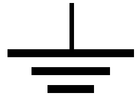
Grounding and earthing

Véronique Beauvois, Ir.
2021-2022

Grounding and earthing

General definition: 

-Earth's ground considered for electrical installations as a reference of 0V

-Variable electrical conductivity – naturally electrical currents are flowing.

Key-roles:

- Lightning current flowing
- Leakage current flowing
- Protection of persons

(IEC 364 – Electrical Installations of Buildings
& IEC 50164 – Lightning protection components)

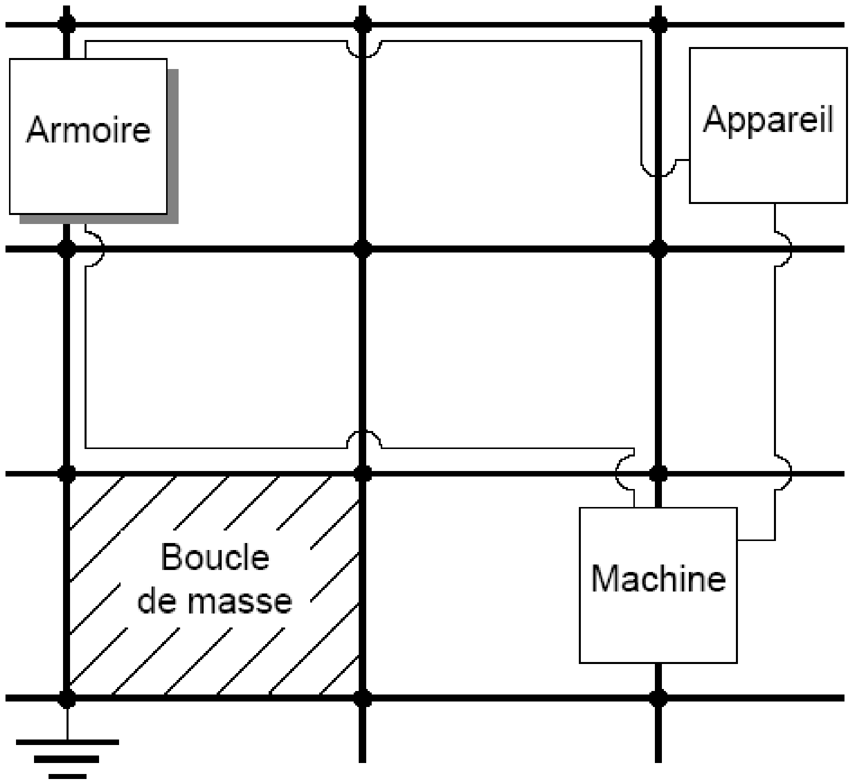
Earthing/grounding and EMC:

For a lot of EMC phenomena (transient disturbances, HF currents…), earthing conductors are not efficient as they are very long and the used topology means a high impedance versus HF.

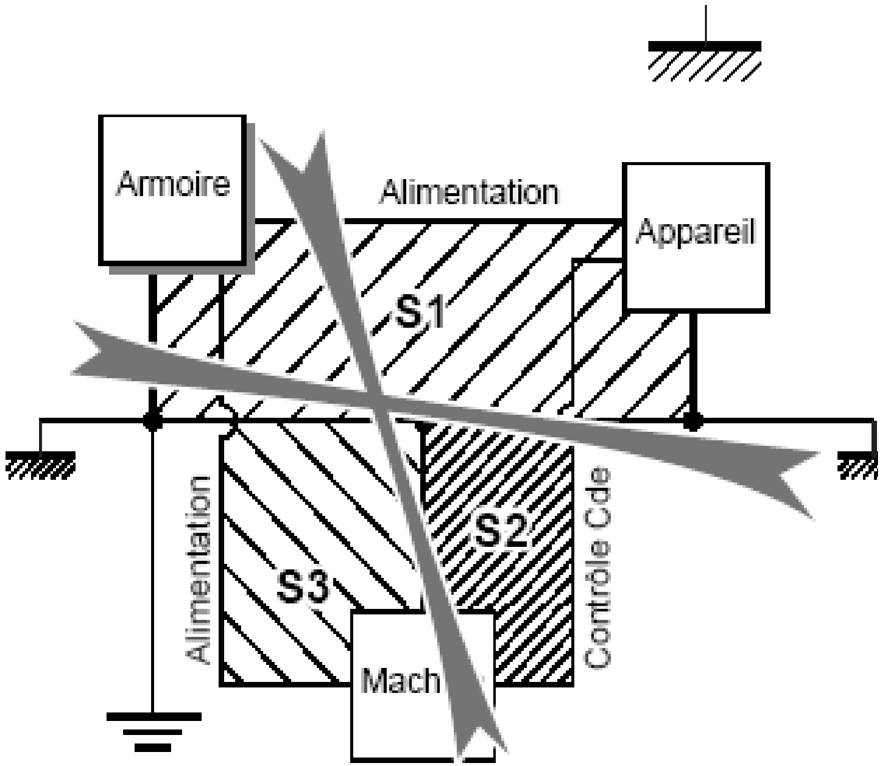
The only solution is **meshing** to get **equipotentiality**.

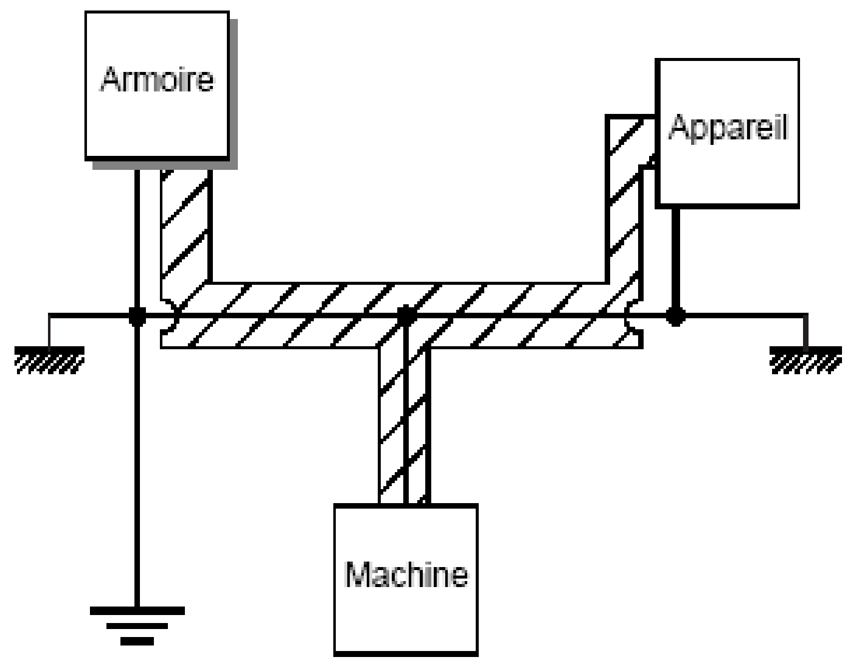
Mesh size: $\pm\ \lambda/10$.

All electrical elements, components, should be connected as shielding, screens, CM connections of filters (remember some remarks on good implementation in *Components*).



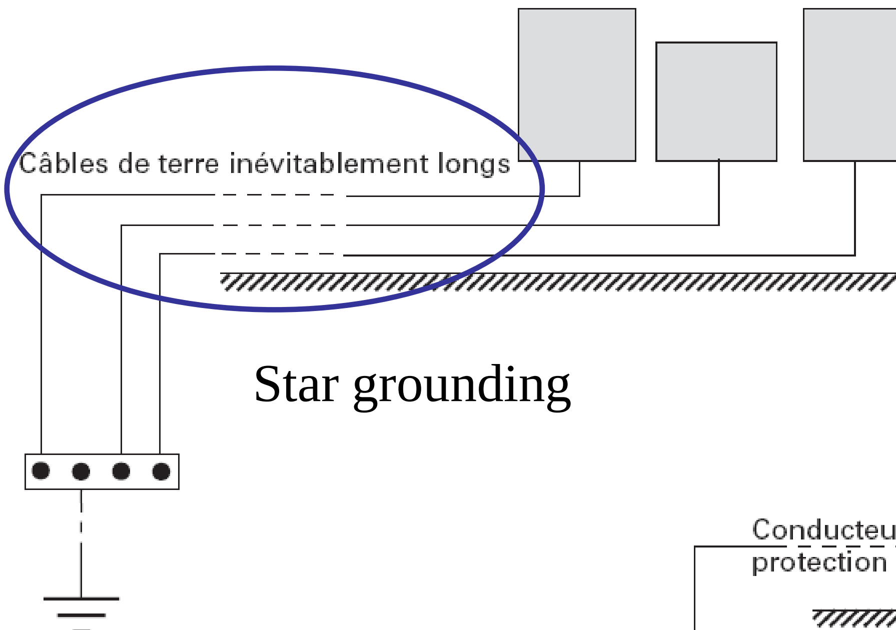
Loop between grounding = surface beween 2 grounding cables, resulting of a systematic meshing of ground to insure equipotentiality.
Solution?
To reduce loop size with a small mesh size.



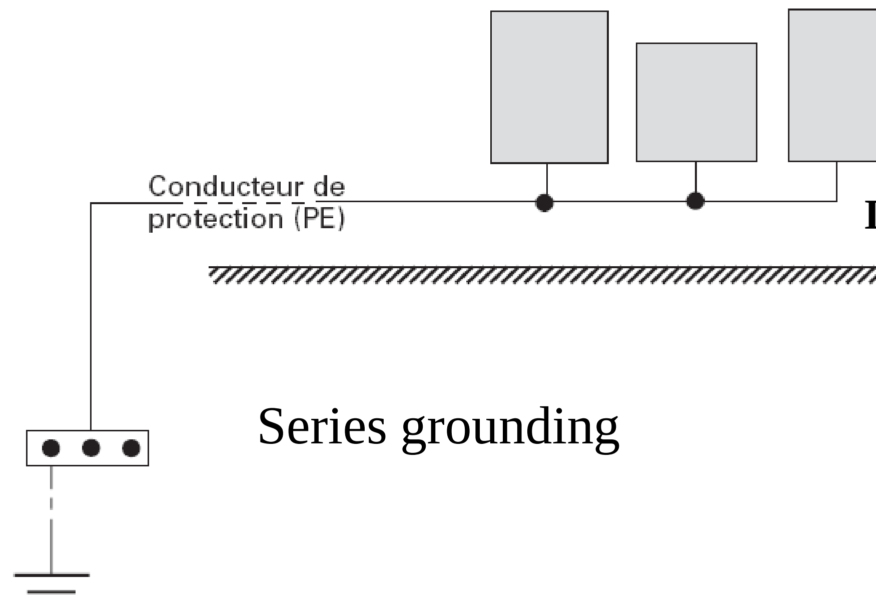


Grounding loop: surface loop between a power/signal cable and a corresponding grounding cable.
Solution? To reduce loop size with a very short distance between power/signal cable and corresponding grounding cable (all along the cables).

Grounding and earthing



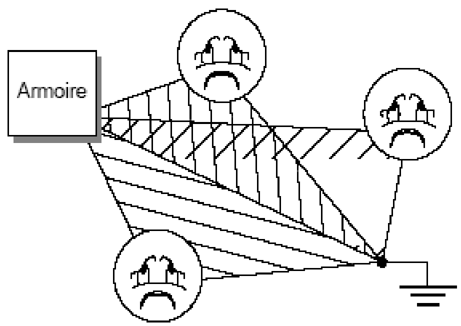
Star grounding



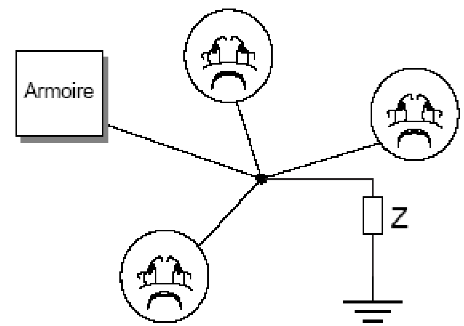
Lmax 50cm

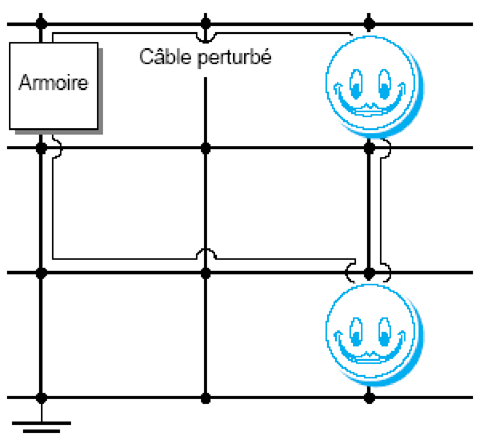
Series grounding

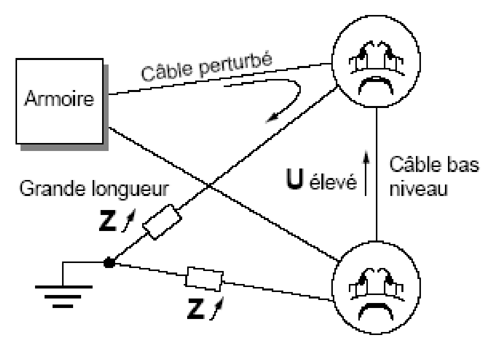
Grounding and earthing



Boucles de masse de grande surface







Forte impédance commune
==> ddp entre les équipements

Grounding and earthing

Building:

• ground meshing by level

• connect all metallic structures of building to the ground (pipes, ducts, duckboards…)

• in sensitive zone (computers, data, measurements), consider a small meshed system

Equipment:

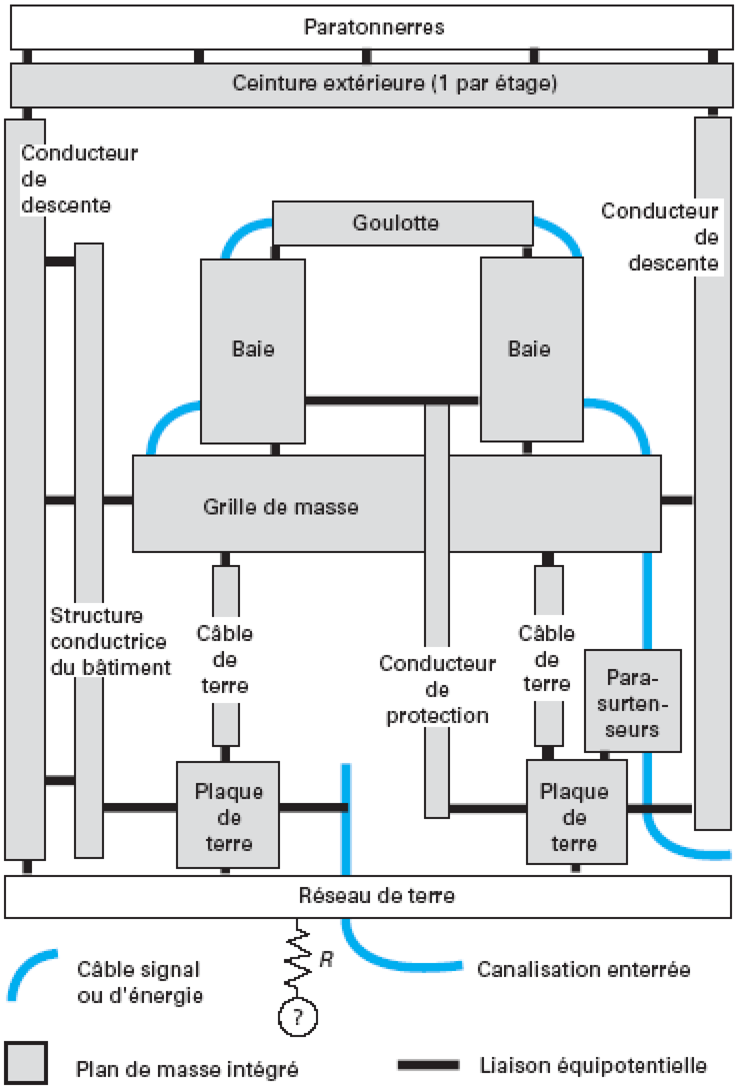
• Connect all metallic structures together

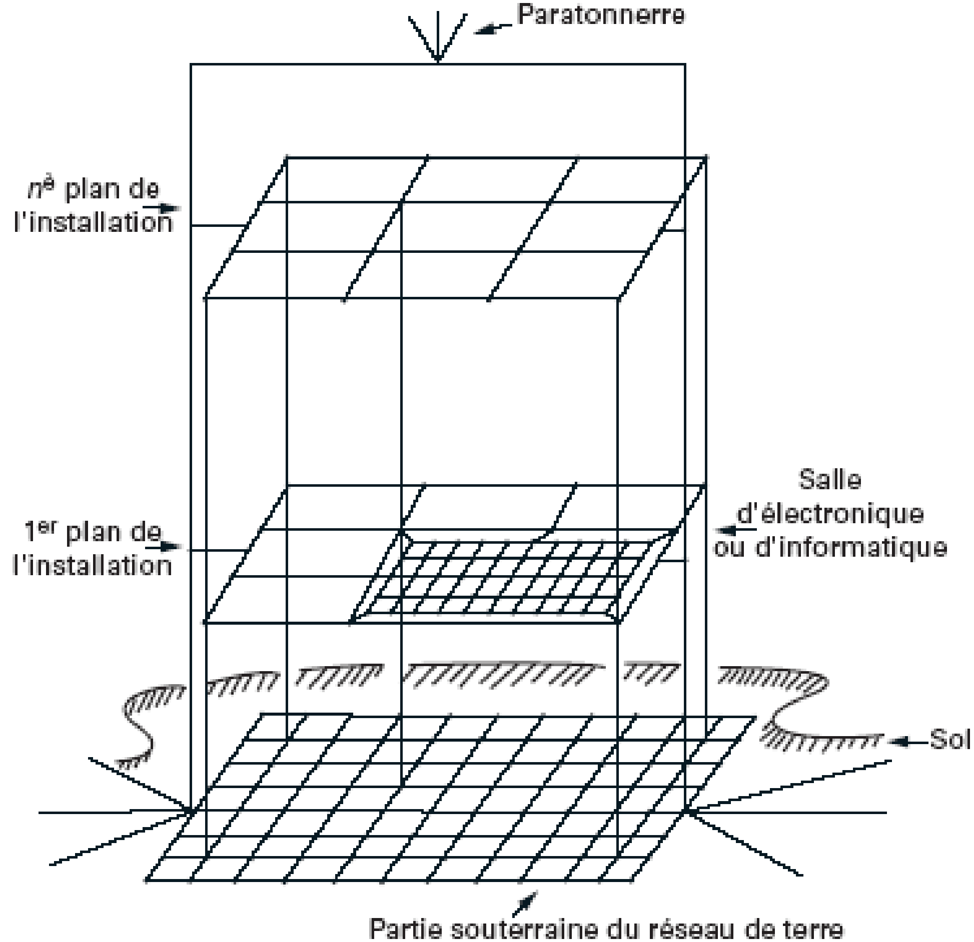
Rack:

• a metal plate in the bottom of the rack

• insulating coating and painting

• good contact between components and metal plate (green-yellow cabling is not sufficient for EMC).


Paratonnerres
Ceinture extérieure (1 par étage)
Conducteur de descente
Goulotte
Conducteur de descente
Baie
Baie
Grille de masse
Structure conductrice du bâtiment
Câble de terre
Conducteur de protection
Câble de terre
Para-surten-seurs
Plaque de terre
Plaque de terre
Réseau de terre
R
?
Câble signal ou d'énergie
Canalisation enterrée
Plan de masse intégré
Liaison équipotentielle


Paratonnerre
nè plan de l'installation
1er plan de l'installation
Salle d'électronique ou d'informatique
Sol
Partie souterraine du réseau de terre

Shielding

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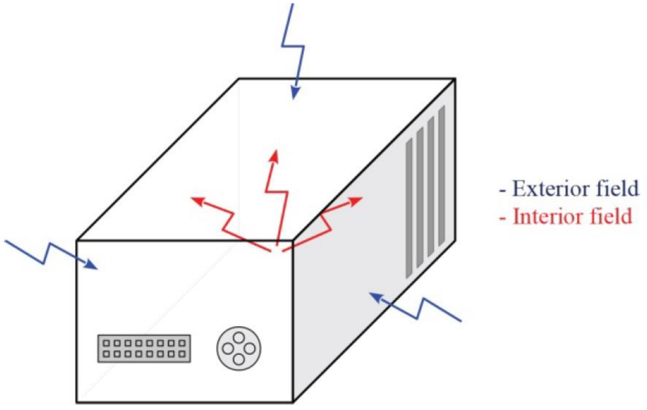
Reasons of Shielding



- Reducing emission:
  - see for related standards
- Improving immunity:
  - radio-frequency magnetic field
  - 50 Hz magnetic field
  - impulsive magnetic field
  - damped oscillating magnetic field
  - see for related standards
- Used locally to protect one sensitive part of a device:
  - internal local problem
  - no corresponding standard

- Important parameters:
  - material,
  - thickness,
  - characteristics of the source,
  - distance from the source,
  - presence of openings
  - presence of traversing conductors

Materials

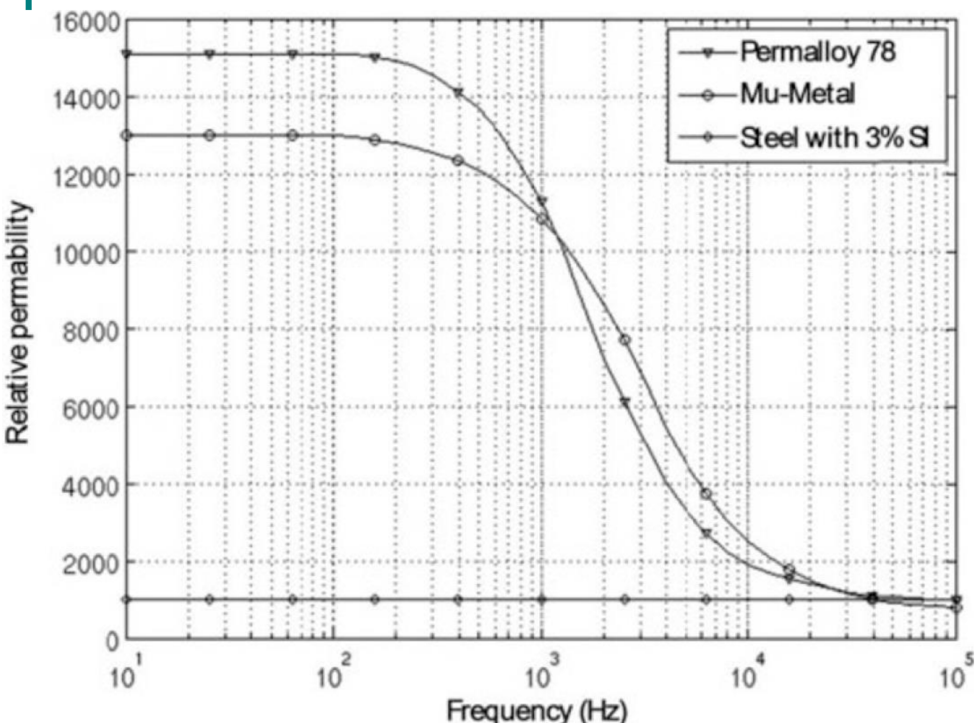
Materials	Relative conductivity in relation to copper	Relative permeability (100 Hz)
	G	μr
Silver	1.05	1
Annealing copper	1.00	1
Gold	0.70	1
Aluminum	0.61	1
Brass	0.26	1
Nickel	0.20	1
Bronze	0.18	1
Tin	0.15	1
Steel, 3% Si	0.10	1,000
Lead	0.08	1
Monel	0.04	1
Stainless steel	0.02	500
78 Permalloy	0.11	15,000
Mu-metal	0.03	13,000

Constants and physical properties			
μ_0	=	$4\pi \times 10^{-7}$	$[\mathrm{H \cdot m^{-1}}]$
ε_0	=	$1/(36\pi) \times 10^{-9}$	$[\mathrm{F \cdot m^{-1}}]$
c	=	3×10^{8}	$[\mathrm{m \cdot s^{-1}}]$
σ_{copper}	=	5.8×10^{7}	$[\mathrm{S \cdot m^{-1}}]$

$$\mu = \mu_0 \times \mu_r$$

$$\sigma = G \times \sigma_{copper}$$

Effect of frequency on materials



Steel, 3% Si									
Frequency	kHz	MHz					GHz		
	≤10	1	3	10	30	100	1	1.5	10
μr	1,000	700	550	400	300	200	50	10	1

Mu-Metal and steel have very high permeabilities but they quickly decrease with frequency.

Material wave impedance and skin depth

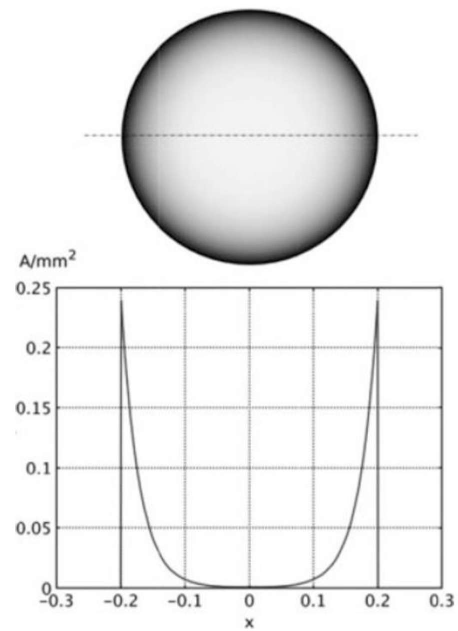
Wave impedance in the metal

$$Z_m = \frac{|\vec{E}_t|}{|\vec{H}_t|}$$

$$Z_m \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}$$

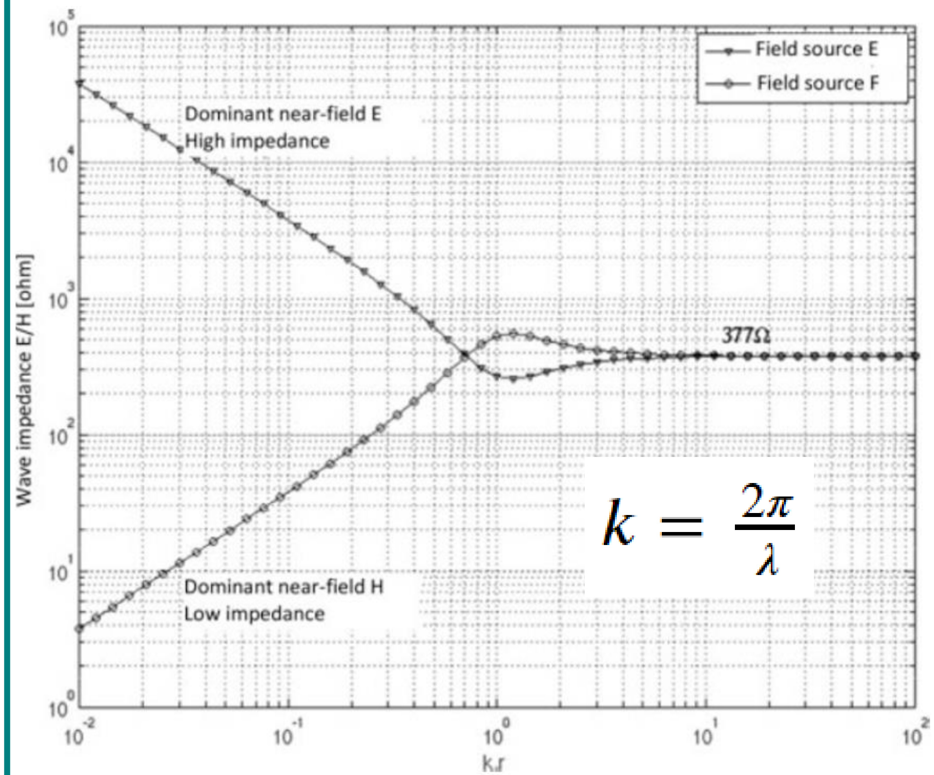
$$\sigma \gg \omega\epsilon \Rightarrow |Z_m| \approx \sqrt{\frac{\omega\mu}{\sigma}}$$

Skin depth $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$



Skin depth at 10 Hz in Aluminium

Incident wave impedance



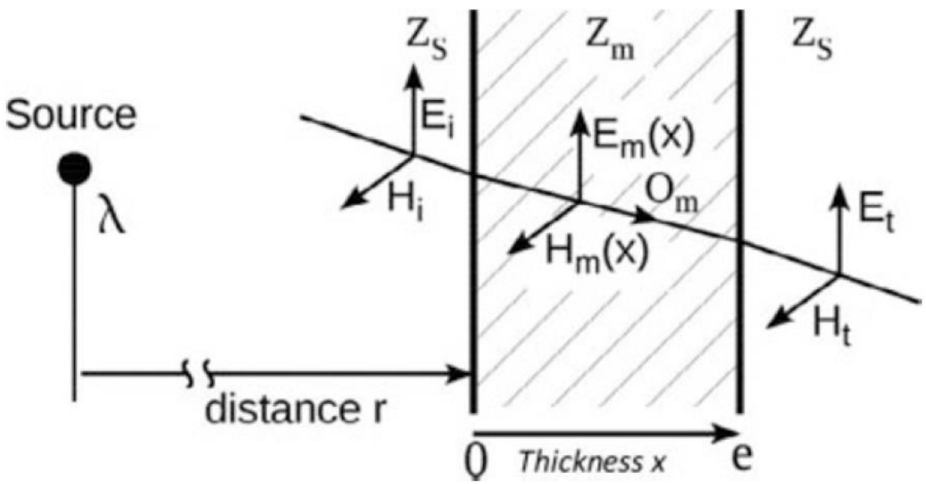
$$k = \frac{2\pi}{\lambda}$$

Wave	Wave impedance	
Far field	$Z_s = 120\pi$	$k.r \gg 1$
Near field, E source	$Z_s = \frac{1}{k.r} \times 120\pi$	$k.r \ll 1$
Near field, H source	$Z_s = k.r \times 120\pi$	$k.r \ll 1$

dv/dt area => E source

di/dt loop => H source

Expression of attenuation



Attenuation is mainly due to:

– Reflection at x = 0
– Attenuation between 0 and e
– Reflection at x = e

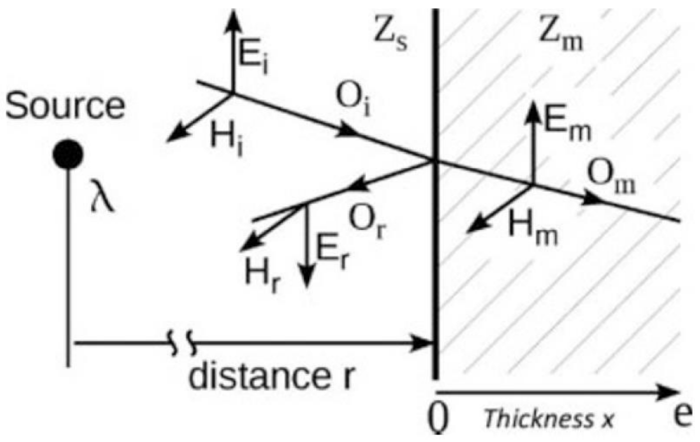
Attenuation: reflection

At x = 0

$$\rho_{AM} = \frac{Z_m - Z_s}{Z_m + Z_s}$$

$$E_m^0 = E_i^0 + E_r^0 = (1 + \rho_{AM})E_i^0 = \frac{2Z_m}{Z_m + Z_s} E_i^0$$

$$H_m^0 = H_i^0 - H_r^0 = (1 - \rho_{AM})H_i^0 = \frac{2Z_s}{Z_m + Z_s} H_i^0$$



Attenuation: reflection

At x = 0:

$$\rho_{AM} = \frac{Z_m - Z_s}{Z_m + Z_s}$$

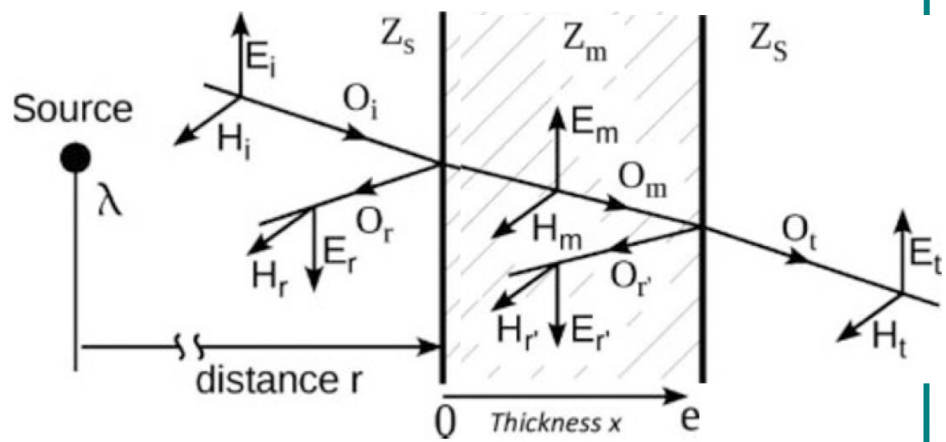
$$E_m^0 = E_i^0 + E_r^0 = (1 + \rho_{AM})E_i^0 = \frac{2Z_m}{Z_m + Z_s} E_i^0$$

$$H_m^0 = H_i^0 - H_r^0 = (1 - \rho_{AM})H_i^0 = \frac{2Z_s}{Z_m + Z_s} H_i^0$$

$$\rho_{MA} = \frac{Z_s - Z_m}{Z_m + Z_s}$$

$$E_t^e = E_m^e + E_r^e = (1 + \rho_{MA})E_m^e = \frac{2Z_s}{Z_m + Z_s} E_m^e$$

$$H_t^e = H_m^e - H_r^e = (1 - \rho_{MA})H_m^e = \frac{2Z_m}{Z_m + Z_s} H_m^e$$



Attenuation: reflection

At x = 0:

$$\rho_{AM} = \frac{Z_m - Z_s}{Z_m + Z_s}$$

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$$\rho_{MA} = \frac{Z_s - Z_m}{Z_m + Z_s}$$

$$E_t^e = E_m^e + E_r^e = (1 + \rho_{MA})E_m^e = \frac{2Z_s}{Z_m + Z_s} E_m^e$$

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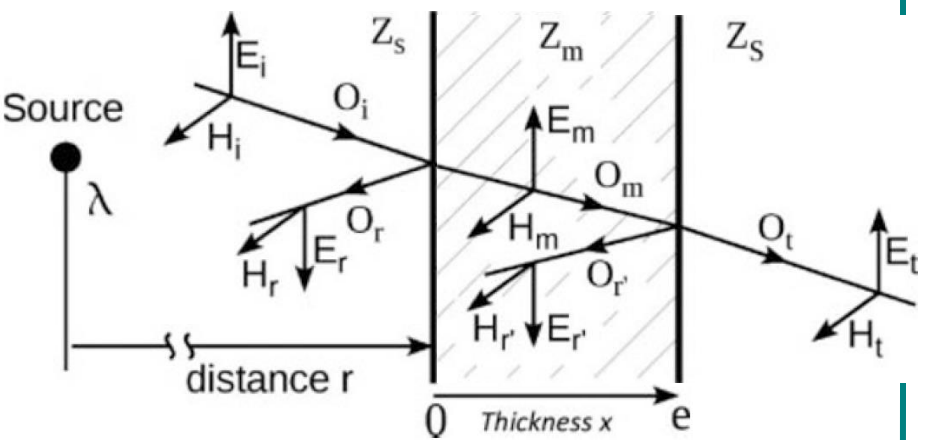


Attenuation due to reflections:

$$R = \frac{4Z_m Z_s}{(Z_m + Z_s)^2}$$

$$R_{dB} = -20 \log\left(\frac{4Z_m Z_s}{(Z_m + Z_s)^2}\right)$$

Attenuation: reflection

$$|Z_m| \approx \sqrt{\frac{\omega\mu}{\sigma}}$$

$$\mu = \mu_0 \times \mu_r$$

$$\sigma = G \times \sigma_{copper}$$

$$R_{dB} = -20\log\left(\frac{4Z_m Z_s}{(Z_m+Z_s)^2}\right)$$

$$Z_m \ll Z_s \Rightarrow R_{dB} = -20\log\left(\frac{4Z_m}{Z_s}\right)$$

Wave	Wave impedance	
Far field	$Z_s = 120\pi$	$k.r \gg 1$
Near field, E source	$Z_s = \frac{1}{k.r} \times 120\pi$	$k.r \ll 1$
Near field, H source	$Z_s = k.r \times 120\pi$	$k.r \ll 1$

Far field : $R_{dB} \approx 168.1 - 10\log\left(\frac{\mu_r f}{G}\right)$

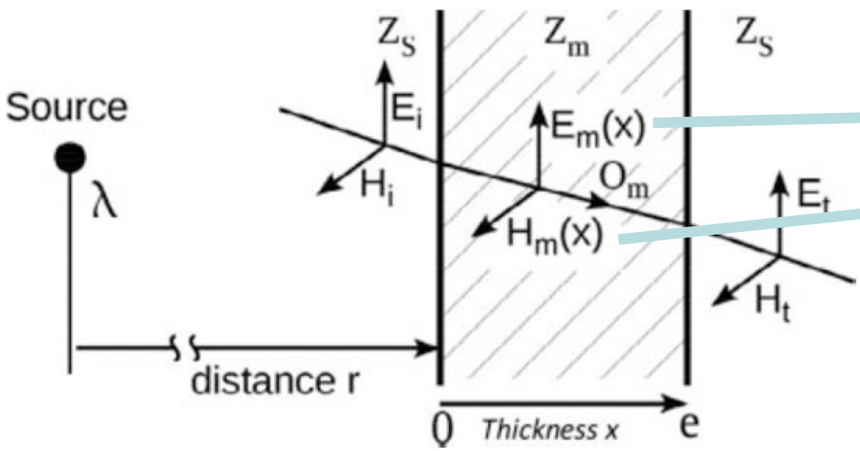
Near field E: $R_{dB} \approx 321.7 - 10\log\left(\frac{\mu_r f^3 r^2}{G}\right)$

Near field H: $R_{dB} \approx 14.6 - 10\log\left(\frac{\mu_r}{f r^2 G}\right)$

$$k = \frac{2\pi}{\lambda}$$

$$c = \lambda f$$

Attenuation: absorption



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

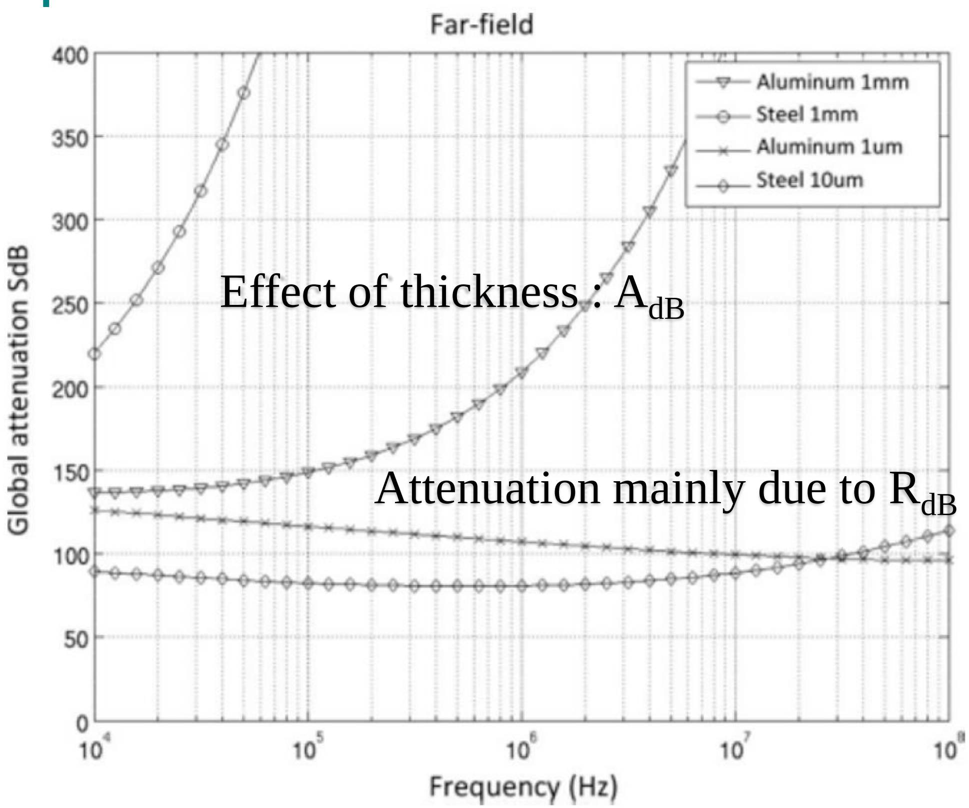
$$E_m(x) = E_m(0) \cdot e^{-\frac{x}{\delta}}$$

$$H_m(x) = H_m(0) \cdot e^{-\frac{x}{\delta}}$$

$$A_{dB} = -20\log(e^{-\frac{x}{\delta}}) = -20\frac{\ln(e^{-\frac{x}{\delta}})}{\ln(10)} = 8.686\frac{e}{\delta}$$

$$\Rightarrow A_{dB} = 131.5 \cdot \sqrt{\mu_r f G} \cdot e$$

Use case: far field attenuation for aluminium and steel



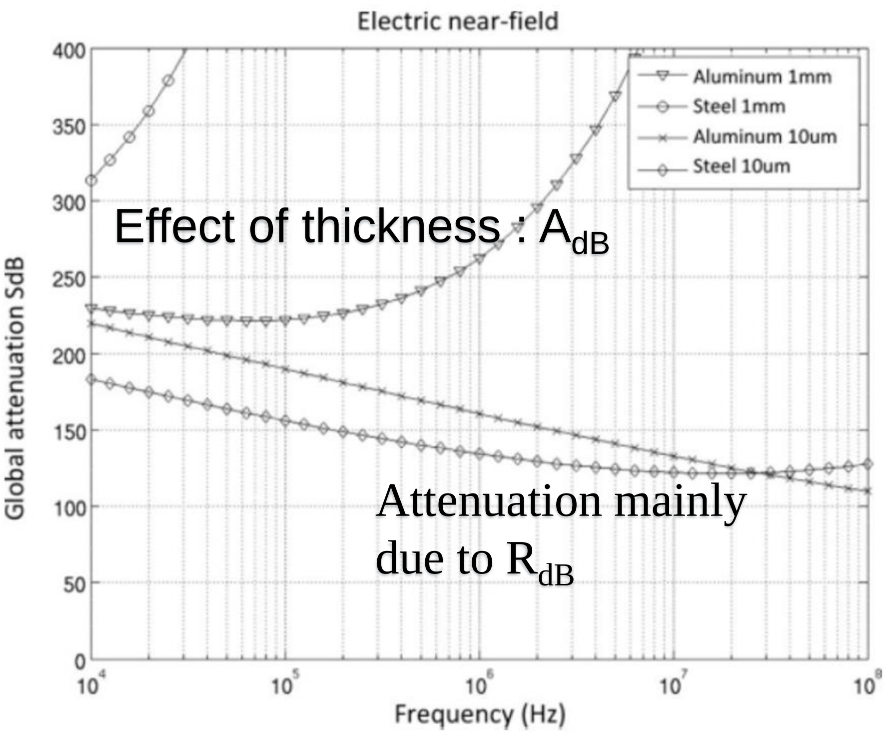
$$\text{Far field}: R_{dB} \approx 168.1 - 10\log\left(\frac{\mu_r f}{G}\right)$$
$$A_{dB} = 131.5 \cdot \sqrt{\mu_r f G} \cdot e$$

	Skin depth (10 kHz)	Wave impedance Z_m (10 kHz)	R_{dB}
Aluminum	850×10^{-6} m	$47 \times 10^{-6}\ \Omega$	126 dB
Steel	66×10^{-6} m	$3.7 \times 10^{-3}\ \Omega$	88 dB

Typical application:

immunity to external radiations

Use case: near field attenuation for aluminium and steel



Note: shield at 10 cm from the source

Near field E: $R_{dB} \approx 321.7 - 10\log(\frac{\mu_r f^3 r^2}{G})$

$$A_{dB} = 131.5 \cdot \sqrt{\mu_r f G} \cdot e$$

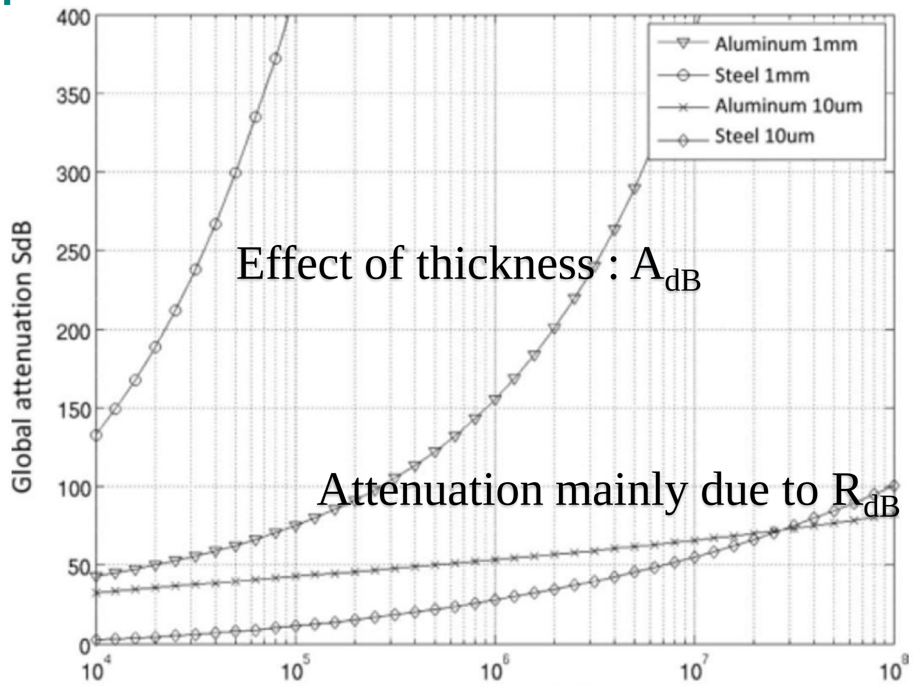
Near field	Electrical
Wave impedance Z_s	$18 \times 10^6\ \Omega$
R_{dB} Steel (10 kHz)	182 dB
R_{dB} Aluminum (10 kHz)	220 dB

Typical application

reduce emission of E field sources = traces with high dv/dt

Use case: near field attenuation for aluminium and steel

Magnetic near-field



Note: shield at 10 cm from the source

$$R_{dB} = -20\log\left(\frac{4Z_m Z_s}{(Z_m+Z_s)^2}\right)$$

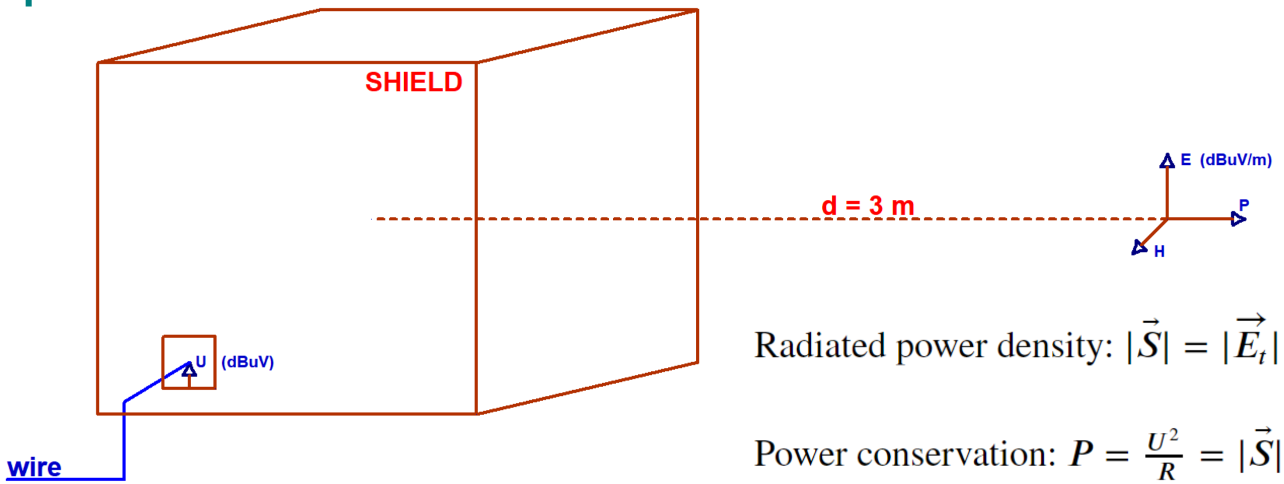
$$A_{dB} = 131.5 \cdot \sqrt{\mu_r f G} \cdot e$$

Near field	Electrical	Magnetic
Wave impedance Z_s	$18 \times 10^6\ \Omega$	$7.9 \times 10^{-3}\ \Omega$
R_{dB} Steel (10 kHz)	182 dB	1.2 dB
R_{dB} Aluminum (10 kHz)	220 dB	32 dB

$$Z_m = 3.69 m\Omega \text{ (Steel, 10 kHz)}$$

$$Z_m = 47 \mu\Omega \text{ (Alu, 10 kHz)}$$

Attenuation: shielding with cables?



Radiated power density: $|\vec{S}| = |\vec{E}_t||\vec{H}_t| = \frac{|\vec{E}_t|^2}{Z_{air}}$

Power conservation: $P = \frac{U^2}{R} = |\vec{S}| \cdot 4\pi d^2 = \frac{|\vec{E}_t|^2}{Z_{air}} \cdot 4\pi d^2 = \frac{|\vec{E}_t|^2}{120\pi} \cdot 4\pi d^2$

$\Rightarrow U_{dB\mu V} = E_{dB\mu V/m} + 20\log(d) + 2.22$

$$U_{dB\mu V} = E_{dB\mu V/m} + 11.76 \text{ , at 3 meters}$$

Attenuation: shielding with cables?

- Expected field (dBµV/m) can be estimated using conducted measurements results, assuming that:
  - the cable behaves like an isotropic radiator,
  - the impedance seen by the wire is 50 Ω.

$$U_{dB\mu V} = E_{dB\mu V/m} + 22.22 \text{ , at 10 meters}$$

- This rough estimation helps to evalutate radiated emission due to cable by using conducted measurements above 30 MHz, keeping in mind the LISN effective bandwith.
- Can be effective up to about 100, 200 MHz.

Design rules
For electrical circuits

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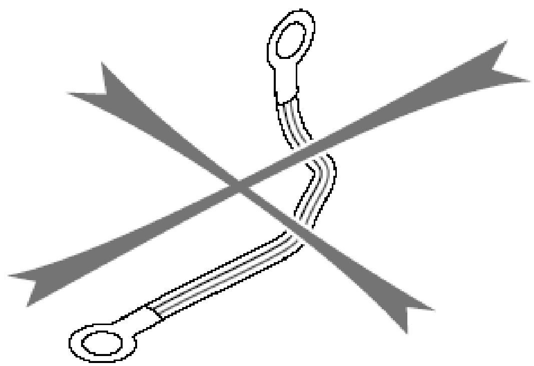
2021-2022

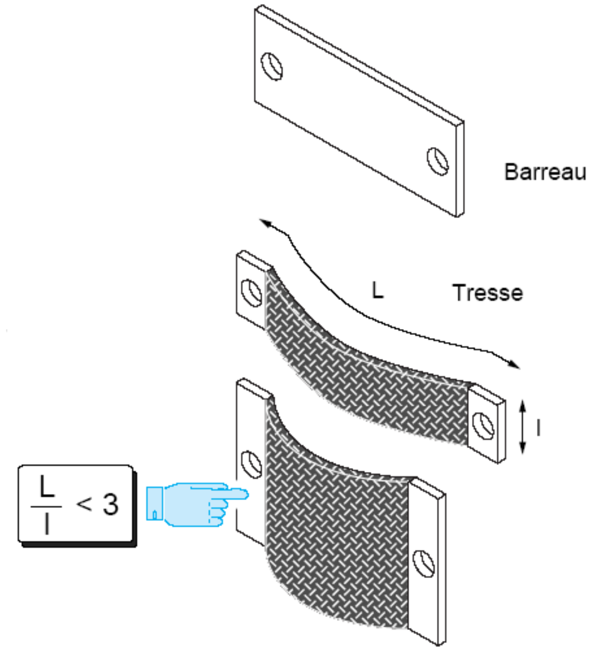
Design rules

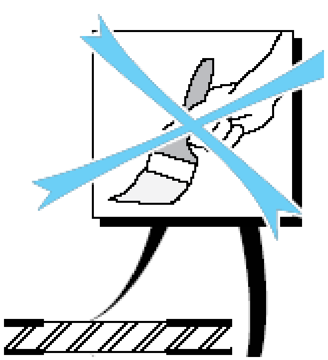
Grounding/earthing in racks - connections

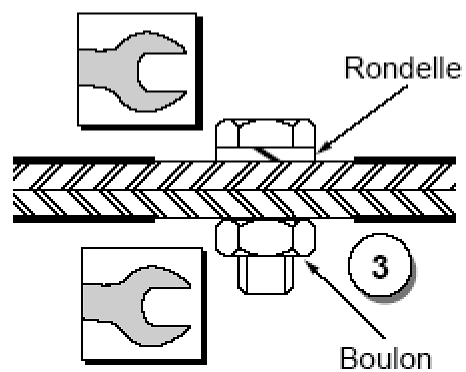
PE - PEN



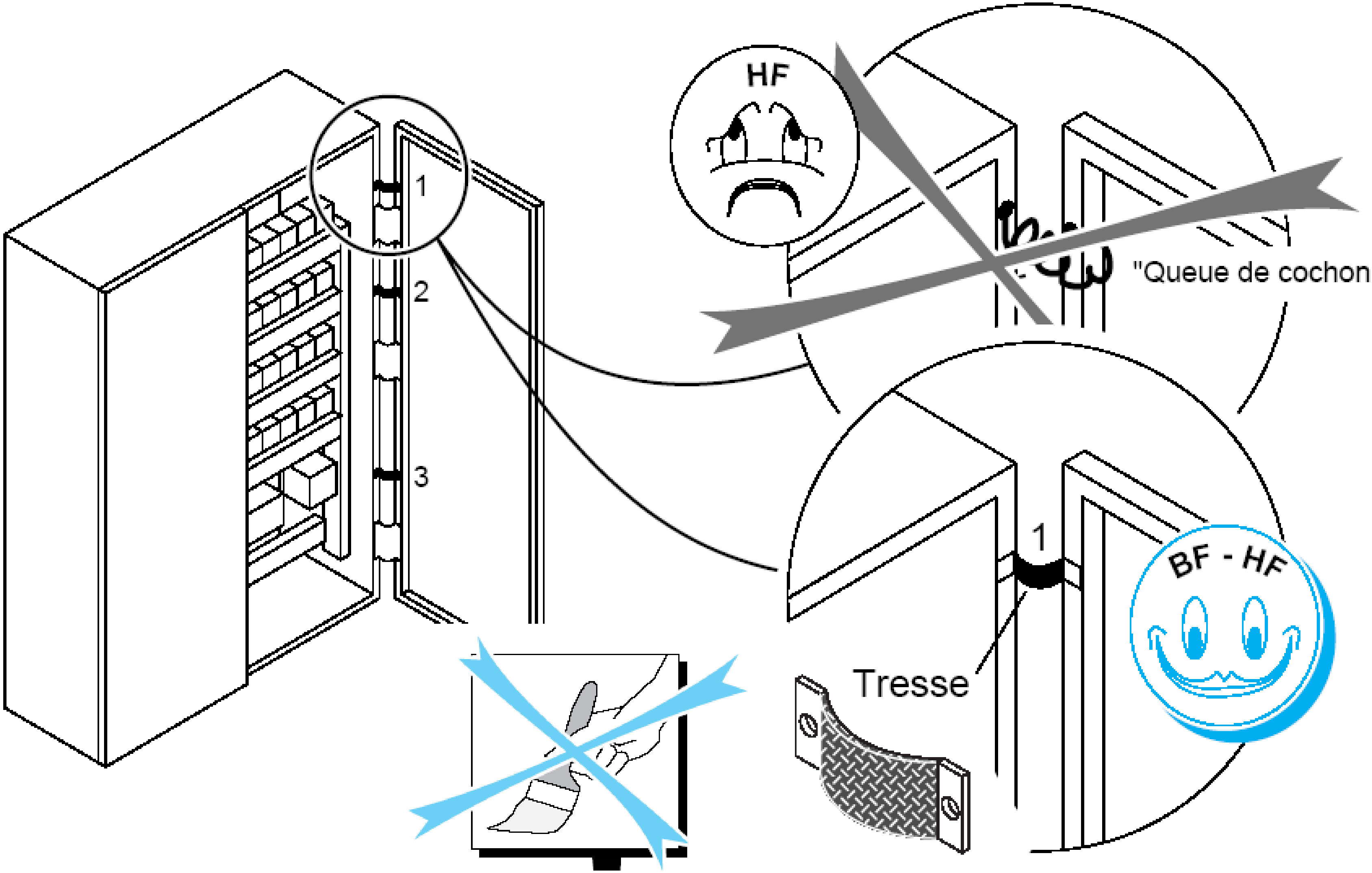
Fil vert / jaune







Design rules



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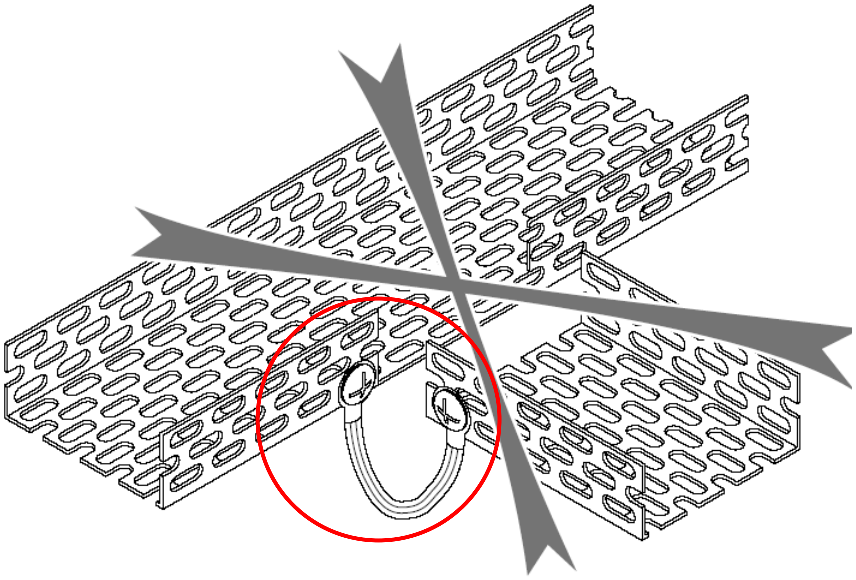
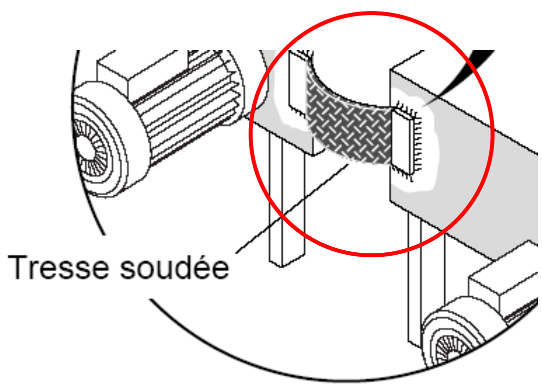
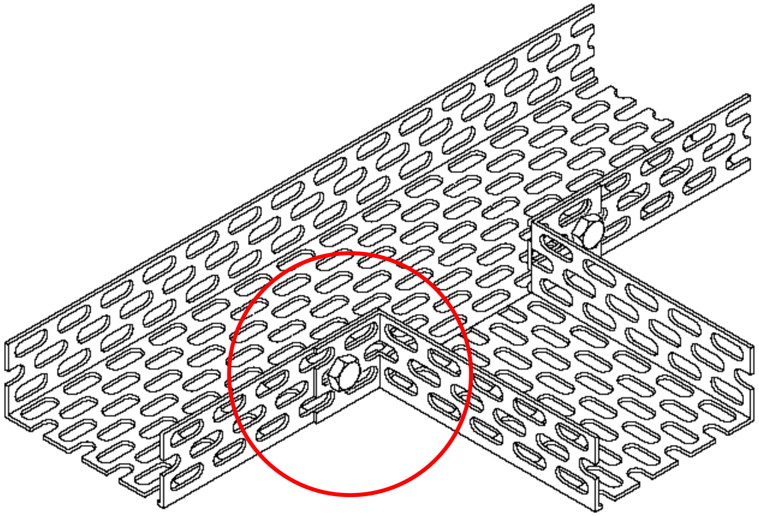
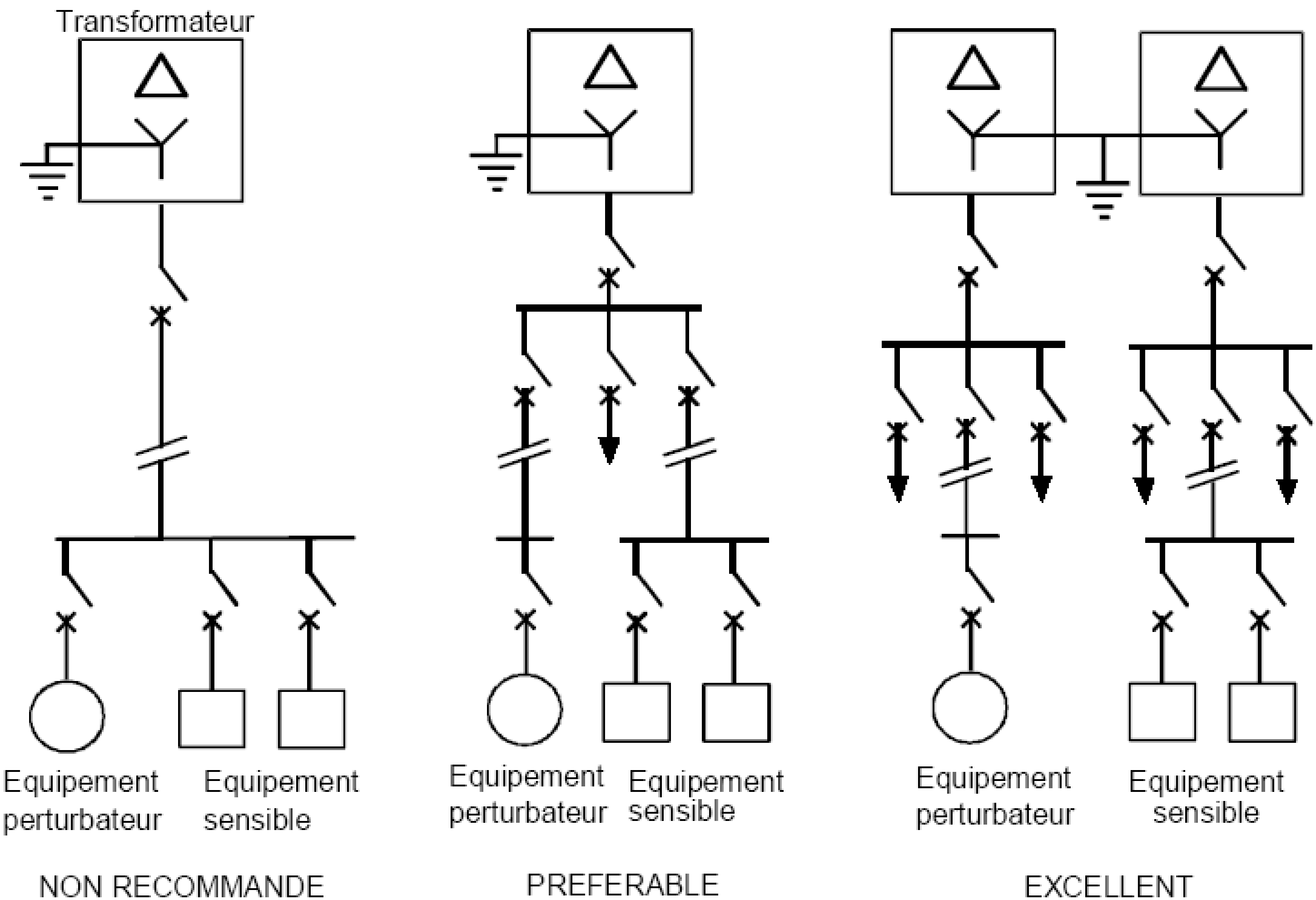






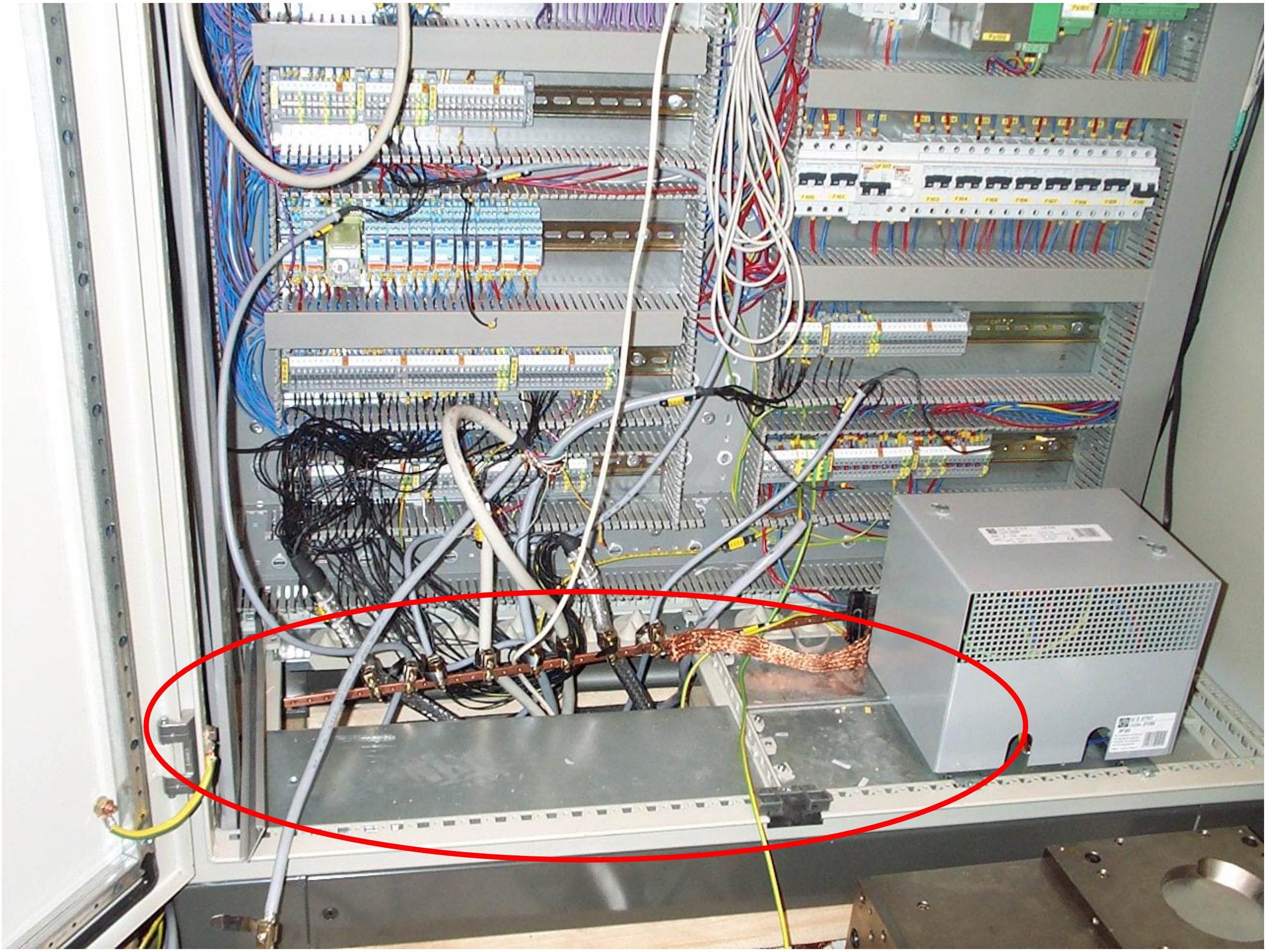
Design rules

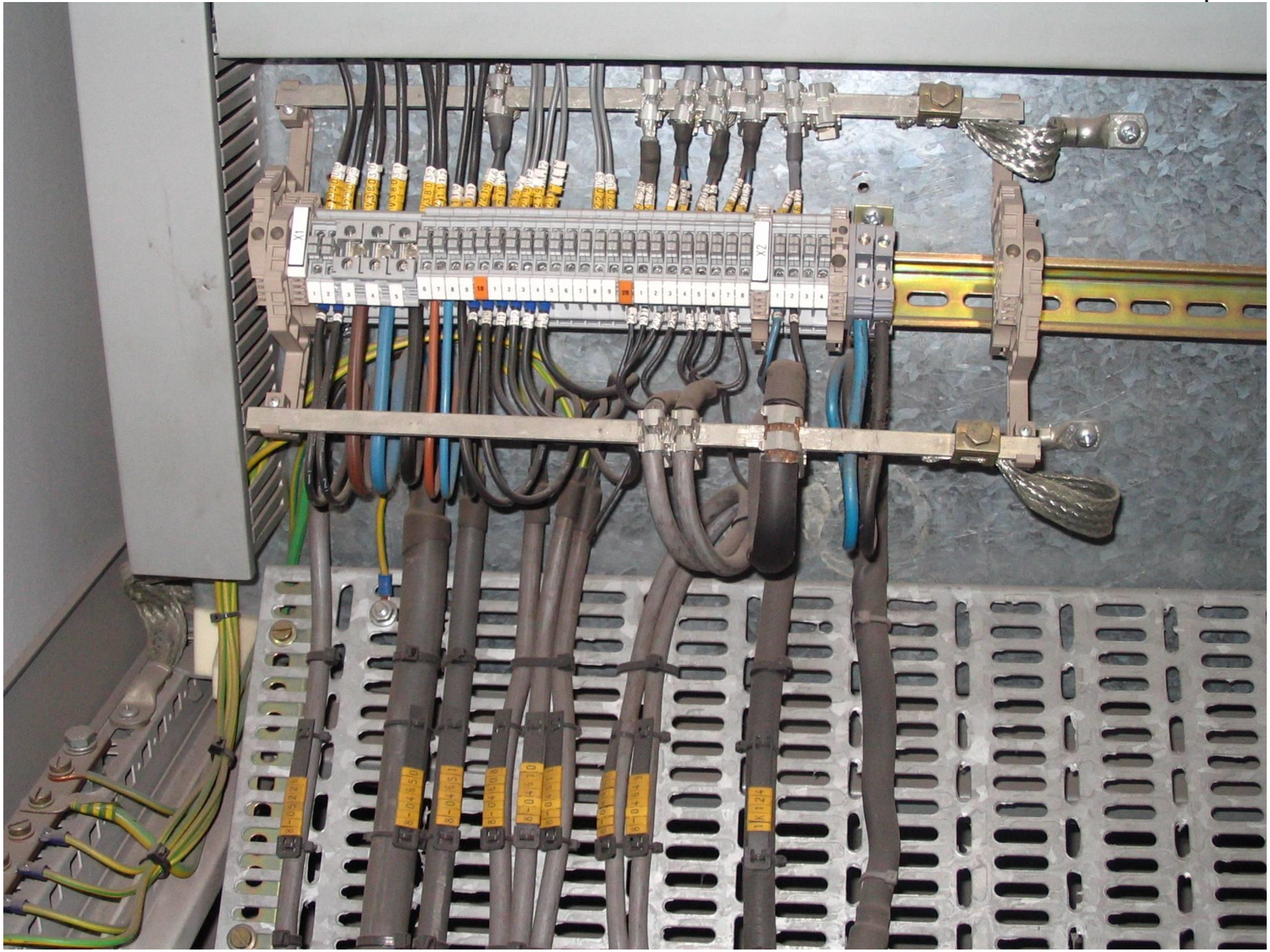
Power supplies management



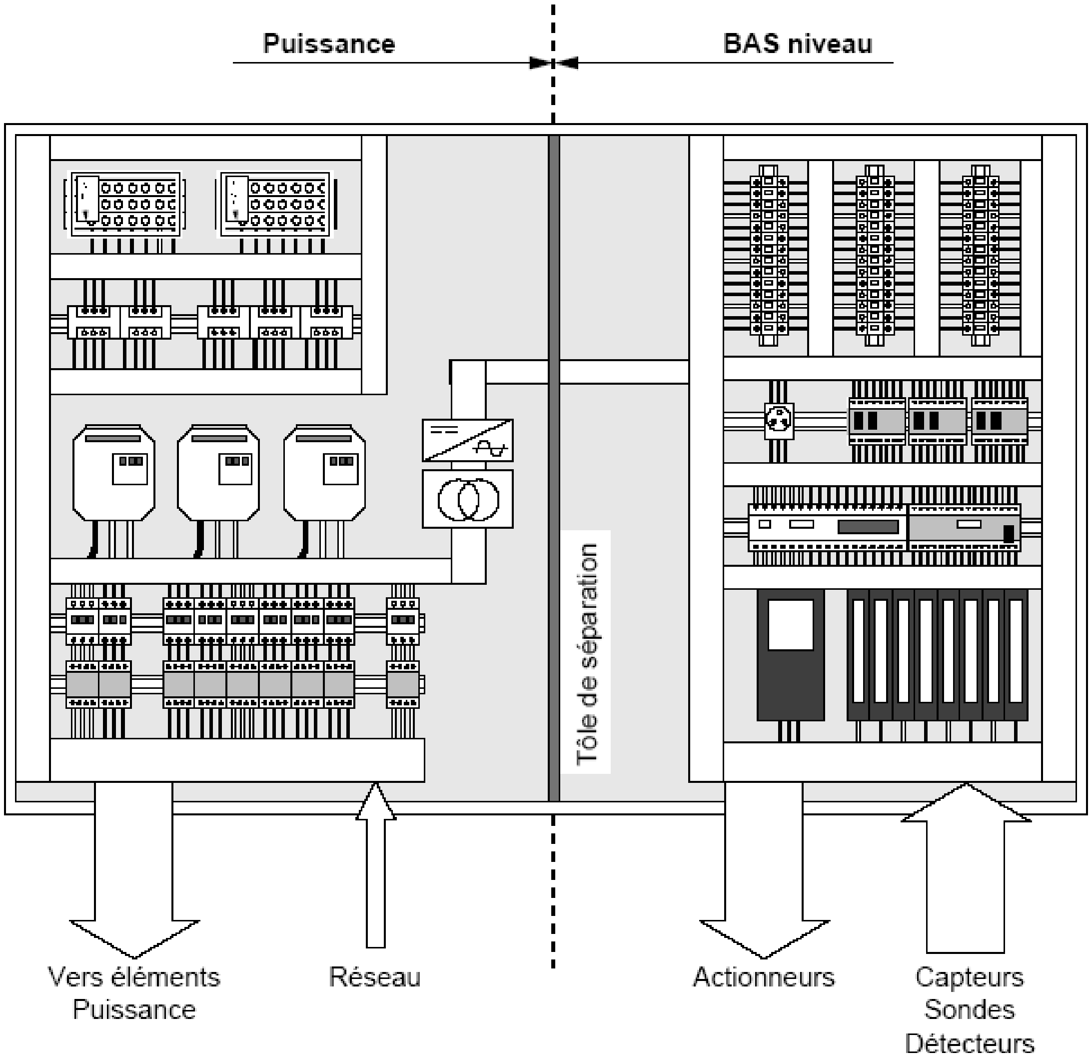
[EN 50174-2]

Design rules

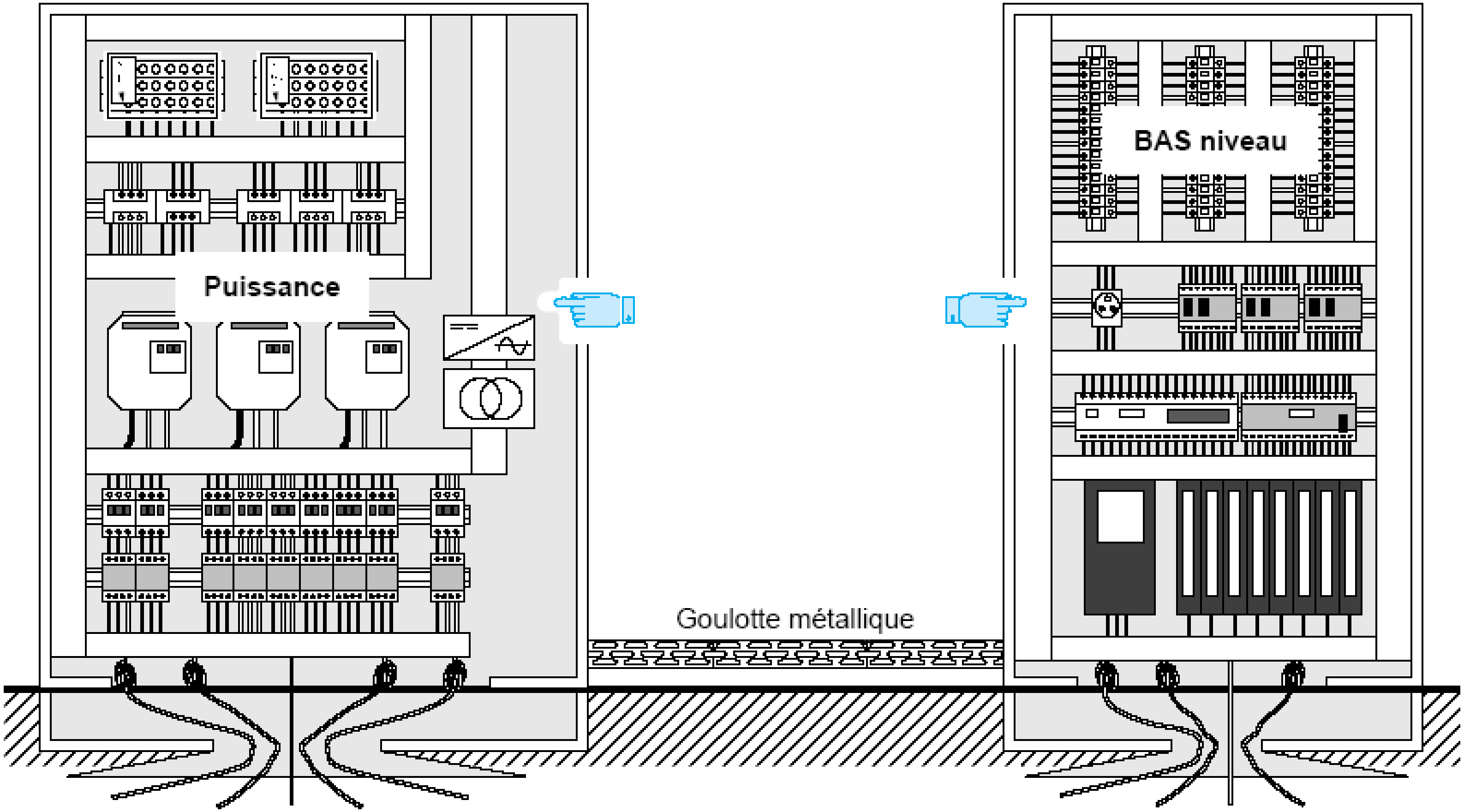




Design rules



Design rules



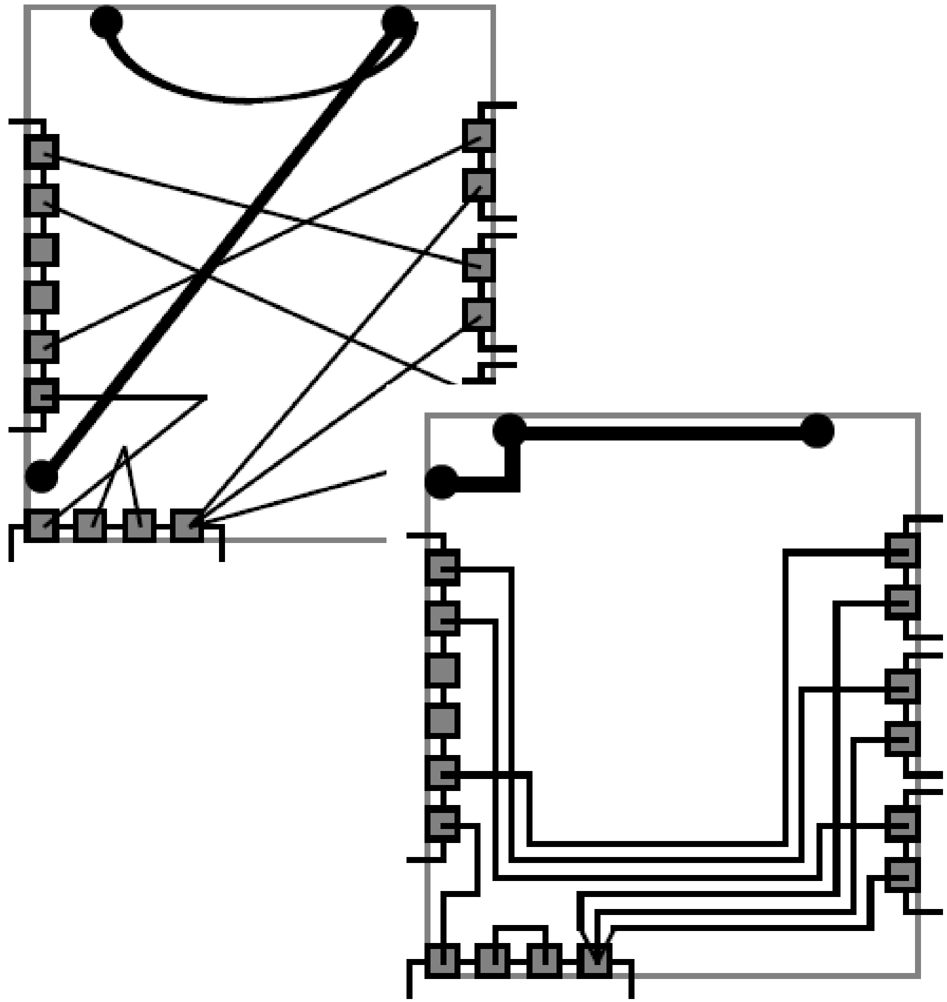
Design rules

mauvais :

angles d'intersections quelconques

nombreuses boucles

courants faibles et courants forts mélangés



bon :

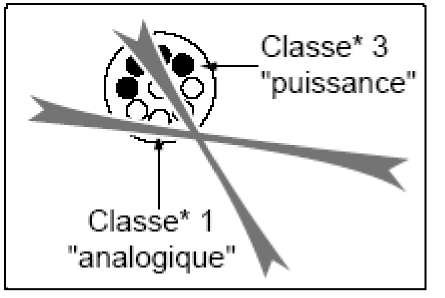
angles droits

boucles de surfaces minimales

courants faibles et courants forts séparés (éventuellement par une séparation métallique)

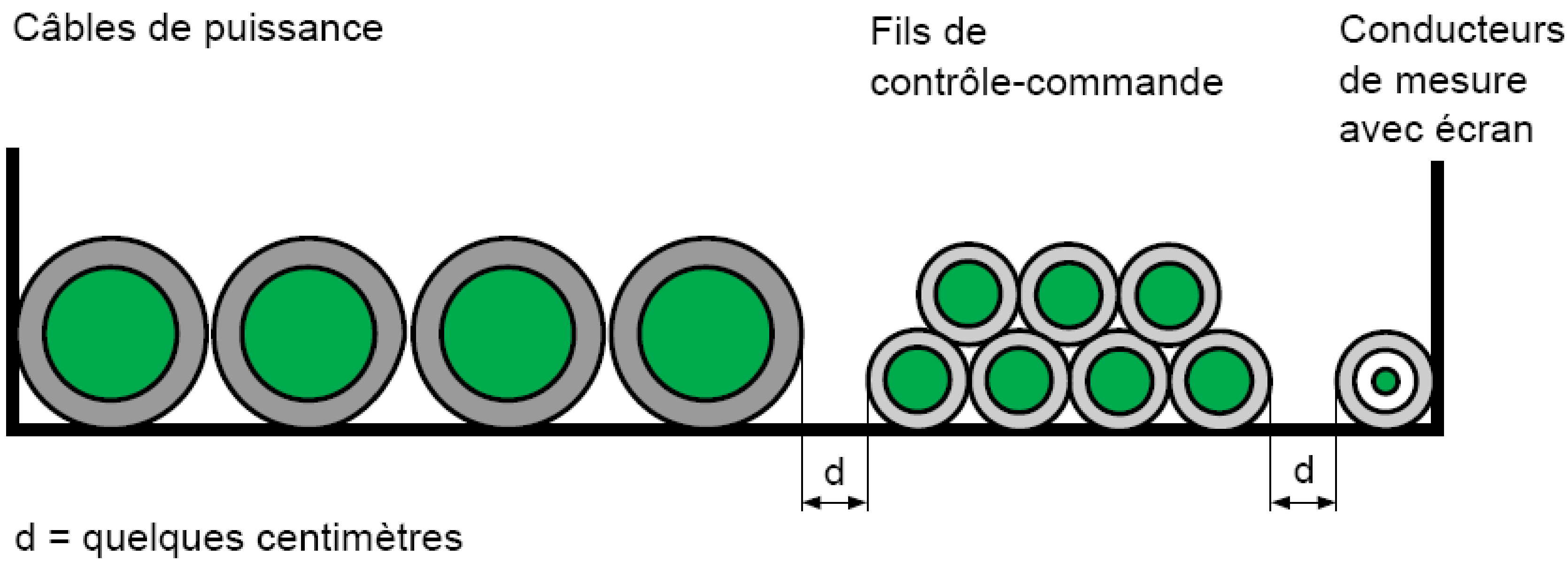
Cabling rules

- Equipotentiality of grounding (LF & HF) is ensured
- Do not use sensitive signals and disturbing signals in the same cable



- Reduce the parallel length of sensitive signals cables and disturbing signals cable
- Limit cable lengths
- Shielded cables permits those signals cables in the same cable tray.

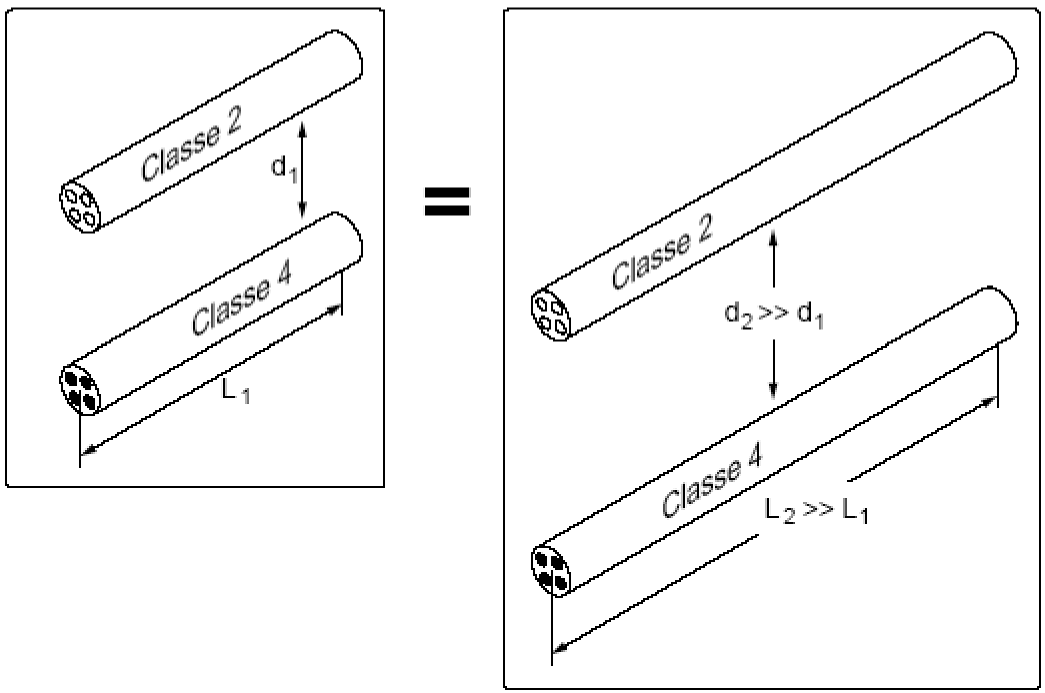
Design rules



Design rules

Cabling rules

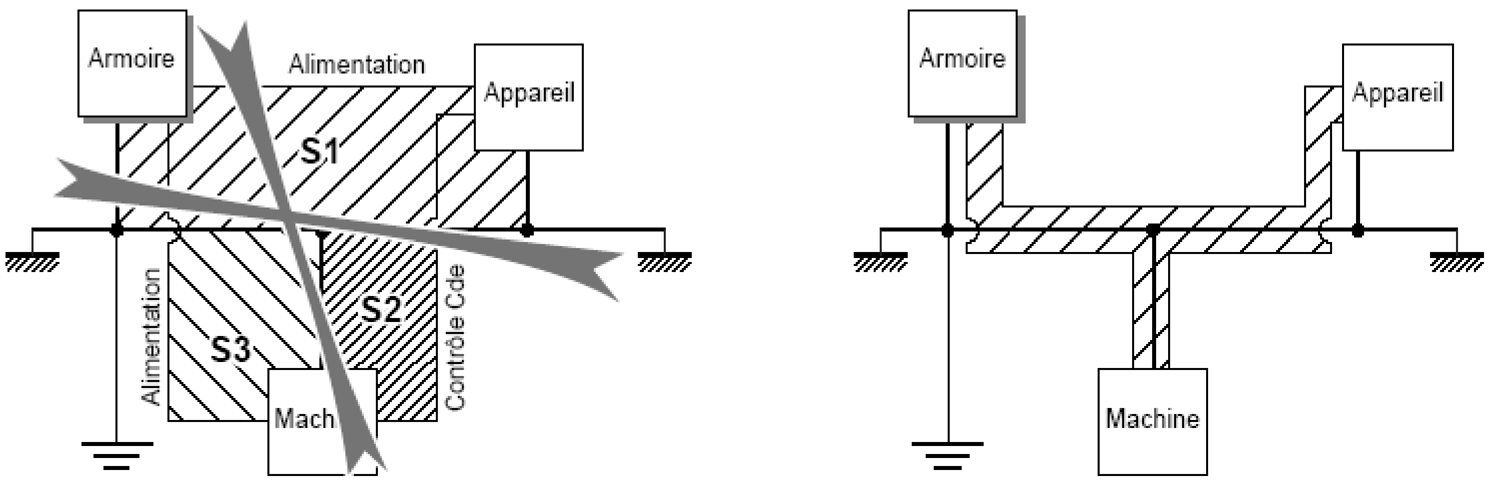
- Keep distance between sensitive cables and disturbing cables (costless and efficient solution) – this distance increases with the length of parallel cables.



Design rules

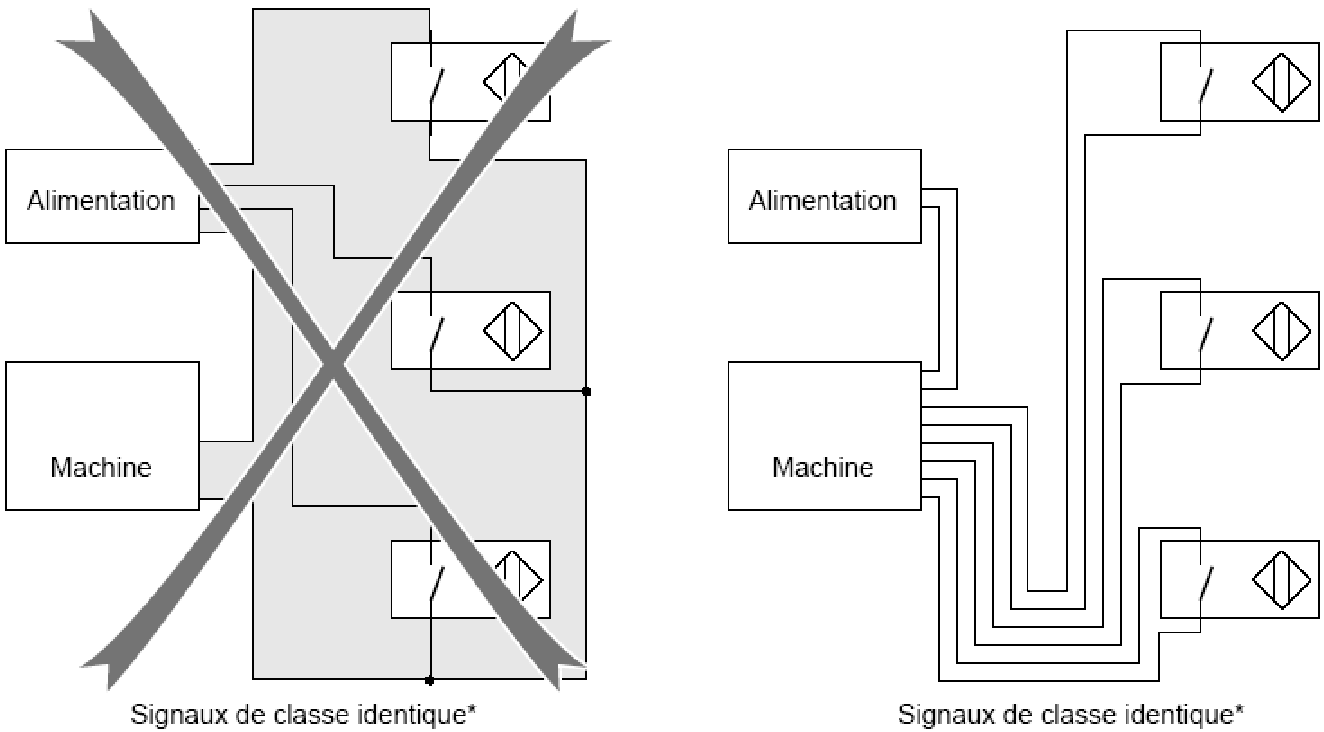
Cabling rules

- Reduce grounding loop surfaces



Cabling rules

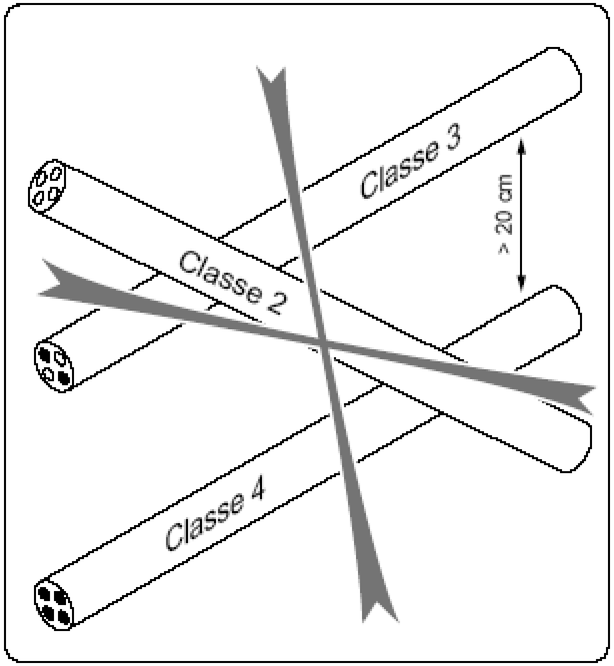
- Signal conductor near grounding conductor

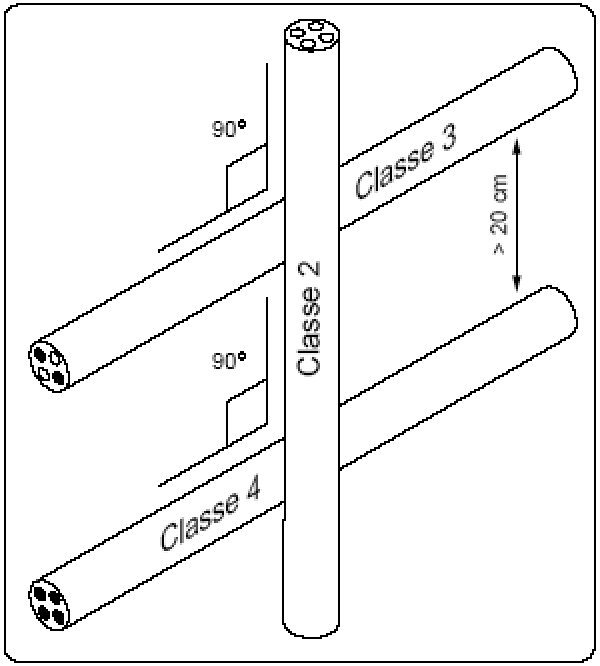


** : capteurs bas niveau ==> classe 2*

Design rules

Cabling rules

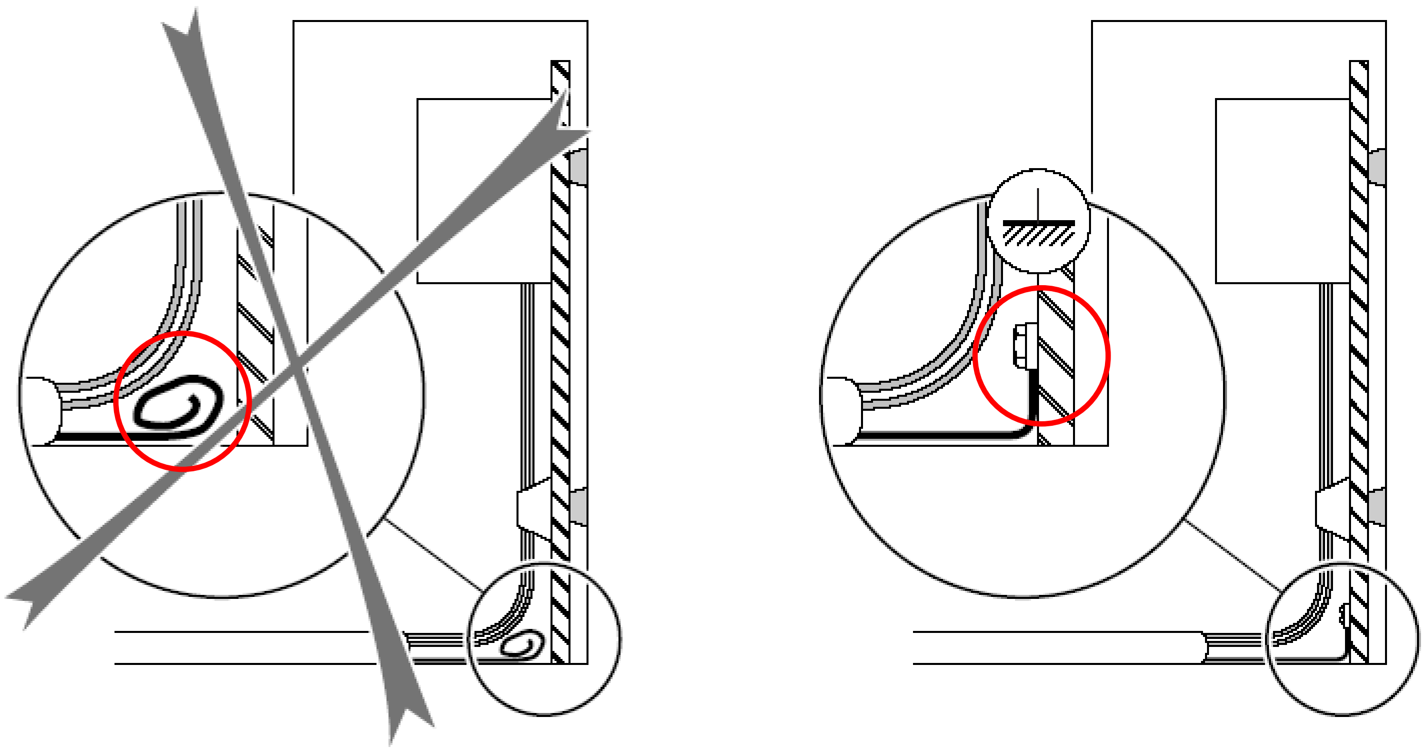




Design rules

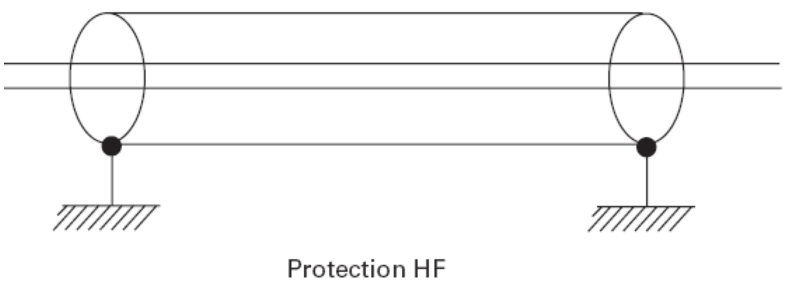
Cabling rules

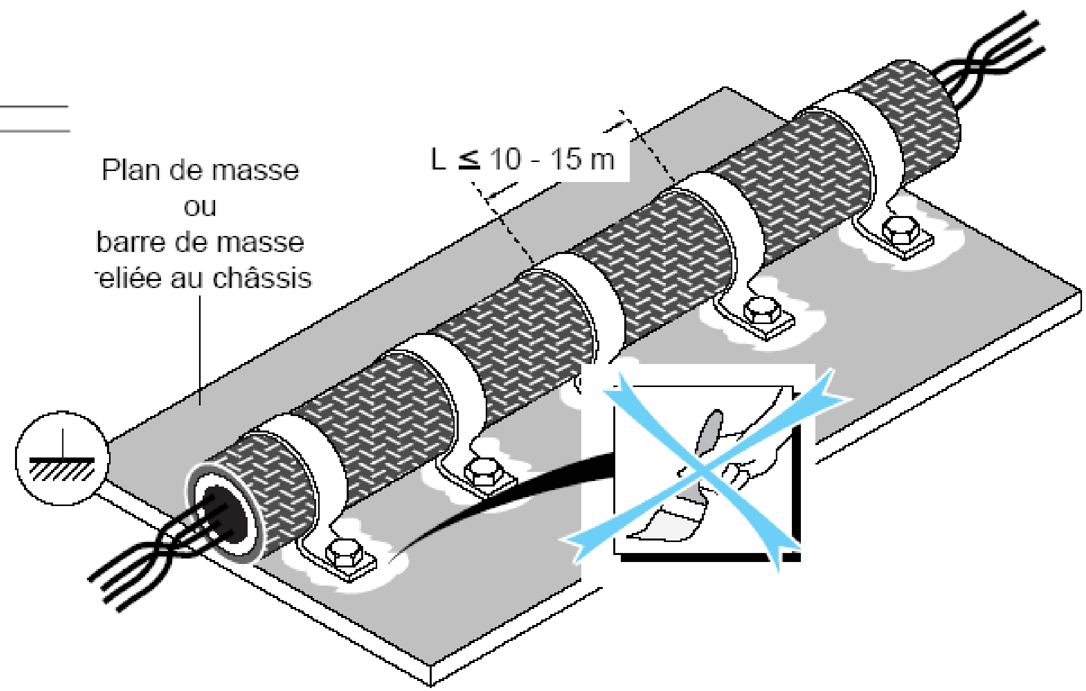
- Any unused conductor should be connected to ground at both ends



Cabling rules

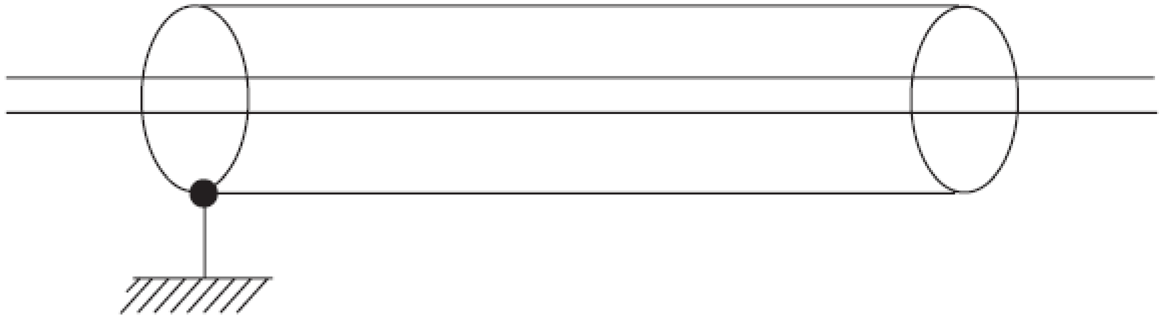
- Shielding connections?
    - at both ends?
        - very efficient against external HF disturbances
        - no voltage between cable and ground





Design rules
Cabling rules

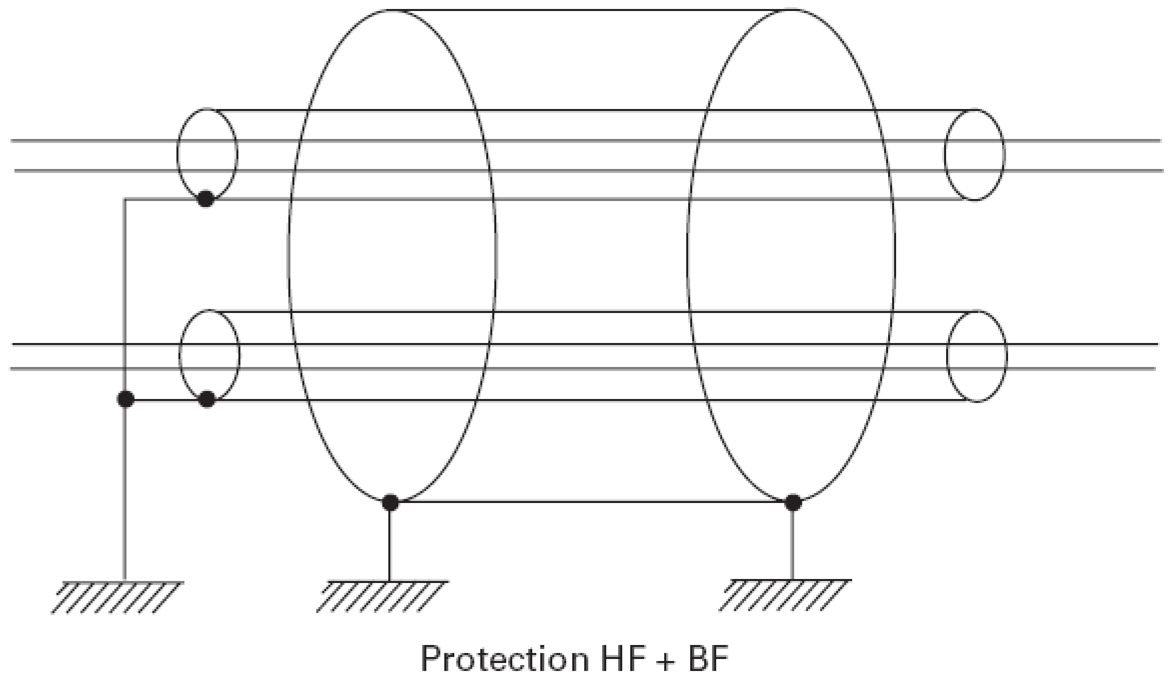
- Shielding connections?
    - at 1 end?
        - not efficient against external HF disturbances
        - to delete low frequency signals in shielding called « ronflette »



Protection BF

Design rules

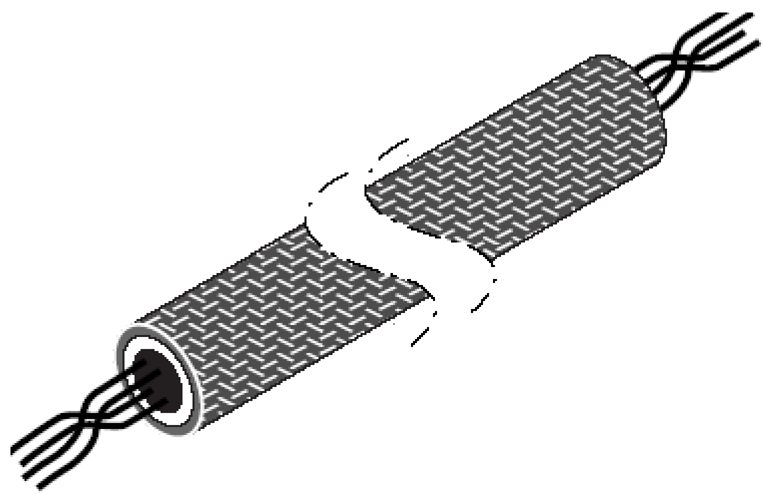
Cabling rules



Design rules

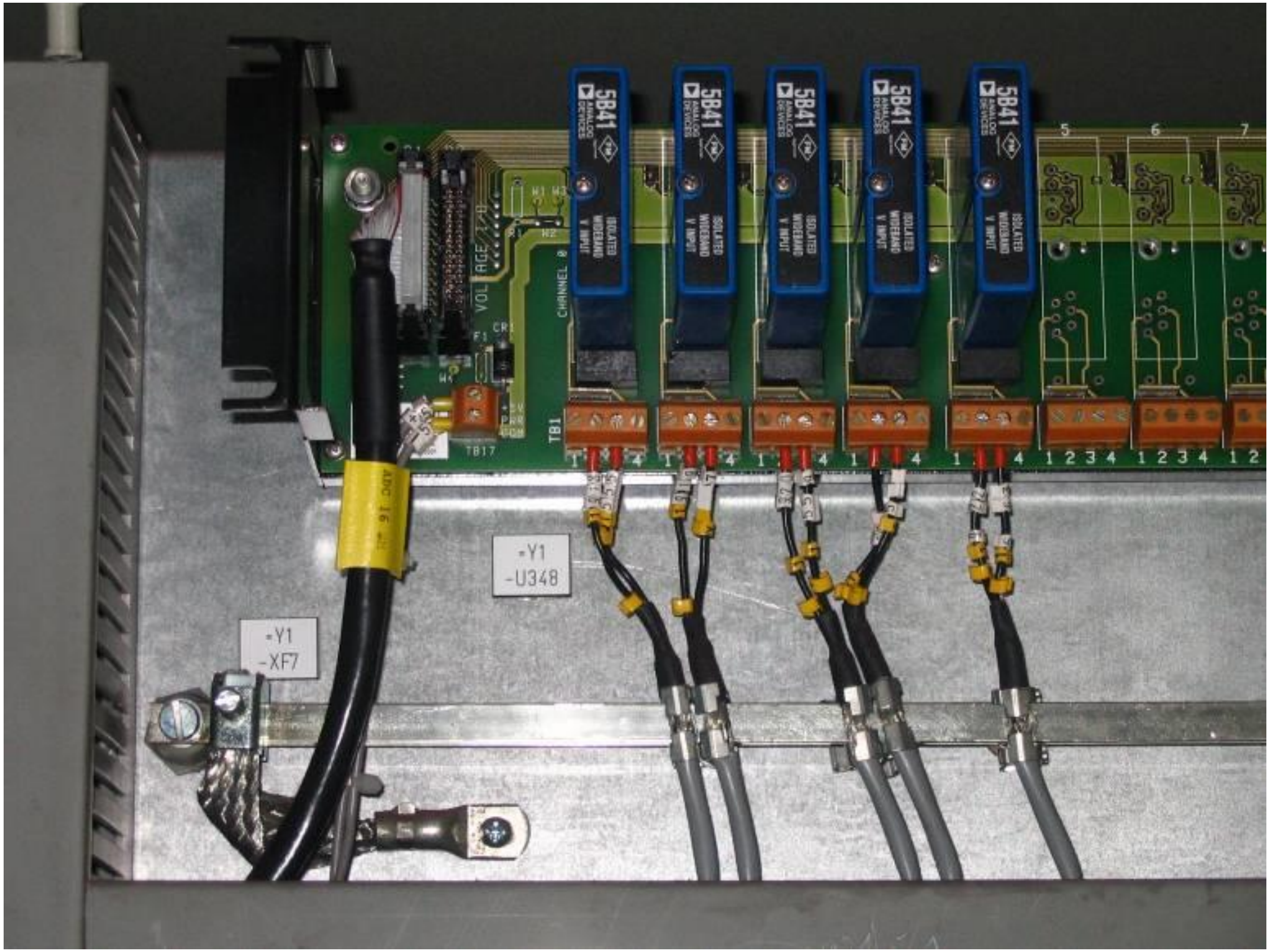
Cabling rules

- Shielding connections?
  - not connected?
    - ⚠ - FORBIDDEN if accessible to touch (voltage between shielding and ground)
    - - not efficient against external HF disturbances



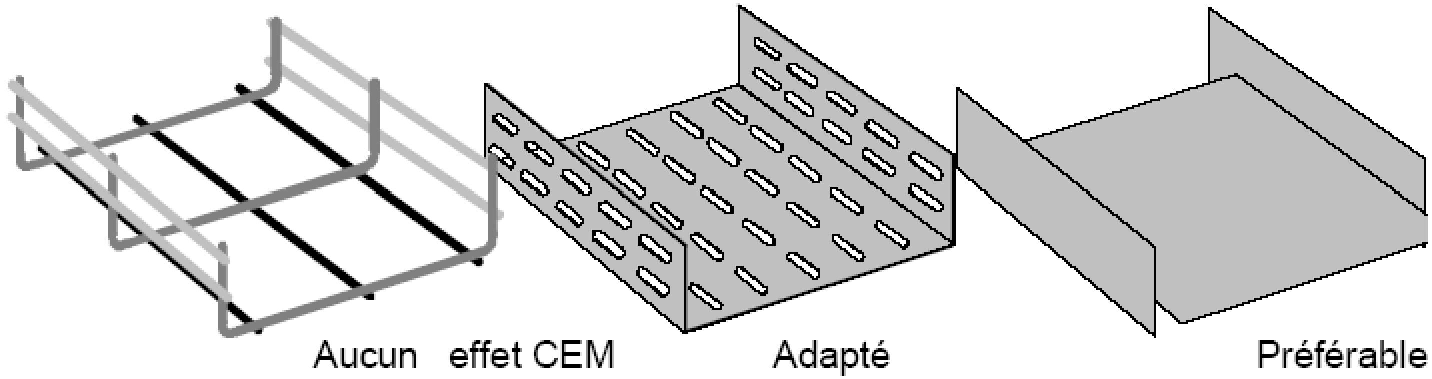
Design rules

Cabling rules

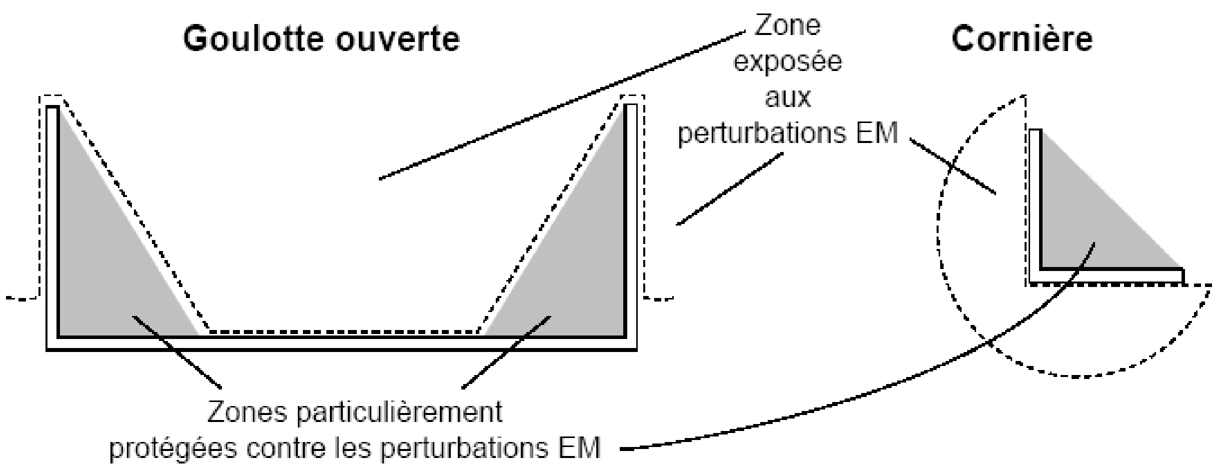


Design rules

Cabling rules

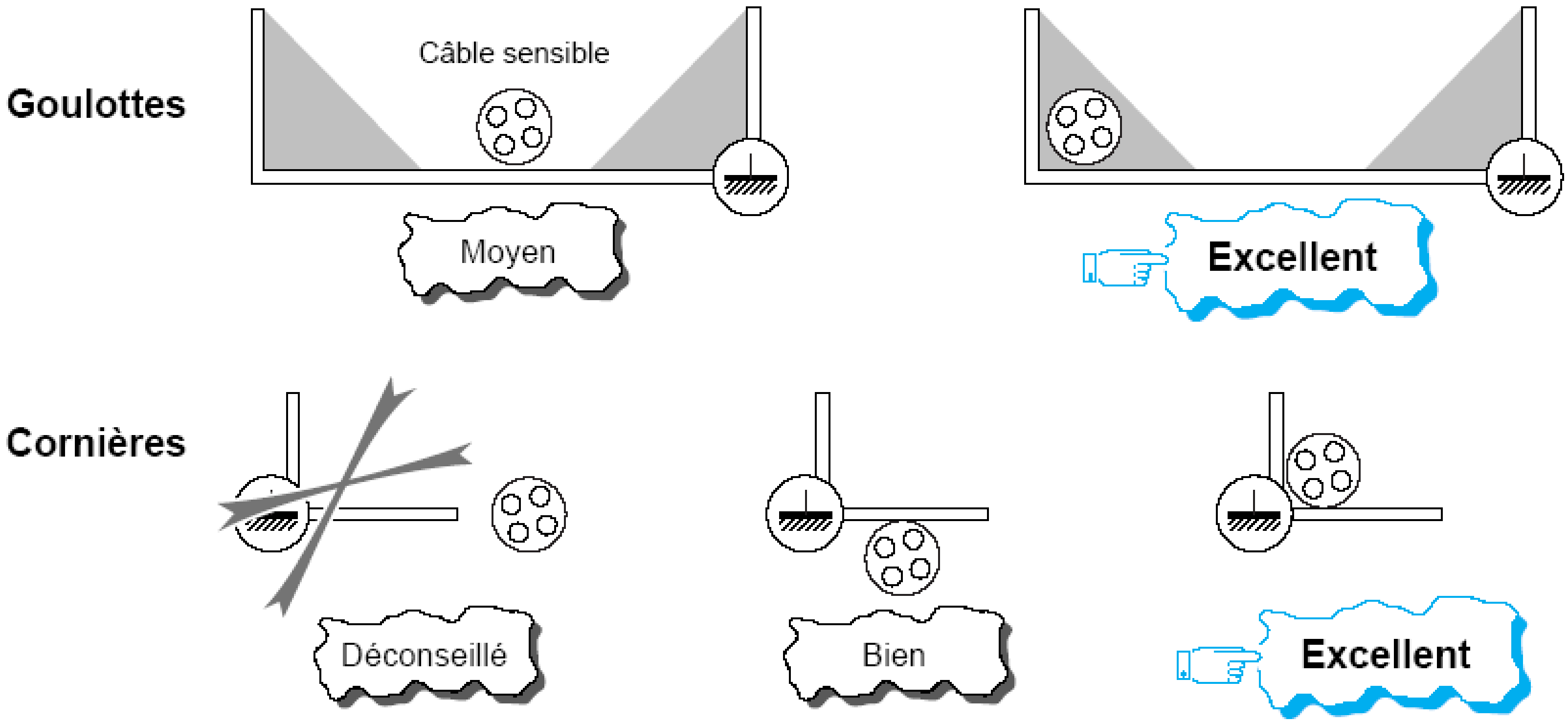


[EN 50174-2]

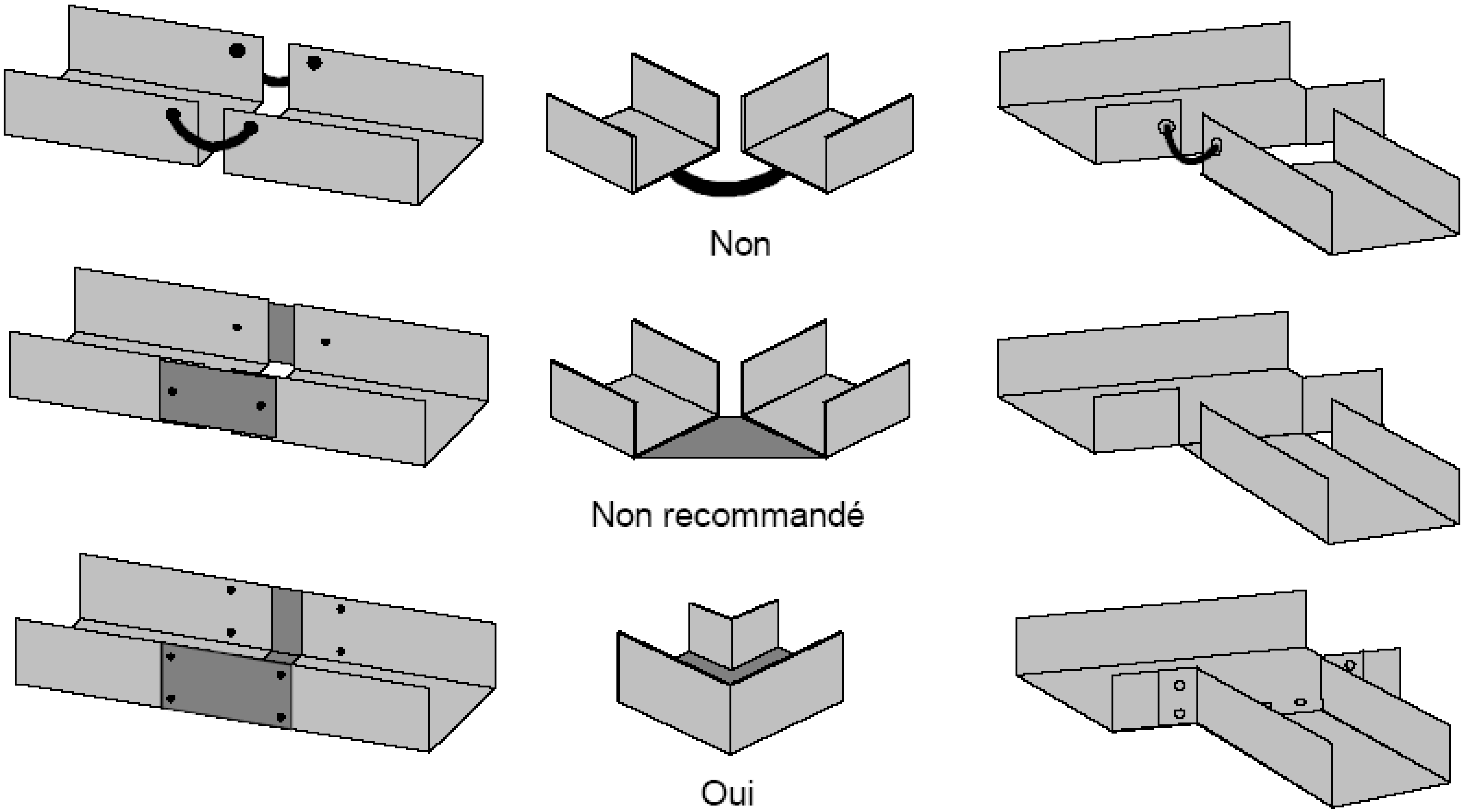


Design rules

Cabling rules



Cabling rules



[EN 50174-2]

Design rules
For electronic circuits and PCBs
(part I)

Véronique Beauvois, Ir.
2021-2022

Why?

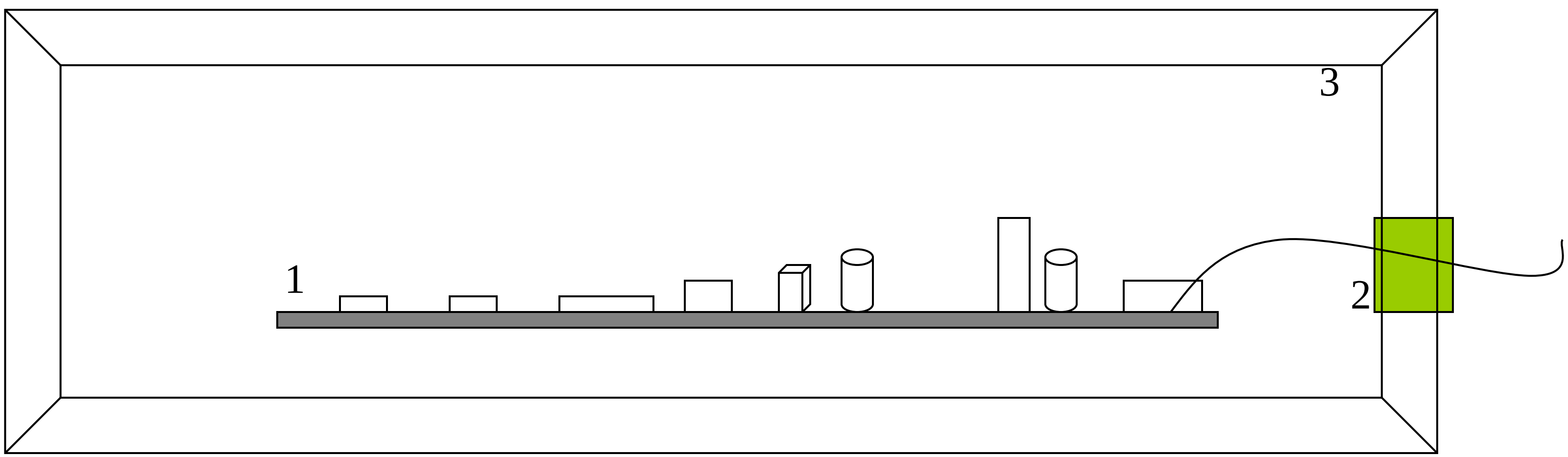
-Frequency is increasing (wireless, Bluetooth)
-Speed is increasing (clock, Mbit/sec)
-t_r and t_f are decreasing
-Components density is increasing (SMD)
-Tracks density /cm² is increasing

→ Broadband spectrum interferences
PCB design (PCB design software!)

Circuit design and grounding

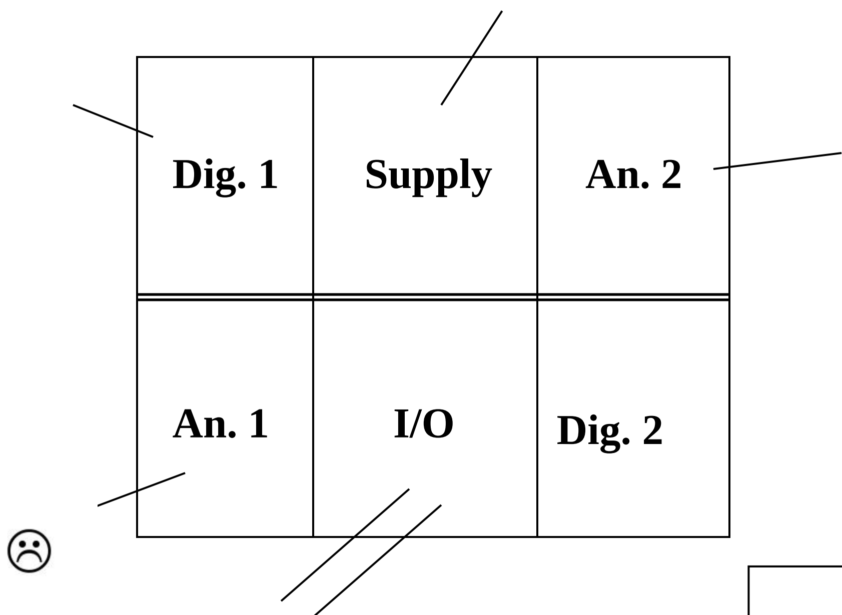
Protections classification:

- Primary: circuit design (decoupling, balanced configuration, speed and bandwidth limitations) - PCB design and grounding,
- Secondary: external circuit interfaces, cabling (filtering), connectors,
- Tertiary: full shielding (cost)



Circuit design and grounding

1st step: to take care of the division of the circuit

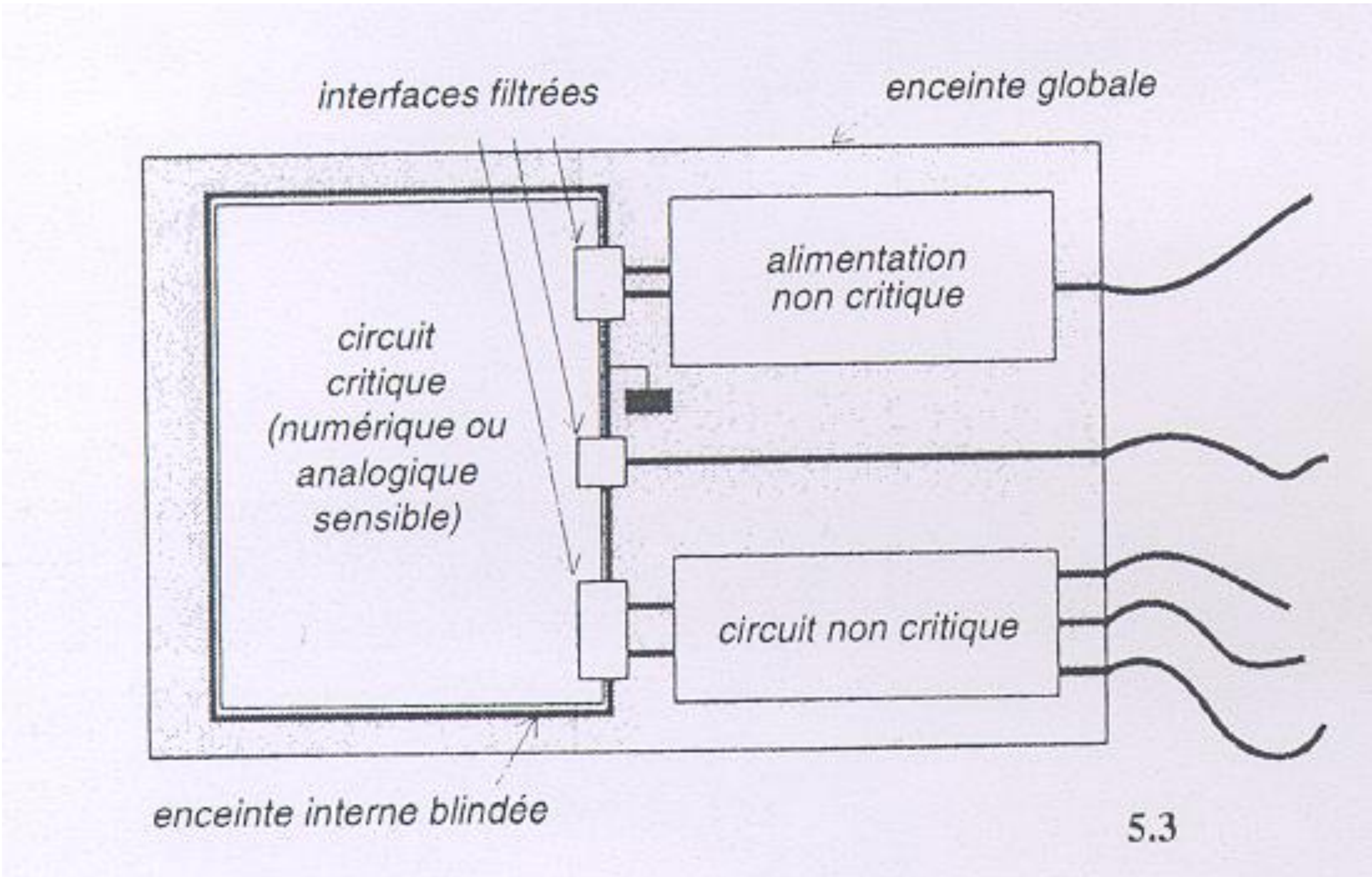


Different ports are all over the perimeter – shielding and ports filtering

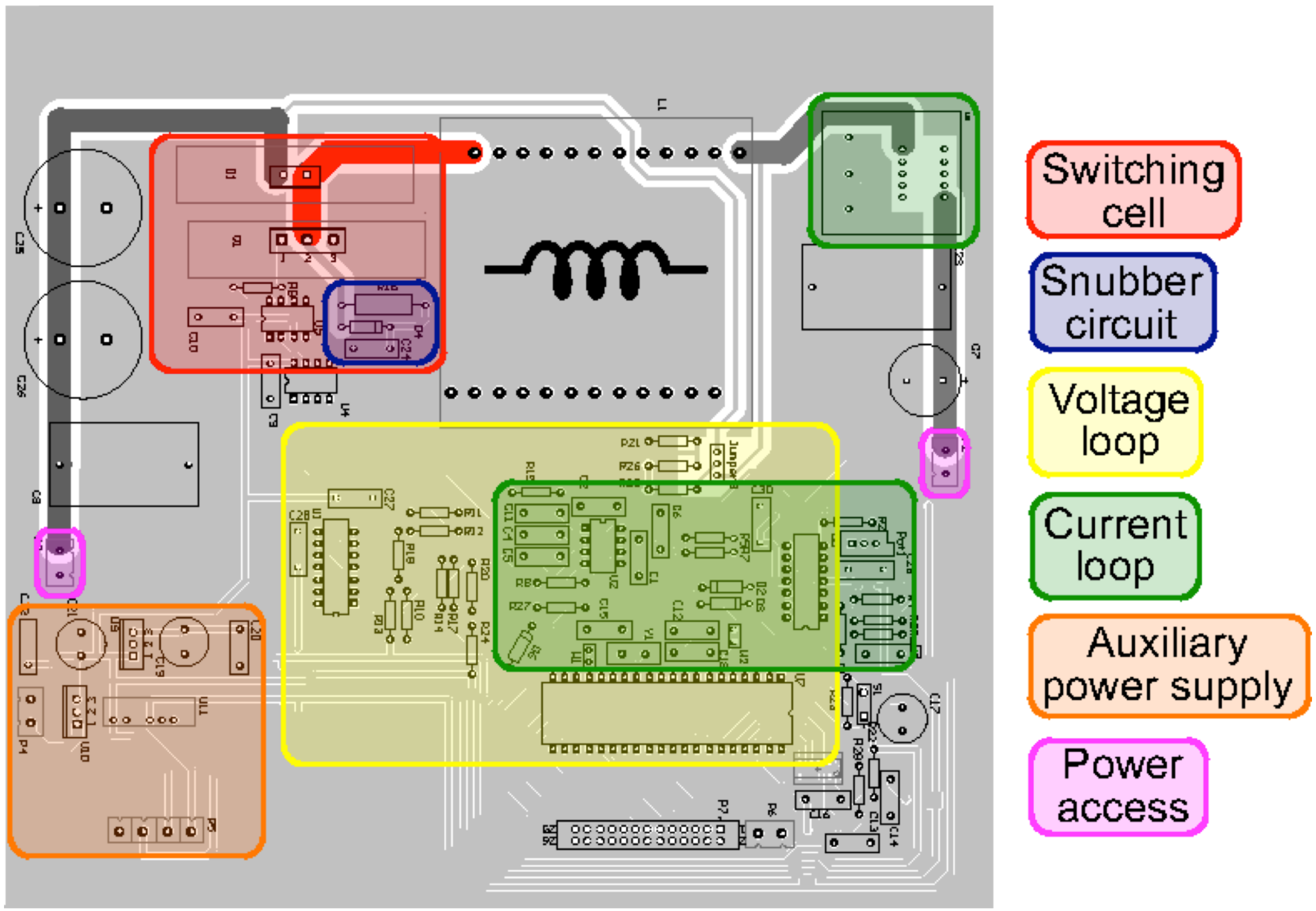
To spot critical zones:
- Sources (µP, video…)
- Victims (low level analogue…)

Circuit design and grounding

Divided circuit



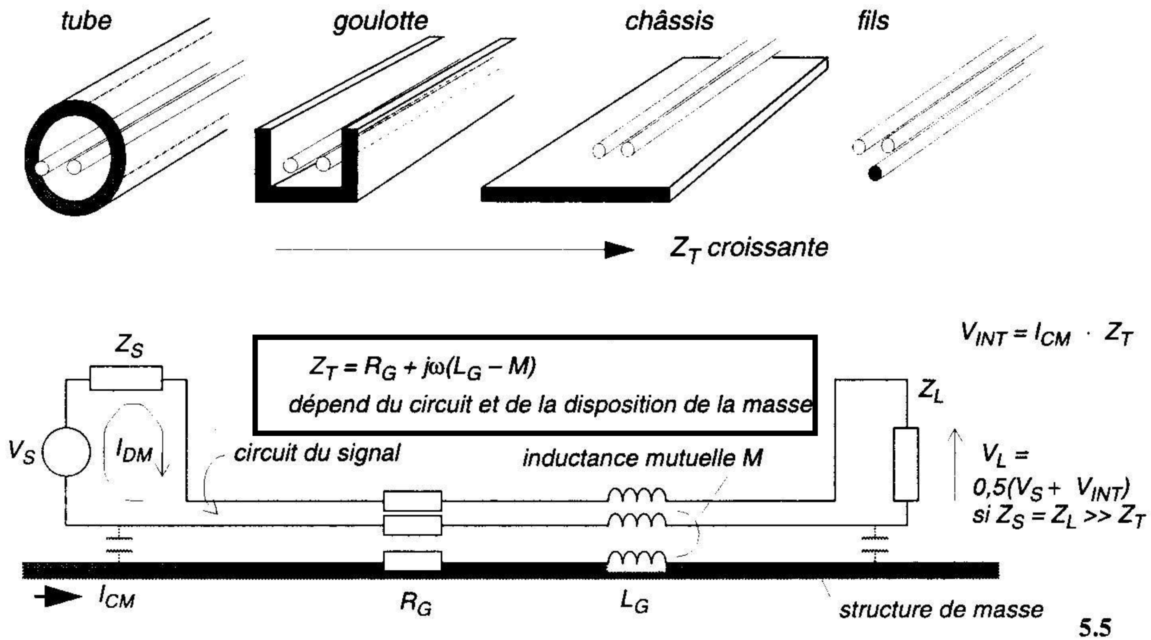
Divided circuit



Circuit design and grounding

2nd step: Grounding

- do not confuse ground and earth (PE)
- grounding role: to give a reference for all connections
- low impedance track to send the current to the source
- low transfer impedance solutions

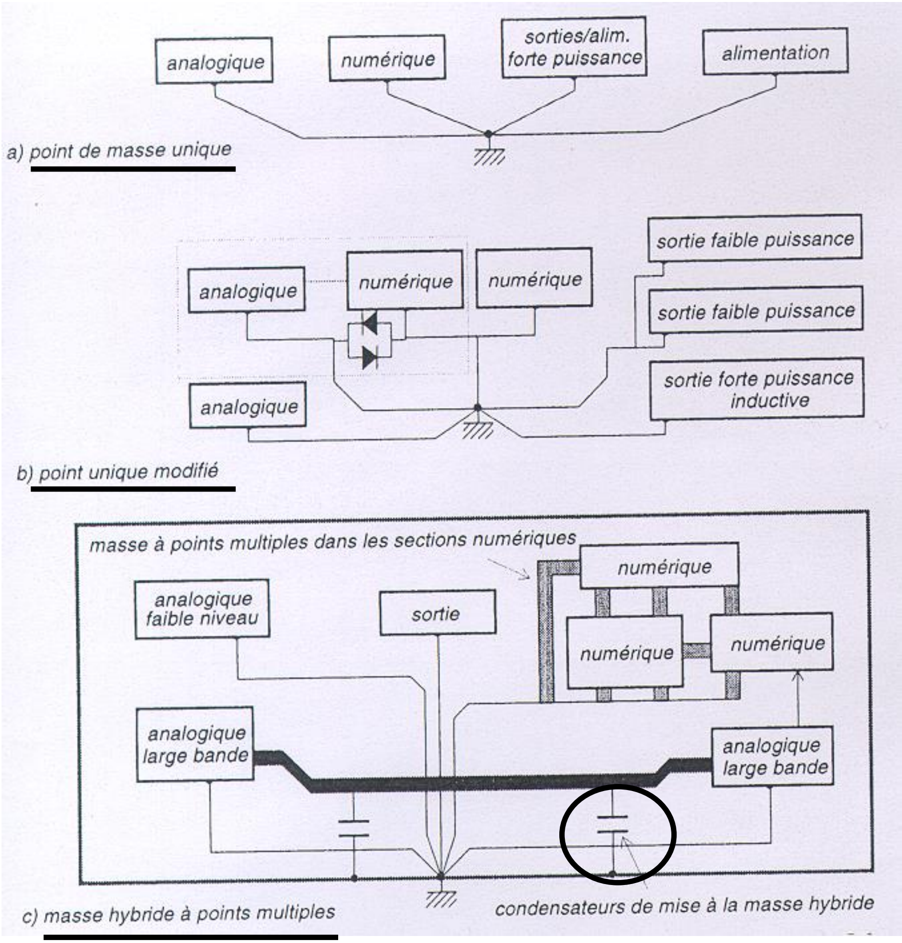


Circuit design and grounding

a) To suppress common grounding Z (OK up to some MHz, then Cp et U_{CM} due to length of links).

b) Similar circuits linked together, noisy circuits near grounding point.

c) A lot of short connections (<0.1λ) for digital circuits.

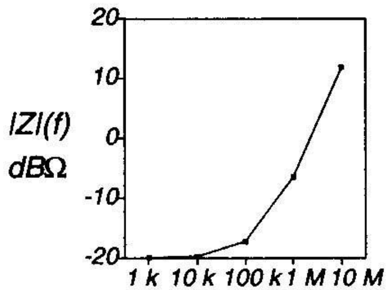


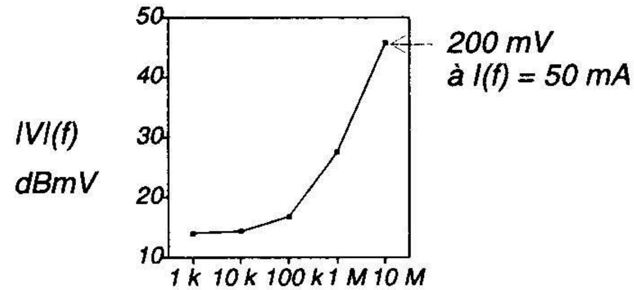
Circuit design and grounding

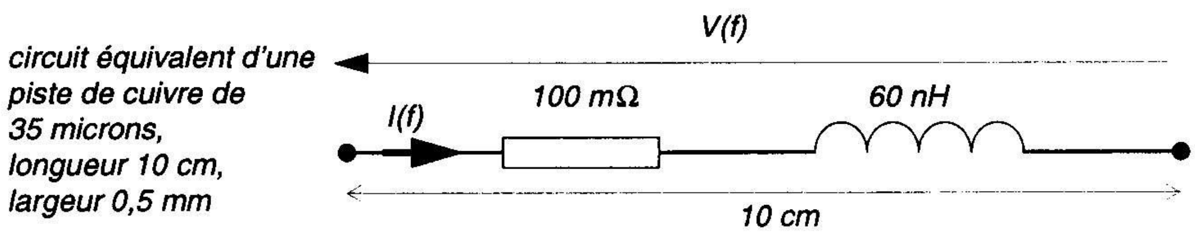
- 1 PCB side/ 1 side versus 2 sides
- Multi-layer PCB (ground plane)
- Reduce impedance
- Grounding track // and near signal track
- Grounding: grid or ground plane
- SMD (to reduce loop surface, length, PCB size)
- ...

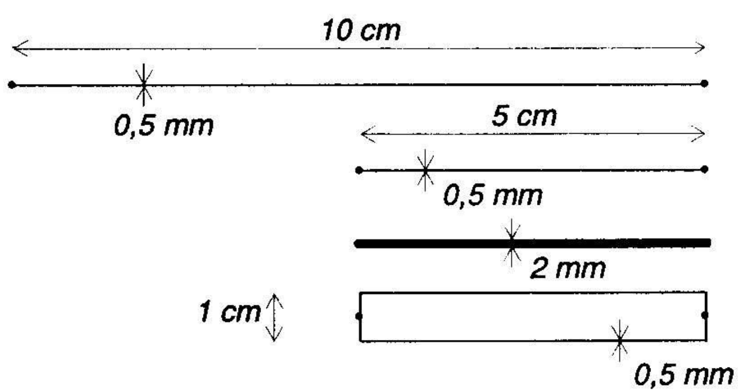
Circuit design and grounding

Track impedance





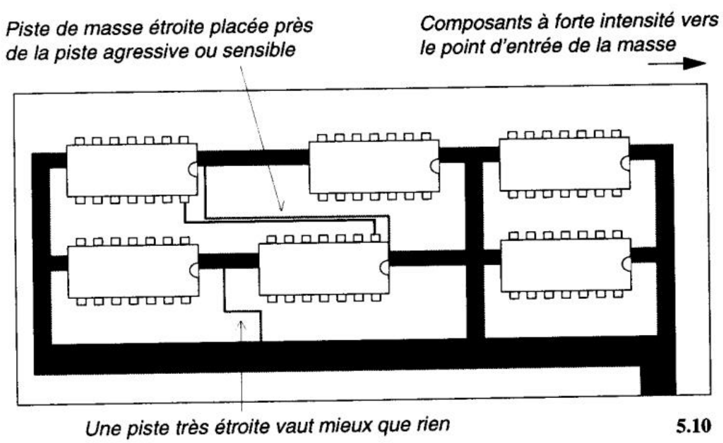


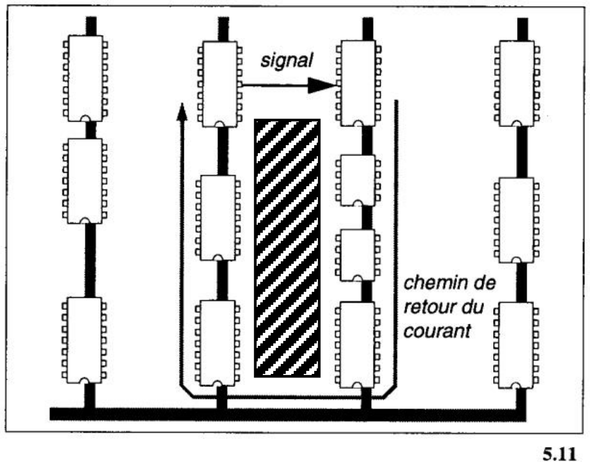


inductance approx.	impédance à 30 MHz
60 nH	11,3 Ω
30 nH	5,6 Ω
16 nH	3,0 Ω
18 nH	3,4 Ω
	5.9

Circuit design and grounding

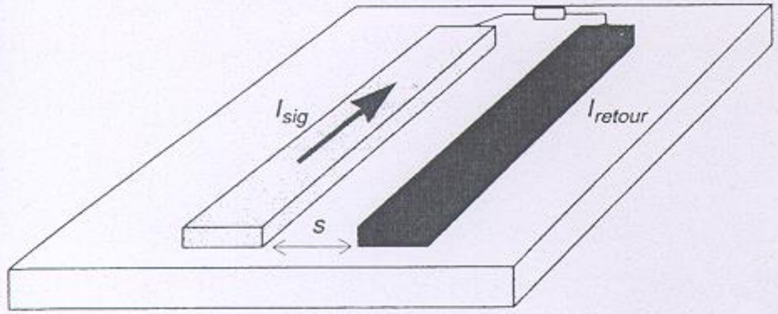
Grid or meshed grounding





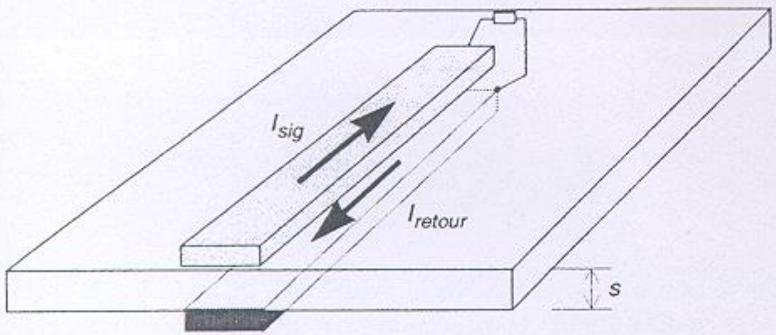
The number of return path for current to ground should be important to reduce L.
Tracks with width >>

The comb configuration is not a good solution.

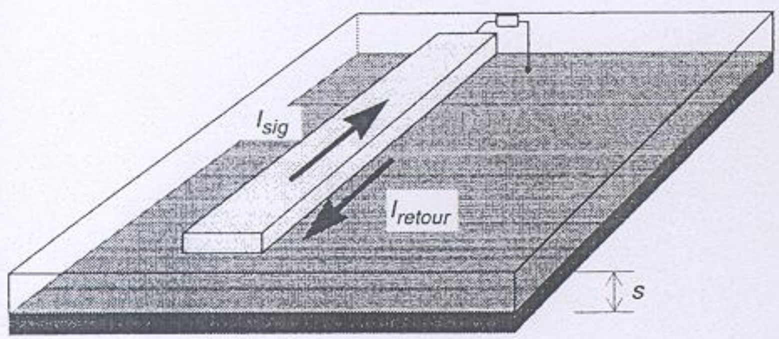


S détermine dans tous les cas l'inductance globale de la boucle

pistes parallèles

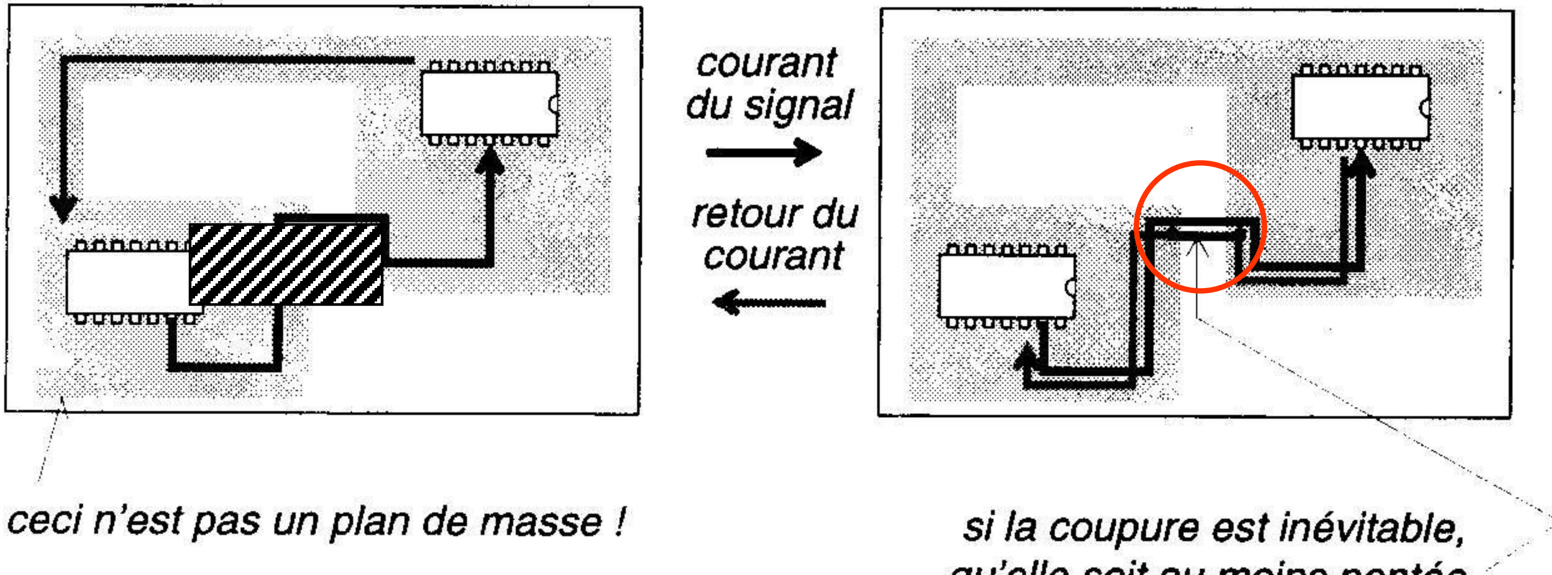


pistes de part et d'autre de la platine



plan de masse sur la face opposée de la platine, offre un chemin de retour à toute piste de l'autre côté

5.13



5.14

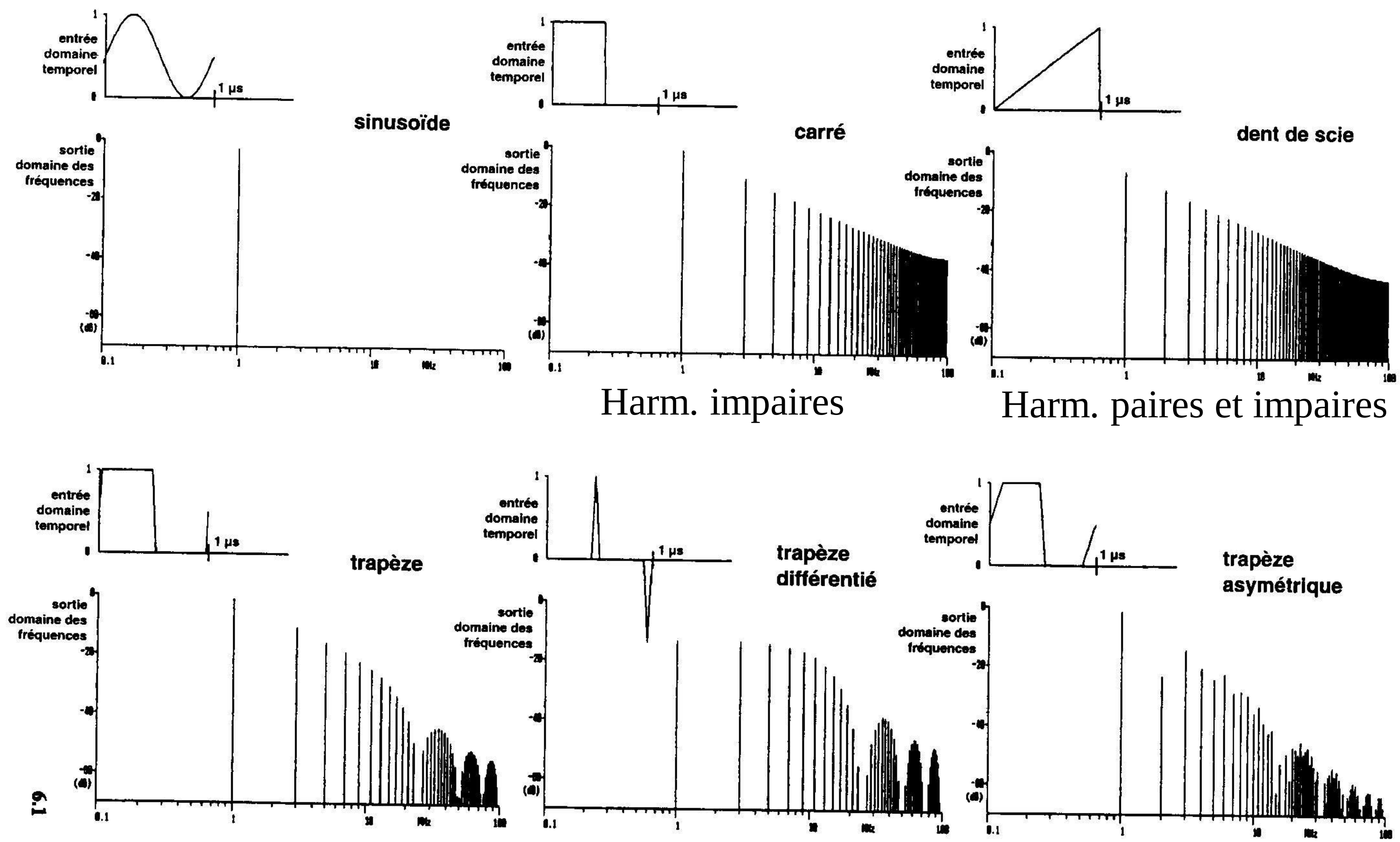
- Do not interrupt ground plane
- If this interruption is mandatory, add a bridge (as short as possible and near the critical track)
- No slot in the ground plane (multi-layer is ideal).

Design rules
For electronic circuits and PCBs
(part II)

Véronique Beauvois, Ir.

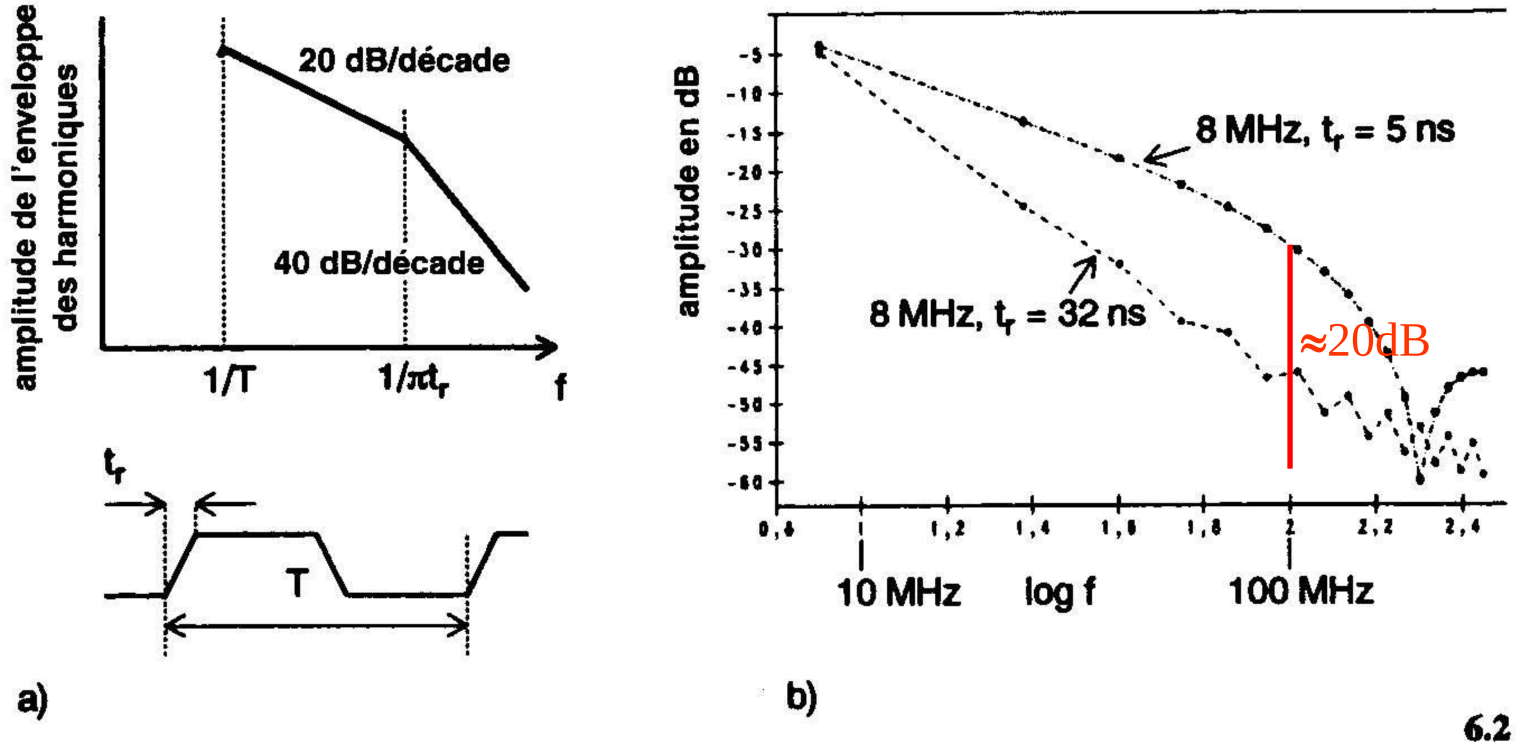
2021-2022

t <---> f



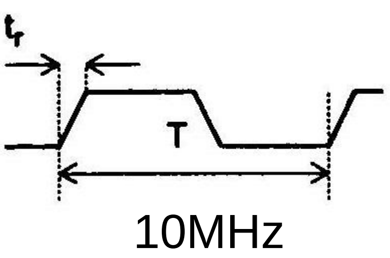
entrée domaine temporel
1 µs
sinusoïde
sortie domaine des fréquences
entrée domaine temporel
1 µs
carré
sortie domaine des fréquences
Harm. impaires
entrée domaine temporel
1 µs
dent de scie
sortie domaine des fréquences
Harm. paires et impaires
entrée domaine temporel
1 µs
trapèze
sortie domaine des fréquences
entrée domaine temporel
1 µs
trapèze différentié
sortie domaine des fréquences
entrée domaine temporel
1 µs
trapèze asymétrique
sortie domaine des fréquences

t <---> f

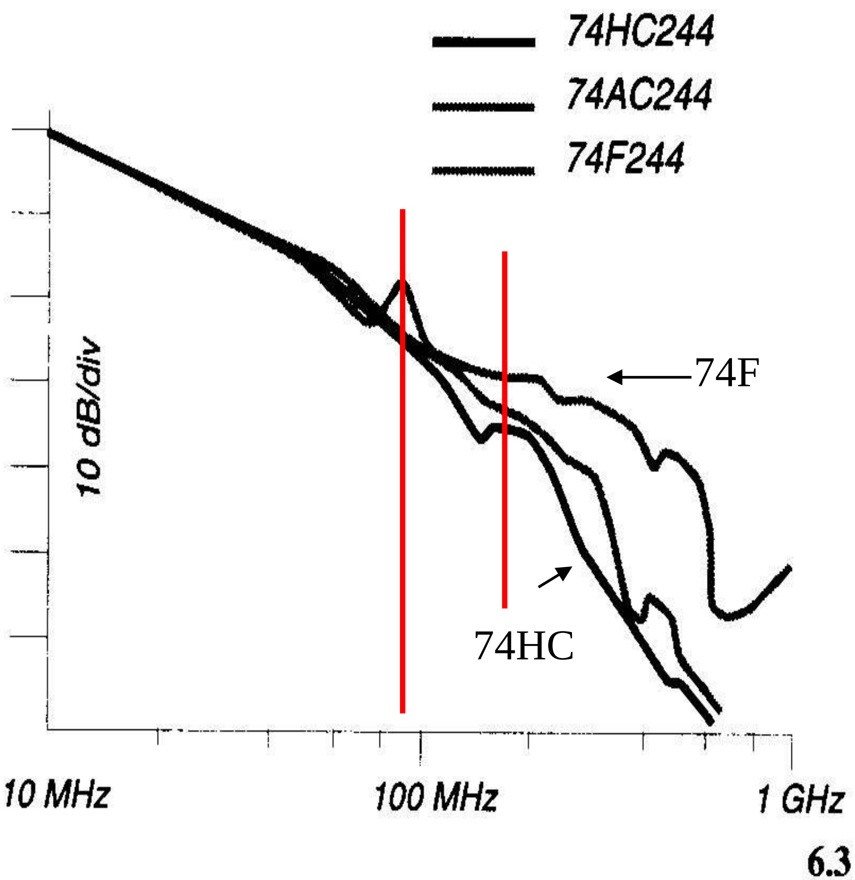


How to choose the logic family?

t <---> f

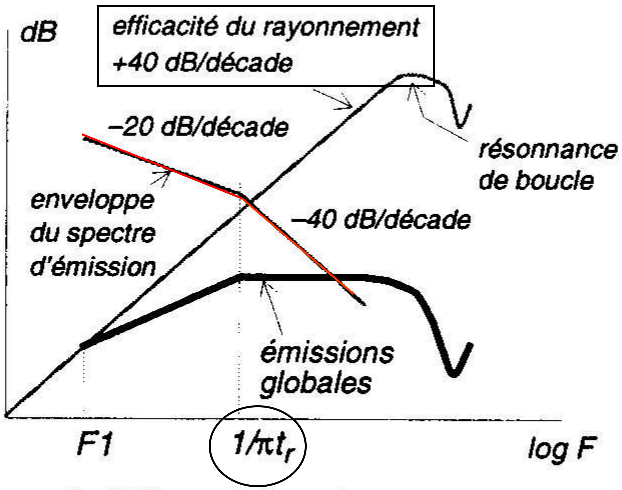


t_r
T
10MHz

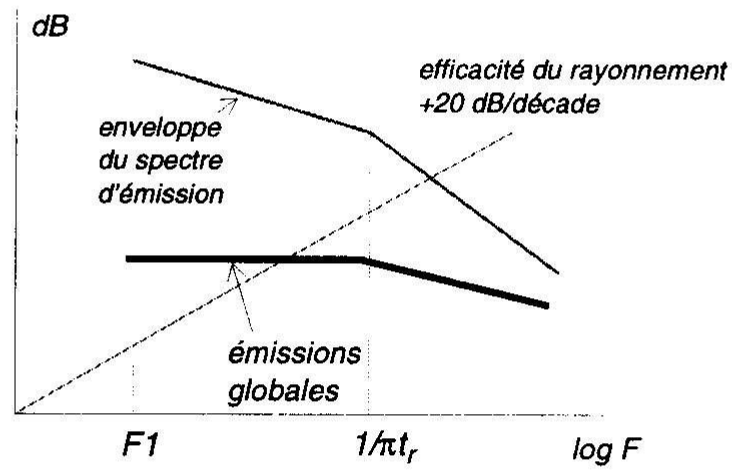


74HC244
74AC244
74F244
10 dB/div
74F
74HC
10 MHz
100 MHz
1 GHz
6.3

Differential mode R.E.	Common mode R.E.



a) Differential mode radiation



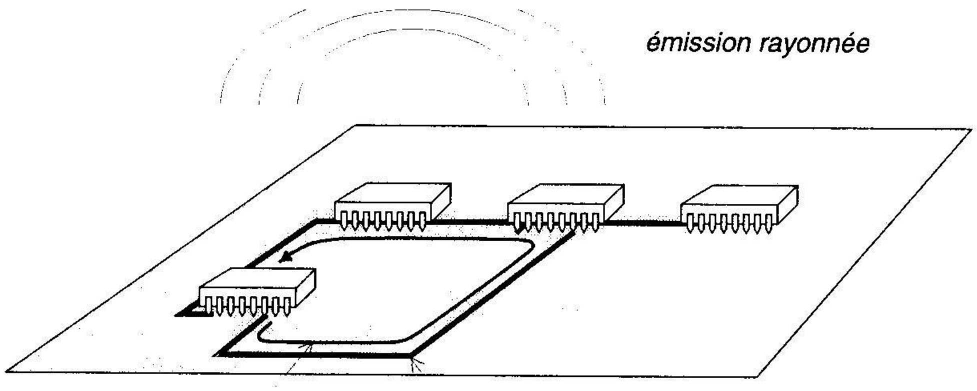
b) Common mode radiation

6.4

⇓ Table 6.1

⇓ Table 6.2

D.M. ----> R.E. of PCB



4.10

Loop = small if dimensions < $\lambda/4$, means 1m @ 75MHz
IC loops could be considered as small up to some 100 MHz
Maximum E-field of this loop @ 10 m measurement distance:
E (V/m) = 263 x 10^{-12} x $f(MHz)^2$ x $A(cm^2)$ x I_S (mA) ---> +40dB/dec

D.M. ----> R.E. of PCB

According to:

$E\ (V/m) = 263 \times 10^{-12} \times f(MHz)^2 \times A(cm^2) \times I_S\ (mA)$ ---> 40 dB/dec

Question: this PCB needs or not an additional shielding?

$A=10\ cm^2$; Is=20 mA and f=50 MHz

E=42 dBµV/m means 12dB over the limit in class B

So if current I and frequency f are fixed, A could not be reduced, a shielding is necessary.

dynamic commutation current / component to charge or discharge the capacitor

Limit EN 55022 cl.B

≈ Dim. case

Shielding + filtering

Famille logique	t_r/t_f ns	ΔI mA	Surface de boucle en cm² ; fréquence d'horloge 4 MHz	10 MHz	30 MHz	100 MHz
4000B CMOS à 5 V	40	6	1000	400	-	-
74HC	6	20	45	18	6	-
74LS	6	50	18	7,2	2,4	-
74ALS	3,5	50	10	4	1,4	0,4
74AC	3	80	5,5	2,2	0,75	0,25
74F	3	80	5,5	2,2	0,75	0,25
74AS	1,4	120	2	0,8	0,3	0,15

Surface de boucle pour 30 dBµV/m 30 MHz - 230 MHz, 37 dBµV/m 230 MHz - 1000 MHz à 10 m

Utilisation : prenons l'exemple de la famille 74ALS avec F_{clk} = 30 MHz.
Le cas le plus défavorable est à 150 MHz (5ème harmonique)

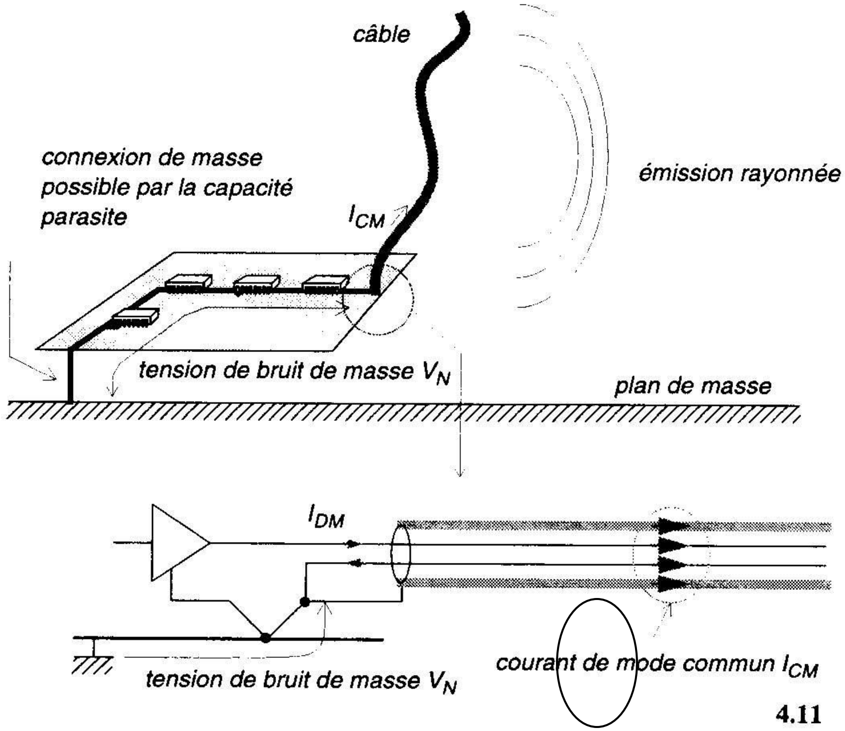
L'analyse de Fourier de la source de courant, en utilisant la section C.7 avec $(t + t_r)/T = 0,5$; T = 33,3 ns ; t_r = 3,5 ns et I =50 mA, donne 3,83 mA pour $I_{(5)}$, le courant du cinquième harmonique.

De l'équation (4.6), pour un champ E de 30 dBµV/m et $I_{(5)}$ comme ci-dessus à 150 MHz, la surface de boucle admissible est de **1,395 cm²** (arrondi à 1,4 dans le tableau).

Tableau 6.1 – Émission en mode différentiel : surface maximale permise.

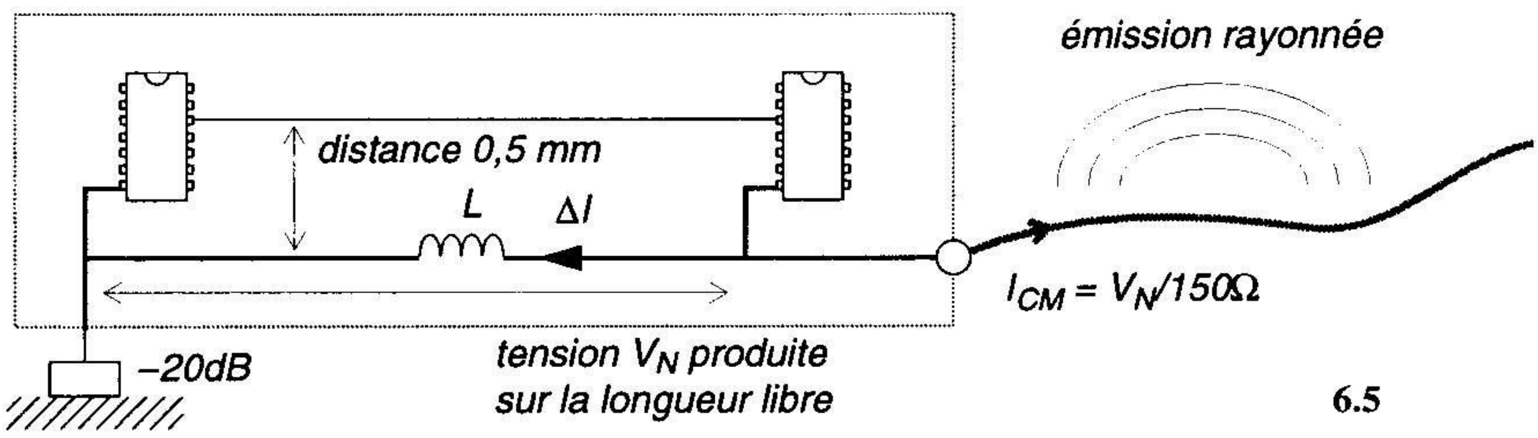
C.M. ----> R.E. of PCB

Cable length
resonance @30-100MHz



E (V/m) = 1,26 x 10^{-4} x f(MHz) x L(m) x I_{MC} (mA)
if the cable is represented by a short monopole (L<λ/4) @ 10m of the ground
e.g. 1m of cabling, E = 42dBμV/m, then Is = 20μA (/1000#I_{MD})

C.M. ----> R.E. of PCB



CM voltage to cable, ΔI on ground path
Differential noise voltage $V_N = \Delta I . j\omega . L$
(between reference ground and cable connection)
$Z \approx 150\Omega$ (constant with f)

Limit 55022 cl.B

Famille logique	t_r/t_f	ΔI	Longueur de piste en cm ; fréquence d'horloge			
	ns	mA	4 MHz	10 MHz	30 MHz	100 MHz
4000B CMOS à 5 V	40	6	180	75	-	-
74HC	6	20	8,5	3,2	1	-
74LS	6	50	3,25	1,3	0,45	-
74ALS	3,5	50	1,9	0,75	0,25	0,08
74AC	3	80	1	0,4	0,14	0,05
74F	3	80	1	0,4	0,14	0,05
74AS	1,4	120	0,4	0,15	0,05	-

Longueur de piste autorisée pour 30 dBμV/m 30 MHz - 230 MHz, 37 dBμV/m 230 MHz - 1000 MHz à 10 m ;
longueur du câble = 1 m ; agencement : pistes parallèles de 0,5 mm distantes de 0,5 mm (2,8 nH/cm).

Utilisation : prenons par exemple la famille 74HC avec F_{clk} = 10 MHz. Le cas le plus défavorable est à 90 MHz (9ème harmonique).

À partir de l'équation (4.7), pour une intensité de champ E de 30 dBμV/m et 1 m de câble, I_{CM} doit être égal à 2,8 μA.

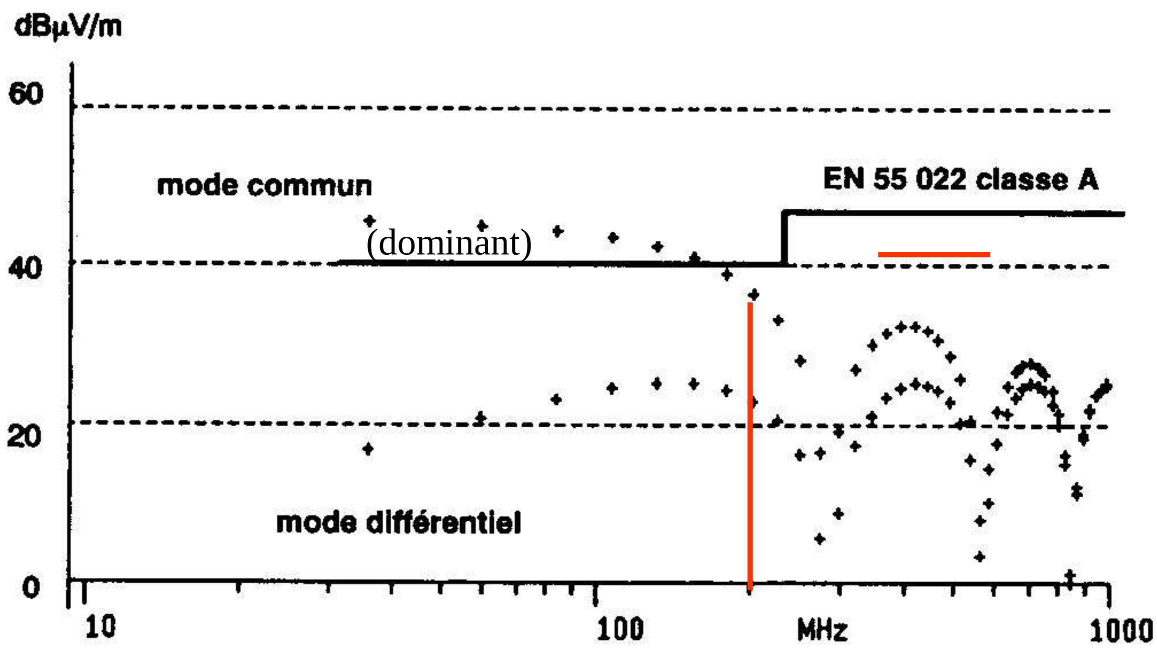
Selon $V_N = I_{CM} \times 150$, avec l'atténuation de couplage de 20 dB, V_N = 4,18 mV.

L'analyse de Fourier de la source de courant, en utilisant la section C.7 avec $(t + t_r)/T = 0,5$; T = 100 ns ; t_r = 6 ns et I = 20 mA, donne 0,826 mA pour $I_{(9)}$, le courant du neuvième harmonique.

Ensuite, suivant $L = V_N/2\pi f I(9)$, l'inductance aux bornes de laquelle on peut admettre V_N à $I_{(9)}$ et 90 MHz est de 8,95 nH, soit **3,19 cm** autorisés à 2,8 nH/cm.

Tableau 6.2 – Émissions en mode commun : longueur de piste admissible.

R.E. - Comparaison CM / DM



For the same signal in DM or CM

trapezoidal @12MHz, with t_r and t_f 3.5ns

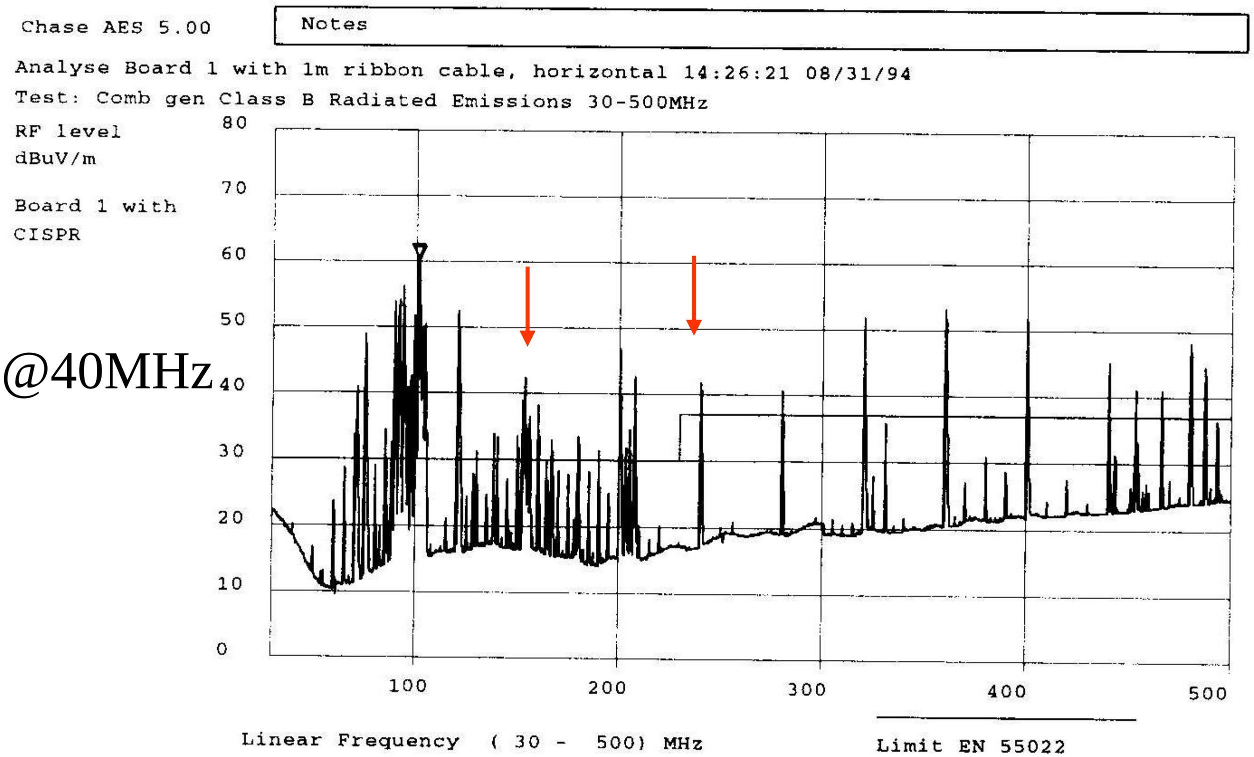
CM Ipk 0.1mA in cable, with L 2m

DM 20mA in a loop of 5cm²

$E\ (V/m) = 263 \times 10^{-12} \times f(MHz)^2 \times A(cm^2) \times I_S\ (mA)$ loop-IC

$E\ (V/m) = 1{,}26 \times 10^{-4} \times f(MHz) \times L(m) \times I_{MC}\ (mA)$ antenna-cable

R.E. > main source processor clock



Clock @40MHz

Commercial standards: no difference between N.B. and B.B.

- To reduce N.B. with buffer on lines and take care of ground plane.
- To reduce B.B. sources on data lines, video...