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Mu2e Electrical Grounding and Shielding Policy

Abstract

This document describes the plans and policy for the implementation of electrical grounding and shielding in the Mu2e experiment. It includes the grounding of the detectors, the DAQ room, the solenoid, and the associated services in the Mu2e facility. The document covers two related areas: grounding for electrical safety; and grounding and shielding to reduce or eliminate the sensitivity of the detectors and instrumentation to *Electromagnetic Interference (EMI)*. This document defines the plans and methods for implementing grounding and shielding in the experiment, to ensure that the safety requirements are met, and to ensure that the noise performance of the detector and instrumentation meet experimental goals.

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History of Changes

Rev. No.	Date	Pages	Description of Changes
1.0	11 Nov 2015	All	First draft, with contributions from subsystem leads.
1.1	04 Feb 2016	All	Major edits to address safety issues. Major reorganization of document.
1.2	12 Feb 2016	All	Minor changes to correct safety terminology.
1.3	05 Apr 2016	All	Semi-final editing of all sections by subsystem leads. The Calorimeter section had a major revision to reflect a recent technology decision. Significant revisions to the Extinction Monitor and the Solenoid sections.
1.4	13 Apr 2016	p. 18	Update component values for the Tracker.
		p. 54	Clarify Tracker FEB connection to Detector Ground.
		p. 71	Clarify connections of QPM Quench Detection System to Safety Ground.
		p. 73	Fix typos; Remove extraneous wording.
		p. 74	Clarify requirements vs. goals.
		p. 77	Change reference to Fig. 4.6.4.
		p. 64	Major rewrite of Section 4.4.
		p. 1	Update author list.
		p. 42	Fix figure number, Figure 3.3.3.
		p. 42	Update Figure 3.3.3.
		pp. 45-46	Clarify Sections 3.7.2 & 3.7.3
		p. 52	Add Fig. 3.9.1

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1. Introduction

1.1. Scope

This document describes the plans and policy for the implementation of electrical grounding and shielding in the Mu2e experiment. It includes the grounding of the detectors, the DAQ room, the solenoid, and the associated services in the Mu2e facility. It also includes certain aspects of process controls, to the extent that they interconnect with the detector, and therefore may have an impact on grounding and noise. Currently, there are no plans for accelerator power supplies or controls to interconnect to the detector electronic systems, so these aspects are not covered in this document.

The policy covers two related areas: grounding for electrical safety; and grounding and shielding to reduce or eliminate the sensitivity of the detectors and instrumentation to Electromagnetic Interference (EMI). The policy is concerned with direct or indirect connections to the experiment that either can or will provide a path for the flow of electrical current. The primary purpose of this document is to define the plans and methods for implementing grounding and shielding in the experiment, to ensure that the safety requirements are met, and to ensure that the noise performance of the detector and instrumentation meet experimental goals.

The Mu2e Grounding and Shielding policy draws upon the following standards and policies:

- *National Electrical Code (NEC), NFPA70* [1]
- *Standard for Electrical Safety in the Workplace, NFPA 70E* [2]
- *Occupational Safety and Health Administration (OSHA) Standard OSHA 29 CFR1910, Subpart S, OSHA General Industry Standards, Electrical* [3]
- *IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment, IEEE Standard 1100-1992* [4]
- *Fermilab Environment, Health and Safety Manual (FEHSM)* [5]
- *Department of Energy Handbook, Electrical Safety, DOE-HDBK 1092-2013* [6]

The highest priority in this grounding policy is to ensure the safety of personnel and facilities, and it is the expressed intention of this policy that safety never be compromised. The Fermilab electrical safety organization has contributed to the writing and vetting of this document. The plans and implementation of the grounding and shielding for EMI abatement were obtained through discussions with representatives from each of the experiment subsystems, and also integration managers, project engineers, and project management.

1.2. Definitions

1.2.1. *Ground* is a general term that refers to a reference conductor that serves as a common potential for a specific circuit, subsystem, or facility. As there can be different kinds of grounds or ground references in an experiment, it is generally desirable to indicate the type of ground that is being referred to, as indicated below. Note that in the vernacular, the term "ground" does not always refer to a connection to Earth.

1.2.2. *Earth* or *Earth Ground* refers to the connection point of an electrical conductor or network to the soil. This is referred to as *Grounding Electrodes* in the NEC. The implementation of Earth Ground is often achieved by driving conductive rods into the soil, either inside of a facility or exterior to it, in locations where the resistivity of the soil is low. Ideally, this provides an infinite source or sink of electrons for the network connected to it. Generally, this is defined as the zero volt potential for a facility or instrument.

1.2.3. *Safety Ground* refers to the system of conductors and equipment ground connections that provide a connection to the Earth Ground or the Grounding Electrode for the purpose of ensuring that hazardous electrical energy has a shunt path to Earth and away from personnel in the case of a fault.

1.2.4. *Common* is a term that is used to describe the local electrical reference node or net or plane for a circuit or set of circuits. It is often called "ground" or "ground plane" in a schematic or electronics design, although there may or may not be a direct connection to ground or Earth in the system. It is also often taken to be the "0 Volt Reference" for a circuit or system. When multiple power supplies are used in a circuit or system, often the power returns of the supplies are connected to this common node or plane.

1.2.5. *Chassis Ground* refers to a connection between electrical or electronic circuitry and a chassis or mechanical structure such as a relay rack. Chassis Ground may or may not be connected to Safety Ground, although this connection is often dictated by safety requirements.

1.2.6. *Detector Ground* refers to the system of conductors and connections that provide a reference or common for the sensitive instrumentation of the experiment. This is analogous to the Signal Reference Structure in [7, 8]. There are often certain noise requirements for this network that require special treatment. It is often distinguished from Safety Ground in HEP detector instrumentation systems, although the NEC places requirements on how this is connected and configured. This will be described in greater detail in Section 3.3.

1.2.7. *Current Return* refers to the path by which electrical currents are returned to the source that created them. This concept applies to both power supplies and signal currents. In a well-designed instrumentation system, the current return is carefully controlled, although sometimes the current return path is through the shielding (as in a single-ended coaxial cable.) In some systems, the current return can be through other metallic or mechanical structures (as is done in automobiles.) Generally, in HEP experiments, most current return paths are through dedicated conductors.

1.2.8. *Bond or Bonding* refers to the making of a connection to establish electrical continuity and conductivity.

1.2.9. *Hazardous Electrical Energy* is defined, for the purposes of this document, as electrical sources or electrical energy storage elements that contain greater than 50 Volts [9]. Additional limits may apply for current and stored energy.

1.2.10. *Shielding* refers to the application of metallic surfaces that interrupt the flow of electromagnetic energy, either radiated or conducted, to isolate sensitive circuits or conductors from the effects of interference. Generally, shields do not carry any signal current, although they may in certain circumstances.

1.3. Grounding Systems

A grounding system has three main parts: Safety Ground; Signal Reference Ground; and Lightning Protection [10]. In this context, the Detector Ground is analogous with Signal Reference Ground. The basic elements of these three subsystems are described below.

1.3.1. *Safety Ground*

Safety Grounding in facilities is required for the protection of both personnel and equipment against electrical faults, such as an inadvertent or unintended connection of a conductor or metallic structure to a hazardous energy source. Safety Ground establishes a low-impedance connection between earth and metallic mechanical structures, enclosures, and supports, to ensure that they do not become energized if a fault occurs. Without a safety ground connection, a fault could energize a structure with hazardous energy, and could cause a shock to personnel who might come in contact with it while being at ground (earth) potential, i.e. standing on a floor and touching an energized structure. In addition, the power distribution system for facilities generally includes over-current protection devices such as circuit breakers, fuses, or ground-fault current interrupters (GFCI), so that when a fault comes in contact with a mechanical structure that is connected to Safety Ground, the source energy will become disconnected (i.e. the circuit breaker trips, or the fuse blows.) Any system or subsystem that contains or processes hazardous energy must have a connection between the metallic structures that contain it and to Safety Ground. The requirements and implementation of a Safety Ground system in the United States are specified by the NEC [11].

Generally, a Safety Ground network in a facility connects to all equipment that contains hazardous voltages, resulting in a complex network of conductors and connections. Because of this, the Safety Ground often carries leakage currents from this equipment. This is usually acceptable for the safety and performance of most equipment. However, these leakage currents can have frequency content that manifest as noise currents. Furthermore, the leakage currents produce voltage drops across the network due to the non-zero resistance of the wiring. These currents and voltage drops can be a dominant source of noise for sensitive electronic and instrumentation systems (like a detector), if the signal reference for the instrumentation is common with the leakage current path.

In a complex Safety Ground network, the grounding conductors can be circuitous and connect back upon themselves, forming a loop or multiple loops. Sometimes a mesh network is employed. While this reduces the impedance in the path, the formation of ground loops creates sensitivity to electric and magnetic field pickup [12]. This can exacerbate the noise voltages in the Safety Ground network, and further adversely affect the performance of sensitive electronics and instrumentation systems that may have the Safety Ground connected to the signal reference.

To summarize, a Safety Ground network in a facility has the following general properties:

- The Safety Ground network may have multiple connections to Earth. This is dictated by safety considerations that include the impedance of the network and the resistivity of the soil. These connections to Earth form ground loops.
- The network of Safety Ground conductors may have multiple conductive paths between a given piece of electrical equipment and another. Ground loops may be created in the process. Generally, there is no concern about having conductive loops in a Safety Ground network.
- There is no attempt to limit the connectivity of equipment to Safety Ground. Generally, all equipment that contains hazardous energy, including metallic infrastructures in a facility, is required to connect to Safety Ground.
- There is no attempt to control the leakage currents in a Safety Ground network.

1.3.2. *Detector Ground*

Detector Grounding is a means by which a common reference is created that is low-noise and low-impedance, for the purpose of ensuring that voltage potential differences do not adversely affect the precision of a measurement. Generally the conductors in this network have little or no current flow in normal operation so that voltage drops across the network are minimal. Given the large physical size of many detectors, it can be a challenge to implement a Detector Ground network over a large distance that has low-noise and no leakage currents.

Unlike the Safety Ground system, there are few universal rules governing the implementation of Detector Ground in High Energy Physics experiments. The nature and implementation of the Detector Ground tend to be different for each experiment, often dependent on detector size, detector type, signal magnitude, interconnections to other systems, and cost. However, while not universally true, there are certain principles that are often incorporated in the design of a Detector Ground network, which differ substantially from those used in Safety Ground networks:

- The Detector Ground network often has one connection to Earth, in order to avoid ground loops. In some experiments, there is no connection to Earth, and the concept of Detector Ground merely establishes equal potential between subsystems or components. Regardless, the avoidance of ground loops is usually the goal in the design of a Detector Ground network.
- The network of Detector Ground conductors usually has a single conductive path for a given piece of electrical equipment. By its nature, this helps avoid ground loops by design.
- The connectivity of instrumentation to Detector Ground is carefully controlled. Only that instrumentation that requires a quiet ground reference is connected to it.
- Generally, instrumentation that connects to Detector Ground should have low leakage currents. Currents in the Detector Ground network create voltage drops, which can introduce potential differences and noise in the network.

1.3.3. *Lightning Ground*

Lightning strikes to a power or ground system can have direct effects, indirect effects, or both. Direct strikes inject energy directly into the system, resulting in current flow through the grounding system. The magnitude of the current can range from a few thousand amps to several hundred thousand amps

[13]. Indirect effects result from high voltage "flashovers" from the primary current path to other grounding paths that can occur due to the high impedance of the conductors from the fast edges of the energy flow. Indirect effects can also occur from induced voltages that result from current flow in ground loops or grids, which can produce voltage potential in the range of volts to thousands of volts [14].

Generally, protection against lightning has two parts [15]. The first is proper installation of a grounding system to shunt lightning surge currents to ground and away from sensitive equipment or building infrastructure. This may consist of a lightning ground ring around the outside of the building that is solidly connected to Earth and to Safety Ground. This includes all metallic structures and components that are part of the infrastructure of the building. The closer that the connectivity resembles a solid conductive mass, the less susceptible the system will be to effects from surge currents. The second part of a lightning protection system is the use of *transient voltage surge suppressors* (TVSS). These are devices that are generally connected between power and ground at various points in a power distribution system. They either block or short to ground voltage surges that occur above a prescribed threshold. The choice and location of TVSS devices depend on the application.

Like Safety Ground, Lightning Ground is most effective when there is a highly-connected network of grounding conductors and Earth connections. Again, this topology differs from the concept of Detector Ground. The implementation for Mu2e will be discussed in Section 3.

Lightning Ground is considered to be part of the building infrastructure, and will not be considered further in this document.

1.3.4. *Grounding Interconnectivity*

Electrical or electronic systems must be solidly grounded to Earth to meet safety regulations, as specified by the NEC [16]. Furthermore, the three ground subsystems should be solidly interconnected for best performance [17]. The requirements for Safety Grounding and grounding for Lightning Protection are clearly specified by the NEC, and for Mu2e, there are no issues with how these are to be instantiated. However, concerning Signal Reference Ground (Detector Ground), there are few requirements from the standards, such as NEC, OSHA, IEEE, etc., other than that the instantiation must conform to safety regulations and best practices. The requirements are generally determined by the application, and are often dependent upon the nature of the instrumentation, the guiding philosophy behind the design, cost, and to some extent, the backgrounds and experiences of the principal designers.

The functional differences between Safety Ground and Detector Ground are significant. Each performs a critical function, but they are often not interchangeable. This is recognized in the standards [18-19], with the concept of a Signal Reference Ground or Detector Ground permitted within constraints. The challenge in designing a large instrumentation system is to implement both effectively while not compromising each other. While the desire to restrict noise currents in a Detector Ground system tends to prefer isolation from other grounding structures, this isolation is in conflict with NEC requirements that restrict the use of separated grounding systems, as well as robustness against lightning strikes. As the design of a Detector Ground structure becomes more and more isolated, safety issues may arise, requiring safety review and ultimately approval from the Electrical Authority Having Jurisdiction (AHJ). This has been carefully considered for the Mu2e Experiment, and will be discussed in Section 3.

1.4. Ground Symbols Defined

1.4.1. The symbol for *Earth Ground* is shown in Figure 1.4.1. It refers to the point at which a physical connection into the earth is made. This is usually a rod that is driven into the earth.

Figure 1.4.1. Left: Earth Ground Symbol. Right: Earth Ground Rod.
Image courtesy of Wikipedia: https://en.wikipedia.org/wiki/Ground_(electricity)

1.4.2. The symbol for *Safety Ground* is shown in Figure 1.4.2. It is used to indicate any conductors and connections that comprise the safety ground network. The connection may be an intentional bond, or realized through the mechanical interconnections.

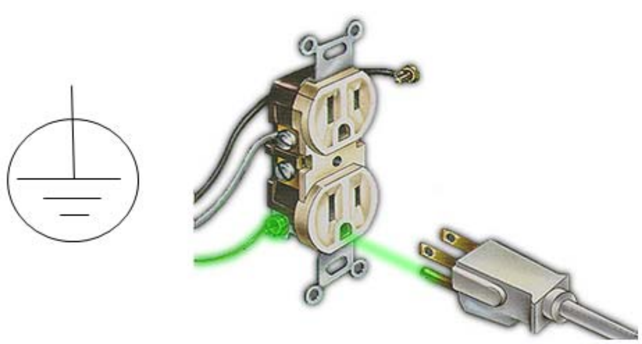

Figure 1.4.2. Left: Safety Ground Symbol. Right: The green wire is part of the safety ground network. Picture courtesy of Northwestern Energy:
http://c03.apogee.net/contentplayer/?coursetype=foe&utilityid=northwestern3&id=4673

1.4.3. *Chassis Ground* refers to the metallic structure that houses electrical, electronic, or instrumentation systems. It may or may not be connected to Safety Ground or any other ground. The symbol for Chassis Ground is shown in Figure 1.4.3. On the right side of the figure shows an explicit connection between a metal frame (a chassis) and Safety Ground.

Figure 1.4.3. Left: Chassis Ground Symbol. Right: Explicit connection of Chassis Ground to Safety Ground. Picture courtesy of: Doz's Blog: http://andydoz.blogspot.com/2015_10_01_archive.html

1.4.4. *Detector Ground* refers to the system of conductors and connections that provide a reference or "quiet ground" for the sensitive instrumentation of the experiment. The symbol used is shown in Figure 1.4.4.

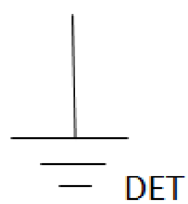

Figure 1.4.4. Detector Ground Symbol.

1.4.5. *Other Nets that are referenced to "Ground"* will generally be defined as a specific net for the purposes of this document. An example is shown in Figure 1.4.5, where analog ground is defined as a net with an explicit connection to Detector Ground. This makes clear the identification of all conductors, and how they are explicitly connected (or not) to any type of ground.

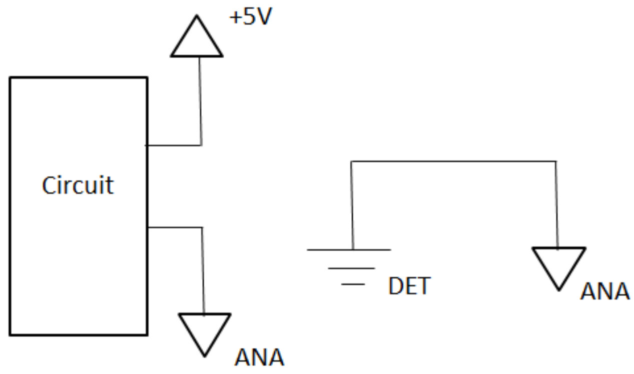

Figure 1.4.5. Example of identifying other nets that are referenced to a ground.

2. Subsystem Identification and Description

A drawing of the overall detector is shown in Figure 2.1, showing the Solenoids, the Tracker, and the Calorimeter. The Stopping Target Monitor resides to the right of the Calorimeter and is not shown in the figure. The downstream part of the Transport Solenoid and the Detector Solenoid are covered with the Cosmic Ray Veto, as shown in Figure 2.2. Downstream from the Production Solenoid is the Extinction Monitor, as shown in Figure 2.3. The experimental hall has two main parts, as shown in Figure 2.4: the detector floor, and the DAQ room that resides on the upper level. There are also utility rooms on both the detector floor and the upper level that have supporting infrastructure that are electric or electronic in nature.

A short description of each subsystem follows, with identification of the aspects that are important for system grounding. A complete description of the detector and the experiment can be found in [20].

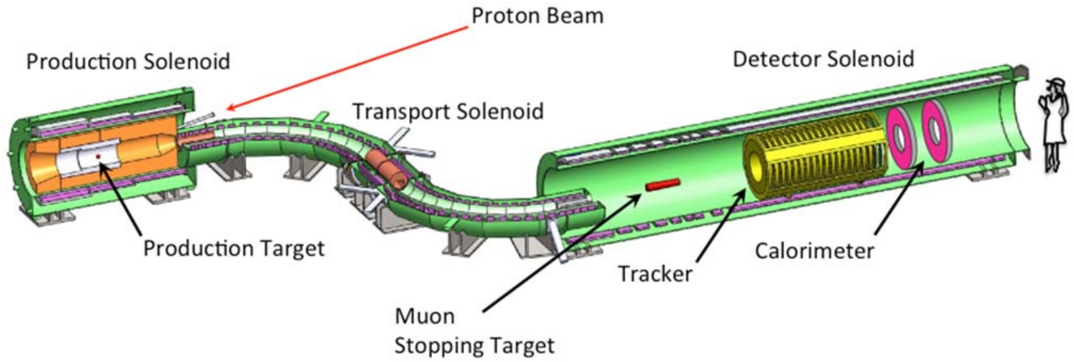

Figure 2.1. Overview drawing showing the detector and solenoids.

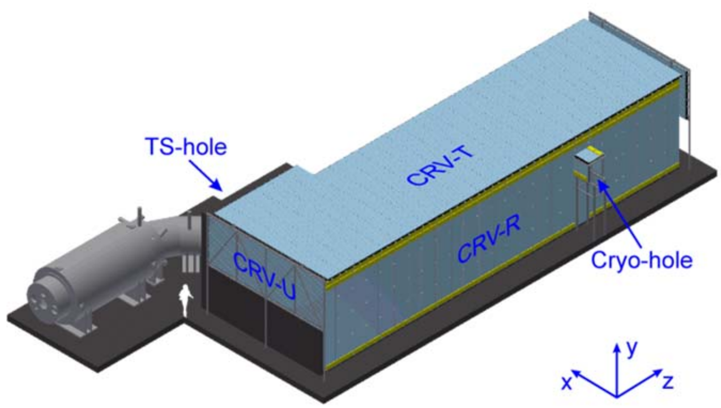

Figure 2.2. Overview drawing showing the Cosmic Ray Veto that covers the downstream half of the Transport Solenoid and the Detector Solenoid.

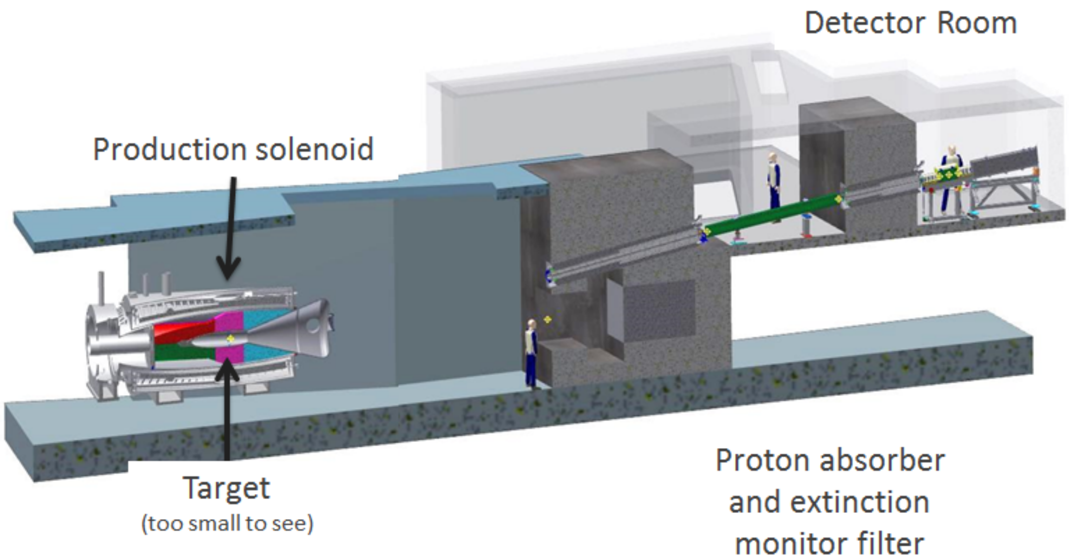

Figure 2.3. Overview drawing of the Production Solenoid, the proton absorber and the Extinction Monitor area.

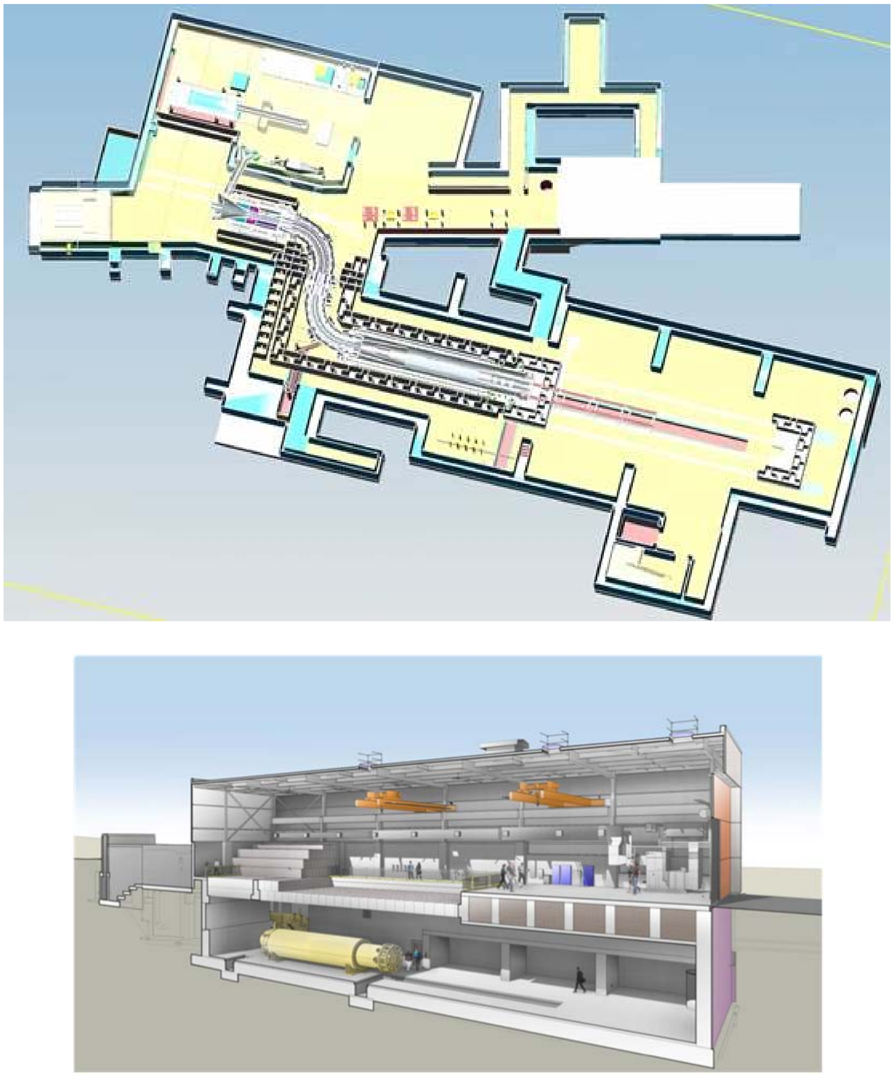

Figure 2.4. Drawing showing the layout of the detector floor (top) and a cross-sectional view of the two floors of the building (bottom).

2.1. The Straw Tube Tracker

The Straw Tube Tracker consists of a low-mass array of straw drift tubes aligned transversely to the axis of the Detector Solenoid. Each straw tube is configured with a 25 μm sense wire inside of a 5 mm diameter tube made of 15 μm thick metalized Mylar. The drift gas in the straw tubes is planned to be a mix of 80:20 $Ar:CO_2$ with the possibility of adding CF_4 to obtain higher drift velocity. The straw tubes are biased with an operating voltage of $\lesssim$1500 V. Groups of 96 straws are assembled into roughly trapezoidal panels as shown in Figure 2.1.1. The panels are then assembled into planes, each of which has two layers, rotated by 60 degrees from the other. There are 6 panels per plane, as shown in Figure 2.1.2. A pair of planes then forms a station, with the second plane rotated 30° relative to the first. The full detector consists of 18 stations. A drawing of the full tracker is shown in Figure 2.1.3. It has 36 total planes, 216 panels, with a total of 20,736 straw tubes. The Tracker resides in the warm bore of a superconducting solenoid, which provides a uniform magnetic field of 1 Tesla. The bore in which the Tracker resides is evacuated to 10^{-4} Torr.

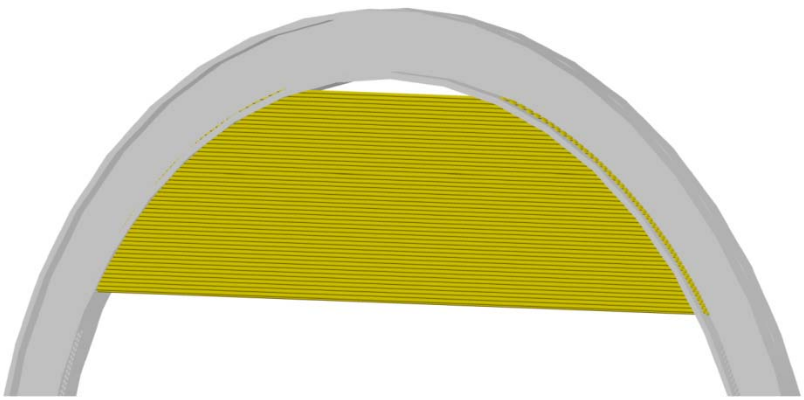

Figure 2.1.1. Drawing showing the Straw Tubes comprising a panel.

The electronics is organized so that a front-end unit services one panel. It has two parts. Each straw tube has a preamp on each end of the straw. High voltage is fed to each straw through a 110 kΩ current limiting resistor. A 220 pF blocking capacitor on each straw end couples to the preamps. The output of the preamp is differential analog. The amplified signals are sent on a micro-strip transmission line to the digitization electronics located approximately in the center of the panel on the outer ring, as shown in Figure 2.1.4. Each panel requires one readout controller, which handles all of the data and slow control communication for the panel. Each controller includes communication via an optical cable (one or more fibers) to outside the cryostat, resulting in 216 optical cables penetrating the cryostat.

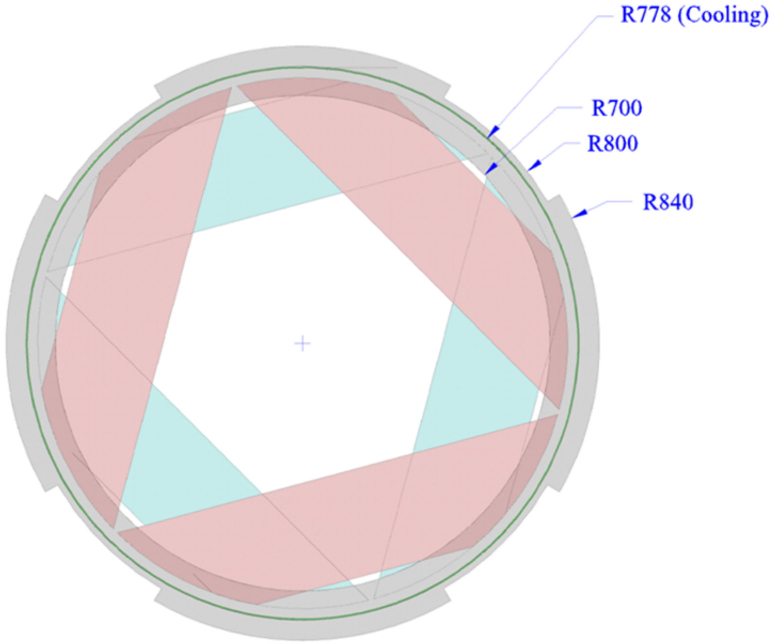

Figure 2.1.2. Front view of a Tracker plane showing the 6 panels per plane. The green tube is for cooling. Two such planes form a station. Dimensions are in millimeters.

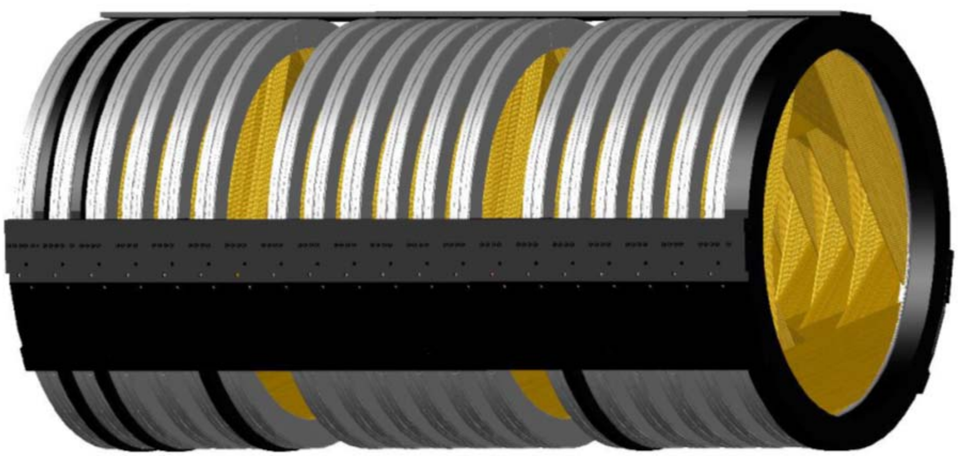

Figure 2.1.3. Drawing showing the 18 stations of the full Tracker.

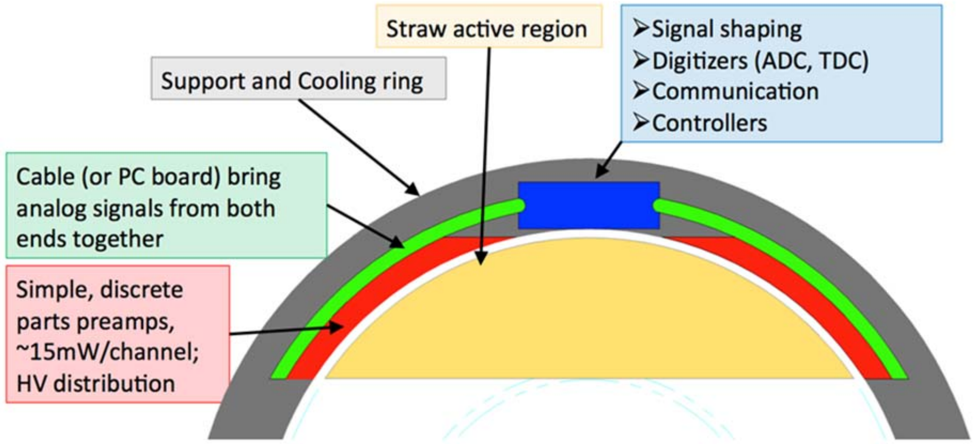

Figure 2.1.4. Layout of the electronics for a single straw panel.

The high-voltage power supplies reside in the DAQ room. There is one cable for each panel, resulting in 216 high voltage signal pairs (power and return) penetrating the cryostat. The connector has not been specified, but may be multi-conductor. It is planned to have the power returns on the outputs of the high voltage power supplies isolated with respect to the power supply chassis using passive fault protection circuitry. The low voltage power supplies will reside in the electronics alcove on the detector floor. The supplies will be powered by 120V, 60 Hz main power. The outputs are +48V DC, with isolated returns. The front-end electronics will use local point-of-load (POL) regulators to produce the voltages needed by individual circuits from the +48V. Each panel will have one low voltage connection, resulting in 216 low voltage signal pairs (power and return) penetrating the cryostat. The connector has not been specified, but may be multi-conductor.

2.2. The Calorimeter

The design for the Mu2e Calorimeter is shown in Figure 2.2.1. The detector uses an array of pure cesium-iodide (CsI) crystals arranged in two annular disks. Electrons following helical trajectories spiral into the front faces of the crystals. Each crystal is read out by two large-area (6x6 mm^2) silicon photo-multipliers (SiPMs). SiPMs are used instead of conventional photo-multiplier tubes because the calorimeter resides in a 1 Tesla magnetic field. The front-end electronics is mounted on the rear of each disk, while voltage distribution, slow controls and digitizer electronics are mounted behind each disk. A laser flasher system provides light to each crystal for relative calibration and monitoring purposes. A circulating radioactive liquid source system provides absolute calibration and an energy scale.

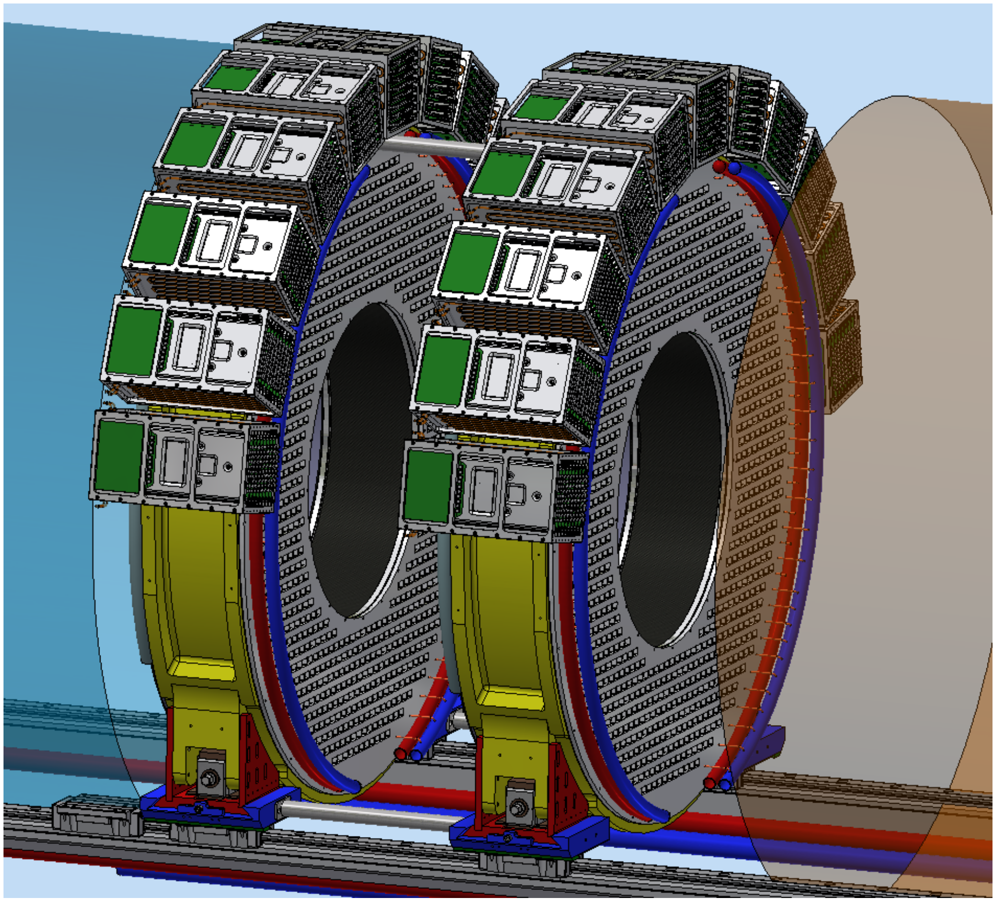

Figure 2.2.1. CAD model of the Mu2e Calorimeter. The Mu2e calorimeter consisting of an array of pure CsI crystals arranged in two annular disks. Electrons spiral into the upstream faces.

Each disk has an inner radius of 374 mm, an outer radius of 660 mm, and consists of 674 trapezoidal crystals. The crystals are 200 mm long with square base whose side is 34 mm. Each crystal will be wrapped with 1 layer of 150 µm thick of Tyvek reflective film. Each disk will be supported by two coaxial cylinders. The inner cylinder must be as thin as possible in order to minimize the passive material in the region where spiraling background electrons are concentrated. The outer cylinder has been designed to support the load of the crystals. Each disk has two cover plates. The plate facing the beam will be made of low radiation length material to minimize the degradation of the electron energy deposition. The back plate supports the photo-sensors, the front-end electronics, and cooling pipes. The back plane will most likely be built of aluminum. The HV/LV supply and digitizers are arranged in eleven crates per disk placed around the outer cylinder.

The crystal readout system is composed of two arrays 3x2 of silicon photo-multipliers (SiPMs), as shown in Figure 2.2.2. The front end electronics (FEE) is attached on the back side of the module. There are two AMP-HV chips, which were designed by Laboratori Nazionali di Frascati (LNF) Electrical Design Department. The Amp-HV chip is a multi-layer, double-sided discrete component chip, which has two functions: it amplifies the incoming detector, and it provides a locally regulated bias voltage for the SiPMs, which helps to reduce the noise loop-area for the power distribution. The two functions are implemented on individual layers, named the Amp and HV sides, respectively.

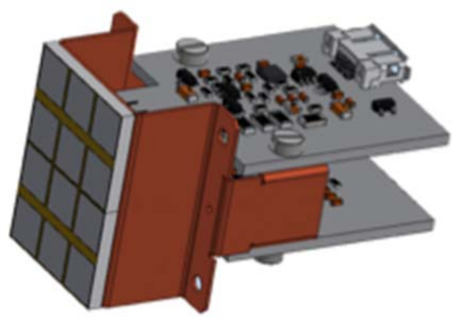

Figure 3.2. CAD drawing of the SiPM holder with the Front End Electronics attached.

A block diagram of the front-end electronics (FEE) is shown in Figure 2.2.3. The front-end electronics uses a single stage transimpedance preamplifier, with two selectable trans-impedance gain of 750 and 1400 Ω (voltage equivalent, V_{out}/V_{in} of 15 and 30) while maintaining an equivalent noise charge (ENC) level of about 1000 electrons with no input capacitor source. The basic requirement for the linear regulator is to provide an extremely precise 16-bit voltage regulation and long-term stability of better than 100 ppm and high current capability. The current limit of the device is conservatively set to about 3 mA; this value will be optimized in a latter design stage. To reduce the noise the two Amp-HV stages will be inserted in a Faraday cage, as shown in Figure 2.2.4 (right). The leakage current and the temperature for each SiPM will be also acquired. A pulse signal will be generated to test the electronics performance during the run period of the experiment.

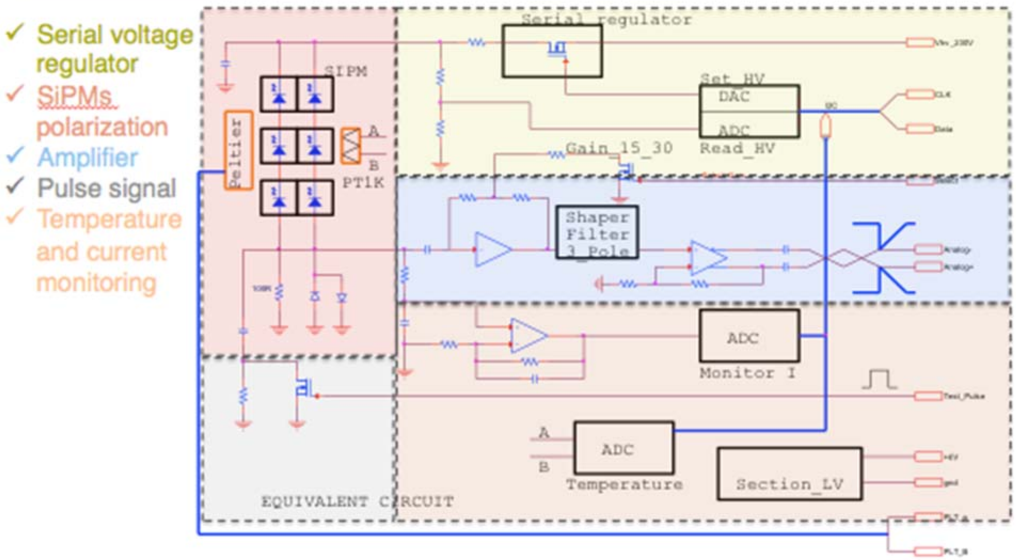

Figure 2.2.3. Block diagram of the calorimeter Front End Electronics.

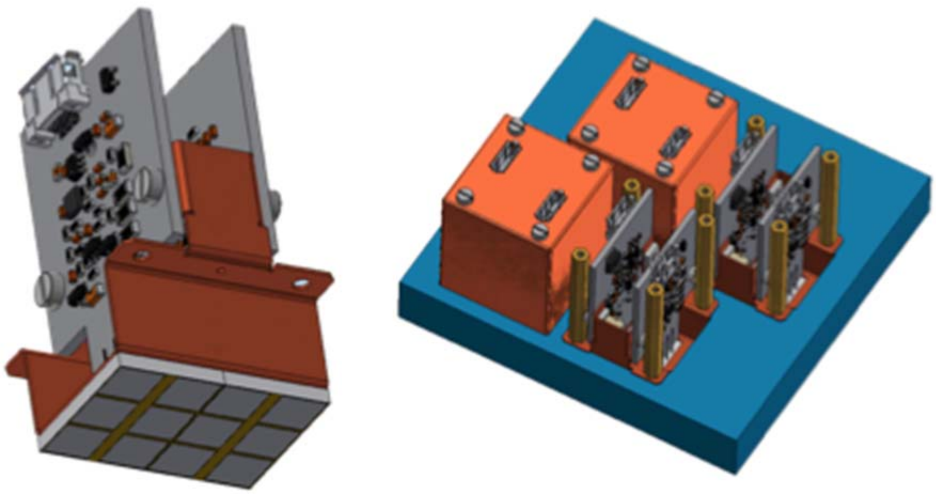

Figure 3.4. CAD of the SiPMs holder and Faraday cage used for the FEE.

Nine prototypes were built during 2015 and have been used for testing a 3x3 pure CsI matrix prototype. A picture of the Amp-HV prototypes is shown in Figure 2.2.5.

Figure 3.5. Amp-HV prototypes and assembling in the pure CsI crystals matrix.

The high voltage required for the SiPMs is provided by power supplies that reside outside the detector in the DAQ room. Each supply generates a voltage of 230 V using low-noise switching technology. For each crate, there are four cables, resulting in 176 high voltage signal pairs (power and return) penetrating the cryostat. The ON and OFF states of the channel are controlled by an ARM processor locally on the detector. The input voltage of 230 V is followed by a linear shunt regulator, programmable through appropriate adjustment resistors, which provides a stabilized voltage with local feedback to the SiPM detector. The output voltage is regulated by a DAC and is then read out again via an ADC, with 16-bit accuracy.

The low voltage power supplies for the detector will also reside also in the DAQ room. The supplies will be powered by 120V, 60 Hz main power. The outputs are +28 VDC, with isolated returns. The front-end electronics will use local point-of-load (POL) regulators to produce the voltages needed by individual circuit from the +28 V. Each crate will have one low voltage connection, resulting in 352 low voltage signal pairs (power and return) penetrating the cryostat. The connector has not been specified, but may be multi-conductor. The total power required, including a safety factor of 40%, is about 2 kW for the high voltage and about 4.5 kW for the low voltage.

Signals from the front-end electronics are sent to a Waveform Digitizer (WFD) board to be digitized and read out. With a granularity of 20 electronic channels per board and a total of 674 crystals per disk, each disk can be subdivided into 11 sectors of about 60 crystals each. The electronics is instrumented in 11 crates per disk, where each crate houses about six or seven sets of AMP-HV and Waveform Digitizer boards as shown in Figure 2.2.6. Each WFD board requires one readout controller, which handles all of the data and slow control communication for the 20 channels. Each controller includes communication via optical cable (one or more fibers).

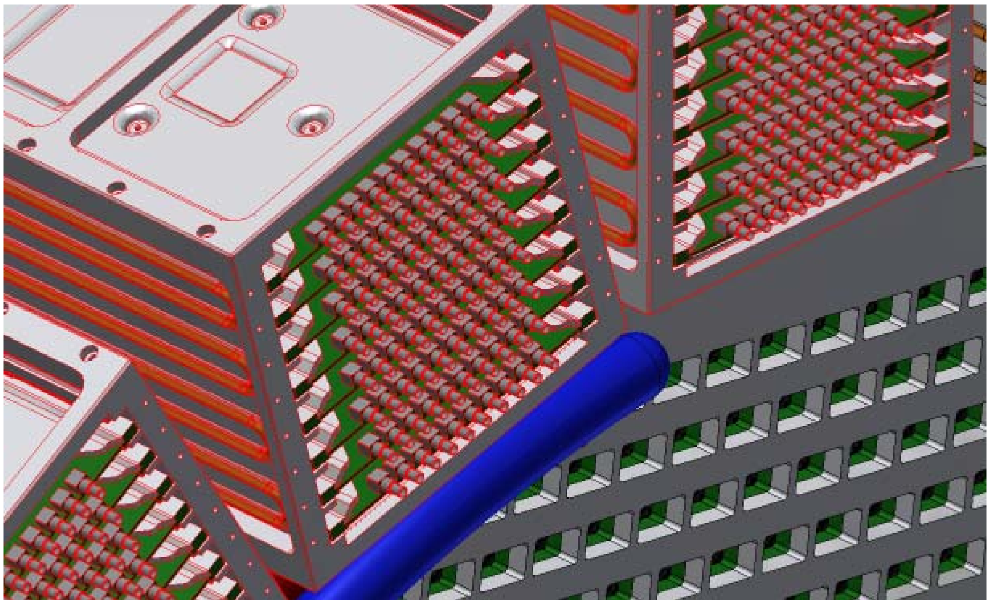

Figure 3.6. One crate of the calorimeter: Each crate contains 8 slots and each slot houses one WFD+HV/LV boards.

The laser monitoring system needs at least 8 fibers from outside the cryostat, with a total result of more of 120 optical cables penetrating the cryostat. The laser system is shown in Figure 2.2.7 and it will be placed in the DAQ room. The laser will be split, by means of semi-transparent mirrors to eight beams and focused by optical lens to 1 mm diameter Fused Silica fibers. 1/3 of the light will be sent to a 2" diffusing sphere with 3 pin-diodes for monitoring (sector A). Eight 100 m long fibers, routed from the counting room to the DS bulkhead brings the light to eight 2" diffusing spheres on the mechanical structure (sector B). Each sphere will have 1 pin diode for monitor and 3 bundles of 200 μm silica fibers. Each fiber will be inserted into a lodging in the back of the crystals close to the SIPM holders (sector C).

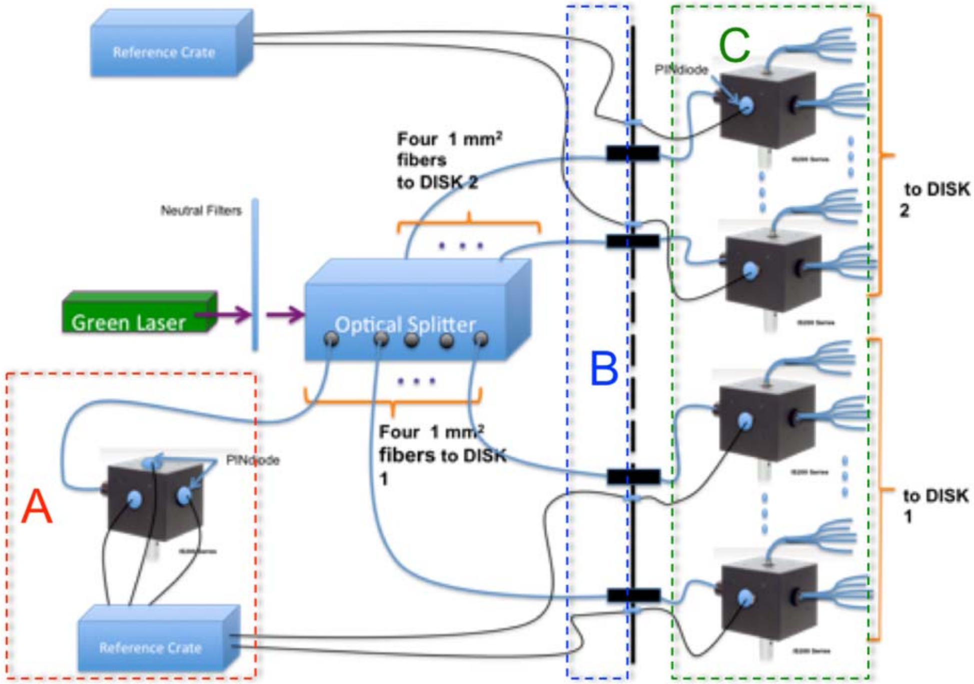

Figure 2.2.7. Schematic of the calorimeter laser system.

2.3. The Cosmic Ray Veto

The cosmic ray veto consists of four layers of long extruded scintillator strips, with aluminum absorbers between each. The scintillator surrounds the top and sides of the detector solenoid and the downstream end of the transport solenoid, as shown in **Error! Reference source not found.**.3.1. The strips are 2.0-cm thick with aluminum absorbers between the layers. The scintillator light is captured by embedded wavelength shifting fibers, whose light is detected by silicon photomultipliers (SiPMs) at each end of the fibers (of most modules). The electronics consists of: (1) a counter motherboard mounted directly on the ends of the counters and onto which the SiPMs, flasher LEDs, bias pulsing, and temperature sensors are connected; (2) a front-end board (FEB), which reads out and digitizes signals from the SiPM, controls the flasher LED, runs calibrations, and provides bias to the SiPMs; and (3) a readout controller which sits in the DAQ room, which takes the data from the front-end boards and sends it to the data acquisition system and provides a means of communication with the front-end boards. A block diagram of the system is shown in Figure 2.3.1. There are a total of 310 FEBs and 15 controllers with a total power consumption of 7.5kW.

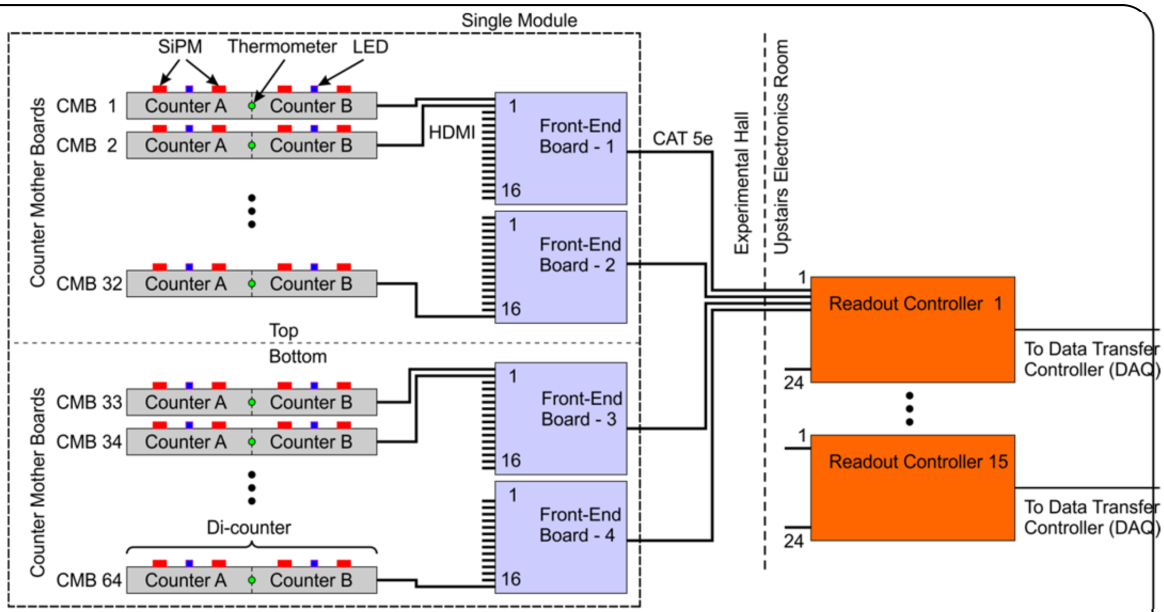

Figure 2.3.1. Block diagram of the readout system for the CRV.

2.4. The Extinction Monitor

The Extinction Monitor shown in Figure 2.4.1, consists of mini spectrometer and muon range stack located in its own enclosure above and behind the primary proton beam dump.

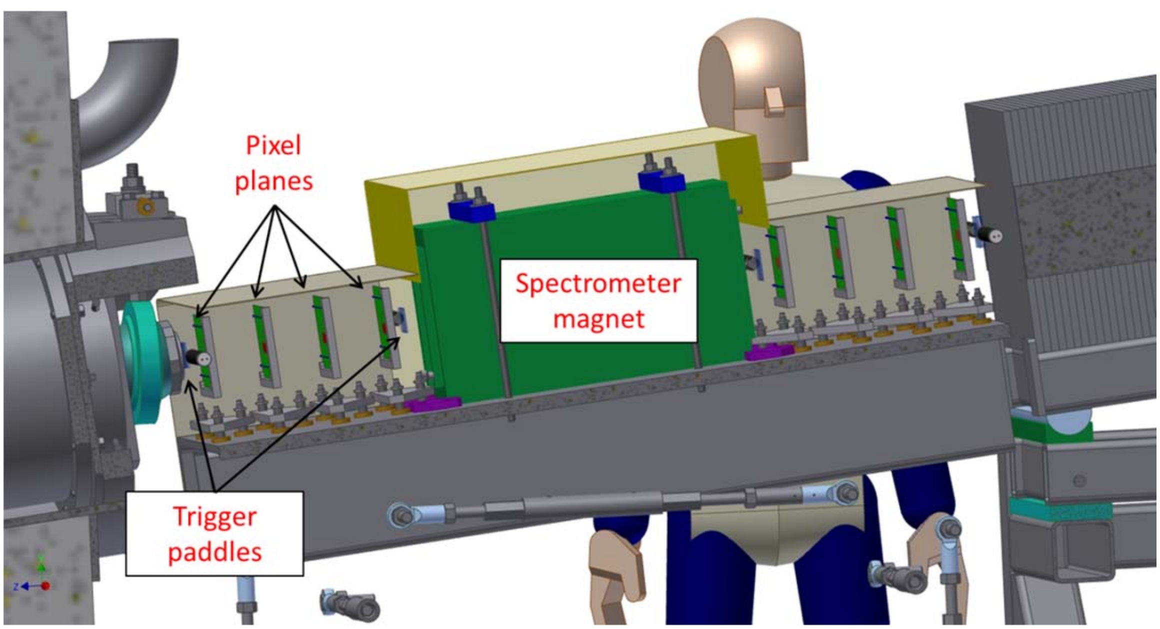

Figure 2.4.1. Drawing showing the Extinction Monitor spectrometer.

The spectrometer consists of a total of 8 planes of silicon pixels arranged on either side of a permanent dipole spectrometer magnet. Depending on its location, a pixel plane will consist of either two or three pairs of the FE-I4 silicon pixel chips developed for the ATLAS detector upgrade using a 130 nm CMOS technology. Each chip reads out 26,880 pixels arranged into 80 columns on a 250 μm pitch by 336 rows on a 50 μm pitch.

The muon range stack, shown in Figure 2.4.2, consists of steel plates with 4 imbedded scintillator paddles. Smaller and faster scintillator paddles will be used to form a trigger for the pixels. There are three trigger paddles upstream of the spectrometer magnet and another three downstream. All scintillator counters will be read out with PMT's.

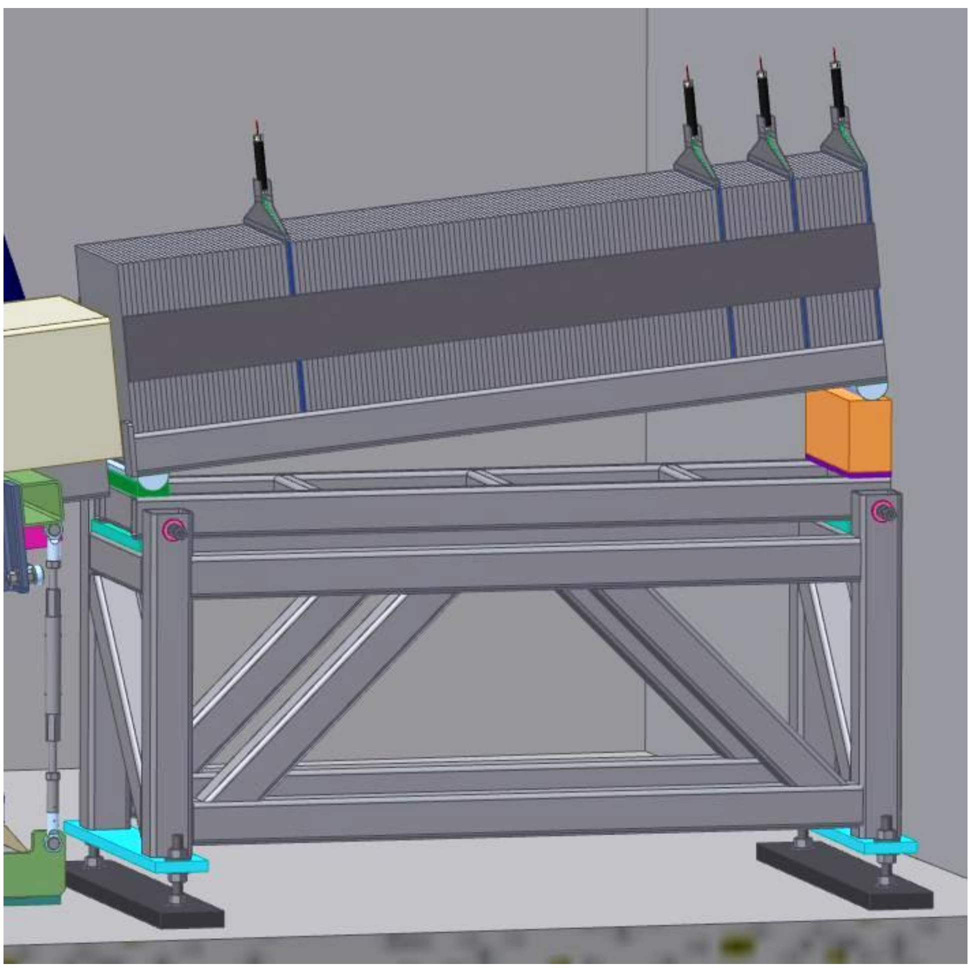

Figure 2.4.2. Drawing showing the muon range stack.

A block diagram of the data acquisition system for the Extinction Monitor is shown in Figure 2.4.3. The DAQ will be implemented in a single MicroTCA crate mounted in a standard relay rack located beside the detector. On-line signal processing, trigger generation, and data formatting for readout are performed using FPGA's that receive data from the front-end electronics by means of FPGA Mezzanine Cards (FMC's). The digital signals used to control and read out the FE-I4B chips on the pixel planes are passed directly from the FPGA on the carrier AMC to the Pixel Interface Board via FMC cards that simply provide a connector for the 68-conductor VHDCI cables. FMC discriminator and wave form digitizer cards will provide digital signals from the scintillator counters to their respective FPGA's.

A rack mounted computer will be used to run the high level DAQ and track reconstruction code and send signal data to the main DAQ.

Apart from the high and low voltage power supplies required to operate the pixels and PMT's, the only other electrical equipment associated with the Extinction Monitor will be a chiller that will be required to maintain the pixels at their required operating temperature.

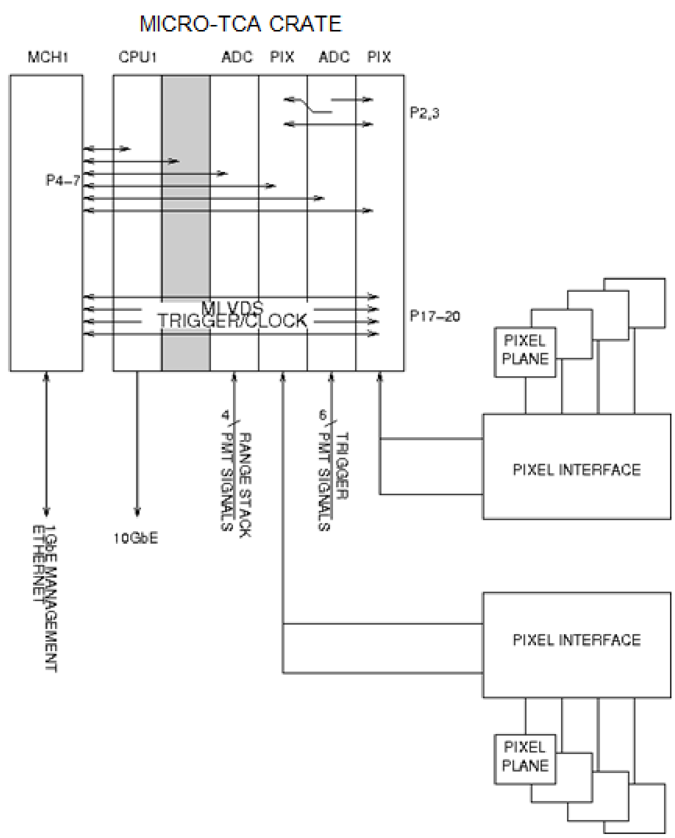

Figure 2.4.3. Block diagram of the Extinction Monitor data acquisition system.

2.5. The Muon Stopping Target Monitor

The Muon Stopping Target Monitor (MSTM) is a subsystem designed to monitor the rate and total number of muon stops in the stopping target, providing an estimator of the normalization for the experiment. During the muon stopping process, photons with characteristic energies will be emitted as the muonic atom transitions to lower energy atomic states. The stopping muons generally either decay in orbit (~40%) or are eventually captured by the nucleus (~60%). Muon captures result in excited nuclear states, which also emit characteristic photons. The muon stopping rate will be monitored by positioning photon detector(s) downstream of the Detector Solenoid near the east end of the detector floor, with a view of the stopping target through a thin window in the downstream muon beam line vacuum chamber endcap (which is referred to as the Instrumentation Feedthrough Bulkhead). See Figure 2.5.1.

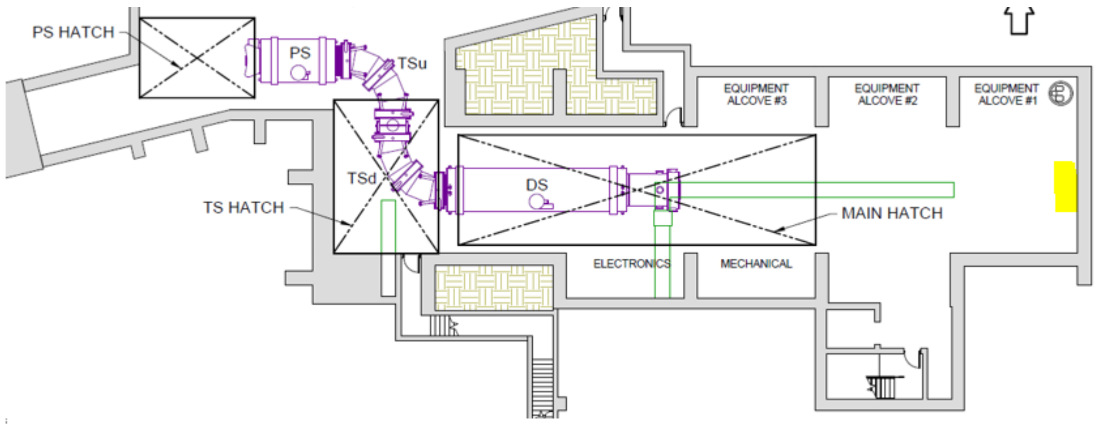

Figure 2.5.1. Layout of the lower level (detector floor) area, with a yellow block highlighting the anticipated location of the Muon Stopping Target photon detector(s).

The space between the end of the Detector Solenoid and the MSTM will include a beam pipe and a (permanent) sweeping magnet to divert charged particles from the photon detector or detectors, as well as collimators to limit the field of view of the photon detectors. If necessary, a beam shutter may also be installed between the end of the Detector Solenoid and the photon detectors to block the direct beam flash. It will likely also be necessary to surround the photon detectors with shielding.

The photon detectors will likely require high rate capability and good energy resolution. Depending upon the precise choice of characteristic signal adopted for monitoring, either germanium detectors or lanthanum bromide detectors (or perhaps both) are currently being explored as candidate photon detectors. These photon detectors will require a high voltage source, and the associated electronics will require low voltage supplies as well as clock and sync signals. Digitized output information will need to be integrated into the DAQ stream. The photon detector may require cryogenics and associated controls. The beam line may also require process controls and monitoring. If a beam shutter is necessary, that system will also require power and controls. It is likely that the photon detector calibration system will include radioactive sources.

2.6. The Solenoids

The solenoid system is housed in four cryostats, which operate as a single integrated magnetic system, as shown in Figure 2.1. All the solenoids employ windings made from aluminum-stabilized NbTi superconducting cables. The Production Solenoid (PS) is a high field magnet with a graded solenoidal field varying smoothly from 4.6 Tesla to 2.5 Tesla. The gradient will be formed by 3 axial coils with a decreasing number of windings. The solenoid is approximately 4 m long with an inner bore diameter of approximately 1.5 m that is evacuated to 10^{-5} Torr. The S-shaped Transport Solenoid (TS) consists of a set of superconducting solenoids and toroids that form a magnetic channel that efficiently transmits low energy negatively charged muons from the Production Solenoid to the Detector Solenoid. The Transport Solenoid consists of five distinct regions: a 1 m long straight section, a 90° curved section, a second straight section about 2 m long, a second 90° curved section that brings the beam back to its original direction, and a third straight section of 1 m length. The major radius of the two curved sections is about 3 m and the resulting total magnetic length of the Transport Solenoid along its axis is about 13 m. The inner warm bore of the Transport Solenoid cryostat has a diameter of about 0.5 m. The Detector Solenoid (DS) is a large, low field magnet that houses the muon stopping target and the components required to identify and analyze conversion electrons from the stopping target. It is nearly 11 m long with a clear bore diameter of about 2 m. The muon stopping target resides in a graded field that varies from 2 Tesla to 1 Tesla. The actual detector components reside in a field region that is relatively uniform at 1 Tesla. The inner bore of the Detector Solenoid is evacuated to 10^{-4} Torr.

The solenoids will be powered via re-purposed Tevatron low-beta quad and electron lens power supplies described in Table 2.1. These supplies will be located in the solenoid power supply room. The solenoids will be divided into several independent power circuits. Each circuit will have an external energy extraction resistor. The value of the resistor will be chosen so that the peak voltages will be limited during a quench to less than 300 V to ground and 600 V across the magnet terminals. A simple schematic of a generic solenoid electrical circuit is shown in Figure 2.6.1.

POWER SUPPLY NAME	SOLENOID NAME	VOLTAGE	CURRENT
E:PS	PRODUCTION (using 2 TeV Low Beta 375kW)	50/25	15,000
E:TSu	TRANSPORT UPSTREAM (using TEL 1)	20	2,500
E:TSuT 2 each	TRANSPORT UPSTREAM TRIM New Supply	10	250
E:TSd	TRANSPORT DOWN STREAM (using TEL 2)	20	2,500
E:TSdT 2 each	TRANSPORT DOWN STREAM New Supply	10	250
E:DS	DETECTOR SOLENOID (1 Low Beta 375kW)	50/25	7,5 00

Table 2.1: Solenoid power supply systems

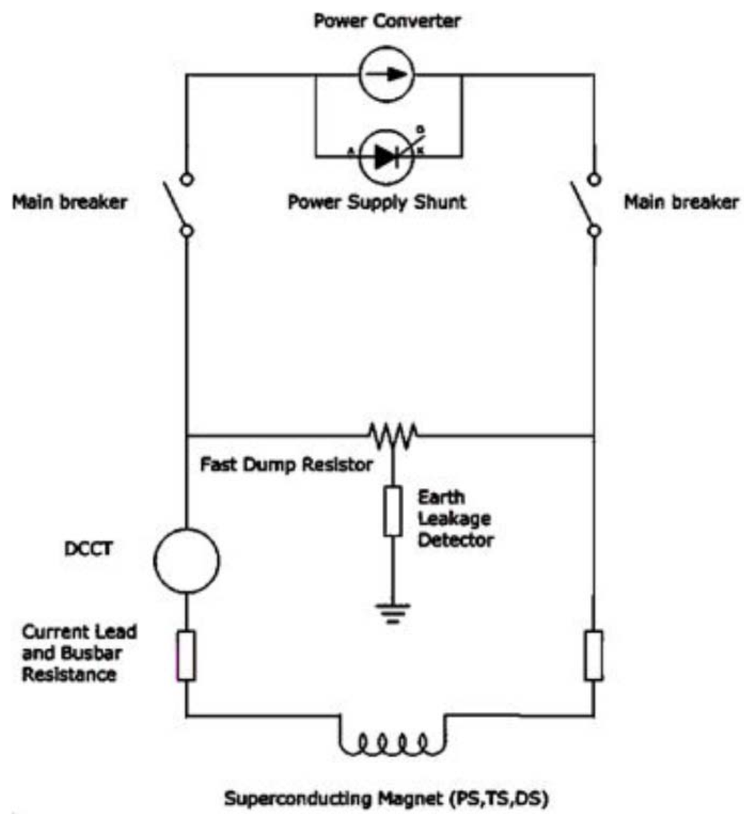

Figure 2.6.1: Solenoid power supply and protection circuit

The solenoids are instrumented with voltage taps, low-temperature superconducting (LTS) wire resistance monitors, resistive temperature detectors (RTDs), strain gauges, residual resistance ratio (RRR) monitors, optical position sensors, and Hall probes. The solenoid instrumentation and associated cryogenic process instrumentation serve as inputs to the Quench Protection and Monitoring (QPM) system. The QPM system includes the quench detection system for all four solenoids, superconducting leads and bus, and the vapor cooled copper leads; the slow logging system for making precision measurements of the magnet instrumentation such as splice measurements and RRR measurements; and the cryogenic instrumentation and controls system.

2.7. The Trigger and Data Acquisition System

The Trigger and Data Acquisition System (TDAQ) consists of the necessary components for the collection of digitized data from the Tracker, Calorimeter, Cosmic Ray Veto and Beam Monitoring systems, and handles delivery of that data to online and offline processing for analysis. It is also responsible for detector synchronization, control, monitoring, and operator interfaces. A block diagram of the TDAQ system is shown in Figure 2.7.1.

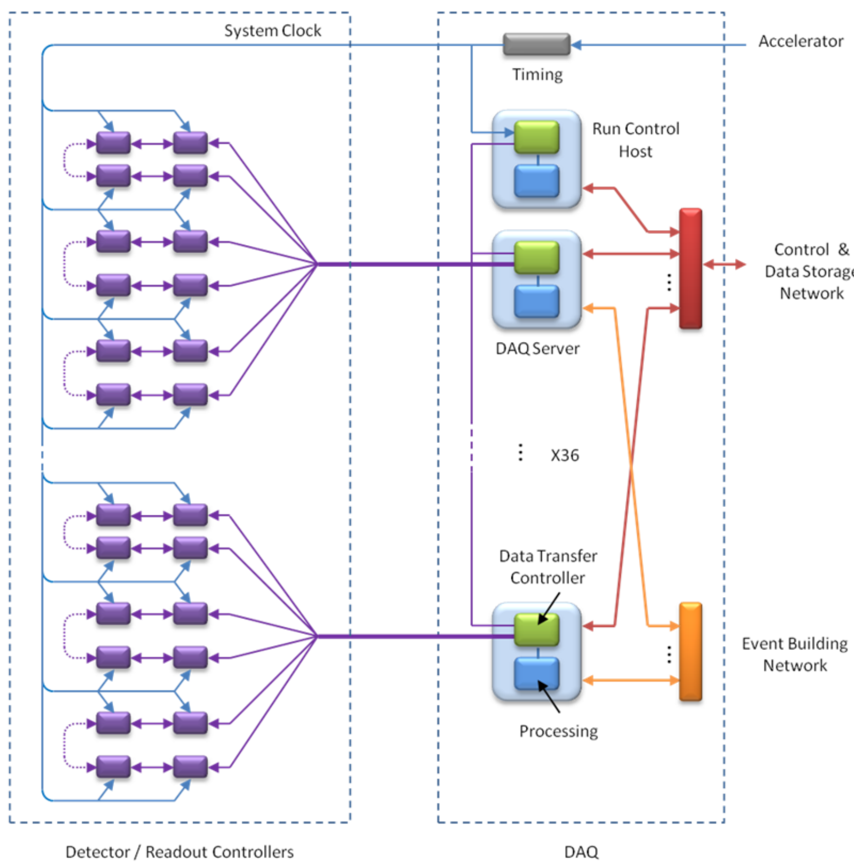

Figure 2.7.1. System design overview for Trigger & DAQ.

There are several key features of the TDAQ system. The architecture supports both streaming readout, which will be the primary readout mode for the Tracker and the Calorimeter, and also and triggered readout, which will be used for the CRV. The TDAQ servers handle all of the data readout, event building and processing. All interfaces between TDAQ and the front-ends are optical links, providing a bidirectional interface for fast control and readout. TDAQ also provides timing information (clocks, timestamps, and synchronization) to the front-ends, which also uses an optical interface.

The Readout Controllers have large front-end buffers for uniform data transfer over the full 1.4 second super-cycle. The TDAQ hardware (i.e. server, event building network, and Data Transfer Controller) are all commercial products. The system is scalable, with ~1 GByte/sec of processing power per TDAQ server, If more processing capability is needed, additional servers may be added. The current rack plan with space is shown in Figure 2.7.2.

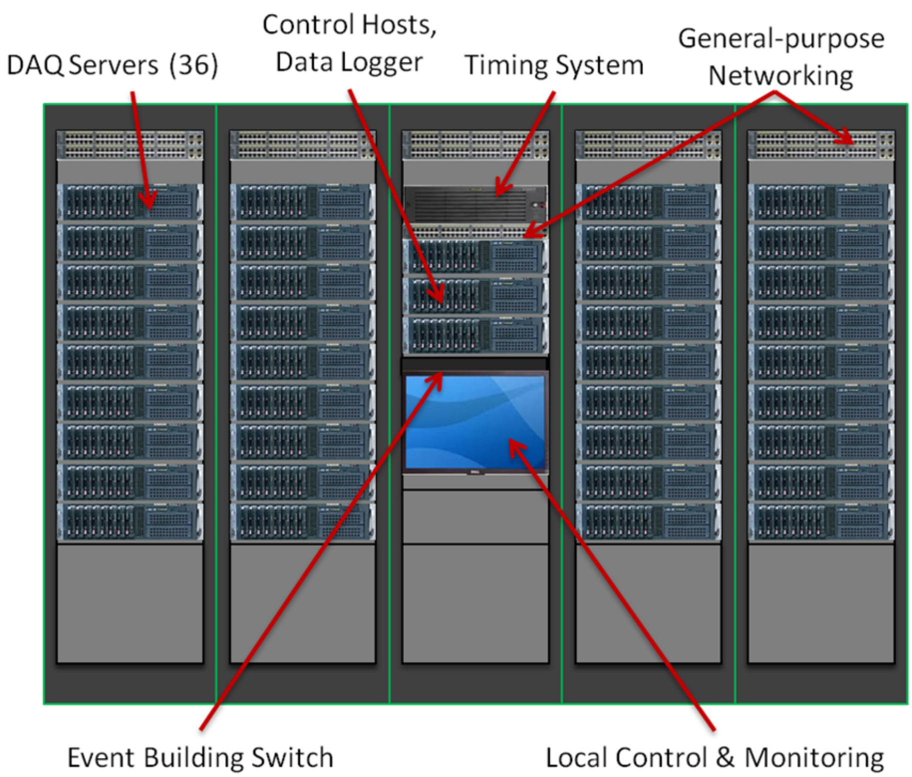

Figure 2.7.2. Rack plan for Trigger & DAQ in the electronics room of the Mu2e building.

2.8. The Detector Controls and Monitoring System

A block diagram of the Detector Controls and Monitoring System (DCS) is shown in Figure 2.8.1. It consists of hardware and software to implement the monitoring and control of various devices and systems throughout the experiment. Generally, the monitor devices provided as part of the individual subsystems, e.g., front end boards in the DAQ, computers, power supplies, etc. Connections to the DCS system are made via Ethernet. Two pieces of hardware currently have special monitor functions: rack monitors and the ground isolation monitor.

Generally it is desired to monitor the temperature inside any electronics racks. The electronics racks will also have a rack protection system, although this is still in the planning stages at this time. The monitoring of the rack environment will be included in DCS. Planning is in progress to develop a uniform system for the different racks in the experiment. A hardware device for monitoring the isolation of the experiments' grounding systems would also be included in the DCS.

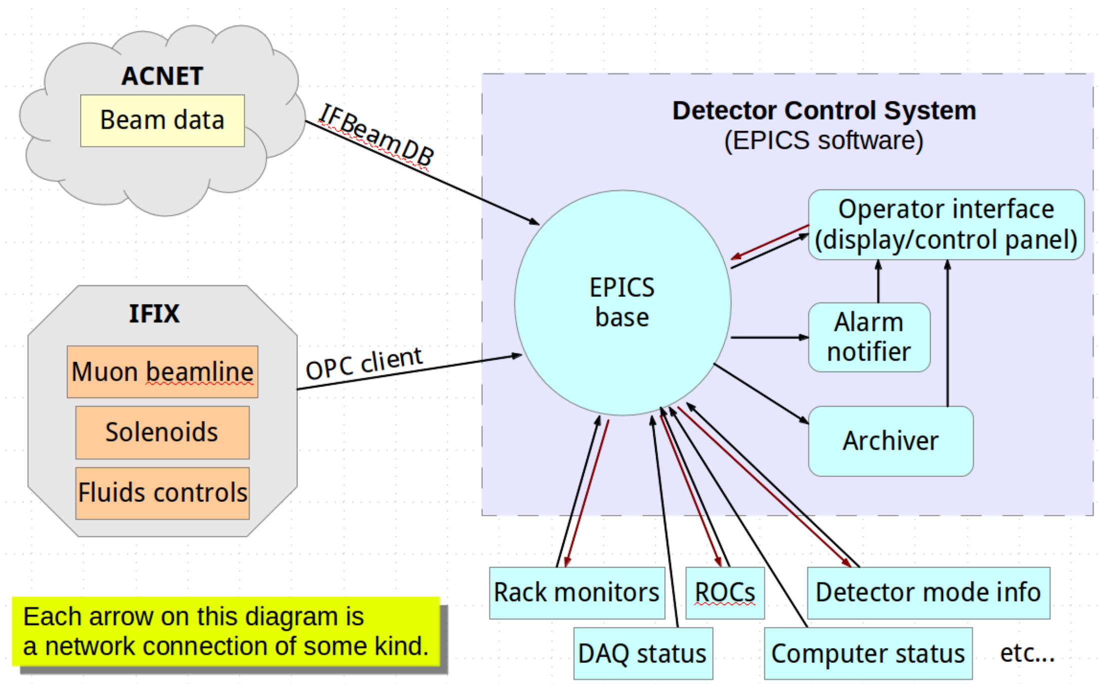

Figure 2.8.1. Network connections between the Detector Control System and other subsystems.

2.9. Facilities and Infrastructure

The construction of the conventional facilities and infrastructure for the experiment includes the design and installation of the AC power distribution system that supports the experiment. The power system consists of transformers, electric panel boards and sub panel boards, and the wiring infrastructure. It also includes the design and installation of the Safety Ground network, as well as the Detector Ground network.

The power distribution system for the Mu2e building is fed from two 13.8 KV – 480Y/277 VAC transformers located external to the building. Two transformers are used to isolate the beam line loads from conventional service and power for the experiment. The main service enters the building through underground conduit duct banks, and terminates in the main service panel board. This panel board is used to distribute power to transformers and sub-panel boards located throughout the facility. The transformers downstream are used to reduce the input voltage to a useful level of 208Y/120 VAC, which then feed small power panels. The sub-panel boards and small power panels are located throughout the facility.

The grounding of the facility has two primary parts. The first part is network of connections to Earth that comprise the Safety Ground system. Generally, these are copper rods, spaced at a prescribed distance apart, and connected together using heavy-gauge bare stranded copper wires. These connections often form a loop around the outside of the facility, or may be configured as a grid. Branch connections from this network are brought to the interior of the facility to provide bonding points for connections of equipment and infrastructure to Safety Ground.

The second part of the grounding system concerns the connections (bonding) to Safety Ground inside the facility. Branch connections from exterior Safety Ground network are brought in and bonded to critical points in the facility. All steel columns are connected. The rebar in the concrete is connected at various points. For Mu2e, the pads in the concrete that support the solenoids have a special dedicated Safety Ground connection.

Branches are also brought to grounding points in the facility associated with the power system. The transformers usually have additional grounding rods located close by, to provide a short, low-impedance connection to Earth. It is common practice to connect the neutral (current return) conductor in the power distribution system to Safety Ground at the service transformer. A branch from the exterior Safety Ground network is brought into the main service panel board, often terminating on a small bus bar in the panel board that also connects to the metallic structure of the box. From here, the Safety Ground is routed downstream to the transformers and sub panel boards along with the power. In some cases, the transformers and sub panels may also have branch connections to the exterior Safety Ground network. This configuration creates a low impedance path from any place in the electrical distribution system back to the source transformer to allow adequate current flow to operate over-current devices in the event of a ground fault.

Branch connections from the exterior Safety Ground network are also brought in and routed to grounding bus bars throughout the facility, for use by other equipment needing Safety Ground connections. All cable trays and conduit are connected to Safety Ground. All cabinets and enclosures that contain electrical or electronic equipment or conductors are connected to Safety Ground. Virtually all metallic objects in the proximity of AC power will generally have a connection to Safety Ground.

3. General Grounding & Shielding Plan for the Experiment

The general guidelines for grounding and shielding in the Mu2e experiment are described below. The details for how each subsystem will implement the grounding scheme are described in Chapter 4.

3.1. Subsystem Connections to Safety Ground

3.1.1. Any subsystem that contains hazardous electrical energy must have a connection to Earth, through the Safety Ground network.

The NEC requires that all electrically-conductive objects that house hazardous electrical energy be connected to Earth through Safety Ground [21]. This ensures that fault currents are shunted to Earth.

3.1.2. Unless there is a compelling reason, metallic structures and surfaces in the subsystems of the experiment should be grounded. Any deviations from the National Electrical Code must be approved by the Fermilab AHJ.

The NEC requires that all electrically-conductive objects within a facility be connected to earth [22-23]. Connection to earth ensures that conductive objects do not charge up to hazardous voltage levels through electric or magnetic field coupling. This also helps reduce potential differences across a grounding system due to surge currents from lightning strikes.

3.1.3. All subsystem connections to Safety Ground will be reviewed and approved by Fermilab Electrical Safety personnel. Any deviations from the National Electrical Code must be approved by the Fermilab AHJ.

This is requires by Fermilab safety policy [24].

3.1.4. All connections that involve electrical safety must be permanent or semi-permanent (i.e. screw lug) bond. Grounding for safety may not be implemented using a pluggable connector. Any deviations from the National Electrical Code must be approved by the Fermilab AHJ.

The NEC has specific requirements on how connections are made to Safety Ground. [25].

3.1.5. Having been established, disconnection of a subsystem from a safety ground must have a defined procedure. A Safety Ground associated with a system may not be disconnected while the system is energized, and the system may not be operated while an associated Safety Ground is disconnected.

The un-grounding of an electrical system may create hazardous conditions that have similar issues to work on energized systems. A system that is required to have a Safety Ground may not be operated without one [26].

3.2. Instantiating a Detector Ground

3.2.1. The experiment shall implement a Detector Ground that has a separate conductive branch from Safety Ground. This will be used only by detector subsystems that require a quiet reference ground. Subsystems that do not require a quiet reference shall use Safety Ground for grounding. The general topology is shown in Figure 3.2.1.

Mu2e will incorporate a Signal Reference system, as described in [27]. This will provide an electrically-quiet zero volt reference for the sensitive detector subsystems, as outlined in section 1.3.2. To accomplish this, Detector Ground must not include conductive paths from the Safety Ground that could include leakage currents from heavy machinery or other electrical equipment can adversely affect sensitive instrumentation.

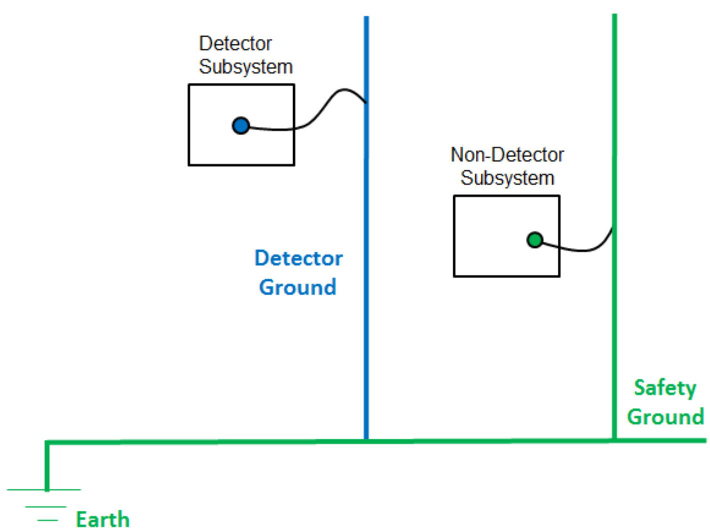

Figure 3.2.1. General connective topology of the Detector Ground.

3.2.2. Each subsystem that connects to Detector Ground should do so in one and only one place.

Single point connections avoid ground loops, and help reduce noise pickup from EMI.

3.2.3. Some subsystems may elect to have a private Detector Ground branch connection to Safety Ground, provided that the internal Detector Ground structure is independent from other subsystems. The topology is shown in Figure 3.2.2.

Certain subsystems have no direct electrical connectivity with all others, and may also be situated relatively far away from the main Detector Ground branch. In these cases, it may be advantageous for such subsystems to have their own Detector Ground branch, provided that they meet the general requirements and the safety requirements as described in this document.

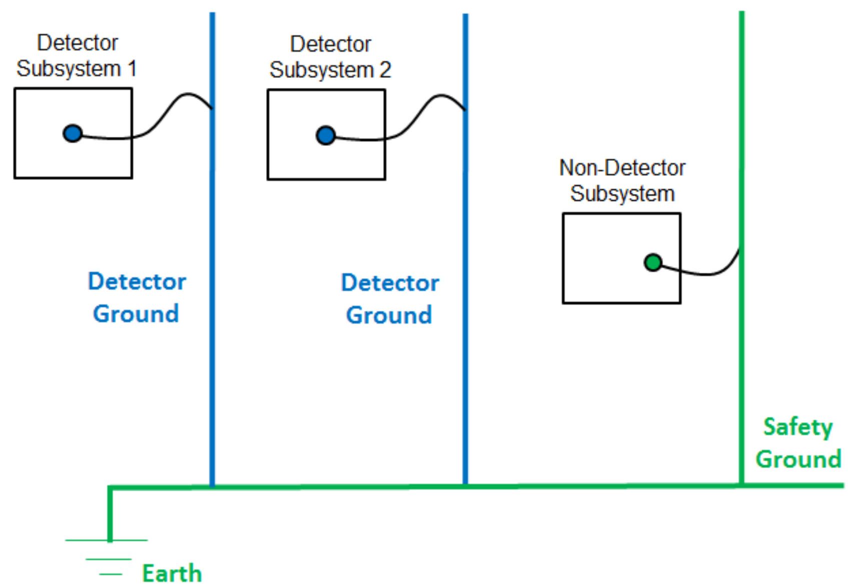

Figure 3.2.2. Alternate connective topology of the Detector Ground.

3.3. Single point Ground for Detector Ground

3.3.1. The experiment shall implement a single point ground system for the connection of Detector Ground to Safety Ground using a "star topology" as shown in Figure 3.3.1.

Single point connections avoid ground loops, and help reduce noise pickup from EMI.

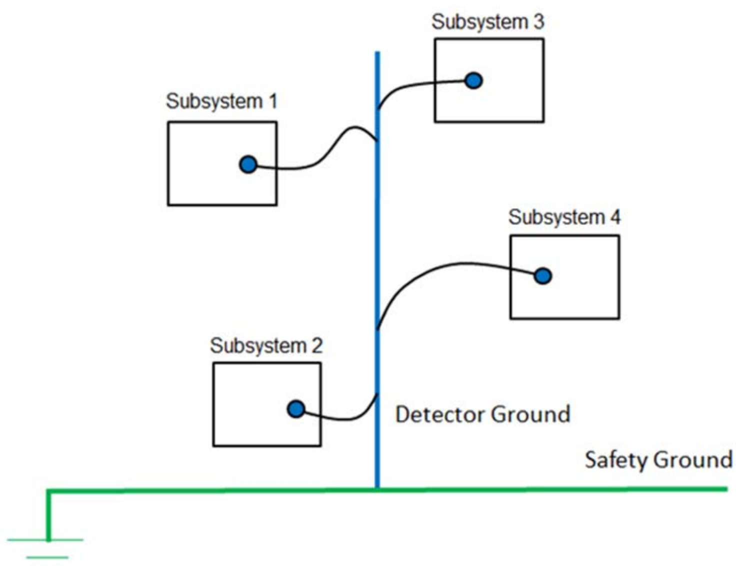

Figure 3.3.1. Illustration of Star Topology for Detector Ground.

There are two primary ways of grounding an experiment: star topology, or mesh topology. In mesh grounding, connections to ground (Earth) are made in many places, often in a periodic array or mesh structure. This configuration has the advantage of having lower inductance in the ground connections, resulting in better high-frequency performance. It has the disadvantage that the ground network may include leakage currents from other equipment. The flow of current is less well controlled in this configuration. It also has the disadvantage that the grounding network must be part of the civil construction. This adds cost to the civil construction, requires significant planning, and is more difficult to implement.

In the star ground topology, the currents that are allowed to flow in the ground network are carefully controlled, and therefore may have better immunity to noise from leakage currents, depending on the environment. The disadvantage is that the grounding network is more inductive, resulting in poorer performance at high frequencies. This is illustrated conceptually in Figure. 3.3.2. The impedance of the star ground is mainly resistive at low frequencies. For 500 MCM cable, the resistivity is of order 0.02 ohms/1000 feet [28]. For a 100 meter cable, the resistance would be 6 ohms. The cable has self-inductance (~130 nH/ft for 500 MCM cable), and at intermediate frequencies, it becomes dominant. The star ground of the detector typically remains effective up the point in frequency where the impedance reaches ~100 ohms, although this can depend on the noise environment. At a frequency defined as the cutoff frequency in Figure 3.3.2, the parasitic capacitance between the system and the surrounding surfaces connected to Earth becomes significant. This includes parasitic capacitance of the front end boards, the detectors, and the ground cable itself (~100 pF/ft for 500 MCM cable.) At this point, the star ground stops being the preferred path to Earth, and the parasitic capacitance dominates. Thus, there is a cross-over point, where the detector grounding changes from relying on the Detector Ground network, to being parasitically coupled to the local structure, which is also connected to earth. The value of this cutoff frequency is strongly dependent on the physical nature of the detector. Typical values are in the 100 Hz to 100 KHz range [29]. In most detectors, the low frequency noise is more prevalent and more difficult to control after a system is built.

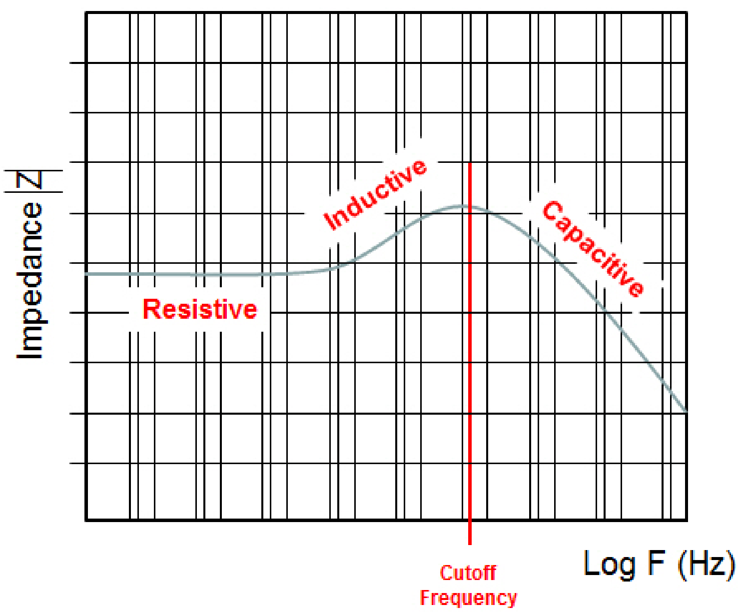

Figure 3.3.2. Approximate impedance versus frequency for a single point ground system for a detector.

3.3.2. The location of the connection of Detector Ground to Safety Ground shall be done at a location that offers the lowest overall impedance to the system.

The default location for the Tracker and the Calorimeter connection to Safety Ground is the Earth connection at the detector floor level. An alternate location is at the isolation transformer on the main floor level. The Stopping Target Monitor will have a separate Earth connection point, which will also be connected to Safety Ground. The grounding for the Extinction Monitor is not defined at this time.

3.3.3. The experiment may incorporate a saturable core in the Detector Ground at the connection to Safety Ground, as shown in Figure 3.3.3. There would be a separate core for each Detector Ground branch as shown.

Saturable cores are inductive. They offer low impedance connectivity at low frequencies, and increase in impedance as the frequency increases, effectively becoming a low-pass filter. However, they contain a magnetic core that saturates at a specified current, which then limits the impedance. This allows transmission of fast fault currents to Safety Ground for safety considerations.

Saturable cores have been implemented in a number of experiments at Fermilab, and have been shown to be safe and effective [30].

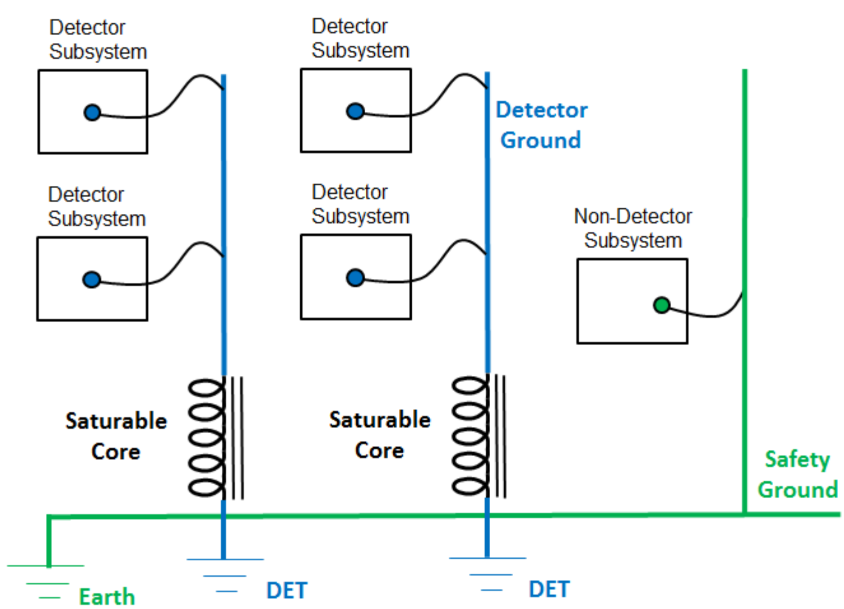

Figure 3.3.3. Use of a saturable core at the connection point of Detector Ground and Safety Ground.

3.3.4. It is desirable to attempt to reduce the capacitive coupling of Detector Ground to Earth.

Parasitic coupling of Detector Ground to Earth can degrade the high-frequency performance of the Detector Ground system.

3.4. Subsystem Isolation

3.4.1. For on-detector components, the commons of the detectors and associated front-end electronics in each subsystem shall be electrically isolated from the support structure, unless the support structure is part of the Detector Ground for that subsystem.

This requirement addresses the need to avoid ground loops. By designing the subsystems so that the commons are isolated from Earth, the connection to ground can be carefully controlled, which is provided by the connection to Detector Ground.

3.4.2. For on-detector components, the commons of the detectors and associated front-end electronics subcomponents in each subsystem shall be electrically isolated from other detector subsystems, other than through the Detector Ground connection.

This requirement also addresses the need to avoid ground loops. Subsystem designers may determine the physical configuration of circuitry for which there would be one connection to Detector Ground. Generally this is circuitry that has a contiguous common ground. One convenient grouping of circuitry is that serviced by a single power supply of power supply unit, since the load would have a common return.

3.4.3. For off-detector components, there may be parts where the electrical commons connect to Detector Ground, and other parts that connect directly to Safety Ground or the local support structure. In this case, the components must maintain electrical isolation between the two parts.

This requirement also addresses the need to avoid ground loops. An example is a power supply with a primary side that is powered by 120V, 60Hz power, with a secondary side that powers front-end electronics. The primary side must have the common of the circuit connected to safety ground. The secondary side may be floating, if the output voltage is less than 50V.

3.5. Isolation Line

3.5.1. In the design of the grounding for each subsystem, it must be possible to draw an Isolation Line in a system block diagram showing how and where the electrical isolation is achieved that prevents ground loops.

This requirement aids in the design of the Detector Grounding, and facilitates the review of the integrity of the grounding system.

3.6. Shielding

3.6.1. Each detector component may incorporate electrostatic or magnetic shielding, depending on the anticipated noise environment, as well as mechanical constraints or environmental factors. This is left to the discretion of the subsystem designers.

Since each detector subsystem is isolated from others, the need for shielding and how it is incorporated into the design are discretionary. If shielding is employed, each detector subsystem may determine the grounding scheme of the shield, whether to the local support structure or to Detector Ground. As per the requirement of section 3.1.2, shields should not be left floating.

EMI shielding is used to guard instrumentation systems against noise from stray electromagnetic fields. It is used both to shield a source against radiating to other subsystems, and also at potential receiving points where sensitive instrumentation resides. Three types of EMI noise that are often found in detector subsystems are: 60 Hz (and the third harmonic) electric and magnetic fields from the power distribution system; magnetic fields from ballasts in the 20 KHz range; and high frequency far-field noise from fast switching transients in the 1-100 MHz range. Generally, a subsystem will act as an antenna if the circuit can act as an antenna of length 1/20 of a wavelength or more. For most subsystems, only the high frequency noise can be a problem, although large detector components can be susceptible to lower frequencies.

Generally, it is difficult to predict the noise environment on a detector a priori, and whether EMI shielding is needed. The nature of the shielding may be different depending on whether the noise fields are near-field magnetic, near-field electric, or far-fields. The thickness of the shielding must also be determined, since skin depth effects can come into play that are a function of frequency. Shielding introduces mass into the detector, which may affect the performance of the detector. Other issues include space, mechanical details of how the shields connect, cooling, holes through the shielding needed for services, etc. Because of these issues, there are no requirements for EMI shielding specified by this document. It is strongly recommended that each detector subsystem evaluate their susceptibility to EMI noise, as well as the potential for neighboring subsystems to generate this noise, and determine if shielding is needed.

3.7. Low Voltage Power Supply Configuration

3.7.1. The Low Voltage Power Supplies (LVPS) that reside off the detector and provide power to on-detector components shall be configured with floating outputs on the secondary side. This assumes that there is transformer isolation between the primary side and the secondary side. If the primary side is powered by voltages greater than 50V, then the unit must conform to NEC requirements with respect to bonding to Safety Ground.

For the purposes of this document, "Low-Voltage" is defined as voltage sources that produce less than 50 Volts on the output. This is regarded as a non-hazardous energy source. The code has few requirements on grounding for this case [31]. How and where earth grounding is applied is not specified, and therefore it is left to the requirements dictated by the application.

For powering the on-detector electronics, the experiment will use low voltage bulk supplies that have floating outputs, i.e. the power return net on the secondary side is not connected to the Safety Ground in the supply. These supplies will generally be off the detector. In most subsystems, the output voltages are in the 24VDC to 48VDC range.

Generally, the primary side of the bulk low voltage power supplies will use "high voltage," voltages greater than or equal to 50V. The primary side must have the proper connections to Safety Ground, and be reviewed for compliance by safety personnel. Because the outputs on the secondary side are floating, a connection to Safety Ground on the primary side does not compromise the isolation with Detector Ground.

3.7.2. For single-stage power distribution systems, the low voltage power is used directly to power the load of the front-end electronics, as shown in Figure 3.7.1. The low voltage power is sourced by the secondary side of the LVPS. It is received by the front-end electronics on the detector, which generally has the power return referenced to the common of the front-end circuitry. The common in turn may be referenced to Detector Ground. If this is desired, it is done locally within each subsystem at the load via a connection from the common of the component to Detector Ground. Note that for systems with voltages less than 50V, a hard connection to Detector Ground is not required. Subsystems may also elect to use a “soft connection” between the common of the front-end circuitry and Detector Ground.

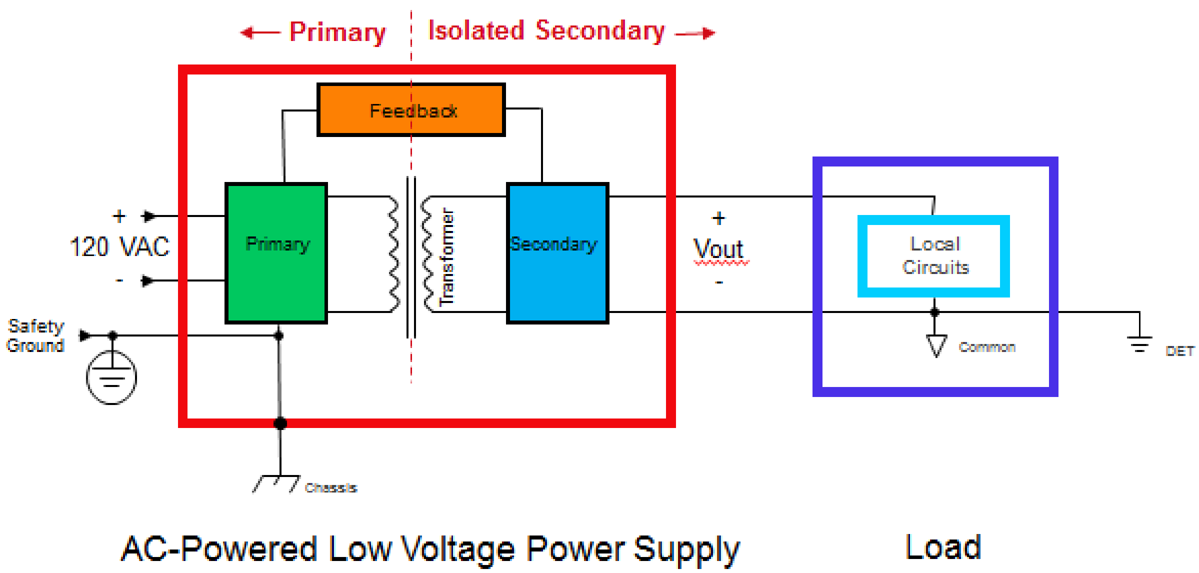

Figure 3.7.1. Referencing of the power return of the LVPS to Detector ground for a single-stage power distribution system.

3.7.3. Some subsystems may incorporate a multi-stage power distribution system, where the low voltage power that is received from off-detector bulk supplies will be further regulated down to specific voltage levels as needed by the front-end electronics using point-of-load (POL) regulators. This can be done in several ways. Generally these schemes involve the use of an intermediate DC-DC converter, which receives the DC output voltage from the first power supply, and regulates it (down or up) to the voltages needed by the load. One configuration is shown in Fig. 3.7.2, which uses a transformer-coupled supply. In this case, the transformer is used to isolate the load. Another scheme that is often used incorporates point-of-load (POL) regulators, which are generally integrated circuits or small modules. Most point-of-load regulators use a common power return for the primary and secondary sides, and this will generally be the common for the front-end electronics, which in turn will be connected to Detector Ground. This is shown in Figure 3.7.3. Some designs may have additional levels of powering, where one POL regulator powers another. As was the case for the single-stage power system, systems with voltages less than 50V may elect to use a soft connection to Detector ground, or no connection at all, depending on the requirements of the subsystem.

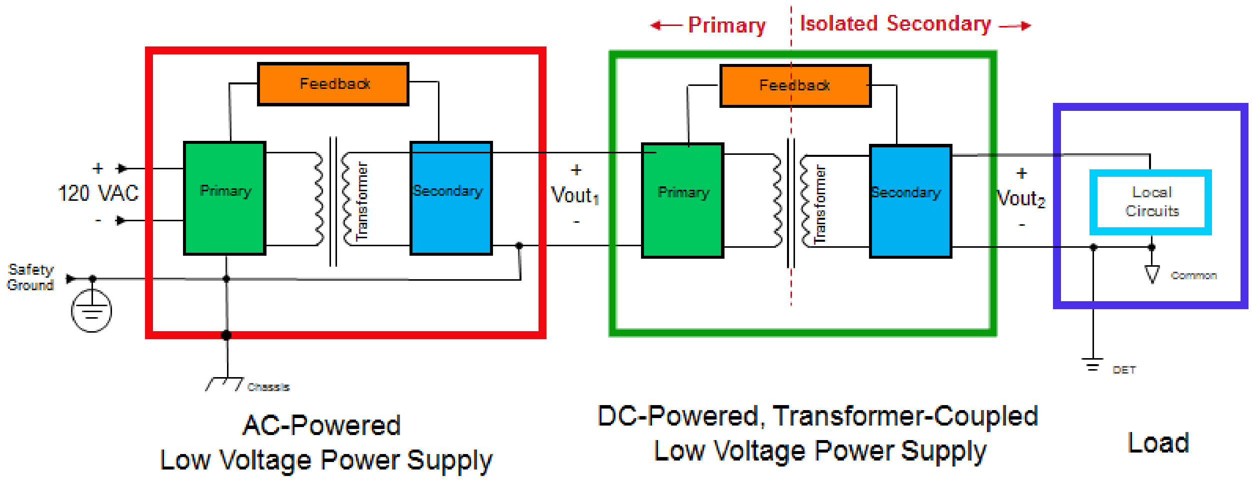

Figure 3.7.2. Referencing of the power return of the LVPS to Detector ground for a two-stage power distribution system with transformer coupling.

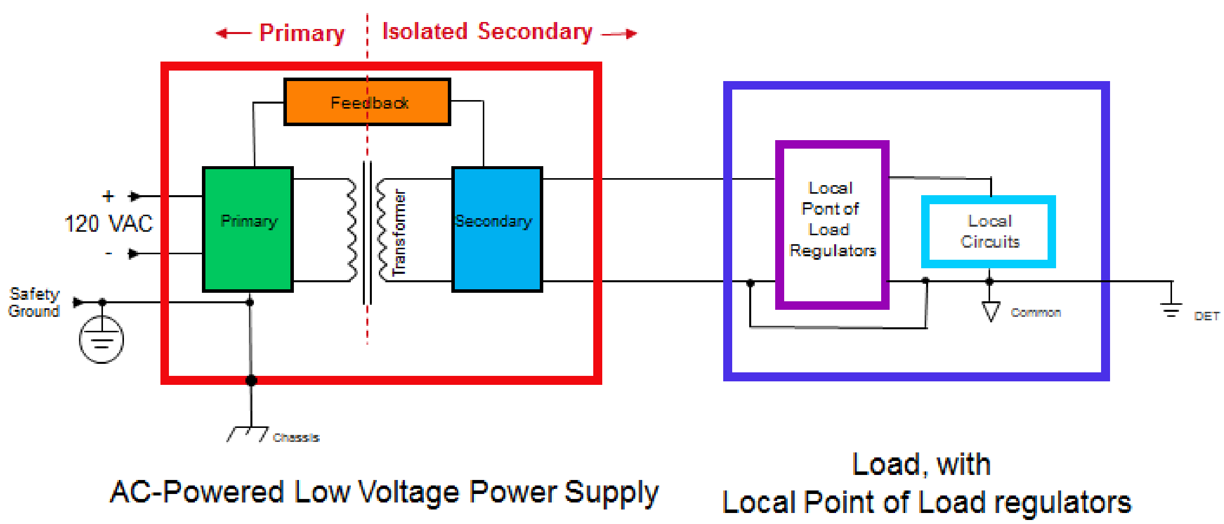

Figure 3.7.3. Referencing of the power return of the LVPS to Detector ground for a two-stage power distribution system with point-of-load regulators.

In the case where multiple voltages are present in a design, it may be necessary to have split or isolated ground plans, such as analog ground, digital ground, etc. If split ground planes are used, the different grounds may need to be coupled at some point in the circuit to provide a common point for Detector Ground (or zero volt referencing). As specified above, the referencing of the common power return plane to Detector Ground (and hence to earth) will be done at the detector component level, one connection per logical unit.

3.7.4. The power supplies must have isolation circuitry for feedback control and output monitoring inside of the power supply, such as transformer coupling or opto-isolators, to achieve isolation of the secondary-side outputs.

Most DC power supplies have feedback inside the supply for controlling either the output voltage or output current. This feedback connection usually connects the secondary outputs back to the primary side. Because the power return of the secondary is floating with respect to the primary side, the feedback would either need to be implemented as a differential signal, with high impedance between the primary and secondary side, or implemented using optical isolation. Both techniques are commonly used in modern DC power supplies, although not all DC supplies use this. The subsystem designers should ensure that the low voltage power supplies that are selected have isolated feedback. In addition, some power supplies provide monitoring capability of the output voltage and current. This circuitry also requires a connection between the primary and secondary sides. Again, with the requirement that the power return be isolated and floating, any monitoring circuitry of the output voltages and currents must also be isolated between the primary and secondary. The subsystem designers should ensure that the low voltage power supplies that are selected have isolated output voltage and current monitoring circuitry as well, if this feature is desired.

3.8. High Voltage Power Supply Configuration

3.8.1. The low current, High Voltage Power Supplies (HVPS) that are used in the experiment for biasing detector component and reside off the detector shall be configured with isolated outputs on the secondary side. This assumes that there is transformer isolation between the primary side and the secondary side. The isolation between the power return and the chassis inside of the HVPS unit shall use over-voltage protection circuitry connected between the power return of the secondary and the local Safety Ground in the unit, to provide safety protection against abnormal charging of the power return. The primary sides of the HVPS units are generally powered by line voltage (120VAC), so the units must conform to NEC requirements with respect to bonding to Safety Ground.

The Mu2e experiment will use several types of low current, high voltage power supplies, most of which are used for biasing the detectors. For bulk supplies that have outputs greater than or equal to 50V, Fermilab defines this as being “hazardous-voltage”, for which there are specific requirements on grounding. The NEC also specifies that the power return on the secondary side must be connected to Safety Ground in the supply, to prevent circuitry from floating to dangerous voltage levels [32]. All of the high voltage power supplies that are being planned for the experiment are off-detector. Because the grounding scheme for the detector incorporates a connection to Detector Ground at the detector, the power return of the high voltage power supplies should be isolated from the Safety Ground in the supply itself in order to prevent ground loops, as was the case with the low voltage power supplies. Under normal circumstances, this connection prevents the power return of the HVPS from charging to dangerous levels.

To guard against the case where the output is disconnected, or where the ground referencing at the load is disconnected, a variation that has been accepted in HEP instrumentation by safety organizations is to allow the power return of the secondary to be isolated from the internal safety ground in a high voltage power supply, but to use active or passive over-voltage protection circuitry connected between the power return output and the local safety ground in the unit. Typical over-voltage protection levels are 10-20 volts before the protection circuitry is activated. This has become somewhat common in the instrumentation field, and several commercial manufacturers of high voltage power supplies offer this as an option [33]. All such instances in Mu2e will be reviewed by Fermilab safety personnel.

3.8.2. Referencing of the HVPS secondary side power return shall be done locally within each subsystem via a connection from the common of the component to Detector Ground. This is the primary safety connection.

The high voltage power received by the front-end systems on the detector will have the power return referenced to the common of the front-end circuitry. The common will in turn be referenced to Detector Ground. In general, the common of the high voltage bias to a detector is part of the signal processing instrumentation, so there is a need for these to be connected together on the front ends. In normal operation, the power return side of the high voltage power supply output will be connected to Detector Ground at the front-end, and this provides the primary method of safety.

3.8.3. The HVPS units must have isolation circuitry for feedback control and output monitoring inside of the power supply, such as transformer coupling or opto-isolators, to achieve isolation of the secondary-side outputs.

As was the case with the LVPS, isolation is needed between the internal connections of the primary side and the secondary side of the HVPS units, such as the feedback circuitry that regulates the output voltage or current, and any internal monitoring of the output voltage or current. This feedback circuitry must be either high impedance or optically coupled with the primary side. The subsystem designers should ensure that the high voltage power supplies that are selected have isolated feedback, and isolated output voltage and current monitoring circuitry as well if this feature is desired.

3.9. Data, Clock, & Trigger

3.9.1. All data, clock, and trigger transmission into and out of the subsystems shall have optical or electrical isolation at some point in the signal processing chain to break ground loops.

Because the grounding scheme uses Detector Ground as the reference on the detector, all data, clock, and trigger transmission into and out of the on-detector subsystems must be isolated at some point in the signal processing chain to break ground loops. The primary concern is to break any ground loops that would otherwise exist between the detector and the DAQ room upstairs. The preferred method is the use of fiber optic communications. These are common and ubiquitous in the instrumentation field now, and most processors support the hardware.

A second option is to use Low Voltage Differential Signals (LVDS). The common mode return current is very small, and often the circuits function well without a current return path. This is shown in the top of Figure 3.9.1. However, for long runs, common mode compliance can be an issue, if there is not direct ground connection between the two and a substantial difference between grounds on the sending and receiving end results. Also, susceptibility to EMI noise impingent on the differential pair can exceed the common-mode compliance of the driver or receiver circuits. If LVDS is used, it is recommended that the cables be shielded and that the shield be connected hard on the sending end and softly connected (through an impedance of 100 ohms or more) on the receiving end. One scheme for doing this is shown in the bottom of Figure 3.9.1. Other acceptable schemes have been developed as well.

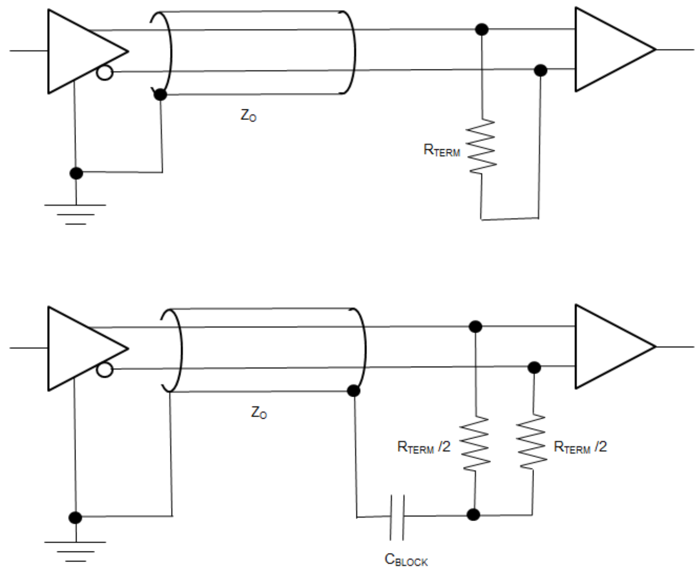

Figure 3.9.1. Two schemes for using shielded cables with LVDS signals. The top figure is acceptable for short distances. The bottom figure allows a return for the common mode signal back to the source.

3.10. Monitor & Control Signals

3.10.1. Slow control and monitoring circuits on the detector shall incorporate optical or electrical isolation at some point in the signal processing chain between the common of the associated circuitry and Detector Ground.

Because the grounding scheme uses Detector Ground as the reference on the detector, all slow control and monitoring circuits on the detector must incorporate electrical isolation of some kind between the common of the circuitry and Detector Ground. The implementation of slow controls and monitoring on the detector is often at odds with detector grounding schemes. Because the grounding scheme of the detector has the Detector Ground reference at the detector, all control and monitor signals into and out of the detector subsystems must be isolated at some point in the signal processing chain to break ground loops. The primary concern is to break any ground loops that would otherwise exist between the detector and the DAQ room upstairs.

The preferred method is the use of fiber optic communications. These are common and ubiquitous in the instrumentation field now, and most processors support the hardware. Low Voltage Differential Signaling (LVDS) is an alternative, although a current return path may be needed for the common-mode imbalance current, which would have to be isolated from Detector Ground. The recommended isolation between the control & monitoring system common (DAQ room) and Detector Ground is 1 megohm for each component or logical unit.

3.11. Monitoring Current Flow in Detector Ground

3.11.1. The experiment may implement a Detector Ground current flow monitor, to ensure that no subsystem is causing current to flow in the Detector Ground network. This would be installed at the connection point between detector ground and Safety Ground. Such systems have been used successfully in other experiments, as in [34]. The nature and requirements of this monitor are not defined presently, and are to be determined.

3.12. Isolation with the Accelerator Beam Lines

3.12.1. It is desirable for the grounding systems in the detector to be isolated from the beam lines of the accelerator. The high-power RF systems in the accelerator complex can produce noise currents in the beam pipes, and these can couple through detector ground systems if isolation is not implemented [35]. This isolation would be done at the point where the beam pipe interfaces to the Production Solnoid. It is desirable from the point of view of the experiment to incorporate an electrical insulator at this interface. Preliminary discussions with the accelerator subsystem principles indicate that this should be possible, although the technical design and details have not been worked out yet [36]. This will be a goal in the implementation of the grounding system for the experiment.

3.13. Safety Considerations

As previously stated in Section 1.3, all facilities at the laboratory are required to follow the National Electrical Code (NEC). The grounding of the facility infrastructure and the detector will not deviate from the requirements of the NEC. The facility infrastructure will also provide electrical power to other detector subsystems. Some of these subsystems may be negatively affected by ground currents that would be considered negligible for most other purposes. A process exists for permitting systems that deviate from the requirements of the NEC through the Electrical Authority Having Jurisdiction (AHJ).

The Fermilab Site Office (FSO) has been assigned the AHJ authority by the DOE, and has delegated this authority to the Laboratory for “limited and routine activities.” Any deviation from the requirements of the NEC would be considered non-routine, and would have to be approved as an equivalency, variance, or exemption. These three terms represent increasing levels of departure from code requirements, and need progressively higher levels of approval from the DOE to implement them.

Obtaining approval for any deviation will hinge on demonstrating that four primary objectives of a grounding system are as well served by the alternative proposed (equivalency), or that one or more of these objectives cannot be met and comparing the benefit gained or negative impact avoided against the worst probable incident that may occur (variance and exemption). Those four objectives are: preventing exposure of individuals to a harmful difference in electrical potential; limiting the voltage imposed on the electrical system by external surges; limiting the buildup of static charge that could damage insulation; and ensuring prompt response of overcurrent protective devices to faults.

Of particular concern to any attempt to create isolated or "quiet" grounding systems is the requirement in NEC Article 250.50 that "All grounding electrodes (the same as the "earth grounds" defined in Section 1.2.2 as described in 250.52(A)(1) through (A)(6) that are present at each building or structure served shall be bonded together to form the grounding electrode system." Under conditions in which substantial currents flow through the soil, such as utility distribution system faults and lightning strikes, independent grounding systems within the same structure can exhibit a substantial voltage differential. NEC Article 250.6, Objectionable Current over Grounding Conductors, provides guidance on what measures are and are not permissible in the effort to reduce grounding conductor currents

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Even ungrounded electrical systems, which are permitted under NEC Article 250.4(B), must have "Non-current-carrying conductive materials enclosing electrical conductors or equipment [to] be connected to earth in a manner that will limit the voltage imposed by lightning or unintentional contact with higher-voltage lines and limit the voltage to ground on these materials, and these materials shall be connected together and to the supply system grounded equipment in a manner that creates a permanent low-impedance path for ground-fault current that is capable of carrying the maximum fault current that is likely to be imposed on it." The same applies to other electrically conductive materials that may become energized. As described in NEC Article 150.4, the code specifically states that the earth shall not be considered an effective fault-current path.

4. Grounding and Shielding Plans for Detector Subsystems

As stated in Section 3, the experiment will use a single-point ground with a star topology. There are two options: connection on the detector floor level through the building wall, and near the isolation transformer upstairs. The experiment shall implement a Detector Ground main line that runs between these two connection points. Only one connection will be made, with the connection on the detector floor level being preferred. The main line will consist of insulated 500 MCM cable. Branch connections to the detector components will generally be made using 2" or 3" braids, acting as branches in the star ground topology. A description of how each subsystem will implement the grounding scheme and connect to Detector Ground is described below.

4.1. The Straw Tube Tracker

The design of the grounding system for the Tracker is shown in Figure 4.1.1. The front-end boards host both low voltage needed for the electronics, and high voltage needed for the detector bias. The common ground of each front-end board will be connected to the aluminum support ring through the mounting screws. The support ring in turn, is then connected to detector Ground.

The 36 planes that comprise the Straw Tube Tracker are each made from 6 panels, as described in section 2.1. There is one front end board per panel. The panels are mounted onto a ring, which is made out of aluminum. The baseline plan has each plane to be constructed into stations as a single mechanical and electrical unit. Each front end board will have a single connection from the board common to the support ring for that station. The assembled stations are supported in the tracker using horizontal beams. The stations are electrically isolated from the horizontal beams and from each other. Each station will then have an independent connection to Detector Ground, one per station.

The low voltage power supplies of the tracker reside in the Electronics Alcove on the detector floor. Power will be supplied per plane, with independent supply and return paths for each plane. The supplies will have isolated power returns. There is one pair (power and return) for each panel. The power connections through the vacuum penetration will be electrically-isolated from the detector support structure. Ground loops are eliminated by having isolated power supply outputs.

The high voltage power supplies of the tracker reside in the DAQ room. They will also have isolated power returns. The supplies will use either active or passive over-voltage protection on the power returns in the power supply unit to protect against abnormal faults. (Note that this is a backup protection scheme.) The ground reference for the high voltage power return will be made at the detector panel through the connection to Detector Ground. There is one pair (power and return) for each panel. The power connections through the vacuum penetration will be electrically-isolated from the detector support structure. Ground loops are eliminated by having isolated power supply outputs. In this case, safety ground on the detector is provided by the Detector Ground connection.

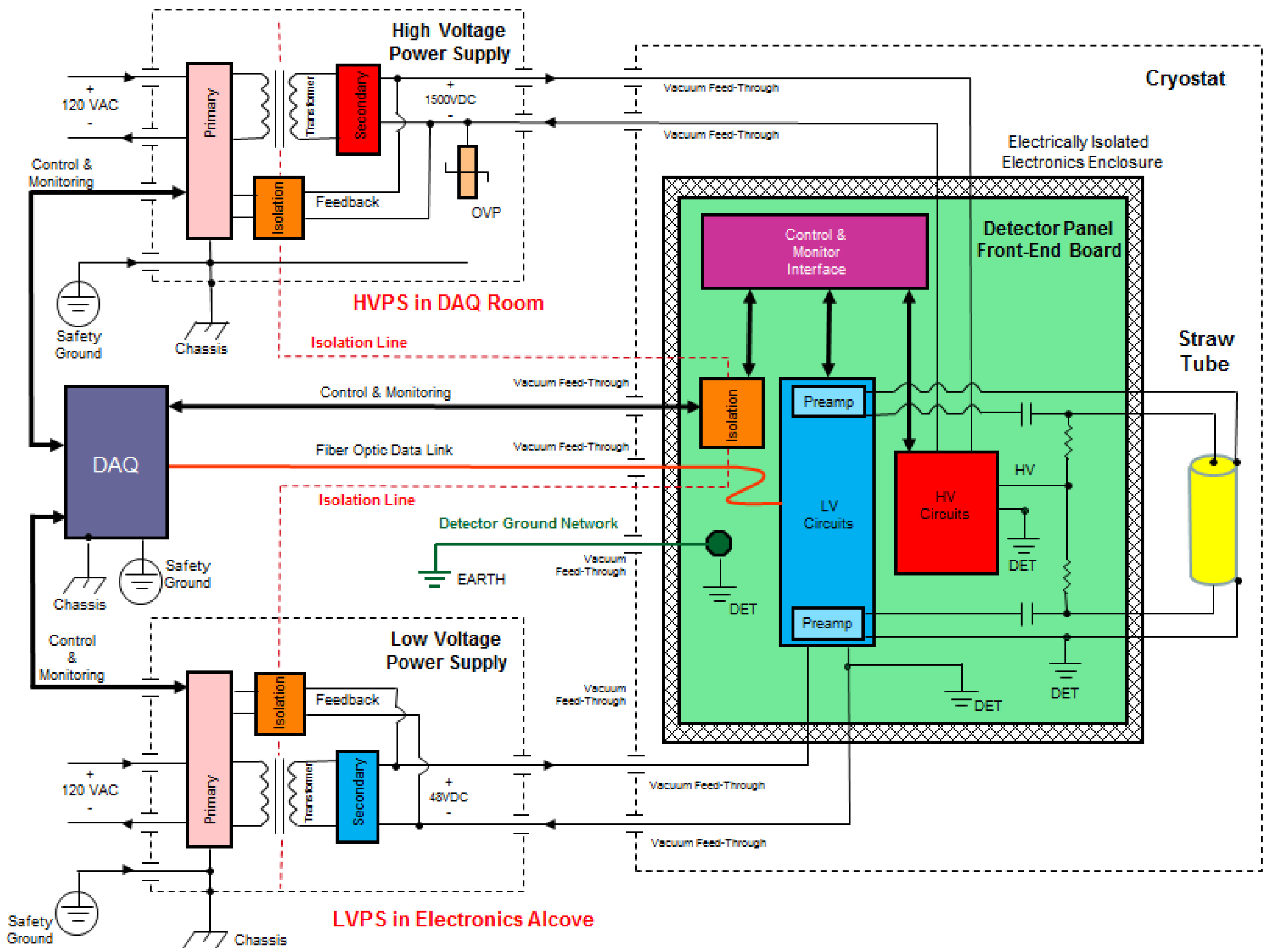

Figure 4.1.1. Block diagram of the grounding system for the Tracker.

Details of the connections from the Straw Tube front end electronics to Detector Ground is shown in Figure 4.1.2 and Figure 4.1.3. There will be one Detector Ground connection per station. The grounding cable will be a flat cable with an insulating jacket, as shown in Figure 4.1.4, and will connect to each support ring using screws. Because the tracker resides in a vacuum, the ground connections will have to pass through the vacuum flange in order to get out of the detector volume and connect to Detector Ground. This will be accomplished through the use of a vacuum-tight, DB25 connector as shown in figure 4.1.5. Each connector will provide connections for five stations. The connections from the flat strips to the DB25 connector will be done using a short pigtail, occupying 5 pins of the connector per strip. A braid will be used for the connector outside of the vacuum volume. The braid collect 5 station ground together and make a connection to the Detector Ground tab.

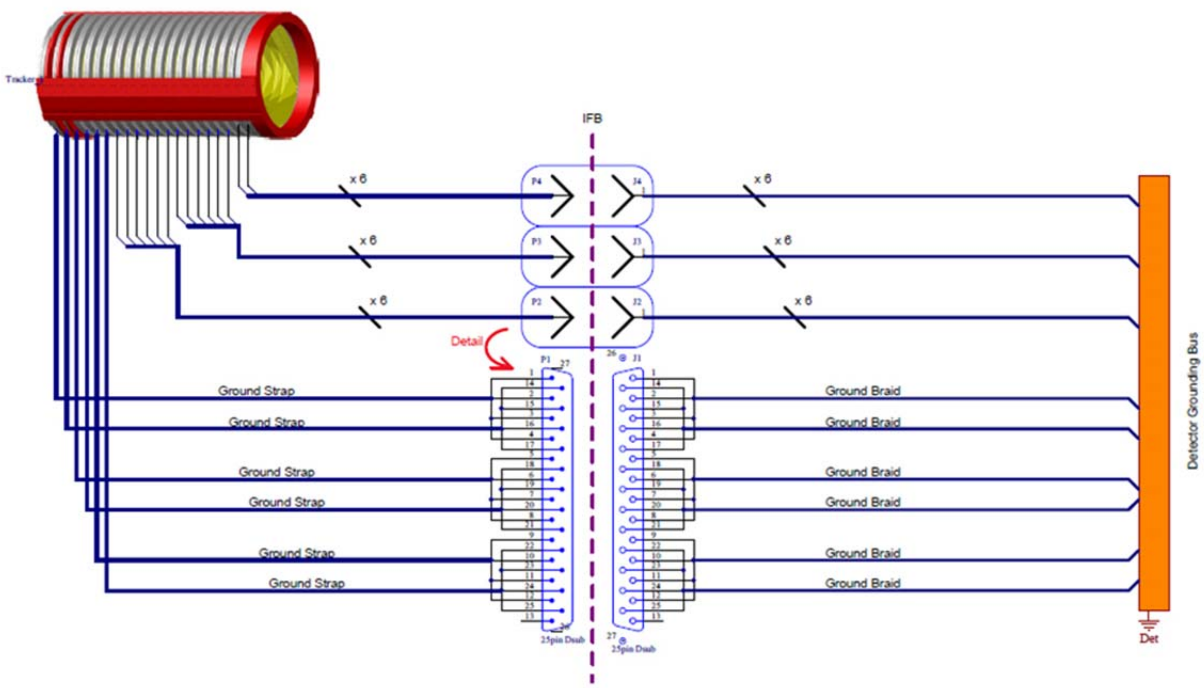

Figure 4.1.2. Scheme for connecting the Tracker to Detector Ground.

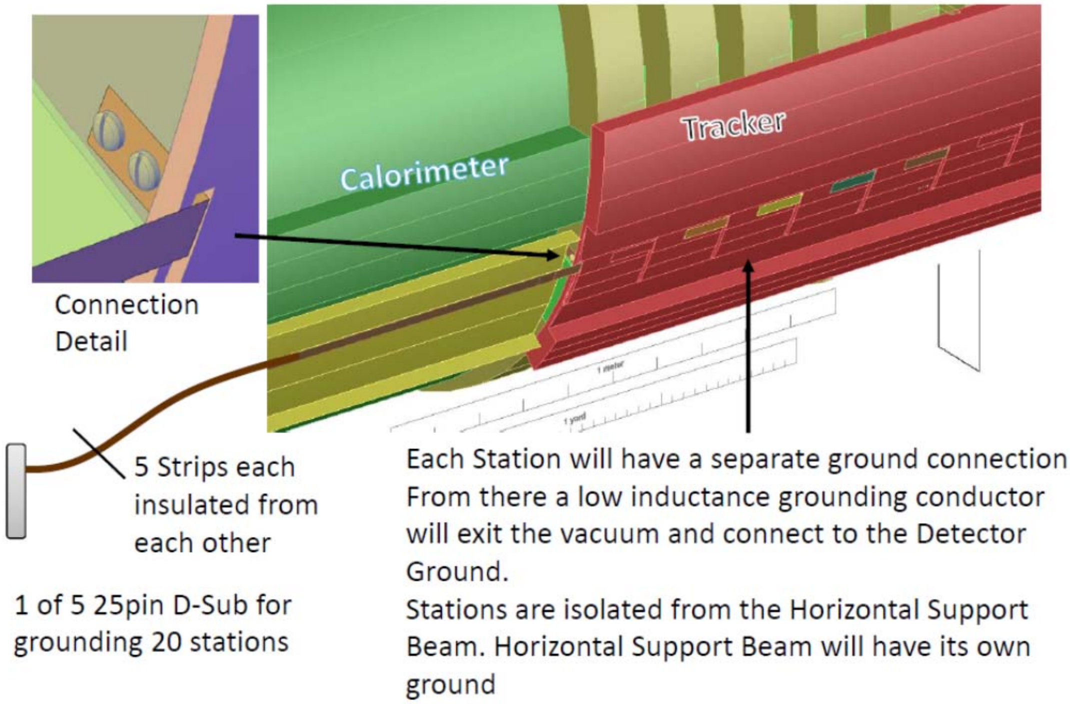

Figure 4.1.3. Another view of connecting the Tracker to Detector Ground.

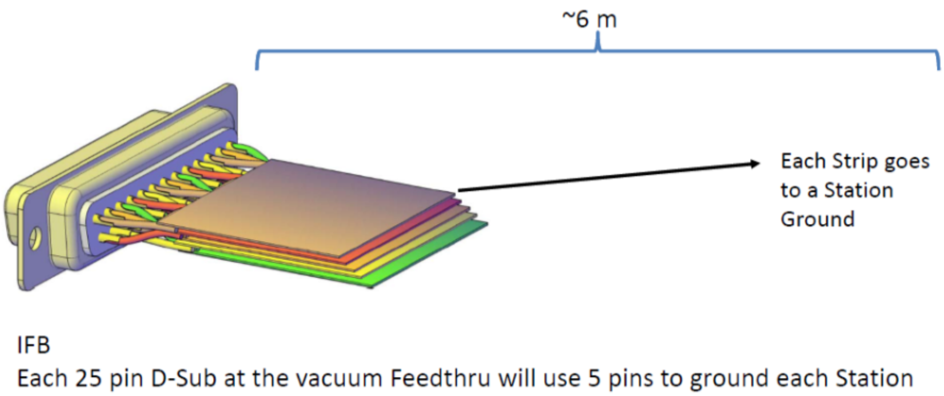

Figure 4.1.4. Detail showing how the ground braid connects to the DB25 connector for feed-through the vacuum flange (Interface Board, or IFB).

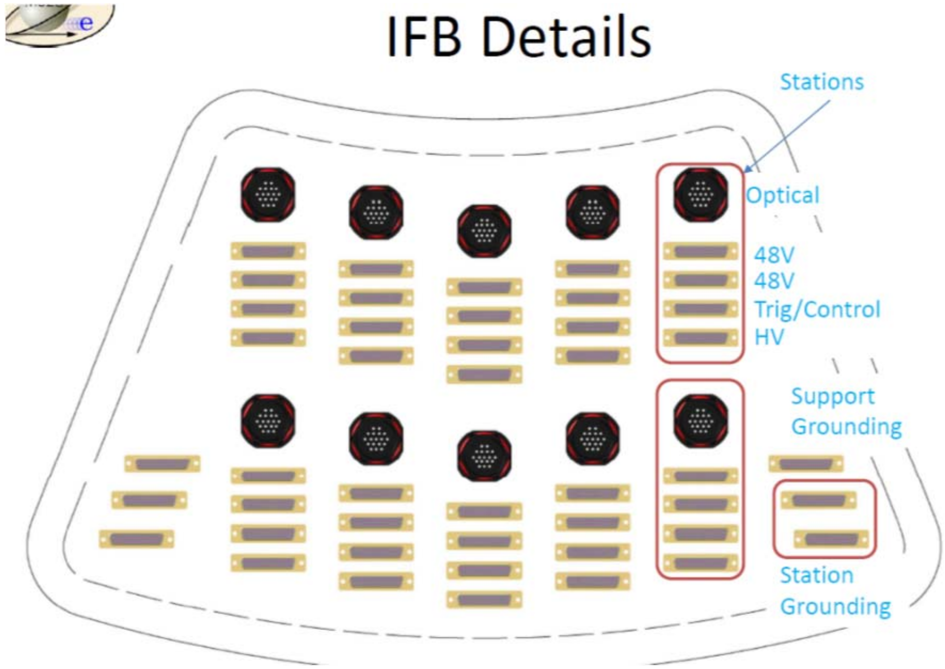

Figure 4.1.5. Detail showing one of two IFB vacuum flange panels.

The connection of Detector Ground to each station must be a permanent or semi-permanent (i.e. screw lug) bond, as it will provide the safety ground for the high voltage. However, the connection through the vacuum flange will use DB-25 connectors. In order to comply with safety rules, the disconnection of the Tracker subsystem from safety ground will have a defined procedure. The connectors will be labeled with a warning that disconnections must be approved by a safety officer. There will be a policy written that disconnections can be made only with the high voltage turned off. Two additional DB25 connectors are used to bring the support beam ground out of the vessel.

The ring formed by each plane creates the potential for ground loop issues. In addition to ground currents, the ring may act as a loop antenna to both to radiate noise and to pick up noise. A completed plane will be tested before committing to the baseline plan. Tests include verifying no current (DC or AC) on the earth ground line; and looking for increased noise relative to an isolated panel. If a problem is encountered, the alternative plan is to electrically isolate panels from each other when assembling the plane. This is a major complication to the assembly process and will increase the cost of both labor and fixturing. It also compromises the mechanical rigidity of the completed structure, which increases the risk that optical survey conducted before insertion into the detector solenoid will not accurately reflect the final position of the panels.

4.2. The Calorimeter

The design of the grounding system for the Calorimeter is shown in Figure 4.2.1. The calorimeter structure is electrically isolated form the cryostat, as shown in Figure 4.2.2, using G11 material with 2 mm of thickness in many sectors.

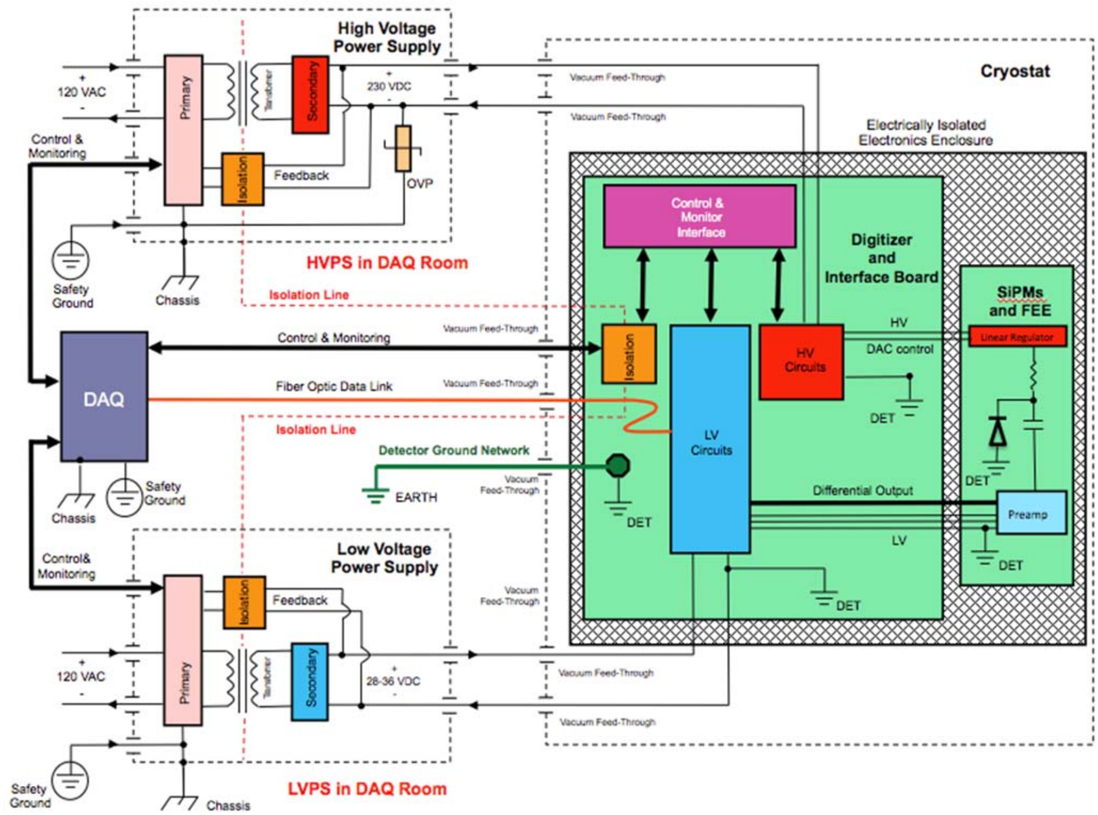

Figure 4.2.1. Block diagram of the grounding system for the Calorimeter.

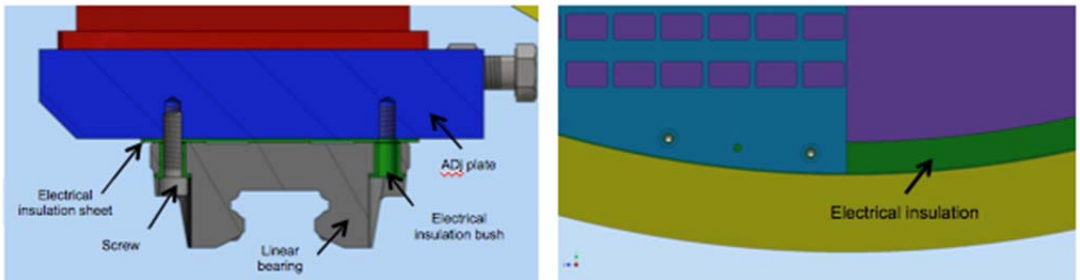

Figure 4.2.2. The calorimeter structure is electrically isolated form the cryostat (left). Also the back plate of the photo-sensors and FEE is thermally and electrically isolated from the structure (right).

The common ground of each front-end board will be electrically isolated from the local calorimeter support structure. The complete insulation is made using thermal bridge resistor design to transport heat from the back plate to the FEE using an electrically isolated Aluminum Nitride substrate material, see Figure 4.2.3. Each front-end board will have one connection to Detector Ground to provide the ground reference.

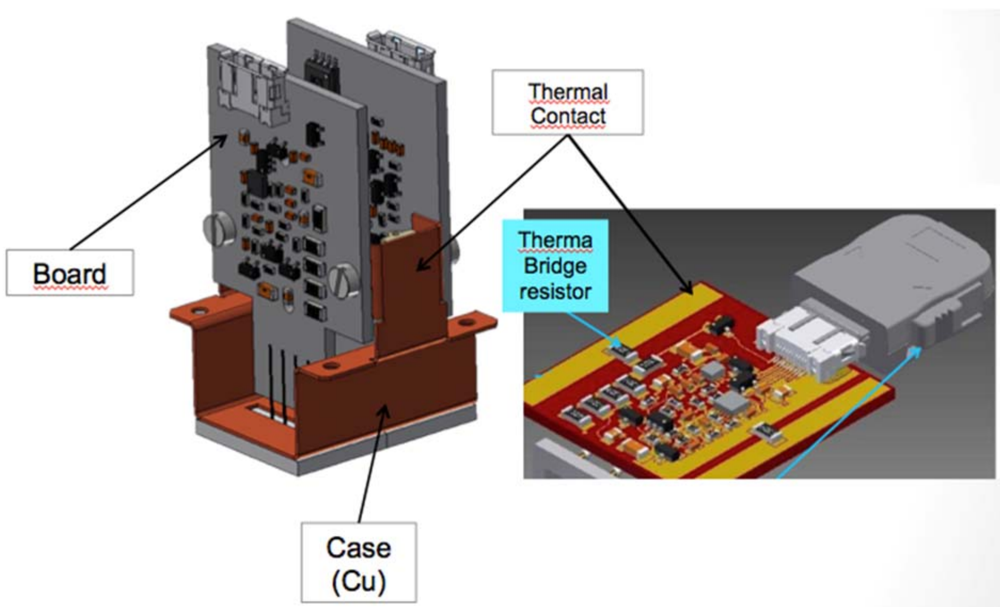

Figure 4.2.3. Calorimeter FEE and the SiPMs are isolated from the back plate using thermal bridge resistors.

The low voltage power supplies of the calorimeter reside in the DAQ room. They will have isolated power returns at the supplies. There are eight pairs (power and return) for each crate. The power connections through the vacuum penetration will be electrically isolated from the detector support structure. Ground loops are eliminated by having isolated power supply outputs.

The high voltage power supplies of the calorimeter reside also in the DAQ room. They will also have isolated power returns at the supplies, using either active or passive over-voltage protection on the output power returns in the power supply unit to protect against abnormal faults. This will require approval from safety personnel. (Note that this is a backup protection scheme.) The ground reference for the high voltage power return will be made at the detector panel through the connection to Detector Ground. There are four pairs (power and return) for each crate. The power connections through the vacuum penetration will be electrically isolated from the detector support structure. Ground loops are eliminated by having isolated power supply outputs. In this case, safety ground on the detector is provided by the Detector Ground connection.

The basic scheme for connecting to Detector Ground is shown in Figure 4.2.4. The idea is to have two ground cables (one per disk), made of copper braid of 3 cm wide with an insulating jacket, going through the flange and then to connect them to the Ground Cable. The ground will be distributed on the disk using a copper braid going along the disk circumference. The copper braid will be connected to the ground cable (one for each disk) or directly or using a high power connector. The ground connection must pass through the vacuum flange, as shown in Figure 4.2.5. This will be accomplished using one of the hermetically-sealed 25-pin connectors (Positronics #XAVAC-25-M/S-I.0), the same type that will be used to pass the low voltage through the vacuum flange. The braids will be connected to the connector using all 25 pins, in a similar fashion as described for the tracker (Section 4.1.) Outside the flange, the 25 pins in the mating connector will be connected to an insulated braid, which in turn will connect to the Detector Ground main line.

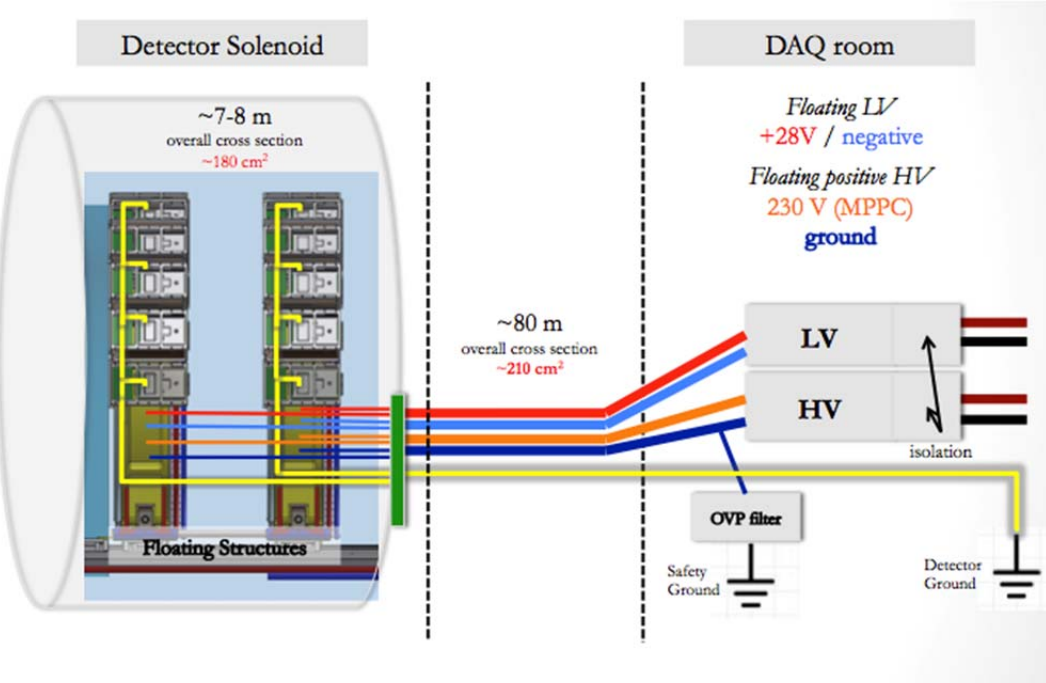

Figure 4.2.4. Scheme for connecting the Calorimeter to Detector Ground

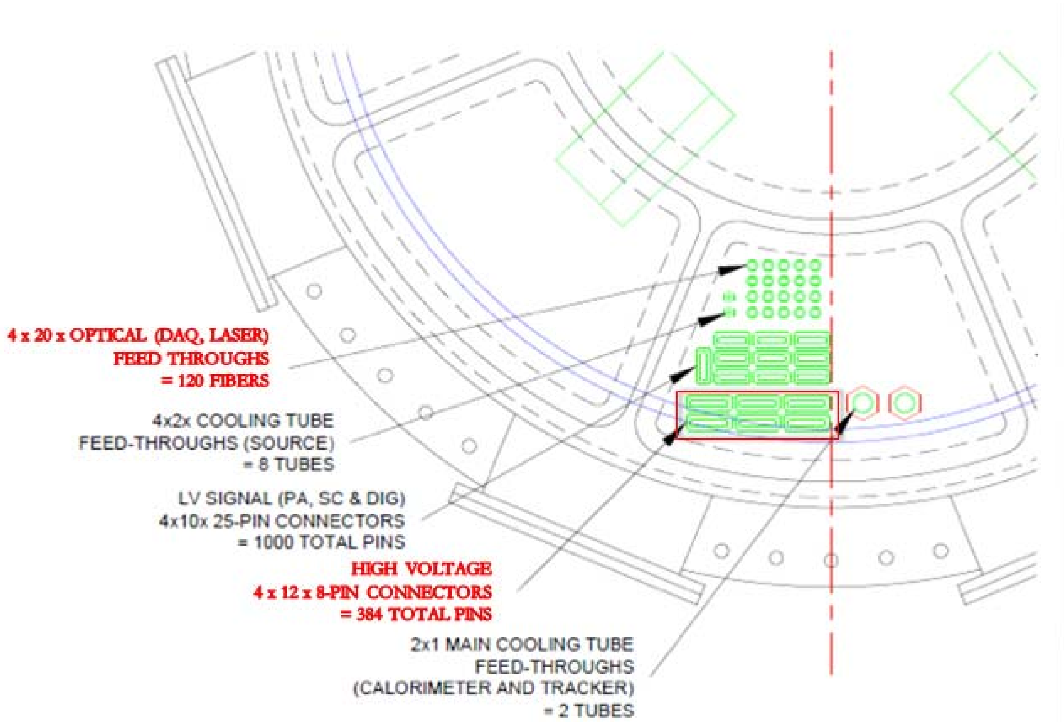

Figure 4.2.5. Conceptual design of the vacuum flange board for the Calorimeter.

4.3. The Cosmic Ray Veto

The both the front end and back end electronics will be powered by 48V power supplies. The power is distributed to the front ends over the Cat 6 cables using the power over Ethernet (POE+) standard. A block diagram of the power distribution system is shown in Figure 4.3.1. The 48V supply on the front end board is transformer isolated, with optical feedback for regulation. Each controller port is fitted with voltage and current monitoring. The bias voltage generators for powering the SiPMs reside on the front end boards. The bias voltages are derived from the 48V.

The signal standards for the data link between the Controller Master Boards (CMB) and the Front-End Boards (FEBs) are a combination of Fast Ethernet and low voltage differential signaling (LVDS) levels which radiate very little. There are no Detector Ground connections to the FEBs or the CMBs. The floating ground plane of the CMBs and FEBs are the local signal reference. One meter long HDMI cables connect the FEBs to the CMBs.

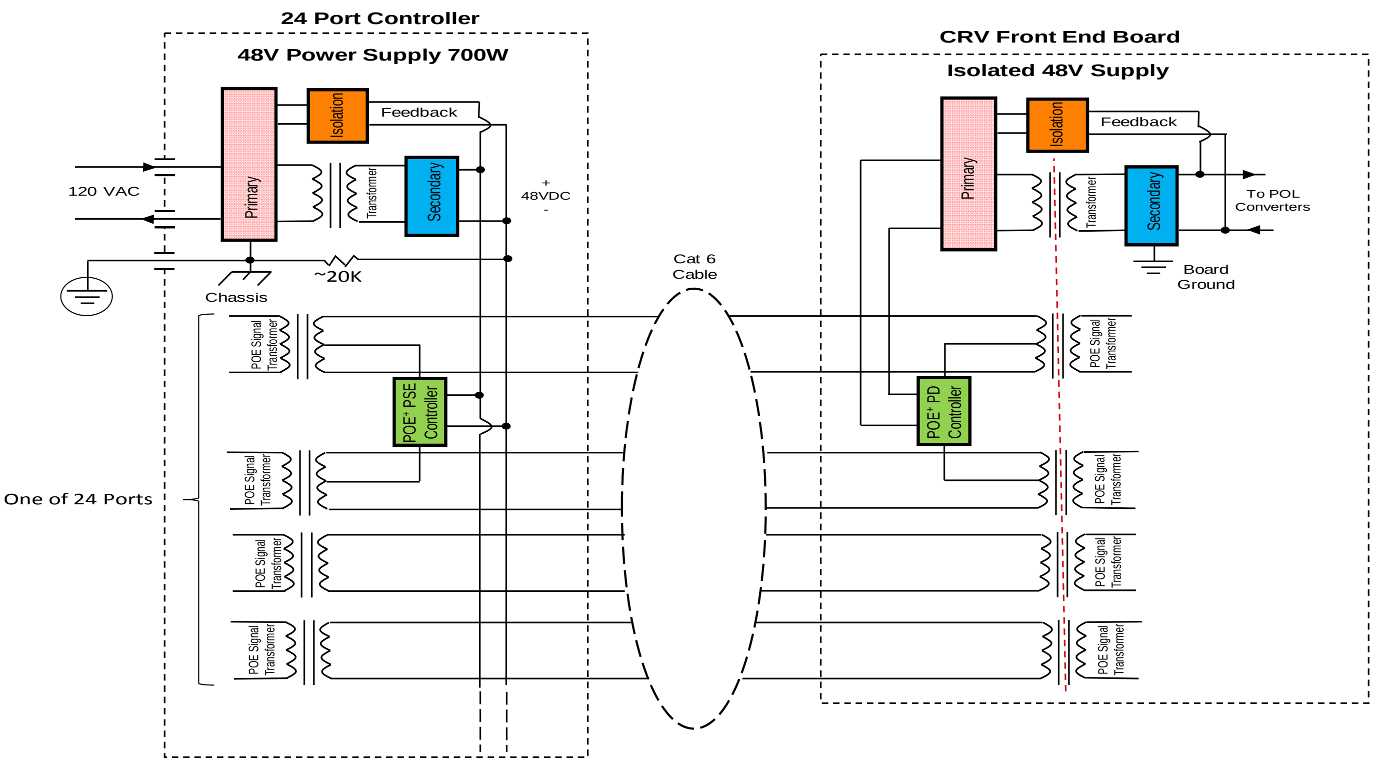

Figure 4.3.1. Block diagram of the power distribution CRV. The system will be entirely floating with respect to earth, with no connections to Detector Ground.

The SiPMs require 54V for the bias voltage. The grounding plan for this subsystem is to have the front-end boards float and have no connection to Detector Ground. This may require an exception (equivalency or variance) from the Electrical AHJ, since the bias voltage is over 50V. If this becomes an issue, the backup plan is to connect a Safety Ground to the magnetic shield that encases this circuitry. This might be implemented by running a Safety ground connection along the top and the bottom of the CRV modules that has branch connections to the shields. A screw on the outside surface of the shield will be provided for the Safety Ground connection, in the event that it is required.

4.4. The Extinction Monitor

There are two types of detector in the Extinction Monitor: photo-multiplier tubes (PMTs) used in the trigger counters and the particle ID/range stack counters; and pixel sensors that are used for tracking. The readout of these detectors uses a common DAQ architecture, based on MicroTCA. A block diagram of the grounding scheme for the system is shown in Figure 4.4.1. The chassis for all electrical equipment in racks will be attached to the Safety Ground. Since the PMT signals are carried on coaxial cable, their shields will be tied to the analog ground on the ADC daughter boards. Thus, the common of the PMTs and that of the preamps will be floating rather than being tied to Detector Ground, to avoid the creation of a ground loop. The signals between the FPGA and the pixel system are digital LVDS signals which provide the electrical isolation between the MicroTCA crate and the ground on the Pixel Interface Board. The ground on the pixel planes are tied to the quiet Detector Ground.

The trigger counters and the range stack counters will be instrumented using PMTs. The PMTs will be configured with passive resistor dividers in the bases, with the cathode at negative high voltage so that the anode is at ground potential. The high voltage return will be isolated from the HV power supply chassis and will be common to the LV power used for the preamplifiers. As is being done in other systems, the HV supplies will use either active or passive over-voltage protection on the output power returns in the power supply unit to prevent the HV return conductor from floating to a hazardous voltage level in the event that the output cable is disconnected. The PMT anode is the input to a preamplifier which drives the amplified signal on coaxial cable to the ADC's in the MicroTCA crate. The shield of the coaxial cable is connected to the analog ground in on the ADC mezzanine card which is mounted on an FPGA carrier board in the MicroTCA crate. In this way, the PMT and preamplifier system will float, with the ground potential determined by the analog ground voltage on the mezzanine cards in the MicroTCA crate. There is no other direct path for signals to flow to ground because the outputs of the HV and LV supplies are electrically isolated from the inputs. The grounding scheme for the trigger counters and range stack counters is shown in Figure 4.4.2.

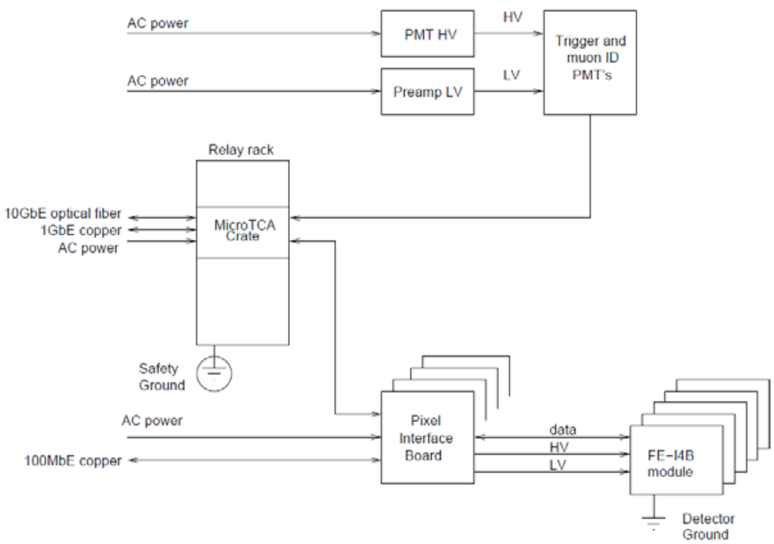

Figure 4.4.1. Block diagram of the grounding system for the Extinction Monitor.

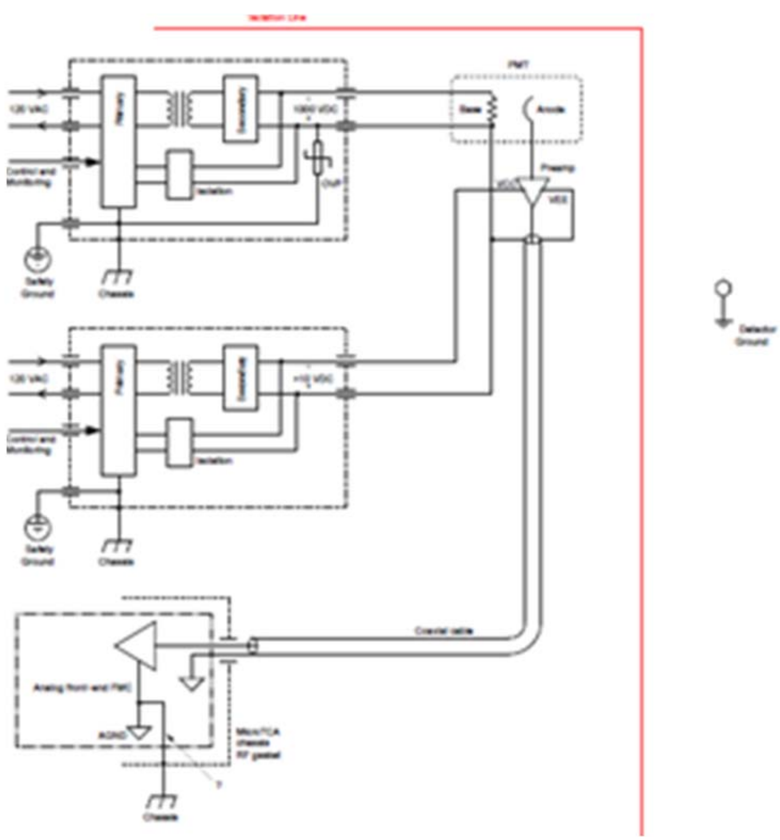

Figure 4.4.2. Block diagram of the grounding scheme for the front-end electronics of the Trigger Counters and Range Stack Counters.

The front-end instrumentation for reading out pixel planes resides on Pixel Modules, and consists of FE-I4B readout chips bump bonded to silicon sensors. The readout chip operates from a 1.8/1.2 volt supply with all communication implemented using differential Current Mode Logic (CML) signals. The total current drawn by each sensor module, which consists of two FE-I4B readout chips, is less than 1 A. There are a total of 16 modules in the pixel telescope upstream of the bending dipole and 24 modules downstream of the dipole. A block diagram of the pixel system is shown in Figure 4.4.3.

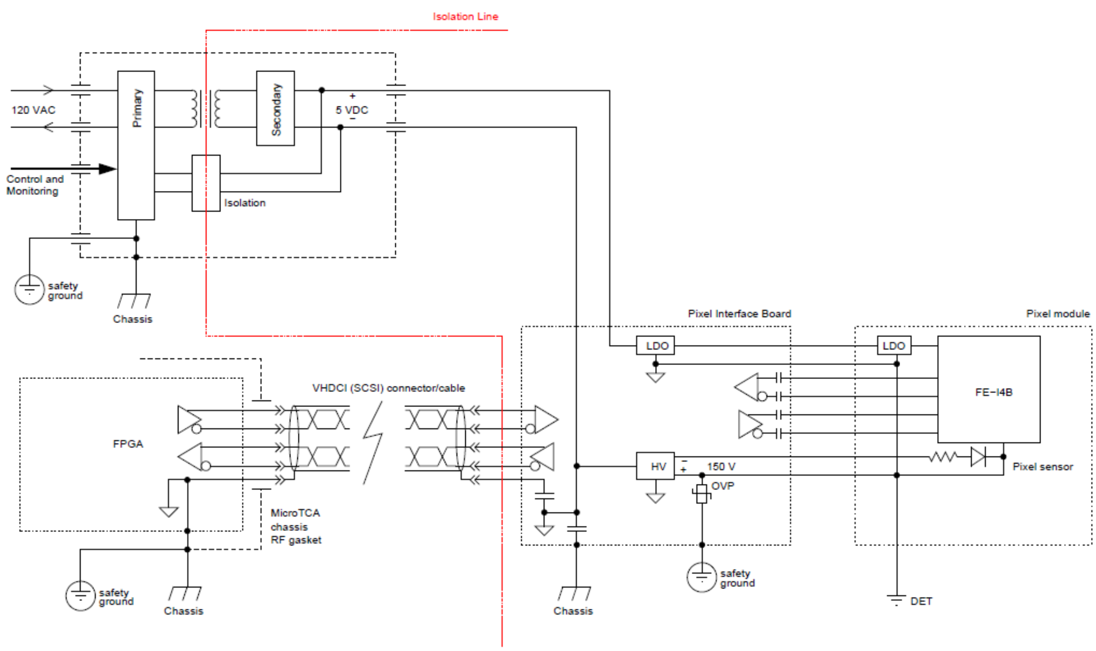

Figure 4.4.3. Block diagram of the grounding scheme for the front-end electronics of the Pixel Planes.

The commons for the pixel sensors and readout chips will be connected to Detector Ground. Aluminum cooling tubes will be located in close proximity to the pixel modules and will be electrically isolated from the rest of the cooling system to prevent capacitive coupling of noise via the TPG sheet on which the sensors are mounted. The TPG sheet will be directly tied to the ground on the pixel modules which will be connected to the local detector ground.

Services for the Pixel Planes are provided by the Pixel Interface Board (PIB). The PIB receives regulated low voltage power (eg +3.3, +5 volts @ < 1 A and +2.5 V @ 25 A) from external low-voltage supplies, and provides further conditioning and regulation before the power is sent to the Pixel Planes. The system will have the capability to control and monitor the voltage and current on each Pixel Module, including current limiting.

The pixel detectors require a bias voltage of approximately -150 V. This is provided using small DC-DC converter modules (eg, PicoVolt) that reside on the PIBs. The converter modules will use the +5V as the input voltage. The HV output will be referenced to the local ground on the pixel module but will require overvoltage protection on the Pixel Interface Board. This will protect against the pixel module floating to an unsafe electrical potential in the event that the low voltage ground reference is broken. The pixel modules shall also implement overvoltage and reverse polarity protection.

The PIB also acts as the interface between the DAQ system and the front-end. Clock signals from the timing system will be received and fanned out to the electronics, including level translation between the DAQ system and the readout chips. The signals are provided using multi-conductor signal cable between the PIB and the back-end MicroTCA shelf. The PIB performs logic level translation between the pixel modules and the DAQ. The pixel DAQ is entirely digital. The signal processing is implemented using FPGAs that reside on ATCA Mezzanine Cards (AMCs) in a MicroTCA crate. The FPGAs communicate with the Pixel Interface Board via LVDS signals.

The differential logic translators will provide isolation between the differential signals from the FPGA and the differential CML signals that interface with the FE-I4B readout chips. It will be important to isolate any single-ended signals that interface to the FPGA so that no return current can flow in the ground reference for these signals. Otherwise, a fault in the return path to the bulk LV supply could result in large currents flowing in the conductors of the signal cable that interfaces with the FPGA. Prototypes have demonstrated that reliable, high-speed communication with the FE-I4B readout chips and a Virtex-5 FPGA can be achieved using capacitively coupled differential CML logic translators and unshielded twisted pair cable (Cat 5 Ethernet cable). This lowers the latency for sending triggers, because the transition from an idle pattern to the unique trigger pattern requires a few additional clock cycles, but this does not appear to present a fundamental limitation to the operation of the system. The capacitive coupling breaks any DC ground return path along signal cables between the pixel modules and the Pixel Interface Board. The DC path between grounds on the Pixel Interface Board and the FPGA in the MicroTCA crate will be broken by tying the shield of the VHDCI cable to the MicroTCA chassis ground and leaving the end attached to the Pixel Interface Board floating, or by optionally providing an AC return path via a capacitor.

The common on the Pixel Interface Board will be decoupled using capacitors from the chassis, which is connected to the Safety Ground. Power and data signals are distributed to the pixel sensors/readout chips from PIB modules, which are all located in one rack. The intent is to ensure that all current flowing into the pixel plane is returned to the same PIB module. The electrical ground on the Pixel Planes will be tied to the quiet detector ground. Aluminum cooling tubes will be located in close proximity to the pixel modules and need to be electrically isolated from the rest of the cooling system to prevent capacitive coupling of noise via the TPG sheet on which the sensors are mounted. The TPG sheet will not be directly tied to the ground on the pixel modules but can be connected to either the local detector ground or safety ground via the mechanical support structures.

4.5. The Muon Stopping Target Monitor

The design of the grounding system for the MSTM will be developed once the choice of signal and detector and the details of the detector geometry and design have been established.

As a result of the downstream location of the Muon Stopping Target Monitor, the implementation of the grounding of this subsystem will likely be relatively independent of the majority of the detector systems. In addition, the residual magnetic fields in the vicinity of this detector will be small (<10 gauss). Consequently, low voltage and high voltage power supplies could potentially be located in the vicinity of the photon detector(s) near the east end of the detector floor. The expectation is that any clock and sync signals would be distributed via optical fibers, and digitized output will also be routed to the DAQ via optical fiber. The intent is to integrate any required slow controls into the experiment scheme. Any necessary process controls will be integrated into the process control scheme for the solenoids and the muon beam line. Provisions have been made for the Muon Stopping Target Monitor to utilize a Detector Ground reference that is separate from the others in the experiment, in an attempt to reduce the length of the cable run. The building plan for this Detector ground is illustrated in Figure 4.5.1. As with the other detector grounds in the experiment, there will be a connection to Safety Ground at the point of penetration through the wall.

A significant constraint on the Muon Stopping Target Monitor subsystem implementation is that any equipment located between the end of the Detector Solenoid up to near the east wall of the detector floor will need to be designed to be removed each time the detector train needs to be accessed since extraction of the detector train utilizes almost all the space between the end of the detector train and the east wall. As a result, it is possible that beam pipe, sweeping magnets, and perhaps other Muon Stopping Target Monitor related infrastructure might need to be designed for rapid and reliable removal and replacement.

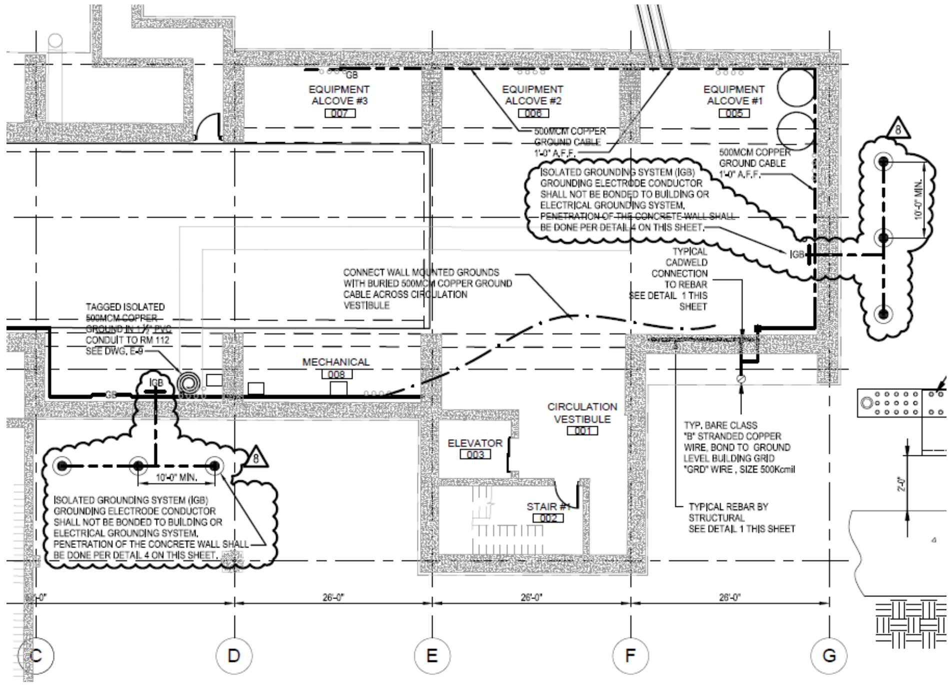

Figure 4.5.1. Excerpt from conventional construction drawing E-8 from project 6-10-2 showing a penetration in the east wall providing an isolated ground reference for use of the Muon Stopping Target Monitor system.

4.6. The Solenoids

The design of the grounding system for the solenoids is shown in Figure 4.6.1. Generally, the solenoid system is referenced to Safety Ground, although there are certain aspects of the control and monitoring system that interact with the grounding of the rest of the experiment.

The magnet power supplies are powered from power supplies with floating outputs, although there is a "soft" connection to Safety Ground as part of the fault detection circuit that will be described. All metal parts of the magnet support and cryostat will be connected to a Safety Ground through steel pads in the floor to which the supports are welded. The solenoid power supplies will be powered from a transformer that is shared with the accelerator systems and separate from the rest of the Mu2e experiment. The connection to the Safety Ground for this system will be provided by a panel in the solenoid equipment room. The Safety Ground of the Quench Detection and Slow Monitoring racks are connected with a minimum AWG 8 wire. Each crate inside the racks is also connected to Safety Ground via the grounding pins of the power cords. Shields of the sensor cables will be connected on one side only to the Detector Ground. The internal commons of the modules and crates will be referenced to the Detector Ground. To avoid grounding loops the solenoids voltage taps signals are isolated at the instrumentation inputs. In case of a single ground fault the quench voltage tap current is limited to approximately 1A by current limiting resistors and by the symmetrical grounding resistors at the power supply. If the Detector Ground resistance is much below 1 Ohm the voltage drop on the QPM Detector Grounding subnetwork will be small and not dangerous to people or equipment. In case of a quench without a ground fault, small currents are present due to capacitive coupling, which are usually negligible.

Each of the QPM systems has unique grounding and shielding requirements. These are described in the following sections.

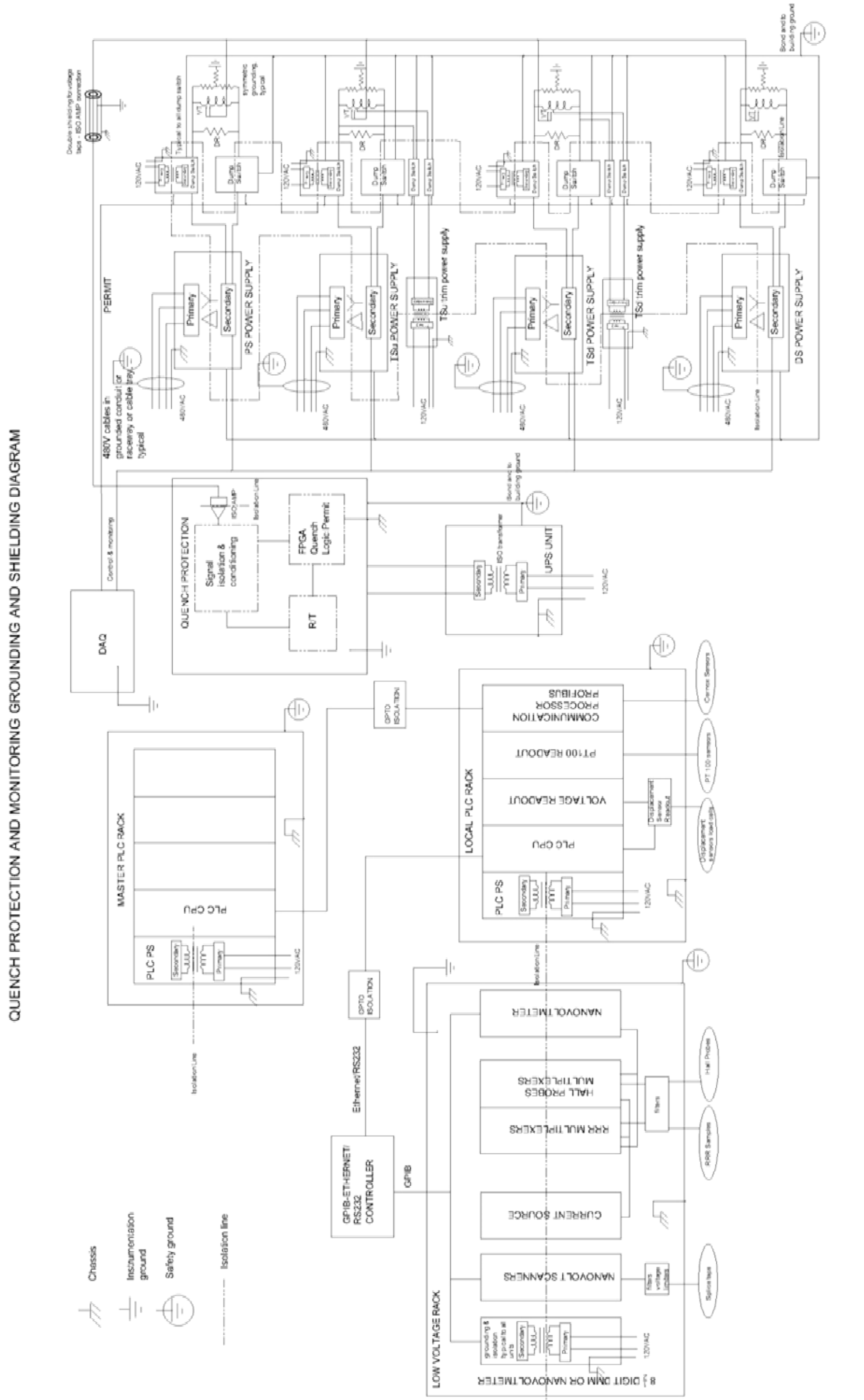

Figure 4.6.1 Block diagram of solenoid PS and QPM systems

4.6.1. *The QPM Quench Detection System*

The quench detection system monitors voltages of the magnets, bus, and leads, which are powered by the four power supply systems, and communicates with the power system to remove current from the magnet circuit when a quench is detected. Inputs to the quench detection system are from wires that are connected to the live coil/bus, which can reach 600V during a quench event. The quench system also provides hardwired quench status input signals to the power systems for the ramp down and dump control logic.

The grounding plan for the quench detection system is shown in Fig. 4.6.2. All quench protection relay racks and cable trays will be grounded via Safety Ground. The chassis of all equipment powered from HV (>50V) will be connected to Safety Ground.

The voltage tap wires from the magnet coils, leads, and bus will be routed such that the loop area formed by wire pairs is minimized and parallel to the magnetic field. For instance, the two wires that form the whole coil segment will be routed parallel to the magnetic field to minimize the magnetic loop area formed by the coil and the two wires and magnetic flux through this area. The voltage tap wires are then twisted from the point they are brought together and routed out of the magnet. Once these twisted wires are brought out of the magnet they will be double-shielded and routed to the quench protection relay racks. The inner shields will be connected to the Detector Ground on the receiving end, and the outer (overall) shield will be connected to Safety Ground at the magnet, at the connector shell of the feed through connector. All voltage taps will be isolated at the QPS relay racks.

All digital signals between the quench detection circuitry and power supplies will be isolated from ground using isolation techniques. The signal returns for the analog control signals and monitoring outputs will be isolated from ground. Input signals are received differentially and processed. Some of the outputs are single-ended at the source, but are floating with respect to local grounds at the solenoid.

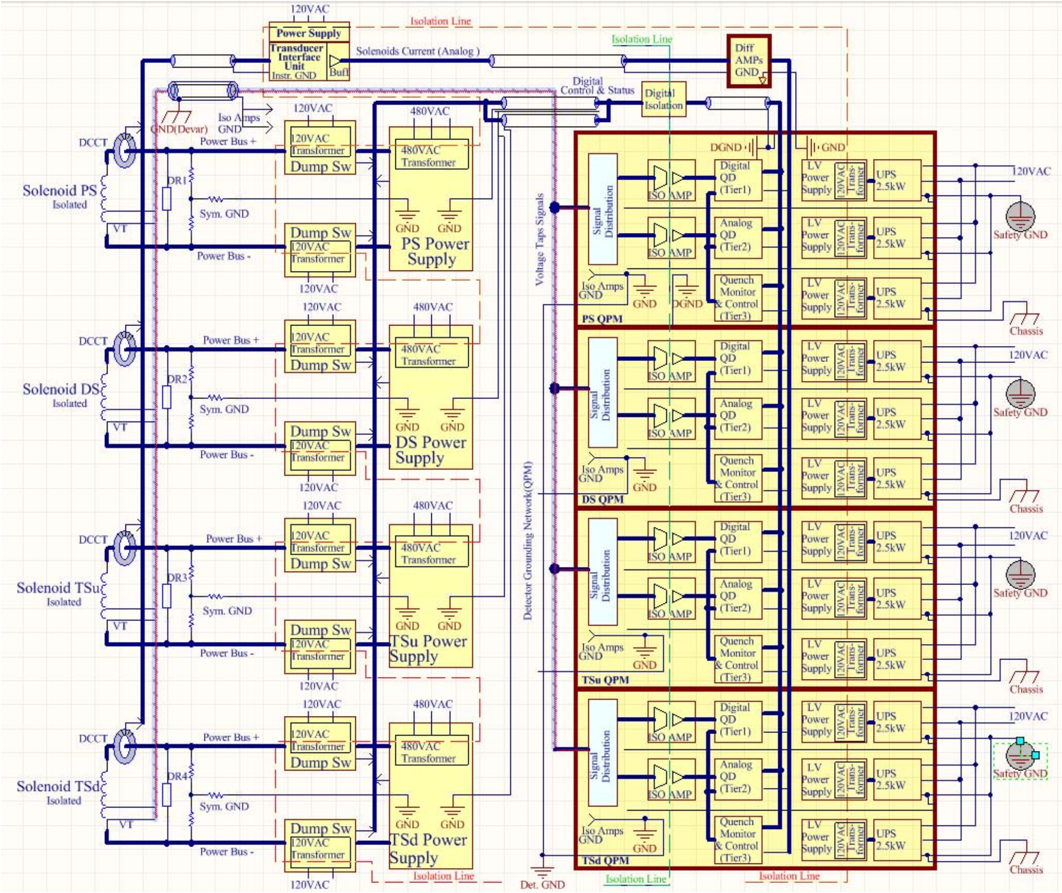

Figure 4.6.2. Quench Detection grounding and shielding diagram

4.6.2. *The QPM Slow Logging System*

The slow logging system must make precision measurements of the magnet instrumentation. The grounding plan for the slow logging system is shown in Fig. 4.6.3. Most of this instrumentation, such as the strain gauges and temperature sensors, are isolated from ground and are received off the solenoid using isolation amplifiers. The signal returns for the analog monitoring outputs will also be isolated from ground. Most measurements are very low level signals so proper shielding and routing of signal wires is important. Double-shielded cables will be used with the inner shields connected to the Detector Ground and the outer shield connected to the Safety Ground via the feedthrough connector shell.

The coil conductor splice measurements require connecting wires to each side of the coil splice. These wires will follow the same wire routing practice as the quench voltage tap wires. They are received by a Keithley voltmeter and have limiting protection. During a quench, overload currents are shunted to Safety Ground using limiting circuits. Both the RRR and splice resistance measurements are in the nano-ohm range, so precautions must be taken to preserve the necessary signal to noise. Special care must be taken to shield EMI between high power machines and the splice resistance / RRR measurement cabling so magnetic and electric shielding will be necessary. Double-shielded cables will be used where the inner shields are connected to Detector Ground and the outer shield is connected to the Safety Ground.

All slow monitoring relay racks will be grounded via a connection to Safety Ground. The chassis of all equipment powered from HV (>50V) will be connected to safety ground as well.

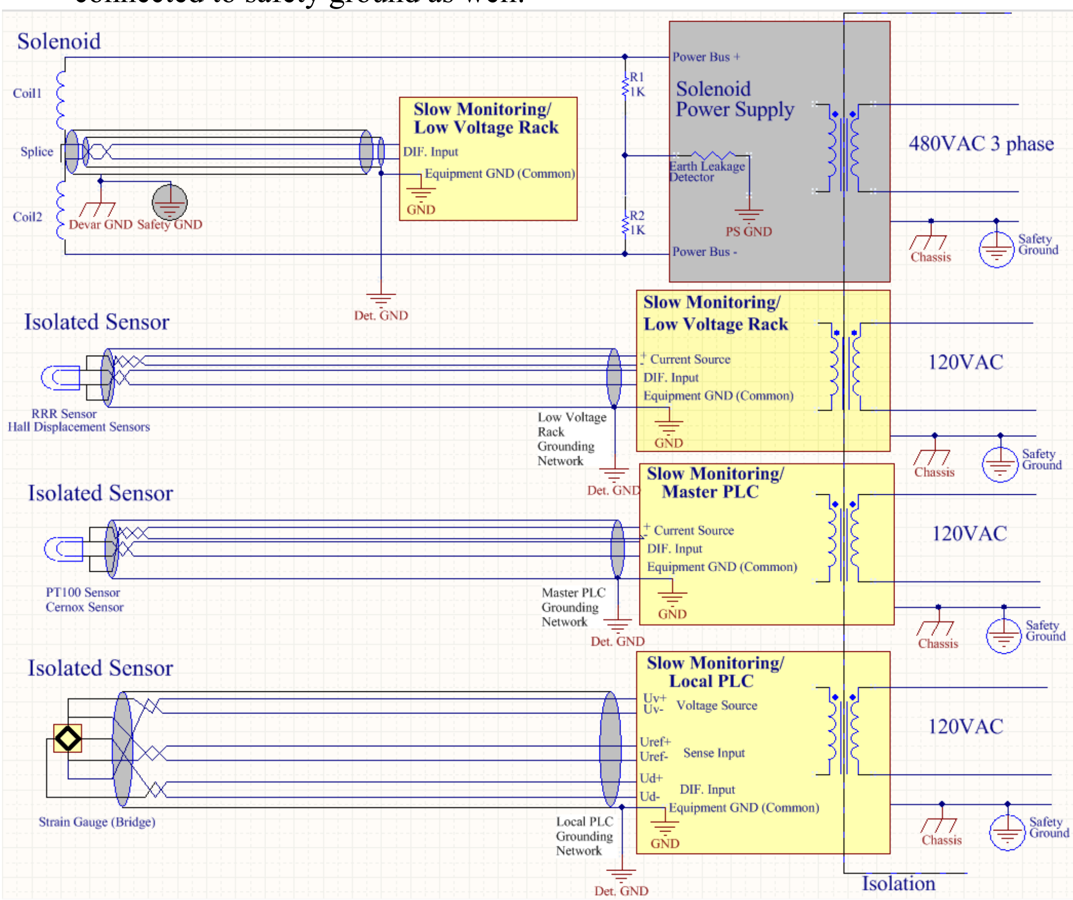

Figure 4.6.3. Grounding and shielding diagram for the Slow Monitoring System

4.6.3. *The Process Instrumentation and Controls System*

The process controls and instrumentation system monitors process variables from many components including: the main cryogenic distribution box, solenoid feedboxes, vacuum systems, and the magnets. It also controls the cryogenic processes of the magnets such as cool down and warm up.

All process sensors, heaters, valve controllers, etc. are monitored and controlled by a PLC. All electrical equipment will be grounded to Safety Ground. All relay racks and cable trays will also be grounded via a Safety Ground. The chassis of all equipment powered from HV (>50V) will be connected to Safety Ground.

Twisted-shielded cables will be used for all low level sensor signals; such as temperature sensors, pressure transducers, and liquid level probes, etc. The shield wire in these twisted cables will be attached on PLC equipment (safety ground) side only, removing any physical connection to Detector Ground.

All process sensors, heaters, valves coils, are floating on the solenoid. Status monitoring of digital outputs and analog outputs are referenced to the instrumentation common on the receiving end. This instrumentation will not be connected to Detector Ground. Signal isolation may be optical, galvanic, differential, or isolated I/O modules on the receiving end.

4.6.4. *The Ground Fault Detection System*

The basic scheme used for the Ground Fault detection System is shown in Figure 4.6.4. The magnet coils are referenced to Safety Ground at one point using a voltage divider. The technique, referred to as ***Distributive Grounding***, incorporates balanced impedances to provide a ground reference point rather than a hard connection to ground. For the solenoid power supplies, the two terminals of the magnet system are connected together through two resistors that are much higher resistance than the magnet resistance. The center point of these resistors is then connected to Safety Ground. This defines the voltage at the magnet terminals to be half of the power supply output voltage. By monitoring the voltage across the resistor connected to ground, a non-zero value indicates that the circuit is imbalanced, which results when current is flowing out of the magnet circuit to ground.

The magnet and power supply systems will be operated using the Distributive Grounding technique. This provides a center tap ground referenced point with a source resistance low enough to swamp the leakage currents from normal voltage monitoring. The center tap then is used to detect ground current flowing using a load resistance connected to earth ground and by monitoring the voltage across this resistor current flowing out the system can be detected.

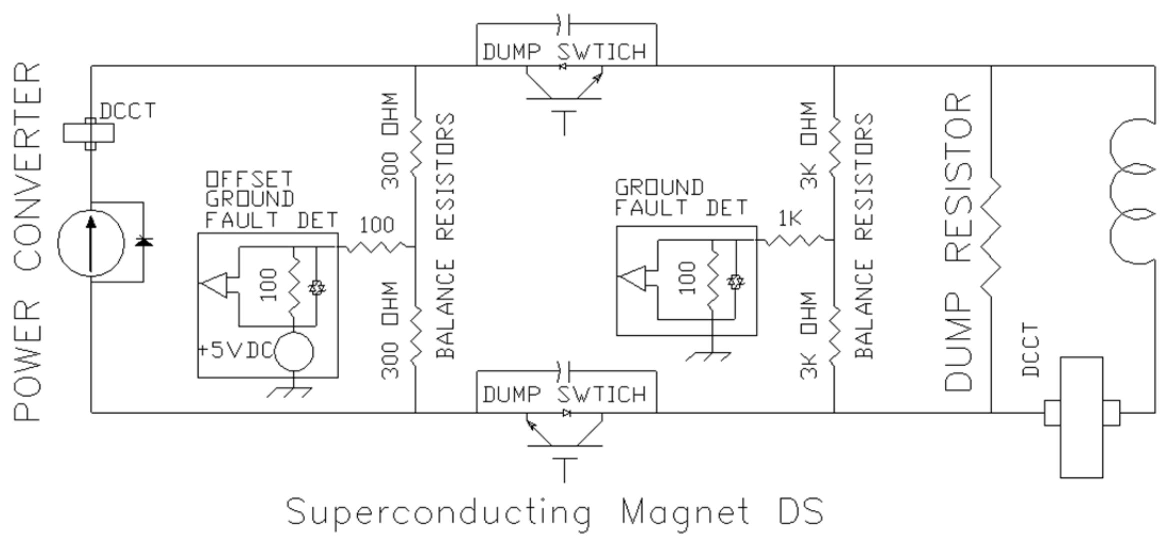

Figure 4.6.4. Ground Fault Detection Circuit

The power system is divided into three sections, power supply, dump switch and magnet load. The power supplies are 25 volts or less and the dump switch system is set to be a maximum of 600 volts. With the Distributive Grounding technique, the voltage will be half of the operating voltage to ground under normal operation. That means when the power supply is ON then the voltage to ground using a distributive grounding system will be 12.5 volts and during dumping the magnet voltage will be 300 volts. The offset detector will shift the voltage to +17.5 and -7.5 volts to ground, detail of the operation of this is shown below.

The dump switch will act as an isolator to separate the power supply from the magnet system when dumping. When the dump switch is on, then the power supply and magnet systems are one system. The low voltage power supply has an Offset Ground Fault Detector system. This allows the detection of a ground fault in the system before the magnets are ramped up, and more importantly, before the dump voltage is applied. If a ground fault exist in the power supply, it will be detected, which prevents the system from being energized. If a ground fault exists in the magnet system, it will not be detected until the dump switches are turned on. Normal response to ground faults during operation is to only bypass the power supply and not energize the dump switches unless a quench is detected.

The Offset Ground Fault Detector uses a control power supply to hold the system +5VDC from ground. This allows for detection of a ground fault internal to the power supply before system start-up. Typically the ground fault detectors are set below 10 mA, which corresponds to 1V on the detector resistor. The response to this detection is that the power supply will be either placed in Bypass or held in Bypass if a ground fault exists. When the dump switch is closed then the magnet system will also be connected to the offset detector and lifted 5 volts from ground. If a ground fault is detected, then the power supply Bypass will not allow current to be injected into the magnet.

A Passive Ground Fault Detector is connected to the magnet/load side of the dump switches. The dump switches disconnect the power supply from the magnet when the dump is energized. The Passive Ground Fault Detector senses whether there is a voltage imbalance on the load caused by ground current flowing out of the magnet system and back through the detector. This detector is also set to a 10 mA threshold, and is monitored by an independent system. A magnet system ground fault would need to be investigated if this ground fault is detected and prevents the system from turning on. The detection system as shown in Figure 4.6.4 will detect a shift in the average voltage of 40 volts during the dump. If ground current flows during a dump near the magnet voltage center within a range of +/-40 volts then a ground fault will not be detected.

4.7. The Trigger and Data Acquisition System

The design of the grounding system for the Trigger and Data Acquisition System (TDAQ) is shown in Figure 4.7.1 and Figure 4.7.2. In Figure 4.7.1 for data, timing, and slow control connections, the isolation is afforded by the optical connections shown in blue. In Figure 4.7.2 for power and ground connections, the isolation comes from the transformers.

All interfaces to external networking, on-detector electronics, near-detector slow control electronics, and accelerator synchronization signaling will be isolated using fiber optic connections.

The scope of TDAQ does not include on-detector electronics or the detector power supplies. TDAQ does not have any power supplies other than those contained in the servers and networking devices. These all run off 120V AC (208V 3-phase with PDUs to break out the individual phases). The TDAQ racks will be connected to Safety Ground. The power and ground plan is shown in Figure 4.7.2.

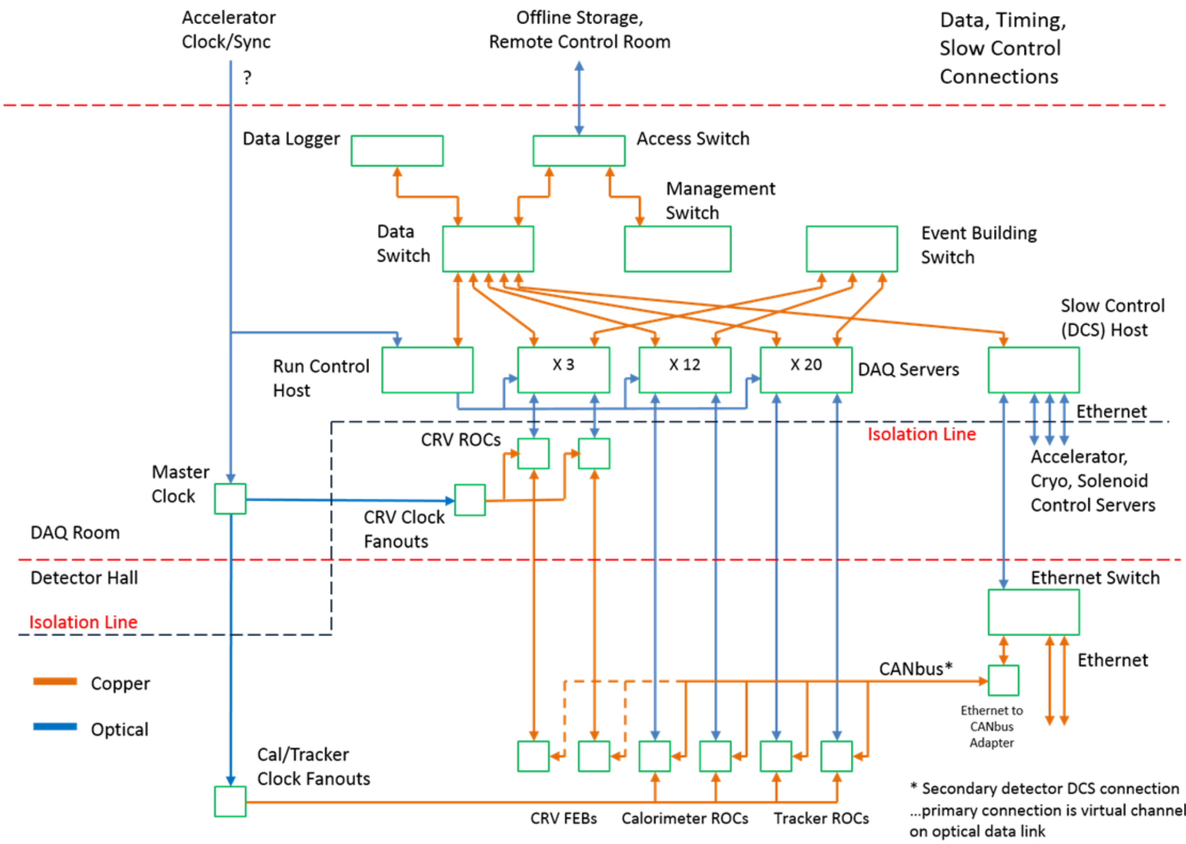

Figure 4.7.1. Block diagram for power and ground connections for TDAQ showing the isolation between detector ground and electronics room ground.

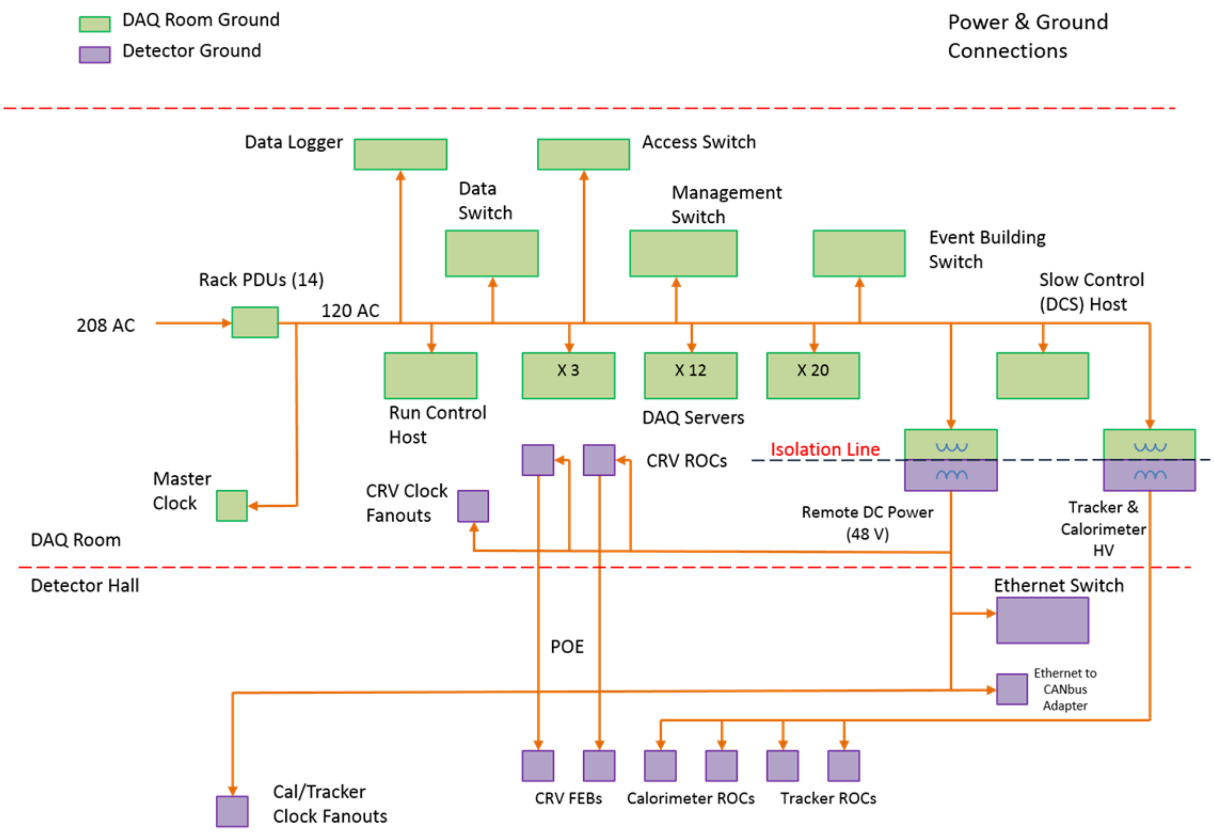

Figure 4.7.2. Block diagram for power and ground connections for TDAQ and Detectors showing the isolation between detector ground and electronics room ground.

4.8. The Detector Controls and Monitoring System

The design of the grounding system for the bulk of the Detector Controls and Monitoring System (DCS) is very simple. Almost all of the devices monitored and controlled are part of other systems, with the connections made through standard networking. All that is required is that the network connections respect the experiment grounding rules and ground isolation. The simplest way to accomplish this is to make all the network connections via optical fiber, with the possible exception of devices that are all contained within a single rack or similar metal enclosure in which all devices are on the same ground.

The rack monitor hardware will be based on the MicroBooNE design. The rack monitor will contain a single-board microcomputer running EPICS software under Linux. Currently, only temperature monitoring and monitoring of the rack status are envisioned, all contained within the same rack. The temperature probes are based on the MicroBooNE/MINERvA design, and have no exposed metal. The rack protection system connection is via a RG-58 cable with BNC connectors. A terminal lug is provided to ground the frame of the rack monitoring box to the rack.

4.9. Facilities and Infrastructure

The construction drawing showing the main power distribution is shown in Figure 4.9.1. The main entry point is in the lower left corner of the drawing, which is the location of the two 13.8 KV – 480Y/277 VAC transformers.

The construction drawing showing the location of the exterior Safety Ground network is shown in Figure 4.9.2. The ground rods depicted as large black dots with an outer concentric circle. They are 1” x 10’ copper clad rods, spaced ~50’ apart. The rods are connected together using 500 MCM (approximately 1” diameter) bare stranded copper wires, which is bonded to the rods using Cadweld (thermal welding). The bonds are approximately 18” below grade. These connections form a loop around the facility. Branch connections to this network are brought to the interior to the facility as shown, again using 500 MCM cables, to provide bonding points for connections to Safety Ground inside the facility.

The Detector Ground network has two parts. These are shown in Figure 4.9.3. There is one network for the Stopping Target, and another for the rest of the detector, out the south end of the building. A picture of the exterior Detector Ground network is shown in Figure 4.9.4. Each consists of three 1” copper clad bars spaced 10’ apart, and connected together using Cadweld with 500 MCM copper braid. Note also in Figure 4.9.3 the ground connections for the steel plates that reside under the solenoid, and the specification of the ground bus bars that will be located at various points in the facility.

The full set of construction drawings can be found in [37].

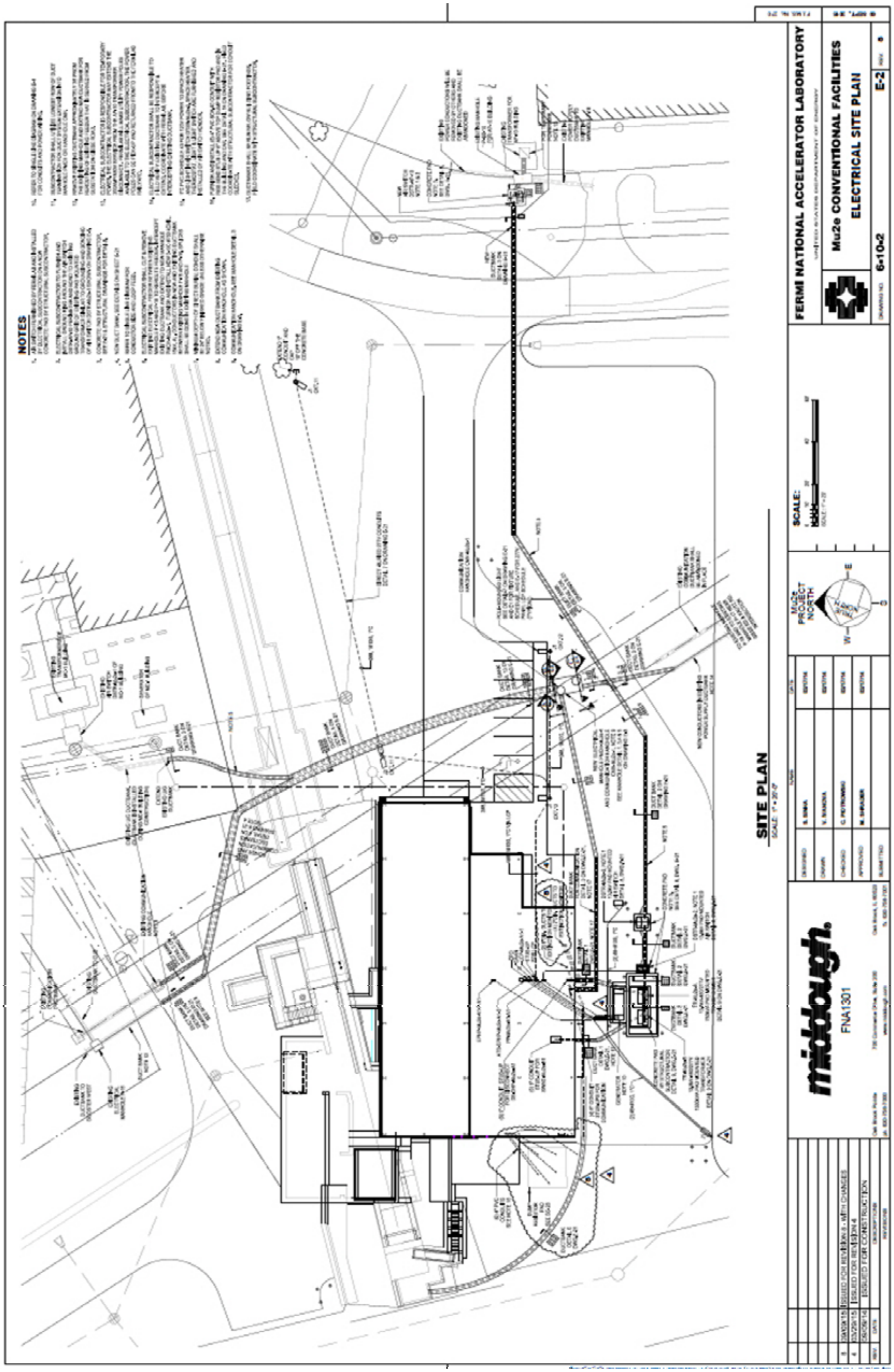

Figure 4.9.1. Construction drawing showing the site electrical plan..

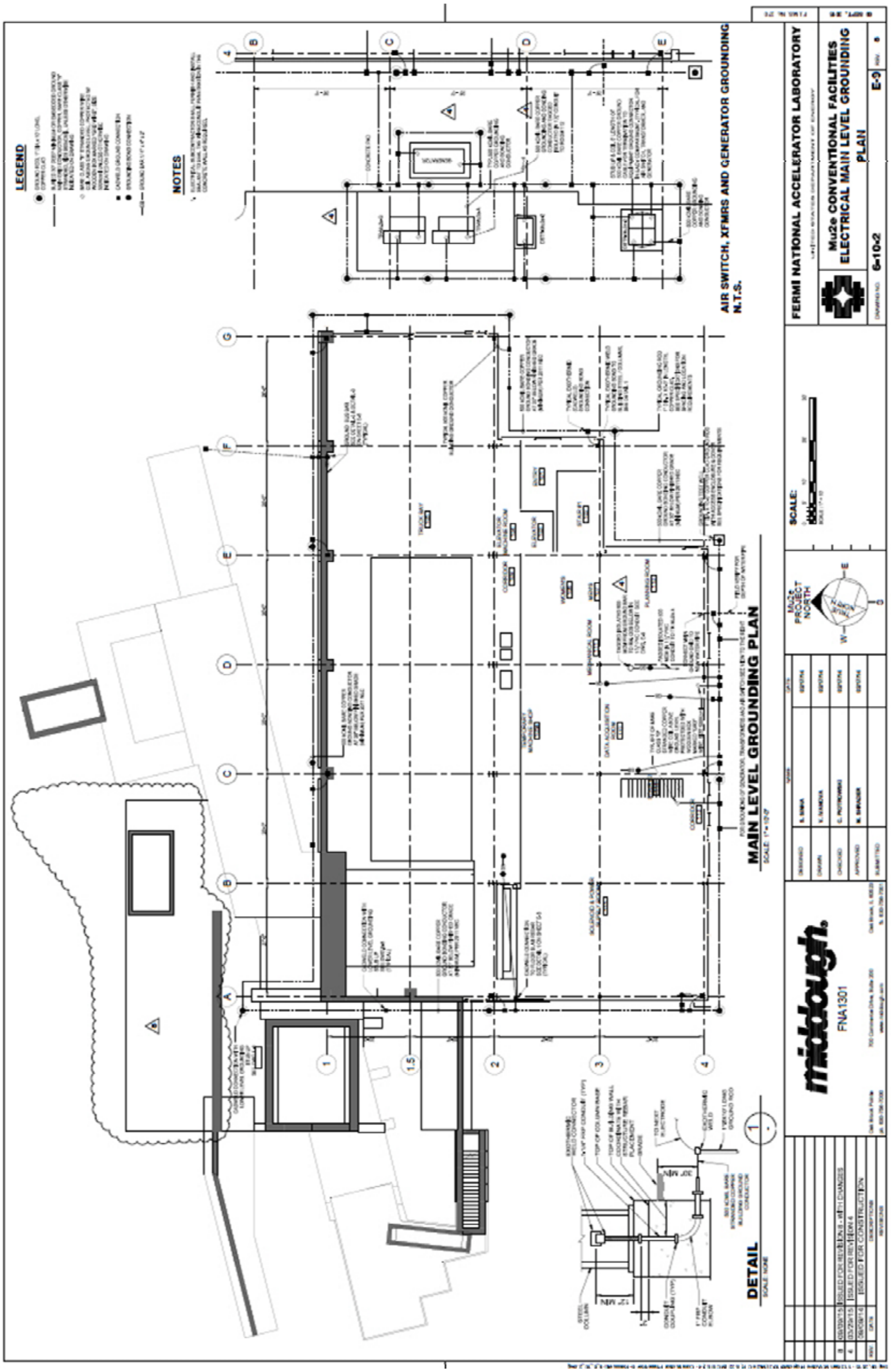

Figure 4.9.2. Construction drawing showing the Exterior safety Ground network.

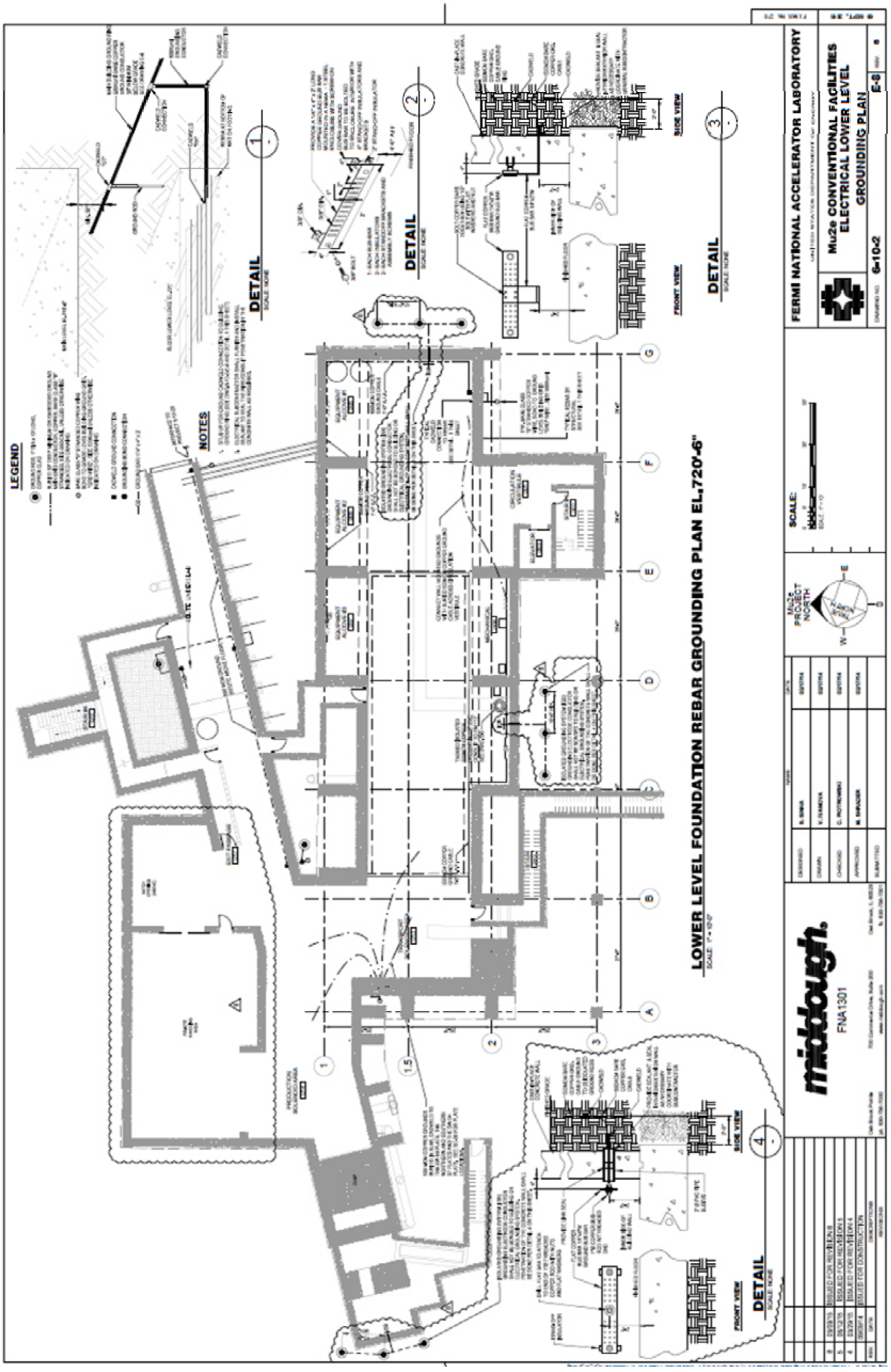

Figure 4.9.3. Construction drawing showing the Detector Ground network.

Figure 4.9.4. Implementation of one of the Detector Ground networks.

5. References

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[8] IEEE 1100-1992, p.25

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[10] IEEE 1100-1992, article 4.6, p. 59.

[11] NFPA 70, article 250.

[12] IEEE 1100-1992, article 4.5.2.2, p. 56.

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[15] IEEE 1100-1992, article 9.10.10, p. 150.

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