Grounding, Shielding and Power Distribution in LHCb

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Abstract

The LHC-b collaboration needs some basic rules on grounding, shielding and power distribution to minimise noise susceptibility. The content of this note is to propose some primary guidelines that must be followed by each subsystem. These guidelines will be submitted to the Technical Inspection and Safety Commission (TIS).

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1. Introduction

Noise problems in High Energy Physics experiments are often not encountered during the design phase of a detector system. Unfortunately they tend to show up when the full system is installed and operating in its intended environment. Most particle detectors work with very low signal levels on a considerable number of channels and are therefore very sensitive to all kinds of external noise sources. Because prevention is usually cheaper than suppression, each subdetector must pay close attention to grounding, shielding and the power and signal distribution. Other LHC experiments have their own documentation on grounding and shielding [2], [3]. Between different experiments there may be significant difference in the recommended grounding scheme (Ground mesh versus star coupling).

The purpose of this note is to propose some basic guidelines that must be considered by each subdetector group during the design stage of their detector. Once the LHCb grounding policy has been approved by the Safety Community, each sub-system will be required to provide a written description on how it intends to achieve the defined guidelines.
2. Grounding

Unfortunate grounding has in previous experiments been found to cause significant problems. The general scheme to prevent problematic noise being injected by ground loops into sensitive circuits is to prevent sensitive signal paths to be a direct part of a ground loop covering a large surface area. The larger the surface area of the loop the larger ground loop currents will be collected. Ground loops in mechanical structures and within a solid grounding mesh should not be considered problematic as long as it does not inject noise into the critical analog front-ends. The use of a low impedance ground mesh where ground loop currents circulate (instead of in other signal paths) prevents the ground loop currents to be injected into other signals and assures a well defined reference point for the total system (equipotential). The two figures below shows how the addition of a simple solid ground cable in a cable tray can significantly decrease the effective area of a ground loop seen by a signal transmitted over long distance. In the case with the ground cable in the cable tray there may be a large ground loop within the grounding network but this is much less serious than a large pickup loop for the sensitive signal itself.

![Figure 1. Significant noise pickup on cable shield with no ground cable in cable tray](image1)

![Figure 2. Total area of pickup loop significantly reduced with ground cable in cable tray](image2)

It must be assured that possible relatively large ground currents are not traversing local weak and sensitive ground paths and therefore inject noise. It can therefore in some cases be needed to use a local grounding
structure with a star configuration to assure that ground currents from other sources are not traversing a local ground connection.

![Diagram showing prevention of injection of ground currents into sensitive circuits](image)

**Figure 3. Prevention of injection of ground currents into sensitive circuits**

Individual sub-detectors should be connected to the ground network in a fashion that prevents possible ground currents from one system to traverse sensitive local ground connections in another system to ensure minimum coupling between independent sub-systems. Even within a local sub-system it may be difficult (impossible) in practice to ensure the total absence of local ground loops. It is therefore important to define a local low impedance grounding mesh (well connected to the global ground mesh) that prevents possible ground currents to propagate to sensitive signals. The grounding scheme used within each sub-detector is in principle up to each sub-detector group to define. It must as a minimum be ensured that no individual system forces large ground currents into the local grounding network of another system. It must be mentioned that even with a local grounding scheme without any DC ground loops, multiple AC ground loops will always be present because of capacitive coupling between neighboring elements.

In earlier large scale high energy physics experiments it has in some cases been found that the best configuration to minimize noise in a sensitive detector and its electronics is to use a different configuration than initially planned. If a tightly connected grounding system with many wanted (and also unwanted) ground connections have noise problems it may be very difficult to identify the possible cause of this as it is impossible to define and measured the coupling between its different components. It is therefore important to have a well defined grounding scheme with some flexibility that can be used to resolve possible problems when used in the final application. A well-organized local grounding structure with a limited number of ground connections can normally be modified into a heavily interconnected structure if really needed. A heavily interconnected structure can normally not easily be changed into a structure where a specially sensitive circuit can be “isolated” from problematic currents in the grounding network.

An effective ground mesh (global and local) must consist of a highly interconnected network with low impedances. The use of many low inductance connections with low resistance minimizes resonances and ensures a high damping factor.

Obtaining good electrical contact to certain materials can pose practical problems. Some materials form a natural surface layer of oxidized material (e.g. Aluminum) that prevents good reliable electrical contacts to be made with simple means. Direct connections between materials of different types may also develop galvanic voltage differences and potential problems with long-term corrosion.

### 2.1. Safety grounding

Grounding of all accessible conducting structures are required for safety reasons. All ground connections must be designed to be capable of carrying the full currents from a possible grounding fault (e.g. power line accidentally connected to conducting surface because of an insulation fault) without danger for personnel.
touching such structures. Damage to the electronics itself in case of an insulation or grounding fault should also be minimized. Large parts of the electronics used in the front-ends are not readily available commercial components and if a significant part of the electronics is damaged it may not be possible to procure the required components (ASIC’s, obsolete commercial components, special radiation tolerant components, etc.)

It is not allowed to have conducting objects of any size “floating”, especially in the presence of high voltages in detector modules. At CERN, the protective ground and the neutral conductor are separated. They are both connected to a common earth at the secondary star point of the main distribution transformer. All connections to the safety earth are referenced to this point. In practice, due to the poor conductivity of the rock, there will be no “local” earth connections in the cavern. Nevertheless, it is considered by TS/EL (Electrical installation group of the technical support department at CERN) that the iron reinforcement in the concrete of the cavern walls and floor is “naturally” linked to earth via the touching parts of the cavern with earth. A “strong earth conductor” runs from the safety earth reference point to the surface buildings, control rooms and the experimental cavern. This “strong ground conductor” runs on both sides of the cavern and connects in addition to the safety ground for the LHC machine. A similar “strong ground conductor” connecting the rails in the cavern floor will be installed on each side of the experiment in parallel to the beam pipe. All safety ground connections must be made to this ground network.

Ground connections should NOT be used as a power supply return path and should not carry any current except in case of a fault. When a system has once been connected to the grounding network it cannot be disconnected, unless a special safety procedure has been followed. During commissioning and installation of the sub-detectors leakage currents and possible return current in the ground connections must be verified while the sub-detector and its complete electronics systems are fully working.

### 2.2. Low voltage power supplies

To prevent power supply return currents in the grounding network, it is necessary to have the power supply outputs (both plus and minus terminals) isolated from ground. Multiple outputs from the same power supply unit should also be isolated from each other and only be connected together in the required configuration at the load. The power supply should be connected to ground at the load to introduce minimum disturbances to sensitive front-end electronics. If grounding were performed at both the power supply side and at the load, the power return current would be carried by both the power return wire and by the grounding system which is not allowed. If power supply return currents were carried by the grounding network, voltage differences between different parts of the grounding system will be generated which is against the purpose of equipotentiality. The power supply “box” itself must be connected to ground for safety reasons as indicated on Figure 4.

![Diagram](image)

**Figure 4.** Grounding of low voltage power supplies.
DC power supplies up to 120 V are at CERN considered as extra low voltages [25]. In principle any power supply can be left floating if the system is sufficiently insulated according to CERN safety rules [23]. Once a floating power supply is mounted, it will not be allowed to connect any of its output terminals directly to ground as this will generate return currents in the ground network.

A safety connection to ground is required for voltages larger than 50 V DC (not common in HEP applications except for HV). Saturable inductors are not recommended in detectors due to the presence of external magnetic fields and because their impedance varies strongly with frequency. Using diodes for the ground connection is interesting but the short circuit and the transient currents must be carefully rated. Over-voltage protector elements like Voltage Dependent Resistors, designed to absorb energy in case of faults, is also a possibility. The choice of device to use depends on the voltage range, the response time and the amount of energy to be absorbed in case of a fault.

The partitioning of the power supply system may also have significant impact on grounding. If individual power supplies are used for each individual power consumer then there is no direct interaction between the different consumers. If a power supply scheme based on bulk power supplies is used with a distribution from each power supply source to multiple users then a problem of power return currents between users via the local grounding network arises. A simple situation is sketched in Figure 6. The individual users have connected one of the power supply terminals to their local grounds. Now the local ground connections and the power distribution lines with currents I1, I2, to IN forms a loop. If I1 = I2 = IN and R1 = R2 = RN then the potential of the local grounds are identical and no currents are carried by the grounding system. If this is not the case the local grounds will have a tendency to have different potentials which will force currents into the grounding network which is unfortunate. If the distance between power consumers are short (low R1, RN resistance) and they have similar power consumption the current in the grounding network will be limited. The situation is similar to a grounding plane in a PCB which is part of both the grounding and the power distribution system. A solid ground bar or ground plane can be used, as indicated on the figure, to assure that possible power return currents does not introduce local voltage differences in the ground reference.

It can alternatively be chosen to use the power fan-out point to connect to the ground. The problem of currents in the grounding network is in this case resolved but the local ground potentials seen by each power consumer will be modulated with the voltage drop in the power return distribution wires. A similar situation will be the case if a bulk power supply is used to feed a set of linear regulators that then feeds local consumers at some distance. Linear power regulators do not give galvanic isolation between the different outputs.
2.3. High voltage power supplies

High Voltage (HV) power supplies are often needed in detectors and requires special attention to their distribution and cabling for reasons of safety. Floating high voltage power supplies can be used, as described above for low voltage power supplies, if and only if a ground fault safety connection is made at the power supply side as illustrated in Figure 7. This ground fault safety connection must prevent the high voltage power supply to become freely floating, in case the ground connection to the detector side is lost. HV supplies are often distributed using coaxial cables where the shield of the cable should be connected to ground.

In some cases high voltage power supplies are hardwired to ground and this ground is connected directly to the shield of the coaxial cable. The HV must normally also be connected to ground on the detector side and a problematic ground loop is created. This low impedance ground loop can potentially be “broken” by connecting the shield of the cable through a 1kΩ to 10KΩ resistor at the detector side as shown in Figure 8. As the currents used from high voltage power supplies are normally quite small the voltage drop introduced by the resistor in the return path can often be accepted. The problem of this approach is that the return currents will tend to use the low resistance ground network as the power return. As the grounding
network in principle should not be used as a power return, this must be considered a very unfortunate approach that should only be used in exceptional cases when no other implementation is possible.

![Diagram](image1.png)  
Figure 8. Grounding of non floating high voltage power supplies with resistor in return path.

High voltage power supply distribution systems will normally use a simple R-C low pass filter on the detector side to prevent noise pick-up in the distribution cables to be propagated to the noise sensitive detectors and their analog front-end electronics.

It is sometimes recommended to use double isolated shielded cables for HV power distribution (tri-axial cables). This gives the possibility to make a separation between the shielding and the return line of the HV power distribution cable. With this implementation, the first shield is used as a return line as it is usually done in LV distribution systems and the second shield of the cable as a shielding for the HV line.

![Diagram](image2.png)  
Figure 9. Grounding of high voltage power supply using tri-axial HV cable.

### 2.4. Data transmission

Data transmission from the front-end electronics to the DAQ system and the distribution of timing and control signals to the front-end electronics should be performed via optical links whenever possible to be immune to RF, inductive and capacitive noise coupling. Optical links are completely immune to external electrical noise sources and therefore ensures a reliable data transmission.

In cases where optical links cannot be used, all data transmission must be performed via differential electrical connections with a good immunity to common mode noise (e.g. > 1V) (see more details on differential signal transmission in paragraph 4: Shielding). To eliminate ground loops via the shield of the cable one can decide to not connect the shield at both ends directly to ground. Nevertheless there are many different opinions about this subject. Some EMC experts believe that it is more effective to be well connected to ground at both ends with the shielding screen of a copper cable. Two important details have to be considered before interconnecting the shielding at both ends to ground. First this interconnection should be done only if the ground at start and end locations of the cable is well connected with a low impedance ground connection (this is the case in the LHCb experimental cavern, see chapter 6). This is to avoid having the interconnection between local grounds made only via the shield of a sensitive signal cable. If it is not
the case, the current circulating in the shielding screen may be high (possible fire risk). The second thing to be considered is that large ground loops created by the interconnection of the shielding of a cable should be avoided. Such large ground loops can be avoided by having the concerned cables installed in grounded cable trays.

It is often recommended by EMC experts to connect one end of the shielding to ground and the other end of the shield to ground via a capacitor. The capacitor will act as a short circuit at high frequencies keeping the efficiency of the shielding, while breaking ground loops at low frequencies. It can be recommended to use a solder bridge to choose between the two options as indicated in Figure 10. As the common mode rejection of all differential transmission schemes is limited it must be ensured that the possible voltage difference between the ground levels at the two ends is kept as small as possible.

![Figure 10: Use of solder bridge to connect the cable shield, either via a capacitor or directly to ground at receiver end.](image)

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### 2.5. Cooling and gas distribution pipes

Cooling pipes and gas distribution pipes are often made of conductive materials and can possibly be used as an integral part of a local grounding network. They should though normally not be considered to be the main component of a grounding scheme. Attention must also be made to how the electronics components to be cooled are electrically connected to the cooling pipes. Good thermal contact is needed but in many cases it is not appropriate to electrically connect a sensitive front-end chip directly to such a cooling pipe.

If a system is required to be isolated from ground, a potential cause of an undesired ground connection are liquid cooling systems for front-end electronics located inside detectors and gas systems for the detectors themselves. To obtain isolated sub-systems it is needed to have pipes going to different parts of the system isolated from each other. This is normally obtained using a dedicated isolation piece in the pipes between different segments as indicated in Figure 11.

![Figure 11: Electrical isolation of cooling pipes.](image)
2.6. Mechanical support structures

Unintended ground connections can occur via metallic mechanical support structures. Great care can possibly be made to prevent this kind of ground connections to occur via the mechanical fixtures to the support structures. This is though in practice quite difficult to guarantee for large complicated structures. In most cases ground loops via mechanical support structures, or loops between grounds, are of low impedance and are not (must not be) part of sensitive signal transmissions.

In case it is found that the best grounding scheme is to ground all modules directly via the mechanical support structure it is advisable to have envisaged connection straps for this purpose.

2.7. Front-end electronics

The analogue front-end electronics is normally the main victim of ground loop problems (and other noise problems from external sources). Collected detector signals are very small and low noise preamplifiers for HEP applications are often implemented with single ended input stages and therefore have no means of rejecting common mode noise. It should be noted that differential amplifiers should be used whenever possible to have the best possible rejection of external noise sources. Differential pre-amplifiers normally have slightly worse intrinsic noise characteristics, but they are much more powerful to reject external noise. The connection between the detector and the preamplifier is very delicate and the grounding scheme used for these two elements is critical.

Front-end modules/hybrids often use separate ground planes in the PCB to prevent noise from local digital logic to disturb the sensitive analogue electronics. The use of such “clean” and “dirty” grounds must be done with great care. In some cases the approach of two separate grounds has been seen to provoke more problems than a single common ground plane. Especially the circuit bridging the signals from one domain to the other may be a victim of the differences between the two grounds. In a printed circuit board ground plane the function of grounding and the local power return is mixed and may therefore induce specific problems. It is clear that for instance the power return currents from a noisy digital circuit should not be made to traverse the ground plane where sensitive analogue circuitry is located. Splitting the ground plane into two regions can prevent power return currents to circulate between two regions. To ensure that the ground still has an effective function as a common reference the two grounds should be well connected in one low inductance and low resistance connection. If two separate ground planes are used in two neighbor layers with significant overlaps one must also be aware of the significant capacitive coupling between two such layers. The ground plane of a printed circuit board should normally only connect to the surrounding shield (Faraday cage) in one location to prevent possible ground loop currents to propagate across the ground plane in the PCB and to prevent power return currents in the PCB to be forced into the faraday cage. This means that the mechanical mounting of the front-end module should not connect the ground plane to its surroundings in more than one location (use of isolating screws, etc.). Coupling between analogue and digital circuits on the same board is also often occurring via power supplies. It is therefore important to have independent power domains for analogue and digital electronics when possible.

The signal ground from the detector must have the smallest possible noise in relationship to the sensitive pre-amplifier and its local ground reference. This normally requires the detector ground reference to be connected with the shortest possible connection to the analogue ground reference of the pre-amplifier. The distance between the signal wire and the ground wire must be kept as small as possible to minimize collected noise and minimize inductance. To have the smallest possible ground loop from each detector signal to ground the ideal configuration is a ground wire per signal wire. This will in many cases not be possible but as many ground connections as possible between the two should be implemented.
Figure 12. Possible grounding of sensitive front-end electronics
3. EMC

To obtain the best possible inter-operation of multiple electronics equipment it must be ensured that they generate the minimum noise possible and are as insensitive as possible to external noise sources. This problem of minimizing radiated and received noise is often referred to as Electro-Magnetic Compatibility (EMC). EMC rules often refer to a variety of guidelines used in industry to describe electrical and electronic appliances for radiated influence and susceptibility in an increasingly rich electronics environment. A standardized EMC approach was first used in space and aeronautic programs for safety requirements. Due to the increasing amount of vital electronics equipment used in medical applications, a systematic EMC approach is now also used extensively in this domain. EMC qualification is now a standard procedure used in industry before commercialization of standard consumer electronics [16]. Some other good references about EMC can be found [17], [18].

A general rule in ensuring a stable function of sensitive electronics is to optimize (minimize) the bandwidth of the electronics used to only cover the frequency range of real interest. In this simple way noise sources outside this frequency range will be effectively rejected. In high energy physics experiments the collected and digitized signals will often be treated with some final digital signal processing which can reject certain types of noise quite effectively. Low frequency noise is often removed using pedestal and common mode correction schemes on an event by event basis. Simple binary detectors can though obviously not profit from such DSP based correction schemes.

It is known that high energy physics experiments located in underground caverns have very little noise from external sources as the earth and the iron in the cavern walls acts as very efficient shields. Noise in HEP experiments will originate from the experiment itself, the particle accelerator or other equipment present in the cavern. Radio frequency noise from radio, television and other transmitters will not pose problems in an underground experiment. Potential noise sources seen at LHCb can therefore in principle be quite well predicted. All harmonics of basic frequencies must obviously also be taken into account (e.g. 80 MHz, 120MHz, 160MHz , ).

The 40 MHz bunch crossing rate of the LHC accelerator is the most obvious source of noise. In detector electronics sampling detector signals with the same frequency and a fixed phase, all noise sources from the 40 MHz operation will normally show up as fixed pedestal levels in detector signals. This can therefore in most cases be rejected easily by adjusting threshold levels or using pedestal and common mode compensation schemes.

In the start of LHC running a 75ns bunch spacing will most likely be used because of bunch to bunch interaction problems in LHC at startup. Detector signals will though still be sampled at 40 MHz so this may become a visible noise component.

The LHC machine runs with a RF frequency of 400.8 MHz that may potentially propagate to the LHCb experimental cavern. In addition to the fact that this should also be seen as a fixed pedestal (due to the correlated sampling frequency), the noise rejection of such high frequencies should be obtained by limiting the bandwidth of the front-end electronics to what is really needed.

The LHC machine generate bunches in identical groups of 80* 25ns = 2us. This Regularity in the machine structure will generate a potential noise source of 500 KHz.

The LHC machine cycle consists of 3654 bunch cycle periods of 25ns equal to a 10946 Hz signal.

Switching mode power supplies are known to generate significant noise at their basic switching frequency and its harmonics. Modern switching mode power supplies use switching frequencies
between 500KHz to a few MHz. Especially common mode noise from floating power supplies can
give surprises as it is known to have large differences between different manufactures [19].

The triggering of the LHCb front-end electronics will occur at the first level (L0) trigger rate which
has been defined to have a nominal frequency of 1MHz. This is not a fixed frequency, as the trigger
in principle is random. The noise from this will therefore have of a relatively wide spectrum. As the
L0 trigger is often used on the same front-end modules containing the analog front-end, this will
often be a major source of noise. Noise can be generated when event data is copied from the L0
pipeline into the L0 derandomizer or when the event is read out of the L0 derandomizer (see below).
This noise will often be seen as a coupling from previous events and the “trigger history” which in
practice will be difficult to compensate for in later processing stages.

The readout of events accepted by the L0 trigger will occur after a derandomizer at a speed of 900ns
per event (1.1111 MHz). The L0 trigger system will most likely run close to saturation to maximize
the physics output of the experiment. The 1.111MHz will therefore be seen as a narrow bandwidth
signal.

The second level trigger (L1) rate is defined to have a nominal frequency of 40kHz. In the same
fashion as the L0 trigger, this is in principle a random source and will have a wide spectrum.

50Hz noise from all mains installations is a well-known source of low frequency noise.

The LHCb main magnet will be powered by a 12 way rectifier power supply which will have a small
ripple of 600Hz. This ripple should not be seen in the main magnet field, as the iron core of the
magnet (and other structures) will filter out this AC component (the magnet has a very large
inductance). The ripple will tend to concentrate to the stray fields in air close to the magnet coils and
the power feed lines.

Florescence light tubes are a well known source of EMC noise when they turn on because of the use
of a glimmer startup relay. Worn out tubes tend to continuously flicker and therefore generate wide
bandwidth EMC noise from the spark generated in the startup relays. Electronics starter circuits
should be used in critical areas and tubes must be exchanged before they start to pose problems.

The installation of mobile phone networks and wireless computer networks in the cavern will be a
possible source of RF noise at 900MHz and 2.4 GHz. (can possibly be turned off during data taking)

Most electronics systems used in high energy physics experiments are very sensitive to noise. It is therefore
strongly recommended to follow basic EMC rules in the design of the electronic systems and PCBs.
Specific design rules must be used where high speed clock and fast voltage or current transients are used. A
short list of basic EMC design guidelines is given below:

• Fast changing voltages or currents will generate Electro-Magnetic Imittance (EMI).

• Identify potential sources of EMI: electrostatic discharges, detectors close to particle beams, crosstalk
on cables, clock or trigger signals, magnetic and conductive coupling via common supply or parallel
cabling, etc.

• Minimize the bandwidth of the electronics to what is really needed.

• Use a solid and well thought off grounding point.

• Use ground planes or ground mesh whenever possible.

• Keep ground runs as short as possible.
• Avoid using thin wires for grounding.

• Use multi-layer PCBs wherever possible with dedicated power and ground planes.

• Extensive use of decoupling capacitors on power supplies. (Use different values of decoupling capacitors. This helps to avoid having possible resonance effects)

• Use shortest possible signal traces.

• Avoid sharp corners on critical signal traces.

• Avoid un-terminated inputs and outputs.

• Design clock distribution with great care to minimize clock correlated noise.

• Use differential circuits and signals wherever possible.

• Group components to minimize interconnectivity and thereby minimize interference.

• Analyze carefully and maximize Power Supply Rejection of sensitive analog front-end electronics.

• Use if possible local linear power regulators for sensitive analog front-end electronics to minimize noise from power supplies.

• Multiple ground planes must be used with great care.
4. Shielding

To obtain the best separation between possible noise sources and noise sensitive electronics it will be necessary to use an extensive system of shielding. The best way to have maximum immunity against external electromagnetic fields is to locate the detector and its electronics in a closed Faraday cage. This Faraday cage must usually be connected to ground for safety reasons but this grounding has no direct relation to the shielding effect of the faraday cage.

There are three basic reasons for the use of shields: shielding against capacitive coupling, shielding against inductive coupling, and finally RF shielding.

Capacitive coupling involves the passage of interfering signals through mutual and stray parasitic capacitances. Capacitive crosstalk is often seen in multi-wire cables. The way to block capacitive coupling is to enclose the circuit or conductor to be protected in a metal shield (Faraday shield). The shield does in principle not need to be grounded but this is usually done to ensure that circuit capacitances to the shield go to the ground reference rather than act as possible feedback and crosstalk elements. Also from the mechanical point of view, grounding metallic pieces is often inevitable.

The physical mechanism of inductive coupling is magnetic flux lines from external interference sources, via current loops in the victim circuit, which finally generates a voltage component in accordance with Lenz law. There are basically two schemes to defend a circuit against inductive pickup. Offensive fields should be prevented at their source when ever possible. Minimizing the area of the current loop at the source to promote field cancellation is the most efficient approach. The other aspect is to minimize the inductive pickup in the victim circuit by reducing the area of the receptive current loops. In the cavern a ground cable will be located in each cable tray to minimize the pickup loop between the cable shields and the ground. For inductive coupling shielding will in most cases not have a significant effect, except from the fact that the shield and the signal wire will normally get the same induced effect. Potential ground loops (DC and AC wise) can cover large areas and can therefore pick up significant induced noise components. The use of twisted pairs, where the small local current loops between the two wires constantly change direction, is a powerful scheme to minimize generated and received inductive coupling. The common mode signal of a differential pair will still be a victim of induced noise but this will not be seen in the differential voltage on the twisted pair. Induced noise is normally seen in the low frequency range and can be removed effectively by using differential signals. Low frequency noise components can also often be compensated for in sensitive analog front-end electronics by using automatic pedestal/common-mode compensation circuits. A potential source of significant inductive noise in the LHCb environment is the coils of the main spectrometer magnet. The main magnet will be powered from a 12-way rectifier with some 600Hz ripple, which will be seen in the magnetic field as a small 600Hz varying field. Such an AC component will get concentrated in the stray fields in air close to the coil windings and the power feed. During the first tests of the main magnet, foreseen for 2004, this inductive noise component will be measured, as it is difficult to get precise estimates of this from simulations. Other potential sources of inductive coupling are transformers, coils for light tubes, electric motors and power supply lines.

Changing electrical and magnetic fields may also generate Radio Frequency (RF) interference problems. Generated and received RF interference is strongly depending on the wavelength of the signals present and the dimensions of the electrical structures. The smaller the size of the circuit the higher frequencies will pose potential problems. All signal wires are potential antennas for the transmission or reception of RF noise. When these antennas have dimensions comparable to the wavelength of the signals (e.g. ¼, ½, ¼, 1, wavelength) in question, resonance phenomena will make the noise coupling significantly stronger. A ¼ wavelength antenna for a 40 MHz signal is 7.5 meters long, which is comparable to some structural dimensions in LHCb. An 80 MHz harmonic could easily be picked up by the wires in a ~3.75m long drift tube of the outer tracker if not sufficiently shielded. The general idea behind RF shielding is that time-varying fields induce currents in the shielding material. The induced currents dissipate heat from resistive
losses or are re-radiated as RF reflections. Reflections, being a surface effect, are basically independent of the thickness of the shielding material. The efficiency of a RF shield is strongly dependent on the frequency and the permeability and conductivity of the material used.

It has in some cases been seen that the shielding of a cable only connected to the reference ground of the detector electronics, and not to the faraday cage, act as a source of noise. The shield may act as an antenna picking up noise outside the faraday cage and then retransmit this inside. Signals should when possible be filtered at the input/output to a faraday cage to prevent propagating external noise inside. DC signals like power and power return can be filtered with a simple LC circuit as indicated in the figure below. The inductor can in most cases be made with a simple ferrite choke around the cable [18]. In regions with strong magnetic fields, or possible large inductive noise, inductors should be used with great care and it may be better to use only a capacitor as filter.

![Faraday cage with filter](image)

Figure 13. Signal filtering at entrance to faraday cage

Copper and aluminum have both the same permeability, but copper is slightly more conductive, and will provide greater reflection losses to an electric field. Steel is less effective because it contains iron that elevates its permeability, and reduces its conductivity. Absorption losses to an electro-magnetic field are higher at higher frequencies, making shielding more effective at high frequencies. A different shielding mechanism can be used for low frequency magnetic fields using high permeability materials, such as mu-metal. This kind of material diverts the field by presenting a very low reluctance path to the magnetic flux. Above a few kilohertz, the permeability of such materials is the same as steel.

Differential signal transmission is in principle immune to external noise sources that couples to the two signal wires in the same fashion. A good symmetry of the cable is vital to ensure that induced noise is only seen as a common mode component. The differential receiver must obviously have a very good Common Mode Rejection Ratio (CMRR) to remove all common mode noise components. It is also vital to ensure that common mode noise do not get transformed into differential mode noise via the output impedance of the driver and the input impedance of the receiver. These two impedances must be perfectly symmetrical to prevent such a transformation of a common mode noise signal into a differential signal. A good common mode rejection and symmetrical impedances are normally only obtained up to a given frequency. At higher frequencies it is vital that the cable shield prevents pickup of high frequency noise components.
5. Power supply distribution.

The detector geometry or the signal cabling of a sub-detector often defines the power grouping of a detector. All channels connected to one receiver module form a natural group. Any inherent grouping should not be broken by the power supply distribution system. The number of groups supplied by one power supply should be kept as small as possible. Having large amounts of electronics powered by one single strong power supply often looks attractive and simple but is in many cases an unfortunate approach. Small well-isolated groups connected to a small power supply source located in the vicinity may avoid several problems. Separate power supplies for natural groups are desirable but may in some cases be cost exclusive.

Power supply monitoring should be available remotely via the ECS system. Protection of the electronics circuits during faults should be made using power supplies with short circuit protection circuits with fold-back operation. Local fusing should be used to protect local circuits, but may require repair to exchange a blown fuse. Resetable fuses now commercially available are in this respect an attractive solution for electronics in locations with difficult access (especially for cases of Single Event Latchup). Active low impedance current monitors and protection switches are also available at low cost [22].

In cases where power is distributed to multiple sources via thin cables from a single high current power source it must be ensured that a local short circuit in one of the local consumers can not overload a thin power cable in a way risking to generate a fire. In such cases it will be required to have local fuses as indicated in Figure 14.

![Figure 14. Use of local fuses to prevent fire hazards](image)

In cases where power must be distributed over long distances and remote sensing is used to compensate for the voltage drops in the cables a whole set of precautions must be taken. The response time of the remote sense control loop must be carefully matched to the resistance, capacitance and inductances in the power system to ensure a stable function without risks of oscillations. The inductance and resistance in long power cables and the matched response time of the remote sense circuit pose special problems for feeding power to electronics with largely varying power consumption. If the power consumption in a remote circuit suddenly is decreased by a significant factor the accumulated energy in the cable inductance, the reduction in resistive voltage drop and a relatively slow reaction time of the remote sense may result in a significant over-voltage at the electronics. This problem is especially present with the use of modern CMOS technologies. CMOS circuits (digital) have a power consumption proportional to their operating frequency. If the clock to a digital CMOS circuit is suddenly stopped its power consumption will basically instantly fall to zero. A significant over-voltage on the CMOS circuit in such a case may cause damage, as modern CMOS technologies cannot tolerate a significant increase of its supply voltage without damaging the circuit or affecting its long-term reliability. The use of passive decoupling capacitors can in many cases reduce this problem to an acceptable level. In other cases more elaborate schemes using local linear power regulators or alternatively using zener-diode or normal diode voltage clamps will be required.
Remote sense lines are normally routed using shielded twisted pairs to obtain a good immunity to external noise sources. In case of a short circuit fault on the twisted pair the sense line will short circuit the power supply with large currents flowing in the sense wires as a result. As the sense wires are not designed to carry large currents this failure can potentially start a fire. To ensure that the sense wire can never be forced to carry the whole current of the power supply, protection resistors or fuses must be used at the load side as current limiters. The effect of such protection resistors/fuses must obviously be taken into account in the operation of the remote sense control loop.

Some care must be taken in defining the specifications for the remote sense capabilities of power supplies. Not all power supplies have a fully differential sense circuit. This may imply special restrictions on the voltage loss in the power cables and the effective common mode range (this is a known limitation of the radiation tolerant linear regulators from ST that only have single ended sense capability).

It should also be mentioned that normal power supplies can only supply current on its positive terminal and can normally not sink current. In certain unfortunate power supply configurations a power supply may under certain working conditions be required to sink current. For a normal power supply this will lead to a not correctly working power supply system with a possible danger of damaging supplied circuits. In power supply systems with long power supply cables with relative large voltage drops a careful analysis must be made to verify that this type of problem can not occur. Special source and sink capable power supplies exist but are much more expensive and should be avoided if possible.

Cables used to deliver power to the electronics should also use twisted pairs or similar schemes to minimize the generated magnetic field and induced noise to a minimum. In some cases the power cables even need to be shielded. Power cables must in general be as short as possible to have the lowest possible resistance and inductance. Increasing the distributed capacitance (eg. Using flat bus bars with small distance between the two terminals) will also in some cases improve the quality of the distributed power.
Switching mode power supplies should be physically separated and shielded from low noise electronics as the large current peaks seen in this kind of power supplies may generate significant Electromagnetic noise. Floating power supplies have in some cases been seen to have significant common mode noise [19]. Customized output filtering may be required for special sensitive applications.

Below are given some generic rules that can be used for the design of the power supply distribution:

- Add 25% to nominal load when using DC voltages and currents
- Avoid using power supplies as local references for sensitive front-end electronics as power supplies will inevitable have noise and ripple.
- Test electronics against realistic ripple on power supplies
- Separate return path for each power supply
- Keep the distance between supply and load to a minimum
- Avoid double grounding at supply and load
- Sense lines must follow power lines.
- Use shielded twisted pairs for sense lines.
- Use twisted pairs for power lines
- Bandwidth of sense circuit must be well matched to used cable distances
- Use low resistance and low inductance cables for power distribution
- All safety aspects must be verified
- Fuses must be used to prevent possible fire hazards.

![Diagram of protection resistors/fuses on sense wires for fire protection.](image-url)
6. Grounding in the cavern

In the experimental area, all metallic structures are connected to ground [26]. The iron rails in the cavern floor [21], the iron reinforcement structure in the concrete of the experimental area, the cable trays, as well as all other metallic support structures are connected to ground. Two 120mm² ground cables, connecting all the previously mentioned parts via 50mm² cables [20], are running along the sides of the experimental cavern. This whole structure can be considered as a heavily interconnected grounding mesh. This grounding mesh is connected at one point to a cable connected to the central grounding point of the main transformer at the surface via the PM shaft. The LHCb grounding mesh is also connected to the grounding of the LHC machine on both sides of the LHCb cavern (RB84 and RB86).

Several different ways of connecting equipment to the global grounding mesh can be considered in the cavern. The first possibility is to connect the equipment to the grounded rails with a well dimensioned short cable. The second possible way to connect the equipment to the ground is the connection plates that are located on the walls of the cavern, on both sides. These plates are simple metallic plates with a number of holes to screw many cable lugs. Finally it can be considered to use the mechanical support structure as a grounding connection but it must in this case be well assured that the support structure is well connected to the central ground network. In this case a separate safety ground strap may be required.

All cable trays have a ground cable that connects to each separate part of the tray to ensure that all parts are well grounded.

In the counting house the raised floors for the racks are considered as a grounding mesh connected to the global LHCb grounding. Each rack is assured to be connected to this mesh via ground braids.
Elements connected to earth via a 50mm$^2$ cable:

- Green: Metallic structures (platforms)
- Dotted: Concrete reinforcement
- Red: Support rails
- Grid: Reinforcement structure in the floor tile
- Blue: Counting house

To the:

- 120mm$^2$ earth cable

Figure 17. Top view of the grounding principle in the experimental area.
Elements connected to earth via a 50mm$^2$ cable:

- Metallic structures (platforms)
- Concrete reinforcement
- Support rails
- Reinforcement structure in the concrete
- 50mm$^2$ earth cable in the cable trays
- Grounding plates

To the:
- 120mm$^2$ earth cable

Figure 18. Side view of the grounding principle in the experimental area.
7. Grounding examples

The general system grounding of LHCb is based on a heavily interconnected ground mesh structure, made from the grounding network, rails, iron reinforcement and finally all mechanical support structures, to have a well defined ground potential with the smallest possible differences between different locations. Within such a general grounding scheme there is still “room” for different local grounding schemes to match the different requirements of different sub-systems. Two implementations are shown as examples of extremely different approaches. In practice a compromise of the two may be chosen as each type of sub-detector has different constraints (e.g. Vertex within LHC beam pipe and ST tracker with independent double faraday cages).

7.1. Floating detector with one ground strap (star structure)

Figure 19 below shows an example of a grounding scheme for a sub-detector where it has been chosen to have the whole front-end floating except for a single compulsory ground strap. The detector has been insulated from its support structure using insulators and has a single well defined short ground strap for safety grounding. With such a grounding approach it is assured that no group loops are generated with the grounding wires. Even the cooling system and/or gas distribution pipes are insulated from the main system through insulators. All power supplies are fully floating and each supply has its own return path. Signal cable shields are connected on the transmitter side and connected to the receiver side via a capacitor. The whole detector is located in a Faraday cage. The detector module is connected to earth at only one point. The ground connection is done via the Safety connection line and this connection must never be removed for safety reasons.
Figure 19. Example of star grounding of a sub-system.

It must be noted that this grounding scheme may not have any ground loops via the ground connections themselves and therefore in principle have no ground loop currents in the grounding network. The loops though still exist and the currents/voltages generated by the pick up loops will be forced to occur via the signal connections themselves.

7.2. Heavily interconnected ground configuration (mesh structure)

In this approach the opposite principle is used. Ground connections to the global grounding network are made on “all possible locations”. The power supplies are still kept floating to prevent return currents via the ground connections. A large set of ground loops exist in such a configuration but the low impedance of the grounding network assures that these currents are “neutralized” instead of being forced into sensitive signals. In such a configuration it must be ensured that large ground currents from other systems are not forced to traverse a weak local grounding network in a circuit dealing with small signals. The different ground connections and their integration into the global grounding network must therefore be well thought out.
Figure 20. Example of mesh grounding of a sub-system
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