EMC at CERN

This talk was presented 2018 for the first time at the EPFL Lausanne and is now re-produced for the UPHUK VIII conference 2022 as an overview.

Its intended, to share with this community some of the EMI experience we have gained at CERN over the last 4 decades.

speaker F. Caspers (now in CERN-EP-UGC)

Fritz Szoncsó HSE-DI
(Daniel Valuch BE-RF, Fritz Caspers=ex CERN RF Group)
2018

Part 0 Some Prerequisites - skipped

Part 1 **What is special at CERN?**

Part 2 CERN's Internal Limits

Part 3 Equipotentiality (2 slides)

Part 4 Conducted Noise, Filters- skipped

Part 5 Radiated Noise and screening - skipped

Part 6 Cabling, Cables, Connectors

Part 7 Physics Experiment EMC Applications

Part 8 Accelerator EMC Applications

Part 9 Safety System EMC Applications

Part 10 Conclusions

CERN does not have a unique approach

CERN has about 100 groups of its own, plus 400 so-called user groups, totalling more than 12000 scientists.

Classical EMC-solutions are only partially used, because scientists tend to import the traditional knowledge of electronics in physics

Reducing EMC to "grounding and shielding" deprives research of the rich experience EMC engineers can offer.

This talk will cover things that I consider interesting for students who are ready for the challenge of EMC

Of course some CERN groups follow the ideal path where possible

The picture is taken from the internal website of the CERN power converter group.

Reality outside the industrial part, however, haunts the ideal path:

- Millions of highly sensitive measurement channels
- Economic solutions for power conversion, harmonics compensation, cabling
- Dislocated power supplies far from load
- Political reality of an international organisation (need to buy in certain countries, including countries outside EU)

The great CERN divide: Physics and Electrical Engineering

Electronics, detector construction and cabling in physics follow traditional principles that are bred in the various physics institutes. There is neither a standard nor a common approach. The situation is similar to the ISS where the Russian part is powered with an insulated 28VDC, whereas the other parts runs 117VAC grounded.
By the way, CERN runs one of its experiments on board of the ISS (Experiment AMS)

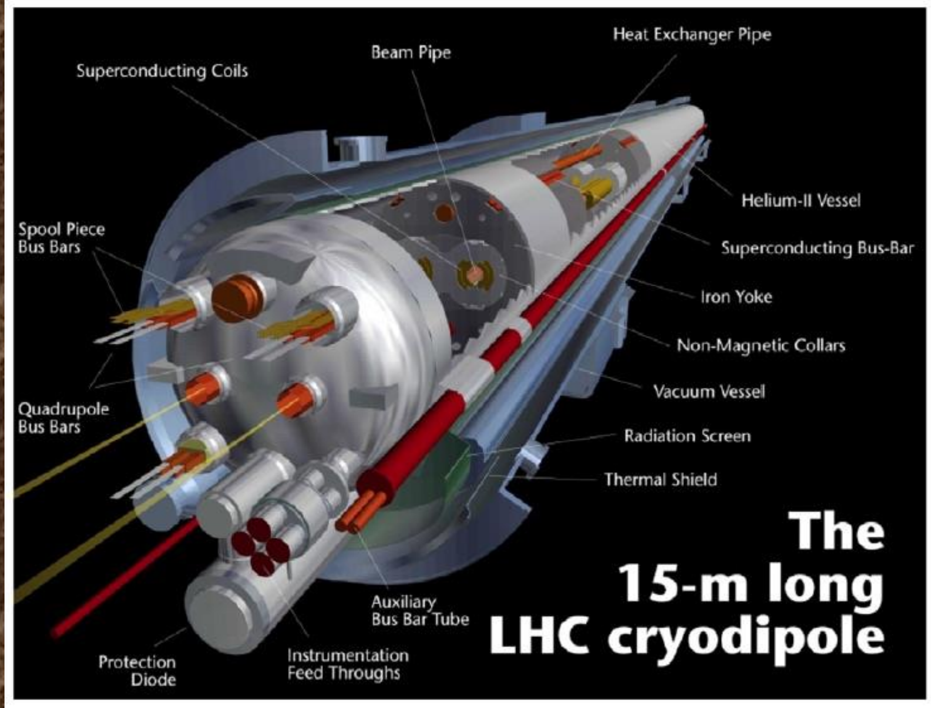
CERN infrastructure, electricity distribution, cryogenic compressors, tunnel ventilation, electrical network, alarm and security installations follow the standards and are mostly done by companies under contract. EMC is NOT the primary issue.

The accelerators are in between:
They need pulsed power in the MW-range, precise magnet currents, power radio frequency installations, a perfect vacuum system and precise beam monitoring.
They also need a fail-safe protection, including quench protection and a safe energy transfer.
EMC is organised centrally by the biggest polluters, namely the power converters. The other groups solve their EMC-problems in very different ways.
In the accelerator tunnel there are, experimental areas excepted, about 15 different groups representing different professions but all using electricity as the only power source.

CERN's generates its noise itself

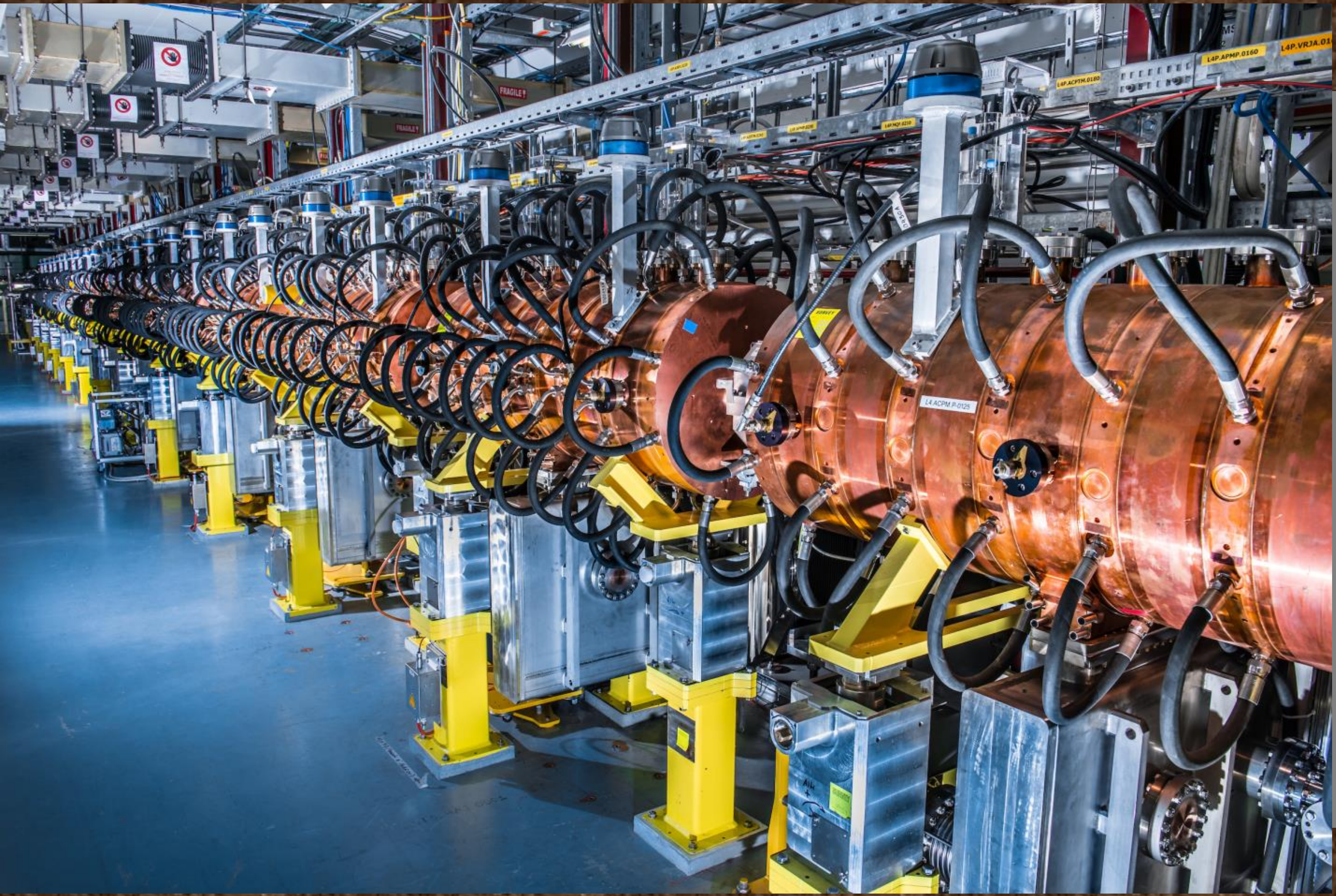
CERN needs compatibility between very exotic services, such as the bunched beam current, the beam tube under the world's best vacuum, the vast cryogenic installations, the superconducting magnets, the powerful pulsed radio frequency systems, the infrastructural services and many other things all the way down to the installations that guarantee the Safety of persons.

100m underground there is no noise other than CERN's.
The accelerator tunnels are even a noise absorbing environment.



Compatible with the environment: CERN respects EN 55011 (CISPR11)

CERN must not radiate anything into the environment.
This dogma is respected for both ionising and non-ionising radiation.
"At the fence" and above our premises EN 55011 is fully respected, in spite of many Megawatts of pulsed RF-power up into the microwave range.



LINAC 4 with RF system.

Top left on photo: 400MHz waveguides

This accelerator is NOT underground.

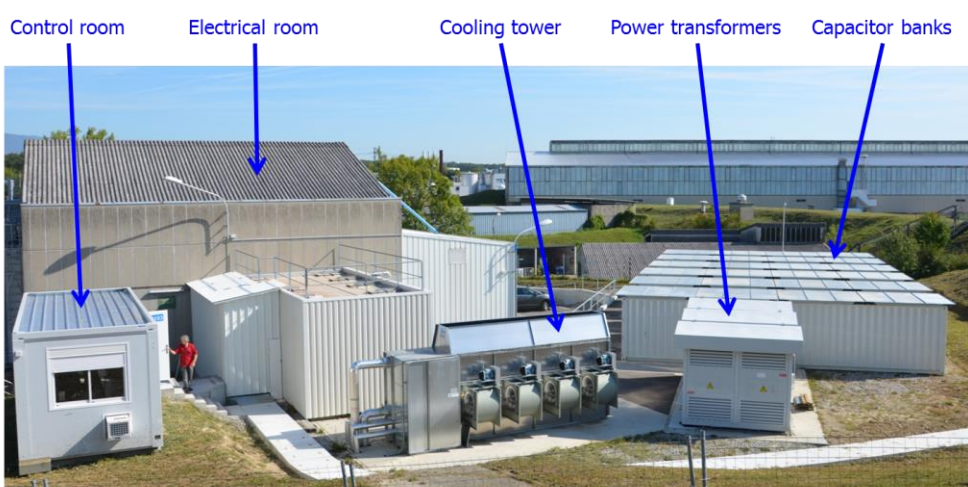
The closed-circuit RF is interlocked against leaks.

Internal Limits because of power electronics

Internal limits are required because the internal electromagnetic pollution is handled in peculiar ways, depending on the technology of the accelerators active at CERN.

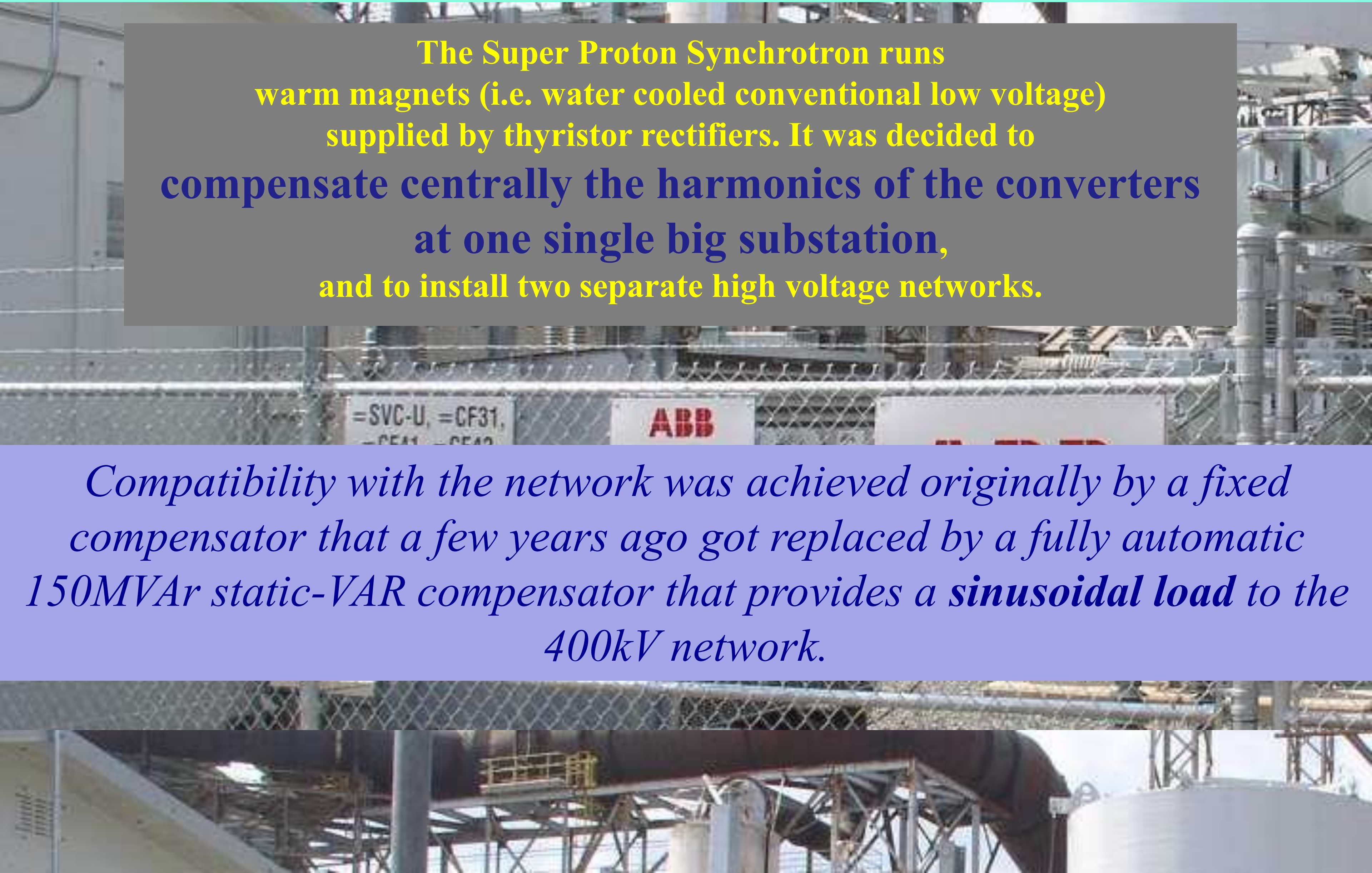
CERN's (now) oldest accelerator, the Proton Synchrotron, runs 256 magnets connected in series, supplied with high voltage pulsed DC. At the time of its inauguration CERN had a moderate 18kV supply network that could not absorb Megawatt-cycles spaced only by seconds. Compatibility with the network was achieved by a 46MVA (96MVA peak) synchronous machine that accelerated and slowed down synchronously with the particle pulses.

Meanwhile the machine, still operational, has been replaced by a high-tech powering scheme using HV-capacitors and DCDC-converters.



The SPS

Thyristor phase control technology



The Super Proton Synchrotron runs warm magnets (i.e. water cooled conventional low voltage) supplied by thyristor rectifiers. It was decided to compensate centrally the harmonics of the converters at one single big substation, and to install two separate high voltage networks.

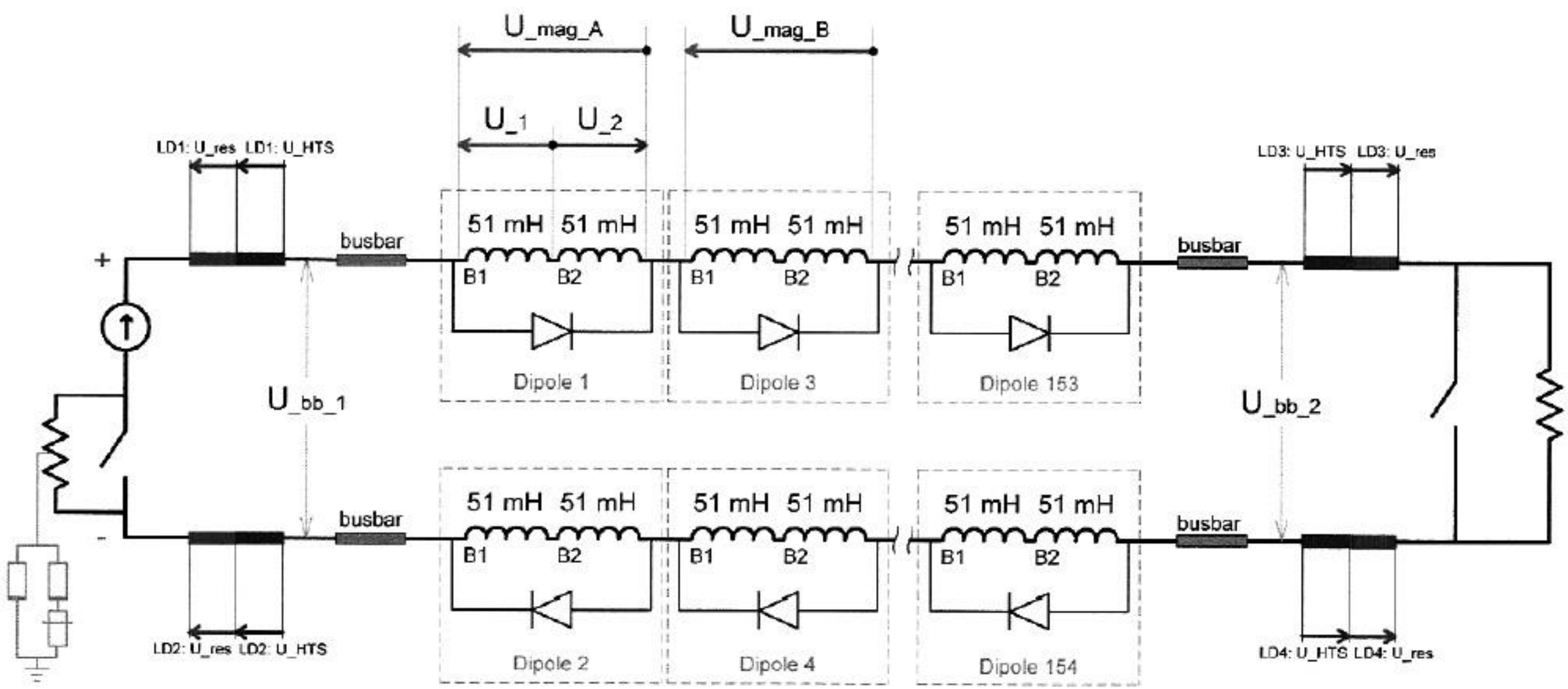
Compatibility with the network was achieved originally by a fixed compensator that a few years ago got replaced by a fully automatic 150MVAr static-VAR compensator that provides a ***sinusoidal load*** *to the 400kV network.*

The LHC – the superconducting machine

The LHC needed less power but higher precision and, above all, switch-mode power converters and a fail safe energy transfer system because of the stored magnetic energy in a virtually lossless system.

For protecting the LHC CERN built a quench protection that successfully checks the 100mV safety limit across the EACH COIL in a very noisy place.

Internal limits exceed the classic EMC range because ripple on the high current DC lines would introduce unwanted beam modulation.

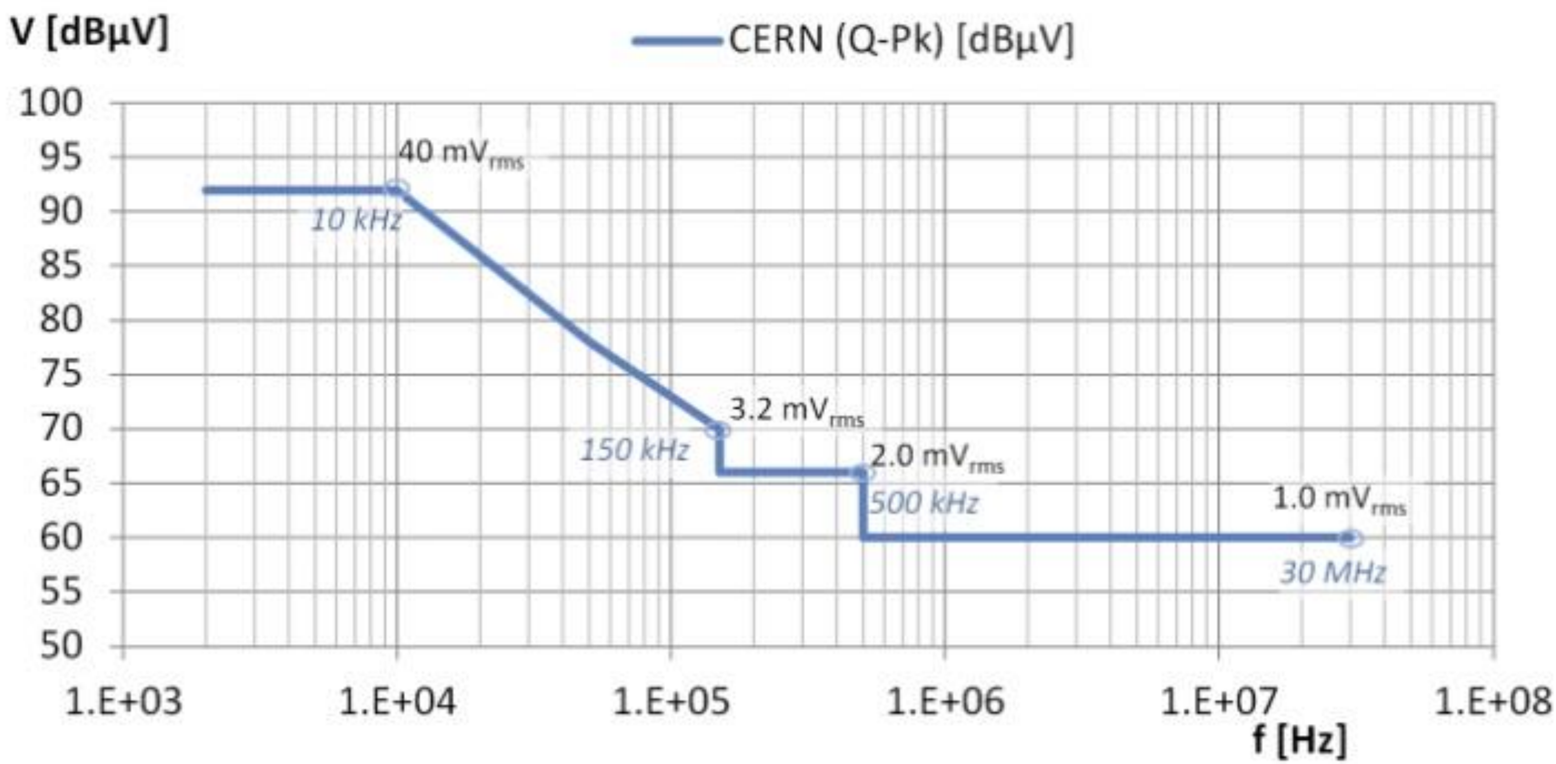


Internal EMC Limits: Electrical Engineering Power Converter group, extension below 9kHz

CERN Frequency Reference Gabarit/Levels

CERN gabarit is historically based on IEC-478-3 Curve C (replaced by IEC-61204-3), with extension down to 2kHz.

- [2kHz..10kHz] range is out of standard EMC equipement range (impedance and measurement capability) and should be treated following CERN recommandations.
- Quasi-Peak Measurement required, even if peak could be used (saving time) initially to point at possible issues to be later studied more carefully. *A Peak measurement below limit confirms entirely the compliance with Quasi-Peak limit. The more noise signal "duty cycle" reduces (its frequency of apparition) the more Quasi-Peak Measurement result differs strongly from Peak one. Converter noise (by nature) typically generates less than 6dB of difference between Q-Peak and Peak.*

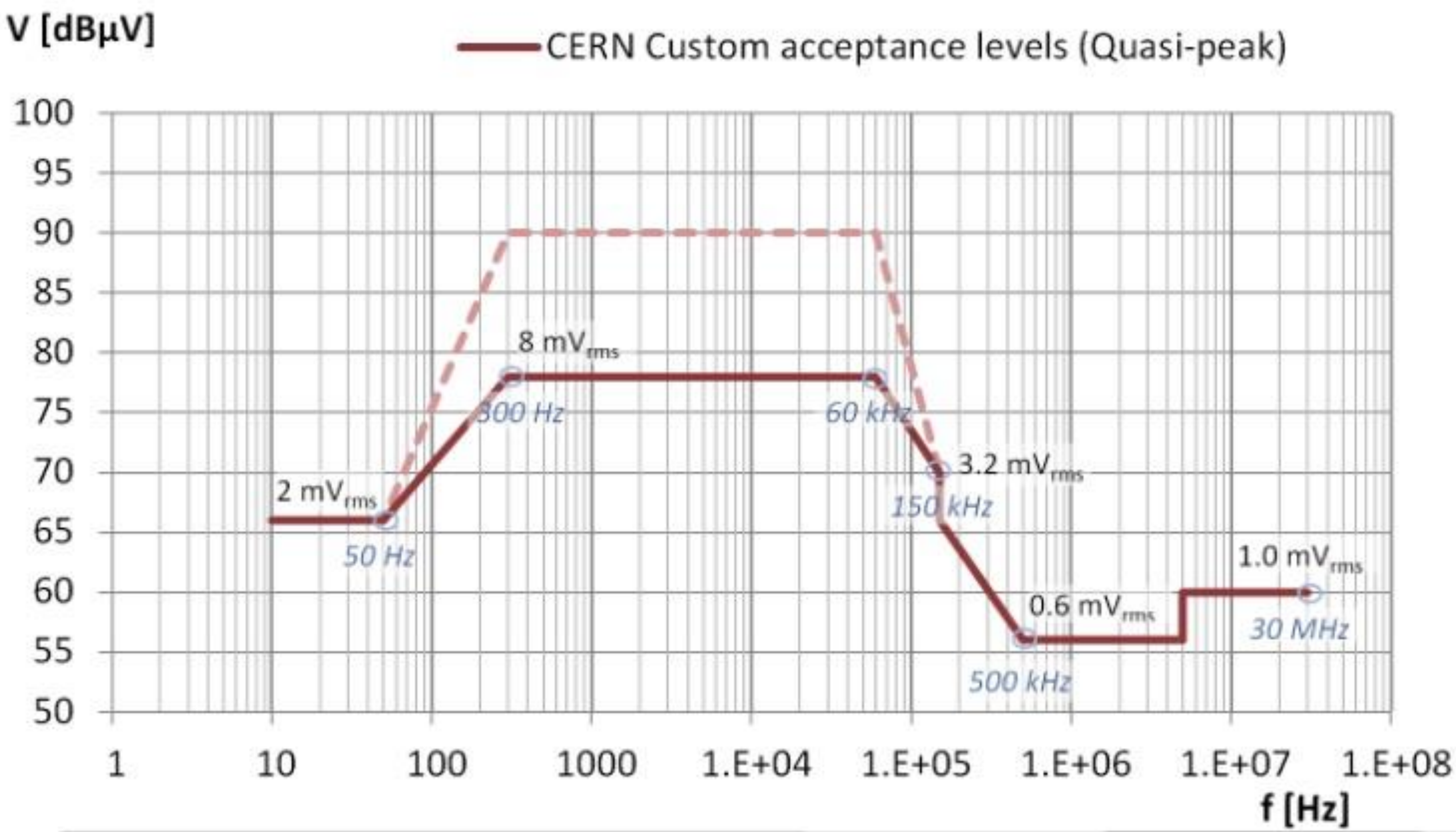


Internal EMC Limits: Electrical Engineering Power Converter group: extension down to 10Hz

CERN Reference Gabarit/Levels

CERN gabarit is based on IEC-478-3 Curve C, extended for low frequencies *(magnet current ripple constraints)*.

- [10Hz..10kHz] range is out of standard EMC equipement range (impedance and measurement capability) and should be treated with adequate material (bandwidth issue on 1500 Ohms probe for example, with a 35dB rejection for frequency higher than 10kHz usually).
- A time domain reference level $V_{peak-peak}$ measured with 100 MHz bandwidth capability should always be performed in parallel to this test.
- Reference gabarit is given (strong line) for a DC output voltage of less than 50V. *Dashed line shows an hypothetic level for a higher range / purpose / topology application. This limit level is defined from final user requirements.*



Internal EMC Limits for Physics Experiments
Many groups, no common approach

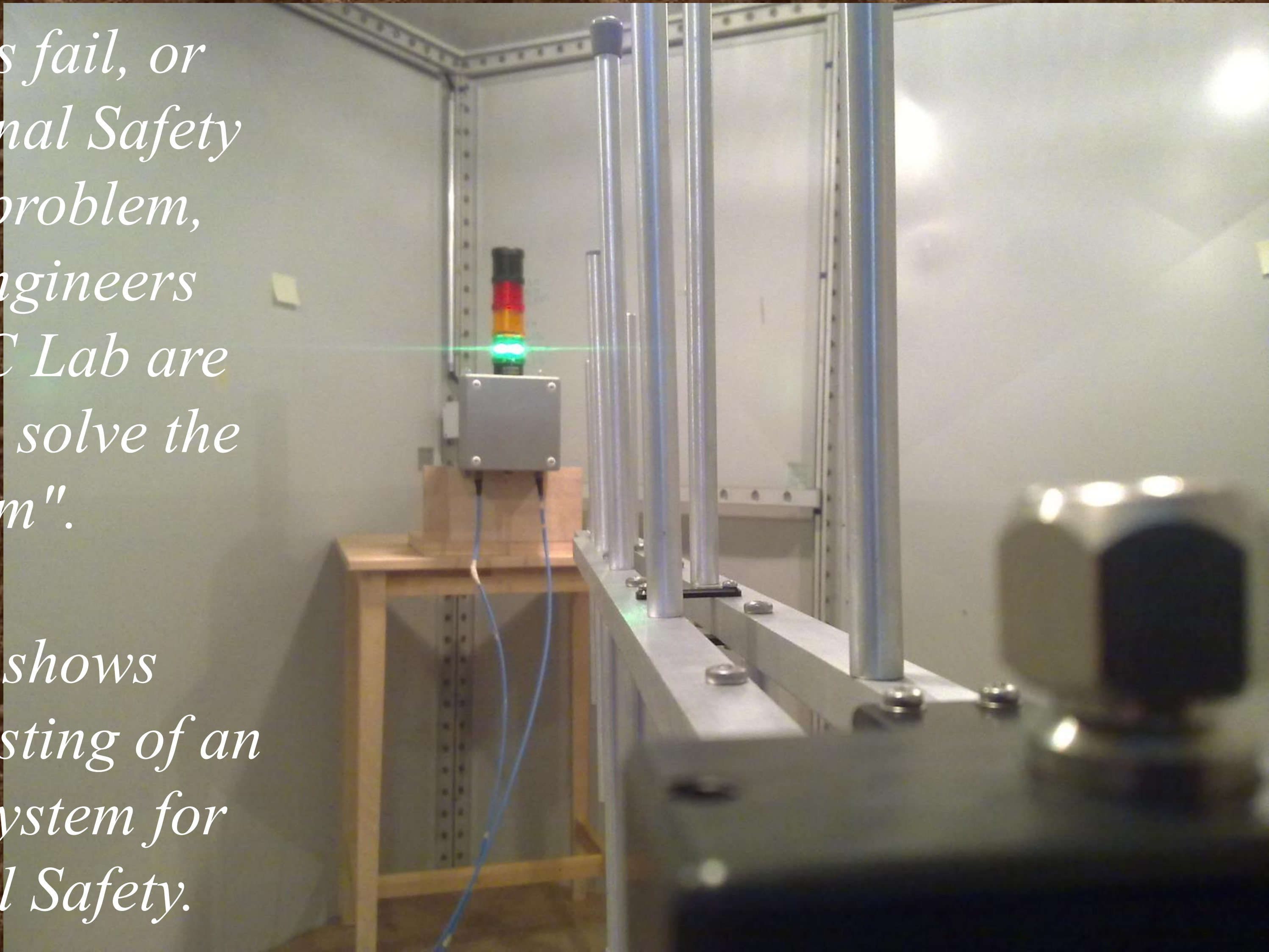
Common points:

- Insulation of measurement entities against each other
- Bad equipotentiality
- Expensive shielded cables with arbitrary shield connections
- No more analogue outputs
- Software EMC (workarounds by computing/processing data)
- The only driving force is the impeccable physics measurement
- EMC engineer talks to a majority of physicists who consider EMC as "grounding and shielding"

Today CERN (and most physics groups from around the world) does not have any commonly applicable EMC procedure or limit for all physics installations.

Immunity testing in CERN's EMC-Lab

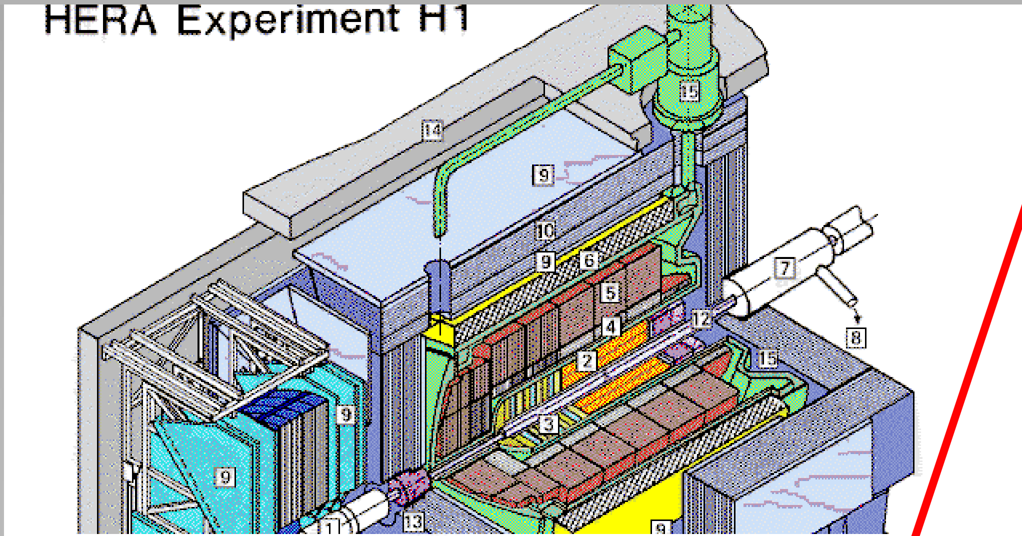
Field exposure to more than 100V/m, screened room, no tiles



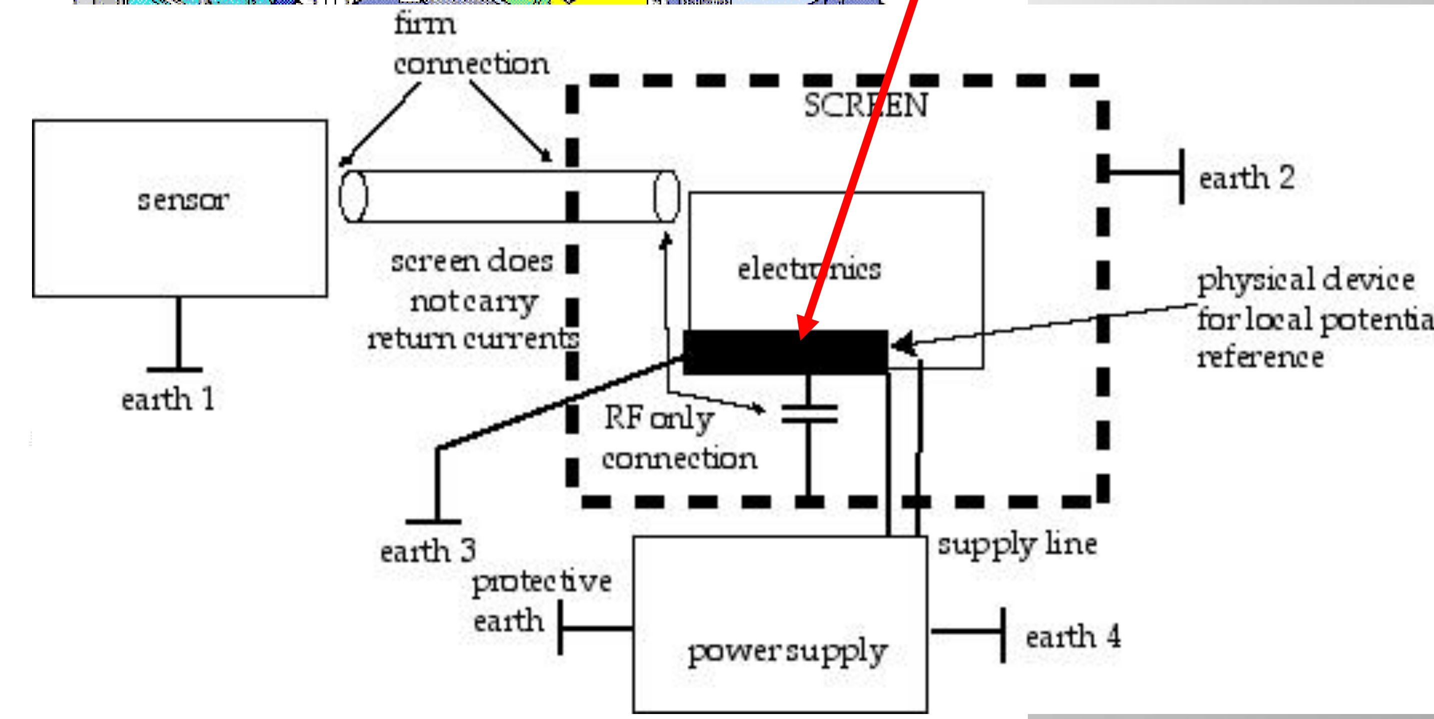
When things fail, or when functional Safety becomes a problem, the EMC engineers and the EMC Lab are requested "to solve the problem".

Picture shows immunity testing of an in-house system for personnel Safety.

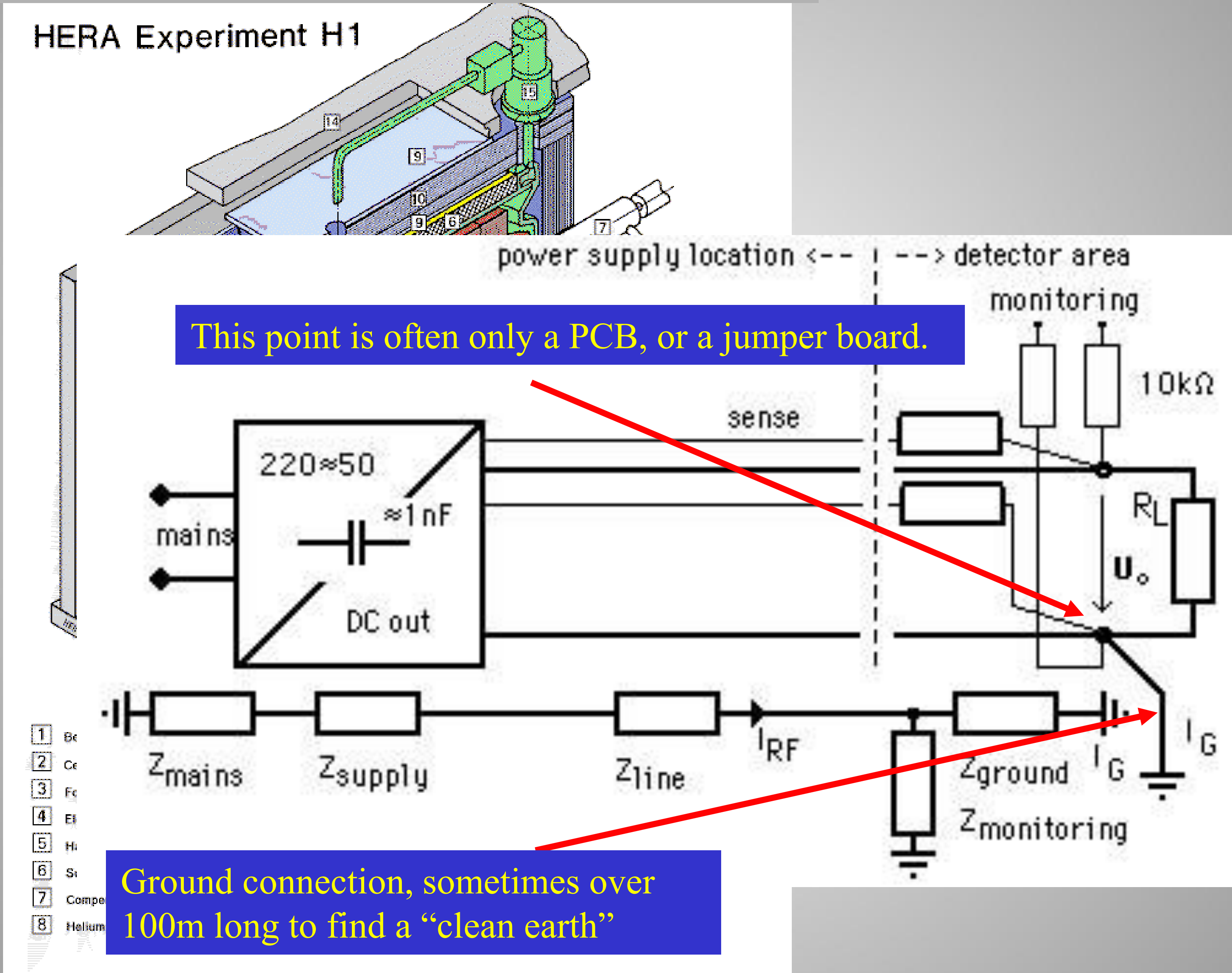
Typical configuration in a large experiment



The EMC-relevant earth point is inaccessible and small. The designs are physics driven, EMC knowledge (and approach) varies considerably amongst groups.



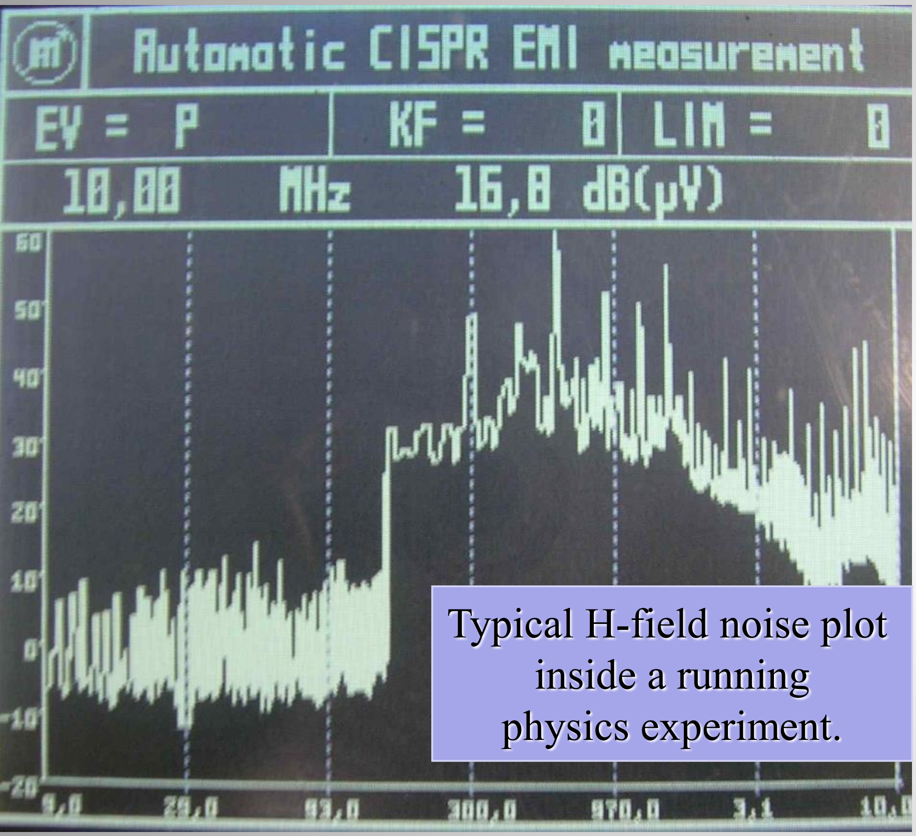
"Floating" sensor electronics



This point is often only a PCB, or a jumper board.

Ground connection, sometimes over 100m long to find a "clean earth"

Noise generation inside physics experiments



Typical H-field noise plot inside a running physics experiment.

The noise threats are:

- •ELF (not on picture)
- •Common Mode on random path
- •RF background from particles and electronics
- •Digital signals
- •Badly terminated fast links
- •Asymmetrically operated twisted pairs
- •Discharges
- •General lack of immunity to E-fields
- •Lack of immunity to network transients
- •Common ground interference

Often suspected to generate noise and “disturb measurements”:
Remotely located power supplies; transmitters (!!); the magnet; the LHC and its powerful systems; the power network; neighbour apparatus.

Part 0	Some Prerequisites
Part 1	What is special at CERN?
Part 2	CERN's Internal Limits
Part 3	**Equipotentiality** (two slides)
Part 4	Conducted Noise, Filters
Part 5	Radiated Noise and screening
Part 6	Cabling, Cables, Connectors
Part 7	Physics Experiment EMC Applications
Part 8	Accelerator EMC Applications
Part 9	Safety System EMC Applications
Part 10	Conclusions

CERN needs to be compatible with standards

CERN tries to convince researchers not to follow the ***religions*** *of equipment insulation, separate earthing, broken Faraday cages, wild cabling, open loops and fear of ground currents.*

TECHNICAL REPORT

IEC 61000-5-2

First edition
1997-11

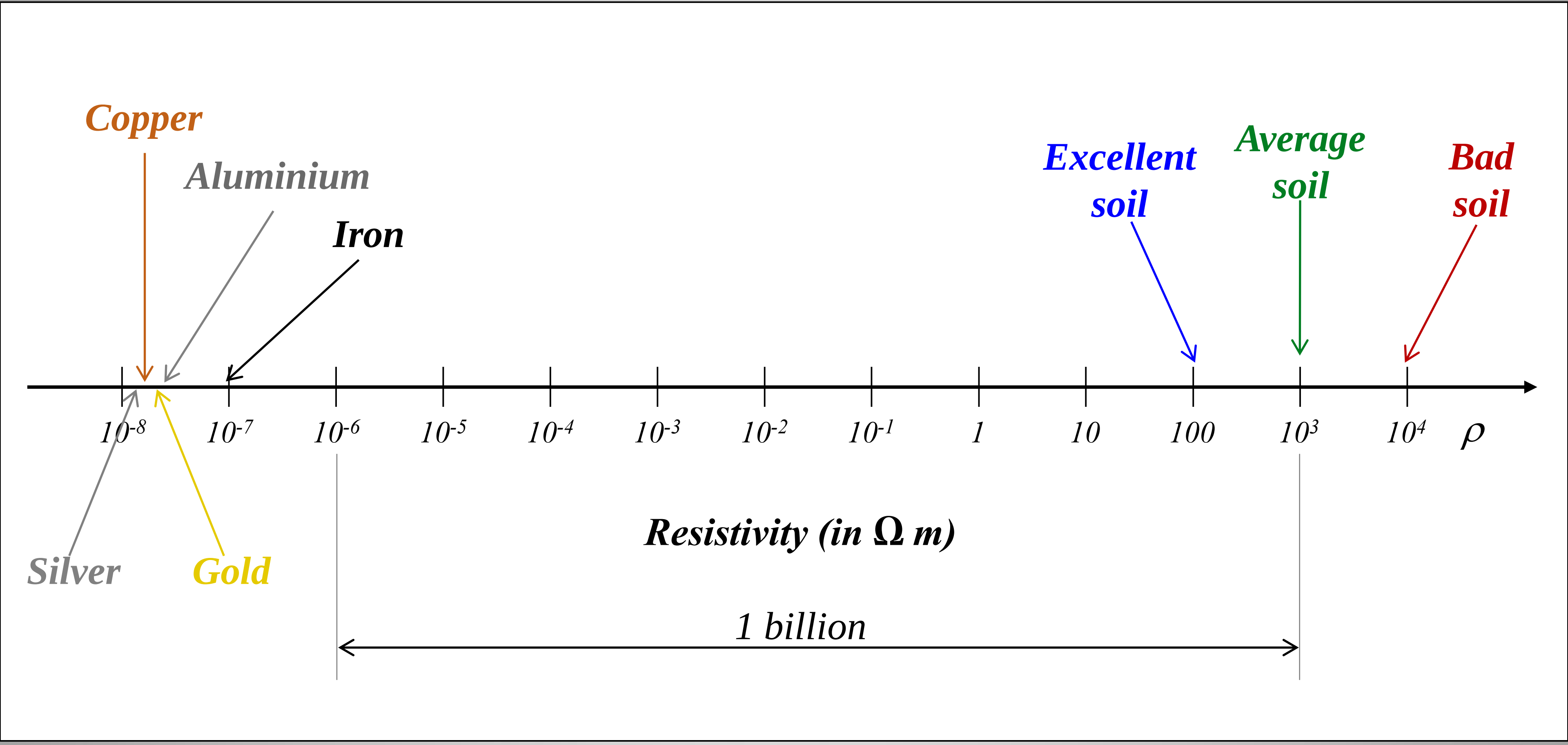
Electromagnetic compatibility (EMC) –

Part 5:
Installation and mitigation guidelines –
Section 2: Earthing and cabling

CERN's problem is its physical size.
A physics laboratory is not able to follow such guidelines throughout 50km of tunnels, intersections and experimental areas.
In spite of good engineering practice the EMC teams are never out of work.

Metal conductor versus soil (=earth) resistivity

The graph used when equipotentiality is put in doubt



Derive yourself the usefulness of independent earthing...

Part 0 Some Prerequisites
Part 1 What is special at CERN?
Part 2 CERN's Internal Limits
Part 3 Equipotentiality
Part 4 Conducted Noise, Filters
Part 5 Radiated Noise and screening
Part 6 **Cabling, Cables, Connectors**
Part 7 Physics Experiment EMC Applications
Part 8 Accelerator EMC Applications
Part 9 Safety System EMC Applications
Part 10 Conclusions

Part 6 Cabling and Consequences

- Cable “mechanics”
- Parallel Cabling
- Cable Screens
- Cable geometry vs. EMC-behaviour
- Connectors
- Termination

Cable “mechanics” and EMC

Improved EMC by

a) cable bending radius within manufacturer’s specifications

b) mating connectors AND 360 degree screen connection

c) physical separation of signal & power

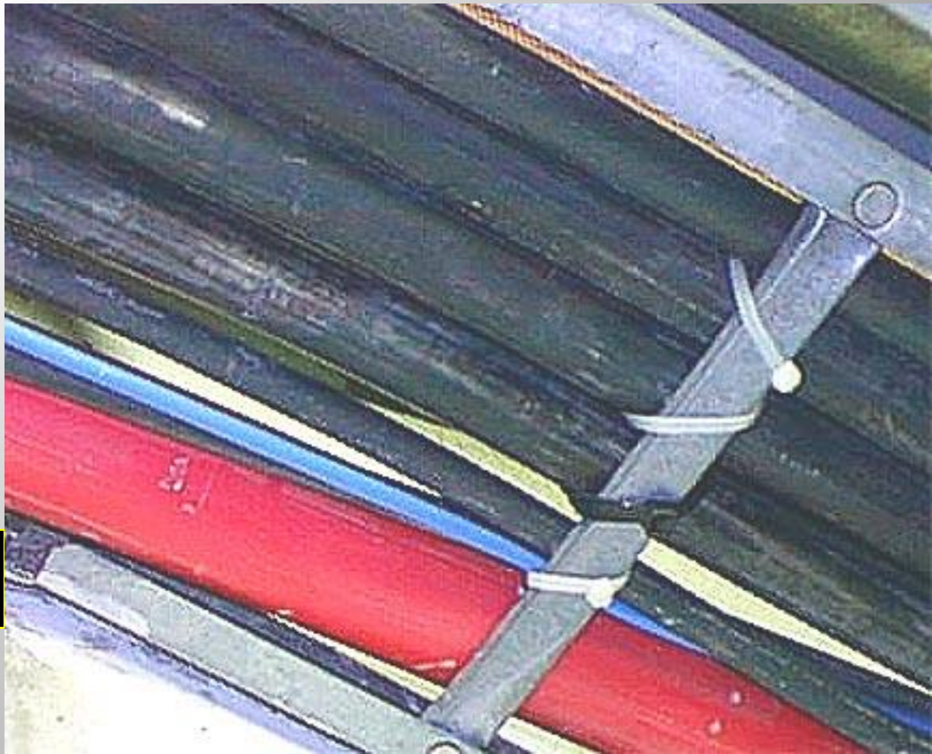
Diminished EMC by

d) Reeling

e) sharp bends or squashing

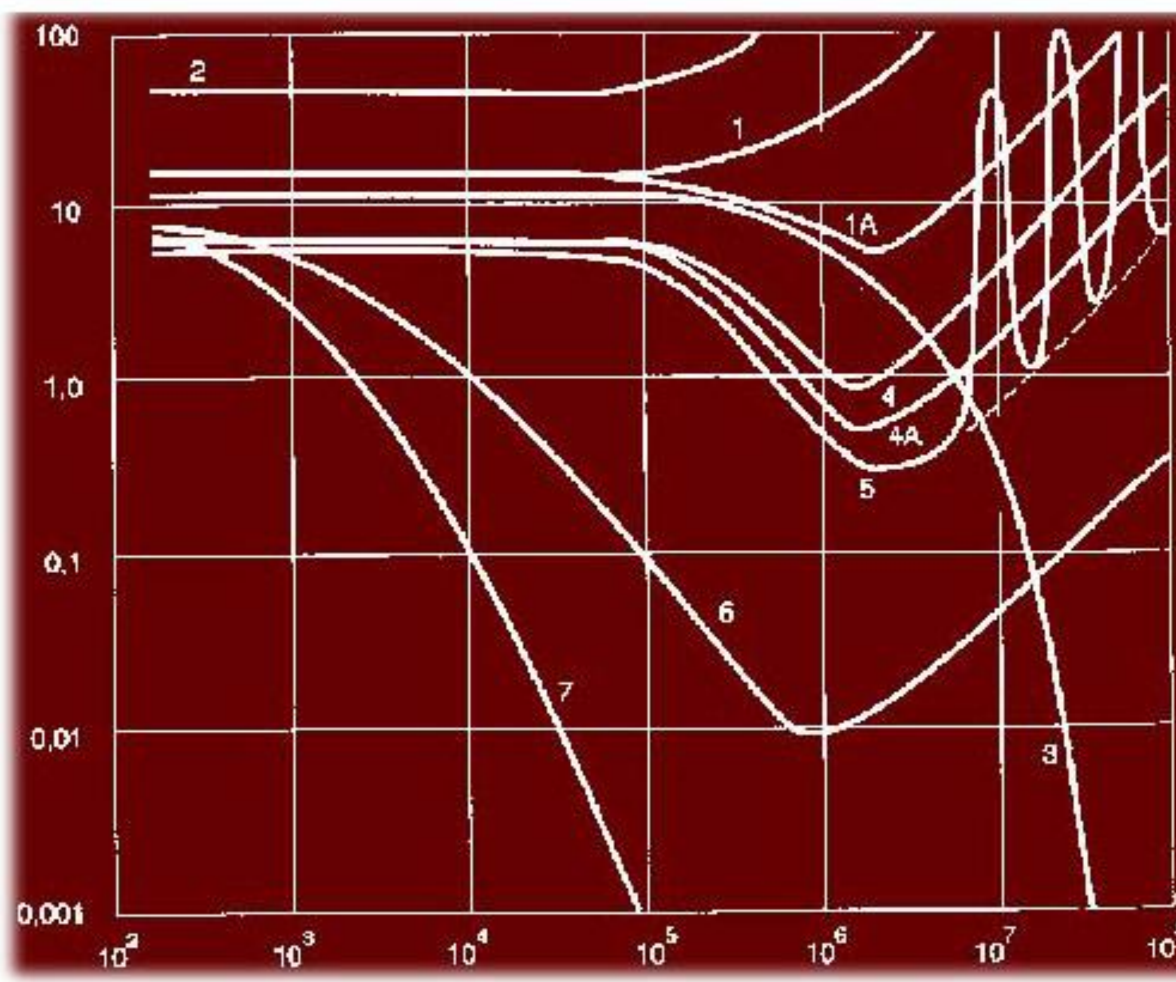
f) disconnected screens

g) wide area loops in circuit



Coupling impedance

Cables leak, cables pick up noise, convert noise, radiate noise, most of it by performing conversions.

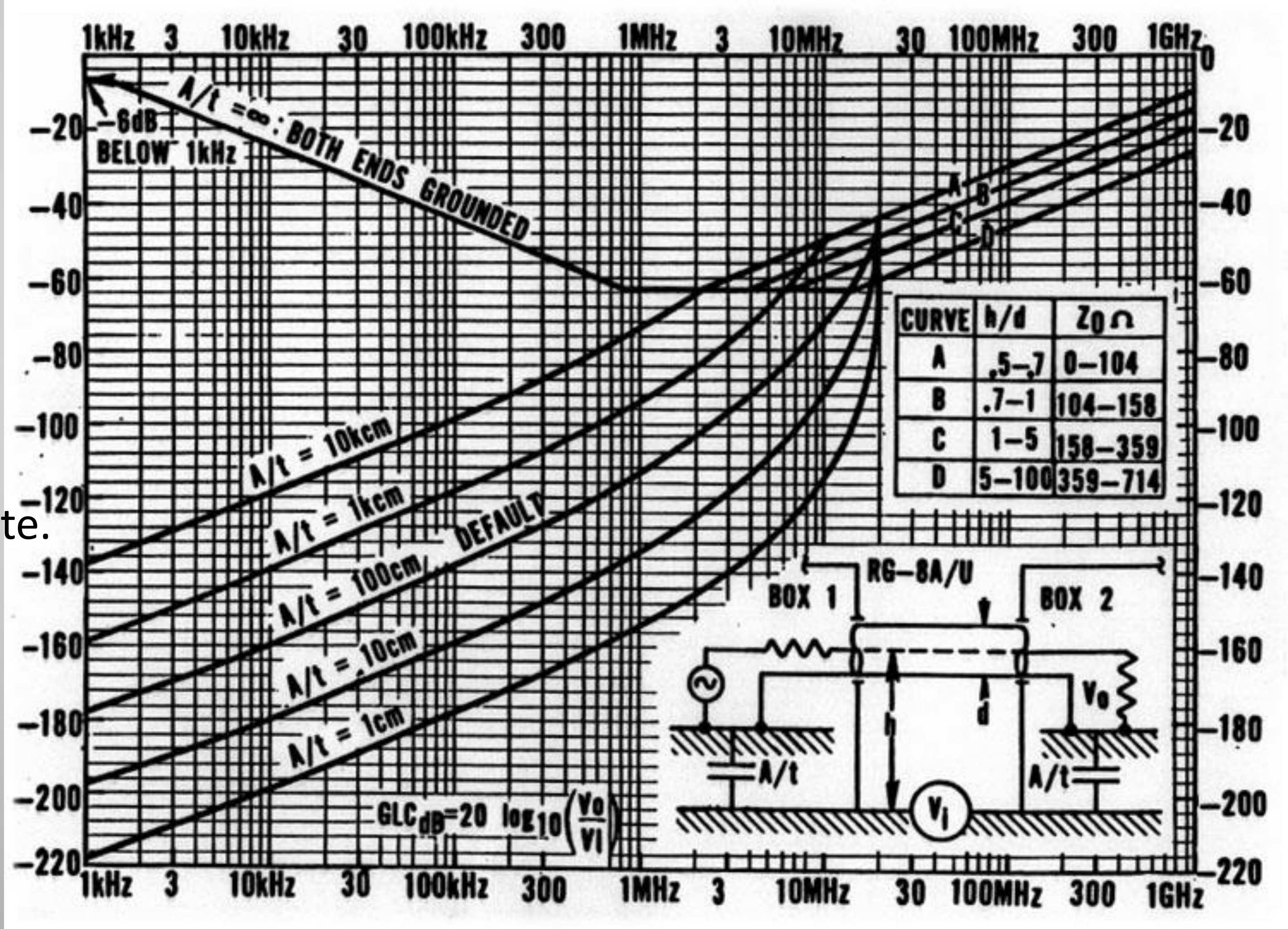


1: single mesh
1a: optimized single mesh
2: Aluminium/Mylar foil
3: massive copper
4: double mesh
5: optimized double mesh
5a: triple mesh
6: double mesh plus single μ-metal layer
7: triple mesh plus double μ-metal layer

At low frequency all cables are fairly equal because ELF penetrate deeply into the cable and cause CM to DM conversions.

Once you have a given cable:
the geometrical configuration determines how well external fields may be attenuated.
Don't forget about conversions...

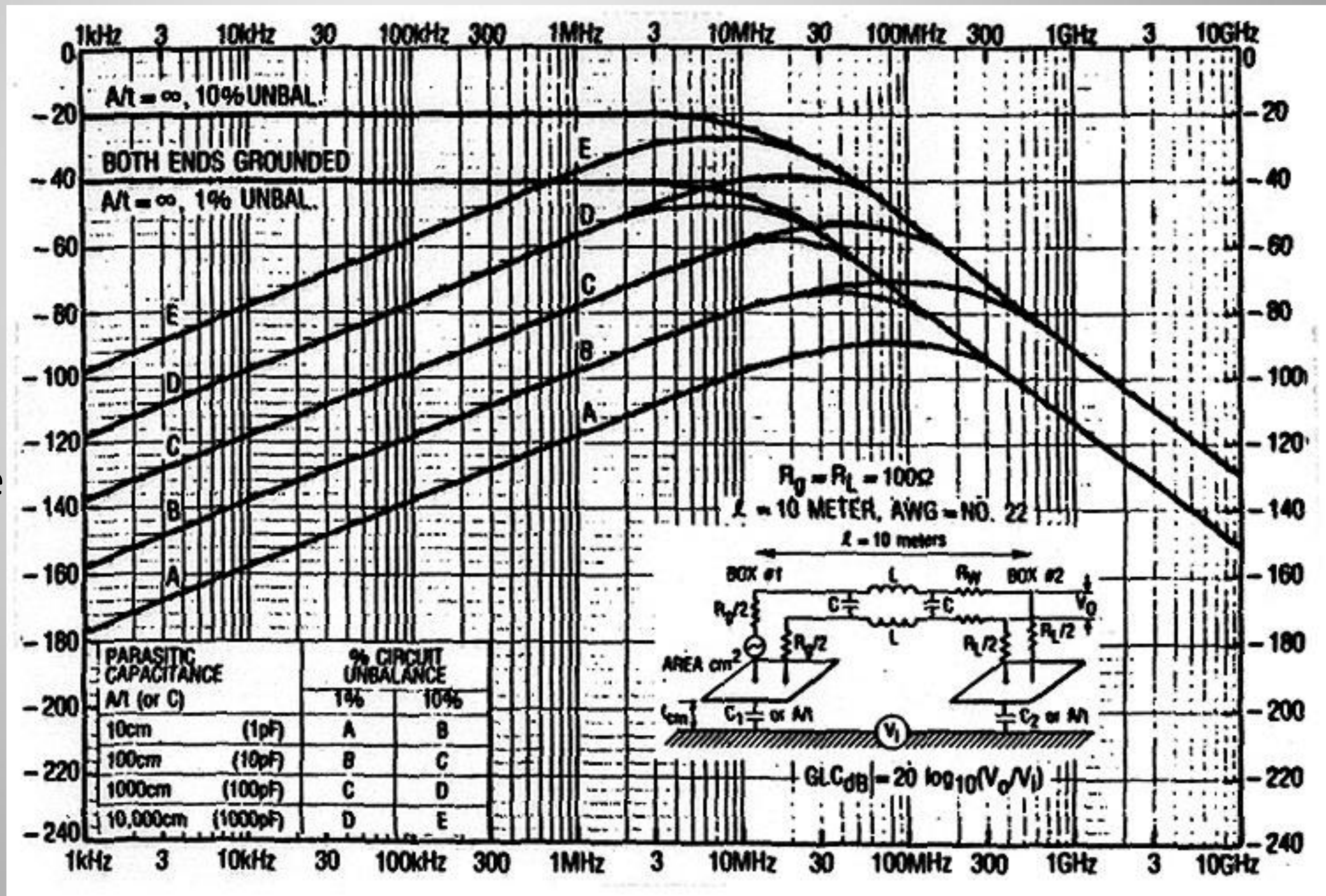
Note:
Below 1 MHz currents induced by ground loops dominate.
Above 1 MHz the difference disappears.



CURVE	h/d	Zo Ω
A	.5–.7	0–104
B	.7–1	104–158
C	1–5	158–359
D	5–100	359–714

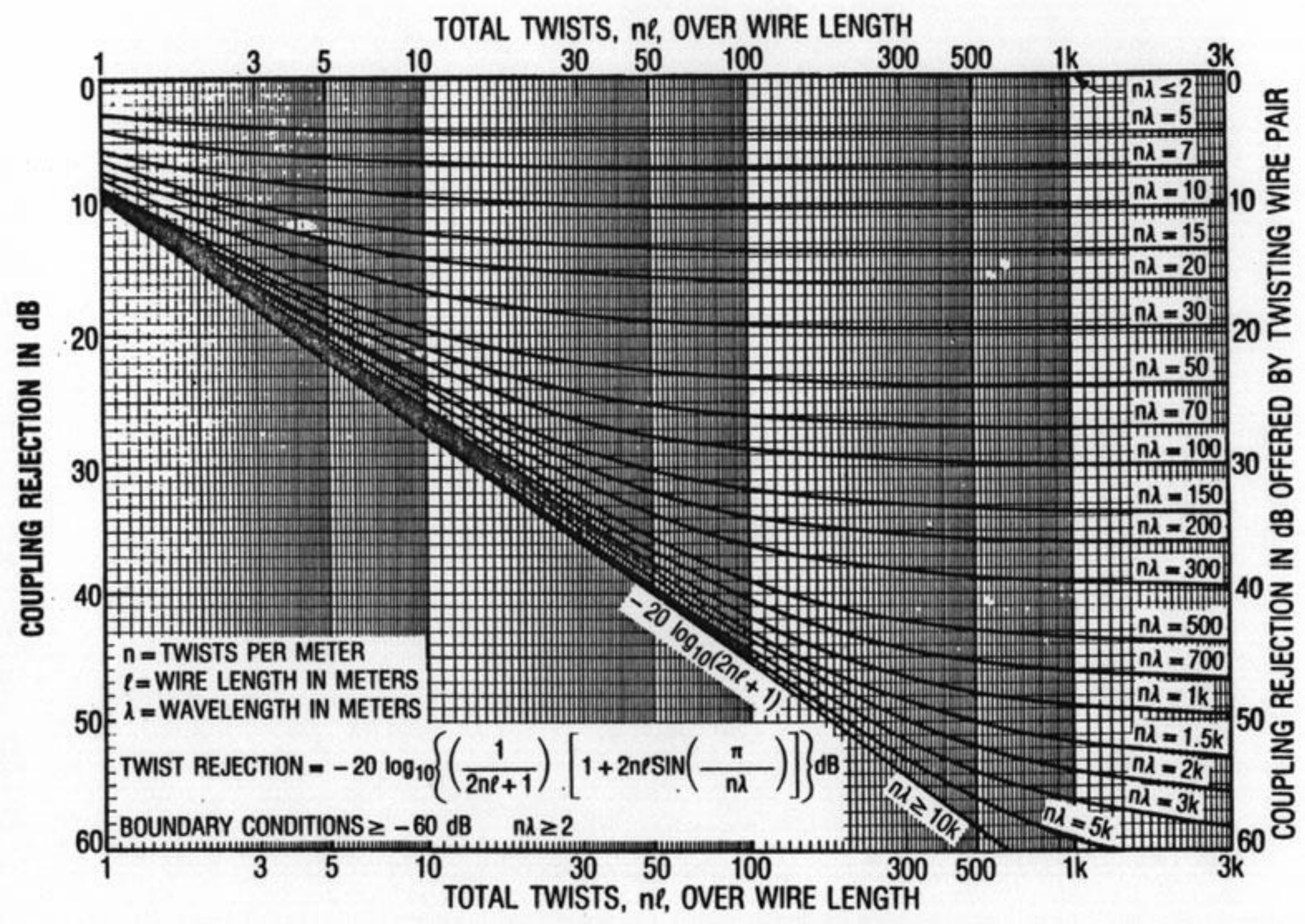
Leads of symmetric cables (twisted pair)
should have equal impedances to ground.

Note:
Below 10 MHz
shield currents and
asymmetry dominate
over geometry.
Above 10 MHz
the difference
disappears.



Twisting has its limitations, entails some cost and does not solve everything. Lower frequencies remain problematic...

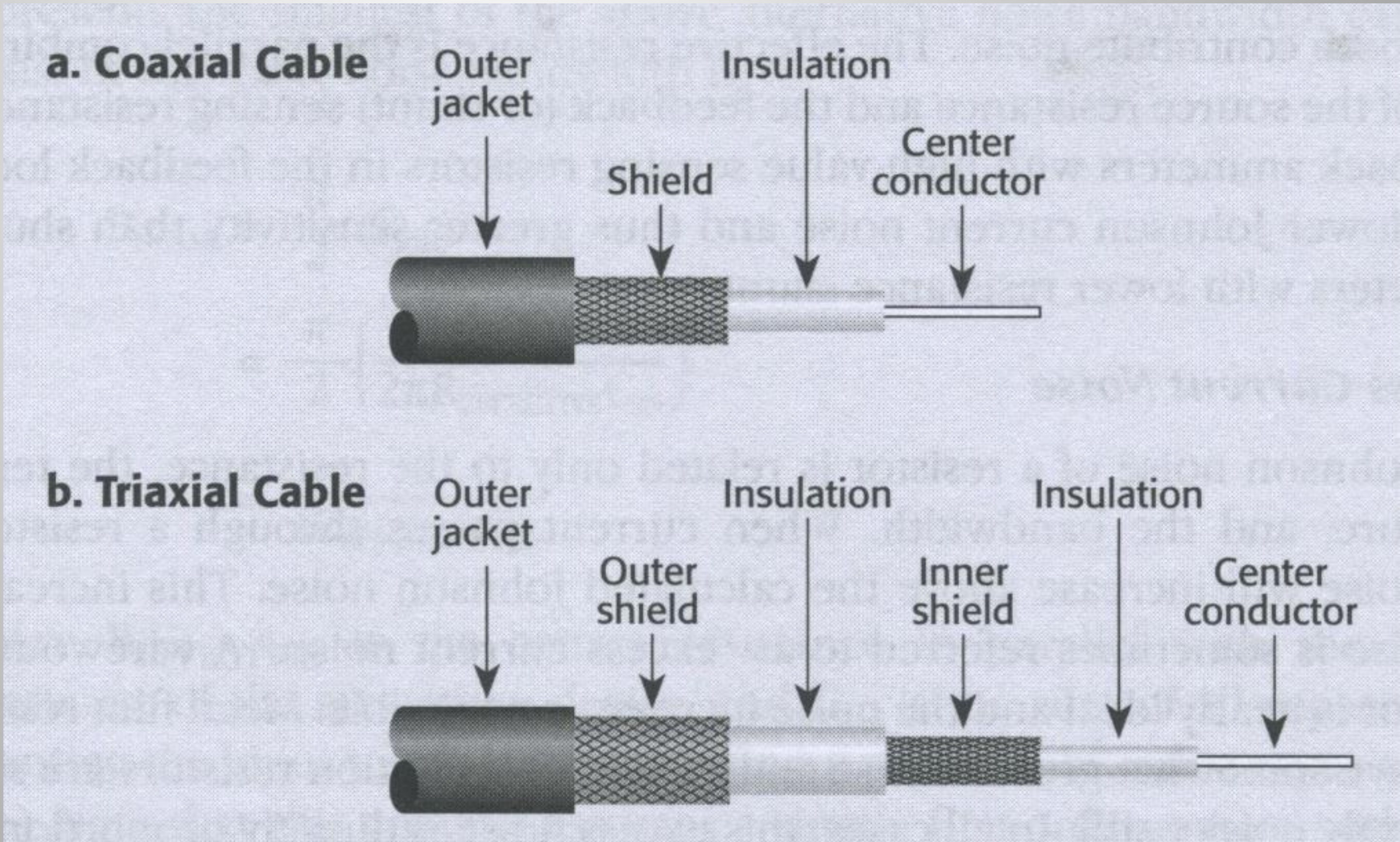
Curves are applicable under the assumption of perfect symmetry.



Coaxial and Triaxial

Coaxial only when you know how much noise current at which frequency will challenge the screens

Alternating magnetic near fields:
None of the two cable types is able to suppress these.
Allow for standing voltages in the ELF domain.

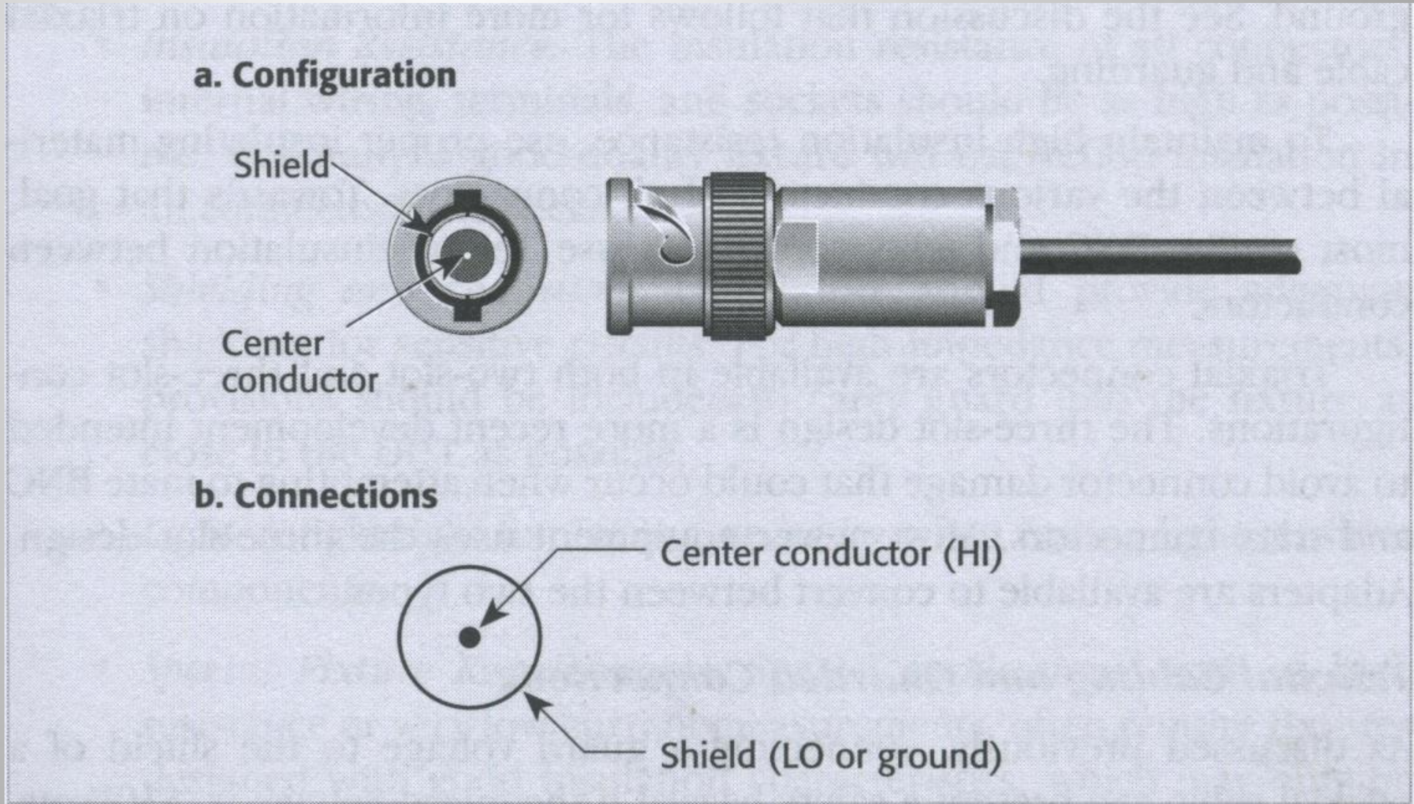


BNC (and all single ended coaxial connectors)

Grounded or insulated:
Screen and signal return use the same path

Screen currents (wherever they come from) mix with the signal return.

CM to DM conversion because screen impedance different from centre conductor impedance



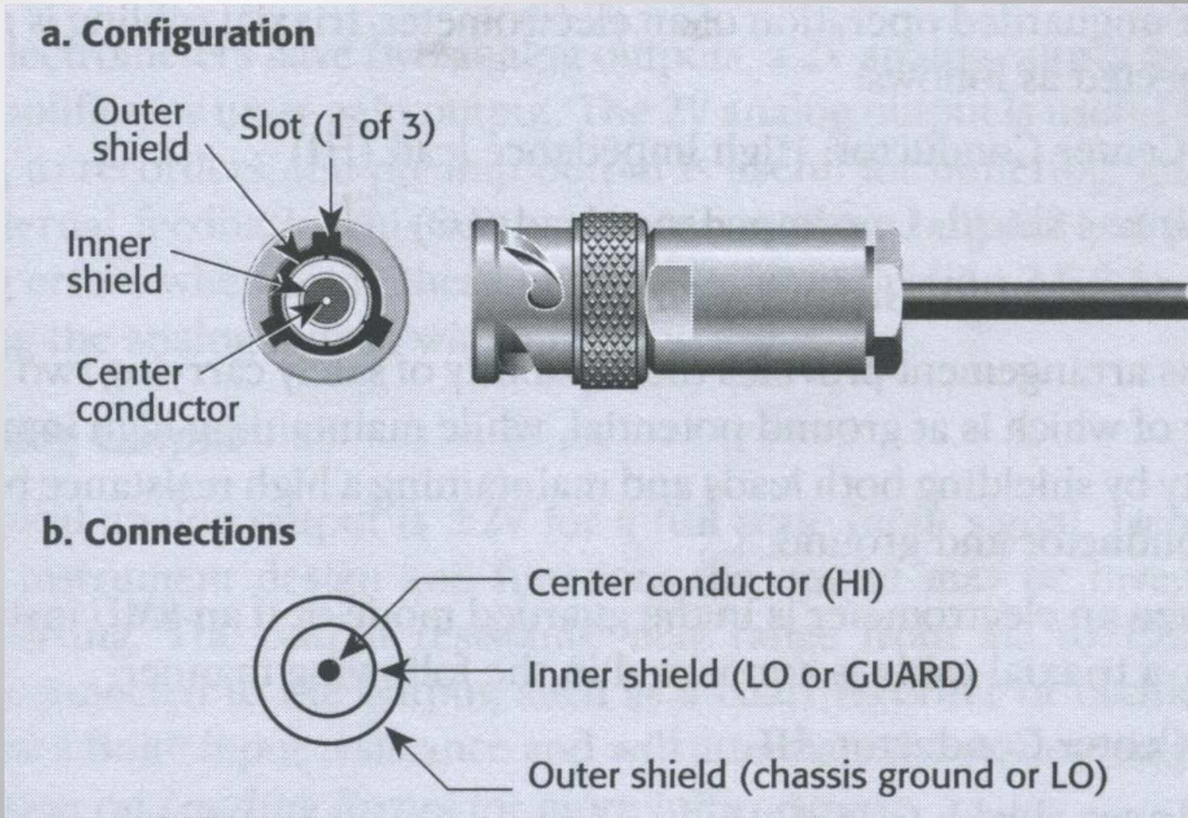
Triaxial Cables and Connectors

Grounded or insulated:
Screen and signal return are now separated

Screen currents (wherever they come from) cannot mix with the signal return.

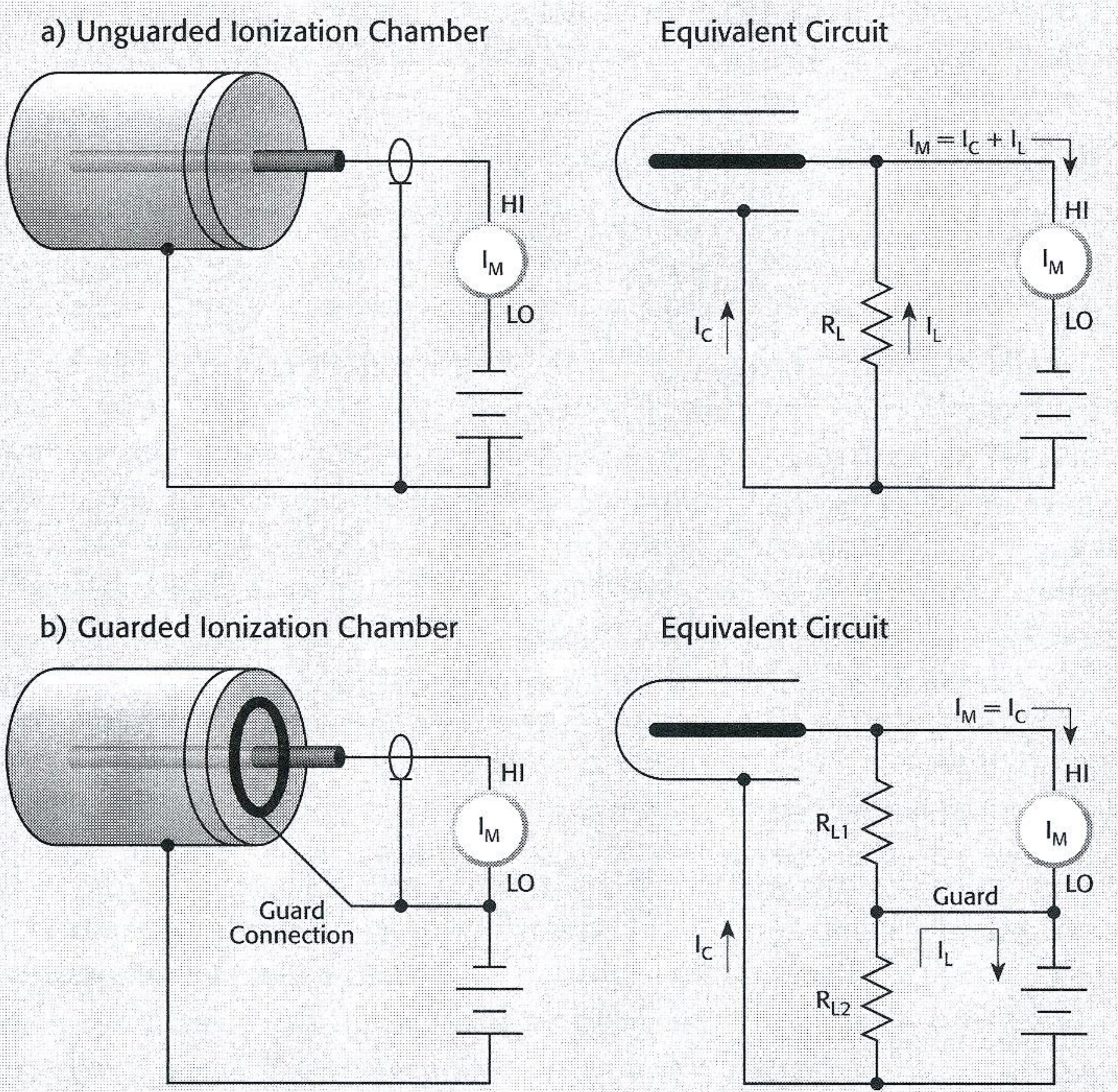
CM to DM conversion is muss less dominant.

Guard shield configuration eliminates leakage.



Ionisation chamber with and without Guard

Circuit below compensates cable leakage.
Attention:
One cable screen is on high voltage.
EMC:
Guarded configuration is more robust against ambient noise.

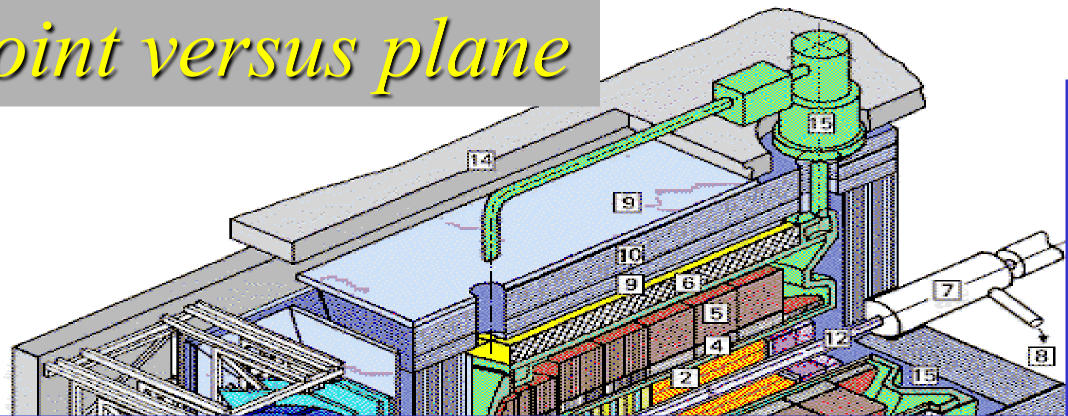


Part 0 Some Prerequisites
Part 1 What is special at CERN?
Part 2 CERN's Internal Limits
Part 3 Equipotentiality
Part 4 Conducted Noise, Filters
Part 5 Radiated Noise and screening
Part 6 Cabling, Cables, Connectors
Part 7 **Physics Experiment EMC Applications**
Part 8 Accelerator EMC Applications
Part 9 Safety System EMC Applications
Part 10 Conclusions

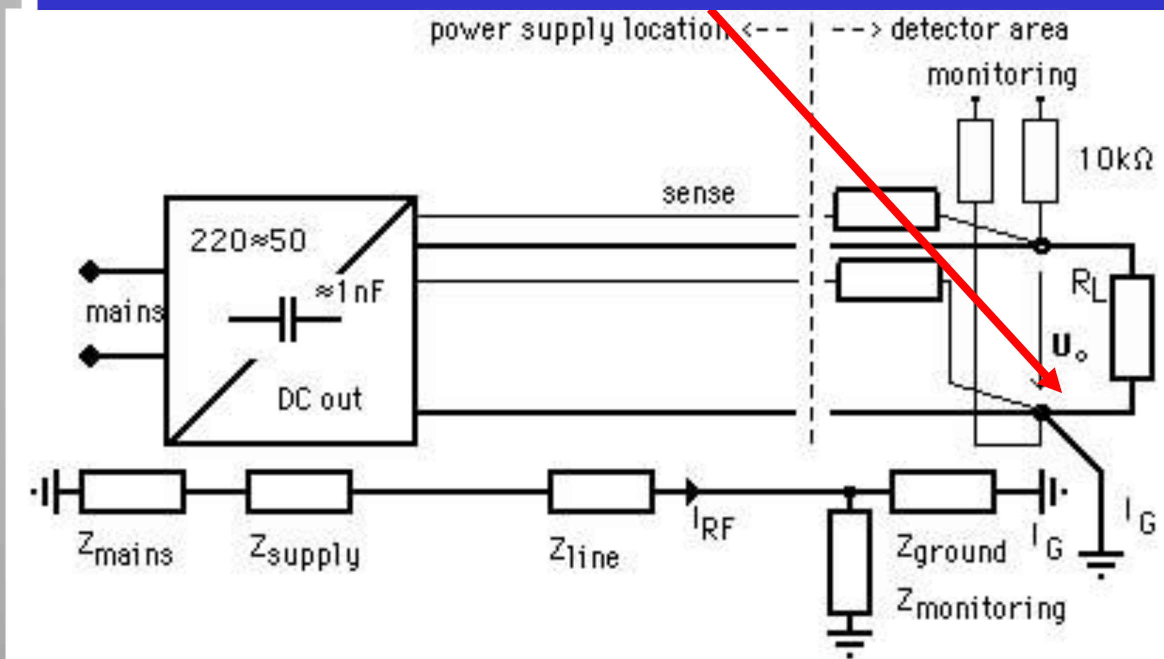
Part 7 Physics Experiment EMC Applications

- Switch Mode Power Supplies (SMPS)
- Physics Experiments
- Air & spacecraft, Cars
- Linear power supplies
- System layout basics

Point versus plane



earth star point=as much metal as possible



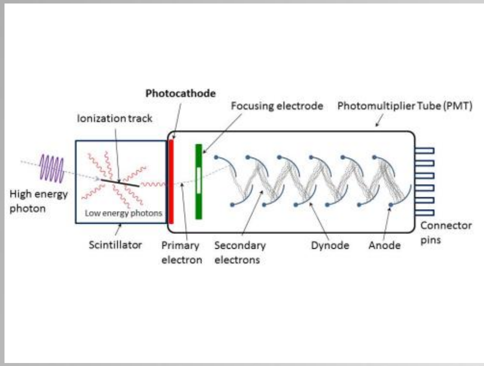
Unfortunately many physics apparatus are built using "subdetectors" insulated from each other galvanically.
This approach makes practically all experiments very sensitive to noise.

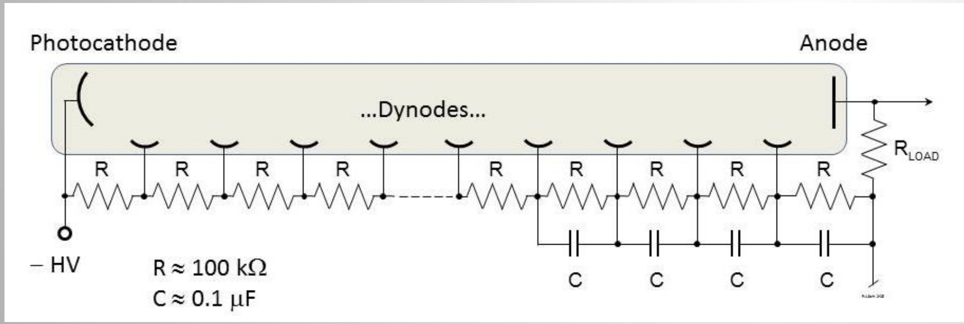
A new phenomenon in physics is software EMC, i.e. the cancellation of unwanted parts of a signal through extensive processing, or through relative measurements at very high sampling rates.

A PMT is a current source

Photomultiplier

How to establish the CBN?





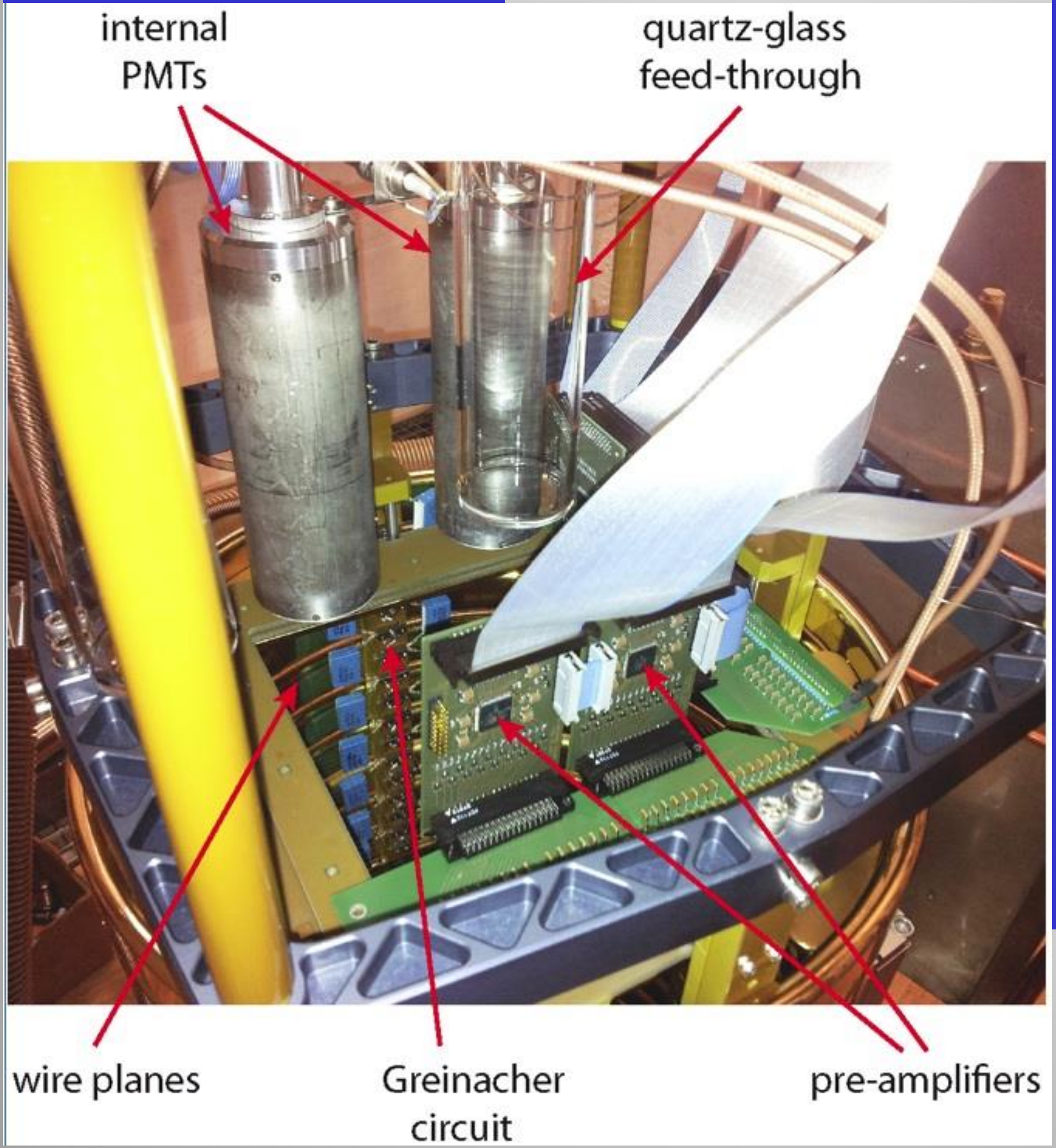
EMC on PMT:

- Signal=current source
- Noise=current source
- Magnetic fields influence electron cascading

Electronics far from PMT:
a) Establish local ground planes
b) Connect continuous shield WHICH IS NOT THE SIGNAL RETURN

A typical small physics detector

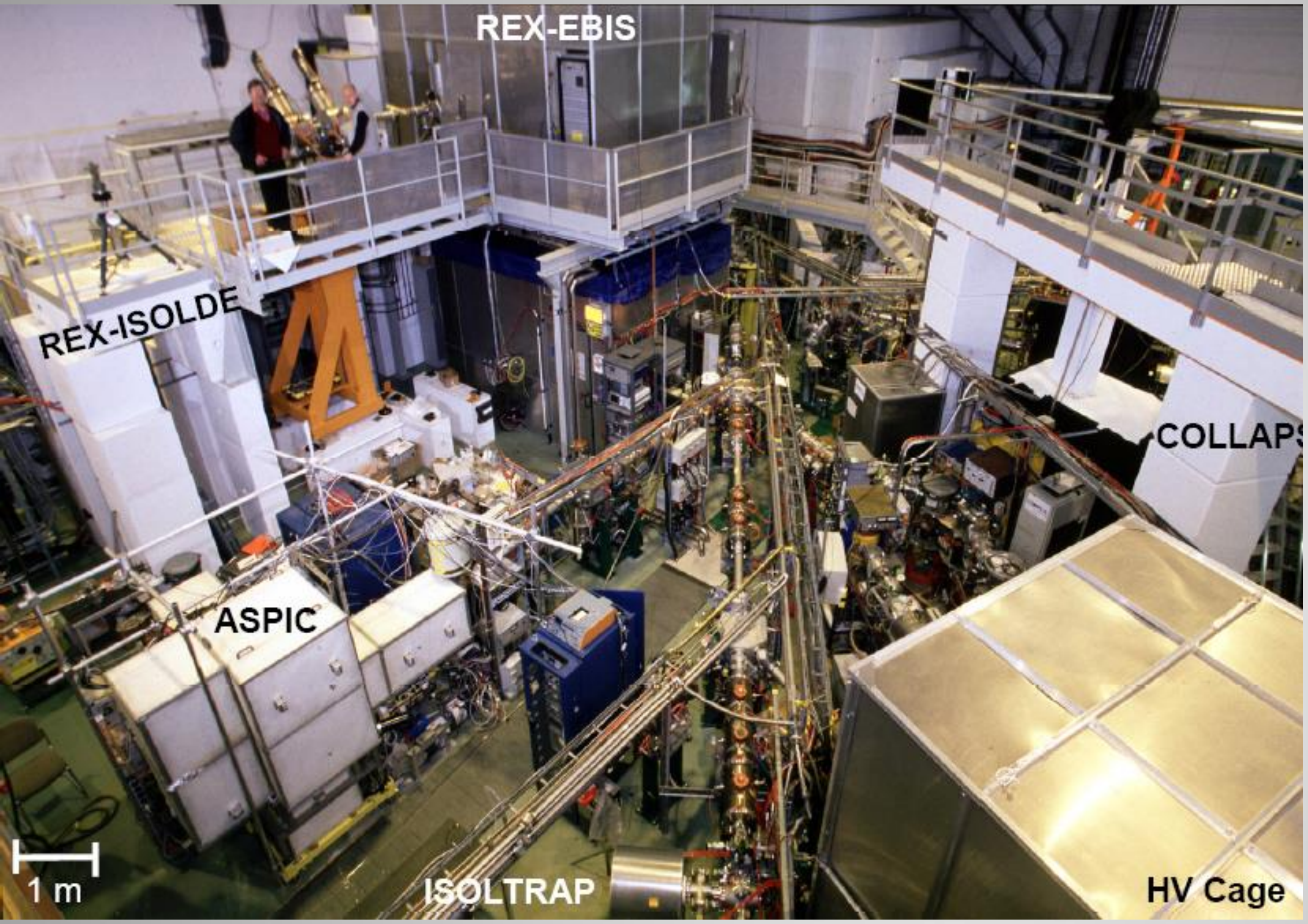
No apparent CBN



Miraculously internal bonding occurs through the PCB-ground-planes. However, there is neither RF-immunity nor any tolerance to support ELF magnetic near fields (induction).

Bonding would make the setup more robust, safer, cheaper and more reliable.

A crowded experimental hall



In terms of EMC:

a random collection of apparatus.

No metal sheets on the floor, no proper high frequency CBN.

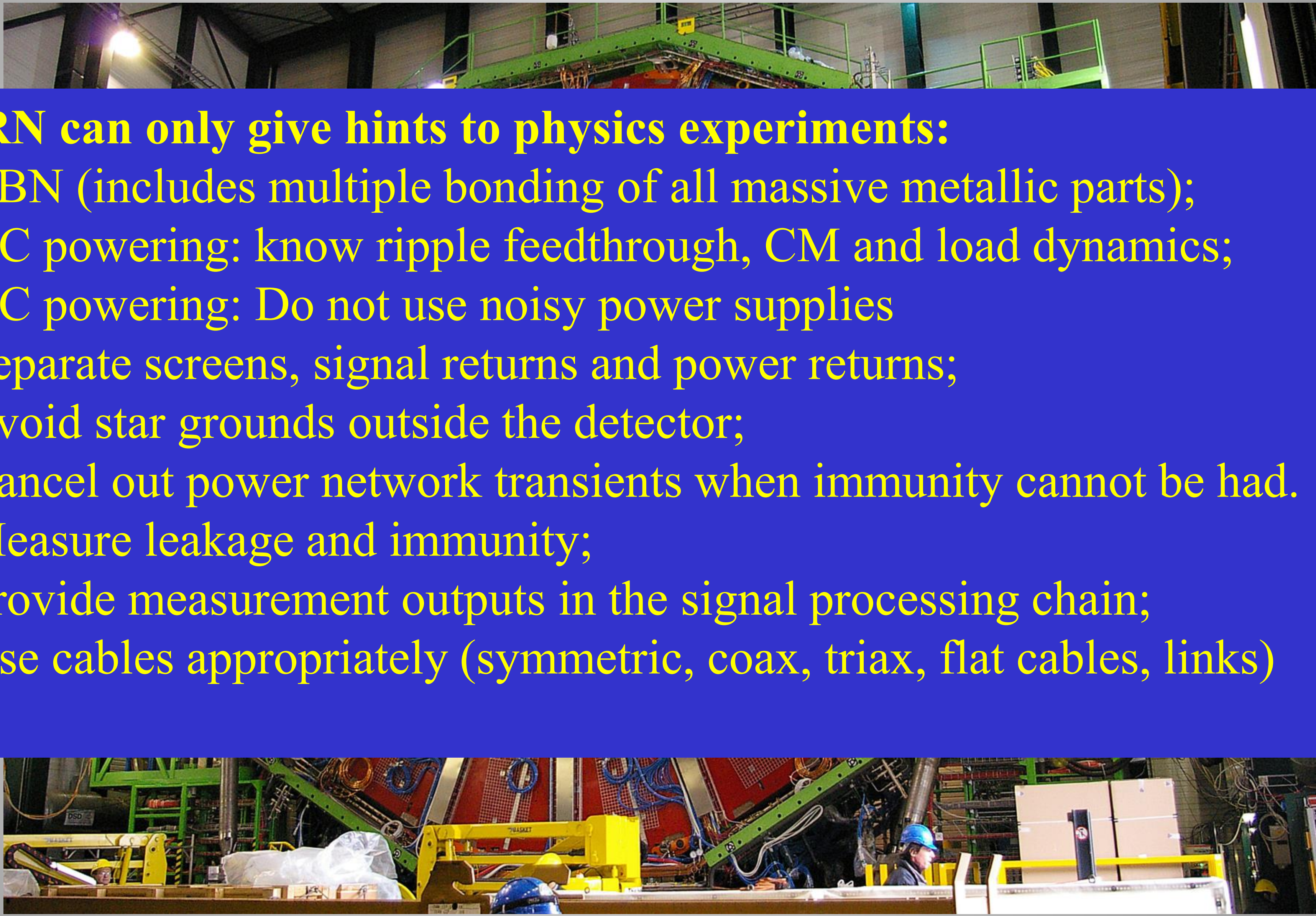
Fortunately there are metallic cable trays.

EMC:

CERN recommends local ground planes and as much shielding as possible

Leakage is measured and cured because it would affect all measurement apparatus

Professional approach for physics detector EMC



CERN can only give hints to physics experiments:

- CBN (includes multiple bonding of all massive metallic parts);
- DC powering: know ripple feedthrough, CM and load dynamics;
- DC powering: Do not use noisy power supplies
- Separate screens, signal returns and power returns;
- Avoid star grounds outside the detector;
- Cancel out power network transients when immunity cannot be had.
- Measure leakage and immunity;
- Provide measurement outputs in the signal processing chain;
- Use cables appropriately (symmetric, coax, triax, flat cables, links)

Examples of EMC solutions

in High Energy Physics Apparatus

(CERN jargon: "Detector", "Experiment")

UA1 matter-antimatter-collisions

RD5 muon puchthrough in magnetic field

NA48 Charge parity violation

ATRAP Antihydrogen Trap

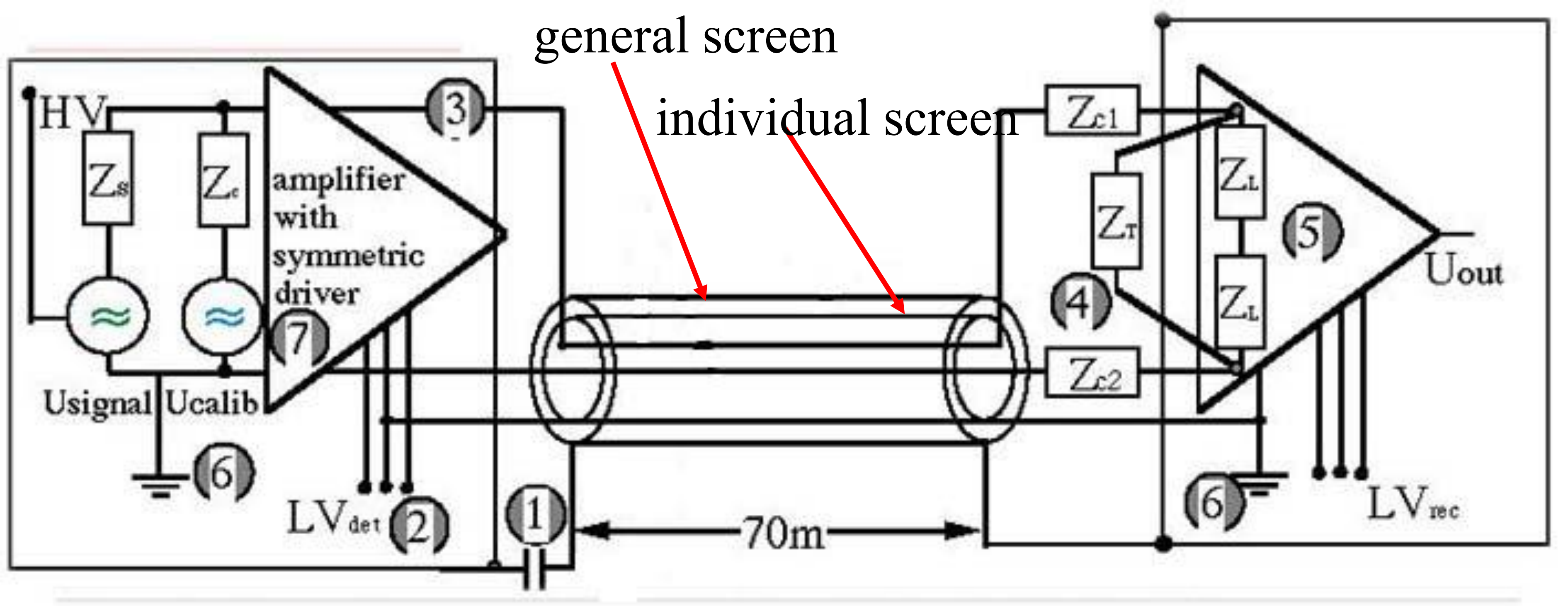
CMS Compact Muon Solenoid

and many others of lesser importance

UA1 Matter Antimatter collisions Analogue readout, bandwidth 100 MHz, dynamic range 10^3

Task: Make readout chain free of noise because it directly defines calibration and measurement accuracy of a Nobel Prize experiment. Noise was 32dB above limit.

1 open general shield for low frequency, close it for high frequency
2 insulate very low voltage supply lines from earth
3 let individual screen become part of the individual earth system (guard shield)
4 terminate signal line symmetrically 5 improve RF symmetry of receiver
6 let general shield act such that it carries the least amount of current
7 make driver truly symmetric (see next slide)



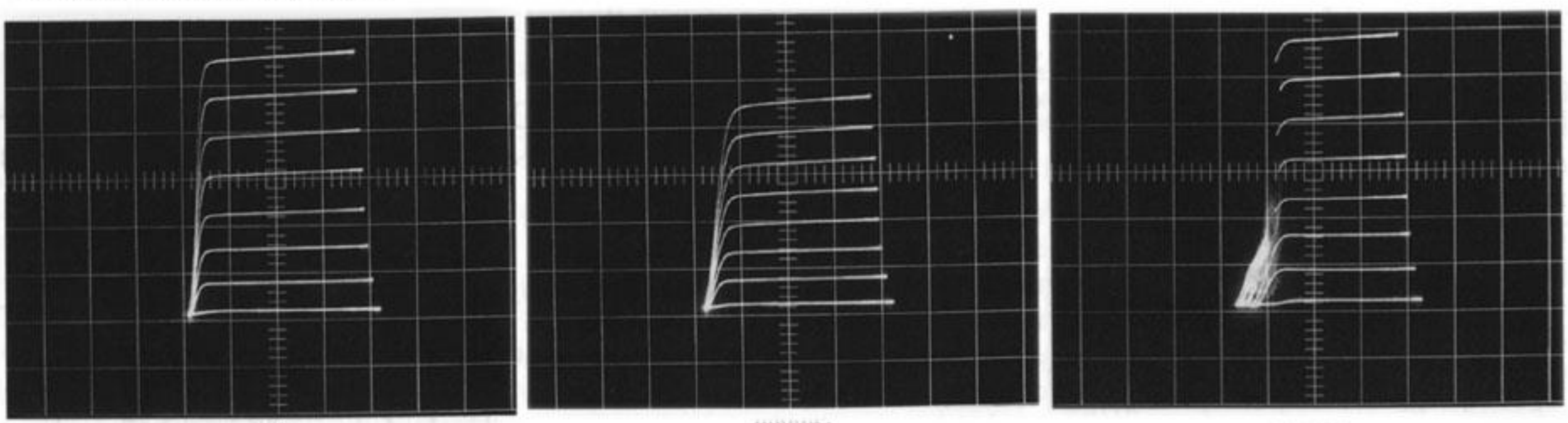
UA1 Matter Antimatter collisions Analogue readout, bandwidth 100 MHz, dynamic range 10^3

Due to the 70m long twisted pair cables and rather low impedance towards ground the common mode induced by the 600Hz fringe field of the huge 2000 ton-magnet (600V, 10kA, 12-pulse thyristor rectifier with some residual ripple) altered the operating point of the driver transistors, thus causing common-to-differential conversion.

The effect is well known but it is very difficult to discover and determine in situ.

Transistor Data change with Radiofrequency Exposure

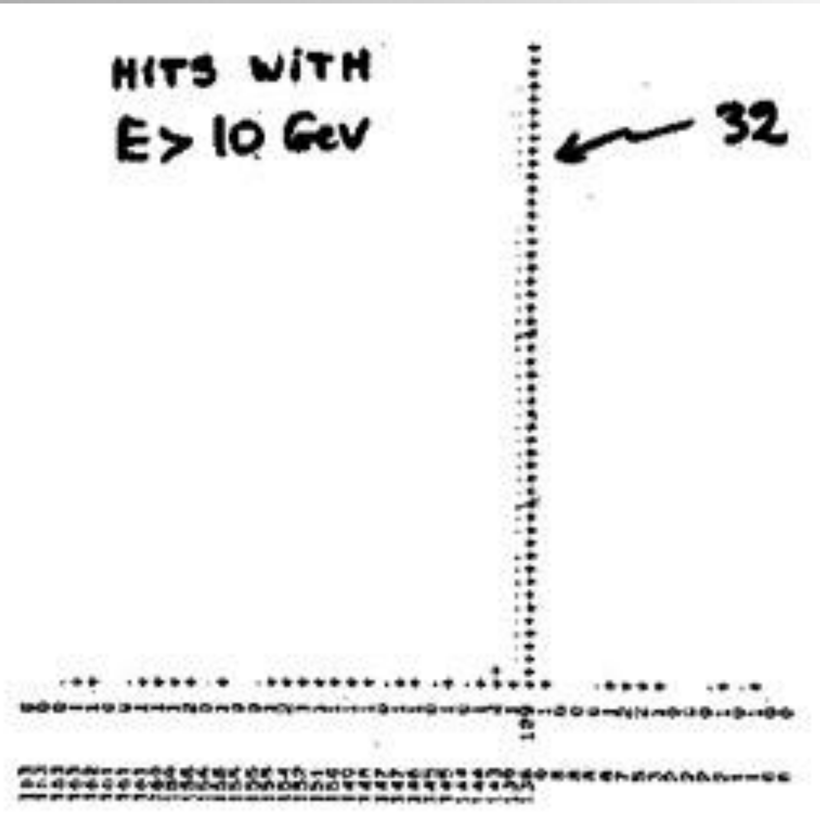
Solutions: Design change or higher ground impedance

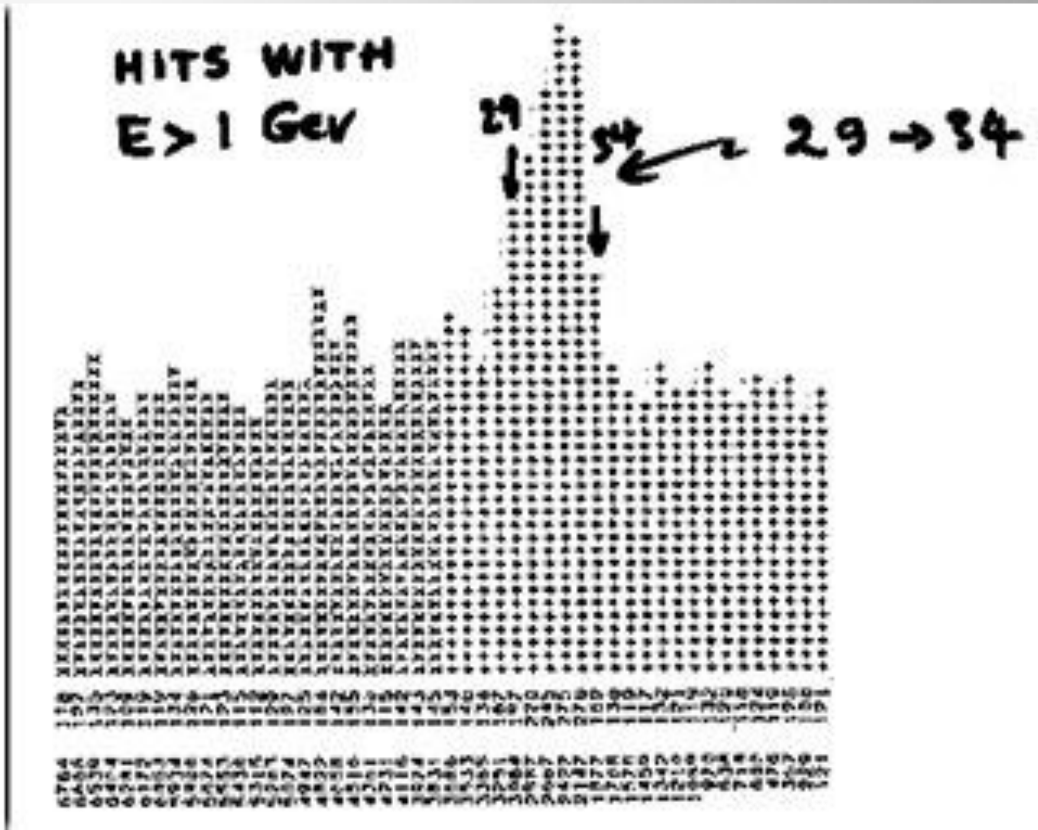


Normal curve traces — 300 mV RF base to emitter — 3 V collector to emitter

UA1 Matter Antimatter collisions
Perturbed calorimeter trigger

After extensive analysis and measurements the solution was a simple repair of a cable screen causing not only common-to-differential conversion but also radiating out to neighbour channels.





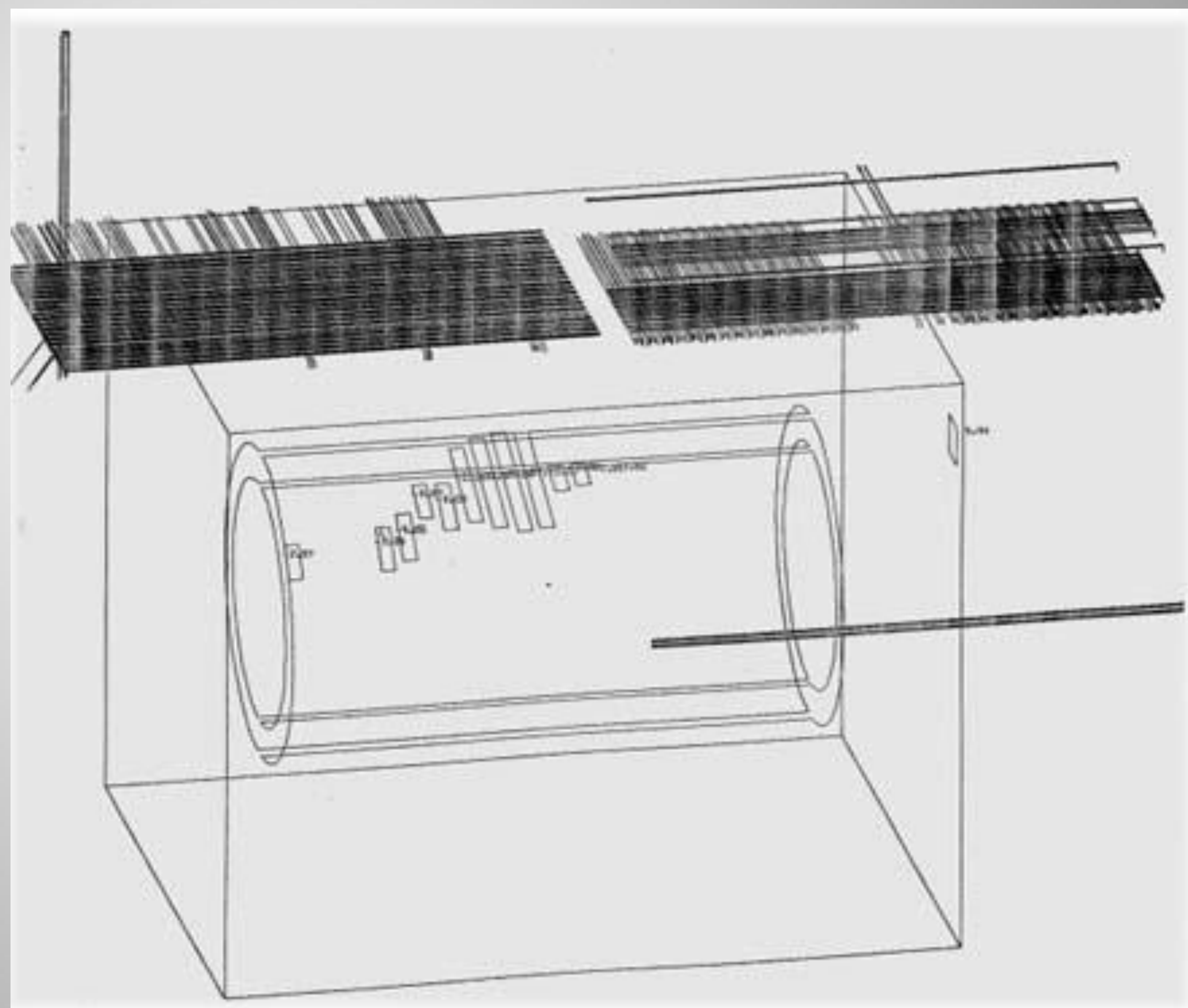
UA1 Matter Antimatter collisions Oscillating muon chambers

Readout chain with 70ns discriminators/shapers on the chamber, 70m of twisted pair cabling NOT DRIVEN SYMMETRICALLY, i.e. one lead on ground and one lead on single ended driver.

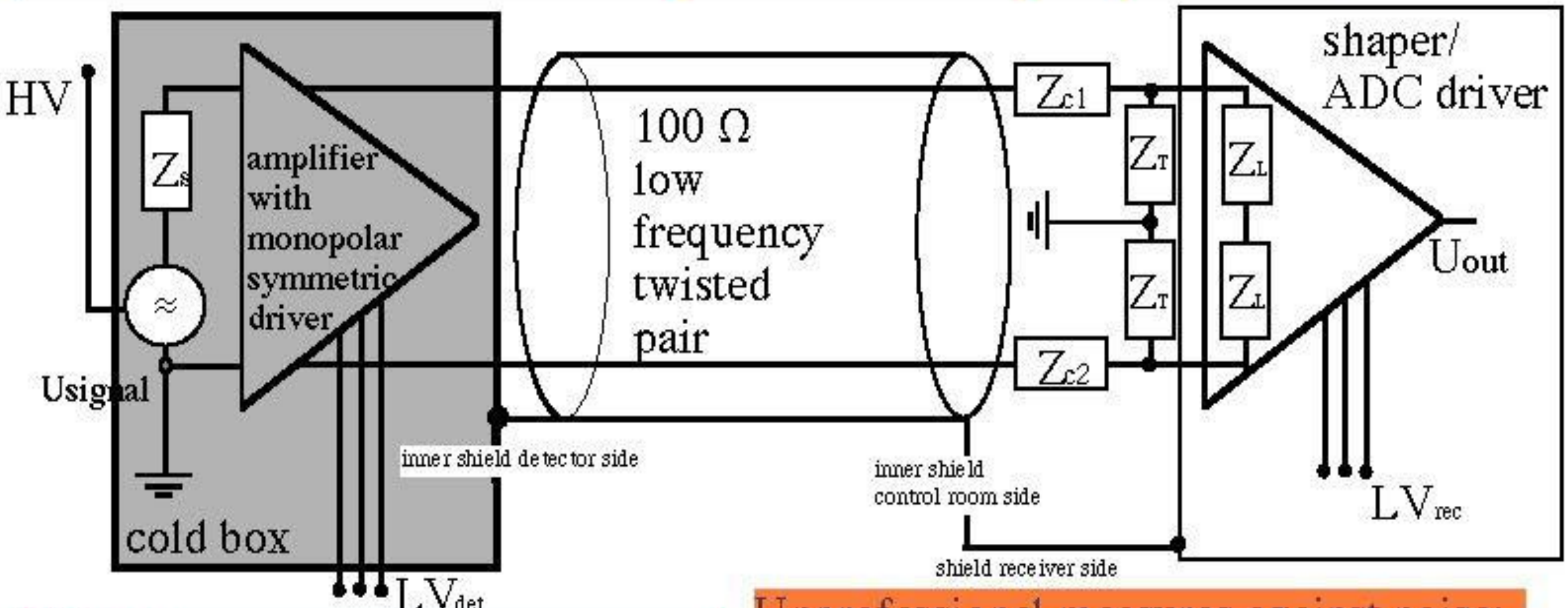
Such systems have a strong susceptibility in the range of the shaping time (70ns→14MHz).

The system is conditionally stable.

When enough sensors trigger the entire system is triggered by auto-interference and runs as oscillator. See image.



NA48 charge parity violation experiment with analogue readout in liquid argon vessel volume 60m below ground



Effects:

1) oscillations of all amplifiers exhibiting extremely narrow spectral line
2) strong susceptibility to RF noise

Reasons:

1) common mode to differential mode conversion on cable and shaper (RF asymmetry)
2) bad shielding against RF in spite of Faraday cage around detector
3) Combination (also) yields oscillations

Unprofessional measures against noise:

1) Search for noise sources (always bad)
2) Modification of Faraday cage, low voltage, ground configuration, readout
3) Extensive measurements on single channel behaviour, conclusions for doing 1) and 2)

Professional measures against noise:

1) Improve Faraday cage by creating RF guard shield
2) Improve receiver of shaper for better RF symmetry and termination

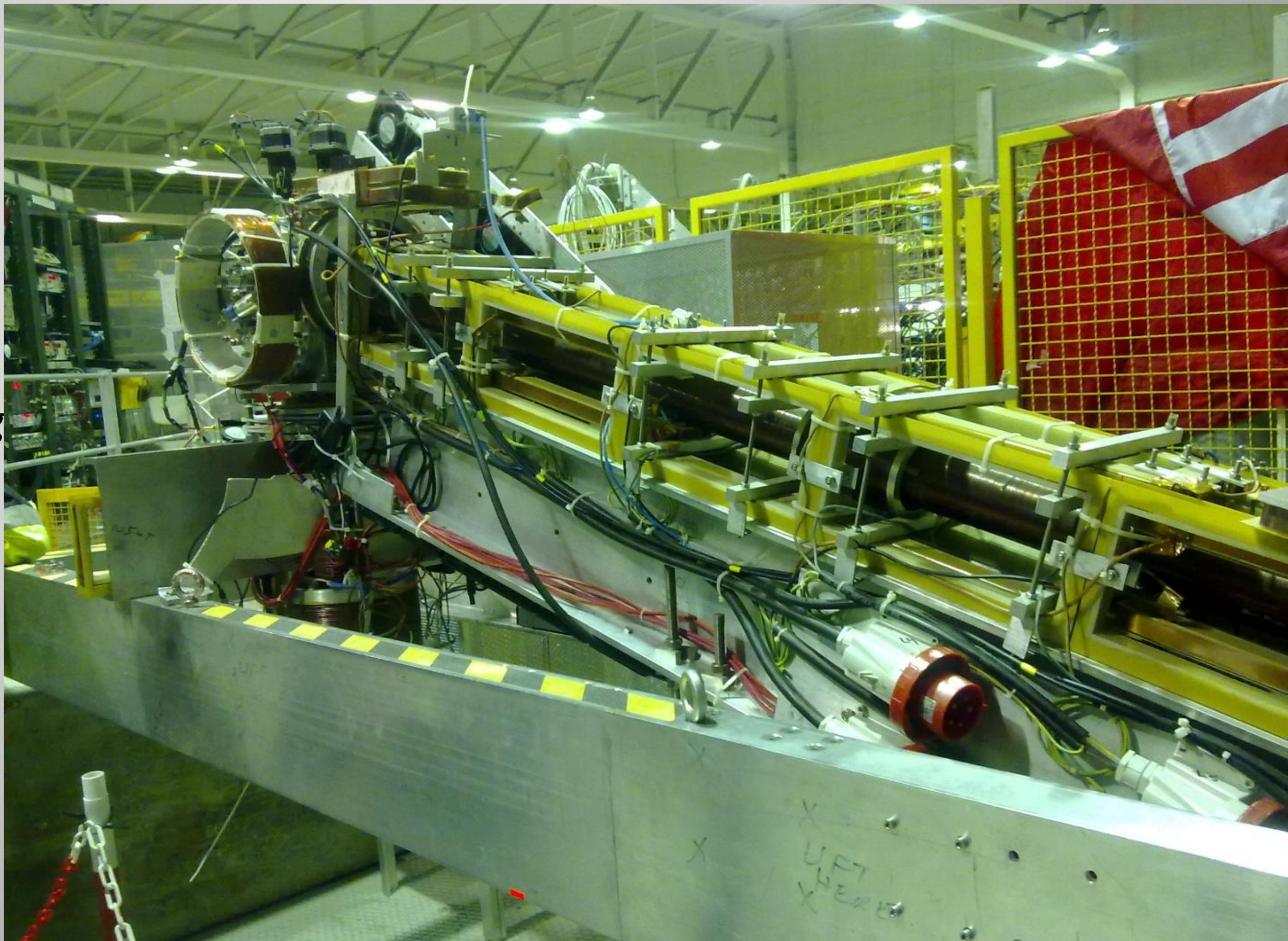
Experiment ATRAP – Magnetic field interference

EMC Lab was called for determining influence onto the precision magnet determining the path of antimatter in an antihydrogen trap.

Solution:

The field was disturbed by the presence of iron (magnetic material) moving across the experiment:
The overhead travelling crane.

There was no electrical interference.

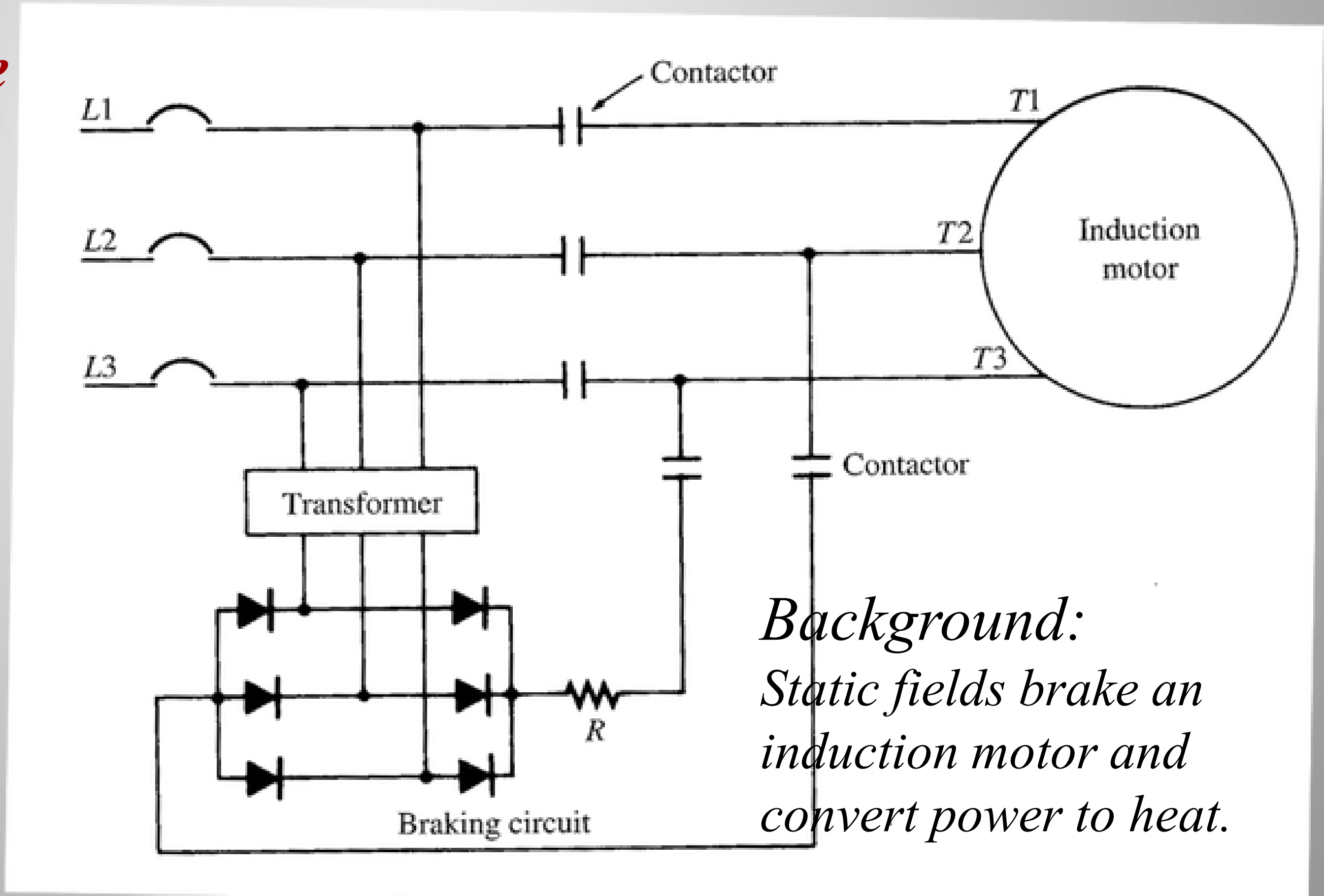


Experiment CMS – 30mT fringe field interference with induction motor

A coolant circuit pump motor (P=30kW) had to be replaced several times after only a few days of running below nominal load.

The 20-100mT fringe field of the CMS magnet, the biggest worldwide, constantly induced voltage in the squirrel cage of the induction motor.

Hence the bearings overheated.



Background:
Static fields brake an induction motor and convert power to heat.

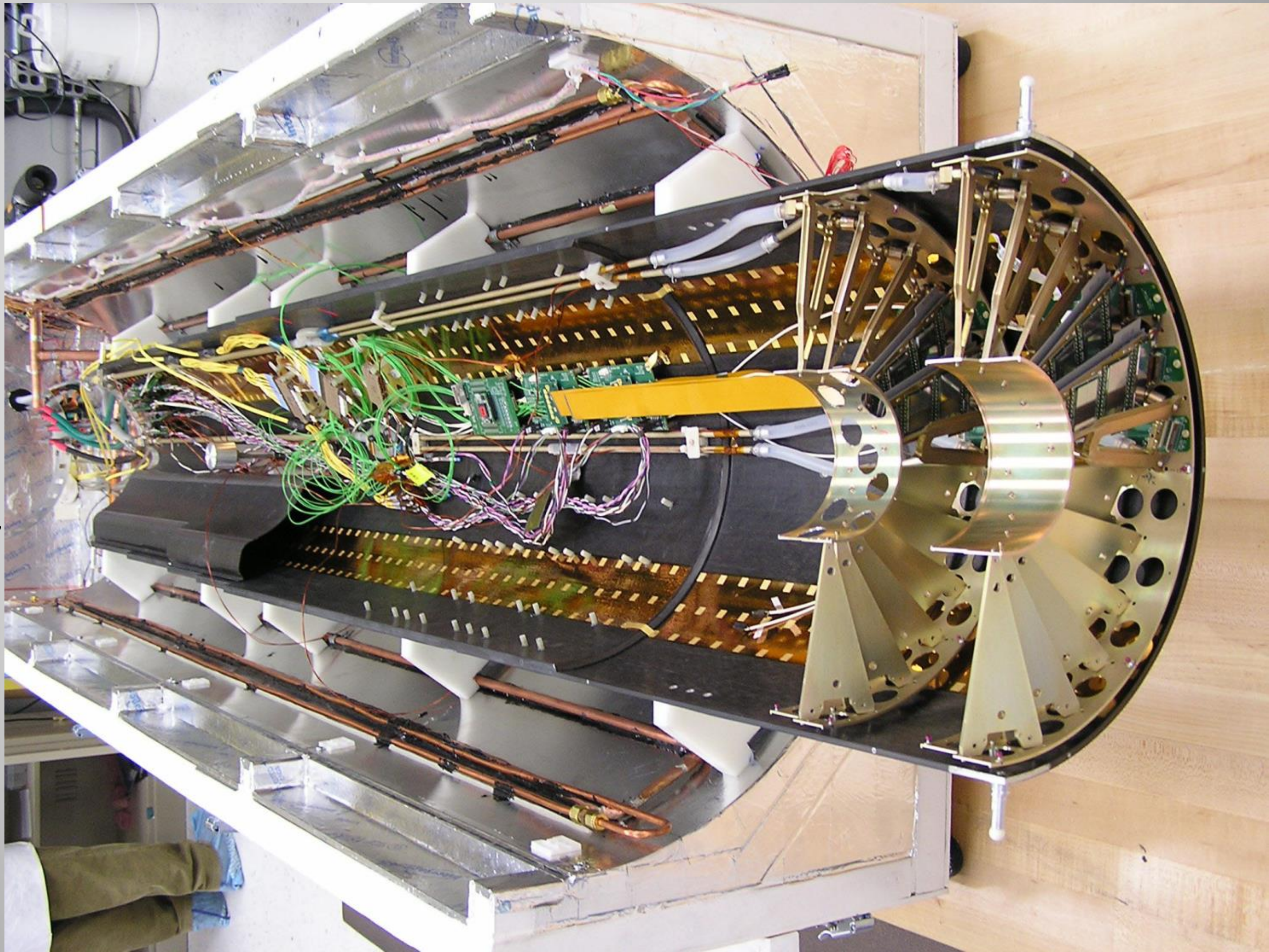
CMS PIXEL Detector with DCDC-converters
A recent example of interesting EMC trouble

Cabling and cooling of the DCDC-converters

In the centre of this detector is the beam tube (not on picture). The beam current (i.e. the particle bunches) is only centimetres away from the electronics.

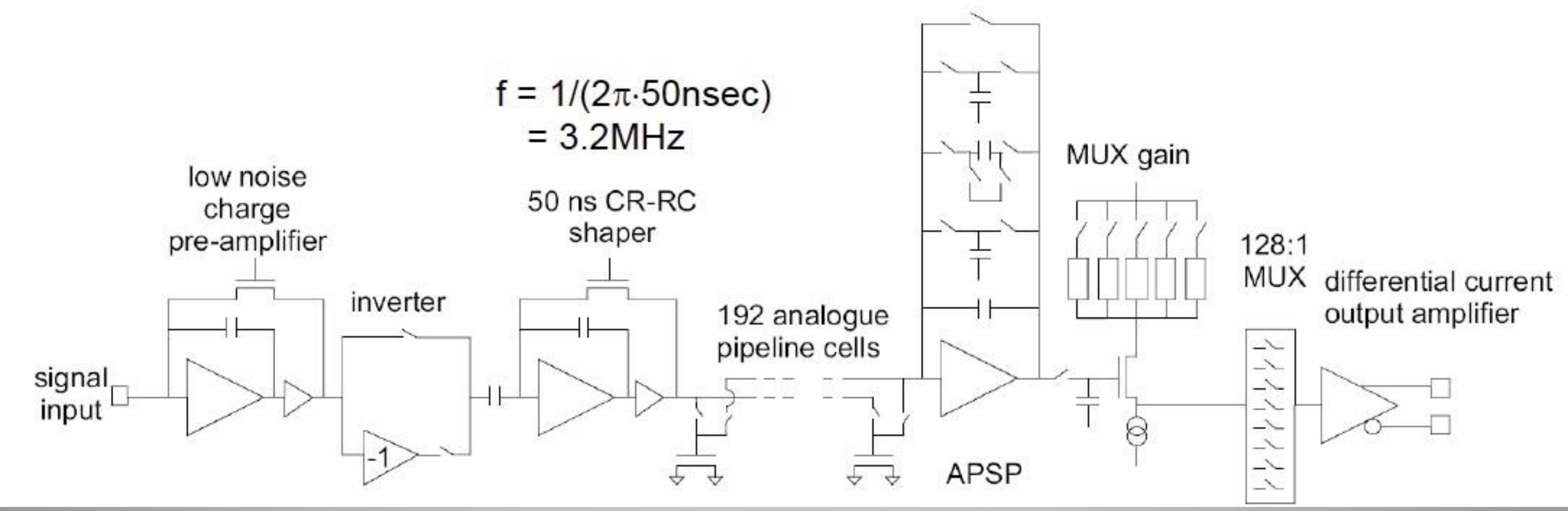
In principle the electronics is completely shielded.

The cabling geometry is far from being optimal and also varies from quadrant to quadrant.



Millions of CCD's are powered with 2.5VDC

Supply voltage 2.5 VDC. No transients above 4 V. Significant power line noise feedthrough, plus pickup from sensors. No analogue output.



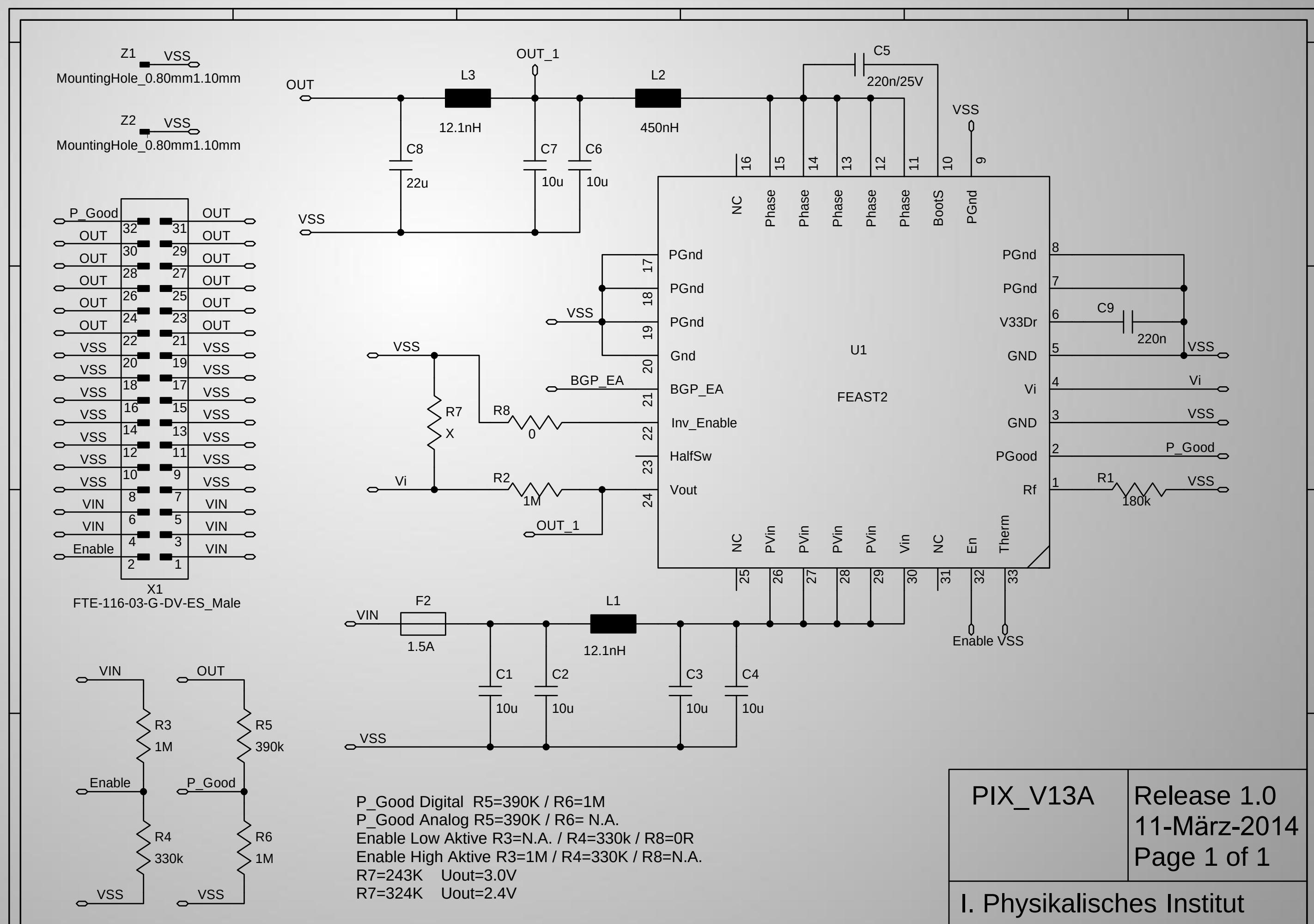
EMC of the radiation hard DCDC-converter

11VDC to 2.5VDC DCDC-converter with π-filter at input and output. There also are an "enable" line without any protection at all, plus a status output "power good".

The designers tested all components, then the system, then the system implementation.

The chip is supplied via 120m long cables with 11VDC, and the enable line is a 130cm long twisted pair with one lead on ground (!!).

Challenge: The converters were partially or totally destroyed after the accelerator changed its bunch structure and yielded higher peak currents. It was urgent to find a solution.

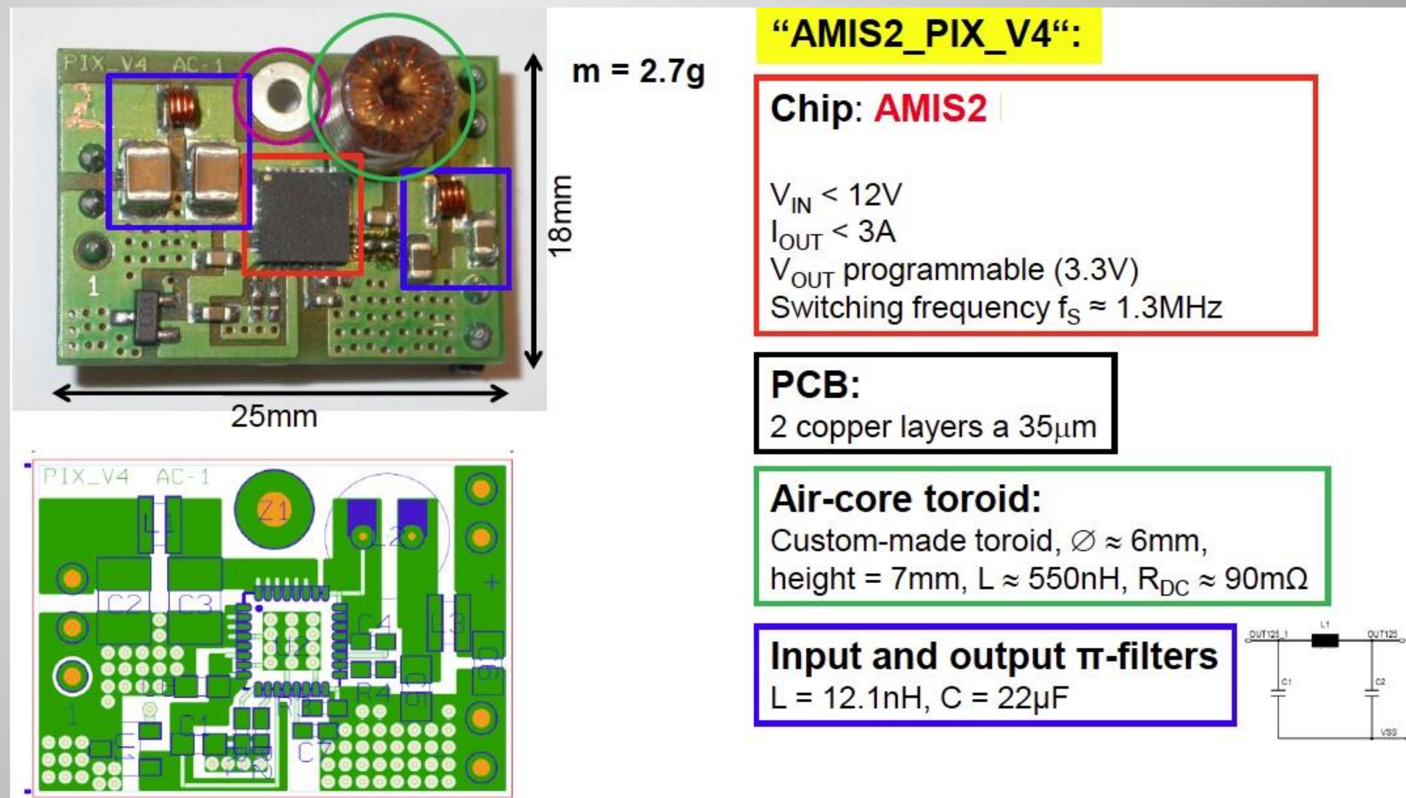


DCDC-converter technical data plus filters

Switching frequency: 1.3MHz
Chip needs “enable” logical signal and hands back “power good” logical signal

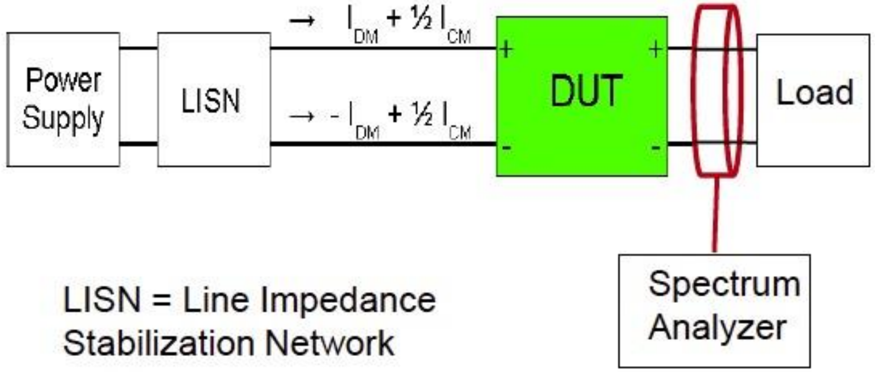
Board layout with radiation tolerant chip in the centre

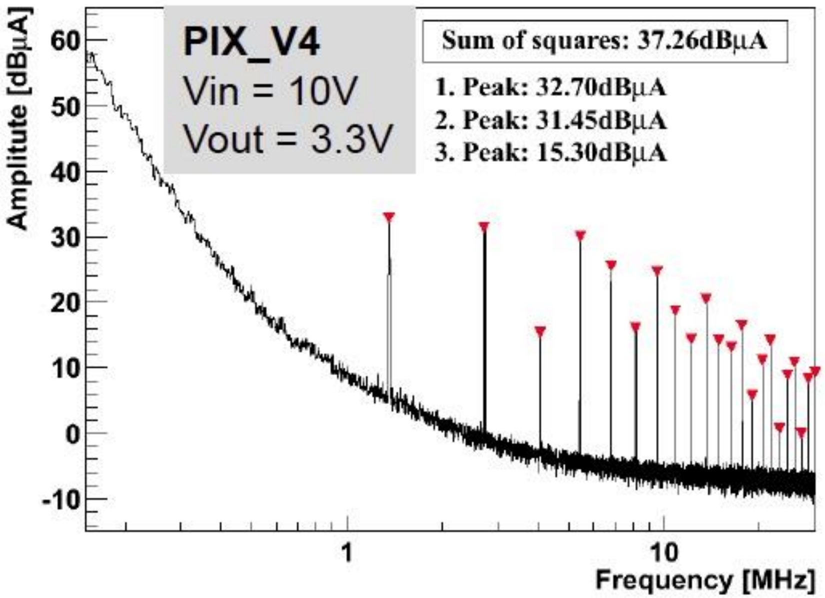
PCB

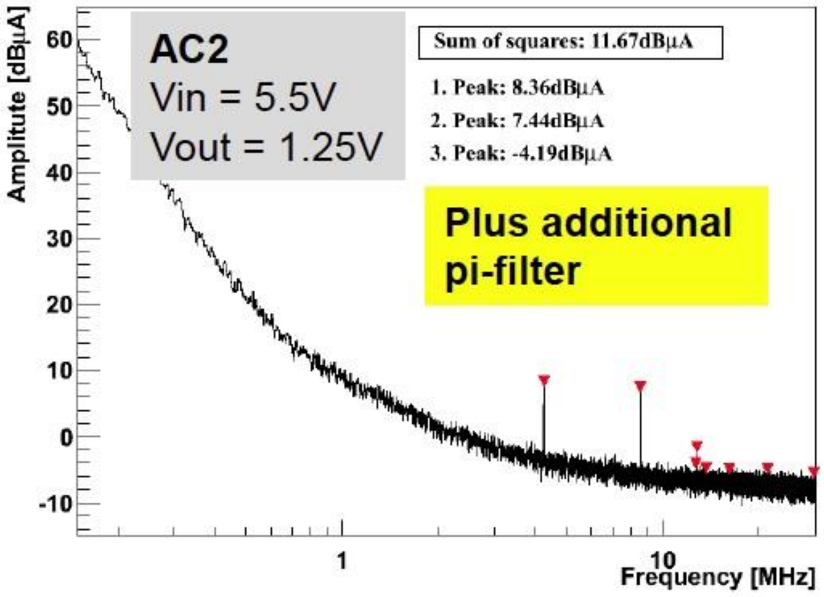


Noise comparison in-house to commercial version

Setup and arrangement are not standard EMC measurement approach but anyway the noise measurements differ significantly between commercial and CERN version

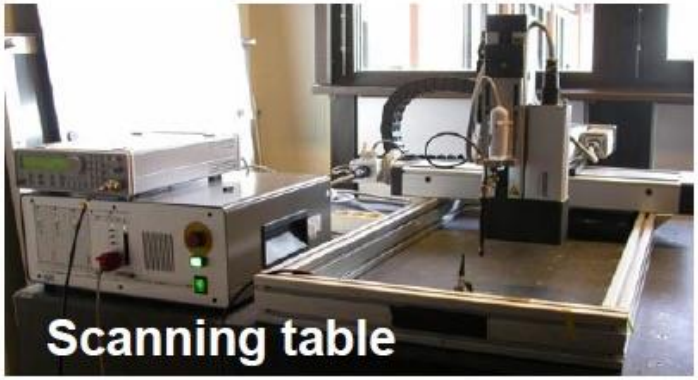


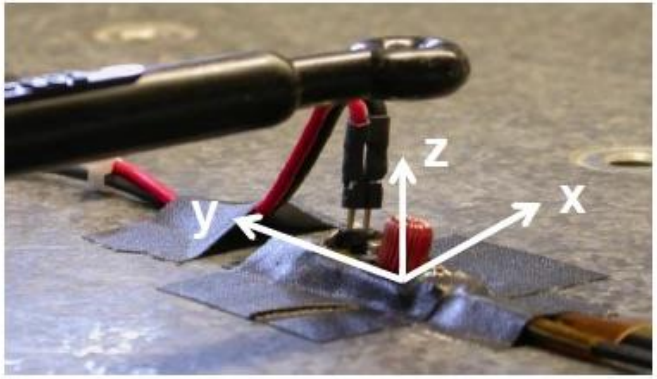




Measurements for minimising RF-radiation

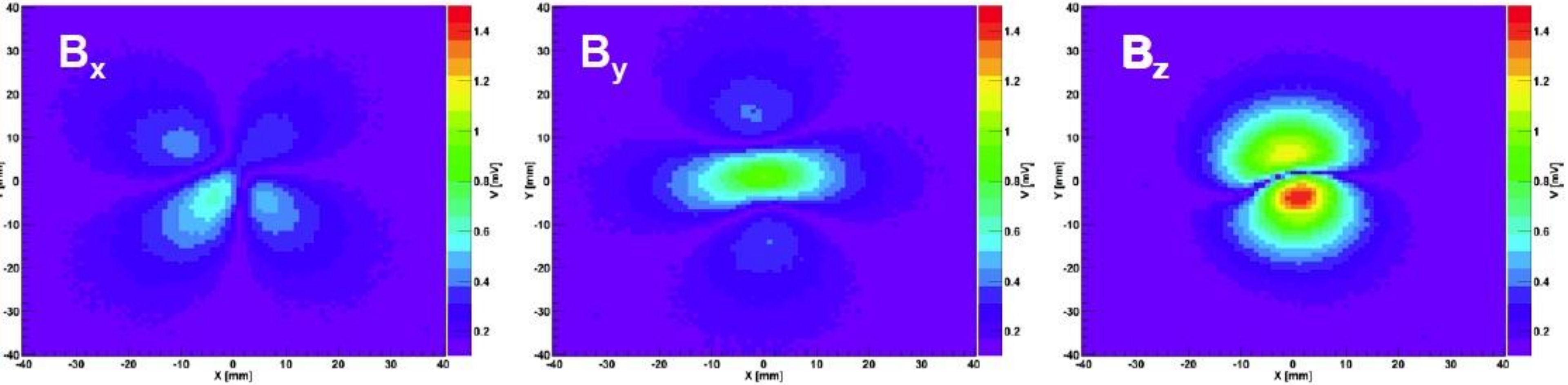
Extensive three dimensional H-field measurements to find best configuration and to identify hot spots





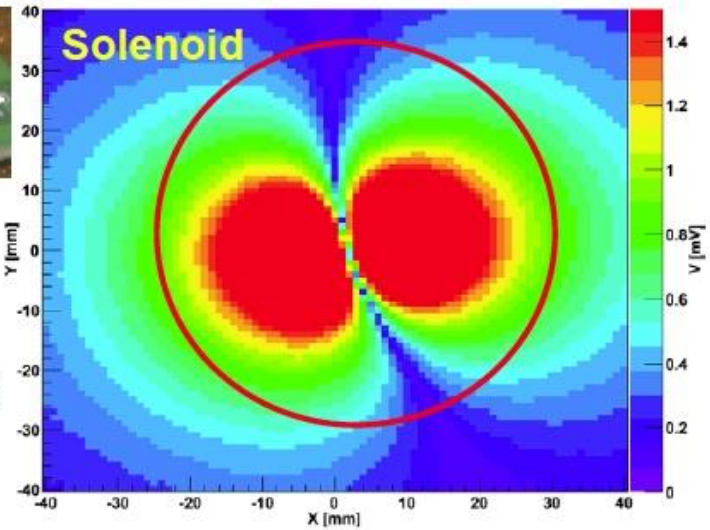
Emitted field is measured with a pick-up probe and spectrum analyzer [height of 1. peak]

Measured components of magnetic field in x-y-plane, 1.5 mm above coil:

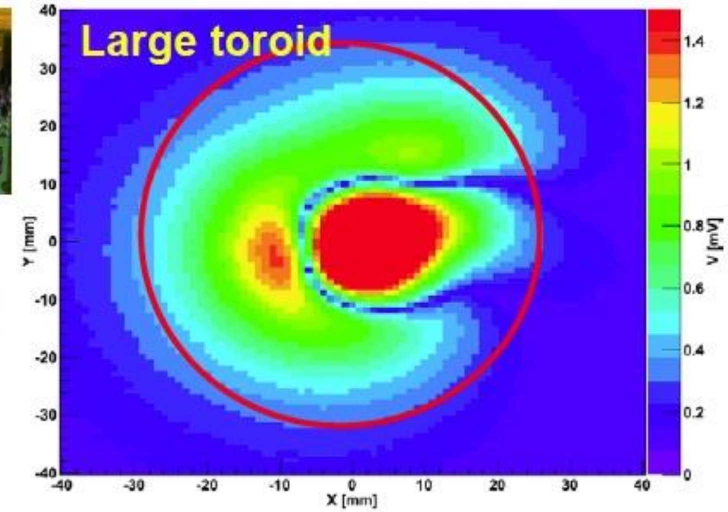


Measurements for minimising RF-radiation

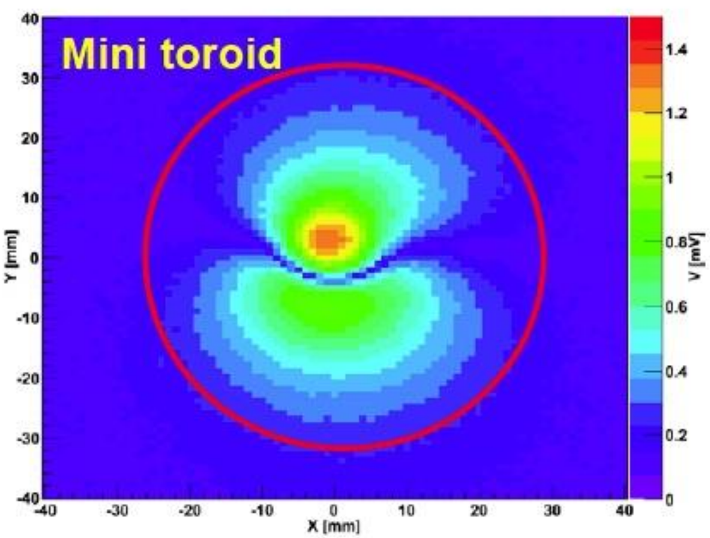
Various different inductor versions were placed onto the DCDC-converter PCB



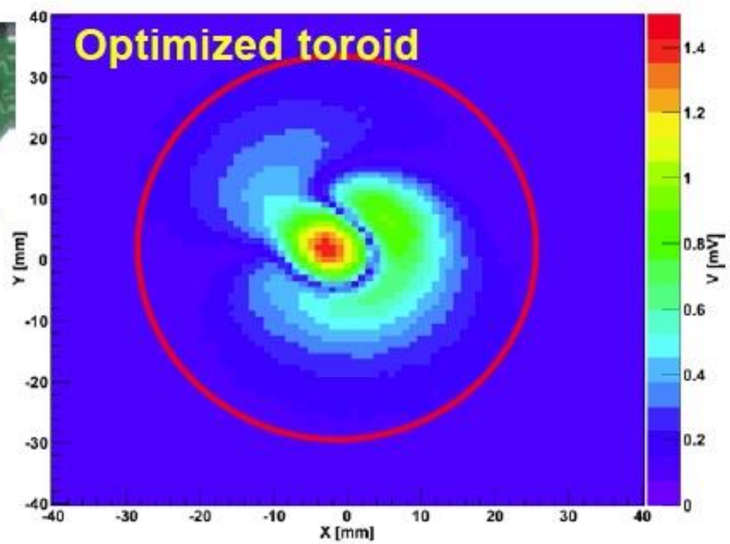
Nom.:
538nH,
90mΩ,
~ 500mg



618nH,
104mΩ,
783mg

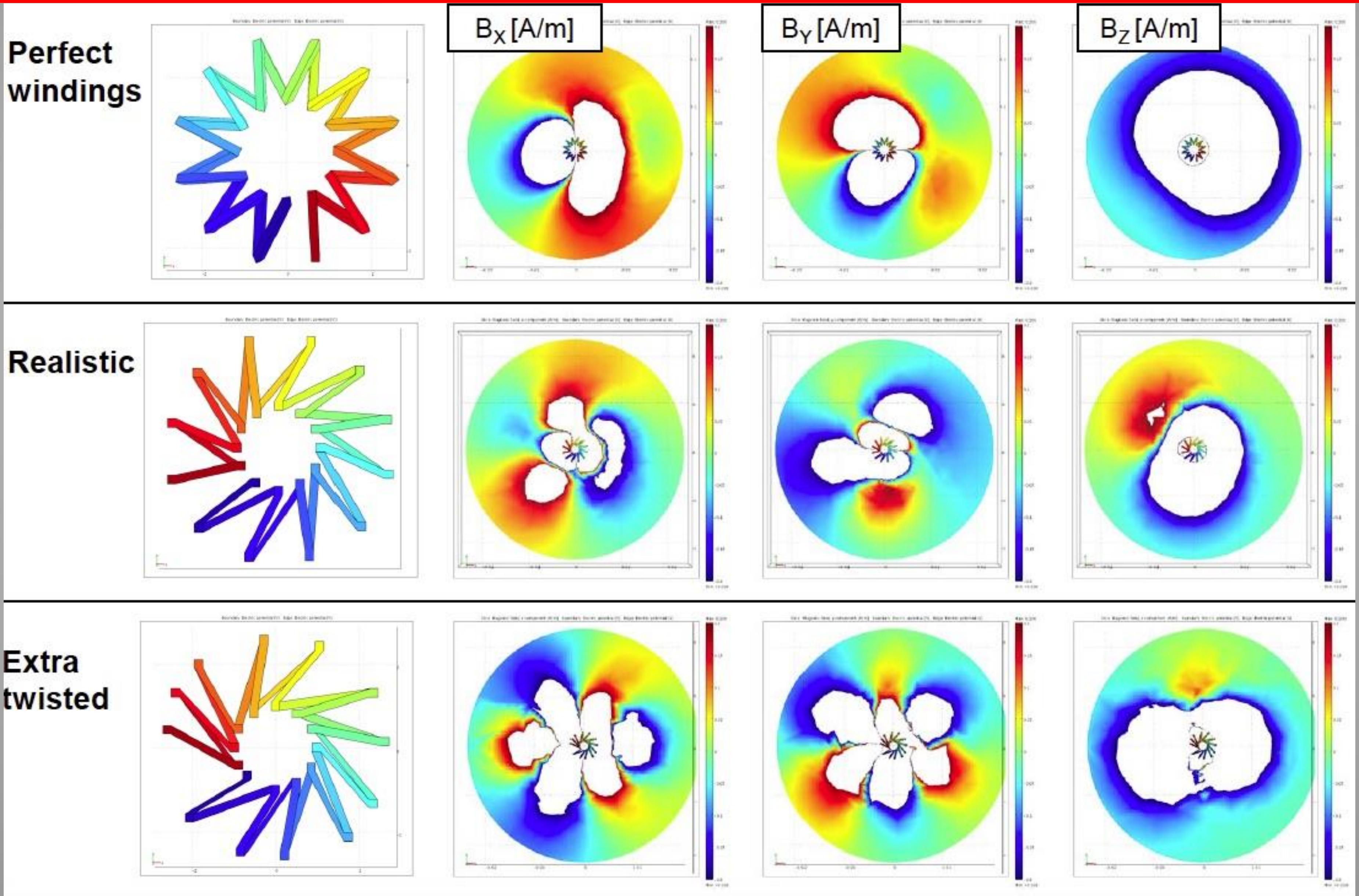


460nH,
80mΩ,
330mg



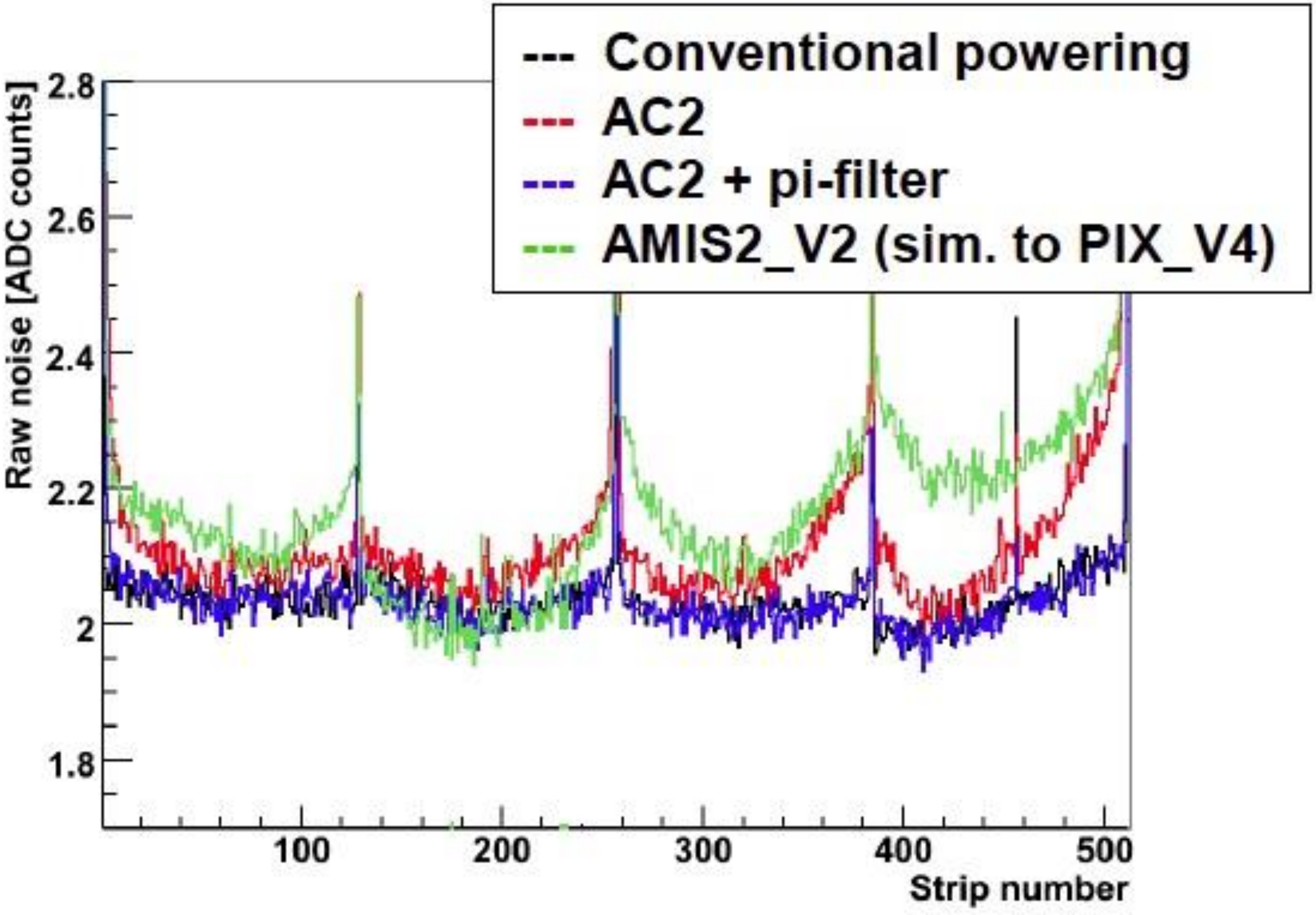
596nH,
38mΩ,
660mg

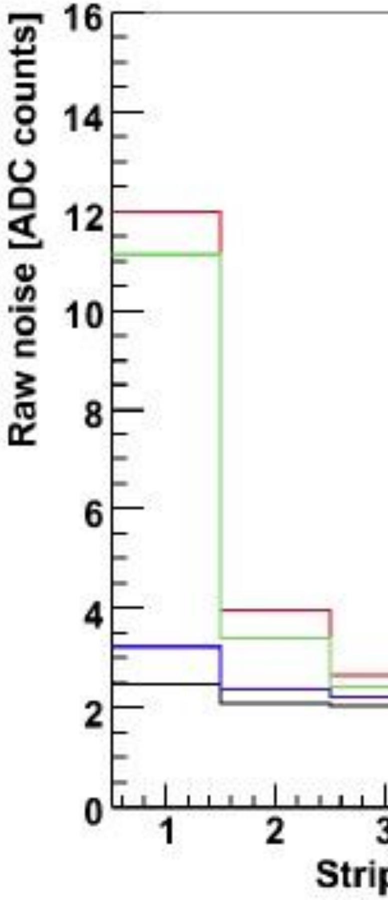
Windings were simulated and optimised



Noise measurement through physics readout chain

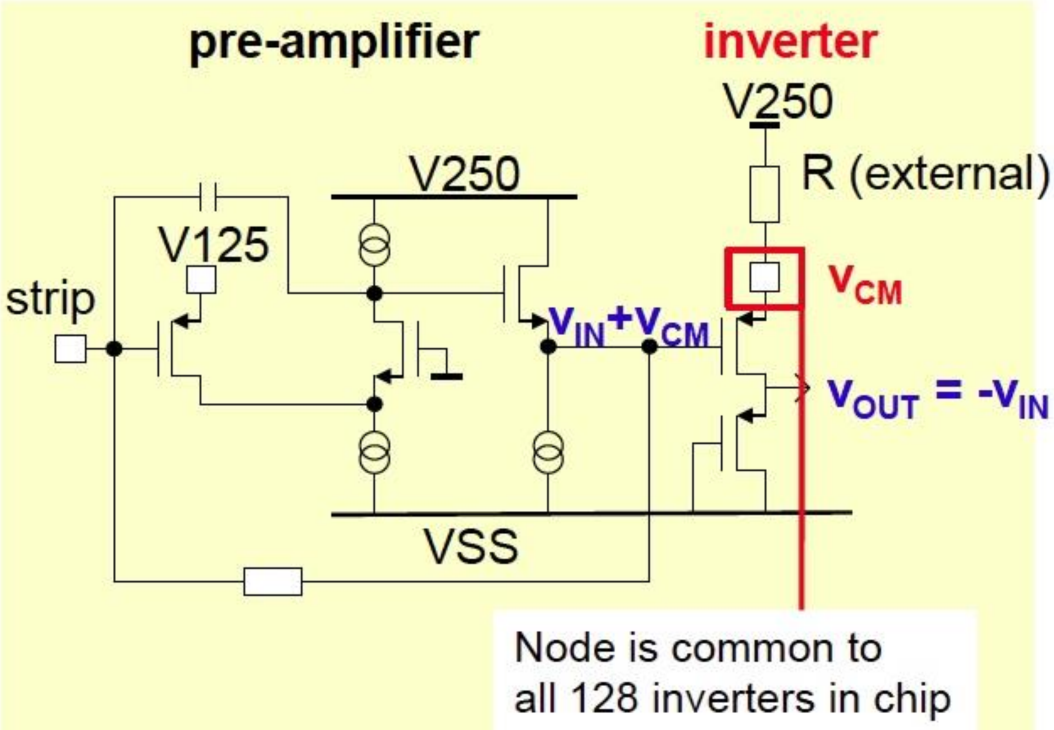
Typical for physics measurements: Statistic sum of no-signal ADC counts determine the noise
Problem: All time and frequency information lost, all noise in the bandwidth mixed together





An attempt to cancel some noise by re-injecting it out of phase

- 128 APV inverter stages powered from 2.5V via common resistor (historical reasons) ⇒ mean common mode (CM) of all 128 channels is effectively subtracted on-chip
- Works fine for regular channels which see mean CM
- CM appears on open channels which see less CM than regular channels
- CM imperfectly subtracted for channels with increased noise, i.e. edge channels



The problem was CERN-wide, potentially affecting core measurements and accelerator schedule

Because of the importance of the project and the enormous workload and operational impact that goes along with installing new DCDC-converters (There are 1200 installed) CERN mobilised its entire EMC engineering force to find a solution.

In such cases it is important to get hold of professionals that

1) are not biased by previous work, measurements, political implications

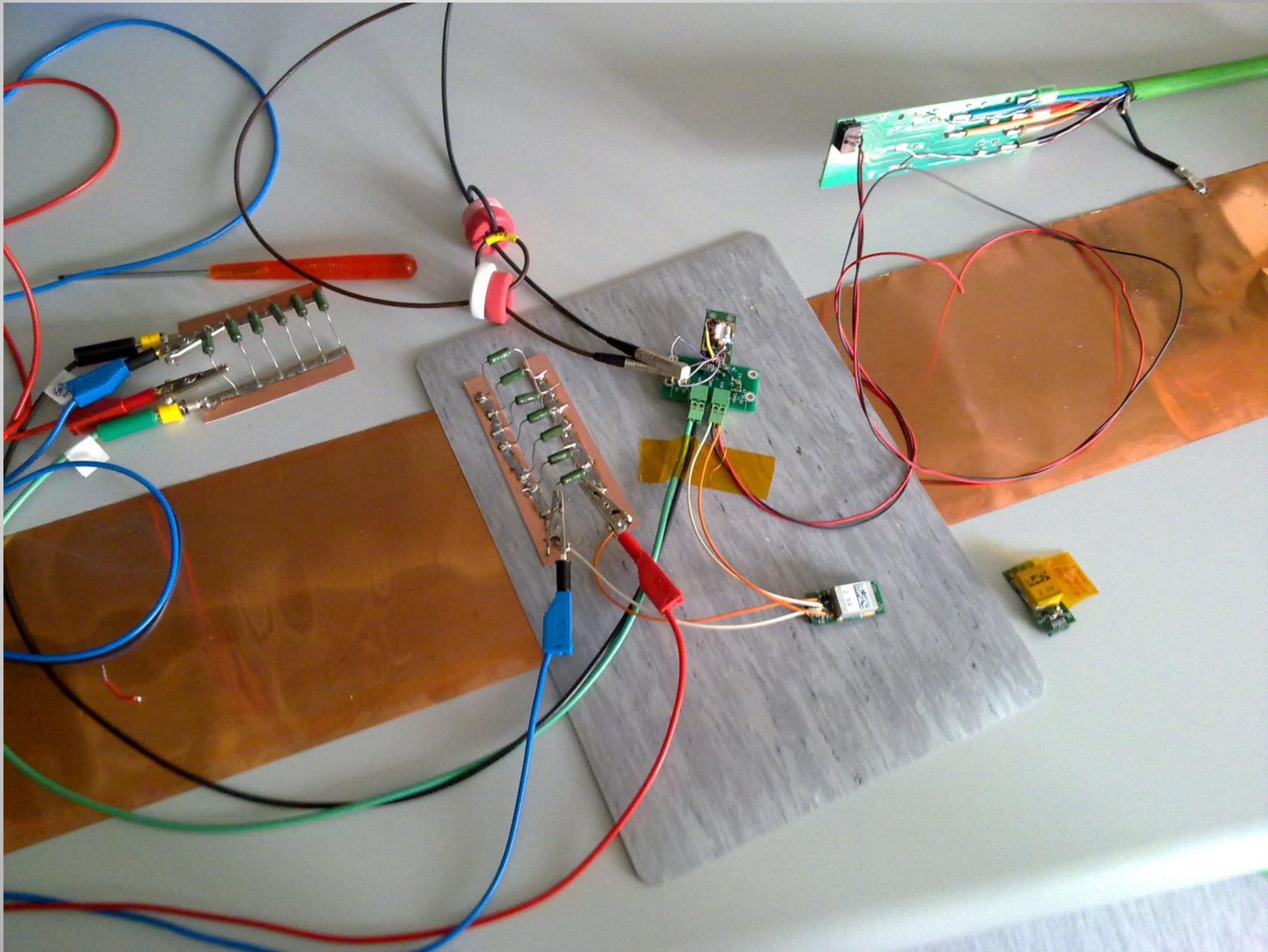
2) have a different background and/or point of view when approaching problems.

Findings and measurements done by the EMC Lab which is run together with the CERN RF-group

The entire power setup was rebuilt and set up at the EMC lab.

The cooling, normally dry ice, was replaced by fans.

The chip needs a number of control input that needed either to be simulated or set up by additional hardware.



Assumption: The DCDC-converters are being destroyed by transients on the 120m long DC-supply cables, or transients from the control lines, or by RF coupled in from the beam current (RF spectrum up to GHz-range)

Tests included FFT on all lines, overvoltage, undervoltage. EM-fields up to 200V/m

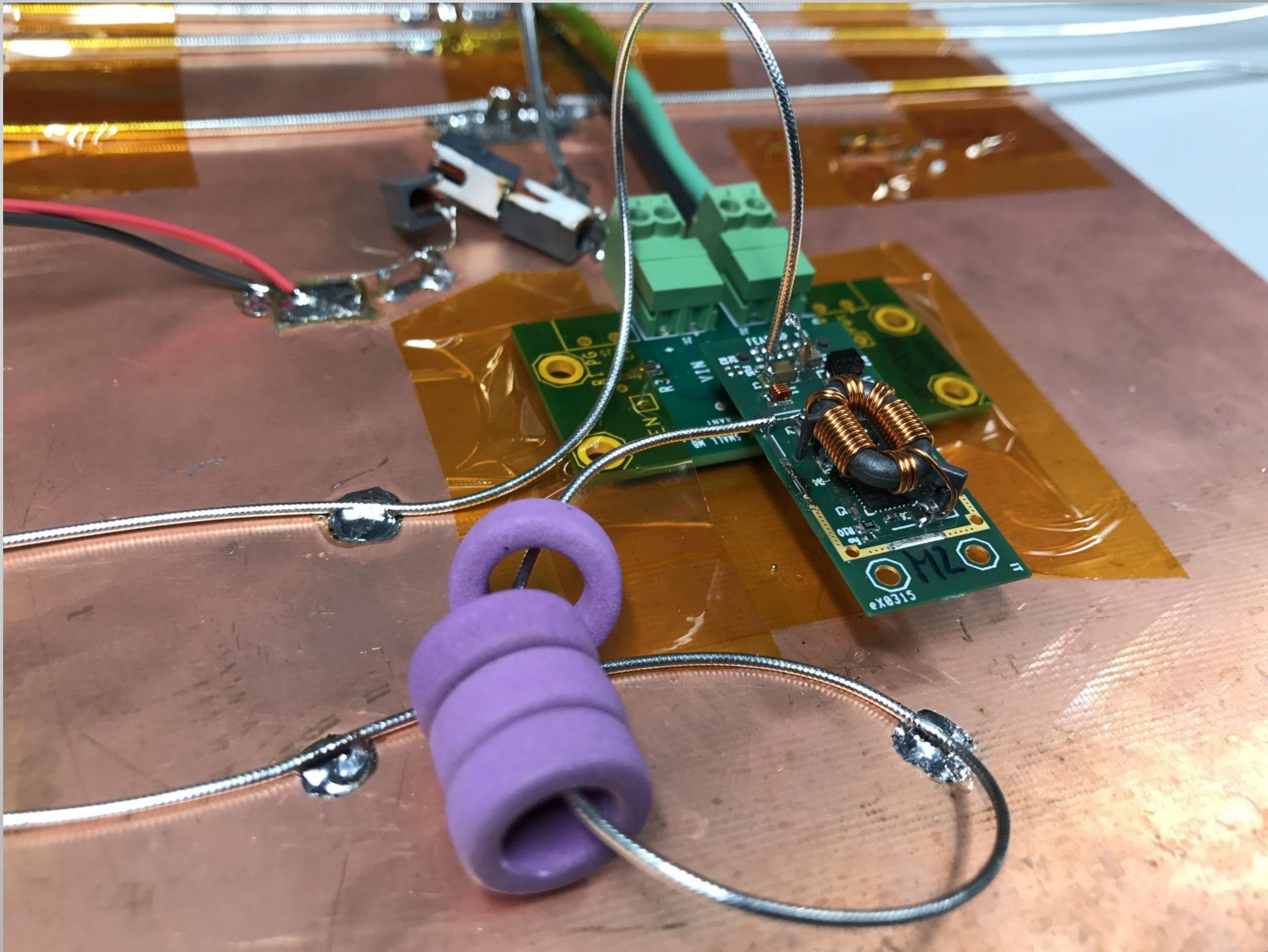
None of the tests was conclusive because

1) No chips COULD be destroyed.
2) The more aggressive the tests the less they mirrored reality
3) The original load could not be connected because of the risk to destroy a silicon detector of very high value.

Separate testing of the DCDC converter board and its components

Testing of circuit and components:

Calibrate VNA, use high quality coax lines and of course a continuous metal sheet ground, separated from the circuit by a kapton foil. Some traces of common mode from the VNA are reduced by toroids.

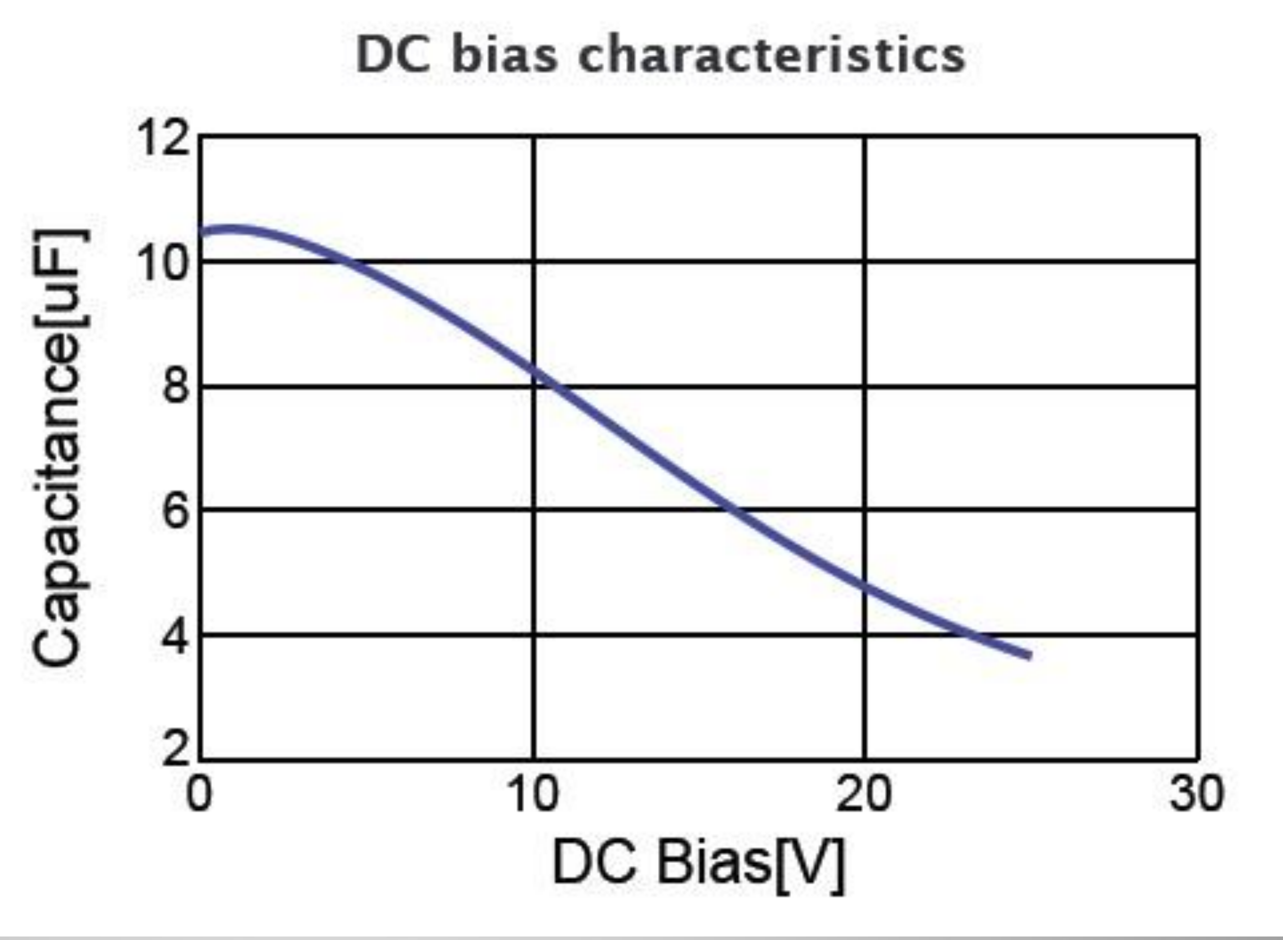


The "variable" filter capacitors

First surprise:

The high density SMD filter capacitors operate rather on constant energy and not on constant capacitance

The capacitance drops with the voltage applied.

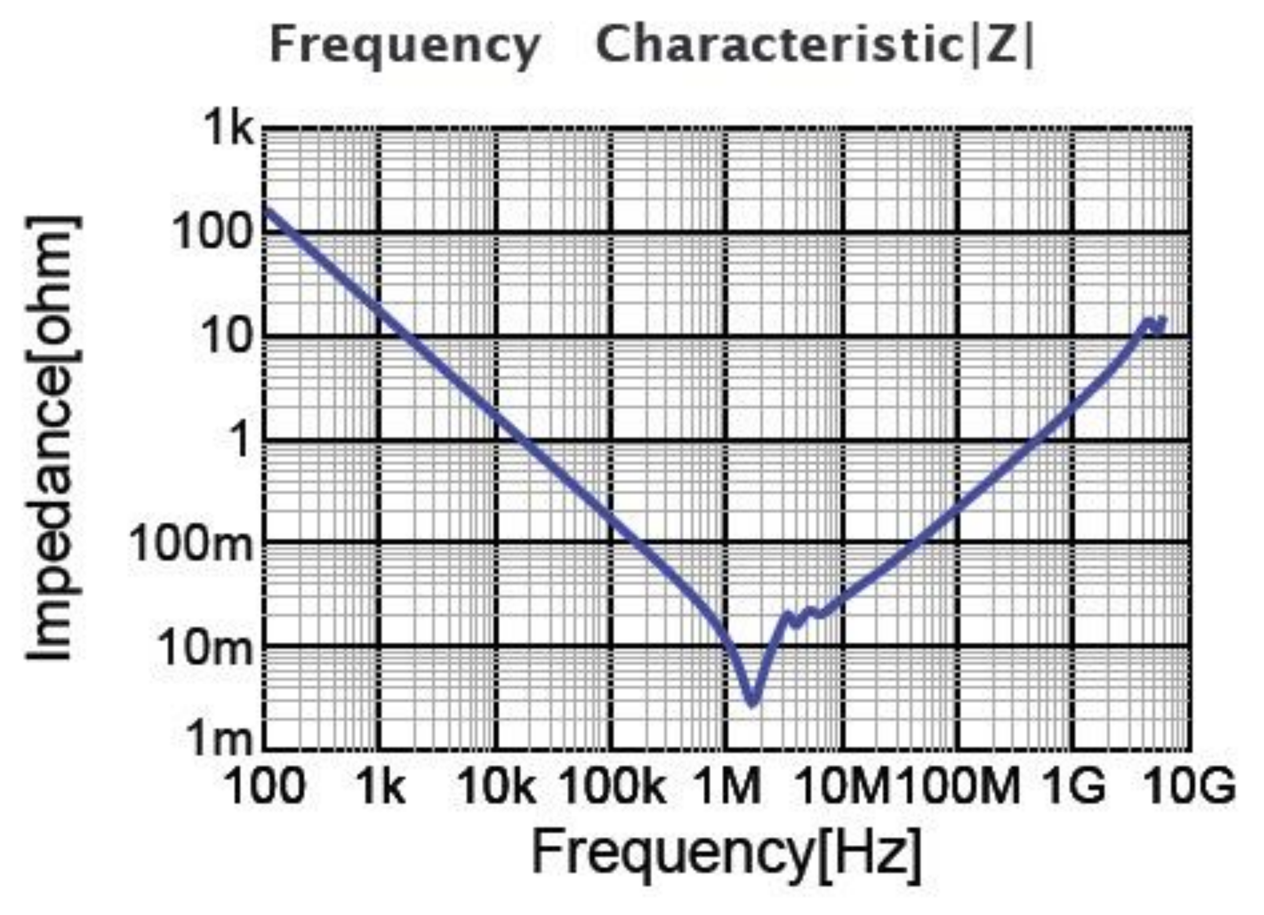


The filter capacitors resonate at DCDC-operating frequency

Second surprise:

According to the datasheet the filter capacitors have a series resonance at the operating frequency of the DCDC-converter

Purpose of the π-filter:
1) Attenuate incoming noise from the cable, and supply peak current for switching
2) Attenuate noise produced by the converter
3) Do not radiate off too much of this noise



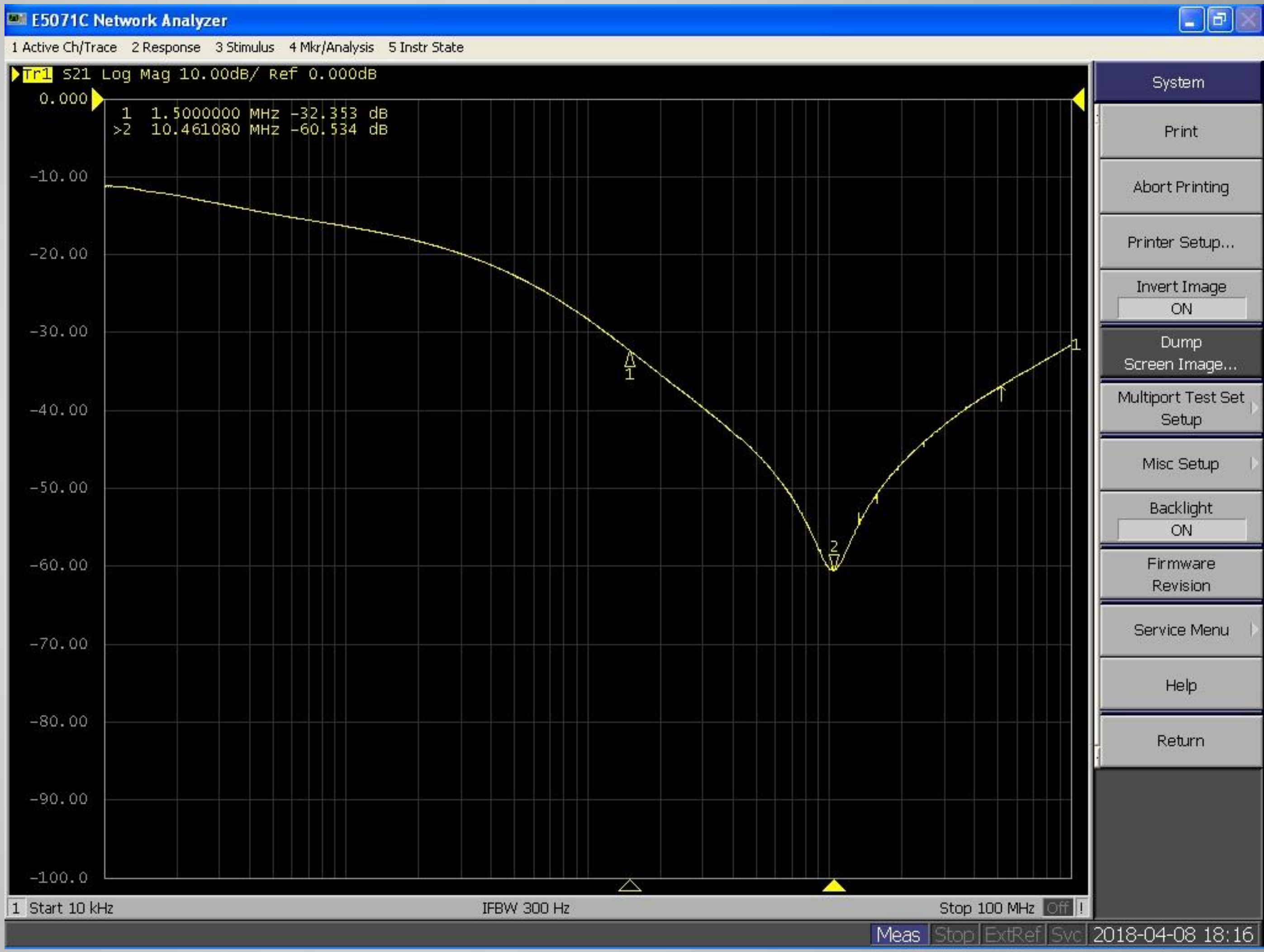
Series resonance of the 10µF capacitor

No surprise:

Indeed the biased capacitor resonates just above 1 Mhz

Third surprise:

Problems were found but nothing was able to reproduce the damage seen in the circuits installed next to the particle beam.

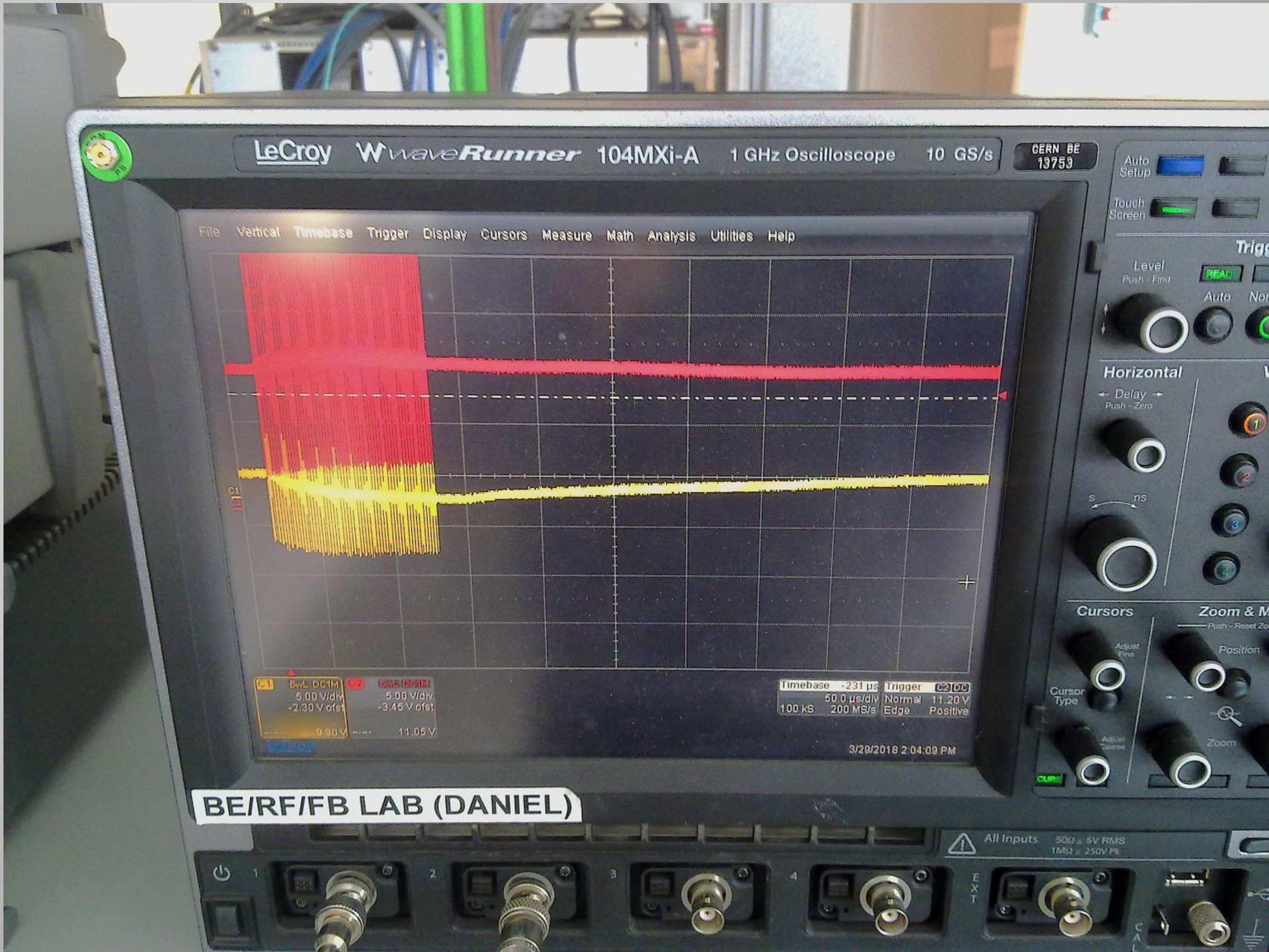


Slow discovery of the real problem

Upper track red: *Inflicted noise from fast transient generator via a toroid around the input lines*

Lower track yellow: *output voltage*

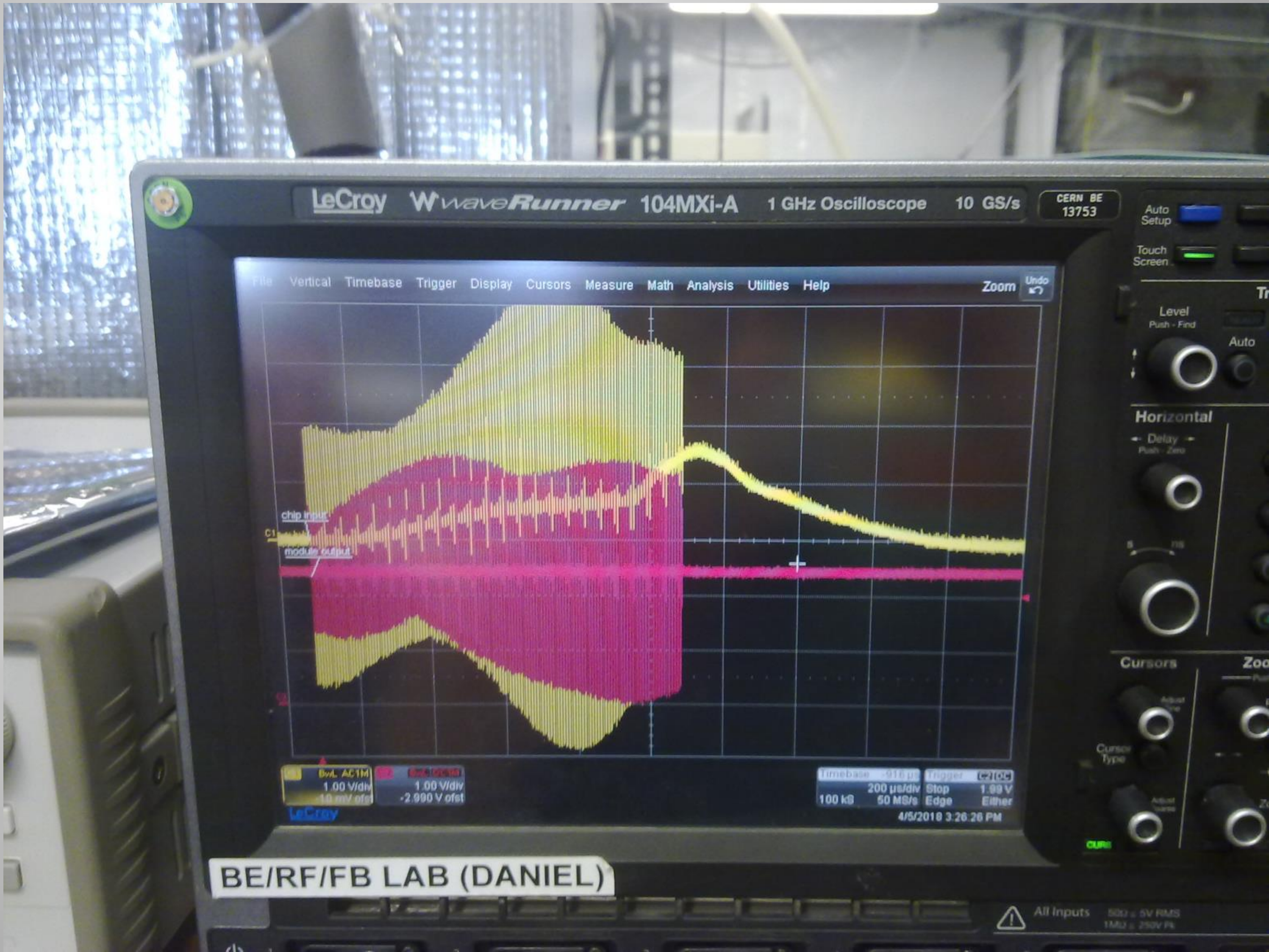
At a certain transient repetition frequency the perturbations are carried through to the output. Remarkable is the integration of the noise pulses and the relatively long recovery time of the converter.



Fast transients severely disturb inner functions

Lower track red:
Inflicted noise from fast transient generator via a toroid around the input lines

Upper track yellow:
internal auxiliary voltage of 3.3V. Deviation and shifting of dependent operating points.



Much detail but no directly useable result yet

Screen continuity:
During measurements a general lack of screening was detected. Over a broad frequency range E-fields heavily disturbed the converters.

Equipotentiality
Major parts of the system were not interconnected: Screening elements against each other, cooling plate to printed circuit board, ground of DC-circuits to anything.

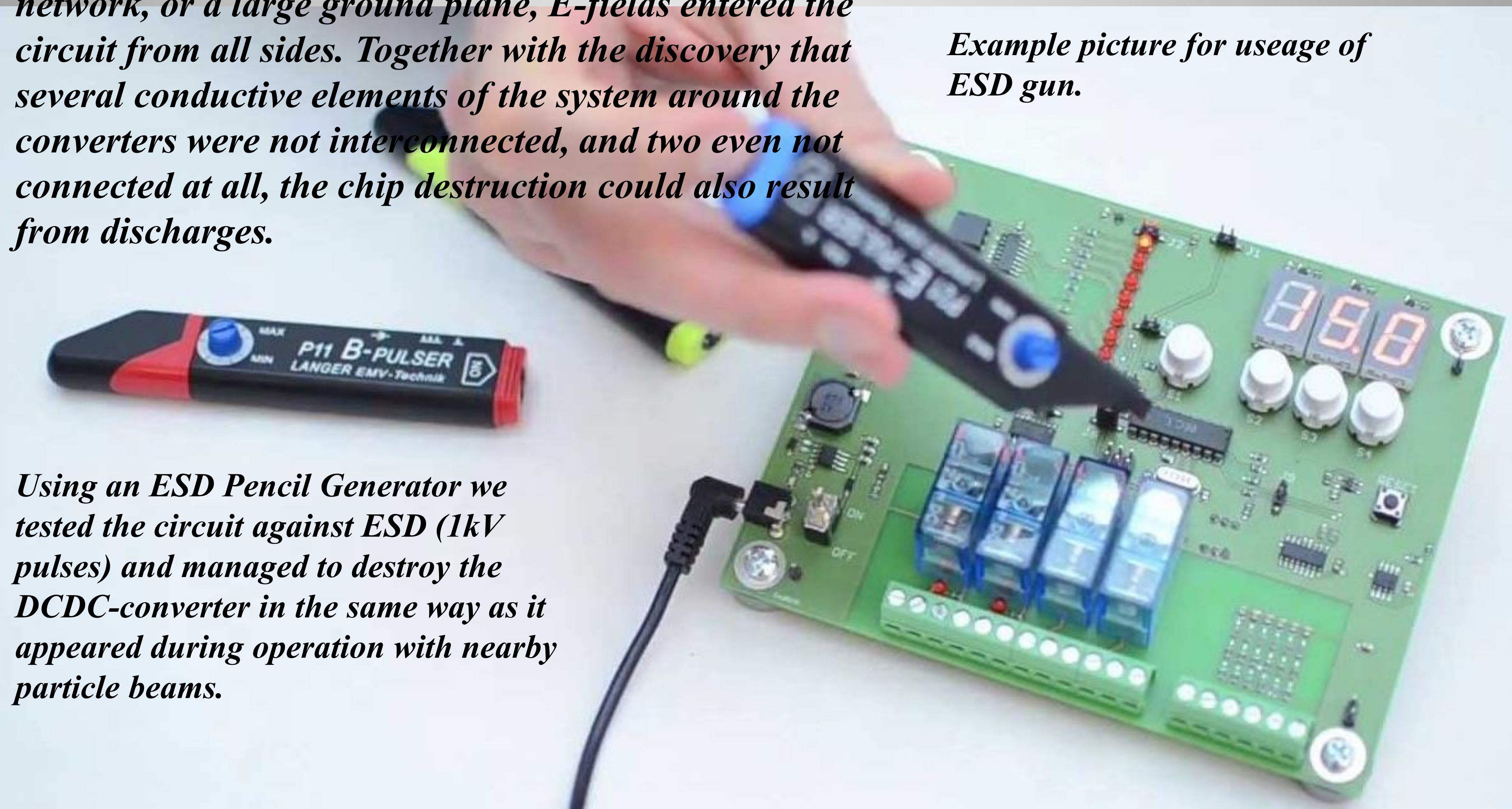
Cabling
DC cables are screened but screens were left open
Twisted pairs for control purposes as well as for all short power runs from converters to the actual sensor electronics are not used in any way symmetrically but rather as interconnection wires. All ambient noise freely coupled in and out.

Converter destruction
All tests could not, even at this point, reproduce the precise damage scenario of the converters failing inside the setup.

The extensive tests revealed an abnormally high E-field susceptibility

Due to the non-existence of a local common bonding network, or a large ground plane, E-fields entered the circuit from all sides. Together with the discovery that several conductive elements of the system around the converters were not interconnected, and two even not connected at all, the chip destruction could also result from discharges.

Example picture for useage of ESD gun.



Using an ESD Pencil Generator we tested the circuit against ESD (1kV pulses) and managed to destroy the DCDC-converter in the same way as it appeared during operation with nearby particle beams.

Measurements after absorbing ionising radiation

Finally the original design group measured the E-field destruction level against the absorbed dose, with the result that with increasing dose the chip withstood less ESD attacks, which was the final scientific explanation why the chips failed only after a certain time under certain particle beam conditions.

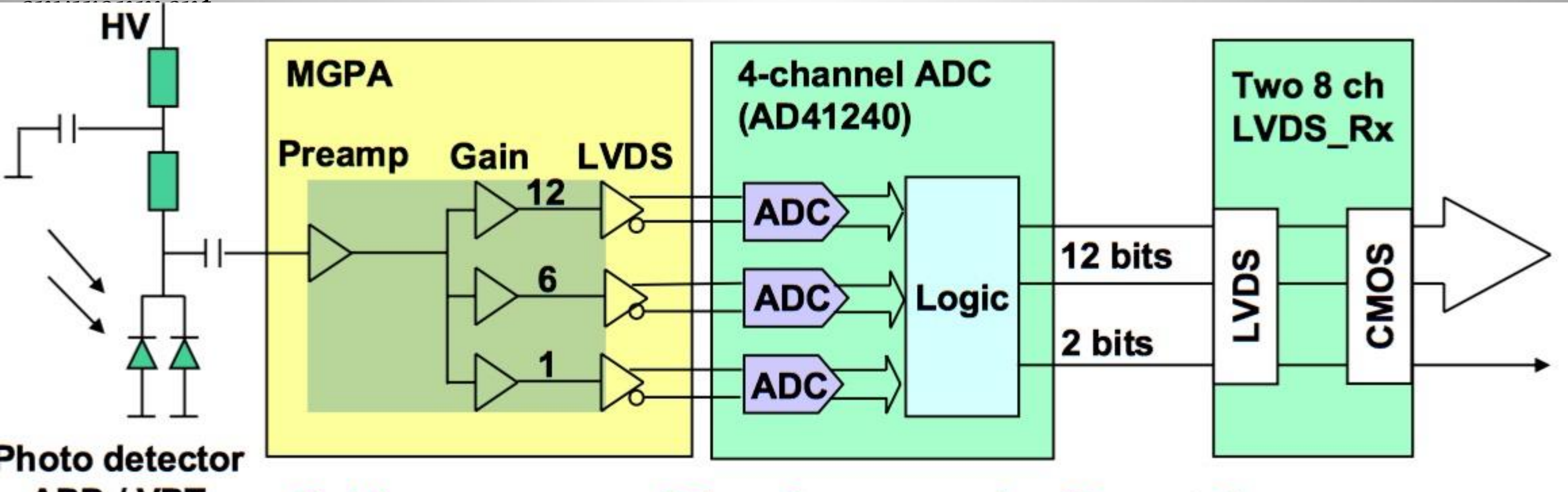
New design:
EMC became a decisive factor for improvements

Such complex EMC engineering effort touches all fields of electrical engineering and needs the view of several experts for achieving robust results. In this case much preventive EMC was done but ground continuity and ESD sensitivity were not considered.

CMS experiment, different subdetector Electromagnetic calorimeter with crystal detectors

Task: EMC immunity measurement on prototype
Bias supply lines were tested with ca. 1µA of common mode up to 100MHz which is an assumption of the required immunity.

Preventive discovery of wrong component choice cured at prototype stage:
The original HV-filter was a double RC filter with carbon resistors that are capacitors in the MHz range. The filter was modified as on the picture. Immunity now sufficient for CERN environment



digitize once every 25 ns the energy in all crystals

Experiment ALICE: Small experimental setup: only two PMT's and a counter

Two PMT's were connected via a few meters of RG58 cable to a preamplifier/discriminator lying on top of a crate in the rack.

Many earth connections were tried out, external fields (transmitters) were suspected to influence the setup.

The rack issued some electromagnetic radiation, namely alternating magnetic near fields in the kHz range. The missing CBN caused cable screens to carry both signal return and noise currents because of cables creating loops.

Solution:

Install u-shaped broad metal plate between rack and PMT. Make sure there is good connection the rack. Lay all cable onto this plate in order to minimise pickup and coupling.

Remarks on powering physics apparatus

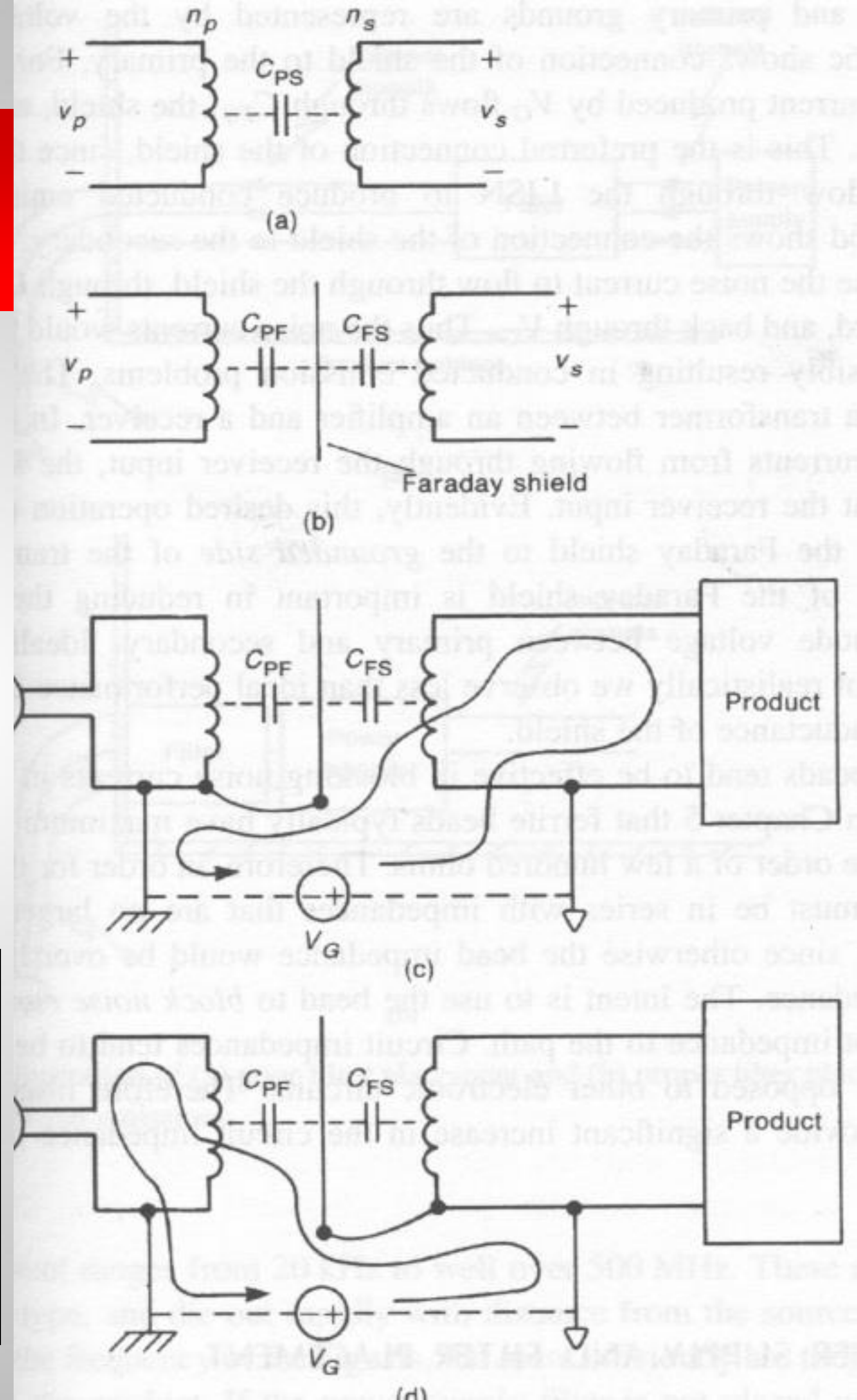
Most EMC problems in physics result from remote powering. Power supplies are located up to 150m from the load.
Multiple power conversions cannot be avoided when radiation tolerance, efficiency and tight space need to be matched.

The following slides are a summary of problems that were experienced at CERN, with, where possible, solutions.

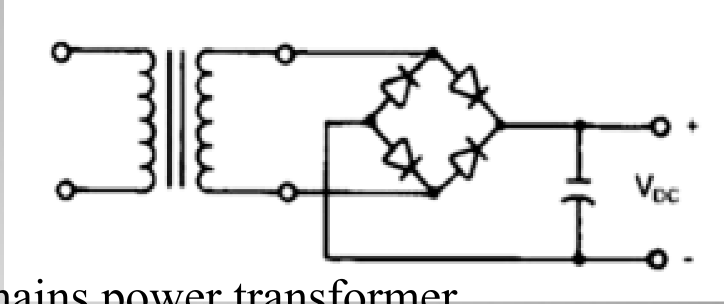
Electrostatic screens inside (separation) transformers

Certain transformers have an ES winding.

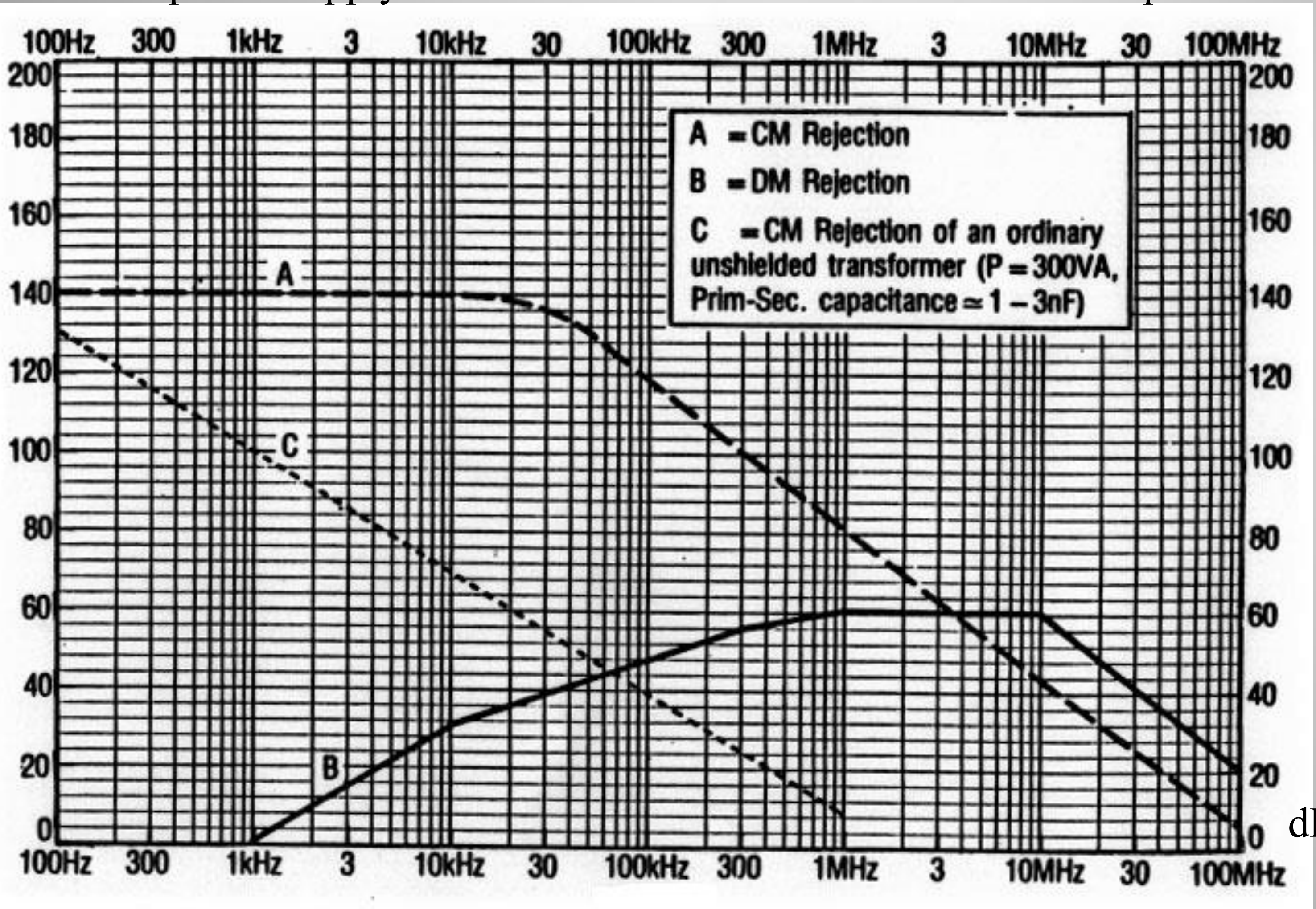
The ES winding breaks the winding-to-winding capacitive coupling and allows to route HF-common mode back to its source, usually via ground or via metallic structures.



The linear power supply also conveys noise



Linear power supply: Common Mode transfer occurs via mains power transformer



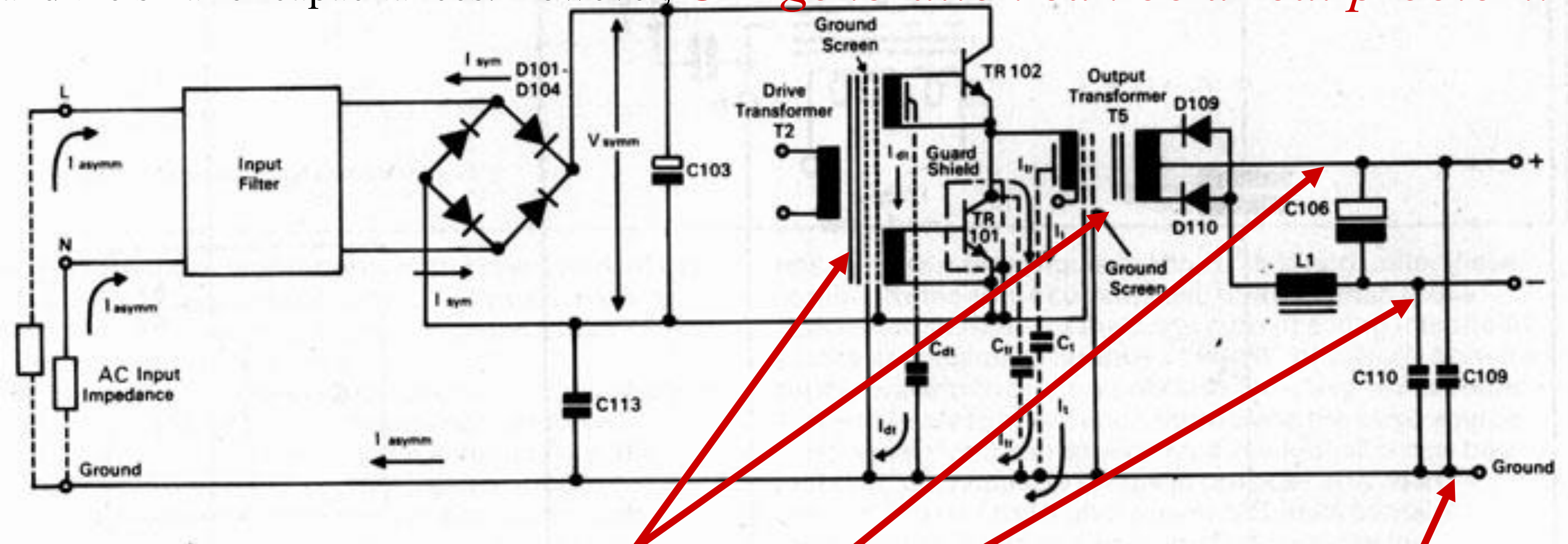
dB

Linear regulators of high quality reject quite some low to medium frequency CM but much less DM.

A,B curves: CM & DM rejection for screened xformer C curve: CM without screen

Switch Mode Power Supplies and UPS are common mode generators

SMPS generate some DM (ripple) and CM (ground currents). EM radiation is generally small. CM transfer is smaller compared to linear power supplies because of the screening efforts and the smaller capacitances. However, *CM generation can be a real problem.*

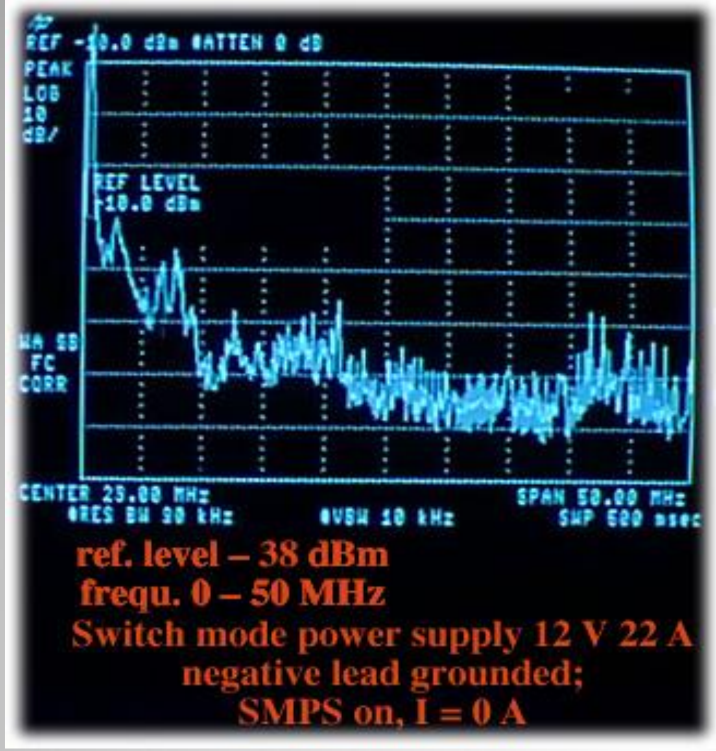


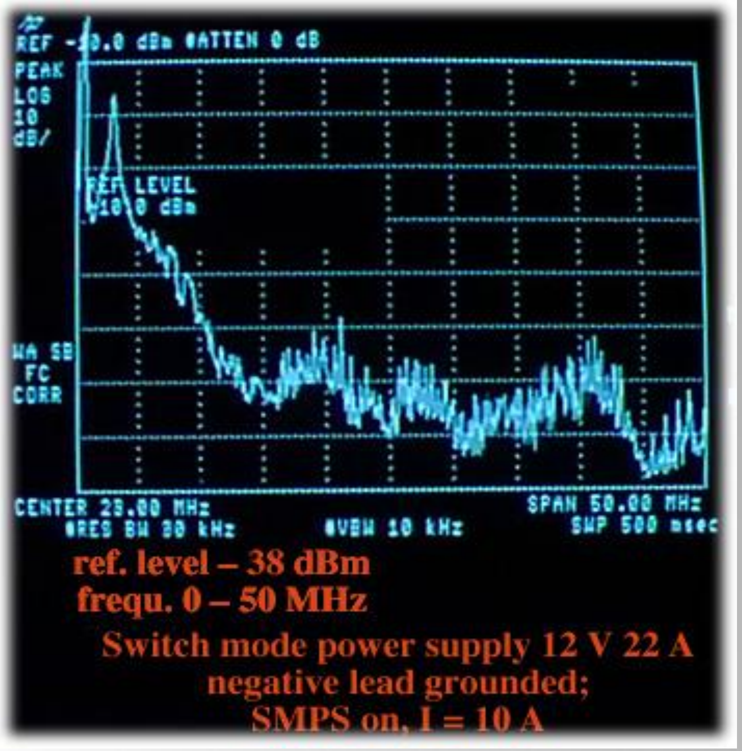
coupling ≠ Ø

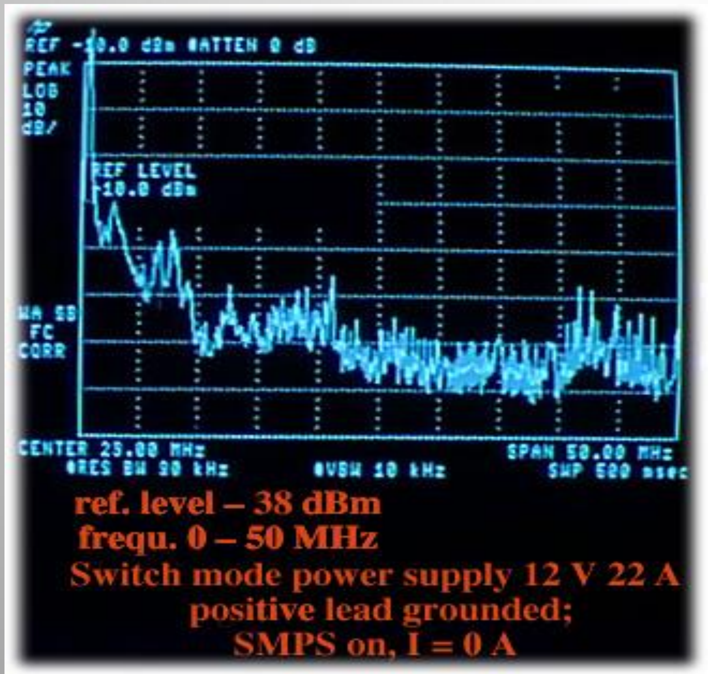
impedance from terminals to ground is slightly asymmetric –
<u>It is this asymmetry that needs to be kept small</u>

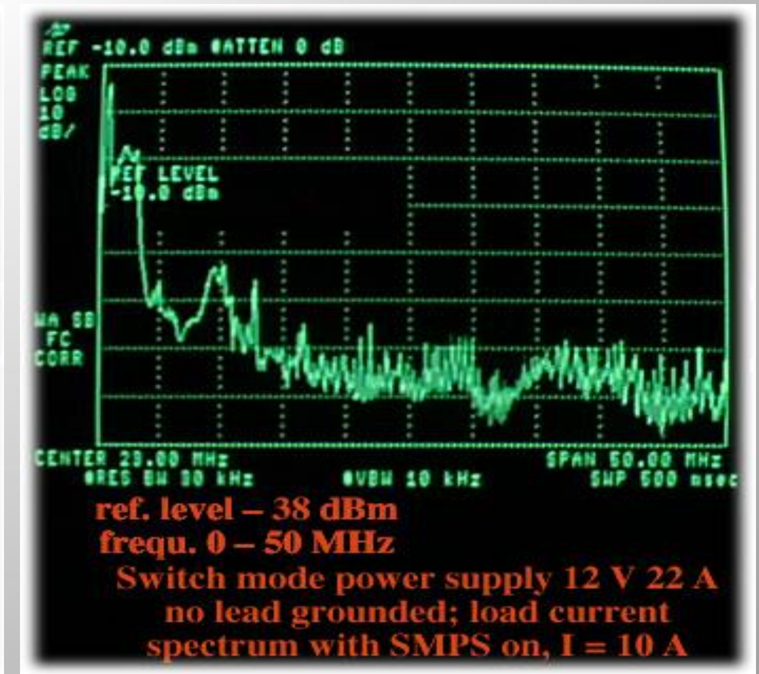
leakage currents towards load need to be limited

Switch-mode power supply CM measurements in situ



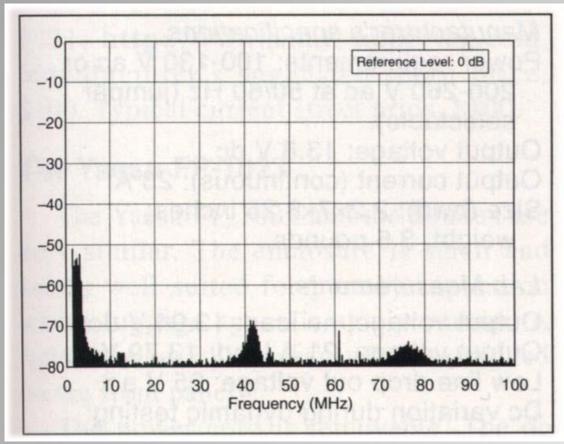




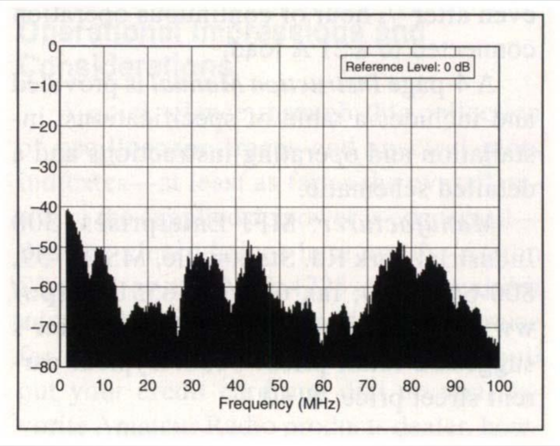


SMPS: comparisons between different makers

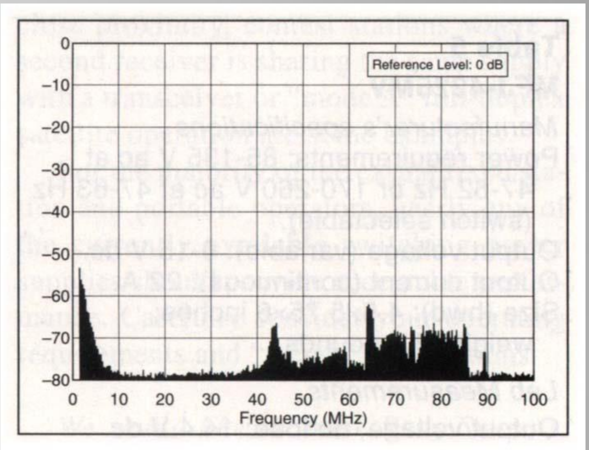
for same load
for same environment
for same initial spec's



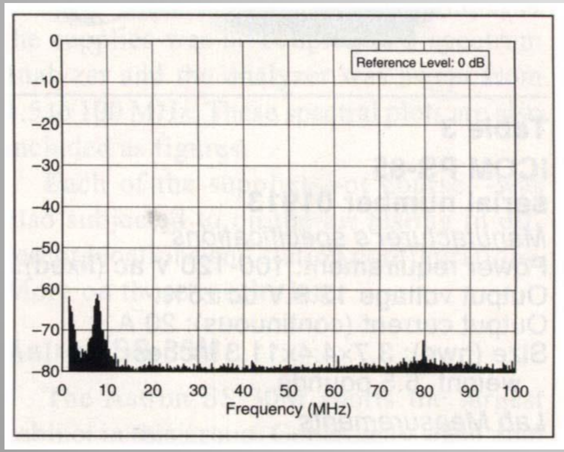
Supplier A



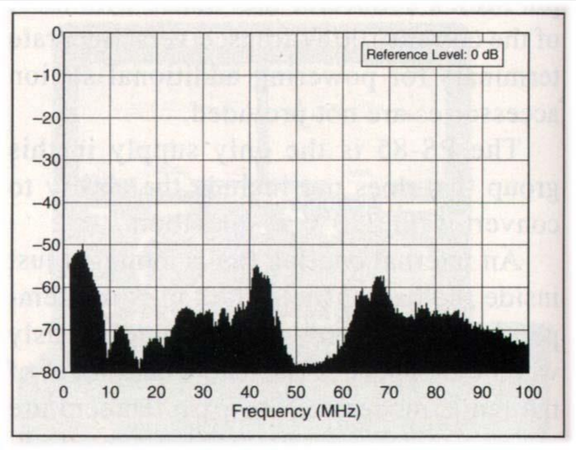
Supplier I



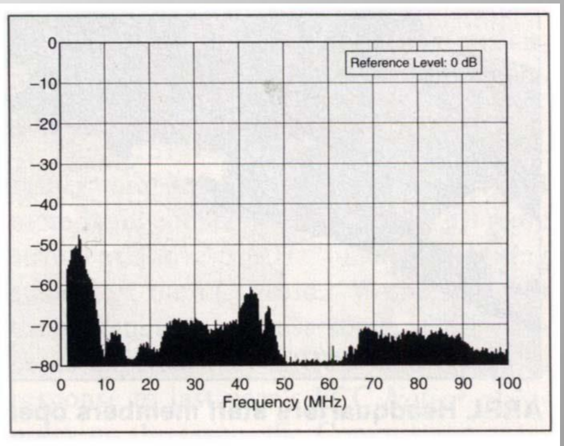
Supplier K



Supplier M



Supplier S



Supplier Y

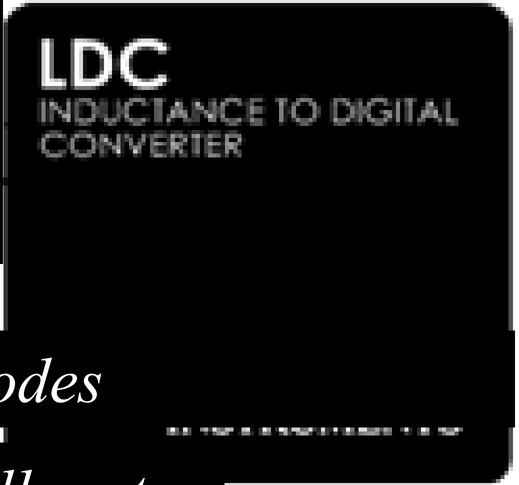
Parametric Coupling

A sensor where it shouldn't be

E.g. for an inductance:

$$E = \frac{d}{dt}(Li) = \underbrace{\frac{Ldi}{dt}}_{\text{Flux Coupling Term}} + \underbrace{i\frac{dL}{dt}}_{\text{Parametric Coupling Term}}$$

Although being rare it has been seen in physics
(It is mentioned here for the sake of completeness):



Neon tube coupling into preamplifier protection diodes

Microphonic Coupling into detector chambers of all sorts

Alteration of electrical parameters due to mechanical stress

Vibration of electronics placed in strong magnetic field

CERN experienced all of the above. In all cases the search for the noise path was confusing and time consuming.

Part 0	Some Prerequisites
Part 1	What is special at CERN?
Part 2	CERN's Internal Limits
Part 3	Equipotentiality
Part 4	Conducted Noise, Filters
Part 5	Radiated Noise and screening
Part 6	Cabling, Cables, Connectors
Part 7	Physics Experiment EMC Applications
Part 8	**Accelerator EMC Applications**
Part 9	Safety System EMC Applications
Part 10	Conclusions

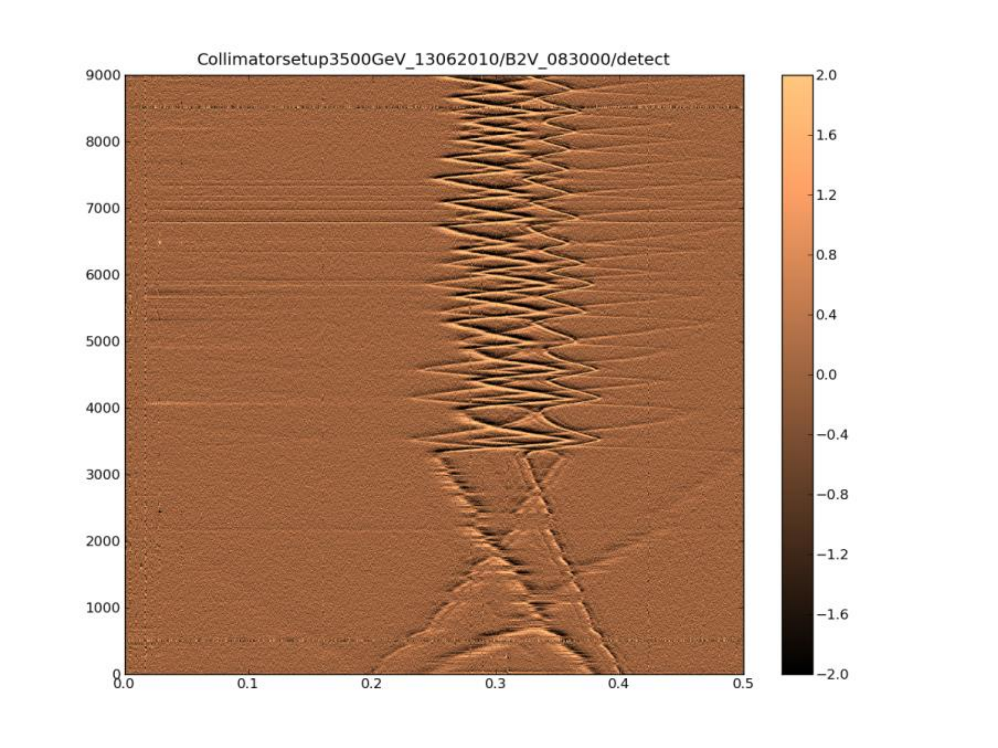
Part 8 Accelerator EMC Applications

- The hump
- The trains
- The functional earth
- The open cable screens
- EMC Systems Engineering

LHC: Noise from the backup power source

CERN uses UPS systems up to 1.5 MVA power. UPS produce strong common mode outside the EMC "legal band" from 9 kHz to 30 MHz, usually just below 9 kHz.

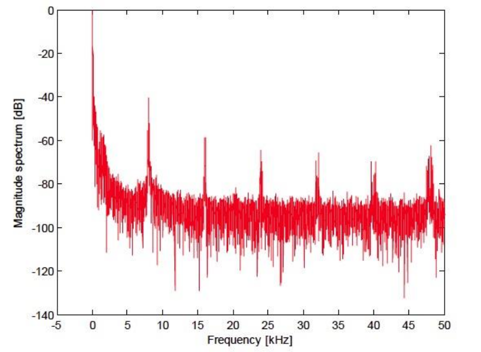
Strong 8 kHz (plus harmonics) common mode signals could be found throughout the LHC. The LHC found its beam modulated ("beam humps") with these (and other) frequencies.

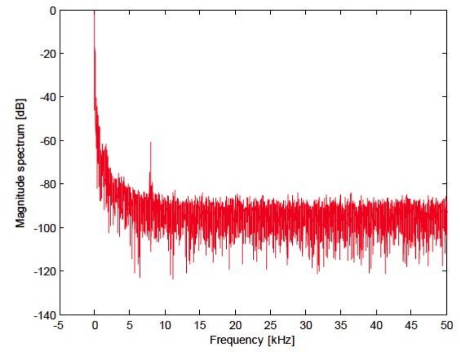


LHC accelerator beam hump with interference from various sources, amongst them the UPS common mode of certain services.

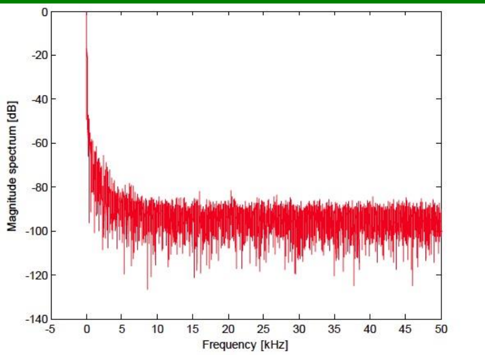
LHC – first attempt to remove as much as possible common mode with an LC-low pass that fits into the restricted space

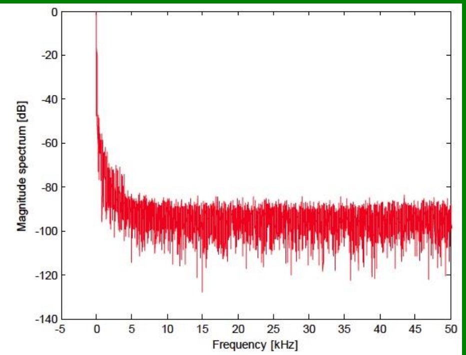
WITHOUT FILTER | WITH FILTER | DATA: 3 phase 10µH, 80µF on the output side



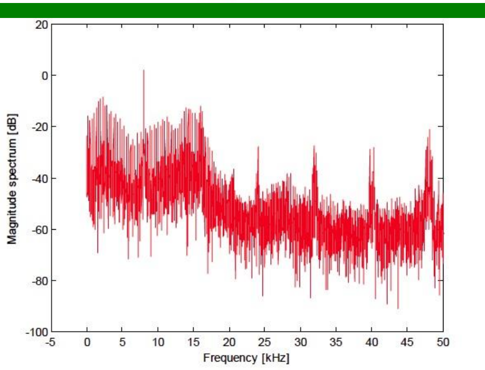


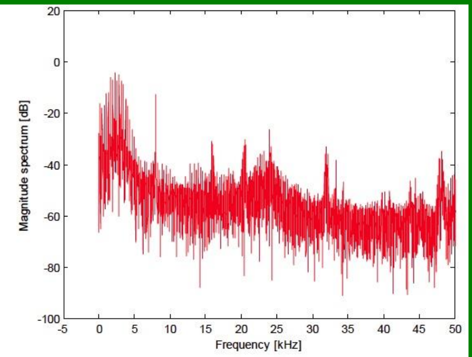
Phase L1 to neutral (8kHz @ 8V)
Battery operation 50% load





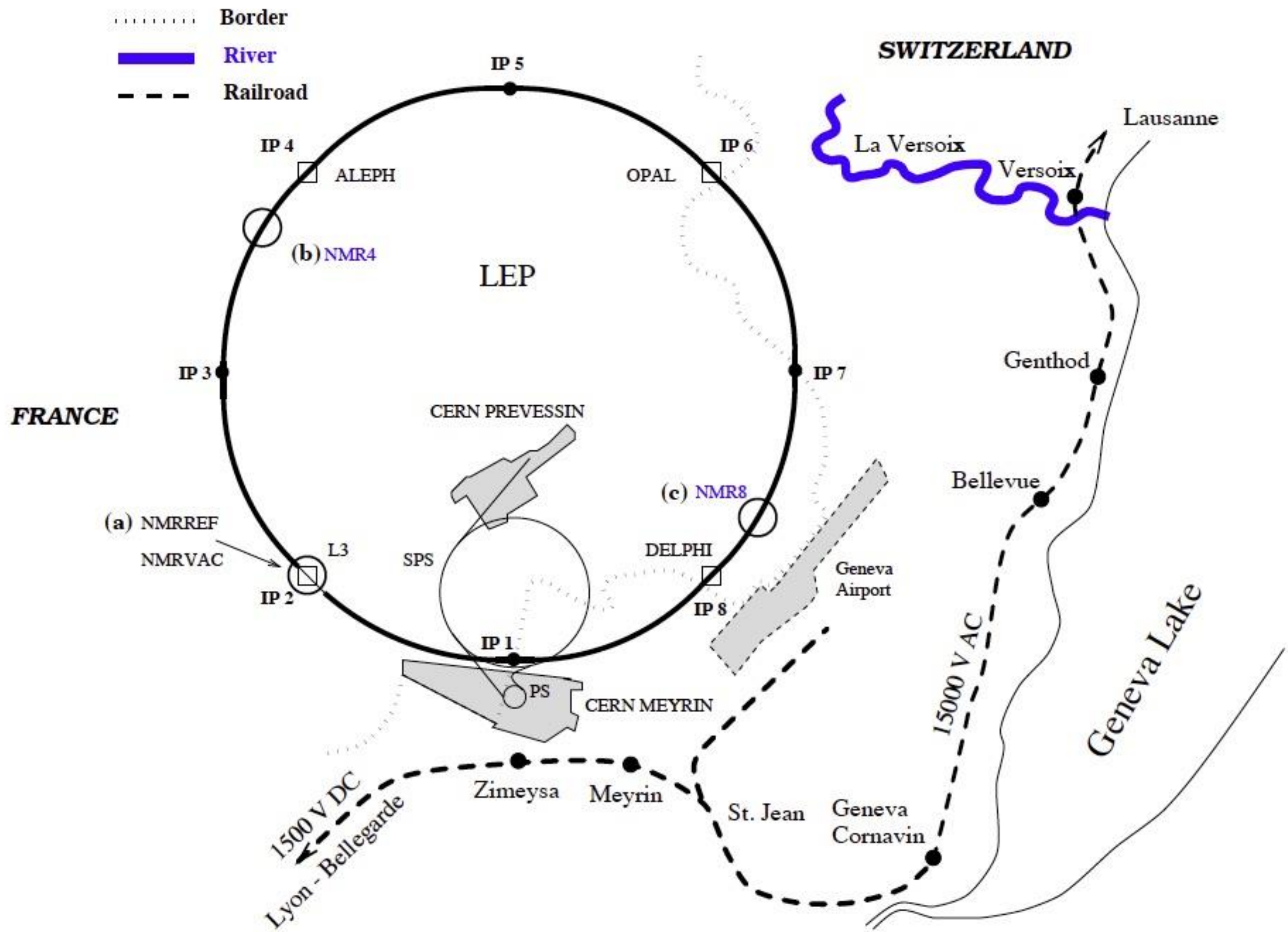
Phase L1 to neutral
Operation via bypass (=UPS off)



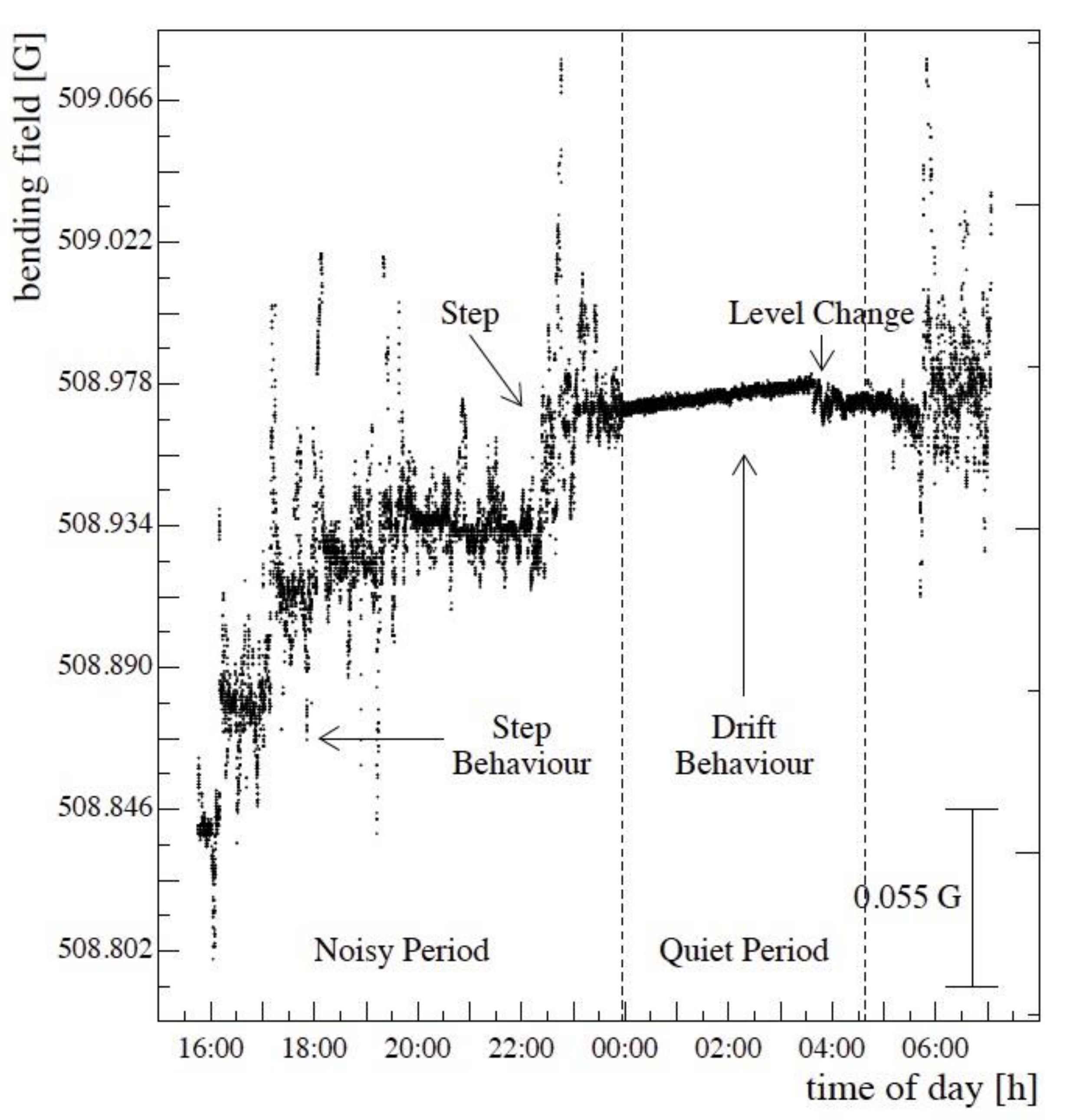


Neutral to ground (8kHz @ 8V)
Battery operation 50% load
Clearly visible the solicitation of the ground system as path for the filtered out common mode

CERN's trouble with the French 1500VDC railway



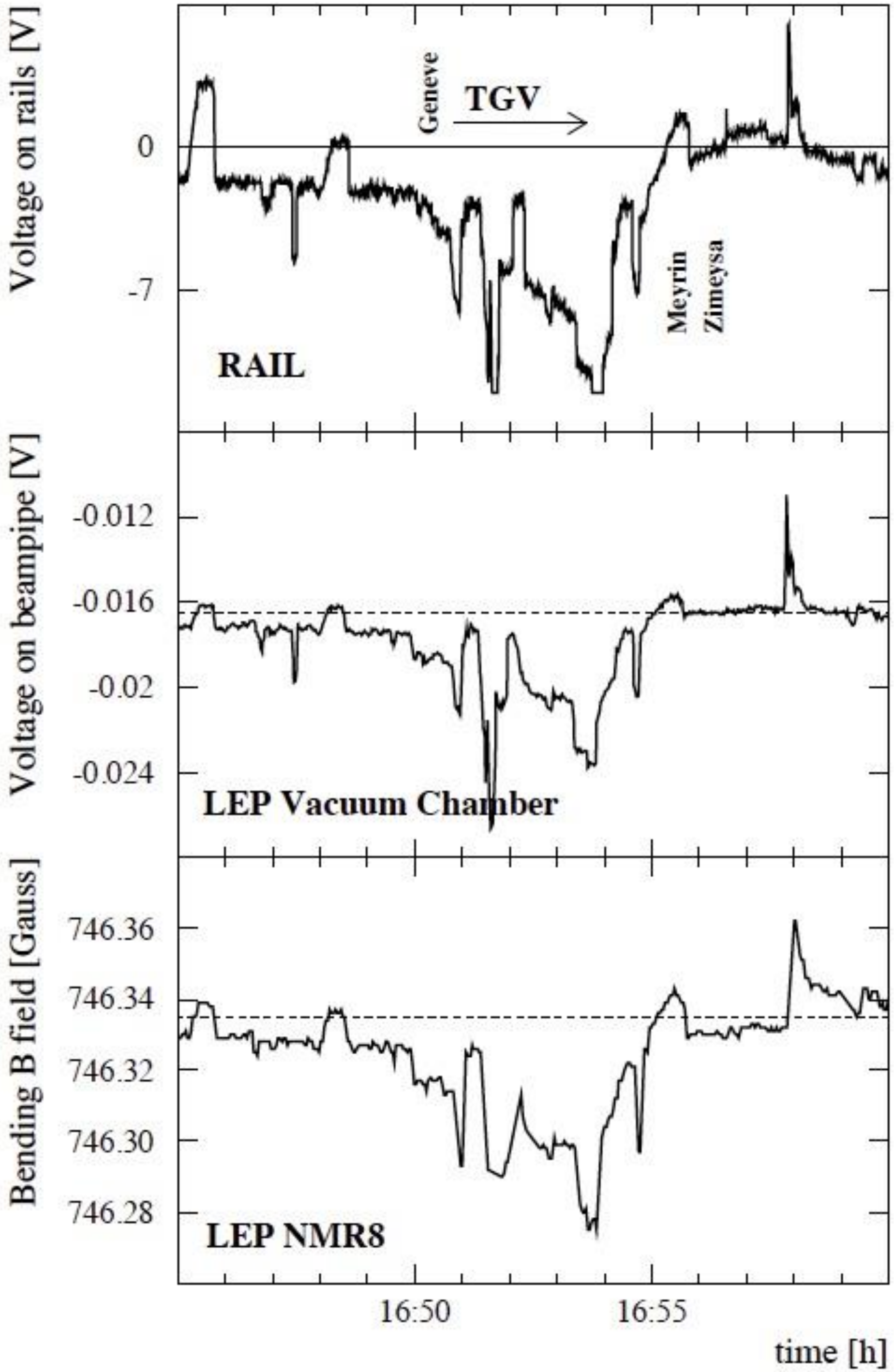
Deviations of accelerator bending field vs time



Deviations of several 10^{-5} are observed, with distinct similar patters every day.

Scientists started to look for the path, and for correlations with operations in the area.

Most interesting are the peaks at distinct times, followed by a quiet night.



The afternoon peak expanded and compared with field measurements and train return currents

Because of experience with the DC tramway SIG pointed out first that the influence could be routed to DC stray currents that theoretically close in an infinitely wide area.

The comparisons proved that the assumptions were correct.

Functional Earth

Functional earthing means that earth (ground) is part of the active circuit.

Functional earthing is not used inside buildings any more because of the evident common ground interference risk.

Attention:

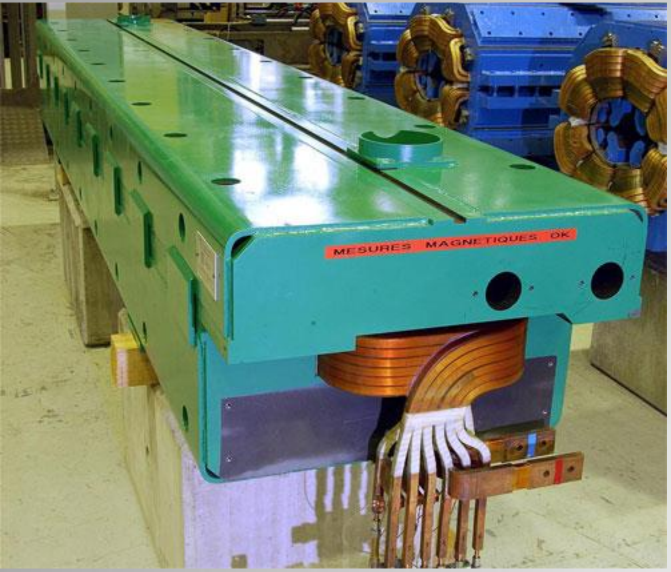
The term "functional earth" is sometimes used to distinguish between CBN and power return."Only our company offers functional earthing..."

Outside CERN, low frequency communications:

(used in marine, military, speleology, mine emergency comm's)

The earth is part of the circuit, e.g. as counterweight for an aerial.

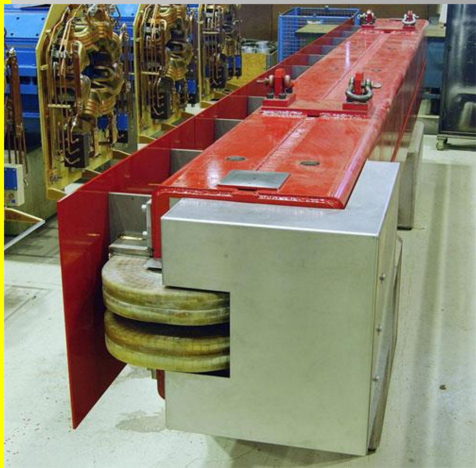
(Half a) Functional Earth at CERN



CERN kickers use high transient currents originating from discharges. Peak currents reach many kiloAmpères

Part of the return current runs through the (locally copper plate re-enforced) accelerator CBN.

We expect (and see) common mode transients in nearby CBN and cabling. For the circuit designers rare transients are difficult to understand and handle.



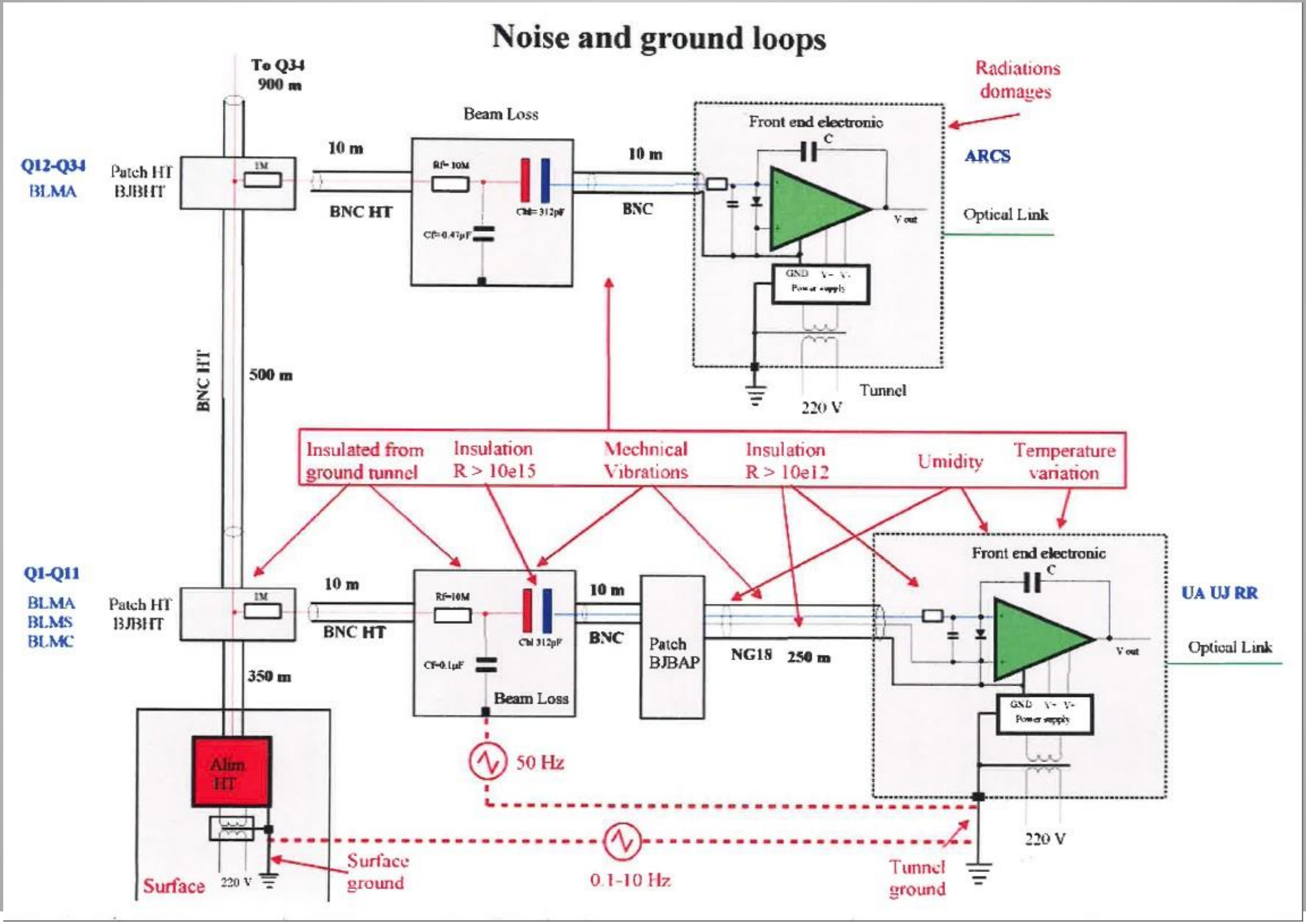
Immunity against transients riding the ground system

Most screened cables end up earthed only on one end

All methods of common mode suppression are used: optocouplers, transformers, symmetric lines, physical separation

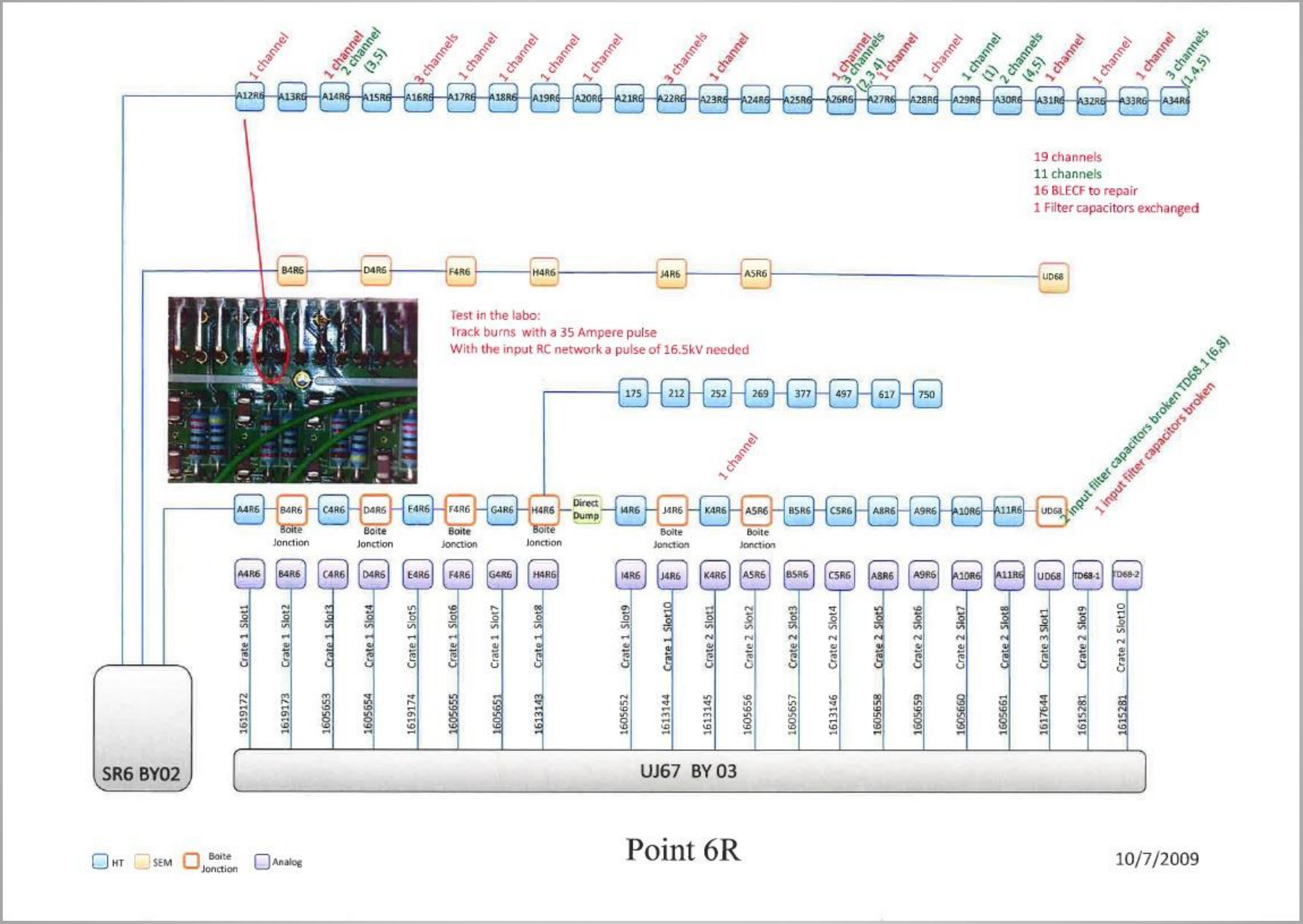
Nevertheless violent ADDITIONAL transients (e.g. a short circuit, or an arc in the power system) cause damage

Effects of open earth connections

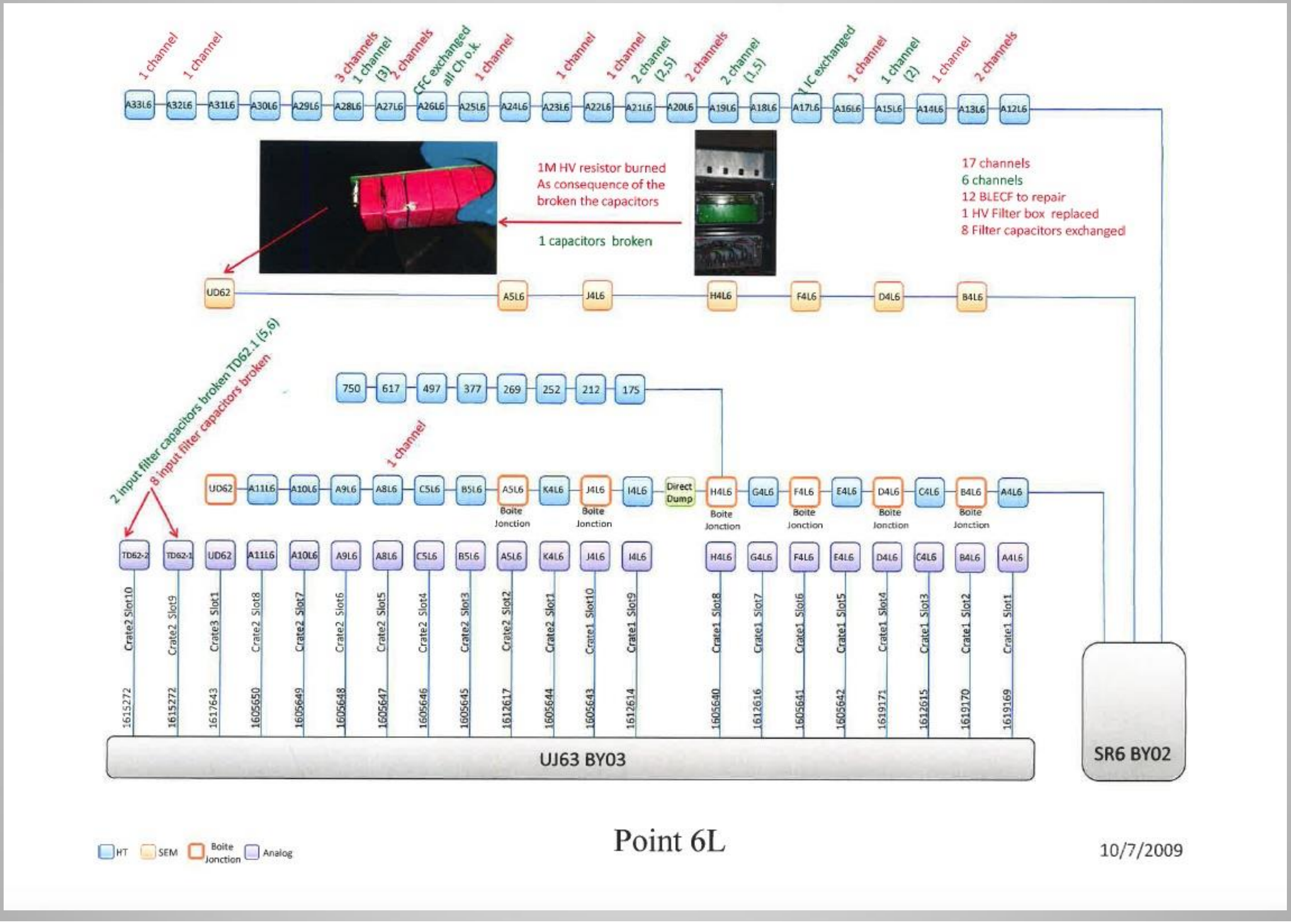


"Different grounds" means huge loops

Circuit destruction by induction caused by a transient



Open screen connections are not only an EMC problem but also a hazard for equipment and personnel



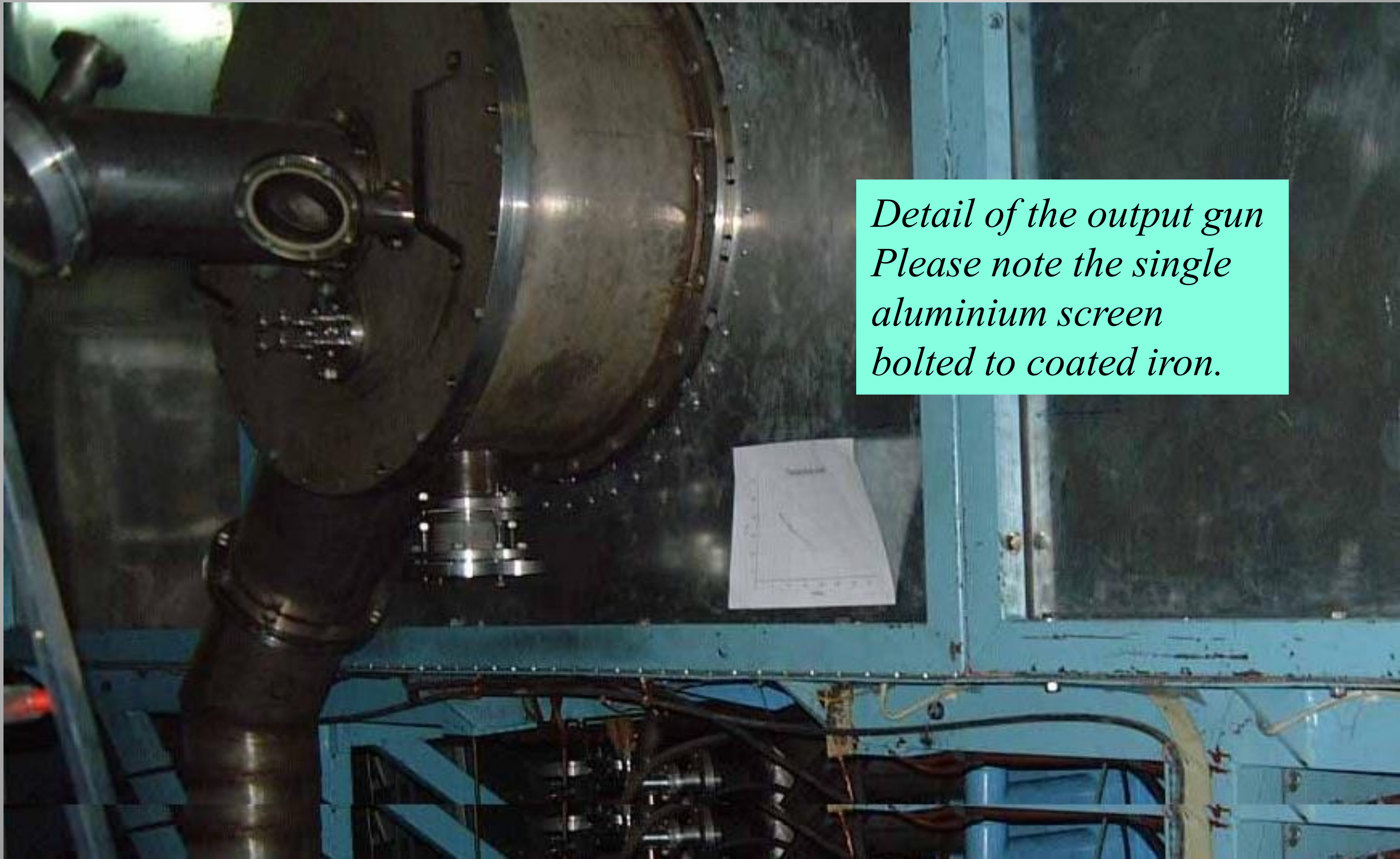
The same transient also burnt capacitors and PCB traces.

LASER Ion Source

View of set-up and capacitor bank of the 100J CO_2 LASER.

A capacitor bank is charged to 400kV which supplies the energy for the amplifier of the LASER which delivers more than 1GW of power during the invisible infrared light pulse.

Set-up at ITEP Moscow



Detail of the output gun
Please note the single
aluminium screen
bolted to coated iron.

Starting point in Moscow: Fields up to 1 kV/m

Initial situation during first tests in Moscow

***Problems**:*

Very sloppy cabling

Screen discontinuity

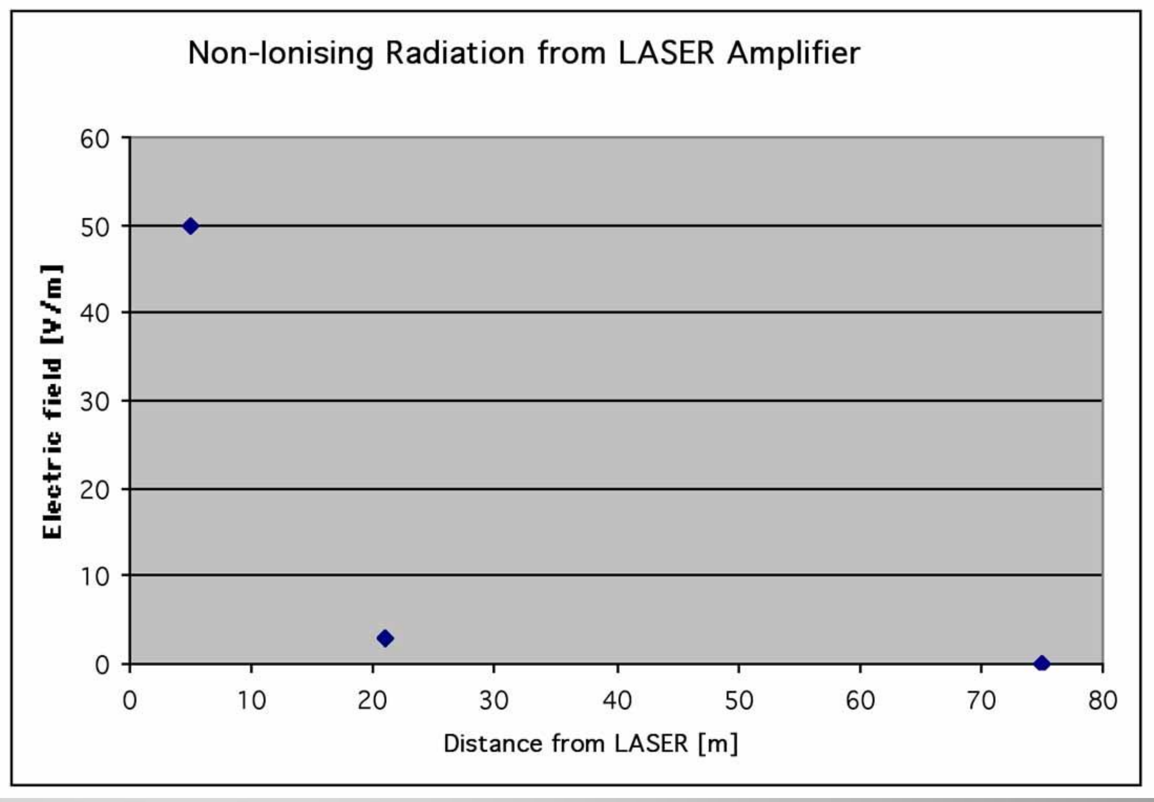
Bad cable selection

Random connections

Aggressive waveforms

Manual control

Auto-interference



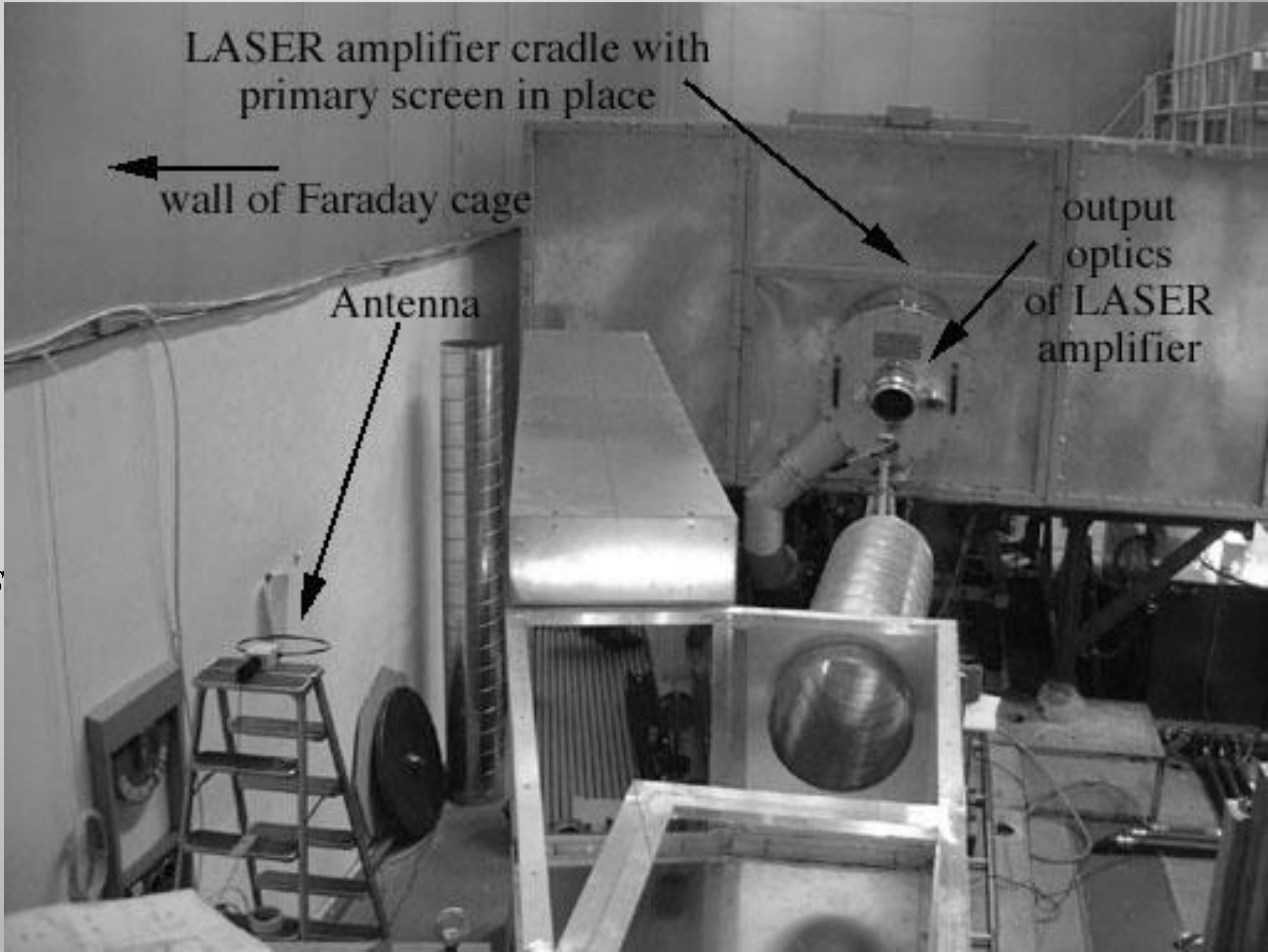
Radiation was so strong that the input divider of the handheld battery powered oscilloscope was not able to divide correctly any more

400kV 20kA pulses: Multiple screening required

Discharge device is in box behind

Objectives:
1) Protect humans.
2) Keep noise level outside building below CISPR11 values

Building attenuation was measured but due to large holes for cable ducts the attenuation was as low as 20 dB for certain frequency ranges



Reassembly at CERN using EMC expertise

The cabling of the LASER was entirely redone at CERN.

All classic EMC and high power switching knowledge was rigorously applied, which meant changing practically all cabling, improve screen bolting, common bonding and placing of apparatus.

Decrease loop sizes and pigtails

Multiple Screen continuity measured

All cables inside iron tubes

Star configuration with strict routing

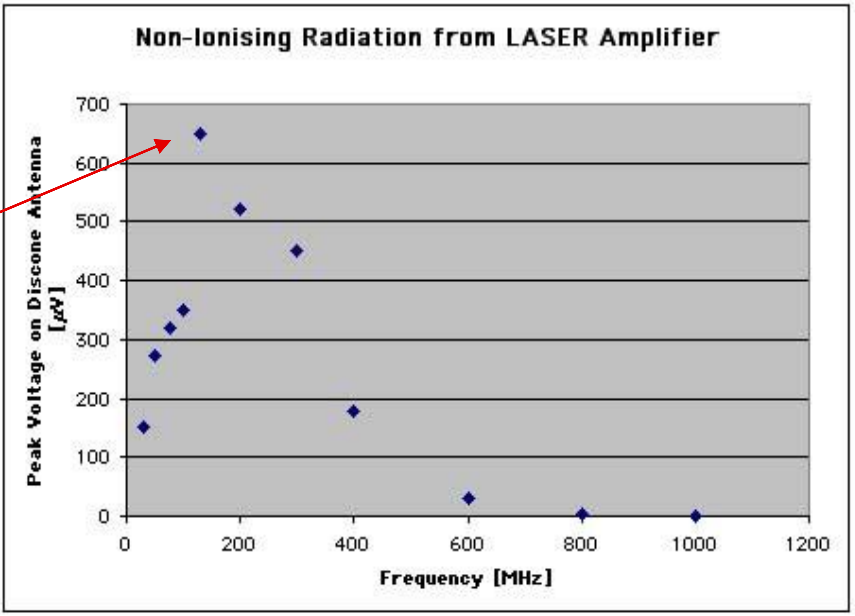
Improve waveforms

Improve control system

Stop Auto-interference by cable separation

Resulting Radiation Pattern of LASER

A loop antenna was mounted at 3 meters distance inside building, and a discone outside.

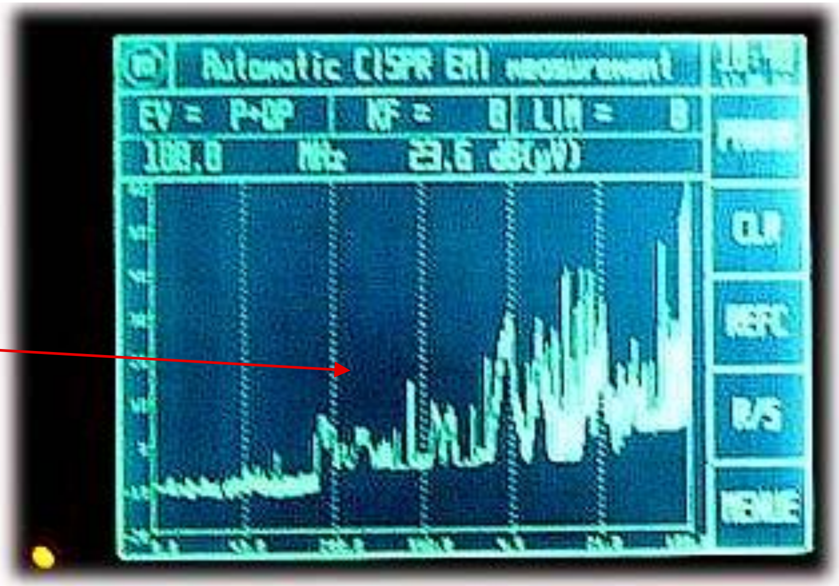


Field values at 3m from LASER below 1 V/m

Conducted noise compatible with experiment running nearby

Scientists were amazed by flawless operation

Very small noise level outside building

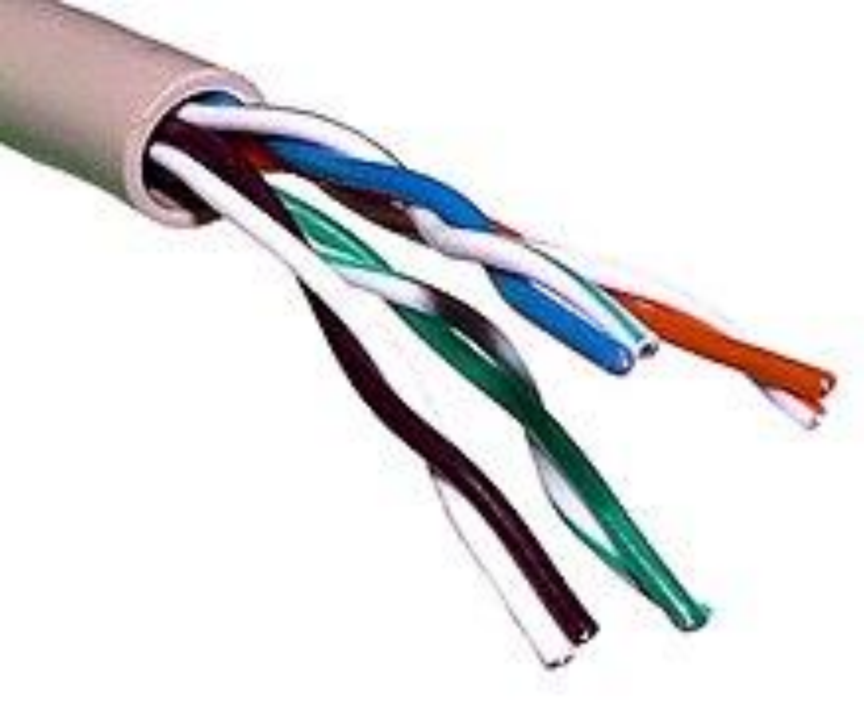


Perfect example of preventive and successful EMC engineering

Part 0	Some Prerequisites
Part 1	What is special at CERN?
Part 2	CERN's Internal Limits
Part 3	Equipotentiality
Part 4	Conducted Noise, Filters
Part 5	Radiated Noise and screening
Part 6	Cabling, Cables, Connectors
Part 7	Physics Experiment EMC Applications
Part 8	Accelerator EMC Applications
Part 9	**Safety System EMC Applications**
Part 10	Conclusions

Part 9
Safety System EMC & Incidents

- Current loops are not unconditionally safe
- Hi-Tech systems: service denial upon perturbation

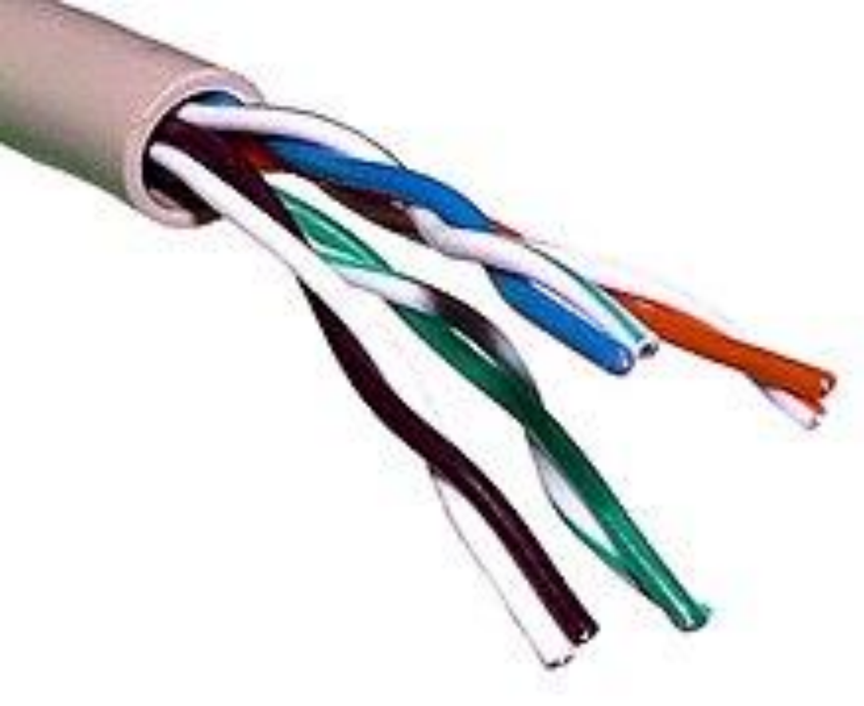


CERN operates many high power devices equipped with the required multi-level interlocks.

CERN's interlock systems cover all stages, including a system that cuts power at the high-voltage level ("AUG"). Many of these systems use currents loops that run over up to 250 contacts in series.

The safety loops use 48VDC battery backed-up power.

There is a connection to the access system which prevents persons from entering premises that are exposed to particle beams.

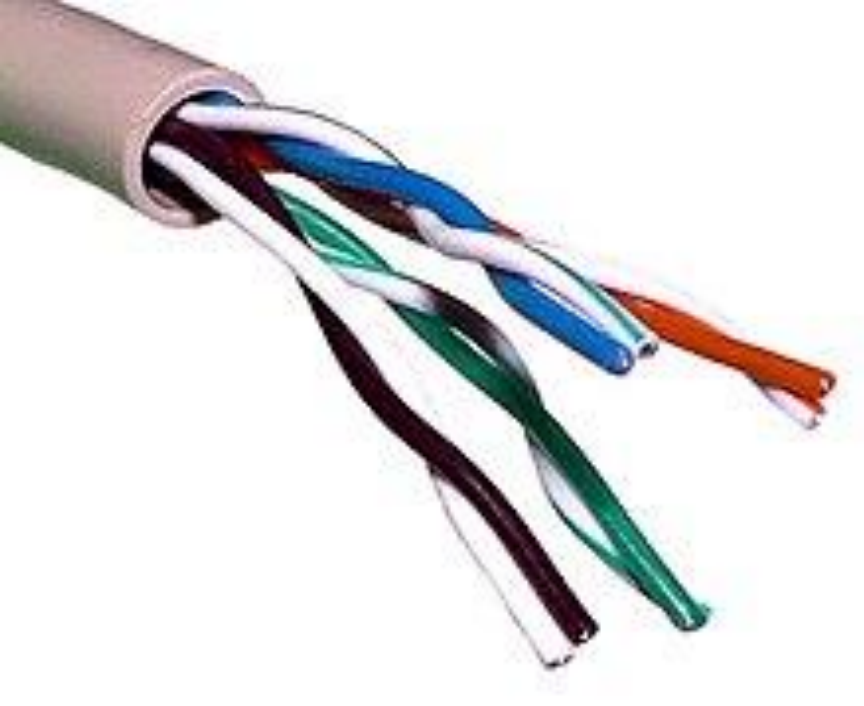


EMC may be well engineered but fitters sometimes err. Tests will not show everything.

We talk about a simple current loop that is conceived to be fail-safe.
The installation is made of multi-twisted pair control cables.
One pair was assigned to accommodate the safety loop.

The safety loop is driven by a PLC and holds closed a 3.3kV power contactor via 4 contacts connected in series ("wired NOR"):

coolant flow sensor
overtemperature sensor 1
overtemperature sensor 2
equipment emergency stop



A fitter messed up the pairs. He connected one lead of one pair and one lead of another pair. A simple cabling error.

The immunity of the twisted pair had vanished. The control cable ran in parallel with power cabling issuing severe harmonics.

When all 4 sensors opened following a cooling failure enough inductive energy was coupled into the safety loop via stray capacitances and magnetic near fields to HOLD THE POWER CONTACTOR CLOSED.

Consequence: A 600kW cryogenic piston compressor overheated and was destroyed, inflicting damage to itself and the building. The EMC team needed several days to understand the reason of the incident.

CERN access system performs a scan of the iris

The scanner, a commercial device, is known to react to microwaves.

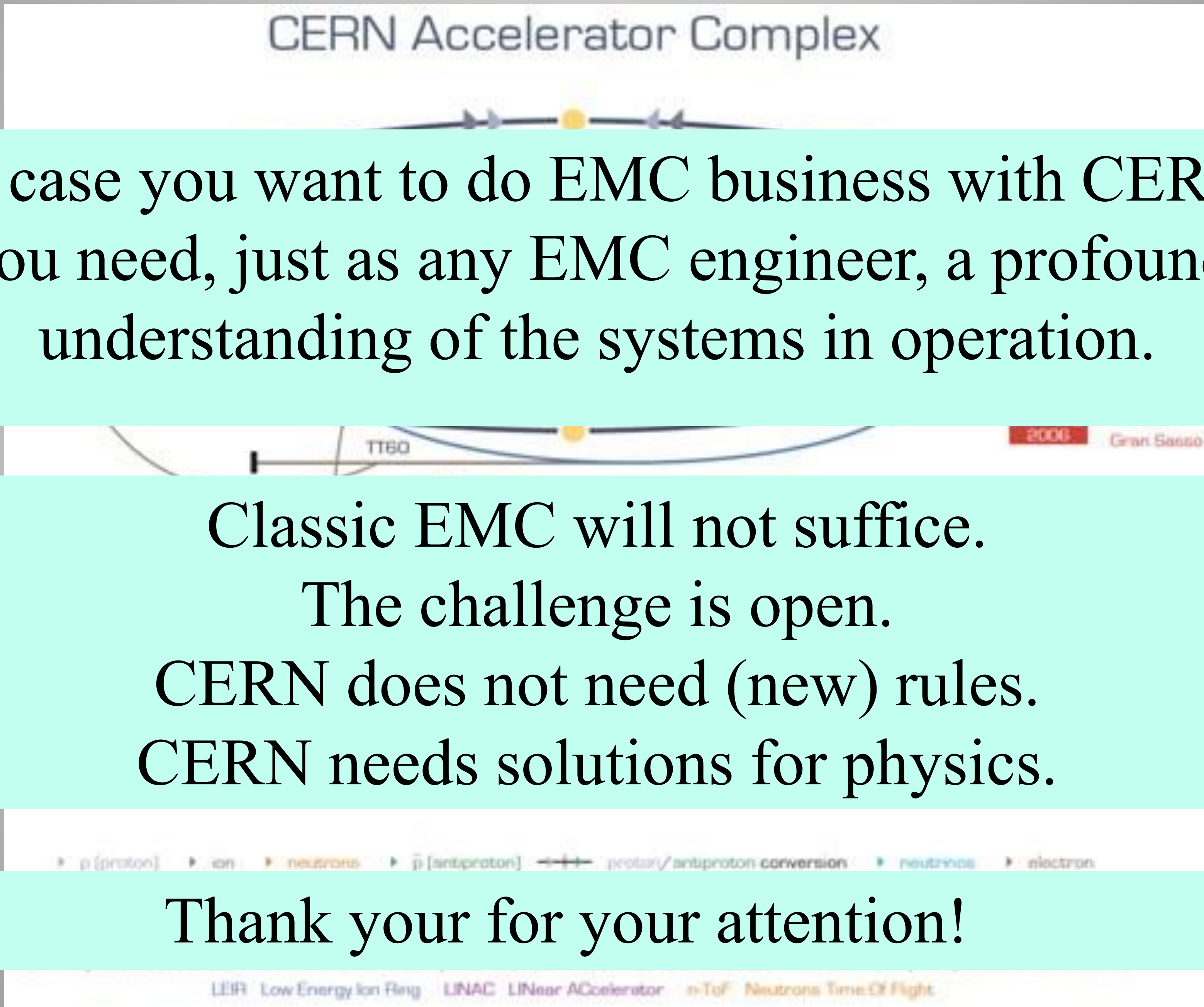
The mobile telephone, when sending packets, disturbs the system which promptly denies access.

CERN cannot alter the device because of legal reasons.

The EMC community might have a solution...

Part 0 Some Prerequisites
Part 1 What is special at CERN?
Part 2 CERN's Internal Limits
Part 3 Equipotentiality
Part 4 Conducted Noise, Filters
Part 5 Radiated Noise and screening
Part 6 Cabling, Cables, Connectors
Part 7 Physics Experiment EMC Applications
Part 8 Accelerator EMC Applications
Part 9 Safety System EMC Applications
Part 10 **Conclusions**

Conclusions



In case you want to do EMC business with CERN you need, just as any EMC engineer, a profound understanding of the systems in operation.

Classic EMC will not suffice.
The challenge is open.
CERN does not need (new) rules.
CERN needs solutions for physics.

Thank your for your attention!