PH-ESE Seminar

Practical EMC Issues in Large Experiments

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Selected Topics

- Introduction to EMC
- Grounding
- Back end EMC requirements.
- Front-end EMC requirements.
- How to deal with EMI couplings.
- Selected good design practices.

Introduction to EMC

Why do we need to care about this thing !?

"EMC = Electro Magnetic Compatibility"

Means:

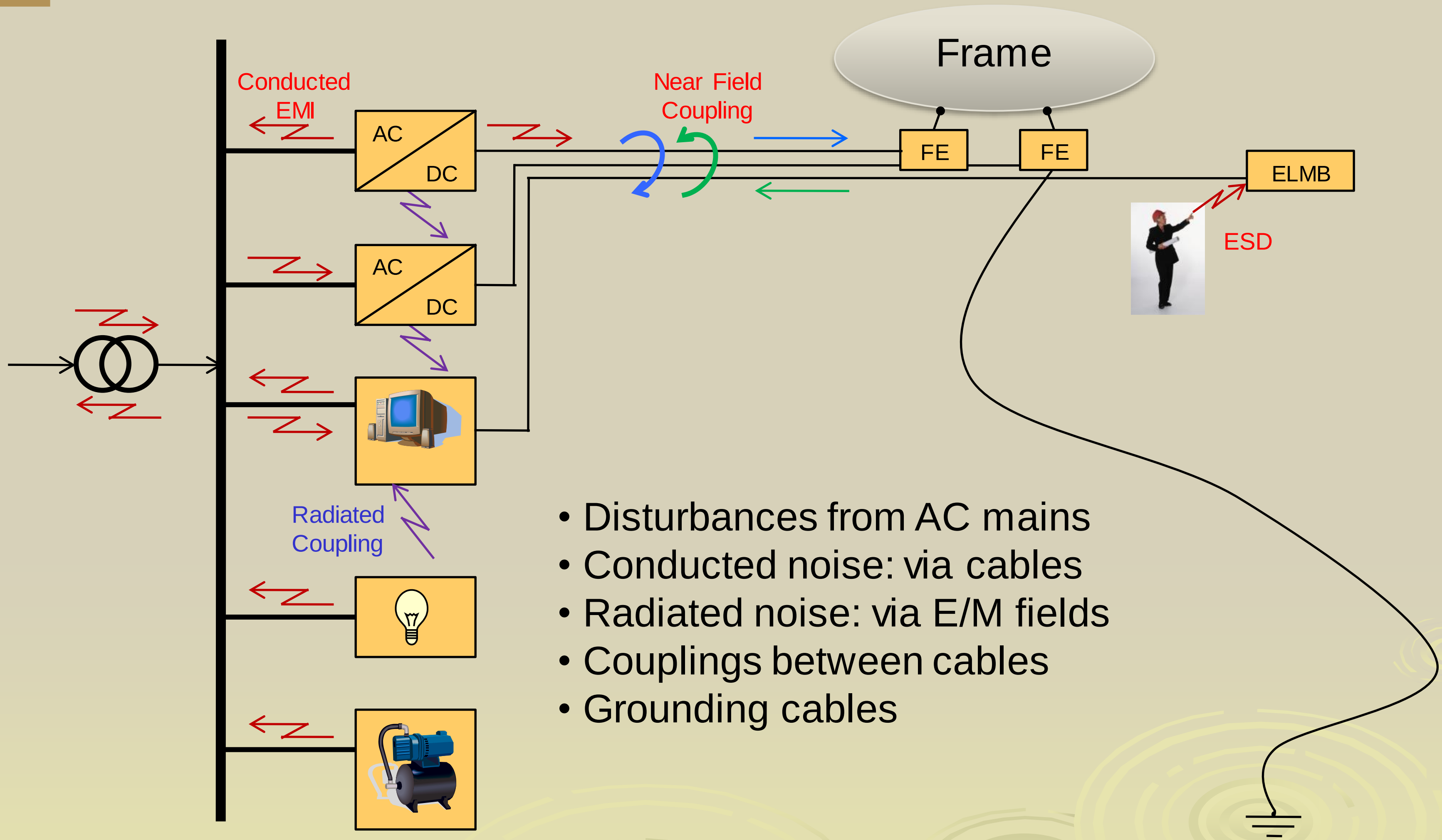
- Ability of a system to operate as required in presence of electro magnetic disturbances.

and also:

- Ability of a system to operate without compromising the normal operation of other systems

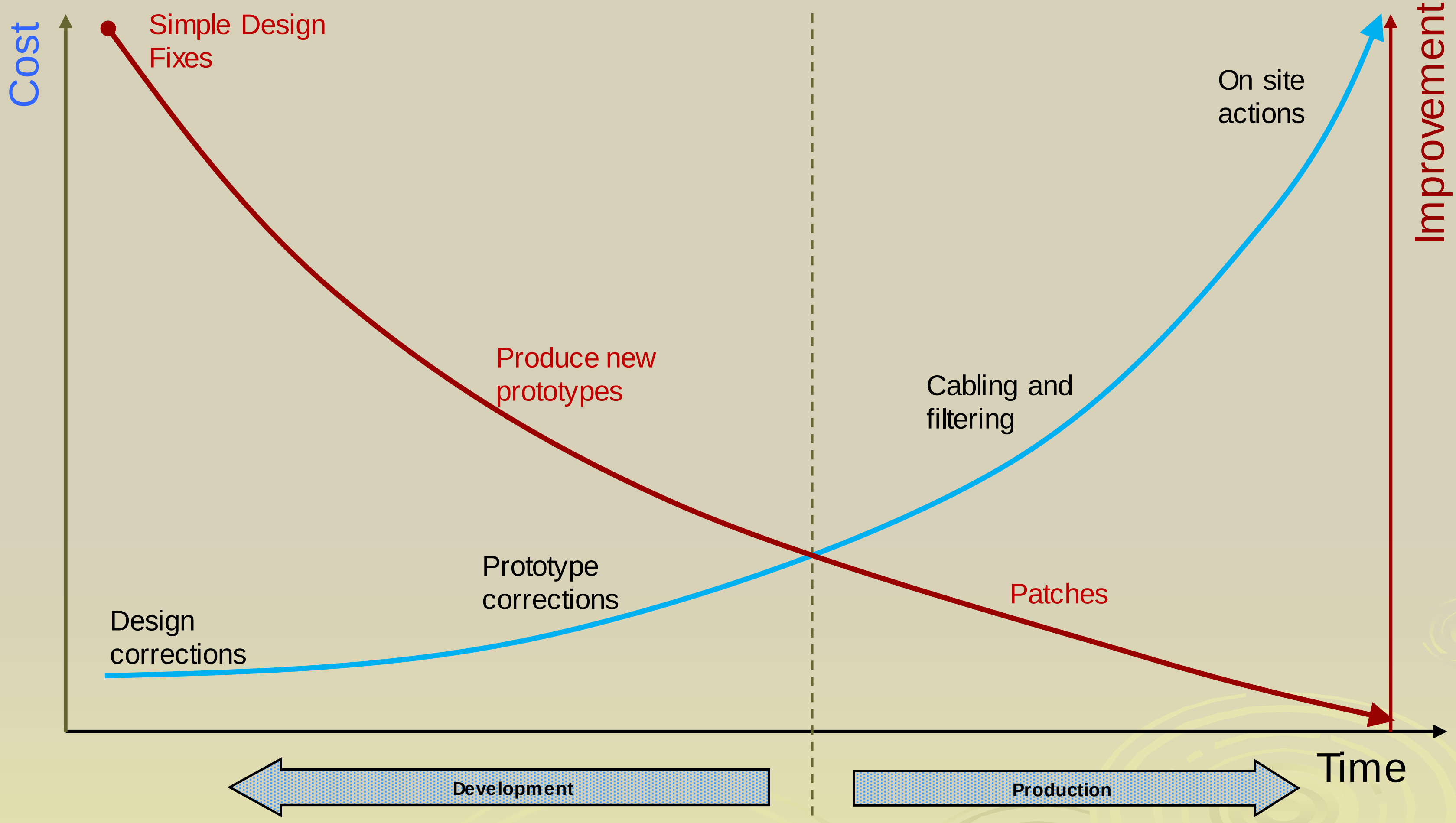
- The compatibility between systems is achieved:
  - Defining methods and tools to quantify the disturbances.
  - Defining limits that will ensure the good operation of all systems.

Interconnection of Systems



- Disturbances from AC mains
- Conducted noise: via cables
- Radiated noise: via E/M fields
- Couplings between cables
- Grounding cables

EMC in the Design Process



Some reference documents

Non exhaustive list:

1. Conducted emissions and radio disturbances:
   1. CISPR11: ISM
   2. CISPR22: ITE
2. AC Mains:
   1. Harmonic current: EN-61000-3-2, EN-61000-3-4.
   2. Immunity levels (industrial env.): EN-61000-6-2
   3. Emission levels (industrial env.): EN-61000-6-4
   4. Fast transient/burst immunity: EN-61000-4-4
   5. Surge immunity : EN-61000-4-5
   6. Voltage dips immunity: EN-61000-4-11
3. LHC-EM-ES-0001 rev 2 (EDMS 113154): Main Parameters of the LHC 230/400V distribution system.

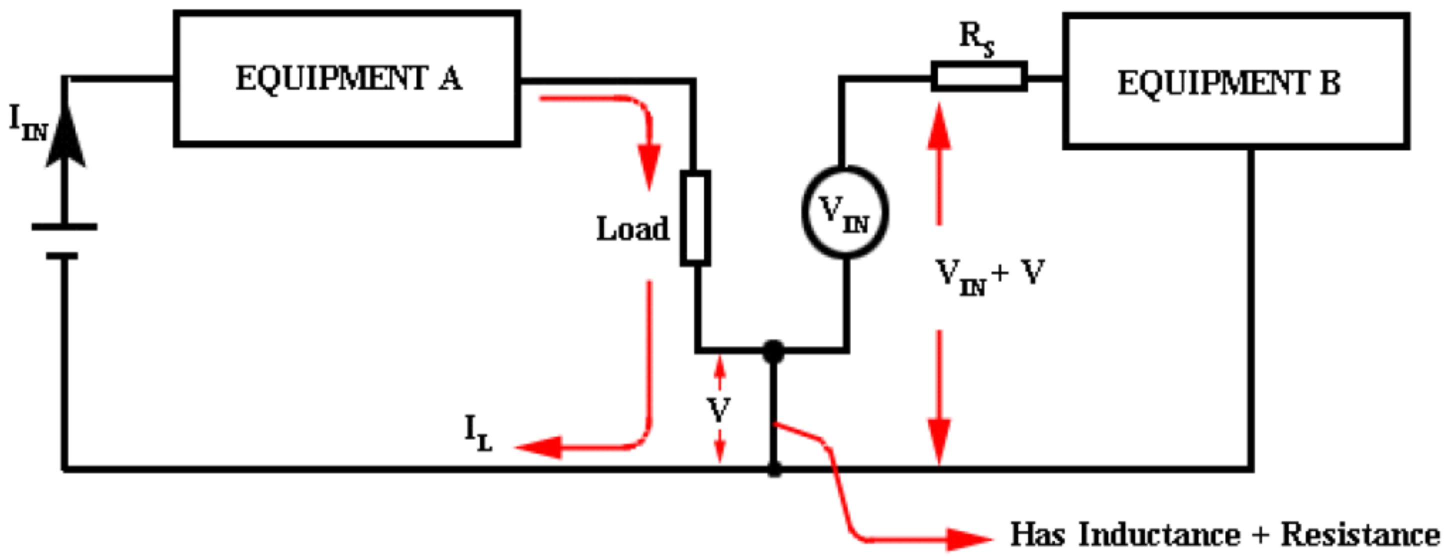
About the Grounding

What to expect from a ground wire?

- A ground wire is an inductor of typically 1uH/m that carries about 20 mA.
  - ZL = 6 Ω/m at 1 MHz.
    - It develops typically 125 mV/m at 1 MHz and 20 mA.
  - ZL = 125 Ω/m at 20 MHz with currents that <u>*should be*</u> below 1 mA.
    - It develops again 125 mV/m at 20 MHz and 1 mA.
    - 20 MHz is typically the peak of susceptibility of our front-ends.
- Given this:
  - Long ground cables are unable to sink high frequency noise currents without developing common mode voltages.
    - Grounding cables will often fail to reduce a front-end noise unless they are kept short (<< 10 cm).
  - Large structures, with interconnected conductors and frames, offer much lower impedances: they are better references for systems.

Development of CM through Grounding cable

Electrical coupling:



But grounding is still needed

- Electrical Safety:
  - To carry fault or short circuit currents without developing hazardous voltages within systems
- Protection against ESD:
  - Carry the ESD charge away from system (without developping hazardous voltages).
- To enable shielding feature of frames, boxes, etc.

EMC by Design

- If grounding is not useful to insure the requested performance, what is the way to follow?
- Good design practices!
  - Design taking into account all the disturbances present in real life.
  - Minimize disturbances sent to others.

Back-End EMC Requirements

The back end interfaces between the electrical AC network and the front-end systems.

Usually commercial off-the-shelve equipment: EU EMC regulations apply!

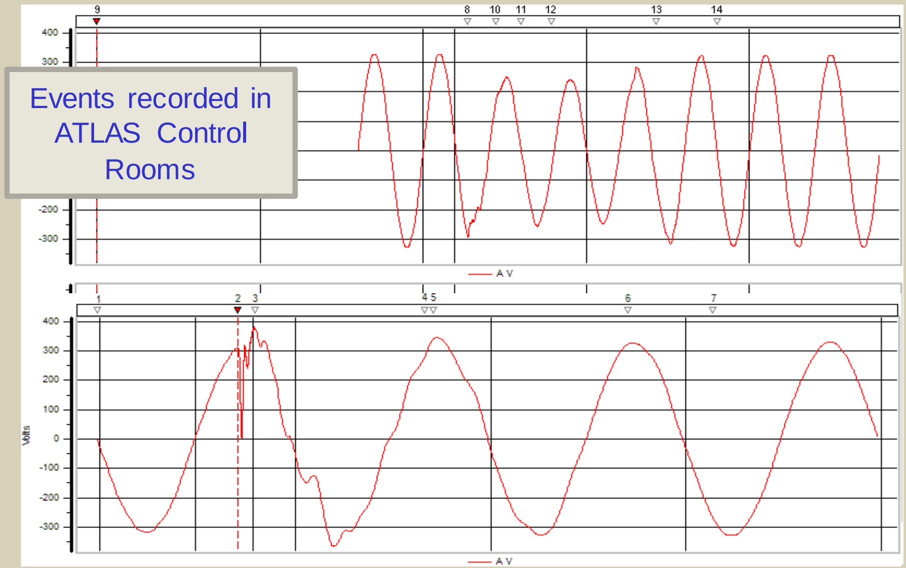
Power Supplies

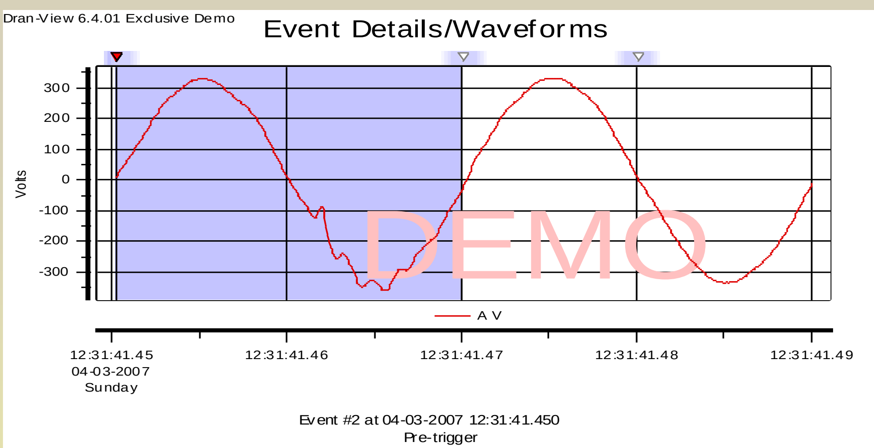
Computing equipment

Pumps, Motors, Switches

Interfaces

Tolerance to AC disturbances





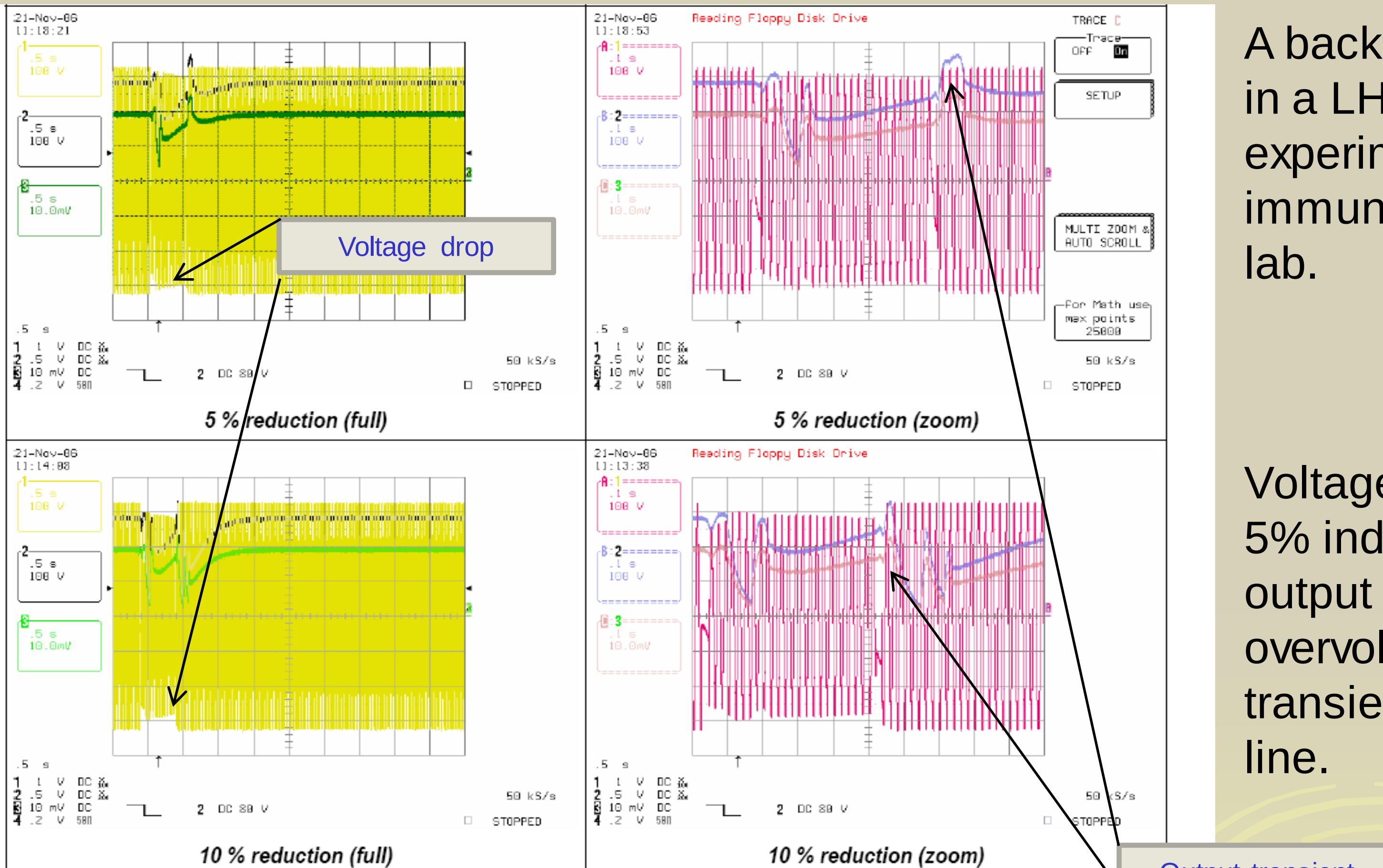
Microcuts, voltage dips, overvoltages, non sinusoidal waveforms: they occur many times per day, every day in all control rooms of all experiments.

The behaviour of any equipment is determined by *immunity tests* with specialized equipment, according to an international standard.

The pool is equipped with tools to characterize system immunity according to IEC standards.

Schaffner Modula Test System

Effect of AC disturbances



Channel 1 (yellow) : Input 400 VAC
Channel 2 ((black) : Output 280 VDC
Channel 3 (green) : Output current

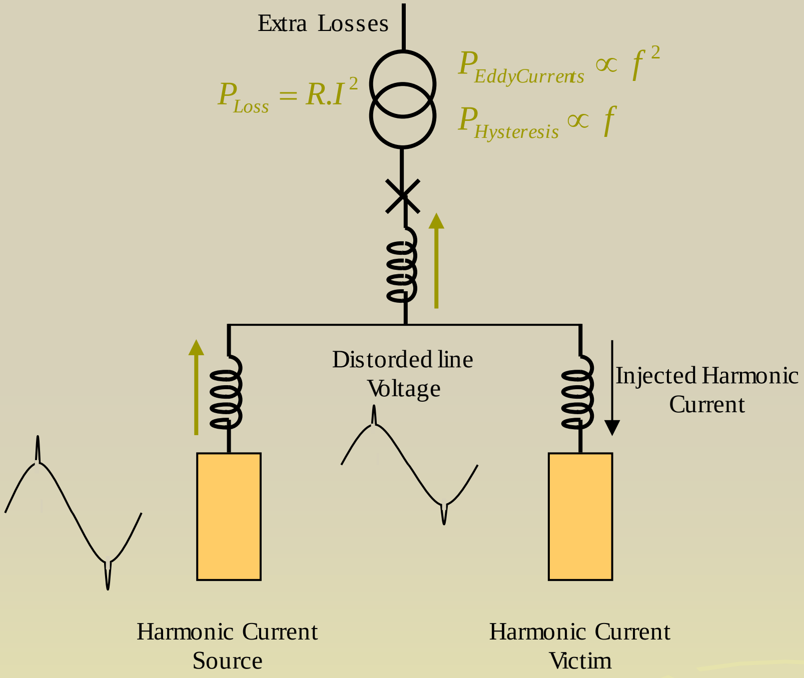
Channel 1 (red) : Input 400 VAC
Channel 2 (blue) : Output 280 VDC
Channel 3 (pink) : Output current

A back end LVPS in a LHC experiment: immunity test in lab.

Voltage drop of 5% induces output overvoltage and transients on DC line.

Emission of Harmonic Current

The harmonics in the load current drawn from the mains is a source of disturbance for the electrical distribution network and for other users



- Transformer Losses.
  - Heat up the transformers and reduce their lifetime.
  - To cope with harmonic current, transformers must be derated (=cost).
- Increased Neutral Current.
- Voltage Distortion.
  - Distortion due to voltage drops caused by harmonic currents.
  - AC mains received by other equipment is distorted and can cause malfunctions.
- Low frequency Interferences.
  - Harmonic current cause induction noise.
  - Noise below few kHz is hard to filter, need to use regulators.
- Degraded Power Factor

Harmonic Currents

Increased Neutral Current:

$$I_{N_{RMS}} = 3.\sqrt{\sum_{j=1}^{\infty} I_{j\times 3}^{2}}$$

In practice, the neutral RMS current can double at most the phase RMS current.

Limit set by the facility.

Total Harmonic Distortion:

$$THD_{\%} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100$$

Each harmonic current is a source of extra losses

Limit set by the facility.

Limits specified in EMC standards.

Degraded Power Factor:

$$F_{Tot} = \frac{P}{V_{1_{RMS}}.I_{1_{RMS}}.\sqrt{1+\left(\frac{THD_{\%}}{100}\right)^2}}.$$

Remedies are either passive filters for simple cases, or active power factor correction (APFC) for complex harmonic current sources such as power converters.

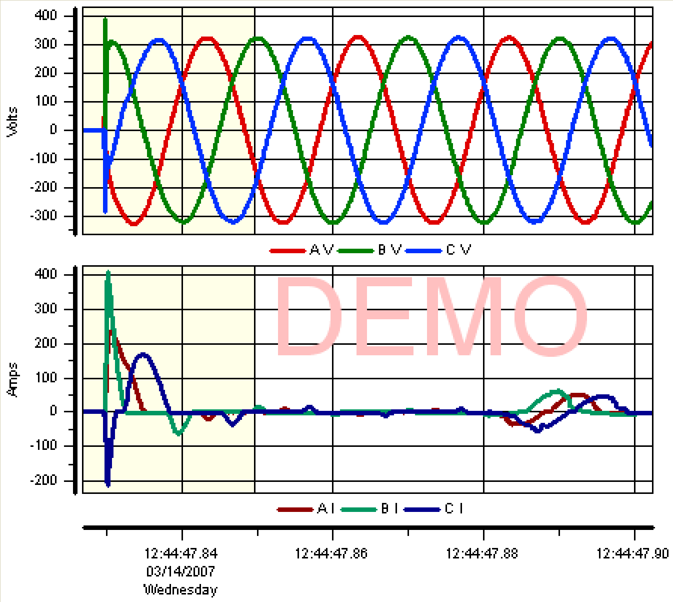
User gets charged for bad power factor.

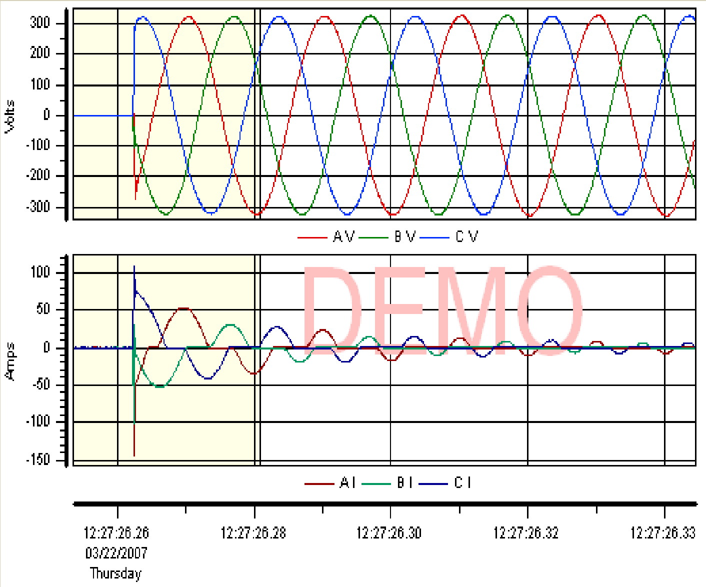
No explicit limit.

Limits on each harmonic content is defined in IEC-61000-3-2, it is achievable using PFC circuits or filters. Line diode bridge rectifiers cannot be used without PFC.

Inrush Currents

DAQ Rack in ATLAS





Inrush currents in rack equipment can pose difficulties to the electrical network (tripping computing farms): PFC and passive dampers help to smooth down the startup.
Inrush, harmonics, voltage distortions can all be measured with Power Xplorer available at the Pool.

Noise emission/immunity

- Noise emission
  - Limits on conducted noise (common mode) on all IO and power ports.
  - Limits on radiated noise (EM fields): cannot be tested at CERN (only qualitative near field).
- Immunity
  - Incoming noise degrades the performance:
    - This can be tested and quantified at CERN.
- *All these are common with front-end requirements and will be described on next slides.*

Front-End EMC Requirements

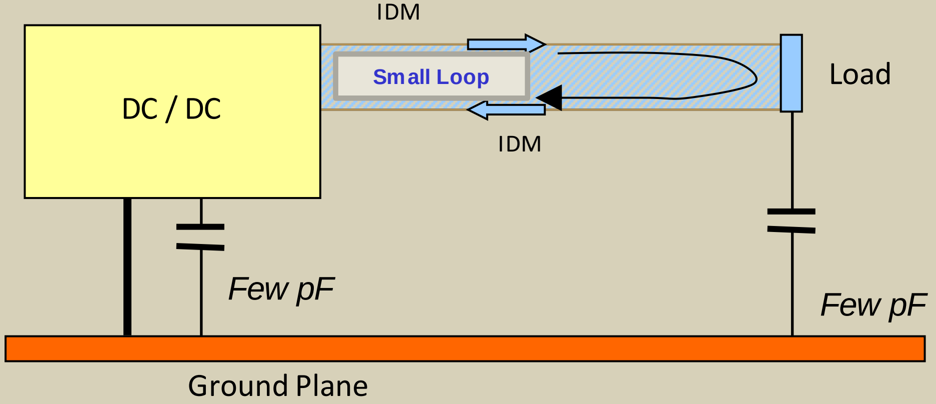
Front-end = Sensing Device

Always custom made circuits, EMC performance will depend of the designer experience and of its awareness of the EMC problems

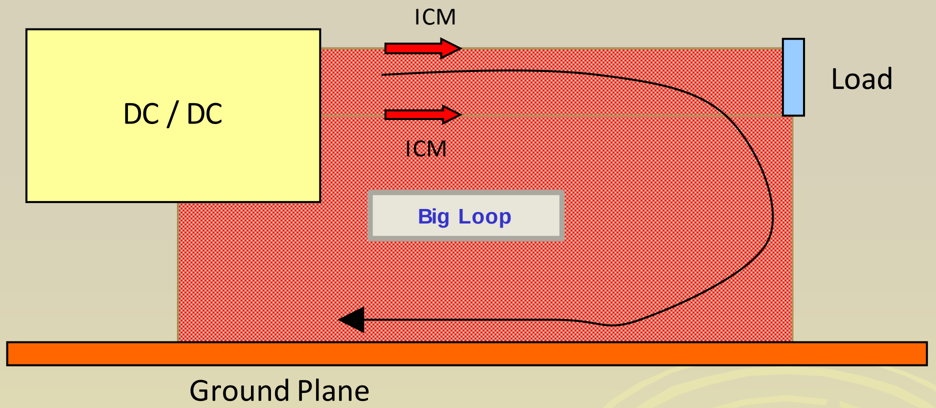
- Sensitive to conducted noise from its back end
  - Noise current that enters through ports and cables.
  - Is translated in larger RMS in data.
  - Setup dependent.
- Sensitive to couplings from neighbors (systems and cables)
  - Near field: electric, magnetic.
- Source of conducted and radiated noise as well
  - Can compromise neighboring systems.

Common and Differential Modes

Differential Mode:
The functional current carried by a wire and its intentional return: *the electromagnetic field is mostly contained within the cable*



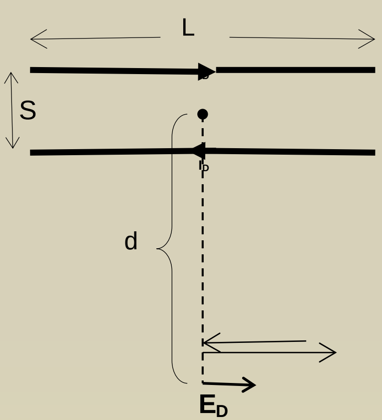
Common Mode:
A non functional current carried by a set of wires and some surrounding conductive structures or elements: *the electromagnetic field is mostly contained between the cable and the conductive structures*



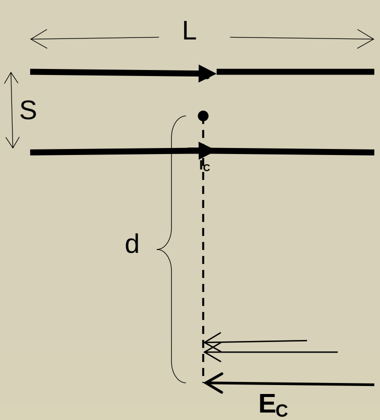
EMI Sources

- Radiated Noise from system is small because at f=40MHz λ=7.5m that is easily shielded by the system faraday cages and enclosures.

- Radiated Noise from cables comes mainly from CM noise (far field* from electrically short cables).



Differential Mode: the far fields are opposed and cancel each other



Common Mode: the far fields add up.

<u>The contribution of CM current to EMI is typically more than 3 orders of magnitude stronger than the contribution of the same DM current.</u>

<u>Need to control the sources of CM noise:</u>

- Switched power circuits and converters.
- Digital circuitry.
- CM coupling across cables.

* Far field region starts at a distance d = λ/6, i.e. 1 m at 40 MHz.

LVPS Conducted Noise

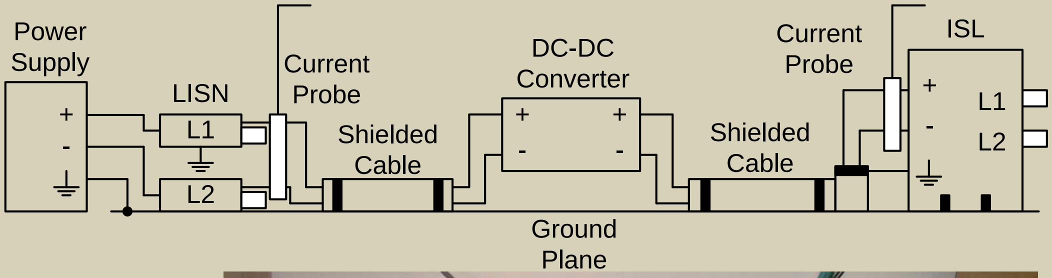
A dominant source for FE noise is the power supply. It can be characterized on a reference setup that is independent of the front-end and of the primary source.

Ground plane

- Reference return path for CM currents

- Cables lay on the plane.

- Source, load and filters earthed to the plane.



LISN: Line Impedance Stabilization Network

- Calibrated, standardized filter.

- Filters noise from bulk LVPS.

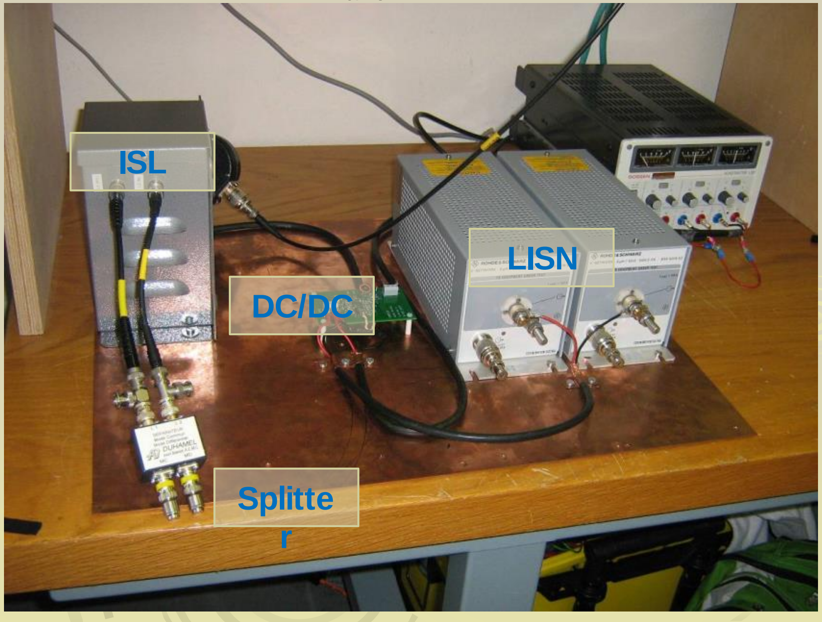
- Provides reference impedance seen by the converter towards its source of power, over the whole frequency range of interest.

ISL: Impedance Stabilized Load

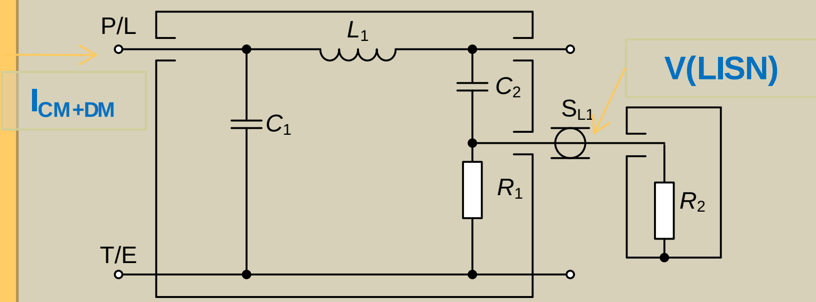
- Calibrated load:

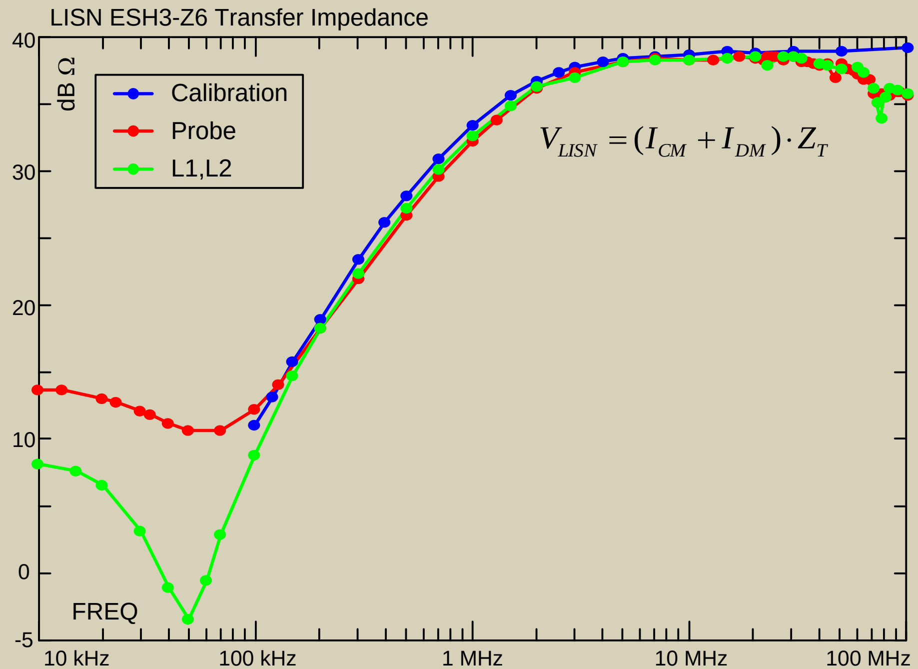
    - DM (load).

    - CM (output to earth plane).



Line Impedance Stabilization Network (LISN)





<u>LISN</u>

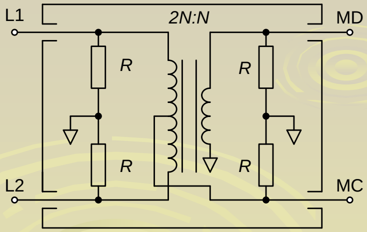
- Provides a standardized voltage measurement of the symmetric and asymmetric noise between line and earth (ICM + IDM).

- The impedance is calibrated from 100 kHz to 100 MHz.

- Above 1 MHz: Z=50 ohms.

- To measure accurately the CM current only, a calibrated current probe is used. Alternatively, a CM/DM splitter can be used (less accurate).

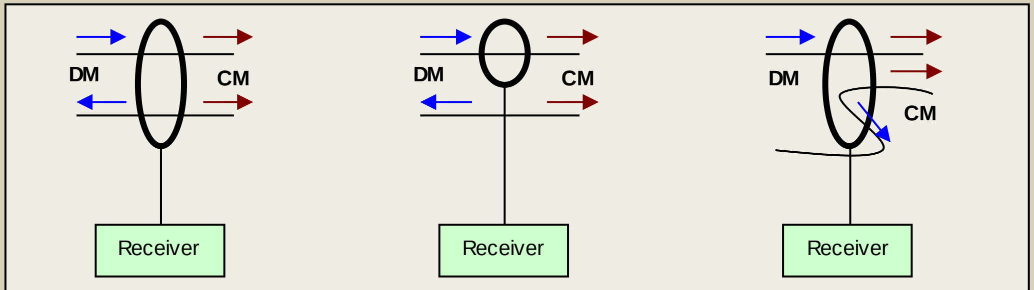
Current probe



CM/DM splitter

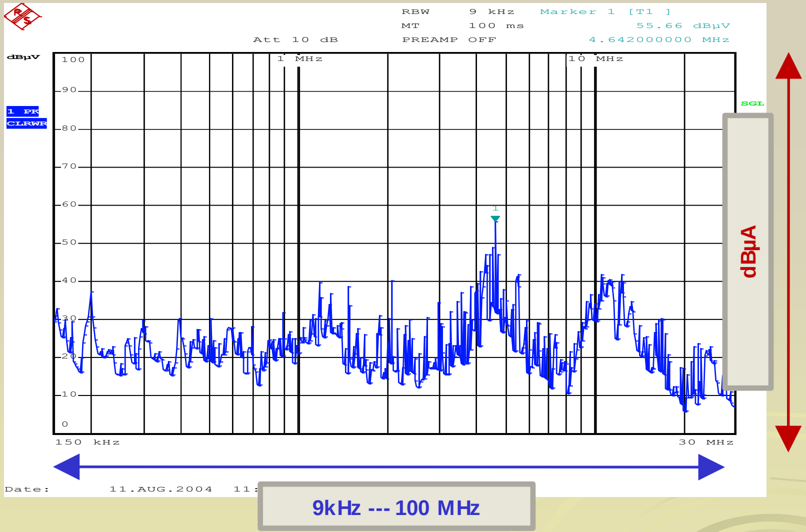
Instruments and Tools for conducted EMI measurements

Conducted EMI.



$I = 2 \cdot I_{CM}$ (a) $I = I_{DM} + I_{CM}$ (b) $I = 2 \cdot I_{DM}$ (c)

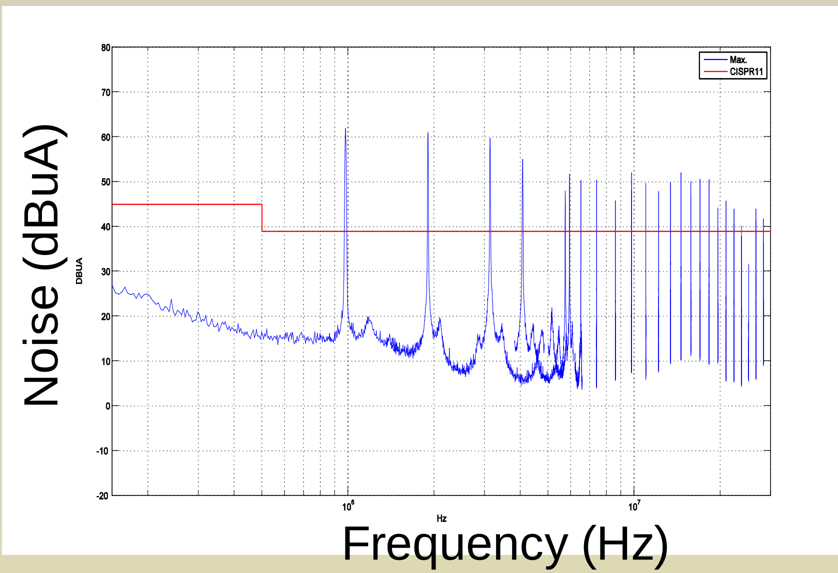
Current Probes and Injectors

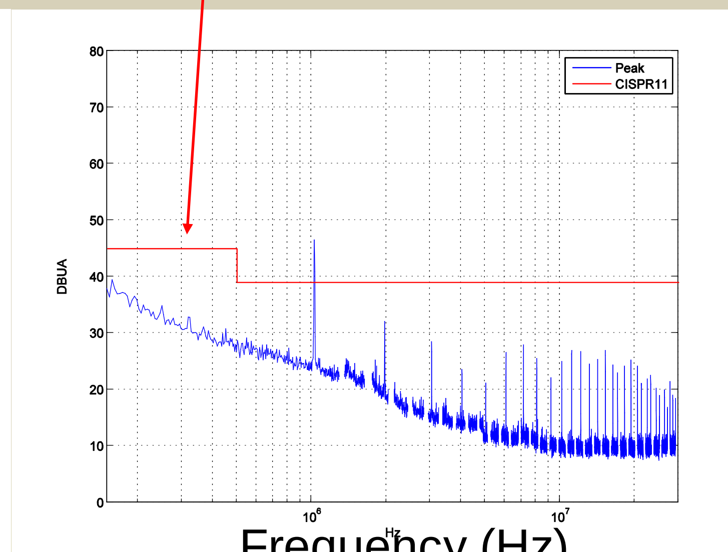


EMI Receiver (9kHz to 3GHz)

CM Noise Measurements

“Reference” level based on Class A limit from CISPR11 converted to current on a given impedance (Careful: this is NOT a real limit)





Example: output common mode noise for 2 custom prototypes using identical discrete components (commercial driver + switches). Only the design of the PCB and the passive components differ

Importance to limit the noise currents in experiments

- CM currents (on all cables) must be contained under a limit that is reasonably set under 100uA in the sensitivity band of our front-ends.
- CM currents above few mA will definitively collapse front-ends.
- Patches are always difficult to put in place.
- The sensitivity of FE is determined with susceptibility tests.

Typical Limits

Conducted emissions limits in LHC experiments

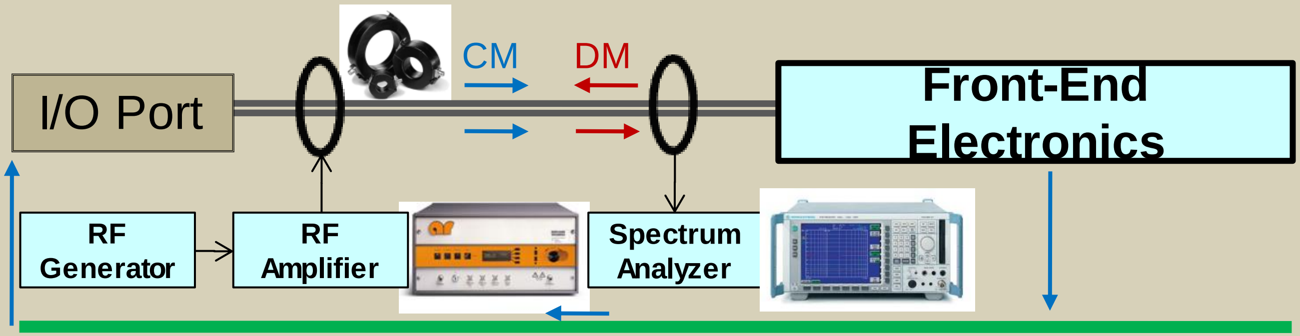
- ***Extension of CISPR11 Class A Group 1:***
  - *to all power links in experiment zones*
  - *to high voltage and data links*
- ***Conversion of limits in terms of dBµA that can be easily measured on site:***

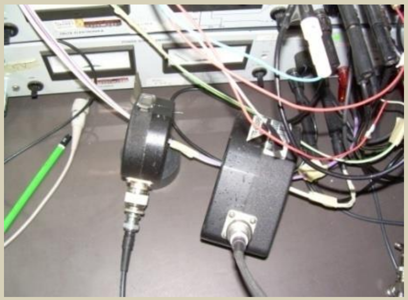
Frequency Band [MHz]	Class A Group 1			
	dBµV into 50Ω/50µH		dBµA	
	QPK	AVG	QPK	AVG
0,15 – 0,50	79	66	45	32
0,50 - 5	73	60	39	26
5 - 30	73	60	39	26
30 -100	-	-	39	26

= 89 uA

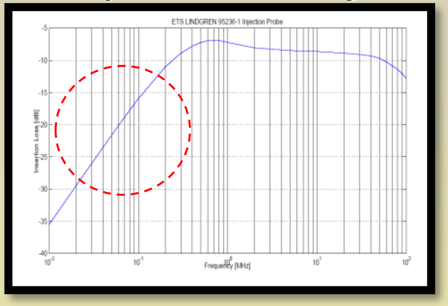
- ***Extension of frequency:***
  - *up to 100 MHz to cover the LHC clock and its first harmonic.*

Measuring Susceptibility





- The injected signal is provided by a RF generator that delivers a low distortion single frequency (swept).
- CM or DM currents are injected inductively on the tested port using an injection current probe.
- The injected current must be monitored with a calibrated probe and an accurate spectrum analyzer.

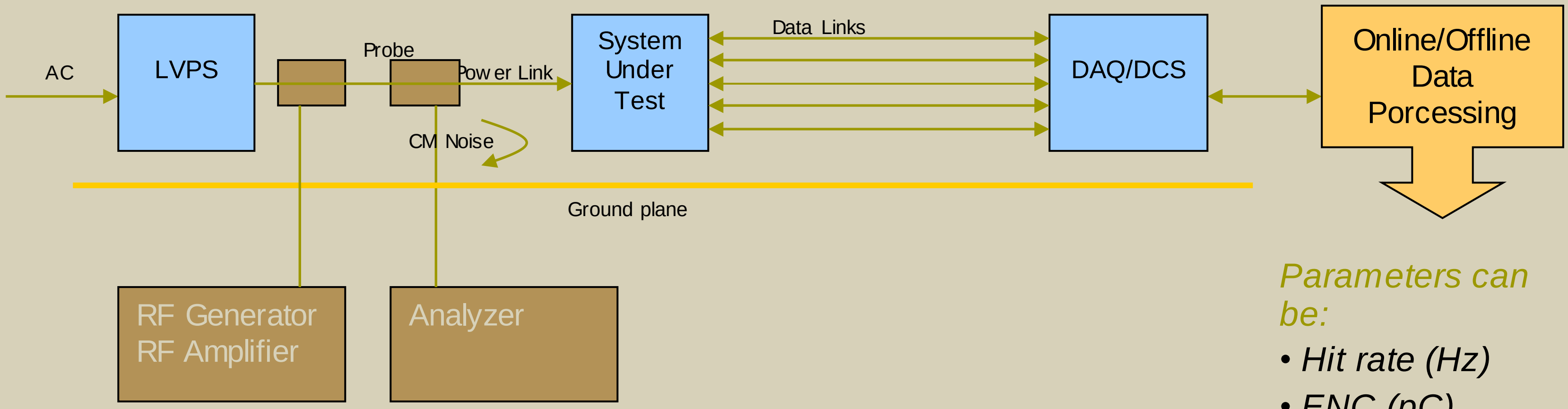


The injection of current is not very effective at low frequencies: amplifiers are often required.

The injected currents usually vary from few uA to few mA.

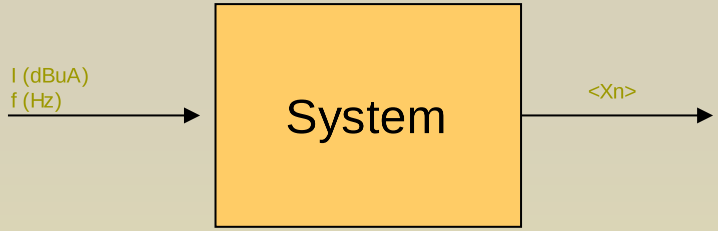
The frequency of interest ranges from 100 kHz up to 100 MHz: beyond this, radiated couplings take place.

Measuring Susceptibility



EMI Couplings will degrade the noise performance of the system:

The relationship between EMI coupling and resukting noise is determined with immunity tests.

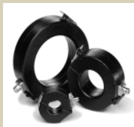


Parameters can be:

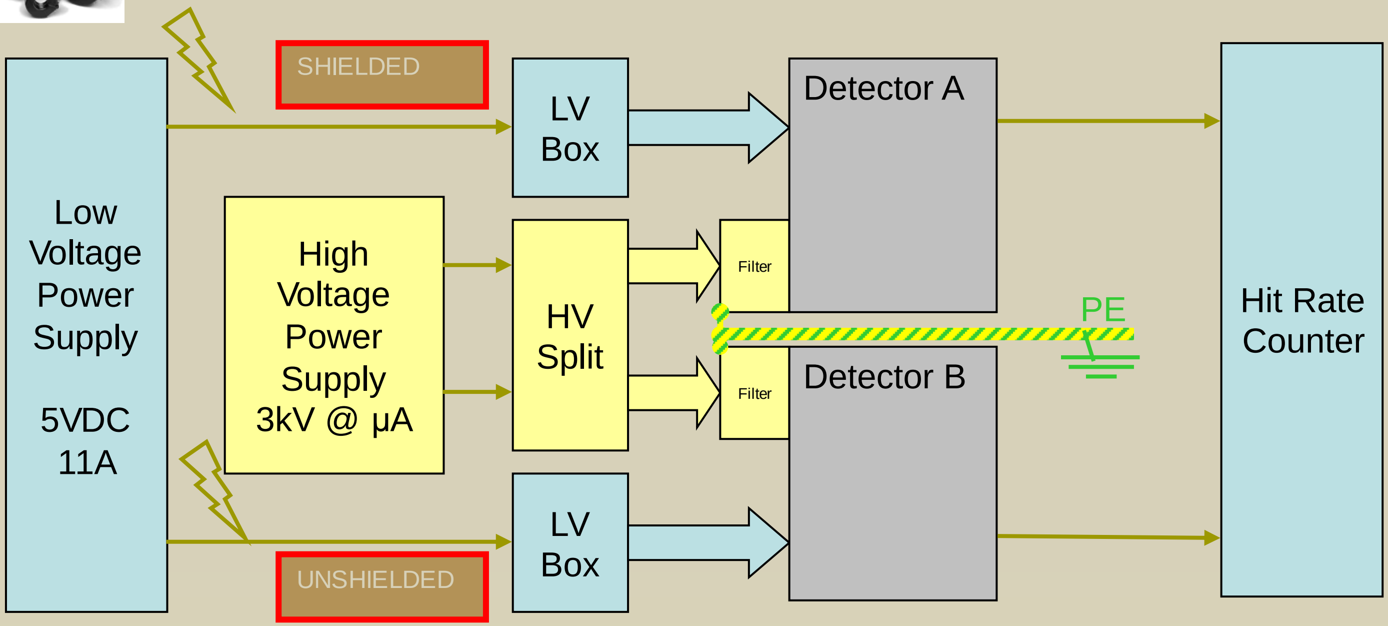
- *Hit rate (Hz)*
- *ENC (pC)*
- *Vrms, Irms*
- *Any combination of those, chi2, linearity coefficients, etc…*

The system must define the parameter that sets the quality of its data.

Susceptibility example



ATLAS MDT Prototype (2004)



Two identical detector systems:

Detector A is powered through a 15 meter shielded cable.

Detector B is powered through 15 meter unshielded cable.

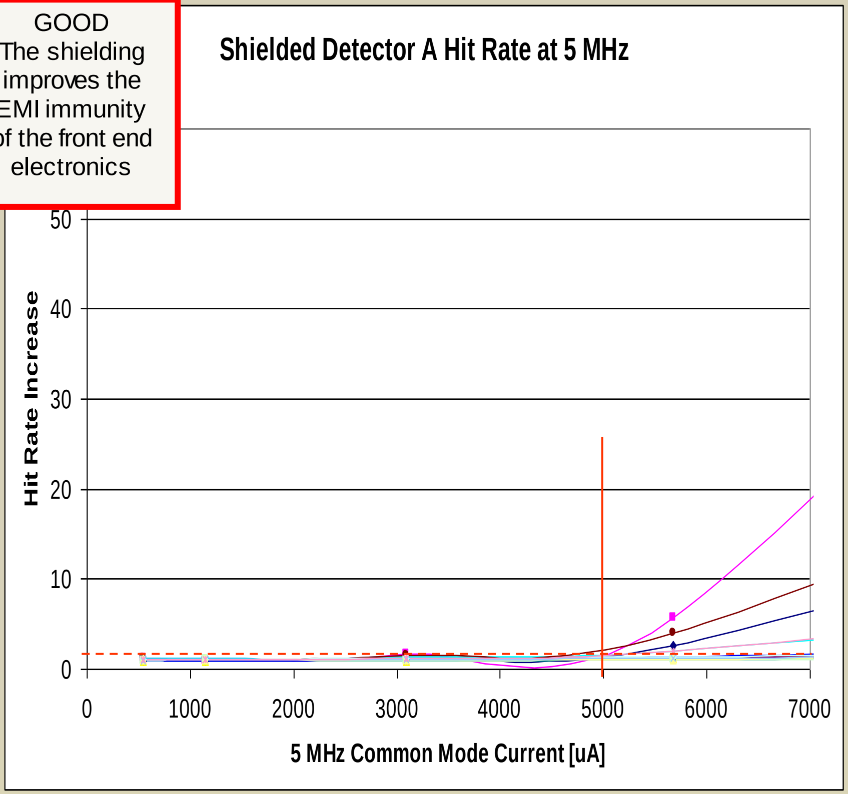
The power supply is common.

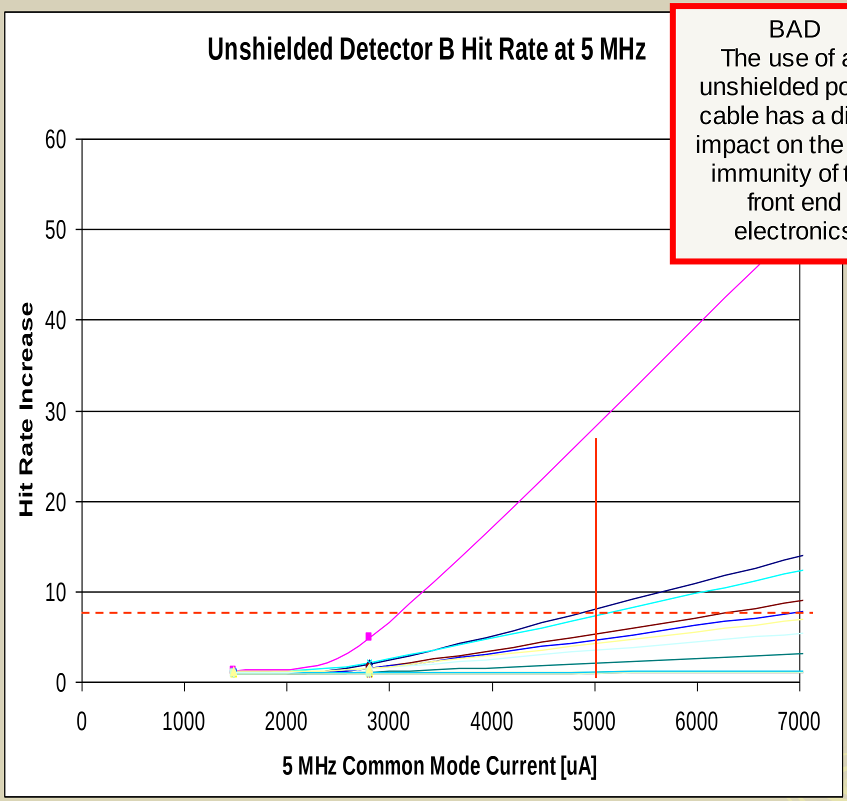
The DAQ is common.

The noise evaluation parameter is set as hit rate recorded by counters.

Susceptibility Curve

GOOD
The shielding improves the EMI immunity of the front end electronics





BAD
The use of an unshielded power cable has a direct impact on the EMI immunity of the front end electronics

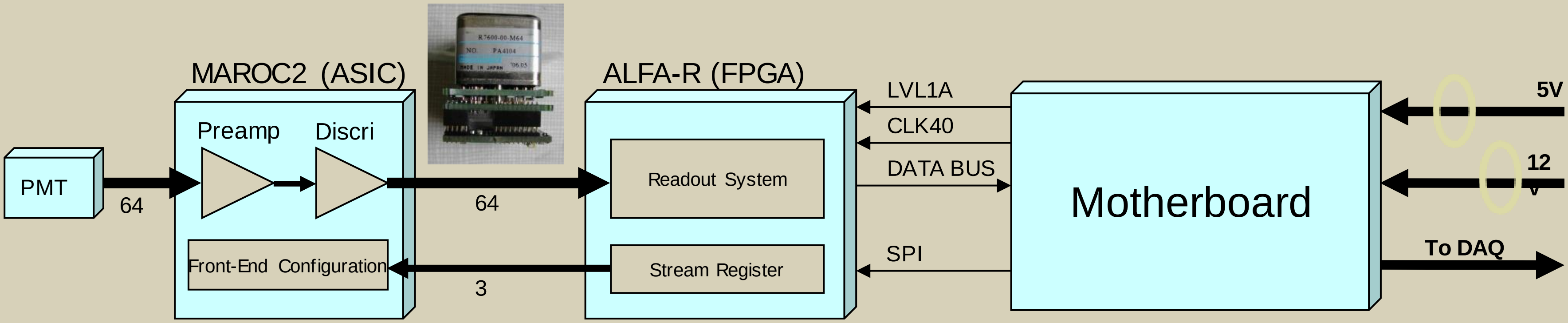
Threshold: 5mA doubles the hit rate.

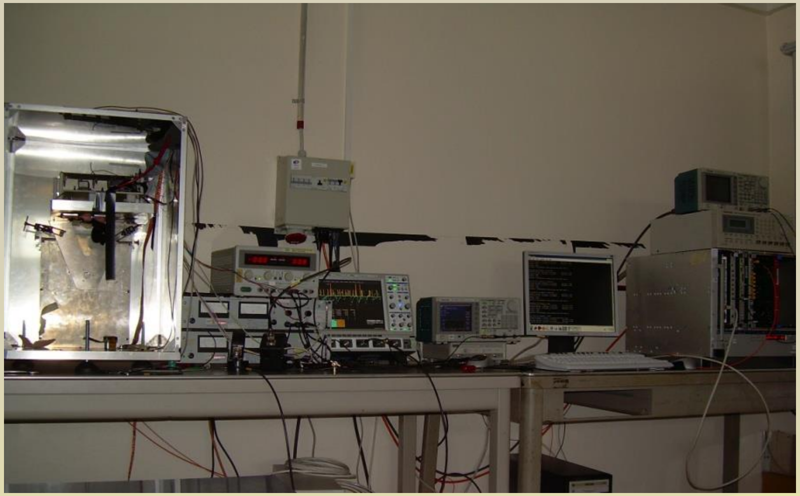
Threshold: 2mA doubles the hit rate.

One channel is particularly sensitive to CM.

Few mA are sufficient to screw up the best low noise front end electronics by more than one order of magnitude; it is also very easy to pick up few mA of noise.

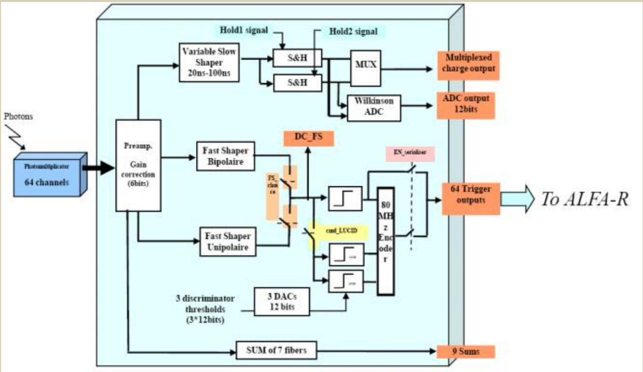
Another example: ATLAS ALFA





- Common mode currents are injected in the 12V input port first, after in the 5V port, with magnitudes up to 10 mA in the ferquency range between 150 kHz and 30 MHz.
- The 12V powers exclusively the motherboard, which is fully digital. It was found to be insensitive to the injected current.
- The 5V powers the front-end chips (MAROC, FPGA), with analog circuitry. It was found to be sensitive to the injected current.

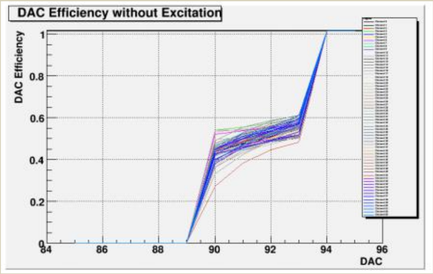
ALFA Conducted Susceptibility



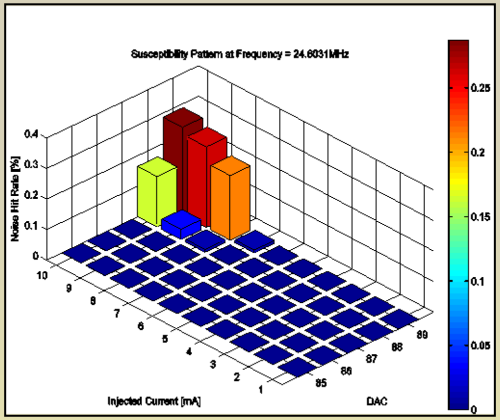
Refer to: "MAROC: Multi Anode Readout Chip", S. Blin, TWEPP 2007.

The front-end chip is configured at nominal gains and the susceptibility is measured for different thresholds (DAC) in the transition region of the S curves.

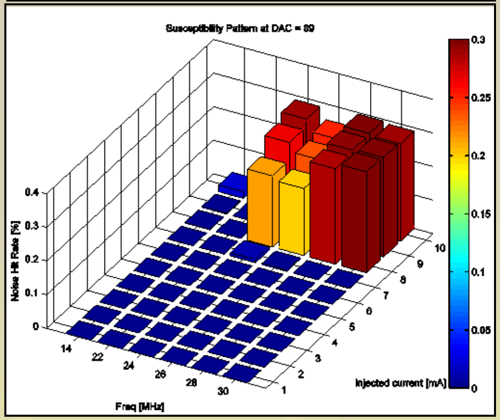
The sensitive DAC range at nominal gain is found to be between 88 and 94.

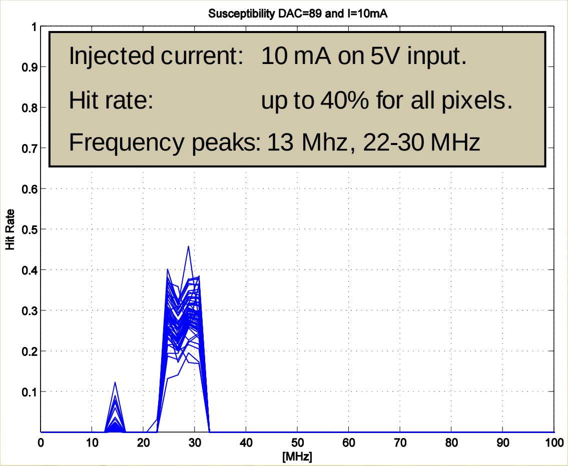


The noise hit rate is a function of current, frequency and DAC



At a given threshold, the maximum noise current permitted is established for every critical frequency





Injected current: 10 mA on 5V input.

Hit rate: up to 40% for all pixels.

Frequency peaks: 13 Mhz, 22-30 MHz

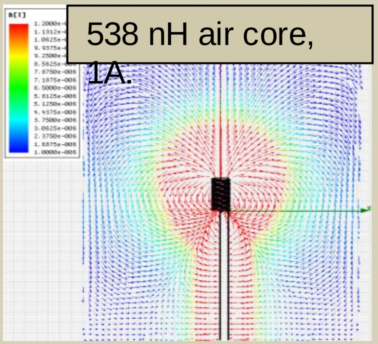
Susceptibility to radiated fields

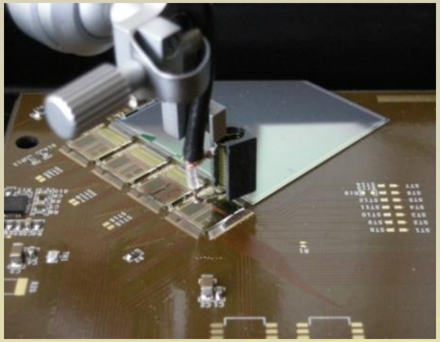
- Qualitative tests to evaluate susceptibility to E field (capacitive coupling) and H field (inductive coupling) are easy to perform.

- Accurate and quantitative measurements are much more difficult and require more specialized infrastructure.

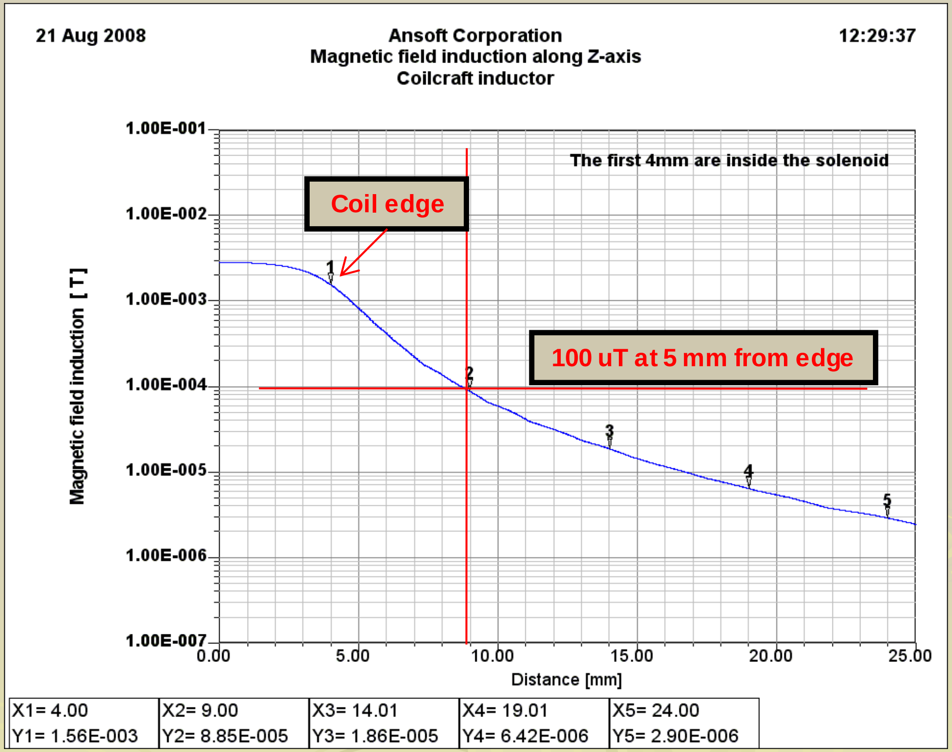
Example: TOTEM near field susceptibility

The susceptibility of systems to the magnetic field emitted by inductors of power converters is a major concern. System tests were carried out on TOTEM, with a coil driven by an amplified RF source. The coil is accurately positioned above the detector, the bondings and the ASICs and the induced noise is analyzed from the test DAQ.

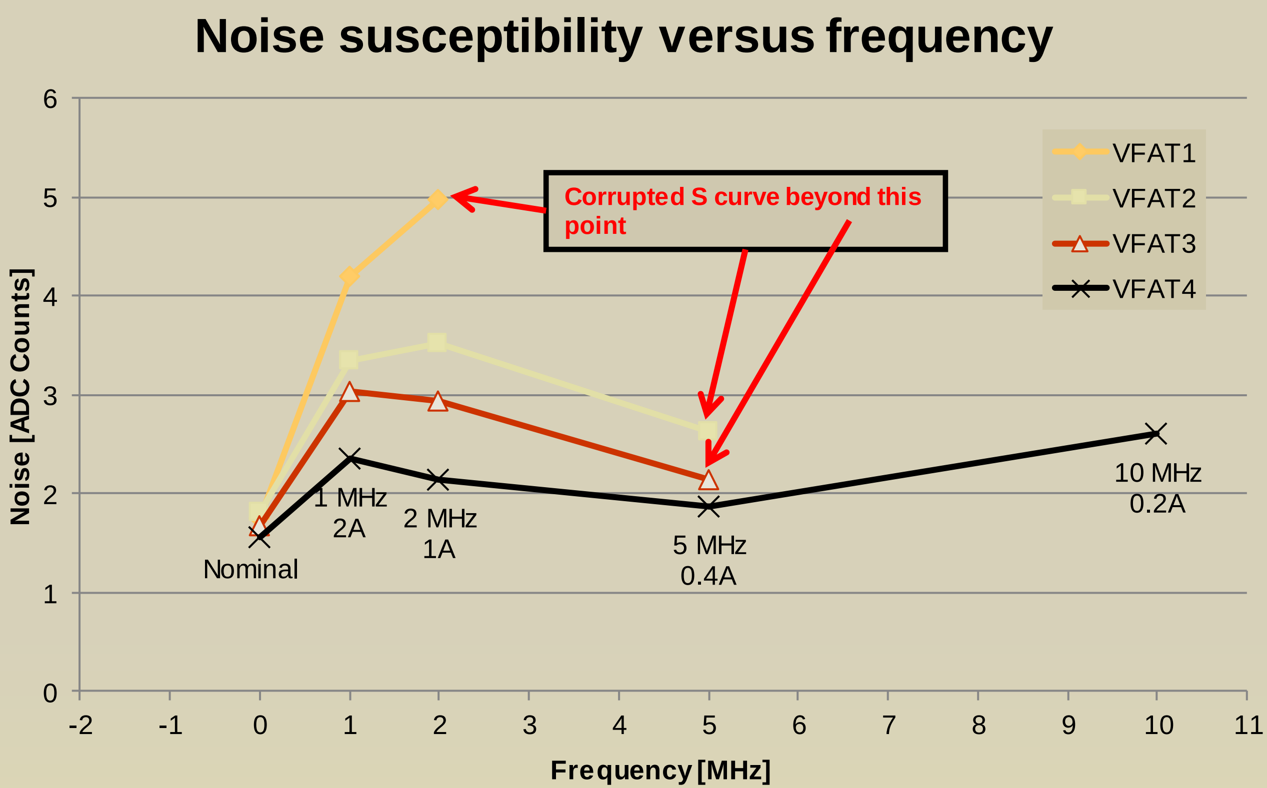




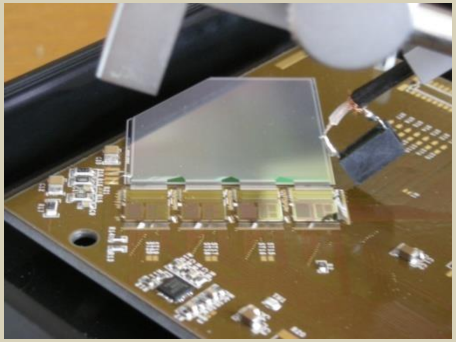
Distance to center (mm)	Field (uT)
4	1560
9	88
14	19
19	6.4
24	2.9



H Field Susceptibility Example



Inductor focused obliquely on the bonding

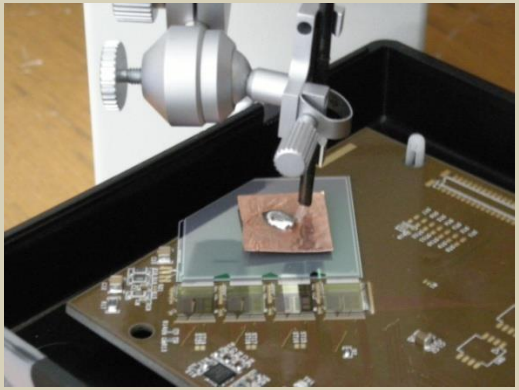


The TOTEM system showed noise sensitivity increasing with the frequency:

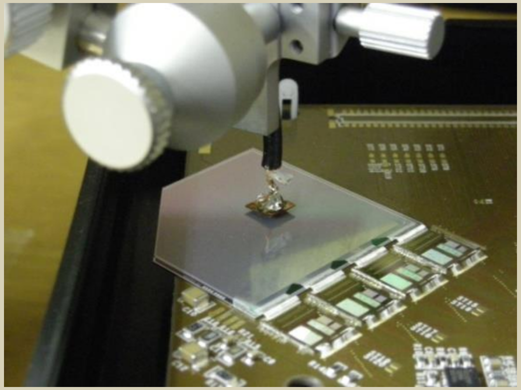
- System not able anymore to extract correct S curves parameters.
- The test was made at constant dB/dt: (I*f = constant).

E Field Susceptibility Example

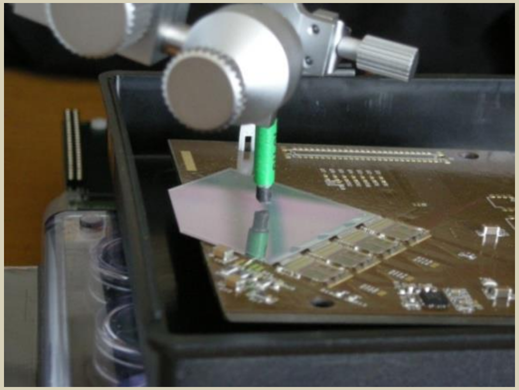
Large plate cap. coupling



Small plate cap. coupling.



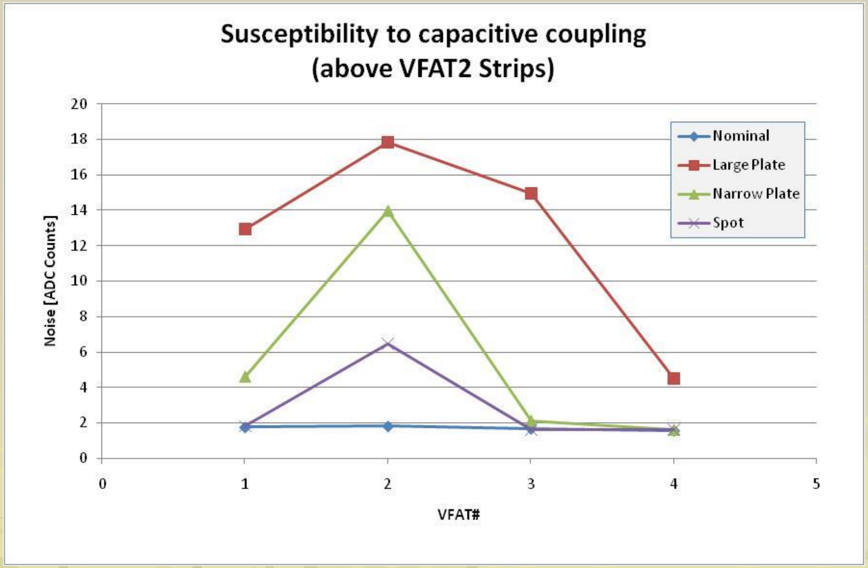
Spot cap. Coupling (wire end).



<u>The system showed also sensitivity to capacitive coupling (electric field):</u>

• 3.4V/1MHz: signal equivalent to the one present on the inductor wires.

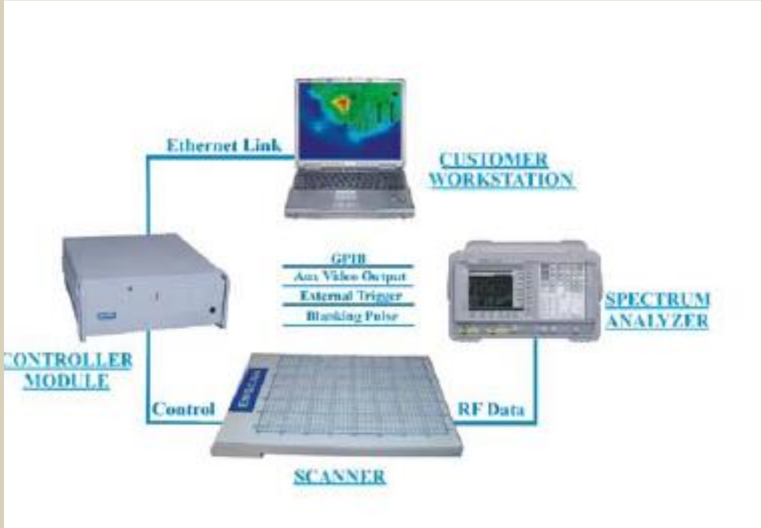
• Exposed areas develop large noise.

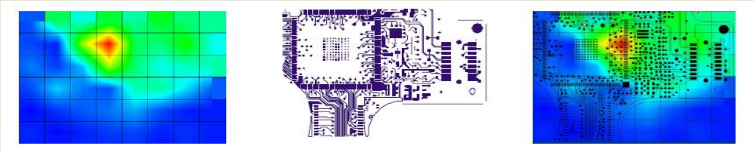


Want better tools?

ETS-Lindgren Near Field Probing Kit

Provides calibrated measurement of emitted fields, but can be used as EMI sources as well!





Nexus B field Scan

Locate EMI spots, evaluate shields

Agilent Near Field Probing Kit

Have a different sensitive geometry, to be used for calibrated measurements

Dealing with EMI Couplings

How to mitigate the coupling effects?

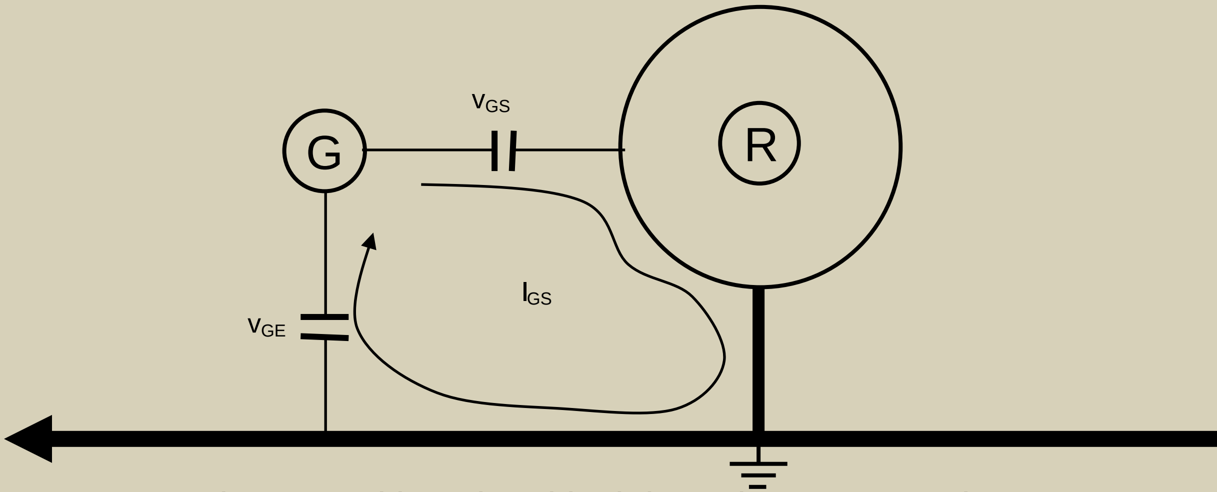
- A front-end can be designed with some degree of immunity against conducted or radiated noise.
- It can be connected to a compatible power supply (emits CM currents lower than the acceptable limit of the front-end system).

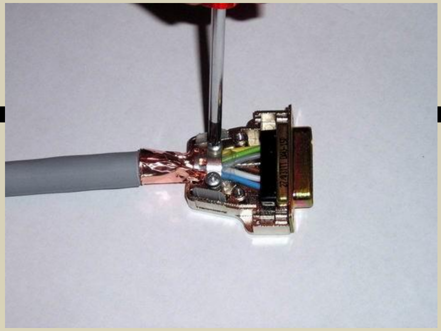
- Still, unexpected couplings often come from unknown neighbors, in particular within the cable trays.
  - The only protection is to SHIELD.

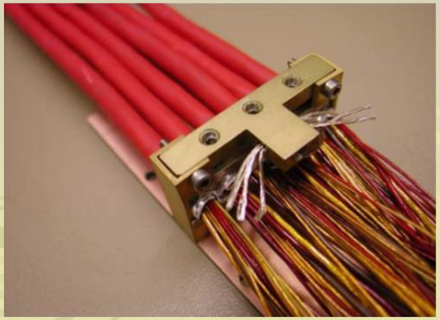
A wonderful world!

Shielding against E Field

Equivalent circuit: Shielding against external E field







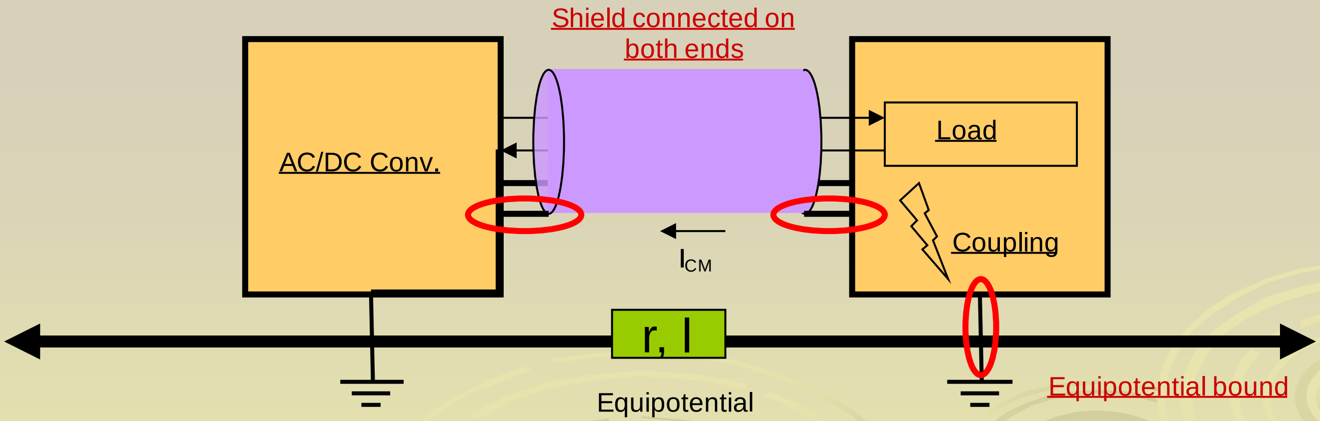
- A current is coupled into the shield through stray capacitances
  - Capacitance to shield
  - Capacitance to ground

- Performant shield is only achieved if current can flow easily
  - E field shielding is achieved by grounding one side only.
  - Connectors must be metallic, all around bonded to the shield, without straps, capacitors or resistors.
  - Enclosure must be well bonded to the equipotential network.

About grounding both ends

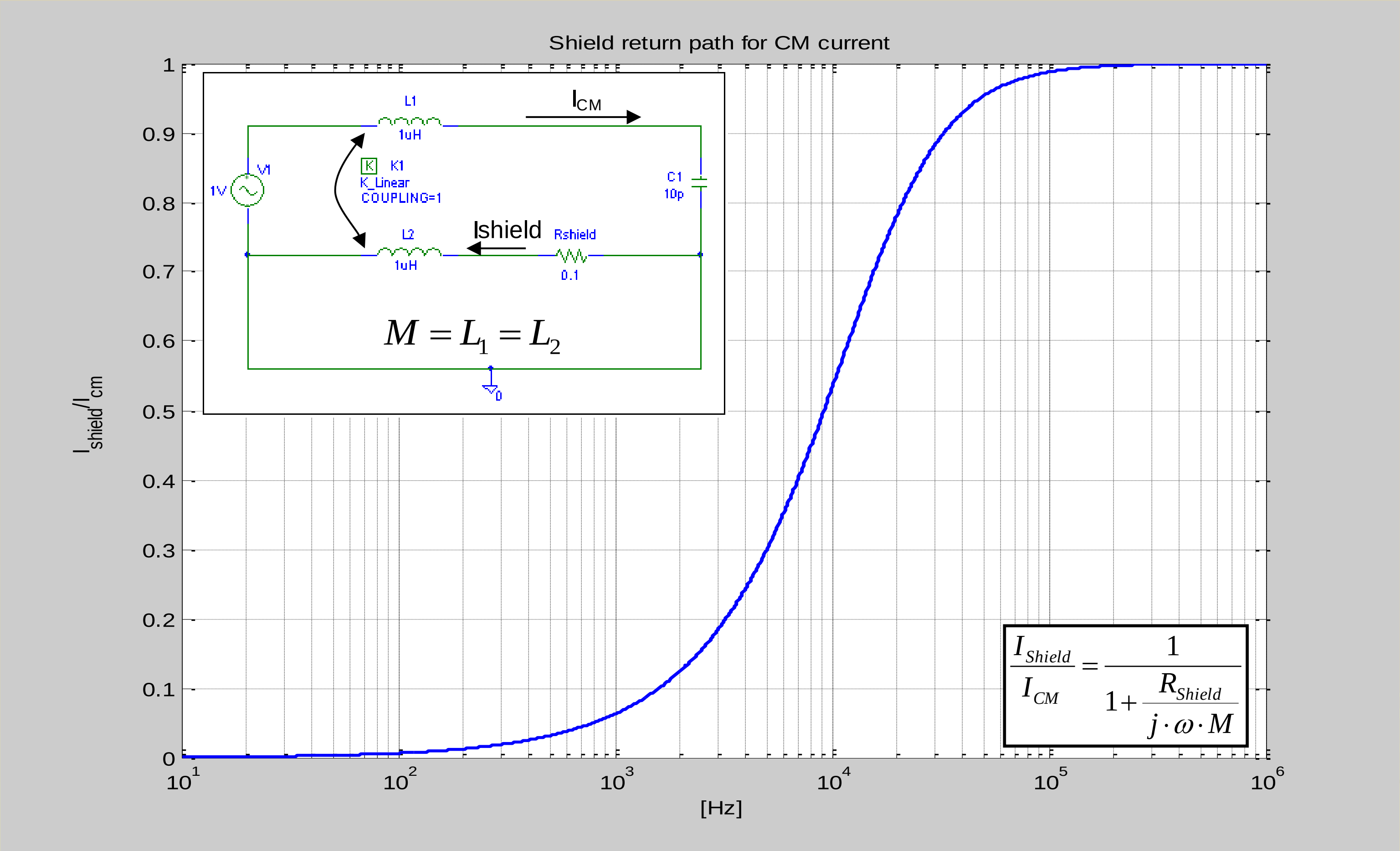
Grounding of the shield: <u>on both ends</u>

- Reduced common mode loop.
  - The CM current is forced to return in the shield (mutual inductance)
  - CM emissions are reduced *radically*.
- Reduced electric field
  - Contained within the shield
- Magnetic field shielding
  - The inductively coupled current is cancelled in the live conductor by mutual inductance.
- **Electric field shielding is improved**
  - Two paths instead of one!



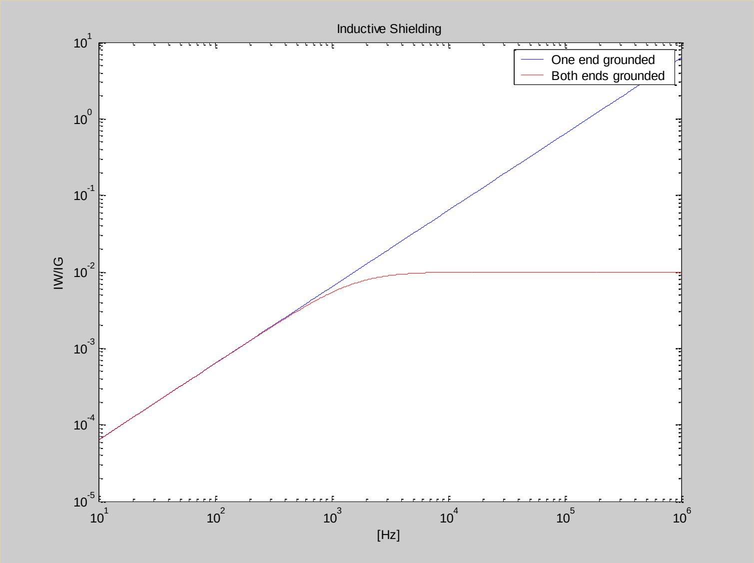
Shield is return path for CM Current

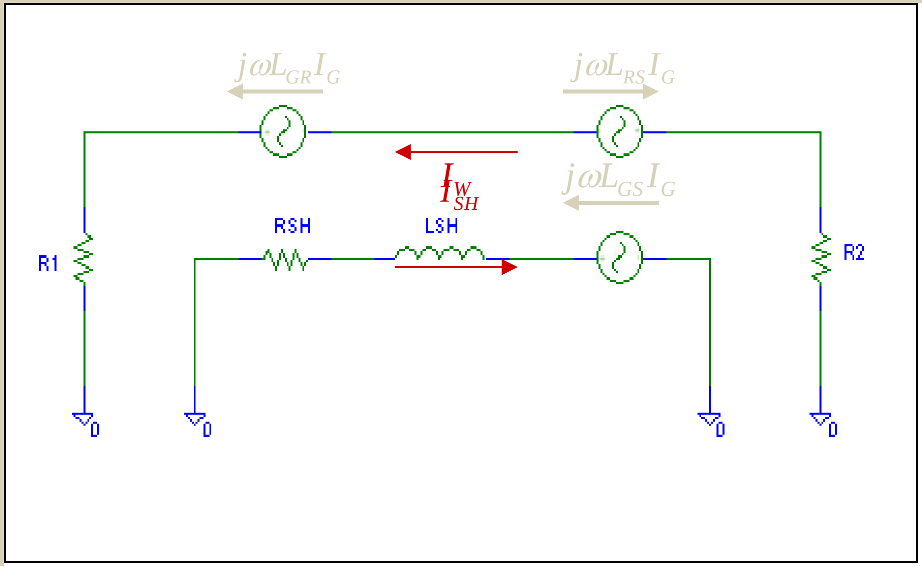
Equivalent circuit: mutual inductance forces CM current to return into the shield



Shielding for B field

Equivalent circuit: shielding against external B field.





$$\frac{I_W}{I_G} = j\omega L_{GR} \frac{R_{SH}}{R_{SH} + j\omega L_{SH}}$$

$$SF = \begin{cases} 1 & \text{for} \quad \omega < \dfrac{R_{SH}}{L_{SH}} \\ \dfrac{R_{SH}}{j\omega L_{SH}} & \text{for} \quad \omega > \dfrac{R_{SH}}{L_{SH}} \end{cases}$$

Shielding Effectiveness

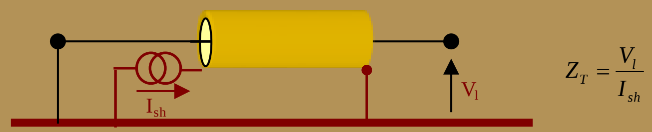


Figure : Transfer impedance of a shielded cable.

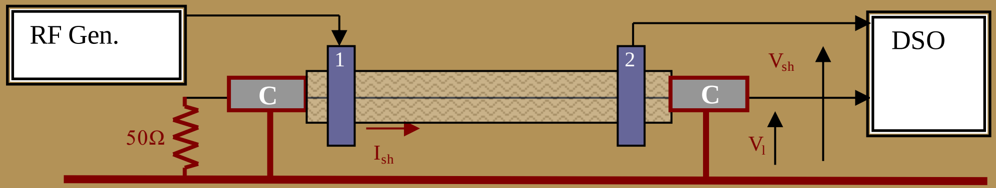


Figure : Current probe test setup: grounded connectors (C), injection probe (1), current probe (2).

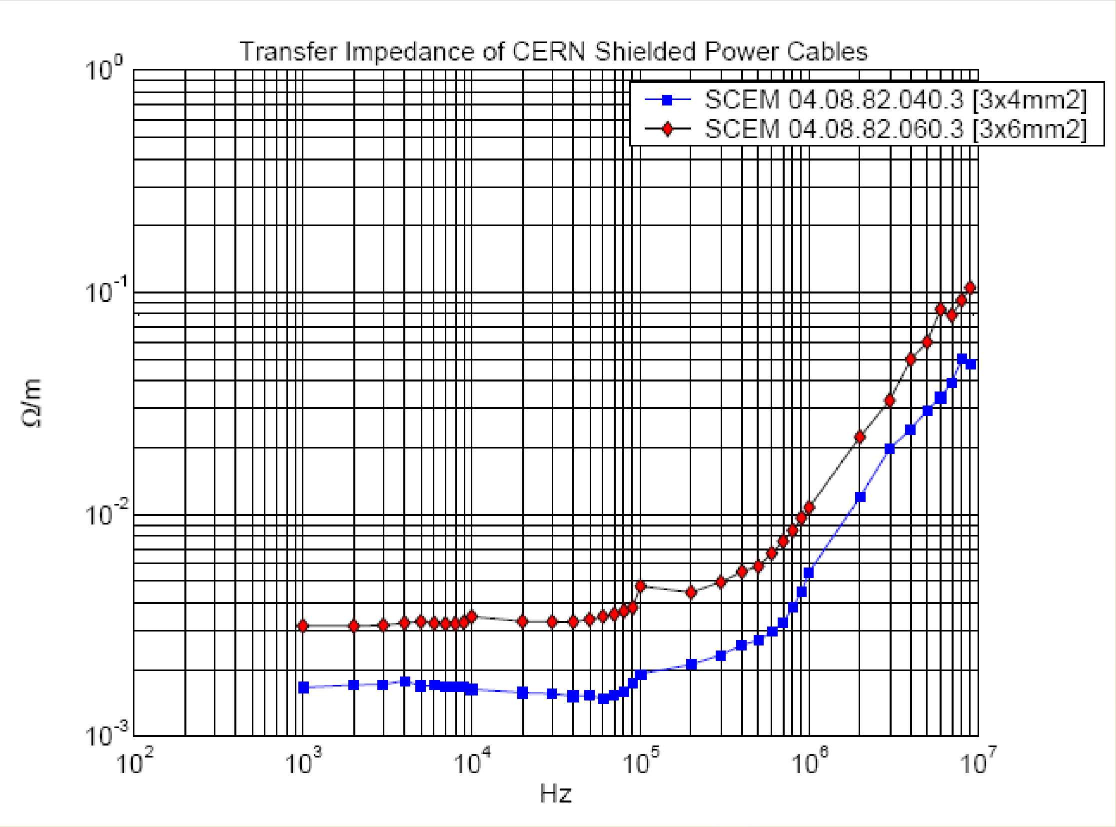
ZT = transfer impedance <-> shielding effectiveness

The effectiness to shield depends of the shield construction: RSH, LSH, coverage.

It can be measured on a section of 1 meter of cable injecting a reference shield current as shown.

Optical coverages greater than 85% are always recommended.

Transfer Impedance

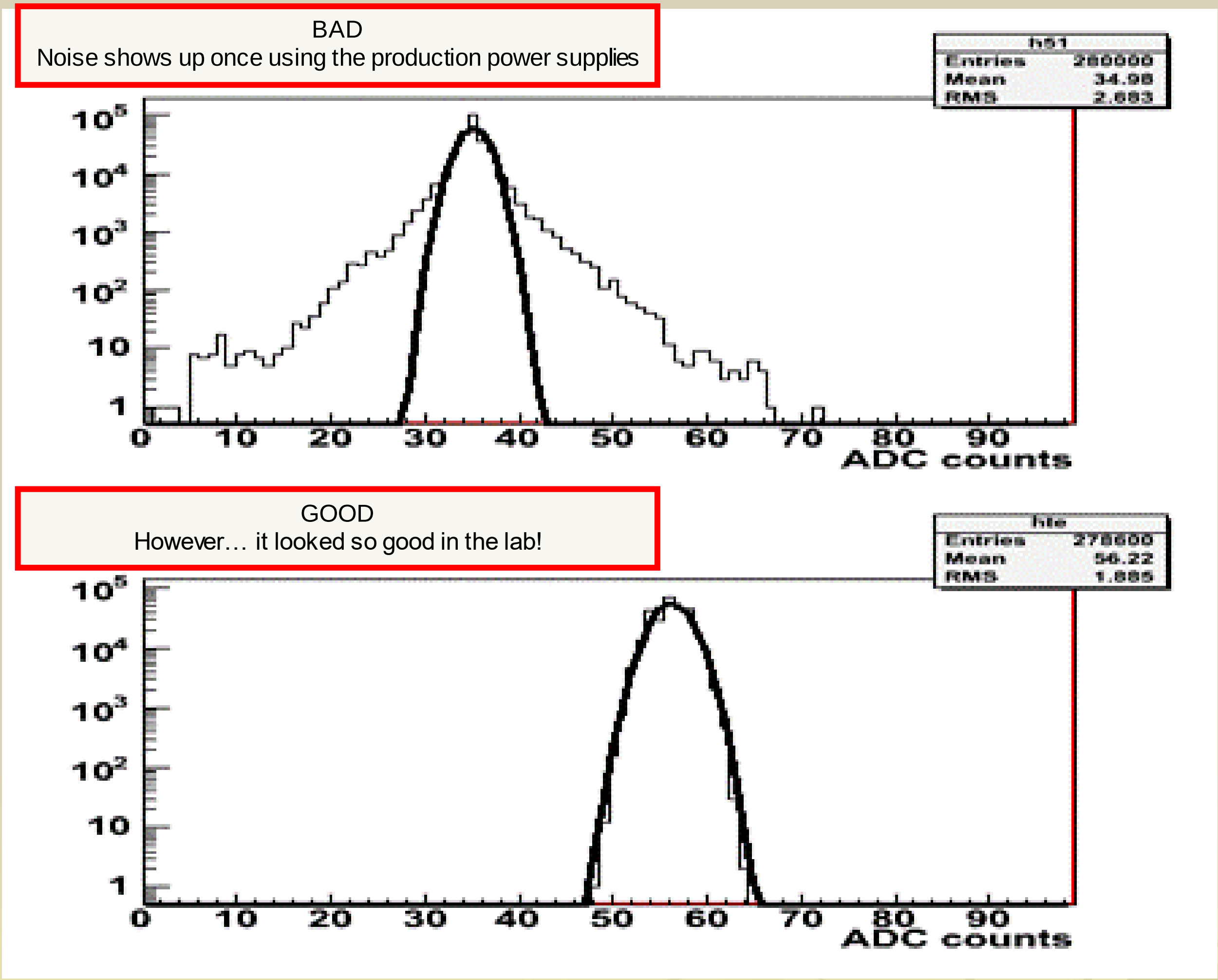


Example of 2 shielde dpower cables from CERN stores.

The shield effectiveness starts degrading at 100 kHz!

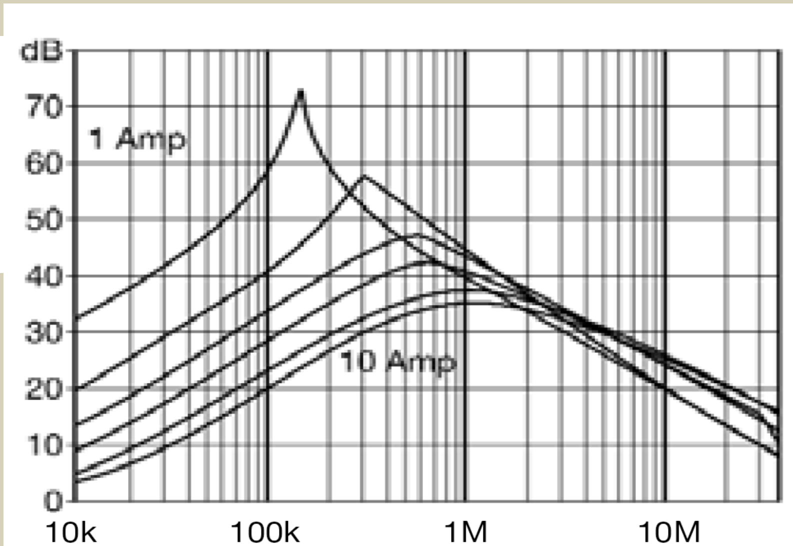
The corner frequency depends in particular of the shield inductnace and of its connection to the plane: pigtails add inductance and therefore degrade the shielding effectiveness.

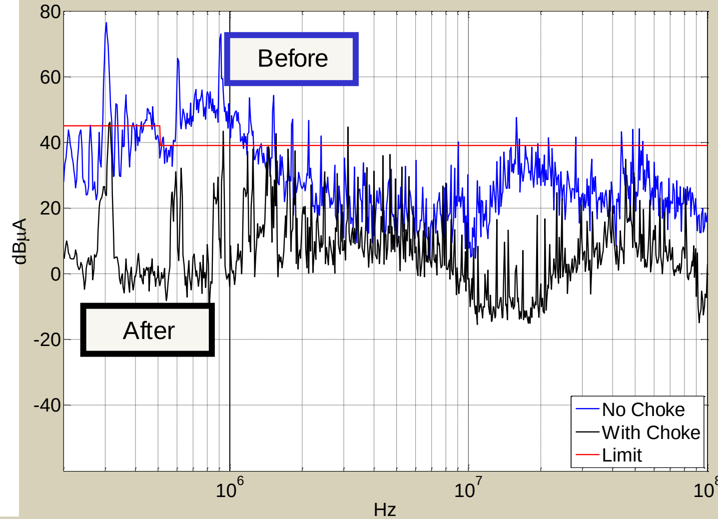
When susceptibility is discovered late

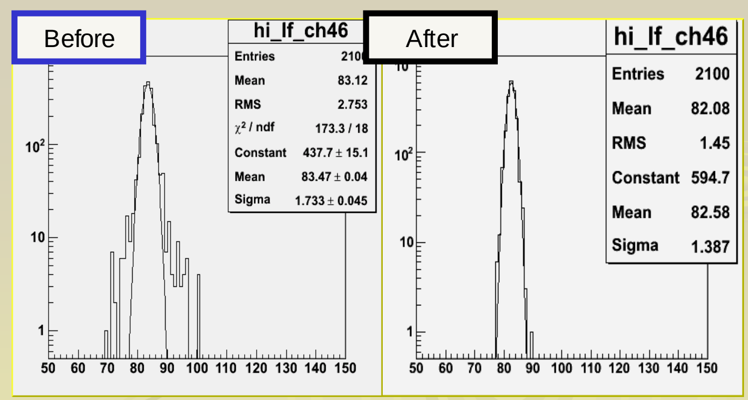


Unnamed detector suffered from LVPS noise during commissioning.

Adding Chokes





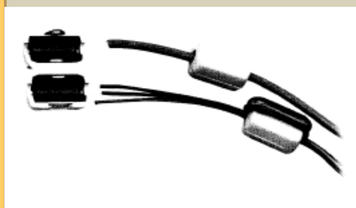


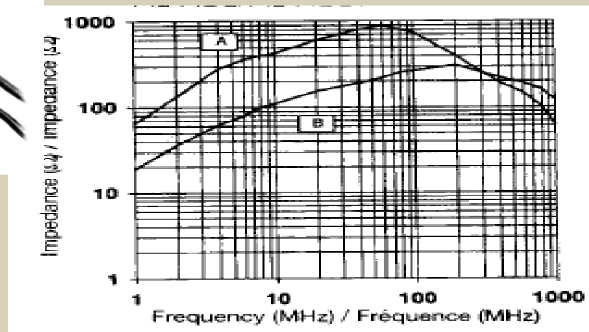
- Bulky common mode chokes provide the best attenuation of switch frequency noise.

- Very hard to add on site: it is much better to insert them at the beginning of the design.

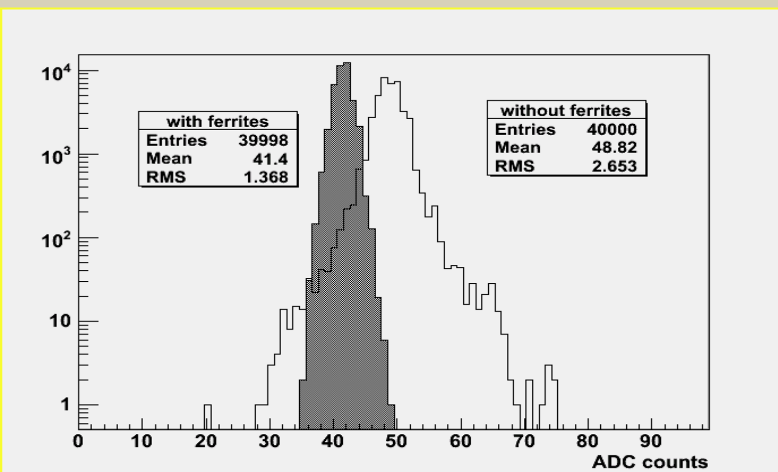
- Limitation: magnetic field of experiments.

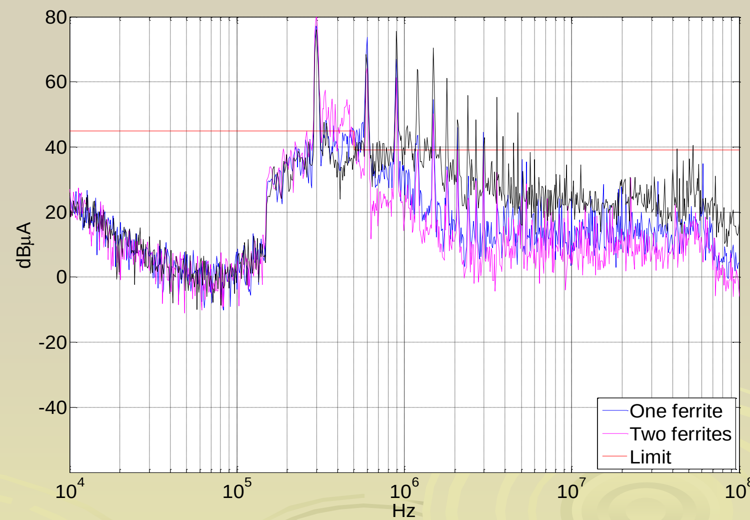
Adding ferrites



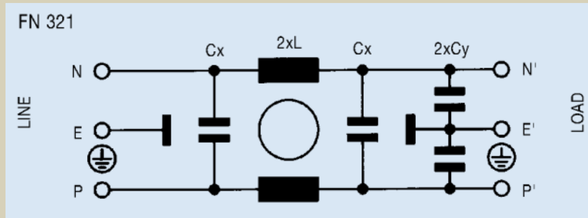


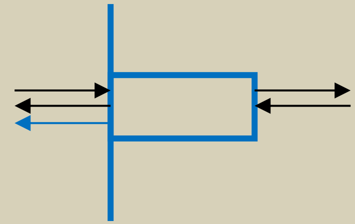
- Last resource!
- Compromised in presence of magnetic field.
- Works better at few tens of MHz in the sensitivity range of typical front-end amplifiers.

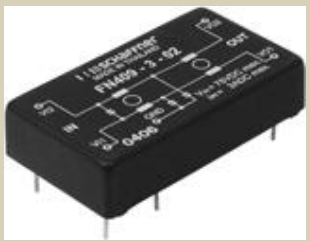


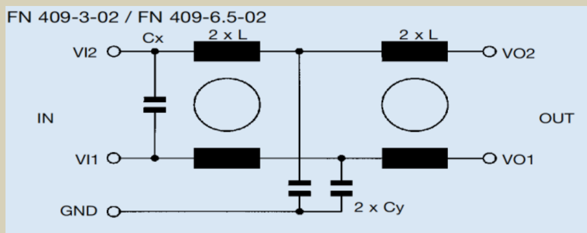


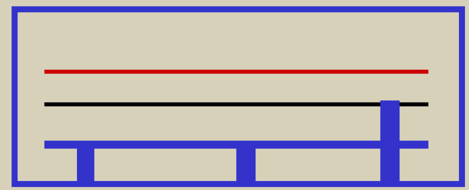
Other filters



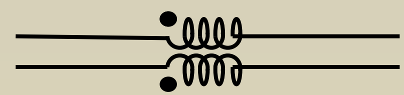




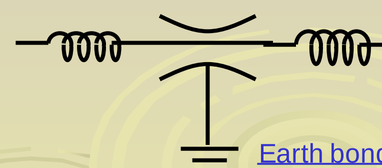




Power plane (VO2)
Ground Plane (VO1)
Earth bonding (GND)



Whatever filter is used, make sure that the CM current never enters in your system



Earth bonding (CM)

Recommended Practices

How can I apply all this to my designs?

1. Always prefer back end systems that are compliant with EU EMC regulations: LV directive, EMC directive, CE mark.

2. Look for PFC in back end equipment.

3. Never leave floating any conductive frame, chassis, structure, box
   - Interconnect them and tie them to earth with the shortest connection
   - This is necessary for safety, also it radically improves the protection against EMI couplings.
   - Earth loops are never a hazard: they are not part of active circuits.

4. Use shielded data and power cables whenever possible.
   - It is almost always better to earth the shield to the frames on both ends.
   - Shields are tied to earth via frames, not to active return paths.

Recommended Practices

5. Fit the power lines with common mode filters in the back end side.

6. Reference your front-end system to the closest ground connection.

7. Design with an eye on EMC aspects:
   - Measure the noise emissions of prototypes.
     - This leaves a chance to correct easily before production/installation.
   - Measure the susceptibility of prototypes.
     - It brings invaluable information that is then used to specify power supplies and cables.

8. Design for the real world!

Thanks for your attention!