EMI and EMC – Basic Concepts

- The absence of Electromagnetic Interference (EMI) in a system is called Electromagnetic Compatibility (EMC).
- I am trying to ensure this state for the European XFEL facility (work package 39).
- If you find this an entertaining afternoon, more talks can be hooked in indicated places.

Herbert Kapitza (FLA)
MDI Technical Forum
DESY, 02.03.12

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Noise, Interference and Compatibility

For better understanding, let's start with some definitions:

- EM: electromagnetic
- EM noise: All electric signals in our system, except the ones we‘re interested in. It is extremely difficult – if not impossible – to have no noise in a system.
- EM interference (EMI): The unwanted effect of EM noise interfering with our signals.
- EM compatibility (EMC): Here I like to cite the definition from the European EMC directive 2004/108/EC: *EM compatibility means the ability of equipment to function satisfactorily in its EM environment without introducing intolerable EM disturbances to other equipment in that environment.* A remarkably clear sentence in a legal text!

EMC implies a balance: Don‘t disturb others and don‘t get disturbed by them.

The Evolution of EM Noise

Why has EMC more and more become an issue in the past decades?
It is interesting to look at the evolution of randomly selected EM subjects:

(1) Radio and TV: Before 1984 three TV programs were broadcasted in Germany. With the advent of cable and satellite TV the number of programs (not their quality) exploded. New territories in the EM spectrum were occupied.

(2) Telecommunication: This telephone inside the DESY tunnel must be from the 1960s when only Big Bosses had “mobile” phones installed in their cars. Today we have the atmosphere filled with EM smog from cell phones, WLAN etc. But imagine the ionizing radiation hardness of this black thing ☺

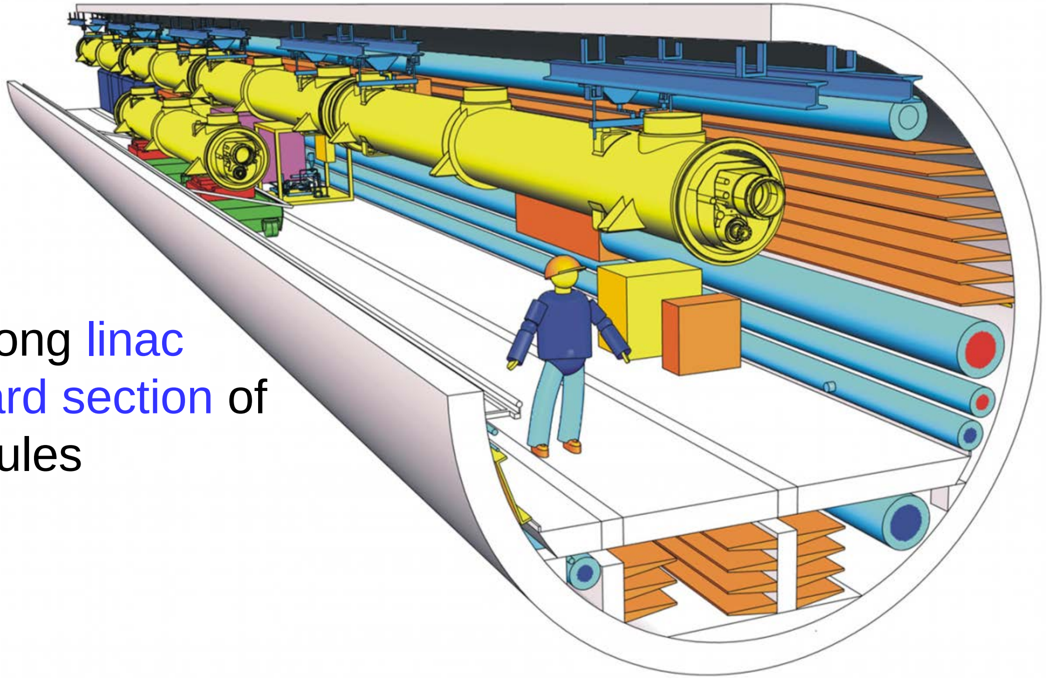
The Evolution of EM Noise

(3) Automotive: My 1977 beetle had the following electric parts: battery, generator, ignition system, lamps, horn, rear window heating, radio. Nowadays almost everything is operated electrically and there are many intelligent assistant systems: A modern Fiat Panda has more computing power embedded than the DESY computing center of 1977 (IBM 370/168). Cars are among the toughest EMI places.

(4) Power supply: For a long time the majority of loads in the power grid was linear, i.e. composed of R, C, L. Today's switched power supplies are energy-efficient but leave a lot of noise in the mains due to their pulsed current consumption. more

The Evolution of EM Noise

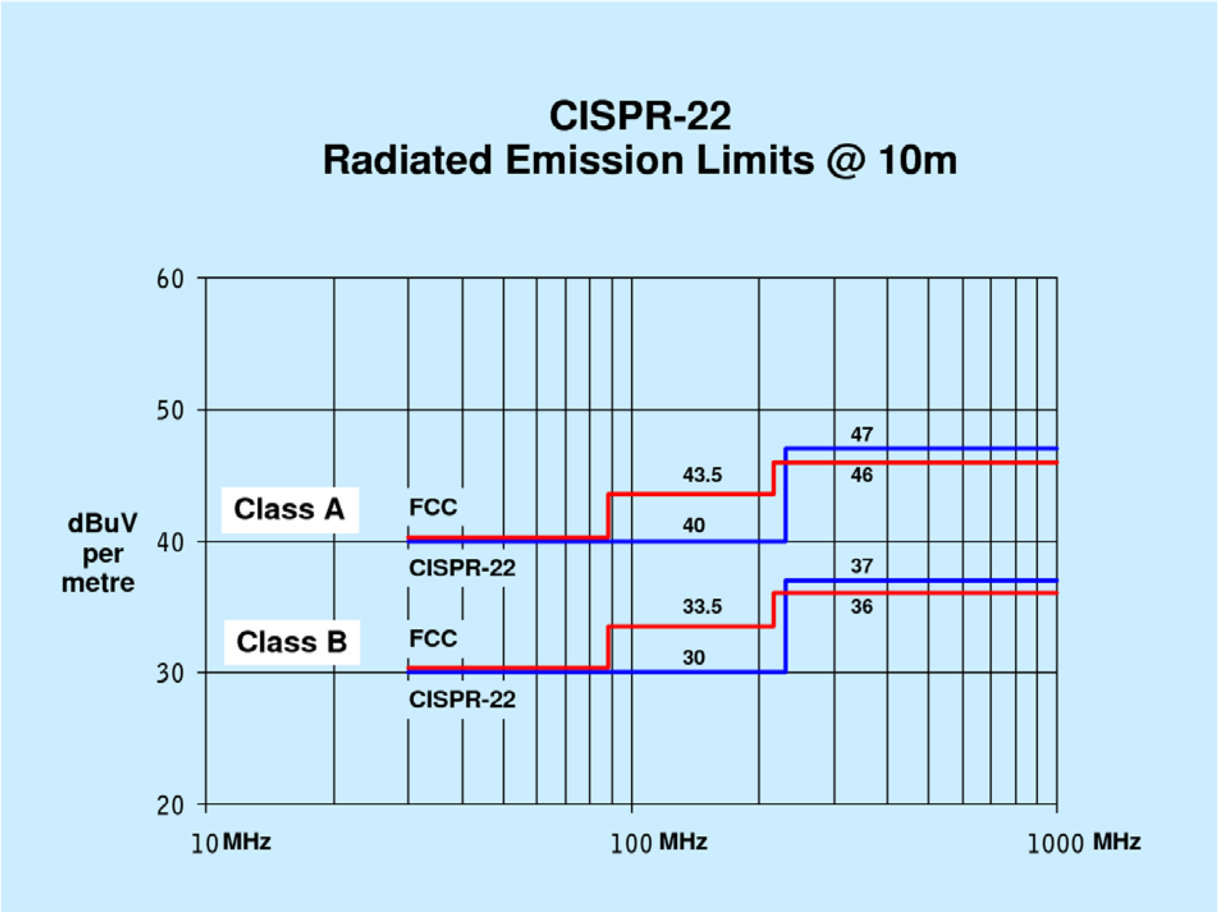
(5) HEP and FEL research: By definition these hit the limits of what is possible. In the European XFEL fs-timing must be possible next to MW-pulses, so EMC must be an issue here.



50 m long linac standard section of 4 modules

(6) Meanwhile EMC is considered so important that it is legally regulated in the EMVG of 26.02.2008.

Limits between Good and Evil



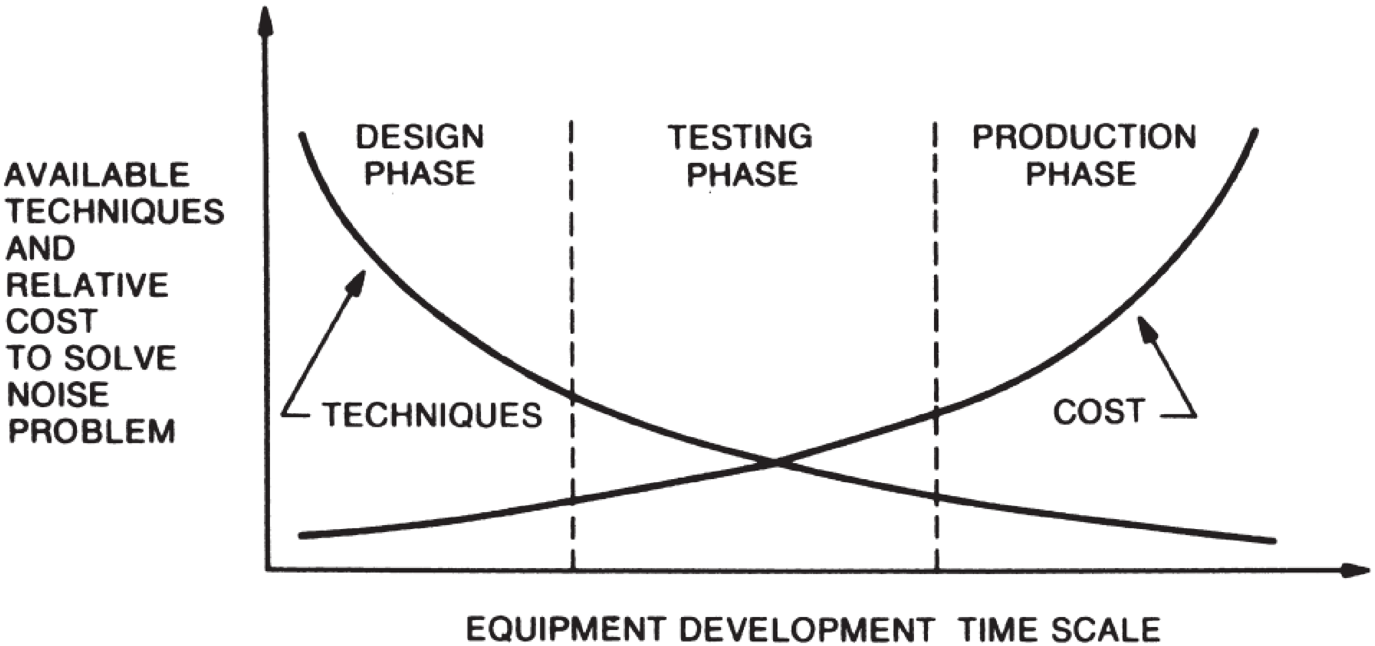
FCC: Federal Communications Commission (USA)
CISPR: Comité International Spécial des Perturbations Radioélectriques (EU)
Class A: industrial environment
Class B: residential environment

EMC Approaches: Crisis Management vs. System Design

EMC can be approached in two very different ways:

> Crisis Management: Design your stuff with total disregard of EMC, see how it works, fix problems with add-ons if needed (and if possible!!!)

> System Design: Consider EMC right from the beginning. Then it will be designed into instead of added onto the product.



Example: XFEL Tunnel Grounding

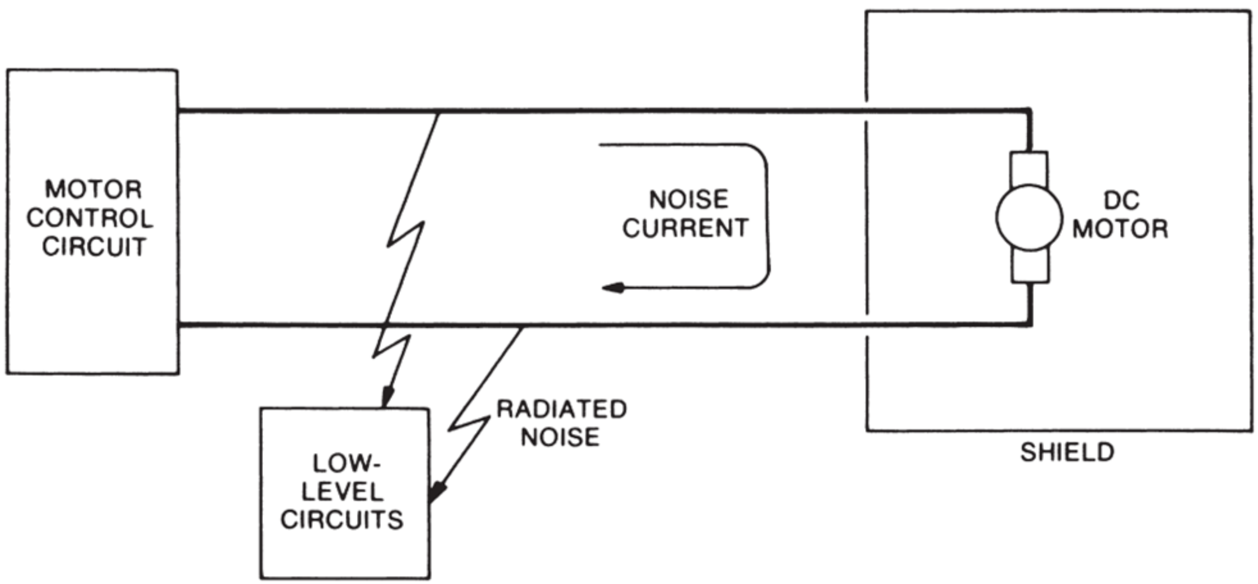
Figure 2 from the DESY Particle Physics Annual Report 2010

Inclusion of the tunnel steel in the XFEL facility ground: 1 Steel cages – 2 Ground connector – 3 Tubbing mould – 4 Produced tubbings – 5 Tubbings in place (with yellow grounding points) – 6 Connected tubbings

EMC Problem Structure

Each EMC problem can be modelled in a very simple way:

The identification of the noise source, the susceptible receptor and their coupling channel is always the first step in an EMC system analysis. This is mostly much more difficult than in this example:



Basic EMI Fighting Methods

The EMC problem structure suggests three basic EMI fighting methods:

(1) *Change the noise characteristics at the source.* Promising parameters are amplitude, frequency, di/dt. This is always the first option because curing one source problem may solve many receptor problems. more

(2) *Improve the immunity of the receptor.* Proper grounding may help here. more

(3) *Break the coupling path.* For this we use shields, filters, common mode chokes and such. more

These methods are not strictly separated from each other, which doesn't matter because in most cases all of them are employed at the same time.

This quite simple model describes many interference situations in life (canteen conversation, international relations…)

The EMC Toolbox

Since EMI is mediated by EM fields, fighting it is not based on black magic but on CLASSICAL ELECTRODYNAMICS:

Gauss:	$\oiint_S \vec{D} \cdot d\vec{S} = q$	$\vec{\nabla} \cdot \vec{D} = \rho$
Gauss:	$\oiint_S \vec{B} \cdot d\vec{S} = 0$	$\vec{\nabla} \cdot \vec{B} = 0$
Faraday-Henry:	$\oint_L \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \iint_S \vec{B} \cdot d\vec{S}$	$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
Ampere-Maxwell:	$\oint_L \vec{H} \cdot d\vec{l} = I + \frac{d}{dt} \iint_S \vec{D} \cdot d\vec{S}$	$\vec{\nabla} \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$

$\vec{D} = \varepsilon_r \varepsilon_0 \vec{E}$ and $\vec{B} = \mu_r \mu_0 \vec{H}$ for simple materials.

The EMC Toolbox

> For practical calculations it is useful to introduce potentials $\vec{A}$ and φ from which the fields are calculated as

$$\vec{B} = \vec{\nabla} \times \vec{A} \quad \text{and} \quad \vec{E} = -\vec{\nabla}\varphi - \frac{\partial \vec{A}}{\partial t}$$

> The potentials $\vec{A}$ and φ can be calculated from the current and charge densities $\vec{j}$ and ρ. The most general expressions (retarded potentials):

$$\vec{A}(\vec{r},t) = \frac{c\mu_0}{4\pi} \iint \frac{\delta(ct - ct' - |\vec{r} - \vec{r}'|)}{|\vec{r} - \vec{r}'|} \vec{j}(\vec{r}',t')dt'dV'$$

$$\varphi(\vec{r},t) = \frac{c}{4\pi\varepsilon_0} \iint \frac{\delta(ct - ct' - |\vec{r} - \vec{r}'|)}{|\vec{r} - \vec{r}'|} \rho(\vec{r}',t')dt'dV'$$

For some simple $\vec{j}$ and ρ the integrals can indeed be solved.

Electric Dipole Radiation in a Nutshell

- Given an electric dipole with dipole moment $\vec{d} = Q\vec{a}$.
- Charge and current densities: $\rho_e(\vec{r}) = -\vec{d}\cdot\vec{\nabla}\delta^3(\vec{r})$ and $\vec{j}_e(\vec{r}) = c\vec{d}'\delta^3(\vec{r})$.
- Potentials: $\varphi_e(\vec{r},t) = \frac{1}{4\pi\varepsilon_0}\left[\frac{\vec{r}\cdot\vec{d}'(ct-r)}{r^2} + \frac{\vec{r}\cdot\vec{d}(ct-r)}{r^3}\right]$ and $\vec{A}_e(\vec{r},t) = \frac{c\mu_0}{4\pi}\frac{\vec{d}'(ct-r)}{r}$.
- Fields: $\vec{E}_e = \frac{1}{4\pi\varepsilon_0}\left[-\frac{\vec{d}''}{r} + \frac{(\vec{d}''\cdot\vec{r})\vec{r}}{r^3} - \frac{\vec{d}'}{r^2} + \frac{3(\vec{d}'\cdot\vec{r})\vec{r}}{r^4} - \frac{\vec{d}}{r^3} + \frac{3(\vec{d}\cdot\vec{r})\vec{r}}{r^5}\right]$

$$\vec{B}_e = \frac{\mu_0 c}{4\pi}\left[\frac{\vec{d}''\times\vec{r}}{r^2} + \frac{\vec{d}'\times\vec{r}}{r^3}\right]$$

- Oscillating dipole: $\vec{d}(ct) = \vec{d}_0 e^{-i\omega t} = \vec{d}_0 e^{-ikct}$ with $k = 2\pi/\lambda = \omega/c$

$$\vec{E}_{ec} = -\frac{d_0}{4\pi\varepsilon_0}\frac{e^{-i(\omega t-kr)}}{r^3}\{[(kr)^2 + ikr - 1]\sin\theta\,\vec{e}_\theta + 2(ikr-1)\cos\theta\,\vec{e}_r\}$$

$$\vec{B}_{ec} = -\frac{\mu_0\omega d_0}{4\pi}\frac{e^{-i(\omega t-kr)}}{r^2}[kr+i]\sin\theta\,\vec{e}_\phi$$

more

Magnetic Dipole Radiation in a Nutshell

- Given a magnetic dipole with dipole moment $\vec{m} = I\vec{S}$.
- Charge and current densities: $\rho_m(\vec{r}) = 0$ and $\vec{j}_m(\vec{r}) = -\vec{m} \times \vec{\nabla}\delta^3(\vec{r})$.
- Potentials: $\varphi_m(\vec{r},t) = 0$ and $\vec{A}_m(\vec{r},t) = \frac{\mu_0}{4\pi}\vec{\nabla} \times \frac{\vec{m}\,(ct-r)}{r}$.
- Fields: $\vec{B}_m = \frac{\mu_0}{4\pi}\left[-\frac{\vec{m}''}{r} + \frac{(\vec{m}''\cdot\vec{r})\vec{r}}{r^3} - \frac{\vec{m}'}{r^2} + \frac{3(\vec{m}'\cdot\vec{r})\vec{r}}{r^4} - \frac{\vec{m}}{r^3} + \frac{3(\vec{m}\cdot\vec{r})\vec{r}}{r^5}\right]$

$$\vec{E}_m = -\frac{\mu_0 c}{4\pi}\left[\frac{\vec{m}'' \times \vec{r}}{r^2} + \frac{\vec{m}' \times \vec{r}}{r^3}\right]$$

- Magnetic and electric dipole fields are related:

$$\vec{E}_m = -\mathrm{c}\vec{B}_e \;\text{ and }\; \vec{B}_m = \frac{1}{c}\vec{E}_e \;\text{ with }\; \vec{d} = \vec{m}/c$$

more

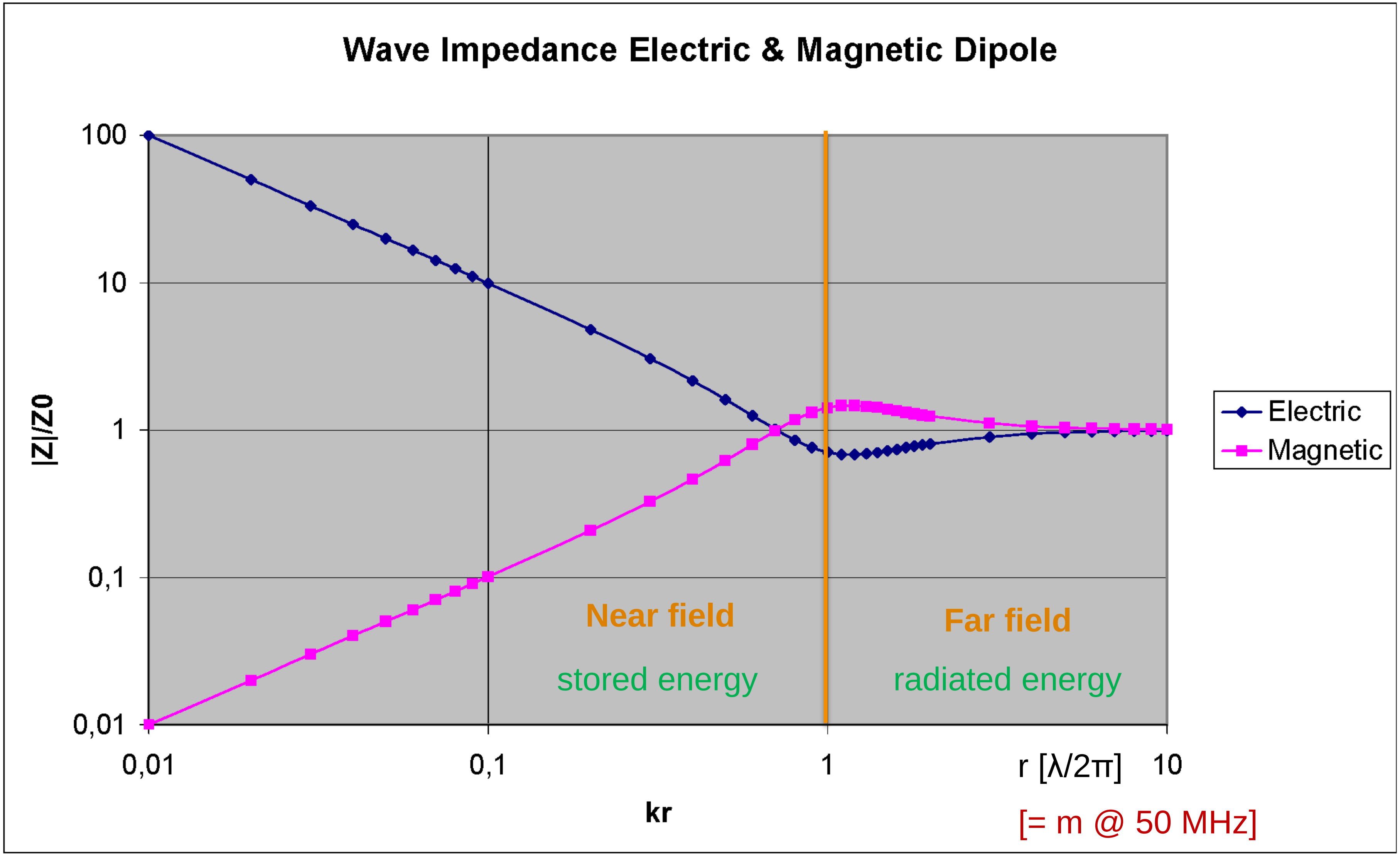
EM Field Impedance

- EM fields may be characterized by their complex resistance
$$Z_c = \frac{E_c}{H_c} = \mu_0 \frac{E_c}{B_c}$$
The unit indeed is (V/m)/(A/m) = V/A = Ω. Its modulus $Z = |Z_c|$ is the impedance of the field, its phase is the phase difference of $\vec{E}$ and $\vec{B}$.

- In the equator plane of an electric dipole one obtains
$$Z_{ec} = Z_0 \frac{(kr)^4 + ikr}{(kr)^4 + (kr)^2} \quad \text{with} \quad Z_0 = \frac{1}{\varepsilon_0 c} = \mu_0 c = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377\Omega$$
being the characteristic impedance of the vacuum. This yields the field impedance as shown in the next plot.

- Electric and magnetic dipole field resistances are related by
$$\frac{Z_{mc}}{Z_0} = \frac{Z_0}{Z_{ec}}$$

EM Field Impedance vs. Distance



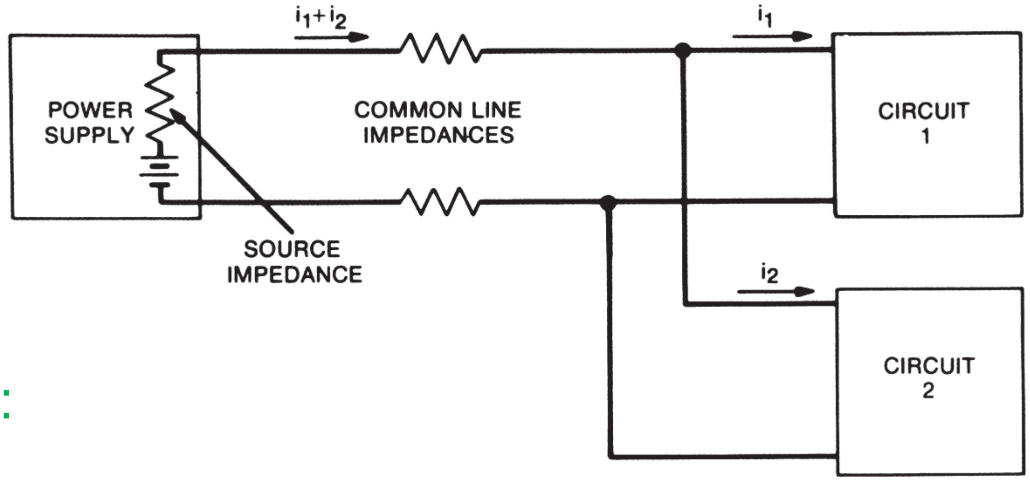
EMI Couplings

Corresponding to the different regimes of the EM field impedance there are different EMI coupling mechanisms:

- > Capacitive coupling by electric near fields: unexpected shortcuts @ high f
- > Inductive coupling by magnetic near fields: a nuisance @ low f
- > Radiation coupling by electromagnetic far fields
- > Galvanic coupling by conductive connections

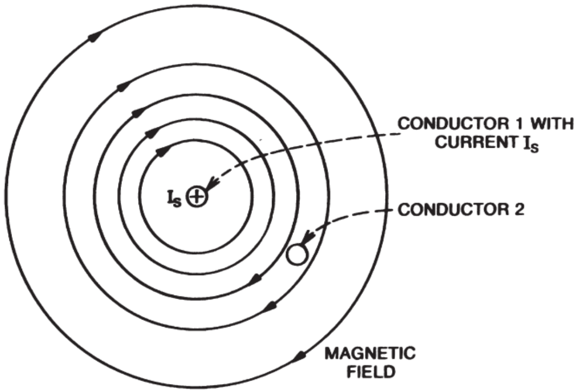
Galvanic coupling comes in various forms:

- > Pickup on power and other supply lines, even through shields
- > Common impedance coupling: current 1 modulates voltage 2



Linear Networks and Circuit Analysis

If the system dimensions are small compared to the wavelengths of interest, electric near fields can be confined in capacitors and magnetic near fields in coils. EMI problems can then be handled by the methods of circuit analysis for linear networks.



PHYSICAL REPRESENTATION

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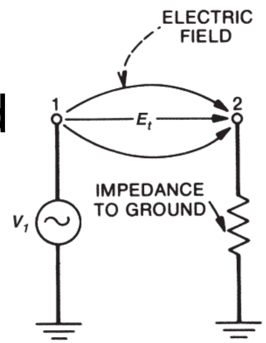
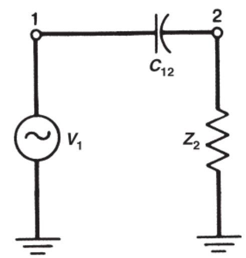
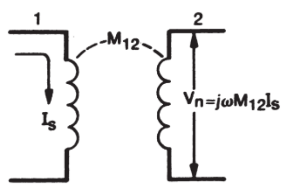
Much insight can be gained using simulation programs like SPICE. This here is an approximation of the steel reinforcement cage of an XFEL tunnel tübbing:



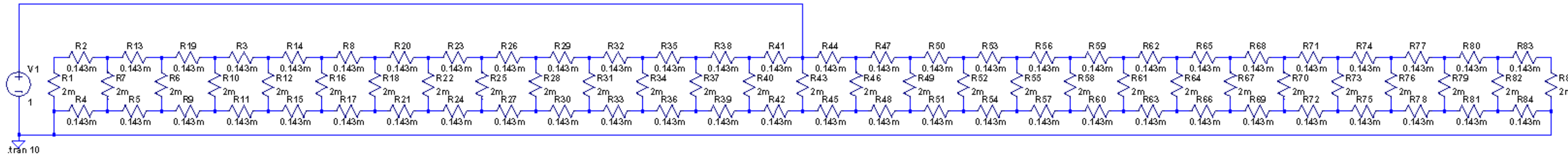
PHYSICAL REPRESENTATION



EQUIVALENT CIRCUIT

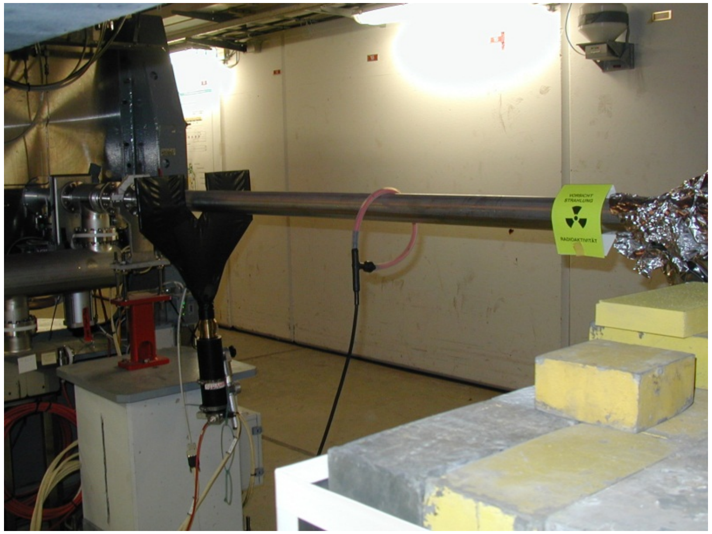


EQUIVALENT CIRCUIT

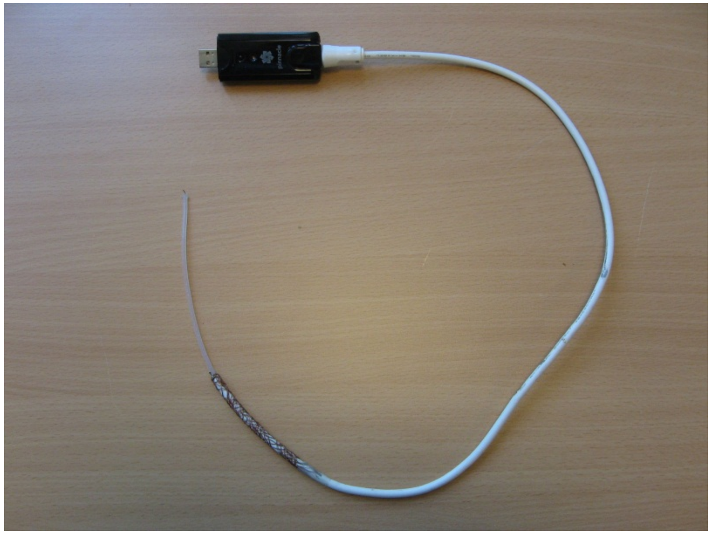


EMC Hardware Tools

- Since much EMI trouble stems from low f magnetic fields, it is important to know their sources, the currents. Rogowski coils are very useful here.
- A portable spectrum analyzer with several antennas is useful for quick overviews.



But we also used a DVB-T receiver on a laptop for some tests.



Last Words

Spoken by Alain Charoy at CAS 2004 in Warrington:

Please, let us remember…

- EMC is not black magic (Just simple physics…)
- Some measurement equipments are required
- Usually, only simple equipments are sufficient
- It's good to be experienced (& confident enough)
- It's important to understand how system works
- It's useful to methodically analyse what happens
- It's efficient to foresee and simplify EMC problems
- It's necessary to know the orders of magnitudes
- It's politically effective to be persuasive (& smiling)
- It's essential never to become discouraged !…