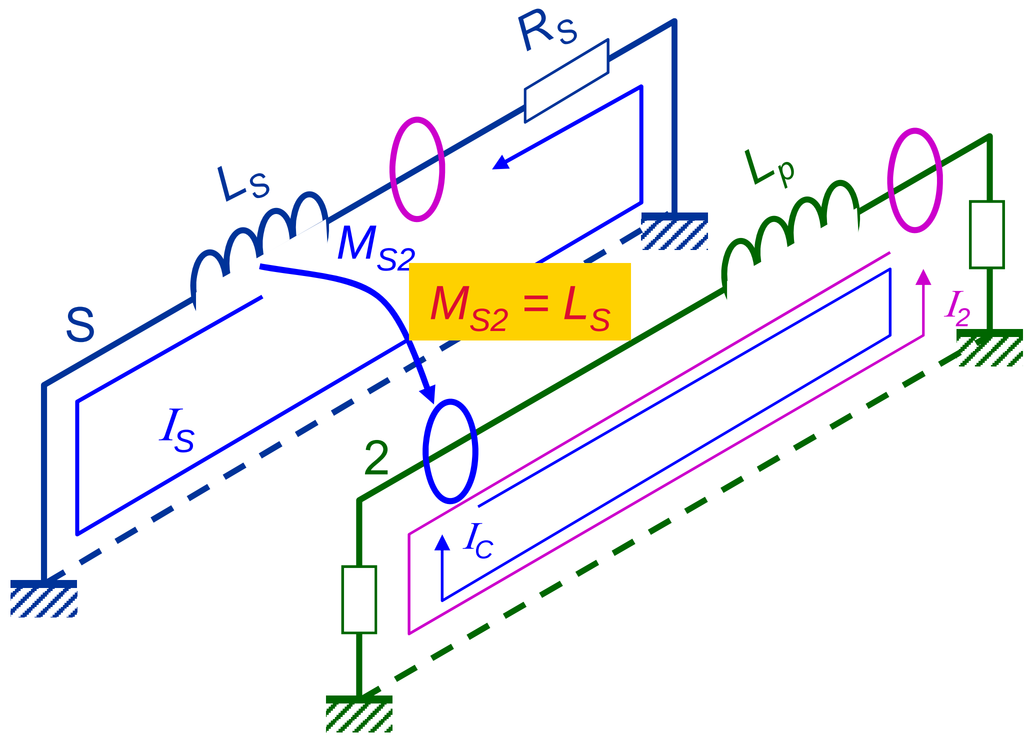
What if the shield does not completely cover the inner wire?





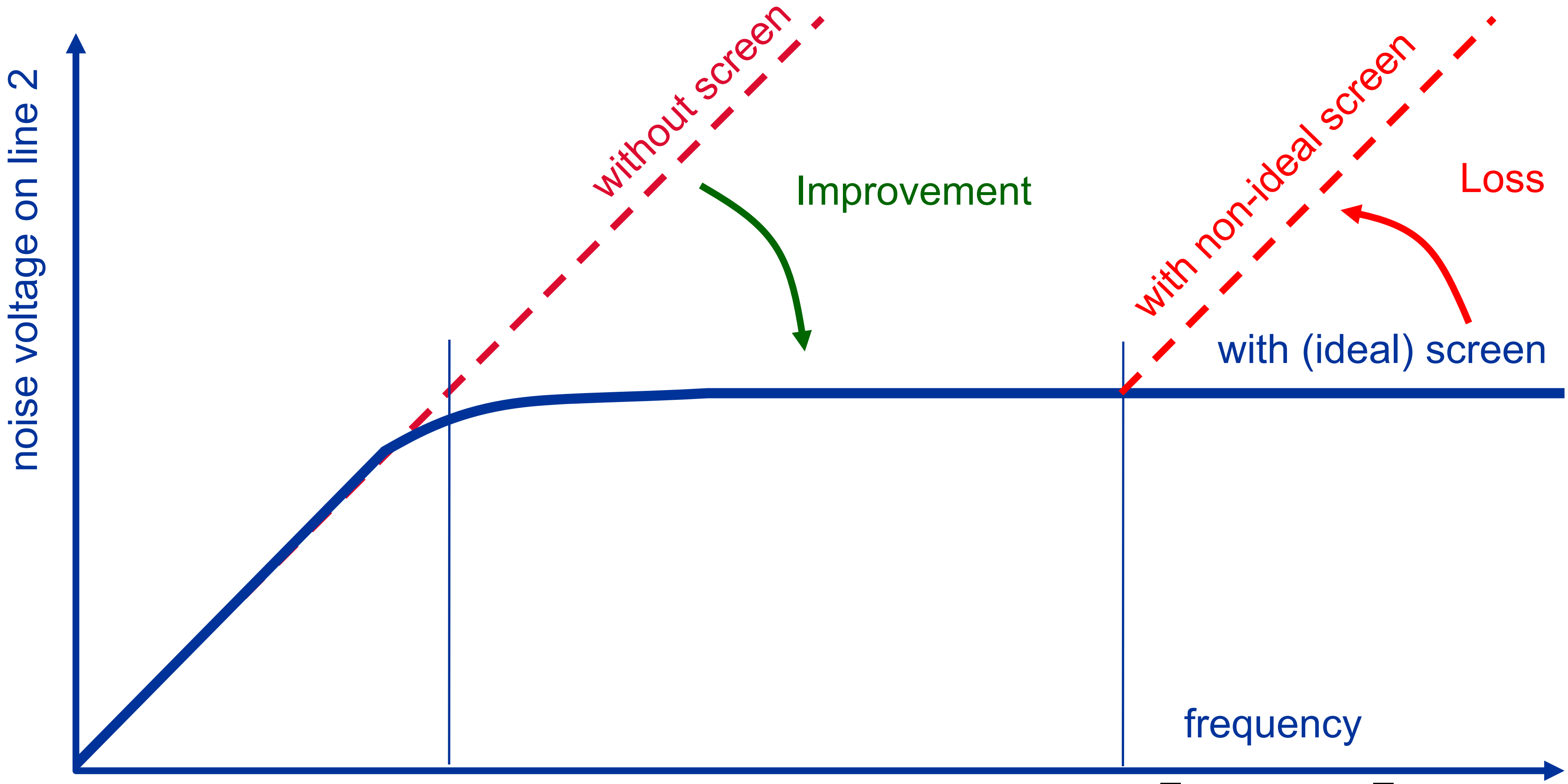


$$M_{S2} \neq L_S$$

e.g. $M_{S2} = 0.95 \cdot L_S$

Incomplete shielding

in relation to the crosstalk in the complete- and un-shielded situation



$$\omega_{SC} = \frac{R_S}{L_S}$$

$$\omega_{HF} = \left[\frac{1}{1-0.95}\right]\frac{R_S}{L_S}$$

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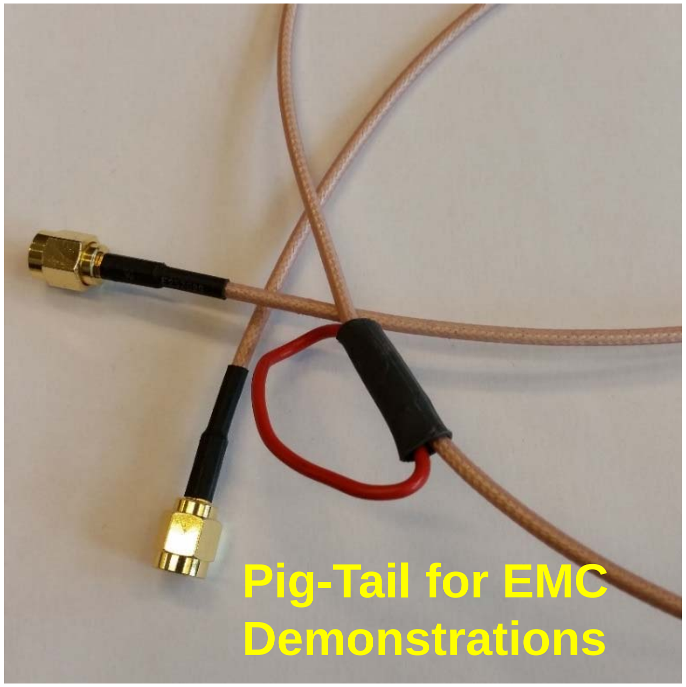
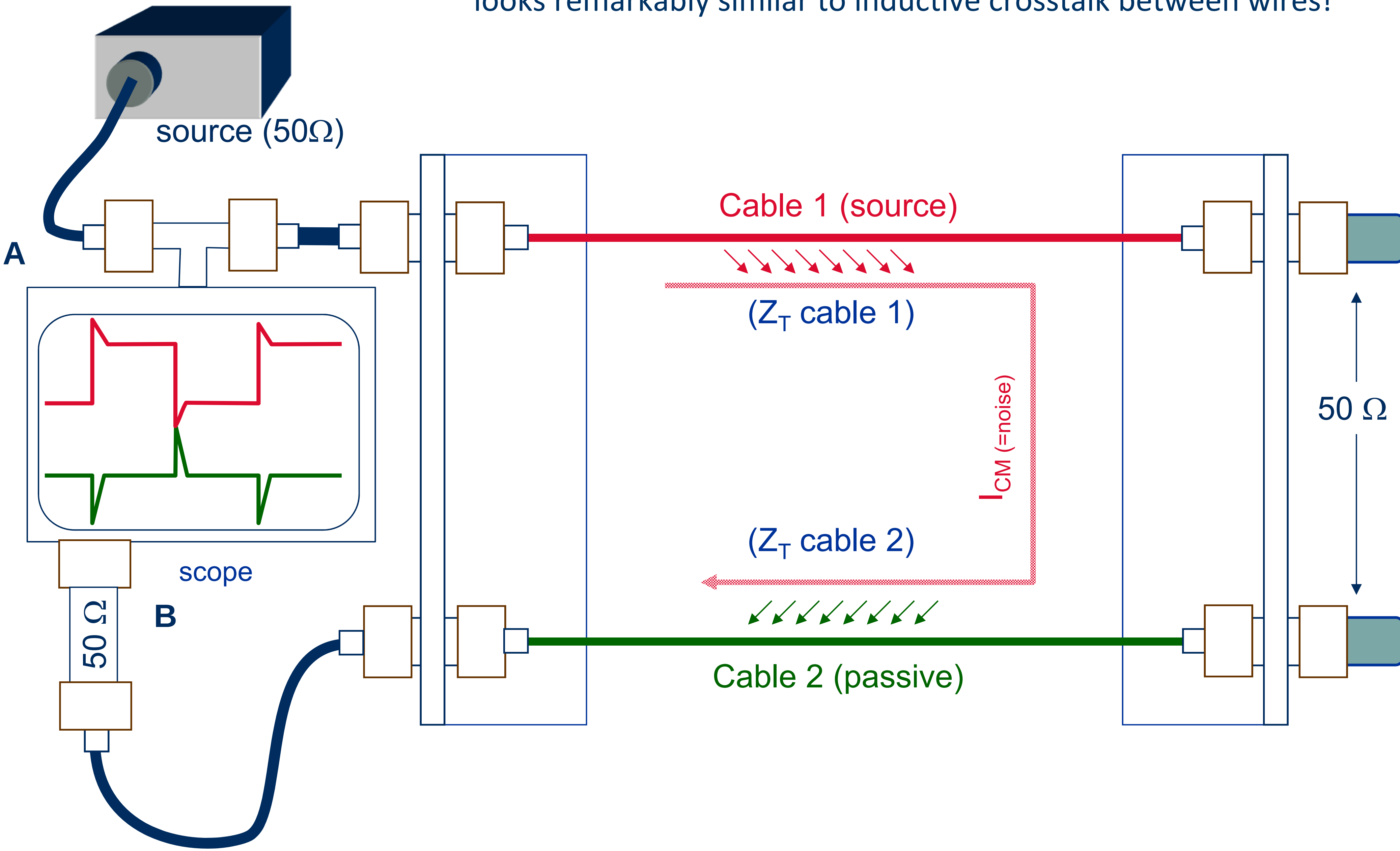
to some extent, pig-tails are unavoidable



Transfer Impedance Crosstalk in practice

looks remarkably similar to inductive crosstalk between wires!



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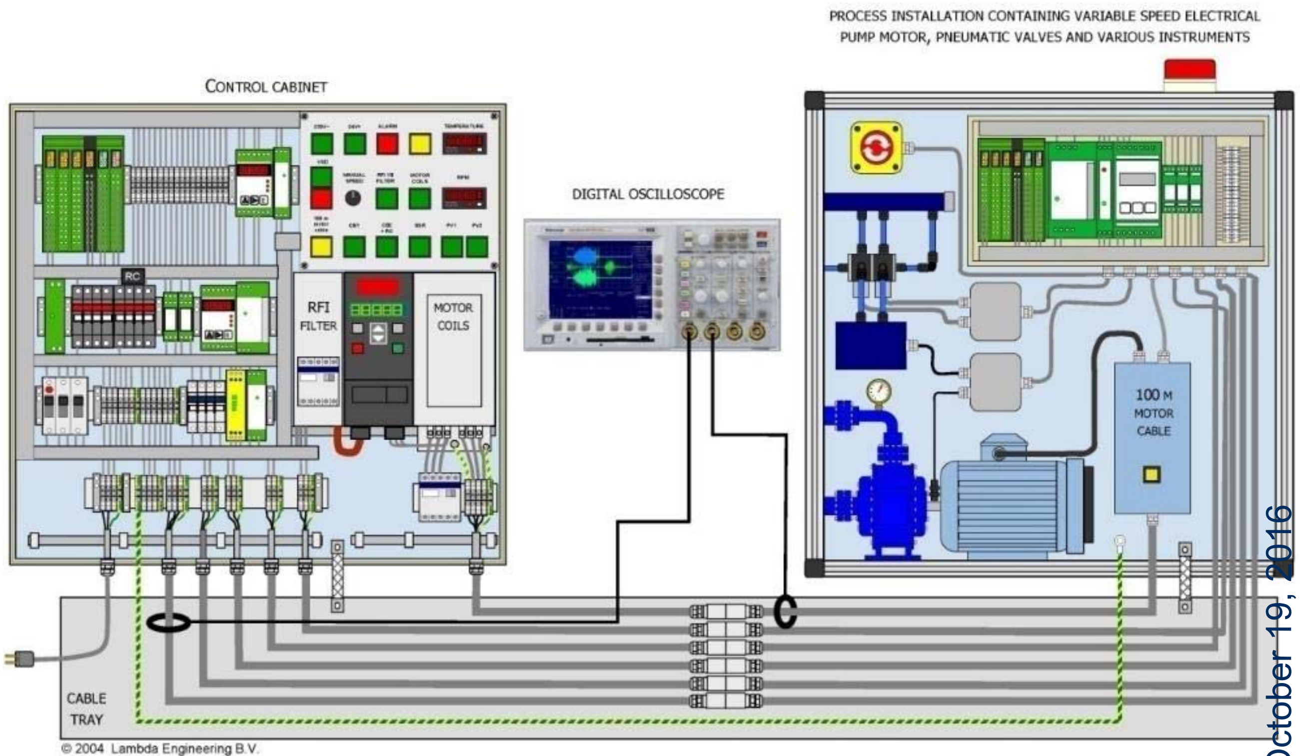
Time for a Break!

- EM sources: variable speed drive, circuit breaker, RF transmitter
- EM victims (analog measurement/control, protection relay)
- Coupling paths
- Cable shielding



EMC specification + installation requirement

2.3. (EMC) electromagnetic compatibility

CE Complies with EMC Directive 2004/108/EC

Immunity to interference in acc. with EN 61000-6-2

• Electrostatic discharge (ESD)	EN 61000-4-2	Criterion B 8 kV discharge in air
• Electromagnetic HF field: Amplitude modulation Pulse modulation	EN 61000-4-3	Criterion A 10 V/m 10 V/m
• Fast transients (Burst)	EN 61000-4-4	Criterion B I/O/S: 2 kV/5 kHz 1)
• Surge voltage capacities (Surge)	EN 61000-4-5	Criterion B I/O: 2 kV/42 Ω 1)
• Conducted disturbance	EN 61000-4-6	Criterion A I/O/S: 10 V 1)

Noise emission in acc. with EN 61000-6-4

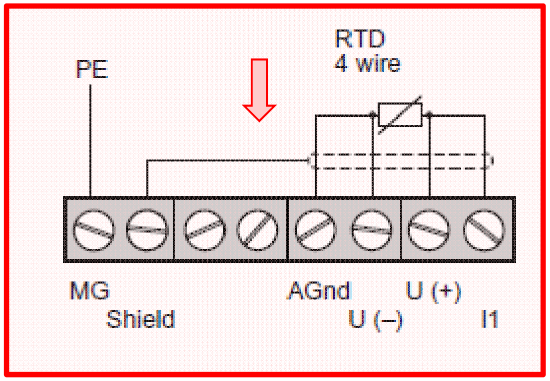
EN 61000 corresponds to IEC 1000
EN 55011 corresponds to CISPR11

1) I ≙ Input / O ≙ Output / S ≙ Supply

Criterion A: Normal operating behavior within the defined limits.
Criterion B: Temporary impairment of operational behavior that the device corrects itself.

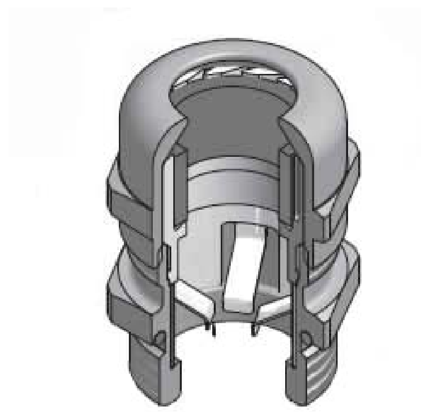
Class A: Area of application: industry, without special installation measures.

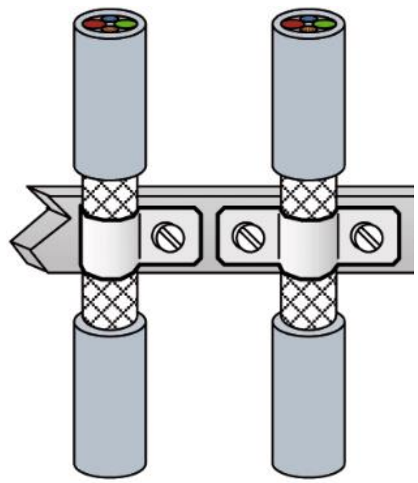
4.3. Connecting an RTD sensor in 4-conductor technology



5126A007

Fig. 10





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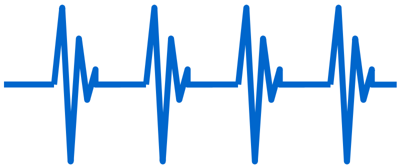
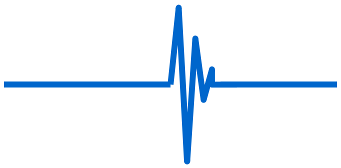
Frequently experienced EM sources

- **Power electronics** (variable speed drives/VSD, thyristor controllers, softstarters, UPS, HF lighting)
- **Switched devices** (relays, circuit breakers, contactors, vacuum/GIS, pneumatic- and hydraulic valves/solenoids)
- **Lightning and induction effects**
- **HF transmitters** (portable transmitters, mobile telephones, fixed transmitters for communication en navigation)
- **ESD** (moving materials, machines with non-conductive elements, conveyor belt, oil tanks, etc.)

Continuous and transient sources

Continuous 

- VSD
- Servo drive
- UPS
- Switched mode power supply (SMPS)

Transient 

- Relay, circuit breaker/ contactor
- Valve (solenoid)
- ESD
- Lightning, short circuit

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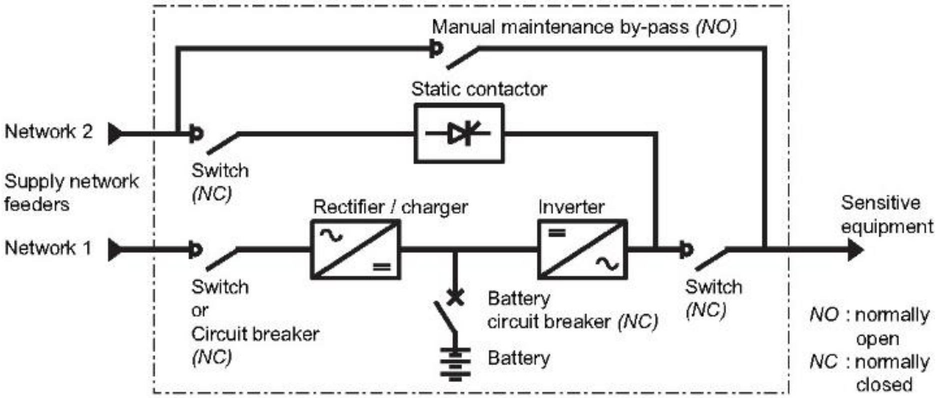
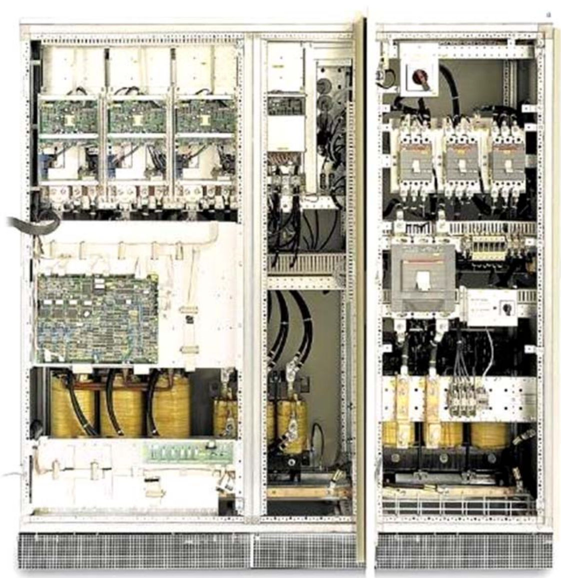
Power electronics (UPS and VSD)

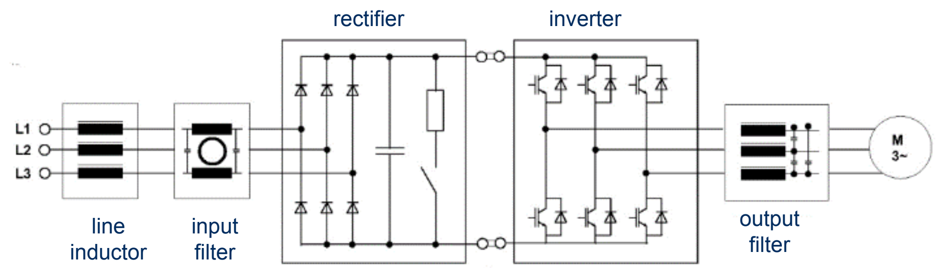
UPS = Uninterruptible Power Supply



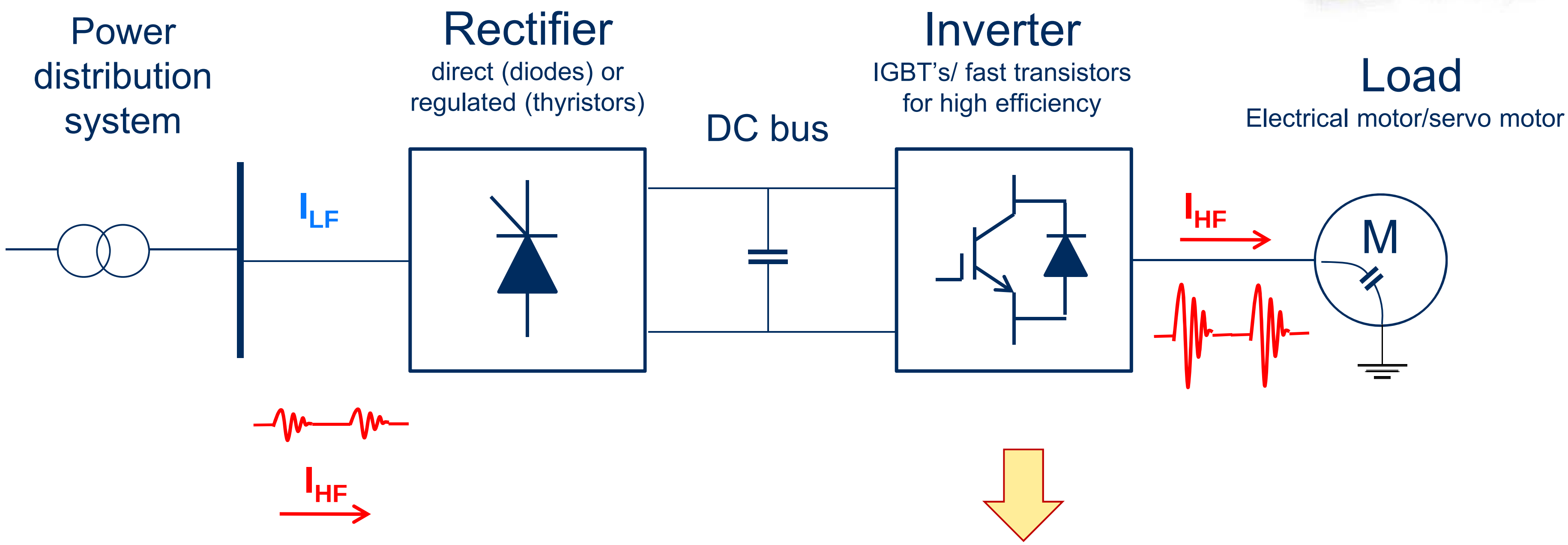


VSD = Variable Speed Drive

FC = Frequency Converter



VSD/servo drive

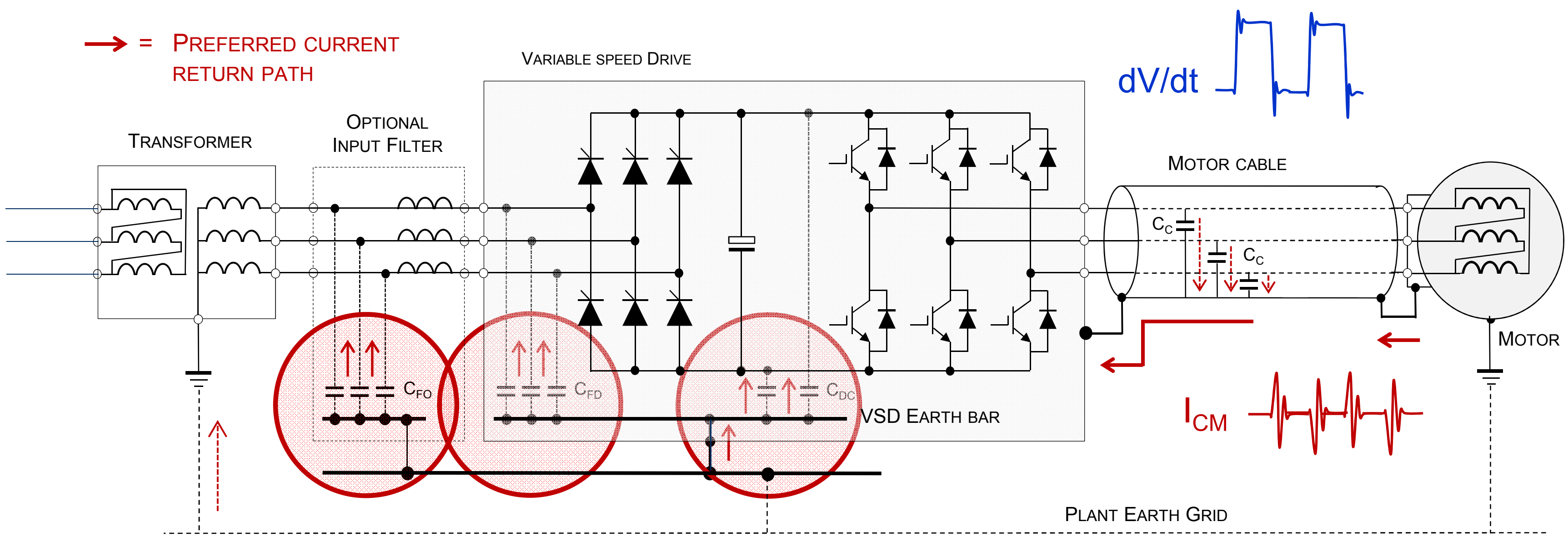


Low Frequency (LF)
- harmonic currents
- notches (from thyristors)

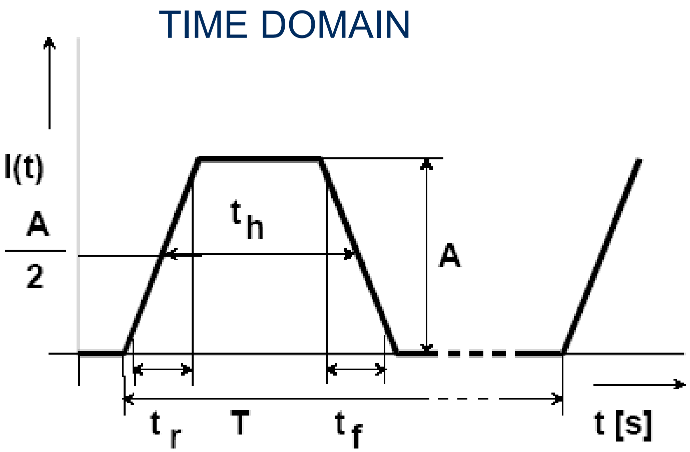
High Frequency (HF) transient currents and voltages from inverter (harmonics of inverterfrequency)

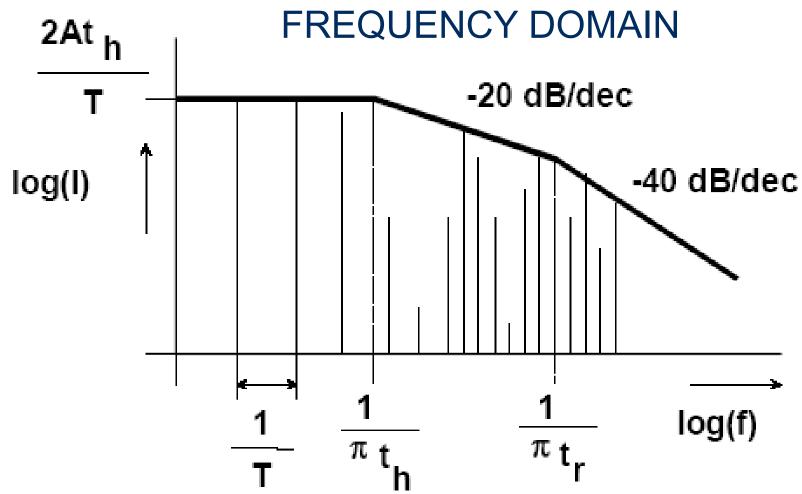
Basic EMC concepts of VSD

- Capacitance of motor winding(s) and motor cables causes capacitive current due to high dV/dt: $I = (C_M + C_C).dV/dt$
- Output filter required to mitigate dV/dt
- Motor cable shield provides preferred return current path
- Internal return path capacitors required in VSD (in DC bus and/or in power supply filter)



FOURIER





$$I(f) = \frac{2At_h}{T}\,\frac{\sin(X_h)}{X_h}\,\frac{\sin(X_r)}{X_r}$$

with $f_o = \dfrac{1}{T}$ $\quad X_h = n\pi f_o t_h \quad X_r = n\pi f_o t_r$

Typical IGBT switching rate: 5kV/µs (high efficiency)

Example: f_{inv} = 4kHz → T=250µs
t_h = 50µs → 1/π t_h = 6.4kHz
t_r = 100ns → 1/π t_r = 3.2MHz

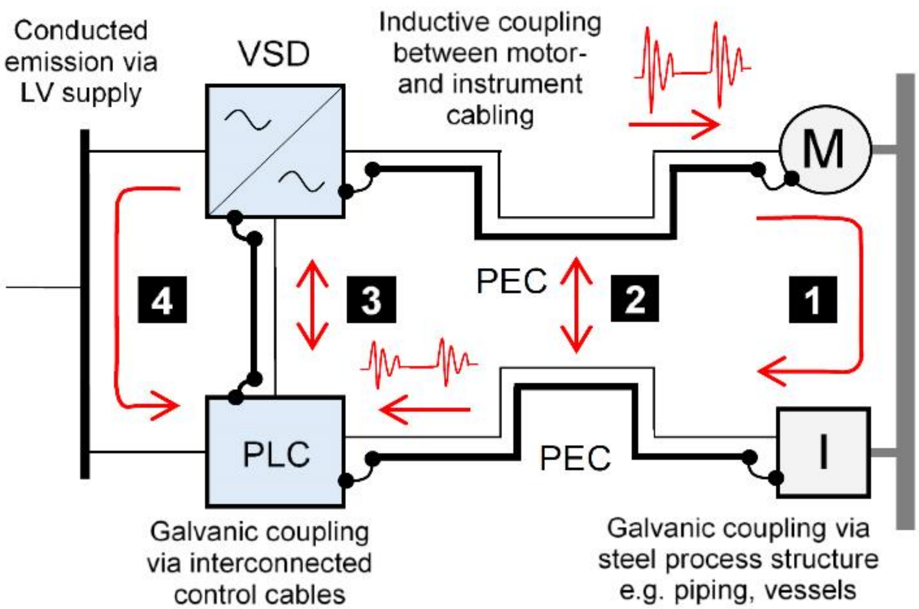
Under construction

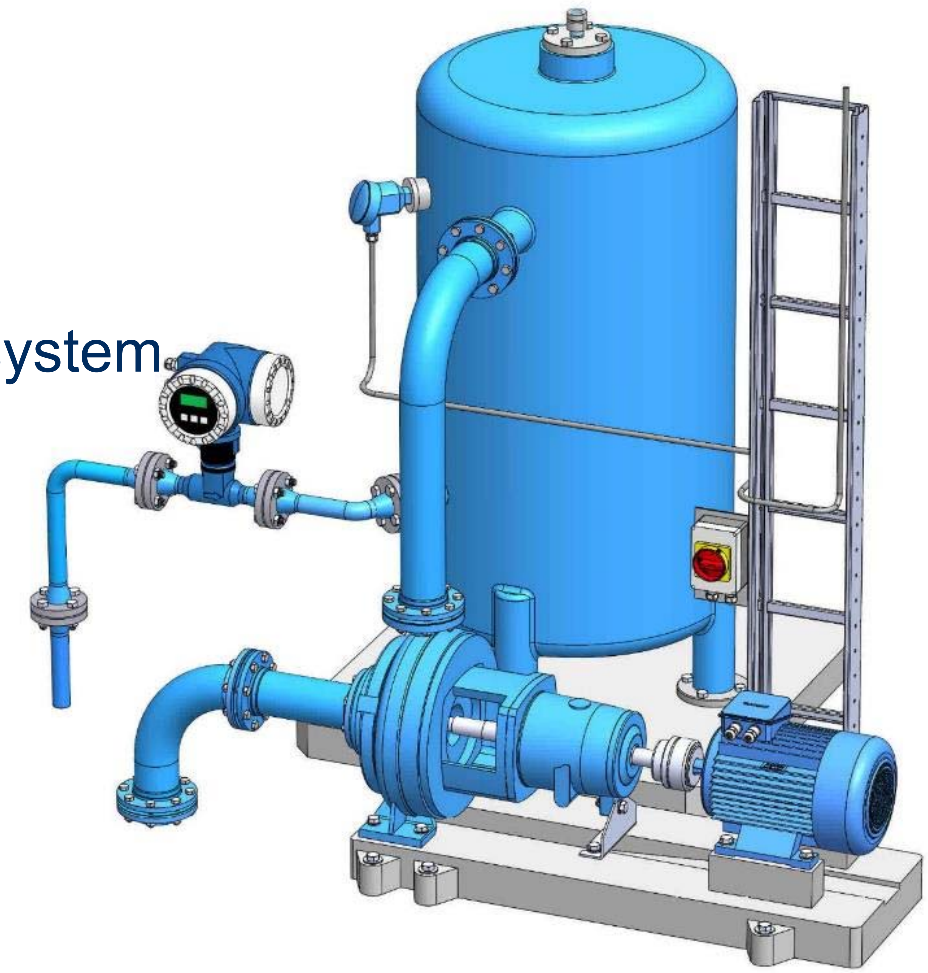
In the field

1. Coupling via process piping, vessels and instruments
2. Coupling via parallel cables

In the control room

3. Coupling via local control ports
4. Coupling via LV power distribution system





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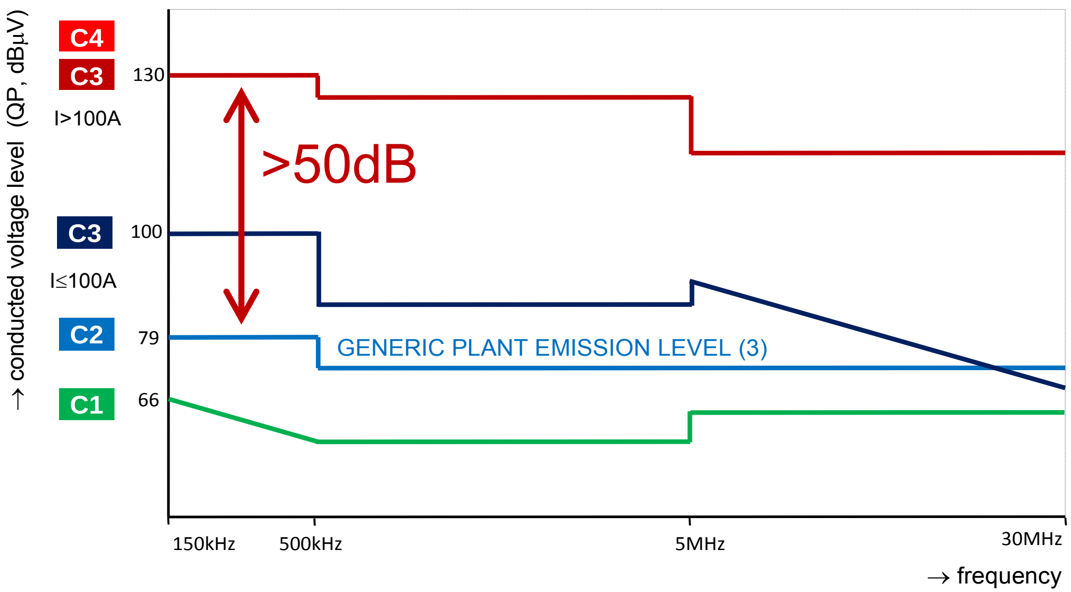
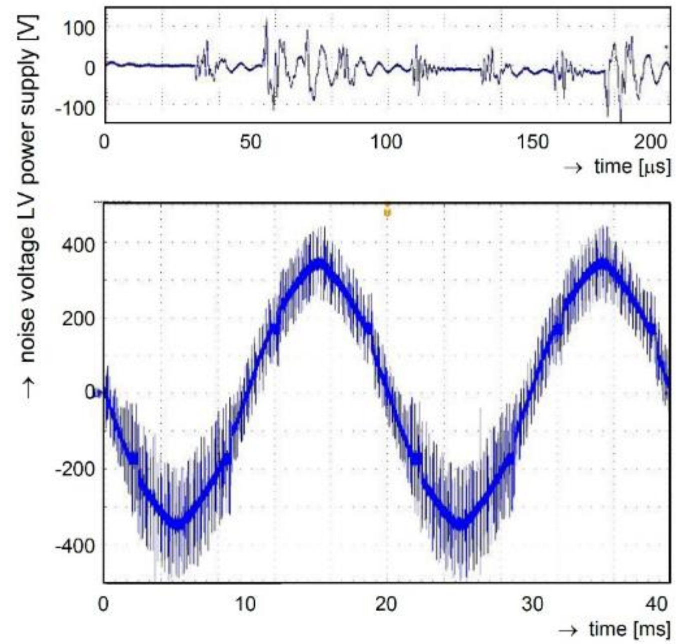
Installation aspects of VSD/servo drive

1. Type of motor (isolation class, eddy current losses)
2. Motor cable length (cable capacitance, I_{CM}, transient peak voltage at motor winding)
3. Shielding quality of motor cable (transfer impedance)
4. Low impedance terminations of cable shields (drive, motor, safety switch etc.), control cables
5. In- and output filters: reduction of dV/dt, noise voltage reduction on power supply
6. Segregation of power supplies
7. Segregation with other cables

Conducted emission via power supply

- Emission level as per the product standard IEC 61800-3
- EMC plan required for category C4





IEC 61800-3 categories and emission limits:

- C1 Equivalent to generic emission level for residential environment (IEC 61000-6-3)
- C2 Equivalent to generic emission level for industrial environment (IEC 61000-6-4)
- C3 I_{PH} ≤100A. No reference to generic standard. Severe industrial emission level (EM level 4)
- C3 I_{PH}>100A. Very severe industrial emission level (EM level 4+)
- C4 No emission limit (I_{PH}>400A and/or V>1000V)

Category C3/C4
EMI voltage in time domain

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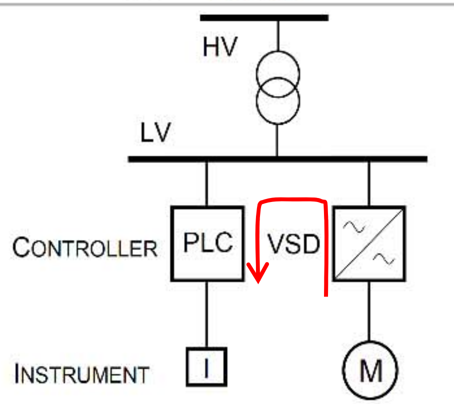
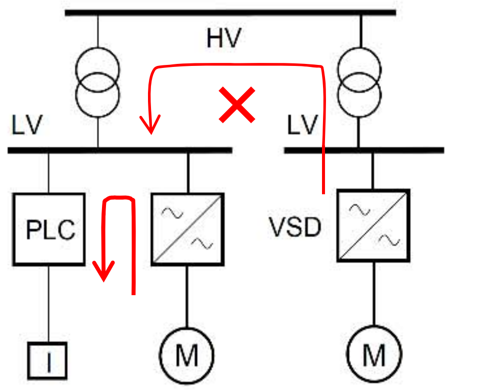
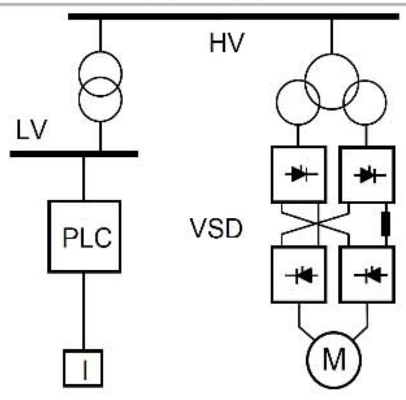
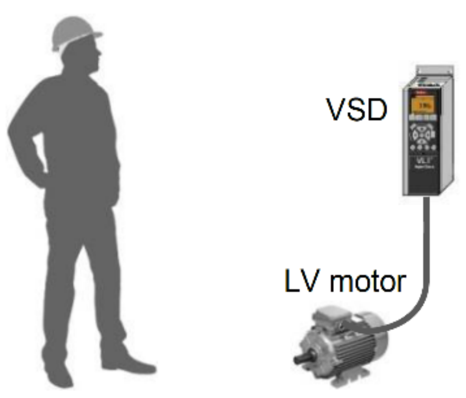
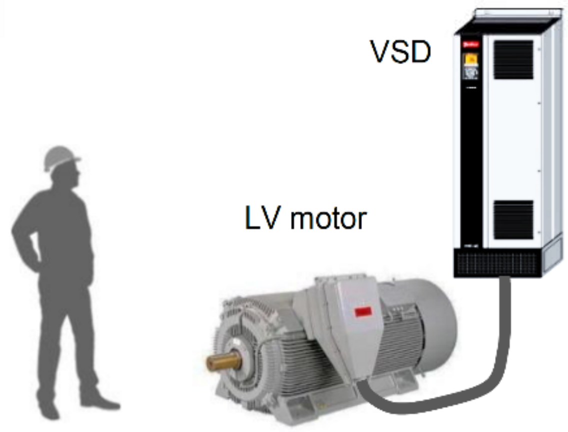
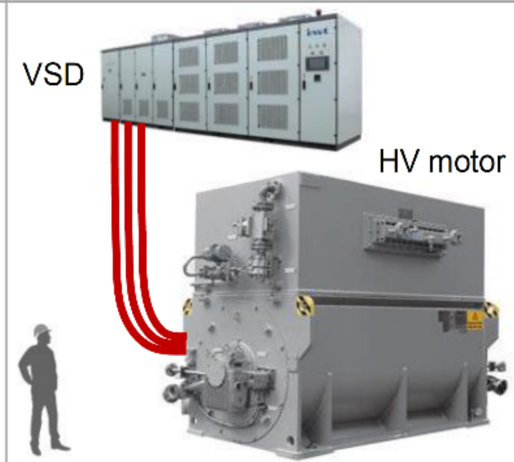
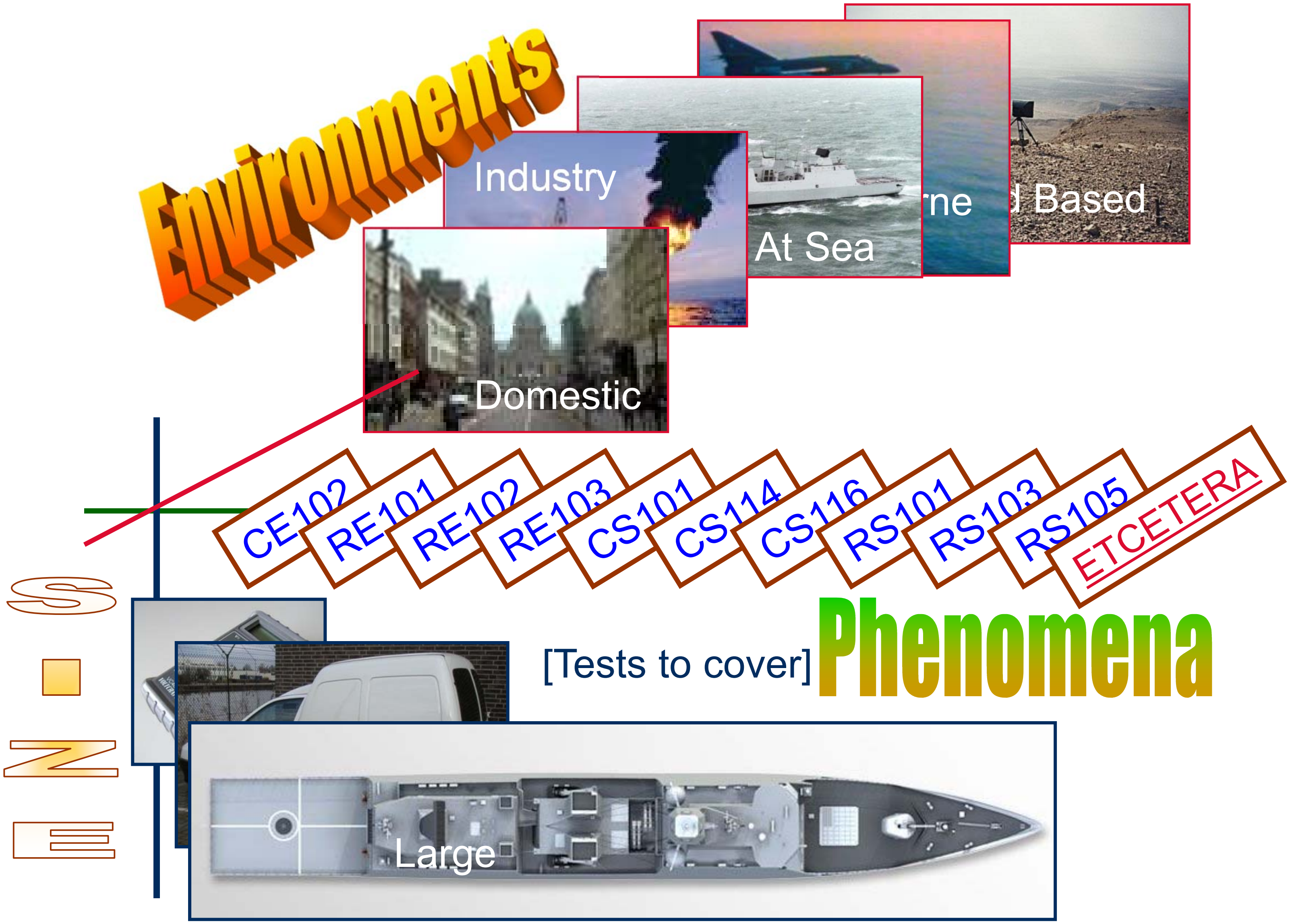
Overview of VSD per power range

VARIABLE SPEED MOTOR DRIVES					
Power range	0.1 – 100 kW		100 kW – 1 MW		1 MW – 40 MW
Typical power supply arrangement					
Size					
Cond. emission IEC 61800-3	C1 (Domestic)	C2 (Industrial)	C3 ($I_{PHASE} \leq 100A$)	C3 ($I_{PHASE} > 100A$)	C4 ($I_{PHASE} > 400A$, $V_{PHASE} > 1000$ V)
	56-66 dBµV QP	79-73 dBµV QP	86-100 dBµV QP	115-130 dBµV QP	No limit, EMC plan required
EMI risk	Low	Low	Medium	High	Medium

The Three Dimensions of EMC

systems EMC requirements are set by the environment it is intended for



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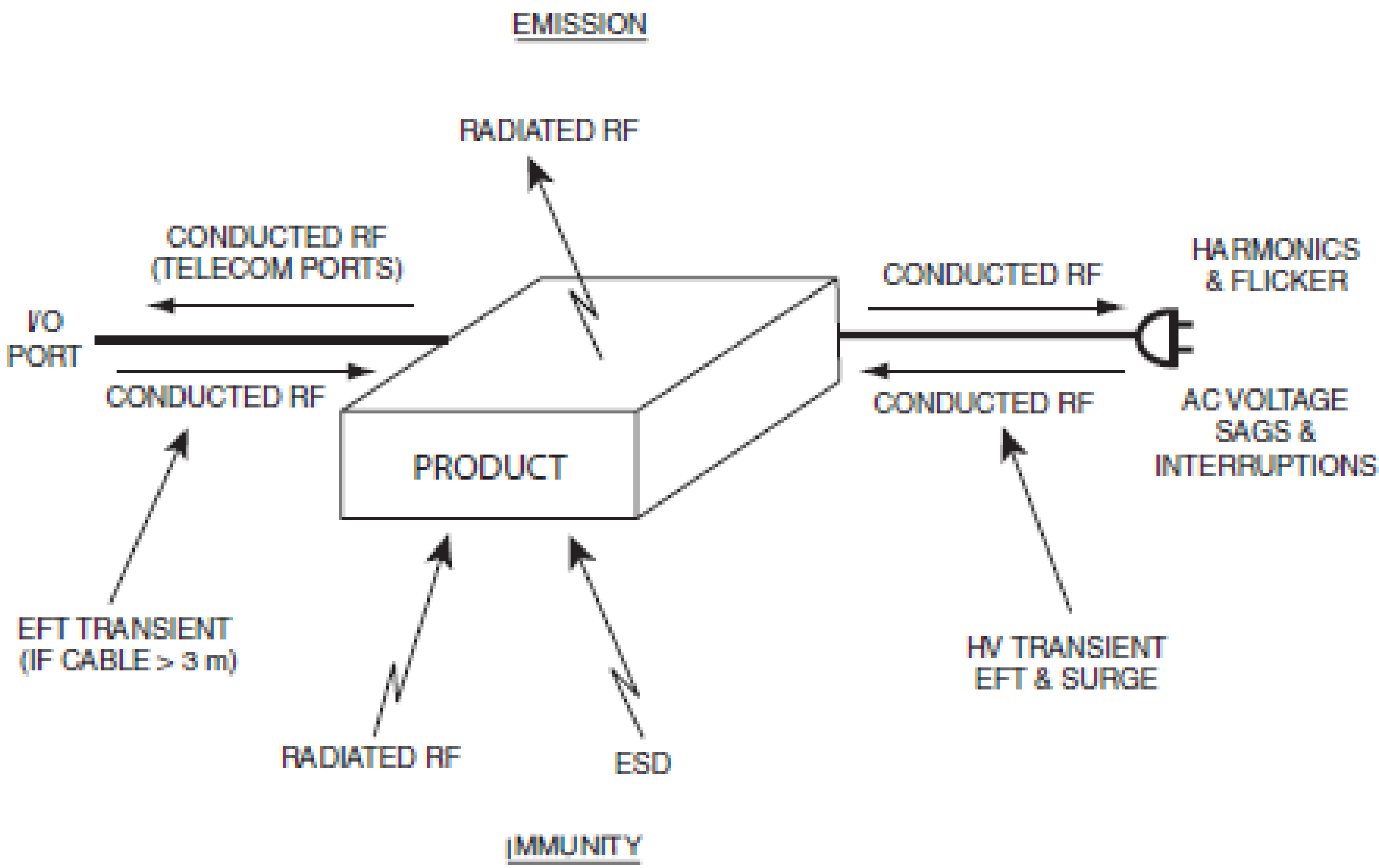
Standards address different EM Phenomena

tests are defined to check each relevant aspect



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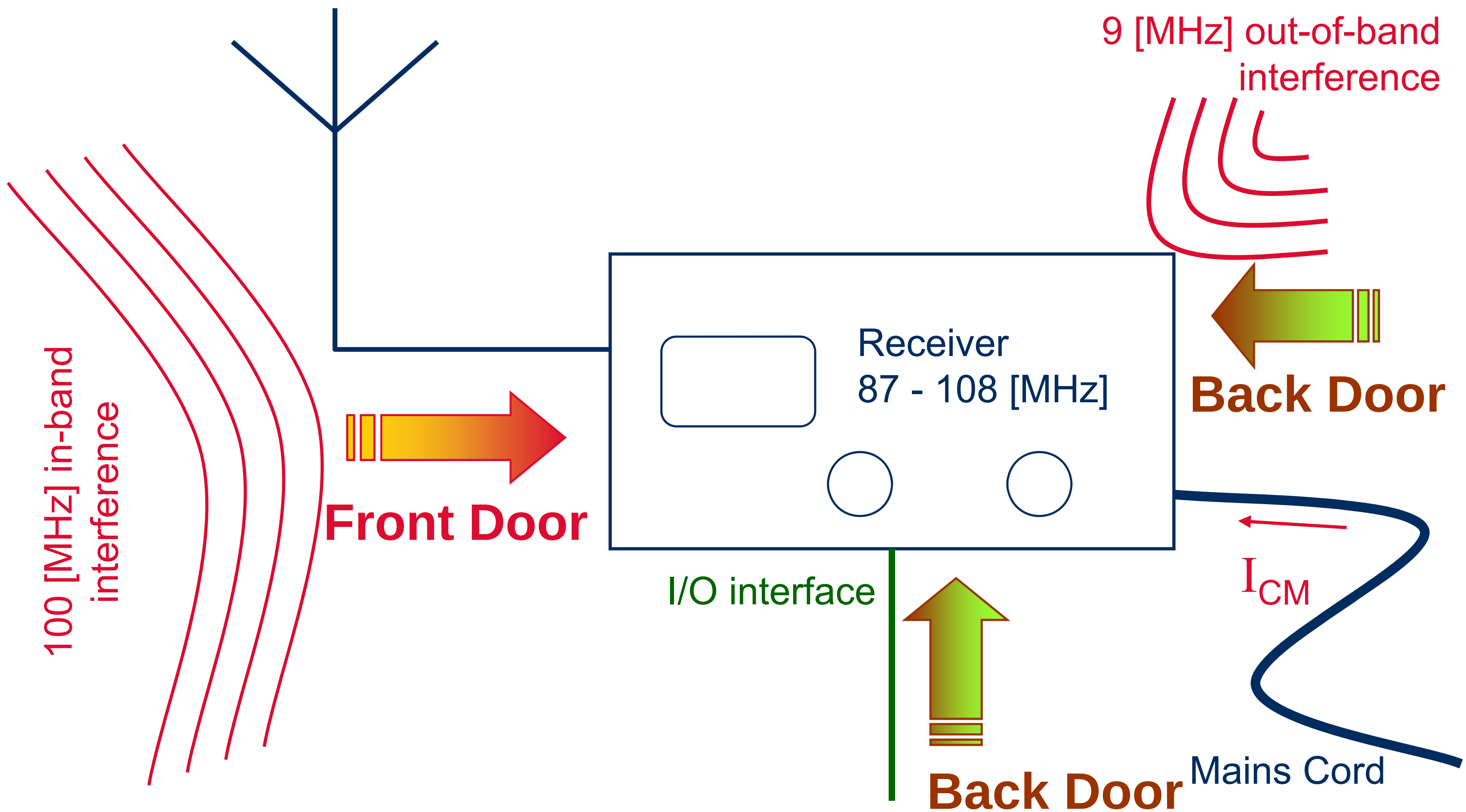
Front Door / Back Door EMI

Front Door: Intended Coupling Path; Back Door: Unintended Coupling Path



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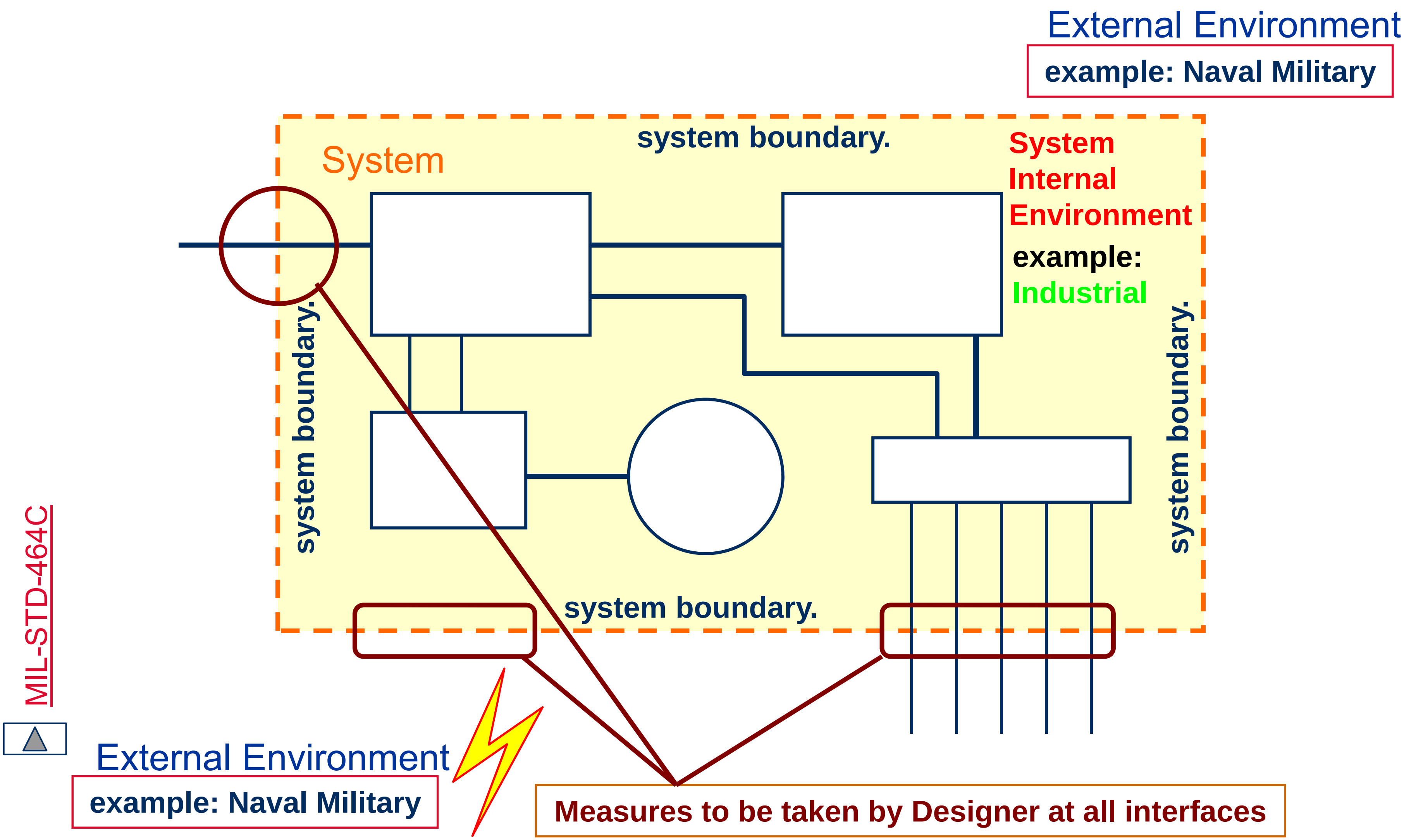
Performance Criteria Determine Urgency of Measures

depending on criticality of failure, a criterion is selected (usually in test standard)

A	System continues to work according to specification Degradation not acceptable Generally applies to all interference with a continuous nature
B	Temporary degradation acceptable, auto recovery. Usually applies to sporadic interference to a non-critical function.
C	Degradation acceptable. Recovery after manual RESET. e.g. at mains interruptions. Only for non-critical functions.

System Boundary is EM-Environment Boundary

within the system boundary, compatibility levels can, in theory, be set as desired



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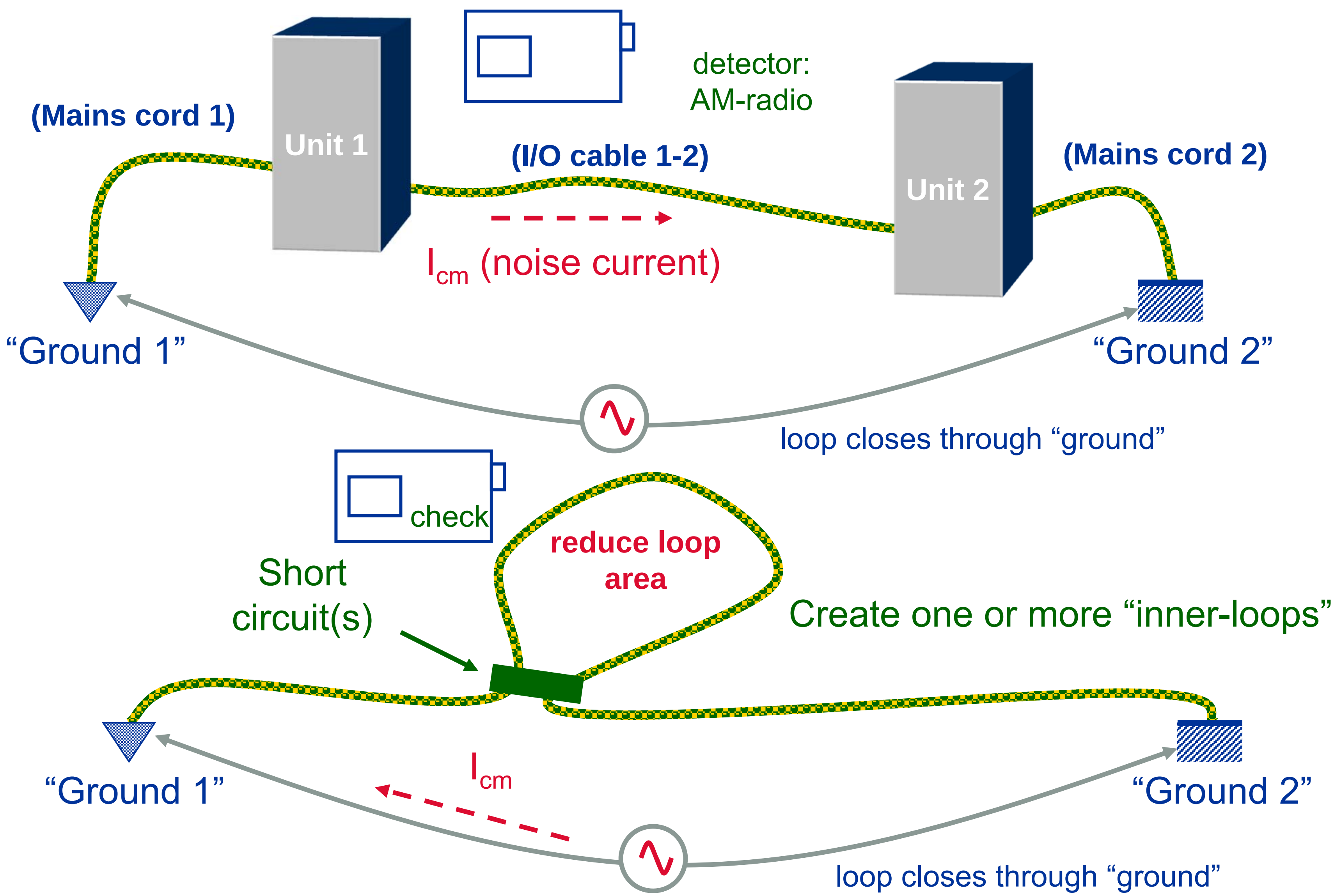
The Current Boundary

a provision to split loops (and shut out noise sources)



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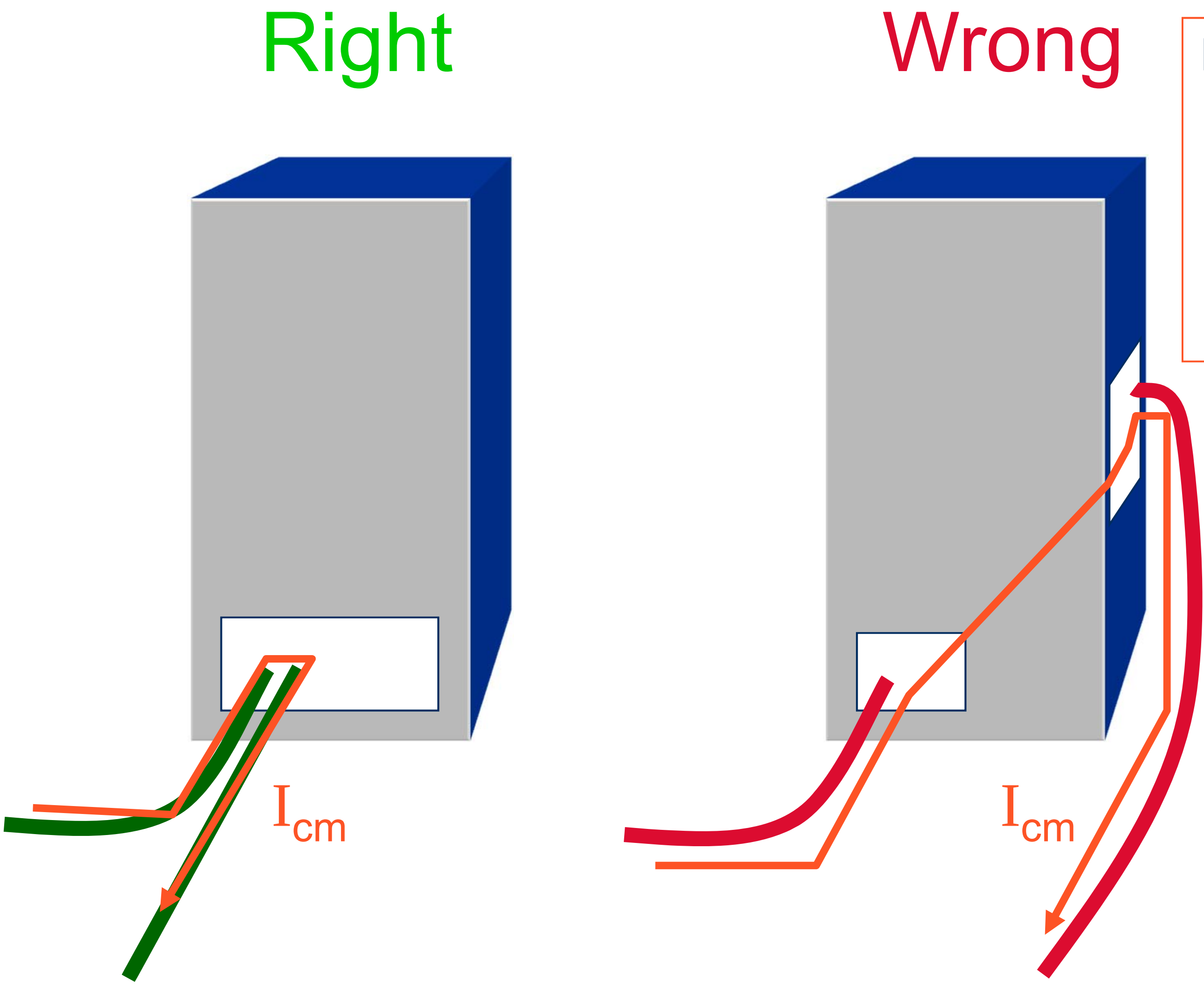
Install current boundaries at natural interfaces

edge of PCB, cabinet wall, basement of a building; one boundary per unit!



Drawbacks:

- Current follows long path over equipment
- Loop area cannot easily be minimized

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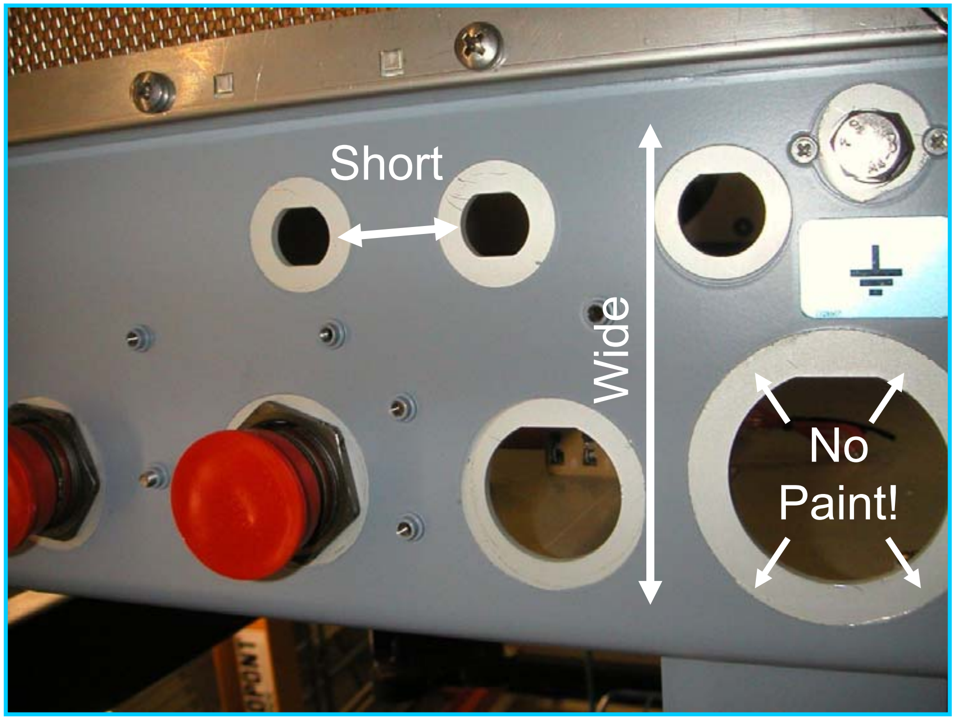
Examples of current boundaries on equipment

wide conductors and low-resistance transitions (be careful with paint) !



protect all units with a current boundary!
(and check any conductor that passes it)

check DC resistance with
a milli-Ω meter: < 1 mΩ!

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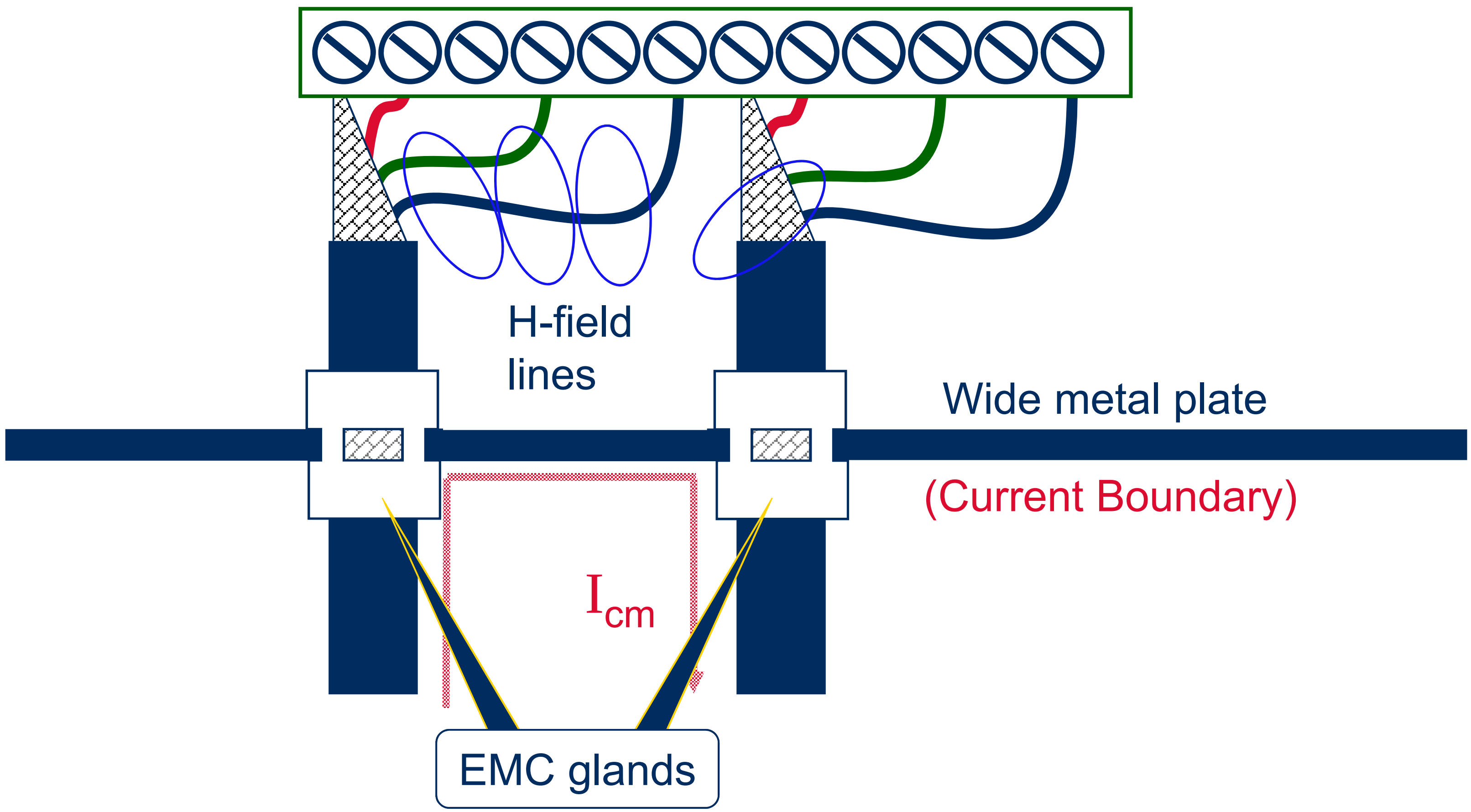
Use Current Boundary to protect existing "pig-tail"

pig-tails can be acceptable as long as CM currents are kept away from it



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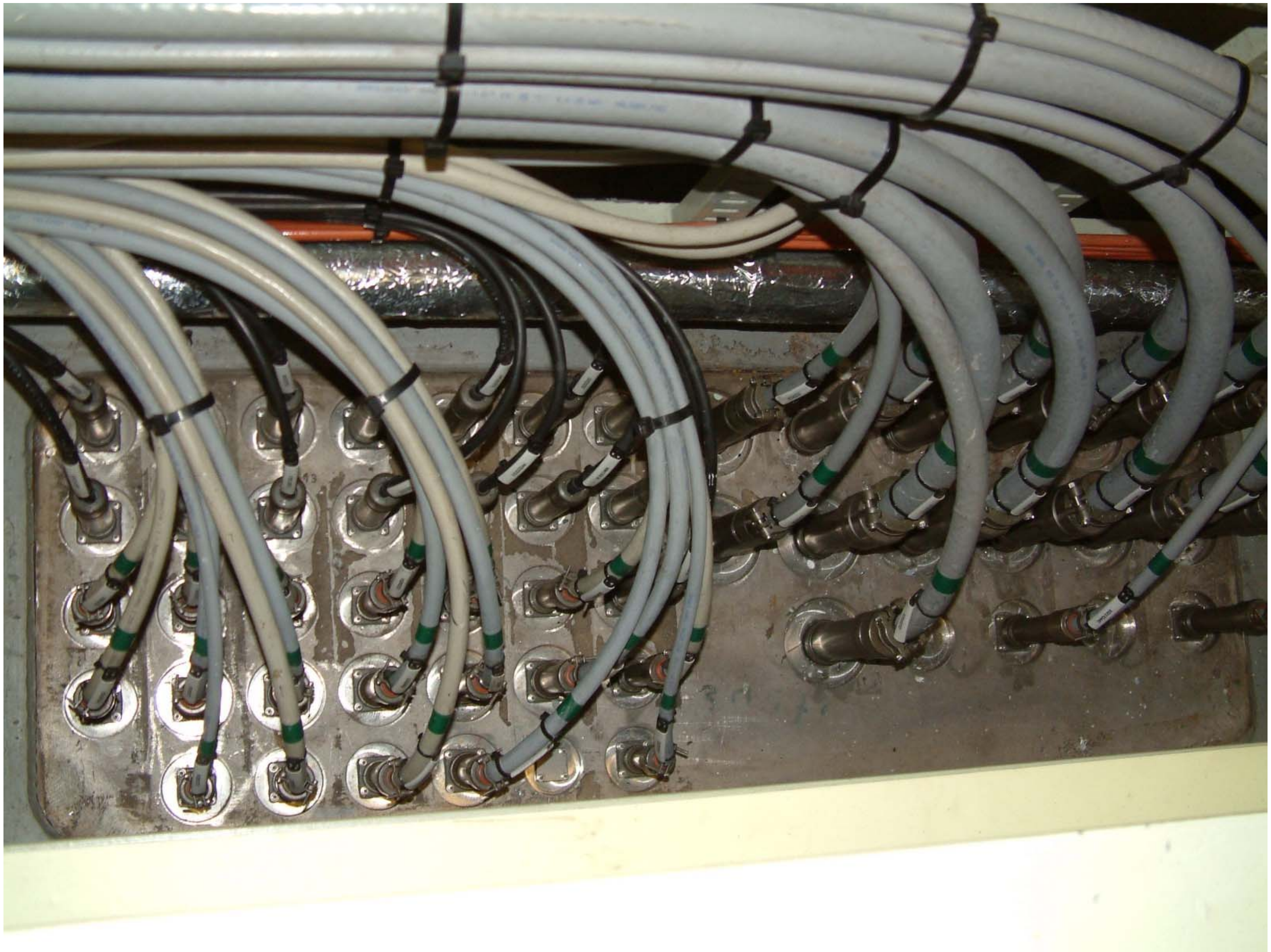
If many Cables are Guided through Shielding Wall..

other options exist



Roxtec / Brattberg Glands

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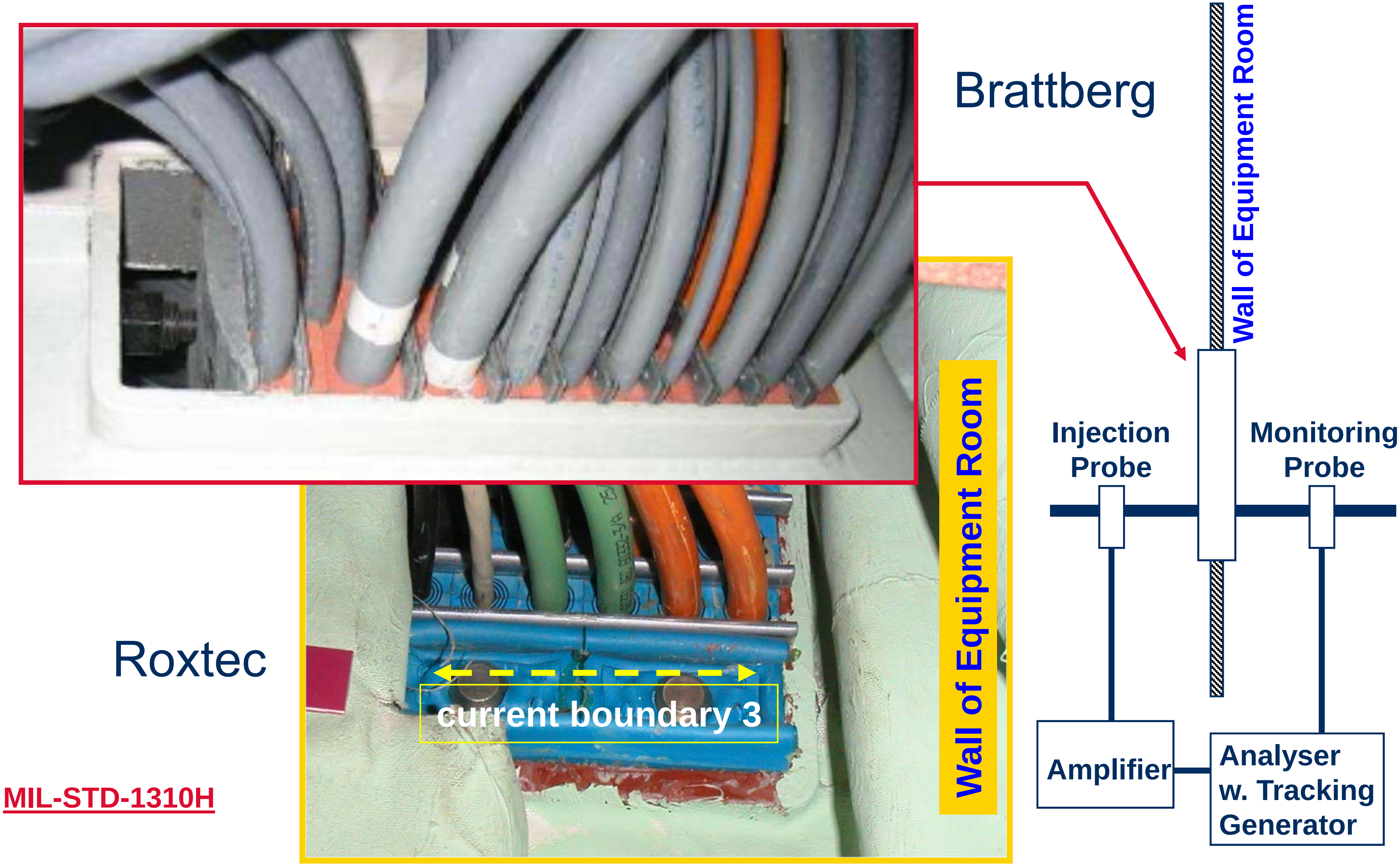
Special Gland System: Many Cables Through Wall

all make good electrical contact in wall (< 10 mΩ)



MIL-STD-1310H

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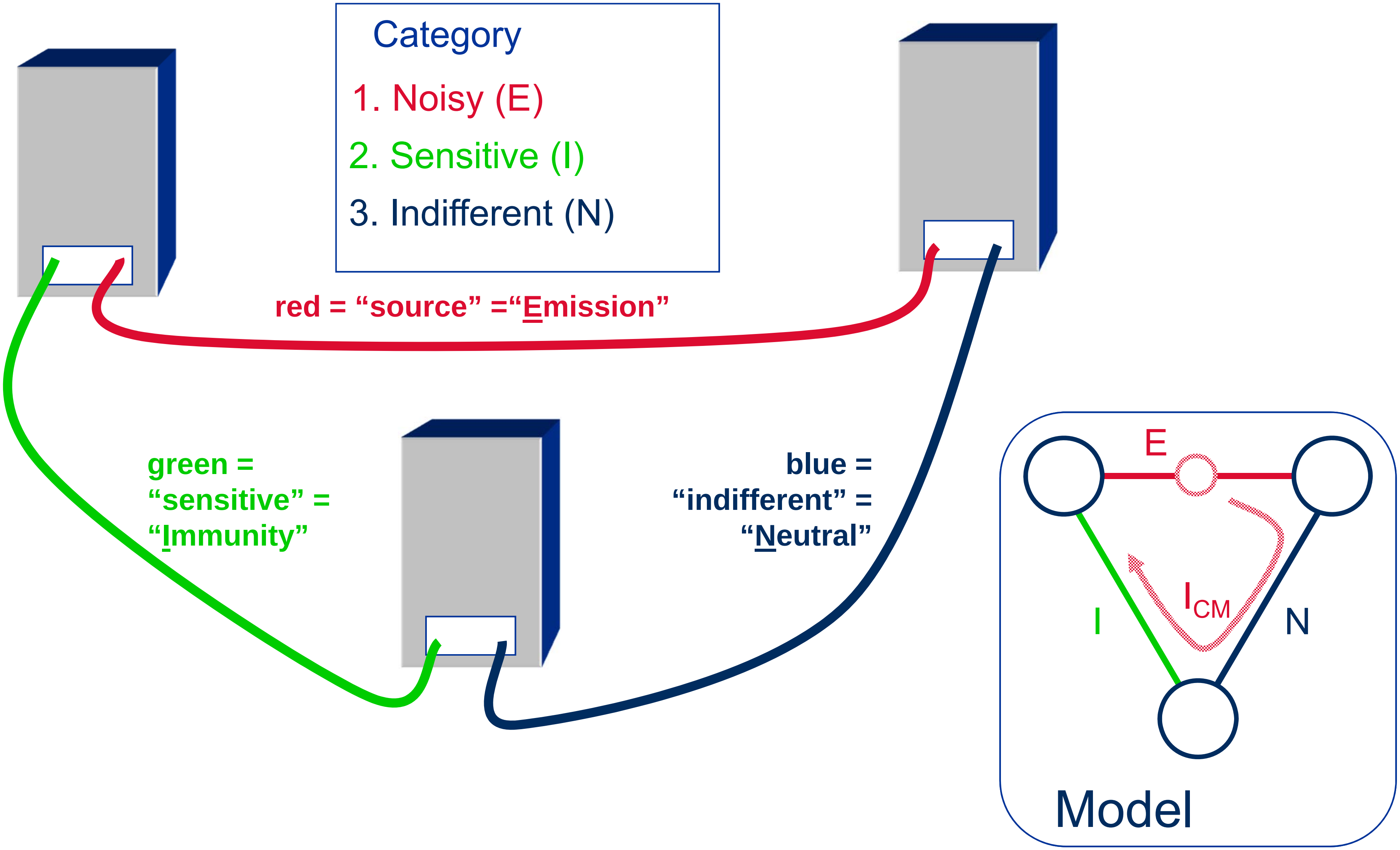
Next: Separate *Cables* with Current Boundaries

classify cables into categories



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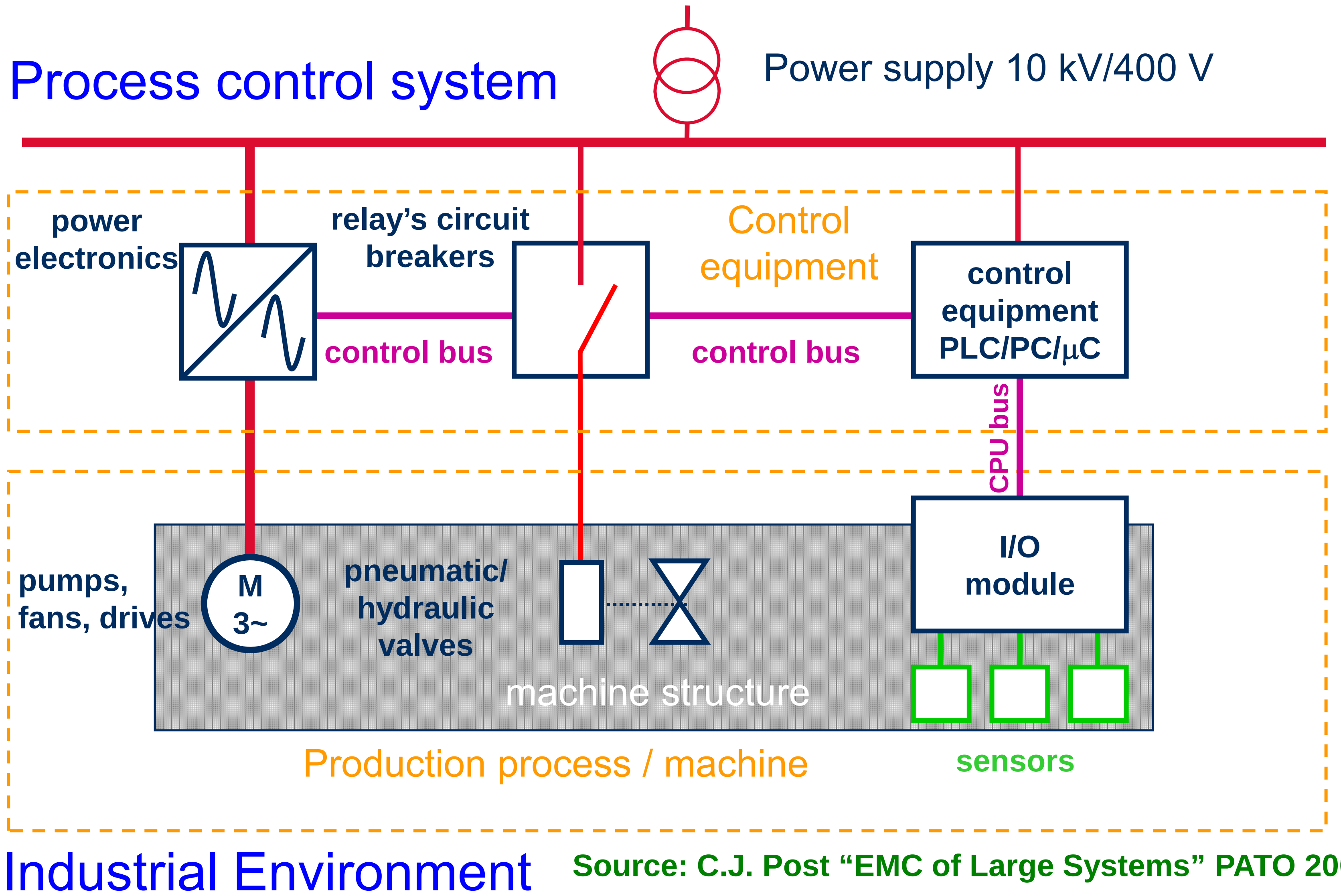
Model the Real System in CM loops

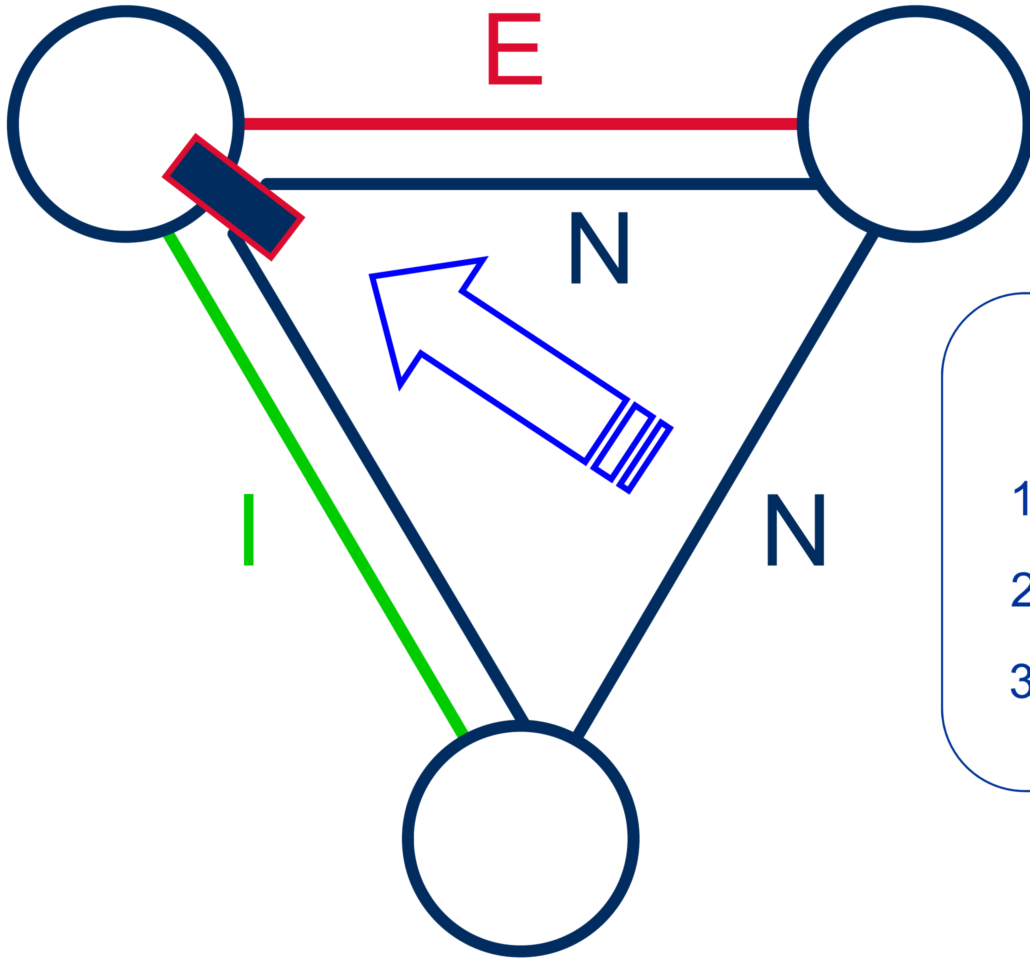
Both sensitive (analog, various busses) and (polluted) power lines



Source: C.J. Post "EMC of Large Systems" PATO 2007

Separating Cables with Current Boundaries

use Neutral conductor to reduce loop area; then insert current boundary



Steps:

1. recognize loop
2. reduce looparea
3. add boundary

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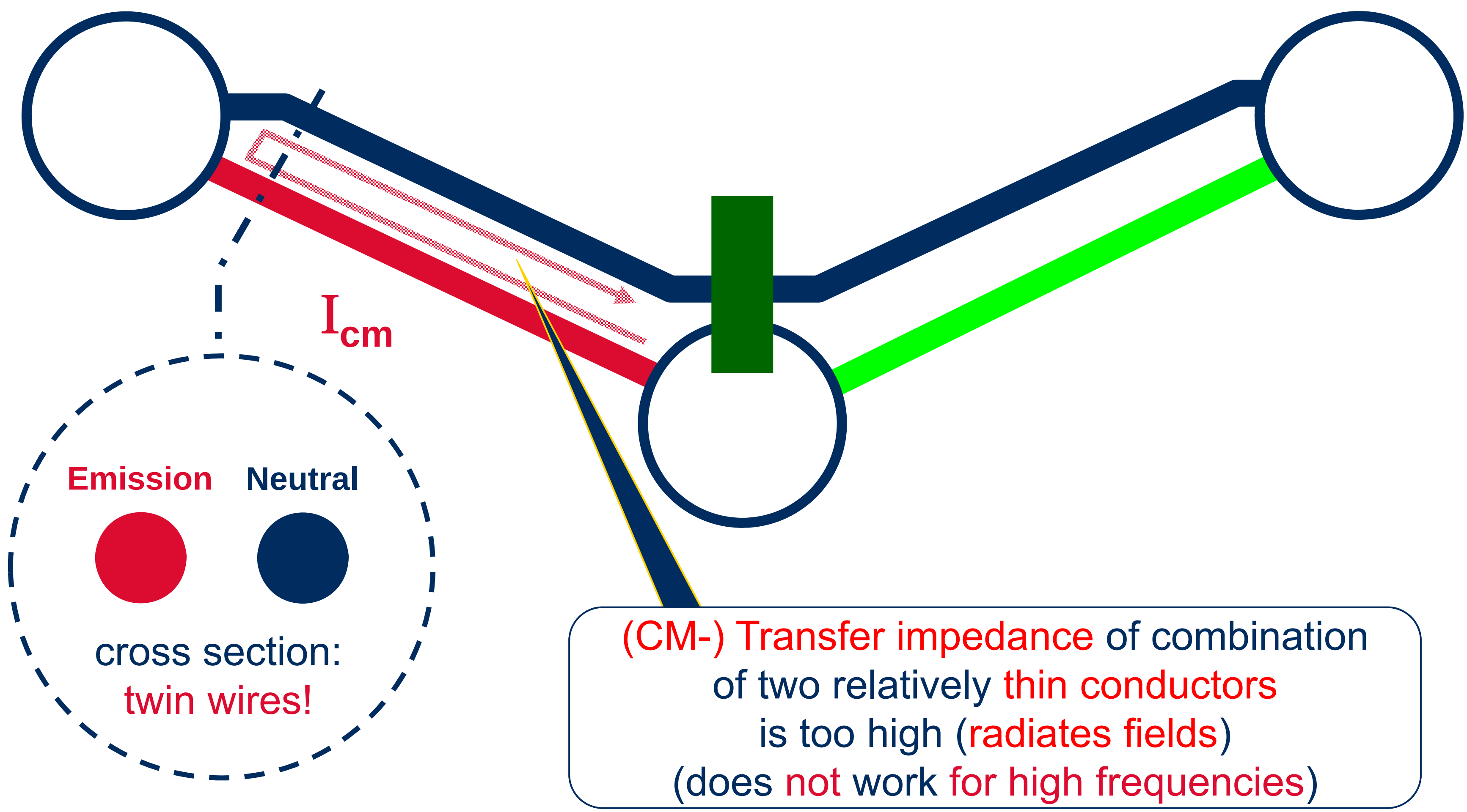
Separating Cables with Current Boundaries

neutral conductor in practical cases: never a “wire”, always a structure part



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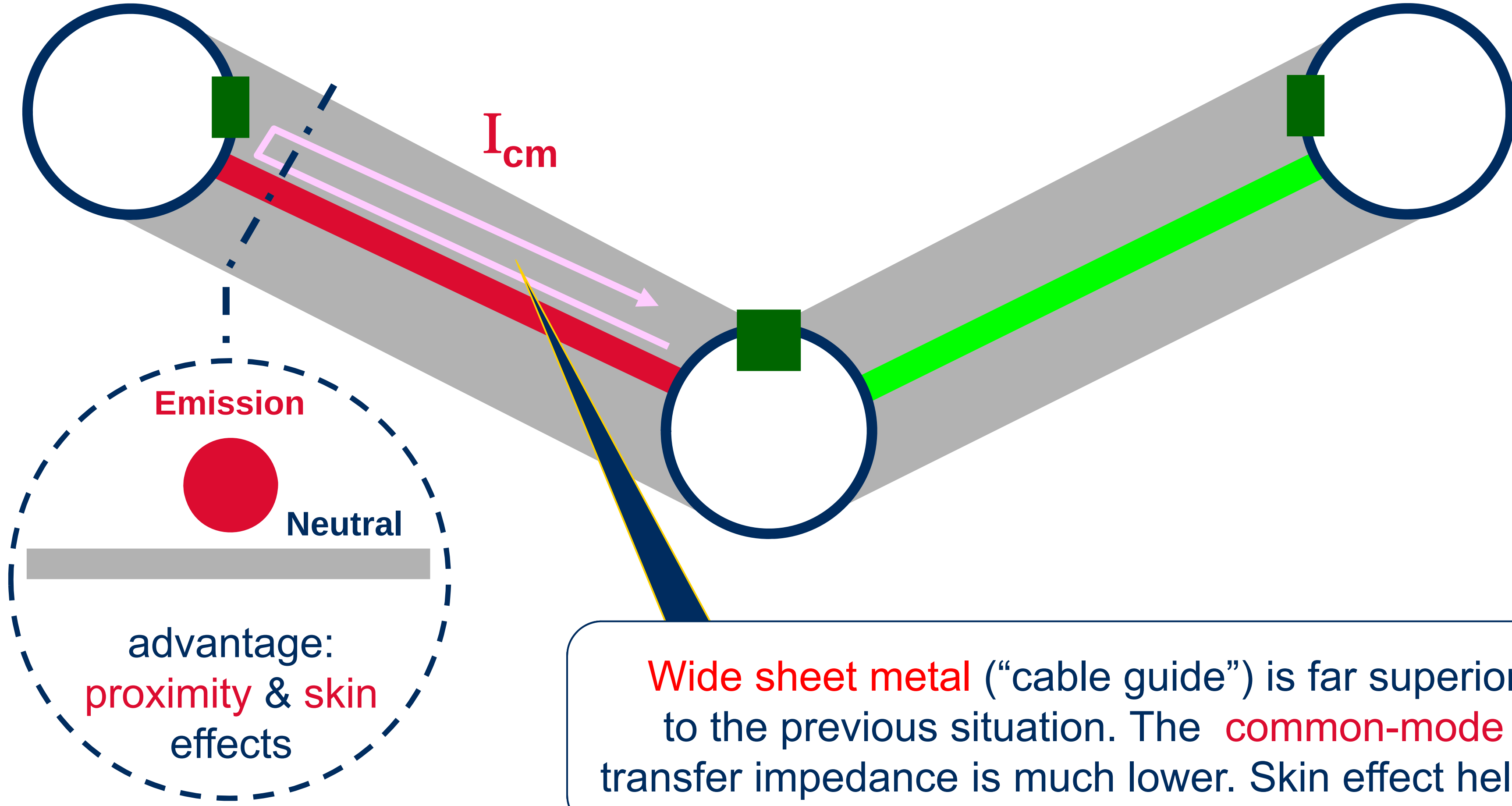
wide metal reduces fields i.e. the transfer-impedance of the cm-current loop



Wide sheet metal ("cable guide") is far superior to the previous situation. The common-mode transfer impedance is much lower. Skin effect helps.

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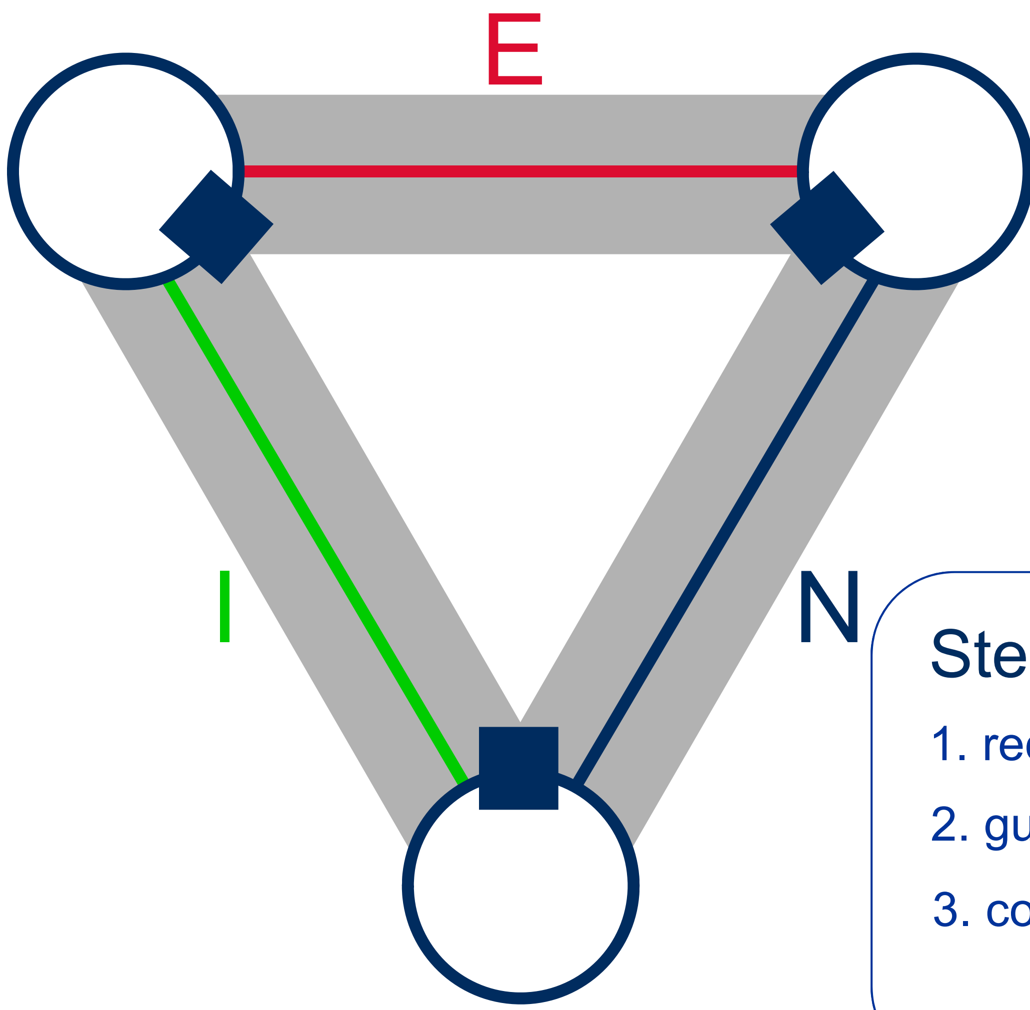
use structure metal parts to “guide” cables and insert current boundaries

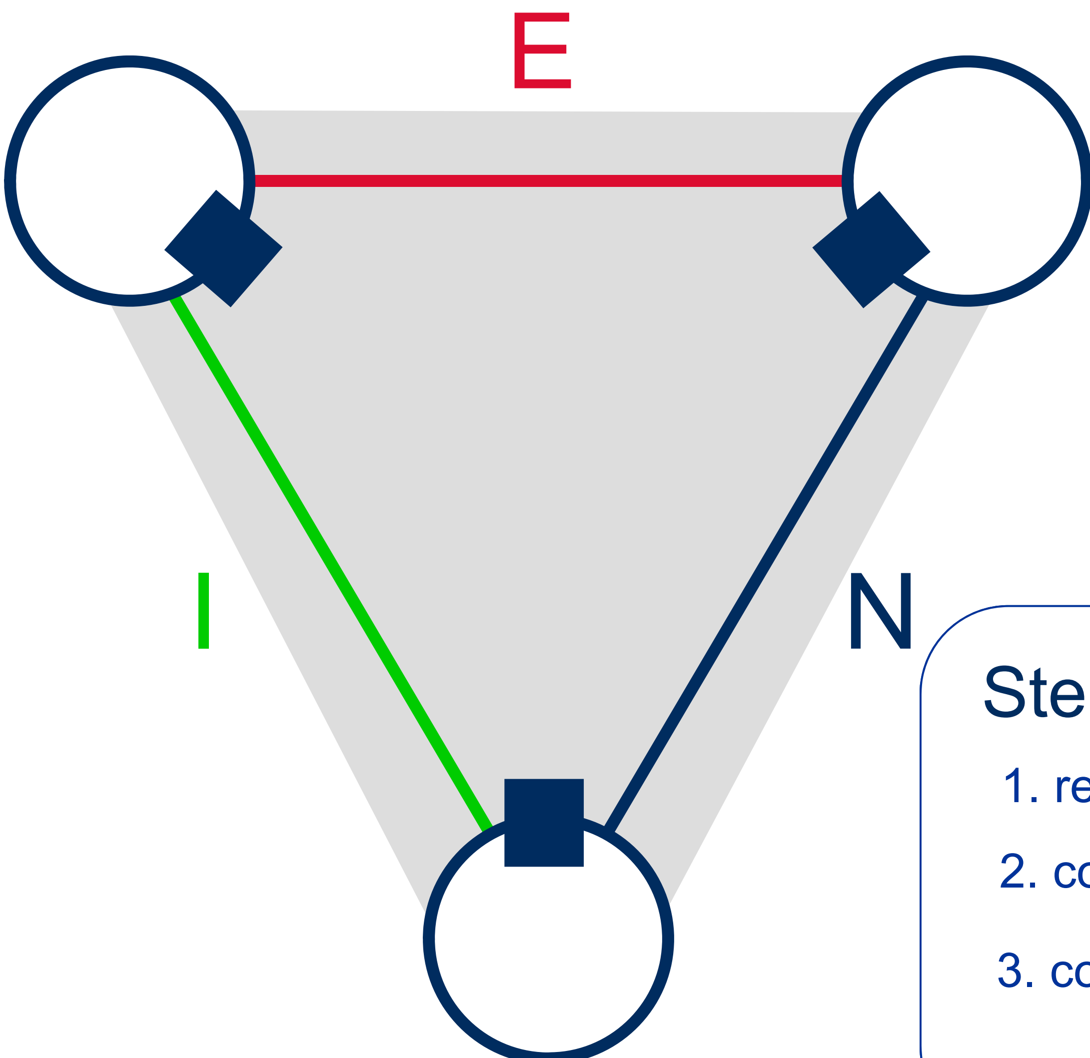


Steps:

1. recognize loop
2. guide cables with metal strips or trays
3. connect current boundaries to strips

Separating Cables with Current Boundaries

use (Ground-) Plane to reduce loop area; then insert current boundaries



Note: we are actually reducing *CM-loop* areas here, using *wide* metal *"short-circuits"*

Steps:

1. recognize loop
2. cover loop with metal (ground-)plane
3. connect current boundaries to plane

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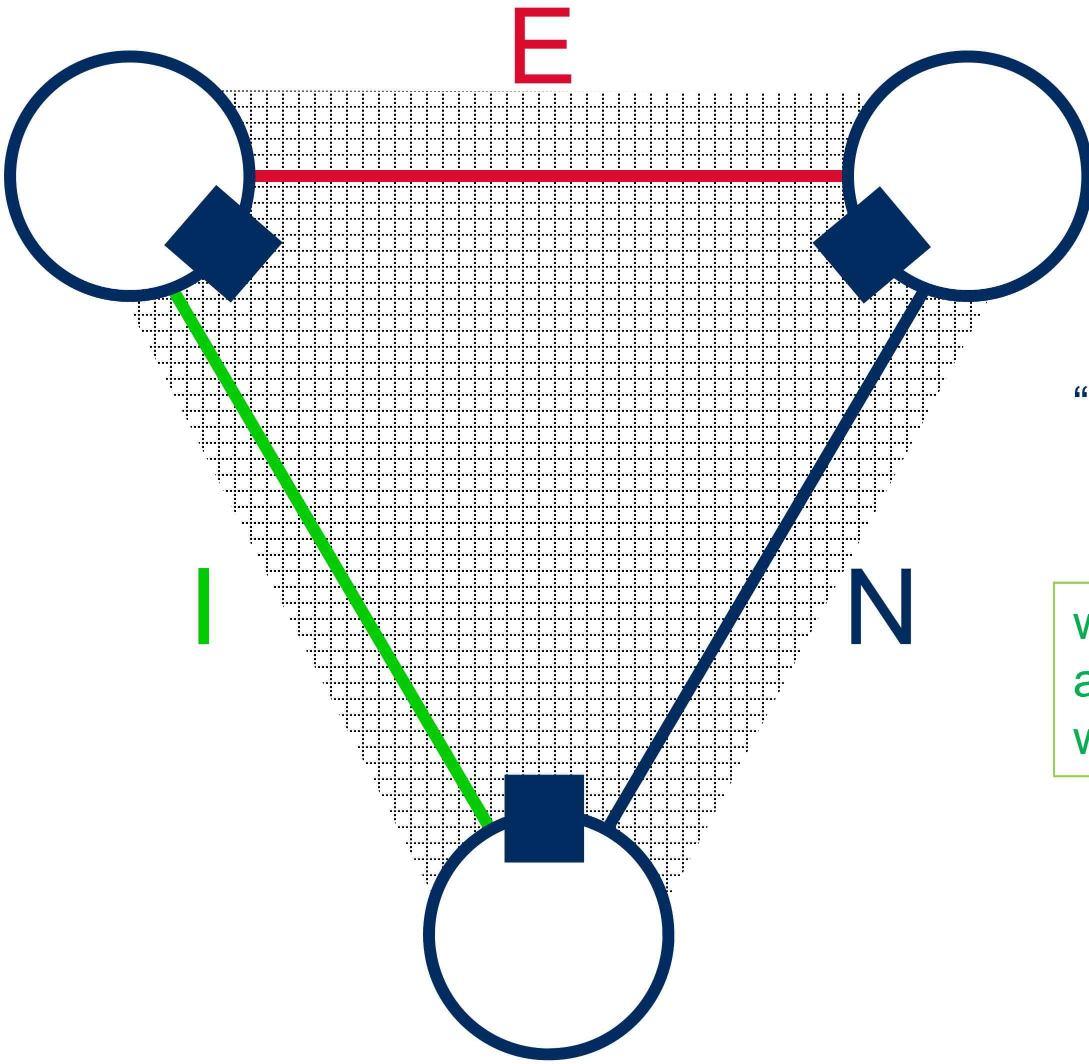
Separating Cables with Current Boundaries

instead of a metal plane a metal mesh could be used



“Plane” could be metal mesh

wavelength is key to mesh size: apertures should be very small with respect to ¼ wavelength ($\lambda/4$)

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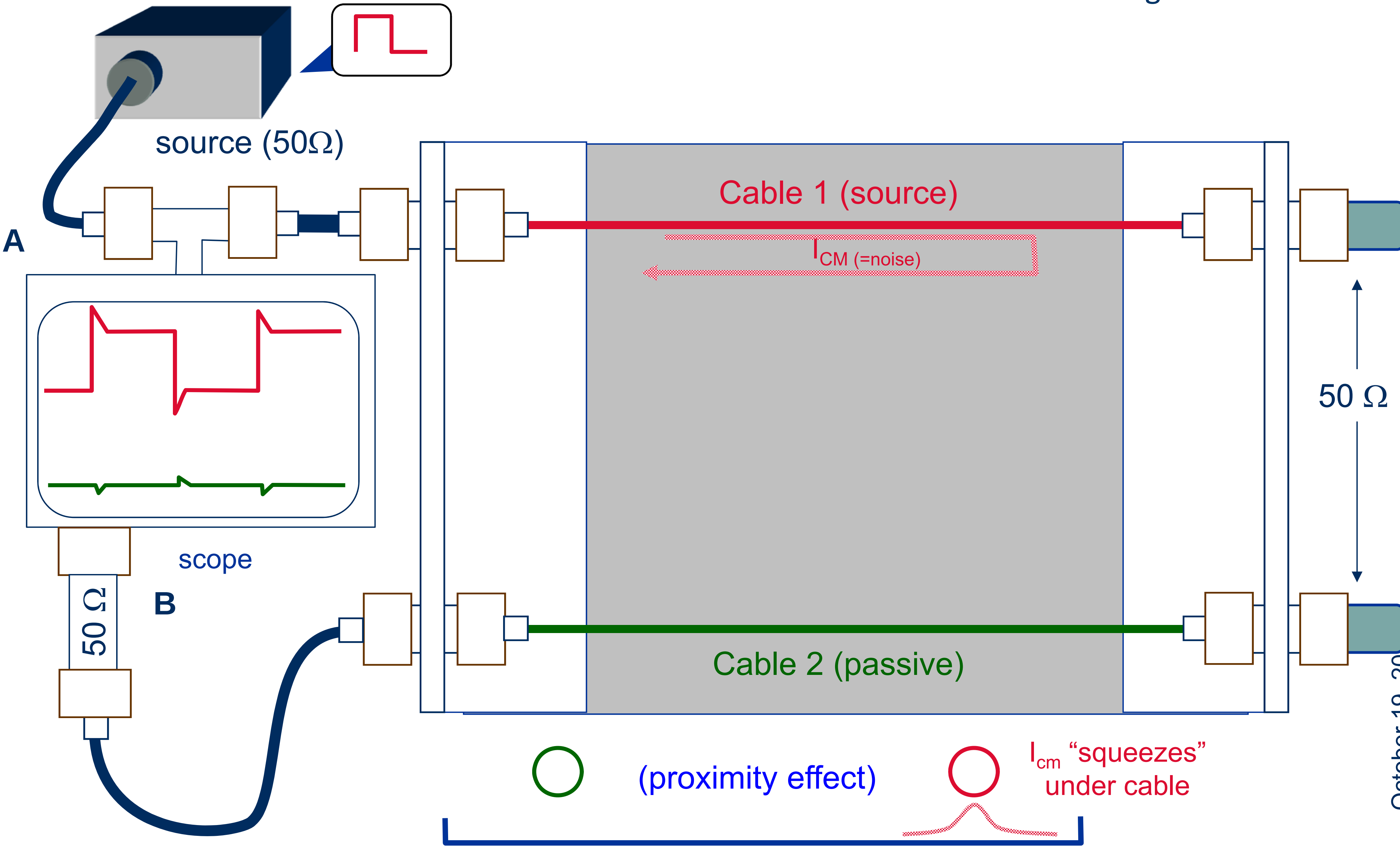
Transfer Impedance improvement

mechanism identical to the single wire case



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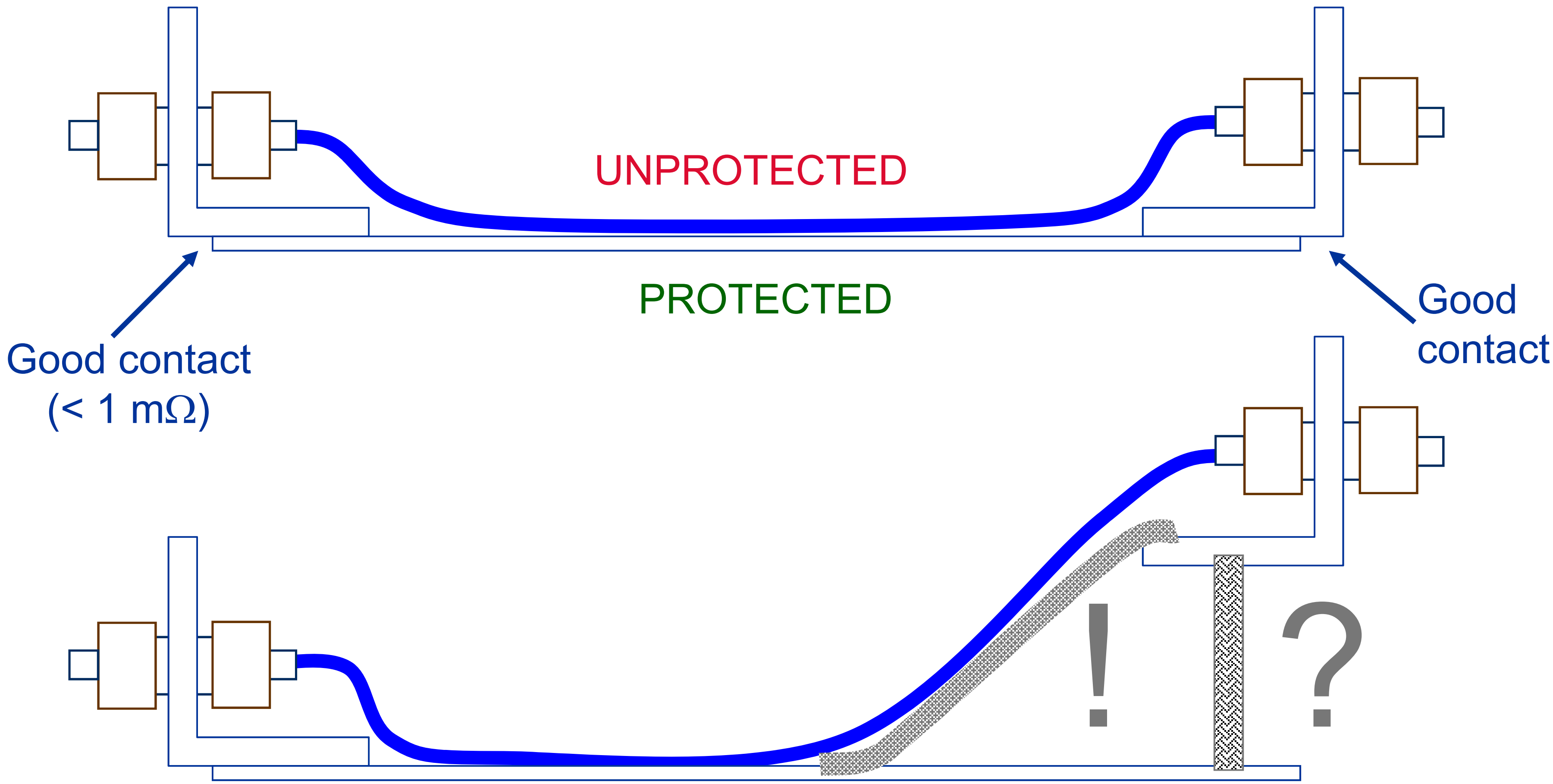
Use available metal to “short-out” CM-currents

e.g. a ship’s deck and walls can be used as groundplane(s)



Important: keep cables near metal over their full length!
(unless cables have sufficient shielding to go “unprotected”)

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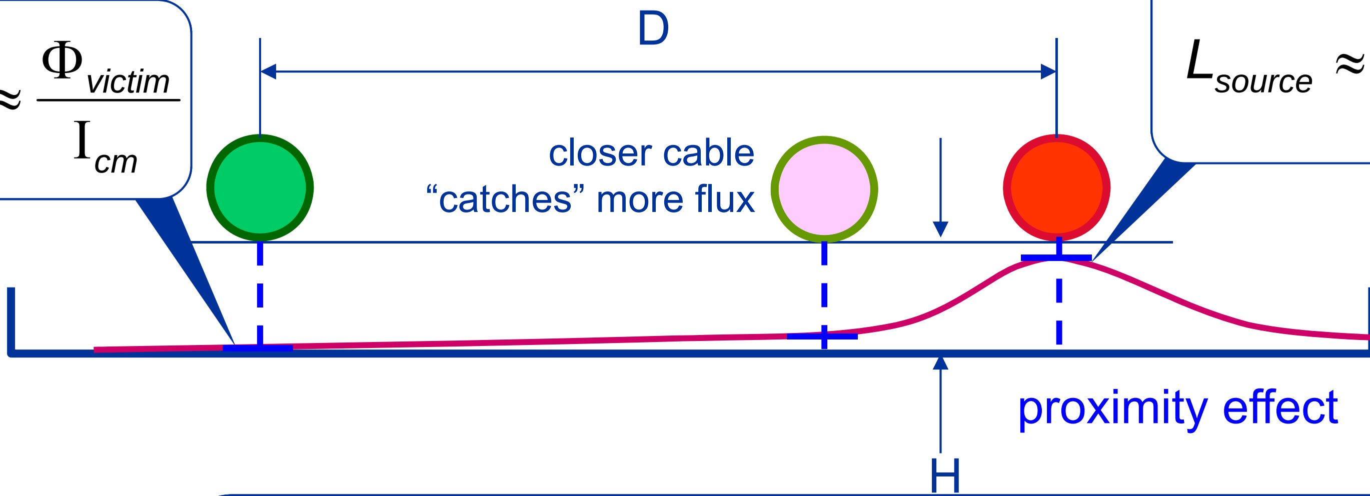
once a cable guide is used for protection

Current distribution of I_{cm} in cable guide is measure of flux density, Φ, coupling into cable: at source ~L, at victim ~M!

$$M_{\frac{source}{victim}} \approx \frac{\Phi_{victim}}{I_{cm}}$$

$$L_{source} \approx \frac{\Phi_{source}}{I_{cm}}$$



COUPLING FACTOR: *k*

$$M \approx \frac{L_{source}}{1+\left(\frac{D}{H}\right)^2}$$

$$k = \frac{M}{L_{source}} = \frac{1}{1+\left(\frac{D}{H}\right)^2}$$

Source:
Johnson, H
“High-Speed
Digital Design”
1993

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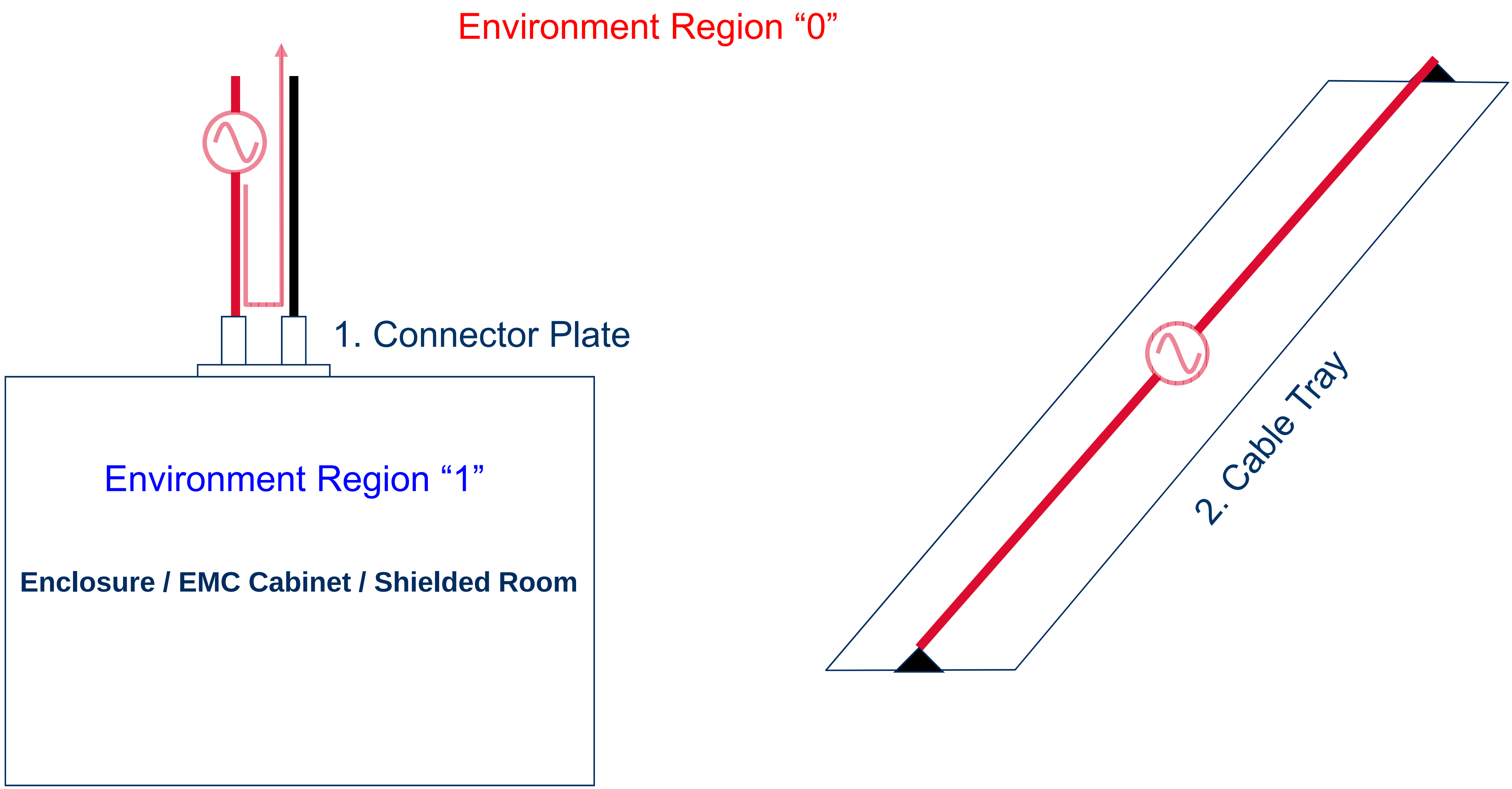
Two Types of Current Boundaries

Short Circuit for Common-Mode "Sources"



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Conducted and Radiated Emission / Susceptibility

type determines the approach to EMC measures

	Conducted	Radiated
Emission	CE	RE
Susceptibility	CS	RS

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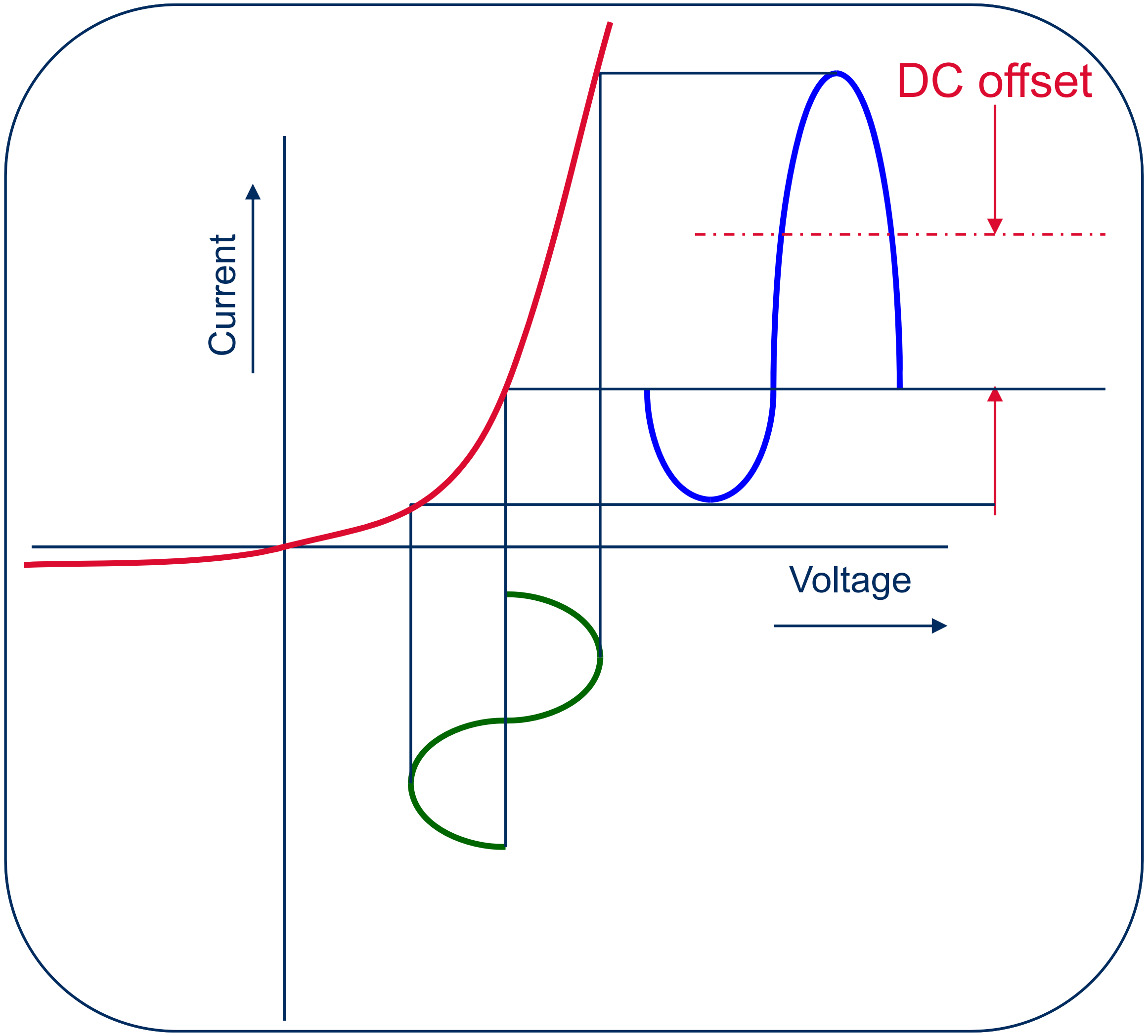
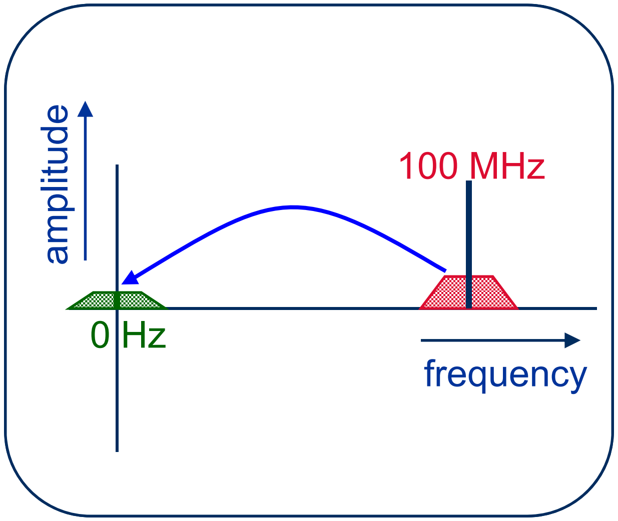
Non-linear Effects

out of band interference



- Prevent HF signals from reaching semiconductors
- Do not amplify HF signals that did get in



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Non-Linearity Disaster Pictures

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ElectroStatic Discharge

charges built on persons or equipment cause electric sparks (and currents)

Source: YouTube

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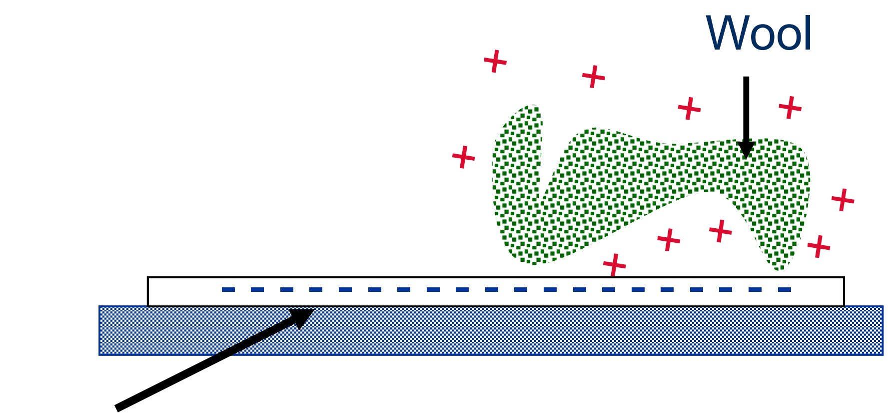
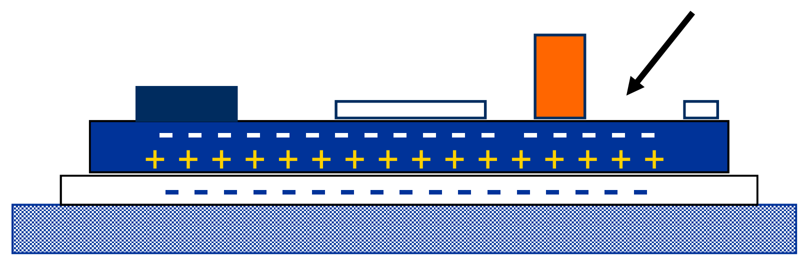
Electric charging by induction

direct contact not necessary!



1. Charging of an insulator



2. Insulated PCB on charged surface

Source:
IEEE EMC Education Manual
Page 13-15: “ESD”
Tony Nasuta
Westinghouse Electric Corp.

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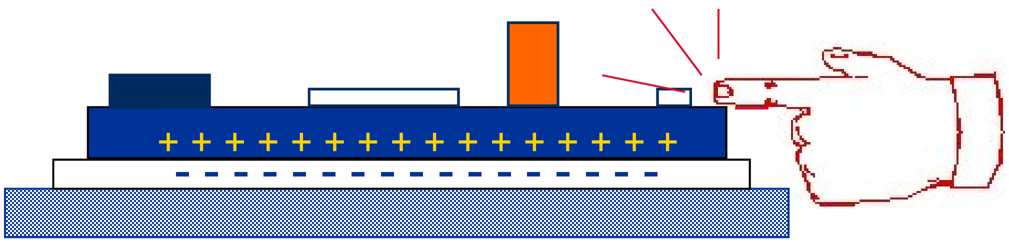
Electric charging by induction

direct contact not necessary!

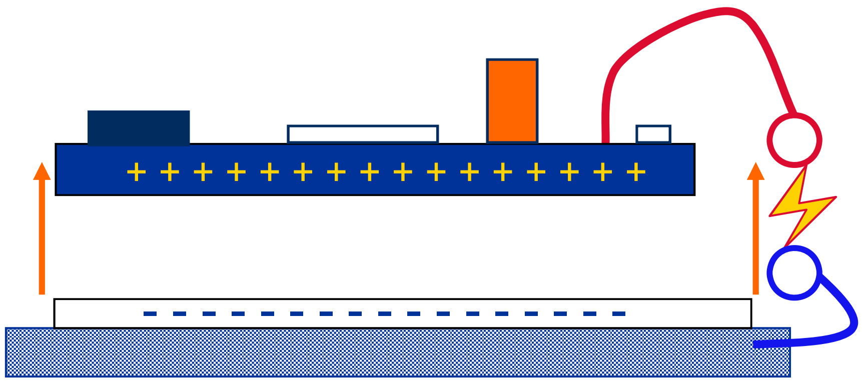


3.Touch or Ground PCB:

negative charge disappears (spark)
(PCB possibly damaged)

$$V_{PCB} = \frac{Q_{PCB}}{C_{PCB}}$$

(C_{PCB} decreases)



4. Lift PCB: voltage increases! Sparks fly!

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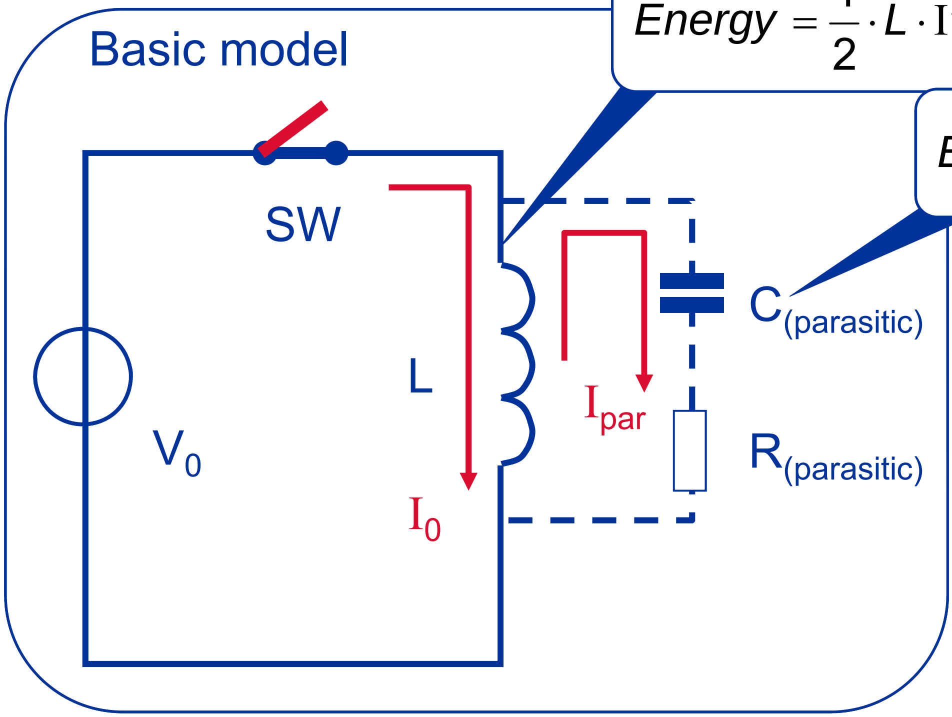
Inductive load switching

Relays, Valves, and PWM motor control systems



$$Energy = \frac{1}{2} \cdot L \cdot I^2$$

$$Energy = \frac{1}{2} \cdot C \cdot V^2$$

Analysis:

L= 0.1 H

C= 100 pF

I_0 = 1 A

$$\frac{1}{2} \cdot L \cdot I^2 = \frac{1}{2} \cdot C \cdot V^2$$

V = 32 kV (!)

Source: Jasper J. Goedbloed, “EMC”
Prentice Hall/Kluwer 1992

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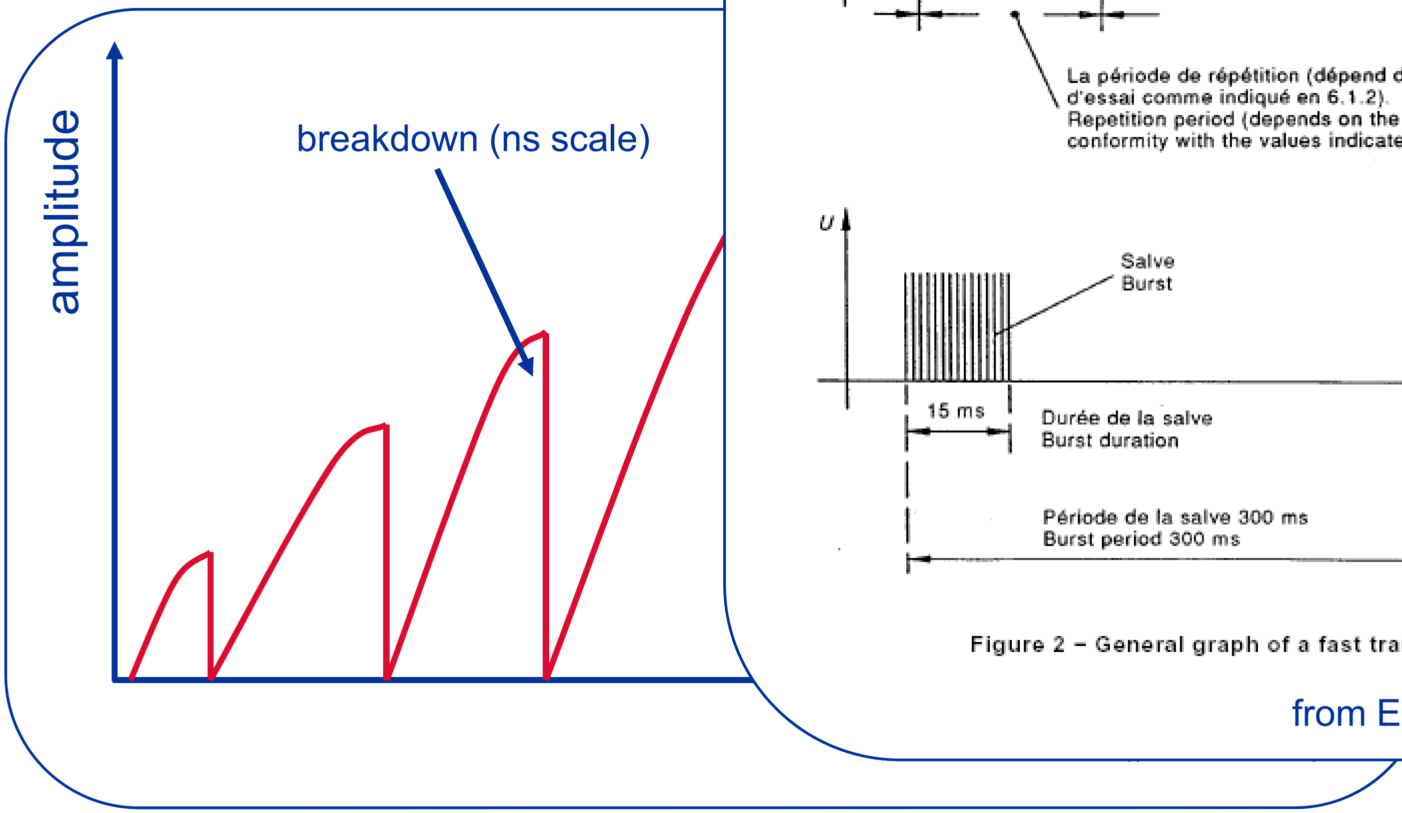
High Voltage in Switch Arcs and Creates Spikes

reason for Electrical Fast Transients (EFT) tests on equipment



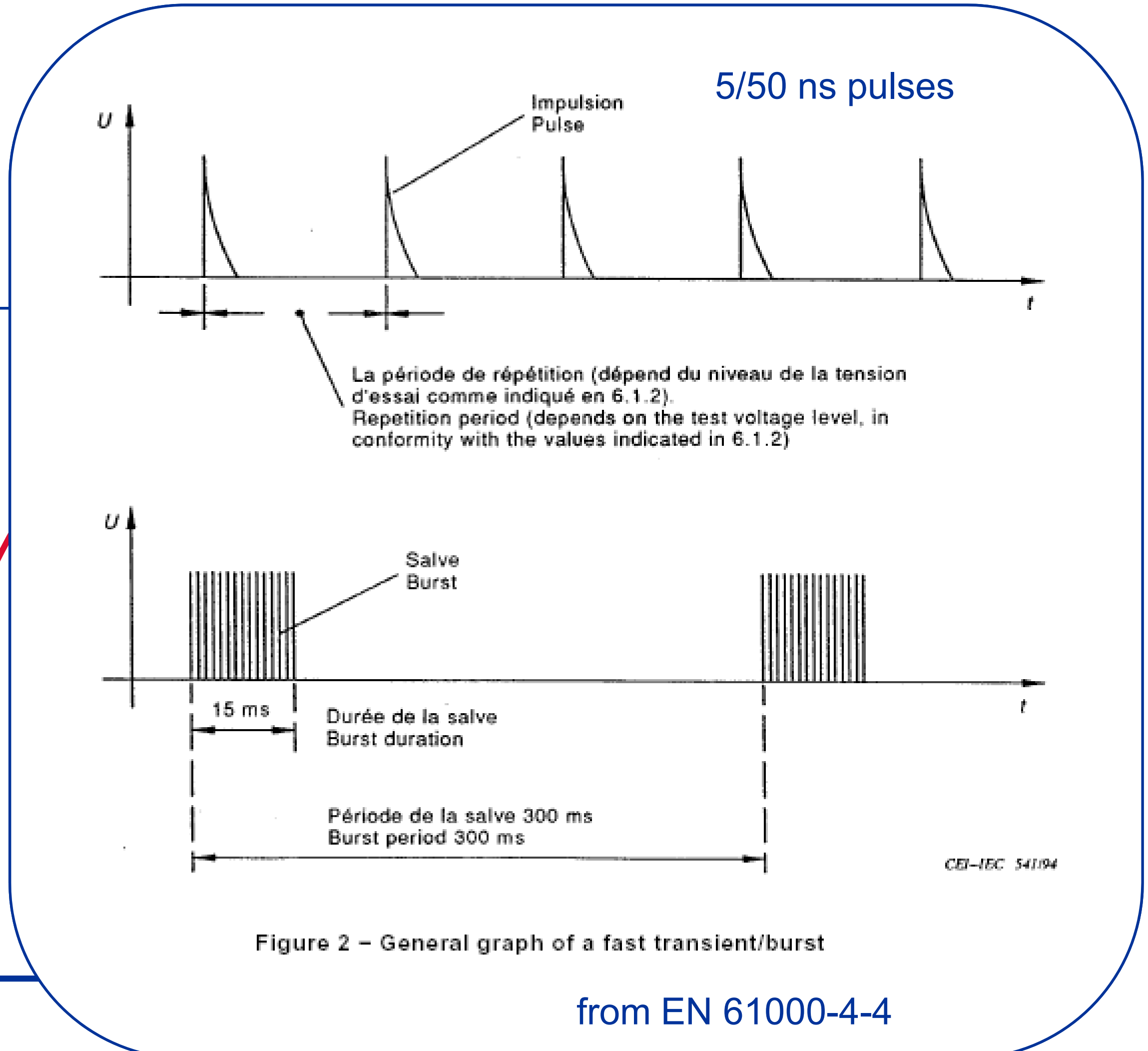


Figure 2 – General graph of a fast transient/burst

from EN 61000-4-4

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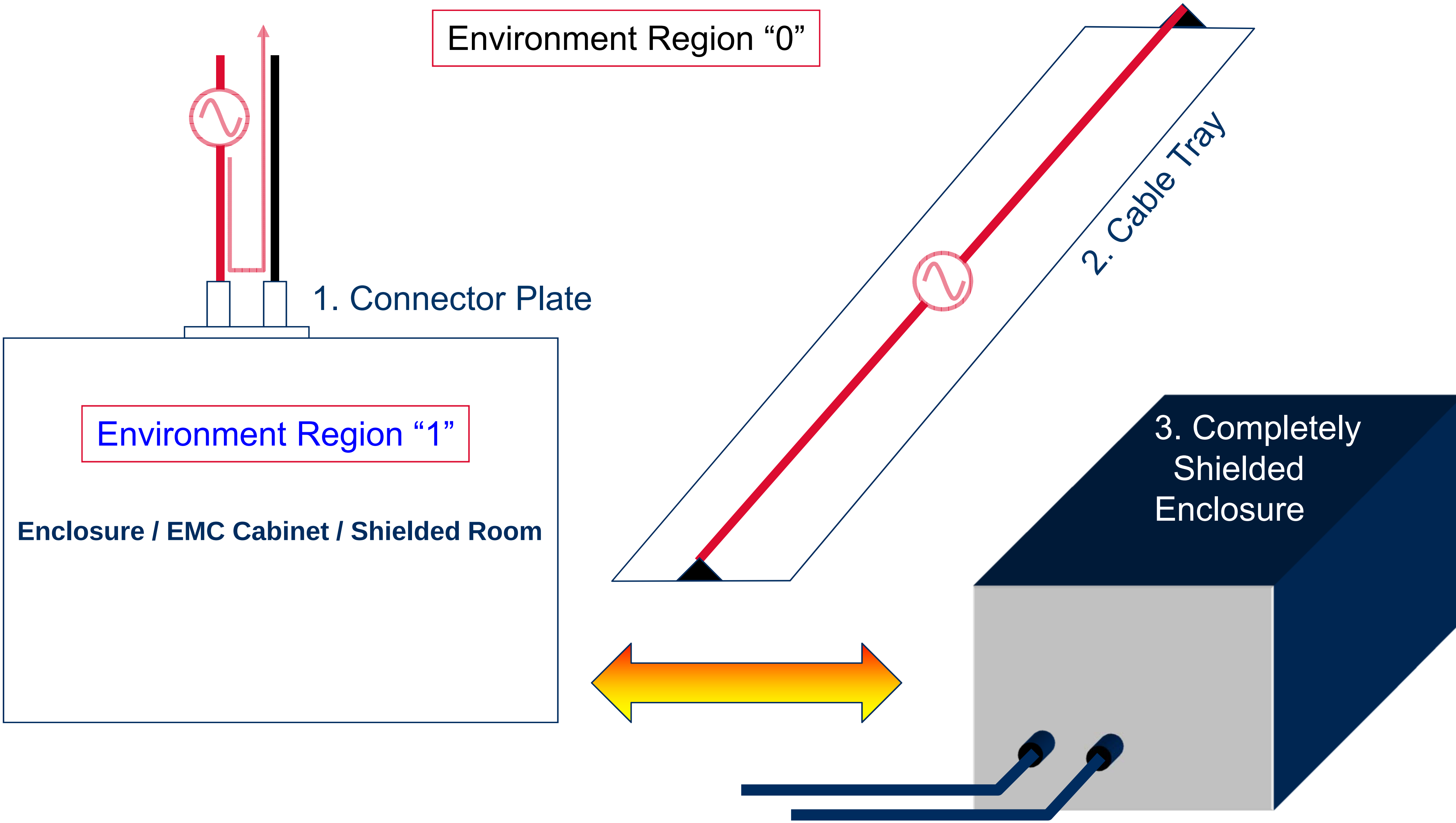
Three Types of Current Boundaries

Short Circuit for Common-Mode “Sources”



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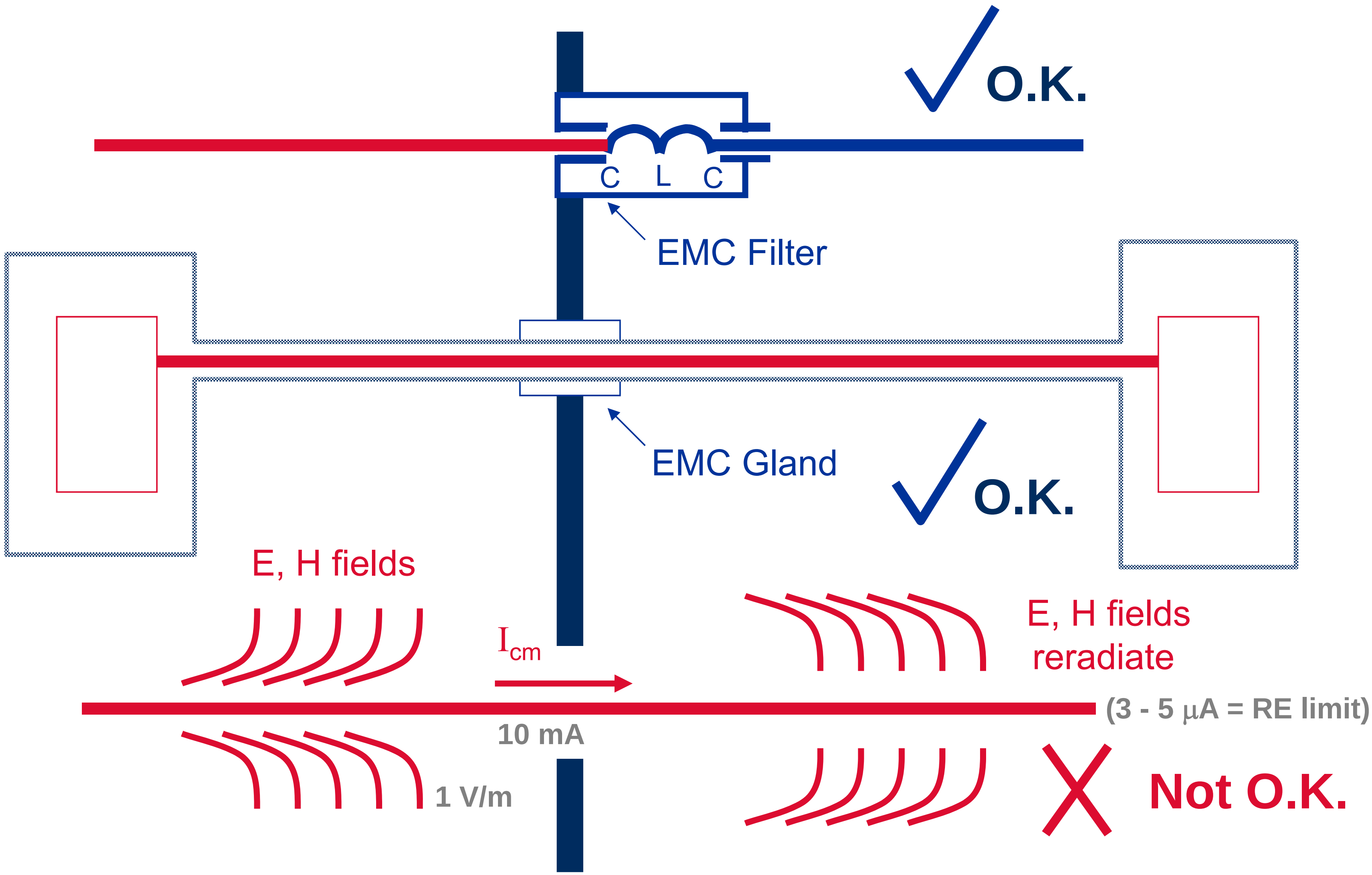
Either filter or shield entire cable

when passing through shielding wall



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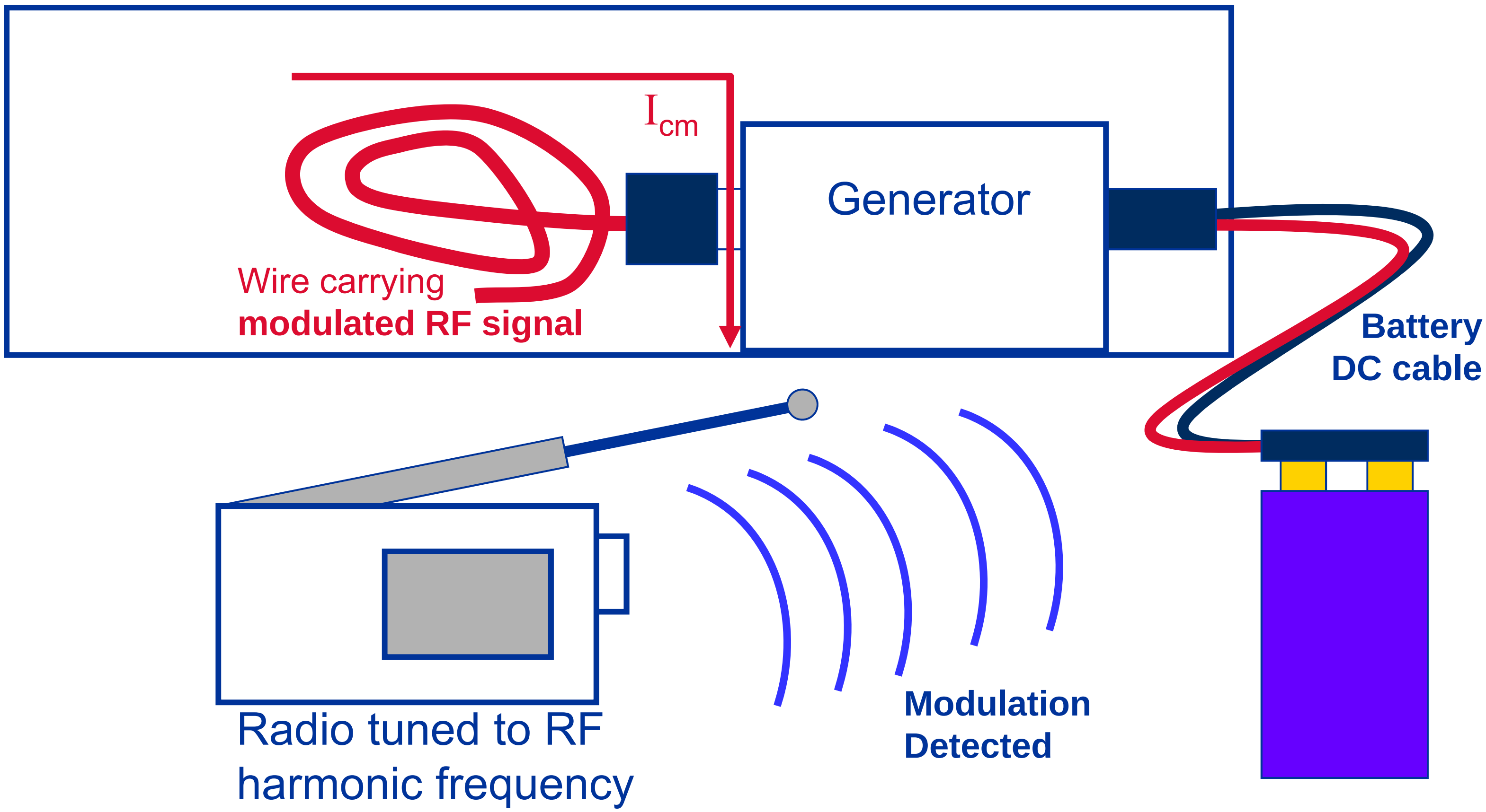
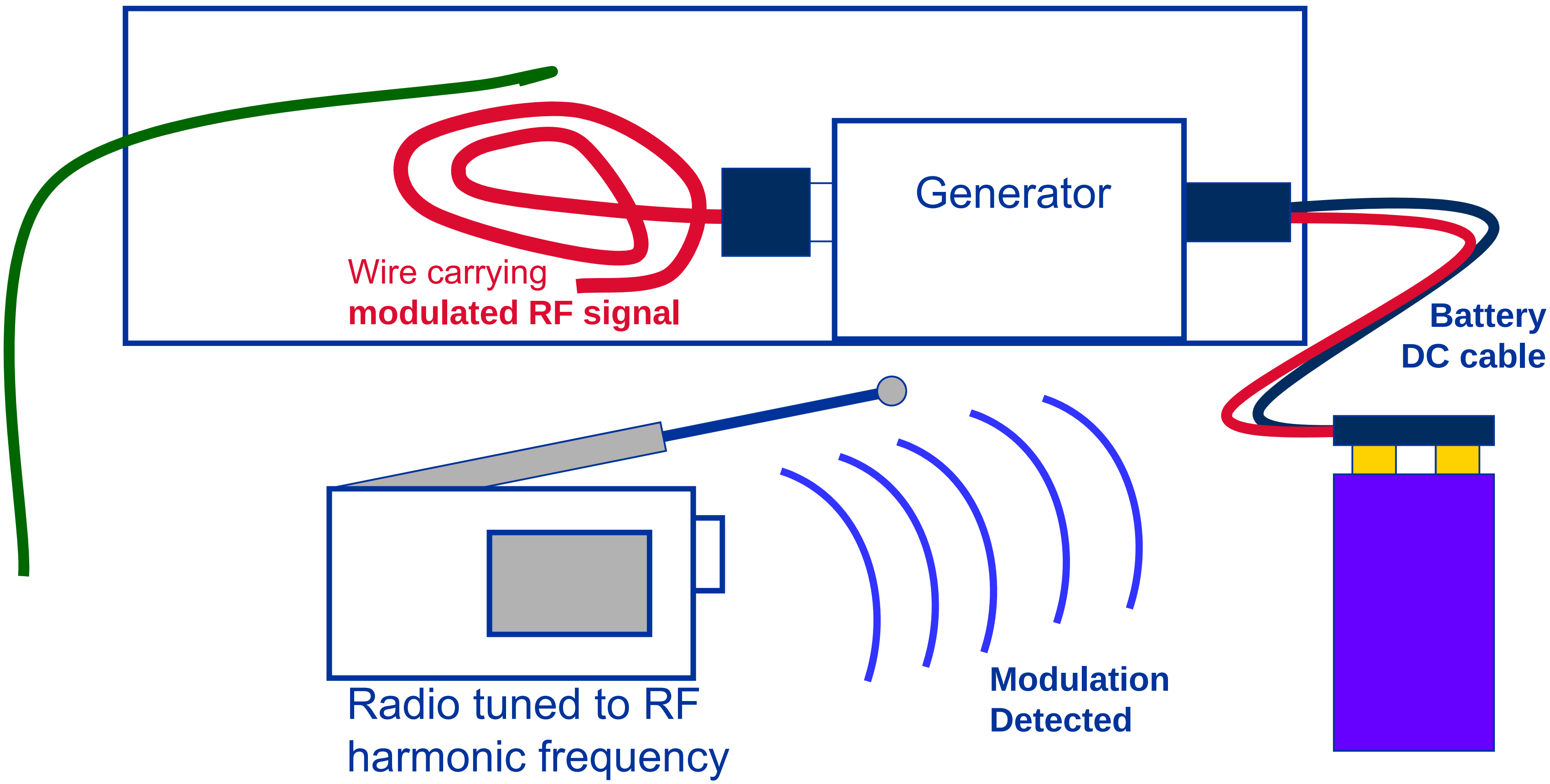
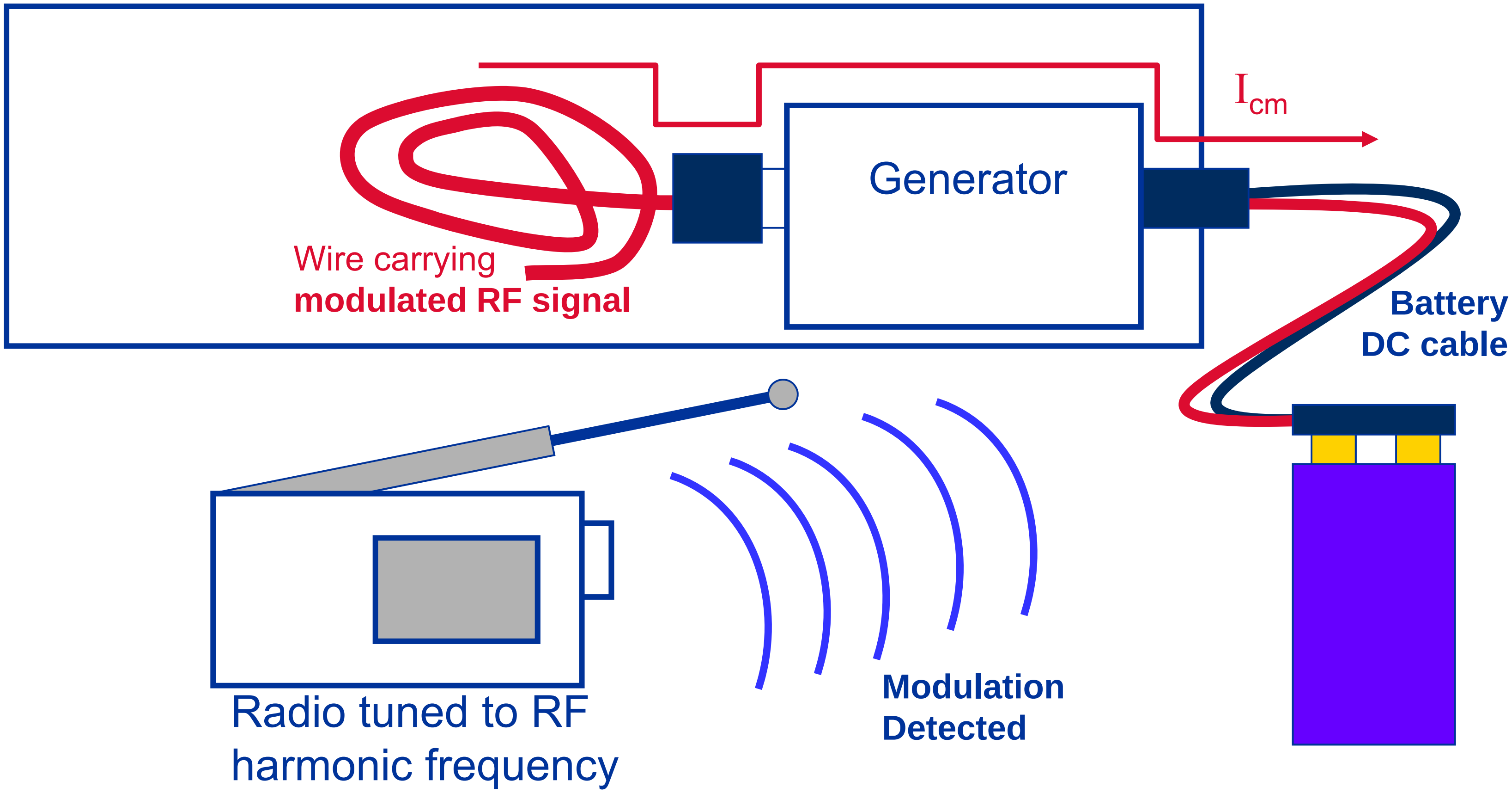
Shielding a noisy interconnection using a metal tube (wave guide)



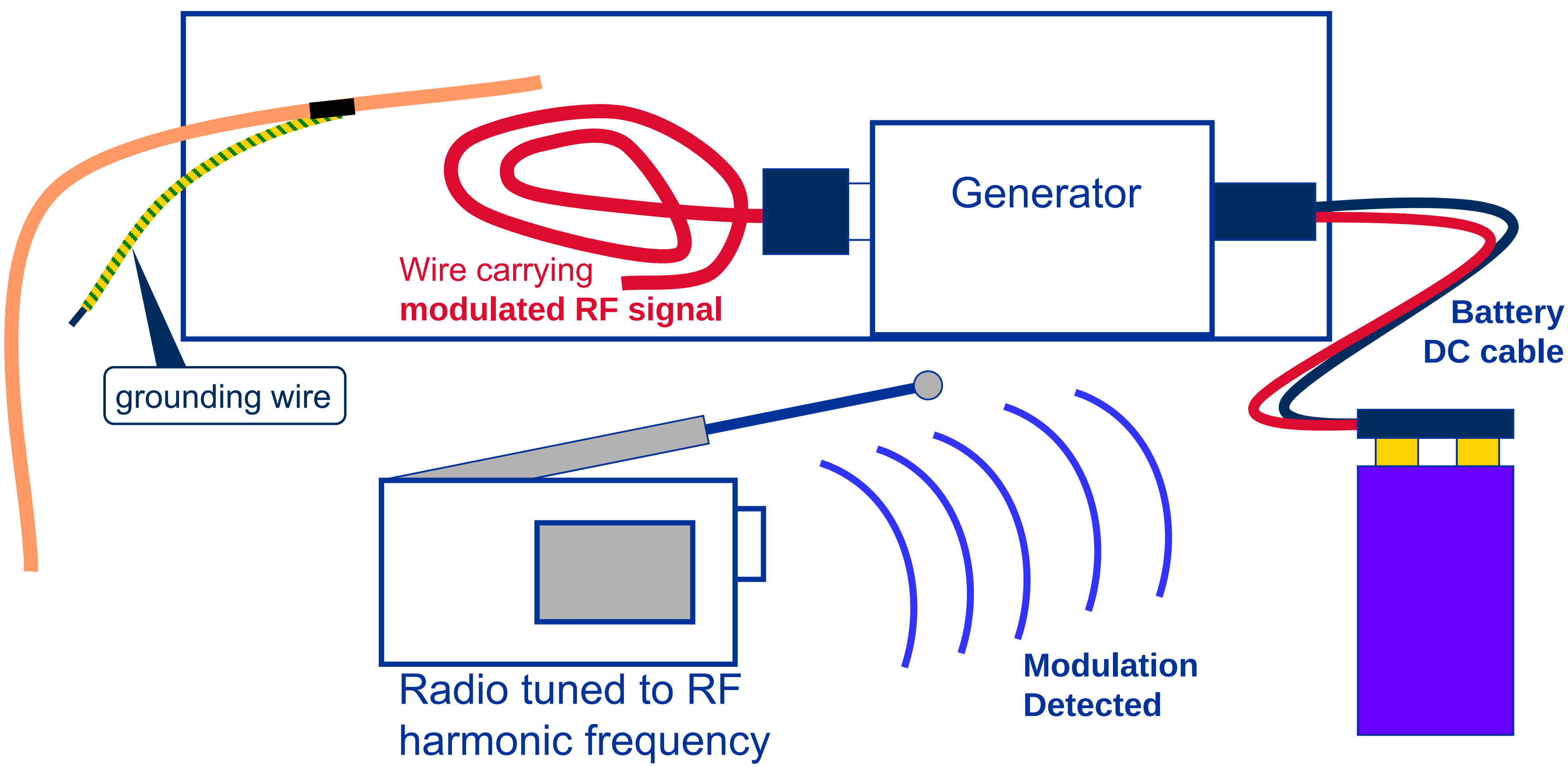
Entering a conductor into tube couples out the noise again



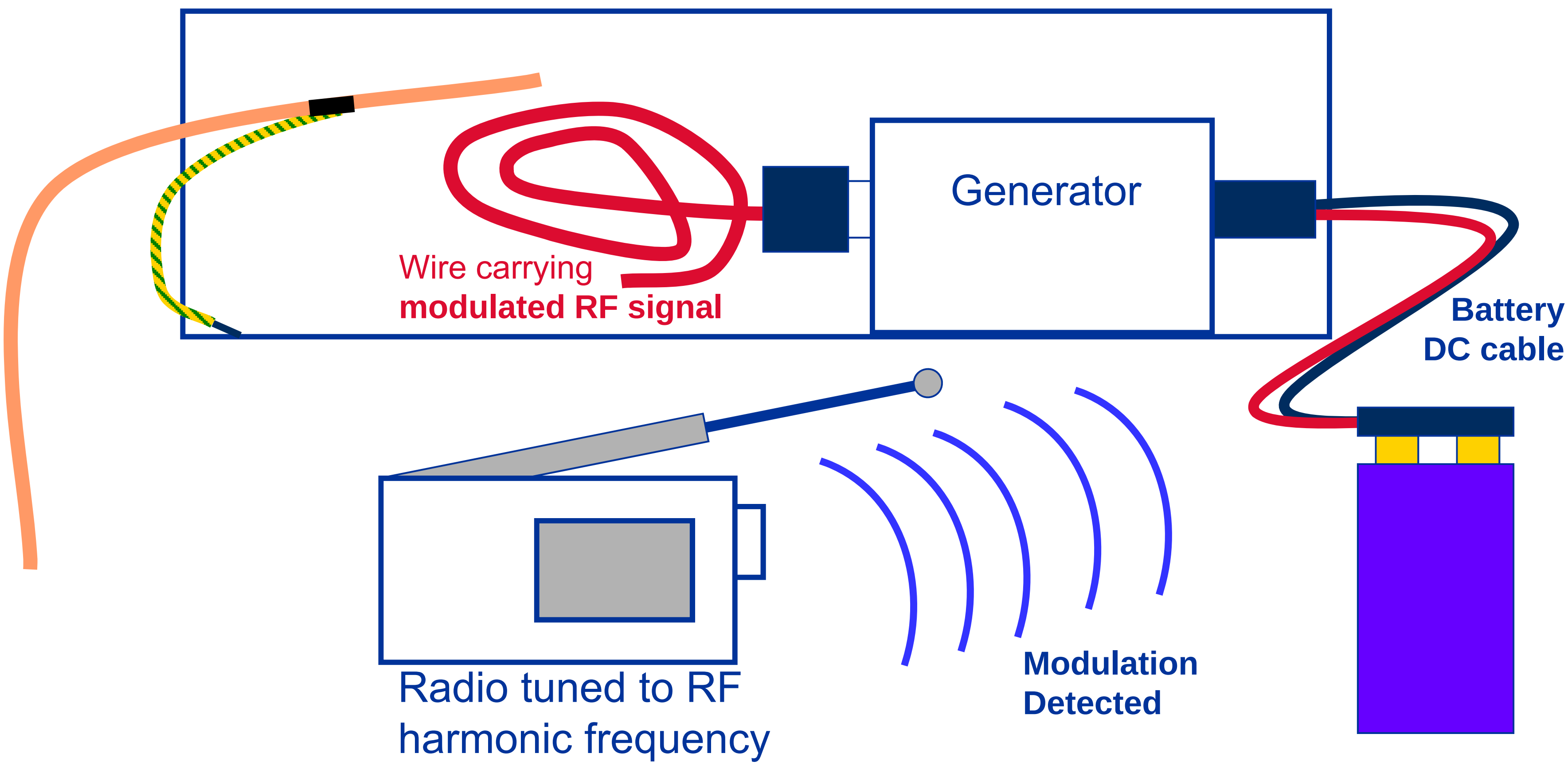
Insulating generator case: battery cable now reradiates noise (antenna)



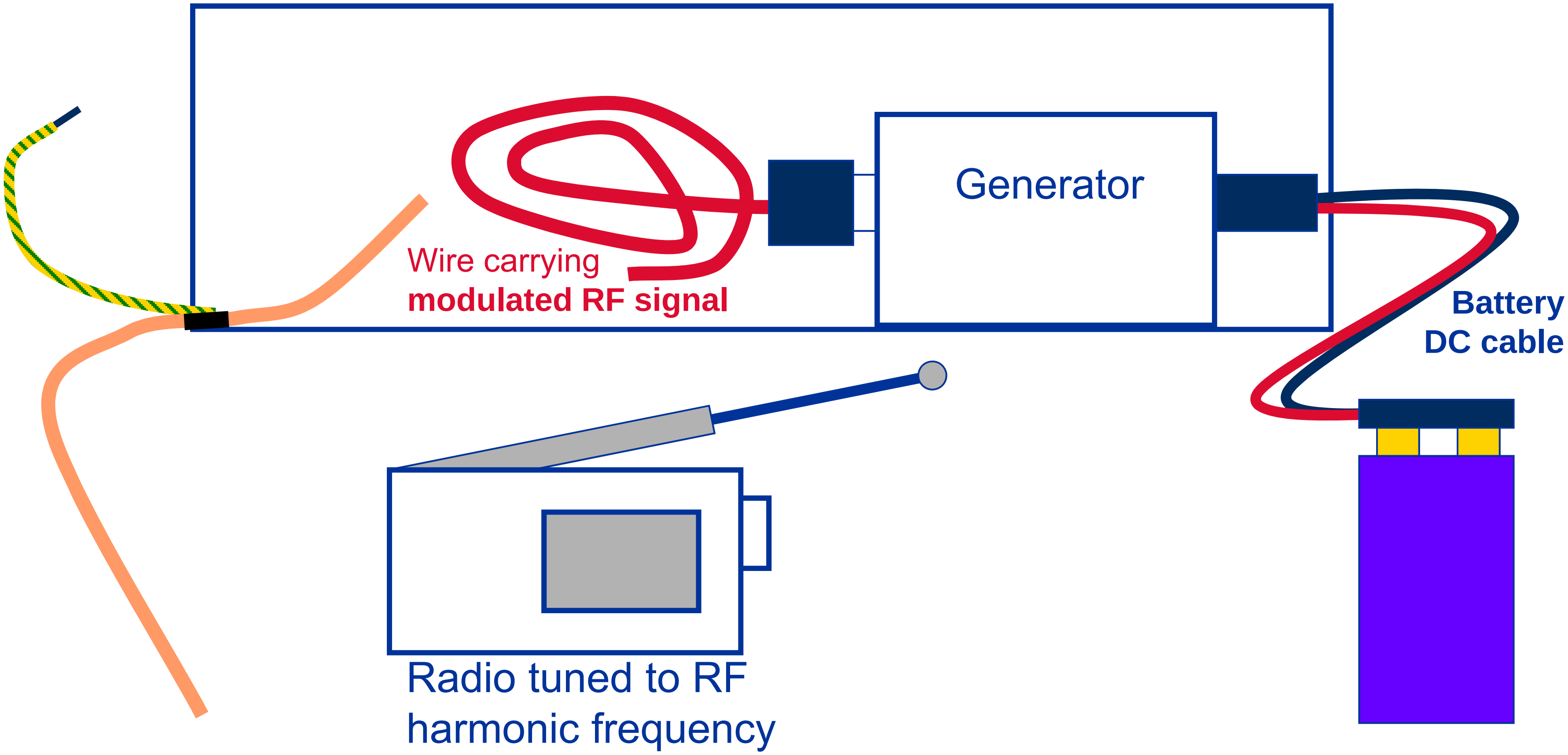
Entering a screened conductor into tube also couples out the noise again



Grounding the shield with the wire does not solve the interference problem!

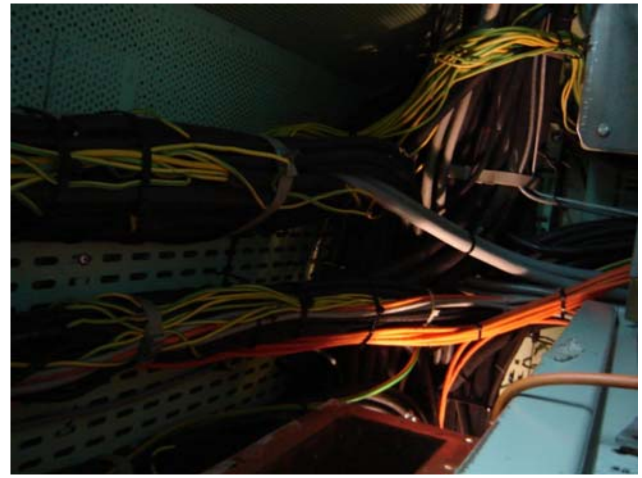


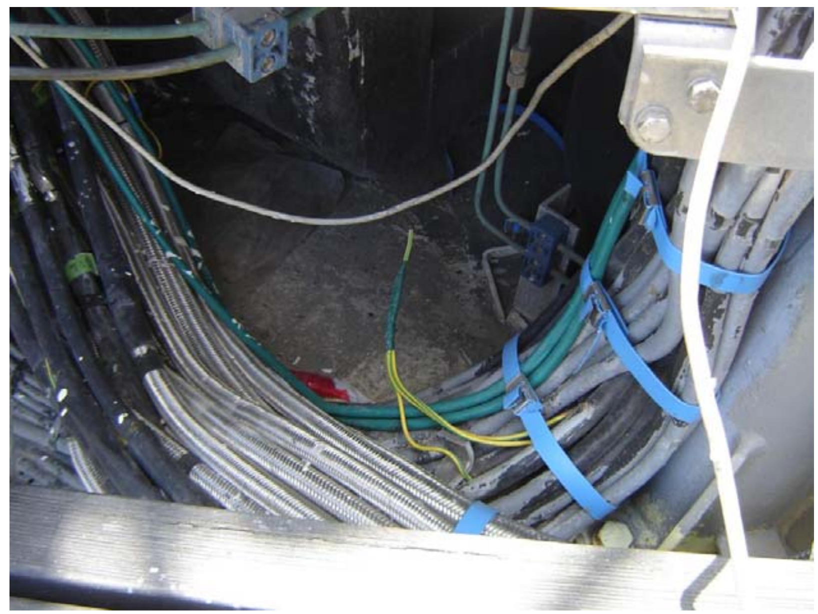
Cable shield must be grounded directly to the metal shield to stop the noise



Bad “Grounding” habits

it is Inductance, not the milliOhms that count!





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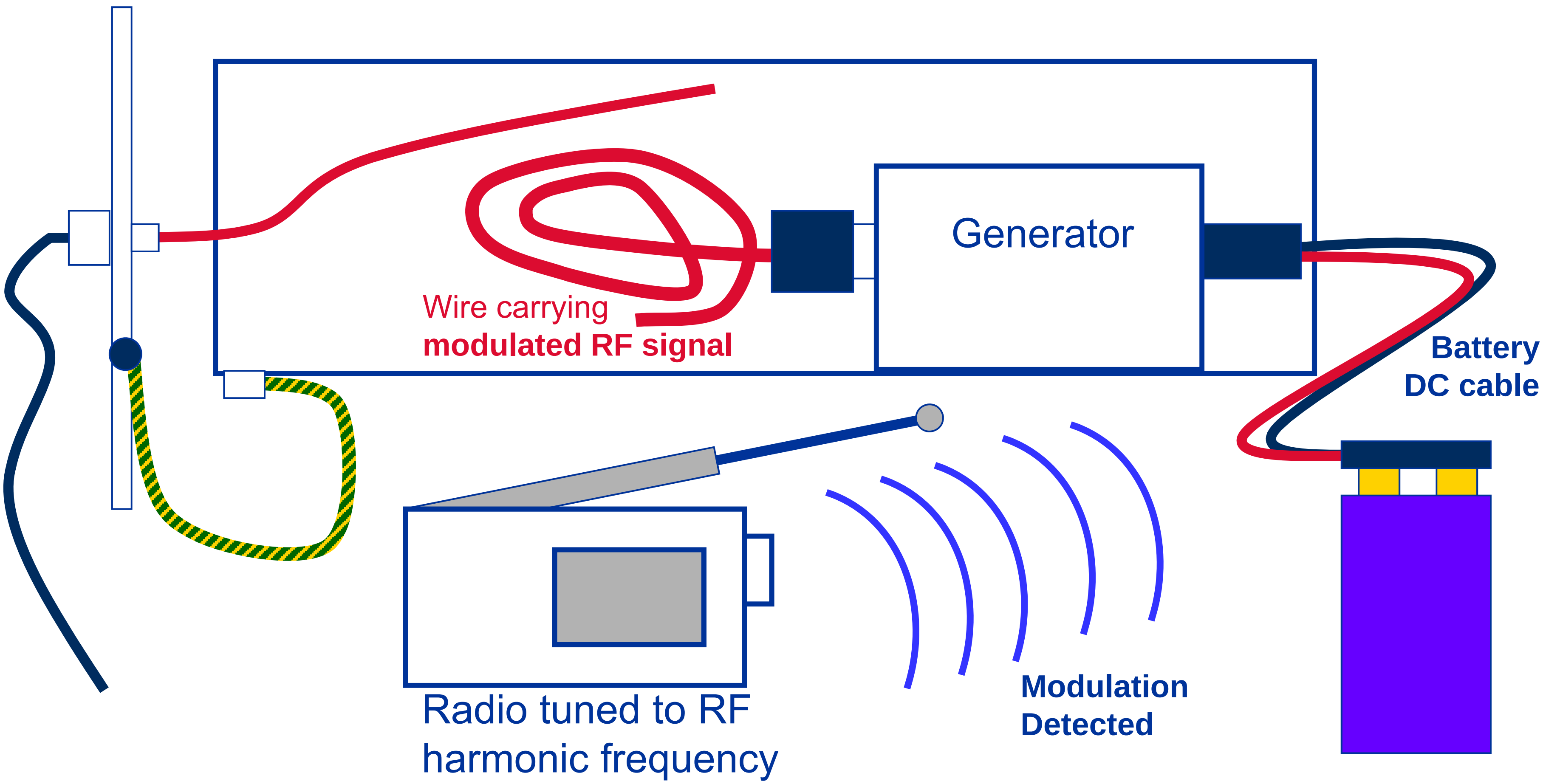
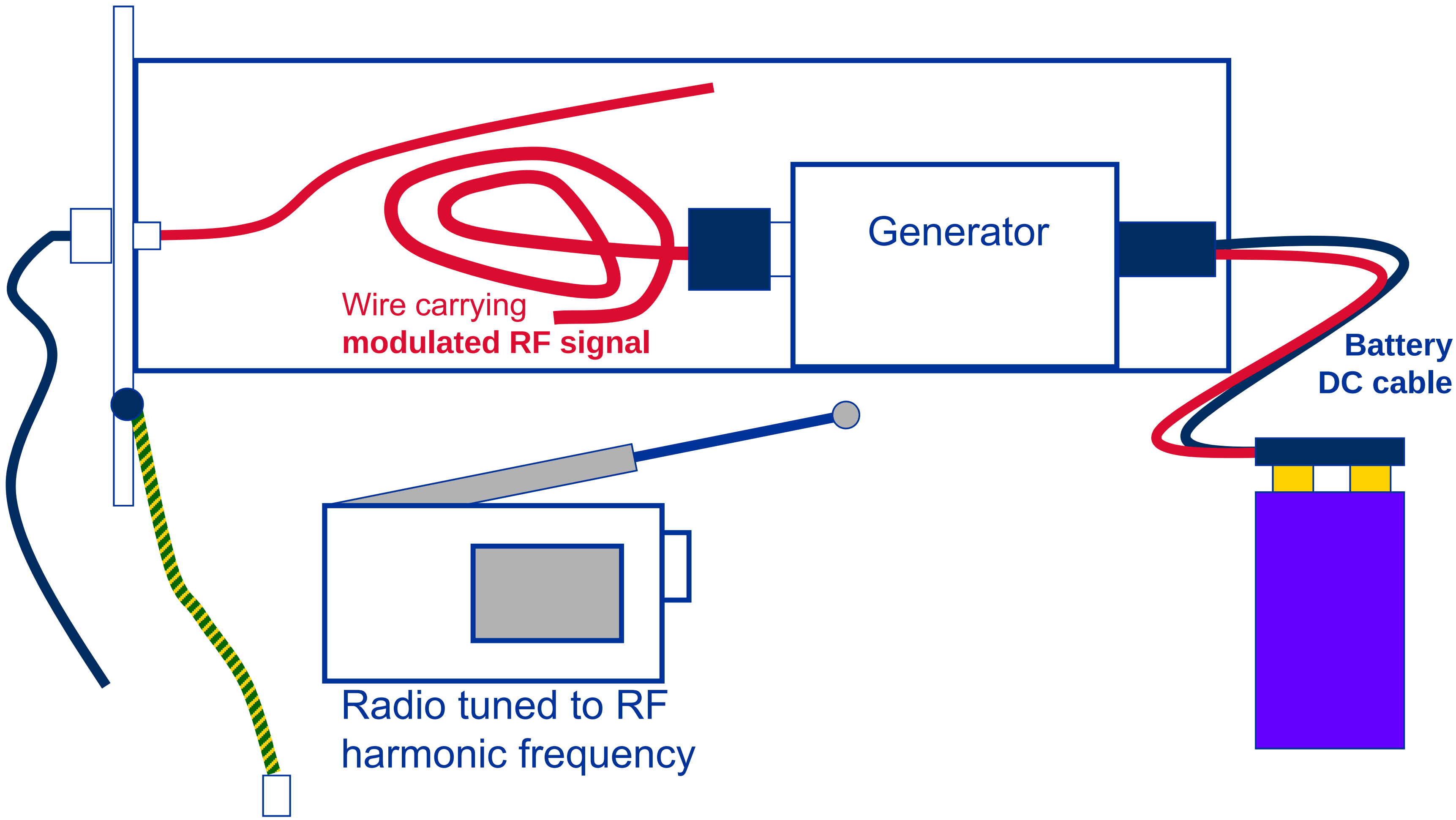
A filter in the inserted wire does not help if only grounded with a wire

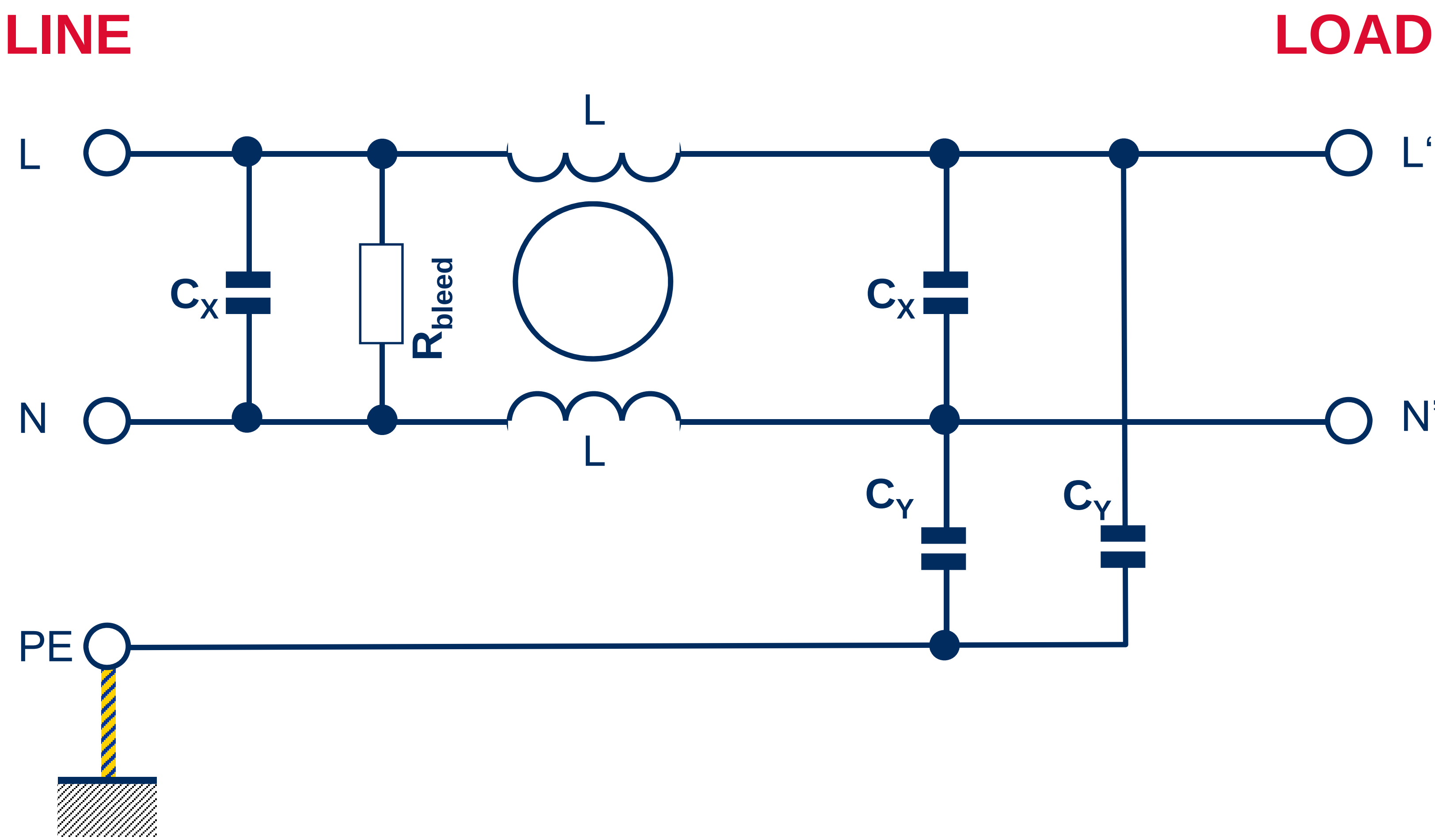


only when the wide metal filter plate touches, the shielding works



Filter = "Frequency Dependent" Current Boundaries

EMI filter is usually employed as frequency dependent current boundary



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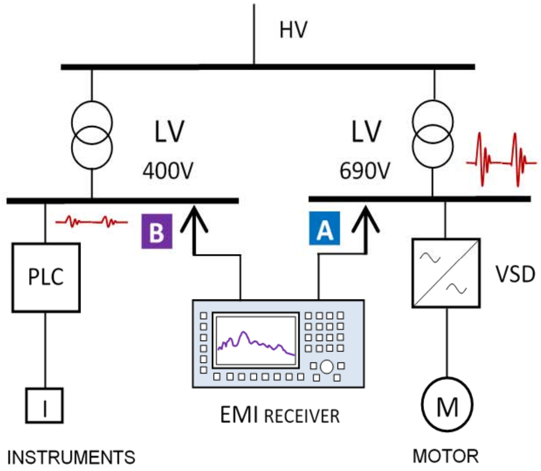
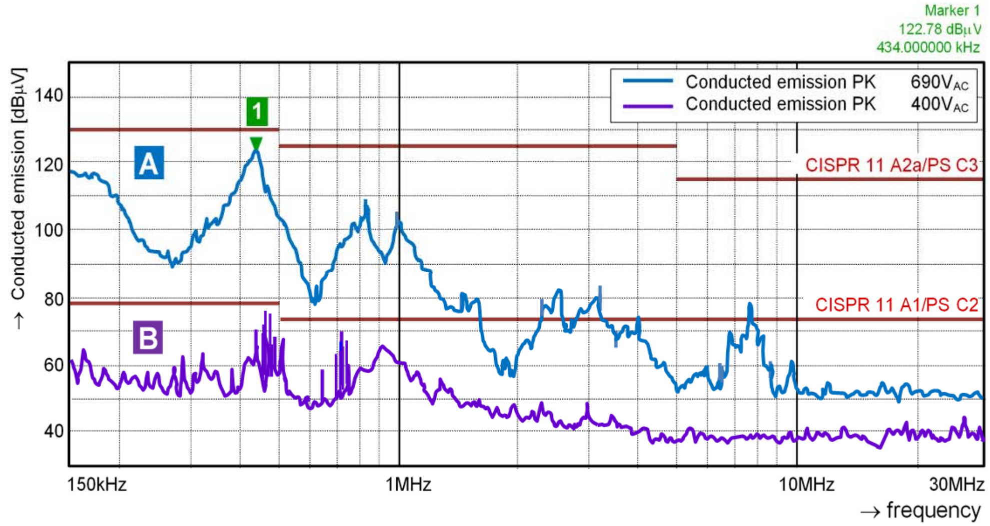
Conducted emission via power supply

- Example of intended segregation of power supply





- Alternative in case of shared power supply: power supply filter

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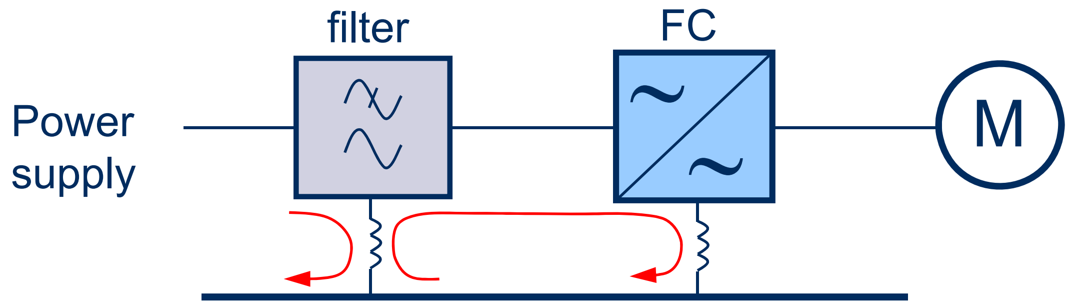
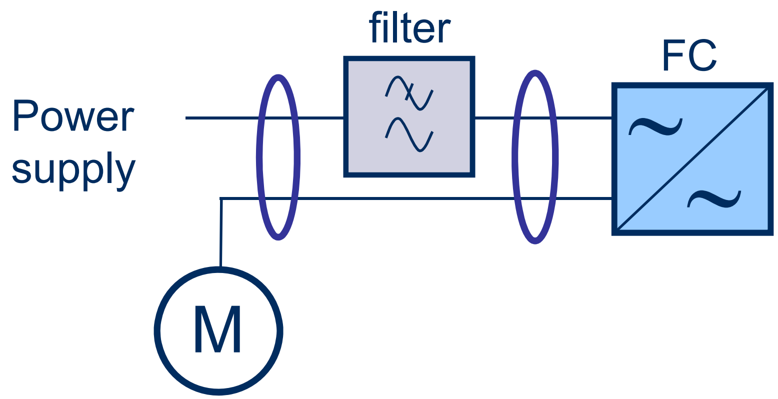
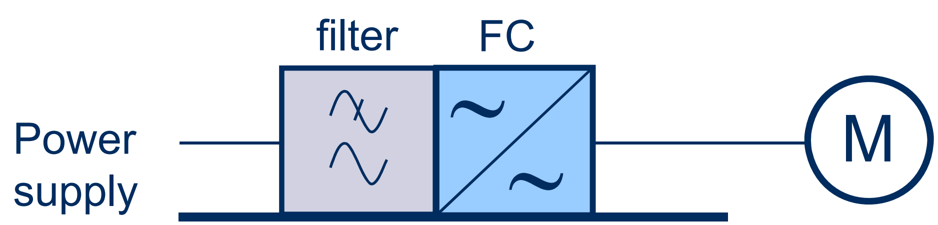
1) Earthing of filter and drive



2) Inductive coupling between in- and output of filter



OK



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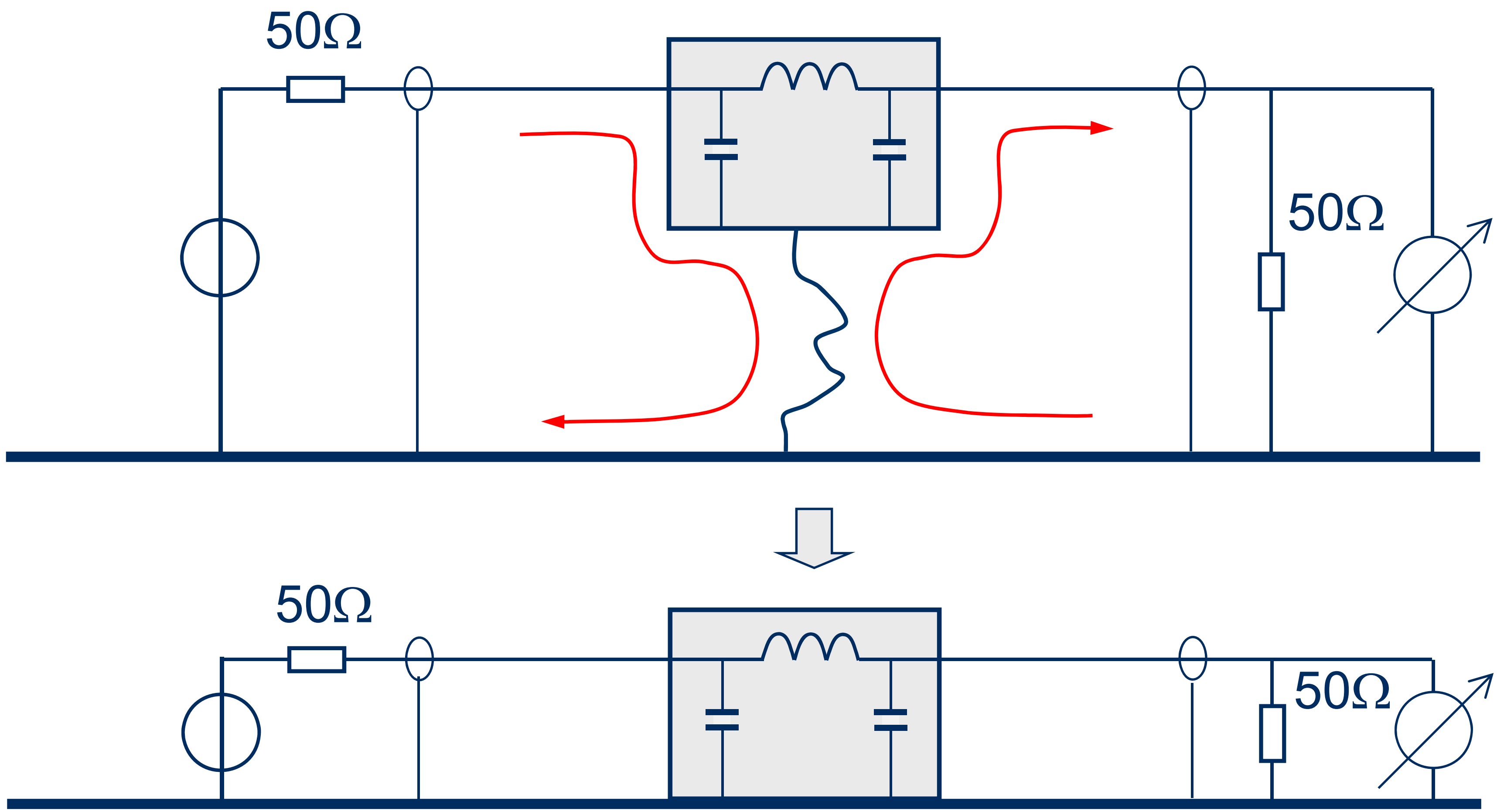
Filter demo



Source: Goedbloed

Examples of bad installation practice of filters

Inductive coupling between input and output wiring makes the filter ineffective → segregate input and output wiring

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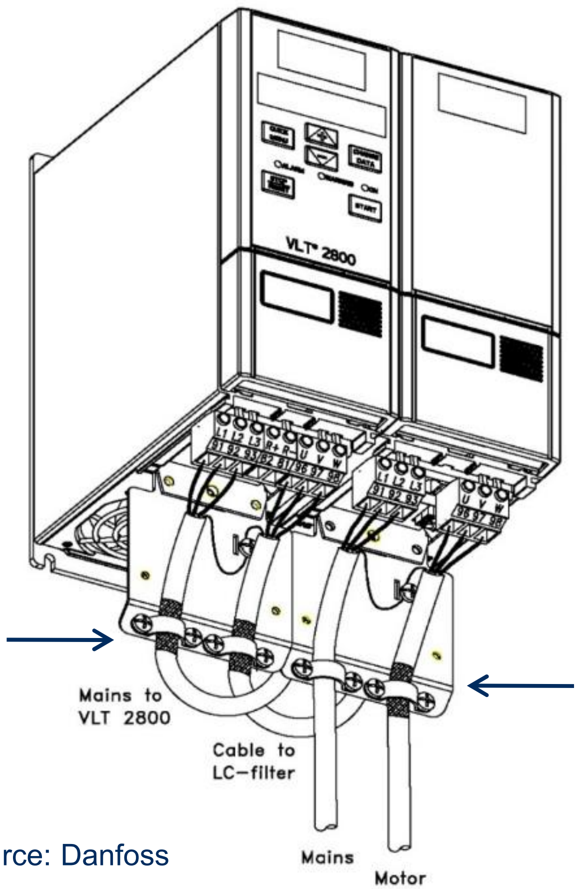
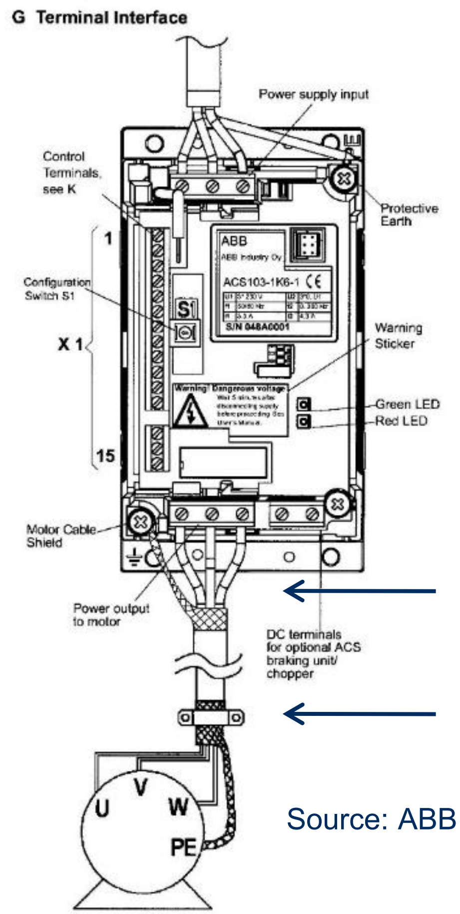
Vendor EMC installation requirements



Source: Danfoss



Source: ABB

Installation of mains RFI and output filters

Installation of shielded motor cable and cable termination details

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Installations with switched loads (transients)

- Large number of switched applications (motors, valves etc.)
- No EMC requirements for single component
- Disturbing potential is determined by reactive properties of load, cable lengths, switching frequency and supply voltage
- Emission standard for switching transients (clicks) not up to date (based on radio interference (CISPR), whereas immunity of digital circuits, field buses etc. is the main issue.

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Emission as per EN-IEC 61000-6-4

Port	Frequency range	Limits	Basic standard	Applicability note	Remarks
1) Enclosure port – Open area test site or semi-anechoic method	30 MHz – 230 MHz 230 MHz – 1 000 MHz	40 dB(μV/m) Quasi-peak at 10 m 47 dB(μV/m) Quasi-peak at 10 m	CISPR 16-2-3	See Note 1.	May be measured at 30 m distance using the limits decreased by 10 dB.
2) Low voltage AC mains port	0,15 MHz – 0,5 MHz	79 dB(μV) quasi-peak 66 dB(μV)average	CISPR 16-2-1, 7.4.1 CISPR 16-1-2, 4.3	See Note 2.	
	0,5 MHz – 30 MHz	73 dB(μV) quasi-peak 60 dB(μV) average			
3) Telecommunications/network port	0,15 MHz – 0,5 MHz	97 dB(μV) – 87 dB(μV) quasi-peak 84 dB(μV) – 74 dB(μV) average 53 dB(μA) – 43 dB(μA) quasi-peak 40 dB(μA) – 30 dB(μA) average	CISPR 22	See Notes 3, 4 and 5.	
	0,5 MHz – 30 MHz	87 dB(μV) quasi-peak 74 dB(μV) average 43 dB(μA) quasi-peak 30 dB(μA) average		See Notes 3 and 5.	

Continuous emissions

NOTE 1 If the internal emission source(s) is operating at a frequency below 9 kHz then measurements need only to be performed up to 230 MHz.

NOTE 2 Impulse noise (clicks) which occur less than five times per minute is not considered. For clicks appearing more often than 30 times per minute the limits apply. For clicks appearing between 5 and 30 times per minute, a relaxation of the limits is allowed of 20 log 30/N dB (where N is the number of clicks per minute). Criteria for separated clicks may be found in CISPR 14-1.

NOTE 3 At transitional frequencies the lower limit applies.

NOTE 4 The limits decrease linearly with the logarithm of the frequency in the range 0,15 MHz to 0,5 MHz.

NOTE 5 The current and voltage disturbance limits are derived for use with an impedance stabilization network (ISN) which presents a common mode (asymmetric mode) impedance of 150 Ω to the telecommunication port under test (conversion factor is $20 \log_{10} 150 / 1 = 44$ dB).

Transient emission

EN-IEC 61000-6-4: generic emission standard for industrial environment

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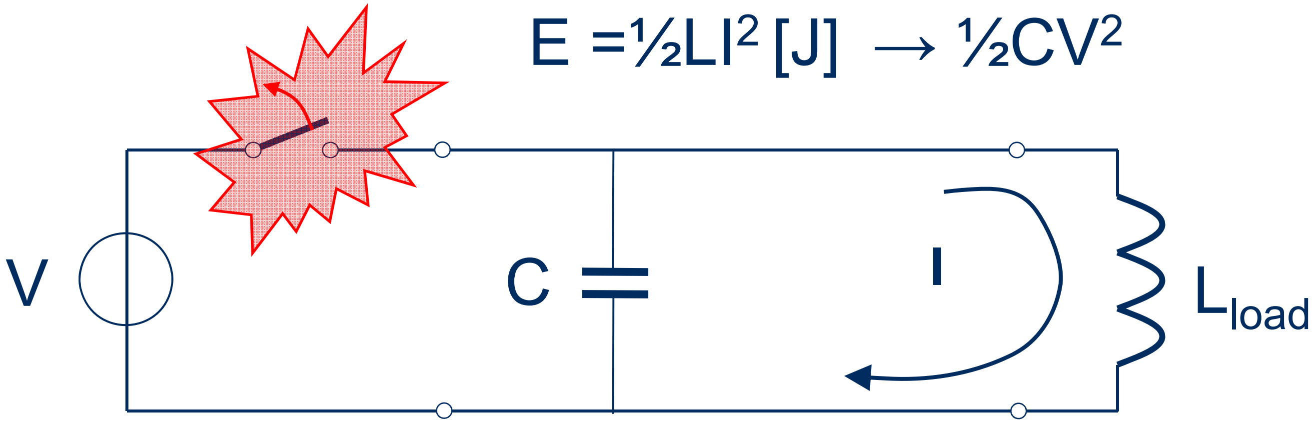
Ageing of switching contacts

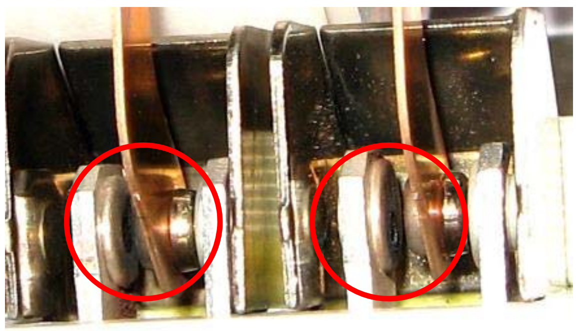
$$E = \tfrac{1}{2}LI^2\ [J] \rightarrow \tfrac{1}{2}CV^2$$



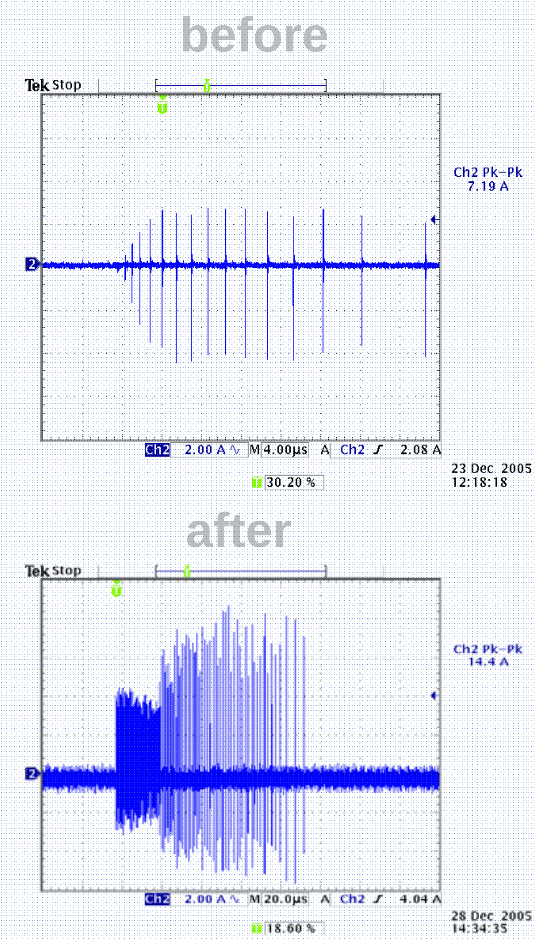
Typical specification of relay:

Maximum Operating Frequency (No-Load Operation):	?	3000 Operations / Hour
Mechanical Durability		10,000,000 Operations
Electrical Durability		1,000,000 Operations

Ageing of contacts due to repetitive sparking across contact material



Measurement of transients after 60.000 switching events



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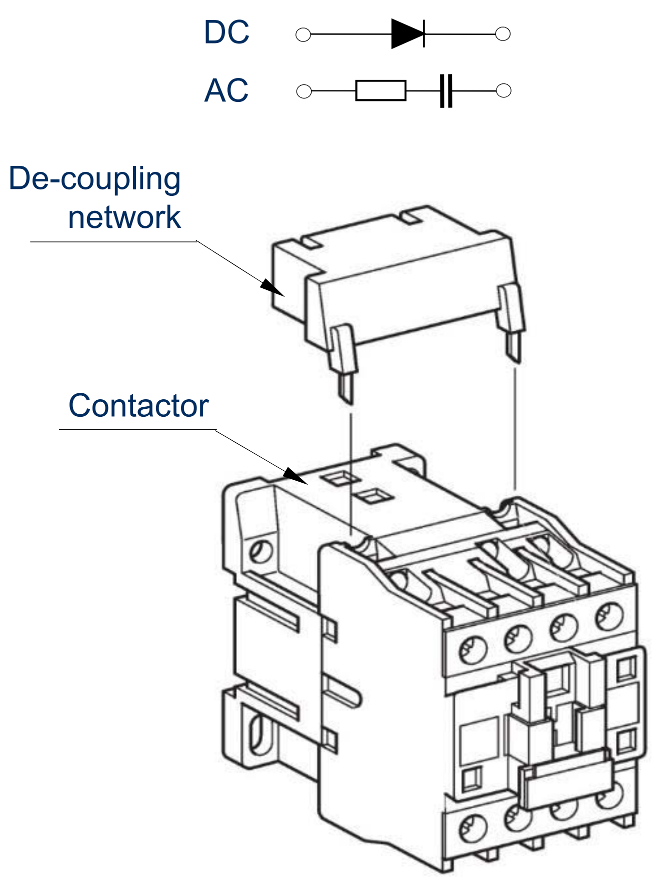
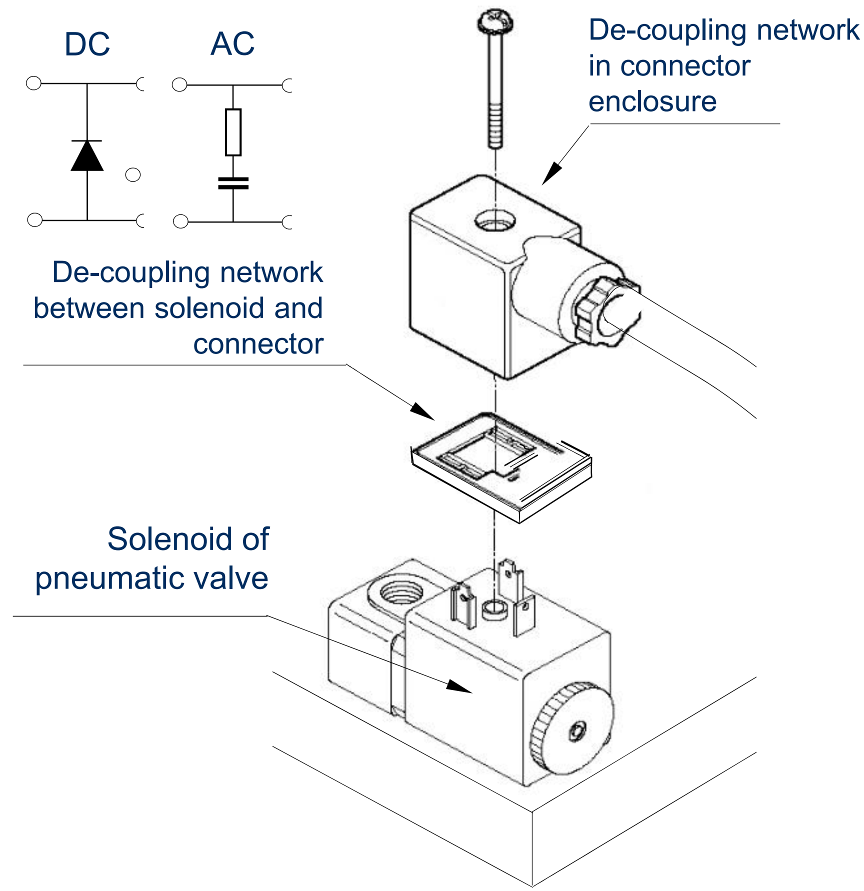
Mitigation of switching disturbance

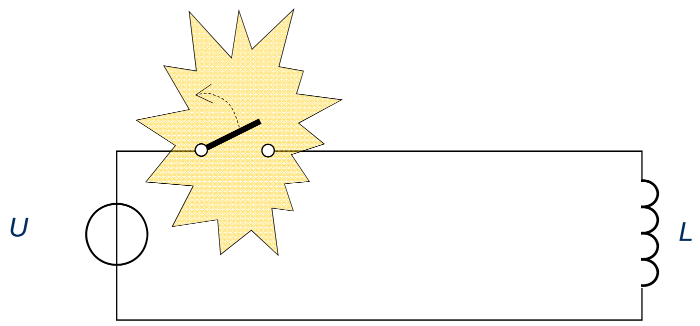




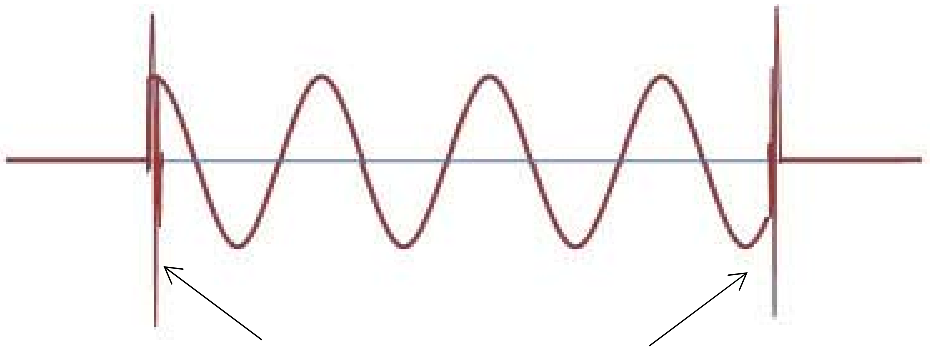
AC applications:

Solid state relay (switching at zero-crossing, no stored energy)

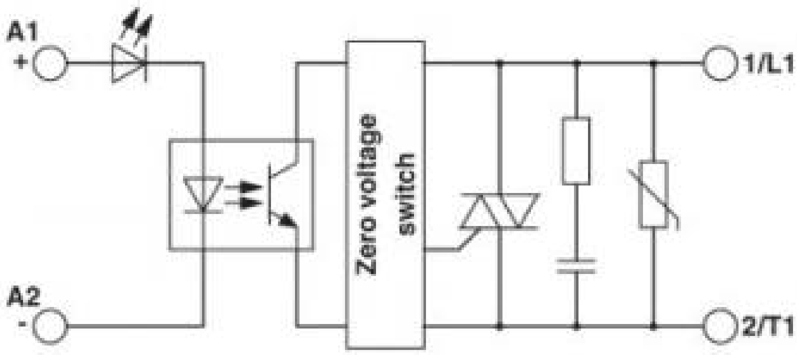
Mechanical switch versus solid state relay



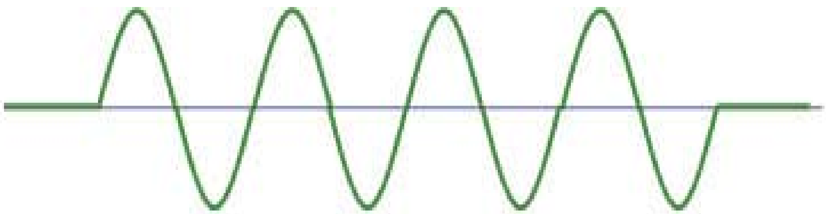
Mechanical relay



Switching transients
due to dI/dt



Solid state relay



No switching transients due
to dI/dt = 0

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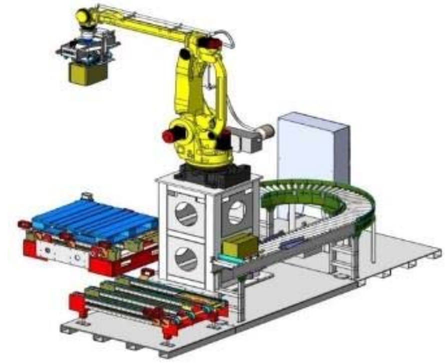
Electromagnetic environments

- Residential or industrial
- But also:
  - Medical/laboratory
  - Public space
  - Heavy industry
  - Shipping/offshore
  - Railways
  - etc.



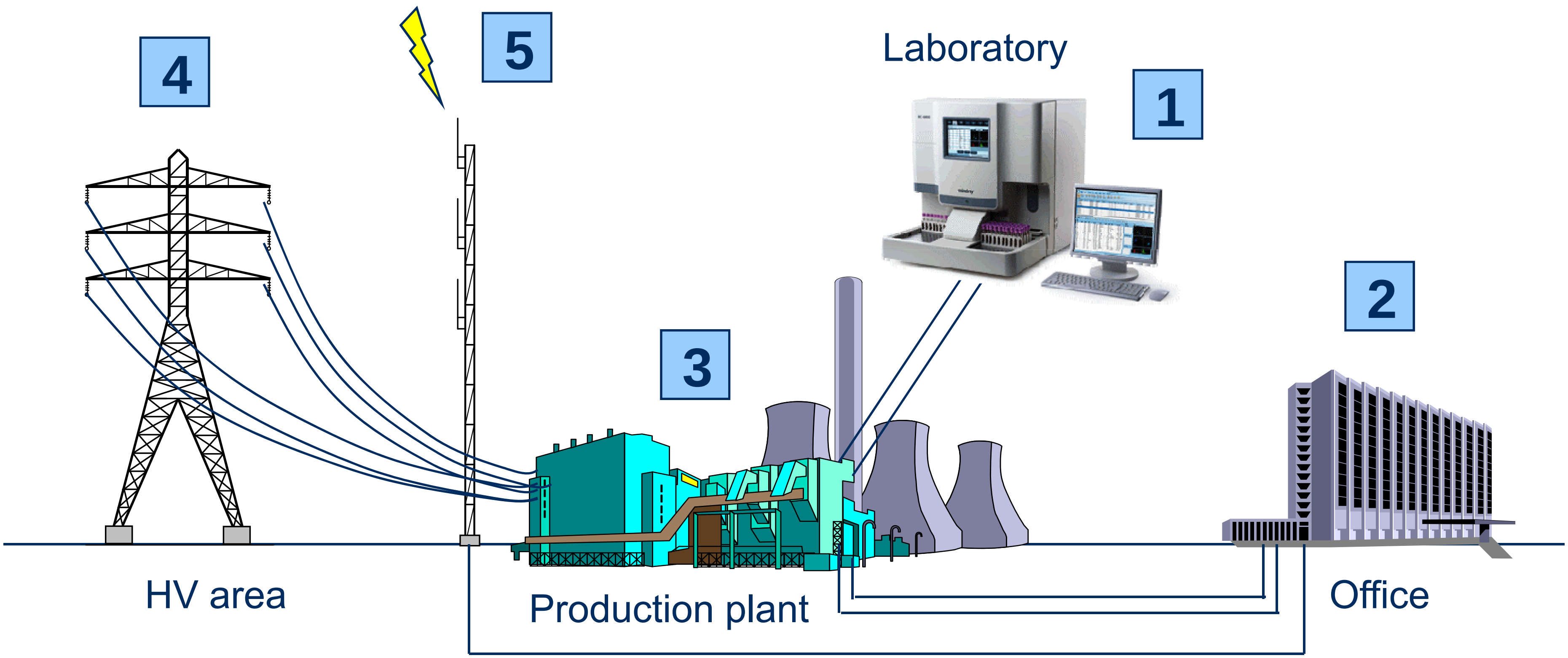
Appropriate EMC specifications of equipment required to fit the EM level!

Electromagnetic zones in large installations

IEC: 1. very sensitive
2. sensitive, domestic / office
3. disturbing/noisy, industrial
4. very disturbing/noisy, heavy industry
5. exception disturbance

Interfaces between EM levels

→ **Installation measures**



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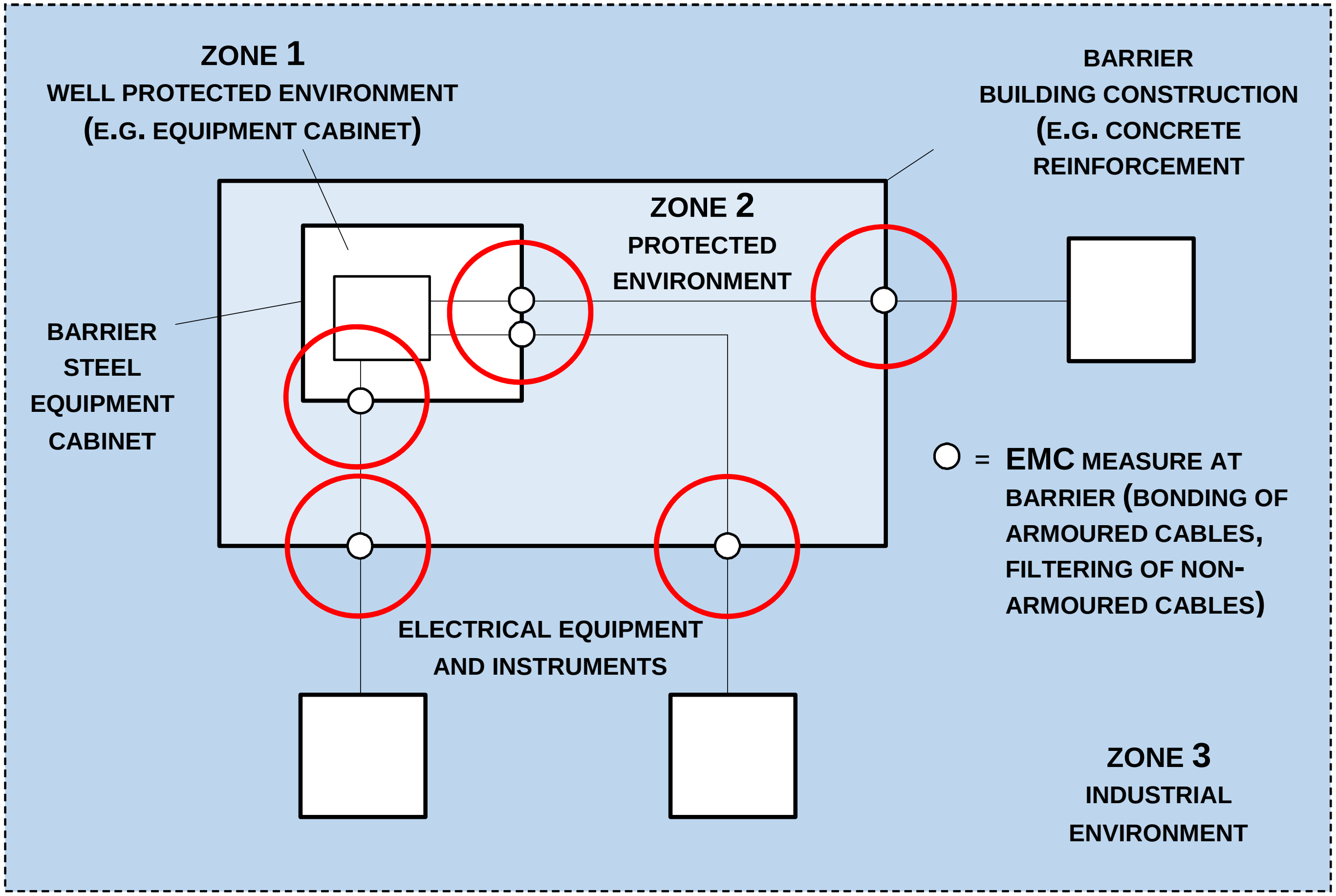
EM zones

- Specify EM levels for equipment in various EM environments
- Specify interfaces between EM zones
- Similar to LPZ (Lightning Protection Zones) in EN-IEC-62305-3 and -4



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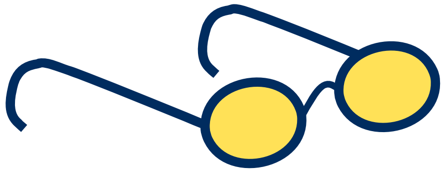
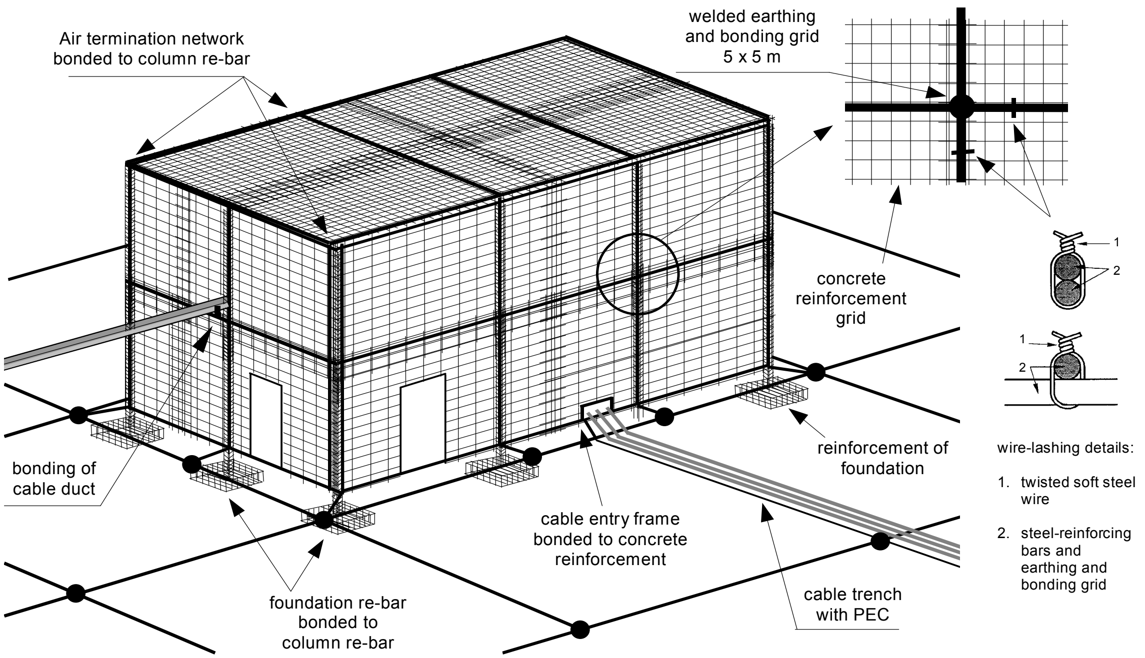
Different look at civil engineering

Required:



EMC spectacles

Control building of plant



Building observed through spectacles

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Cable entry of building

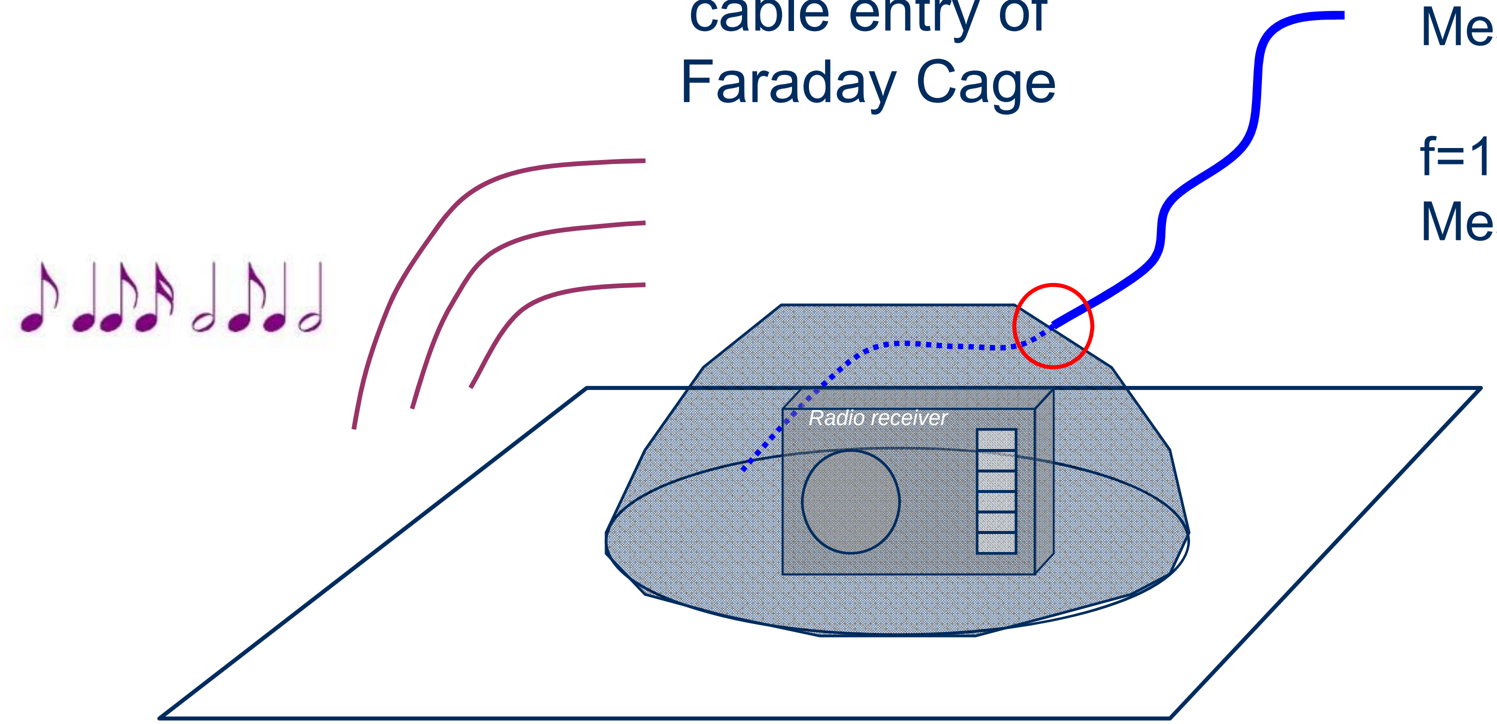
Demo cable entry

λ=c/f = 3.10^8 / f
λ[m] =300 / f[MHz]

f=100MHz (λ=3m)
Mesh size: 1x1mm

f=1MHz (λ=300m)
Mesh size: 10x10cm

Current barrier at cable entry of Faraday Cage



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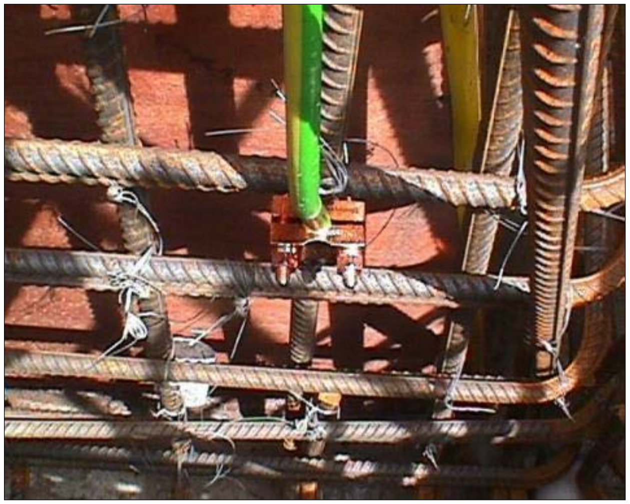
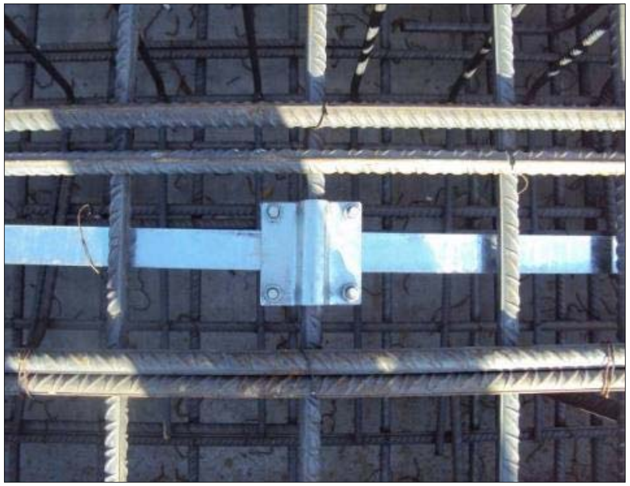
Planning of concrete reinforcement bonding





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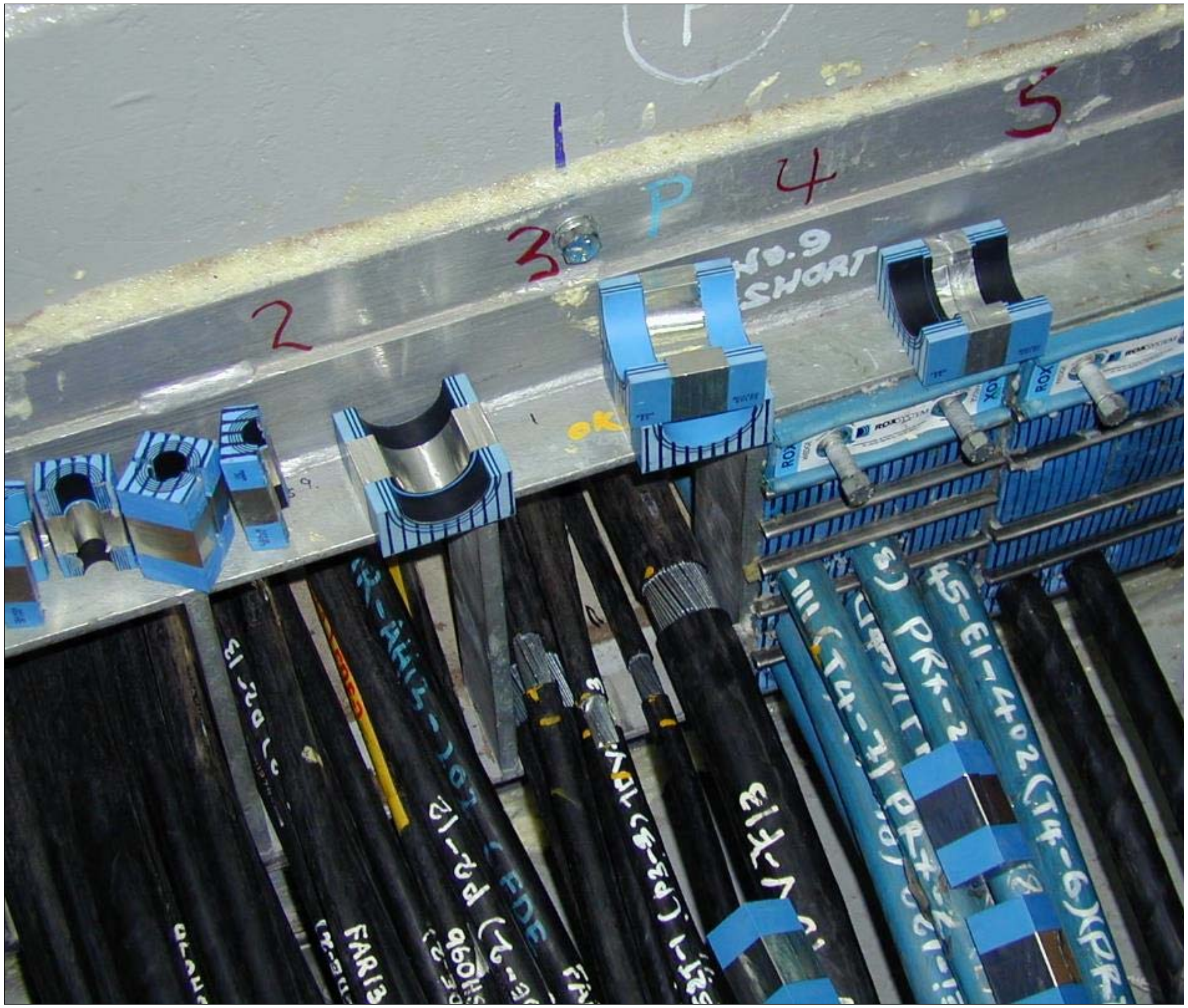
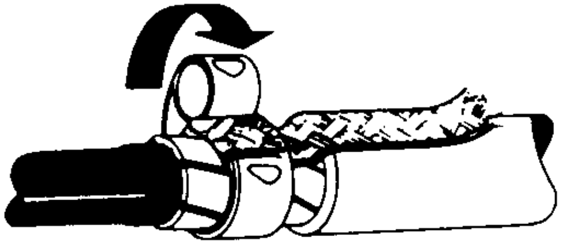
Cable entry inside (bonding of shield to cage)





springclip

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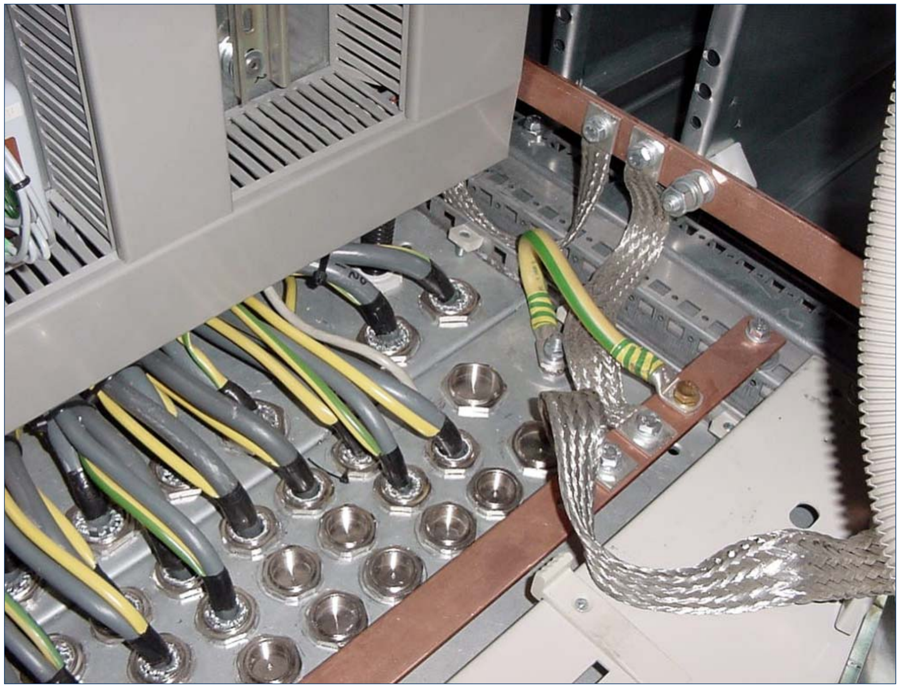
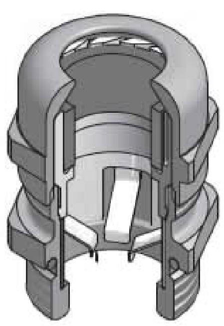
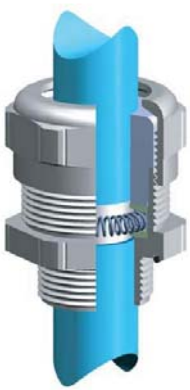
Cable entry in equipment panel



Gland plate

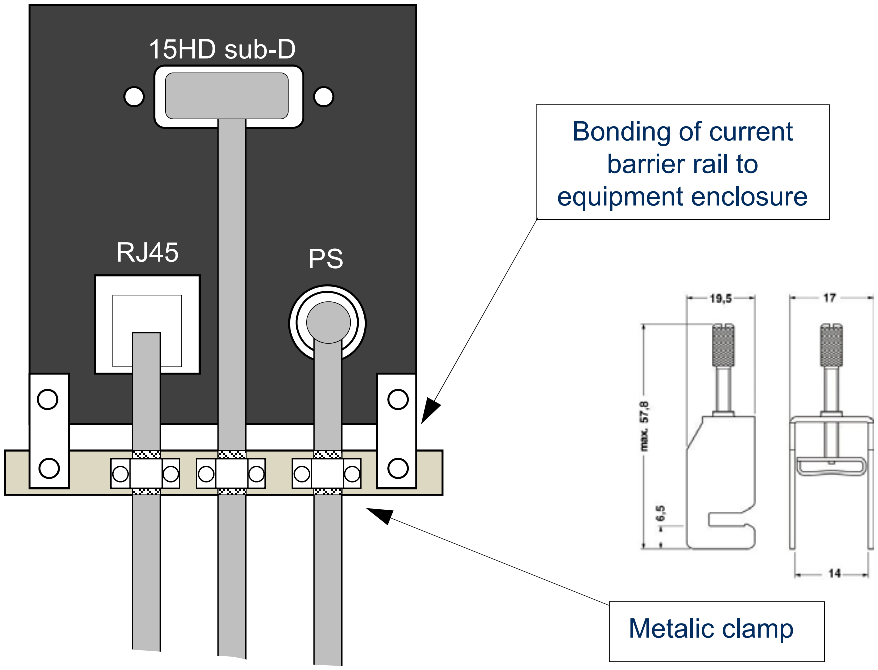




Shielding clamps at panel entry

Cable entry at equipment enclosure

Preferred: metalic enclosure with metalic connectors (cable shield terminated in connector)



Additional current barrier in case of non-metalic connectors

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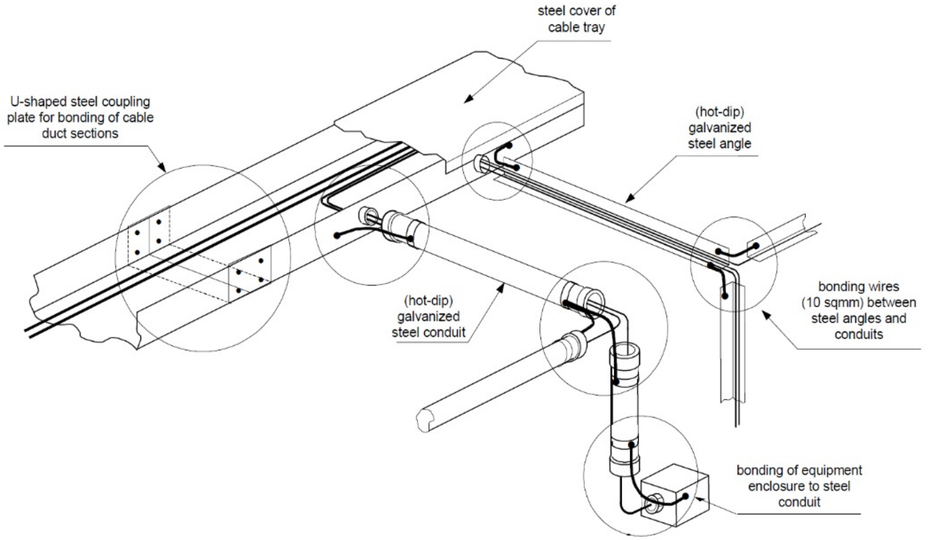
Project approach for LARGE installations

- EPCC:
  - Engineering
  - Procurement
  - Construction
  - Commissioning
- Assign EMC focal point
- EMC management of sub-contractor
- Clarify typical EMC installation details in drawings for field installation



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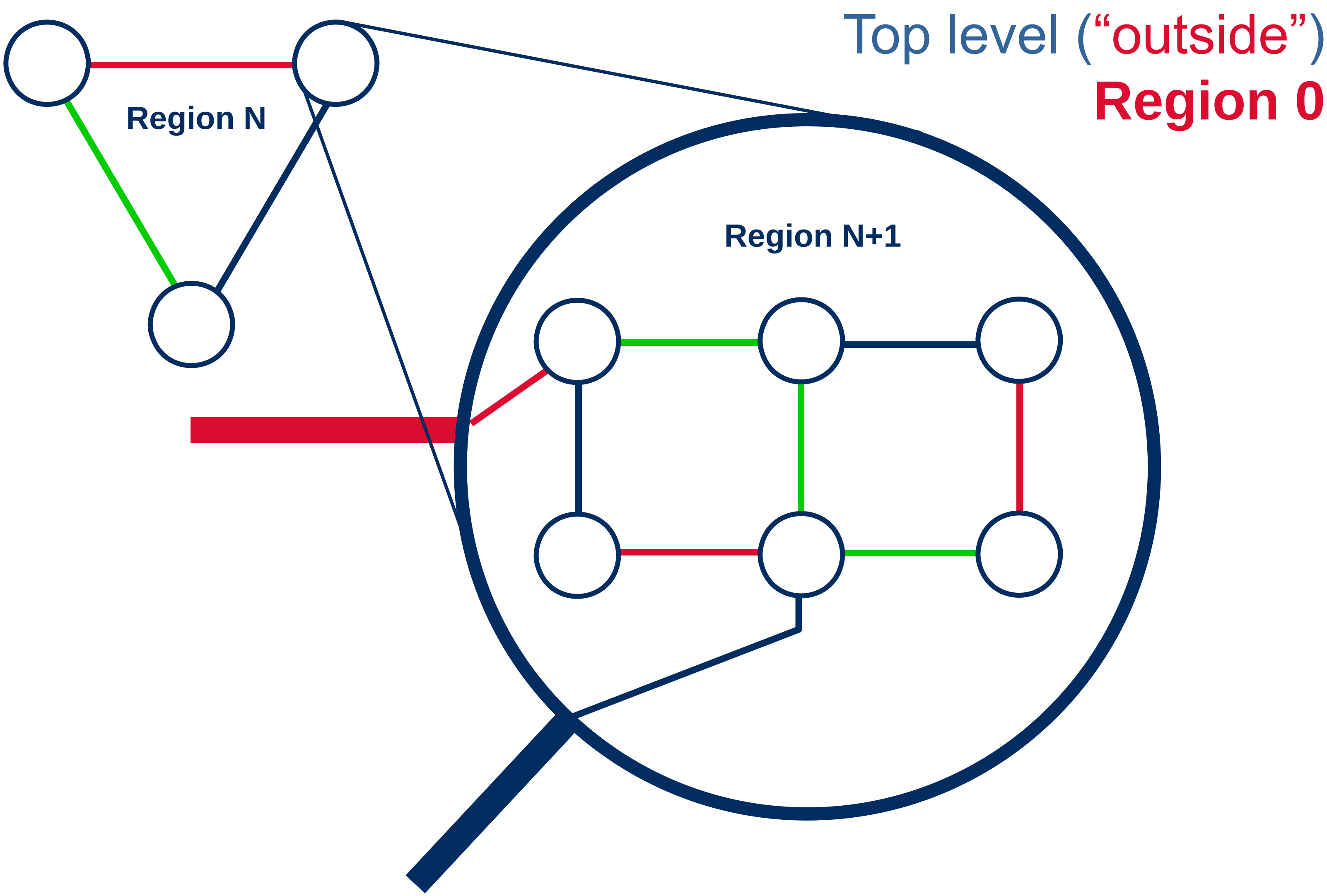
Separating Regions using Current Boundaries

enclosures with current boundaries form individual "environments"



Regions/Environments can be Nested

example: generator in waveguide demonstration

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Only Limited Shielding can be achieved per Enclosure

20 -40 [dB]; but it can be applied recursively!

In EMC terms, sometimes referred to as: Multipoint Grounding…

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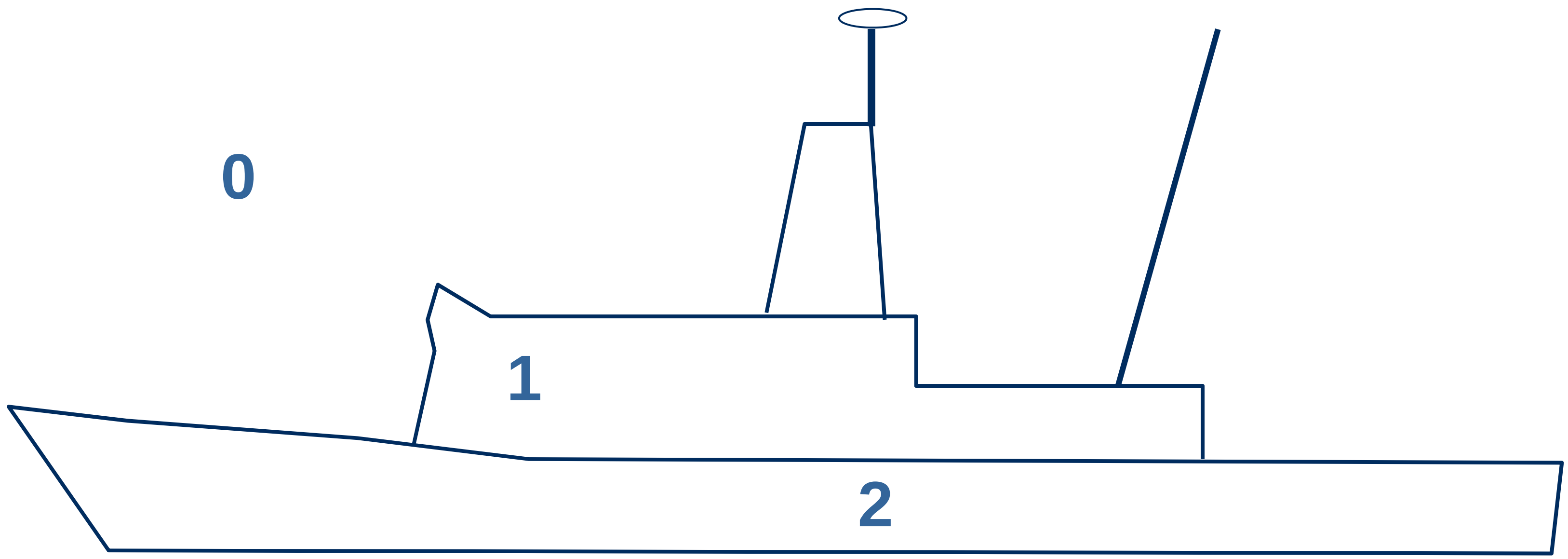
Regions are defined Electromagnetic Environments

(example) region 0: MIL-STD-464A, region 1: bridge, region 2: below deck



Aim: use commercial equipment in region 2 (susceptibility level 10 V/m)

Shielding between successive regions: 20 - 40 dB (factor 10 to 100)

- ❑ Define where EM zones will be
- ❑ Define the EM levels per region
- ❑ Use adequate current boundaries between regions

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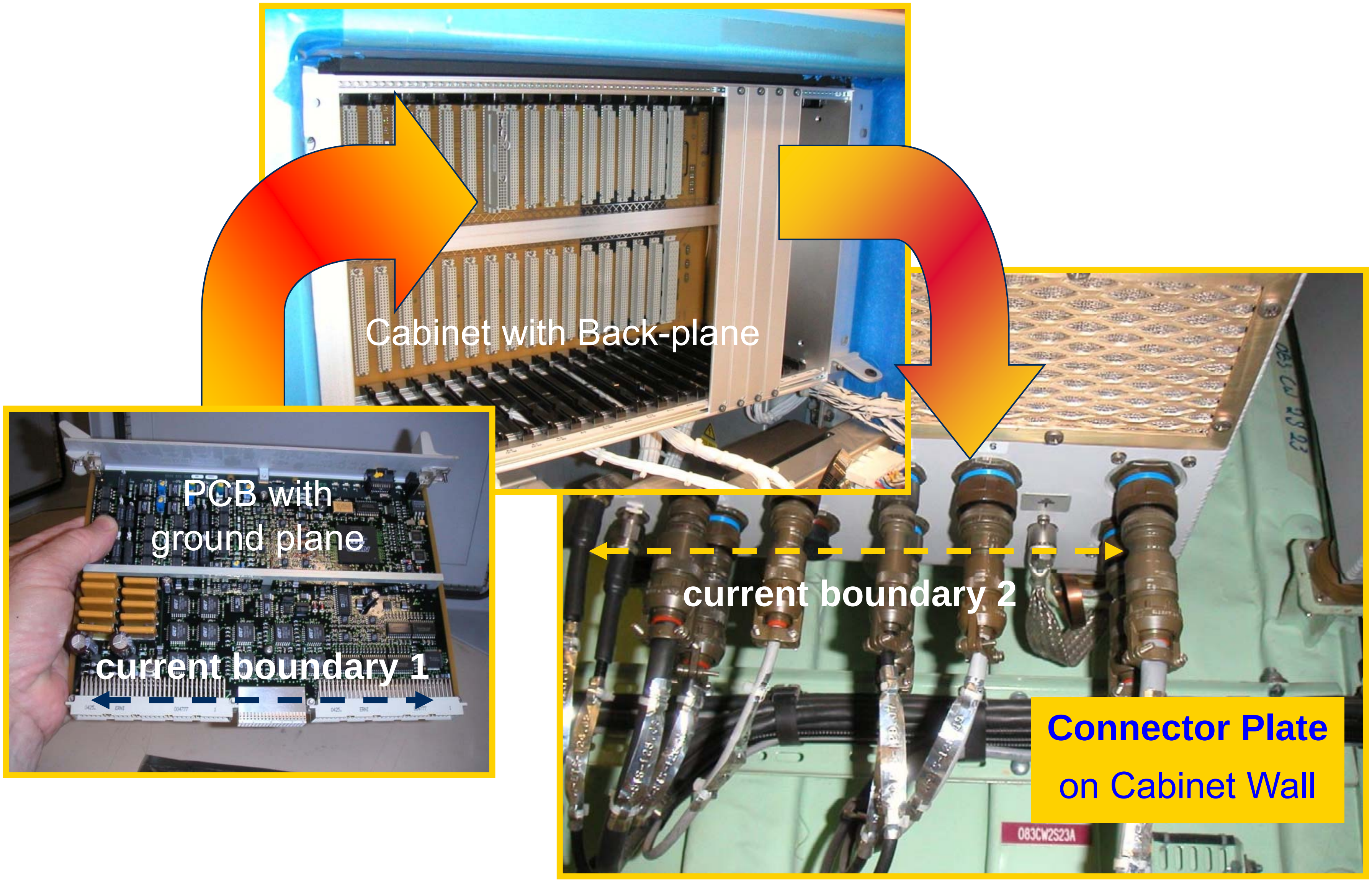
Multipoint Grounding

hierarchy of current boundaries



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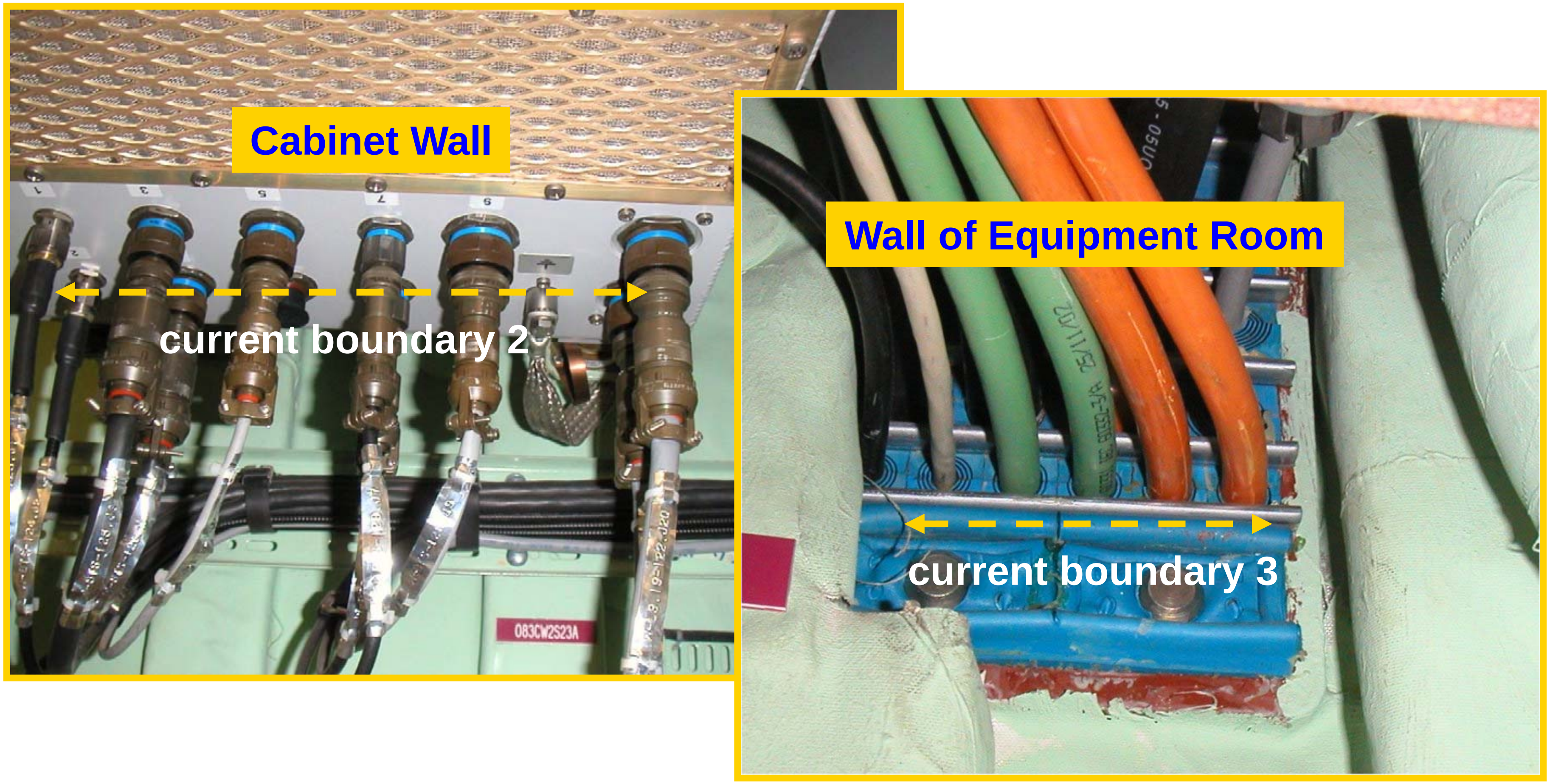
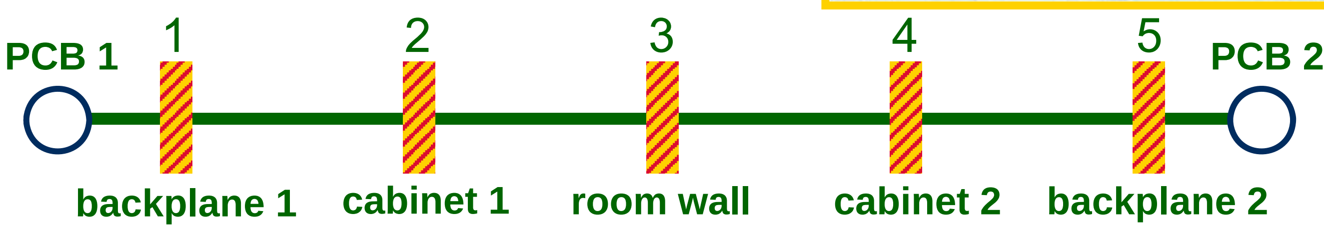
separating rooms in a ship is called Zoning (partitioning into EM-Regions)





20 dB per boundary:
= 100 dB!

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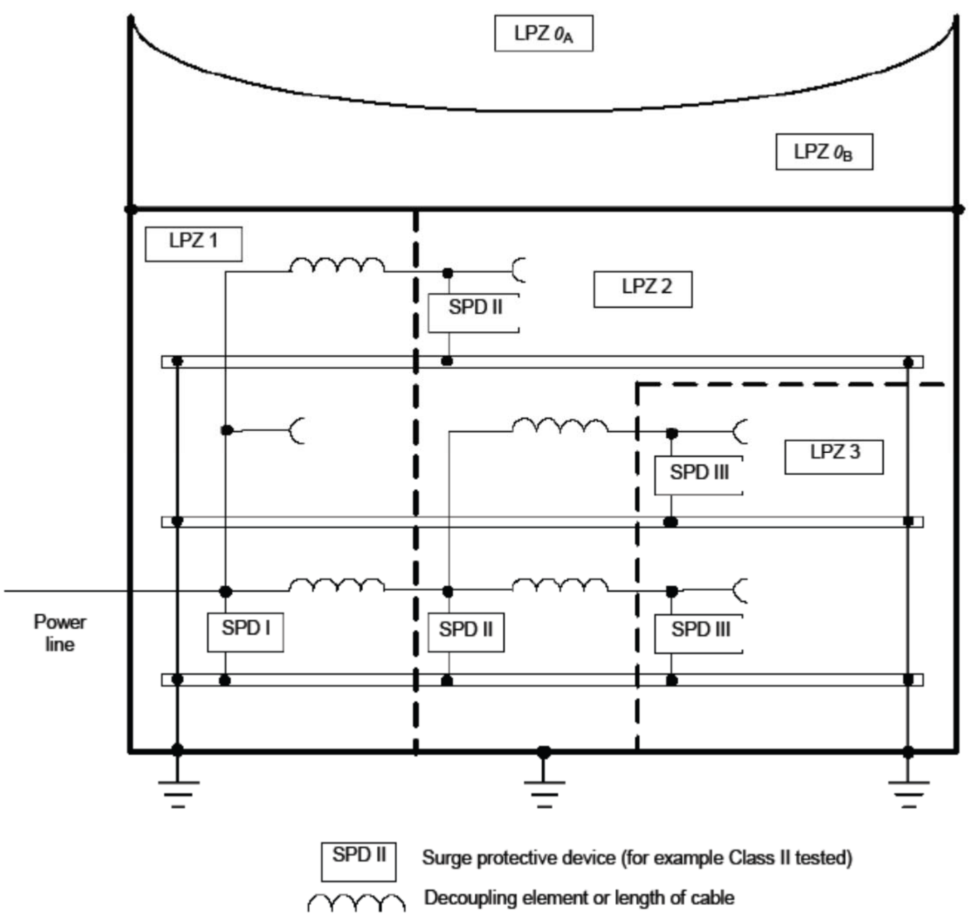
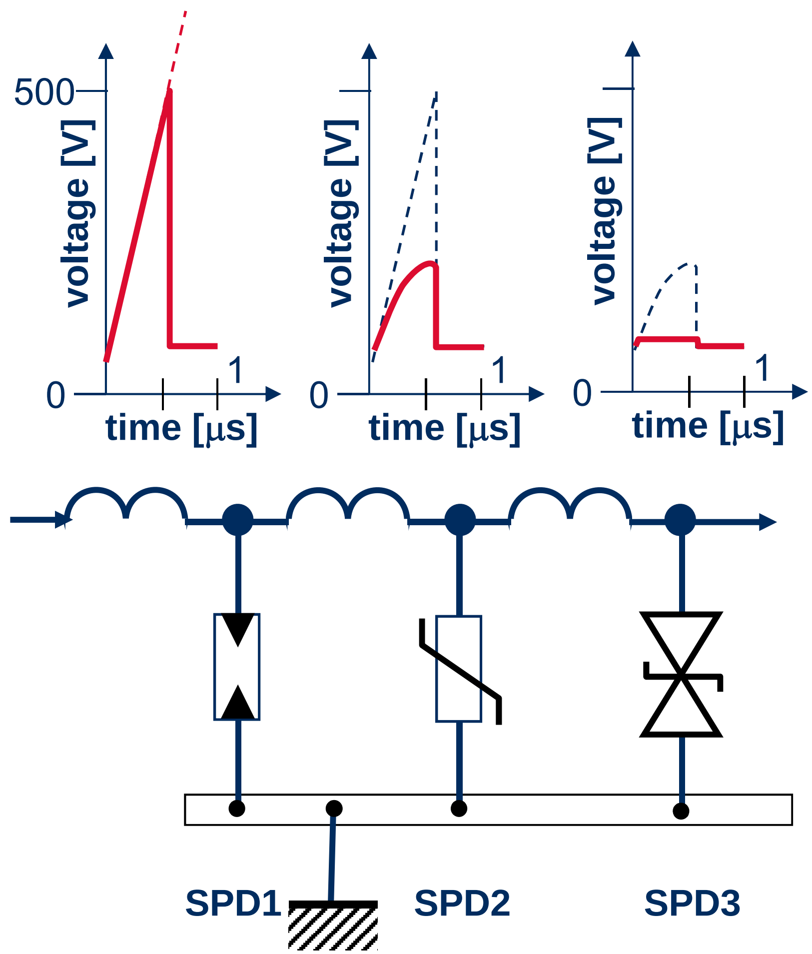
Voltage Dependent Current Boundaries

varistors and tranzorbs are often used to absorb DM or CM spikes



Example from IEC 62305 part 4 (Annex C)

note: 1 [m] cable ≈ 1 μH



Source: Jasper J. Goedbloed, "EMC"
Prentice Hall/Kluwer 1992

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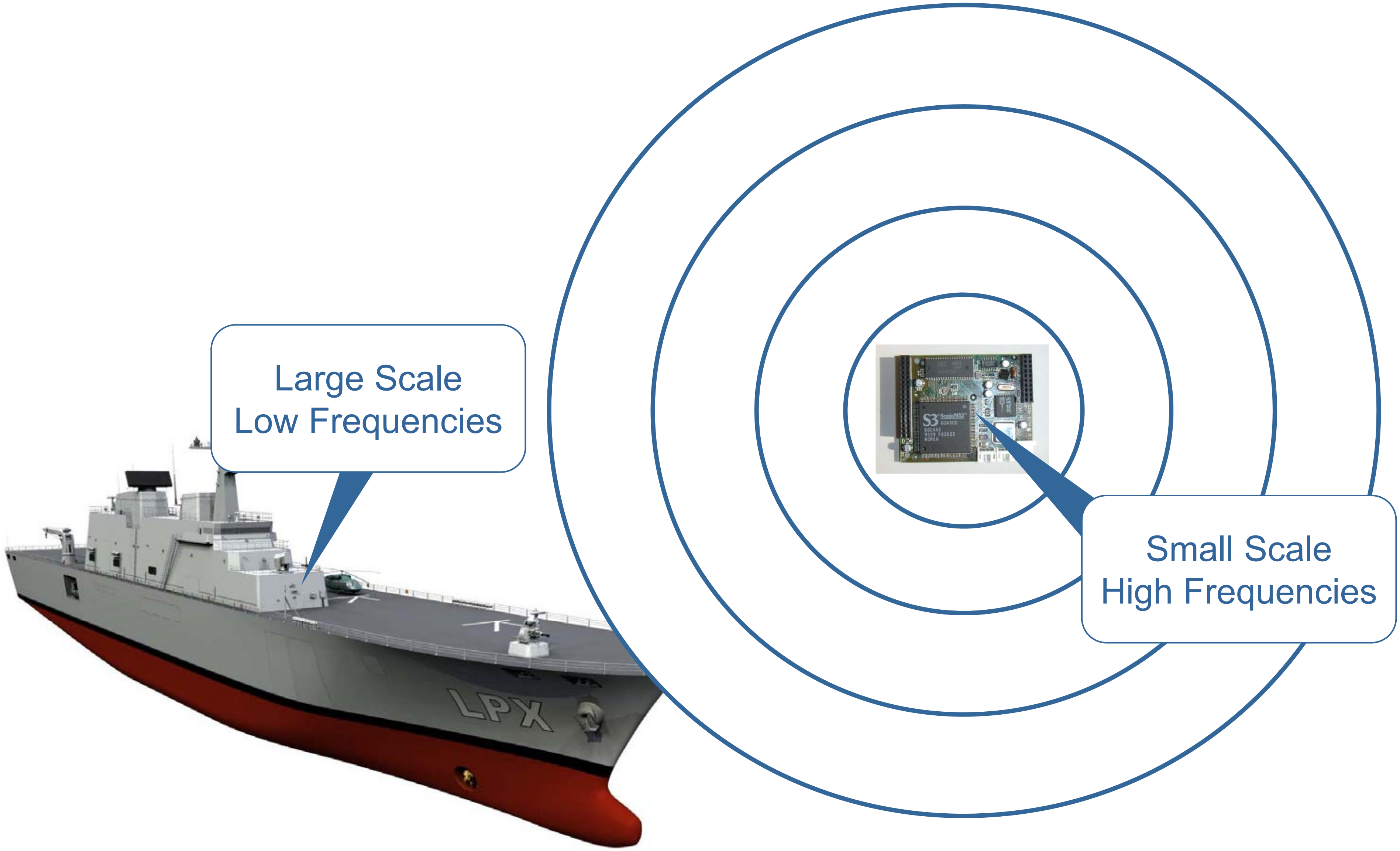
Try to stick to the "Low Frequency Approach"

use current boundaries to restrain sizes to way below half-wavelength



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Conclusions, summary of EMC measures

- Take the EM level of the user's environment, including EM zones, as basis of design for EMC specifications
- Design and procure equipment with corresponding emission and immunity levels (verify and avoid any pitfalls in product standards)
- Adhere to installation requirements mentioned in "user manuals"
- Install de-coupling devices on inductive (switched) loads, use solid state relays for high switching frequencies
- Apply generic installation rules in terms of earthing, bonding at EM zone interfaces and cable segregation, e.g. IEC/TR 61000-5-2

EMC Basic Rules

- Do not use high frequency signals (voltages and currents)

If you do use them:

- Do not transport them over large distances

If you do:

- Provide adequate current boundaries

Reduce Loop Areas

Use Connector plates

EMC Glands

Metal cable guides

Properly terminate transmission lines

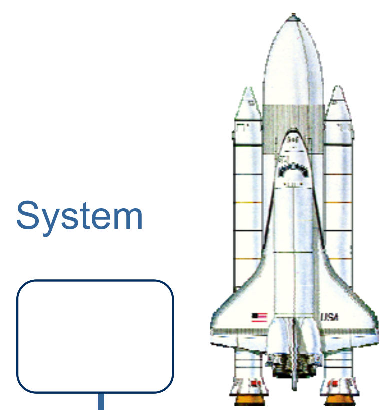
- Specify the EMC performance of your system

“Systems Designers Heaven”

independent building blocks with “abstract” behaviour

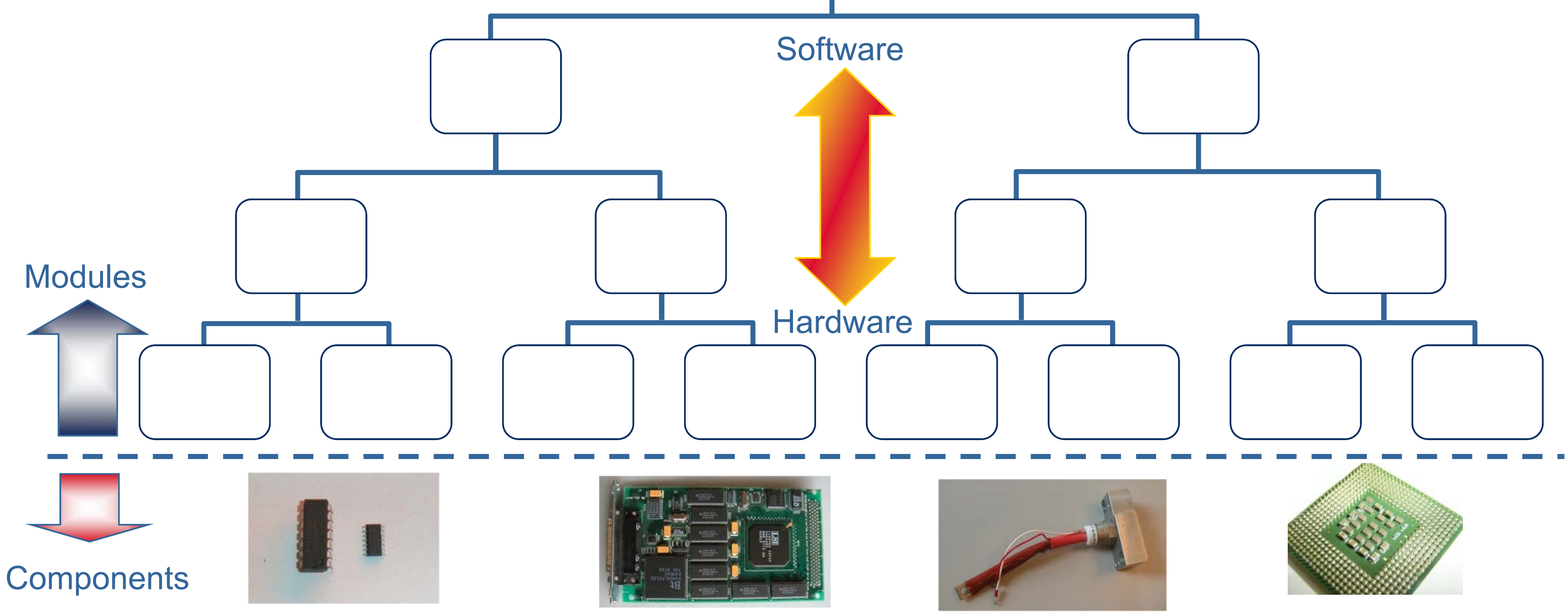
Object Oriented

- ❑ realise complex from simpler behaviour
- ❑ make assemblies independent
- ❑ solve “undesired” as low as possible



EMC Principal Laws

- ➢ No high frequencies
- ➢ Do not transport them
- ➢ Use adequate boundaries



October 19, 2016

Two ways to achieve EMC: 1. The Crisis Approach

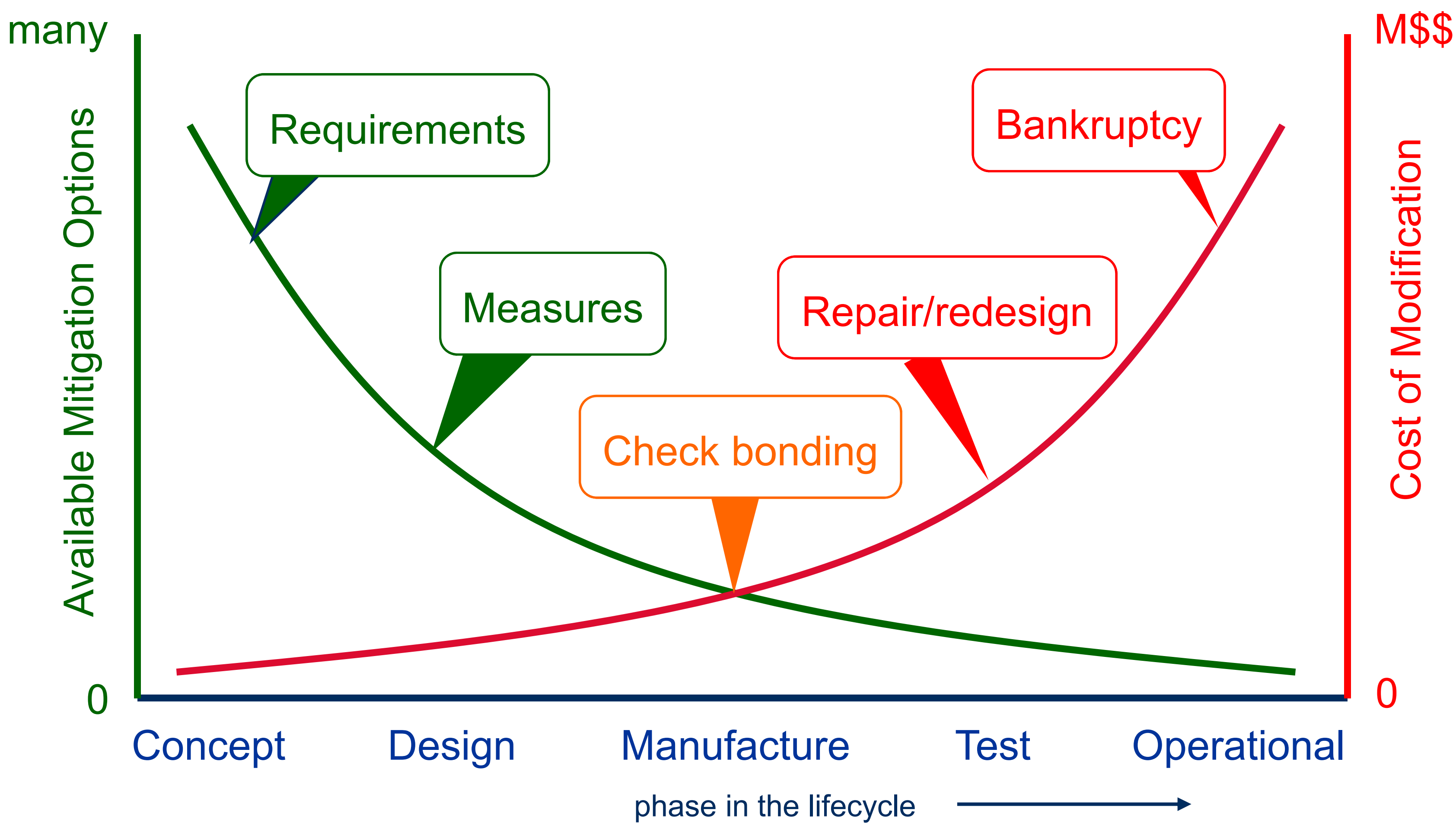
"Build the plane, push it off the cliff, let it crash and start all over again"

Source: YouTube

October 19, 2016

2. The “Systems Approach”

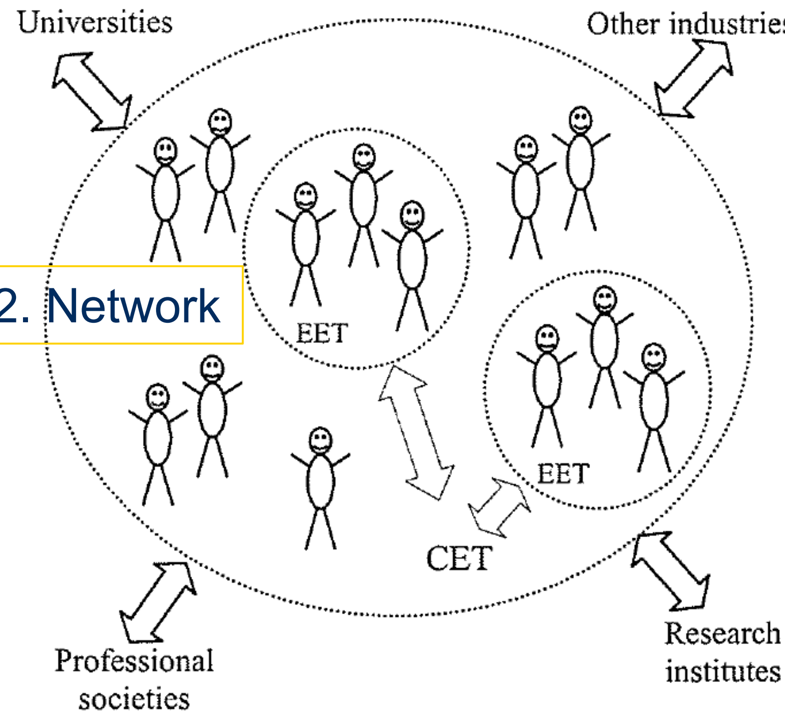
Consider EMC right from the start throughout the design



Four Key Elements

of EMC implementation in large organizations

1. Awareness

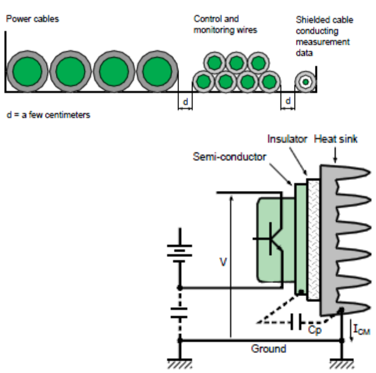


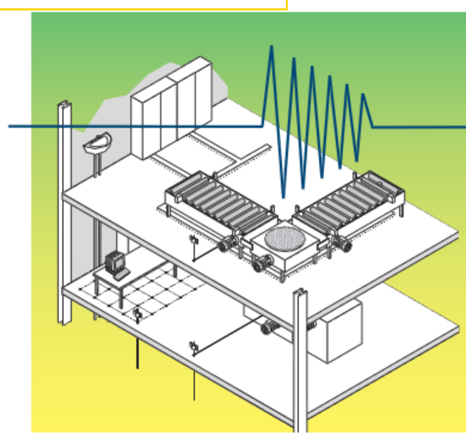
2. Network

Practical Installation guidelines

«EMC»

3. Rules & Guidelines





MODULE No 15 - HARDWARE DEVELOPMENT

METHODOLOGY

4. Program support

EMC CONTROL PLAN

MIL-HDBK-237B
01 OCTOBER 1997

SUPERSEDING
02 FEBRUARY 1981

DEPARTMENT OF DEFENSE HANDBOOK

GUIDANCE FOR CONTROLLING ELECTROMAGNETIC ENVIRONMENTAL EFFECTS ON PLATFORMS, SYSTEMS, AND EQUIPMENT

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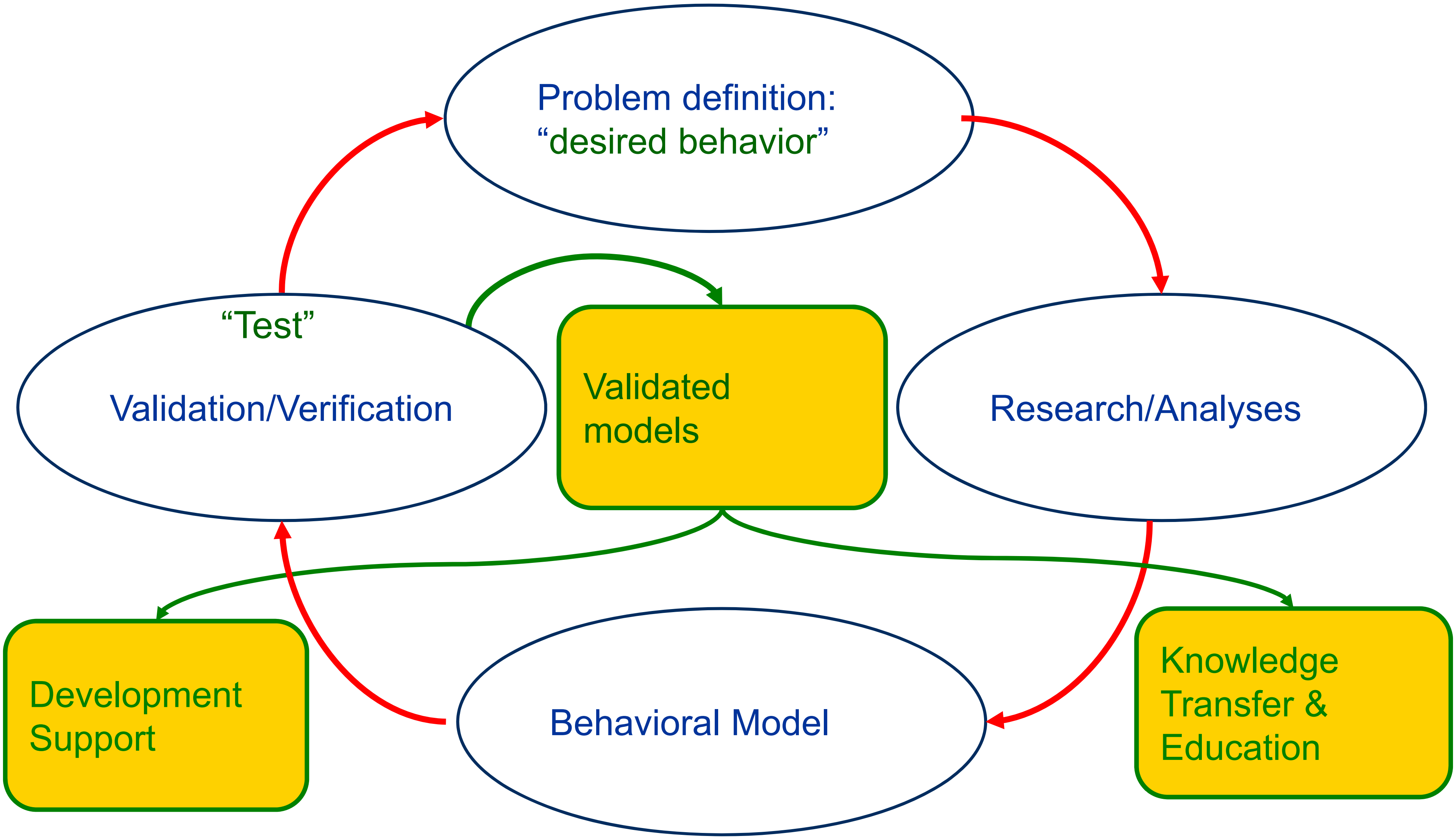
Build EMC assurance through the Knowledge Cycle

insert electro magnetic behavior up front



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EMC Rules and Guidelines

a lot of information on EMC engineering can be found on the internet

Practical Installation guidelines

«EMC»

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Rules and Guidelines

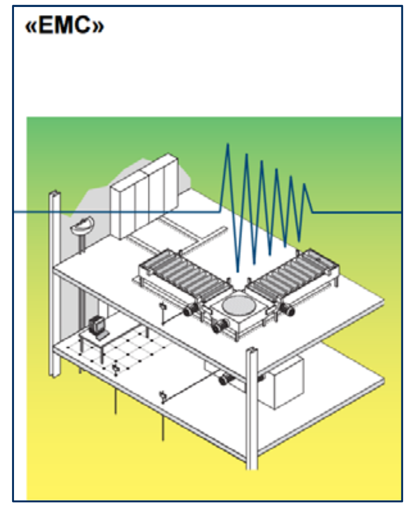
a lot of good literature is available on the internet

Schneider Electric

http://www.eschneider.pl/download/10%20Poradniki/EMC.pdf

Or try one of the EMC “Cahiers Technique” e.g. #149:

http://genesis.ee.auth.gr/dimakis/egatastaseis/groupe%20schneider/cashier%20techn/ECT149.pdf



Design Techniques for EMC – Part 1

Circuit Design, and Choice of Components

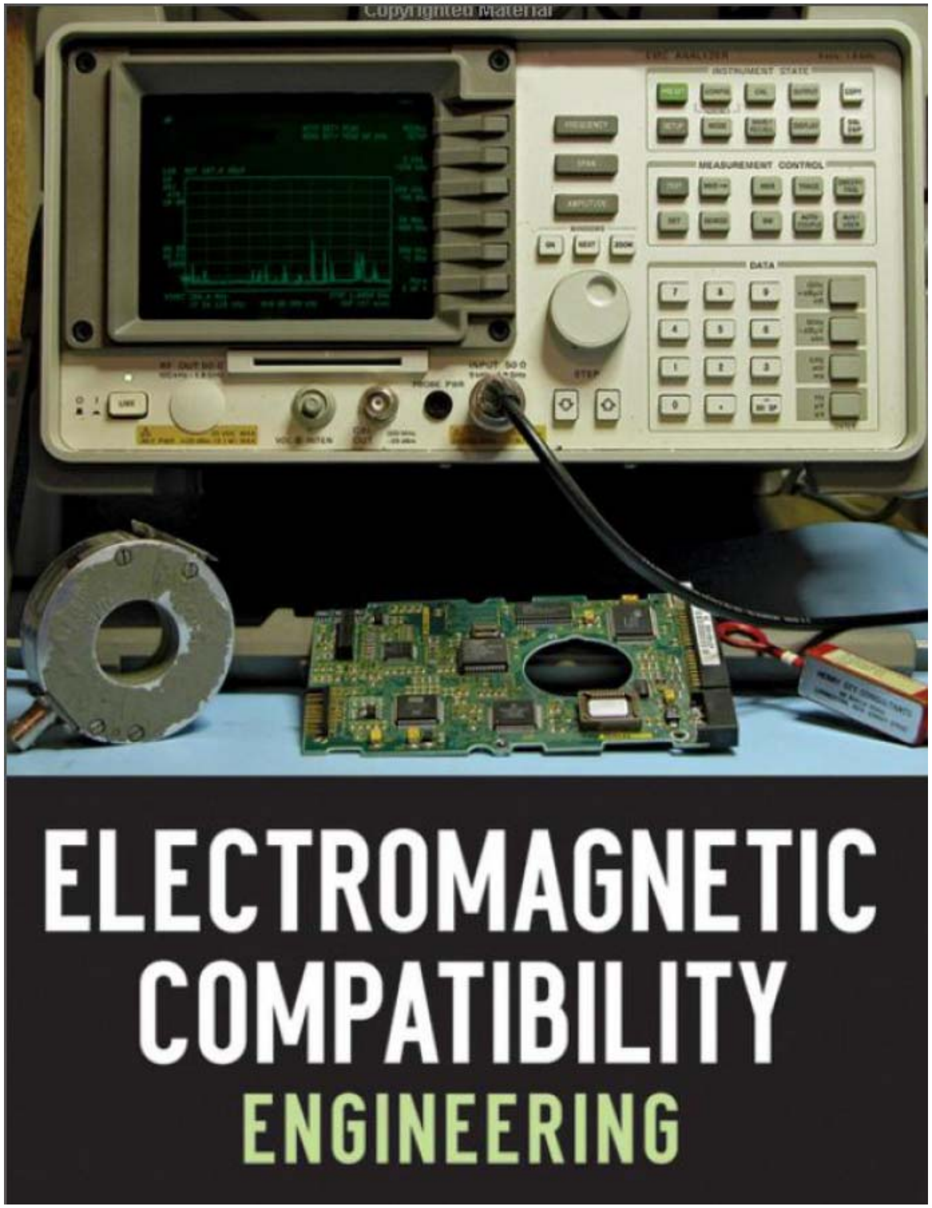
By Eur Ing Keith Armstrong CEng MIEE MIEEE
Partner, Cherry Clough Consultants, Associate of EMC-UK

http://www.humerboard.at/ftkl/Design_Techniques_For_%20EMC.pdf

Allen-Bradley

System Design for
Control of
Electrical Noise

http://literature.rockwellautomation.com/idc/groups/literature/documents/rm/gmc-rm001_-en-p.pdf or: buy a book!



ISBN 978-0-470-18930-6

Product Development/Program Support

perform engineering & qualification tests

October 19, 2016

Further questions?

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