EMC in High Energy Physics

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Introduction

Electromagnetic compatibility for high energy physics detectors cannot be bought by passing an order to one of the specialized EMC-companies. Far too many uncommon technical details may be found in readout electronics for LHC.

The baseline LHC-detectors do not tolerate any noise except the intrinsic noise classes. Any noise originating from so-called interference must be kept out in order to able to fulfill dynamic range requirements. When crosschecking possible noise behaviour against technical parameters like cable leakage, system density, power dissipation etc. one finds that channel-to-channel crosstalk alone could make up more coherent noise than designers would like to allow. Testbeams running LHC equipment prototypes clearly show signs of considerable noise cancellation effort both by hardware and software.

Up to now physics detectors remained more or less accessible for modifications. LHC-detectors, however, are required to be built in a different way. Quality control is put forward, access is limited, the possibilities for later modification are nonexistant or, which is the same, the price tag and development effort for a technical modification are out of consideration.

Electromagnetic compatibility (EMC) as a science of its own is introduced as part of what could be general quality control. Inside large systems a number of parameters look like free choice to innocent designers. They are not. EMC provides many clear guidelines on how to run systems together in a way so they do not interfere. It also mentions effects that the design engineer may not be aware of. Finally EMC provides standardized sets of technical parameters that proved to work elsewhere which is a good starting point for any large system including particle detectors.

Particle detectors of the past showed many weak points, many electromagnetic incompatibilities. Putting prototypes or samples of the electronics on EMC test benches would reveal in a matter of a few weeks why entire chamber system oscillate under certain conditions or why the accuracy baseline of a calorimeter was never met due to inexplicable noise.

Noise sources, noise propagation

Noise sources are either wide-band or narrow band sources. Wide-band coverage is experienced for thermal noise, noise from fluorescent lamps, brush motors, car ignition, data links. Narrow band noise may be confined to a single sprectral line (transmitter, oscillator, parametric effect). Narrow band noise may also consist of a number of spectral lines originating from a transient or from harmonics (switching power supplies, power lines, discharges). Particle showers are themselves noise sources in the RF-spectrum. Noise propagates to a disturbed device by a coupling path [fig.1]. x is the size of the exposed part of the device. Galavnic coupling (conducted noise) is present for all interconnections, whereas other forms of coupling depend strongly on geometry and the type of emission.

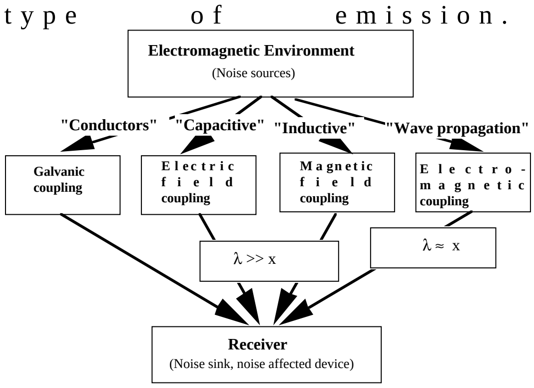

Fig.1 Coupling paths for noise propagation

It is the skill of the design engineer to avoid noise, to cut coupling paths and to render the system as immune as possible against interference. Preventive measures must be accompanied by tests. Preventive EMC-measures are very moderate in cost. The majority of the classic noise suppression circuit and methods may directly be applied even to the inner part of the LHC-detectors.

Equipment for a small EMC laboratory

Large EMC-laboratories for standardization and equipment certification are a considerable investment. However, a small EMC-laboratory capable of crosschecking parameters for a particle detector would not at all be expensive. The most apparent item is the anechoïc chamber which is a screened room equipped with RF-absorbing walls and filtered lines. RF measurements are done using calibrated receivers and antennas. For susceptibility tests a signal generator and amplifier are used. Conducted noise is generated using either mains simulators or signal generators with power amplifiers. Calibrated measurements for conducted noise are expensive and difficult to do. However it is rather easy to do comparative measurements.

Field and noise levels in a particle detector

A number of papers indicates noise levels at LHC-experiments to be a difficult issue. In [2] there is mention of what needs to be achieved. Frontends might look like the one in [fig. 2]. A symmetric driver drives a double-shielded line. Care should be taken to make use of the cables' shielding capacity. It is important to avoid currents as a consequence of noise voltages appearing on the cable screens. The capacitor "C" is decoupling low-frequency and high frequency noise by avoiding low frequency currents yet allowing for high frequency connection to the RF-potential of the amplifier's case.

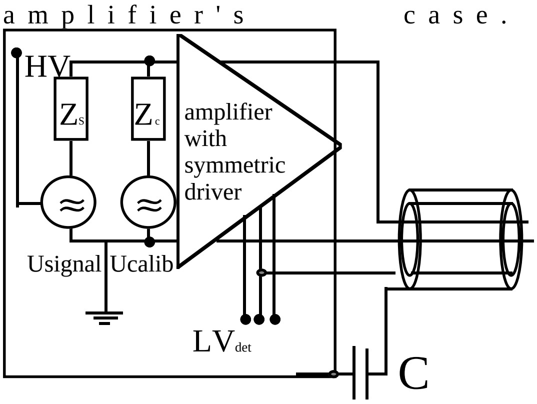

Fig. 2 Layout of a frontend with decoupled low frequency and high frequency shielding

The capacitor C might also be located at the receiving end. Systems able to tolerate certain voltage induced or driven by ambient noise avoid what is called conversions. Most conversions of noise voltages into differential signals are the direct consequence of shield currents. There are different types of conversions. The common point is noise that looks like signals. It cannot any more be separated from the real signals when the spectrum overlaps.

All experimental setups that limit the available ground and shielding configurations could end up with a noise figure that cannot be reduced any more. In particular any length of cable or other conductor ahead of the preamplifier is to be kept free of RF. Shielding attenuation must exceed the dynamic range of the whole chain. Extremely low noise and hence very low RF-field levels are required when preamplifers are located outside a sensor box. A connecting cable of considerable length must be used. The cable must run from the preamplifier box into the sensor box. A minimum of one additional independent shield is required considering the fact that a perfectly connected and terminated cable manages to attenuate outside fields by some 80dB. This number includes many assumptions concerning cable quality, type of field penetration, quality of installation and should be taken as a guideline.

Four noise sources contribute to what is called coherent noise in data analysis. Much of the in-phase RF comes from neighbouring channels and is generally called crosstalk. Charged particles originating from showers inside the vessels will also affect neighbour channels by the electromagnetic radiation. Ambient RF will leak into the frontend by some amount that is primarily determined by the screens and connectors in use. The high voltage supply lines shoud not be forgotten in the noise consideration because they lead directly into the vessels and must have proper RF-filtering. Finally conducted noise will appear in the preamplifiers coming from the power supply as well as from neighbouring preamplfiers. Contributions to the noise contamination may be separated easily. In general coherent noise originates primarily from inside the vessel. Once the disturbed electronics device resides inside a particle detector it is almost perfectly screened. However it is not protected against conducted noise of all kinds. It is vulnerable against its own ambient RF-fields.

A proposal to making EMC standard practice at LHC-experiments

Electronics and system designers of LHC detectors should follow basic EMC guidelines already during the design phase. EMC guidelines [1] would help to avoid most fundamental problems. Fine-tune EMC like conducted noise measurements or radiated noise simulation would remain reserved for the EMC-specialist. He (she) would follow the design of electronics and check prototypes for EMC-parameters like shield leakage etc. At the same time system components like cables, power supplies, cable routing etc. would be checked against each other in order to assess interference levels the designers would have to live with.

In public life there is executive power for independent standardization laboratories. Equipment must fulfill the standards, one of which is an EMC-test. The test usually asks for emission levels to meet limits imposed by standards. Electronics for medical purposes as well as aviation equipment, military equipment and space technology must undergo severe immunity and emission tests.

Physics laboratories and particle detector engineers have not yet imposed such standards or requirements everywhere. However, national or regional standards have to be met. Safety has to be guaranteed.

Particle detectors are recommended to adopt EMC standards similar to standards used in public life (see fig. 3). More stringent requirements than known in the standards could evolve at a later time when noise parameters of frontend electronics become available.

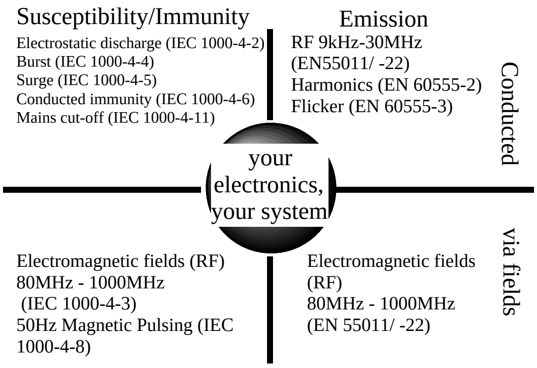

Fig. 3 Public EMC standardization at present

The choice of parameters could also be influenced by the rather exotic environment inside and close to a particle detector.

EMC during experiment operation and commissioning

The experiment's EMC monitoring would follow experiment installation and commissioning. Field levels and spectra in the experimental hall, in the couting rooms and in the vicinity need to be monitored in order to establish an EMC-record for more difficult problems or for sporadic EMC. New equipment giving trouble or faulty equipment is quickly localized and modified. One should not wait until everybody complains about too much ambient noise. The commisioning phase is the most important one. Only then crate after crate comes into operation, only then things can clearly be separated. EMC-monitoring gives clear hints to potential problems.

Switching power supplies need particular attention during commissioning because their noise behaviour dependes strongly on interconnections and local geometry. They also issue conducted noise via the mains. Noise contains mains harmonics as well as many multiples of the switching frequency.

A set of EMC guidelines for collaborating laboratories

Collaborating institutes divide sharply into the ones who take care about EMC and the ones who do not. It is common practice in High Energy Physics to see custom electronics that in principle could be bought off the shelf elsewhere.

Some executive power would be needed in order to certify delivered equipment. Help with modification and some cost compensation must be provided.

Collaborating institutes should be required to produce proof of an EMC-test that would reflect the environmental conditions of the final place in the experiment. This EMC-test could also be done in a dedicated laboratory serving one or more (LHC-) experiments.

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Amendment: Writeup of compatibility standards for experiments (preliminary)

1) Introduction

Industrial electronics productions follow certain engineering guidelines, the most unknown in physics being Electromagnetic compatibility (EMC). EMC is a major ingredient for avionics, spacecraft electronics, medical electronics, automotive electronics and many others. No systematic approach is known for physics experiments although some more recent experiments tried to implement certain standards. Knowing about the difficulty to implement such rules we will limit our standards to details that may be assessed using commonly available equipment. More difficult measurements could be done within a small group of specialists who have access to more elaborated equipment or laboratories.

2) Noise propagation and definition

Any signal that is not intentionally present in a specific circuit is considered noise.

Note: Intrinsic noise such as shot noise or thermal noise is not under consideration in this document because these types of noise are inherent in electronic devices.

The noise source transmits noise via a coupling path to the noise receiver.

These three elements, noise source, coupling path, receiver, are treated separately throughout the document.

3) Noise sources

The general assumption is that all electrical circuits (and certain other things too) create a noise level known as emission. Mechanical dimensions, shielding, current balancing, power, rise-times and many other factors will determine the emission types and levels in dependance of the emission spectrum. Limits are given as national or international standards for certain types of equipment and cables runs. Emissions inside detectors should be limited to the smallest possible levels which means all frontend electronics (plus power installation) would be subject to the most stringent requirements.

Cable runs:

Attenuation capabilities of shielded cables reach into the 80dB-range. However, the attenuation may virtually disappear under certain conditions. One of the worst combinations are single-ended cables that carry additional currents due to ground potential differences. In addition all single-ended cables will need some sort of ground return which results in potential shifting.

It is therefore generally recommended that all cable runs to and from the detector be twisted pair twin lead with proper shielding that does not carry any operational currents. Proper shielding will limit crosstalk and cable emissions in general. Cables should either have the individual pairs shielded or the cable bundles shielded or both. Drivers and receivers of twisted pair cables need to be truly symmetric. Single ended drivers that drive twisted pairs with one lead connected to the circuit common are not considered symmetric. They cannot suppress very much noise. In addition such configurations introduce common ground interference. Power cables radiate rather strong magnetic fields in addition to radiation caused by ripple currents riding on top of the fundamental frequency. Static fields usually do not have much of an effect. Dynamic currents such as mains AC plus its many harmonics and the ripple currents of mediocre DC-supplies radiate a low-to-medium frequency magnetic spectrum that generates standing voltages on all cables cutting through the cable's magnetic field lines. A limit on both ripple and rise-time of alternating or ripple power currents on power lines will be required.

Clock circuits, digital signal transmission

Transmissions must be done via differential copper or via optical links. Any high speed link, including computer links, must be run via shielded cables and employ data-framing to balance currents if at all possible.

Conversions

Signal conversion from common mode into differential mode happens when cable drivers and/or receivers are incapable of absorbing standing voltages that the cable picks up from another noise source. This type of conversion is also widely known for coaxial cables where standing voltages have very different effects on shield and inner conductor. The connection impedances differ. So do the residual voltages.

Monitoring links, detector control

Control and monitoring circuits constitute an additional noise path. Emission levels for the detector control must be low because control and monitoring circuits often use DC-coupled devices.

Power supplies

In the low to medium frequency spectrum the main emissions will originate from power supplies. Makers of power supplies will limit their efforts on emissions to what is required by standards. Noise suppression on power supplies is an expensive undertaking. Linear power supplies (no regulation, magnetic regulation, series regulation via drop transistor) will not radiate much noise except some low frequency magnetic near-field. Switching power supplies, thyristor phase-controlled power supplies, DC-motors, AC-contactors etc. will radiate strong noise if nothing is done to prevent it. These emissions will, due to the impossibility of putting any power supplies near or inside the detector, be present mainly in areas at some distance from the detector as well as in the counting room.

Ground

Grounding is a direct DC-connection to a very powerful and widely distributed noise source. Systems must be grounded for safety reasons but the ground connection should not carry any operational current. All operational currents must flow elsewhere, which distinguishes the ground clearly from the common. The ground is established by a grid in the floor of the experimental hall and electronics house. Electronics must be properly grounded for electrical safety. Ground as such should in no case be confused with a local RF-potential reference linking together fast paths of a circuit. Only locally an RF-ground may be defined at all. Circuits located at a certain distance must be linked by a device that is able to tolerate differences in RF-potential (symmetric link, optical link).

Beam pipe

The beam pipe is a potential noise source. Near field levels produced by the beam itself are presently being worked out. The field levels obtained will be a requirement for electronics noise susceptibility levels on tracker electronics.

4) Noise paths

The cabling layout of an experiment contains some obvious noise paths. Knowledge about potential paths helps avoiding false cable routing or a bad choice of the cable itself.

Ground connections

All connections to ground make a system vulnerable to common ground interference. As no system needs to be grounded in order to work the number of ground connections should be kept as small as possible. Systems connected to long cable runs should not accept ground transfer currents on a routine basis. It is bad practice to buy even more copper mesh in order to keep the ground potential between two points to a minimum. Such practices can result in large currents, which can cause hazards and inadvertant potential differences between other locations. In general ground potential differences are inherent and may not be altered by copper links.

Ground loops

The so-called ground loop is not strictly speaking a noise path. It is, however, a way of generating noise from stray ground currents which happens mainly by converting stray currents into differential mode on the cable. Ground loops may also be closed by capacitances but this leads into the high frequency region where loops do not exist any more but antennas or antenna parts have to be introduced into the modelling.

Cable leakage (crosstalk)

Strict obedience to the use of shielded twisted pair lines should keep crosstalk below the 60 - 80 dB range. Crosstalk varies with frequency and shield connection so the only recommendation is the proper use and installation of cable shields and connectors.

Path mains to DC power rails

Coupling from the mains to the DC power rails is small provided the power supplies have electrostatic shielding. Low frequency ripple is small on state-of-the-art power supplies. The main concern could be switching transients when large groups of power supplies go on or off. Severe transients might stop microprocessors which is disruptive in large arrays. Clear requirements on uninterruptible power supplies and sequencing of power supply turnon/off should be specified.

Detector electronics to detector electronics

Coupling between adjacent detectors is a very likely noise path because the amounts of energy needed to disturb a neighbouring system are rather small and may easily be brought in via stray capacitances. It is imperative to require good susceptibility for frontend electronics. Shielding and, if necessary, guard shielding should be part of the electronics layout for everything that requires a signal to noise ratio in excess of 100:1.

Power rail ripple feedthrough

Ripple on DC power rails feeds through to the electronics. Electronics must be capable of suppressing a small amount of DC supply ripple over a certain frequency range. Ripple rejection also protects against small common ground interference and switching transients.

High voltage supply to frontend

High voltage supplies also carry ripple because the generation of high voltage is done using medium frequency inverter cascades. In addition the high voltage cables bring in another ground connection and hence a noise path from DC to very high frequencies. Decoupling should be done with an eye on safety requirements.

Magnetic stray fields to cable runs and electronics

Dynamic magnetic stray fields come from ripple and AC on power lines. The path exists in the range of the magnetic near field. There is no good shielding against magnetic near field radiation. Electronics must be capable of tolerating induced standing voltages in the mV-range. No currents should be provoked by the presence of such voltages.

5) Noise receivers, immunity

Noise enters systems most visibly where signal levels are at their lowest. Most efforts focus on the frontends. There is a tendency to neglect higher level drivers and receivers/shapers.

Frontend susceptibility

The dynamic range of LHC detectors requires elimination of all noise sources at the frontend. The guard shield configuration may be adopted systematically. It eliminates capacitive stray currents via the inner shield of cable runs. Frontend electronics should be tested by exposure to small radio frequency noise over the spectrum of operation. A testing programme should be established from prototype through to production to ensure sufficiently low susceptibility.

Line driver and line receiver

Systems (still) using line drivers/receivers must meet high noise suppression capabilities over the entire exposure spectrum. In addition cabling may cut through very different noise areas. Tests using normal laboratory equipment may be done to get a first idea on noise immunity.

Digital versus analogue

Digital signals are always present close to analogue circuits. The line of separation is a grey area where we separate the grounding for the digital part from any more sensitive devices. Chipmakers issue clear guidelines for such cases (e.g. ADC's).

Digital circuits

It is widely believed that digital circuits do not experience interference problems. The density of electronics inside detectors will require a closer look on digital signal transmission. There will be an extensive control system and many densely packed fast digital devices. Interference on digital devices has origins similar to the analogue problems but the digital cases are much more difficult to assess. Measurement of digital interference is more complicated, the effects observed are misleading and often blamed on software or synchronization. Common ground interference, crosstalk, reflections, power supply ripple, ground potential shifting - the reasons for digital interference list the same way as the analogue counterparts. Use of commercial equipment will reduce the chance of digital interference. For electronics made by laboratories it is recommended to seek susceptibility improvement wherever the large currents flows in large numbers of digital signals can cause ground currents and change the characteristics of digital signals. These must be checked with full-scale system tests.

6) Parametric susceptibility

Static magnetic field

Inside the detector the magnetic field will prohibit operation of any motors or fans, all power supplies, all chokes using iron, iron powder or ferrite cores. Outside the detector there will also be magnetic field at an assumed field density of 0.05-0.1 Tesla in one meter distance of the detector. Restrictions apply as above but some specially designed or oriented equipment of the above-listed might work. As the field values are rather exotic compared to normal standardization requirements it must be made sure that the equipment close to the detector is able to function. The field in the electronics barracks will reach 0.01 Tesla (100 Gauss). Equipment must be tested for functionality in such a field.

Temperature, Humidity, Light

Condensation provokes quasistatic discharges. Temperature effects translate into cooling effects - all electronics will have forced cooling. Pipes must be grounded. Charge displacement by the cooling medium is a rare source of interference. Light occasionnally interferes into frontends, mainly into exposed glass-diodes.

Mechanical displacement and vibration

Even very small vibration amplitudes at low frequencies inside the superconducting coil will cause considerable emf in any (open) loop that vibrates perpendicularly to the field lines. Outside the coil the effect will be less pronounced but mechanical amplitudes may be much higher. Calculations show that the effects are not negligible at all. Low impedance loops do not vibrate because a compensating force is generated by the loop current.

EMF due to changes in main coil current

The current of the main coil has a large time constant due to the small resistance of the superconducting coil. Cables cutting through the magnetic field lines will be subject to transient emf in case of quenching. Amounts are still unknown.

EMF due to loss of power on DC-rails

The same effect occurs when DC-rails supplying electronics in and on the detector loose power. It should be noted that these rails carry kiloamperes of DC. The fall-time of the rail current will determine the emf caused in all cable runs (or shields) situated in the near-field.