Grounding Requirements Document for STAR

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Controlled STAR Note 202A

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Version A. Transformers are now on the north platform. Items on the north platform will use conventional power, while items on the south will use clean power. Power transformers are grounded to the north platform. Isolated north platform from detector and made appropriate changes. Increased capacitance budget of magnet and integration reserve.

Because there are many small voltage and current signals in the STAR detector, it is necessary to insure that there is a low noise environment. Consequently, proper precautions must be done when planning the grounding of the detector as improper grounding can produce voltage gradients and unanticipated electrical paths. These can produce unanticipated currents and consequently electrical noise. Signal return currents must be well defined. This means that the return current will pass through a well defined path that does not interfere with other signals. A preliminary plan has been described in STAR Note #148. We define clean power as electric power used for the STAR electronics and conventional power as electric power used for items that typically generate extraneous electrical signals in the electrical power grid.

STAR Power Distribution

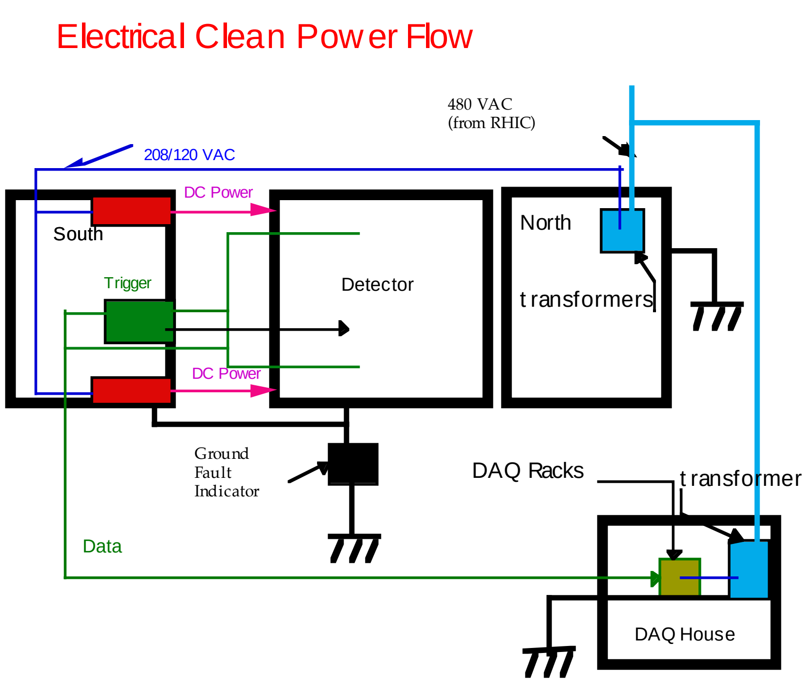

Figure 1. Electrical clean power schematic of STAR.

It is important to understand the full electrical flow in STAR to establish appropriate electrical guidelines for grounding. The main distribution of power will come from the west wall of the Assembly Hall or the Wide Angle Hall (depending on where the detector is located). RHIC will supply power to that area in the form of 480V. The distribution of that power is the responsibility of STAR. A block diagram of the system is shown in Figure 1. This figure indicates that all clean power will be on the south platform. The south platform will then supply power to the detector.

A ground fault detector, which is shown in the bottom of Figure 1, provides an important monitor on the quality of grounding. It can provide an alert when an inadvertent connection is made so that appropriate actions can be done.

The system will be described from the stand point of signals being introduced from external sources. Figure 2 shows a grounding diagram. The primary ground is G1 (located at least 50′ from the beam line) and G6. G1 is one of the columns in the WAH while G6 is the building ground in the DAQ house. Both are well defined; the G1 and G6 connections have very low resistance.

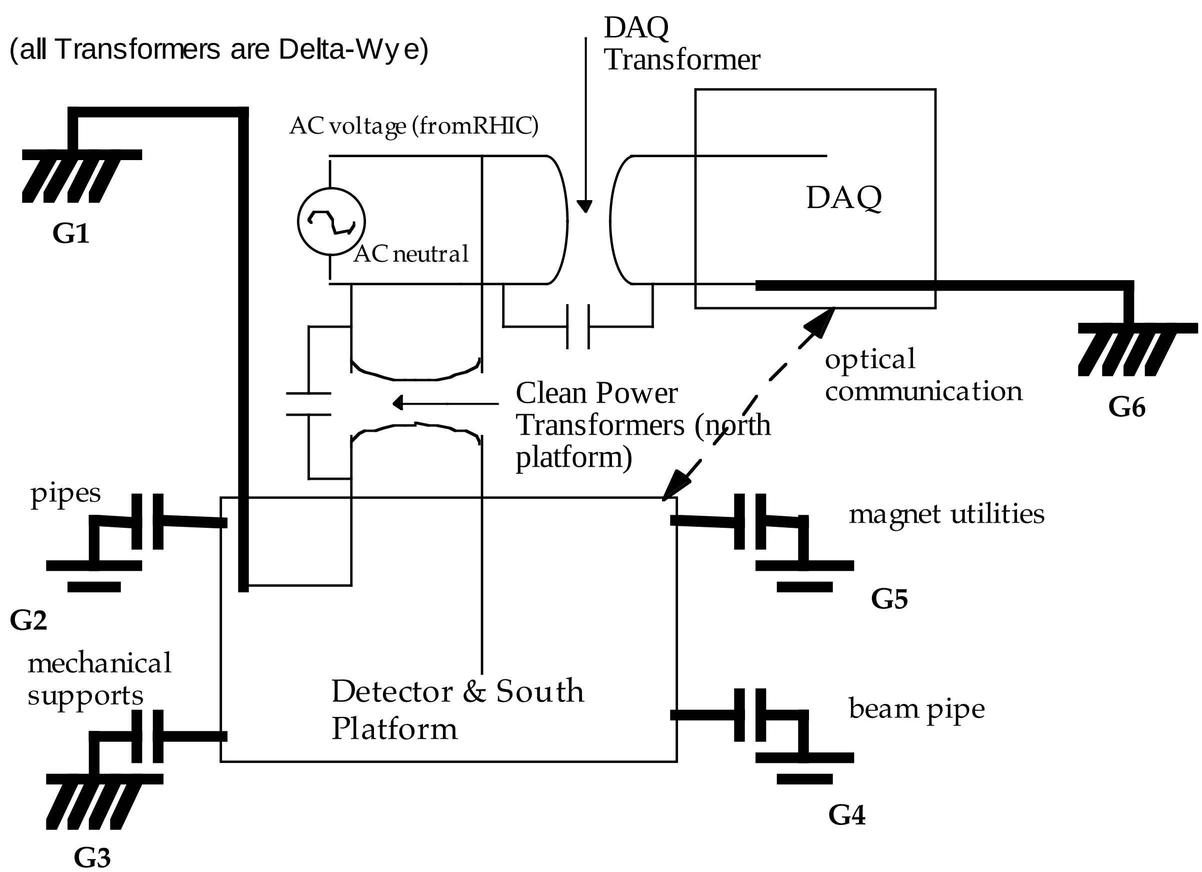

Figure 2. The ground path is shown by the thick lines.

Even though the pipes, Hillman Rollers, etc. are insulated there is still a capacitor coupling to ground shown by G2-G5. As there is no guarantee that the different grounds are at the same potential, signals will flow in ill defined paths. It is most important that the capacitive coupling to G2-G5 be reduced.

Formulas used to establish grounding guidelines

Various noise frequencies are expected to be generated at RHIC. The expected sources include:

Noise Source	Expected Frequency	Assumed Voltage
RF from the accelerator	9.1 MHz for the beam 26.7 MHz for RF 200 MHz for storage RF	0.01V
cryogenic system	60 Hz	0.1 V
Magnet Supplies	360-720 Hz (+ spikes)	0.1 V
SCR power supplies	60 - 240 Hz with spikes of 1 ms (10 KHz)	0.5 V 0.1 V
nearby FM stations	100 MHz	0.02 V
building ground	60 Hz	0.5 V
motors, pumps, compressors	60 Hz	0.5 V

Table 1. Anticipated noise sources at STAR.

From this table, we can estimate the noise as a function of frequency. For frequencies not listed in Table 1, we interpolate from these numbers.

Frequency	Expected Induced Voltage	Interpolated
60 Hz	0.5 V	no
10 KHz	0.1 V	no
100 KHz	0.077 V	yes
200 KHz	0.059 V	yes
250 KHz	0.056 V	yes
500 KHz	0.051 V	yes
1 MHz	0.044 V	yes
10 MHz	0.01 V	no
100 MHz	0.02 V	no

Table 2. Estimate of noise in the STAR detector.

Capacitance coupling to the ground is very significant at high frequency. The impedance, X_c can be expressed by the following formula:

$$X_c = \frac{1}{2\pi f C}$$

where f is the frequency of interest and C is the capacitance. The following table shows the impedance (ohms) at different frequencies:

	1 pf	**10 pf**	**100 pf**	**1000 pf**
100 Hz	$1.6 \cdot 10^9$	$1.6 \cdot 10^8$	$1.6 \cdot 10^7$	$1.6 \cdot 10^6$
100 KHz	$1.6 \cdot 10^6$	$1.6 \cdot 10^5$	16,000	1,600
100 MHz	1600	160	16	1.6

Table 3. Variation of impedance for a capacitor as a function of frequency.

We assume that the most sensitive element of the detector is the TPC pad amplifier, all requirements will be established to minimize any additional noise on the TPC. The capacitance of the pad and traces is 40 pf with noise of 1000 electrons RMS. We require that any noise source be a level less than 1/10 of the intrinsic TPC noise. The figure below shows our model of the system:

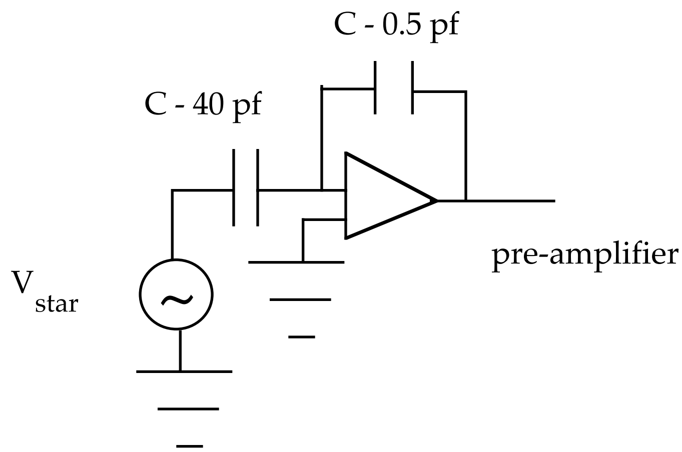

Figure 3. Model of noise into TPC pre-amplifier.

Using the formula, $V_{noise}=Q/C$, we calculate that the maximum allowed noise contribution is 0.4 µV at 2 MHz, the peak frequency of the TPC pre-amplifier. Using the frequency response of the pre-amplifier which has a loss of 20 dB below the peak frequency and 40 dB above the peak, we can calculate the maximum allowed noise at different frequencies. The following table shows the results:

	100 Hz	**1 KHz**	**10 KHz**	**100 KHz**	**1 MHz**	**10 MHz**	**100 MHz**
$\mathbf{V_{max}(f)}$	1000 µV	800 µV	80 µV	8 µV	0.8 µV	10 µV	1000 µV

Table 4. Maximum allowed noise input to TPC pre-amplifier.

Because of saturation effects in the amplifier, the maximum allowed noise is 1000 μV.

To understand the effect of noise on the STAR detector we need to make a model. To completely describe the detector and its coupling to RHIC would involve an extremely complicated model. Unfortunately, there are too many unknowns to make such a calculation. Therefore, we make several believable approximations, and make a simplified diagram which is shown in Figure 4. In addition, we make a assumption that all the signal across the inductance, L_D, will appear as V_{STAR}.

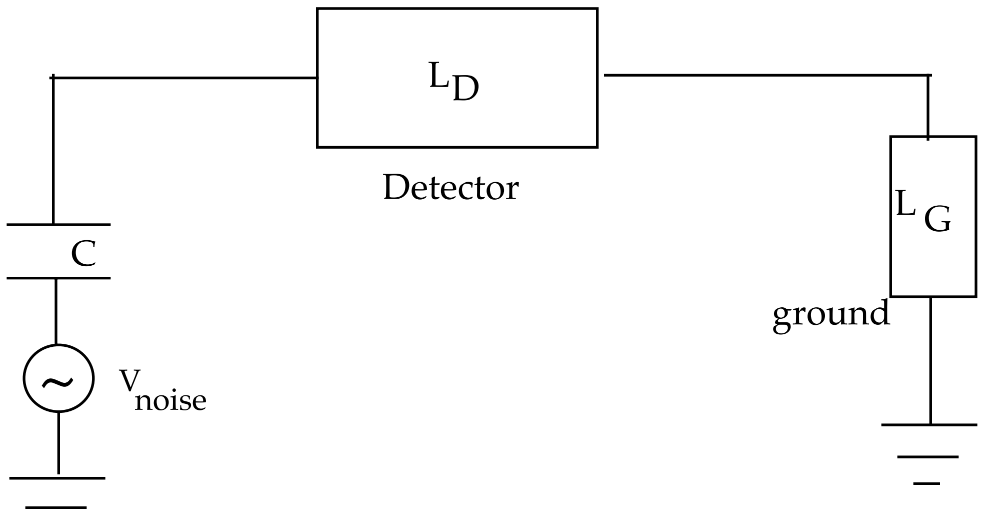

Figure 4. **The block components are a noise source, V_{noise}, a capacitive coupling, C, the detector inductance, L_D and the inductance due to the ground, L_G.**

We can approximate the inductance of the ground wire, L_G, by the formula which expresses the inductance of a wire above a ground plane.

$$L_G = \frac{1}{3}\left[138 \cdot \log\left(4\frac{h}{d}\right)\right] \cdot l \cdot 10^{-10}\,\frac{henry}{cm}$$

where d is the diameter of the wire, h is the distance the wire is above the wire plane, and l is the length of the transmission line. The impedance of the transmission line can be calculated by the formula $X_L = 2\pi f L$. For the case where a ground wire of diameter 0.5" , length 50' and distance away from ground plane of 1.0", we obtain an inductance of 2.5 μh.

The impedance of the STAR detector can be approximated by assuming that the detector is a parallel-strip line.

$$L_D = \frac{1}{3}\left[377\frac{w}{s}\right]\cdot l_D \cdot 10^{-10}\frac{henry}{cm}$$

For the detector, 50 cm (*w*) above the floor of the WAH and width 285 cm, (which is along the beam direction), and length l_D, we calculate an inductance of 1.8 μh. LD can be found by adding the width of the detector (320") and size of the north (173") and the south (313").

Using the model described in Figure 4, the voltage induced on the STAR detector can be approximated by:

$$V_{Det} = \left(\frac{X_{L_D}}{X_{L_G} + X_{L_D} + X_C}\right)\cdot V_{noise}$$

In this simplified model, both resistance and phase effects are neglected.

Assuming that the noise will be distributed uniformly through the detector, then the noise over the most sensitive element, the TPC pre-amplifiers can be estimated by:

$$V_{STAR} = V_{Det}\cdot f_{TPC} = \left(\frac{X_{L_D}}{X_{L_G} + X_{L_D} + X_C}\right)\cdot V_{noise}\cdot f_{TPC} \qquad (1)$$

The fraction of the noise, f_{TPC}, induced on the TPC pre-amplifier can be estimated by dividing the length of the circuit board (10 cm) by the length of the detector l_D. This formula, equation (1), will be used to estimate the capacitance limits.

We can determine the maximum allowed capacitance by taking $V_{noise}(f)$ from Table 1 and V_{Det} from Table 4. The result is displayed in Table 5:

Frequency	**Maximum Allowed Capacitance**
60 Hz	> 1 f
10 KHz	23.4 μf
100 KHz	33.5 nf
200 KHz	5.3 nf
250 KHz	2.8 nf
500 KHz	377 pf
1 MHz	54.0 pf
10 MHz	267.7 pf
100 MHz	> 1 nf

Table 5. Maximum allowed capacitance to produce acceptable noise on the TPC pre-amplifier.

The assumptions break down at 60 Hz because the impedance of the detector becomes unreasonably low. At 100 MHz, the amplifier is insensitive to the input because of the 40 dB role-off/decade. We have estimated the required capacitance at each frequencies.

Due to the physical size of the geometry, it becomes very difficult to achieve the low capacitance needed in the MHz range. Fortunately, appropriate shielding can be used to screen the apparatus or absorb the noise in the frequency range above 100 KHz. An electrostatic shield (a copper sheet), which is grounded at one end, can provide sufficient shielding. Another technique is to surround a partially resistive coupling around an object. For instance, running a pipe through a ferrite core would decrease the high frequency noise component.

From this table and the fact the we can reduce the high frequency noise component, *we can set the total maximum allowed capacitance to 5 nf.* This value of the capacitance is good up to 200 KHz. We need to partition this capacitance over different items. We can itemize the total contribution of capacitance to the detector and produce a budget that each element of the detector must not exceed. Table 6 shows the allotment. The numbers are based on reasonable dimensions that can be achieved by each element. These numbers are the basis of the requirements that are described in the next section.

	#	**C_{max}**	**C total - nf**
Pipes (gas and water)	50	10 pf	0.5
Magnet	1	2000 pf	2.0
Platform	1	700 pf	0.7
EMC electronics	1	200 pf	0.2
SVT	1	225 pf	0.225
FTPC	2	200 pf	0.4
Management Reserve	1	600 pf	1.0
Total			**5.0**

Table 6. Capacitance budget (@ 200 KHz) for various STAR elements.

REQUIREMENTS:

1. Single Point Clean Power Ground - South Platform and Detector.

It is necessary to have a well planned grounding to ensure the electrical integrity of the detector. *A fundamental grounding principle is that all grounds should be well defined.* The building ground in the WAH is expected to have different potentials throughout the hall. If the detector is connected to two separate potentials, a current would be produced and would cause additional noise in the detector. The single point ground is used to minimize the current induced in the detector due to these ground variations. *Furthermore, grounding must be done in a safe manner.*

In order that there be no other ground paths, it will be necessary to make sure that the electronics do not have another path to the ground. Several steps must be done to isolate the detector from other unplanned ground paths. These paths include the concrete floor and beam pipe. The capacitance coupling due to the magnet, insulated pipes, and the platform and detector supports, and power transformers must be minimized to reduce the potential ground current. The following actions must be done to ensure that there is a single point ground:

1.1) **Pipes, entering the detector and the south platform, shall have their electrical path broken with a capacitance of < 10 pf.** The main sources of noise are produced from the pump motors and the variation in the building ground. A secondary noise source is the RF pick-up from accelerator operations and from nearby FM radio stations. With an estimated 50 pipes, this results in a total capacitance of 500 pf.
The place where the isolation occurs shall be clearly marked. Care must be done so that the insulating material is not flammable and does not provide a hazard for flammable gas or introduce unwanted impurities into the fluid.
The length of insulating material, *l*, can be calculated by the following formula:

$$l = \frac{\kappa \varepsilon_0 A}{C} \qquad (2)$$

where κ is the dielectric constant, ε_0, is the permittivity of the vacuum.

$$\varepsilon_0 = 8.859 \cdot 10^{-12} \frac{coul^2}{newton \cdot m^2}$$

The effective area of the pipe can be estimated by the full radius of the pipe or the cross section of pipe. The actual capacitance will probably be a value between the calculations of those geometrical shapes. For a pipe of radius 1.77 cm and thickness of 3 mm, then the minimum length to achieve a capacitance of 10 pf varies from 1.3 to 3.4 cm depending on which model is chosen. The dielectric constant of water is 78 which is high compared to a gas whose value is slightly higher than 1. Consequently, the distance for gas isolation will be less.

1.2) **All pipes and conductive structures shall be isolated > 6 inches from the detector and the south platform and labeled that they are isolated** There are many potential conductive paths entering the detector. Due to the fact that there could be a physical connections between nearby pipes, we need a well defined place where the isolation occurs. In this way, the possibility that there is an accidental connection is reduced. Furthermore, labeling will help us visually detect improper ground connections.

1.3) **All connections from the detector to the DAQ or Operations Room shall be fiber or have fiber optic isolators.** This prevents stray signals from traveling between these different areas. Signals which need to have isolation include Ethernet, TV, communication signals, and any analog signals. If transformer coupled signals are the only practical solution, then their use must be justified.

1.4) **RHIC signals shall to be fully isolated from our electronics.** The simplest way to do this is for RHIC to send us only fiber optic signals. This is certainly a practical solution for most signals. However, it is much more difficult for TV signals.

1.5) **Electrical shields shall be grounded at one end.** In this way extra loops are not introduced. If this requirement has to be violated, then there must be a formal review. RHIC safety rules might require that all HV be grounded at both ends.

1.6) **All signals from the platform to the detector shall be fiber or differential.** Using fiber optic or differential cable reduces the potential for any ground coupling problems.

1.7) **Grounds from the 480 VAC power transformers shall be tied to the north platform which is tied directly to the metal rails.** This grounding scheme is needed so that the current produced from a transformer short does not produce a safety hazard.

1.8) **The magnet shall be electrically isolated from the concrete floor and metal rails with a total capacitance less than 2 nf.** Care must be taken to prevent extraneous grounds from connecting to the steel plates on the floor and the concrete floor. The Hillman Rollers assembly bear several kilotons of weight. It will be necessary to have an insulator bear this weight and be able to handle the shear stresses of the detector. If Torlon is used as the insulator (κ *=6.5 at 1 MHz)*, then according to equation (2), an insulator with an area of 8″ by 32″ must have a thickness of 1.9″ to achieve the required capacitance of 200 pf. With 4 rollers, there will be a contribution of 1.6 nf to the capacitance. This leaves 0.4 nf for other magnet supports.

1.9) **The south platform and the magnet iron shall be tied together electrically. The south platform is tied to the detector. The ground from the detector is connector to a building column at least 50′ from the beam line.** This enables a common potential for signals which will communicate with each other. The 50′ requirement is made so that there is minimal coupling between the RHIC beam and its associated noise from the STAR detector. Different columns may be used when the detector is in the WAH or the Assembly Hall. It is important that the ground wire be isolated from all other grounds until it reaches the building column.

1.10) **The north platform shall be electrically isolated from the magnet.** The capacitance coupling between the north platform and the magnet is included in the capacitance budget of the platform.

1.11) **The EMC bridge shall be isolated from the north platform and grounded to the south.** People working on the bridge will be using scopes and other electrical equipment which is connected to the magnet. The platform and magnet steel ground is most appropriate.

1.12) **The south platform coupling to the steel plates and the north platform coupling to the magnet shall be limited to a total of 700 pf.** A contribution of 700 pf is a reasonable amount of the capacitive budget. If we assume the coupling of the platform to the steel plates is similar to two parallel plates, then the area is the length of the north (173") and the south (313") times the width of the rails (37.5"). For a height of 39", the total capacitance to both plates is 277 pf. This leaves 443 pf for the platform supports and the north platform coupling. It would be best if the platform supports were on the concrete and not the steel plates. Great care should be made for a beam or metal supports which pass over the steel plates. If possible any rail over the plates should be elevated in this region.

1.13) **The beam pipe shall be physically isolated from the detector.** Care must be made so that there is no physical electrical contact.

1.14) **The capacitance between detectors and the beam pipe must be less than 10 pf.** For instance, the capacitance between two metal cylinders is

$$c = \frac{2\pi eol}{\ln(b/a)} \qquad \text{where } l >> b.$$

In this expression, *a* is the diameter of the beam pipe, *b* is the diameter of the object, and *l* is the length of the object. In the case of a 4 cm beam pipe, the capacitance per unit length is 4.7 pf/cm for an object that is 4.5 cm in diameter. A 50 cm object then has 225 pf of capacitance which is much too high. Clearly the capacitance coupling of the SVT needs to be carefully checked. It may be necessary to put an electrostatic shielding plane between the SVT and beam pipe. The effect of capacitive coupling to the SVT must be justified. Also, the capacitance of the VPD and FTPC will need to be evaluated and justified.

1.15) **The EMC electronics coupling to the steel concrete plates shall be limited to 200 pf**. EMC electronics on the bottom of the detector will be several inches above the steel plates which are imbedded in the concrete. Care should be made to reduce this capacitive coupling.

1.16) **Future detectors that are supported from the concrete floor shall be insulated.** Future detectors must be isolated from the concrete floor so not to compromise the grounding scheme. From a grounding point of view, mounting to the pole tip is best. Any electronics or racks located on the concrete must be insulated.

1.17) **Items not mentioned here shall be limited to a total of 10 pf/item.** Several smaller objects, such as the VPD, have not yet been itemized in this document. These components need to have their capacitance limited and their contributions will be included in management reserve.

2. Clean Power

To insure the integrity of the clean power several steps need to be undertaken. It makes no sense to separate clean and conventional power and then haphazardly put equipment there. Equipment will be evaluated to determine which power system is appropriate.

2.1) **Clean power transformers shall be electrostatically shielded.** These transformers are slightly more expensive than unshielded models. They are used to reduce high frequency noise. For instance, in the 100 KHz to 1 MHz range they provide an extra ~40 dB noise reduction for Common Mode and ~26 dB reduction for Transverse Mode over standard isolation transformers. These transformers have an effective capacitance between the secondary and primary coils in the range of 30-50 pf.

2.2) **Clean power receptacles shall be clearly labeled.** Labels will be made so that casual users will know that these outlets can only be used for equipment designated for clean power. Users will also be instructed not to plug items such as drills in these outlets with very clear signs.

3. Conventional Power

To reduce the possibility that unwanted electrical noise is introduced on the detector by motors and similar devices, there will be separate circuits to provide power to these systems. At this time all items (except for possibly the TPC laser) that use conventional power will reside on the north platform.

3.1) **Pumps and similar motorized devices shall use conventional power.** These devices produce unacceptable electrical noise and need to be isolated from the detector electronics.

3.2) **Any device which uses conventional power shall be placed on the north platform. If conventional power is needed on the south platform, isolation should be at a level of 5 pf.** A 15 cm^2 pad needs to be 0.4 cm thick for rubber ($\kappa = 3$), or 0.7 cm thick for G10. The dielectric constant for rubber varies, so that the particular type should be checked. Pipes should be isolated from devices using conventional power as soon as practical. Suitable isolation is described in section 1. Note, that the isolated part of the pipes should be grounded as appropriate for safety purposes.

3.3) **Conventional power outlets shall be clearly labeled.** As conventional and clean power are on separate sides, it is difficult for detector electronics to use conventional power. Still, there needs to be signs to prevent inappropriate conventions.

3.4) **The magnet controls shall be connected to conventional power and isolated from clean power.** Care must be made that any signal from clean power be isolated. For instance, the slow control signal to the magnet crates must be isolated.

4. Magnet

There will be a large amount of power (5 MVA) going through the magnet. We must be very careful that ripple and SCA noise does not couple to our electronics.

4.1) **The magnet steel is tied to the detector.** Because of the numerous mechanical connections, it is not practical to isolate the steel.

4.2) **The coils are isolated from the magnet steel**. Large currents go through the coils to produce the magnetic fields. The coils need to be carefully designed so they are electrically isolated. All exposed metal should be carefully protected so that there is no personnel safety problems and that there is no possible ground connection. The water pipes need to be isolated from the aluminum coils.

4.3) **The voltage induced by the magnet power supplies on the magnet return must be limited.** It should be limited to 80 μv at 10 KHz so that there is no possibility of adding significant noise to the TPC.

5. Signal return currents between racks and detectors

Signals from various detectors should not interfere with each other over the ground path. The ground path can be isolated by either having all signals sent by optical fiber or else differentially. It is essential that all detector signals be identified including slow control signals.

6. Operational procedures

Even with the most stringent guidelines, it will be necessary to police the cabling so that inappropriate grounding can be detected and corrected. It will be very important to educate the collaboration and establish that the proposed grounding plan be implemented.

6.1) **There shall be a "Grounding Czar" whose responsibility is to ensure that this plan is followed.** The Grounding Czar shall monitor frequently the construction of the detector. The Grounding Czar shall have sufficient authority to stop construction which adversely affects grounding.

6.2) **A change control procedure must be implemented to ensure that any differences do not adversely affect the grounding.** A person or a committee will review the proposed change and establish that the change is suitable. The control mechanism shall be sufficiently flexible so that unanticipated changes to the plan can be evaluated rapidly.

6.3) **Frequent user education is needed so that all members of STAR are familiar with this plan.** It is most important that all personel who do construction understand the grounding plan and follow it. Any person who works on any STAR equipment must be familiar enough to avoid introducing any extraneous grounding paths. Appropriate training will need to be developed and offered.

6.4) **There shall be a procedure such that temporary structures that influence the grounding be noted.** During certain times of constructions, items such as ladders and scaffolds will be needed and these could introduce extraneous paths. These items will need to be removed before data taking begins.

6.5) **Sufficient documentation shall be maintained on the grounding.** This document will contain the grounding plan and all changes. It needs to be continually updated as needed.

6.6) **Unused cables must be carefully secured.** It is very easy for their shields to make an unexpected electrical contact. All cables shall be supported in such a manner that they will not come in contact with any ground path.

6.7) **A ground fault indicator shall be installed and monitored as soon as possible in the construction of the platform.** A ground fault indicator shall be installed on the lead from the detector to the Assembly Building/ WAH ground column. This indicator should be monitored carefully during construction of the detector so that any change to the grounding can be quickly noticed and the offending item corrected. Slow controls should monitor the indicator to provide a historical log of the ground current and provide sufficient alarms to warn of excessive current.

There are numerous references for grounding. In particular we have relied on:

- *Grounding and Shielding Techniques in Instrumentation* - Third Edition, by Ralph Morrison. John Wiley & Sons (New York - 1986).
- *Preliminary Design Report for the Grounding, Surge Protection and Noise Reduction for Electrical power Distribution at the IR 8 Region*, prepared by W. Kampmeier, SDC-SGT-00016 (1992).
- *Grounding and Shielding in Facilities,* Ralph Morrison and Warren H. Lewis. John Wiley & Sons (New York - 1990)

Many of the formulas for capacitance and inductance can be found in:

- *Reference Data for Radio Engineers* -Sixth Edition, Howard W. Sams & Co., Inc. (Indianapolis - 1977).